Urbanization influences on stream temperature behavior within low-discharge headwater streams

Joshua S. Rice¹, William P. Anderson, Jr.² and Christopher S. Thaxton³

¹ Environmental Science Program, College of Arts and Sciences, Appalachian State University, Boone, NC, 28608-2021, USA
² Department of Geology, Appalachian State University, Boone, NC, 28608-2067, USA
³ Department of Physics and Astronomy, Appalachian State University, Boone, NC, 28608-2106, USA

Abstract:

Urbanization has compromised water quality globally, especially stream temperature, by reducing shading and converting natural landscapes to impermeable surface coverage (ISC). We analyze stream-air temperature relationships in a low-order, moderate-gradient urban stream using three years of stream temperature data collected at nine monitoring sites. At the sub-catchment scale, ISC increases from 13.7% to 24.3% among sites, causing mean summer temperatures to increase 4–5°C or 0.37°C for each 1% increase in ISC. ISC at these spatial scales influences stream-air temperature relationships at daily-, weekly-, and monthly-averaged time scales. ISC at smaller spatial scales within a 25-m buffer of the stream, which ranges from 1% to 75%, does not correlate with mean stream temperatures at any temporal scale; however, buffer ISC does correlate with short-term temperature surge events, which we define as an increase of at least 1°C within 15 minutes. Mean surge amplitudes range from 1.90°C to 3.27°C in areas with low and high buffer ISC, respectively. Our results show that ISC influences stream temperatures at stream buffer and sub-catchment spatial scales and daily, weekly, and monthly temporal scales, and may render the concept of equilibrium temperature obsolete for predicting stream temperatures, especially in low-order, headwater streams.

KEYWORDS stream temperature; air temperature; equilibrium temperature; headwater; urbanization; impervious surface

INTRODUCTION

As global population continues to grow, the demands placed on water resources by the growing population will increase as well. The forecasted growth in world population is also expected to be increasingly centered in urban areas (Paul and Meyer, 2001). Population growth in conjunction with increasing migration into urban areas will only exacerbate the stress placed on available water resources and further compromise water quality. This makes the activities that will result from these trends and that will negatively impact water quality, such as urbanization, vital to explore and understand. The increasing area of urbanization makes it important to understand and be able to accurately predict the impacts of increasing urbanization on water quality, especially in a warming climate. Stream temperature, in particular, is an important aspect of water quality and has wide-ranging implications for overall stream health (Bogan et al., 2003; LeBlanc et al., 1997; Constantz, 1998; Nelson and Palmer, 2007). Stream temperature is also a measure of water quality, which previous work has shown to be subject to influence by urbanization (Klein, 1979; LeBlanc et al., 1997; Nelson and Palmer, 2007; Pluhowski, 1970).

Past work has shown that there is a strong correlation between stream temperature and air temperature. For example, models using air temperature as a predictor have been used to accurately forecast daily, weekly, and monthly stream temperatures with and without adjusting for time lag (Johnson, 1971; Crisp and Howson, 1982; Stefan and Preud’homme, 1993; Pilgrim et al., 1998; Erickson and Stefan, 1996). These models are particularly useful as they only require one input variable, air temperature (Mohseni and Stefan, 1999). The simplicity of these models makes them particularly attractive for studying the effects that a warming climate may have on stream temperatures (Mohseni and Stefan, 1999); however, the effects of urbanization may render stream-air temperature relationships obsolete. As a result, it becomes prudent to examine the impact that urbanization may have on stream temperature, particularly in low-order urban streams whose low thermal inertia makes them sensitive to changes in the surrounding environment.

While stream temperature is known to be influenced by many variables, several effects of urbanization play a large role and are readily quantifiable. Urbanization often results in an increase in impervious surfaces and reduced shading of land surfaces by vegetation (Herb et al., 2008). To examine the effect of these variables upon stream temperature, we use impervious surface coverage (ISC) as a general measure of urbanization within the study area catchment. ISC has been found to be a fairly accurate measure of urbanization and urban impacts on streams (McMahon and Cuffney, 2000; Schueller, 1994; Wang et al., 2003). Though previous work has shown that urbanization can influence stream temperature, there are relatively few studies in the literature that focus on long-term, in-stream temperature series in low-order urban streams. This is largely due to fact that maintaining temperature data loggers in such streams can be difficult as they have a tendency to get washed away, silted in, or buried (Nelson and Palmer, 2007). It is this lack of research focused specifically on low-order urban streams that provides the motivation for this study;
we aim to provide insight into the effects of increasing urbanization upon stream temperature behavior within low-order urban streams.

**METHODS**

**Site Description**

The study area (Figure 1) consists of a 1.8 km portion of Boone Creek, which flows through the Town of Boone, North Carolina, U.S.A., and the Appalachian State University campus. Boone Creek is a moderate-gradient urban stream that is influenced by high-gradient tributaries and is a tributary of the South Fork New River. The upper and lower reaches of the stream are separated by a 700 m culvert, effectively creating two streams within the study area (Anderson et al., 2010). While the majority of the study area experiences extensive urbanization, the upper segment has limited areas of riparian buffering and shading due to vegetation. In contrast, the lower section has no shading from riparian coverage and minimal vegetation that occurs in the form of non-native grasses as well as extensive artificial channelization and riprapping.

**Temperature Data**

Temperature time-series were collected between January 1, 2007 and October 1, 2010. Stream temperature measurements for this period were collected from 9 sites in the study area (Figure 1) at 15-minute intervals using HOBO Water Temp Pro v2 loggers. Hourly air temperature averages and precipitation data from the nearest weather station (BOON-ECONET, ~4.5 km away from the midpoint of the study area) were obtained from the NC State Climate Office (requested from http://www.nc-climate.ncsu.edu/ on various dates). Temperature data loggers were submerged in the stream and fixed in place along the stream bed in a manner that allowed them to float freely in the water column while avoiding the direct influence of solar radiation. Stream temperature means were calculated using programs written in MATLAB as the dataset was updated.

**Land Coverage Quantification**

Catchment boundaries of each study site were determined using the stock watershed delineation tools within the ArcHydro extension of ArcGIS v9.4 and a 3 m resolution, LIDAR-generated DEM obtained in 2008 covering the study area. The area of the Boone Creek drainage basin is 5.2 km². ISC was quantified by differentiating between impervious and pervious surfaces within each study sites’ catchment using stock tools found within ArcGIS and a 15 cm resolution true-color orthorectified aerial photo from 2009 covering the study area. ISC was measured both as a percentage within the catchment draining to each monitoring site as well as within a buffer area that extended 25 m from each side of the channel. The 25 m buffer areas were created using tools within ArcGIS and were measured as the upstream area between one site and the next upstream site. The buffer area of the furthest upstream site (site 1) was extended 100 m upstream from the site to the point where the main trunk of the stream splits into a number of smaller tributaries.

**ANALYSIS AND RESULTS**

Our analysis of approximately three years of stream and air temperature data along with quantitative measures of ISC within the study area demonstrates a significant relation between urbanization and stream temperature behavior at daily, weekly, and monthly time scales. Urbanization has an impact on stream temperature behavior at varying temporal scales and at the sub-catchment and 25 m buffer spatial scales. The relation between stream temperature and with increasing ISC is seen through (1) increases in average stream temperature; (2) short-term surges in stream temperature due to runoff that increases in amplitude as ISC increases; and (3) a downward trend in correlation of stream and air temperature as ISC increases. We expect these results based on previous work (Herb et al., 2008; Klein, 1979; LeBlanc et al., 1997; Nelson and Palmer, 2007; Pluhowski, 1970); however, unlike previous studies, the data of this study include a much higher level of spatial and temporal resolution and represent a headwater stream in an urban setting.

**Catchment Effects**

Many of the effects that urbanization has on stream temperature behavior can be seen in Figure 2, which plots stream versus air temperature for the site with the least urbanized catchment (site 1) and a site with one of the most heavily urbanized catchments (site 2). Figure 2 also shows a variable representing a fictional 1:1 stream and air temperature series for reference. The data represented by Figure 2 portray increasing variation in stream temperature, (2) short-term surges in stream temperature due to runoff that increases in amplitude as ISC increases; and (3) a downward trend in correlation of stream and air temperature as ISC increases. We expect these results based on previous work (Herb et al., 2008; Klein, 1979; LeBlanc et al., 1997; Nelson and Palmer, 2007; Pluhowski, 1970); however, unlike previous studies, the data of this study include a much higher level of spatial and temporal resolution and represent a headwater stream in an urban setting.
At the catchment scale, ISC increases from 13.7% to 24.3% within the study area. As urbanization increases from catchment to catchment, average temperatures steadily increase during summer and winter months. Summer averages at monitoring sites with heavily urbanized catchments are as much as 4–5°C higher than the least urbanized catchment. This increase in summer stream temperature occurs in the daily, weekly, and monthly stream temperature averages. Urbanization also influences stream temperature averages during winter months. Winter stream temperature averages in heavily urbanized sub-catchments were as much as 3–4°C higher than less urbanized catchments. Rising average stream temperature with increasing urbanization agrees with the findings of Galli (1990), who suggests a 0.09°C increase in temperature for each 1% increase in ISC. In Boone Creek, however, we find that average stream temperature rises by 0.37°C for each 1% increase in ISC. We suspect that the large rise is a result of the low thermal inertia of Boone Creek and the combined influence of long-term and short-term temporal effects of increasing urbanization within the study area. This trend also strongly influences correlation between stream and air temperatures, as shown in Figure 3, which compares the correlation of stream versus air temperature (represented by $R^2$) with percentage ISC within each catchment. In Figure 3 values for $R^2$ are derived from plots of stream versus air temperature, such as what is shown in Figure 2, for each monitoring site. As Figure 3 clearly shows, there is a steady downward trend in the correlation of stream and air temperature as ISC within catchments increases. Values of $R^2$ ranged from 0.70 to 0.42, 0.89 to 0.52, and from 0.89 to 0.52 at daily, weekly, and monthly time scales, respectively. The largest decrease in $R^2$ of stream and air temperature was seen at the weekly and monthly scales; $R^2$ decreased by 0.37 at both weekly and monthly scales. This, in addition to the increases seen in stream temperature averages, suggests that effects of urbanization within catchments have a more pronounced effect upon stream temperature behavior over long-term temporal scales rather than short-term.

Buffer Area Effects

ISC of the 25 m buffer areas was found to range from 1% to 75% for the study sites. A relation between stream temperature and increasing urbanization within these 25 m buffers was seen when comparing ISC and correlation of stream versus air temperature. As urbanization in the buffer area increases, correlation of air and stream temperature decreases, though the decrease is not as pronounced as what was observed at the catchment scale. This effect occurs at daily, weekly, and monthly temporal scales. A relation was not found between ISC in the buffer area and stream temperature averages. This is due to the low ISC within a 25 m buffer of each side of the channel in the downstream areas which, though vegetated, provide no shading and therefore have relatively low ISC but are still associated with increased stream temperature. The general lack of
stream shading in these areas despite the presence of landscaped, non-native vegetation within the buffer areas of these sections suggests that in an urban setting, riparian vegetation that provides little shading has negligible effect on moderating long-term stream temperature changes in low-order urban streams. This suggests the importance that shading has on stream temperature and agrees with earlier work on this subject (Beschta and Taylor, 1988; Brown, 1969; LeBlanc et al., 1997; Nelson and Palmer, 2007; Sinokrot and Stefan, 1993).

Over short-term temporal scales ISC in the 25 m buffer influences stream temperature primarily through increased amplitude of stream temperature surges from storm runoff, as Figure 4 illustrates. This agrees with previous findings, though the increase we see in Boone Creek is more drastic than previous studies (Anderson et al., 2007; Herb et al., 2008; Nelson and Palmer, 2007). During a portion of the monitoring period of this study (Spring and Summer 2010), 44 temperature surge events, which we define as a change of at least 1°C within 15 minutes of monitoring, occurred in Boone Creek. To avoid including cumulative effects of the downstream transport of thermal energy, temperature surge amplitudes were calculated for each monitoring site from simultaneous readings of the initial 15 minute temperature surge from each surge event. The surge events had amplitudes whose means ranged from 1.90°C to 3.27°C. The mean temperature surge duration of these events was above three hours, which is comparable to the findings of Nelson and Palmer (2007), and the maximum surge duration exceeded ten hours. While these durations last less than one day, there were several instances in the dataset in which storms occurred on multiple consecutive days or multiple times in a single day, rendering their influence to slightly longer temporal scales. Figure 4 plots the mean amplitude of these surges for each site versus 25 m buffer ISC and shows a significant increase in mean temperature surge amplitude as ISC increases. As ISC within the 25 m buffer increases, mean temperature surge amplitude quickly responds and peaks at 3.27°C for the site whose upstream section has 75% ISC. The sharp increase of mean temperature surge amplitudes above 40% ISC is suggestive of a threshold response, though additional data needs to be collected to support this.

**DISCUSSION**

Previous studies have shown that with distance downstream, air and stream temperatures trend towards equilibrium (Mohseni and Stefan, 1999; Stefan and Preud’homme, 1993). Our results show that increasing urbanization within a watershed can cause this relationship to break down within low order, urban streams. Rising levels of ISC within a watershed relate to a downward trend in the correlation of stream versus air temperature which is seen at daily, weekly, and monthly time scales. The results of our analyses and previous work both suggest that this can be largely attributed to the effects of increased exposure to solar radiation as well as increased runoff from impervious surfaces (Beschta and Taylor, 1988; Brown, 1969; LeBlanc et al., 1997; Nelson and Palmer, 2007; Sinokrot and Stefan, 1993). Over short time scales (e.g., days to a week), the effects of runoff are more pronounced due to surges in stream temperature that occur during some storm events. Over longer periods (e.g., weeks to months), exposure to solar radiation due to the lack of shading is the dominant variable. Low-order urban streams are particularly susceptible to these influences due to their low thermal inertia. Analysis suggests that the cumulative influences of these short- and long-term variables within catchments as well as the immediate vicinity of a stream have a significant effect. Analysis also suggests that the impact of urbanization upon stream temperature within low-order urban streams can be seen at daily, weekly, and monthly temporal scales. Previous research suggests that similar results can be expected not only in other low-order streams, but also in larger discharge streams (Klein, 1979; LeBlanc et al., 1997; Nelson and Palmer, 2007; Pluhowski, 1970), though response times and the magnitude of the effects may be dampened as a result of higher thermal inertia. If urbanization, however, becomes increasingly widespread in the headwaters of larger streams, then the cumulative effects of urbanization may prove to be more significant than the dampening caused by the higher thermal inertia.

As world population and urban areas are both expected to expand in the future, it is likely that the impact of urbanization upon streams will also become more pronounced. Planning for urban effects may become more difficult because many existing models focus on, or at least heavily involve, the tendency of stream temperature to trend toward equilibrium with air temperature. The concept of equilibrium temperature is a relationship that appears to be negatively impacted by urbanization, and may become obsolete as a tool for predicting stream temperatures, especially in low-order, headwater streams. These issues highlight the need for careful urban planning that takes into account the need to protect urban waterways, not only from chemical pollution, but thermal pollution as well. It is our hope that this study demonstrates the need for focusing on the significant role that urbanization has on thermal water quality issues.

![Figure 4. ISC (%) within 25 m buffer area versus mean stream temperature surge amplitude.](image-url)
ACKNOWLEDGEMENTS

The authors would like to thank the University Research Council of Appalachian State University (ASU), the ASU Office of Student Research, and the ASU Department of Geology and Department of Physics and Astronomy for funding portions of this research. This manuscript also benefitted from comments by Chuanhui Gu and Roy C. Sidle.

REFERENCES


