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# Bank thermal storage as a sink of temperature surges in urbanized streams

William P. Anderson Jr.[a,*], Rachel E. Storniolo[b], Joshua S. Rice[c,1]

[a] Department of Geology, Appalachian State University, ASU Box 32067, Boone, NC 28608-2067, USA
[b] Department of Earth and Planetary Sciences, University of Tennessee, 306 EPS Building, 1412 Circle Dr., Knoxville, TN 37996-1410, USA
[c] Environmental Science Program, College of Arts and Sciences, Appalachian State University, Boone, NC 28608-2021, USA

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SUMMARY

A poorly-studied benefit of bank storage is the ability of the streambed to act as a thermal sink to streams influenced by urban runoff (e.g. bank thermal storage). Headwater streams, with their low thermal inertia, are particularly susceptible to thermal pollution. We utilize numerical modeling to quantify the amount of heat exchanged with the subsurface during temperature surges, which we define as greater than a 1 °C stream temperature increase in 15 min. We base our study on Boone Creek, a low-order stream in northwestern North Carolina with stream discharge and temperature data dating to March 2006. The catchment is heavily urbanized, and although the stream is of moderate gradient, it is fed by tributaries that lose up to 200 m/km. The combined effect of urbanization and steep gradient produces a flashy response: stream discharge averages 0.10 $m^3$/s, but may increase up to two orders of magnitude during storm events. These events also affect stream and streambed temperatures. Four summers of monitoring (2006–2008, 2010) indicate that 71 temperature surges occurred with a mean temperature increase of 2.39 °C and a maximum increase of 6.36 °C.

We model generic storm events based on typical Boone Creek storms and streambed hydrogeology with the U.S.G.S. finite-difference groundwater flow and heat transport code VS2DH. The one-dimensional model domain includes a diurnally-oscillating stream temperature and specified head at the upper boundary, a constant streambed temperature and head at the lower boundary, and gaining stream conditions. Reference storm simulations use a temperature increase of 3.66 °C and a stream stage increase of 0.66 m. Simulations show that at a depth of 4.5 cm, nearly half of the temperature-surge signal has dissipated and lag times are 30 min. By a depth of 9.5 cm, however, peak temperatures are only one-third of storm levels and lag times are 2 h. At depths beyond 49.5 cm, the perturbation is less than 0.1 °C and lags the storm event by more than 17.5 h. Storm influence extends to a depth of 2 m and persists for days. Sensitivity simulations suggest that hydraulic conductivity, sediment heat capacity, and thermal conductivity are the most sensitive model parameters. Calculations show that temperature-surge induced heat storage in the simulated streambed is 72% of the heat storage in the stream.



## 1. Introduction

The urbanization of watersheds, a process which involves the removal of riparian vegetation and the replacement of natural land cover with pavement, buildings, and urban infrastructure (e.g. stormwater systems), has long been described as a detriment to stream water quality, one component of which is stream temperature (Webb et al., 2008). Much of the literature on watershed urbanization describes long-term trends in water-quality degradation such as an increase in average stream temperatures due to urban infrastructure (Wang and Kanehl, 2003; Nelson and Palmer, 2007) and the lack of riparian vegetation (Moore et al., 2005; Nelson and Palmer, 2007), but also variations induced by climate change (Webb, 1996; Mohseni et al., 1999) and the decline in baseflow because of reduced infiltration (Wang et al., 2003). These factors affect stream habitats because of compromised water quality (Wang et al., 2003; Wang and Kanehl, 2003).

Several studies in the literature look at the direct effects of urbanization on stream temperatures. A study of the effects of urbanization on stream temperatures using a process-based thermal energy balance finds that the most important factors are shading from riparian vegetation, baseflow to the stream, and stream width (LeBlanc et al., 1997). There is a need for studies of low-order urban streams because we lack long-term datasets for this stream class, most notably due to the difficulty in maintaining monitoring sites in flashy streams (Nelson and Palmer, 2007). They address the

* Corresponding author. Present address: School of Geography, Earth and Environmental Sciences, University of Plymouth, Drake Circus, Plymouth, Devon PL4 8AA, United Kingdom. Tel.: +1 828 262 7540; fax: +1 828 262 6503.
E-mail address: andersonwp@appstate.edu (W.P. Anderson Jr.).
[1] Present address: North Carolina State University, Department of Forestry and Environmental Resources, 3120 Jordan Hall, Campus Box 8008, Raleigh, NC 27695-8008, USA.

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importance of this type of study because of the influence of heated runoff from the urban infrastructure, which they acknowledge will have a strong influence on stream temperature due to the small thermal inertia of low-order streams. Another study of the effects of the urban infrastructure on the thermal regime of streams finds that in addition to the factors of LeBlanc et al. (1997), urbanization is an important factor in habitat loss (Herb et al., 2008). Their study also utilizes a process-based model of thermal energy balance; however, they use it to model runoff temperatures during typical storm events. Their modeling results demonstrate that 34% of the studied precipitation events produce runoff temperatures greater than 20 °C, with maximum runoff temperatures approaching 33 °C. A study involving a process-based model of runoff from a paved surface tests the model using measured and modeled runoff temperatures from a small asphalt parking lot that exceed 34 °C (Janke et al., 2009). Another study of the mitigation effects of stormwater detention finds that while overall daily-average stream temperatures with pond storage increase slightly (0.03 °C) above unrestricted runoff conditions, the overall daily maximum stream temperature declines by 0.15 °C with detention (Herb et al., 2009).

Few studies in the literature describe the effects of urbanization on stream and streambed temperatures at short temporal scales. Rapid increases in stream temperature during storm events in urban landscapes, known as temperature surges, have detrimental effects on cold-water stream habitats (Wang et al., 2003; Wang and Kanehl, 2003; Quigley and Hinch, 2006). Nelson and Palmer (2007) classify temperature surges as a greater than 2 °C increase in stream temperature within 30 min, which was their stream temperature monitoring interval. Their data, collected in watersheds with a range of land coverage classifications in central Maryland, USA, suggest that relatively undisturbed monitoring locations such as agricultural sites do not experience temperature surges, whereas urbanized monitoring locations experience temperature surges up to 10% of the monitored days. Temperature surges at their urbanized monitoring locations averaged 3.7 °C with temperatures returning to normal diurnal oscillations within an average of 2.8 h.

Here, we study the temperature surge phenomenon with a process-based model of streambed heat transport in the context of groundwater–surface water interactions in a gaining stream. We use data collected over a four-year period (2006–2008, 2010) to guide a generic modeling study of storm influence on stream and streambed temperatures. The stream was not monitored in 2009. Lautz (2010) notes that groundwater–surface water interactions increase stream residence times, thereby initiating contact between groundwater and solutes, microbes, and reactive sediments. We extend this suggestion to the exchange of heat between water flowing into the alluvial aquifer during flood events and the streambed sediments. Thus, our goal is to assess the ability of the streambed to act as a thermal capacitor during temperature surge events. In other words, can process-based groundwater flow and heat transport models recreate the streambed temperatures that we have measured in the field? We provide our dataset as a contrast to the Nelson and Palmer (2007) study conditions: the stream upon which we base our study has a smaller mean annual discharge and a higher gradient, thus providing a study stream with a low thermal inertia and a high likelihood of temperature surge effects. In this paper we demonstrate that stream temperature surge effects, although relatively short in duration, cause elevated streambed temperatures at depth that lag in time. It is our hope that this paper will prompt further research into quantifying the amount of heat that a streambed may store in the aftermath of temperature surge events, and the effect that this storage may have on stream temperatures both during and after the storm event.

## 2. Site description

Boone Creek flows through the Town of Boone and the Appalachian State University campus in the Blue Ridge Mountains of northwestern North Carolina, USA (Fig. 1). Four previous studies of the stream have documented (1) estimates of runoff temperatures during storm events (Anderson et al., 2007a), (2) basic water quality conditions (Anderson et al., 2007b), (3) the influence of baseflow on stream temperatures (Anderson et al., 2010), and (4) the influence of urbanization on stream temperature variations along the stream (Rice et al., 2011). Within the relatively small catchment of the study site, which has an area of 5.2 km$^2$, total relief is approximately 480 m and tributary streams have gradients of greater than 20%; however, the overall gradient of the main stem of Boone Creek is a modest 2% (Anderson et al., 2010). The stream has a mean width of approximately 2.8 m and a mean depth of 20 cm in the vicinity of monitoring site MS-2 (Fig. 1), although this varies with changes in stream stage (Anderson et al., 2010). In general, the streambed sediments comprise sand and gravel with larger cobbles and boulders with occasional clay lenses.

A previous study of temperature surges in the catchment utilizing a thermal mixing model (Anderson et al., 2007a) suggests that runoff temperatures must exceed 30 °C in order to produce measurable changes in stream temperatures during surge events. This is comparable to the findings of both Herb et al. (2008) and Janke et al. (2009). Anderson et al. (2010) use a modeling study to demonstrate that baseflow to gaining streams of low thermal inertia exerts a strong control on stream temperatures. They also note that restoration of groundwater–stream interaction through the removal of long culverts may reduce stream temperatures. Rice et al. (2011) examine detailed stream temperature records along the length of Boone Creek, noting that the stream–air temperature relationship becomes less correlated with increasing urbanization.

Boone Creek is a headwater stream that has a relatively low mean annual discharge of less than 0.10 m$^3$/s (Anderson et al., 2010); however, during high-intensity precipitation events, especially those deriving from summer convective thunderstorms, stream discharge may increase by two orders of magnitude within 15 min (Anderson et al., 2007b). Moreover, during the summer months these convective storm events transfer heat stored in the urban infrastructure to runoff, prompting rapid increases in stream temperatures that range from just over 1 °C to greater than 6 °C. We define temperature surges for this study as an increase of greater than 1 °C within 15 min of monitoring. We use a smaller change in temperature over a shorter time interval to define temperature surges in Boone Creek than that of Nelson and Palmer (2007) to reflect our smaller sampling interval.

Rice et al. (2011) document the effects of urbanization on stream temperatures in Boone Creek with distance downstream. They describe an increase in urbanization within the watershed from 13.7% impervious surface coverage (ISC) in the headwater portion of the stream up to 24.3% at downstream points within a distance of less than 1.6 km. ISC within a 25 m buffer on either side of Boone Creek at locations along the study reach is up to 75%, while ISC at the upstream-most reach is just 1%. The area around the monitoring site has some riparian vegetation, as does much of the stream length upstream of the monitoring site (Anderson et al., 2010).

## 3. Methods and data

### 3.1. Data collection

We began monitoring stream temperatures in March 2006 with three monitoring stations (Anderson et al., 2007b), including site