

Variation of stream temperature among mesoscale habitats within stream reaches: southern Appalachians

S. Lynsey Long* and C. Rhett Jackson

Warnell School of Forestry and Natural Resources, The University of Georgia, Athens, GA 30602, USA

Abstract:

Stream mesoscale habitats have systematic topographic relationships to hyporheic flow patterns, which may create predictable temperature variation between mesoscale habitat types. We investigated whether systematic differences in temperature metrics occurred between mesoscale habitats within reaches of small streams tributary to the upper Little Tennessee River, southern Appalachians. Surface water temperature was recorded over three or four mid-summer days in four mesoscale habitat types: riffle, main riffle, pool and alcove in 44 stream segments (sites). Temperature metrics were calculated for each mesoscale habitat relative to the mean value of the metric over the stream: Δ maximum temperature, Δ average maximum temperature and Δ maximum daily variation and also for each site: standard deviation of the maximum temperature and average diurnal variation (ADV). Sites were categorized as fully or partially forested. Pool tailouts had statistically significantly lower Δ maximum temperature and Δ average maximum temperature than riffle tailouts in partially forested sites, although differences were small. This was the opposite of what was expected in the presence of hyporheic exchange, indicating hyporheic exchange is not a dominant driver of mesoscale habitat temperatures at these sites. Temperature differences between mesoscale habitat units were small and unlikely to have ecological significance. We also evaluated relationships between stream temperature and riparian condition, watershed % impervious surfaces, watershed % non-forested and elevation. ADV and standard deviation of the maximum temperature were significantly higher in partially forested sites, indicating that partially forested sites have greater temperature ranges and spatial variation of maximum temperatures. ADV decreased with elevation and increased with % impervious surfaces. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS hyporheic exchange; stream temperature; mesoscale habitat; pool; alcove; riffle

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INTRODUCTION

Stream water temperature is a measurement commonly addressed in standardized surface water quality sampling protocols and in stream research. Stream temperature directly influences the life history, metabolism and physiology of aquatic organisms that inhabit streams (Allan, 1995). Temporary changes in the natural thermal regime modify the physiology and behaviour of aquatic organisms, whereas permanent temperature changes decrease habitat suitability (Holby, 1988; Quinn *et al.*, 1997). However, most studies that use stream temperature as an indication of stream health do not specify where in the stream channel the temperature data were collected (e.g. Brown and Krygier, 1970; Swift and Messer, 1971; Ringler and Hall, 1975; Johnson and Jones, 2000; Danehy *et al.*, 2005). Typically, the reported temperature is either a single measurement taken in one location or an average value of several temperature measurements from several locations (e.g. Huryn and

Wallace, 1987; Newbold *et al.*, 1994; Isaak and Hubert, 2001). This suggests that there is no standard method for the placement of the temperature sensors within a stream channel, probably because it is assumed that temperature is well-mixed in streams. This lack of standardization could mean that some of the differences found between the streams in these studies may result not from an actual difference between the streams but from placing the temperature sensors in different locations within the stream channels.

Some spatial variations in stream water temperature are attributed to the influx of hyporheic flows into the stream (Ebersole *et al.*, 2003). The hyporheic zone encompasses down-valley subsurface flow located below and beside the channel in which surface waters and groundwater mix (White, 1993) and where heat is exchanged back and forth between the hyporheic flows and the sediment (Burkholder *et al.*, 2008). Arrigoni *et al.* (2008) evaluated the question whether hyporheic return flows are cooled, damped or lagged with respect to stream temperature, and showed that hyporheic flows could cool, warm, or not change stream temperatures depending on travel times and time of year. However, with respect to the summer daily maximum stream temperatures addressed in this study, areas of

*Correspondence to: S. Lynsey Long, Warnell School of Forestry and Natural Resources, The University of Georgia, Athens, GA 30602, USA
E-mail: lynsey73@gmail.com

hyporheic discharge would be cooled regardless. Hyporheic exchange is controlled by the local and the regional geomorphology of the channel (Brunke and Gonser, 1997; Burkholder *et al.*, 2008). Channel flow enters the channel bed where the longitudinal profile is convex, where permeability or depth of substrate increases in the downstream direction (Vaux, 1968) or where the pressure is high from flow forcing against the upstream face of a bed form (Savant *et al.*, 1987; White, 1990; Elliott and Brooks, 1997a; Elliott and Brooks, 1997b). Subsurface flow enters surface flow under the opposite conditions, where the longitudinal profile is concave, the permeability or depth of substrate decreases in the downstream direction (Vaux, 1968) or where pressure decreases at the trough of the bed (Savant *et al.*, 1987; White, 1990; Elliott and Brooks, 1997a; Elliott and Brooks, 1997b). For example, surface water downwells into the streambed at the convex head of riffles and ends of pools and re-enters the stream at the end of riffles and the head of pools where the streambed becomes concave (Vaux, 1968; Thibodeaux and Boyle, 1987; White *et al.*, 1987; Hendricks and White, 1991; Harvey and Bencala, 1993; White, 1993). In other words, the topography associated with mesoscale habitats of streams influence hyporheic flow.

The different flow and hyporheic patterns found between these mesoscale habitats have potential to create considerable differences in temperature (Burkholder *et al.*, 2008; White *et al.*, 1987; Hendricks and White, 1991; Evans and Petts, 1997). Infiltrating surface water is cooled as it flows through the subsurface by direct conduction (Burkholder *et al.*, 2008) with the substrate or by advective transfers with groundwater flowing into the bed or a combination of both and is returned to the surface flow over a relatively short distance (Ringle and Hall, 1975; Comer and Greney, 1977; Boulton *et al.*, 1997; Evans *et al.*, 1998). If there are consistent and significant temperature differences between mesoscale habitat types as a result of hyporheic exchange, then future researchers and managers need to be aware of these differences so that they can account for them.

The purpose of this study was to determine if there is a systematic difference in water temperature metrics between four mesoscale habitat types: pool tailouts, riffle tailouts, alcoves and the middle of the largest riffle in the segment as a result of hyporheic exchange. These habitat units respectively represent local channel high points, low points, poorly mixed areas and very well-mixed areas. On the basis of hyporheic flow models developed by Vaux (1968), Thibodeaux and Boyle (1987) and White *et al.* (1987), it was expected that the tailouts of riffles would have the coolest temperatures because of hyporheic upwelling, the middle of the main riffle, being the most mixed location, would be cooler than pools and alcoves and have the least diurnal variation, the tailouts of pools would

be warmer because of surface water downwelling and alcoves would have the warmest and most variable temperatures. Secondary objectives were to quantify the variability of water temperature between stream reaches with land use and riparian cover and to evaluate the relationship between stream temperature and environmental controls including elevation and impervious surfaces.

METHODS

Study sites

Stream temperature data were collected from eight named tributaries to the upper Little Tennessee River basin: Cowee, Darnell-Jerry, Nickajack, Ball, Jones, Caler-Dalton, Skeenah and Hickory Knoll Creeks (Figure 1) sampled during 8 weeks of the summer of 2009. Up to eight stream reaches within each watershed were chosen with the goal of representing variation from the headwaters to the outlet. Sites were chosen to represent as many stream sizes and watershed conditions as possible within the watershed, and sites above and below confluences were chosen where practical. Public access and/or landowner permission constrained the possible stream reaches. One watershed was sampled per week (Table I).

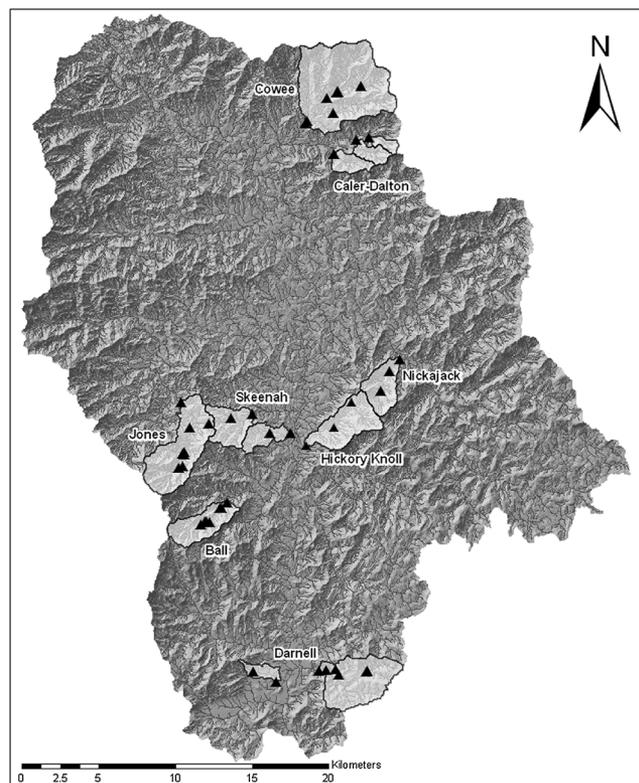


Figure 1. Map of the eight watersheds and their respective stream sites studied within the Upper Little Tennessee River Basin

Table I. Number of sites, sampling dates, elevation range, basin area range and % impervious surfaces range for each watershed

Watershed	# Sites	Sampling dates, summer 2009	Elevation range (m)	Basin area range (km ²)	% Impervious surfaces range
Cowee	8	June 9–12	632.5–801.3	0.16–28.49	0.00–0.03
Darnell-Jerry	8	June 16–19	658.7–930.9	0.04–13.40	0.00–1.85
Nickajack	3	June 23–26	708.7–711.1	1.53–6.06	0.21–0.36
Ball	7	June 30–July 6	673.0–853.7	0.10–7.16	0.00–0.47
Jones	8	July 14–17	763.5–896.7	0.22–15.32	0.00–0.52
Caler-Dalton	3	July 20–24	680.9–760.2	1.22–2.81	0.01–0.51
Skeenah	4	July 28–31	643.1–676.1	2.19–6.03	0.44–0.83
Hickory Knoll	3	August 12–24	627.9–31.5	0.15–9.56	0.18–0.47

Data collection

Elevation and Universal Transverse Mercator coordinates were recorded at each site using a Garmin Oregon® handheld GPS unit. Riparian conditions were described for each site including the type of vegetation and the width of the riparian buffer.

Stream temperature data were collected using HOBO® Temperature/Light Pendant Data Loggers (Onset Computer Corporation, Pocasset, MA), resolution: 0.14 °C at 25 °C. Each logger was zip-tied to a standard modular brick with dimensions 19.5 × 5.6 × 8.9 cm. This allowed each logger to be placed easily into its predetermined mesoscale habitat type while providing enough weight to keep the logger in the same stream position during high flow events. Typically, the logger was tucked into one of the holes of the brick, leaving it about 2.8–4.4 cm above the streambed depending on brick orientation. Often, the brick was placed between cobbles or boulders, and was thus tucked into the stream bed.

Each site had a total of ten temperature loggers placed within a 150 m reach. Mesoscale habitats were identified on the basis of the US Forest Service Stream Habitat Classification and Inventory Procedure (McCain *et al.*, 1990). Three loggers were placed in the tailouts of three separate pools, three loggers were placed in the middle of three separate alcoves, three loggers were placed at the ends of three separate riffles and one logger was placed in the middle of the main riffle defined in this study as the largest riffle in a given reach where the water is most mixed.

Each logger/brick apparatus had a unique name according to its designated site and mesoscale habitat type and each was labelled with permanent marker. In this way, it would be known where each brick should be placed in the stream while allowing the retriever to know whether high flows had moved a brick out of its designated spot during retrieval. Each logger recorded temperature at 15-min intervals and was deployed for a period of at least three complete days.

Because of differences in channel complexity and morphology, not all stream reach sites had well-defined mesoscale habitat types. When this was the case, as much hydraulic diversity as possible was captured by designating

the deeper and slower water as pools, the faster and well-mixed water as riffles and any water out of the main flow as alcoves. This was only necessary in the Darnell-Jerry watershed at site H and in the Skeenah watershed sites A, B and D.

There was partial loss of data from one site each of the Nickajack, Cowee and Darnell-Jerry watersheds because of vandalism. These data included one alcove, one riffle and two pool loggers from one site in each of these watersheds.

Error screening

To verify the quality of the data and check for potential sources of error caused by dewatering, we graphed all the data to visually inspect the time series for any abnormalities (Dunham *et al.*, 2005). Some data points displayed a sudden excessive increase in temperature relative to previous data points likely caused by logger dewatering. The loggers were considered dewatered if the temperature was suddenly extremely high, relative to the preceding or following points or if the pattern of the logger’s temperature graph was very

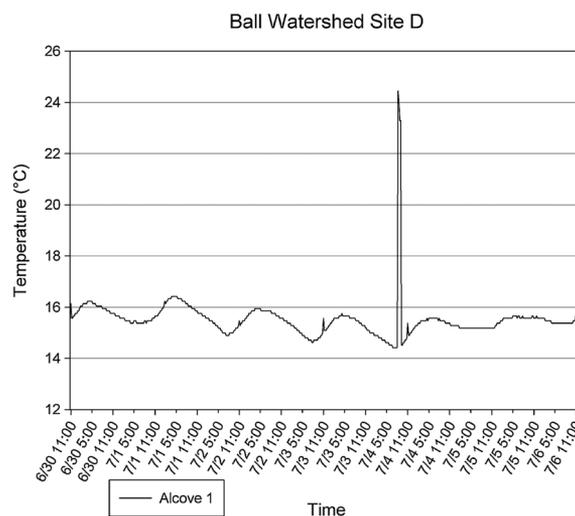


Figure 2. Example of a logger that was temporarily dewatered. Note the abnormally high temperature points relative to the preceding and following temperature points

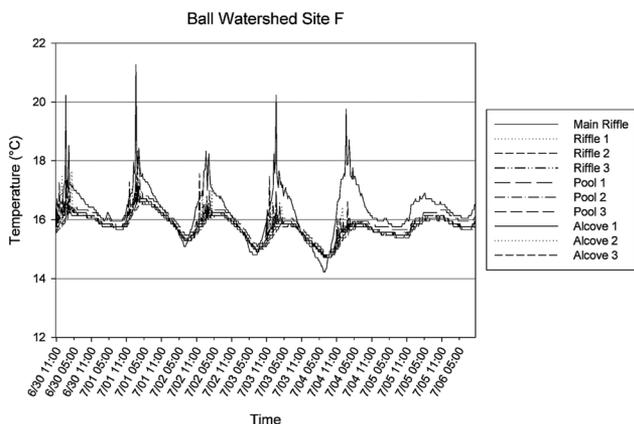


Figure 3. Example of a logger (Alcove 1) that was dewatered during the sampling period. Note the extreme temperature range and the irregular pattern

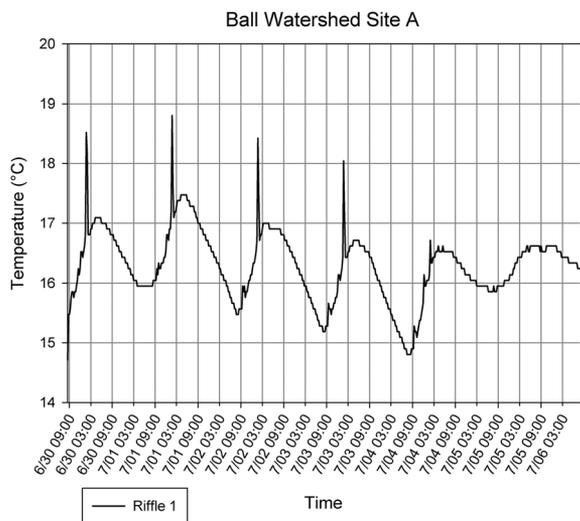


Figure 4. Example of temperature spikes caused by sunlight in Ball Watershed Site A riffle habitat

different than itself on other days or from other data loggers (e.g. Figure 2, Figure 3). These data points were removed from the dataset to prevent these abnormalities from falsely skewing the results. Some sites required only one or a few points to be removed, whereas others required whole days or data loggers to be removed. This was most common with alcoves, whose shallow flows make them most sensitive to decreases in flow and therefore most likely to be exposed to air during low flows.

After removing data points which resulted from dewatering there still existed smaller spikes in temperature that were not caused from dewatering but from direct sunlight. These occurred before or after and exceeded the actual daily maximum temperature, which typically occurred between 3 and 5 PM, and at approximately the same time during at least 2 days during the sampling period (Figure 4). These sunlight-created temperature spikes were identified and removed from the dataset because they

represented a process not affecting the other loggers and were not related to hypotheses of this study. In addition, all of the metrics calculated for analysis rely on the maxima, so it was important that the maxima were not skewed by solar insolation affecting only some loggers.

Environmental controls

The riparian condition data were used to assign a riparian code (0, 1, 2 or 3) to each site: 0 = occasional or no trees, 1 = <3-m buffer width, 2 = a 3–10-m buffer width or a one-sided buffer and 3 = full forest cover extending 10 m or more on both sides of the channel.

The watersheds were delineated for each site using ESRI’s ArcMap 9.2 mapping software and the basin area of each watershed was determined. Percent area of each watershed that was non-forested was obtained using the level I NLCD 2001 Land Cover Class definitions.

Percent impervious surfaces for the watershed of each site were calculated using the level II NLCD 2001 Land Cover Class definitions to achieve a higher resolution of % impervious surfaces. The Level II definitions for Developed Land contain four categories: Open Space (0–20% impervious surfaces), Low Intensity (20–49% impervious surfaces), Medium Intensity (50–79% impervious surfaces) and High Intensity (80–100% impervious surfaces). The median of the ranges of percent impervious surfaces were used to calculate percent impervious surfaces: 10% for Open Space, 35% for Low Intensity, 65% for Medium Intensity and 90% for High Intensity. The percent area that each site’s watershed had in each of the four classes was multiplied by the median percent of impervious surface. The four values were then added together to retrieve the total percent impervious surface for each site’s watershed.

Data analysis

There are several sources of variability in this study. Each watershed was sampled on different dates and each watershed and its sites have unique hydrology, land use, riparian cover and environmental controls. To account for these sources of variability, we used the deviations of each logger from the average of all the loggers in its site as the raw data.

Each logger’s maximum temperature (MT (logger)) for the total time the logger was in the stream was subtracted from the average of all ten logger’s MT for the total time the loggers were in the stream (MT (site)) to retrieve the deviation of each logger’s MT from the site average (Δ MT (logger)).

$$\Delta MT(\text{logger}) = MT(\text{logger}) - MT(\text{site})$$

The average of each day’s MT (i.e. average maximum temperature, AMT) for each data logger was calculated. This value was subtracted from the average of all ten data loggers

average daily maximum (AMT) in the site to retrieve the deviation of each logger from the AMT (Δ AMT).

$$\Delta\text{AMT}(\text{logger}) = \text{AMT}(\text{logger}) - \text{AMT}(\text{site})$$

The maximum daily variation (MDV) of temperature was calculated for each of the ten loggers by calculating the range of temperatures found within each 24-h period for each logger. The largest range was selected for each logger and called the MDV. Each logger's MDV was subtracted from the average of all ten logger's MDV (MDV(site)). This gave Δ MDV the deviation of each logger from the average MDV of the site.

$$\Delta\text{MDV}(\text{logger}) = \text{MDV}(\text{logger}) - \text{MDV}(\text{site})$$

The standard deviation of all ten logger's MT of all days (SD_{MT}) was calculated for each site to demonstrate diversity in maximum temperatures between loggers. The average diurnal variation of each site (ADV), used to demonstrate the range of diel temperatures, was calculated by taking the average of all ten logger's average diurnal variation.

Statistical analysis

It was known that fully forested sites would have less sunlight, whereas partially forested sites would have more sunlight and so temperature would behave differently between these two riparian conditions. Therefore, all 44 sites were divided into either fully forested (riparian code = 3) or partially forested (riparian code = 0, 1 or 2) to better discern temperature differences among mesoscale habitat units. Data were tested for normality with a Shapiro–Wilk test. All treatment groups failed normality except the main riffles in the fully forested Δ AMT and Δ MDV; however, all variances were equal between treatment groups. No transformations were apparent from histograms. A one-way analysis of variance (ANOVA) was performed to determine if a significant difference in temperature metrics occurred between mesoscale habitat types within fully forested sites and partially forested sites. A one-way ANOVA was performed because it is a robust procedure with respect to the assumptions of normality, and the validity of the test is only affected slightly by deviations from normality (Zar 1984; Dowdy *et al.*, 2004). Where a significant difference was found, the Tukey's Studentized Range (HSD) Test was used to determine where the difference occurred.

The SD_{MT} and ADV for each site were grouped into either fully forested (riparian code 3) or partially forested (riparian code 0, 1 and 2) sites to determine if there was a significant effect of riparian condition on SD_{MT} and ADV. The data were not normally distributed and

transformations did not normalize the distributions; also, the variances were not equal. The data were rank-transformed and analysed using the Wilcoxon rank-sum nonparametric test (Conover and Iman, 1981; Zar, 1984; Dowdy *et al.*, 2004).

The relationship between four environmental controls (% non-forested, % impervious surfaces, riparian code and elevation) and the SD_{MT} and ADV for each site was analysed. The data did not have bivariate normal distributions, and transformations did not improve the distributions. The data were rank-transformed, and the Spearman rank correlation test was performed (Conover and Iman, 1981; Zar, 1984; Dowdy *et al.*, 2004). In addition, the relationship of the four environmental controls to each other was analysed using a correlation matrix.

RESULTS

Water temperatures ranged from 13–18°C in fully forested sites and 14–26°C in partially forested sites. Peaks in daily water temperature typically occurred between 3 and 5 PM and minimum daily water temperature typically occurred between 7 and 8 AM. Most of the temperature variability between mesoscale habitat types in a site occurred at the maxima. The fully forested sites in each watershed are all located upstream of the partially forested sites in the same watershed, and as the sites move from upstream headwaters to downstream mid-order streams, the riparian code value decreased in all watersheds with the exception of Skeenah sites A and B.

An ANOVA analysis found no significant difference between the four habitat types in fully forested sites for Δ MT ($F_{.05,3,167} = 0.37$, $P = 0.7754$), Δ AMT ($F_{.05,3,167} = 0.35$, $P = 0.7894$) or Δ MDV ($F_{.05,3,167} = 1.32$, $P = 0.2708$) (Figure 5). In fully forested sites, the largest differences in the means of Δ MT, Δ AMT and Δ MDV between mesoscale habitat types were 0.04 °C, 0.03 °C and 0.09 °C, respectively (Figure 6).

For the partially forested sites, ANOVA analysis found a significant difference in Δ MT between habitat types ($F_{.05,3,240} = 4.81$, $P = 0.0028$) (Figure 5). Tukey's Studentized Range (HSD) Test was performed, which found a significant difference between pool and riffle tailout habitat, with pools having lower Δ MT, although differences in Δ MT were small. The difference in the means of Δ MT between pool and riffle tailout habitat was 0.28°C (Figure 6). ANOVA results also showed a significant difference between mesoscale habitats with Δ AMT in the partially forested sites ($F_{.05,3,240} = 3.32$, $P = 0.0205$) (Figure 5). A Tukey's test found a significant difference between pool and riffle tailout habitats with pool tailouts having lower Δ AMT. The difference in the means of Δ AMT between pool and riffle tailout habitat

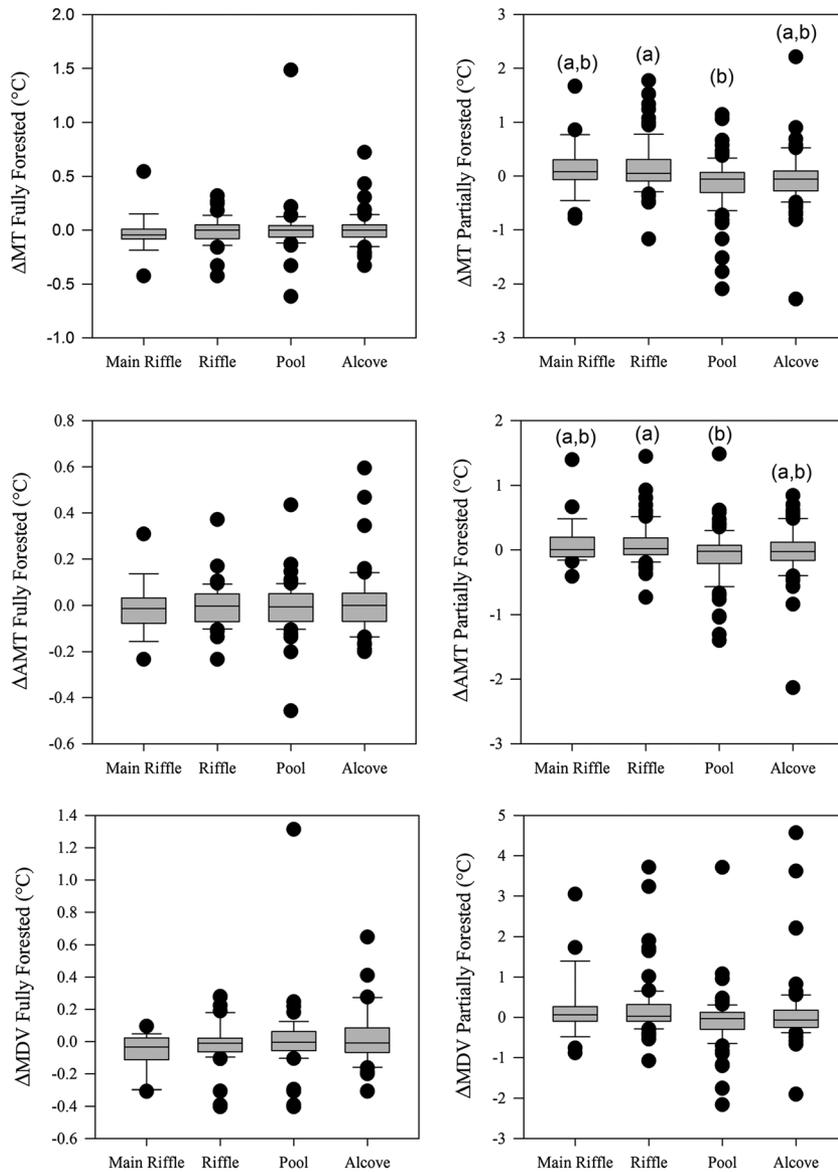


Figure 5. Boxplot of ΔMT , ΔAMT and ΔMDV versus habitat type for partially and fully forested sites. Boxes represent the 25th–75th percentile, the line marks the median, error bars indicate the 90th and 10th percentiles. Habitats with the same letter are not significantly different according to the results of the Tukey’s (HSD) test

was small, $0.17\text{ }^{\circ}\text{C}$ (Figure 6). ANOVA results did not show a significant difference between mesoscale habitat types with respect to ΔMDV in the partially forested sites ($F_{.05,3,240}=2.41$, $P=0.0675$) (Figure 5). In general, for the partially forested sites, pools had the lowest mean ΔMT , ΔAMT and ΔMDV values followed by alcoves then riffle tailouts and finally main riffle habitats with the highest mean ΔMT , ΔAMT and ΔMDV values (Figure 6).

The Wilcoxon rank-sum nonparametric test found a significant difference in SD_{MT} between fully forested and partially forested sites ($z=-3.2822$, $P=0.0005$). The fully forested sites had a lower mean rank (smaller SD_{MT})

than the partially forested sites (Figure 7). The Wilcoxon rank-sum nonparametric test also found a significant difference in ADV between the fully forested and partially forested sites ($z=-5.0486$, $P<0.0001$). The fully forested sites had a lower mean rank (smaller ADV) than the partially forested sites (Figure 7).

All watersheds and sites had extremely low percent impervious surfaces with only one site having above 1% impervious surfaces (Table I). The Spearman rank correlation found a significant relationship between SD_{MT} and % non-forested ($r_s=0.41157$, $P=0.0055$), and SD_{MT} and riparian code ($r_s=-0.5857$, $P<0.0001$). There was not a significant relationship between SD_{MT}

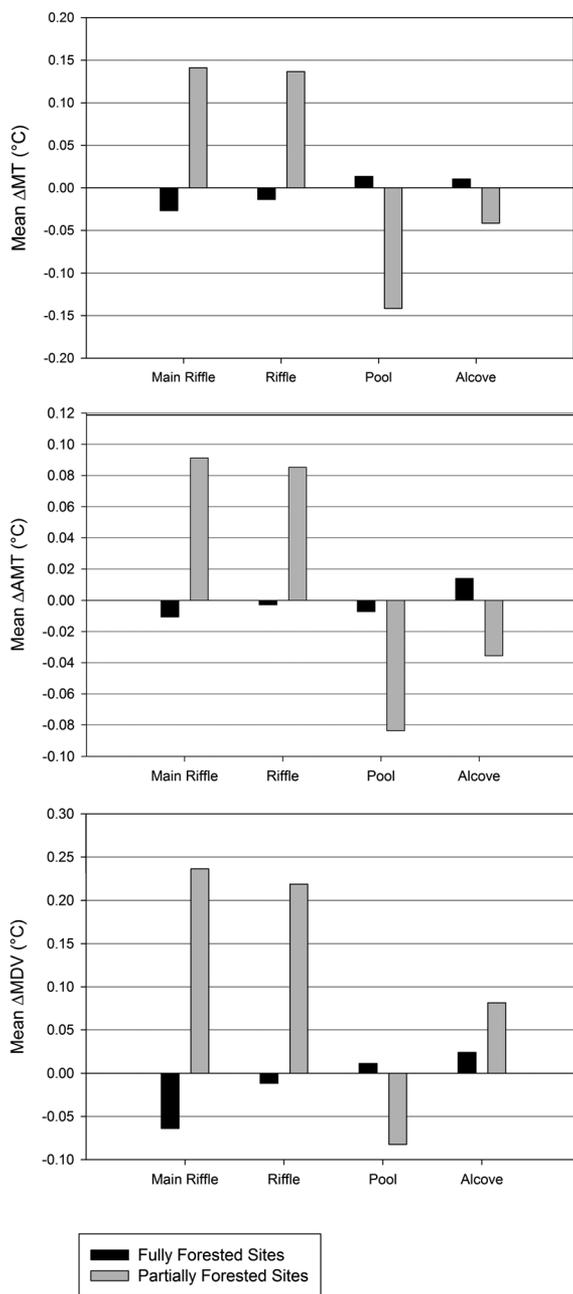


Figure 6. Mean ΔMT , ΔAMT and ΔMDV values for each mesoscale habitat for fully forested and partially forested sites

and elevation ($r_s = -0.27175$, $P = 0.0744$) or between SD_{MT} and % impervious surfaces ($r_s = 0.23459$, $P = 0.1253$) (Figure 8).

The Spearman test found a significant relationship between ADV and % non-forested ($r_s = 0.70185$, $P = 0.0001$), ADV and riparian code ($r_s = -0.77747$, $P = 0.0001$) ADV and elevation ($r_s = -0.71014$, $P < 0.0001$), and ADV and % impervious surfaces ($r_s = 0.61472$, $P < 0.0001$) (Figure 8). The four environmental factors were found to be correlated to each other in varying

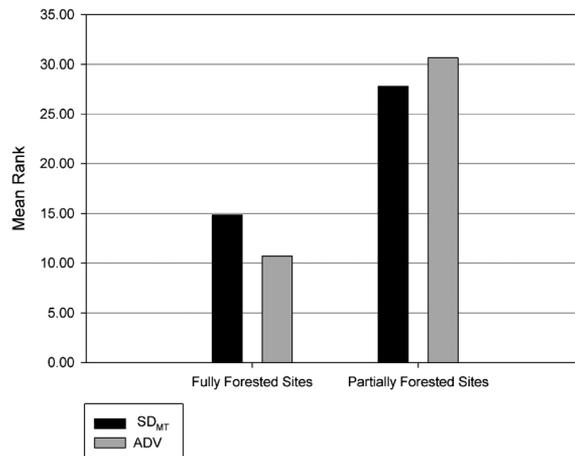


Figure 7. Mean Wilcoxon rank for SD_{MT} and ADV for fully and partially forested sites

degrees with elevation and riparian code having the strongest correlation (Table II).

DISCUSSION

The results of the statistical analyses disagree with the original hypothesis that the ends of riffles and the middle of the main riffle would exhibit cooler temperatures than pool tailouts and alcoves. Also, although there was a significant difference found in ΔMT and ΔAMT between pool tailouts and the ends of riffles in the partially forested sites, the actual difference in their values was not substantial (Figure 6). Because there was a significant difference found between these two mesoscale habitats but that the actual differences are very small and the opposite of what is expected if hyporheic exchange is occurring (e.g. White *et al.*, 1987; Hendricks and White, 1991; Evans and Petts, 1997), hyporheic exchange is not substantially affecting maximum summer temperatures among mesoscale habitat units in these streams. It is possible that the streamflow is so well mixed that hyporheic effects would have to be measured within the substrate. The reasons for the lack of hypothesized hyporheic effects on maximum temperatures at these sites cannot be extrapolated from the data collected in this study because it was beyond the scope of this study to collect the intensive data necessary to draw such conclusions. However, some possibilities will be discussed on the basis of literature from other studies.

In general, as is typical for the development in the southern Appalachian Mountains, there is more agricultural and urban development in the valleys leaving greater forest cover at higher elevations and less forest cover and greater impervious surfaces at lower elevations. Fully forested sites were consistently located upstream of the partially forested

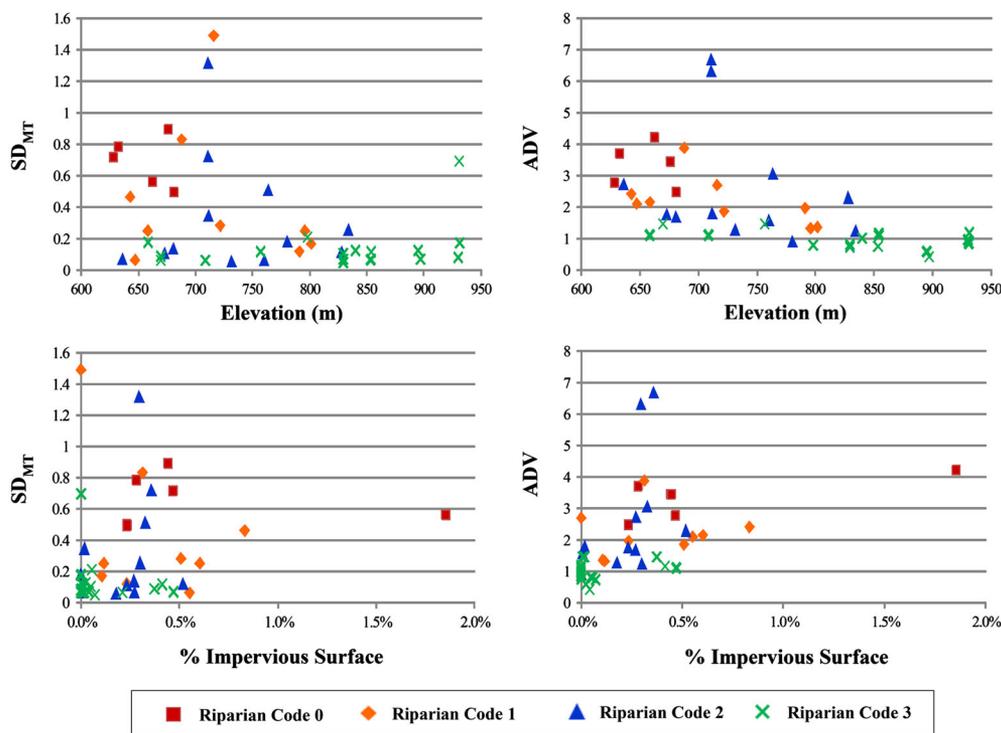


Figure 8. Scatter plot of SD_{MT} and ADV versus elevation and % impervious surfaces

Table II. Correlation matrix of the four environmental factors

	Riparian code	% Non-forested	Elevation (m)	% Impervious surfaces
Riparian code	1	—	—	—
% Non-forested	-0.47	1	—	—
Elevation (m)	0.61	-0.36	1	—
% Impervious surfaces	-0.54	0.58	-0.43	1

sites and, in general, as the sites in each watershed moved from upstream headwaters to downstream mid-order streams, the riparian code value steadily decreased. The partially forested sites receive greater solar radiation as a source of heat energy, which results in warmer surface water temperatures and increased diurnal variation relative to the fully forested sites (Swift and Messer, 1971; Johnson and Jones, 2000; Moore *et al.*, 2005). If hyporheic damping of maximum temperatures occurred at any of the sites, it would be most obvious in the partially forested sites because the heating of the surface water via solar insolation would increase the temperature differences between stream water, hyporheic water and groundwater (Sinokrot and Stefan, 1993; Evans *et al.*, 1995). At the partially forested sites during the summer months, insolation may exert significant controls on subsurface temperatures and supersede hyporheic effects at these sites (Evans *et al.*, 1998; Danehy *et al.*, 2005).

The ends of riffles may have been warmer than pool tailouts in partially forested sites because they are shallow and occur in the centre of stream channels, making them more susceptible to the effects of solar insolation relative to pools. Alcoves were not significantly different from the other three mesoscale habitats but, interestingly, their mean ΔMT and ΔAMT values in partially forested sites were cooler than riffles and warmer than pools (Figure 6). This may be because they are located along the edges of channels where shading from banks and bank vegetation is most likely to occur (Beschta, 1997; Webb and Zhang, 1997), potentially explaining why they were generally cooler than the riffle habitats. Pools may be more buffered against the warming effects of solar radiation because they are deeper than riffles and alcoves and so would be cooler with less diel variation in a system where solar insolation is dominant and may negate hyporheic cooling effects (Hawkins *et al.*, 1997; Matthews and Berg, 1997;

Clark *et al.*, 1999; Elliott, 2000). In contrast, a possible combination of hyporheic upwelling at the heads of pools along with the buffering effects of greater depth may be working together to create cooler pools. The downwelling water occurring at pool tailouts may consist primarily of recently upwelled cooler hyporheic water that has also been buffered against the warming effects of insolation.

There are studies that did not find evidence of hyporheic mixing where it was expected to occur (e.g. White *et al.*, 1987; Wright *et al.*, 2005; Wondzell, 2006). Within a single riffle there is potential for patchy hyporheic upwelling and downwelling caused by heterogeneous subsurface features (Brunke and Gonser, 1997; Godbout and Hynes, 1982; Storey *et al.*, 1999; Sliva and Williams, 2005). Surface disturbances such as boulders and logs and subsurface features such as buried rocks and shallow bedrock sills may alter the flow of water through the hyporheic zone (White *et al.*, 1987; White, 1990; Gooseff *et al.*, 2006). Heterogeneity within the streambed and the resulting heterogeneous hydraulic conductivity of the streambed causes significant flux in the hyporheic zone (Cardenas *et al.*, 2004). In addition, different stream bed materials have different thermal conductivities, which can create spatial variation in the conduction rate of the channel bed and affect the rate of heat flux between the infiltrating water and the bed material (Sinokrot and Stefan, 1993; Evans *et al.*, 1998). It is unknown whether any of the aforementioned conditions exist in the streams in this study, but it is likely that at least some of the channel beds in this study possess some degree of channel bed heterogeneity, which would result in irregular heat conduction capabilities and hyporheic flow paths.

The partially forested sites have significantly higher SD_{MT} than the fully forested sites, indicating that the partially forested sites have greater diversity of maximum water temperatures between the ten loggers within each site. This signifies that temperature sensor location is

more important in the partially forested sites than in the fully forested sites. The partially forested sites also demonstrate greater ADV than the fully forested sites, indicating that their waters experienced a wider range of temperatures than the fully forested sites. This increase in temperature range likely stems from increased maxima caused by increased solar radiation and diurnal air temperature range due to decreased riparian cover (Moore *et al.*, 2005).

In this study, elevation, % impervious surfaces, % non-forested and riparian code were found to be related to each other, making it impossible to completely separate their effects on stream temperature; instead, their likely combined effects on stream temperatures will be discussed. The significant correlation between SD_{MT} and % non-forested and riparian code demonstrate that as forest cover within the watershed and riparian forest cover decreases, the diversity of maximum temperatures between loggers within the site increases. The range of temperatures (ADV) found at a site also increased with decreasing riparian cover and forest cover in the watershed. These results support the previous conclusions that SD_{MT} and ADV are higher in the partially forested sites, further stressing the importance of forest cover and insolation on the spatial variability of maximum temperatures and range of temperatures within a site.

Stream temperature ADV was positively associated with % impervious surfaces despite the fact that the actual percentages were relatively low for all sites (Table I), implying a high sensitivity of ADV to even modest development at these sites. Similar conclusions were drawn by Price and Leigh (2006) in a study of streams also in the upper Little Tennessee River basin.

Stream temperature ADV was negatively associated with elevation possibly in part because sites at lower elevation in this study were more likely to have less riparian cover than sites at higher elevation. Sites that have less riparian cover receive greater solar inputs, which increase the ranges of stream temperatures by increasing maximum stream temperatures (Swift and Messer, 1971). Streams under forest cover also have a different microclimate than sites with no forest cover. They generally have less diurnal variation of air temperature than more open sites (Moore *et al.*, 2005), which, on the basis of the relationship between air and stream temperature, may also be acting to mute the ADV of stream temperatures at these sites (Cluis, 1972; Stefan and Preud'homme, 1993; Mohseni and Stefan, 1999). In addition, elevation may be exerting a direct negative effect on maximum stream temperature in the fully forested sites (Isaak and Hubert, 2001; Scott *et al.*, 2002; Hunter and Quinn, 2009), which would decrease the ADV.

Solar insolation created brief but substantial spikes in the recorded temperatures, although we cannot be sure that the sunlight was not warming the temperature sensor

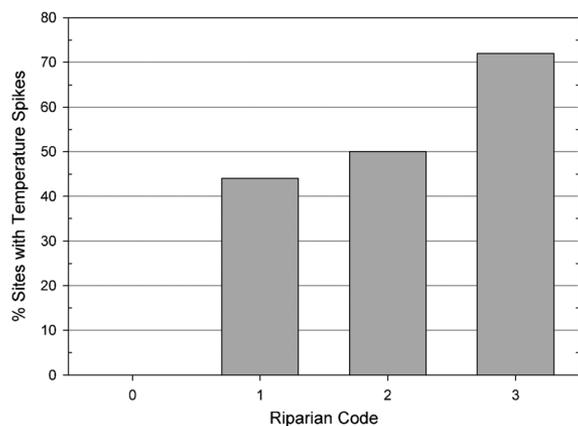


Figure 9. Percent of sites by riparian code that had temperature spikes created by sunlight

itself. Temperature spikes typically occurred between 12 and 3 PM, before the normal maximum stream temperature. These spikes greatly exceeded the normal daily maximum temperatures and reflect the importance of shade gaps on local thermal regimes. They likely resulted from patchy riparian cover and shading, which would make sudden exposure to direct sunlight as the angle of the sun changed obvious in the stream temperature record. Brown (1969) reported similar findings with streams that had discontinuous riparian cover, which produced 'moving spots of sunlight'. Sites with a riparian code of 0 lacked these spikes, most likely because they are constantly exposed to full sunlight. In fact, as riparian code increases, the percent of sites that experienced these temperature spikes increases (Figure 9), signifying that these temperature spikes become more common as sites become more forested.

CONCLUSIONS

Statistically significant differences in stream water temperature metrics between mesoscale habitats were found only in the partially forested sites; however, they were the opposite of what was expected in the presence of hyporheic mixing at these geomorphic features. Pool tailouts were found to be consistently cooler than the ends of riffles in the partially forested sites. In addition, the actual differences in temperature metrics between mesoscale habitats were small, indicating that there were no important hyporheic influences on the water temperature with mesoscale habitats at these sites. Fully forested sites featured no statistically significant differences in maximum temperatures or diurnal variation between habitat types.

It is likely that other factors influenced water temperature and hyporheic mixing more than the topography of the mesoscale habitats. These factors are numerous, including geologic and geomorphic characteristics, channel morphology, thermal mass and residence time of each mesoscale unit, depth and permeability of the streambed, meteorological conditions, stream curvature, presence of tributaries, riparian cover and land use (Vaux, 1968; Brunke and Gonser, 1997; Evans *et al.*, 1998; Stanford and Ward, 1993; Cardenas *et al.*, 2004; Wright *et al.*, 2005; Wondzell and Swanson, 1996). In addition, the relative importance of these processes is dynamic and likely to vary at different scales and for different stream orders and different seasons (Webb and Zhang, 1997; Kasahara and Wondzell, 2003; Cardenas *et al.*, 2004; Anderson *et al.*, 2005; Gooseff *et al.*, 2006).

Solar insolation and riparian condition were important to the thermal regimes of the streams in this study. This is evident from the differences in temperature metrics between partially forested and fully forested sites. The partially forested sites had increased spatial variability of MT and

range of temperatures and a significant difference in ΔMT and ΔAMT between habitat types. This indicates that the location within the stream channel where temperature measurements are recorded are more important at partially forested sites. However, sudden temperature spikes created by sunlight temporarily shining through riparian cover occurred more often in full riparian cover. These spikes are brief, and it is unknown what effects they may have on stream biota. It is important to note the incidence of these sunlight-created spikes in recorded temperatures in streams with partial to full riparian cover so that their influence on stream temperature can be taken into account when monitoring stream temperature or designing a study involving stream temperature. The data indicate that temperature sensors should be shielded from direct sunlight to avoid complications of solar radiation warming the sensor itself. Whereas short duration temperature spikes occurred more often in forested reaches, more consistent, although slight, spatial variability of temperatures occurred in partially forested reaches between mesoscale habitats. Because of these differences in temperature between mesoscale habitat types, especially between the ends of riffles and pool tailouts, the location within a reach where stream temperature data are collected is important for partially forested streams in the upper Little Tennessee River basin. These results suggest a need for standardization of temperature sensor placement within a stream channel, or at least accurate reporting of where in the channel temperature data were collected. In general, greater care should be given to stream temperature sampling methodology and reporting.

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