# VARIATION OF STREAM TEMPERATURE AMONG MESOSCALE HABITATS IN THE UPPER LITTLE TENNESSEE RIVER BASIN

by

#### SARAH LYNSEY LONG

(Under the Direction of Rhett Jackson)

#### ABSTRACT

The purpose of this study is to determine if there are systematic differences in stream temperature between mesoscale habitats as a result of hyporheic exchange in the upper Little Tennessee River basin. Secondary objectives are to evaluate relationships between stream temperature and riparian condition and environmental controls. Data loggers were set out in 44 sites in the upper Little Tennessee River basin with ten loggers in each site: three in riffles, three in pools, three in alcoves and one in the main riffle. The temperature differences between habitat types are the opposite of what was expected in the presence of hyporheic exchange, indicating that hyporheic exchange is not a dominant driver of mesoscale habitat temperatures at these sites. Partially forested sites exhibit greater spatial variation and temperature ranges than fully forested sites, indicating that location of temperature logger placement is important in partially forested sites.

INDEX WORDS: Stream temperature, Hyporheic exchange, Mesoscale habitat, Riffle, Pool, Alcove, Elevation, Impervious surfaces, Riparian, Forest cover, Sunlight

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## SARAH LYNSEY LONG

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Major Professor: Committee: Rhett Jackson Todd Rasmussen James Shelton

Electronic Version Approved:

Maureen Grasso Dean of the Graduate School The University of Georgia December 2011

### DEDICATION

Dedicated to:

Jason Scarbrough, whose love and laughter keeps me sane

My parents, whose love and support encourages me to do more than I knew I could

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## TABLE OF CONTENTS

Page
ACKNOWLEDGEMENTSv
INTRODUCTION
BACKGROUND
Stream Temperature4
Importance of Stream Temperature4
Riparian Condition Effects6
Environmental Controls
Hyporheic Exchange Effects
METHODS
Study Sites
Data Collection
Error Screening16
Environmental Controls
Data Analysis
Statistical Analysis
RESULTS67
Variation of $\Delta$ MT, $\Delta$ AMT and $\Delta$ MDV with Mesoscale Habitat67
SD <sub>MT</sub> & ADV70
DISCUSSION113

Variation of $\Delta$ MT, $\Delta$ AMT and $\Delta$ MDV with Mesoscale Habitat113
SD <sub>MT</sub> & ADV118
Sunlight120
CONCLUSIONS
REFERENCES
APPENDICES
A Graphs of sites with temperature spikes caused by sunlight134
B Results of the Kruskal-Wallis nonparametric tests for $\Delta MT$ , $\Delta AMT$ , and $\Delta MDV$ with
respect to habitat type for all sites, fully forested, and partially forested sites146

#### **INTRODUCTION**

Stream temperature is a measurement collected in standardized surface-water sampling protocols and in research on stream health because of the known effects that stream temperature has on overall stream water quality and the aquatic organisms that reside within streams. Stream temperature directly influences the life history, metabolism, and physiology of aquatic organisms that inhabit streams (Allan 1995). While the thermal regime of streams naturally varies daily and seasonally, certain land uses (e.g., logging, agriculture, urbanization) can create temporary or permanent shifts in this regime by decreasing riparian shade and increasing solar radiation (Brown and Krygier 1970; Johnson and Jones 2000). Temporary changes in the natural thermal regime modify the physiology and behavior of aquatic organisms, while permanent temperature changes decrease habitat suitability (Holtby 1988; Quinn et al. 1997). Therefore, it is important to monitor stream temperature and evalutate how anthropogenic change affects it. However, most previous 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). This suggests that there is no standard method for the placement of the temperature sensors within the stream channel. 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. 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 lack of resolution can oversimplify the potential spatial variations of temperature within a stream reach.

Some spatial variations in stream temperature are attributed, in part, to the influx of cooler hyporheic flows into the stream (Ebersole et al. 2003). The hyporheic zone is the saturated area located below the channel bed where surface and groundwater mix (White 1993). Hyporheic zone exchange is controlled by the local and regional geomorphology of the channel (Brunke and Gonser 1997; Burkholder et al. 2008). Vaux (1968) concluded that a concave streambed surface generates upwelling of hyporheic flow into surface flow while a convex streambed generates downwelling of surface flow into the channel bed. 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 mesoscale habitat of streams influences hyporheic flow. The different flow and hyporheic patterns found between these mesoscale habitats have potential to create considerable differences in temperature (White et al. 1987; Hendricks and White 1991; Evans and Petts 1997). Spatial heterogeneity of stream temperatures is important for aquatic fauna and several studies have reported fish seeking out refuge within a stream channel in areas that are cooler than the main channel flow (Baltz et al. 1987; Matthews and Berg 1997; Torgersen et al. 1999; Ebersole et al. 2001; Burkholder et al. 2008).

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 is to determine if there is a systematic difference in temperature metrics between four mesoscale habitat types: riffle tailouts, the middle of the main riffle, pool tailouts, and alcoves as a result of the exchange of surface water and hyporheic flow. Specifically, it is expected (based on hyporheic flow models developed by Vaux (1968), Thibodeaux and Boyle (1987), and White et al. (1987)) that the tailouts of riffles will have the coolest temperatures because of hyporheic upwelling, the middle of the main riffle, being the most mixed location, will be cooler than pools and alcoves and have the least diurnal variation, the tailouts of pools will be warmer because of surface water downwelling and alcoves will have the warmest and most variable temperatures. Secondary objectives are to quantify the variability of temperature between stream reaches with land use and riparian cover and to evaluate the relationship between stream temperature and environmental controls such as elevation and impervious surfaces.

#### BACKGROUND

#### **Stream Temperature**

Water temperature is a measure of the density of heat energy in water. Natural stream temperatures exhibit two cycles: a seasonal cycle with a diurnal cycle superimposed upon it. Both cycles are controlled primarily by solar radiation and air temperature (Sinokrot and Stefan 1993). The energy budgets of streams are controlled by several parameters: net long-wave and short-wave radiation, air temperature, evaporation, condensation, sensible heat transfer, precipitation, streambed heat transfer and friction (Comer and Grenney1977; Sinokrot and Stefan 1993; Evans et al. 1998). The importance of each of these parameters changes with stream size, discharge, season, and meteorological conditions (White 1993; Evans et al. 1998). For small mountain streams like those in this study, important controls of energy budgets are generally incoming solar radiation reaching the streambed, groundwater advection, and molecular heat conduction between surface water and the streambed (Comer and Grenney 1977; Sinokrot and Stefan 1993; Evans et al. 1998).

#### **Importance of stream temperature**

The water temperatures of streams play an important role in their biotic and abiotic processes. Temperature controls rates of chemical reactions, the solubility of oxygen in water (Davis 1975) and the density of water (Hynes 1983). The internal body temperatures of poikilothermic species that inhabit streams are dependent on the temperature of their surrounding environment, i.e., the temperature of the water. Different fish species have different upper and lower preferred and lethal temperature ranges (Brett 1956; Ferguson 1958). Sudden exposure to low temperatures increases stress in fish which reduces immune function (LeMorvan et al. 1998), and can cause death via failure of the nervous system (Brett 1956). Sudden exposure to high temperatures may cause death from low amounts of dissolved oxygen in the water (Brett 1956; Davis 1975). Temperature affects fish metabolic rate and reproduction through gonad development, timing of spawning, and egg quality (Cech et al. 1990; Gillet 1991; DeHaven et al. 1992; Hutchings and Myers 1994; Lee et al. 2003). Stream temperatures also affect fish distribution within a channel; some are known to seek refuge from warm water in the main channel in patches of cooler water more suited to their preferences (Baltz et al. 1987; Berman and Quinn 1991; Matthews and Berg 1997; Torgersen et al. 1999). Stream temperature affects aquatic macroinvertebrates similarly by influencing their reporduction, growth, emergence, feeding ecology, life cycle and assemblage structure (Cummins and Klug 1979; Vannote and Sweeney 1980; Huryn and Wallace 1987; Newbold et al. 1994; Hawkins et al. 1997; Richards et al. 1997; Sponseller et al. 2001). Stream temperature affects aquatic macroinvertebrates differently according to the species but all macroinvertebrate species are sensitive to temperature changes during all stages of their life cycle (Sweeny 1993).

Stream water temperature affects the nutrients available in a stream both directly and indirectly. For example, phosphorus retention is affected by the annual cycle of stream temperatures. During the spring and summer months warmer stream temperatures result in greater phosphorus retention than during the winter months (D'Angelo et al. 1991). Stream temperature indirectly affects nitrogen cycling through microbial activity. Microbial activity is regulated by seasonal and diurnal temperature fluctuations and generally increases as temperature increases (Peters et al. 1987). Increased microbial activity during warm seasons is correlated to decreases in stream nitrate (NO<sub>3</sub>) concentrations (Brookshire et al. 2010). Fecal and total coliform abundance in a southern Appalachian stream were also found to be regulated

by stream temperatures while enteric bacteria abundance was found to be positively correlated to stream temperature (McSwain and Swank 1977).

#### **Riparian Condition Effects**

Riparian condition controls the amount and intensity of solar inputs which in turn directly affect temperatures depending on bank height, type and amount of riparian cover and orientation of the channel relative to the sun (Brown 1969; Beschta 1997; LeBlanc et al. 1997; Li 2006; Clark et al. 1999; Johnson and Jones 2000; Danehy et al. 2005). Leaf area index and average height of riparian vegetation strongly affects maximum stream temperatures through shading (Sridhar et al. 2004) and causes lateral variation in temperatures within a stream (Clark et al. 1999). Streams with forested riparian zones have different microclimates than those in open areas. In addition to reducing solar radiation, the canopy reduces precipitation, wind speed and diurnal air temperature range and increases relative humidity (Johnson 2004; Moore et al. 2005). Forested riparian zones also affect channel complexity through organic inputs into the system (Vannote et al. 1980; Charlton 2008). For example, large woody debris (LWD) inputs create debris dams, log jams, steps, backwater pools and plunge pools (McCain et al. 1990; Hawkins et al. 1993; Abbe and Montgomery 1996). These features increase hydraulic roughness and therefore encourage hyporheic mixing (Harvey and Bencala 1993; Buffington and Montgomery 1999; Baxter and Hauer 2000; Leach 2010).

There may be substantial changes in stream temperature when the riparian zone is removed or reduced. Many logging effects are short term (Johnson and Jones 2000, Webster et al. 1992) and localized (Wilkerson et al. 2006) while the effects of permanent land-use changes (development of agriculture and urbanization) are generally long term. Removal of the riparian buffer increases shortwave solar radiation which increases stream maximum temperatures and diurnal fluctuations (Swift and Messer 1971; Swift and Baker 1973; Sweeny 1993; Johnson and Jones 2000; Wilkerson et al. 2006). Even moderately impacted streams show a significant difference in temperature from lightly impacted streams (Price and Leigh 2006). Overall, unnatural increases in stream temperatures decreases the water quality and is considered thermal pollution when temperatures exceed fish species' and other organisms' preferred range. In addition, as riparian cover changes along a stream channel, and therefore the available light, it alters food sources which adversely affect the macroinvertebrate community structure (Vannote et al. 1980). For example, increased light (as a result of reduced or absent streamside vegetation) causes an increase in periphyton primary production rates (Hornick et al. 1981). This change in light availability creates shifts in the aquatic macroinvertebrate community in response to the changing food sources (Wallace and Gurtz 1986).

If the riparian buffer is altered or removed the changes in the natural thermal regime would have numerous effects on the aquatic macroinvertebrate community. Changes in stream temperature following the removal of a streams riparian buffer can also push temperatures above the optimum or lethal limit for fish (Swift and Messer 1971). In summary, when the riparian buffer is diminished or removed, the resulting modification of the thermal regime affects the entire ecosystem of the stream.

There is evidence that while increased solar radiation may raise main channel temperatures above the preferred levels for fish (Beitinger and Fitzpatrick 1979) there can exist cooler patches of water within the stream channel as a result of groundwater upwelling and hyporheic exchange (Danehy et al. 2005; Burkholder et al. 2008). This lateral heterogeneity of temperatures within a stream can be exploited by fish that use these cooler areas as refuge from the warmer main channel temperature (Baltz et al. 1987; Matthews and Berg 1997; Torgersen et al. 1999; Ebersole et al. 2001; Burkholder et al. 2008). This indicates that cold-loving species may persist in a stream where the average water temperature is above the preferred range, but that has locations within the channel which are within the appropriate temperature range.

#### **Environmental Controls**

In addition to riparian cover, two additional environmental controls are investigated in this study: impervious surfaces and elevation. These controls also affect stream temperatures both directly and indirectly. The amount of impervious surfaces in the watershed of a stream has been used as an indication of the intensity of the urban environment and its effects (Wang et al. 2001; Brabec et al. 2002). Impervious surfaces also have direct adverse affects on streams. Stormwater becomes heated as it flows over warm impervious surfaces in an urban environment, often above the natural range, (Paul and Meyer 2001; Allan and Castillo 2007) this water subsequently flows into local streams. Thermal pollution such as this can cause shifts in the aquatic population of a stream (Dodds 2002). Impervious surfaces also create flashier hydrographs by rapidly delivering storm water to the streams and preventing the storm water from to infiltrating into the ground (Leopold 1968).

Elevation exerts an indirect negative effect over stream temperature (Isaak and Hubert 2001; Hunter and Quinn 2009) and has been found to have a negative correlation to maximum stream temperature (Scott et al. 2002). This is caused by the relationship between ambient air temperature and stream temperature (Cluis 1972; Stefan and Preud'homme 1993; Mohseni and Stefan 1999).

#### **Hyporheic Exchange Effects**

The hyporheic zone is the saturated area below a streambed that contains some proportion of surface water (White 1993). Hyporheic flow occurs when stream water infiltrates

into the subsurface and returns to the surface flow over a relatively short distance (Kasahara and Wondzell 2003), while hyporheic exchange is mixing between surface and subsurface water in a stream (Robertson and Wood 2010). Streams contain a variety of mesoscale habitats, defined by their characteristic geomorphology, which have different flow depths, velocities and hyporheic exchange patterns (Vaux 1968; Thibodeaux and Boyle 1987; Charlton 2008) which may lead to differences in water temperature between these mesoscale habitat types. The size and exchange rate of the hyporheic zone depends on the topography, depth, and permeability of the streambed (Vaux 1968; Brunke and Gonser 1997; Wondzell 2006). 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) and where the pressure is high from flow forcing against the upstream face of a bed form (Savant et al. 1987; White 1990; Elliot and Brooks 1997a, 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) and where pressure decreases at the trough of the bed (Savant et al. 1987; White 1990; Elliot and Brooks 1997a, 1997b).

This exchange of hyporheic and stream water has been found to have significant effects on stream heat budgets especially in small shallow streams during the summer months (Hondzo and Stefan 1994; Webb and Zhang 1997; Poole and Berman 2001). This is due to the buffering capacity of the substrate which shields the subsurface waters from atmospheric contact resulting in lower water temperatures within the hyporheic zone (Evans and Petts 1997). Infiltrating surface water is cooled as it flows through the subsurface by direct conduction with the substrate or by advective transfers within the bed or a combination of both and is returned to the surface flow over a relatively short distance (Ringler and Hall 1975; Comer and Grenney 1977; Boulton et al. 1997; Evans et al. 1998). Along the vertical infiltration gradient within the streambed, there is a general decline of the thermal influence that surface water has on subsurface water and a general decrease in temperature range with depth (Comer and Grenney 1977; White et al. 1987; Evans et al. 1995; Brunke and Gonser1997; Evans and Petts 1997). In short, as depth within the hyporheic zone increases the subsurface water is influenced more by and behaves more like groundwater than surface water (Constanz 2008). Heat flux between the infiltrating surface water and the streambed depends on the temperature gradient within the streambed and the thermal and hydraulic conductivity of the streambed material (Sinokrot and Stefan 1993; Constanz 2008). Low hydraulic conductivity within the hyporheic zone acts to increase the residence time of the infiltrating surface water which increases the opportunity for heat flux between infiltrating surface flow and the stream bed (Evans et al. 1995). Typically, hyporheic water temperatures are warm in the winter and cool in the summer relative to surface water and the streambed acts as an energy sink during the day and an energy source at night (Sinokrot and Stefan 1993; Evans et al. 1995) however, as long as the substrate within the streambed is cooler than the surface water the streambed acts as an energy sink (Evans et al. 1998). The differences in temperature between surface and hyporheic flow are most pronounced during the summer months during low flows when surface water is most susceptible to the influences of solar insolation (Evans et al. 1995). The rate of hyporheic exchange and therefore the extent of hyporheic influence within the stream depends on the subsurface sediment heterogeneity and hydraulic conductivity and the amplitude and wavelength of the bed topographical features (Brunke and Gonser 1997; Evans and Petts 1997; Marion et al. 2002).

The longitudinal pattern of convexity-concavity-convexity which promotes hyporheic exchange is exhibited in the natural riffle-pool sequences of streams. Pools, riffles, and alcoves

are common mesoscale habitat types in streams and because of their unique geomorphology each has unique hydrology (Charlton 2008).

Pools are areas of deeper water with low velocities that provide resting habitat for fish (McCain et al. 1990). They are created by scour elements such as boulders, large woody debris (LWD), stream banks, and roots protruding into the stream and are common at bends where turbulence is high and the bed are erodible (Beschta and Platts 1986). For example, water flowing over a boulder or log in a streambed may create a pool immediately downstream (Beschta and Platts 1986; Baxter and Hauer 2000). Hyporheic upwelling is expected to occur at the upstream end of a pool where the longitudinal profile becomes concave and downwelling at the downstream end of the pool where the longitudinal profile becomes convex (Vaux 1968; Thibodeaux and Boyle 1987; White et al. 1987; Hendricks and White 1991; Harvey and Bencala 1993). Therefore, it is expected that water at the pool tailouts should be warmer than pool heads, where cooler hyporheic water is upwelling, because of downwelling surface water.

Riffles occur in steepened sections of channels with shallow, higher velocity flow and coarser substrate. They typically cover gravel and/or cobble substrate which water flows over in a turbulent sheet. Main riffles are a subgroup of riffles classified in this study as the largest riffle in a given reach where the water is most mixed. Downwelling of stream water into the stream bed is expected to occur at the head of a riffle where the stream bed becomes convex; it then travels for some distance along the longitudinal gradient until the stream bed becomes concave at the foot of the riffle where upwelling is expected to occur (Vaux 1968; Thibodeaux and Boyle 1987; White et al. 1987; Hendricks and White 1991; Harvey and Bencala 1993; Elliot and Brooks 1997a). Studies have found evidence of this pattern in riffles using temperature, with generally warmer water at the heads of riffles and cooler water emerging from the tails of

riffles (White et al. 1987; Hendricks and White 1991; Evans and Petts 1997). Evans and Petts (1997) found that groundwater is closest to the streambed at the ends of riffles and that riffles displayed little daily variation in temperature because of upwelling groundwater-influenced hyporheic flow.

Alcoves are depositional areas shallower than pools commonly found along the edges of streams where there is less mixing with main channel flow (McCain et al. 1990). Clark et al. (1999) found that alcoves displayed warmer temperatures and increased diel variation relative to the main flow temperature. This was said to be caused by alcoves' sensitivity to solar inputs because they are shallow and have slow flows.

These differences in hyporheic flow paths between mesoscale habitats may cause consistent temperature variations between mesoscale habitat types and could affect the results of a stream temperature study if data is collected in different mesoscale habitat types and this is not taken into account.

#### **METHODS**

#### **Study Sites**

This study was conducted in collaboration with the Coweeta LTER (Long Term Ecological Research) Program. In 2009, the Coweeta LTER conducted an interdisciplinary synoptic study of streams located in various watersheds around Franklin, NC within the upper Little Tennessee River basin (Figure 1.1). Stream temperature data were collected for ten of the watersheds used for the synoptic surveys. The ten watersheds were Cowee, Darnell, Nickajack, Ball, Fulcher's, Jones, Caler-Dalton, Skeenah, Burningtown, and Hickory Knoll (Figure 1.2). Up to eight stream reaches within each watershed were chosen with the goal of representing variation from the headwaters to the outlet (Figures 1.3-1.10). 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 1.1).

#### **Data Collection**

Elevation and UTM coordinates were recorded at each site using a Garmin Oregon<sup>®</sup> handheld GPS unit. Riparian conditions were described for each site including the type of vegetation and width of the riparian buffer.

Temperature data were collected using HOBO<sup>®</sup> Temperature/Light Pendant Data Loggers (Onset Computer Corporation, Pocasset, MA). These data loggers have a temperature range from -20°C - 70°C, accuracy of +/- 0.54°C from 0°C - 50°C, resolution of 0.10°C at 25°C and a response time of five minutes. Each logger was zip-tied to a standard modular brick (Figure 1.11). 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.

A total of eighty loggers were available for use. Each site had a total of ten temperature loggers placed within a 150meter reach. Three loggers were assigned to pools, three to alcoves, three to riffles, and one to the main riffle as defined by the U.S. Forest Service Stream Habitat Classification and Inventory Procedure (McCain et al. 1990) so that up to eight sites could be selected for each watershed.

The three pool loggers of each site were assigned to three separate pools (areas of relatively deeper, slower water) within a 150m reach so that each of the three pools had one logger. The bricks with the loggers attached were placed at the tailouts of the pools. The three alcove loggers were placed in the middle of three separate alcoves, the shallow areas along the edges of the stream that are separated from the main flow. The three riffle loggers were each placed at the lower end of three separate riffles (steepened sections of the stream with faster, shallower water). One logger was assigned to the largest riffle of each 150m reach (main riffle) and was placed in the middle of the riffle.

Each of the eighty logger/brick combinations had a unique name according to its designated site and mesoscale habitat type. Ten logger/brick combinations were assigned to each of the eight possible sites (A, B, C, D, E, F, G, or H) in a watershed. Each brick was labeled with permanent marker according to the site it belonged to and to which mesoscale habitat it was assigned. The main riffle brick for each site was labeled '1' along with the site letter to which it was assigned. The three riffle bricks were labeled either 11, 12, or 13. The three pool bricks were labeled either 21, 22, or 23 and the three alcove bricks were labeled either 31, 32, or 33.

This allowed each of the 80 loggers to have a unique name. For example, the pools for site E in a watershed would be labeled E21, E22, or E23, and the main riffle of site B would be labeled B1. This same naming procedure was also used to name the individual HOBO<sup>®</sup> temperature data loggers during initial set up in the description box before deployment to match the name of the brick to which it was assigned. 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.

Because of differences in channel complexity and morphology, not all stream reach sites had well defined mesoscale habitat types. When this was the case it was attempted to capture as much hydraulic diversity as possible. This was done 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 and then recording at which sites this method was necessary. This was only necessary in the Darnell watershed at site H (synoptic site #54) and in the Skeenah watershed sites A, B and D (synoptic sites #40, #39 and #38 respectively).

Each logger was set to record temperature at 15-minute intervals to allow for detailed temperature records that would not miss the daily maximums and minimums. Deployment and retrieval dates and times for the loggers were recorded for each site. All loggers were deployed for a period of at least three days so that average daily metrics could be calculated.

During the third week of sampling the data loggers were deployed in the Nickajack watershed. When retrieving the data loggers from site B (synoptic site #24-Nickajack Midstream) it was discovered that four had been vandalized and smashed. These included one alcove, one riffle and two pool loggers. This caused loss of data not only from these habitats in site B of the Nickajack watershed but also for these habitats in the B sites of the Cowee and Darnell watersheds that were sampled the two previous weeks. It was intended to do three weeks of sampling between each download to save time downloading data from 80 loggers each week. The data would then be clipped according to the recorded times of deployment and retrieval for each site. However, after this incident, all data were downloaded for each watershed after the loggers were retrieved each week.

Two loggers were set out for the entire summer (June 12 - August 7), one in South Fork Skeenah Creek and one in Ball Creek (Figures 1.2, 1.6 and 1.9) to be used as references for the temperature pattern of the entire summer for two different riparian conditions. Both loggers were placed in the center of the channel in riffle habitat. The South Fork Skeenah site had occasional-to-no trees while the Ball Creek site was fully forested. Mean daily discharge data for the summer were collected from USGS gage #03500240 Cartoogechaye Creek near Franklin, NC from the USGS website.

#### **Error Screening**

Because of extreme changes in stream flow, data for the Fulcher and Burningtown watersheds could not be used. When retrieving the data loggers from Fulcher's watershed sites A and B, it was discovered that high stream flows moved all of the bricks out of their designated mesoscale habitats and were scattered randomly within the stream so the data could not be used from this watershed. When the data loggers were retrieved from Burningtown watershed sites A and B, it was noted that most of the loggers were exposed to the air or 'dewatered'. The data were downloaded and graphed to check for abnormalities. It was determined that the loggers were probably dewatered for most of the sampling period due to a drop in water level so the data could not be used for this watershed. After all the loggers were retrieved the data were downloaded and graphed. All data were trimmed according to the recorded deployment and retrieval dates and times. To verify the quality of the data and check for potential sources of error caused by dewatering, all the data were graphed in order to visually inspect the time series for any abnormalities (Dunham et al. 2005). It was noticed that some data points displayed a sudden excessive increase in temperature relative to previous data points 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 different than itself on other days or from other data loggers (e.g. Figure 1.12, Figure 1.13). 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 while 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.

A second kind of anomaly revealed in the graphs was created by solar insolation. After removing data points that were dewatered there still existed smaller spikes in temperature that were not caused from dewatering but from direct sunlight. Temperature spikes were said to be caused by solar insolation when they occurred before or after and exceeded the actual daily maximum temperature, which typically occurred between 3-5pm, and at approximately the same time during at least two days during the sampling period (Figure 1.14). These solar insolation-generated spikes were identified and removed from the dataset because they represented a process not affecting the other loggers. Although these spikes in temperature demonstrate the importance of solar insolation in these streams they are not related to hypotheses of this study. They were often greater than and occurred before the normal daily maximum. As all of the

metrics calculated for analysis rely on the maximums and because the goal is to evaluate hyporheic effects it is important that the maximums are not skewed by solar insolation affecting only some loggers. Preliminary analyses showed that keeping these spikes in the dataset would mask the true daily temperature fluctuations and prevent the accurate calculation of the metrics necessary to test the hypotheses of interest. Graphs of the sites containing these temperature spikes are located in Appendix A.

There were three loggers whose data was not found (Ball watershed D22 and Jones watershed D22 and F33) possibly caused by an error while downloading and saving the files. The amount of lost data however is inconsequential compared to amount of usable data.

#### **Environmental Controls**

The collected riparian condition data were used to assign a riparian code for each site as follows: occasional or no trees = 0, < 3meter buffer width = 1, a 3-10meter buffer width or a one-sided buffer = 2, and full forest cover = 3 (Table 1.2 and 1.3).

The watersheds were delineated for each site using ESRI's ArcMap 9.2 mapping software and basin area of each watershed and elevation of each sampling point was determined (Table 1.2 and 1.3). Percent forest cover for the watershed of each site was obtained using the level I NLCD 2001 Land Cover Class definitions (Table 1.2 and 1.3).

Percent impervious surfaces for the watershed of each site were calculated using the level II NLCD 2001 Land Cover Class definitions instead of the level I (Developed) to achieve a higher resolution of % impervious surfaces. Level I (Developed) only includes areas with 30% or greater development. The Level II definitions for Developed Land are broken into 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). There was no High Intensity Developed Land in any of the sampling sites' watersheds. The median of the ranges of percent impervious surfaces were used to calculate percent impervious surfaces: 10% for Open Space, 35% for Low Intensity, and 65% for Medium Intensity. The percent area that each site had in each of the three classes was multiplied by the median percent of impervious surface. The three values were then added together to get the total percent impervious surface for each site's watershed (Table 1.2 and 1.3). All sites had extremely low percent impervious surfaces with only one site having above 1% impervious surfaces (Darnell H).

#### **Data Analysis**

There are several sources of variability in this study design. Each watershed was sampled on different dates, each site within a watershed had different logger deployment and retrieval times, and each watershed and its sites have unique hydrology, land use, riparian cover, and environmental controls. To account for these sources of variability, the deviations of each logger from the average of all ten loggers in its site is used 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 maximum temperature for the total time the loggers were in the stream ( $\overline{MT}_{(site)}$ ) to get the deviation of each logger's maximum temperature from the site average ( $\Delta MT_{(logger)}$ ).

 $\Delta MT_{(logger)} = MT_{(logger)} - MT_{(site)}$ 

The average of each day's maximum temperature (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 ( $\overline{AMT}$ ) in the site to get the deviation of each logger from the AMT ( $\Delta$ AMT).

 $\Delta AMT_{(logger)} = AMT_{(logger)} - AMT_{(site)}$ 

The maximum daily variation (MDV) of temperature was calculated for each of the ten loggers. This was found by calculating the range of temperatures found within each 24-hour period for each logger, the largest range of all the 24-hour periods was selected for each logger and called the maximum daily variation (MDV). Each logger's MDV was subtracted from the average of all ten logger's MDV ( $\overline{MDV}_{(site)}$ ). This gave  $\Delta MDV$ , the deviation of each logger from the average MDV of the site.

 $\Delta MDV_{(logger)} = MDV_{(logger)} - \overline{MDV}_{(site)}$ 

The standard deviation of all ten logger's maximum temperature of all days was calculated for each site ( $SD_{MT}$ ). The average diurnal variation of each site (ADV) was calculated by taking the average of all ten logger's average diurnal variation.

#### **Statistical Analysis**

#### Variation of $\Delta MT$ , $\Delta AMT$ and $\Delta MDV$ with Mesoscale Habitat

#### All Sites

A Shapiro-Wilk normality test was performed for each of the four treatment groups (main riffle, riffle, pool, and alcove) for each of the three temperature metrics ( $\Delta$ MT,  $\Delta$ AMT and  $\Delta$ MDV). All treatment groups for all three temperature metrics rejected the null hypothesis of normality (Tables 1.4-1.6), possibly because of extreme observations (Figures 1.15-1.26). No transformations were apparent from the histograms because the distributions appeared more normal than anything else (Figures 1.15-1.26). Extreme observations were not excluded from the analysis because it is believed that the extreme values are valid data. However, the variances between treatment groups were equal for  $\Delta$ MT,  $\Delta$ AMT, and  $\Delta$ MDV (Tables 1.4-1.6). A oneway 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 especially with large sample sizes ( $n \ge 30$ ) because of the central limit theorem (Zar 1984; Dowdy et al. 2004).

A Kruskal-Wallis non-parametric test was also used to determine the effect of the four mesoscale habitat types on  $\Delta$ MT,  $\Delta$ AMT and  $\Delta$ MDV. This test was used because the treatment groups were not normally distributed and the effect of the possible outliers would be diminished using this type of test (Conover and Iman 1981; Zar 1984; Dowdy et al. 2004). However, the ANOVA results are used in this study because it is an appropriate test for this data and is therefore more powerful because the data is assumed to follow a normal distribution because of the central limit theorem (Dowdy et al. 2004); the results of the non-parametric tests are located in Appendix B.

#### Fully Forested and Partially Forested Sites

All 44 sites were subsequently divided into either fully forested (riparian code = 3) or partially forested (riparian code = 0, 1, or 2) to determine if a significant difference in temperature occurred between mesoscale habitat types within fully forested sites and partially forested sites (Table 1.7). A Shapiro-Wilk normality test was performed for all four treatment groups for the three temperature metrics for fully forested sites and partially forested sites. All treatment groups failed normality except the main riffles in the fully-forested  $\Delta$ AMT and  $\Delta$ MDV; however, all variances were equal between treatment groups (Tables 1.8-1.13). No transformations were apparent from the histograms (Figures 1.27-1.50). Non-normality was most likely caused by extreme data. However, it is believed these points are valid data and so they were not removed from the data sets. A one-way ANOVA was performed for the fully forested sites and the partially forested sites 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 especially with large sample sizes because of the central limit theorem (Zar 1984; Dowdy et al. 2004).

To account for possible effects of outliers, a Kruskal-Wallis nonparametric test was also used to determine if there was a significant difference of the  $\Delta$ MT, the  $\Delta$ AMT, and the  $\Delta$ MDV with respect to habitat type for the fully forested and partially forested sites (Conover and Iman 1981; Zar 1984; Dowdy et al. 2004). However, the ANOVA results are used in this study because it is more powerful than a nonparametric test when the data follow a normal distribution (Dowdy et al. 2004); the results of the non-parametric tests are located in appendix B.

#### SD<sub>MT</sub> & ADV

#### **Riparian** Condition

The SD<sub>MT</sub> and ADV for each site were grouped into either fully forested (riparian code 3) or partially forested (riparian code 0, 1, & 2) sites to determine if there was a significant effect of riparian condition on SD<sub>MT</sub> and ADV. The data for these were not normally distributed (Figures 1.51-1.54) and the variances were not equal (Table 1.14-1.15) making a t-test inappropriate. No transformations were appropriate and the central limit theorem does not apply because of the small sample sizes so the data were rank transformed and analyzed using the Wilcoxon rank-sum nonparametric test (Conover and Iman 1981; Zar 1984; Dowdy et al. 2004).

#### **Environmental Controls**

The relationship between the four environmental controls (% non-forested, % impervious surfaces, riparian code, and elevation) and the  $SD_{MT}$  and ADV for each site were analyzed. The data did not have bivariate normal distributions (Figures 1.55-1.60) and transformations did not improve the distributions, so 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 analyzed using a correlation matrix and scatter plots.



**Figure 1.1** Map of the Upper Little Tennessee River Basin (grey area with topography) and surrounding counties in North Carolina and Georgia



**Figure 1.2** Map of the eight watersheds studied within the Upper Little Tennessee River Basin. Fulcher's and Burningtown watersheds are not shown because the data from these watersheds could not be used. Yellow markers indicate location of two data loggers deployed all summer, one in South Fork Skeenah Creek (square) and one in Ball Creek (circle).



Figure 1.3 Cowee Watershed with location of eight sites sampled from June 9-12, 2009



Figure 1.4 Darnell Watershed with location of eight sites sampled from June 16-19, 2009



Figure 1.5 Nickajack Watershed with location of three sites sampled from June 23-26, 2009


**Figure 1.6** Ball Watershed with location of seven sites sampled from June 30-July6, 2009. Yellow circle marker is approximate location of the Ball Creek logger sampled from June 12- August 7, 2009.



Figure 1.7 Jones Watershed with location of eight sites sampled from July 14-17, 2009







**Figure 1.9** Skeenah Watershed with location of four sites sampled from July28-31, 2009. The square yellow marker is approximate location of the South Fork Skeenah Creek logger sampled from June 12 – August 7, 2009.



**Figure 1.10** Hickory Knoll Watershed with location of three sites sampled from August 12-24, 2009



Figure 1.11 Example of brick and data logger assembly



Figure 1.12 Example of a logger (D31) that was temporarily dewatered. Note the abnormally high temperature points relative to the preceding and following temperature points. Site was sampled from June 30-July 6, 2009.



**Figure 1.13** Example of a logger (F31) that was dewatered during the sampling period. Note the extreme temperature range and irregular pattern. Site was sampled from June 30-July 6, 2009.



Fig 1.14 Example of temperature spikes caused by sunlight in Ball Watershed Site A riffle habitat



**Fig 1.15** Histogram for the main riffle treatment group for  $\Delta MT$  for all sites



Figure 1.16 Histogram for the riffle treatment group for  $\Delta MT$  for all sites



Figure 1.17 Histogram for the pool treatment group for  $\Delta MT$  for all sites



Figure 1.18 Histogram for the alcove treatment group for  $\Delta MT$  for all sites



Figure 1.19 Histogram for the main riffle treatment group for  $\Delta AMT$  for all sites



Figure 1.20 Histogram for the riffle treatment group for  $\triangle$ AMT for all sites



Figure 1.21 Histogram for the pool treatment group for  $\triangle$ AMT for all sites



Figure 1.22 Histogram for the alcove treatment group for  $\triangle$ AMT for all sites



Figure 1.23 Histogram for the main riffle treatment group for  $\Delta$ MDV for all sites



Figure 1.24 Histogram for the riffle treatment group for  $\Delta$ MDV for all sites



Figure 1.25 Histogram for the pool treatment group for  $\Delta$ MDV for all sites



Figure 1.26 Histogram for the alcove treatment group for  $\Delta$ MDV for all sites



Figure 1.27 Histogram for the main riffle treatment group for  $\Delta MT$  in the fully forested sites



Figure 1.28 Histogram for the riffle treatment group for  $\Delta MT$  in the fully forested sites



Figure 1.29 Histogram for the pool treatment group for  $\Delta MT$  in the fully forested sites



Figure 1.30 Histogram for the pool treatment group for  $\Delta MT$  in the fully forested sites



Figure 1.31 Histogram for the main riffle treatment group for  $\Delta AMT$  in the fully forested sites



Figure 1.32 Histogram for the riffle treatment group for  $\Delta AMT$  in the fully forested sites



Figure 1.33 Histogram for the pool treatment group for  $\triangle$ AMT in the fully forested sites



Figure 1.34 Histogram for the alcove treatment group for  $\Delta AMT$  in the fully forested sites



Figure 1.35 Histogram for the main riffle treatment group for  $\Delta$ MDV in the fully forested sites



Figure 1.36 Histogram for the riffle treatment group for  $\Delta$ MDV in the fully forested sites



Figure 1.37 Histogram for the pool treatment group for  $\Delta$ MDV in the fully forested sites



Figure 1.38 Histogram for the alcove treatment group for  $\Delta$ MDV in the fully forested sites



Figure 1.39 Histogram for the main riffle treatment group for  $\Delta MT$  in the partially forested sites



Figure 1.40 Histogram for the riffle treatment group for  $\Delta MT$  in the partially forested sites



Figure 1.41 Histogram for the pool treatment group for  $\Delta$ MT in the partially forested sites



Figure 1.42 Histogram for the alcove treatment group for  $\Delta$ MT in the partially forested sites



Figure 1.43 Histogram for the main riffle treatment group for  $\Delta AMT$  in the partially forested sites



Figure 1.44 Histogram for the riffle treatment group for  $\Delta AMT$  in the partially forested sites



Figure 1.45 Histogram for the pool treatment group for  $\Delta AMT$  in the partially forested sites



Figure 1.46 Histogram for the alcove treatment group for  $\Delta$ AMT in the partially forested site



**Figure 1.47** Histogram for the main riffle treatment group for  $\Delta$ MDV in the partially forested sites



Figure 1.48 Histogram for the riffle treatment group for  $\Delta$ MDV in the partially forested sites



Figure 1.49 Histogram for the pool treatment group for  $\Delta$ MDV in the partially forested sites



Figure 1.50 Histogram for the alcove treatment group for  $\Delta$ MDV in the partially forested sites



Figure 1.51 Histogram of  $SD_{MT}$  for the fully forested sites



Figure 1.52 Histogram of  $SD_{MT}$  for the partially forested sites



Figure 1.53 Histogram of ADV for the fully forested sites



Figure 1.54 Histogram of ADV for the partially forested sites



Figure 1.55 Histogram of SD<sub>MT</sub> for all sites for the correlation analysis



Figure 1.56 Histogram of ADV for all sites for the correlation analysis



Figure 1.57 Histogram of % non-forested for correlation analysis



Figure 1.58 Histogram of % impervious surfaces for correlation analysis



Figure 1.59 Histogram of riparian code for correlation analysis



Figure 1.60 Histogram of elevation for correlation analysis

Watershed	# Sites	Sampling Dates	# Sampling Days
Cowee	8	June 9-12, 2009	3
Darnell	8	June 16-19, 2009	3
Nickajack	3	June 23-26, 2009	3
Ball	7	June 30- July 6, 2009	6
Fulcher's	2	July 7-10, 2009	3
Jones	8	July 14-17, 2009	71 hours
Caler-Dalton	3	July 20-24, 2009	4
Skeenah	4	July 28-31, 2009	3
Burningtown	2	August 3-7, 2009	4
Hickory Knoll	3	August 12-24, 2009	12

 Table 1.1 Sampling dates and number of sites and sampling days for each watershed

Site	Basin Area (km <sup>2</sup> )	Elevation (m)	Riparian Code	% Non- Forested	% Impervious Surfaces
Ball-A	7.16	673.00	2	2.89%	0.23%
Ball-B	3.86	669.95	3	3.99%	0.37%
Ball-C	2.28	669.95	3	1.50%	0.02%
Ball-D	2.02	853.74	3	4.84%	0.47%
Ball-E	2.42	853.74	3	4.29%	0.41%
Ball-F	0.24	839.72	3	0.00%	0.00%
Ball-G	0.10	853.14	3	0.00%	0.00%
Caler- Dalton-A	2.38	721.77	1	4.92%	0.51%
Caler- Dalton-B	1.22	760.17	2	0.37%	0.01%
Caler- Dalton-C	2.81	680.92	2	3.24%	0.27%
Cowee-A	4.16	632.46	0	6.81%	0.28%
Cowee-B	28.49	636.42	2	5.65%	0.27%
Cowee-C	5.54	687.93	1	4.87%	0.31%
Cowee-D	5.47	780.29	2	0.07%	0.00%
Cowee-E	5.51	790.96	1	5.14%	0.23%
Cowee-F	10.98	795.53	1	2.61%	0.12%
Cowee-G	0.16	797.97	3	15.64%	0.06%
Cowee-H	3.81	801.32	1	2.17%	0.11%
Darnell-A	0.04	715.98	1	50.00%	0.00%
Darnell-B	1.26	658.67	3	0.00%	0.00%
Darnell-C	0.27	930.86	3	0.00%	0.00%
Darnell-D	0.19	930.55	3	0.00%	0.00%
Darnell-E	0.08	929.64	3	0.00%	0.00%
Darnell-F	13.07	756.82	3	0.79%	0.01%
Darnell-G	13.40	711.70	2	0.92%	0.02%
Darnell-H	2.01	662.03	0	42.77%	1.85%
Hickory Knoll-A	9.56	627.89	0	8.26%	0.47%
Hickory Knoll-B	5.92	680.62	0	3.83%	0.23%
Hickory Knoll-C	0.15	731.52	2	1.78%	0.18%

**Table 1.2** Basin area, elevation, riparian code, % non-forested and % impervious surfaces forBall, Caler-Dalton, Cowee, Darnell and Hickory Knoll watershed sites

Site	Basin Area (km <sup>2</sup> )	Elevation (m)	Riparian Code	% Non- Forested	% Impervious Surfaces
Jones-A	5.44	829.36	3	1.29%	0.07%
Jones-B	2.32	829.36	3	0.47%	0.00%
Jones-C	3.71	894.59	3	0.68%	0.02%
Jones-D	0.22	896.72	3	0.41%	0.04%
Jones-E	7.78	829.36	3	1.04%	0.05%
Jones-F	0.45	827.84	2	6.37%	0.52%
Jones-G	15.32	763.524	2	6.16%	0.33%
Jones-H	0.40	833.93	2	3.00%	0.30%
Nick-A	6.06	711.10	2	5.69%	0.36%
Nick-B	5.20	711.10	2	5.15%	0.30%
Nick-C	1.53	708.66	3	5.53%	0.21%
Skeenah-A	2.28	676.05	0	8.55%	0.44%
Skeenah-B	6.03	658.67	1	11.20%	0.60%
Skeenah-C	3.66	643.13	1	20.69%	0.83%
Skeenah-D	2.19	647.40	1	13.14%	0.55%

**Table 1.3** Basin area, elevation, riparian code, % non-forested and % impervious surfaces forJones, Nickajack and Skeenah watershed sites.

All AMT	n	mean	variance	W	p- value
main riffle	43	0.07	0.16	0.84	<.0001
riffle	128	0.74	0.14	0.78	<.0001
pool	124	-0.10	0.18	0.78	<.0001
alcove	120	-0.02	0.16	0.77	<.0001

**Table 1.4** The Shapiro-Wilk normality test results for each of the treatment<br/>groups for  $\Delta MT$  for all sites

**Table 1.5** The Shapiro-Wilk normality test results for each of the treatment<br/>groups for  $\Delta AMT$  for all sites

All AAMT	n	mean	variance	W	p- value
main riffle	43	0.05	0.08	0.72	<.0001
riffle	128	0.05	0.06	0.80	<.0001
pool	124	-0.05	0.10	0.78	<.0001
alcove	120	-0.02	0.32	0.78	<.0001

**Table 1.6** The Shapiro-Wilk normality test results for each of the treatment<br/>groups for  $\Delta$ MDV for all sites

All AMDV	n	mean	variance	W	p- value
main riffle	43	0.11	0.39	0.67	0.0001
riffle	128	0.12	0.31	0.57	<.0001
pool	124	-0.05	0.28	0.67	<.0001
alcove	120	0.06	0.42	0.54	<.0001

Mesoscale Habitat Type	All Sites	Fully Forested Sites	Partially Forested Sites
Main Riffle	43	18	25
Riffle	128	53	75
Pool	124	50	70
Alcove	120	50	74

**Table 1.7** Sample size of each mesoscale habitat type for all sites, fully forested sites and partially forested sites

**Table 1.8** The Shapiro-Wilk normality test results for each of the treatmentgroups for  $\Delta$ MT for the fully forested sites

FF ΔMT	n	mean	variance	W	p- value
main riffle	18	-0.03	0.03	0.78	0.0008
riffle	53	-0.01	0.02	0.95	0.0165
pool	50	0.01	0.06	0.54	<.0001
alcove	50	0.01	0.03	0.84	<.0001

**Table 1.9** The Shapiro-Wilk normality test results for each of the treatmentgroups for  $\Delta AMT$  for the fully forested sites

FF ΔAMT	n	mean	variance	W	p- value
main riffle	18	-0.01	0.01	0.92	0.1535
riffle	53	-0.003	0.01	0.92	0.0017
pool	50	-0.01	0.01	0.86	<.0001
alcove	50	0.01	0.02	0.84	<.0001
FF AMDV	n	mean	variance	W	p- value
----------------	----	-------	----------	------	-------------
main riffle	18	-0.06	0.01	0.9	0.0664
riffle	53	-0.01	0.02	0.86	<.0001
pool	50	0.01	0.05	0.61	<.0001
alcove	50	0.02	0.03	0.90	0.0006

**Table 1.10** The Shapiro-Wilk normality test results for each of the treatmentgroups for  $\Delta$ MDV for the fully forested sites

**Table 1.11** The Shapiro-Wilk normality test results for each of the treatment groups for  $\Delta MT$  for the partially forested sites

N-FF ΔΜΤ	n	mean	variance	W	p- value
main riffle	25	0.14	0.24	0.9008	0.0191
riffle	75	0.14	0.22	0.866	<.0001
pool	74	-0.14	0.26	0.867	<.0001
alcove	70	-0.04	0.26	0.8301	<.0001

**Table 1.12** The Shapiro-Wilk normality test results for each of the treatment<br/>groups for  $\Delta AMT$  for the partially forested sites

N-FF ΔΑΜΤ	n	mean	variance	W	p- value
main riffle	25	0.09	0.12	0.77	<.0001
riffle	75	<.0001	0.10	0.88	<.0001
pool	74	-0.08	0.16	0.86	<.0001
alcove	70	-0.04	0.16	0.82	<.0001

N-FFAMDV	n	mean	variance	W	p- value
main riffle	25	0.24	0.63	0.78	<.0001
riffle	75	0.22	0.50	0.67	<.0001
pool	74	-0.08	0.44	0.74	<.0001
alcove	70	0.08	0.70	0.60	<.0001

**Table 1.13** The Shapiro-Wilk normality test results for each of the treatment<br/>groups for  $\Delta$ MDV for the partially forested sites

 $\begin{array}{c} \textbf{Table 1.14 Summary statistics for $SD_{MT}$ for fully forested and partially} \\ forested sites \end{array}$ 

<b>SD</b> <sub>MT</sub>	n	mean	variance
Full Forest	18	0.14	0.02
Partial Forest	26	0.44	0.15

 Table 1.15 Summary statistics for ADV for fully forested and partially forested sites

ADV	n	mean	variance
Full Forest	18	0.10	0.09
<b>Partial Forest</b>	26	2.6	2.05

### RESULTS

The temperatures at these sites ranged from 13-26°C (13-18°C in fully forested sites and 14-26°C in partially forested sites) (Figures 2.1-2.45). The peak in daily temperature typically occurred between 3-5 pm and the minimum daily temperature typically occurred between 7-8 am. Most of the temperature variability between mesoscale habitat types in a site tended to occur at the maximums. Mean daily discharge data from USGS gage #03500240 were graphed (Figure 2.46). The fully forested sites in each watershed are all located upstream of the partially forested sites in the same watershed (Figures 1.3-1.10) and as the sites move from upstream headwaters to downstream mid-order streams the riparian code value decreases (with the exception of Skeenah sites A and B).

## Variation of $\Delta MT$ , $\Delta AMT$ and $\Delta MDV$ with Mesoscale Habitat

## All Sites

In the ANOVA analysis, there was a significant difference in  $\Delta$ MT between habitat types (F<sub>.05,3,411</sub>=3.64, P=.0129) which necessitated further investigation using a multiple comparison procedure to determine which habitat types were significantly different with regards to  $\Delta$ MT (Figure 2.47).

A Fisher's Least Significant Difference (LSD) Test was performed and it was found that pool habitat had significantly lower  $\Delta$ MT values than the riffle and the main riffle but neither the riffle, main riffle nor the pool habitats had significantly different  $\Delta$ MT from the alcoves. A more conservative multiple comparison procedure, Tukey's Studentized Range (HSD) Test, was also performed which found a significantly lower  $\Delta$ MT in the pool habitats than the riffle habitats. The results of these tests show that pools have the lowest average  $\Delta$ MT values followed by alcoves then main riffle and finally riffle habitats with the highest average  $\Delta$ MT, and that pools have significantly lower maximum temperatures than the riffle and main riffle habitats (Figure 2.48).

The ANOVA analysis showed a significant difference in  $\Delta$ AMT between habitat types (F<sub>.05,3,411</sub>=2.99, P=.0310) which necessitated further investigation to determine which habitat types had significantly different  $\Delta$ AMT values (Figure 2.49).

A Fisher's (LSD) test was performed and it was found that pool habitat had significantly lower  $\Delta$ AMT values than riffle habitats. A Tukey's test was also performed which also found significantly lower  $\Delta$ AMT values in the pool habitats than the riffle. The results of these tests show that pools have the lowest average  $\Delta$ AMT values followed by alcoves then main riffle and finally riffle habitats with the highest average  $\Delta$ AMT values, and indicating that pools have significantly lower maximum temperatures than riffle habitats (Figure 2.50).

The ANOVA analysis found no significant difference in  $\Delta$ MDV between habitat types (F<sub>.05,3,411</sub>=1.92, P=.1260) (Figure 2.51-2.52).

The results of the Kruskal-wallis non-parametric test for  $\Delta MT$ ,  $\Delta AMT$ , and  $\Delta MDV$  with respect to habitat type are located in Appendix B.

#### Fully Forested Sites

The ANOVA analysis found no significant difference between the four habitat types in the fully forested sites for  $\Delta$ MT (F<sub>.05,3,167</sub>=0.37, P=0.7754) (Figure 2.53),  $\Delta$ AMT, (F<sub>.05,3,167</sub>=0.35, P=0.7894) (Figure 2.54), or  $\Delta$ MDV (F<sub>.05,3,167</sub>=1.32, P=0.2708) (Figure 2.55).

The results of the Kruskal-wallis non-parametric test for  $\Delta MT$ ,  $\Delta AMT$ , and  $\Delta MDV$  with respect to habitat type in the fully forested sites are located in Appendix B.

# Partially Forested Sites

For the partially forested sites, the ANOVA analysis found a significant difference in  $\Delta$ MT between habitat types (F<sub>.05,3,240</sub>=4.81, P=0.0028) which necessitated further investigation to discover which habitat types were significantly different (Figure 2.56).

A Fisher's (LSD) Test was performed which found a significant difference between the pool habitat and the riffle and main riffle habitats and also a significant difference between alcove and riffle habitats (Figure 2.56). A more conservative multiple comparison procedure, Tukey's Studentized Range Test, was also performed which also found a significant difference between pool and riffle habitat, with pools having a lower  $\Delta$ MT value than riffle habitats (Figure 2.56 and 2.48).

The ANOVA results showed a significant difference in the partially forested sites between mesoscale habitat types with respect to  $\Delta$ AMT (F<sub>.05,3,240</sub>=3.32, P=0.0205) which necessitated further investigation (Figure 2.57).

A Fishers (LSD) test was performed which found a significant difference between pool habitat and riffle and main riffle habitats. A Tukey's test was also performed which found a significant difference between pool and riffle habitats with respect to  $\Delta$ AMT. The results of these tests show that pools in partially forested sites have the lowest average  $\Delta$ AMT values followed by alcoves then riffle and finally main riffle habitats with the highest average  $\Delta$ AMT values with pools having significantly lower maximum temperatures than the riffle and main riffle habitats (Figure 2.50).

The ANOVA results did not show a significant difference between mesoscale habitat types in the partially forested sites with respect to  $\Delta$ MDV (F<sub>.05,3,240</sub>=2.41, P=0.0675) (Figure 2.58)

and Figure 2.51). The results of the Kruskal-wallis non-parametric test for  $\Delta$ MT,  $\Delta$ AMT, and  $\Delta$ MDV with respect to habitat type in the partially forested sites are located in Appendix B.

## SD<sub>MT</sub> & ADV

The calculated  $SD_{MT}$  and ADV for each site are listed in Table 2.1-2.2.

## **Riparian Condition**

The Wilcoxon rank sum non-parametric 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 score (smaller  $SD_{MT}$ ) than the partially forested sites (Table 2.3).

The Wilcoxon rank sum non-parametric test found a significant difference in ADV between the fully forested and partially forested sites (z=-5.0486, p<.0001). The fully forested sites had a lower mean score (smaller ADV) than the partially forested sites (Table 2.3).

## Environmental Controls

The Spearman rank correlation was used to determine the relationship between  $SD_{MT}$  and ADV and four environmental factors: % non-forested, elevation, % impervious surfaces, and riparian code. The Spearman test found a significant relationship between  $SD_{MT}$  and % non-forested ( $r_s$ =0.41157, P=0.0055) (Figure 2.59), and  $SD_{MT}$  and riparian code ( $r_s$  = -0.5857, P<.0001) (Figure 2.60). There was not a significant relationship between  $SD_{MT}$  and elevation ( $r_s$  = -0.27175, P=0.0744) (Figure 2.61) or between  $SD_{MT}$  and % impervious surfaces ( $r_s$ =0.23459, P=0.1253) (Figure 2.62).

The Spearman test found a significant relationship between ADV and % non-forested ( $r_s$  =0.70185, P<.0001) (Figure 2.63), ADV and riparian code ( $r_s$  = -0.77747, P<.0001) (Figure 2.64) ADV and elevation ( $r_s$  = -0.71014, P<.0001) (Figure 2.65), and ADV and % impervious surfaces ( $r_s$  =0.61472, P<.0001) (Figure 2.66). The four environmental factors were found to be correlated to each other in varying degrees with elevation and riparian code having the strongest positive correlation (Table 2.4, Figures 2.67 - 2.72).



**Figure 2.1** Graph of mesoscale habitat temperatures in Ball watershed site A from June 30- July 6, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.2** Graph of mesoscale habitat temperatures in Ball watershed site B from June 30- July 6, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.3** Graph of mesoscale habitat temperatures in Ball watershed site C from June 30- July 6, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.4** Graph of mesoscale habitat temperatures in Ball watershed site D from June 30- July 6, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.5** Graph of mesoscale habitat temperatures in Ball watershed site E from June 30- July 6, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.6** Graph of mesoscale habitat temperatures in Ball watershed site F from June 30- July 6, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.7** Graph of mesoscale habitat temperatures in Ball watershed site G from June 30- July 6, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.8** Graph of mesoscale habitat temperatures in Caler-Dalton watershed site A from July 20-24, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.9** Graph of mesoscale habitat temperatures in Caler-Dalton watershed site B from July 20-24, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.10** Graph of mesoscale habitat temperatures in Caler-Dalton watershed site C from July 20-24, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.11** Graph of mesoscale habitat temperatures in Cowee watershed site A from June 9-12, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.12** Graph of mesoscale habitat temperatures in Cowee watershed site B from June 9-12, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.13** Graph of mesoscale habitat temperatures in Cowee watershed site C from June 9-12, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.14** Graph of mesoscale habitat temperatures in Cowee watershed site D from June 9-12, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.15** Graph of mesoscale habitat temperatures in Cowee watershed site E from June 9-12, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.16** Graph of mesoscale habitat temperatures in Cowee watershed site F from June 9-12, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.17** Graph of mesoscale habitat temperatures in Cowee watershed site G from June 9-12, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.18** Graph of mesoscale habitat temperatures in Cowee watershed site H from June 9-12, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.19** Graph of mesoscale habitat temperatures in Darnell watershed site A from June 16-19, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.20** Graph of mesoscale habitat temperatures in Darnell watershed site B from June 16-19, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.21** Graph of mesoscale habitat temperatures in Darnell watershed site C from June 16-19, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.22** Graph of mesoscale habitat temperatures in Darnell watershed site D from June 16-19, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.23** Graph of mesoscale habitat temperatures in Darnell watershed site E from June 16-19, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.24** Graph of mesoscale habitat temperatures in Darnell watershed site F from June 16-19, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.25** Graph of mesoscale habitat temperatures in Darnell watershed site G from June 16-19, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.26** Graph of mesoscale habitat temperatures in Darnell watershed site H from June 16-19, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.27** Graph of mesoscale habitat temperatures in Hickory Knoll watershed site A from August 12-24, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.28** Graph of mesoscale habitat temperatures in Hickory Knoll watershed site B from August 12-24, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.29** Graph of mesoscale habitat temperatures in Hickory Knoll watershed site C from August 12-24, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.30** Graph of mesoscale habitat temperatures in Jones watershed site A from July 14-17, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.31** Graph of mesoscale habitat temperatures in Jones watershed site B from July 14-17, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.32** Graph of mesoscale habitat temperatures in Jones watershed site C from July 14-17, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.33** Graph of mesoscale habitat temperatures in Jones watershed site D from July 14-17, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.34** Graph of mesoscale habitat temperatures in Jones watershed site E from July 14-17, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.35** Graph of mesoscale habitat temperatures in Jones watershed site F from July 14-17, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.36** Graph of mesoscale habitat temperatures in Jones watershed site G from July 14-17, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.37** Graph of mesoscale habitat temperatures in Jones watershed site H from July 14-17, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.38** Graph of mesoscale habitat temperatures in Nickajack watershed site A from June 23-26, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.39** Graph of mesoscale habitat temperatures in Nickajack watershed site B from June 23-26, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.40** Graph of mesoscale habitat temperatures in Nickajack watershed site C from June 23-26, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.41** Graph of mesoscale habitat temperatures in Skeenah watershed site A from July 28-31, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.42** Graph of mesoscale habitat temperatures in Skeenah watershed site B from July 28-31, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.43** Graph of mesoscale habitat temperatures in Skeenah watershed site C from July 28-31, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



**Figure 2.44** Graph of mesoscale habitat temperatures in Skeenah watershed site D from July 28-31, 2009. X1= main riffle, X11-X13= riffle, 21-23= pool, X31-X33= alcove.



Figure 2.45 Thermal regimes of South Fork Skeenah and Ball Creek from June 12 – August 7, 2009



Figure 2.46 Mean daily discharge at USGS Gage #0350024, Cartoogechaye Creek near Franklin, NC, from June 12-August 7, 2009



**Figure 2.47** Boxplot of ΔMT versus habitat type for all 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; lowercase letters located above the distributions are from Fisher's (LSD) test, uppercase letters below are from Tukey's (HSD) test.



**Figure 2.48** Average  $\Delta$ MT values for each mesoscale habitat for all sites, fully forested sites, and partially forested sites



**Figure 2.49** Boxplot of ΔAMT versus habitat type for all 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; lowercase letters located above the distributions are from Fisher's (LSD) test, uppercase letters below are from Tukey's (HSD) test.



Figure 2.50 Average  $\Delta$ AMT values for each mesoscale habitat for all sites, fully forested sites, and partially forested sites



Figure 2.51 Average  $\Delta$ MDV values for each mesoscale habitat for all sites, fully forested sites, and partially forested sites



**Figure 2.52** Boxplot of  $\Delta$ MDV versus habitat type for all sites. Boxes represent the 25th-75th percentile, the line marks the median, error bars indicate the 90th and 10th percentiles.



**Figure 2.53** Boxplot of  $\Delta$ MT versus habitat type for the fully forested sites. Boxes represent the 25th-75th percentile, the line marks the median, error bars indicate the 90th and 10th percentiles.



**Figure 2.54** Boxplot of  $\triangle$ AMT versus habitat type for the fully forested sites. Boxes represent the 25th-75th percentile, the line marks the median, error bars indicate the 90th and 10th percentiles.



**Figure 2.55** Boxplot of  $\Delta$ MDV versus habitat type for the fully forested sites. Boxes represent the 25th-75th percentile, the line marks the median, error bars indicate the 90th and 10th percentiles.



Figure 2.56 Boxplot of △MT versus habitat type for the partially 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; lowercase letters located above the distributions are from Fisher's (LSD) test, uppercase letters below are from Tukey's (HSD) test.


**Figure 2.57** Boxplot of ΔAMT versus habitat type for the partially 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; lowercase letters located above the distributions are from Fisher's (LSD) test, uppercase letters below are from Tukey's (HSD) test.



**Figure 2.58** Boxplot of  $\Delta$ MDV versus habitat type for the partially forested sites. Boxes represent the 25th-75th percentile, the line marks the median, error bars indicate the 90th and 10th percentiles.



Figure 2.59 Scatter plot of  $SD_{MT}$  versus % non-forested



Figure 2.60 Scatterplot of SD<sub>MT</sub> versus riparian code



Figure 2.61 Scatter plot of  $SD_{MT}$  versus elevation (m)



Figure 2.62 Scatter plot of SD<sub>MT</sub> versus percent impervious surfaces



Figure 2.63 Scatter plot of ADV versus % non-forested



Figure 2.64 Scatter plot of ADV versus riparian code



Figure 2.65 Scatter plot of ADV versus elevation (m)



Figure 2.66 Scatter plot of ADV versus percent impervious surfaces



Figure 2.67 Scatter plot demonstrating reltionship between % non-forested and riparian code



Figure 2.68 Scatter plot demonstrating relationship between % non-forested and elevation



Figure 2.69 Scatter plot demonstrating relationship between % impervious surfaces and riparian code



Figure 2.70 Scatter plot demonstrating relationship between % impervious surfaces and % nonforested



Figure 2.71 Scatter plot demonstrating relationship between elevation and riparian code



Figure 2.72 Scatter plot demonstrating relationship between elevation and % impervious surfaces

Site	<b>SD</b> <sub>MT</sub>	ADV
Ball-A	0.114	1.779
Ball-B	0.090	1.466
Ball-C	0.064	1.465
Ball-D	0.069	1.104
Ball-E	0.117	1.170
Ball-F	0.127	1.023
Ball-G	0.067	0.761
Caler-Dalton-A	0.281	1.865
Caler-Dalton-B	0.067	1.577
Caler-Dalton-C	0.142	1.697
Cowee-A	0.790	3.721
Cowee-B	0.072	2.745
Cowee-C	0.830	3.880
Cowee-D	0.182	0.920
Cowee-E	0.119	1.963
Cowee-F	0.250	1.329
Cowee-G	0.211	0.787
Cowee-H	0.169	1.366
Darnell-A	1.488	2.686
Darnell-B	0.178	1.115
Darnell-C	0.176	1.187
Darnell-D	0.694	0.847
Darnell-E	0.082	0.955
Darnell-F	0.119	1.464
Darnell-G	0.350	1.816
Darnell-H	0.566	4.222

Table 2.1  $SD_{MT}$  and ADV for Ball, Caler-Dalton, Cowee and Darnell sites

Site	<b>SD</b> <sub>MT</sub>	ADV
Hickory Knoll-A	0.719	2.777
Hickory Knoll-B	0.499	2.490
Hickory Knoll-C	0.060	1.284
Jones-A	0.049	0.739
Jones-B	0.071	0.762
Jones-C	0.125	0.587
Jones-D	0.069	0.431
Jones-E	0.105	0.819
Jones-F	0.121	2.312
Jones-G	0.513	3.074
Jones-H	0.257	1.253
Nickajack-A	0.723	6.700
Nickajack-B	1.318	6.316
Nickajack-C	0.063	1.106
Skeenah-A	0.896	3.461
Skeenah-B	0.251	2.163
Skeenah-C	0.463	2.420
Skeenah-D	0.064	2.100

Table 2.2  $\mathrm{SD}_{\mathrm{MT}}$  and ADV for Hickory Knoll, Jones and Nickajack sites

	<b>Fully Forested</b>	Partially Forested		
SD <sub>MT</sub>	14.83	27.81		
ADV	10.72	30.65		

**Table 2.3** Mean ranks of the Wilcoxon rank sum non-parametric tests for SD<sub>MT</sub> and ADV for fully forested and partially forested sites

Table 2.4 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

#### DISCUSSION

### Variation of $\Delta MT$ , $\Delta AMT$ and $\Delta MDV$ with Mesoscale Habitat

The results of the statistical analyses show that pool tailouts have significantly lower  $\Delta$ MT and  $\Delta$ AMT values than the ends of riffles and the middle of main riffles for all sites. When analyzing the fully forested and partially forested sites separately, the same results were found for partially forested sites while there was no statistically significant difference found between mesoscale habitat types in the fully forested sites. When examining Figures 2.48, 2.50 and 2.51 it is evident that partially forested sites had a greater influence than the fully forested sites on the statistical results for all sites.

The results of the statistical analyses disagree with the original hypothesis that the ends of riffles and the middle of the main riffle exhibit cooler temperatures than pool tailouts and alcoves. Also, while there was a significant difference found between pool tailouts and riffle and main riffle habitats and between alcoves and riffles in the partially forested sites in the statistical analyses of  $\Delta$ MT and  $\Delta$ AMT, the actual difference in their values is not substantial (Figure 2.48, 2.50). Because there was a significant difference found between mesoscale habitat types 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), it is likely that there are no real hyporheic effects at these sites. The reasons for the lack of hyporheic effects 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 based on literature from other studies.

Most of the variability between mesoscale habitat types at each site tended to occur at the maximums (Figures 2.1-2.45). In watersheds which contained fully forested sites, the fully forested sites were consistently located upstream of the partially forested sites (Figures 1.3-1.10). As the sites in each watershed move from upstream headwaters to downstream mid-order streams the riparian code value steadily decreases with the exception of Skeenah sites A and B.

The partially forested sites receive greater solar radiation as a source of heat energy than the fully forested sites due to absent or reduced riparian cover which results in warmer surface water temperatures and increased diurnal variation relative to the fully forested sites (Swift and Messer 1971; Swift and Baker 1973; Sweeny 1993; Johnson and Jones 2000; Johnson 2004; Moore et al. 2005; Wilkerson et al. 2006). If hyporheic mixing occurs 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 surface and groundwater (Sinokrot and Stefan 1993; Evans et al. 1995). However on the same note, insolation during low flows in the summer months may act to dominate subsurface temperature patterns. Several studies have reported the importance of insolation as a dominant driver of stream maximum temperatures (Brown 1969; Sinokrot and Stefan 1993; Webb and Zhang 1997; Johnson 2004) and it is possible that the dominant driver of maximum stream temperature metrics at the partially forested sites is insolation which, especially during the summer months, may exert significant controls on subsurface temperatures and supersede hyporheic effects at these sites (Evans et al. 1998; Danehy et al. 2005).

In retrospect, riffle habitats may have been found to be warmer because riffle habitats are shallow and occur in the center of stream channels, making them more susceptible to the effects of solar insolation relative to deeper pools and alcoves. Alcoves, although shallow, 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) which may shield alcoves at least partly from insolation potentially explaining why they were found to be 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; Elliot 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.

It is possible that the physical properties of the hyporheic zones in the partially forested sites are different than expected and so do not exhibit the expected effects on surface water temperatures. Studies have found that hyporheic zone water temperatures are higher in streams with warmer surface waters (Ringler and Hall 1975; Boulton et al. 1997). Alexander (2003) found that the temperature of hyporheic flow is determined by what proportion of it is made up of groundwater or surface water, if it is surface water dominated it is usually warmer. A warm surface water dominated hyporheic zone would not display much temperature variation from the surface water, making hyporheic effects undetectable and/or insignificant with regards to temperature. However, it is impossible to say whether the hyporheic zones in the partially forested sites in this study are dominated by warm surface water inputs based on the data collected in this study.

There are studies which 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 Hynes1982; Storey et al. 1999; Sliva 2005). Surface disturbances such as boulders and logs alter the flow of water through the hyporheic zone (White 1990). White et al. (1987) attributed the irregular subsurface flow path found within a riffle to surface and buried rocks within the riffle that altered the permeability of the substratum and concluded that expected hyporheic flow patterns do not occur in all rifflepool sequences. Gooseff et al. (2006) hypothesized that shallow bedrock sills could create sudden hyporheic upwelling upstream of the sill and downwelling below the sill regardless of the mesoscale habitat type. Heterogeneity within the streambed and the resulting heterogeneous hydraulic conductivity of the streambed causes significant flux in the hyporheic zone (Cardenas and Wilson 2004). Low hydraulic conductivity within the hyporheic zone acts to increase residence time and therefore increases the opportunity for heat flux between infiltrating surface flow and the stream bed (Evans et al. 1995). Different stream bed materials also have different thermal conductivities which affects the rate of heat flux between the infiltrating water and the bed material (Sinokrot and Stefan 1993). Evans et al. (1998) recorded significant spatial variation in the conduction rates of the channel bed as well as micro-scale variations in heat transfer caused by heterogeneous sediments within the channel beds. It is unknown whether any of the above 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.

Different bedform shapes and sizes also produce different rates of hyporheic exchange, namely the amplitude and wavelength of the bedforms; in general the greater the amplitude the greater depth of infiltration (Elliot and Brooks 1997b; Marion et al. 2002). The influence of channel geomorphology on hyporheic flow changes with stream size (Kasahara and Wondzell 2003). Gooseff et al. (2006) and Anderson et al. (2005) found that downwelling zone lengths increase from headwater to mid-order reaches as a result of increases in geomorphic unit size and spacing. In addition, Anderson et al. (2005) found that the concavity of surface water decreases with increasing basin area and that because greater concavity increases hyporheic exchange, headwater streams would have greater hyporheic mixing than mid-order streams where concavity is diminished. This suggests that the partially forested sites in this study, which are located downstream of the fully forested sites in their respective watersheds and have larger basin areas potentially have less surface water concavity and therefore less potential for hyporheic mixing than the fully forested sites located in the headwaters. In addition, Cardenas and Wilson (2004) found that the influences of heterogeneous bed forms on hyporheic mixing are more important when the geomorphic unit size and spacing are increased. So the possible combined effect of increasing geomorphic unit size and spacing with increasing basin area and heterogeneous channel beds could lead to highly unpredictable hyporheic flows in the partially forested sites.

The lack of temperature differences in the fully forested sites between mesoscale habitat types may be caused by several factors. They occur at higher elevation and because of the relationship between ambient air temperature and stream temperature, elevation may be exerting a direct negative effect on stream temperature (Cluis 1972; Stefan and Preud'homme 1993; Mohseni and Stefan 1999; Isaak and Hubert 2001; Scott et al. 2002; Hunter and Quinn 2009).

The fully forested sites also have more shade from solar insolation. Both of these factors decrease stream maximum temperatures which may diminish the differences between stream and subsurface water temperatures (Swift and Messer 1971; Swift and Baker 1973; and Stefan 1993; Sweeny 1993; Evans et al. 1995; Johnson and Jones 2000; Johnson 2004; Moore et al. 2005; Wilkerson et al. 2006). In addition, because the fully forested sites are smaller streams that occur at higher elevations, and compose the headwaters of the watersheds in this study, they are likely to have increased slopes, coarser streambed sediments and increased surface water concavity relative to the partially forested sites which encourages frequent exchange of surface and hyporheic water (Winter et al. 1998; Anderson et al. 2005; Gooseff et al. 2006). This frequent exchange between hyporheic and surface water would further diminish the temperature differences between the two. Therefore, not only is there potentially decreased difference in temperatures between the surface water and subsurface water because of increased shading, but the increased opportunity for hyporheic buffering of the surface water may further decrease the temperature differences between these two, possibly making temperature an ineffective tracer of hyporheic mixing in these sites.

## SD<sub>MT</sub> & ADV

## **Riparian Condition**

The partially forested sites have significantly higher  $SD_{MT}$  than the fully forested sites, meaning that the partially forested sites have greater variation of maximum temperatures between the ten loggers within each site. This indicates that temperature logger 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 maximums caused by increased solar radiation and increased diurnal air temperature range from decreased riparian cover (Swift and Messer 1971; Swift and Baker 1973; Sweeny 1993; Johnson and Jones 2000; Moore et al. 2005; Wilkerson et al. 2006).

#### Environmental Controls

The four environmental factors inspected in this study, elevation, % impervious surfaces, riparian code and % non-forested 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. In general, as is typical for the development in the Southern Appalachian Mountains, there is more agricultural and urban development in the valleys and less in higher elevations where slopes are steeper leaving greater forest cover at higher elevations with less forest cover and greater impervious surfaces at lower elevations (Figures 2.68, 2.71 and 2.72).

The significant correlation between  $SD_{MT}$  and % forest cover and riparian code demonstrate that as riparian forest cover decreases the variability of maximum temperatures between loggers within the site increases. The range of temperatures (ADV) found at a site also increase with decreasing riparian cover. These results support the previous conclusions that  $SD_{MT}$  and ADV are higher in the partially forested sites further stressing the importance of riparian cover and insolation on the spatial distribution and range of temperatures within a site.

ADV was positively associated with % impervious surfaces (developed land) despite the fact that the actual percentages of developed land are relatively low for all sites, implying a high sensitivity of stream water temperature 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.

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 which have less riparian cover receive greater solar inputs which increase the ranges of stream temperatures by increasing maximum stream temperatures, (Swift and Messer 1971; Swift and Baker 1973; Sweeny 1993; Johnson and Jones 2000; Wilkerson et al. 2006). Streams under forest cover also have a different microclimate than sites with no forest cover with generally have less diurnal variation of air temperature than more open sites (Moore et al. 2005) which may also be acting to mute the ADV of stream temperatures at these sites based on the relationship between ambient air temperature and stream temperature (Cluis 1972; Stefan and Preud'homme 1993; Mohseni and Stefan 1999). In addition, because of the relationship between air and stream temperature, 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.

# Sunlight

Solar insolation in the form of brief but substantial spikes in stream temperature imposes major effects on the daily maximum temperatures (Appendix A). These sudden spikes in temperature were not used in the analyses because it would have distorted the data and was not relevant to the questions of interest; however they are likely important to the natural thermal regime of streams in this study. These insolation driven temperature spikes occurred from never at some sites to multiple times per day every day in others. When they did occur it was typically between 12-3pm, before the natural maximum stream temperature (Appendix A). It is most likely that these spikes occurred because of patchy shading by riparian cover which would make sudden exposure to direct sunlight through the trees 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 with that riparian code that experienced sunlight caused temperature spikes increases (Table 3.1) indicating that theses spikes are more important in forested streams. However, these spikes are short lived and temperatures return to the normal diurnal pattern quickly (Appendix A).

Riparian Code	# Sites	# of Sites with temperature spikes	% of Sites with temperature spikes
0 (occasional or no trees)	5	0	0%
1 (< 3m buffer)	9	4	44%
2 (3-10m buffer or one-sided buffer)	12	6	50%
3 (fully forested)	18	13	72%

**Table 3.1** Percent of sites by riparian code that had sudden temperature spikes created by sunlight

#### **CONCLUSIONS**

Statistically significant differences in stream water temperature metrics between mesoscale habitats were found, however, they are the opposite of what is 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 at the mesoscale habitats at these sites that can be detected by the means used in this study.

It is likely that other factors influenced water temperature and hyporheic mixing more than the longitudinal profile of the stream bed. 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 and Wilson 2004; Wright et al. 2005; Wondzell and Swanson1996). In addition, the relative importance of these processes is dynamic and likely to vary at different scales and for different stream orders and under different seasons (Webb and Zhang 1997; Kasahara and Wondzell 2003; Cardenas and Wilson 2004; Anderson et al. 2005; Gooseff et al. 2006).

Solar insolation and riparian condition are 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

distribution and range of temperatures and a significant difference in  $\Delta MT$  and  $\Delta AMT$  between habitat types. This indicates that the locations where temperature measurements are recorded are more important at partially forested sites. However, sudden temperature spikes created by sunlight temporarily shining through riparian cover tend to occur more often in partial and full riparian cover. These spikes are brief and temperatures quickly return to the normal diurnal pattern after these spikes occur and it is unknown what effects they may have on stream biota. Nevertheless, it is important to note the incidence of these sunlight-driven temperature spikes 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. More importantly, however, are the spatial variations of maximum temperature found in partially forested sites. While 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, although not what was expected if hyporheic mixing was the dominant driver of temperatures at these mesoscale habitats. Although hyporheic exchange was probably not the dominant control of temperature for the mesoscale habitats in these streams, the location where stream temperature data are recorded within a reach is still important for streams in the upper Little Tennessee River basin that are not fully forested as some minor differences in temperatures between mesoscale habitat types do exist. These results suggest a need for standardization of temperature sensor placement within a stream channel and that, in general, greater care be given to stream temperature sampling methodology.

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## APPENDIX A



Graphs of sites with temperature spikes caused by sunlight

Figure 4.1 Graph of Ball watershed site A with sunlight produced temperature spikes



Figure 4.2 Graph of Ball watershed site B with sunlight produced temperature spikes



Figure 4.3 Graph of Ball watershed site C with sunlight produced temperature spikes



Figure 4.4 Graph of Ball watershed site D with sunlight produced temperature spikes



Figure 4.5 Graph of Ball watershed site E with sunlight produced temperature spikes


Figure 4.6 Graph of Ball watershed site F with sunlight produced temperature spikes



Figure 4.7 Graph of Ball watershed site G with sunlight produced temperature spikes



Figure 4.8 Graph of Caler-Dalton watershed site A with sunlight produced temperature spikes



Figure 4.9 Graph of Caler-Dalton watershed site C with sunlight produced temperature spikes



Figure 4.10 Graph of Cowee watershed site B with sunlight produced temperature spikes



Figure 4.11 Graph of Cowee watershed site D with sunlight produced temperature spikes



Figure 4.12 Graph of Cowee watershed site F with sunlight produced temperature spikes



Figure 4.13 Graph of Darnell watershed site B with sunlight produced temperature spikes



Figure 4.14 Graph of Darnell watershed site E with sunlight produced temperature spikes



Figure 4.15 Graph of Darnell watershed site F with sunlight produced temperature spikes



Figure 4.16 Graph of Hickory Knoll watershed site C with sunlight produced temperature spikes



Figure 4.17 Graph of Jones watershed site B with sunlight produced temperature spikes



Figure 4.18 Graph of Jones watershed site C with sunlight produced temperature spikes



Figure 4.19 Graph of Jones watershed site E with sunlight produced temperature spikes



Figure 4.20 Graph of Jones watershed site H with sunlight produced temperature spikes



Figure 4.21 Graph of Nickajack watershed site C with sunlight produced temperature spikes



Figure 4.22 Graph of Skeenah watershed site D with sunlight produced temperature spikes

# APPENDIX B

Results of the Kruskal-Wallis nonparametric tests for  $\Delta$ MT,  $\Delta$ AMT, and  $\Delta$ MDV with respect to habitat type for all sites, fully forested, and partially forested sites

\*\*\*\*\* The SAS System 3 17:43 Wednesday, October 5, 2011 The NPAR1WAY Procedure Wilcoxon Scores (Rank Sums) for Variable MT Classified by Variable HABITAT Sum of Expected Std Dev Mean Under HØ HABITAT Ν Scores Under HØ Score 8944.0 744.64186 M.riffle 43 9784.50 227.546512 Riffle 128 29065.50 26624.0 1128.46393 227.074219 Pool 124 23768.50 25792.0 1118.40497 191.681452 Alcove 120 23701.50 24960.0 1107.75414 197.512500 Average scores were used for ties.

Kruskal-Wallis Test

Chi-Square	7.5921
DF	3
Pr > Chi-Square	0.0552

The SAS System 14 17:43 Wednesday, October 5, 2011

The NPAR1WAY Procedure

Wilcoxon Scores (Rank Sums) for Variable AMT Classified by Variable HABITAT

		Sum of	Expected	Std Dev	Mean
HABITAT	Ν	Scores	Under HØ	Under HØ	Score
ffffffff	fffffffffff	<i>ffffffffffffff</i>	, ,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,		, ffffffffffffff
M.riffle	43	9308.50	8944.0	744.66055	216.476744
Riffle	128	28827.00	26624.0	1128.49226	225.210938
Pool	124	24370.50	25792.0	1118.43304	196.536290
Alcove	120	23814.00	24960.0	1107.78195	198.450000

Average scores were used for ties.

Chi-Square	4.7437
DF	3
Pr > Chi-Square	0.1916

## The SAS System

17:43 Wednesday, October 5, 2011

7

8

## The NPAR1WAY Procedure

### Wilcoxon Scores (Rank Sums) for Variable MDV Classified by Variable HABITAT

		Sum of	Expected	Std Dev	Mean
HABITAT	N	Scores	Under HØ	Under HØ	Score
ffffffff	fffffffffff	<i>.</i> <i>.</i> <i>.</i> <i>.</i> <i>.</i> <i>.</i> <i>.</i> <i>.</i> <i>.</i> <i>.</i>	fffffffffffffff		fffffffffff
M.riffle	43	9271.50	8944.0	744.64249	215.616279
Riffle	128	29186.00	26624.0	1128.46488	228.015625
Pool	124	24456.00	25792.0	1118.40591	197.225806
Alcove	120	23406.50	24960.0	1107.75507	195.054167

Average scores were used for ties.

### Kruskal-Wallis Test

Chi-S	quare 6.1366	i i i i i i i i i i i i i i i i i i i
DF		1
Pr >	Chi-Square 0.105	
*******	*****	******

The SAS System

17:43 Wednesday, October 5, 2011

## The NPAR1WAY Procedure

Wilcoxon Scores (Rank Sums) for Variable FFMT Classified by Variable HABITAT

		Sum of	Expected	Std Dev	Mean
HABITAT	Ν	Scores	Under HØ	Under HØ	Score
ffffffff	fffffffffff	fffffffffffff	ffffffffffffffff	ffffffffffff	, ffffffffffffff
M.Riffle	18	1288.00	1548.0	198.632840	71.555556
Riffle	53	4437.50	4558.0	299.328468	83.726415
Pool	50	4506.00	4300.0	294.406078	90.120000
Alcove	50	4474.50	4300.0	294.406078	89.490000

Average scores were used for ties.

Chi-Square	2.2399
DF	3
Pr > Chi-Square	0.5241

## The SAS System

17:43 Wednesday, October 5, 2011

9

## The NPAR1WAY Procedure

### Wilcoxon Scores (Rank Sums) for Variable FFAMT Classified by Variable HABITAT

		Sum of	Expected	Std Dev	Mean
HABITAT	Ν	Scores	Under H0	Under HØ	Score
ffffffff	fffffffffff	fffffffffffff	fffffffffffffff	, fffffffffffffffff	fffffffffff
M.Riffle	18	1441.50	1548.0	198.667535	80.083333
Riffle	53	4607.00	4558.0	299.380751	86.924528
Pool	50	4311.00	4300.0	294.457501	86.220000
Alcove	50	4346.50	4300.0	294.457501	86.930000

Average scores were used for ties.

### Kruskal-Wallis Test

Chi-Square	0.2942
DF	3
Pr > Chi-S	oquare 0.9611
***************************************	***************************************

The SAS System 10 17:43 Wednesday, October 5, 2011

### The NPAR1WAY Procedure

### Wilcoxon Scores (Rank Sums) for Variable FFMDV Classified by Variable HABITAT

		Sum of	Expected	Std Dev	Mean
HABITAT	Ν	Scores	Under HØ	Under HØ	Score
ffffffff	fffffffffff	ſſſſſſ	ffffffffffffffff	fffffffffffff	ffffffffffff
M.Riffle	18	1242.00	1548.0	198.626878	69.000000
Riffle	53	4484.00	4558.0	299.319484	84.603774
Pool	50	4495.50	4300.0	294.397242	89.910000
Alcove	50	4484.50	4300.0	294.397242	89.690000

Average scores were used for ties.

Chi-Square	2.7557
DF	3
Pr > Chi-Square	0.4308

The SAS System

17:43 Wednesday, October 5, 2011

11

## The NPAR1WAY Procedure

Wilcoxon Scores (Rank Sums) for Variable NFFMT Classified by Variable HABITAT

		Sum of	Expected	Std Dev	Mean
HABITAT	Ν	Scores	Under HØ	Under HØ	Score
ffffffff	fffffffffff	ſſſſſſ	ffffffffffffff	fffffffffffffff	fffffffffff
M.Riffle	25	3704.50	3062.50	334.310585	148.180000
Riffle	75	10604.00	9187.50	508.665226	141.386667
Pool	74	7774.50	9065.00	506.755401	105.060811
Alcove	70	7807.00	8575.00	498.633795	111.528571

Average scores were used for ties.

### Kruskal-Wallis Test

Chi-Square	14.8911
DF	3
Pr > Chi-Square	0.0019

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The SAS System 12 17:43 Wednesday, October 5, 2011

### The NPAR1WAY Procedure

Wilcoxon Scores (Rank Sums) for Variable NFFAMT Classified by Variable HABITAT

		Sum of	Expected	Std Dev	Mean
HABITAT	Ν	Scores	Under H0	Under H0	Score
ffffffff	fffffffffff	ffffffffffffff	ſfffffffffffff		fffffffffff
M.Riffle	25	3372.00	3062.50	334.331783	134.880000
Riffle	75	10361.00	9187.50	508.697480	138.146667
Pool	74	8217.50	9065.00	506.787534	111.047297
Alcove	70	7939.50	8575.00	498.665413	113.421429

Average scores were used for ties.

Chi-Square	7.5617
DF	3
Pr > Chi-Square	0.0560

## The SAS System

17:43 Wednesday, October 5, 2011

13

# The NPAR1WAY Procedure

## Wilcoxon Scores (Rank Sums) for Variable NFFMDV Classified by Variable HABITAT

		Sum of	Expected	Std Dev	Mean
HABITAT	Ν	Scores	Under H0	Under H0	Score
fffffffff	fffffffff	,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	fffffffffffffff	ffffffffffffff	fffffffffff
M.Riffle	25	3519.00	3062.50	334.321633	140.760000
Riffle	75	10605.50	9187.50	508.682037	141.406667
Pool	74	8055.00	9065.00	506.772148	108.851351
Alcove	70	7710.50	8575.00	498.650273	110.150000

Average scores were used for ties.

Chi-Square	11.9664
DF	3
Pr > Chi-Square	0.0075