

Approved and recommended for acceptance as a thesis in partial fulfillment of the requirements for the degree of Master of Science

Special committee directing the thesis work of David Brad Fink

Thesis Co-Advisor	Date
-------------------	------

Thesis Co-Advisor	Date
-------------------	------

Member	Date
--------	------

Department Head	Date
-----------------	------

Received by The Graduate School

Date

Artificial Shading and Stream Temperature Modeling for Watershed Restoration and
Brook Trout (*Salvenius fontinalis*) Management

David Brad Fink

A thesis submitted to the Graduate Faculty of

JAMES MADISON UNIVERSITY

In

Partial Fulfillment of the Requirements

for the Degree of

Master of Science

Department of Biology

May 2008

Acknowledgements

I would like to thank Mr. Mark Hudy for his support and leadership through the completion of this study. His assistance in project design, implementation, and data analysis will no doubt benefit my career and future success in the management of natural resources and environmental research.

I would also like to thank additional committee members, Dr. Reid Harris and Dr. Jon Kastendiek, for their useful advice with project design and excellent guidance throughout my time here at James Madison University. I appreciate the assistance of Dr. Grace Wyngaard with statistical analysis of stream temperature comparisons and of Dr. Samantha Bates Prins and Dr. Nusrat Jahan for their statistical assistance in developing the stream temperature model used to indicate major areas for restoration. I would like to thank Dr. Christine May for her useful advice in stream hydrology and project design. I am thankful for the faculty's input and questions on project design and implementation during my department proposal and project status presentations.

I would like to notice fellow graduate students Sara Sweeten, Jeremy Shiflet and Morgan Hyatt for their assistance throughout my study. Their hard work and determination made it possible to simulate a riparian canopy by helping shade the stream reach at the study site. They were also instrumental in reviewing and supplying feedback during the writing of this thesis.

I would like to thank Debbie Rexrode of the Deans Office for her purchasing support during my study. Many trips were made to the hardware store and without her assistance many of the tasks during the project would have been put on hold. Additionally, I would like to thank Robin Stidham and Craig Roghair of the USDA

Forest Service for their exceptional administration support during the hiring of summer technicians.

Our shade cloth provider was also a very important part of this study. Thanks to Chuck Hearn for his willingness to negotiate price for research and excellent coordination skills. PAK unlimited provided a strong useful product for this experiment and their cooperation should not be overlooked.

Additional agencies and organizations that played an important role both in funding and man-hours include: Eastern Brook Trout Joint Venture, U.S. Forest Service, Virginia Department of Game and Inland Fisheries, U.S. Fish and Wildlife Service, Virginia Tech, Trout Unlimited, and Canaan Valley Institute.

Table of Contents

Acknowledgements	ii
List of Tables	v
List of Figures	vi
Abstract	vii
 Chapter One:	
Artificial Stream Shading	
Introduction	1
Methods	3
Study Area	3
Artificial Shading Method	5
Data Collected	8
Data Analysis	9
Results	10
Discussion	12
 Chapter Two:	
Watershed Modeling for Restoration Sites	
Introduction	15
Methods	16
Stream Temperature Model	16
Data Analysis	19
Results	19
Model Validation	19
Discussion	23
 Chapter Three:	
Climate Change vs. Riparian Restoration	
Introduction	25
Methods	26
Results	27
Discussion	31
Bibliography	33

List of Tables

Table 1.1: Daily mean and daily maximum mean differences during the Critical Period before shade in 2006 and after shade in 2007. Differences from Site C to Site D; Site C to Star Site (700 m below Site D); Site C to Site E (1,000 m below Site D).....	11
Table 2.1: Current percent shade produced by canopy cover for each stream segment....	19
Table 2.2: Predicted mean maximum temperatures at 10 to 90 % shade from July 26 to September 15 (Temperature °C)	20
Table 2.3: Current mean maximum temperatures compared to mean maximum temperatures with 80% shade from July 26 to September 15 (Temperature °C).....	20
Table 2.4: Predicted mean daily mean temperatures at 10 to 90% shade from July 26 to September 15 (Temperature °C)	21
Table 2.5: Current mean daily mean stream temperatures compared to mean daily mean stream temperatures with 80% shade from July 26 to September 15 (Temperature °C)...	21
Table 3.1: Predicted mean daily maximum temperature for each segment with a mature forest canopy of 80% shade and 1, 3, and 5 °C increases in mean daily air temperature..	29
Table 3.2: Predicted mean daily mean temperatures for each segment with a mature forest canopy of 80% shade and 1, 3, and 5 °C increases in mean daily air temperature.....	29

List of Figures

Figure 1.1: Study site on Smith Creek in northeast Rockingham County, VA	4
Figure 1.2: Aerial photograph of subwatershed with Fridley Gap brook trout population ..	5
Figure 1.3: Onset Hobo Water Temp Pro temperature loggers, artificial shade locations, and model segment	6
Figure 1.4: Diagram of cable support system constructed to hold shade cloth. Black spots are fence post; dotted lines are high tensile fencing; blue represents stream surface.....	7
Figure 1.5: Rolling maximum temperatures (°C) at site D from July 26 th to September 15 th before shade in 2006 and during shade in 2007.....	12
Figure 3.1: Stream Temperature (°C) at Site D with modeled 80% shade (blue), and predicted increases in stream temperature with mean daily air increases of 1, 3, and 5 degrees	30

Abstract

Increases in stream water temperatures from the removal of riparian vegetation are one of the major reasons for extirpation of brook trout. Recent riparian plantings by the Eastern Brook Trout Joint Venture are long-term restoration efforts and the outcome of these plantings may not be known for decades. I evaluated the feasibility of success on the Smith Creek Restoration Project (Rockingham County, Virginia) by simulating a full riparian canopy through artificial shading of 550 meters of stream. I compared air and stream temperature data before, during and after (June 2006 to November 2007) the shading experiment (July 26 through September 15, 2007) and developed step-wise linear regressions to predict stream temperatures. Additionally, I developed relationships between air and stream temperature to predict the effect of climate change on the Smith Creek Restoration Project. The artificial shading cooled maximum daily temperatures by 1.4 °C at the most downstream site creating a 700 meter (mean daily maximum) thermal refuge (< 23 °C). The model predicted stream temperature decreases of 1.2 °C and 1.0 °C if riparian canopy was restored in the upper reaches. Restoring the riparian canopy to 80 % shade would offset (maintain current daily maximum temperatures) a mean air temperature increase of 2.2 °C from climate change. Biologist can develop models to predict the success of future restoration projects by collecting simple air and water temperature measurements. These measurements can also be used to predict restoration success under different climate change scenarios.

Chapter One: Artificial Stream Shading

Introduction

Stream habitat is often the major factor determining the composition of aquatic communities and stream temperature is a major contributor in determining stream habitat (Bovee 1982). Most aquatic species are subject to physiological thermal limits which are usually most stressful during the summer months (Saila et al. 2004). Activities causing riparian vegetation removal such as agriculture, timber harvest and urbanization can contribute to a high range of diurnal temperature fluctuations and may increase daily mean stream temperature (Barton and Taylor 1985). Studies have indicated a mean increase of 1 to 3 °C following timber harvest activities (Brownlee et al. 1988). Riparian vegetation removal can affect stream temperature for multiple decades before the riparian canopy is restored (Hostetler 1991). Many streams across the country have had riparian ecosystems greatly altered over the last two centuries (Sugimoto et al. 1997) and average stream temperature has been shown to significantly increase after adjacent vegetation is removed (Brown and Krygier 1970; Johnson and Jones 2000).

Brook trout (*Salvelinus fontinalis*) are a coldwater species relying on stream temperatures not exceeding 24 °C (Ricker 1934; MacCrimmon and Campbell 1969; Meisner 1990b). Salmonid mortality increases when stream temperatures reach the 23 to 25 °C range (Matthews and Berg 1997). Barton and Taylor (1985) found that a stream in Ontario with a weekly mean of 22 °C or below supported viable populations of brook trout. Streams with weekly means higher than 22 °C had either weak or non-existing populations. Although brook trout prefer colder temperatures they may survive high critical thermal maximums if other environmental factors such as pH, cover, dissolved

oxygen and other variables are acceptable. Unfortunately, many streams along the brook trouts southern range reach and exceed these maximum limits (Matthews and Berg 1997). Elliot (1994) listed the brook trout thermal limit as 25.3 °C and Saila et al. (2004) determined a reasonable thermal tolerance under summer conditions to be 23 °C based on a literature review. Clearly these upper thermal limits are under ideal conditions and will not benefit feeding or growth of coldwater species. Under ideal situations the most beneficial stream temperature to increase brook trout feeding and growth occurs between 10 to 16 °C (MacCrimmon and Campbell 1969; Cherry et al. 1977).

Stream temperature affects species composition and multiple biological and chemical processes within a watershed's ecosystem (Bovee 1982). Growth and mortality of many species is determined by daily maximum and minimum stream temperatures throughout the year. Additionally, chemical processes such as decomposition may be heavily influenced by stream temperatures (Bovee 1982). Although mean maximum stream temperature may reach lethal limits during the summer for some species, various coldwater refuges are available in most streams. These refuges may be utilized by brook trout and other salmonids which are sensitive to warmwater temperatures. Many of these refuges are located adjacent to tributaries or groundwater inputs that supply cooler water than the mainstream flow (Nielsen et al. 1994; Bonneau and Scarnecchia 1996).

Salmonids have been found to sustain cooler body temperatures during summer months with the use of thermal refuges within a watershed. Berman and Quinn (1991) found chinook salmon (*Oncorhynchus tshawytscha*) maintained a lower body temperature than the mean stream temperature during warmwater periods. Bonneau and Scarnecchia (1996) found juvenile bull trout (*Salvelinus confluentus*) utilized thermal

refuges in pools created by cooler tributary inputs. Many trout species migrate to second and third order headwater streams near groundwater inputs for thermal refuge; however, these streams often experience low flow rates during the summer drought conditions.

Many fish communities and trout populations have been altered due to increasing stream temperatures (Wehrly et al. 2007). Some projects have focused on determining the effects of canopy cover cooling stream temperatures. These studies have indicated stream temperatures decline after entering forest canopy areas (Zwieniecki and Newton 1999). The majority of heat loss under shaded conditions is primarily attributed to convective heat exchanges (Larson et al. 2002). Understanding how shade from riparian vegetation may affect stream temperature is essential in designing watershed restoration projects and managing recovering brook trout populations.

The objectives of this chapter are to determine 1) the effects of shading on daily maximum, daily minimum and mean daily temperatures throughout the Smith Creek Restoration Area and 2) compare shaded temperature metrics to brook trout thermal limits to determine the feasibility of reintroduction.

Methods

Study Area

The study area is located in a subwatershed of Smith Creek in northeast Rockingham County, Virginia (Figure 1.1). The watershed historically sustained a native brook trout population in the Smith Creek Restoration Area. However, agricultural landuse over the last two centuries in the area has degraded the habitat and extirpated the brook trout population in this area. Brook trout still inhabit the headwater areas of the

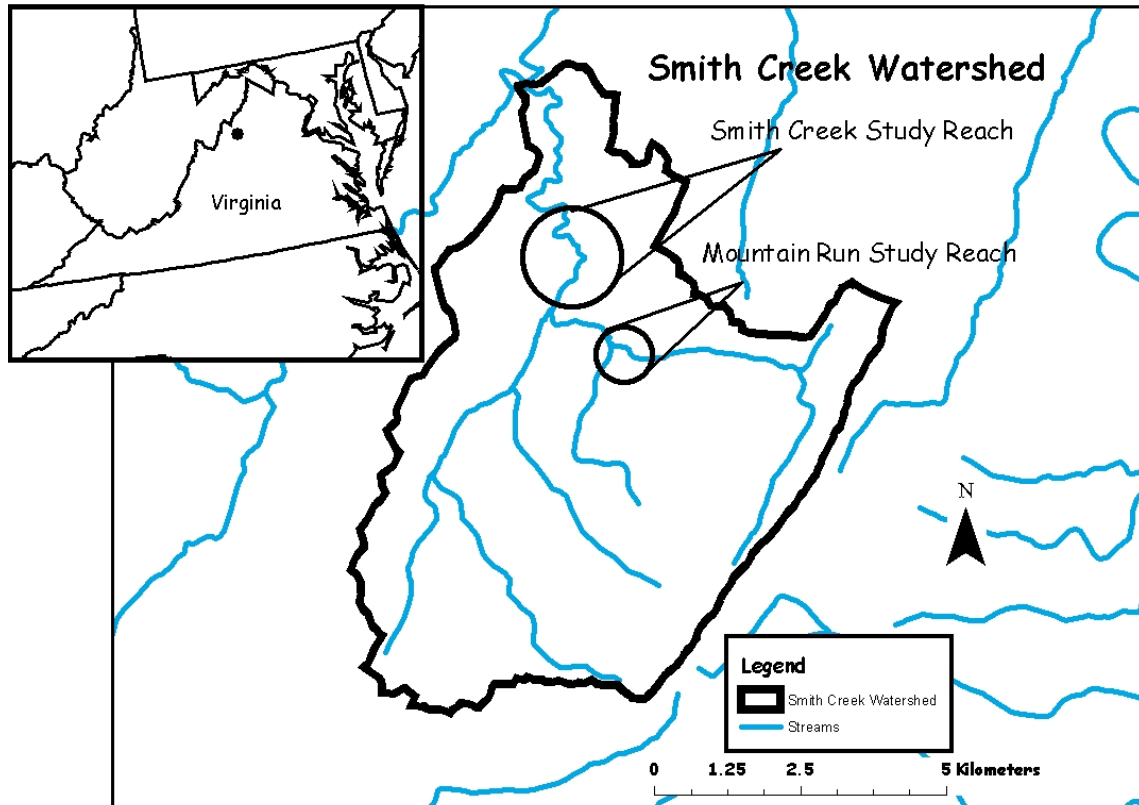


Figure 1.1. Study area on Smith Creek in northeast Rockingham County, VA.

subwatershed in an area known as Fridley Gap (Figure 1.2). The population was almost extirpated before a liming project was conducted in 1993 to buffer the acidity of the stream and restore the population to a yearly average of 300 adult trout (Hudy et al. 2000). However, the existing population may not be large enough for long-term viability. To achieve short-term or long-term viability the population should meet the $N_e = 50:500$ rule. An effective population size (N_e) of 50 is the minimum viable population size to allow survival and reduce the chance of inbreeding for 100 years (Soule 1980). Long-term survival requires a N_e of at least 500 allowing the population to retain genetic viability which is crucial to continue evolving with environmental factors (Franklin 1980).

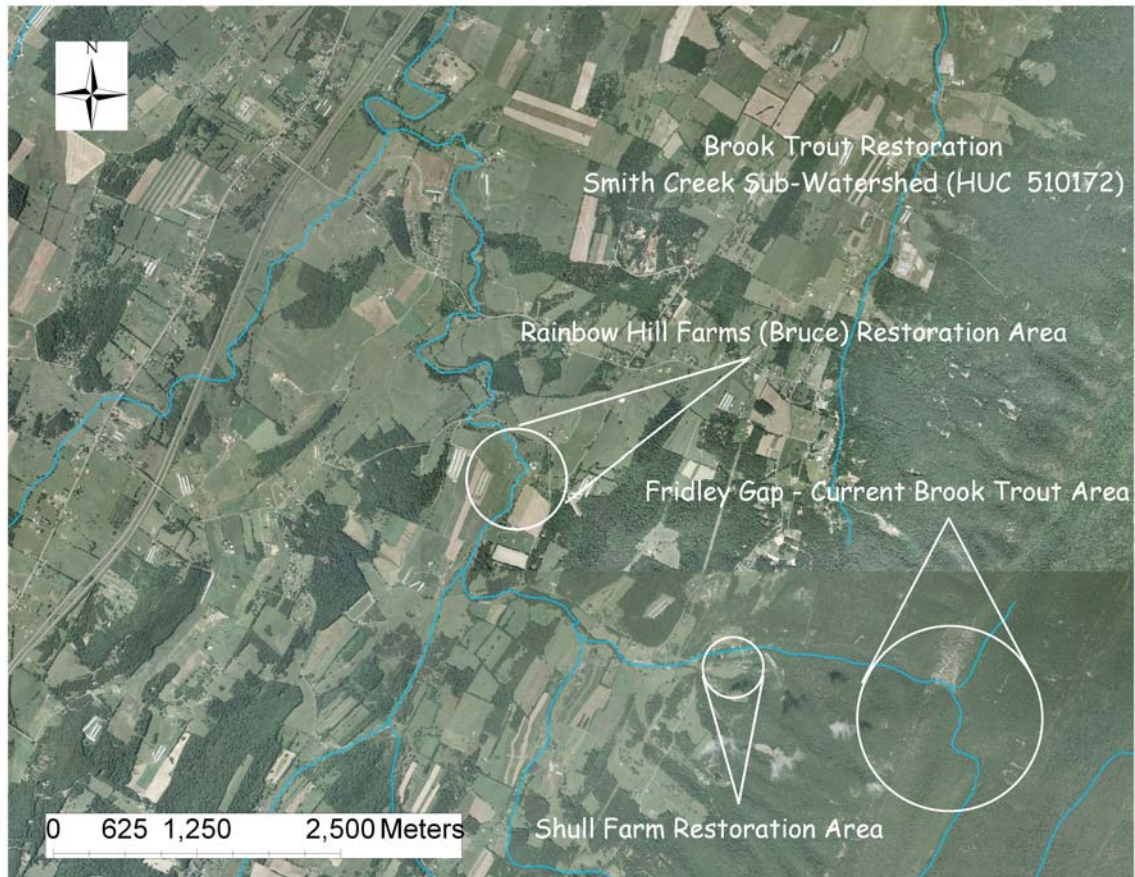


Figure 1.2. Aerial photograph of subwatershed with Fridley Gap brook trout population.

Current restoration efforts are underway to restore riparian vegetation in past agriculture areas downstream of Fridley Gap. The restoration efforts are underway to create coldwater refuge areas in the lower reaches for brook trout during the summer months. This would allow the current reproducing population in the headwaters to extend its range downstream and potentially increase population viability.

Artificial Shading Methods

We shaded 550 meters of stream in the Smith Creek Restoration Area on Rainbow Hill Farms Inc. (Figure 1.3). Ten centimeter fence posts were placed every 9.1 meters along the stream bank on both sides. Trees were used in place of fence post where they were present. We attached three pieces of 9.5 gauge high tensile fencing to

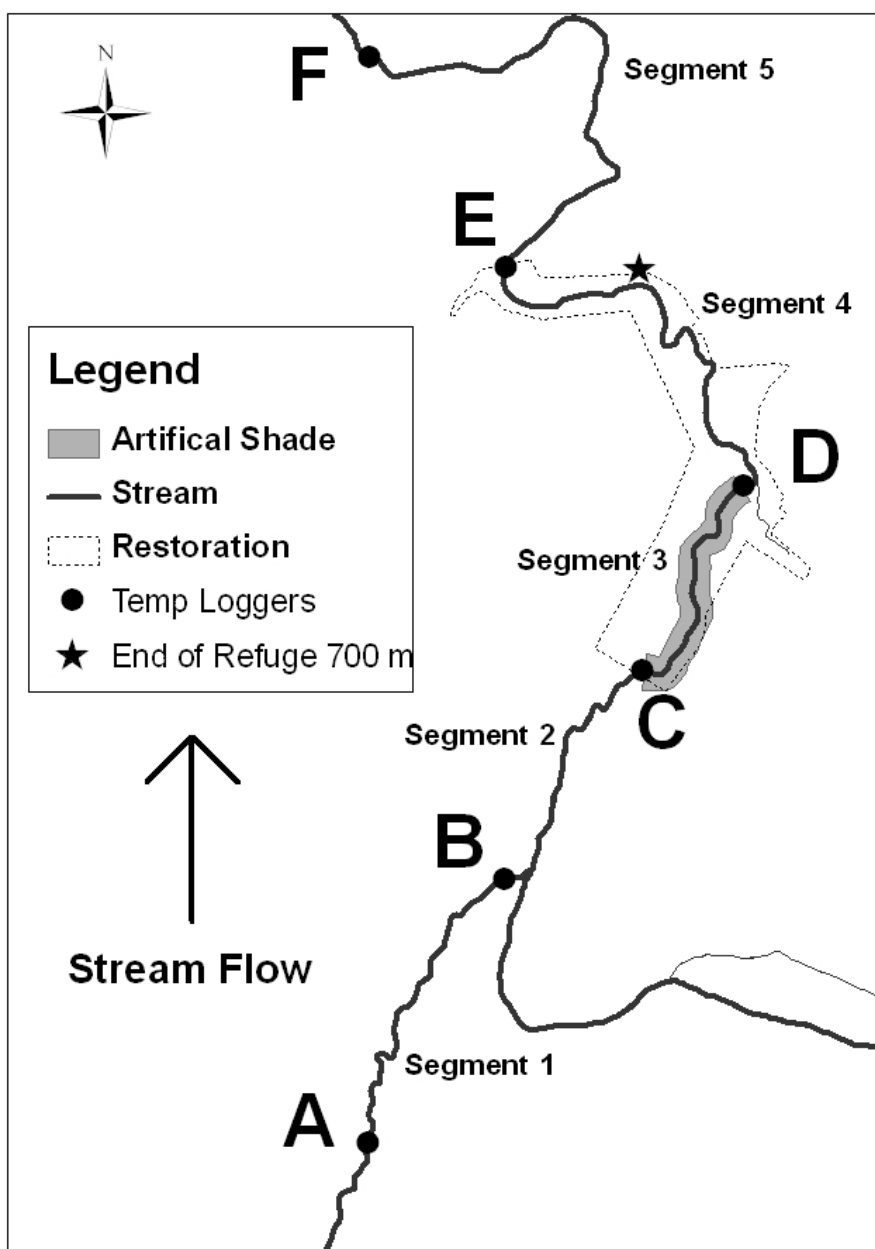


Figure 1.3. Onset Hobo Water Temp Pro temperature loggers, artificial shade locations, and model segment

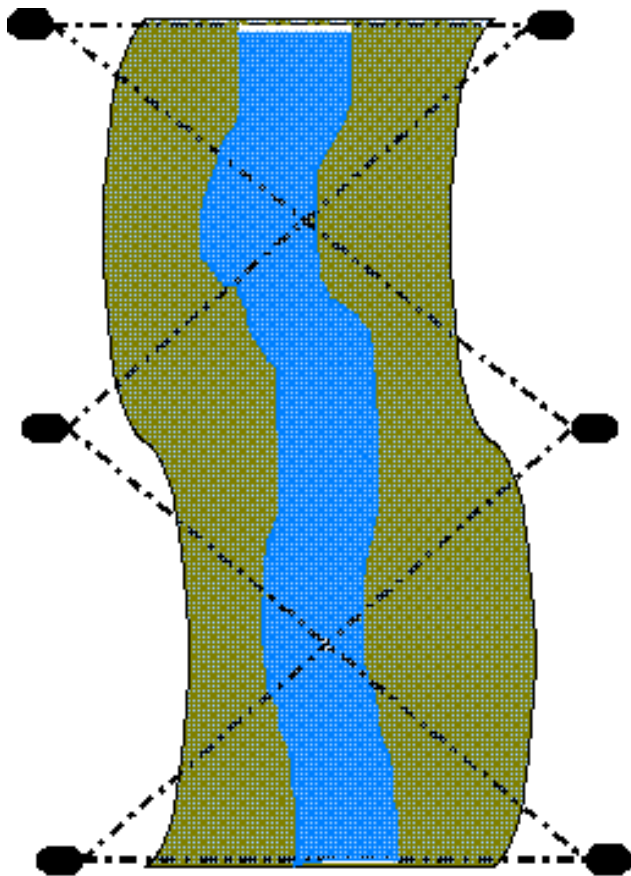


Figure 1.4. Diagram of cable support system constructed to hold shade cloth. Black spots are fence post; dotted lines are high tensile fencing; tan is shade cloth; and blue represents stream surface underneath of shade.

the top 15 cm of each fence post and stretched it across the stream. One piece of fencing was stretched straight across the stream to the other side. The other two pieces were stretched at 45 degree angles one downstream and one upstream to create a crossing cable support system (Figure 1.4).

Ninety percent tan shade cloth was purchased from PAK Unlimited Inc, Cornelia Georgia. The cloth reduced sunlight reaching the stream to only 10%. Tan colored cloth was used to eliminate any heat that may be absorbed by darker colors. Cloth fabric was used in the place of plastic to allow better air and water flow through the artificial canopy. The cloth was purchased in 6.5 x 18.3 meter panels with grommets every 1.5

meters along the sides and ends. Six and a half meters was wide enough to cover all but the edges of the average wetted width of the stream (7.05 m). The cloth was attached to the cable support system using zip ties every 18.3 meters. Ropes were tied from side grommets to fence post or stakes when necessary. This provided extra support and reduced the amount of movement during heavy winds.

Shade cloth was attached to the cable system on July 26, 2007 and remained up until November 1, 2007. Two heavy thunderstorm events occurred on the nights of August 7 and 10 resulting in seven fence post being broken. These posts were replaced immediately the following mornings.

Data Collected

Hobo Pro v temperature loggers (Onset 2008) were used to collect hourly air and stream temperature data from June 2006 to September 2006 and then again from March 2007 to November 2007. One logger was placed at site A, B, E, and F each year (Figure 1.3). Two loggers were placed in the stream at the top of the shaded reach, site C. One logger was used for primary collection and one as a backup. Similarly, two loggers were placed at the downstream end of the shaded reach site D for the same purpose. Additional temperature loggers were deployed to determine how shade affected temperatures downstream of the shaded area. Air temperature was collected from three locations at the study site. One logger was placed under the shade cloth and one was placed in the shade adjacent to the shade cloth to determine if the cloth had any affect on air temperature. The other air temp logger was placed in the shade on the bank under a white PVC tube to avoid direct sunlight. Temperature loggers are accurate to ≤ 0.2 °C. To determine drift, temperature loggers where submerged in ice water (0.0 °C) before

placing them in the stream and before downloading. If records where not 0.0 °C data was re-calibrated before analyzing. Solar smart sensors (Onset 2008) were used to determine the difference in shortwave radiation penetrating the shade cloth. One sensor was placed under the shade cloth and the other sensor was mounted on the bank in direct sunlight.

Data Analysis

Past stream temperature data from 2005 and 2006 indicated the major warm stream temperature period ranged from July 15th to September 15th for brook trout in the restoration area. Therefore, data for before and after shade comparisons were made from July 26th to September 15th, which is referred to as the Critical Period from here on.

To determine the heating/cooling effects of the shade cloth on maximum stream temperatures the mean difference of daily maximum stream temperatures from site C to site D were analyzed during the Critical Period in 2006 before shade and 2007 during shade. The mean difference in daily mean and daily minimum temperatures were also analyzed during these periods. Additionally, site C and E were compared to determine what effect shading would have further downstream. Site E is located 1 km downstream of the shaded reach. Since data was paired and not normally distributed a Wilcoxon Signed Ranks test was used to determine statistical differences among sites. Differences were considered significant at the $p \leq 0.05$ level. To determine if shade reduces daily temperature range, diurnal fluctuations were calculated for site C and site D in 2007.

Rolling averages were calculated to investigate both short and long-term temperature means in the Smith Creek Restoration Area (Wehrly et al. 2007). Three day rolling averages were calculated by averaging the daily means and daily maximums for every three day period throughout the Critical Period. The highest temperature of these

averages was then selected as the maximum three day rolling average. Maximum rolling averages were calculated for 1, 3, 7, 14, 21, 28, 35, 42, and 49 days for comparison to Wehrly et al. (2007) findings in Wisconsin and Michigan streams. Rolling maximums were also analyzed during the Critical Period before and after shading to determine how shading affects long-term stream temperatures.

Results

In 2006, before shading, the mean difference of daily maximum temperatures for the Critical Period increased significantly (Wilcoxon Signed Ranks, $Z = -5.729$, $N = 52$, $p\text{-value} < 0.001$) from site C to site D by 0.4°C (Table 1.1), with a one day maximum increase of 0.9°C . In 2007, after shading, the mean daily maximum temperatures decreased significantly (Wilcoxon Signed Ranks, $Z = -6.275$, $N = 52$, $p\text{-value} < 0.001$) from site C to site D by 1.0°C with a one day maximum cooling affect of 1.9°C . Additionally, there was not one-day when the daily maximum temperature was higher at site D than site C during the shaded period. Daily mean temperatures increased from site C to site D by 0.2°C (Wilcoxon Signed Ranks, $Z = -4.034$, $N = 52$, $p\text{-value} < 0.001$) in 2006 and decreased during the shaded period by 0.5°C (Wilcoxon Signed Ranks, $Z = -6.275$, $N = 52$, $p\text{-value} < 0.001$). Mean daily minimum temperatures for the Critical Period varied little, decreasing from site C to site D by 0.2°C in 2006 and 0.1°C during shade in 2007. Mean daily diurnal fluctuations during shade at site C averaged 3.2°C with a maximum of 5.7°C and mean daily fluctuations at site D were significantly lower (Wilcoxon Signed Ranks, $Z = -6.140$, $N = 52$, $p\text{-value} < 0.001$) at 2.2°C with a maximum of 4.2°C .

Table 1.1. Daily mean and daily maximum mean differences from July 26 to September 15 during the Critical Period before shade in 2006 and after shade in 2007. Differences from Site C to Site D; Site C to Star Site (700 m below Site D); Site C to Site E (1000 m below Site D). Refer to Figure 1.3.

	Daily Mean Difference 2006	Daily Mean Difference 2007	Daily Maximum Difference 2006	Daily Maximum Difference 2007
Site C to Site D	0.14	-0.46	0.43	-1.01
Site C to Star	-1.03	-1.35	-0.66	-1.94
Site C to Site E	-0.53	0.18	-0.04	-0.28

To determine the effect of shading one kilometer below the shaded area mean daily maximum, mean daily mean, and mean daily minimum were also compared from site C to site E before and during the shade period. In 2006, before shading, the mean difference of daily maximum temperatures from site C to site E did not differ (-0.04°C) (Wilcoxon Signed Ranks, $Z = -0.697$, $N = 52$, $p\text{-value} = 0.486$). During the shaded period the mean difference in daily maximum temperatures from site C to site E increased by 0.3°C (Wilcoxon Signed Ranks, $Z = -2.983$, $N = 52$, $p\text{-value} = 0.003$) (Table 1.1). Before shading the difference in mean daily mean temperature was 0.5°C (Wilcoxon Signed Ranks, $Z = -6.275$, $N = 52$, $p\text{-value} < 0.001$) cooler at site E than Site C. Following shading the mean daily mean temperature at site E was 0.2°C (Wilcoxon Signed Ranks, $Z = -5.665$, $N = 52$, $p\text{-value} < 0.001$) cooler than site C. Mean daily minimum temperatures decreased for both years from site C to site E with a decrease of 0.8°C (Wilcoxon Signed Ranks, $Z = -6.275$, $N = 52$, $p\text{-value} < 0.001$) before shading and 0.6°C (Wilcoxon Signed Ranks, $Z = -6.257$, $N = 52$, $p\text{-value} < 0.001$) throughout shading.

The one day maximum temperature at site D before shading was 26.2°C and 24.3°C during shading. The mean difference of rolling maximums at site C (control) for days

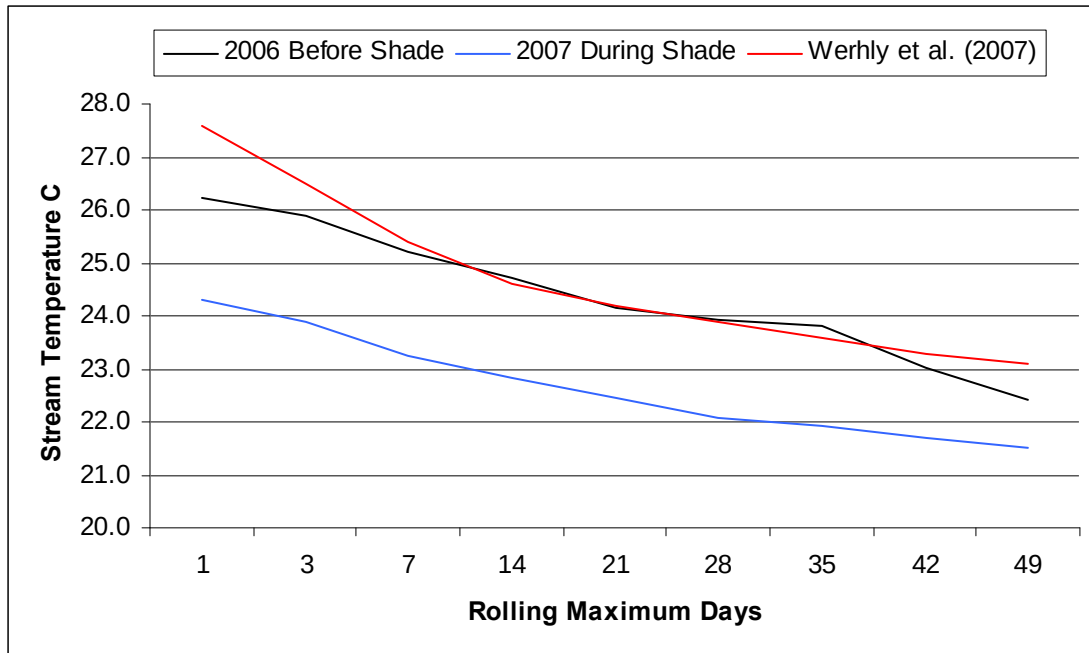


Figure 1.5. Rolling maximum temperatures (°C) at site D from July 26 to September 15 before shade in 2006, during shade in 2007, and thermal tolerances indicated by field observations on presence of trout by Werhly et al. 2007.

1 to 49 was 0.1 °C (Wilcoxon Signed Ranks, $Z = -.0602$, $N = 9$, $p\text{-value} = 0.547$) warmer in 2007 than in 2006. The mean difference of rolling maximums at site D (treatment) for days 1 to 49 was 1.7 °C (Wilcoxon Signed Ranks, $Z = -2.689$, $N = 9$, $p\text{-value} = 0.007$) cooler in 2007 during shade than in 2006 (Figure 1.5). Additionally, as the stream traveled from site C to site D the mean rolling maximums increased 0.6 °C (Wilcoxon Signed Ranks, $Z = -2.680$, $N = 9$, $p\text{-value} = 0.007$) in 2006 and cooled 1.2 °C (Wilcoxon Signed Ranks, $Z = -2.716$, $N = 9$, $p\text{-value} = 0.007$) in 2007 during shade. Before shade, the seven day rolling maximum temperature was 25.2 °C at site D and 23.3 °C during shade or 1.9 °C cooler.

Air temperatures were not significantly different (Wilcoxon Signed Ranks, $Z = -0.016$, $N = 52$, $p\text{-value} = 0.987$) above and below the shade cloth (0.16 °C). Mean daily

solar radiation was compared to determine the shade cloth effectively block 79% of the daily solar radiation from reaching the stream surface.

Discussion

Brook trout one-day maximum temperature tolerance has been documented from 23 °C to 29 °C (Lee and Rinne 1980; Saila et al. 2004). Stream temperature at the lower shade site (D) was 26.2 °C before shade and was much closer to the lower range at 24.2 °C after shade. Werhly et al. (2007) calculated rolling maximum temperatures from field observation with trout present or not present from 285 locations in Wisconsin and Michigan streams. The rolling maximums before shade in 2006 at site D were similar to the rolling maximum thermal limits for brook trout discussed by Wehrly et al. (2007). However, the rolling maximums (1 to 49 Days) from site D during the shading experiment were all lower than the rolling maximum temperatures reported by Werhly et al. (2007) for brook trout survival (Figure 1.5). This indicates a suitable long-term stream temperature in Smith Creek for brook trout survival following riparian restoration.

The present work indicated the usefulness of riparian shade in reducing daily mean and daily maximum temperatures. Swift and Messer (1971) found stream temperatures warmed from 66 °F and 73 °F following removal of riparian vegetation on southern Appalachian streams. Another study found daily maximum stream temperatures decreased up to 4.0 °C over a 200 meter segment during the daytime in shaded reaches (Story et al. 2003). However, Story et al. (2003) also indicated groundwater input as responsible for 3.0 °C of that change. The stream flow from Site C (mean 5.5 cfs) to Site D (mean 6.0 cfs) was similar (< 10% difference) during all discharge measurements indicating minimal cooling effects from groundwater in this segment. Streams with

bedrock streambeds have been shown to warm quicker than streams with cobble or gravel during daytime hours (Johnson 2004). Smith Creek is mainly a cobble and gravel stream which helps to buffer stream temperature increases with hyporheic flow (Rothwell et al. 2005).

The effects of artificial shade 1 km downstream of site D were minimal. This is probably due to an increase in groundwater input approximately 450 meters downstream of site D. However, additional temperature loggers were placed downstream that indicated a trout refuge area of approximately 700 meters before stream temperatures warmed above 23 °C (Figure 1.3). Additionally, a recently restored (2006) 180 meter coldwater spring is located just below site D (30 meters) with restored habitat which now contains both adult and young-of-year brook trout. Baird and Krueger (2003) found when stream temperatures exceeded 20 °C brook trout were able to locate refuges and maintain body temperatures 4.0 °C cooler than river temperatures. The 700 meter refuge and spring habitat (180 meter) should maintain brook trout through the summer months. This important refuge could potentially allow connectivity with the upstream Fridley Gap brook trout population.

Chapter Two: Watershed Modeling for Restoration Sites

Introduction

Previous studies have created stream temperature prediction models to manage habitat and determine refuge areas within watersheds for coldwater species (Saila et al. 2004; Gaffield et al. 2005). Influences on stream temperature such as air temperature, daily solar radiation, riparian shading, air velocity, relative humidity, and shade are often

used to create these models (Adams and Sullivan 1989). Understanding the location of coldwater refuges and temporal patterns within a watershed is essential in coldwater species management, conservation, and restoration of stream ecosystems.

Stream models are generally created using either physical or stochastic models. Physical models are designed to calculate the heat gained or loss as water flows through a segment of stream. These models are often complex and are useful for larger river systems (Saila et al. 2004). Stochastic models are based on calculations using linear regressions. These models use parameters such as stream temperature, air temperature, and discharge over a period of time. The advantages of a stochastic model are the minimal data requirements and simplicity (Saila et al. 2004). However, stochastic models often have to account for lag time, which can be up to seven days in larger river systems (Stephan and Preud'homme 1993). Therefore, the stochastic model is more useful on first and second order headwater streams. Additionally stochastic models are quick to compute, less intensive and simpler to validate leading to simpler implementation of the model. The goal of a linear regression model is to fit a set of data

$$\text{Equation 2.1} \quad T_s = a_0 + a_1x_1 + a_2x_2 + \dots + a_nx_n$$

to Equation 2.1. Where T_s equals the predicted stream temperature; a_0 equals constant; a_1 equals the first predictor coefficient; and x_1 equals the observed or desired measurement of the first predictor.

One of the contributing predictors affecting stream temperature during the summer months is stream discharge. Studies have found that low flowing streams warm quicker in the summer than high flowing streams (Neumann et al. 2003). This can often result in fish kills of coldwater species. Gu et al. (1999) found that flow was an effective

parameter in creating stream temperature models when meteorological data such as wind and humidity were not useful predictors. Utilizing the output of stream temperature models, biologists are able to determine management actions that will benefit stream ecosystems and determine potential fisheries objectives.

The objectives of this chapter are to 1) define the areas and amount of shading needed within the watershed to reduce the summer maximum daily temperature to 24°C in the Smith Creek restoration area and 2) explain a modeling process that can be utilized by fisheries managers and biologist in other areas to evaluate the feasibility of restoration projects and affects of potential riparian restoration.

Methods

Stream Temperature Model

Five segments totaling 4.2 km were chosen for modeling stream temperature to gain a better understanding of thermal patterns throughout the study area and determine high priority sites for restoration (Figure 1.3). Stream temperature was collected hourly using Hobo Water Temp Pro v temperature loggers for each segment during the summer of 2006 and 2007 (Onset 2008). Two stream temperature loggers were lost (sites B and F) in 2007 so this data was not used to determine model variables. Air temperature was collected just below site D for all reaches in both 2006 and 2007. Temperature loggers were placed in fully shaded areas adjacent to the stream bank to collect air temperatures. Hourly discharge was collected just below site D at the same location as air temperature. Discharge was collected at sites A, B, C, D, E, and F (Figure 1.3) multiple times using a Marsh-McBirney flow meter. A simple linear regression was calculated using the gauge station measurements and the site discharge. Discharge was then predicted at each site

using mean daily discharge for 2006 and 2007 from the gauge station (Gormley et al. 2005). Stream discharge measurements were taken at moderately high flows, approximate base flow and during drought conditions at all sites in the summers of 2006 and 2007. Spherical densimeters were used following Lemmon (1956) methods in shade surveys conducted on October 2, 2007 before leaf off to determine shade percentage for each segment.

Other meteorological data collected included hourly solar radiation, relative humidity, and wind speed. Sensors were placed in direct sunlight to record mean hourly solar input in watts per meter squared (W/m^2) (Onset 2008). The daily mean W/m^2 was calculated to use as an independent variable for the model. Hourly recordings of relative humidity and wind speed were obtained from the Shenandoah Valley Regional Airport weather station located 26 km south of the study site. Hourly samples were converted to daily means for modeling.

To model the daily mean and daily maximum stream temperature in the watershed, a step-wise linear regression was used to illustrate variables responsible for stream temperature throughout the five segments. Step-wise linear regression interprets all possible model predictor combinations and selects the most relevant predictors (Neumann et al. 2003). Variables excluded from the model included mean daily humidity, mean daily wind speed, mean daily solar radiation, and mean daily upstream temperature input. Mean daily solar radiation and daily mean upstream temperature input were excluded due to the close correlation with mean air temperature. Although correlated (Pearson Correlation, $p < 0.05$), discharge had little impact on stream temperature (coefficient value = -0.007) or the R^2 value of the regression model and

therefore was excluded to simplify the model. The dependent variable stream temperature and two significantly correlated independent variables air temperature (Pearson Correlation, $p < 0.01$) and percent shade (Pearson Correlation, $p < 0.05$) were used for both the daily mean model and daily maximum model.

Data Analysis

The percentage of shade was altered in the regression equation for all segments of the stream to determine potential restoration responses. Each segment with the study area was modeled at 80% shade to indicate how the riparian canopy would affect stream temperature once vegetation in the restoration area matures. We modeled the affect a mature canopy would have on stream temperature in all five segments of the study area. Twenty percent shade was used in the model to determine how further riparian degradation would affect stream temperature. Current stream temperatures were compared to both the 80% shade and 20% shade models to determine how restoration or further degradation would affect suitable brook trout habitat in each segment.

Results

Model Validation

Predicted temperatures were plotted against observed temperature at each site to determine the accuracy of the model. The R^2 values at each site using the predicted versus observed regression for the mean daily mean model were: Segment one ($R^2 = 0.88$), Segment two ($R^2 = 0.88$), Segment three ($R^2 = 0.86$), Segment four ($R^2 = 0.83$) and Segment five ($R^2 = 0.85$). The same method was used to determine the accuracy of the

model generated for daily maximum temperatures. The R^2 values were as follows: Segment one ($R^2 = 0.78$), Segment two ($R^2 = 0.82$), Segment three ($R^2 = 0.79$), Segment four ($R^2 = 0.74$), and Segment five ($R^2 = 0.72$). All regression were significant to p-value < 0.05 (Pearson Correlation).

The shade survey conducted in 2007 resulted in segment one having the lowest amount of shade (19%) followed by segment two (27%), segment three (35%), segment four (56%), and segment five (66%). The stream temperature, air temperature, and percent shade model indicated shade had a relationship with mean and maximum stream temperatures. If percent shade increases from 0% to 100% the mean daily stream temperature would be 1.45 °C cooler at site X and daily maximum stream temperature would be 1.97 °C cooler at site X. Although the affect of shade may vary among segments it was significantly (Pearson Correlation, $p < 0.05$) correlated to daily maximum and daily mean stream temperature throughout all five segments. Daily maximum temperature model had an $R^2 = 0.71$ and the daily mean temperature model produced an R^2 value of 0.83.

Table 2.2. Predicted mean maximum temperatures at 10 to 90 % shade from July 26 to September 15 (Temperature °C).

Segment	10%	20%	30%	40%	50%	60%	70%	80%	90%	Current
One	21.3	21.1	20.9	20.8	20.6	20.4	20.2	20.0	19.8	21.2
Two	22.0	21.8	21.6	21.4	21.2	21.0	20.8	20.6	20.4	21.7
Three	22.6	22.4	22.2	22.0	21.8	21.6	21.4	21.2	21.0	22.1
Four	22.5	22.3	22.1	21.9	21.8	21.6	21.4	21.2	21.0	21.6
Five	22.9	22.7	22.5	22.3	22.1	21.9	21.7	21.5	21.3	21.8

Table 2.3. Current mean maximum temperatures versus mean maximum temperatures with 80% shade from July 26 to September 15 (Temperature °C).

Segment	Current Shade %	2006 Mean Max	Predicted Mean Max (80% Shade)	Δ From Current Shade
One	19	21.2	20.0	-1.2
Two	27	21.7	20.6	-1.0
Three	35	22.1	21.2	-0.9
Four	56	21.6	21.2	-0.5
Five	66	21.8	21.5	-0.3

Segment one (between sites A and B) had a mean daily maximum stream temperature during the Critical Period of 21.2 °C (Table. 2.2) under the current conditions of 19% riparian canopy. Similarly, the model predicted a mean daily maximum of 21.1 °C with 20% shade. Simulating a mature forest canopy with 80% shade resulted in a mean daily maximum stream temperature of 20.0 °C or 1.2 °C cooler than current riparian conditions (Table 2.3). Additionally, this segment had a mean daily mean stream temperature of 19.5 °C (Table 2.4) under current conditions. The model predicted 19.5 °C with 20% shade. The 80% riparian shade model resulted in a mean daily mean temperature of 18.6 °C (Table 2.5) or 0.9 °C cooler than current riparian conditions.

Segment two (between sites B and C) had a mean daily maximum stream temperature of 21.7 °C under the current 27% shade conditions. The 20% shade model resulted in a mean daily maximum stream temperature of 21.8 °C. Under a forest canopy

Table 2.4. Predicted mean daily mean temperatures at 10 to 90% shade from July 26 to September 15 (Temperature °C).

Segment	10%	20%	30%	40%	50%	60%	70%	80%	90%	Current Temps
One	19.6	19.5	19.3	19.2	19.1	18.9	18.8	18.6	18.5	19.5
Two	20.2	20.0	19.8	19.7	19.6	19.5	19.3	19.2	19.0	19.9
Three	20.4	20.3	20.1	20.0	19.9	19.7	19.6	19.4	19.3	20.1
Four	20.1	19.9	19.8	19.6	19.5	19.4	19.2	19.1	18.9	19.4
Five	20.9	20.7	20.6	20.5	20.3	20.2	20.0	19.9	19.7	20.1

Table 2.5. Current mean daily mean stream temperatures versus mean daily mean stream temperatures with 80% shade from July 26 to September 15 (Temperature °C).

Segment	Current Shade %	2006 Mean Max	Predicted Mean Max (80% Shade)	Δ From Current Shade
One	19	19.5	18.6	-0.9
Two	27	19.9	19.2	-0.7
Three	35	20.1	19.4	-0.7
Four	56	19.4	19.1	-0.3
Five	66	20.1	19.9	-0.2

scenario representing 80% shade, the model predicted a mean daily maximum stream temperature of 20.6°C or 1.1 °C cooler than present conditions. During the Critical Period the mean daily mean stream temperature was 19.9 °C under current conditions. The 20% shade model indicated a slight increase to 20.0 °C, where the 80% simulated shade canopy resulted in a 0.7 °C decrease from existing conditions to 19.2 °C.

The riparian canopy in segment three (between sites C and D) was 35% shade in 2006 and 86% in 2007 under artificial shading. The mean daily maximum stream temperature for segment three during the Critical Period in 2006 was 22.1 °C. With riparian shade reduced to 20% the model predicted a mean daily maximum stream temperature of 22.4 °C. The 80% shade model, representing conditions in 20 to 30 years, resulted in a mean daily maximum stream temperature of 21.2 °C or 0.9 °C cooler than current conditions. In 2006, the mean daily mean stream temperature during the Critical Period was 20.1 °C. A shade reduction to 20% indicated a mean daily mean stream temperature of 20.3 °C. Simulating an 80% shade canopy indicated a mean daily maximum stream temperature of 19.4 °C or 0.6 °C cooler than the present 35% shade conditions.

Segment four is located on the downstream reach of the Smith Creek Restoration area between sites D and E and currently has a stream canopy shading 56% of the stream. The mean daily maximum stream temperature was 21.6 °C under current conditions. A

modeled reduction of riparian shade to 20% resulted in a mean daily maximum stream temperature of 22.3 °C or 0.7 °C warmer than present conditions. The future restored conditions (80% canopy) resulted in a mean daily maximum stream temperature of 21.2 °C or 0.4 °C cooler than current conditions. The mean daily mean stream temperature during the Critical Period was 19.4 °C under current conditions. A modeled 20% riparian shade warmed the mean daily mean stream temperature to 19.9 °C. The simulated mature forest canopy of 80% shade resulted in a mean daily mean stream temperature of 19.1 °C.

Segment five at the lower reach of the study area currently has a 66% shade canopy cover. The importance of this segment is to illustrate how riparian degradation can increase stream temperatures. The mean daily maximum stream temperature was 21.8 °C under current conditions (66% shade). A modeled mature forest canopy (80% shade) predicted similar temperatures (21.5 °C). However, if the riparian vegetation was reduced to 20% shade, the mean daily maximum stream temperature would increase from 21.8 °C (66% shade) to 22.7 °C. The mean daily mean stream temperature under current conditions was 20.1 °C. A modeled increase of shade (80% shade) predicted a mean daily mean stream temperature of 19.9 °C. Modeling a shade reduction to 20% increased the mean daily mean temperature from 20.1 °C to 20.7 °C.

Discussion

Restoration of both segments one and two has the most potential for decreasing stream temperature. These segments are upstream of the restoration area in cattle grazed pastures with little shade. All segments in the model had upstream temperatures correlated with both downstream temperatures and air temperatures. However, since two

independent variables that are strongly correlated should not both be used in the same model, upstream temperature was eliminated. Although not used in model, upstream temperature is still important due to its influence of downstream temperature (Bartholow 2000). Restoration of segments one and two can only have beneficial effects on downstream temperatures potentially increasing thermal summer refuge areas for brook trout.

Segment five had the least potential for cooling stream temperatures due to the existing 66% forest canopy. However, if riparian vegetation were removed the effects would be very detrimental to brook trout restoration possibilities. It is important to maintain or increase this canopy to prevent future degradation of aquatic community (Durance and Ormerod 2007).

The model predicted that an increased riparian canopy had a larger effect on daily maximum temperatures than on daily mean temperatures. Other studies conducted in the field investigating the effects of shade have illustrated similar results (Sugimoto et al., 1997; and Johnson 2004). Since one-day maximum stream temperature is often a deciding factor in survival of aquatic species the cooling affect of shade on maximum daily temperatures is crucial to ensure restoration of coldwater species.

Fisheries biologist and managers can have a difficult time determining the potential benefits of stream restoration projects. Modeling offers an important tool to determining the feasibility of restoration projects. Although some stream temperatures have been found to recover from clear-cutting as quickly as 10 years (Moore et al. 2005), a restoration site with little or no hardwood seed bank is less likely to recover as quickly. By only modeling 4.2 km of stream it was possible to determine the average affect of

shade in five segments. Many studies focus on long reaches and how restoration may improve these reaches. However, the results of this model indicate the ability to create suitable coldwater refuge areas within short segments (1 km) that have minimal groundwater inputs. These coldwater refuge areas are important for survival of brook trout populations throughout their native range.

Chapter Three: Climate Change vs. Riparian Restoration

Introduction

Predicted climate change may offset the reduction in stream temperatures from riparian restoration and reduce our ability to reintroduce coldwater species. Climate changes in response to a buildup in greenhouse gases have recently become an important topic in ecological studies. While increased global temperatures are predicted to raise stream temperatures as much as 3 °C (Morrill et al. 2005) degraded riparian vegetation in timbered areas have been shown to increase stream temperature up to 4 °C (Bartholow 2000). Restored riparian vegetation in degraded landuse areas may play a crucial role in buffering stream temperatures and conserving many coldwater aquatic species under changing climate.

Carbon dioxide concentrations have increased as much as 11% over the past three decades and may potentially double in the next 100 years (Hengeveld 1990). The Intergovernmental Panel on Climate Change (IPCC 1999) has stated the global annual air temperature is expected to increase 1 to 3 °C in the next 50 to 100 years. Other studies indicate models predicting annual average air temperature to increase up to 5 °C over the United States (National Assessment Synthesis Team (NAST) 2000). The Goddard Institute for Space Studies predicted an increase in annual air temperature of 4.8 °C in the southern Appalachian region (Meisner 1990b). A one degree increase in air temperature may increase stream temperature 0.3 to 1.0 °C dependent upon groundwater inputs and riparian vegetation. These increased stream temperatures will most likely decrease the range of many salmonid species (Flebbe et al. 2006). Ries (1995) indicated a loss of brook trout habitat at both 2 and 4 °C increases in mean air temperature. Brook trout in the southern native range are extremely vulnerable to an increase in stream temperature as they are already bordering their thermal limits (Meisner 1990a).

Latitude and altitude are also factors determining stream temperature and stream habitat (Meisner 1990a; Rahel and Hubert 1991). Systems above 305 m are considered representative brook and rainbow trout streams in the southern Appalachians (Kelly et al. 1980; Flebbe 1994). Increased summer air temperatures will increase this elevation further isolating populations and reducing possible trout habitat.

Past landuse has reduced and degraded riparian vegetation throughout much of the brook trout's native range. Without restored riparian areas, climate change will result in even greater increases in stream temperatures dramatically reducing potential restoration areas. Restored riparian areas are thought to buffer affects climate change

will have on these streams. Determining future stream temperature will enable resource managers to protect already threatened and endangered coolwater and coldwater species.

The objectives of this chapter are to 1) determine how stream temperatures in Smith Creek will be affected by mean daily air temperature increases of 1, 3, and 5 °C (Morrill et al. 2005) in restored stream segments (80% shade) and 2) illustrate how restoring riparian canopies may buffer the effect of increased stream temperature from climate change.

Methods

Due to evaporative cooling, increases in air temperature do not result in a linear pattern for water temperature. For example, if air temperature increases from 20 °C to 21 °C stream temperature may increase by 0.6 °C, while an increase of air temperature from 29 °C to 30 °C may result in a stream temperature increase by 0.4 °C. The relationship between air and stream temperature needs to be understood when evaluating the effects of climate change. Mohseni et al. (1998) suggested using the sigmoid function (S-curve shape) when using air temperature as the single independent variable to predict stream temperature. To conserve the s-curve relationship for climate change predictions the difference between predicted mean daily temperatures at 80% shade and 2006 observed temperatures were subtracted from the observed temperatures. Then mean daily air temperature (independent variable) and mean daily stream temperature (dependent variable) were plotted to create a sigmoid curve. The function produced an equation (3.1) used to determine stream temperature with increasing air temperatures where

$$\text{Equation 3.1} \quad T = a / (1 + \text{EXP}(-(x - x_0) / b))$$

T = stream temperature, a = predicted maximum stream temperature, x = measured air temperature, x_0 = air temperature at the inflection point of the curve, and b = measure of the steepest slope of the curve.

A sigmoid curve was created for sites B, C, D, E and F for both daily mean and daily maximum temperatures. One, three, and five degrees were added to daily mean air temperatures observed during the Critical Period. This resulted in predicted daily mean and daily maximum temperatures for each site during the Critical Period under varying climate change scenarios.

Results

Segment one under a restored forest canopy (80% shade) scenario predicted a mean daily maximum stream temperature of 20.0 °C during the Critical Period. A one degree increase in mean air temperature during the Critical Period resulted in a mean daily maximum stream temperature of 20.6 °C. Three and five degree daily mean air temperature increases indicated a mean daily maximum stream temperature increase to 21.7 °C and 22.6 °C (Table 3.1), respectively. The mean daily maximum stream temperature under existing conditions in segment one is 21.2 °C. Under a restored canopy cover (80% shade), segment one could withstand a 2.2 °C increase in mean air temperature and maintain the existing maximum stream temperatures.

The predicted mean daily mean stream temperature during the Critical Period was 18.6 °C under an 80% canopy scenario. By increasing the mean daily air temperature by one degree the mean daily mean stream temperature increased to 19.1 °C. Raising the mean daily air temperature by three and five degrees resulted in a mean daily mean stream temperature of 20.1 °C and 20.9 °C respectively (Table 3.2). A restored canopy

cover would buffer a 2.0 °C increase in mean air temperature and maintain the current mean stream temperatures.

Similar to segment one, segment two also has a lower percentage of riparian shade with only 27% shade. The predicted mean daily maximum stream temperature in segment two under a mature forest canopy (80% shade) was 20.6 °C. By increasing the mean air temperature by one degree, the mean daily maximum stream temperature increased to 21.3 °C. By increasing the mean air temperature by three and five degrees, the mean daily maximum stream temperature increased to 22.3 °C and 23.2 °C, respectively. The current mean daily maximum stream temperature at segment two is 21.7 °C. A restored canopy cover of 80 percent shade would allow the segment to withstand a 1.8 °C increase in mean air temperature and maintain the existing daily maximum stream temperatures

Table 3.1. Predicted mean daily maximum stream temperature for each segment from July 26 to September 15 with a mature forest canopy of 80% shade and 1, 3, and 5 °C increases in mean daily air temperature.

	Seg 1	Seg 2	Seg 3	Seg 4	Seg 5
80 % Shade	20	20.6	21.2	21.2	21.5
1 C	20.6	21.3	21.9	21.8	22.1
3 C	21.7	22.3	23.1	22.8	23.3
5 C	22.6	23.2	24	23.6	24.3

Table 3.2. Predicted mean daily mean stream temperatures for each segment from July 26 to September 15 with a mature forest canopy of 80% shade and 1, 3, and 5 °C increases in mean daily air temperature.

	Seg 1	Seg 2	Seg 3	Seg 4	Seg 5
80% Shade	18.6	19.2	19.4	19.1	19.9
1 C	19.1	19.7	20.0	19.6	20.4
3 C	20.1	20.6	21.0	20.4	21.5
5 C	20.9	21.4	21.8	21.2	22.4

For segment two the predicted mean daily mean stream temperature during the Critical Period was 19.2 °C under an 80% canopy scenario. By increasing the mean daily

air temperature by one degree, the mean daily mean stream temperature increased to 19.7 °C. Increasing the mean daily air temperature by three and five degrees resulted in a mean daily mean stream temperature to 20.6 °C and 21.4 °C respectively. A restored canopy cover would buffer a 1.4 °C increase in mean air temperature and maintain the current mean stream temperatures.

Segment three had a predicted mean daily maximum stream temperature of 21.2 °C under 80 percent shade. An increase of one degree in air temperature predicted a mean daily maximum stream temperature of 21.9 °C. Three and five degree increases in mean daily air temperature increased mean daily maximum stream temperature to 23.1 °C and 24.0 °C, respectively (Figure 3.1). If restored, this upper reach of the Smith Creek Restoration area could maintain existing stream temperatures during the Critical Period if climate change increased air temperature by 1.3 °C.

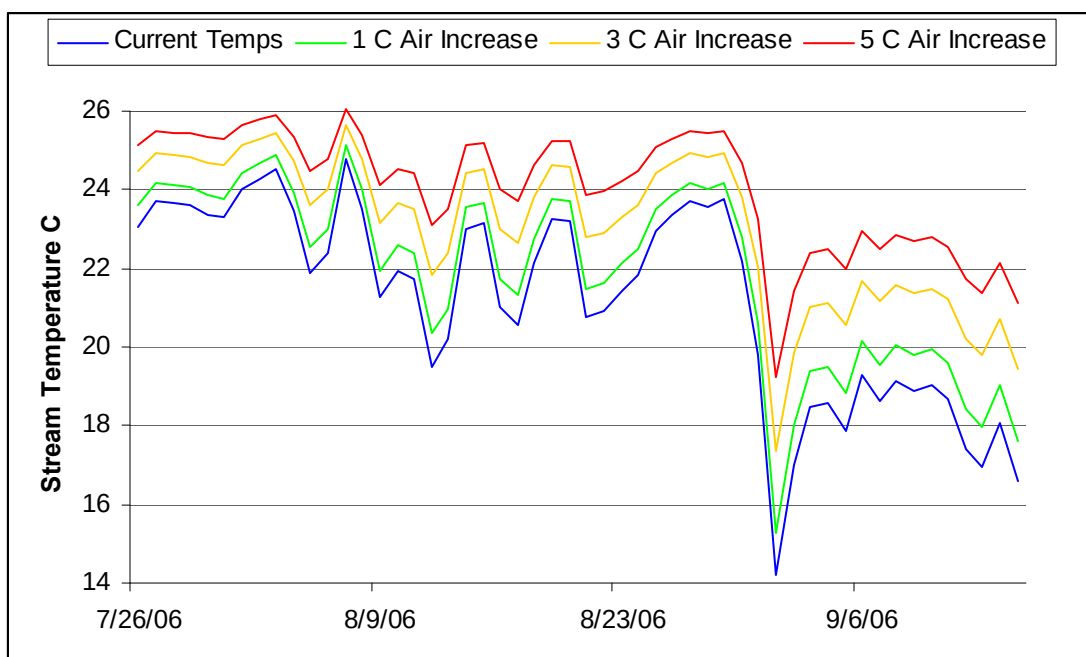


Figure 3.1. Stream Temperature (°C) at Site D with modeled 80% shade (blue), and predicted increases in stream temperature with mean daily air increases of one, three, and five degrees.

The predicted mean daily mean stream temperature in segment three was 19.4 °C under an 80% shade scenario. A one and three degree increase in mean daily air temperature during the Critical Period increased the mean daily mean stream temperature to 20.0 °C and 21.0 °C, respectively. Increasing the mean daily air temperature by five degrees raised the mean daily mean stream temperature to 21.8 °C. A mature forest canopy, expected in 20 to 30 years in this segment will be able to maintain current mean daily mean stream temperatures with a 1.2 °C increase in the mean daily air temperature.

Segment four is located on the lower reach of the Smith Creek Restoration Area and currently has a mean daily maximum stream temperature of 21.6 °C. The expected mean daily maximum stream temperature under 80% conditions is 21.2 °C. With an increase of one degree in the mean daily air temperature, the mean daily maximum stream temperature will increase to 21.8 °C. Three and five degree increases resulted in 22.8 °C and 23.6 °C, respectively. The effects of climate change are less in the upstream reaches due to high percentage of shade throughout the reach. A mature forest canopy in this reach will only buffer an increased mean air temperature of 0.7 °C and still maintain daily maximum stream temperatures.

Segment four has a mean daily mean stream temperature of 19.4 °C with a predicted decrease in stream temperature to 19.1 °C under an 80% shade scenario. A raised mean air temperature of one degree with 80% shade resulted in a mean daily mean temperature of 19.6 °C. Three and five degree increases in mean air temperature increase the mean daily mean stream temperature to 20.4 °C and 21.2 °C. The future restored canopy cover will be able to buffer a 0.6 °C increase in mean air temperature to maintain current daily mean stream temperatures.

Segment five currently has a mean daily maximum stream temperature of 21.8 °C. Under an 80% shade scenario the modeled mean daily maximum stream temperature is 21.5 °C. A mean air temperature increase of one and three degrees is expected to increase of mean daily maximum stream temperatures to 22.1 °C and 23.3 °C. A five degree increase in air temperature will raise the mean daily maximum stream temperature to 24.3 °C. This segment can buffer a 0.5 °C increase in mean daily air temperature and maintain existing stream temperatures. Mean daily mean stream temperatures had a similar warming trend and were only able to buffer a mean air temperature increase of 0.4 °C. Expected stream temperatures with an 80% shade canopy under current condition were 19.9 °C. Increasing mean daily air temperature by one degree resulted in a mean daily mean stream temperature of 20.4 °C. Three and five degree increases indicated the mean daily mean temperature would increase to 21.5 °C and 22.4 °C respectively.

Discussion

Morrill et al. (2005) predicted stream temperatures to increase 2 to 3 °C with a mean air temperature increase of 3 to 5 °C. Similarly, this study indicated an increase in stream temperature of 1.7 to 2.6 °C with mean air temperature increases of 3 to 5 °C. As expected restored riparian canopies at segments one and two showed the most potential to counter the effects of climate change. However, if forest canopies are not restored on streams with brook trout populations, an increase in mean daily air temperature during the summer will extirpate many brook trout populations that are balancing on the edge of their thermal limit. If riparian vegetation is restored it can counter the affects of climate change on stream temperature for many brook trout populations.

Predicting stream temperature change with possible climate change indicated the importance of restoring riparian vegetation in trout streams with little or no canopy cover. Trout populations in streams with little shade may be vulnerable to climate change if they are near the species thermal maximums. Increased stream temperature could also be an issue for survival of macroinvertebrate species or affect chemical process which may reduce dissolved oxygen (Ducharme 2007). Modeling how restored riparian areas can buffer climate change effects on stream temperatures gives biologist and managers a tool to plan ahead for warming global temperatures and to prioritize where to conserve coldwater species. Taking action now to prevent stream temperature warming may benefit stream processes and salmonid populations in future years if predicted air temperature increases for climate change are accurate.

Bibliography

- Adam, T. N., and K. Sullivan. 1989. The physics of forest stream heating: A simple model. Washington Department of Natural Resources, Report TFW-WQ3-90-007, Olympia, WA 98504-7001.
- Baird, O.E., and C.C. Krueger. 2003. Behavioral Thermoregulation of Brook and Rainbow Trout: Comparison of Summer Habitat Use in an Adirondack River, New York. Transactions of the American Fisheries Society 132: 1194-1206.
- Bartholow, J.M. 2000. Estimating cumulative effects of clearcutting on stream temperatures. Rivers 7(4): 284-297.
- Barton, D. R., and W. D. Taylor. 1985. Dimensions of riparian buffer strips required to maintain trout habitat in southern Ontario streams. North American Journal of Fisheries Management 5(3a):364-378.

- Berman, C. H., and T. P. Quinn. 1991. Behavioral thermal regulation and homing by spring chinook salmon (*Oncorhynchus tshawytscha*) in the Yakima River. *Journal of Fish Biology* 39:301-312.
- Bonneau, J. L., and D. L. Scarnecchia. 1996. Distribution of juvenile bull trout in a thermal gradient of a plunge pool in Granite Creek, Idaho. *Transactions of the American Fisheries Society* 125:628-630.
- Bovee, K. D. 1982. Guide to stream habitat analysis using the instream flow incremental methodology. Fish and Wildlife Service Report, Report No. FWS/OBS-82/26, Springfield, VA.
- Brown, G. W. 1969. Predicting temperatures of small streams. *Water Resources Research* 5:68-75.
- Brown, G. W., and J. T. Krygier. 1970. Effects of clear-cutting on stream temperature. *Water Resources Research* 6:1133-1139.
- Brownlee, M.J., B.G. Shepherd and D.R. Bustard. 1988. Some Effects of Forest Harvesting on Water Quality in the Slim Creek Watershed in the Central Interior of British Columbia. Department of Fisheries and Oceans, Vancouver, B.C. (Canada). Pac. Reg. Can. Tech. Rep. Fish. Aquat. Sci., no. 1613. 47 pp.
- Cherry, D. S., K. L. Dickson, J. Cairns Jr., and J. R. Stauffer. 1977. Preferred, avoided, and lethal temperatures of fish during rising temperatures. *Journal of Fisheries Research Board of Canada* 34:239-246.
- Ducharne, A. 2007. Importance of stream temperature to climate change impact on water quality. *Hydrology and Earth System Sciences Discussions* 4(4): 2425-2460.
- Durance, I., and S.J. Ormerod. 2007. Climate change effects on upland stream macroinvertebrates over a 25-year period. *Global Change Biology* 13: 942-957.
- Elliott, J. M. (1994). *Quantitative Ecology and the Brown Trout*. Oxford: Oxford University Press.
- Flebbe P.A., L.D. Roghair, and J.L. Bruggink. 2006. Spatial Modeling to Project Southern Appalachian Trout Distribution in a Warmer Climate. 2006. *Transactions of the American Fisheries Society* 135: 1371-1382.

- Flebbe, P.A. 1994. A regional view of the margin: salmonid abundance and distribution in the Southern Appalachian Mountains of North Carolina and Virginia. *Transactions of the American Fisheries Society* 123: 657-667.
- Franklin, I.A. 1980. Thresholds for survival: maintaining fitness and evolutionary potential. Pages 135-150 in M.E. Soule, and B.A. Wilcox, editors. *Conservation biology: an evolutionary-ecological perspective*. Sinaure, Sunderland, Massachusetts.
- Gaffield, S.J., K.W. Potter, and L. Wang. 2005. Predicting the summer temperature of small streams in southwestern Wisconsin. *Journal of the American Water Resources Association* 41:25-36.
- Gormley, K.L., K.L. Teather, and D.L. Guignon. 2005. Changes in Salmonid Communities Associated with Pesticide Runoff Events. *Ecotoxicology* 14: 671-678.
- Gu, R., R. McCutcheon, and C.J. Chen. 1999. Development of weather-dependent flow requirements for river temperature control. *Environmental Management* 24:529-540.
- Hengeveld HG (1990) Global climate change: implications for morphology. *Transactions - American Geophysical Union* 38:913-920.
- Hostetler, S.W. 1991. Analysis and modeling of long-term stream temperatures on the Streamboat Creek basin, Oregon: implications for land use and fish habitat. *Water Resources Bulletin* 27: 637-647.
- Hudy, M., D.M. Downey, and D.W. Bowman. 2000. Successful Restoration of an Acidified native Brook Trout Stream through Mitigation with Limestone Sand. *North American Journal of Fisheries Management* 20:453-466.
- IPCC (Intergovernment Panel of Climate Change). 1996. 'Climate Change 1995'. In Houghton, J.T., Meria Filho, L.G., Challander, B.A., Harris, N., Kattenberg, A., and Maskell, K. (eds.), *The science of Climate Change*, Cambridge University Press, Cambridge.
- Johnson, S. L. 2004. Factors influencing stream temperature in small streams: Substrate effects and a shading experiment. *Canadian Journal of Fisheries and Aquatic Sciences* 61:913-923.

- Johnson, S. L., and J. A. Jones. 2000. Stream temperature responses to forest harvest and debris flows in western cascades, Oregon. *Canadian Journal of Fisheries and Aquatic Sciences* 57:30-39.
- Kelly, G.A., J.S. Griffith, and R.D. Jones. 1980. Changes in distribution of trout in Great Smoky Mountains national Park, 1900-1977. U.S. Fish and Wildlife Service Technical Paper 102.
- Larson, S. L., L. L. Larson, and P. A. Larson. 2002. Perspectives on water flow and the interpretation of FLIR images. *Journal of Range Management* 55:106-111.
- Lee, R.M., and J.N. Rinne. 1980. Critical thermal maxima of five trout species in the southwestern United States. *Transactions of the American Fisheries Society* 109: 632-635.
- Lemmon, P.E. 1956. A spherical densitometer for estimating forest overstory density. *Forest Science* 2: 314-320.
- MacCrimmon, H. R., and J. S. Campbell. 1969. World distribution of brook trout (*Salvelinus fontinalis*). *Journal of Fisheries Research Board of Canada* 26:1699-1725.
- Matthews, K. R., and N. H. Berg. 1997. Rainbow trout responses to water temperature and dissolved oxygen stress in two southern California stream pools. *Transactions of the American Fisheries Society* 50:50-67.
- Meisner, J. D. 1990a. Effect of climatic warming on the southern margins of the native range of brook trout (*Salvelinus fontinalis*). *Canadian Journal of Fisheries and Aquatic Sciences* 47:1065-1070.
- Meisner, J. D. 1990b. Potential loss of thermal habitat for brook trout, due to climatic warming, in two southern Ontario streams. *Transactions of the American Fisheries Society* 199:282-291.
- Mohseni, O., H.G. Stefan, and T.R. Erickson. 1998. A nonlinear regression model for weekly stream temperatures. *Water Resources Research* 34: 2685-2692.
- Moore, R.D., D.L. Spittlehouse, and A. Story. 2005. Riparian microclimate and stream temperature response to forest harvesting: A review. *Journal of the American water Resources Association* 41(4): 813-834.

- Morrill, J.C., R.C. Bales, M. Asce, and M.H. Conklin. 2005. Estimating Stream Temperature from Air Temperature: Implications for Future Water Quality. *Journal of Environmental Engineering* 131(1): 139-146.
- National Assessment Synthesis Team (NAST). 2000. Climate change impacts on the United States: the potential consequences of climate variability and change – overview report. Cambridge University Press, New York.
- Neumann, D. W., B. Rajagopalan, and E. A. Zagona. 2003. Regression model for daily maximum stream temperature. *Journal of Environmental Engineering* 129(7):667-674.
- Nielsen, J. L., T. E. Lisle, and V. Ozaki. 1994. Thermally stratified pools and their use by steelhead in northern California streams. *Transactions of the American Fisheries Society* 123(4):613-626.
- Onset. 2008. Data Logger Solutions from Onset Computer Corporation. <http://www.onsetcomp.com/>. Accessed: March 31st, 2008.
- Rahel, F.J., and W.A. Hubert. 1991. Fish assemblages and habitat gradients in a Rocky Mountain-Great Plains stream: Biotic zonation and additive patterns of community change. *Transactions of the American Fisheries Society* 120: 319-332.
- Ricker, W.E. 1934. An ecological classification of Ontario streams. *Publications of the Ontario Fisheries Research Laboratory*, 49, 1-114.
- Ries, R.D., and S.A. Perry. 1995. Potential effects of global climate warming on brook trout growth and prey consumption in central Appalachian streams, USA. *Climate Research* 5: 197-206.
- Rothwell, E., J. McNamara, and C. Luce. 2005. The Influence of Hyporheic Flow on the Temperature of a Riffle-Step-Pool Stream. American Geophysical Union, Fall Meeting 2005, abstract #H13B-1337
- Saila, S., M. Cheeseman, and D. Poyer. 2004. Maximum stream temperature estimation from air temperature data and its relationship to brook trout (*Salvelinus fontinalis*) habitat requirements in Rhode Island. Wood-Pawcatuck Watershed Association, Hope Valley, RI.

- Soule, M.E. 1980. Thresholds for survival: maintaining fitness and evolutionary potential. Pages 151-169 in M.E. Soule, and B.A. Wilcox, editors. Conservation biology: an evolutionary-ecological perspective. Sinaure, Sunderland, Massachusetts.
- Stefan, H. G., and E. B. Preud'homme. 1993. Stream temperature estimation from air temperature. Water Resources Bulletin 29(1):27-45.
- Story, A., R.D. Moore, and J.S. Macdonald. 2003. Stream temperatures in two shaded reaches below cutblocks and logging roads: downstream cooling linked to subsurface hydrology. Canadian Journal of Forest Restoration. 33: 1383-1396.
- Sugimoto, S., F. Nakamura, and A. Ito. 1997. Heat budget and statistical analysis of the relationship between stream temperature and riparian forest in the Toikanbetsu River Basin, northern Japan. Journal of Forest Research 2(2):103-107.
- Swift Jr., L.W. and J.B. Messer. 1971. Forest cuttings raise temperatures of small streams in the southern Appalachians. Journal of Soil and Water Conservation 26: 111-116.
- Wehrly, K.E., L. Wang and M. Mitro. 2007. Field-Based Estimates of Thermal Tolerance Limits for Trout: Incorporating Exposure Time and Temperature Fluctuation. Transactions of the American Fisheries Society 136:365-374.
- Zwieniecki, M., and M. Newton. 1999. Influence of streamside cover and stream features on temperature trends in forested streams of western Oregon. Western Journal of Applied Forestry 14:106-112.