Water Temperature Controls in the Sheepscot River, Maine

Author: Michele E Gryga

Persistent link: http://hdl.handle.net/2345/414

This work is posted on eScholarship@BC,
Boston College University Libraries.

Boston College Electronic Thesis or Dissertation, 2006

Copyright is held by the author, with all rights reserved, unless otherwise noted.

Controls on Water Temperature

In the Sheepscot River, Maine

An Honors Thesis

Michele Emily Gryga

Presented to

Dr. Noah Snyder

The Department of Geology and Geophysics

Boston College

Chestnut Hill, Massachusetts

April 28, 2006

CONTROLS ON WATER TEMPERATURE IN THE SHEEPSCOT RIVER, MAINE

The Sheepscot River watershed is 590 km^2 located in mid-coast Maine. Two branches comprise the river: the main stem and the West Branch, which merge in North Whitefield before flowing into the Gulf of Maine. The Sheepscot River has an imposed form that is strongly influenced by the Norumberga Fault Zone and it flows through glacial deposits. The watershed has a temperate climate because of its location in mid-latitudes in the northern hemisphere.

Water temperatures vary in the Sheepscot River over time and along the length of the river. The temporal and spatial variability of the river is due to air temperature, precipitation, discharge from the Palermo Fish Rearing Station, Long Pond, tree shade, confluence, and drainage area. Analysis of these hypothesized controls revolves around field water temperature measurements made between August 2005 and January 2006 and data collected from the North Whitefield gauging station. Supplementary digital spatial data from the Maine Geographic Information Systems data set were also used. Field measurements were taken at seven sites directly upstream and downstream of assumed controls.

Climactic features of the watershed exert the main control over the entire river. Air temperature is the first order controls on water temperatures. Precipitation has some effect on water temperature but of less significance than air temperature. The river system has three areas that are affected by different combinations of the other controls: the upper main stem, the West Branch, and the lower main stem. Discharge from the Palermo Fish Rearing Station is the second major controlling factor of water temperature in the upper main stem. Its buffering effect is diluted downstream. Long Pond also affects the upper main stem by warming the water in the summer and cooling it in the winter. Drainage area explains variability in the West Branch and lower main stem. As drainage area increases downstream, water temperatures are controlled by more integrated factors. As a result of this the West Branch fluctuates more than the main stem because it has a smaller drainage area. Temperatures in the downstream reaches are less sensitive to any single control. Confluence and tree cover exert less influence over the system than other controls.

ACKNOWLEDGEMENTS

First and foremost, thanks to my advisor, Noah Snyder, for his constant guidance, continuous patience, and steady striving during this endeavor. To my cohort in the field, Mike Castele, I could not have kept my sanity nor my smile without your humor. We made it through some long hot summer days on banter and laughter. Of course, to my roommates – Jessica Amato, Chi Ma, and Megan Mattern – who always lent an empathetic ear to my thesis trials and tribulations. Hopefully I will see you more in the last few weeks of senior year! And most dear to my heart, my support team from home. To Brian Hallowell for his words of down-to-earth wisdom and encouragement during the stressful times. And moreover thanks for giving me another reason to schlep to Maine nearly every weekend. To Richard Tucker of Mark T. Sheehan High School, whose freshman Earth Science class got me hooked on nature and science; whose straightforwardness has never led me astray; and who continues to be my mentor and dear friend. Last, but certainly not least, to my parents, Edward and Miriam Gryga, for always believing in my abilities and thinking I can do anything. To my dad whose light humor never let me take myself too seriously. To my mom for ensuring that I returned to my room safe and sound after late nights in the lab. I would also like to thank the entire Geology and Geophysics Department at Boston College, both faculty and students. Working among friends who felt like family made this experience worthwhile. I would also like to thank the U.S. Geologic Survey for making data sets available for this research. To Melissa Laser of the Maine Atlantic Salmon Commission for clarifying existing data and her thoughtful interest and insight in my work. And to Michael Boyer of the Palermo Fish Rearing Station for providing the numerical values I needed to round out the most conclusive areas of my research.

TABLE OF CONTENTS

CHAPTER ONE

INTRODUCTION

Purpose of Study

Salmon populations are endangered or near endangered in many North American rivers. The five species of Pacific salmon- Chinook (*Oncorhynchus tshawytscha*), Chum (*Oncorhynchus keta*), Coho (*Oncorhynchus kisutch*), Pink (*Oncorhynchus gorbuscha*) and Sockeye (*Oncorhynchus nerka*)- as well as Atlantic salmon (*Salmo salar*) have faced many threats to their survival over the past two centuries (Montgomery, 2003) primarily because of their migratory life cycle.

Figure 1 depicts the life cycle of salmon, which are anadromous fish. They are born in river redds that are burrowed out from the river's substrate by adult salmon (Hendry and Cragg-Hine, 2003). They spend the first 2-4 years of their life in this fluvial habitat through the alevin and parr stages of maturation (Hendry and Cragg-Hine, 2003). Once a parr has grown to a length of 100-120 mm, the salmon undergoes physiological, morphological, and behavioral changes in a process called smoltification, in which parr become smolts (Hendry and Cragg-Hine, 2003). At this time they migrate to sea, where they spend 1-4 winters in their marine environment (Hendry and Cragg-Hine, 2003). In the oceans they grow quickly before returning to their childhood rivers to spawn (Montgomery, 2000; Hendry and Cragg-Hine, 2003).

Initial assessments of salmon population cite overfishing and dams as the two main reasons for the startling decline in salmon numbers (Montgomery, 2003). Heavy fishing in both fluvial and marine environments greatly reduces salmon populations (Montgomery, 2003). Mature salmon and their potential offspring are

Figure 1

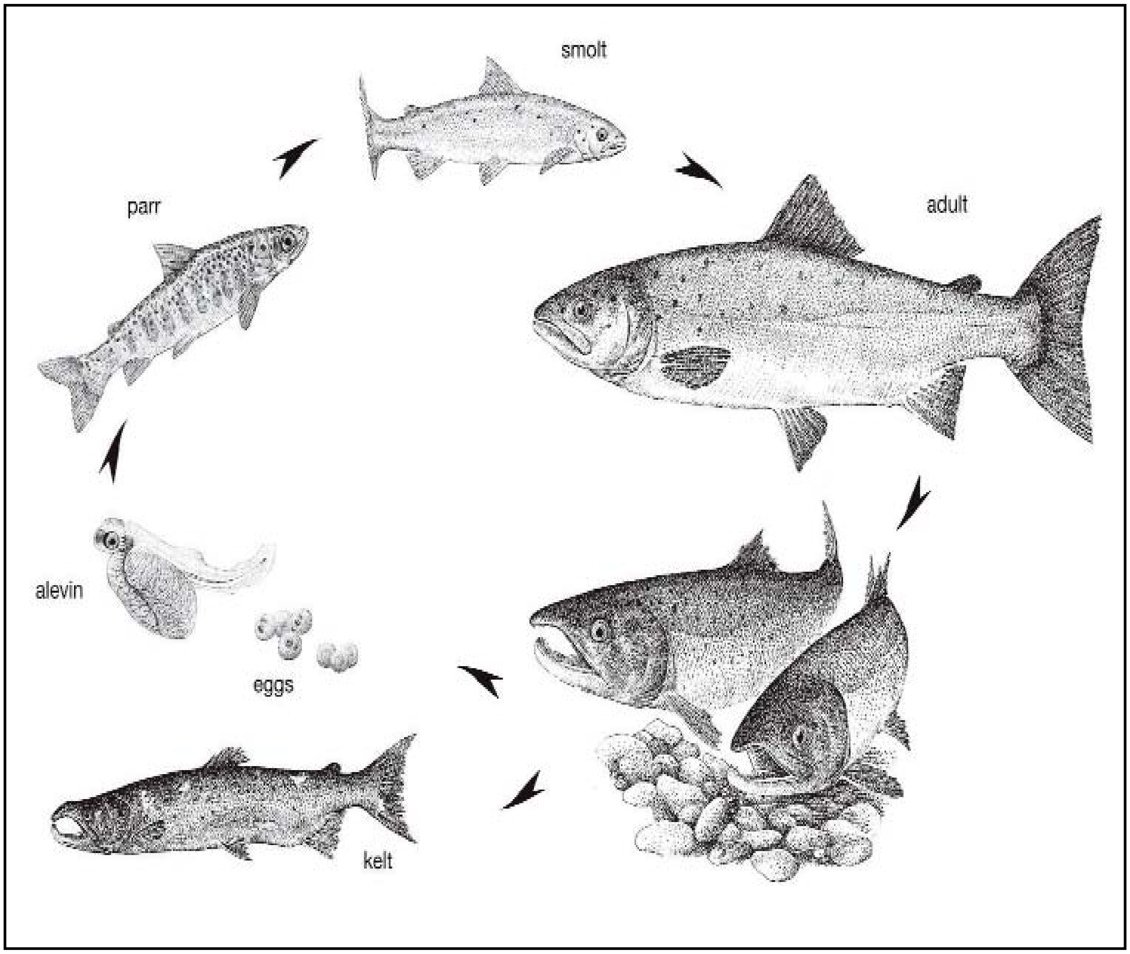


Figure 1: A diagram showing all the stages of the salmon life cycle (from Hendry and Cragg-Hine, 2003, pp. 5). Salmon live in fluvial environments during the alevin and parr stages. They then undergo a physiological change called smoltification that turns them into smolts. As smolts they migrate to sea. After maturing in their marine habitat for two to four years, they return to their indigenous rivers as adults in order to spawn.

therefore lost to fishermen. Salmon that are able to return to their rivers to spawn find that their ascent upstream is inhibited by numerous dams erected to produce hydropower for river mills as early as the 18th century in the northeast United States (SVCA, 2005). Many types of anadromous fish, including salmon, alewives, and trout, have much difficulty reaching spawning grounds because of blocked runs (Montgomery, 2003; SVCA, 2005).

Current evaluations of endangered salmon concentrate on a broader list of contributing factors. Fishing and dams continue to be thought of as leading reasons to the historical decrease in salmon numbers, however, much focus is being given to habitat degradation. The natural state of salmon rivers prior to human development was characterized by narrow, deep rivers filled with pools, cold water, large woody debris (LWD), and mobile gravel beds (Montgomery, 2003; Tetzlaff et al., 2005). These elements are important for salmon habitat. They provide the necessary conditions for procreation as well as protection from predation. Present research is studying the effects of deforestation, splash dams, and log drives, which are believed to have altered these traits by making rivers wider, shallower, lacking LWD, filling pools, reducing riparian shading, and increasing levels of silt to the river bed. Thus, the underlying causes of salmons' reduced populations are multifaceted.

When the problem of salmon population survival was recognized in the 19th century, efforts were made to save them from extermination. The salmon fishing and canning industries attempted to bolster their supply of fish by looking to various solutions. The most popular solution was to raise salmon in hatcheries along rivers, thereby increasing early life-stage survival (Montgomery, 2003). These restocking efforts took various forms. Attempts were made to import thriving populations of salmon from different regions, raise them in fish hatcheries, and then release them into the wild. For example, Canadian Atlantic salmon were brought to the Gulf of Maine as a means of bolstering the dwindling salmon populations in Maine's rivers (SVCA, 2005). In order to stock hatcheries, salmon were caught and their eggs and semen were mixed to breed more salmon. These salmon were later released.

As well intentioned as these measures were, problems soon arose. As salmon were released into the wild from these hatcheries, bacteria and diseases were released into the natural waters (NRC, 2004). Hatcheries also pose threats to the wild genetic pool – the very group they are supposed to help. Extinction, loss of within-population genetic variability, and behavioral changes are other problems arising from hatcheries (NRC, 2004). Also, without addressing the overfishing problem, hatcheries were merely supplying fishermen with a costly catch. Surprisingly, once catch limits were established in the 1940s populations still did not rebound (Tetzlaff et al., 2005). American fishermen were forced to follow strict rules regarding salmon, but nothing prohibited Canadian and Scandinavian fishermen from catching off the coast of Greenland the very fish that resulted from American restocking efforts. Hatcheries were not the answer to the dwindling salmon populations (NRC, 2004).

Salmon numbers continued to decline. Specific to this study of the northeast United States, Atlantic salmon are extirpated from the Housatonic and Connecticut Rivers. The United States Fish and Wildlife Service (USFWS) and National Oceanic and Atmospheric Administration Fisheries Division (NOAA) identified the rivers draining into the Gulf of Maine as having the only population of Atlantic salmon that is not extinct in the United States (SVCA, 2005; NRC, 2004). Efforts to save the remnants of a thriving salmon population in the northeast have pushed researchers to find other ways of bolstering the natural population. Researchers and scientists have identified habitat restoration as the means by which the wild genetic strain of Atlantic salmon can be saved (NRC, 2004).

Table 1 outlines the general characteristics of ideal Atlantic salmon habitat. Hydrologic, geomorphic, climatologic, and ecologic parameters for a suitable and healthy fluvial environment are the main focus. In order for habitat restoration efforts to be successful, all facets of salmon habitat conditions must be met. These specifications outline the goals of habitat restoration. Many sections of rivers within the Gulf of Maine are not within these optimal fluvial criteria because of anthropogenic changes to rivers and their watersheds (SVCA, 2005).

Hydrologically, current velocities may have decreased due to dams, especially in summer months or during periods of natural low flow. Some developing theories point to historic log drives and splash dams, which may have made rivers wider and shallower. Rivers continue to respond to historic land use practices. River water velocity may have decreased with the increase of channel width and decrease in water height.

Ecologic changes have complicated hydrologic conditions. Riparian deforestation of the 18th and 19th centuries and increased farming within watersheds have exposed the rivers to more sun by removing shading by tree cover. Log drives and splash dams also decreased fluvial shade by removing the natural LWD. This has added to a warming effect of river waters (SVCA, 2005). Because dissolved oxygen content is inversely related to water temperatures (Allan, 1995), increases in water temperatures have led to a decrease in dissolved oxygen levels, which in turn increases salmon metabolic rates. These effects result in smaller salmon size and increase predation.

Deforestation and riparian changes have also changed the riverbed substrate of many rivers. Silt and sand have filled these rivers. High flows are needed to transport this material and “clean” the beds. Slowly flowing waters paired with cleared riverbeds from log drives and splash dams have also led to riverbed armoring. In many areas, the beds have become immobilized or stripped to underlying bedrock. Salmon are therefore unable to burrow the needed redds in order to spawn (NRC, 2004).

The quality of fluvial environments of salmon depends on correction of these related parameters (Table 1). Of particular importance are river water temperatures because they directly affect salmon through dissolved oxygen and growth rate levels (NRC, 2004) and indirectly affect other river factors, like pH and overall river ecology. Of the rivers that have wild salmon populations, the Sheepscot River located in mid-coast Maine is of special interest to understanding how potentially warming waters may play a role in the decline of Atlantic salmon populations (Figure 2 and 3). It is speculated that Atlantic salmon in rivers at the southern end of the range face a greater risk of the effects of increased water temperatures due to contemporary climate change than fish in northern rivers. This hypothesis is based on three reasons: (1) temperatures in the northern hemisphere generally warm with decreasing latitude, (2) the Sheepscot River has the southernmost remaining population of wild Atlantic salmon in North America, and (3) climate changes indicate that Maine is currently experiencing warming air temperatures (SVCA, 2005; Hodgkins et al., 2003). The Sheepscot River is

Table 1

Parameter Type	Specification	Value			Source
Hydrologic	Current Velocity	25-90 cm/s			Tetzlaff et al., 2005
	Water Depth	17-70 cm			Tetzlaff et al., 2005
	Dissolved Oxygen Content	> 9 mg/l			Tetzlaff et al., 2005
	Water pH	6-9			Hendry and Cragg-Hine, 2003; Tetzlaff et al., 2005
	Suspended Solids	< 25			Tetzlaff et al., 2005
Geomorphic	Riverbed Substrate	Mobile Gravel and Cobble			Minns et al., 1995; Tetzlaff et al., 2005
	Grain Size	16-256 mm			Fleming and Jensen, 2002; Hendry and Cragg-Hine, 2003; Minns et al., 1995; Tetzlaff et al., 2005
	Gradient of River	≤ 3%			Dudley and Hodgkins, 2002
Ecologic	Shade	From Large Woody Debris & Tree Cover			Fleming and Jensen, 2002; Hendry and Cragg-Hine, 2003; Minns et al., 1995; Tetzlaff et al., 2005
	Biology	Presence of Mayfly, Stonefly, and Caddis fly			Fleming and Jensen, 2002
Climatologic	Water Temperature *Spawning*	Optimal 5-8 °C	Minimum 4.0 °C	Maximum 10-12 °C	SVCA, 2005
	Water Temperature *Egg/Alevin*	Optimal 4.0-7.2 °C	Minimum 0.5 °C	Maximum 12 °C	SVCA, 2005
	Water Temperature *Early Fry*	Optimal 8-19 °C	Minimum 0.5 °C	Maximum 23.5-27.7 °C	SVCA, 2005
	Water Temperature *Parr Feeding*	Optimal 15-19 °C	Minimum 3.8 °C	Maximum 22.5 °C	SVCA, 2005
	Water Temperature *Parr Survival*	Optimal 0.5-20 °C	Minimum 0 °C	Maximum 27-32 °C	SVCA, 2005
	Water Temperature *Smolt (Migrating)*	Optimal 7.0-14.3 °C	Minimum 5 °C	Maximum 19 °C	SVCA, 2005
	Water Temperature *Adult (Migrating)*	Optimal 14-20 °C	Minimum 8 °C	Maximum 23°C	SVCA, 2005

Table 1: An optimal fluvial environment for salmon includes these specifications. The climatologic data derives from a table in SVCA (2005).

Figure 3

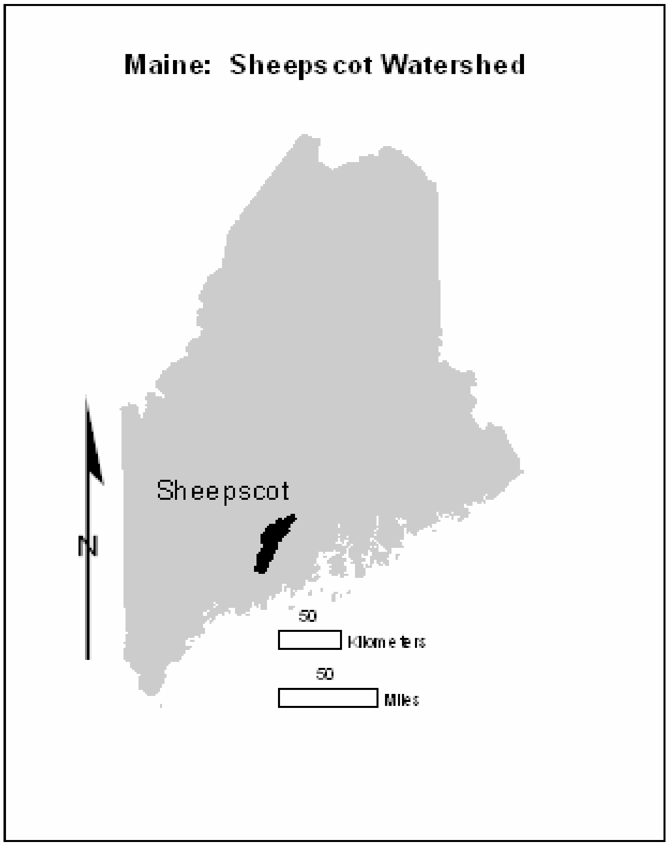


Figure 3: Map of Maine showing the Sheepscot River Watershed.

therefore the ideal river in which to study the effects of warming water temperatures on Atlantic salmon.

Of the many non-profit and volunteer groups working on habitat restoration, the Sheepscot Valley Conservation Association (SVCA) is actively researching six hypotheses regarding habitat restoration of the Sheepscot River (SVCA, 2005). These hypotheses include:

- **Hypothesis #1:** The abundance and distribution of Atlantic salmon in the Sheepscot River watershed have been reduced.
- **Hypothesis #2:** Elevated water temperature is limiting Atlantic salmon production in many reaches and tributaries of the Sheepscot River.
- **Hypothesis #3:** Physical habitat is limiting Atlantic salmon in the Sheepscot River watershed.
- **Hypothesis #4:** Dams are impeding recovery of Atlantic salmon in the Sheepscot River watershed.
- **Hypothesis #5:** Water quality is impeding recovery in some reaches of the Sheepscot River.
- **Hypothesis #6:** Predation by introduced fish species is limiting Atlantic salmon production in the Sheepscot River and its tributaries.

The goal of the research being done on these hypotheses is to assess and address all of the hydrologic, geomorphic, climatologic, and ecological parameters that are collectively causing the demise of the Atlantic salmon population in the Sheepscot River.

I find the work conducted on Hypothesis #2 to be interesting and vital to habitat restoration. Research, data collection, and data analysis of the Sheepscot River watershed and water temperatures have been extensive. Five main findings have been made and reported by the SVCA. First, water temperatures are impaired and outside the optimal feeding range of 15-19 ºC for the river reaches of Choate Brook, Ben Brook, Trout Brook, and Dyer River, which are all tributaries to the main stem (MS) and the West Branch of the Sheepscot (WB), as well as the upper MS and upper WB (Table 1; Figure 2; SVCA, 2005). The second finding is that the lower WB and lower Trout Brook are uninhabitable for salmon during summer months (SVCA, 2005). Third, water temperatures of the lower WB are just below lethal values (31 ºC) during summer months (SVCA, 2005). The fourth conclusion states that in the lower MS during the summer of 2001, temperatures exceeded lethal levels (SVCA, 2005). The tentative fifth finding is that ponds and reservoirs may have warming effects on the reaches just downstream of their location during winter months, as evidenced by lack of freezing in these areas (SVCA, 2005).

These conclusions regarding Hypothesis #2 have established specific problematic areas. Research needs to expand upon these findings in order to pinpoint the reasons why certain areas along the river and certain time periods experience warming. The crux of my research is to expand upon Hypothesis #2 by identifying, analyzing, and understanding how specific controls affect water temperatures of the Sheepscot River. I have expanded on the scope of Hypothesis #2 to assess whether or not and to what extent the Palermo Fish Rearing Station (a rearing station for brook trout), riparian reforestation, tributaries, location of lakes and ponds, precipitation, and air temperature influence water temperatures. I have therefore concentrated on the temporal and spatial controls of water temperature in the Sheepscot River.

STUDY AREA

The Sheepscot River has a 590 km^2 watershed located in mid-coast Maine (Figure 3). The river has two branches, the main stem (MS) and the West Branch (WB), which merge in North Whitefield (Figure 2). The river then flows downstream to Head Tide Dam, below which it mixes with tidal waters and flows into the Gulf of Maine. Sheepscot Pond and Long Pond are the two main bodies of water on the main stem.

The Laurentide ice sheet covered the Sheepscot River watershed during the late Pleistocene (Schnitker et al., 2001). At the last glacial maximum approximately 18-20 ka (Belknap et al., 2002), this ice sheet extended into the Gulf of Maine onto Georges and Browns Banks (Schnitker et al., 2001). Relative world sea levels were also low because of the large amount of water contained in these ice sheets. Isostatic depression occurred where the weight of the ice sheet depressed the underlying continental crust (Belknap et al., 2002). The ice retreated to the present coastline approximately 14 ka (Schnitker et al., 2001). As it continued to retreat and prior to isostatic rebound, the Sheepscot watershed was covered by ocean water because water that was once locked in the glaciers melted and increased world-wide sea levels. Evidence of this within the Sheepscot River watershed is glaciomarine mud that indicates a marine environment in the past. The retreat of the ice sheet at 15-13 ka submerged present day Maine in 70-130 m of ocean water (Belknap et al., 2002). Isostatic rebound followed at approximately 13-11 ka, which allowed the depressed land to emerge and relative sea-level to fall to a lowstand of 60 m below present levels (Belknap et al., 2002). From 10.8 ka to present isostatic rebound was again overtaken by eustatic sea-level rise (Belknap et al., 2002).

Ordovician-Precambrian rocks of mafic to felsic composition are the predominant bedrock geology of the watershed with some mélange along the outside edges (Osberg et al., 1985). The Sheepscot River is strongly influenced by the structure of the Norumbega Fault Zone that runs northeast to southwest along coastal Maine (Osberg et al., 1985). This is evidenced by the path of both branches of the river that also run northeast to southwest, parallel to the trend of the fault and the strike of the rock units. Large drops in elevation along the length of the river occur where the river flows in a nonparallel path across the strike of the rock. Primarily it flows between ridges of harder rock and in the valleys of softer rock.

The Sheepscot River flows through glacial deposits of till and outwash. This coarse sediment provides the primary bed-material load and washload of the river. Because the Sheepscot does not flow through sediment that it eroded and deposited itself, it is an imposed-form channel. Bed sediment grain size is predominantly gravel. Bed substrate is armored in some reaches and in others is bedrock.

CHAPTER TWO

METHODS

Field Measurements

The temporal and spatial analyses largely depend on my field measurements taken from August 2005 through January 2006. Seven monitoring locations were selected based on their positioning just upstream or downstream of areas hypothesized to directly influence water temperatures (Figure 2). Measurements were taken with a Model HH21 Microprocessor Thermometer at the left and right banks and in the middle of each site. Measurements in the middle of the river were taken only during mild times of the year and when flow velocities allowed safe wading into the river. The controls being tested include:

- Anthropogenic inputs (discharge from the Palermo Fish Rearing Station);
- Lakes and Ponds (Long Pond);
- Tributaries (WB); and
- Tree shading.

Hibberts Gore (HG) is located in the upper reaches of the MS, just downstream of the Palermo Fish Rearing Station. Discharge from Palermo includes water pumped from nearby Sheepscot Pond from a depth of approximately 12 m. This discharge is directly injected into the river at temperatures ranging from 14.4 to 16.6 ºC[1]. The North of Long Pond (NLP) and Coopers Mills (CM) sites are upstream and downstream of Long Pond, respectively. The North Whitefield (NW) site was chosen to provide direct comparison between my measurements and those of the North Whitefield Gauging Station (NWGS), allowing for error

---

[1] The Palermo Fish Rearing Station regulates the water temperatures drawn from the Sheepscot Pond but does not have discharge temperature requirements. The regulated temperatures of 14.4 to 16.6 ºC are assumed to be the temperatures of the discharge water from the station into the Sheepscot River.

analysis and linkage between temporal and spatial data sets. I used the average of the absolute values of differences between NWGS and NW temperatures to find the error of my field measurements. The NWGS is operated by the U.S. Geological Survey, and it records water and air temperature, discharge, and flow depth. The compilation of these data is found on the U.S. Geologic Survey station website (http://waterdata.usgs.gov). The NWGS provides a quarter-hourly continuous time series of water and air temperatures on the MS below its confluence with the WB. The Head Tide (HT) station is just below a dam and is the most downstream site unaffected by tidal influences. Dirigo (DR) is the uppermost station on the WB. This site is heavily shaded as well as being relatively narrow compared to other areas of the river. The Howe Road (HR) station is on the WB, just upstream of the confluence with the MS (Figure 2).

Temporal Analysis

Weather conditions are thought to be a main control of water temperature. Both fluctuate over time. The main goal of this analysis was to identify to what extent air temperature and precipitation exert a control on the fluctuations of water temperatures by identifying:

- What is the strongest control on water temperatures.
- When and where river water is warmer and colder.
- Whether the river responds more to maximum or minimum air temperatures.
- Whether the magnitude of diurnal trends fluctuates at certain times of the year.
- Whether precipitation is a control of water temperatures.

The temporal analysis largely depends on the NWGS continuous time series temperature. The database contains 47 years of point temperature measurements. This record, however, is not continuous due to inconsistent measuring and recording throughout the decades. Recent NWGS data from 2004 to the present, which are a continuous record, serves as the data for the temporal analysis. My field measurements of temperature provided a supplementary data set that was used in conjunction with the NWGS data.

Available from the National Climatic Data Center (NCDC), I collected precipitation data from the Newcastle, ME station. This data set extends from February 24, 2004 to October 31, 2005. I used these data in conjunction with the NWGS data in my analysis of temporal controls. The effect of precipitation on water temperature was tested by the calculation of change in water temperature over the course of one, two, three, four, five, six, and seven days from the onset of the precipitation event.

Spatial Analysis

The spatial analysis concentrates primarily on my field measurements. These values are used in conjunction with tree cover data, maps, and discharge calculations.

I downloaded tree cover data from the Maine Geographic Information Systems (GIS) website (dataset “forest91”; http://apollo.ogis.state.me.us). Tree cover data from Lincoln, Kennebec, Knox, and Waldo counties were used in conjunction with digital elevation models (DEMs) and digitized topographic maps downloaded from the same website.

I assembled all maps and watershed-wide calculations in the computer program ArcMap. The calculation of watershed area and the area of tree cover upstream of each respective site yielded the percent of tree cover per watershed area for each respective field site. These calculations were the basis of my tree cover analysis.

The watershed areas for HG, NLP, CM, and NWGS were also used to further my understanding of how Palermo Fish Rearing Station affects water temperature. The effect of Palermo discharge depends on what percent of total discharge it contributes to each site. Discharge (Q) is related to contributing watershed area of a field site (A) by:

$$\mathbf{Q = K_q A^c} \tag{1}$$

where K_q is a coefficient related to watershed runoff properties and rainfall intensity and c is an empirical exponent (usually 0.7-1.0); both values are based on climate (Dunne and Leopold, 1978). K_q and c are assumed to be constant throughout the watershed, and c is assumed to equal 1 during a given storm event. These assumptions are valid if runoff properties and rainfall intensity do not vary spatially during a storm event. Therefore, Q and A of field site and NWGS can be related by the ratio:

$$\mathbf{Q_{NWGS}/A_{NWGS} = Q_{Fieldsite}/A_{Fieldsite}} \tag{2}$$

A manipulation of Equation 2 gives:

$$\mathbf{Q_{Fieldsite} = (A_{Fieldsite} \times Q_{NWGS})/A_{NWGS}} \tag{3}$$

These Q calculations were made for HG, NLP, and CM. Palermo has a constant discharge. This discharge is part of the total discharge in all areas downstream of the Palermo site. $Q_{Palermo}$ was obtained similarly to $Q_{Fieldsite}$. From these values, percent of Q_{HG}, Q_{NLP}, and Q_{CM} from Palermo were calculated for each day field measurements were taken. Lack of data prohibited these calculations for days where NWGS did not record Q because of ice cover at the station.

CHAPTER THREE

RESULTS

Temporal Results

Table 2 and Figure 4 show the results of all field measurements. HG is the coldest throughout the summer with a temperature low of 13.8 °C. HT and DR have peak temperatures over 26 °C in August. Both values exceed optimal temperature thresholds for salmon habitat (Table 1). HT and DR are the only sites to exceed this upper threshold at any time from my field measurements (Table 1 and 2). These measurements correspond to the highest temperatures recorded at NWGS. Subsequent field measurements are less than these temperatures. NWGS has a decreasing temperature gradient from the beginning of August through the summer. NWGS, NLP, CM, NW, HT, DR, and HR stay within 1 °C of each other through October and into the beginning of November (Table 2).

Differences in temperature between all sites decreased until the November 6, 2005 measurements (Table 2). At this time, the rank of sites from warmest to coldest inverted, and the coldest sites became the warmest (Figure 4). During late autumn and winter, HG became the warmest site with a maximum difference from NWGS at this time of 2.4 °C (Table 2). Sites rank from warmest to coldest during November to February: HG, NLP, CM, NW, HT, DR, HR (Table 2 and Figure 4). The water temperatures decrease with each consecutive downstream site along both the MS and the WB. The WB remains colder than the MS throughout the winter (Figure 4). All sites except HG experienced temperatures below the lower threshold of optimal temperatures for salmon in the early fry stages (0.5 °C)

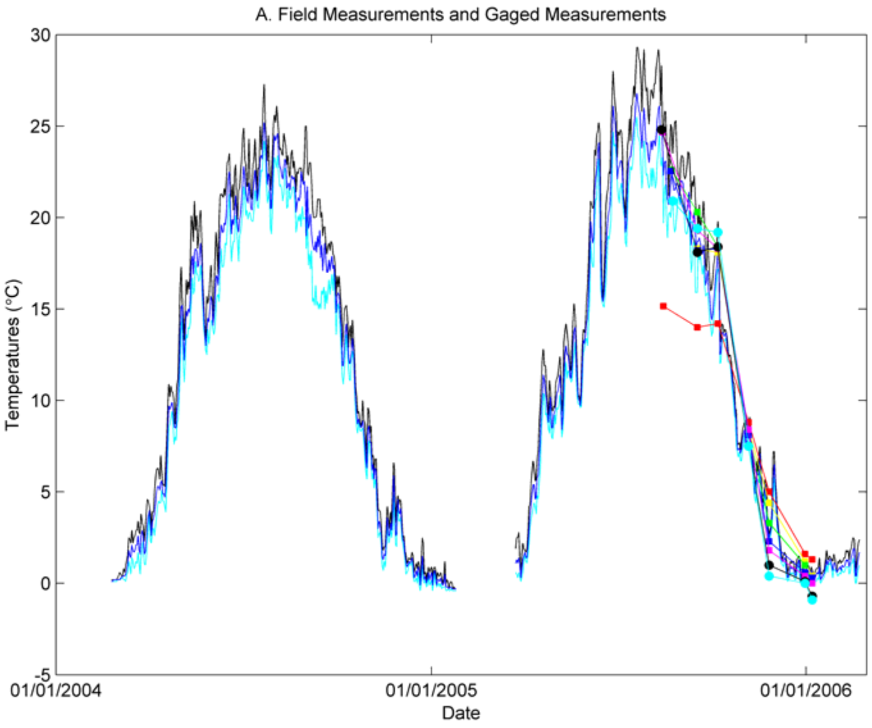
Table 2

Date	Time	Site	Left Temp (°C)	Middle Temp (°C)	Right Temp (°C)	Mean Temp (°C)	Max. Diff (°C)	NWGS Temp (°C)	Mean - NWGS (°C)
08/15/05	11:30	HG	13.9	14.2	13.8	14.0	0.4	22.4	-8.4
08/15/05	13:30	HG	14.8	14.8	14.8	14.8	0.0	22.4	-7.6
08/15/05	14:30	HG	15.8	15.8	15.9	15.8	0.1	22.4	-6.6
08/15/05	15:30	HG	16.0	15.9	16.2	16.0	0.3	22.4	-6.4
09/17/05	16:45	HG	13.8	14.0	14.2	14.0	0.4	19.2	-5.2
10/07/05	10:45	HG	14.4	14.2	14.0	14.2	0.4	18.4	-4.2
11/06/05	11:45	HG	8.8	8.8	8.7	8.8	0.1	8.4	0.4
11/26/05	14:00	HG	5.0	NAN	5.0	5.0	0.0	2.6	2.4
12/31/05	14:00	HG	1.6	NAN	1.6	1.6	0.0	0.3	1.3
01/07/06	14:45	HG	1.3	NAN	1.3	1.3	0.0	0.4	0.9
site average		**HG**					**0.2**		**-4.5**
09/17/05	17:15	NLP	18.0	17.9	18.9	18.3	1.0	19.2	-0.9
10/07/05	11:15	NLP	18.1	18.1	18.1	18.1	0.0	18.4	-0.3
11/06/05	12:15	NLP	8.4	8.4	8.4	8.4	0.0	8.5	-0.1
11/26/05	13:45	NLP	4.4	NAN	4.4	4.4	0.0	2.6	1.8
12/31/05	13:45	NLP	1.2	NAN	1.2	1.2	0.0	0.3	0.9
01/07/06	15:00	NLP	0.4	NAN	0.4	0.4	0.0	0.4	0.0
Site Average		**NLP**					**0.3**		**0.1**
08/23/05	11:15	CM	22.3	22.5	22.5	22.4	0.2	22.3	0.1
08/23/05	12:30	CM	22.7	22.7	23.1	22.8	0.4	22.3	0.5
09/17/05	17:00	CM	20.2	20.3	20.5	20.3	0.3	19.2	1.1
10/07/05	11:00	CM	18.1	18.7	18.3	18.4	0.6	18.4	0.0
11/06/05	12:00	CM	8.0	8.3	8.2	8.2	0.3	8.5	-0.3
11/26/05	13:15	CM	3.2	NAN	3.3	3.3	0.1	2.6	0.7
12/31/05	13:15	CM	1.0	NAN	1.0	1.0	0.0	0.3	0.7
01/07/06	14:30	CM	0.1	NAN	0.1	0.1	0.0	0.4	-0.3
Site Average		**CM**					**0.3**		**0.3**
08/22/05	10:30	NW	20.8	21.1	21.6	21.2	0.8	21.2	0.0
08/22/05	13:30	NW	22.1	22.6	23.3	22.7	1.2	22.3	0.4
08/22/05	14:00	NW	22.7	24.1	24.2	23.7	1.5	22.4	1.3
09/17/05	16:30	NW	18.2	18.3	18.2	18.2	0.1	19.2	-1.0
10/0705	10:30	NW	18.3	18.2	18.3	18.3	0.1	18.4	-0.1
11/06/05	11:30	NW	8.2	8.0	8.2	8.1	0.2	8.4	-0.3
11/26/05	13:00	NW	2.3	NAN	2.3	2.3	0.0	2.6	-0.3
12/31/05	13:00	NW	0.6	NAN	0.6	0.6	0.0	0.3	0.3
01/07/06	14:15	NW	0.3	NAN	0.3	0.3	0.0	0.4	-0.1
Site Average		**NW**					**0.6**		**0.0**
08/14/05	12:00	HT	22.8	22.8	22.8	22.8	0.0	24.1	-1.3
08/14/05	13:45	HT	25.0	24.9	24.8	24.9	0.1	24.1	0.8
08/14/05	15:00	HT	26.4	26.2	26.2	26.3	0.1	24.1	2.2
09/17/05	16:00	HT	19.3	19.3	19.3	19.3	0.0	19.1	0.2
10/07/05	10:00	HT	18.4	18.0	18.4	18.3	0.4	18.4	-0.1
11/06/05	11:00	HT	8.5	8.2	8.6	8.4	0.4	8.4	0.0
11/26/05	12:30	HT	1.8	NAN	1.8	1.8	0.0	2.6	-0.8
12/31/05	12:30	HT	0.4	NAN	0.4	0.4	0.0	0.3	0.1
01/07/06	13:45	HT	0.0	NAN	0.0	0.0	0.0	0.4	-0.4
Site Average		**HT**					**0.1**		**0.1**

Date	Time	Site	Left Temp (°C)	Middle Temp (°C)	Right Temp (°C)	Mean Temp (°C)	Max. diff. (°C)	NWGS Temp (°C)	Mean - NWGS (°C)
08/13/05	12:30	DR	23.3	23.5	23.4	23.4	0.2	24.9	-1.5
08/13/05	15:00	DR	26.1	26.2	26.2	26.2	0.1	25.0	1.2
09/17/05	17:45	DR	18.1	18.1	18.1	18.1	0.0	19.3	-1.2
10/07/05	11:45	DR	18.2	18.4	18.5	18.4	0.3	18.4	0.0
11/06/05	12:45	DR	7.5	7.4	7.6	7.5	0.2	8.5	-1.0
11/26/05	14:00	DR	1.0	NAN	1.0	1.0	0.0	2.6	-1.6
12/31/05	14:00	DR	0.1	NAN	0.1	0.1	0.0	0.3	-0.2
01/07/06	15:00	DR	-0.7	NAN	-0.7	-0.7	0.0	0.4	-1.1
Site Average		**DR**					**0.1**		**-0.7**
08/24/05	12:15	HR	21.0	21.0	21.5	21.2	0.5	19.6	1.6
08/24/05	15:15	HR	20.6	20.6	20.7	20.6	0.1	20.1	0.5
09/17/05	16:45	HR	19.5	19.4	19.4	19.4	0.1	19.2	0.2
10/07/05	10:45	HR	19.0	19.2	19.4	19.2	0.4	18.4	0.8
11/06/05	11:45	HR	7.2	7.5	7.8	7.5	0.6	8.4	-0.9
11/26/05	13:30	HR	0.4	NAN	0.4	0.4	0.0	2.6	-2.2
12/31/05	13:30	HR	0.0	NAN	0.0	0.0	0.0	0.3	-0.3
01/07/06	14:30	HR	-0.9	NAN	-0.9	-0.9	0.0	0.4	-1.3
Site Average		**HR**					**0.3**		**0.0**
Daily		Palermo				15.5			

Table 2: Field measurements taken at seven sites. From upstream to downstream, Hibberts Gore (HG), North of Long Pond (NLP), Coopers Mills (CM), North Whitefield (NW), and Head Tide (HT) are sites along the main stem. From upstream to downstream, Dirigo (DR) and Howe Road (HR) are sites along the West Branch. Middle temperatures were not collected during times of high flow or ice and are represented by NAN. The Palermo site refers to the Palermo Fish Rearing Station that discharges its water between 14.4 to 16.6 ºC just upstream of Hibberts Gore along the main stem.

Figure 4



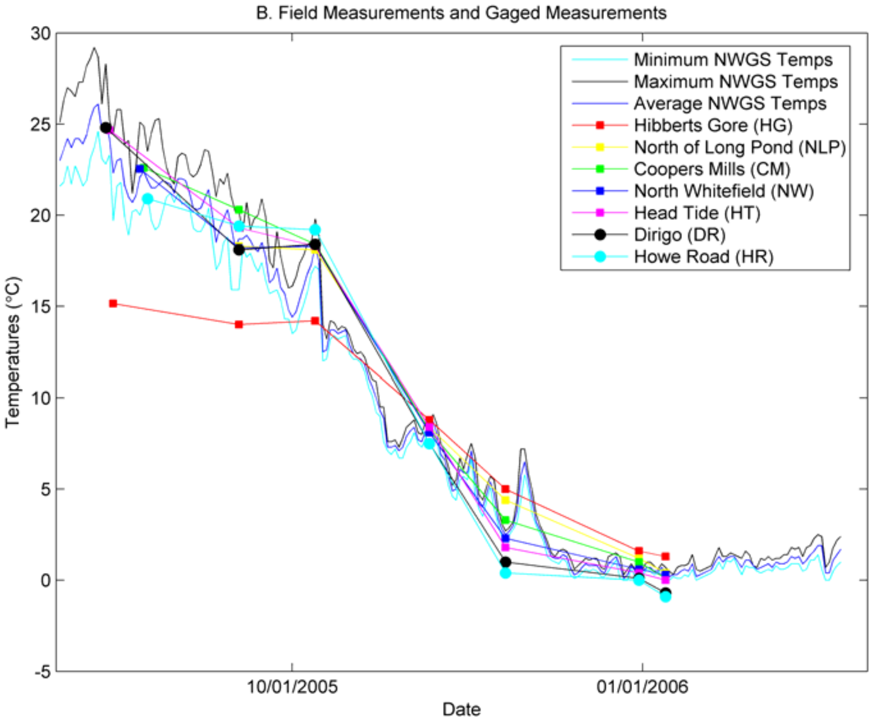


Figure 4: Continuous time series of point minimum, maximum, and average temperatures are from the North Whitefield Gauging Station (NWGS). All sites are plotted against these time series. Breaks in graph A are due to ice cover and the subsequent inability to take water temperature measurements. Graph B expands the part of graph A for the time period during which field measurements were made for this study.

by January 7, 2005 (Table 1 and Table 2).

Across channel water temperature variation (≤ 1.5 °C) occurred from August until November 6, 2005. In the winter both right and left sides of the channel were the same at every site (Table 2).

Figure 5 shows water and air temperatures from the winter of 2004 to the winter of 2006. Air temperatures in 2005 exceeded those in 2004 with a maximum of 32.8 ºC compared to 28.3 ºC (Figure 5). Water temperatures in 2005 likewise surpassed those of 2004 with a high of 29.3 ºC compared to 26.1 ºC (Figure 5). The winter of 2005-2006 also reached colder temperatures than the winter of 2004-2005. Minimum air temperatures reached a low of -18.3 ºC in 2005-2006 compared to -12.8 ºC in 2004-2005. Water temperatures did not fall below nor rise above the minimum or maximum air temperatures at the same point in time (Figure 5). Diurnal fluctuations in water temperature also decreased with time from summer into winter and increased from winter into summer during the years 2004, 2005, and into 2006 (Figure 4).

Figure 6 shows the correlations between water and air temperature. Mean air and mean water temperatures have an R^2 value of 0.86; minimum air and minimum water temperatures have an R^2 of 0.81. These correlations are greater than the relationship of maximum air temperature with maximum water temperature with an R^2 value of 0.74.

Figure 5

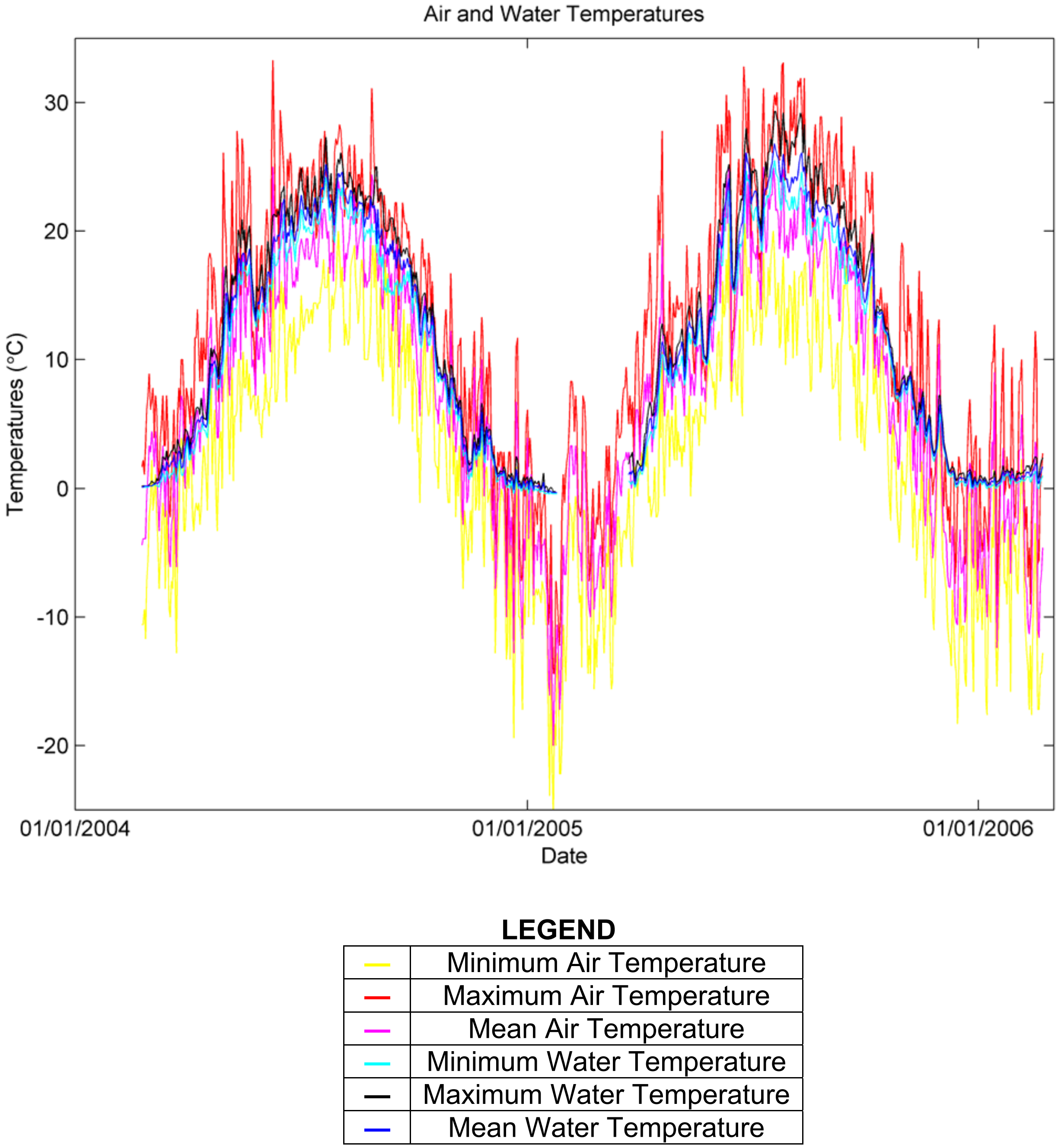
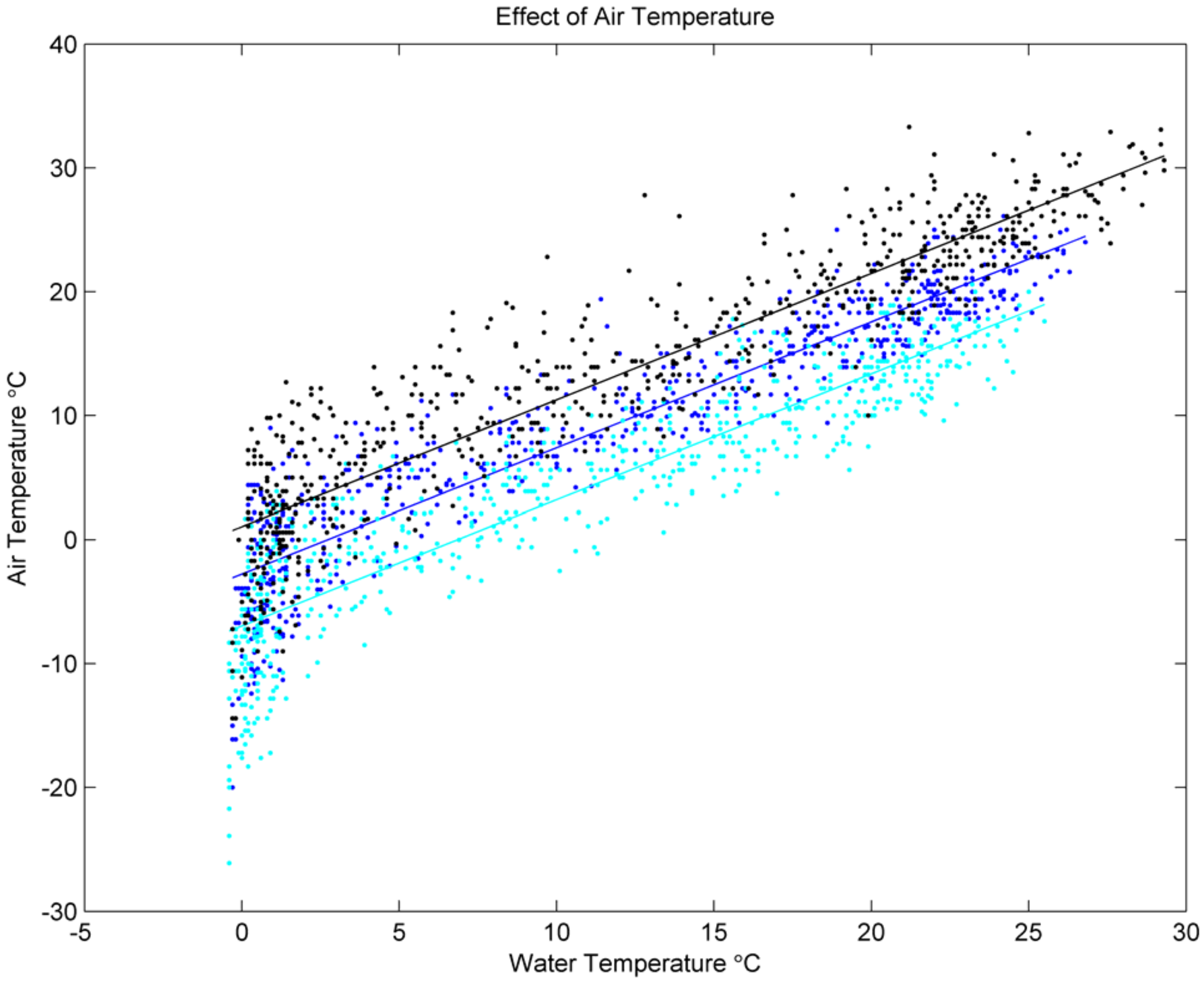


Figure 5: Comparison of air and water temperatures. Air and water temperatures are from the North Whitefield Gauging Station.

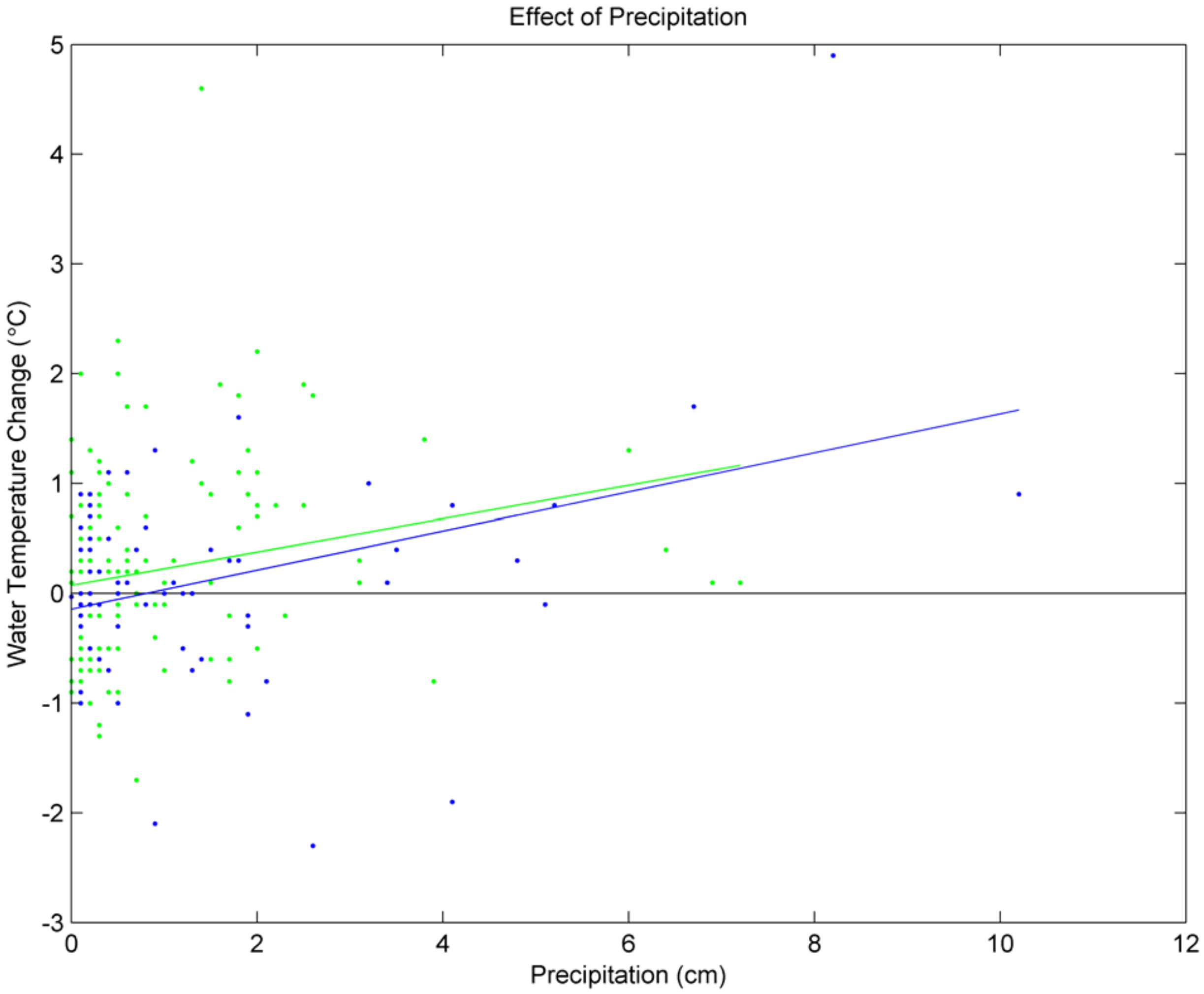
Figure 6



Regression	R^2
Maximum Air vs. Maximum Water Temp. y = 1.02x + 1.06	0.74
Mean Air vs. Mean Water Temp. y = 1.02x – 2.76	0.86
Minimum Air vs. Minimum Water Temp. y = 1.02x – 6.95	0.81

Figure 6: Scatter plot of paired measurements of maximum, mean, and minimum water and air temperatures, along with least-squares best fit regressions lines and accompanying equations.

Figure 7



Regression	R^2	Dates
Summer Precipitation vs. Change in Water Temperature $y = 0.15x + 0.075$	0.62	March 4, 2004 – September 30, 2004
Winter Precipitation vs. Change in Water Temperature $y = 0.18x – 0.014$	0.47	October 1, 2004 – December 26, 2004

Figure 7: Mean daily water temperature changes calculated on days that experienced precipitation, along with least-squares best-fit regression lines and accompanying equations. Change in water temperature was calculated over one day. Subsequent calculations of two, three, four, five, six, and seven days were also made; however, the data presented here has the best correlation. For this reason, these data are believed to reflect the effect of precipitation on water temperatures.

Figure 7 shows the correlations between water temperatures and precipitation. Changes in temperature over a period of one day have the strongest correlation with precipitation.

Spatial Results

Upper Main Stem

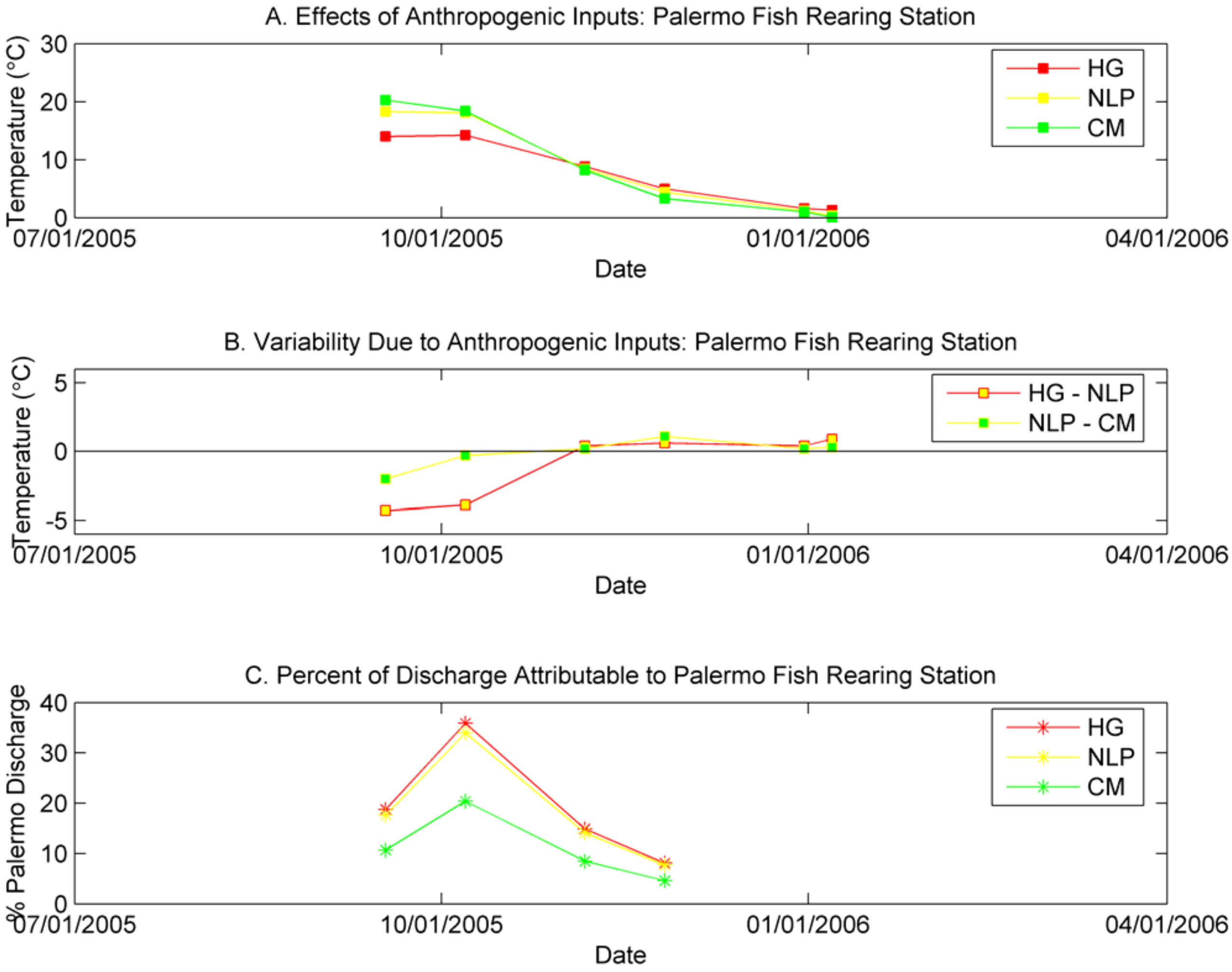
Figure 8 depicts differences in water temperatures of the upper main stem sites – HG, NLP and CM. HG is much colder than all the sites during the summer months. Compared to the station closest to it, NLP, it has a maximum summer difference of 4.3 ºC. The difference between HG and CM is greater than that between HG and NLP with a maximum difference of 6.3 ºC (Figure 8). Differences in temperatures between all three stations decrease from summer to autumn.

During the winter, HG is warmer than NLP and CM; this difference is to a lesser degree than in summer months (Figure 8). Maximum water variability between HG and NLP is 0.9 ºC and 1.2 ºC between HG and CM (Figure 8).

Figure 9 shows the variability in water temperature between NLP and CM due to Long Pond. Long Pond warms the MS during the summer and cools it during the winter. NLP is colder than the downstream site of CM during the summer. This effect has a maximum increase in temperature of 4.1 ºC in the summer. The reverse is true in the winter. Temperature decreases reached a maximum of 1.1 ºC in the winter. The water from Long Pond that flow downriver is colder than the river water flowing into the pond during the winter (Figure 9).

Table 3 and Figure 10 shows the percent tree cover of each station's contributing watershed. The percent of the watershed shaded by tree cover

Figure 8


A. Effects of Anthropogenic Inputs: Palermo Fish Rearing Station

B. Variability Due to Anthropogenic Inputs: Palermo Fish Rearing Station

C. Percent of Discharge Attributable to Palermo Fish Rearing Station

Figure 8: Water Temperatures of Hibberts Gore (HG), North of Long Pond (NLP), and Coopers Mills (CM) are used to determine the effect of the Palermo Fish Rearing Station that discharges water directly into the main stem. The influence of Palermo waters decrease downstream as the percentage it contributes to flow dilutes with increased drainage area in the downstream direction. There is no available NWGS discharge data for dates after December 4, 2005 due to ice.

Figure 9

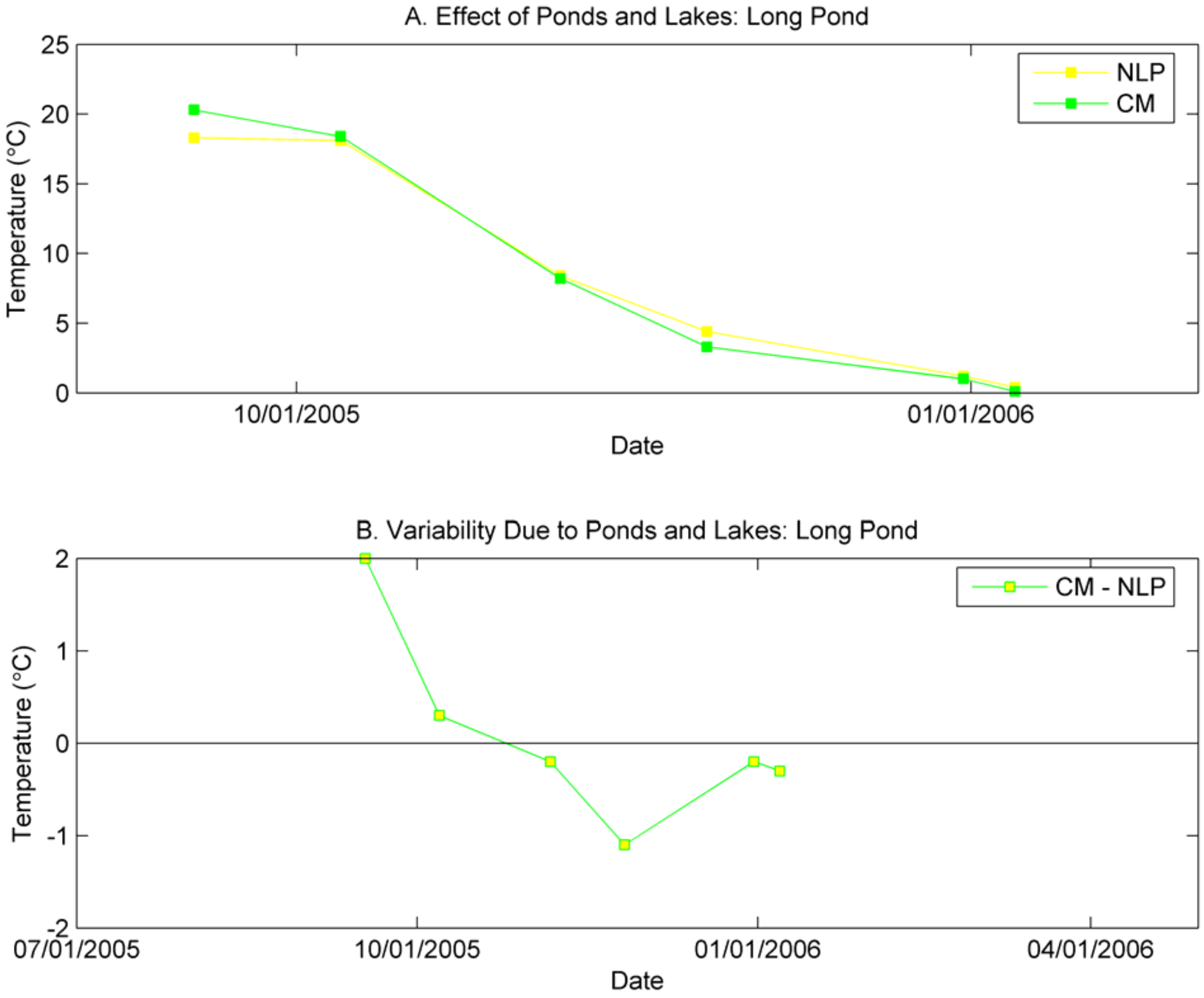


Figure 9: Water temperatures of North of Long Pond (NLP) and Coopers Mills (CM) located respectively upstream and downstream of Long Pond. Graph A shows the point temperature measurements taken at the NLP and CM sites. The differences between these temperatures taken on the same day are shown in Graph B.

Table 3

Site	Watershed Area (km^2)	Forest Area (km^2)	% Tree Cover
HG	118.36	84.20	71.1
NLP	125.19	89.25	71.2
CM	208.06	146.29	70.3
NW	375.87	246.00	65.4
HT	424.91	275.83	64.9
DR	36.95	23.93	64.7
HR	131.76	79.58	60.4

Table 3: The percent tree cover of watershed area upstream of each site calculated from watershed area and forest areas.

decreases downstream along the MS (Table 3). Decreasing tree cover corresponds with increasing water temperatures from consecutive downstream sites in the summer. HG has the highest percent of shaded watershed, 71%, as well as the coldest temperatures in the summer (Table 2 and Table 3). HT has the lowest percent of shaded watershed, 60%, and the highest temperatures in the summer.

West Branch

The water temperature of the WB (as measured at station HR) is fairly close to that of the MS (NW, Table 2). WB water temperatures are slightly colder in the winter and slightly warmer in the summer. HR was the coldest station in the winter with a low of -0.9 ºC. DR was the warmest station in the summer with a high of 26.2 ºC (Table 2). DR also fluctuates more than HR with temperatures that range over 26.9 ºC, where as HR temperatures fluctuated over 22.1 ºC.

Table 3 shows that, like the MS, percent tree cover decreases downstream along the WB. DR has a percent tree shade of approximately 65%, while HR has a percent tree shade closer to 60%. The difference in tree shade between the upstream DR station and the downstream HR station is minimal, only 5% (Table 3).

Lower Main Stem

Figure 11 shows the temperatures of the lower MS stations – CM, NW, and HT – as well as HR on the WB. Temperatures differ slightly at the confluence of the MS and WB, which is evidenced by CM, HR, and NW. The largest difference between CM and HR temperatures was on November 26, 2005 when HR was colder than CM by 2.9 ºC (Table 2). On this date NW was colder than

Figure 11

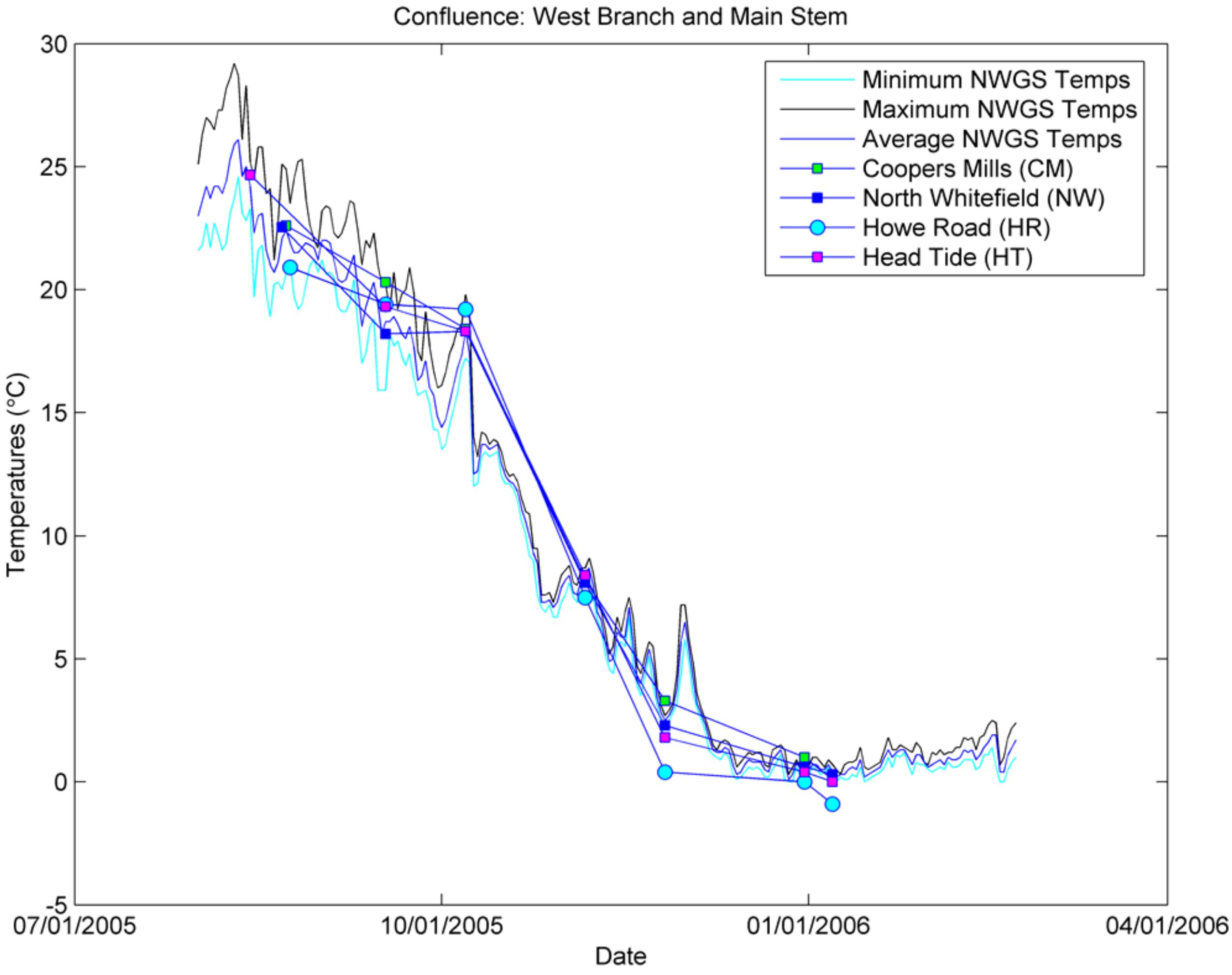


Figure 11: Deviations of water temperatures at Coopers Mills (CM), North Whitefield (NW), Howe Road (HR), and Head Tide (HT) compared to the North Whitefield Gauging Station (NWGS). CM and NW are respectively upstream and downstream of the main stem and West Branch point of confluence. HR represents West Branch temperatures just before confluence with the main stem. HT is the furthest downstream site in this study.

CM by 1.0 ºC. On September 17, 2005 NW was colder than CM by 2.1 ºC even though HR was colder than CM by only 0.9 ºC (Table 2). Large differences between WB water at HR and MS water at NW do not correspond to large differences in CM and NW temperatures on the MS.

HT had the highest fluctuating temperatures along the MS during the study period. This station's temperatures range over 26.3 ºC (Table 2). Its maximum temperature of 26.3 ºC was the highest of all sites on the MS (Table 2). Its minimum temperature of 0.0 ºC was also the lowest temperature experienced on the MS (Table 2). The watershed of HT has the lowest percent of tree shading of the stations along the MS (65%) (Table 3).

Error Analysis

The error of my field measurements is the average of the absolute value of the mean temperatures at NW minus the NWGS temperatures (Table 2). Field measurements have an error of ± 0.4.

CHAPTER FOUR

DISCUSSION

Controls on the Entire Watershed

In assessing controls of water temperature of the Sheepscot River, it is not surprising that air temperature emerges as the primary control. The Sheepscot River watershed is small enough to assume that air temperature varies minimally throughout the watershed. Therefore, diurnal and seasonal water temperature trends correspond with fluctuations in air temperature over the entire watershed. Diurnal water temperature fluctuations are greater in the summer than in the winter (Figure 4). One explanation is that in summer, water responds readily to the cool air temperatures during the night and then warms with the high temperatures of the day (Figure 6). The large temperature gradient of the air and the ability of the water to cool easily at night accounts for a large water temperature variation. In winter, relatively cold temperatures are experienced during both the day and the night, and water, of course, cannot remain liquid below 0 °C. Another contributing factor is that summer flow depths tend to be low, therefore waters warm more readily than at times of higher flows, like the winter and spring.

Other climactic conditions, like precipitation, also exert a control on water temperature, which is shown in Figure 7. Precipitation amounts significantly control summer (R^2 of 0.62) and winter temperatures (R^2 of 0.47), however they are relatively less influential compared to other controls, such as air temperature. Due to the small slope values of both regressed lines, water temperature clearly does not act as a primary function of precipitation (Figure 7). Counterintuitively, the effect that precipitation does have on water temperatures is that it warms water throughout the year.

Upper Main Stem Controls

Aside from air temperature, the primary control of water temperatures on the upper MS is the discharge from Palermo Fish Rearing Station. This discharge is a control that does not change with time but is a constant input of 0.136 m^3/s of water at a mean temperature of 15.5 ºC (Table 2). The effects of this input are greatest in the upstream reaches of the MS that are directly downstream of Palermo. The impact of this control on water temperatures is diluted downstream as drainage area increases and the percent of Palermo discharge comprising total discharge decreases (Table 4 and Figure 8). The constant discharge that is injected into the river from Palermo thus constitutes varying percentages of total discharge at HG, NLP, and CM based on the fluctuations of natural discharge (Table 4). The effect of the Palermo discharge is greatest in the summer because of the high percentage of contributing flow (Figure 8). This high percentage is primarily due to relatively low natural discharges. Palermo discharge acts as a buffering control thereby cooling waters in the summer and warming them in the winter. The percent of discharge from Palermo, and thus its effect, is greatest at HG, less at NLP, and even less at CM (Table 4 and Figure 8). HG has the most buffered water temperatures out of all field sites: it is the coldest in the summer and the warmest in the winter (Figure 4). NLP also experiences the effects of this anthropogenic input but to a lesser degree. Palermo water comprises relatively less of its total discharge than at HG. The effect of Palermo is further diluted at CM where it continues to have an influence on water temperature but to a much less degree. The Palermo Fish Rearing Station exerts the greatest effect during summer periods of low natural flow.

Table 4

Site	NWGS Discharge (m^3/s)	Discharge (m^3/s)	% Discharge from Palermo
Palermo	—	0.14	—
Drainage Area $_{NWGS}$ = 375.91 km^2			
HG $_{09/17/2005}$	2.3	0.72	18.8
HG $_{10/07/2005}$	1.2	0.38	35.9
HG $_{11/06/2005}$	2.9	0.91	14.9
HG $_{11/26/2005}$	5.3	1.67	8.1
HG $_{12/31/2005}$	NAN	NAN	—
HG $_{01/07/2006}$	NAN	NAN	—
Drainage Area $_{HG}$ = 118.37 km^2			
NLP $_{09/17/2005}$	2.3	0.77	17.7
NLP $_{10/07/2005}$	1.2	0.40	34.0
NLP $_{11/06/2005}$	2.9	0.97	14.1
NLP $_{11/26/2005}$	5.3	1.77	7.7
NLP $_{12/31/2005}$	NAN	NAN	—
NLP $_{01/07/2006}$	NAN	NAN	—
Drainage Area $_{NLP}$ = 125.19 km^2			
CM $_{09/17/2005}$	2.3	1.27	10.7
CM $_{10/07/2005}$	1.2	0.66	20.4
CM $_{11/06/2005}$	2.9	1.61	8.5
CM $_{11/26/2005}$	5.3	2.93	4.6
CM $_{12/31/2005}$	NAN	NAN	—
CM $_{01/07/2006}$	NAN	NAN	—
Drainage Area $_{CM}$ = 208.05 km^2			

Table 4: North Whitefield Gauging Station (NWGS) discharge and discharge at the field sites in the upper main stem are used to calculate the percent of total discharge attributable to Palermo Fish Rearing Station. These sites include Hibberts Gore (HG), North of Long Pond (NLP), and Coopers Mills (CM). NAN values refer to dates during which ice prohibited the measurement of discharge at NWGS, thereby disenabling the calculation of discharge based on drainage area of other sites.

Part of the explanation for the reduced effect of Palermo discharge at CM is that it lies just downstream of Long Pond. Lakes and ponds control water temperatures downstream from their outlet points. Long Pond warms water in the summer and cools it in the winter (Figure 9). Water in Long Pond warms in the summer because it flows slowly and is exposed to direct sunlight without the cooling effect of tree shade. In winter the water cools because it is stagnant and more likely to freeze compared to flowing water. This finding challenges the tentative fifth conclusion of SVCA that ponds and reservoirs may have warming affects on the reaches just downstream of their location during winter months. From these results, I infer that water must flow from the surface of the pond or the inverse relationship of water temperature effect and season would be observed (Allan, 1995). Therefore, Long Pond raises water temperatures in the summer and lowers water temperatures in the winter.

Tree shade is another control, however it is not uniform throughout the watershed and it is not a primary control in the upper main stem. Table 3 and Figure 10 show variations in the amount of tree shading for the contributing drainage area for each station on the MS. Water temperatures are inversely proportional to the percent of tree shade covering the contributing watershed area upstream of the respective site (Table 2, Table 3, and Figure 4). For each respective branch, the percent tree cover is most at the upstream sites and consecutively less at each downstream site (Table 3). The upstream sites of each branch have the lowest temperatures in the summer and the highest temperatures in the winter, and the downstream sites have the warmest temperatures in the summer and the coolest in the winter, respectively (Figure 4). Although these correlations potentially indicate that tree cover is a main control, the obvious effects of the Palermo fish hatchery and Long Pond appear to have a more direct control on water temperatures in the upper MS. Heavily shaded areas probably contribute to cooling in the summer and insulating in the winter, but the visible trends between HG, NLP, and CM are primarily a result of the continuous dilution of the effect of the discharge from Palermo and the immediate downstream effect of Long Pond.

West Branch Controls

The WB below DR lacks anthropogenic inputs, lakes, and ponds, which greatly influence temperatures on the upper MS. Tree cover more strongly controls water temperatures in the WB than the MS, but it is not the primary control. DR has a higher percentage of tree shading (65%) than HR (60%) (Table 3). The upstream DR station also has somewhat cooler temperatures (~ 1 °C) in the summer and warmer temperatures in the winter (< 0.5 °C, Figure 4). Water temperatures at this station therefore fluctuate more than water temperatures at the downstream station HR. Although highly tree shaded area seems to indicate more fluctuations in water, I am reluctant to attribute this trend entirely to the effect of tree cover, especially because the difference in percent tree cover is so small (5%). Another explanation is that drainage area has a role in water temperature trends. Upstream sites, characterized by lower drainage areas, are possibly more sensitive to changes in weather (air temperatures and precipitation) than downstream sites, which have larger drainage areas. HR temperatures reflect the integration of more factors and therefore are less variable than DR.

Lower Main Stem Controls

Tributary inputs minimally control water temperatures in the MS. Tributary water temperatures of the WB at HR are extremely close to NW water temperatures located downstream of the point of confluence of the WB and MS (Table 2 and Figure 11). Water temperatures of HR are slightly colder than at NW in the winter and slightly warmer in the summer. WB water temperatures fluctuate somewhat more than the MS because the WB is characterized by a smaller watershed. The WB is therefore more sensitive to changes because flow and controls of the MS are integrated over a larger area. The MS has more tree shade (65% at HT) than the WB (60% at HR) (Table 4). This corresponds with the analysis of tree shade, which indicates that less tree shade indicates water temperatures that vary more; however drainage area size probably has a more prominent role in explaining the observed trends.

Atlantic Salmon Habitat Suitability

Direct field measurements of areas along the Sheepscot that are unsuitable for Atlantic salmon due to high summer temperatures include HT and DR (Table 2). However, temperature measurements were made earlier in the summer at these sites than at other sites. Because all site temperatures, with the exception of HG, stay within the range of diurnal temperatures measured at NWGS and because NWGS temperatures are higher on dates prior to field measurements, all sites are assumed to have exceeded the upper threshold temperature for salmon survival in the parr stages (27-32 °C; Table 1) during July and August of 2005 (Table 2 and Figure 4). Only HG, which is strongly influenced by discharge from the Palermo Fish Rearing Station, and possibly NLP, which is influenced less by Palermo fish hatchery, did not exceed the maximum survivable temperature for salmon in the early fry and parr stages. All site temperatures fell below the lower threshold temperature for optimal salmon fluvial environment conditions during the winter. However, salmon habitats are confined to areas of the world that are naturally prone to temperatures below the optimal 0.5 ºC for parr. In fact, salmon are able to survive below an ice layer in rivers (NRC, 2004). Cold water temperatures of the winter do not pose a threat to salmon as long as habitat is available beneath ice cover (Cunjak et al., 1998). Warm temperatures that exceed the upper threshold of for parr (27-32 ºC are more of a concern because they decrease dissolved oxygen levels and increase metabolic rates (NRC, 2004). Of the stations studied, HG and possibly NLP are the sites most suited for salmon habitat based on water temperatures that are most buffered against high temperatures, due to the influence of the Palermo Fish Rearing Station.

CHAPTER FIVE

CONCLUSION

The primary control of water temperatures over the entire Sheepscot River is air temperature, which controls diurnal and seasonal variations. Precipitation appears to slightly warm water. All other controls either act to buffer water from the effects of air temperature or they intensify the relationship of water temperatures to air temperatures. Discharge from Palermo Fish Rearing Station buffers Sheepscot water temperatures throughout the year and strongly influences the upper main stem. Tree shade has a localized cooling effect in the summer and slight warming effect in the winter. Long Pond exacerbates high summer temperatures and lowers winter temperatures, counter to the preliminary findings by the SVCA (2005) that ponds and lakes warm river water year round. The West Branch has a slight effect of warming the main stem in the summer and cooling it in the winter.

REFERENCES CITED

Allan, D.J. (1995) Stream Ecology: Structure and Function of Running Waters. Champan & Hall, New York, 388 pp.

Belknap, D.F., Kelley, J.T., and Gontz, A.M. (2002). Evolution of the Glaciated Shelf and Coastline of the Northern Gulf of Maine, USA. Journal of Coastal Research. Special Issue 36, pp. 37-55.

Cunjak, R.A., Prowse, T.D., and Parrish, D.L. (1998). Atlantic salmon (Salmo salar) in winter: "the season of parr discontent"? Canadian Journal of Fisheries and Aquatic Science. 55, pp. 161-180.

Dudley, R.W. and Hodgkins, G.A. (2002). Trends in streamflow, river ice, and snowpack for coastal river basins in Maine during the 20th C. U.S. Geological Survey: Water Resources Investigations Report 02-4245, pp. 26 pp.

Dunne, T. and Leopold, L.B. (1978). Water in Environmental Planning. W.H. Freeman and Company, New York 818 pp.

Fleming, I.A. and Jensen, A.J. (2002). Fisheries: Effects of Climate Change on the Life Cycles of Salmon. Causes and Consequences of Global Environmental Change. Encyclopedia of Global Environmental Change. 3, pp. 309-312.

Hendry, K. and Cragg-Hine, D. (2003). Ecology of the Atlantic Salmon. Conserving Natura 2000 Rivers: Ecology Series No. 7. English Nature, Peterborough, Scotland, 32 pp.

Hodgkins, G.A., Dudley, R.W. and Huntington, T.G. (2003). Changes in the timing of high river flows in New England over the 20th Century. Journal of Hydrology. Elsevier Science Publishers. 278, pp. 244-254.

Minns, C.K. and Randall, R.G. (1995). Potential impact of climate change on the habitat and population dynamics of juvenile Atlantic salmon (Salmo salar) in eastern Canada, Chadwick, M.P., Moore, J.E., Green, R, editors. Canadian Special Publication on Fishing and Aquatic Sciences. 121, pp. 699-708.

Montgomery, D.R. (2000). Coevolution of the Pacific salmon and Pacific Rim topography. Geology. 28, pp. 1107-1110.

Montgomery, D.R. (2003). The King of Fish: The Thousand Year Run of Salmon. Westview Press; New York, 304 pp.

National Research Council (NRC). (2004). Atlantic Salmon in Maine. The National Academies Press, Washington, D.C., 275 pp.

Osberg, P.H., Hussey III A.M., and Boone G.M. (1985) Bedrock Geologic Map of Maine. Maine Geological Survey: Department of Conservation.

Schnitker, D., Belknap, D.F., Bacchus, T.S., Friez, J.K., Lusardi, B.A., and Popek, D.M. (2001). Deglaciation of the Gulf of Maine, Weddle, T.K. and Retelle, M.J., editors. Deglacial History and Relative Sea-Level Changes, Northern New England and Adjacent Canada. Geologic Society of America Special Paper 351, pp. 9-35.

Sheepscot Valley Conservation Association (SVCA). (2005). KRIS Sheepscot, http://www.krisweb.com/krissheepscot/krisdb/html/krisweb/index.htm, last updated 7/20/05.

Tetzlaff, D., Soulsby, C., Youngson, A.F., Gibbins, C., Bacon, P.J., Malcolm, I.A., and Langan, S. (2005). Variability in stream discharge and temperatures during ecologically sensitive time periods: a preliminary assessment of the implications for Atlantic salmon. Hydrologic Earth System Scientist Discussions. 2, pp. 691-729.