Processes That Influence the Downstream Propagation of Heat in Streams below Clearcut Harvest Units: Hinkle Creek Paired Watershed Study

AN ABSTRACT OF THE THESIS OF

Timothy Otis for the degree of Master of Science in Forest Engineering presented on November 27, 2007.

Title: Processes That Influence the Downstream Propagation of Heat in Streams from Clearcut Harvest Units: Hinkle Creek Paired Watershed Study.

Abstract approved:

Arne E. Skaugset III

This research investigates the direct and downstream impacts of clearcut harvest units on stream temperature as a part of the Hinkle Creek Paired Watershed Study. The Hinkle Creek watershed is located in the foothills of the Cascade Mountains about 30 kilometers northeast of Roseburg, Oregon, is privately owned, and supports a 60-year old, harvest-regenerated, Douglas-fir forest. The study watershed contains four treatment and two control sub-watersheds within the larger treatment and control watersheds, respectively. The first harvest entry, which took place during the winter 2005–2006, consisted of five clearcut harvest units located adjacent to perennial, non-fish-bearing streams. One year each of calibration and post-harvest data are analyzed. The experimental design for the study was a *Before-After-Control-Impact* (BACI) design. Maximum daily stream temperatures (MDST) were analyzed for the four treatment streams for one year before and one year after harvest. A multiple linear regression model was used to compare the 2005 data with the 2006 data for each stream. Stream temperature data from Myers Creek (temperature probe C04) was the control. The model for this analysis was:

$$y_t = \mu + \alpha_i + \beta x_t + \varepsilon_t$$

where y_t is the temperature of the stream on a day t, μ is the overall mean value of y, α_i is the effect of year, x_t is the corresponding temperature of the control stream on a day t, β is the coefficient estimated by regression, and ε_t is the error term. This method is an analysis of variance of values that are adjusted for regression with an independent variable, in this case the maximum daily temperatures of the control stream. The impact of timber harvest on MDST is small when compared

to the spatial (between-stream) variation in MDST and this impact decreased downstream. At 300 meters, nominally, downstream of the harvest units the impact of timber harvest on MDST was not statistically significant for two streams and only moderately statistically significant for the other two streams.

Stream velocity, discharge, and groundwater advection in the streams downstream of the harvest units were quantified using dye tracer dilution techniques. The **O**ne-dimensional **T**ransport with **I**nflow and **S**torage (OTIS) model was used to quantify longitudinal dispersions, transient storage volumes, storage transfer rates, and hyporheic residence times in four 75 meter reaches in each of the four treatment streams. Stream velocities calculated with OTIS ranged from 0.24 to 0.40 m/sec for the four streams. Dispersions ranged from 0.18 and 0.84 m^2/sec. The estimated cross-sectional area of the 'immobile' zones of water storage divided by the stream cross-sectional area, A_s/A or the storage ratio, varied from near zero to 7.2. The residence times of water in hyporheic storage ranged from 2.3 hrs to 32 hrs. Water stored in a shaded reach of stream, in pools, and in hyporheic zones provides a volume of water that can be exchanged with the water in the active stream channel. This provides for physical mixing with cooler water and heat transfer to the stream bed.

Latent heat, Sensible heat, Longwave Radiant heat and **P**hotosynthetically **A**ctive **R**adiation (PAR) were calculated for August 7-17, 2006 at the center of the 300 meter study reach in Russell Creek. The air temperature was lower than stream temperature during four of those nights and the stream cooled due to a net loss of longwave radiation and evaporative cooling.

Processes That Influence the Downstream Propagation of Heat in Streams from Clearcut Harvest Units:
Hinkle Creek Paired Watershed Study

by
Timothy Leonard Otis

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented November 27, 2007
Commencement June 2008

Master of Science thesis of Timothy Leonard Otis presented on November 27, 2007.

APPROVED:

Major Professor, representing Forest Engineering

Head of the Department of Forest Engineering

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Timothy Leonard Otis, Author

ACKNOWLEDGEMENTS

I wish to express my sincere appreciation for the individuals that made this research possible. Rick Strachan representing the Gibbet Hill Foundation provided generous support for my graduate studies and field research. The Department of Forest Engineering at Oregon State University also provided significant financial support. Roseburg Forest Products has allowed the use of their forest land, devoted staff time, and had the vision to make the entire Hinkle Creek project possible.

I would like to thank the College of Forestry faculty and staff at Oregon State University, who inspire graduate students to find their best selves. In particular, a heartfelt thank you to Arne Skaugset, my major professor, who taught me how to think critically, and to love the Oregon rain.

I would also like to thank all my fellow Forest Engineering graduate students and staff, who both inspired and entertained; in particular: Kelly Kibler, Matt Meadows, Nick Zegre, Amy Simmons, Tim Royer, Dennis Feeney, Chris Surfleet, Elizabeth Toman, and Matt Thompson.

Finally, I thank my family for supporting this project; my son Steve who showed me that I need not fear the unknown, my daughter Erin who shares my thirst for knowledge, and my wife Kathy, whose love and support are most responsible for this milestone.

TABLE OF CONTENTS

Page

1. INTRODUCTION 1

2. OBJECTIVES 2

3. LITERATURE REVIEW 2

  3.1 Stream Energy Budget 3
    3.1.1 Tributary and Hillslope inflows 5
    3.1.2 Longitudinal transport and dispersion 5
    3.1.3 Bed Conduction 6
    3.1.4 Sensible/Latent Heat 6
    3.1.5 Shortwave Radiation/Reflection 7
    3.1.6 Longwave Heat Exchanges 8
    3.1.7 Hyporheic Exchange Flows 8
  3.2 Downstream and Cumulative Effects 9
    3.2.1 Downstream Cooling and Temporal Cycles 10
    3.2.2 Stream Temperature Science and Policy 12
  3.3 Literature Review Conclusions 14

4. STUDY AREA 15

  4.1 Location 15
  4.2 Study Site Characteristics 16
  4.3 First Harvest Entry 16

5. METHODS 18

  5.1 Stream Temperature Sampling 18
  5.2 Stream Tracer Dilution Studies 19
  5.3 Stream Flow Measurement 21
  5.4 Meteorological Measurements 22
  5.5 Data Analysis 23
    5.5.1 Statistical Analysis 23
    5.5.2 One-dimensional Transport with Inflow and Storage (OTIS) Modeling 24
    5.5.3 Stream Energy Budget Calculations 25

6. RESULTS 25

6.1 Multiple Linear Regression 25
6.2 Hillslope Inflows from Steady State Dye Study 31
6.3 One-dimensional Transport with Inflow and Storage (OTIS) Modeling 34

7. DISCUSSION 38

7.1 Statistical Analysis Results 38
7.2 Mass Transfer and Transient Storage 38
7.2.1Advection of Hillslope Water 39
7.2.2 Hillslope Groundwater Temperature 39
7.2.3 Diurnal variation in Hillslope Groundwater Flowrate 40
7.2.4 Storage/Dispersion 42
7.2.5 Stream Velocity and Mean Hyporheic Storage Time 42
7.3 Energy Budget Factors Which May Cool Stream Water 43
7.3.1 Longwave Radiation 45
7.3.2 Latent and Sensible Heat Exchange 45
7.4 Heated Stream Water Entering a Shaded Study Reach 46
7.5 Temperature Effect of Hillslope Advection Alone 47
7.6 Future Research Needs 48
7.6.1Energy Budget Studies 49
7.6.2 Buffered Stream Characteristics 49
7.7 Management Implications 49
7.7.1 Stream Thermal Classification 50
7.7.2 Stream Structure and Storage Volume 50

8. CONCLUSIONS 51

9. LITERATURE CITED 52

LIST OF FIGURES

Figure Page

Figure 1. Ten-Minute temperature data, South Fork Hinkle Creek, Summer 2005 12

Figure 2. Project Vicinity Map 15

Figure 3. Map of Hinkle Creek Watershed 17

Figure 4. Map of Temperature Probe Locations 18

Figure 5. Schematic of Equipment Locations for a Tracer-Dilution Test Reach....................... 20

Figure 6. Maximum Daily Temperatures - at flumes 27

Figure 7. Maximum Daily Temperatures – 1000 ft. below flumes 27

Figure 8. Change in Mean Max. Daily Temp. between years - at flumes 28

Figure 9. Change in Mean Max. Daily Temp. between years – 250 ft. below flumes................ 28

Figure 10. Change in Mean Max. Daily Temp. between years – 500 ft. below flumes............... 29

Figure 11. Change in Mean Max. Daily Temp. between years – 750 ft. below flumes............... 29

Figure 12. Change in Mean Max. Daily Temp. between years – 1000 ft. below flumes............. 30

Figure 13. Mean Max. Daily Temp. change between years, by location 30

Figure 14. N. Fork Hinkle Creek Flowrates by Water Year.. 31

Figure 15. Fenton Creek Steady-State Flowrates by Stream Station..................................... 32

Figure 16. Clay Creek Steady-State Flowrates by Stream Station... 32

Figure 17. Russell Creek Steady-State Flowrates by Stream Station...................................... 33

Figure 18. Beebe Creek Steady-State Flowrates by Stream Station....................................... 33

Figure 19. Fenton Creek Transport Model 35

Figure 20. Clay Creek Transport Model 35

Figure 21. Russell Creek Transport Model 36

Figure 22. Beebe Creek Transport Model 36

Figure 23. Estimated Storage and Dispersion Parameters... 37

Figure 24. Probe C07, 2002-2006 Summer Temperatures 40

Figure 25. Dye Concentrations at Clay Creek, August 2006, Station 300 41

Figure 26. Heat Budget Parameters at Russell Creek, August 2006, Station 150 44

Figure 27. Stream and Air Temperatures, Russell Creek, Station 150..................................... 45

Figure 28. Russell Creek Temperatures by Stream Station and Time 47

Figure 29. Predicted and Actual Stream Temperatures, 2006 Dye Study 48

LIST OF TABLES

Table Page

Table 1. Harvest Area Summary 17

Table 2. Temperature Probes (*Summer data, late May through early September, typically) 19

Table 3. Temperature data collected at flumes (**Continuous data)........ 19

Table 4. Comparison of flow measurement techniques........ 22

Table 5. Statistical Summary........ 26

LIST OF EQUATIONS

Equation Page

Equation 1: Brown and Kryger 1970 Temp. Change....4

Equation 2: Brown and Kryger 1970 Two-part mixing....5

Equation 3: Moore Two-part mixing....5

Equation 4: Streambed conduction....6

Equation 5: Bowen Sensible heat exchange....7

Equation 6: Latent heat exchange....7

Equation 7: Shortwave radiation....8

Equation 8: Longwave radiation....8

Equation 9: Dye mixing model....20

Equation 10: Salt slug flowrate calculation....21

Equation 11: Salt slug flowrate approximation....21

Equation 12: Wind Function....25

Equation 13. Mean hyporheic residence time....42

Processes That Influence the Downstream Propagation of Stream Temperature from Clearcut Harvest Units:
Hinkle Creek Paired Watershed Study

1. INTRODUCTION

Stream temperature is a water quality parameter of concern in Pacific Northwest forests. The Oregon Department of Environmental Quality (DEQ) established criteria for Total Maximum Daily Loads (TMDL) for heat, as measured by stream temperature, in Oregon streams and rivers. The National Marine Fisheries Service (NMFS) of the National Oceanic and Atmospheric Administration (NOAA) prepared recovery strategies for species listed under the Endangered Species Act (ESA), which includes salmonids for which stream temperature is a monitored water quality parameter. Salmonid species have optimum temperature ranges for growth and development. High stream temperatures can cause changes in rates of development and increased susceptibility to disease. (Beschta et al. 1987). Maximum daily stream temperatures increase when shade over the stream channel is removed (Brown and Krygier 1970). Whether the increase in maximum daily stream temperature results in heat being propagated downstream is the subject of research which has had conflicting results (Poole and Berman 2001), (Zwieniecki and Newton 1999), (Johnson and Jones 2000). The processes that affect the propagation of heat downstream are poorly understood. There is agreement that solar radiation is the primary influence on increasing maximum stream temperatures in unshaded reaches compared to shaded reaches (Brown and Krygier 1970), (Webb and Zhang 1999). (Johnson 2004) suggest that changes in stream temperature after they reenter the forest canopy are more complex and variable. Since solar radiation is dramatically smaller under the forest canopy, the other heat exchanges between the stream and its environment also become significant in understanding stream heat. Thus, a reasonable approach to tracking stream temperature in these shaded reaches is to model the physics of energy exchanges between the stream and its environment (Sinokrot and Stefan 1993).

A first step in the process of understanding the downstream propagation of stream heat energy is to measure stream temperature with enough spatial and temporal resolution to aid in determining the magnitudes of the various heat transfer processes affecting stream heat energy. This high-resolution data can provide insight into the variability of stream temperature in space and time and hopefully provides tools for future management, as well as direction for future research. Toward that end, the amount and variability of changes in stream temperature immediately downstream of clear-cut harvest units in four adjacent small non-fish bearing streams were measured. Then, the major sources and sinks of energy were quantified to characterize the magnitudes of the heat exchange processes in these downstream shaded stream reaches.

2. OBJECTIVES

The first objective of this study was to use statistical tests to detect change in temperature patterns downstream of harvest units between the last year pre-harvest and the first year post-harvest.

The second objective was to use tracer-dilution dye study data to characterize the flowrates, velocities, and advection of groundwater on 300-meter reaches immediately downstream of harvest units. This data was then to be used to estimate the longitudinal dispersion of stream water, the in-stream storage volume in stream pools and hyporheic zones, and the transfer of stream flow between the active channel and these storage zones.

The third objective was to estimate the major stream heat budget components on one stream segment, including longwave radiation, shortwave radiation, latent heat, and sensible heat.

The fourth objective was to compare these three research results.

In addition, it is important to place this research in the context of the body of stream temperature studies in the Pacific Northwest, since the overall objective of this study was to add to this body of knowledge. To this end, the following literature review is presented within the framework of the stream energy budget, providing an organizing method for stream temperature analysis and discussion.

3. LITERATURE REVIEW

Stream temperature in forests has been the subject of study in the Pacific Northwestern US for 50 years. In 1958, concern about the growth and development of aquatic species, particularly salmonids (Brett 1956), resulted in the initiation of the Alsea Logging-Aquatic Resources Study (Brown and Krygier 1970). This research documented increases of average monthly maximum stream temperatures of 14°F (7.8°C) following clear-cut logging of a small watershed (Needle Branch) in the Oregon Coast Range. The details of the Alsea study, including logging methods, broadcast burning and stream clearing represent a unique suite of treatments, which may account for the large increases in stream temperature rarely seen elsewhere. Since the time of the Alesa study, other field experiments have characterized stream temperature changes after forest harvesting in the region. The H.J. Andrews Experimental Forest in the Western Cascades, Oregon is the site of ongoing stream temperature studies (Levno et al. 1967); (Johnson and Jones 2000); (Johnson 2004).

These studies have examined temperature patterns and the mechanisms that control stream temperature. Several studies in the Malcolm-Knapp Research Forest in British Columbia, Canada (Moore et al. 2005);(Gomi et al. 2006) examined thermal response of headwater streams within clear-cut harvest areas, and examined both above-stream and stream-bed processes. These studies and other research in this region have shown that changes in stream temperatures resulting from harvest activities vary from no change, to the magnitude of changes observed in the Alsea study (Beschta et al. 1987). The range of geology, forest types, and climate these studies represent, as well as a variety of harvest methods contribute to this range of thermal response.

Following the Alsea study, policies were changed, and state forest practice laws were enacted to identify and manage the forest activities that had significant impacts on aquatic ecosystems and the ability of a forest stream to support fish. Each of the western timber producing states (Oregon, Washington, California) has regulations that require buffer strips to protect riparian areas and provide shade for large perennial (and typically fish-bearing) streams. However, there remains an ongoing disagreement regarding the impact of forest harvest on the downstream propagation of stream heat measured as water temperature. Small, non-fish-bearing headwater streams have minimal or no requirements for buffer strips in many jurisdictions, and forests in these regions are typically harvested to stream boundaries. The amount and variability of stream heating of these streams, as well as the downstream fate of the thermal load are still topics of research and discussion. “Despite decades of research on stream temperature response to forest harvesting, there are still vigorous debates in the Pacific Northwest about the thermal impacts of forestry and how to manage them (Moore et al. 2005)”. The fact that forest management practices vary between study sites, and that forest practices have changed on any particular site over the last several decades, also complicates comparisons between studies.

3.1 Stream Energy Budget

The geographic variability of the forested landscapes that are studied confounds efforts to discern clear patterns of stream behavior, even within the Pacific Northwest (PNW) region. Both climate, driving above ground energy processes, and geology, dictating below stream energy exchange, vary spatially. The results of a study from one geographic region are not easily extrapolated to another region. Both climate and geology vary in time to a lesser degree. Climate change and erosion processes can change the thermal characteristics of a particular site. This has led researchers to expand their tools beyond statistical analysis to include physics-based models of stream temperature behavior.

Pioneering this effort was George Brown, who proposed that, during summer clear-sky conditions, direct solar radiation received by the stream surface dominates the energy budget for small forest streams in clear cut harvest areas. Sensible heat exchanges with the air or latent heat exchange from evaporative cooling were small by comparison. The net heat exchange due to incoming and outgoing longwave radiation between the stream surface and the atmosphere was also small enough to be ignored (Brown and Krygier 1970). The increase in stream temperature was directly proportional to the amount of incoming solar radiation, and inversely proportional to the volume of water in the stream. The equation proposed to determine the amount of increase in the maximum daily temperature change, (ΔT, °F) in a stream flowing through a clearcut harvest unit is:

$$\textit{Equation 1:}\ \Delta T = \frac{A \cdot H}{D} \cdot (0.000267)$$

In Equation 1, A is the surface area of stream exposed to solar radiation (ft^2), H is the rate of solar insolation for the day, year, and latitude of interest (BTU/ ft^2-min.), D is the discharge (ft^3/sec), 0.000267 is a conversion factor from (ft^3 of water/sec) to (lb. of water/min.), and a BTU is defined as the heat required to raise the temperature of 1 lb. of water 1°F. Brown presented a more comprehensive method to predict increases in stream temperature that included latent heat (evaporation), sensible heat (convection), and stream-bed conduction to the energy budget (Brown 1969(2)). Several reach-scale, physics-based stream temperature models have since been developed. These include *TEMPEST* (Adams et al. 1989), *MNSTREAM* (Sinokrot and Stefan 1993), and *Heat Source* (Boyd 1996). These modeling efforts have been valuable in understanding stream temperature processes. However, they are still limited. First, a significant amount of data, both in climate and stream geometry, is required for input, making them impractical for general use. In addition, subsurface conditions are difficult to determine, and hyporheic exchange within the stream channel is poorly understood, and thus may be inadequately modeled. Finally, models must make simplifying assumptions for mass and energy exchange processes which are inherent in model development, and may not adequately represent the complexity of energy exchanges in actual streams. In summary, models can be valuable tools, but given their limitations should not be the only tool used to understand the stream energy budget. Indeed, the first step in modeling the physical environment is an understanding of which processes are significant, and the nature of their interaction. This research explores the stream energy exchange processes downstream of harvest units within forested reaches, with a goal of increasing the understanding for forest managers and modelers.

The components or categories of stream energy fall logically into three categories: 1) those components that involve exchanges of the *mass* of water only [tributary and hillslope inflow, and downstream movement of stream water defined by velocity and dispersion] 2) those components that involve exchanges of *energy* of the water only [bed conduction, sensible/latent exchange, shortwave radiation/reflection, longwave heat exchange, and internal friction of turbulence], and 3) the component that involves the *mass* and *energy* of the water [hyporheic exchange].

3.1.1 Tributary and Hillslope inflows

The effect on stream temperature from small tributary inflows into larger streams can be calculated with a simple two-part mixing model. The temperature of the mixture of stream and tributary flows is (Brown and Krygier 1970):

$$\textit{Equation 2:}\ T_m = \frac{D_t T_t + D_s T_s}{D_t + D_s}$$

where D_t is discharge of the tributary, D_s is the main stream discharge at the upper end of the reach, T_t is the temperature of the tributary, and T_s is the main stream temperature at the upper end of the reach.

If the fraction of total flow in a reach which enters from a tributary is defined as $f_i = D_t/(D_s + D_t)$, then this relationship of temperature for a mixture can be expressed as (Moore et al. 2005):

$$\textit{Equation 3:}\ T_m = T_s + f_i\,(T_t - T_s.)$$

This statement of the mixing model illustrates how both the fraction of tributary inflow f_i, and the difference in its temperature from the stream, $(T_t - T_s.)$ modify stream temperature. The effect of the influx of groundwater on stream temperature can be calculated in the same manner if the temperature and flowrate of the groundwater are known (Brown and Krygier 1970).

3.1.2 Longitudinal transport and dispersion

The velocity of the water in a stream varies across the stream cross-section. This results in longitudinal dispersion of the water and its heat energy as the water moves downstream. The relative importance of dispersion of stream water on stream temperature has been debated. One modeling study of river temperatures found that longitudinal dispersion did not affect modeled temperatures, and thus was set to zero. However all the streams in the study had relatively high velocities and low longitudinal temperature gradients compared to headwater streams (Sinokrot and Stefan 1993). In his review of the literature, (Moore et al. 2005) commented on the impact of longitudinal dispersion on stream temperatures that "no published studies appear to have evaluated its influence in small streams". Clearly, streams with variable cross-sections and depths, and those that have a longitudinal pool/step structure have more potential for longitudinal dispersion than river systems. Thus, further study would be instructive in characterizing the role of longitudinal dispersion on temperatures in headwater stream systems.

3.1.3 Bed Conduction

Heat conduction between the stream water and stream bed depends on the temperature gradient between the stream and stream bed and the thermal conductivity of the substrate (Brown 1985); (Gauger and Skaugset 2004). Bed conduction of the heat in a stream is a significant predictor the diel variations in stream temperature (Brown 1969(2)); (Hondzo and Stefan 1994).

Solving for the magnitude of streambed conduction in a one-dimensional advection-dispersion model requires knowledge of the temperature profile of the stream bed, and how it changes in time. This can be estimated using a slab approximation (Hondzo and Stefan 1994):

Equation 4: $$\rho \cdot c_P \frac{dT}{dt} = k \frac{d^2T}{dx}$$

where ρ is the density of water, c_p is the heat capacity of water per unit mass, T is the streambed temperature, k is the effective heat conductivity of the streambed medium, x is the distance into the streambed, and t is time. Since the heat exchange with the streambed varies with both depth and time, the temperature of the streambed from this differential equation can be estimated using a finite difference approximation of equation 4.

The magnitude of bed conduction in the overall budget of stream heat also depends on the *time* of contact and the *area* of contact between the stream and bed. (Brown 1969) initially hypothesized that bedrock was more important to the heat exchange process than gravel substrate. A recent study found that conduction in a bedrock reach of a headwater stream, conduction was a minor portion of the overall heat budget. (Johnson 2004). The stream in the Johnson study (Watershed 3 [WS3], H. J. Andrews Experimental Forest) flows from a bedrock reach into an alluvial reach, where the velocity of the stream decreased dramatically, and the contact area of the surface of the streambed increased accordingly. The significant dampening of maximum and minimum daily temperatures in this alluvial reach suggested that streambed conduction, in addition to hyporheic exchange play an important role in low-velocity, high-contact area stream reaches (Johnson and Jones 2000).

3.1.4 Sensible/Latent Heat

Sensible heat in air (heat stored as an increase in air temperature, often called convective heat) can be exchanged between air and water. The magnitude of the rate of change is a function of the difference in temperature between the air and water, and of the wind speed, which affects the thickness of the laminar boundary layer at the air/water interface. Sensible heat exchange, H_c, can be expressed as (Bowen 1926):

$$\text{Equation 5: } H_C = 0.61 \cdot \frac{P_a}{1000} \cdot \rho L(Wftn)_Z (T_S - T_{aZ})$$

where P_a is the atmospheric pressure, ρ is the water density, L is the latent heat of vaporization of water, $(Wftn)_z$ is a wind function using wind velocity at height z above the water, T_S is the water surface temperature, and T_{aZ} is the air temperature at height z (Sinokrot and Stefan 1993).

Latent or evaporative heat is the energy transferred between water and air when water evaporates from the stream surface (which removes heat from the system) or condenses on it (which adds heat). It is a function of wind speed, and the vapor pressure gradient between the air and water, and can be calculated as:

$$\text{Equation 6: } H_e = \rho L(Wftn)_Z (e_{SW} - e_{aZ})$$

where e_{SW} is the saturation vapor pressure at the water surface, e_{aZ} is the vapor pressure in air at height z above the stream, and the same wind function as was used for sensible heat. When equations 5 and 6 are compared, the evaporative heat flux and sensible heat flux at a given atmospheric pressure are related by the ratio of the *temperature gradient* to *vapor pressure gradient* between the water surface and the overlying air, which is called the Bowen Ratio.

Sensible and latent heat flux terms have been considered to be small and unimportant to the stream energy budget in forest environments, since wind speeds in are typically low, and vapor pressures above streams are typically high (Beschta et al. 1987). Even though Sensible and Latent heat fluxes tend to be small and counteract each other in forest stream settings, one study hypothesized that evaporative cooling during the day may have been underestimated in closing the energy budget for a shaded headwater stream. (Moore et al. 2005).

3.1.5 Shortwave Radiation/Reflection

Incoming shortwave or solar radiation (H_{si}) is a parameter that is typically measured, and its magnitude at the stream surface varies according to the path of the sun, and any intervening topography or vegetation between the sun and the stream surface. Solar radiation can be diffused or reflected by landscape or plant surfaces. To characterize this complexity, solar (shortwave) radiation can be measured at, or directly above, the stream surface. When the sun angle is within 30° of vertical, more than 90% of the available solar insolation is available to enter the water surface and become available for stream (or streambed) heating, provided it is not intercepted by shade-producing vegetation (Johnson 2004). The remaining solar radiation is reflected, H_{sr}. For modeling purposes, net shortwave solar radiation entering a stream (H_S) can be expressed as the difference between the incoming and reflected solar radiation, modified by a shading factor (SF), which is the percentage of radiation blocked by vegetation or topography. Incoming solar radiation is quantified using the expression (Sinokrot and Stefan 1993):

Equation 7: $H_S = (H_{si} - H_{sr})(1 - SF)$

3.1.6 Longwave Heat Exchanges

Incoming longwave radiation from above the stream is the sum of longwave radiation emitted by the atmosphere, vegetation, and surrounding soil or rock. Outgoing longwave radiation is the longwave radiation emitted by the water into the atmosphere. Net longwave radiation exchange is calculated using the Stefan-Boltzman law:

Equation 8: $H_L = \sigma(\varepsilon_W T_S^4 - \varepsilon_a T_a^4)$

where σ is the Stefan-Boltzman constant, ε_w is the emissivity of the stream water surface, ε_a is the emissivity of the atmosphere, T_s is the stream temperature, and T_a is the air temperature. For Pacific Northwest forest streams, net longwave radiation adds heat to streams during the day, and is a net heat loss from streams at night (Story et al. 2003).

3.1.7 Hyporheic Exchange Flows

Hyporheic exchange flow is defined as the transfer of water between the stream and the saturated sediments in the stream bed and adjacent riparian zone (Moore et al. 2005). (Bilby 1984), in an early study fish habitat in a Western Washington stream (Thrash Creek), found 39 local cool spots in a 3.5 km reach. These cool spots included lateral seeps, pool bottom seeps, cold tributaries, and flow through the bed (hyporheic exchange). They accounted for 1.6% of the stream surface area, and 2.9% of the water volume. Since these areas were considered to be rare by this study, hyporheic exchange has often thought to be a small part of the stream energy budget (Beschta et al. 1987). More recent studies, however, have shown that the hyporheic zone can be an important flow pathway in headwater streams (Haggerty et al. 2002); (Kasahara and Wondzell 2003). The influence of hyporheic flow on stream temperature was dramatically demonstrated in the Watershed (WS3) experiment H. J. Andrews. After the stream had flowed through a bedrock reach, the daily maximum stream temperatures had increased by several degrees. In an alluvial reach immediately downstream, where the stream flowed through a sediment deposit, the daily maximum temperatures then decreased by as much as 8.7°C, and the daily minimum temperatures increased by 3.9°C. (Johnson 2004). (Story et al. 2003), in a study of stream cooling linked to subsurface hydrology, found that maximum daily temperatures in a forested stream reach downstream of a clear-cut cooled 2.3°C in less than 250 meters. Conduction by the stream bed and hyporheic exchange accounted for approximately 60% of the total cooling effect, and groundwater inflow accounted for the rest.

3.2 Downstream and Cumulative Effects

In the context of this research history, two questions have been explored relative to downstream effects:

1) What happens to the temperature of a stream when it re-enters the forest downstream of a clear-cut harvest unit?

2) What factors are responsible for these temperature changes?

A range of testable hypotheses have been presented to explain empirical results. One hypothesis is that forested streams have an equilibrium temperature inherent to the local environment, and any water that is warmer or cooler than that equilibrium temperature will move toward it upon entering the forested reach (Zwieniecki and Newton 1999). Under this hypothesis, this recovery zone, or thermal transition reach, is the only region where temperatures exist above or below the stream's equilibrium temperature.

(Beschta et al. 1987) has offered an alternative hypothesis.

> "Once a stream's temperature is increased, the heat is not readily dissipated to the atmosphere as it flows through a shaded reach. Hence, additional energy inputs to small streams can have an additive effect on downstream temperatures".

They further suggest that:

> "where cooler inflows do not occur, temperature increases from each exposed reach will not decrease appreciably through the shaded reaches, and the result is a 'stair-step' temperature increase in the downstream direction".

Another perspective is that stream energy in the headwater reaches of forest streams are dominated by groundwater inputs, whereas stream energy in the lower reaches is dominated by atmospheric inputs (Poole and Berman 2001). In this context, Poole suggests that any stream temperature increases in the transitional middle reaches between these two thermal regimes can both decrease local cool water habitat, and transport this added heat downstream.

Finally, the downstream effects of timber harvest on stream temperature can be analyzed using statistical tests for change detection. (Beschta and Taylor 1988) analyzed 30 years of stream temperature data (1955 to 1984) from the Salmon Creek watershed, in the Oregon Cascades. An index of 'cumulative harvesting effects' was calculated for the watershed, based on five years of full sun exposure following harvest, and then a linear decrease to zero exposure at twenty years. This sun exposure factor was multiplied by the area harvested in each exposure level. This index was correlated with the average of the maximum daily stream temperatures for the ten warmest days of each year. Using this metric, the authors concluded that 'the cumulative effect of forest land use has apparently been an important factor (r^2=0.65) in stream temperature increases that have occurred in the Salmon Creek drainage over the past 30 years'. They note, however, that several factors make it difficult to draw cause-and-effect conclusions. These factors include the large peak flows in 1964-65 and 1971, and the associated mass soil movements that occurred in riparian areas; the extensive salvage logging that occurred along many streams in the late 1960's and the 1970's; and the introduction of the Oregon Forest Practices Act harvest methods in the late 1970's. Also noted was the historic low summer flows during the years 1976-1981, averaging 20 percent lower than the 30-year average. As with any statistical analysis, the effect of human-caused change (forest harvest, in this case) must, as the authors suggest, be considered in the larger context of all factors that influence the measured impact (here, stream temperature).

3.2.1 Downstream Cooling and Temporal Cycles

The temperatures of headwater streams in the PNW vary primarily in two temporal cycles, diel and annual. The *diel cycle* typically varies between daytime heating and nighttime cooling during the summer. The question of how much energy received by headwater streams is transported downstream is thus linked to the magnitude of these diel energy exchanges relative to magnitude of energy received by the stream in forest openings such as clear cuts. As water warmed in a clear cut re-enters a forested reach and goes through an overnight cooling cycle, the mass and heat transfer processes operate, resulting in the stream water moving toward an equilibrium energy condition with its environment.

There is disagreement among researchers whether the processes that lead to downstream cooling by this diel cycle can bring stream temperatures back to pre-disturbance levels. (Zwieniecki and Newton 1999) concluded that forested streams in western Oregon cooled to an equilibrium temperature pattern within 150 meters after entering forest below harvest unit. (Bartholow 2002) simulated the cumulative effects of harvest and temperature 'recovery' using the SSTEMP model, and found that downstream equilibrium conditions strongly influenced downstream temperatures, but suggest that more study is needed to quantify the rates of recovery and processes involved. (Johnson 2004) notes that longitudinal temperature dynamics in forested streams are complex and dynamic, and a better understanding of the mechanisms of energy exchange is important in future research. In a case study of diel energy flux downstream of a forest harvest unit in the Oregon

Cascades, a drop of 3°C was observed in maximum daily temperature in a 300 meter forested stream reach. An energy budget of the stream reach showed that the sum of ‘above stream’ energy flux and advection of hillslope water could not account for the magnitude of this temperature drop. Conduction by the stream bed and hyporheic exchange were suggested as mechanisms that may be important factors (Gauger and Skaugset 2004).

The *annual cycle* of stream temperature during the summer season is dominated by two processes, solar input (solar elevation and day length), and the discharge of the stream. The date of maximum solar angle roughly coincides with the end of spring rainfall in the PNW. Thus, as the length of day and sun angle decrease, stream discharge also decreases. This results in a period of approximately two months (July and August) where these two primary determinants of stream temperature (Brown 1969) create a period of highest potential for stream heating. Prior to this period, high stream flows moderate water temperatures. After this period, lower solar angles and shorter day length minimize solar inputs. This annual cycle may be significant in determining the temperature dynamics in streams where summer flows are dominated by the contributions of water that has been stored in the hillslope during the winter and spring seasons, or in previous years (McDonnell 1990). Forested streams may be sensitive to seasonal patterns of rain and snow fall that can influence their temperature during the summer, when maximum stream heating potential exists.

Summers in western Oregon are typically characterized by warm weather and clear skies, but periods of warmer and cooler weather do occur on a cycle of days to weeks. This variation in weather overlays a third cycle to the pattern of stream temperature. Figure 1 shows the stream temperature for the South fork of Hinkle Creek during the summer of 2005, and it illustrates the three cyclical patterns.

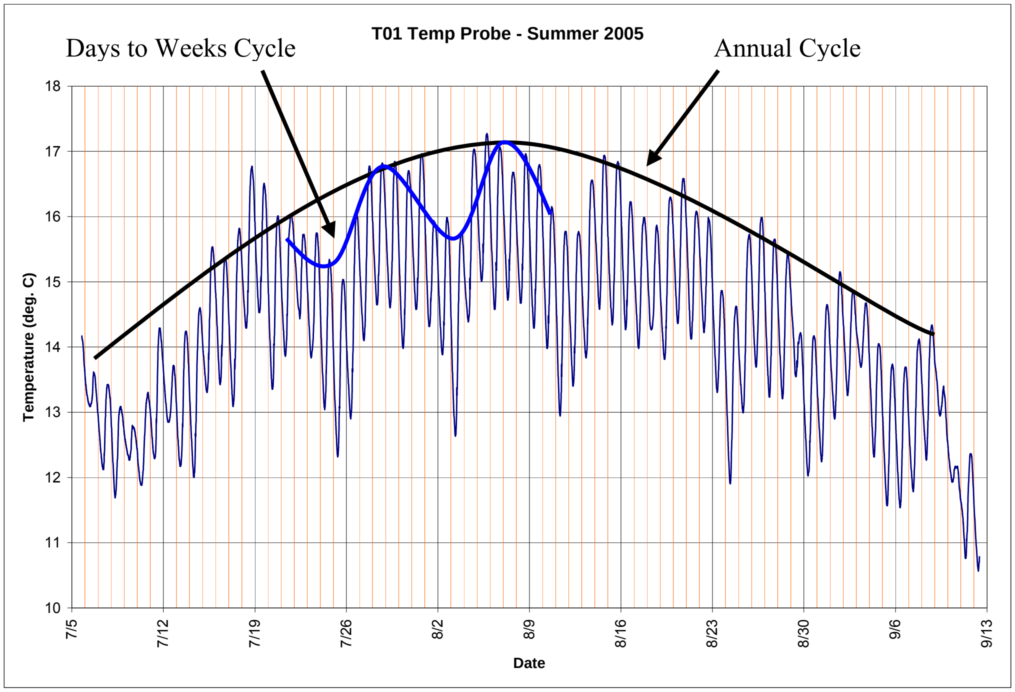

Figure 1. Ten-Minute temperature data, South Fork Hinkle Creek, Summer 2005

3.2.2 Stream Temperature Science and Policy

Clearly, the processes that define the exchange of heat into and out of a stream in space and time remain only partially understood, and further research is important to inform policy decisions. On October 5-6, 2000 the Independent Multidisciplinary Science Team (Norris et al. 2000), was convened to address two issues for the State of Oregon: 1) the influence of human activities on stream temperature, and 2) the existence of cold-water fishes in streams with elevated temperatures. The IMST report from this conference discusses stream energy and temperature in detail and summarizes *Areas of Agreement*, *Areas of Disagreement*, and *Gaps in Knowledge*. This team looked at the current state of scientific understanding of stream temperature processes, and identified the following gaps in knowledge:

- “Understanding the causes of the rate of stream temperature change in shaded reaches
- Understanding the influence of heat conduction into the streambed on stream temperature
- To improve the temperature prediction confidence at the reach scale, we need additional studies to understand processes in the stream energy balance (radiative transfer, evaporation, convection, and advection of heat in the atmosphere, conduction of heat in the streambed), particularly in eastside semi-arid environments. . . .

- Heat transfer from convection and evaporation . . .
- How much localized heating is transferred downstream and for what distance can it be detected? . . .
- Understanding the relationship between Hyporheic flow and stream temperature."

These comments highlight the need for additional research concerning stream energy processes downstream of forest harvest areas. This thesis adds to the growing body of knowledge which seeks to fill some of the 'Knowledge Gaps' identified by the IMST.

There is also a growing debate regarding the legal meaning of a "downstream impact". In January, 2001 the US Supreme Court ruled in the case of Solid Waste Agency of Northern Cook County (SWANCC) v. U.S. Army Corps of Engineers (COE), holding that the COE exceeded their use of the Clean Water Act (CWA) in regulating intrastate, non-navigable, isolated waters as 'waters of the U. S.'. In the majority opinion, the court gave the reasoning that the CWA intended that there be some 'connection' between upland waters and the waters regulated as 'navigable waters', stating that there must be a 'significant nexus' to the navigable waters for the CWA to apply. Since this decision, there have been numerous lawsuits that challenge the jurisdiction of the CWA, specifically dealing with the meaning of the terms 'tributary', 'significant nexus' and 'adjacency' (Nadeau and Rains 2007). Federal Court decisions in most of these cases have upheld the CWA jurisdiction, despite the SWANCC decision. Two cases in the Fifth Circuit Court, however, have succeeded in using the SWANCC decision to deny CWA jurisdiction. On February 21, 2006 the Supreme Court heard oral arguments in these two cases, John A Rapanos et al. v. United States (Rapanos) and June Carabell et. al. v. United States Army COE and United States Environmental Protection Agency (Carabell). Both cases argued that if the CWA covers any wetlands other than those that abut navigable waters, those bodies enforcing the law have exceeded the intent of the commerce clause under which the CWA was enacted. On June 19, 2006, the U.S. Supreme Court handed down a 4-1-4 split decision on these two cases, which had three principle opinions. Four Justices held that the cases should be remanded to the lower courts, and four held that the Fifth Circuit had ruled correctly. Justice Kennedy held with the four judges that remanded the cases, but did not agree with their opinion that the CWA did not apply to ephemeral or intermittent flowing water. He held that the CWA could apply to "wetlands, either alone or in combination with similarly situated lands in the region, that significantly affect the chemical, physical, and biological integrity of other covered waters more readily understood as 'navigable.' " He further stated that, where there are not specific regulations, the COE "must establish a significant nexus on a case-by-case basis".

Scientists are now faced with defining what these words mean in application. In the forested streams of this study, future management regulations, either State or Federal, will certainly be driven by whether there may be a “chemical, physical, and biological” impact on downstream receiving waters. Specific to this study, the question of whether heat added to headwater streams has downstream impacts becomes relevant.

3.3 Literature Review Conclusions

A summary of the present understanding of headwater stream temperature dynamics from the literature is as follows:

- The primary energy input to forest streams during the summer season is direct solar radiation
- Streamside shade is an effective method of limiting the input of solar radiation.
- The factors that influence stream temperature in shaded reaches are complex and variable in both time and space.
- Both mass transfer processes (advection of hillslope water, hyporheic flows) and energy transfer processes (radiation balance, latent and sensible heat exchanges) are important in understanding stream temperature dynamics.

4. STUDY AREA

4.1 Location

This research project was carried out as a part of the Hinkle Creek Paired Watershed study, located near Roseburg, Oregon (Figure 2). The research analyzes the downstream, off-site impacts of clear-cut timber harvest on stream temperature. The study watersheds for the Hinkle Creek Paired Watershed Study are located in the foothills of the Cascade Mountains, about 40 kilometers (25 miles) northeast of Roseburg, Oregon. The entire Hinkle Creek study watershed has an area of approximately 2000 hectares (5000 acres), owned almost exclusively by Roseburg Forest Products, Inc., and support a 60-year old harvest-regenerated Douglas-fir forest, described below.

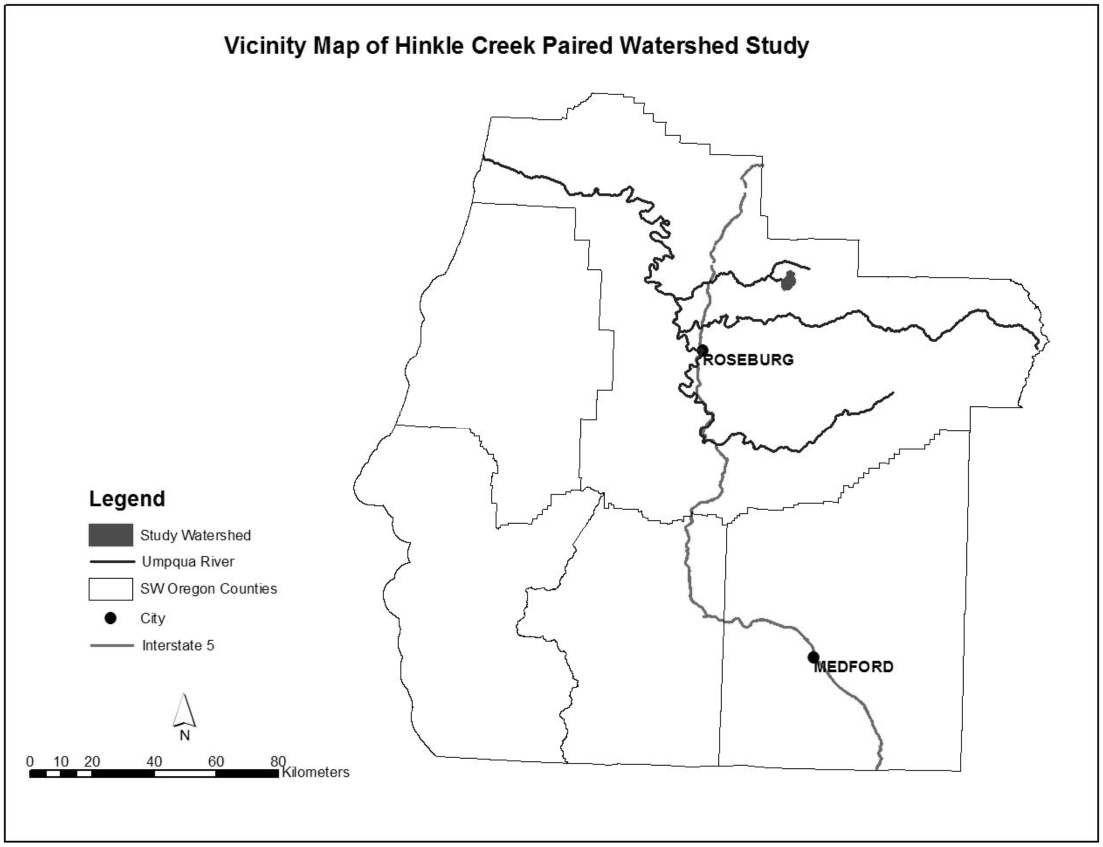

Figure 2. Project Vicinity Map

The Hinkle Creek Paired Watershed Study is a nested paired watershed study, which means that the study takes place at two spatial scales. At the larger spatial scale, 4th order watersheds, the study is composed of a control watershed, the North Fork, and a treatment watershed, the South Fork. There are two small control watersheds, Meyers and DeMerrseman, within the large control watershed and there are four small treatment watersheds, Fenton, Clay, Russell, and BB, within the large treatment watershed (Figure 3). Depending on the location there was between one and three years of calibration data and one year of post-harvest data.

4.2 Study Site Characteristics

The geology of this area was recently mapped by the United States Geologic Survey (USGS). Soils are derived from Brown Mountain Basalts at highest elevations, volcanolithic, sandstone, conglomerate, laharic brechia, rhyolite and dacite flows at intermediate elevations, and Holocene and Pleistocene landslide deposits at lower elevations (Wells 2000). The soils are Typic Ultisols, Humic Inteceptosols, and Andic Inteceptosols. The Lance George study of the stream chemistry and soil resources in the Hinkle Creek watersheds provides a detailed analysis of soil types (George 2006). The forest is predominately Douglas-fir (*Pseudotsuga menziesii*) with minor components of Western Hemlock (*Tsuga Heterophylla*), Western Redcedar (*Thuja plicata*), Red Alder (*Alnus rubra*), and Vine Maple (*Acer Circinatum*). The understory is composed of swordfern (*Polystichum munitum*), rhododendron (*Rhododendron macrophyllum*) vine maple (*Acer circinatum*), salal (*Gaultheria shallon*), Oregon grape (*Mahonia sp.*), and red huckleberry (*Vaccinium parvafolium*). The fish-bearing portions of these streams support a resident population of cutthroat trout. Elevation ranges from 400 meters at the confluence of the North and South forks of Hinkle Creek to 1200 meters at the top of the watershed. Mean annual precipitation ranges from 1400 mm at the mouth of the watershed to 1900 mm at the highest elevations (Skaugset 2005).

4.3 First Harvest Entry

Timber harvest was carried out during the autumn, winter and spring of 2005-2006. Table 1 summarizes the harvest areas and stream lengths in the four treatment watersheds. Timber was harvested from four units in the South Fork, following the Oregon Forest Practices rules. All of the harvest units were put in adjacent to non-fish-bearing streams and no overstory merchantable conifers were left in the riparian areas of these streams. The harvest units were clear cut. The trees were felled by hand and yarded to the landings whole-tree. The logging systems used was a slackline skyline system with a slackline pulling carriage. There was some shovel logging, but it was a minor proportion of the total. All logs were processed, i.e. limbed and bucked to length, on the landings using delimbers or cut-to-length processors.

2005-2006 Harvest Summary						
Watershed	Watershed Area (ha)	Area Harvested (ha)	Area Harvested (%)	Stream Length (m)	Stream Length Harvested (m)	Stream Length Harvested (%)
Fenton	22.7	15.4	68%	893	621	70%
Clay	65.2	24.7	38%	2039	782	38%
Russell	95.9	12.1	13%	1805	630	35%
BB	111	34	31%	2275	1063	47%
S. Fork Hinkle	1083	154	14%	25566	4166	16%

Table 1. Harvest Area Summary

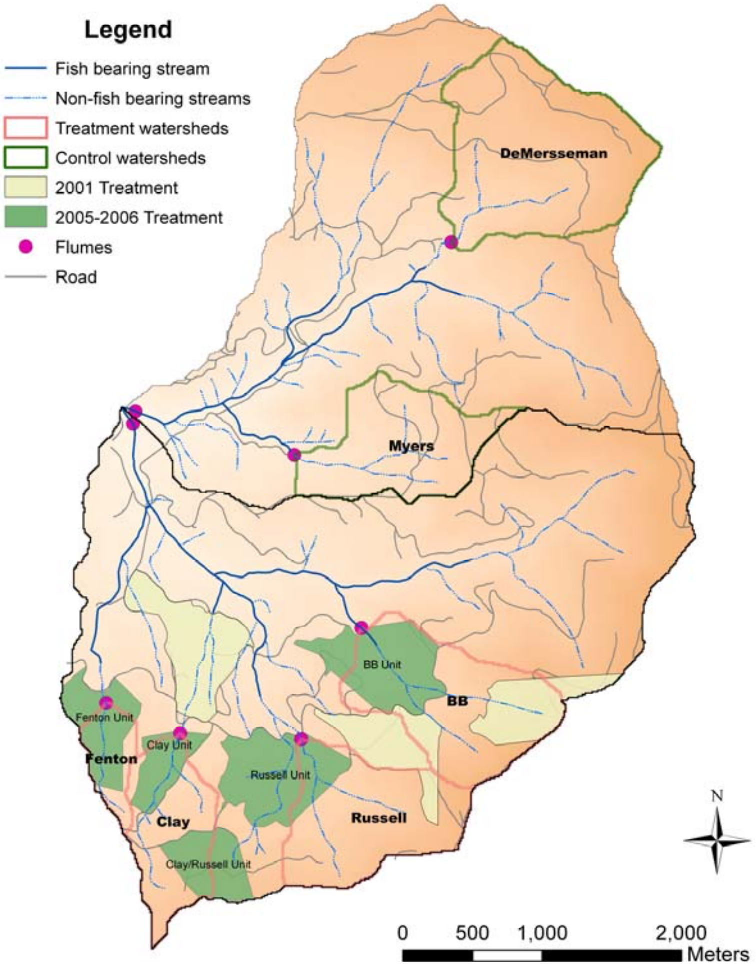

Figure 3. Map of Hinkle Creek Watershed

5. METHODS

5.1 Stream Temperature Sampling

Stream temperature data were collected for four years during the pre-harvest calibration period (2002–2005) and for one year post-harvest (2006). The temperature probes were deployed in the watershed as shown in Figure 4 and Table 2. Temperature data were also collected at the eight flume locations shown in Table 3. Hobo® probes (Onset Computer Corp., Bourne, MA, USA) were checked for accuracy using a two-point calibration with a YSI field Temperature/Specific Conductivity probe. PVC Solar shielding tubes were added to probes deployed in 2006.

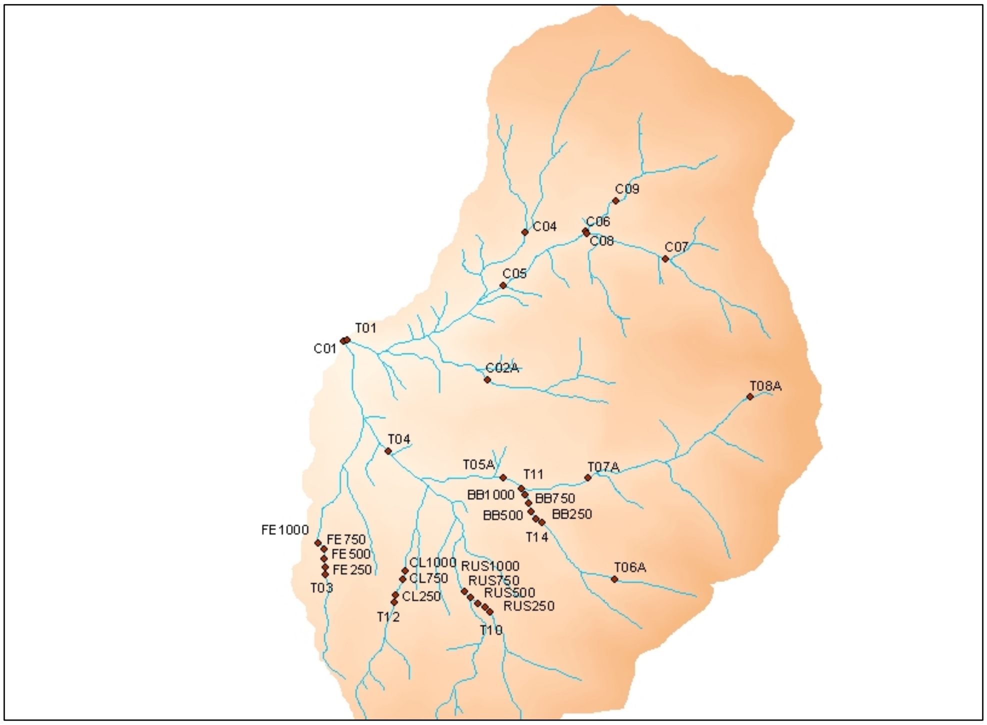

Figure 4. Map of Temperature Probe Locations

Probe locations	Number	Dates Deployed*	Brand	Interval (min)
Mainstem (T01, C01)	2	2002-2004	Vemco	30 Min
		2005-2006	Hobo	10 min
Control (C prefixes)	9	2002-2004	Vemco	30 Min
		2005-2006	Hobo	10 min
Treatment (T prefixes)	11	2002-2004	Vemco	30 Min

		2005-2006	Hobo	10 min
Below Treatment Flumes (FE, CL, RUS, and BB prefixes)	16	2005-2006	Hobo	10 min

Table 2. Temperature Probes (*Summer data, late May through early September, typically)

Flume locations (see Figure 3)	Number	Dates Deployed**	Brand	Interval (min)
Mainstem	2	12/03 to present	Campbell	10 min
Control	2	12/03 to present	Campbell	10 min
Treatment	4	12/03 to present	Campbell	10 min

Table 3. Temperature data collected at flumes (Continuous data)**

5.2 Stream Tracer Dilution Studies

Steady-state tracer-dilution tests were carried out on the first 300 meters of the streams directly downstream of the four harvest units in the South Fork during the summers of 2005 and 2006. These tests were designed to determine the amount and location of tributary and groundwater inflow, the average stream velocity of the active channel, longitudinal dispersion of stream water, approximate storage cross-sections of inactive storage zones (pools and hyporheic zones), and transfer rates between the active and inactive zones.

Tests were carried out using Rhodamine WT dye (Formulabs, Piqua, OH, USA) and two Turner Model 10AU Fluorometers (Turner Designs, Sunnyvale, CA, USA). One fluorometer was set up in the field at the bottom of the 300 meter study reach with a flow-through cell for continuous monitoring. A second fluorometer was set up in a laboratory, and was configured with a discrete cell to analyze hourly samples from intermediate sampling locations. These tests were designed to characterize the discharge, longitudinal velocity, and groundwater flux into the stream for 300 meters downstream of the harvest units. Thirty Hobo water temperature probes were installed at 10m intervals for the 300m study reach during each steady-state tracer test. ISCO Model 3700 automated water samplers (ISCO, Inc., Lincoln, NE, USA) were placed at 25m, 75m, 150m, 225m, and 300m downstream of the dye injection site to collect discrete water samples at these locations.

The ISCO sampler located at 25m was used to diagnose any problems with the injection equipment. Dye fluorescence was continuously monitored by the field fluorometer located at 300m (the bottom of the study reach). Fluorescence was converted to dye concentration, so a continuous trace of real time dye concentration was known at the bottom of each study reach. Figure 3 illustrates the locations of instrumentation along a study reach for a tracer dilution test.

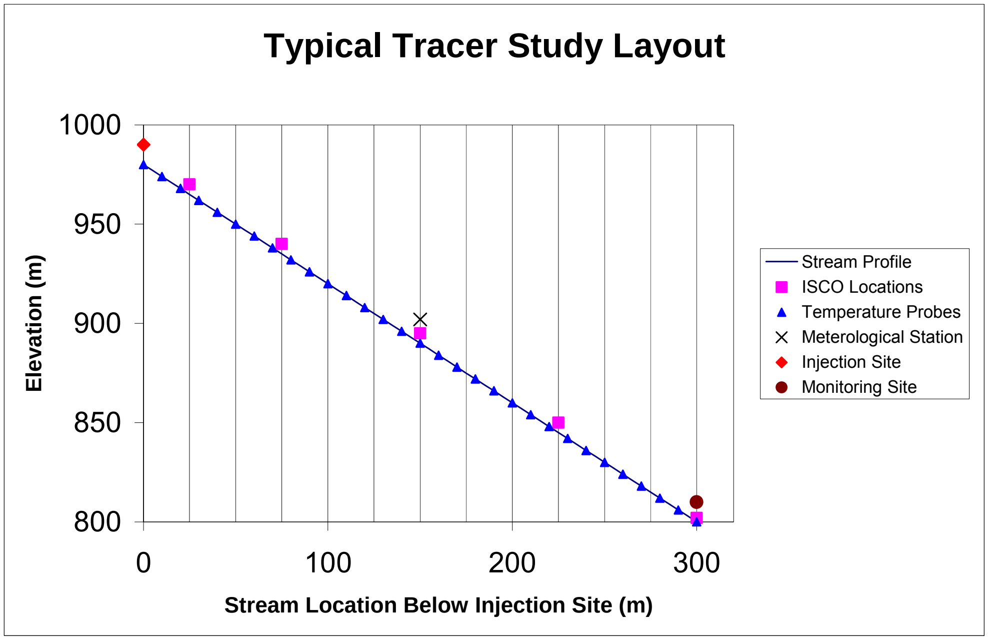

Figure 5. Schematic of Equipment Locations for a Tracer-Dilution Test Reach

When dye concentrations reached approximate steady-state at the downstream fluorometer, grab samples of stream water were taken at 10 meter intervals along the study reach, at the locations of the 30 temperature probes. Discharge was calculated at these 10m intervals using a two-component mixing model of following form:

$$\text{Equation 9: } Q_{STREAM} = Q_{DYE} \cdot \frac{(C_{DYE} - C_{TOTAL})}{(C_{TOTAL} - C_{STREAM})}$$

where Q_{STREAM} is the calculated stream flowrate, Q_{DYE} is the injection flowrate of the dye, C_{DYE} is the concentration of the dye, C_{TOTAL} is the dye concentration of the dye/stream water mixture at the fluorometer, and C_{STREAM} is a background ‘equivalent concentration’ of dye, based on the natural fluorescence of stream water prior to beginning each study.

The discharges of the study streams were measured at the monitoring sites prior to each tracer test to determine the volume, concentration, and injection rates of dye needed. These discharge measurements were made with a Marsh McBirney Flowmate Model 2000 Portable Flowmeter and top-setting rod. For each steady-state tracer test, dye was injected with an FMI Model QG150 Lap pump (115 V.AC, 0-15 ml/min.) for 2005 tests and the first two 2006 tests. This pump was replaced by an FMI Model QBC-1 Lab Pump, (12V.DC, 0-19.2ml/min.)(Fluid Metering, Inc., Syosset, NY, USA) for the balance of the 2006 field season. Stream water/dye mixture for the monitoring site fluorometer was continuously pumped using a 12V. DC peristaltic pump (Masterflex Model 7518-12). All 12Volt equipment was powered with Exide Orbital or Trojan brands Marine Deep cycle batteries. All AC power was supplied from batteries using a Vector VECO 43 750 Watt DC to AC converter.

5.3 Stream Flow Measurement

Tracer dilution measurements of discharge were compared to measurements of discharge obtained with other methods. Three other measurement techniques were compared to the tracer dilution results on August 21, 2006 on Fenton Creek at the top of the study reach. These methods were 1) Slug test using salt, and 2) Direct measurement with a Marsh McBirney flow meter, and 3) the Montana Flume installed at this location. The slug test used salt (NaCl) as a tracer (Rantz 1982; Moore et al. 2005). A YSI Model 556 multiprobe (YSI Environmental, Inc.) was used to measure and record Specific Conductance (SC) of the stream water. A solution containing 0.8 liters of stream water and 155 grams of NaCl (193.75 g/l concentration) was injected at the upper end of a road culvert at upstream end the Fenton study reach. SC measurements, corrected for temperature, were recorded in the stream at one second intervals below the culvert, approximately 30m downstream, until values returned to background levels. A linear calibration relationship was developed between electrical conductance (μS/cm) and NaCl concentration (mg/l) to determine NaCl concentration. Discharge was calculated using the equation:

$$\textit{Equation 10:}\ Q = \frac{V_1 C_1}{\int_0^\infty (C - C_b)\,dt}$$

The denominator, $\int_0^\infty (C - C_b)dt$, was approximated by the equation:

$$\textit{Equation 11:}\ \sum_{i=1}^{N} \frac{(C_i - C_b)(t_{i+1} - t_{i-1})}{2}$$

where, Q is the discharge of the stream, V_1 is the volume of the tracer injected, C_1 is the concentration of the injected tracer, C is the measured tracer concentration at time t at the downstream sampling site, C_b is the background concentration in the stream, t is time, i is the number of the sample, N is the number of samples, and t_i is the time when a sample, C_i was measured (Rantz 1982).

The direct measure of discharge was carried out with a Marsh McBirney flow meter, as described above. Finally, discharge was measured by the Montana flume located approximately 100 meters upstream of the study reach at the time of the other flow tests were done. The flume stage measurement was converted to a discharge value with the flume rating curve. A comparison of the four methods of discharge measurement are summarized in Table 4.

08/21/06 Fenton Flowrates	(l/sec)	ft^3/sec
Salt Slug Inject. Calc. Q	2.1	0.073
Marsh McBirney	1.0	0.037
Flume Q,	1.4	0.051
Steady State Dye Test Q	2.4	0.086

Table 4. Comparison of flow measurement techniques

It is likely that the velocity and cross-section measurements obtained with the Marsh McBirney flow meter method underestimate total stream flowrate for these small streams, since the size of the rock media in the streambed does not allow precise stream velocity or area measurement between rocks or near stream edges. The Montana flume is also subject to measurement error at low flows, since it was sized to measure peak flows, and a small error in water depth at these low flows can dramatically change the calculated flowrate. The salt slug method agrees most closely with the dye test flow rate, and serves as an independent check on the steady-state dye method flowrate calculations used for this study.

5.4 Meteorological Measurements

A Micrometeorological Station was deployed at the midpoint (150m below injection site) of each dye tracer study reach, for the duration of each tracer study, approximately 4 days each. Four atmospheric parameters were measured: Wind speed using a MetOne anemometer, Air temperature and Relative Humidity (RH) using a Vaisala Model 107 Temperature and Humidity probe, and Solar Radiation using a LiCor 200x Silicon Pyranometer. These atmospheric parameters were used to calculate atmospheric heat exchanges for Russell Creek during a 10-day period in August, 2006. A second permanent weather station, located near the center of the watershed, continuously monitored these parameters, as well as Precipitation, using a Texas Electronics 8-inch tipping-bucket rain gage. Permanent weather station data was not used in this study, but was useful in verification of the mobile station data.

5.5 Data Analysis

5.5.1 Statistical Analysis

A first step in understanding this downstream process is to measure temperatures with enough spatial and temporal resolution to determine where further research and management effort should be focused. As noted above, this study seeks to characterize the variability of downstream temperatures before and after the clear-cut harvest in four small non-fish-bearing streams. Specifically, changes in Maximum Daily Temperature are analyzed between the last summer season pre-harvest (2005), and the first summer season post-harvest (2006). Stream temperatures at the harvest boundary are compared to measurements taken at 75m intervals for 300m downstream.

The effect of timber harvest on maximum daily stream temperature downstream of the harvest units was evaluated using statistical tests in the context of a *Before-After-Control-Impact* (BACI) study design. This method is considered to be the most rigorous method of detecting changes to hydrologic processes following forest harvesting (Gomi et al. 2006). Traditional paired watershed studies, in which stream temperatures were evaluated using one annual maximum value, required many years of calibration to detect a statistically significant effect. This paper, however, documents changes in stream temperature pre- and post-harvest, using maximum daily stream temperatures of the four treatment streams for a single year before and after harvest. A multiple linear regression model compared 2005 data with 2006 for each stream, using Myers Creek data (Temp. probe C04) as the covariate control. The model for this analysis was:

$$y_t = \mu + \alpha_i + \beta x_t + \varepsilon_t$$

Where y_t is the temperature of the stream on a day t; μ is the overall mean value of y; α_i is the effect of year; x_t is the corresponding temperature of the control stream on a day t; β is the coefficient estimated by regression; and ε_t is the error term. This method can be described as an analysis of variance of values which have been adjusted for regression on an independent variable, in this case the maximum daily temperatures of the control stream.

This analysis was repeated for stream temperature data at 76.2 m (250 ft), 152 m (500 ft), 229 m (750 ft) and 305 m (1000 ft) below harvest boundaries. These daily maximum temperatures are a time series of relationships between control and treatment streams. For time series, it is important to ensure that the assumptions of the statistical models are met. One concern is that the residuals from a model may be autocorrelated in time. Temporal autocorrelation is exhibited by departures from the regression relationship that are not random but can follow multi-day departures or some cyclic pattern. Thus, data from consecutive days may not be independent. In this case, autocorrelation was found and had a one or two day lag for all streams (Kibler 2007). To ensure independent data, a random start date was chosen, and the maximum daily temperature from every third day was used for analysis. Another statistical concern is that the residuals from modeling be normally distributed and have equal variance in time. Maximum Daily Temperature relationships between treatment and control streams were found to have larger variance during autumn, winter, and spring seasons than during the summer. To improve the residual structure, early and late season data were not used. The analysis presented here uses daily maximum temperatures for the same 21 calendar days in July and August of 2005 and 2006 for all streams.

5.5.2 One-dimensional Transport with Inflow and Storage (OTIS) Modeling

Tracer studies offer the opportunity to estimate the characteristics of both the mobile and immobile water in these headwater streams. The mean stream velocity and discharge, including the inflow of groundwater can be calculated and are important in characterizing the active channel. The amount of immobile water in pools and in the streambed can also be estimated.

The 2006 tracer dilution study data was modeled using the One-dimensional Transport with Inflow and Storage (OTIS) model parameter estimation (OTIS-p) routine (Runkle 1998), originally published in 1991(Runkle and Broshears 1991). This model uses the advection-dispersion equation, with additional terms to account for lateral inflow of water, transient storage, first-order decay, and sorption. These equations are solved using the Crank-Nicolson finite difference method. The parameter estimation routine (OTIS-p) uses a Non-linear Least Squares (NLS) method (Donaldson and Tryon 1990) to minimize the squared differences between the measured and simulated concentrations.

For this study, Rhodamine dye concentrations were modeled assuming no decay. Since this study was concerned with short time-scale processes of transfer between mobile and immobile stream zones, sorption was not modeled. Three parameters were estimated: longitudinal dispersion (D) of dye, transfer rate (α) between the active channel and storage zones, and the cross-sectional area (A_2) of the storage zones. These parameters were estimated as averages for each 75m stream reach. Stream advection velocity was determined by a trial-and-error visual fit to the increasing (arrival) portion of the dye breakthrough curves (Figures 19-22), and a constant velocity was assumed for the entire 300m reach of each study stream. Average stream cross-sectional areas for each 75m reach were calculated by dividing the mean flowrate for each reach by the stream velocity.

5.5.3 Stream Energy Budget Calculations

Four components of the stream energy budget were calculated for the Russell Creek study reach for the time period of August 7-17, 2006 (the post-harvest study period). These were based on measurements taken at 150 meters downstream of the harvest boundary. *Photosynthetically Active Radiation (PAR)*, *relative humidity*, *air temperature*, and *wind speed* were continuously measured during this period at a point one meter above the stream surface. PAR measurements are presented as measured. Latent and Convective heat were calculated using Equations 5 and 6. For these calculations, water density, $\rho = 1000$ kg/m^2, and specific heat, L = 4184 J/kg-°K. The wind function used for these two stream heat components was:

$$\text{Equation 12: } (Wftn)_Z = a + bv$$

where a = 2.2×10^{-9} m/s-mb, b = 1.5×10^{-9} /mb, and v = wind speed (m/sec). Values used for the empirical constants a and b were calculated as the average of nine wind function coefficients summarized by (Boyd 2004).

6. RESULTS

6.1 Multiple Linear Regression

Stream temperature response between 2005 (pre-harvest) and 2006 (post-harvest) varied between streams. The following measure of change detection is included to illustrate changes between the downstream harvest boundary and points further downstream within the forested reach of stream and should be considered as one change-detection metric among the many possible views of the data. For a more complete discussion of pre- and post-harvest differences at the harvest boundary, see the recent Kibler study (Kibler 2007). The box plots in Figures 6 and 7 compare the distribution of the 21 maximum daily temperatures (every third day in July and August) between pre- and post-harvest years at the harvest boundary and at 305 meters (1000 ft.) downstream, respectively. This illustrates the range of maximum daily temperatures between the entry point into the shaded study reach and the bottom of the reach. Also notable is the difference in temperature distribution between years. 2006 had the warmest stream temperatures, but had a lower mean temperature than 2005 for all streams. Boxes represent 25th and 75th percentile, whiskers represent 5th and 95th percentiles, bold (red) lines in boxes represent the average, and light (black) lines represent medians. Myers Creek, as noted above, was used as a control for this analysis. Two effects are apparent. First, Fenton Creek appears cooler while Clay Creek appears warmer following harvest. Second, all effects are diminished downstream.

Table 5 summarizes the statistical findings. Figures 8 through 12 show the changes in the mean maximum daily temperature between years, after accounting for the mean change in the Myers Creek control. Whiskers represent the 95% confidence interval for mean values. At the harvest boundary (Figure 8), Fenton Creek was 0.63 °C cooler between years, Clay Creek was 2.0 °C warmer, Russell Creek was 0.42 °C warmer, and Beebe creek was 0.63 °C warmer. Since none of the confidence intervals include zero, there is strong evidence of a difference between years. Figures 9, 10, and 11 show the differences in the average daily maximum temperature between years for all four streams at 76.2m (250 ft), 152.4m (500 ft.) and 228.6m (750 ft.) below the harvest boundary, respectively. Figure 12 shows the difference in the average daily maximum temperature between years for all four streams at 304.8 meters (1000 ft.) downstream of the harvest units. Fenton and Beebe Creek show no significant change at the 304.8 m location, Clay Creek has a 0.51 °C increase and Russell Creek has a 0.18 °C increase. However, the confidence intervals at Clay and Russell Creeks extend nearly to zero, so there is only moderate evidence of a difference in temperatures between years at this point in the stream. Figure 13 summarizes these temperature differences between years for all five locations. The Clay Creek data at 500 ft. was unable to be downloaded from the probe for the 2006 season.

Statistical Summary

Analysis of Variance of values which have been adjusted for regression on an *independent variable* *

Differences in Maximum Daily Temperature Between Summers of 2005 and 2006

								Confidence Intervals	
	Stream	Estimate	Std. Error	DF	t-value	Pr > |t|	α	Lower	Upper
Sta 000	Fenton	-0.63	0.093	39	6.76	<.0001	0.05	-0.82	-0.44
	Clay	2.00	0.11	39	-18.5	<.0001	0.05	1.78	2.12
	Russell	0.42	0.061	39	-6.88	<.0001	0.05	0.30	0.55
	Beebe	0.63	0.077	39	-8.24	<.0001	0.05	0.48	0.79
Sta 250	Fenton	-0.11	0.091	39	1.18	0.25	0.05	-0.29	0.08
	Clay	1.41	0.11	39	-12.3	<.0001	0.05	1.18	1.64
	Russell	0.18	0.075	39	-2.58	0.01	0.05	0.04	0.32
	Beebe	0.35	0.071	39	-5.01	<.0001	0.05	0.21	0.50
Sta 500	Fenton	-0.23	0.072	39	3.21	0.0026	0.05	-0.38	-0.09
	Clay								
	Russell	0.22	0.067	39	-3.24	0.0024	0.05	0.08	0.35
	Beebe	0.18	0.069	39	-2.57	0.0014	0.05	0.04	0.32
Sta 750	Fenton	-0.02	0.06	39	0.04	0.69	0.05	-0.14	0.10
	Clay	0.37	0.15	39	-2.55	0.01	0.05	0.08	0.66
	Russell	0.16	0.12	39	-1.36	0.18	0.05	-0.08	0.39
	Beebe	0.17	0.07	39	-2.55	0.01	0.05	0.04	0.30
Sta 1000	Fenton	-0.0013	0.052	39	0.02	0.98	0.05	-0.11	0.10
	Clay	0.51	0.24	39	-2.11	0.04	0.05	0.02	1.00
	Russell	0.18	0.085	39	-2.08	0.04	0.05	0.0046	0.35
	Beebe	-0.07	0.060	39	1.15	0.26	0.05	-0.19	0.05

* Independent variable was the maximum daily temperature of Myers Creek.

Table 5. Statistical Summary

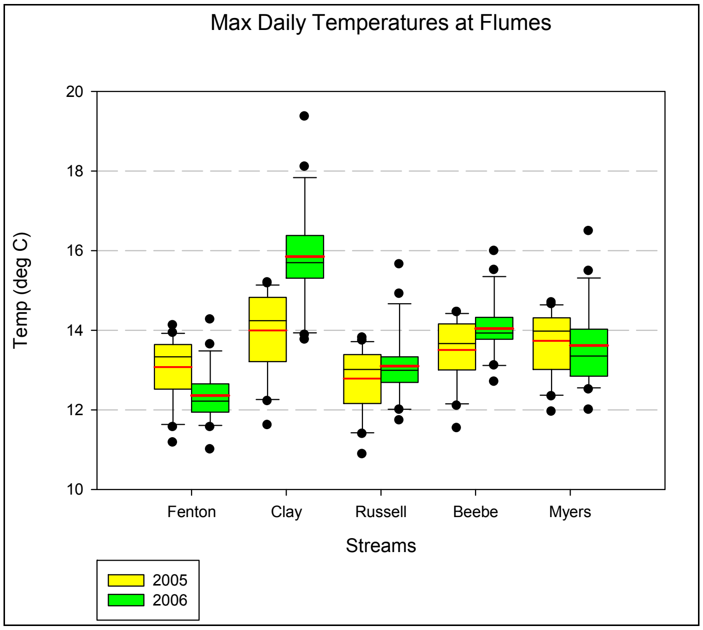

Figure 6. Maximum Daily Temperatures - at flumes

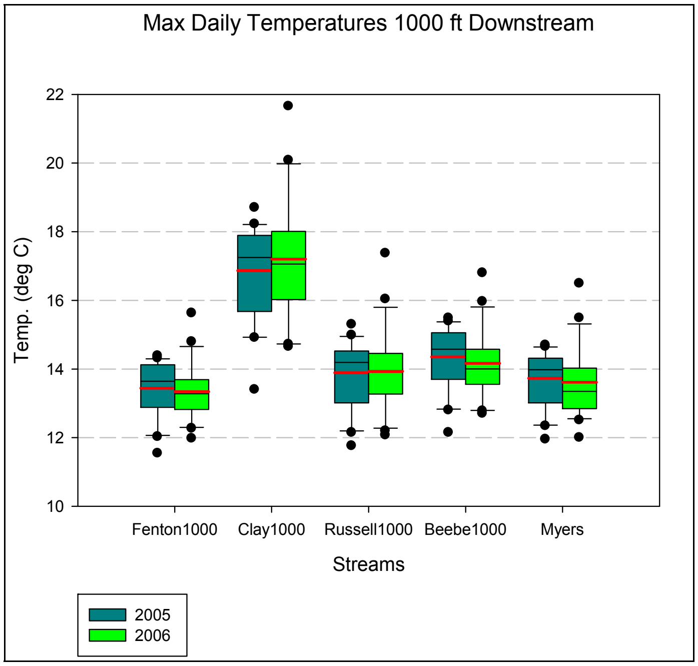

Figure 7. Maximum Daily Temperatures – 1000 ft. below flumes

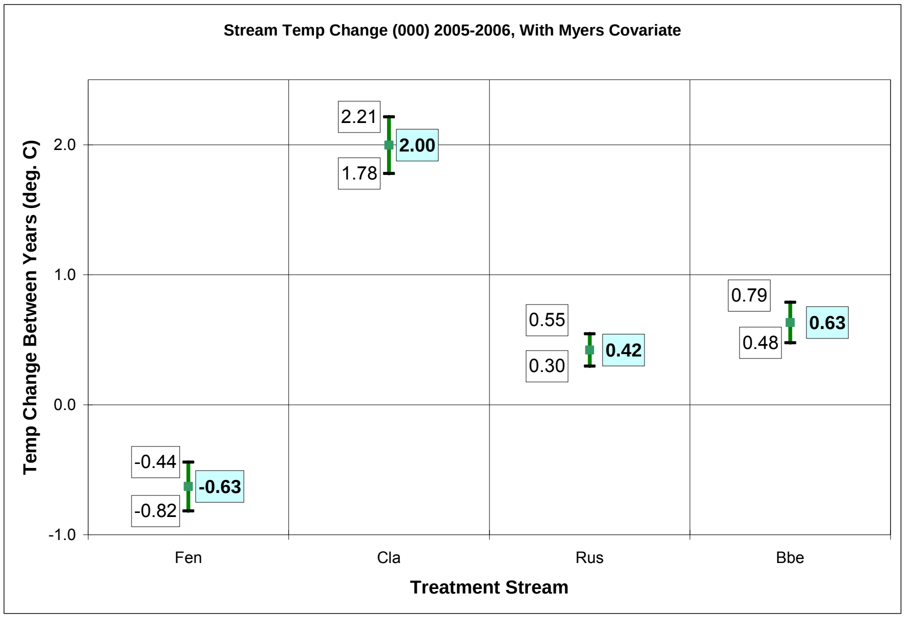

Figure 8. Change in Mean Max. Daily Temp. between years - at flumes

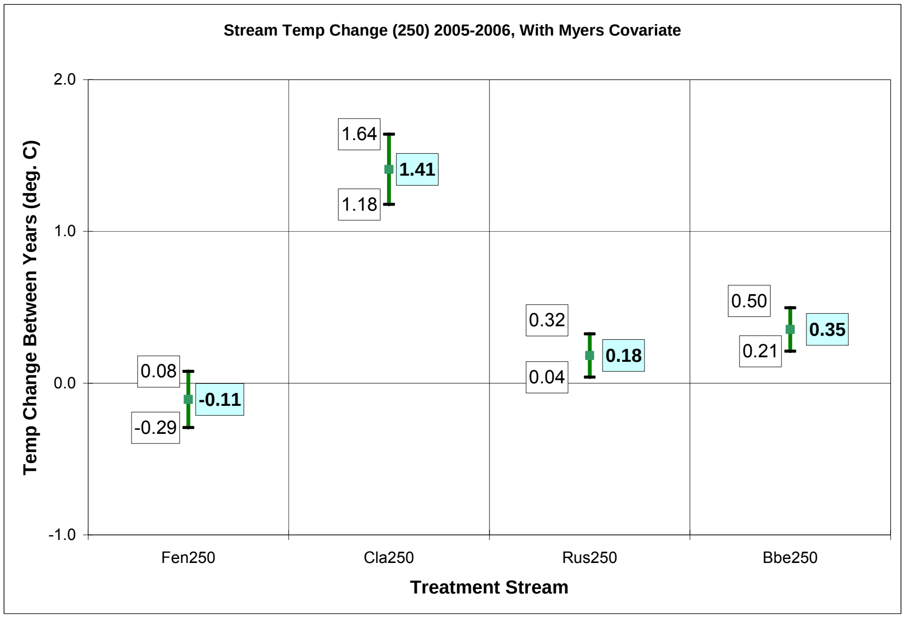

Figure 9. Change in Mean Max. Daily Temp. between years – 250 ft. below flumes

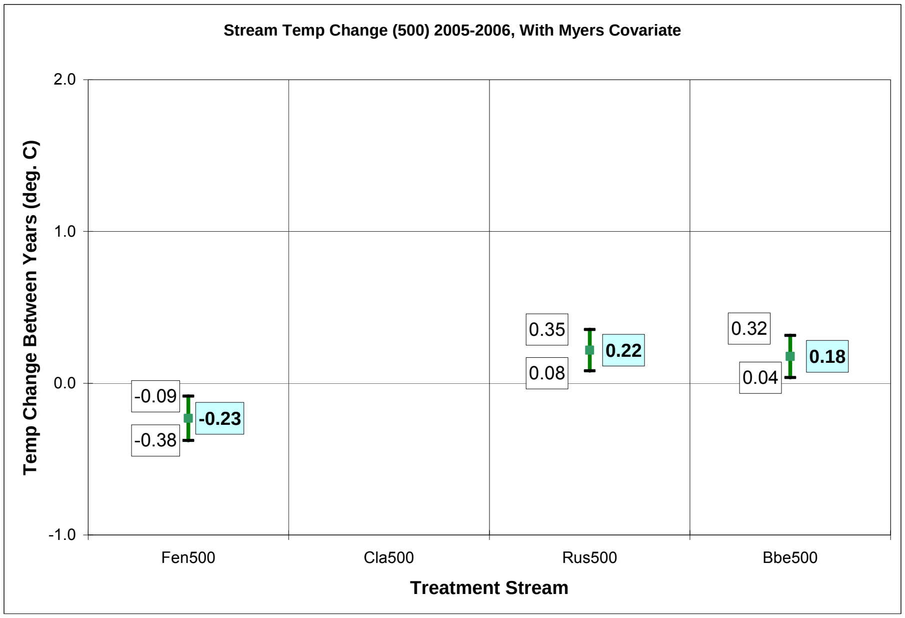

Figure 10. Change in Mean Max. Daily Temp. between years – 500 ft. below flumes

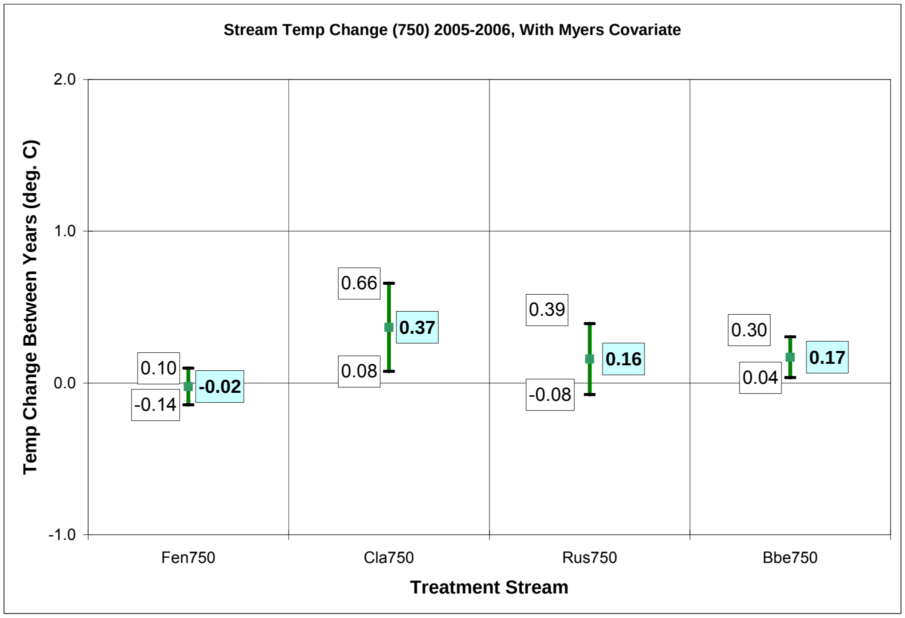

Figure 11. Change in Mean Max. Daily Temp. between years – 750 ft. below flumes

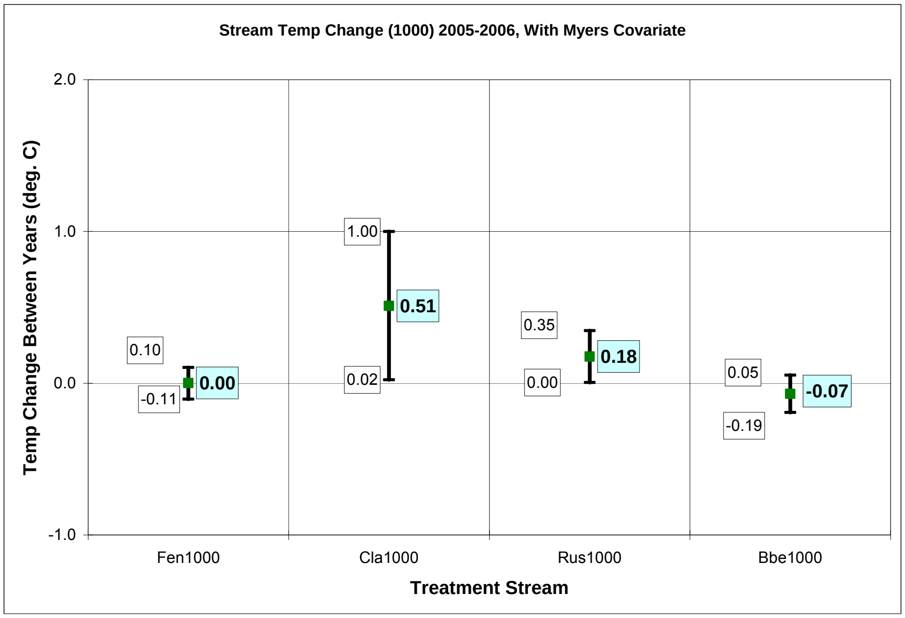

Figure 12. Change in Mean Max. Daily Temp. between years – 1000 ft. below flumes

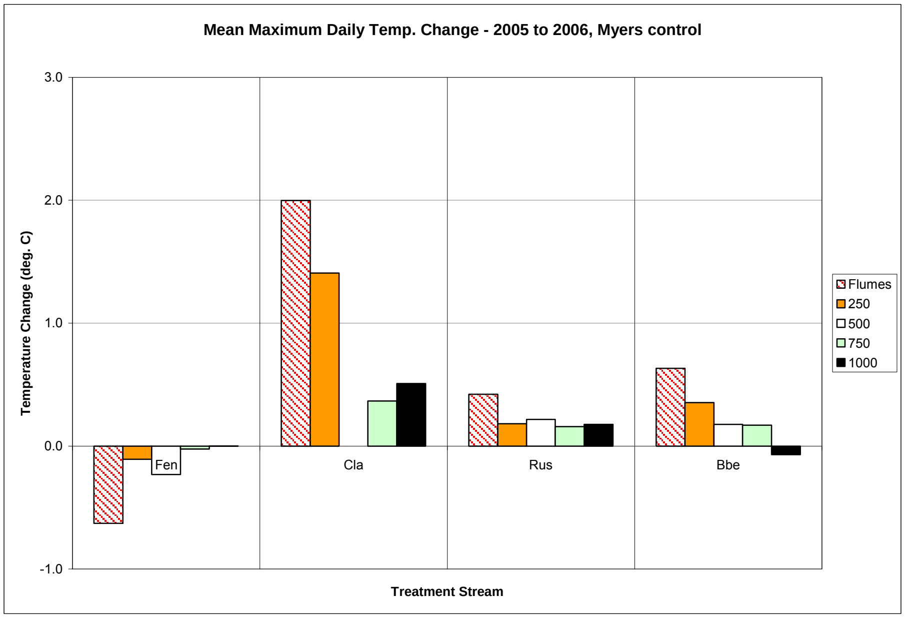

Figure 13. Mean Max. Daily Temp. change between years, by location

6.2 Hillslope Inflows from Steady State Dye Study

All four of these study reaches were gaining flow from adjacent hillslopes, groundwater, and small tributaries. Fenton Creek had a small tributary inflow near station 230 (Figure 15) and Beebe Creek had a significant groundwater seep near station 250 (Figure 18). Comparing the 2005 (pre-harvest) and 2006 (post-harvest), Fenton and Clay creeks had larger flowrates post-harvest (Figures 15 and 16), Russell creek flowrates did not appreciably change (Figure 17), and Beebe Creek had a lower flowrate post harvest (Figure 18). Each of the 2006 dye studies were conducted one or two weeks later in the calendar year in 2006 than in 2005.

It is also noteworthy that the winter and spring rainfall pattern differed between years. This can be illustrated by comparing mean monthly discharge at the North Fork of Hinkle Creek for the last three water years (see Figure 12). Water year 2003-4 could be considered the most ‘typical’ winter pattern, with December through March being the wettest months. Water year 2004-5 had a drier winter and a wetter spring. Water year 2005-6 had the wettest winter, but the lowest runoff in the months of May through September. This illustrates that the recession of stream flow in summer months varies between years, and that individual streams may respond to this variation by delivering varying amounts of summer low flow, depending on hillslope soil moisture storage volumes and delivery rates.

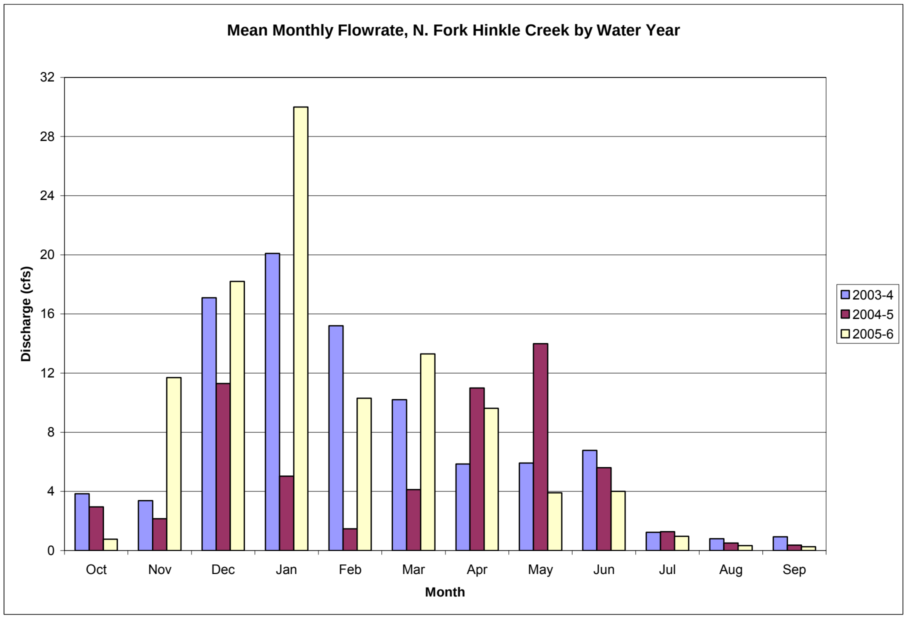

Figure 14. N. Fork Hinkle Creek Flowrates by Water Year

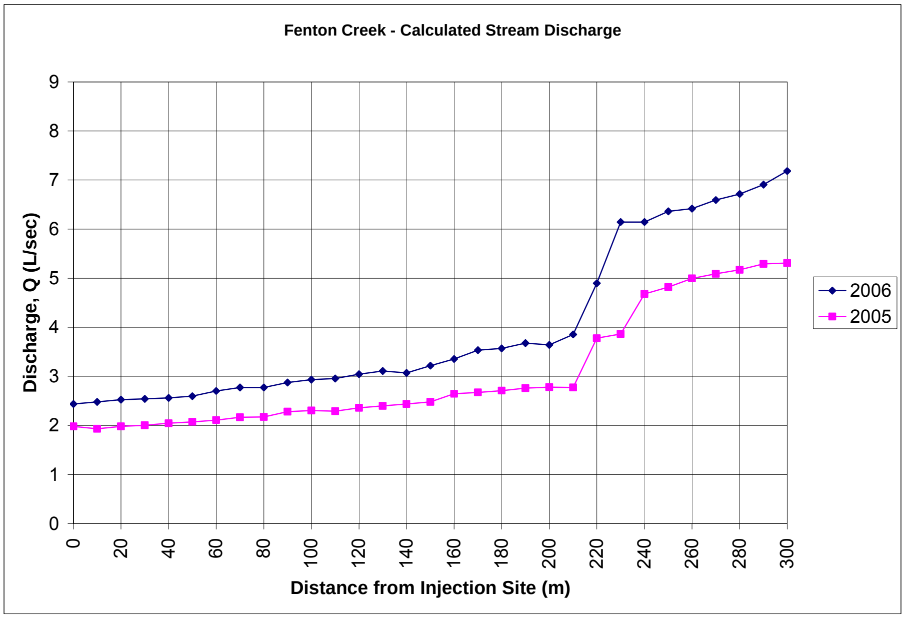

Figure 15. Fenton Creek Steady-State Flowrates by Stream Station

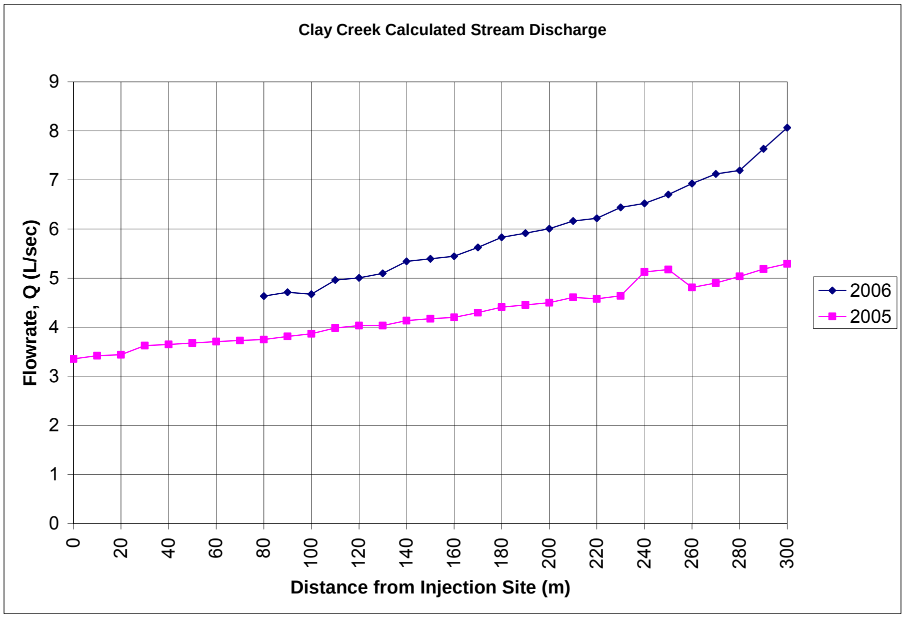

Figure 16. Clay Creek Steady-State Flowrates by Stream Station

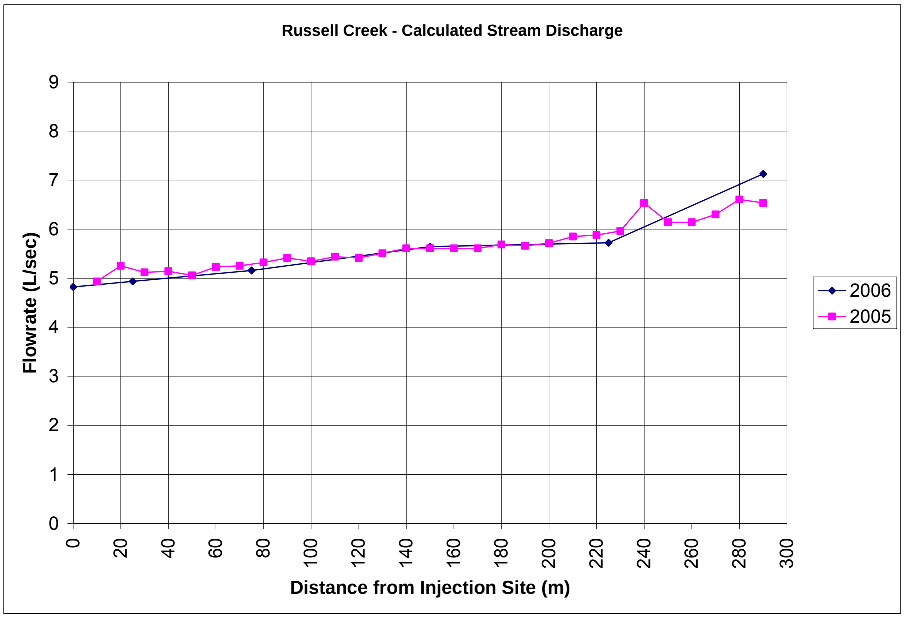

Figure 17. Russell Creek Steady-State Flowrates by Stream Station

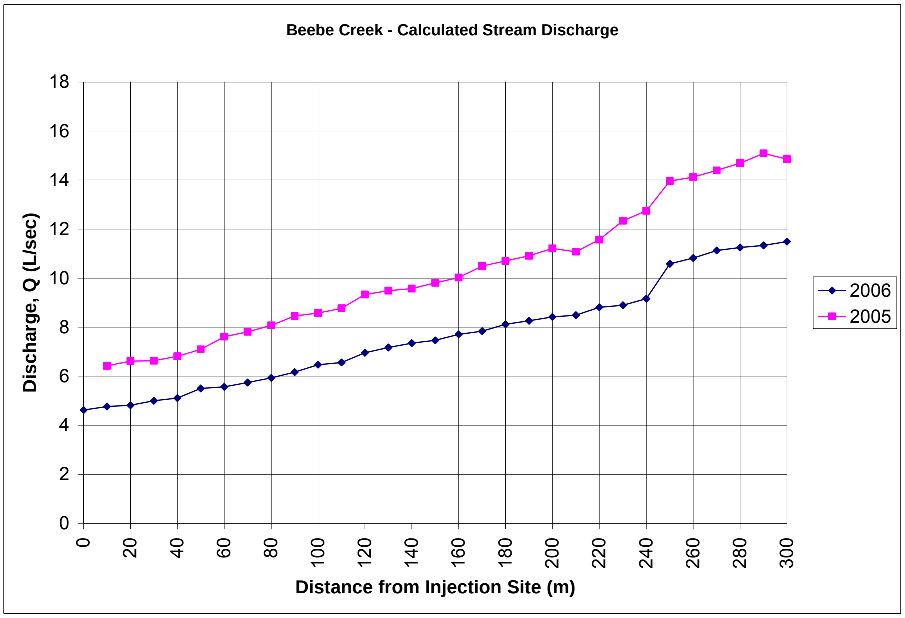

Figure 18. Beebe Creek Steady-State Flowrates by Stream Station

6.3 One-dimensional Transport with Inflow and Storage (OTIS) Modeling

Figures 19, 20, 21, and 22 show the 2006 rhodamine dye breakthrough curves for the 2006 summer season, with the fitted curves from the OTIS-p parameter estimation. For Clay and Beebe Creeks, the parameter estimation routine was most stable in estimating dispersion (D). In these cases, D was fit by trial and error to approximate the shape of the rising and falling limbs of the breakthrough curves, and then refined by the OTIS-p routine. For Russell and Fenton Creeks, The trial-and-error value of Dispersion was used. Finally, the storage parameters (As and α) were estimated by the OTIS-p routine for all streams. Figure 16 summarizes these estimated parameters for all four treatment streams. Dispersions varied between 0.18 and 0.84 m^2/sec. These values are similar to the results obtained on an experimental reach of Uvas Creek in Santa Clara County, CA (Bencala and Walters 1983). They are also similar to the modeled values of Lookout Creek, Oregon, using the 'Solute Transport And Multirate Mass Transfer – Linear coordinates (STAMMT-L) model (Gooseff et al. 2003), where D varied between 0.055 and 0.863 m^2/sec. Storage ratios, A_s/A (the estimated cross-sectional area of the 'immobile' zones of water storage divided by the stream cross-sectional area) varied from near zero to 7.2. This model uses a single value of transfer rate, α, for mass movement between the mobile and immobile zones of transport, and the immobile zone represents both pool and hyporheic storage zones. Modeled mean stream velocities varied from 0.24 to 0.40 m/sec.

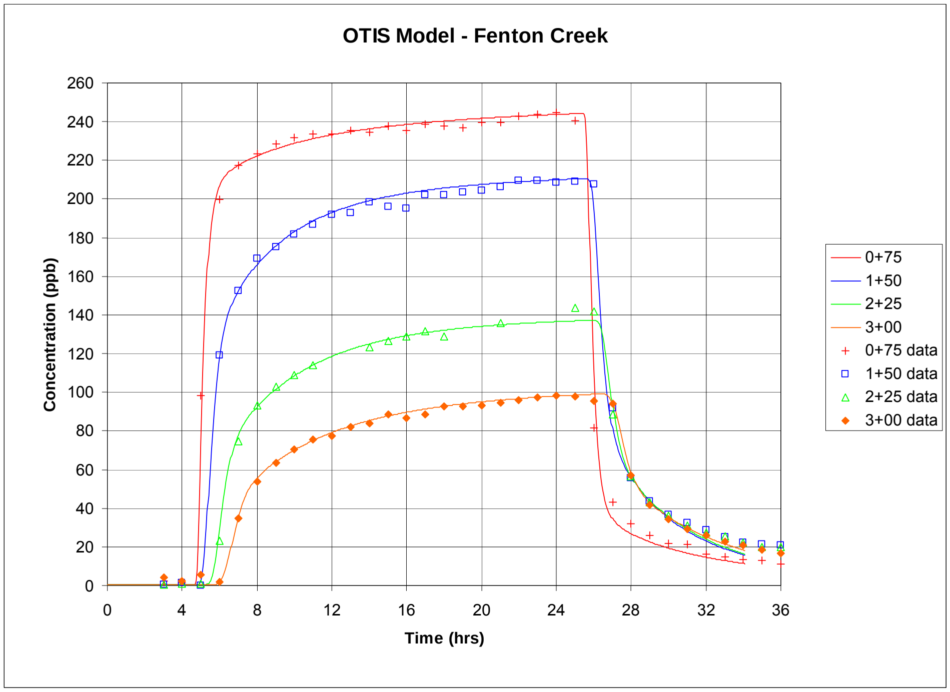

Figure 19. Fenton Creek Transport Model

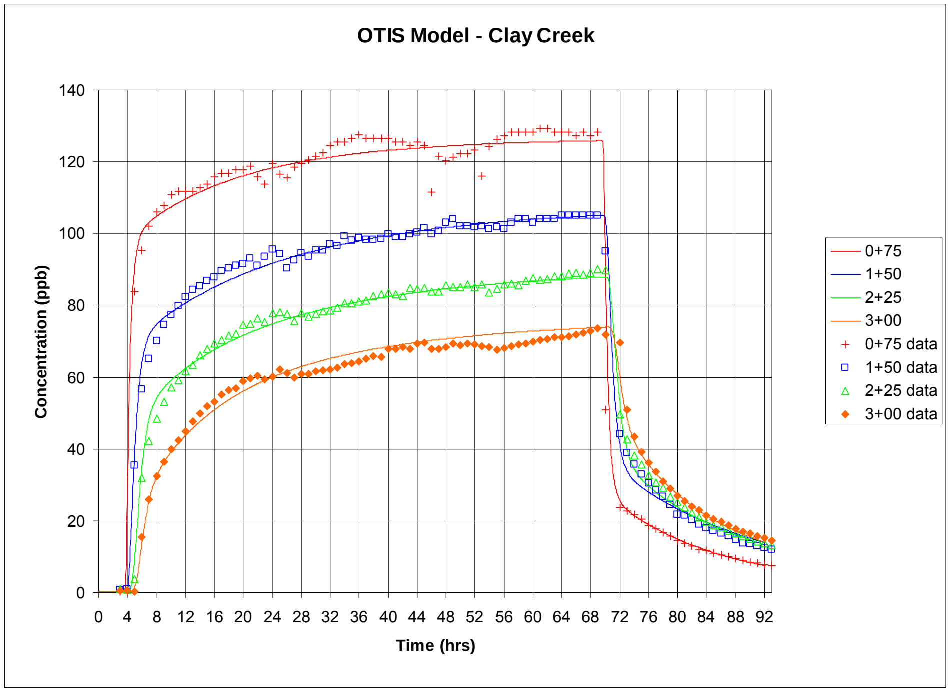

Figure 20. Clay Creek Transport Model

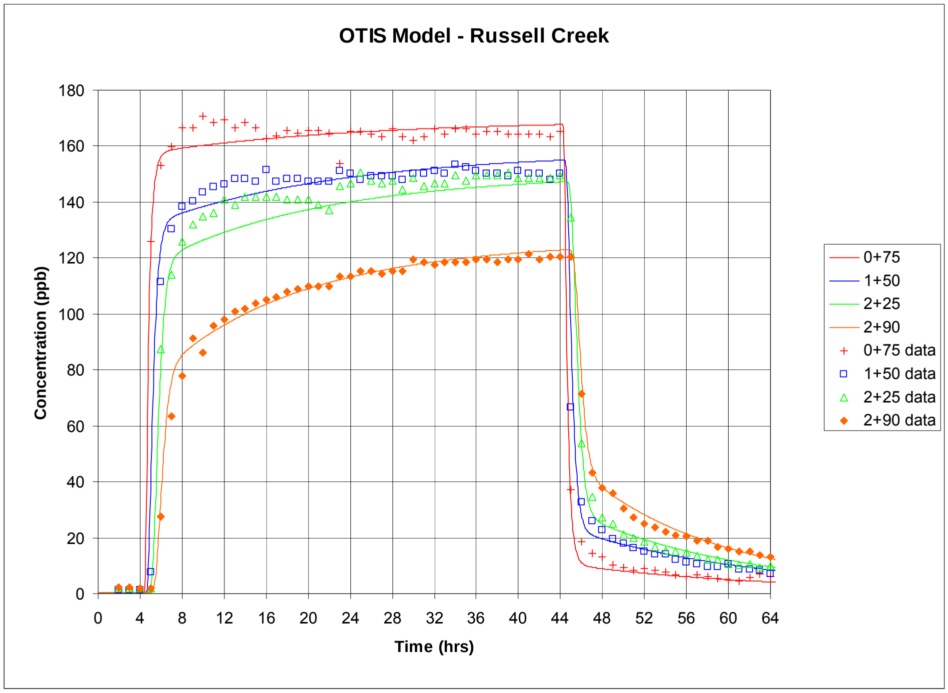

Figure 21. Russell Creek Transport Model

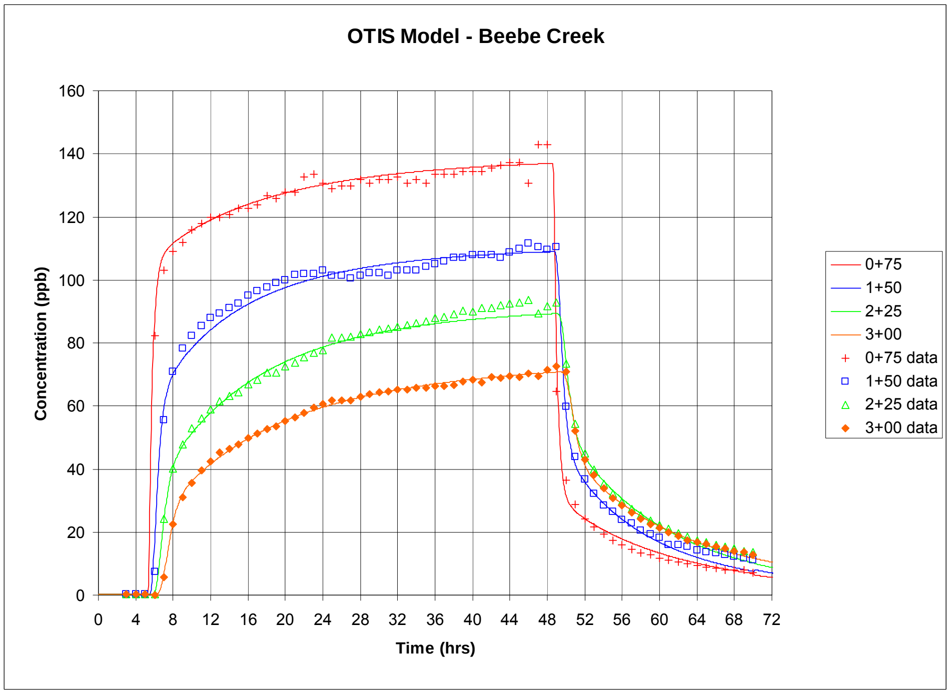

Figure 22. Beebe Creek Transport Model

Fenton Creek

Fen Reach Ending at	Reach Length (m)	Fen Disp. (m^2/sec)	Stream Area, A (m^2)	Fen Stor. Area, A_s (m^2)	Storage Fen Ratio (As/A)	Trans. Rate Fen Alpha (/sec)	Hyporheic Res. Time, t_S (sec)	Hyporheic Res. Time, t_S (hr)	Fen Velocity (m/sec)
0+75	75	0.459	0.074	0.158	2.14	0.0000616	34661	9.6	
1+50	75	0.673	0.085	0.134	1.58	0.0001875	8408	2.3	
2+25	75	0.148	0.118	0.135	1.14	0.0000920	12436	3.5	
3+00	75	0.177	0.190	0.279	1.47	0.0000564	26036	7.2	
Mean	300	0.364	0.117	0.177	1.581	0.0000994	15910	4.4	0.037

Clay Creek

Cla Reach Ending at	Reach Length (m)	Cla Disp. (m^2/sec)	Stream Area, A (m^2)	Cla Stor. Area, A_s (m^2)	Storage Cla Ratio (As/A)	Trans. Rate Cla Alpha (/sec)	Hyporheic Res. Time, t_S (sec)	Hyporheic Res. Time, t_S (hr)	Cla Velocity (m/sec)
0+75	75	0.4	0.184	0.6222	3.38	0.0000807	41902	11.6	
1+50	75	0.6	0.207	1.4982	7.24	0.0000840	86163	23.9	
2+25	75	0.6	0.245	0.1278	0.52	0.0000046	113398	31.5	
2+90	75	0.6	0.295	1.1223	3.80	0.0002085	18247	5.1	
Mean	300	0.550	0.233	0.843	3.736	0.0000945	39559	11.0	0.024

Russell Creek

Rus Reach Ending at	Reach Length (m)	Rus Disp. (m^2/sec)	Stream Area, A (m^2)	Rus Stor. Area, A_s (m^2)	Storage Rus Ratio (As/A)	Trans. Rate Rus Alpha (/sec)	Hyporheic Res. Time, t_S (sec)	Hyporheic Res. Time, t_S (hr)	Rus Velocity (m/sec)
0+75	75	0.771	0.124	0.3180	2.56	0.0000306	83698	23.2	
1+50	75	0.835	0.135	0.5500	4.07	0.0000749	54415	15.1	
2+25	75	0.426	0.142	0.0001	0.00	0.0000001	14085	3.9	
2+90	75	0.719	0.161	0.8210	5.10	0.0001694	30111	8.4	
Mean	300	0.688	0.141	0.422	2.935	0.0000687	42700	11.9	0.040

Beebe Creek

Bbe Reach Ending at	Reach Length (m)	Bbe Disp. (m^2/sec)	Stream Area, A (m^2)	Bbe Stor. Area, A_s (m^2)	Storage Bbe Ratio (As/A)	Trans. Rate Bbe Alpha (/sec)	Hyporheic Res. Time, t_S (sec)	Hyporheic Res. Time, t_S (hr)	Bbe Velocity (m/sec)
0+75	75	0.7	0.180	1.1120	6.18	0.0001286	48039	13.3	
1+50	75	0.5	0.241	0.4318	1.79	0.0001097	16333	4.5	
2+25	75	0.5	0.292	0.9421	3.23	0.0001349	23917	6.6	
3+00	75	0.4	0.382	1.8142	4.75	0.0000522	90981	25.3	
Mean	300	0.525	0.274	1.075	3.986	0.0001064	37483	10.4	0.028

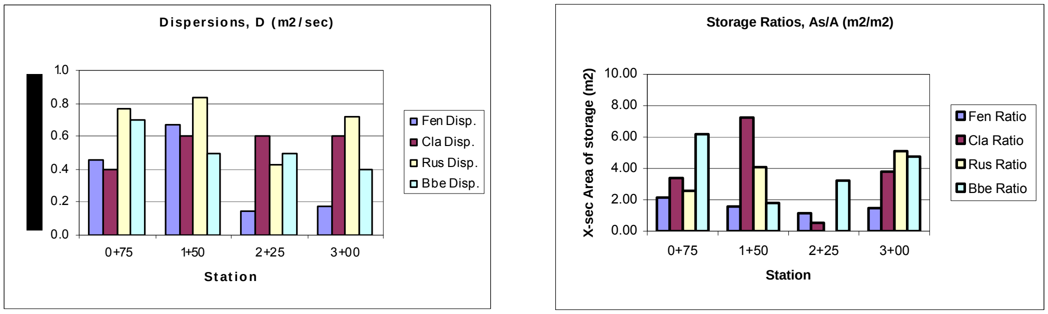

Figure 23. Estimated Storage and Dispersion Parameters

7. DISCUSSION

7.1 Statistical Analysis Results

Using statistical tools to detect change requires that the observed changes be distinguishable from background variation. The response variable used to detect change in this study of downstream effects is Maximum Daily Stream Temperatures (MDST) as described in Section 6.1. In this case, the observed effect on MDST between the pre-harvest and post-harvest years is small when compared to the spatial (between-stream) variation in MDST, and this effect decreased in the downstream direction (Figure 13). At 305 meters below the harvest boundary, the difference in MDST between years was not statistically significant different on two treatment streams, and showed only a moderate possibility of difference on the other two treatment streams (Figure 12).

This study will be instructive as it is compared with future analysis of the between-year variability of pre-harvest MDST downstream of these harvest units. For example, if future years show large variability in MDST on a particular stream, but little variability on another stream, a more complete picture of spatial and temporal variability may emerge. As data is collected in future years, the change during the first year following the harvest disturbance can be compared with variability between future years. Thus, year-to-year variability in future years will provide valuable context to characterize changes attributable to harvest.

Time-series analysis is another tool available to researchers which would give additional insight to this study [see (Gomi et al. 2006)]. A model using daily temperature data could account for temporal autocorrelation within the model, and would provide another valuable metric of change detection.

7.2 Mass Transfer and Transient Storage

The tracer dilution study results highlight the importance of understanding the downstream mass and energy process changes. First, three processes of mass water movement are explored: 1)Advection of hillslope water, 2)Dispersion/storage, and 3)Stream velocity.

It is noteworthy that, in addition to the transfers of heat into and out of the stream, the heat stored in the stream water is not fixed in time and space. One purpose of this study was to characterize the patterns of movement of the ‘mobile’ stream water, the ‘immobile’ water in pools and hyporheic zone, and the hillslope advective flows which are the primary source of summer stream water.

7.2.1Advection of Hillslope Water

Since Oregon Forest Practice Rules do not require conifer buffers on small non-fish-bearing streams, the first harvest in the Hinkle Creek Study was designed to characterize the impact this harvest at the lowest extent of these un-buffered portions of stream. In this study's location, 300-meter reaches below these clear-cut harvest units, all four of these perennial streams are typically gaining water from the hillslopes throughout the summer season. Though variable by both stream and year, all four of these 300m stream reaches gained hillslope flow during both (2005 and 2006) summer low-flow measurement periods. The steady-state dye studies used to quantify these hillslope flows were compared to other flow measurement techniques as described in Section 3.4. There are inherent limits to the steady-state dye injection methods used here, which are noteworthy. The assumption that dye has reached a steady state concentration between the flowing stream water and storage zones, is a simplification of reality, since hyporheic flowpaths longer than the period of injection (two to three days) are not reached by the dye. This limitation tends to overestimate the advection of hillslope water, particularly at the lower portion of the 300m study reaches where dye would have been present for a shorter period of time, and at lower concentrations. As noted above, dye is stored in both pools and hyporheic zones. Thus, the storage zone areas and transfer rates in this study represent an average of these two storage processes.

A future steady-state tracer study would benefit from making redundant measurements of stream flow, using a second tracer, or using another flow measurement technique to confirm the hillslope contribution of water. Though the precision of advected flow measurements can be refined, the methods used for this study represent an important spatial estimate of headwater stream flowrates.

7.2.2 Hillslope Groundwater Temperature

It is evident that the primary mechanism of stream cooling is mixing with advected hillslope and groundwater. Groundwater temperature varies spatially and temporally, and was not quantified for this study. In these headwater gaining reaches, a complete stream heat energy budget benefit from multiple measurements of groundwater temperature. (Mellina et al. 2002) averaged the temperatures of four groundwater seeps during the study period. (Story et al. 2003) assumed the advected groundwater temperature to be the soil temperatures observed below the water table (at 100cm depth) in the stream banks. (Moore et al. 2005) assumed groundwater temperature to be equal to the daily minimum temperature measured 10 meters upstream of the harvest unit edge. This study also notes that the *mean annual air temperature* is often used to approximate groundwater temperature.

One temperature probe (C07) in this control side (North Fork Hinkle Creek) of this study is located near an apparent groundwater seep. This probe has little diel temperature variation. The minimum nightly temperatures at this probe varied by year and by date. Figure 24 shows the temperature variation at this probe for the same 10-week summer period for years 2002 through 2006. If the minimum daily temperature at this probe is assumed as groundwater temperature for the study reaches, a value of 12-13°C could be used for the summer months. Year 2002 shows significant departures from the other years minimal temperature variations, possibly due to the probe being out of the water during these low-flow periods. Another anomaly occurred between 7/20/06 and 8/10/06, and no reason was apparent for this variation. Clearly the issue of the temporal variation in advected groundwater temperature merits further research.

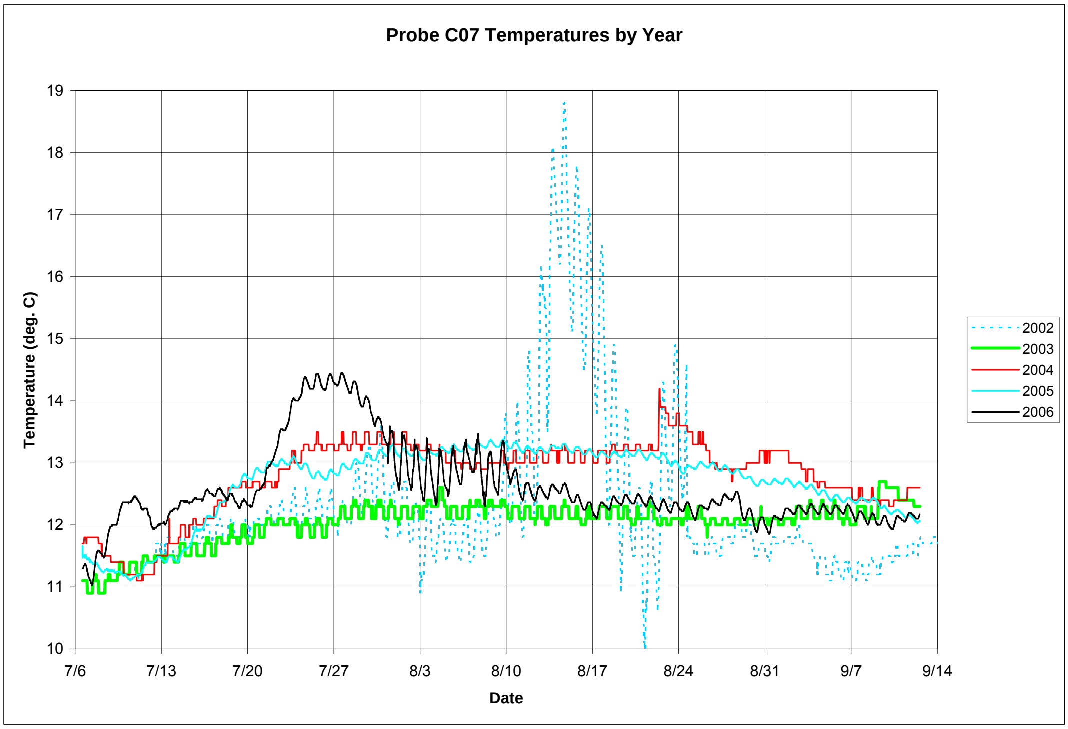

Figure 24. Probe C07, 2002-2006 Summer Temperatures

7.2.3 Diurnal variation in Hillslope Groundwater Flowrate

A visual examination of the dye concentration at the bottom of the study reach shows the transition toward steady-state concentration is shown for the 2006 Clay Creek test (see Figure 25).

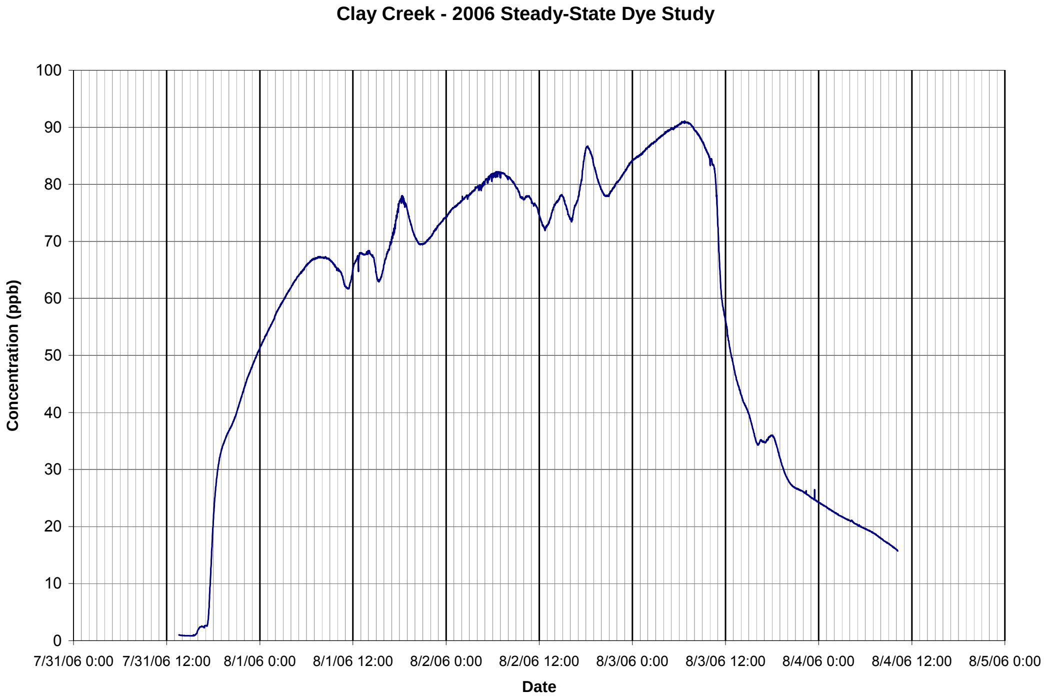

Figure 25. Dye Concentrations at Clay Creek, August 2006, Station 300

This reveals a variation in dye concentration pattern during each day of injection. Grab samples for calculation of steady-state flowrate were taken near the peak concentration on 8/03/06. The daily variation in measured dye concentration was also observed in the hourly ISCO samples. A test was done to determine if variation in *temperature* or *light* might be responsible for this pattern by taking hourly samples from a control solution of known concentration of dye exposed to similar light and temperature conditions, and analyzing the concentrations. No significant variation was found in the measured dye concentration of the control solution, so the current hypothesis remains that this daily variation represents changes to the flowrate of hillslope water. The diurnal variation in water flux from forest soil due to transpiration was examined in detail at the Wind River Canopy Crane Research Facility (WRCCRF) at Wind River, WA (Unsworth et al. 2004). If the observed variations of dye concentration in this study do, in fact, represent changes in the delivery of water from the hillslope, the lowest rate of flow in this case occurred near 8:00 am each day, and the highest daily flow occurred near noon. While this seems counter to the presumption that the maximum demand on hillslope water by vegetation is during the mid-day transpiration period, the time-lag may represent travel time between hillslope and the stream riparian edge, or the vertical redistribution of soil moisture by plant roots. The Unsworth paper also explores the seasonal variation in water flux from the soil. Further investigation of this phenomenon could provide insight into both diurnal and seasonal mechanisms of hillslope flow.

7.2.4 Storage/Dispersion

These headwater streams provide significant storage in pools and hyporheic zones. Storage varied between the 75m study reaches from almost none to over seven times the cross-sectional area of the active stream channel. Studies have shown that water stored on pools varies thermally from the active channel (Bilby 1984; Beschta et al. 1987). While there has been ongoing discussion regarding the importance of these storage zones, some researchers have noted that pool storage (Gooseff et al. 2005) and hyporheic exchange (Story et al. 2003) may be significant contributors to downstream cooling within shaded stream reaches. Particularly where residence times are short (hours), such as in pools or rapidly down-welling pool-step sequences, the physical mixing process with stored water provides a mechanism to decrease maximum daily stream temperatures as water moves downstream.

In addition, a longitudinal dispersion of stream water results from the range of stream velocities across the stream cross-section. Thus, as water that is heated by solar exposure (such as in a clear-cut) moves into a shaded reach, the ‘pulse’ of heated water is dispersed along the length of the shaded reach. This mixing with water within the active channel would tend to lower daily maximum temperatures, since the shaded reaches of these streams are receiving hillslope groundwater which is typically cooler than water entering from upstream during the peak mid-day heating times.

7.2.5 Stream Velocity and Mean Hyporheic Storage Time

Modeled mean stream velocities for the four study reaches varied between 0.024 and 0.040 m/sec. Thus, the average transit time for the 300m reaches ranged from 7,500 sec (2.1 hrs) to 12,500 sec (3.5 hrs). This was most readily evident from the rising limb of the breakthrough curves of the dye study (see Figures 19-22). For the active channel flow in these streams to complete a 24-hour diurnal temperature cycle in the shaded reach, at these mean velocities, would require 2.1 to 3.5 km. The mean transit times can be compared with the mean hyporheic residence time, t_S, which is defined as:

Equation 13. $$t_S = \frac{A_S}{A \cdot \alpha}$$

where As is the average cross-sectional area of the immobile (storage) zone (m^2), A is the average cross-sectional area of the stream (m^2), and α is the transfer rate between them (sec^{-1}).

For the 75 meter modeled reaches, t_s varies from 2.3 hrs to 31.5 hrs. (see Figure 23). Thus, the mean storage time is significantly longer than the mean time of travel within the active stream channel. This illustrates that transient storage cannot be ignored when considering the fate of heated stream water in these headwater streams. Also, researchers must consider the scale of individual stream geomorphic features when studying stream energy. For example, the energy budget for the 75 meter reach in this study having $t_S < 3$ hours differs from the 75 meter reach where $t_S > 30$ hours.

7.3 Energy Budget Factors Which May Cool Stream Water

Though this study does not include a complete heat energy budget for the four 300-meter study reaches, an illustration of stream energy at a point is instructive in demonstrating processes which may cool stream water in shaded reaches. Characterizing stream energy in time and space has been attempted by researchers. One recent study (Moore et al. 2005) attempts to close the stream heat budget for a 225 meter stream reach during a period of high stream temperature (August 13, 2001). Considering the spatial and temporal heterogeneity of headwater stream thermal regimes and the continuous transfer of heat between the stream and its environment, it is not surprising that the authors note “there were significant errors in closing the heat budget”. To illustrate the temporal dynamics and magnitudes of the primary heat budget parameters, values of Latent heat, Sensible heat, Longwave Radiant heat and shortwave Photosynthetically Active Radiation (PAR) were calculated for the 10-day period from August 7-17, 2006 at Russell Creek Station 150 (see Figure 26).

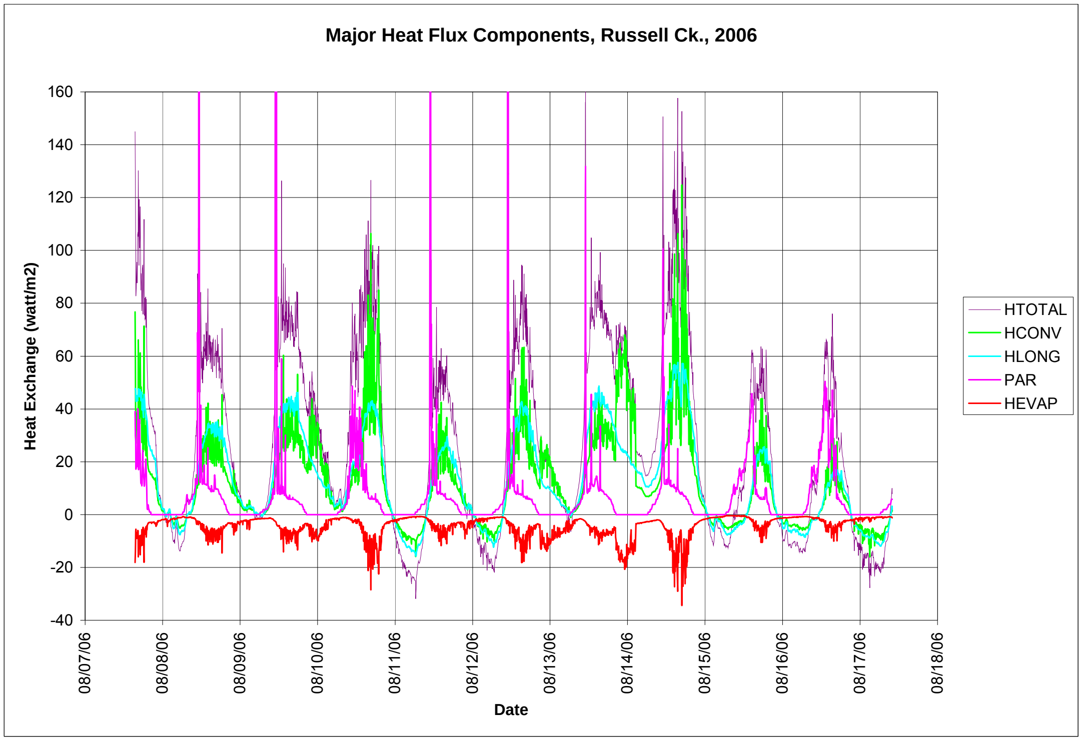

Figure 26. Heat Budget Parameters at Russell Creek, August 2006, Station 150

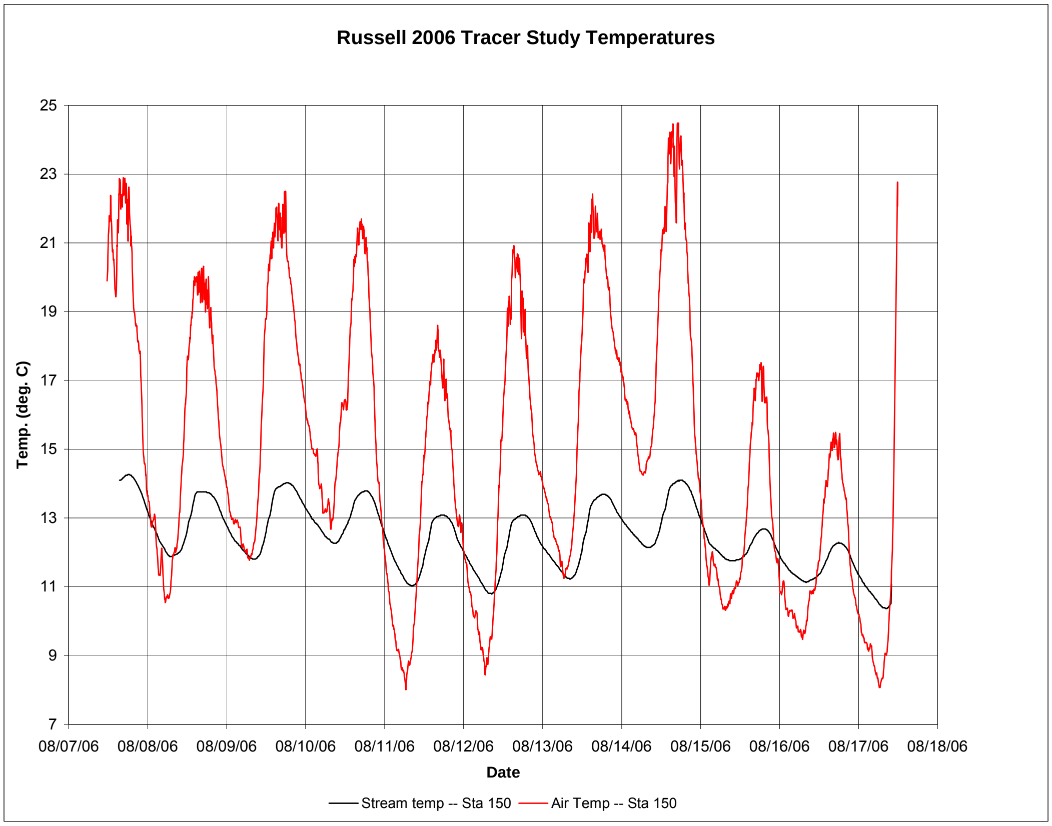

Figure 27. Stream and Air Temperatures, Russell Creek, Station 150

7.3.1 Longwave Radiation

During the four nights of August 10-12, and 15-17 longwave radiant cooling occurs, since air temperatures dropped below stream temperatures (see Figure 27). This illustrates the typical period of radiant cooling and its magnitude with respect to daily heating from warm air and overstory vegetation. Interestingly, this component of the heat budget is significant in this case, providing the primary source of heat loss from the stream during these four nights.

7.3.2 Latent and Sensible Heat Exchange

Figure 26 shows that heat losses from the stream due to latent (evaporative) heat are typically during the warmest time of the day, and are more than offset by convective (sensible) heat into the stream. As air above the stream warms, it can hold more moisture, which evaporates from the stream surface. One noteworthy exception is on the nights of August 12-14. These nights experienced some wind (~1-4 m/sec) and relatively low relative humidity (~50-60%). However, these conditions occurred at times of relatively warm overnight minimum temperatures, so the evaporative cooling was not enough to overcome other positive heat inputs to the stream. This does illustrate, however, the potential importance of wind speed in promoting evaporative cooling. As shown here, air temperature must be below stream temperature for a net cooling from the sum of latent and sensible heat exchanges. Further study of up- and down-valley winds in these forested areas would be instructive in characterizing the importance of this heat budget parameter.

7.4 Heated Stream Water Entering a Shaded Study Reach

To illustrate the spatial dynamics of maximum daily stream temperature below a clearcut harvest unit, consider the 10-minute stream temperature data from Russell Creek dye study on August 13, 2006, between noon and 3:00 pm, from station 10 meters (just below the harvest boundary) to station 150 meters (Figure 28). At noon, all points within the 150m reach are between approximately 12.1 and 12.4 °C. By 2:40 pm, warmer stream water entering the study reach has created a temperature difference of greater than 1.2°C between station 30 and station 150. By 3:00 pm, the highest stream temperatures begin to decrease, as the downstream temperatures continue to increase. This wave of heat energy which arrives during the peak stream heating period has begun to exchange energy with the shaded stream environment. This process includes the mass and energy exchanges discussed above. If we assume that the peak stream temperature moves from station 10m to station 80m in this 3-hour period, the velocity of temperature propagation in this case is 0.0065 m/sec., slower than the modeled mean stream velocity of 0.04 m/sec. by approximately a factor of 6.

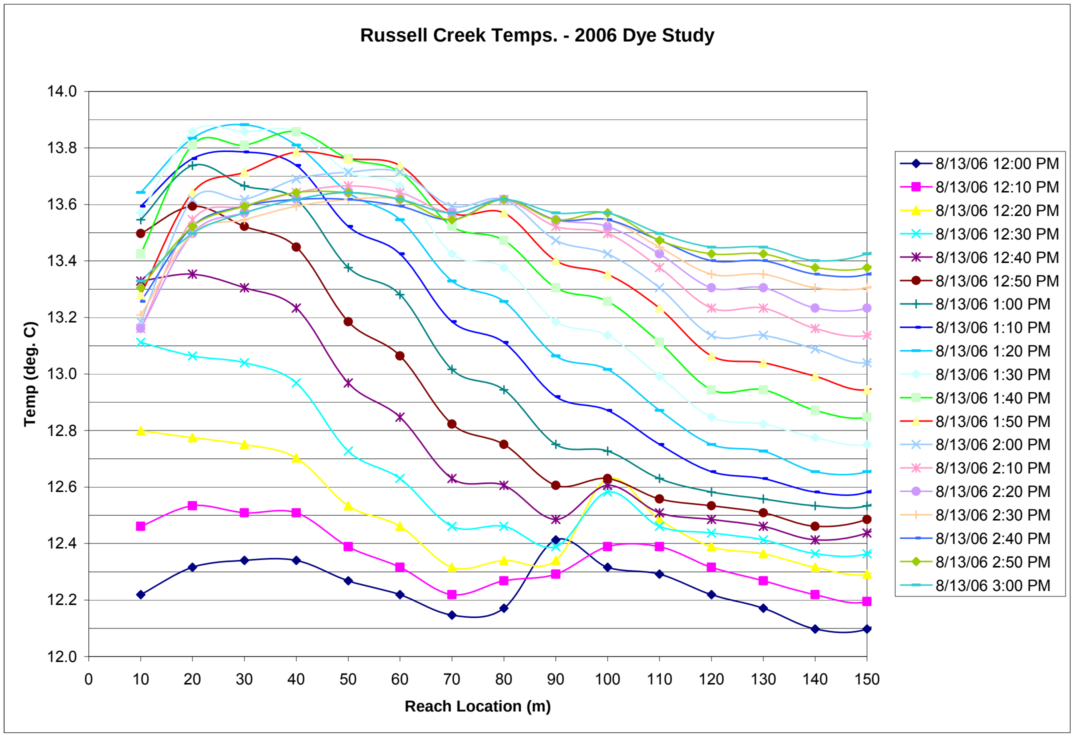

Figure 28. Russell Creek Temperatures by Stream Station and Time

7.5 Temperature Effect of Hillslope Advection Alone

Since the addition of cool water from hillslope groundwater tends to cool streams during the time when stream temperatures are greatest, a calculation was done to predict this effect, assuming no other heat transfer processes were occurring. This prediction of temperatures was then compared with actual stream temperatures. Figure 29 illustrates data from highest two hours of stream temperature during each of the 2006 dye studies on the four treatment streams. Groundwater temperature was assumed to be 12°C. Predicted temperatures at Station 0+00, the top of each reach, was set to the actual highest temperature, and was held constant during the two-hour period. Downstream temperature predictions are based only on two-part mixing with advected. Fenton and Clay creeks had a pattern of cooling in the downstream direction during these periods, which is consistent in scale and direction with the groundwater mixing prediction. Russell Creek had little actual temperature difference along the reach, and the moderate addition of groundwater in this reach is not a good predictor of actual temperatures. Beebe Creek warmed in the downstream direction, counter to the prediction of cooling by groundwater.

While the addition of cool groundwater is clearly an important component of the heat budget in these shaded headwater streams, other energy exchanges cannot be ignored in characterizing their thermal regimes.

Comparison of Actual stream temperatures with a prediction of stream temperatures based on mean inflow temperature during the highest two hours of daily stream temperature during the 2006 dye test
Two part mixing model*

$$* T_m = \frac{D_t T_t + D_s T_s}{D_t + D_s}$$

Tm = temp. of mixture
Dt = Discharge of tributary or groundwater
Tt = Temp. of tributary or groundwater (assumed 12° C)
Ds = Discharge of the stream at upstream end of reach
Ts = Temperature of stream at upstream end of reach

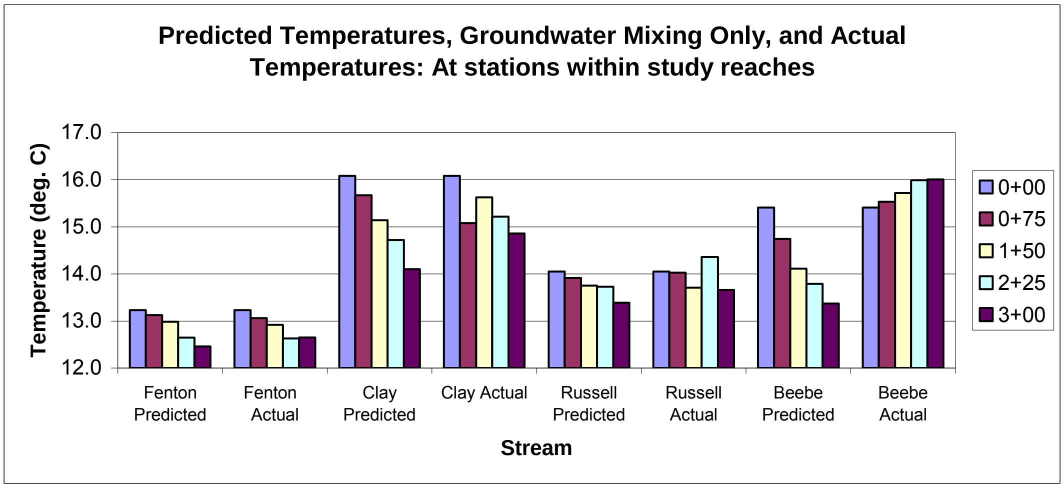

Figure 29. Predicted and Actual Stream Temperatures, 2006 Dye Study

7.6 Future Research Needs

Any consideration of stream energy is necessarily limited by the selection of energy exchange measurements taken. A thorough understanding of these stream energy processes within an intact forest requires that both spatial and temporal scope be carefully planned. If year-to-year variability is of interest, researchers must determine what period of years is necessary to characterize this variability. This primarily relates to variation in the 'above stream' climate. Similarly, if stream-to-stream or broader geographic variability is of interest, a study design must consider the range of variability which needs to be included. This is primarily an issue of 'below stream' structure and geology. Both of these approaches face the challenge of requiring a significant financial investment.

7.6.1Energy Budget Studies

However, a study of limited geographic scope and time would be useful as a starting point for characterizing the stream energy budget within a forested stream. In clearcut harvest areas, the stream heat budget is dominated by radiant heating and cooling (Brown 1969(2)). Within a closed-canopy forest (such as this study), however, radiant heating and cooling are attenuated, and many of the heat exchange dynamic processes may be of similar magnitude. Any such study should attempt to measure as many of the energy budget parameters as possible, and know the range of error associated with those which are assumed or approximated. In an environment similar to Hinkle Creek, it may be beneficial to extend the spatial scope to greater than 300 meters to capture additional variability and further characterize downstream effects. In addition, given the uncertainties of climate, it may be prudent to take measurements for longer than one week. Finally, redundancy in measurement, where possible, provides a check on instrument accuracy, as well as ensures data continuity in the event of equipment failure.

One research question of interest is: When heated stream water exchanges energy in a downstream forested reach, how much energy is exported to the above-stream atmosphere by the diel thermal cycle, and how much is stored in the streambed to be reset by the annual thermal cycle?

7.6.2 Buffered Stream Characteristics

Since stream buffers are the primary source of shade in fish-bearing streams in Oregon, an understanding of their energy dynamics would be instructive to both those who administer current forest practice rules and those who write new ones. The question of how buffered streams differ from intact forest has been explored, but a before-after energy budget comparison of forest streams would certainly add to current knowledge.

7.7 Management Implications

Oregon currently manages forests under a set of rules which have evolved since their creation in the 1971. As scientific understanding has increased, the rules have changed in response to those findings. The stated goal of the Forest Practice Rules is as follows:

“. . .encourage economically efficient forest management in Oregon and the continuous growing and harvesting of trees and maintenance of forestland for such purposes as the leading use on privately owned land, consistent with sound management of soil, air, water, fish and wildlife resources . . . and to ensure the continuous benefit of those resources for future generations of Oregonians” ORS 527.620.

Toward these goals, the following paragraphs suggest two themes which may be of interest in discussions regarding forest headwater stream management.

7.7.1 Stream Thermal Classification

This study demonstrates the difficulty of regulating across a varied geography. These four adjacent streams of similar size, geology, and climate had a range of thermal environments downstream from clear-cut harvest units. One approach to minimizing downstream thermal impacts could be to create a thermal classification system for forest streams. “Sensitive” streams could have buffers increased from current rules, based on buffer-width research findings. “Average” streams could maintain existing buffers, and “Insensitive” streams could have reduced buffers, based on their insensitivity to stream heating. This system would have the benefit of decreasing downstream thermal impact, while maintaining current harvest potential. Since stream buffers provide other ecological and physical benefits to streams, a carefully drafted plan would be required.

7.7.2 Stream Structure and Storage Volume

Many of the recent stream temperature studies emphasize the significance of both step-pool and hyporheic zone storage in moderating peak stream temperatures, and providing thermal refuge areas for fish. One of the goals of forest management, therefore, should be to both maintain these existing stream structures and to improve streams which lack them. These structures allow decreases in stream velocity, and mixing with stored water. This research suggests that these structures may be keys to enhancing the stream’s processes where water heated from upstream clear-cut areas to returns to the thermal equilibrium of the downstream environment.

8. CONCLUSIONS

Based on this study, and a review of the literature, downstream temperature responses to timber harvest in western Oregon is variable between streams. The processes by which heat is transferred between the stream and its environment within these shaded reaches must be considered relative to the diel fluctuation of these transfer mechanisms. Heat losses from the stream to the atmosphere can be significant contributors to the overall stream heat budget. In particular, evaporative cooling during the day, and longwave radiant cooling at night are important.

Streams where the air temperature at night drops below the stream temperature have potential to lose heat to the atmosphere from longwave cooling. If the air is both cooler than the stream and moving, the stream has potential to lose heat by evaporative cooling. Thus, climatic periods during the summer heating season when stream cooling occurs, such as cloud and/or windy days, are important in understanding the mechanisms of downstream cooling.

Water stored within a shaded stream reach, both in pools and in hyporheic zones, can provide a mixing volume through which the active stream channel can exchange stream water, providing both physical mixing with cooler water, and an effective heat transfer to the stream bed. In these study streams, the storage volumes varied from almost none to about seven times the stream active channel volume among the 75-meter reaches. This mixing with stored water, as well as the heat transfer to the streambed tends to dampen temperatures on the daily cycle, lowering maximum temperatures and raising minimum temperatures. In addition, if heat is stored in the stream bed and hyporheic zones during the summer months, this stored heat is then reset over the winter season to provide a heat sink for the next summer season. Thus the annual cycle of heat transfer can be important in closing the heat budget in these streams.

9. LITERATURE CITED

Adams, T. N., K. Sullivan, et al. (1989). The Physics of Forest Stream Heating: A Simple Model, Timber, Fish & Wildlife.

Bartholow, J. M. (2002). "Estimating cumulative effects of clearcutting on stream temperatures." Rivers **7**(4): 284-297.

Bencala, K. E. and R. A. Walters (1983). "Simulation of solute transport in a mountain pool-and-riffle stream: A transient storage model." **19**(3): 718-724.

Beschta, R. L., R. E. Bilby, et al. (1987). Stream temperature and aquatic habitat: forestry and fishery interactions. Streamside management : forestry and fishery interactions / edited by Ernest O. Salo, Terrance, W. Cundy, Seattle, Wash. : College of Forest Resources, University of Washington, 1987**:** 191-232.

Beschta, R. L. and R. L. Taylor (1988). "Stream temperature increases and land use in a forested Oregon watershed." Water resources bulletin **24**(1): 19-25.

Bilby, R. E. (1984). "Characteristics and frequency of cool-water areas in a western Washington stream." Journal of Freshwater Ecology **2**(6): 593-602.

Bowen, I. S. (1926). "The ratio of heat losses by conduction and by evaporation from any water surface." Physical review **27**: 779-787.

Boyd, M. S. (1996). Heat Source: stream temperature prediction. Civil and Bioresource Engineering. Corvallis, OR, Master's Thesis. Departments of Civil and Bioresource Engineering, Oregon State University, Corvallis, Oregon. **MS**.

Boyd, M. S., Casper, B. (2004). "HeatSource 7.0." from http://www.heatsource.info.

Brett, J. R. (1956). "Some principles in the thermal requirements of fishes." The Quarterly Review of Biology **31**(2): 75-87.

Brown, G. W. (1969). "Predicting the effect of clearcutting on stream temperature." JOURNAL OF SOIL AND WATER CONSERVATION **25**(1): 11-13.

Brown, G. W. (1969(2)). "Predicting temperatures of small streams." Water Resources Research **5**(1): 68-75.

Brown, G. W. (1985). Forestry and Water Quality. Corvallis, Oregon, Oregon State University Press.

Brown, G. W. and J. T. Krygier (1970). Effects of clear-cutting on stream temperature. Water Resources Res**:** 1133-1139.

Donaldson, J. R. and P. V. Tryon (1990). User's guide to STARPAC—The standards, time series, and

regression package., National Institute of Standards and Technology.

Gauger, H. and A. Skaugset (2004). Cooling downstream of a harvest operation in Oregon Cascades. Riparian Ecosystems and Buffers: Multi-scale Structure, Function, and Management; AWRA Summer Specialty Conference. Olympic Valley, California.

George, R. L. (2006). Baseline stream chemistry and soil resources for the Hinkle Creek research and demonstration area project. Forest Engineering. Corvallis, OR, Oregon State University. **Master of Science**.

Gomi, T., R. D. Moore, et al. (2006). "Headwater stream temperature response to clear-cut harvesting with different riparian treatments, coastal British Columbia, Canada." Water Resources Research **42**(8).

Gooseff, M. N., J. Lanier, et al. (2005). "Determining in-channel (dead-zone) transient storage by comparing solute transport in a bedrock channel-alluvial channel sequence, Oregon." Water Resources Research **41**(W06014): doi:10.1029/2004WR003513.

Gooseff, M. N., S. M. Wondzell, et al. (2003). "Comparing transient storage modeling and residence time distribution (RTD) analysis and geomorphically varied reaches in the Lookout Creek basin, Oregon, USA." Advances in Water Resources **26**: 925-937.

Haggerty, R., S. M. Wondzell, et al. (2002). "Power-law residence time distribution in the hyporheic zone of a 2nd-order mountain stream." GEOPHYSICAL RESEARCH LETTERS **29**(13): 1640.

Hondzo, M. and H. G. Stefan (1994). "Riverbed heat conduction prediction." Water Resources Research **30**(5): 1503-1514.

Johnson, S. L. (2004). "Factors influencing stream temperatures in small streams: substrate effects and a shading experiment." Canadian Journal of Fisheries and Aquatic Sciences **61**(6): 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**(supplement 2): 30-39.

Kasahara, T. and S. M. Wondzell (2003). "Geomorphic controls on hyporheic exchange flow in mountain streams." WATER RESOURCES RESEARCH **39**(1): 1005.

Kibler, K. (2007). Changes in stream temperature and canopy cover following timber harvesting adjacent to non-fish bearing headwater streams. Forest Engineering. Corvallis, Oregon, Oregon State University. **M.S.**

Levno, A., J. Rothacher, et al. (1967). Increases in maximum stream temperatures after logging in old-growth Douglas-fir watersheds. Portland, Or., Pacific Northwest Forest and Range Experiment Station.

McDonnell, J. J. (1990). "A Rationale for Old Water Discharge Through Macropores in a Steep, Humid Catchment." Water Resources Research **26**(11): 2821-2832.

Mellina, E., R. D. Moore, et al. (2002). "Stream temperature responses to clearcut logging in British Columbia: the moderating influences of groundwater and headwater lakes." Canadian Journal of Fisheries and Aquatic Sciences **59**: 1886-1900.

Moore, R. D., A. Story, et al. (2005). "Riparian microclimate and stream temperature response to forest harvesting: a review." Journal of the American Water Resources Association **41**: 813-834.

Moore, R. D., P. Sutherland, et al. (2005). "Thermal regime of a headwater stream within a clear-cut, coastal British Columbia, Canada." Hydrological Processes **19**: 2591-2608.

Nadeau, T. and M. C. Rains (2007). "Hydrological connectivity between headwater streams and downstream waters: How science can inform policy." Journal of the American Water Resources Association **43**(1): 118-133.

Norris, L., J. Buckhouse, et al. (2000). Influences of human activity on stream temperatures and existence of cold-water fish in streams with elevated temperature: Report of a workshop. IMST. Corvallis, Oregon, Oregon State University.

Poole, G. C. and C. H. Berman (2001). "An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation." Environmental management **27**(6): 787-802.

Rantz, S. (1982). Measurement and Computation of Streamflow: Volume 1. Measurement of Stage and Discharge USGS**:** 284.

Runkle, R. L. (1998). One-dimensional Transport with Inflow and Storage (OTIS): A Solute Transport Model for Streams and Rivers. Water-Resources Investigations Report 98–4018. Denver, CO, United States Geological Survey (USGS).

Runkle, R. L. and R. E. Broshears (1991). One-dimensional Transport with Inflow and Storage (OTIS): A Solute Transport Model for Small Streams. CADSWES Technical Report 91-01. Boulder, CO, University of Colorado**:** 85.

Sinokrot, B. A. and H. G. Stefan (1993). "Stream temperature dynamics: measurements and modeling." Water Resources Research **29**(7): 2299-2312.

Skaugset, A., Li J., Kromack, K., Gresswell, R., Adams, M. (2005). Cumulative Environmental Effects of Contemporary Forest Management Activities in Headwater Basins of Western

Oregon: The Hinkle Creek Paired Watershed Study. Corvallis, OR, Oregon State University.

Story, A., R. D. Moore, et al. (2003). "Stream temperatures in two shaded reaches below cutblocks and logging roads: downstream cooling linked to subsurface hydrology." Canadian Journal of Forest Research **33**(8): 1383-1396.

Unsworth, M. H., N. Phillips, et al. (2004). "Components and controls of water flux in an old-growth Douglas-fir--Western Hemlock ecosystem." Ecosystems **7**: 468-481.

Webb, B. W. and Y. Zhang (1999). "Water temperatures and heat budgets in Dorset chalk water courses." Hydrological Processes **13**(3): 309-321.

Wells, R. E., Jayko, A.S., Niem, A.R., Black, G., Wiley, T., Baldwin, E., Molenaar, K.M., Wheeler, K.L., DuRoss, C.B., and Givler, R.W. (2000). Geologic map and database of the Roseburg 30 x 60 minute quadrangle, Douglas and Coos Counties, Oregon. M. P. U.S. Geological Survey, CA.

Zwieniecki, M. A. 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**(2): 106-113.