

**Stream Temperature Response to Partial Canopy Removal in First and  
Second Order Streams in the Central Oregon Cascades**

by

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## **Stream Temperature Response to Partial Canopy Removal in First and Second Order Streams in the Central Oregon Cascades**

### **Abstract**

Stream temperature response of first and second order streams to the Blue River Landscape Study (BRLS), an alternative land management strategy based on historic fire regimes, was analyzed in the central Oregon Cascades. The BRLS treatment prescription of a 50% canopy reduction and low intensity burn was applied with a 15 to 20 meter stream buffer in one watershed and with no buffer in an adjacent watershed. August minimum and maximum daily stream temperatures in the buffered watershed increased by 1.0°C during the first year after canopy removal before returning to pre-treatment levels during the second year after canopy removal and the first year after the watershed burn. Stream temperatures in the unbuffered watershed remained within the pre-treatment ranges after the BLRS treatments were applied. The relatively small percentage of canopy removal combined with phreatic and hyporehic groundwater inputs to the stream and significant topographic shading contributed to the minimal stream temperature response to the treatments. The buffered watershed showed a slightly higher response to the treatments than the unbuffered watershed. This greater response to the treatments is attributed to a lesser degree of topographic shading in the buffered watershed when compared to the unbuffered watershed, which resulted in a comparatively higher increase in solar radiation received by the stream that was not completely offset by the relatively narrow riparian buffer.

## **Blue River Landscape Study**

The Blue River Landscape Study (BRLS) is located in the central western Cascades within the Blue River watershed, which is the key basin in the Central Cascades Adaptive Management Area. The Adaptive Management Area was created by the Northwest Forest Plan for the purpose of investigating new approaches to land management that would better integrate ecological and social objectives (Cissel 1997). Specifically, the Central Cascades Adaptive Management Area aims to explore land management strategies based on natural disturbance regimes. By managing forest structure in a manner similar to conditions created by historical natural disturbances, it is hoped that the area will maintain habitats consistent with the environments to which native species have adapted. The goal is to meet or exceed the Northwest Forest Plan's standards for sustaining native biodiversity and habitats while still providing a consistent source of wood products (Cissel 1997).

The Blue River Landscape Study utilizes forest management practices to approximate the native habitats and ecological processes created by historical fire regimes of the area. Species in the region have adapted to the habitats and nutrient cycles created by disturbance and successional patterns associated with wild fires, and it is feared that managing the lands outside the range of past environments will lead to a general decline ecological health and sustainability (Swanson et al 1993).

Fire history in the Blue River watershed has been analyzed in three different studies (Teensma 1987, Morrison and Swanson 1990, Weisberg 1998). Weisberg calculated fire frequency and developed a linear regression model to predict fire frequency based on

environmental variables (Weisberg 1998). Mean fire return interval (MFRI) was then used to estimate the historical frequency of stand and partial stand-replacing fires.

Fire severity is inversely proportional to fire frequency, but precise quantification of the relationship has proven difficult (Morrison and Swanson 1990, Weisberg 1998, Cissel 2000). The Blue River Landscape Study represents the variability in fire severity with three levels of overstory canopy retention: low frequency/high severity (85% overstory canopy removal), moderate frequency/moderate severity (70% overstory removal), and high frequency/low severity (50% overstory removal). Information on the frequency and intensity of burns on lower slopes and in riparian zones is limited, but it is estimated that these areas experienced fires of lower intensities than other portions of the landscape (Cissel 2000). For purposes of the BRLS, three sub-basins (landscape areas) within the Blue River watershed, the North Fork Quartz Creek Timber Sale, the Blue River Face Timber Sale, and the Wolf-Mann Timber Sale, were assigned timber harvest and fire prescriptions based on one of the three fire regimes used in the management plan.

The North Fork Quartz Creek sub-basin was assigned a vegetation management plan that approximates a high frequency/low severity fire regime and includes 50% overstory removal followed by a low intensity surface burn set on a 100 year harvest rotation (BLRS 1997, Cissel et al. 1999). Within the sub-basin, the treatment was split among three smaller sub-basins, which include a control area (no treatment), a treated area with 15 to 20 meter stream buffers, and a treated area with no stream buffer. The timber harvest was completed early in 2000 and the burn was completed early in 2001.

While the BLRS aims to replicate the effects of forest fire, an exact replication is impossible. Natural forest fires produce alterations in nutrient cycles, soil physics, and habitat structure that

can only be partially approximated by tree harvest. Prescriptions will vary from historical fires in several ways, including frequency, intensity, spatial extent, patch dynamics, snag retention, and soil alteration. The need to ensure profitable harvest of forest products also fundamentally alters the accuracy with which any plan can mimic natural disturbances.

Although the long-term effects of landscape disturbances can prove very beneficial for ecological health, habitat alteration can have negative short-term impacts at local scales. One of the possible detrimental effects of canopy removal is an increase in stream temperature resulting from an increase in the amount and intensity of solar radiation received by streams in the treatment area. As such, the USDA Forest Service is interested in determining effects of the BRLS on stream temperature. The remainder of this paper investigates the effect of the prescribed timber harvest and burn applications in the North Fork Quartz Creek Timber Sale on the temperatures of small streams located in the treatment area.

### **Stream Temperature Overview**

Stream temperature is vital to maintaining the proper functioning of stream ecosystems and controls a wide variety of chemical and biological processes. Highly elevated stream temperatures can degrade viable freshwater habitats, making life difficult for many of the species that occupy them. The importance of stream temperature has made it one of the water quality parameters of utmost concern for stream management in the Pacific Northwest. The McKenzie River watershed in the central Oregon Cascades has nine stream segments listed under section 303(d) of the Clean Water Act whose water quality is limited by stream temperature, including one in the Blue River basin.

Stream temperature is determined by a heat balance created by the interaction of several hydrological, meteorological, and biological factors. These factors include external drivers that influence water and heat delivery to the system, as well as internal hydrological characteristics that determine how the heat is distributed within the stream ecosystem (Poole and Berman 2001). External drivers include solar radiation, solar angle, air temperature, wind speed, cloud cover, precipitation, upland vegetation, topographic shade, and groundwater inputs. Internal hydrological characteristics include flow rates, channel dimensions, channel geomorphology, and aquifer characteristics (Brown 1969, Poole and Berman 2001).

Direct solar radiation is the principal heat source for streams (Brown 1969, Brown and Krygier 1970, Sinokrot and Stefan 1993, Johnson and Jones 2000). Temporal fluctuations in stream temperature are related to temporal variations in solar radiation. In the Northern Hemisphere, stream temperatures reach their maximum in August, shortly after solar radiation is maximized in June by the combination of high sun angles and long days. Stream temperatures are at a minimum in the winter when solar radiation is decreased by low sun angles and short days (Rishel et al. 1982).

The amount of solar radiation received by streams is influenced by stream azimuth, cloud cover, upland vegetation, riparian vegetation, and topographic shade. In forested first and second order streams, riparian vegetation creates the greatest barrier for solar radiation, reducing the short-wave radiation streams receive by approximately 70% (Lynch et al. 1984, Sinokrot and Stefan 1993, Poole and Berman 2001). The removal of riparian vegetation by timber harvest practices has resulted in significant increases in stream temperature; however, the magnitude of the temperature increase varies by site and harvest practice.

A large volume of research has documented stream temperature increases resulting from the clearcutting of forested watersheds. Research in Oregon, West Virginia, and Pennsylvania has shown that post-harvest summer maxima increased by 4.4 to 12°C (Brown and Krygier 1970, Rishel et al. 1982, Lynch et al. 1984, Johnson and Jones 2000) and minimum stream temperatures were shown to increase by 1-2 °C after 100% timber removal (Brown and Krygier 1970, Lee and Samuel 1976, Rishel et al. 1982). Diurnal temperature ranges increased significantly after complete timber removal (Lee and Samuel 1976, Rishel et al. 1982, Lynch et al. 1984, Sinokrot and Stefan 1993, Johnson and Jones 2000).

While there has been a great deal of investigation into the effects of clearcutting on stream temperature, relatively few researchers have investigated temperature response to partial harvesting. Partial harvest (7-33%) of two watersheds on the Olympic Peninsula in Washington resulted in a 3.5 °C increase in summer maxima 11-15 years after treatment (Murray et al. 2000). Harvest treatments that leave overstory vegetation buffers adjacent to streams have been shown to have no significant impact on stream temperature (Lee and Samuel 1976, Rishel et al. 1982, Lynch et al. 1984, Sugimoto et al. 1997).

While solar radiation is the dominant external influence on stream temperature, hydrological and geomorphic characteristics influence the internal processes that determine heat flux throughout the stream ecosystem. Temperature response to heat loading is greatly affected by stream size. Some research has deemed that stream temperature response to heat influxes is directly proportional to stream surface area and inversely proportional to stream discharge (Brown 1969). As streams increase in order downstream from their source, the increase in discharge and stream area alters their response to solar radiation, resulting in a different heat budget than that of their first and second order origins (Poole and Berman 2001).

Groundwater also contributes to the thermal characteristics of stream ecosystems, driving temperature inputs to the system and buffering stream response to heat loading. Phreatic groundwater, i.e. water gathered in the catchment watershed, determines the baseline stream temperature and can be a dominant influence on the temperature of first and second order streams (Poole and Berman 2001). As the system flows downstream from its source, stream temperature deviates from the baseline temperature towards atmospheric temperatures; however, this trend can be strongly altered by heat drivers and/or buffers at local scales (Constanz 1998, Sullivan et al. 1990). Phreatic inputs downstream from the source buffer stream temperatures, reducing diurnal variation and decreasing elevated stream temperatures (Smith and Lavis 1974, Sinkrot and Stefan 1993, Hawkins et al. 1997, Constanz 1998, Poole and Berman 2001).

Hyporheic groundwater, i.e. water that enters the alluvial aquifer from the stream channel and then returns to the stream channel, also exerts considerable control over stream temperature. As water enters the hyporheic zone, heat is transferred from the stream channel to the alluvial substrate (Smith and Lavis 1974, Sinkrot and Stefan 1993, Hawkins et al 1997, Constanz 1998). The re-emergence of the cooled groundwater provides an important temperature buffering mechanism for shallow streams, reducing diurnal variations in water-gaining reaches (Constanz 1998, Poole and Berman 2001).

The geomorphic structure of the stream exerts considerable control over hyporheic flow and temperature fluxes within the system. As stream channel complexity increases, rates of hyporheic exchange are also amplified (White et al.1987, Henry et al. 1994, Evans et al. 1995, Morrice et al. 1997). Pool/riffle sequences in the stream channel strongly influence hyporheic exchange between the alluvial aquifer and the stream channel at local scales. Water enters the alluvial aquifer on the downstream end of pools, travels through the riffle substrate, transferring

heat to the streambed material, then re-emerges in the channel at the termination of the riffle (White et al. 1987, Morrice et al. 1997).

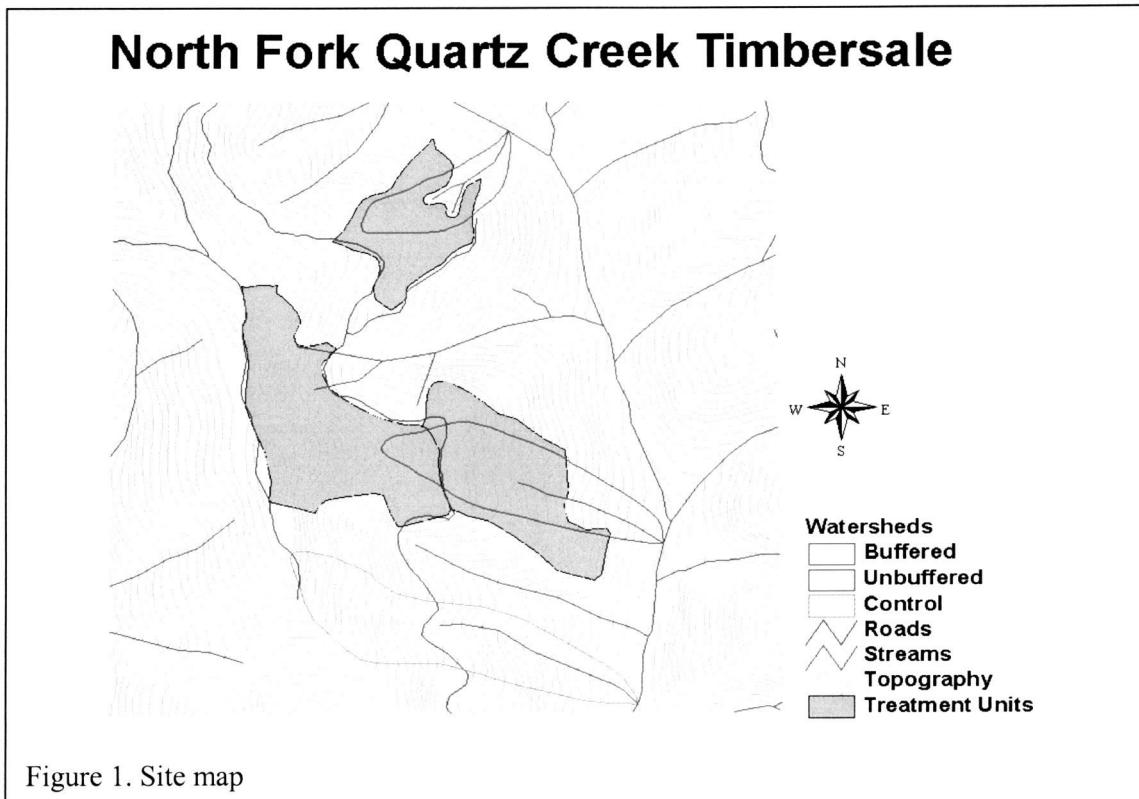
Channel bed materials also influence the stream heat balance and affect hyporheic flow. Water movement through the bed material is largely determined by the pore size of the substrate (Hillel 2000, Morrice 1997). As pore sizes decrease, hyporheic flow is restricted, reducing the buffering capacity of alluvial aquifer. Stream channel material can also act as a heat source. The presence of bedrock and large alluvial rocks store heat received from solar radiation and then slowly transfer it to the stream channel, creating lagged increases in water temperatures (Henry et al. 1994, Morrice et al. 1997).

Alteration of watershed substrate by land management can alter soil characteristics, changing hydrologic pathways within the system. Soil structure alteration by timber harvest and watershed burning reduces infiltration rates, increasing overland flow, and decreasing groundwater flow to the stream and its associated temperature buffering processes (Martin and Moody 2001, Poole and Berman 2001, and Robichaud 2000). Harvest practices can also increase the delivery of fine sediments to the streambed, clogging alluvial pores and decreasing hyporheic exchange (Poole and Berman 2001).

## **Site Description**

The North Fork Quartz Creek watershed is located in the Blue River watershed in the central western Oregon Cascades. The majority (97%) of the watershed is managed by the McKenzie River Ranger District of the Willamette National Forest. The landscape is steep and deeply dissected, reflecting the region's volcanic origins. Annual precipitation exceeds 250 cm and is received mostly between October and April. Vegetation is dominated by Douglas-fir





(*Pseudotsuga menziesii*), Pacific silver fir (*Abies amabilis*), western hemlock (*Tsuga heterophylla*), bigleaf maple (*Acer macrophyllum*), and vine maple (*Acer circinatum*). The majority of the natural forests have developed following wild fires 60-150 and 400-500 years before present (Cissel and Swanson 1999). The North Fork Quartz Creek timber sale was implemented in three small watersheds within the North Fork Quartz Creek watershed: a control watershed in which no treatment was applied, a buffered watershed in which the BLRS was applied with 15 to 20 meter riparian buffers, and an unbuffered watershed in which the BLRS was applied with no riparian buffers (Figure 1).

The control stream is a small, spring-dominated, first order stream draining directly into North Fork Quartz Creek. The watershed is deeply dissected with extremely steep slopes. The stream trends to the east-southeast and channel gradients range from 20-60%. The channel bed is dominated by alluvial deposits consisting of large cobbles and pebbles, with minimal bedrock

exposure. Summer flows are dominated by subsurface transport and average summer discharges are estimated at well under 0.5 cfs.

The buffered stream is a small, spring-dominated, second order stream draining directly into North Fork Quartz Creek. The buffered watershed is also deeply dissected with extremely steep slopes. The stream azimuth trends to northeast and channel gradients vary from 20-45%. The channel material consists of large cobbles and pebbles, with small amounts of exposed bedrock. Average summer discharges are estimated at less than 0.5 cfs.

The unbuffered stream is a small, spring-dominated, first order stream draining to the east-southeast directly into North Fork Quartz Creek. Again, the watershed is deeply dissected with extremely steep slopes. Channel gradients range from 20-70% and the channel is lined with large cobbles and pebbles, with substantial bedrock exposure. Average summer discharges are estimated at less than 0.5 cfs.

### **Monitoring/Data**

Stream temperature monitoring in the North Fork Quartz Creek Timber Sale began during the summer of 1998, two years prior to treatment, and has continued through the summer of 2001, two years after timber harvest and one year after the controlled burn. Stowaway temperature sensors were placed in the control, buffered, and unbuffered streams. Four sensors were placed in each stream at upper, middle, lower, and bottom locations. Upper sensors were placed in pools just downstream from the source, middle sensors were placed in pools mid-way through the treatment area, and lower sensors were placed in pools at the downstream end of the treatment area. Bottom sensors were placed several meters downstream of the harvest units, close to the confluence of the study stream and North Fork Quartz Creek.

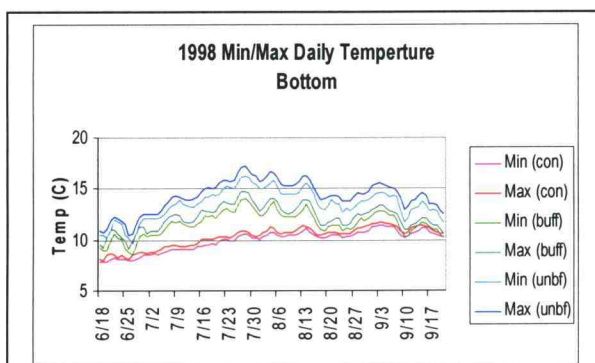
Stream temperature was recorded every 30 minutes. The length of stream temperature records varied between years, with the earliest monitoring dates beginning in mid-June and latest monitoring dates ending mid-October. The majority of data was collected from July through September for all monitoring locations.

## **Analysis**

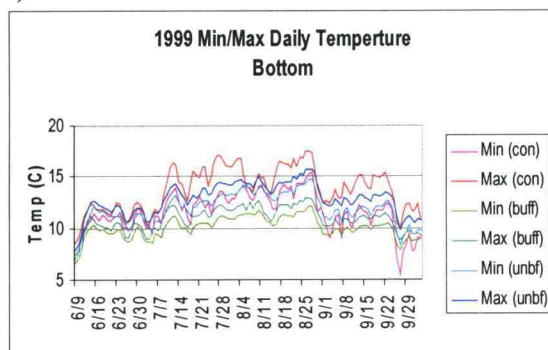
Raw data were obtained from each of the four temperature sensors from the control, buffered, and unbuffered watersheds. The minimum and maximum daily temperatures were summarized from the 30-minute data. These minimum and maximum records were then analyzed to detect high and low outliers that signified faulty temperature recordings. The majority of erroneous readings were associated with low flow periods in mid-September when stream levels dropped below the sensors.

The minimum and maximum daily temperatures were then used to calculate the daily, monthly, summer seasonal, and the seven-day average temperatures, as well as the diurnal temperature range. The minimum and maximum daily temperatures for the control, buffered, and unbuffered streams were then plotted using a uniform scale for each year of data. Similar plots were made to analyze daily average stream temperature and diurnal temperature range. These plots provided an additional quality control measure to detect erroneous readings and served as a preliminary tool to analyze the stream temperature relationships between the three watersheds.

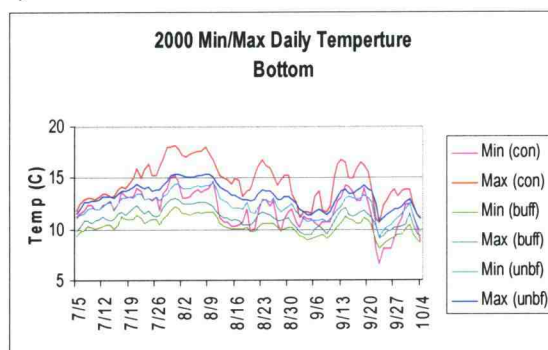
Within the control watershed, questions emerged about the quality of data recorded by the bottom temperature sensor. Beginning July 1999, daily minimum and maximum stream temperatures from the bottom sensor in the control watershed started to show a pronounced



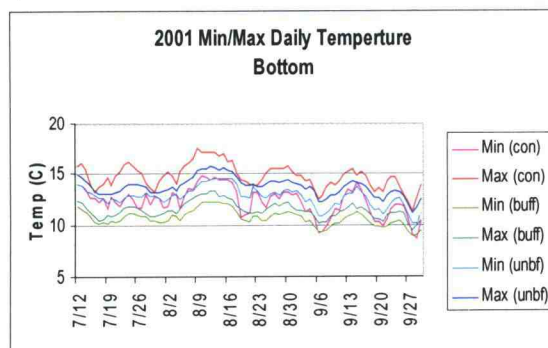
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b)

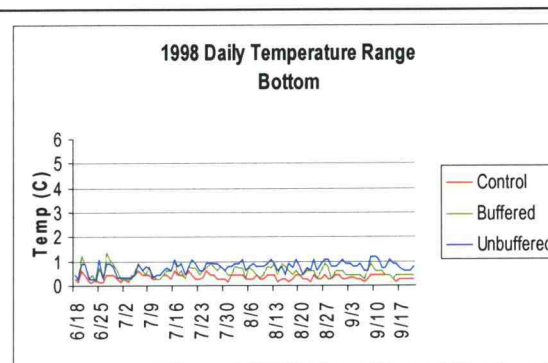


c)

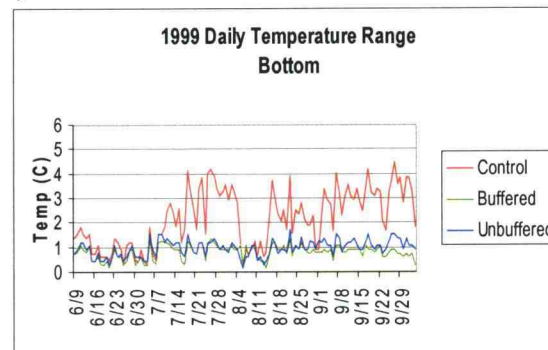


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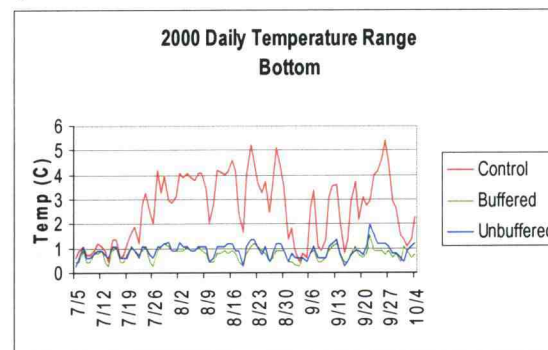
Figure 2. Daily Minimum and Maximum temperatures. Bottom Sensor.



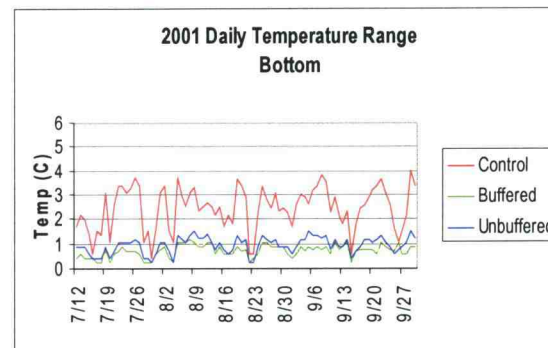
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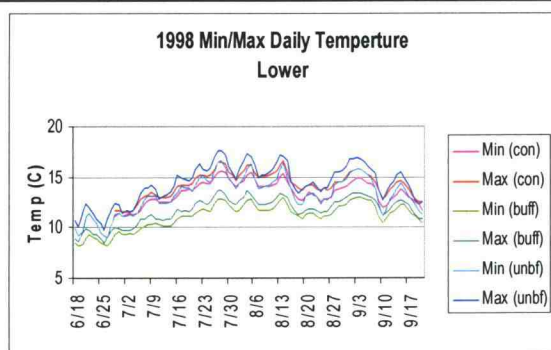


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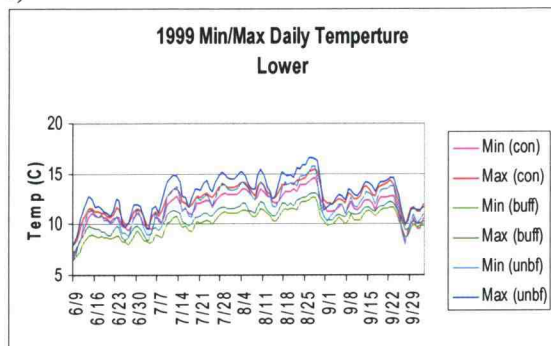
Figure 3. Daily temperature range. Bottom Sensor.

increase (Figure 2), as well as a dramatic increase in diurnal temperature range (Figure 3). Early in the 1999 monitoring season (June 9-July 10), diurnal temperature range averaged 1.0°C, with a maximum diurnal range of 1.9 °C. During the remainder of the monitoring season (July 11-October 3), the daily stream temperature range averaged 2.6 °C, with a maximum diurnal range of 4.5 °C. The same phenomena occurred during the 2000 monitoring season. In 2000, the diurnal temperature range averaged 0.9°C, with a maximum diurnal range of 1.4 °C, during the early season monitoring (July 5-19). During the remainder of the monitoring season (July 20-October 11), stream temperature averaged 3.0 °C, with a maximum diurnal range of 5.4 °C. Elevated temperature ranges also occurred during the late 2001 monitoring season (July 1 – September 5), with an average range of 2.4°C and a maximum of 4.0 °C . These numbers did not compare well with average diurnal temperature range from 1998, which was 0.4 °C, with a max of 0.6 °C. Diurnal stream temperature ranges from the bottom sensors in the buffered and unbuffered streams remained constant during the four-year monitoring period (Figure 3).

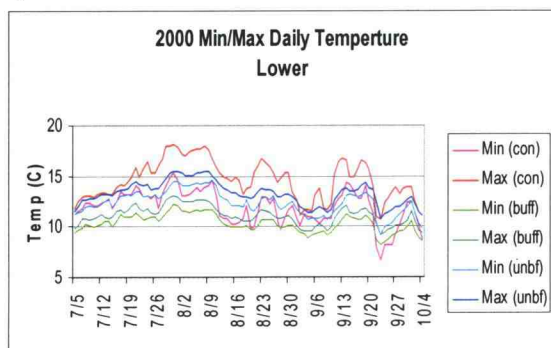
Similar increases in daily stream temperature and diurnal temperature range were also observed beginning in July 2000 from the lower temperature sensor in the control watershed (Figures 4 & 5). The diurnal temperature range averaged 1.1 °C from July 5 – July 22, and then increased to 3.0 °C from July 23-October 4, with maximum of 5.4 °C. The average temperature range was 2.5°C for the 2001 monitoring year, with a maximum of 4.0 °C. Again, these numbers did not compare well with average diurnal temperature ranges from 1998 and 1999, which were 0.8 °C and 0.9°C, respectively (Figure 4 & 5). Mirroring the bottom sensors, diurnal stream temperature ranges from the lower sensors in the buffered and unbuffered streams remained constant during the four-year monitoring period (Figure 5).



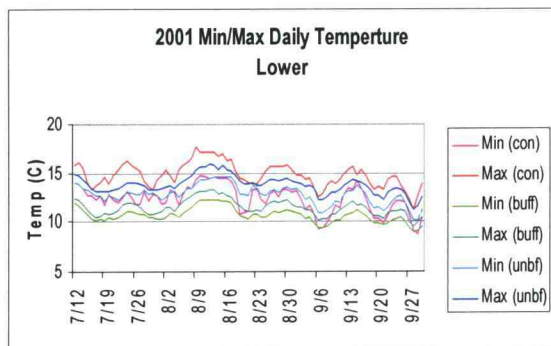
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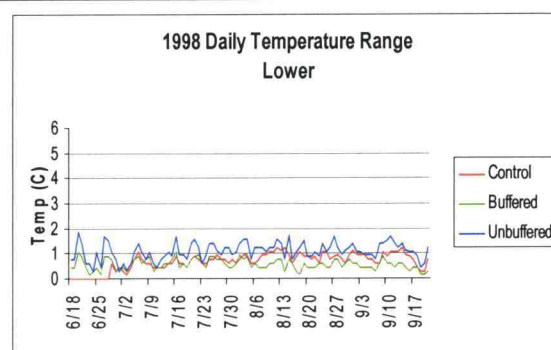


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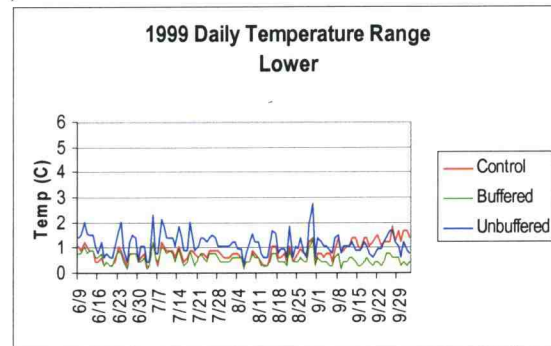


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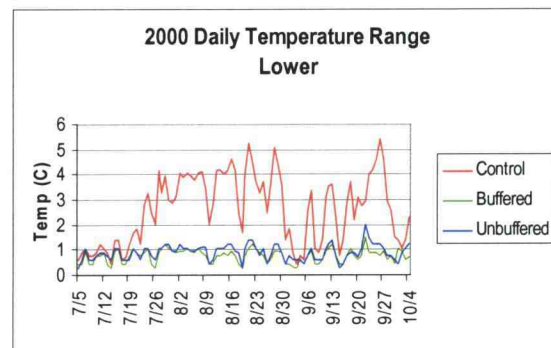
Figure 4. Daily minimum and maximum temperature. Lower Sensor.



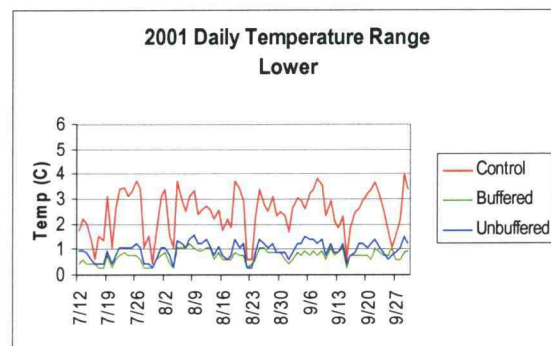
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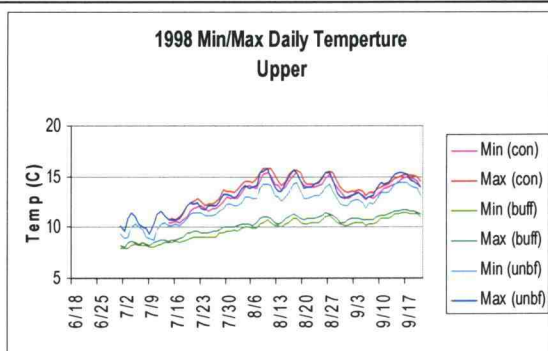
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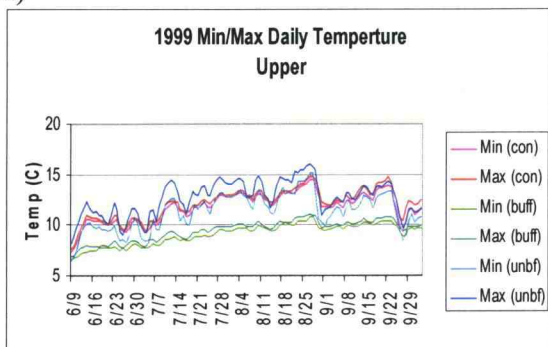
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Figure 5. Daily temperature range. Lower Sensor.

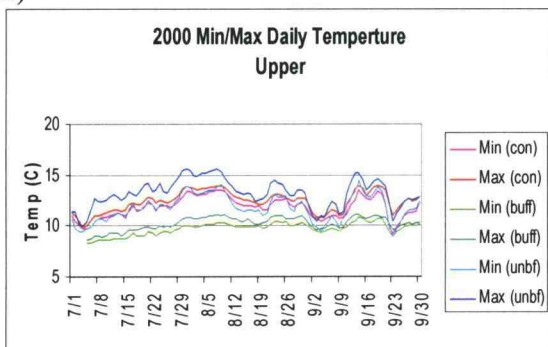




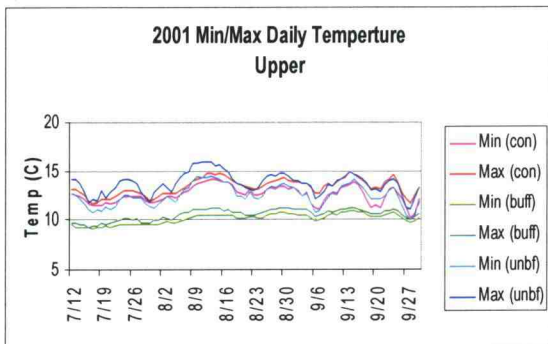
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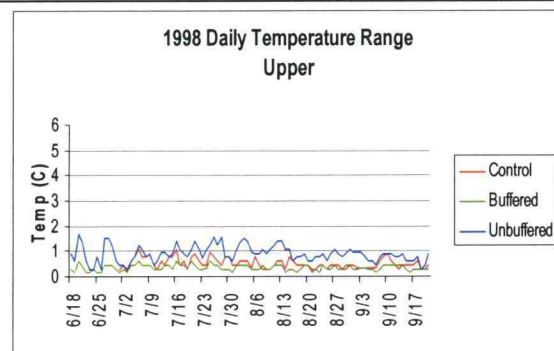


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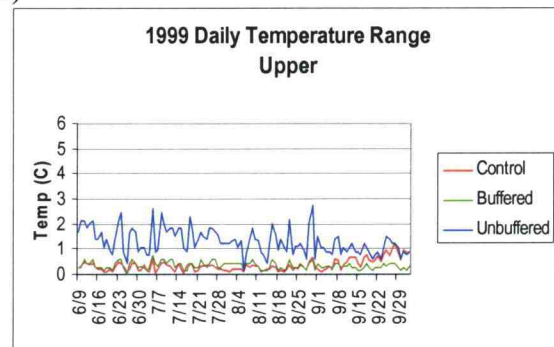


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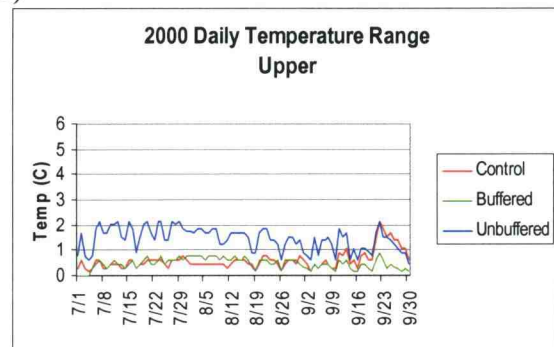
Figure 6. Daily Minimum and maximum temperature. Upper Sensor.



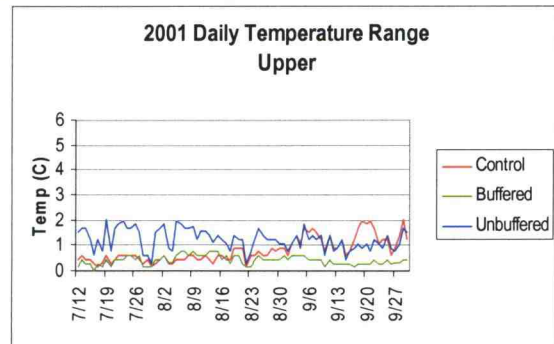
a)



b)



c)



d)

Figure 7. Daily temperature range. Upper Sensor.

Data from the middle temperature sensor in the control watershed was missing for two of the four monitoring seasons (1998 and 2001) and only partial data was gathered during 2000 (monitoring began in 8/23). Due to this incomplete data set, no comparisons were made between the control, buffered, and unbuffered watersheds using the middle sensor.

Stream temperatures recorded by the upper sensor in the control watershed were very similar for all four years of monitoring (Figure 6). Equally important, the diurnal temperature range remained constant, averaging 0.5, 0.4, 0.7, and 0.8 °C, for seasons of 1998, 1999, 2000, and 2001, respectively, with maxima of 1.1, 1.3, 2.2, and 2.0°C (Figure 7).

To further investigate the questions raised by the data from the sensors in the control watershed, scatter plots were constructed to compare the relationship between temperature readings from the different temperature sensors (Figures 8, 9, 10, and 11). Three comparisons of minimum and maximum temperature readings were made for each year, lower versus upper, bottom versus upper, and bottom versus lower. In these plots, comparisons were made by graphing temperature readings from one sensor on the x-axis and the other sensor on the y-axis using a uniform scale. The quality of the match decreased as the scatter of the plot increased. Temperatures were color coded by the month to determine when the readings started to depart from each other.

Originally, data from all four sensors in each watershed were to be used in the analysis of stream temperature response to the treatments. However, due to the wild variations in diurnal temperature range displayed in the data from the bottom and lower temperature sensors in the control watershed and the poor performance of these sensors in the scatter-plot analysis, data from these sensors were excluded from further analysis. Analysis comparing the treatment watersheds to the control watershed will be based on data from the upper sensor only.



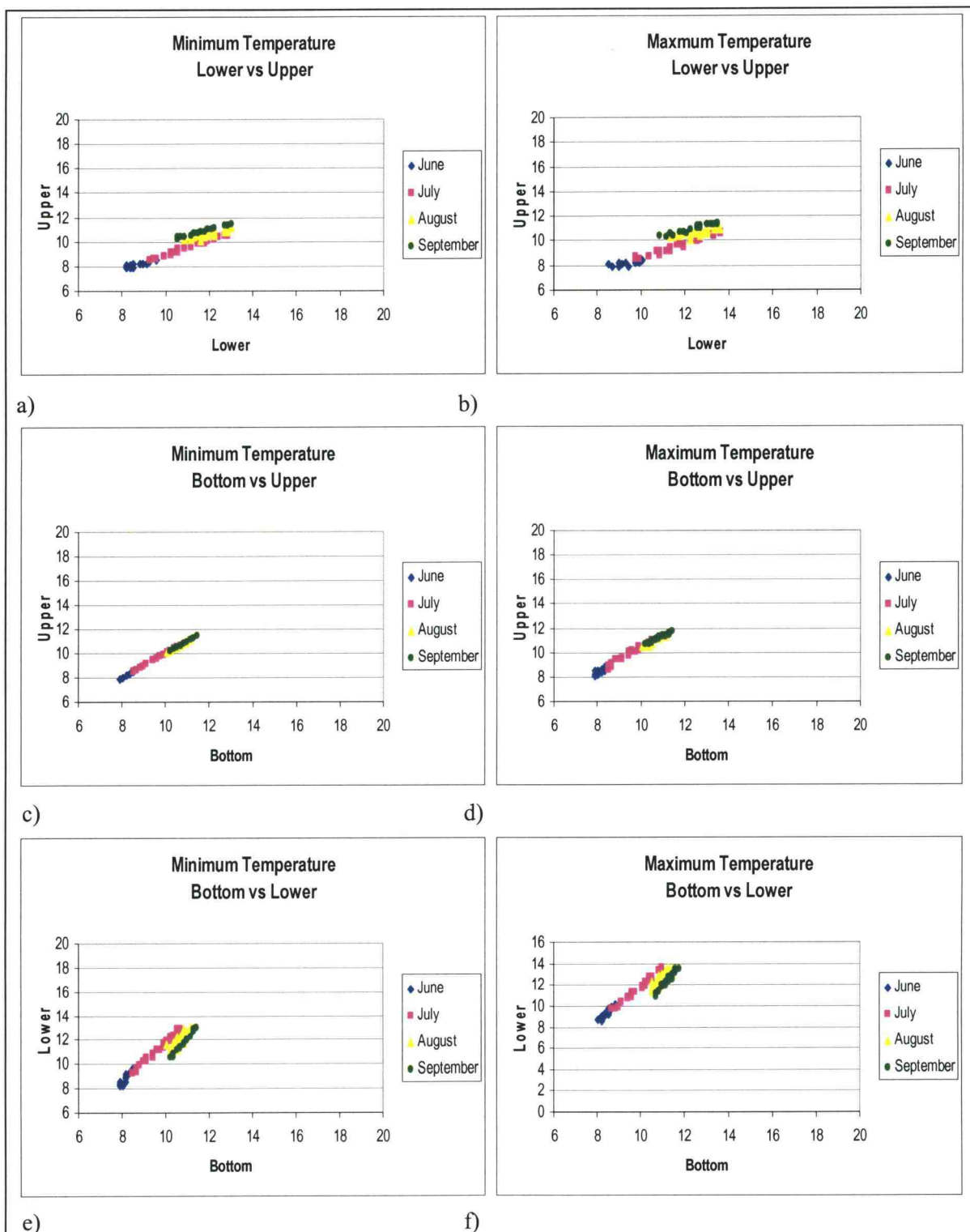


Figure 8. 1998 Sensor comparisons from the control watershed. a) Minimum temperatures, Upper vs. Lower, b) maximum temperatures, Upper vs. Lower, c) minimum temperatures, Upper vs. Bottom, d) maximum temperatures, Upper vs. Bottom, e) minimum temperatures, Bottom vs. Lower, and f) maximum temperature, Bottom vs. Lower.

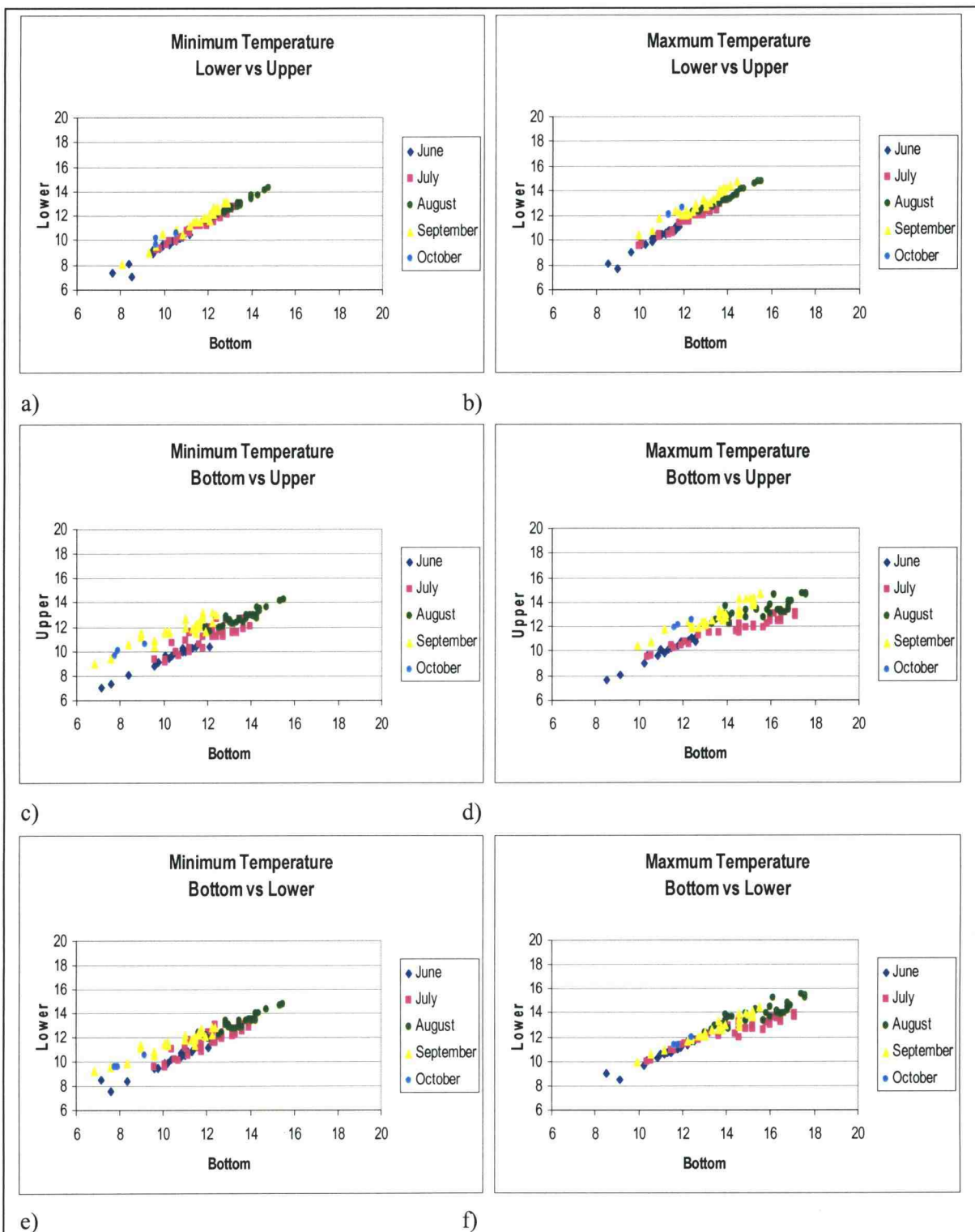


Figure 9. 1999 Sensor comparisons from the control watershed. a) Minimum temperatures, Upper vs. Lower, b) maximum temperatures, Upper vs. Lower, c) minimum temperatures, Upper vs. Bottom, d) maximum temperatures, Upper vs. Bottom, e) minimum temperatures, Bottom vs. Lower, and f) maximum temperature, Bottom vs. Lower.

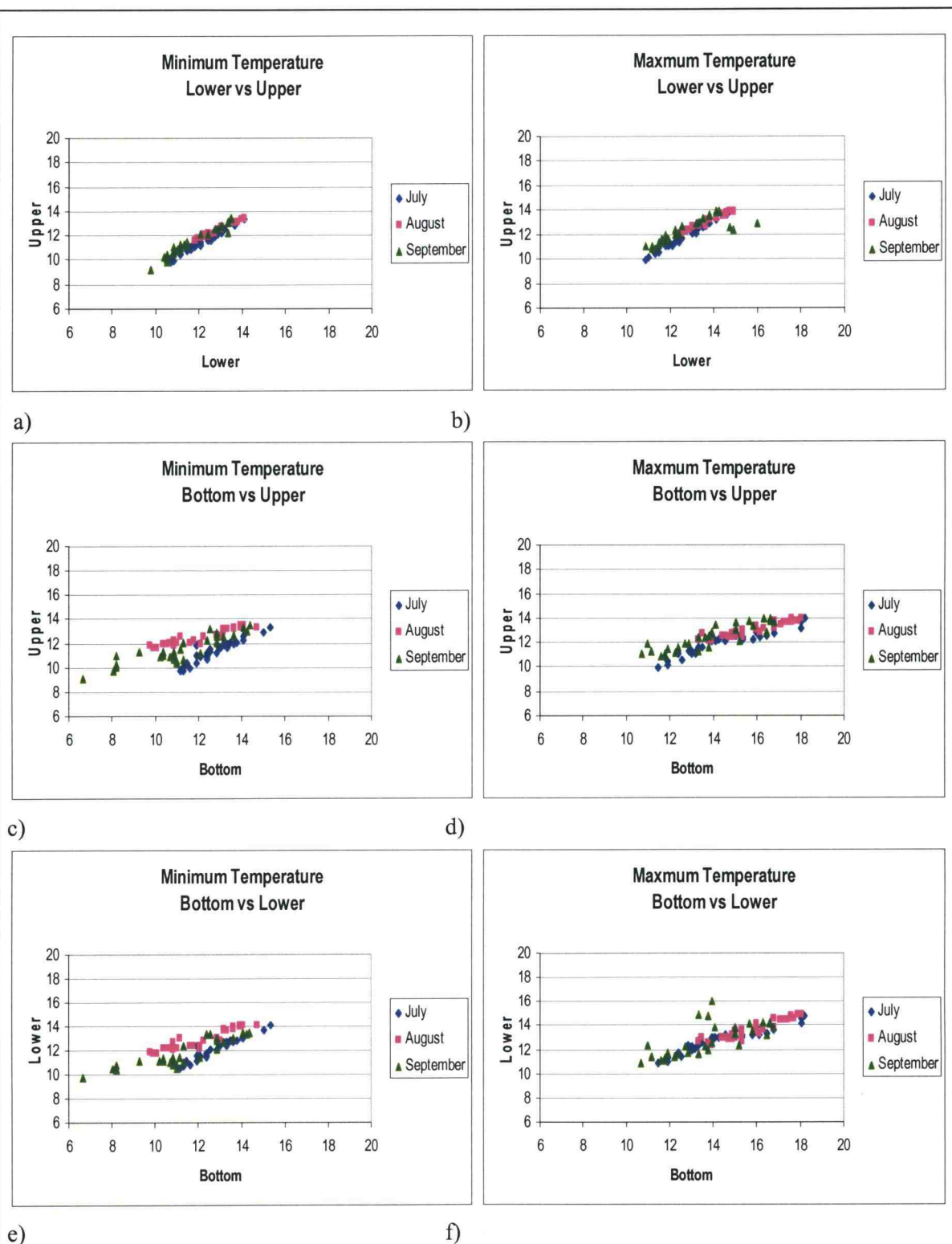


Figure 10. 2000 Sensor comparisons from the control watershed. a) Minimum temperatures, Upper vs. Lower, b) maximum temperatures, Upper vs. Lower, c) minimum temperatures, Upper vs. Bottom, d) maximum temperatures, Upper vs. Bottom, e) minimum temperatures, Bottom vs. Lower, and f) maximum temperature, Bottom vs. Lower.

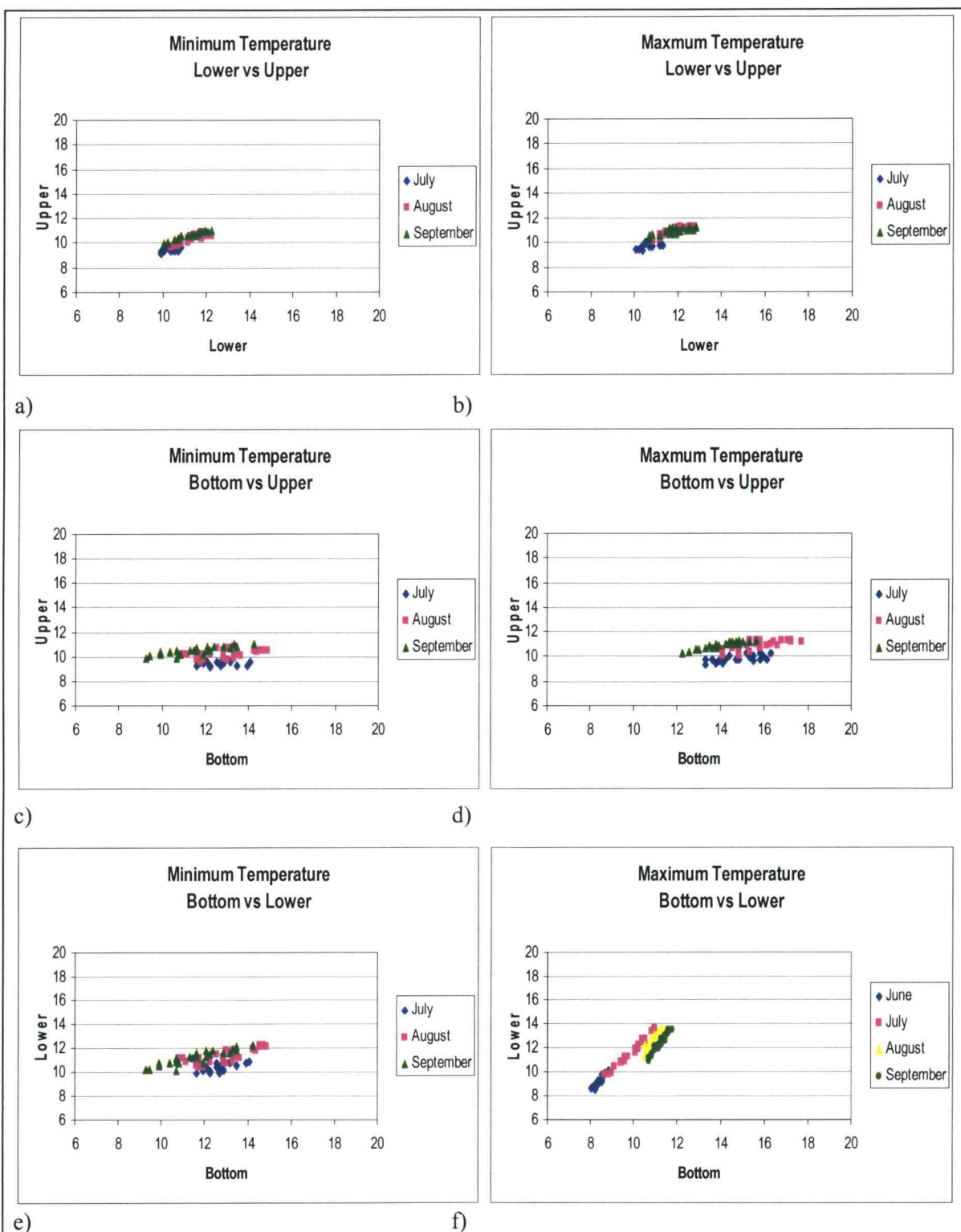


Figure 11. 2001 Sensor comparisons from the control watershed. a) Minimum temperatures, Upper vs. Lower, b) maximum temperatures, Upper vs. Lower, c) minimum temperatures, Upper vs. Bottom, d) maximum temperatures, Upper vs. Bottom, e) minimum temperatures, Bottom vs. Lower, and f) maximum temperature, Bottom vs. Lower.

Faulty Data	Control				Buffered				Upper			
	Bottom	Lower	Middle	Upper	Bottom	Lower	Middle	Upper	Bottom	Lower	Middle	Upper
1998			X									
1999	X											
2000	X	X	X									
2001	X	X	X									

Table 1. Questionable Sensor Data Sets

To assess whether the treatments of the Blue River Landscape Study led to significant increases in stream temperatures, data gathered from the buffered and unbuffered watersheds were subtracted from the data collected in the control watershed. If temperatures from the treatment streams were warmer than those in the control watersheds, then the differences between the stream temperatures would be positive. However, the importance of these analyses does not lie in whether or not the treatment streams are warmer than the control stream, the true test is change in the relationship between the watersheds after the treatments have been completed. Again, the first two years of data, 1998 and 1999, aided in establishing the pretreatment temperature relationships. Data from the summer of 2000 marked the first year of temperature records after the timber harvest was completed and the 2001 data the first year of post-burn readings and the second year of post-harvest data.

Differences between daily minimum temperature, daily maximum temperature, and diel temperature range were created by subtracting data gathered from the treatment watersheds from the control watershed data. Data from each watershed was then plotted on a uniform temporal scale, constrained by limited available data to the period of July 12 to September 21. Differences for monthly average minimum and month average maximum temperatures were also calculated.

Using only the data gathered from the buffered and unbuffered watersheds, plots were also constructed comparing temperatures at the uppermost sensor to those recorded at the bottom sensor to compare linear (upstream to downstream) stream temperature response to the treatments. Changes in the linear relationship between these two sensors in each watershed indicate a stream temperature response to the treatment. Differences between daily minimum temperature, daily maximum temperature, and diel temperature range were created by subtracting data gathered from the upper sensor from data collected from the bottom sensor. The stream temperature relationships were calculated separately for both the buffered watershed and the unbuffered watershed and then plotted with uniform scale and temporal range.

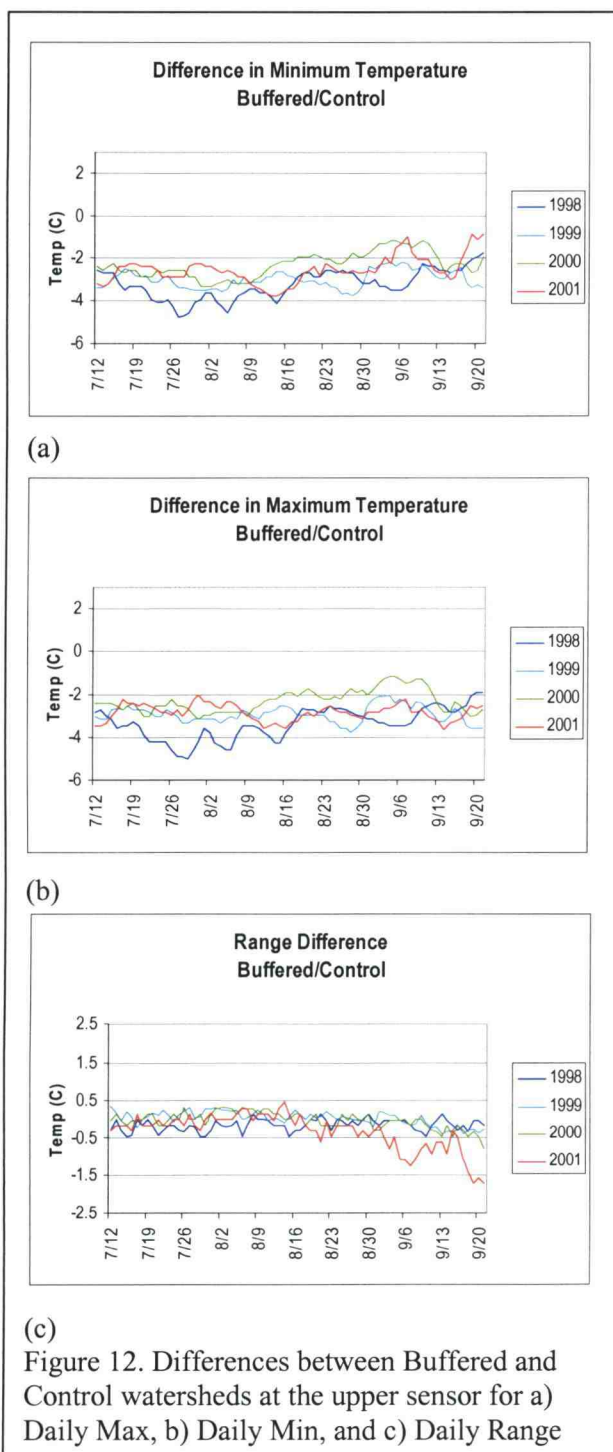
Additional plots were constructed to examine linear temperature relationships in the buffered and unbuffered watersheds only. Stream temperature readings from the upper sensor were plotted as the independent variable along the x-axis, with readings from the bottom sensor plotted as the dependent variable along the y-axis. Separate plots were made comparing both minimum and maximum temperatures in the buffered and unbuffered watersheds. Again, these plots were based on a uniform temporal scale, constrained by limited available data to range of July 12 to September 21. Since upstream temperatures drive downstream temperatures, increases in post-treatment stream temperature should be reflected by an upward shift in the plotted data.

## **Results**

Stream temperatures in the buffered watershed did not vary drastically during the four years of monitoring. Differences at the upper sensor in the daily minimum stream temperature between the buffered and control watersheds ranged from -1.7 to -4.7 °C in 1998, -2.1 to -3.7 in



1999, -1.1 to -3.3 °C in 2000, and -0.8 to -3.7 °C in 2001 (Figure 12). Differences in the daily



Differences in average maximum August temperatures were -3.4, -3.1, -2.3, and -2.9 °C,

respectively, for 1998, 1999, 2000, and 2001. Differences in average minimum September

maximum temperature ranged from -1.9 to -

5.0 °C in 1998, -2.1 to -4.0 °C in 1999, -1.1 to -

3.1 °C in 2000, and -0.5 to -1.7 °C in 2001

(Figure 12). Differences in diurnal temperature

range varied from 0.2 to -0.5 °C, 0.4 to -0.4 °C,

0.3 to -0.8 °C, and 0.5 to -1.7 °C, respectively,

for 1998, 1999, 2000, and 2001.

Differences at the upper sensor in average

seasonal and monthly stream temperatures

between the buffered and control watersheds

remained constant before and after the

treatments (Table 2). Differences in average

minimum July temperatures in the two

watersheds for 1998, 1999, 2000, and 2001,

respectively, were -3.2, -2.8, -2.5, and -2.6 °C.

Differences in average maximum July

temperatures for the same period were -3.4, -

2.6, -2.4, and -2.7 °C. Differences in average

August minimum temperatures for 1998

through 2001 were -3.3, -3.2, -2.4, and -2.9 °C.

Buffered - Control		1998		1999		2000		2001	
Season		Min	Max	Min	Max	Min	Max	Min	Max
Season	Mean	-3.10	-3.26	-2.65	-2.65	-1.99	-2.17	-2.43	-2.81
	SD	0.73	0.77	0.67	0.61	0.77	0.54	0.69	0.42
June	Mean			-2.28	-2.20				
	SD			0.63	0.61				
July	Mean	-3.18	-3.42	-2.77	-2.63	-2.46	-2.43	-2.61	-2.71
	SD	0.87	0.90	0.54	0.51	0.39	0.39	0.35	0.40
August	Mean	-3.31	-3.41	-3.15	-3.05	-2.41	-2.30	-2.86	-2.92
	SD	0.58	0.64	0.33	0.32	0.56	0.43	0.46	0.37
September	Mean	-2.69	-2.82	-2.40	-2.64	-1.53	-2.01	-1.87	-2.77
	SD	0.54	0.53	0.71	0.71	0.64	0.61	0.69	0.46
October	Mean			-1.62	-2.27	-0.88	-1.58		
	SD			0.26	0.23	0.47	0.42		

Table 2. Monthly and Seasonal Temperature Differences. Buffer - Control

temperatures for 1998, 1999, 2000, and 2001, respectively, were -2.7, -2.4, -1.5, and -1.9°C.

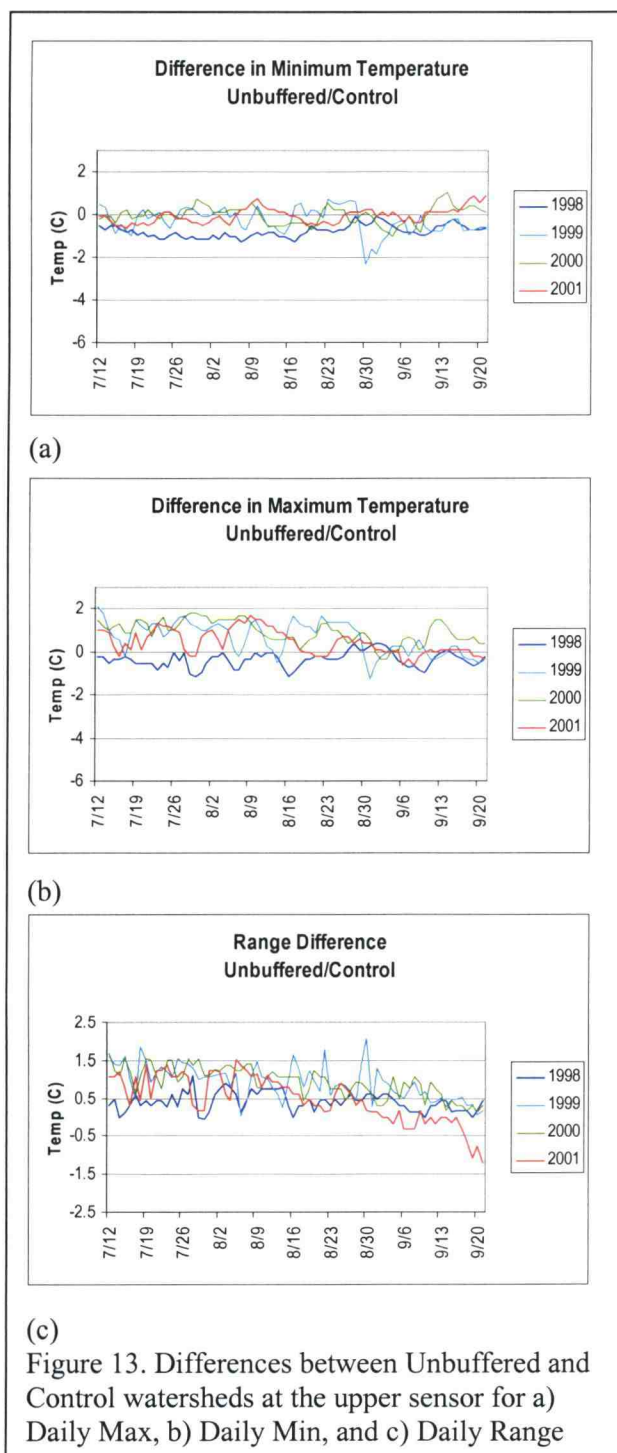
Differences in average maximum September stream temperatures were -2.8, -2.6, -2.0, and -2.8 °C, for the same period.

Stream temperatures in the unbuffered watershed also remained consistent throughout the four years of monitoring. Differences at the upper sensor in the daily minimum stream temperature between the unbuffered and control watersheds ranged from 0.0 to -1.3 °C in 1998, -0.8 to -2.3 in 1999, -1.0 to -1.0°C in 2000, and 0.9 to -0.7°C in 2001 (Figure 13). Differences in daily maximum temperature ranged from 0.4 to -1.1 °C in 1998, 2.1 to -1.3°C in 1999, -1.8 to -0.4°C in 2000, and 1.7 to -0.7 °C in 2001 (Figure 13). Differences in diurnal temperature range varied from 1.1 to 0.0 °C, 2.1 to 0.0 °C, 1.7 to 0.2 °C, and 1.5 to -1.2°C, respectively, for 1998, 1999, 2000, and 2001.

When comparing seasonal and monthly average stream temperatures at the upper sensors, the relationship between the unbuffered and control watershed remained consistent throughout the four years of monitoring (Table 3). Differences in average minimum July temperatures in the two watersheds for 1998, 1999, 2000, and 2001, respectively, were -0.7, -0.2, 0.0, and -0.3°C.



Differences in maximum July temperatures were  $-0.4$ ,  $1.1$ ,  $1.2$ , and  $0.6^{\circ}\text{C}$ . August minimum temperatures differed by  $-0.8$ ,  $-0.1$ ,  $0.0$ , and  $-0.3^{\circ}\text{C}$  in 1998, 1999, 2000, and 2001, respectively. August maximum temperatures differed by  $-0.3$ ,  $0.8$ ,  $1.0$ , and  $0.7^{\circ}\text{C}$  for the same period.



(c)  
Figure 13. Differences between Unbuffered and Control watersheds at the upper sensor for a) Daily Max, b) Daily Min, and c) Daily Range

Differences in September minimum temperatures for the four years of monitoring were  $-0.6$ ,  $-0.7$ ,  $0.0$ , and  $0.0^{\circ}\text{C}$ . Differences in the September average maximum temperature were  $-0.3$ ,  $-0.2$ ,  $0.4$ ,  $0.0^{\circ}\text{C}$ , respectively, for 1998, 1999, 2000, and 2001.

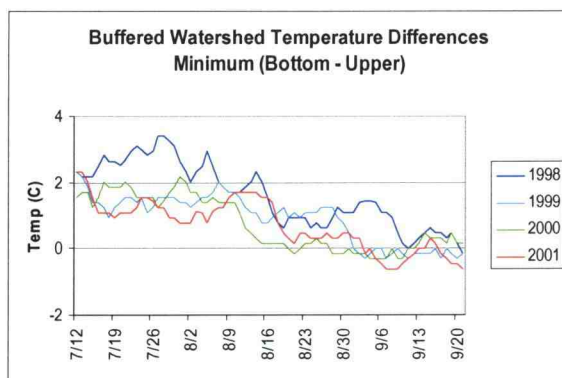
Linear stream temperature relationships in the buffered watershed remained unaltered after the treatments. Differences in the daily minimum stream temperature between the upper and bottom sensors ranged from  $-0.1$  to  $3.4^{\circ}\text{C}$  in 1998,  $0.0$  to  $2.3$  in 1999,  $0.0$  to  $2.2^{\circ}\text{C}$  in 2000, and  $-0.6$  to  $3.4^{\circ}\text{C}$  in 2001 (Figure 14). Differences in daily maximum temperature ranged from  $0.0$  to  $3.8^{\circ}\text{C}$  in 1998,  $0.3$  to  $2.8^{\circ}\text{C}$  in 1999,  $-0.1$  to  $2.5^{\circ}\text{C}$  in 2000, and  $0.0$  to  $2.7^{\circ}\text{C}$  in 2001 (Figure 14). Differences in diurnal temperature range varied from  $0.0$  to  $0.6^{\circ}\text{C}$ ,  $0.0$  to  $0.9^{\circ}\text{C}$ ,  $-0.3$  to  $0.6^{\circ}\text{C}$ , and  $-0.1$  to  $0.8^{\circ}\text{C}$ , respectively, for 1998, 1999, 2000, and 2001.

Unbuffered - Control		1998		1999		2000		2001	
Season	Mean	Min	Max	Min	Max	Min	Max	Min	Max
	SD								
Season	Mean	-0.70	-0.33	-0.37	0.57	0.00	0.75	-0.07	0.36
	SD	0.31	0.34	0.55	0.78	0.38	0.65	0.35	0.61
June	Mean			-0.56	0.69				
	SD			0.38	0.57				
July	Mean	-0.68	-0.40	-0.20	1.05	-0.03	1.18	-0.29	0.62
	SD	0.33	0.30	0.51	0.67	0.30	0.49	0.22	0.51
August	Mean	-0.83	-0.30	-0.10	0.86	-0.03	0.99	-0.02	0.70
	SD	0.29	0.35	0.68	0.72	0.36	0.44	0.33	0.57
September	Mean	-0.57	-0.28	-0.65	-0.17	0.03	0.35	0.04	-0.16
	SD	0.26	0.39	0.38	0.40	0.50	0.54	0.39	0.27
October	Mean			-0.68	-0.71	-0.09	-0.14		
	SD			0.12	0.09	0.30	0.25		

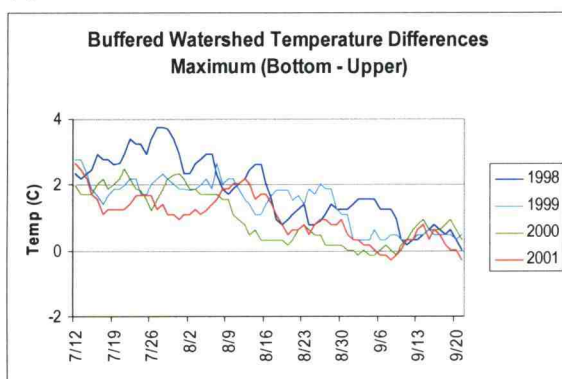
Table 3. Monthly and Seasonal Temperature Differences. Unbuffered - Control

In the unbuffered watershed, linear stream temperature relationships also remained unchanged after the treatment. Differences in the daily minimum stream temperature between the upper and bottom sensors ranged from -0.7 to 1.8 °C, -1.1 to 2.3 °C, -1.4 to 1.7 °C, and -1.0 to 1.8 °C, respectively, for 1998, 1999, 2000, and 2001 (Figure 15). Differences in daily maximum temperature ranged from -0.4 to 1.7 °C in 1998, -1.0 to 2.3 °C in 1999, -1.4 to 1.2 °C in 2000, and -0.8 to 1.7 °C in 2001 (Figure 15). Differences in diurnal temperature range varied from -0.2 to 0.6 °C in 1998, -1.6 to 0.5 °C in 1999, -1.4 to 0.1 °C in 2000, and -1.1 to 0.5 °C in 2001 (Figure 15).

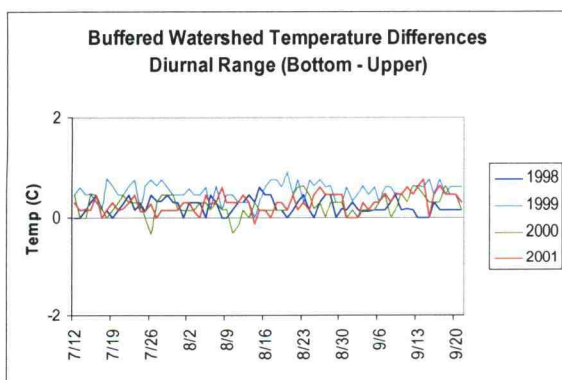
The scatter plots comparing upstream and downstream temperature recordings in the buffered watershed illustrate a consistent relationship during the four years of monitoring, shifting downward slightly between 1998 and 1999, while remaining stable during the rest of the monitoring period (Figure 16). Upstream to downstream temperature relationships also remained consistent in the unbuffered watershed, again only shifting downward slightly between 1998 and 1999 (Figure 17).



(a)

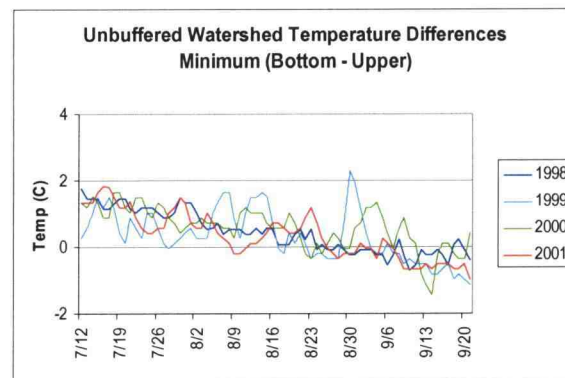


(b)

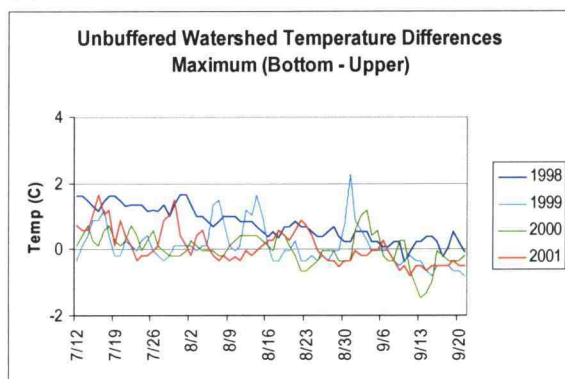


(c)

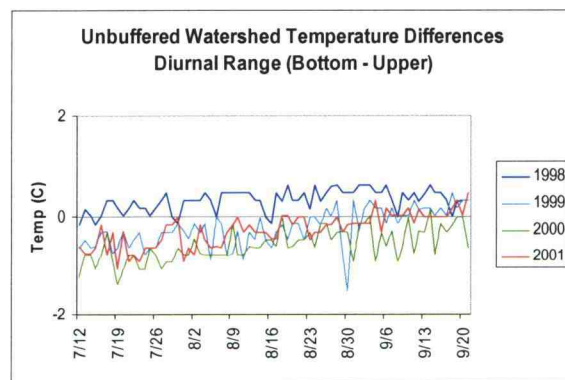
Figure 14. Differences between upper and bottom sensors in the buffered watershed for a) Daily Min, b) Daily Max, and c) Daily Range



(a)



(b)



(c)

Figure 15. Differences between upper and bottom sensors in the unbuffered watershed for a) Daily Min, b) Daily Max, and c) Daily Range

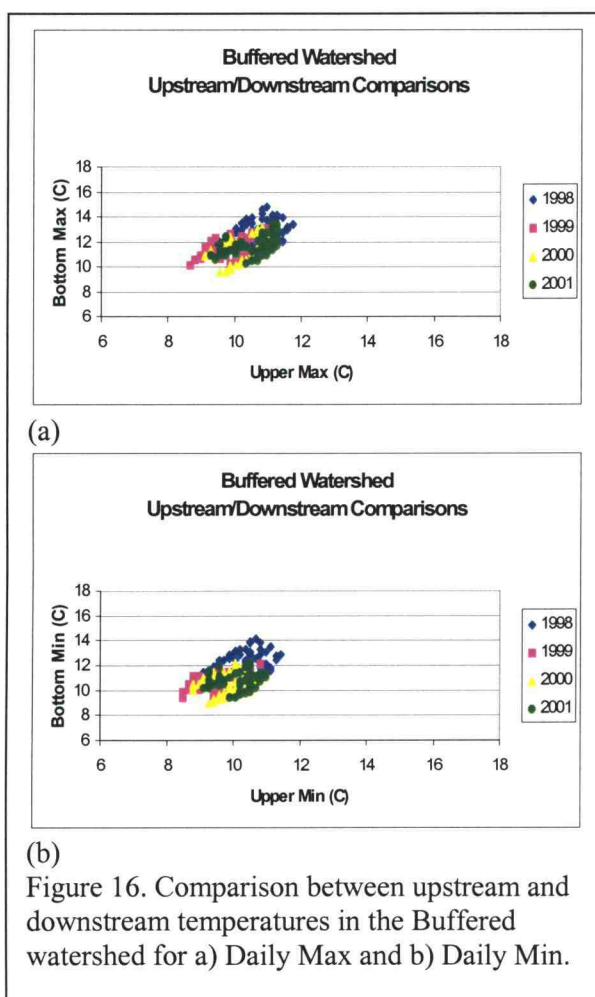


Figure 16. Comparison between upstream and downstream temperatures in the Buffered watershed for a) Daily Max and b) Daily Min.

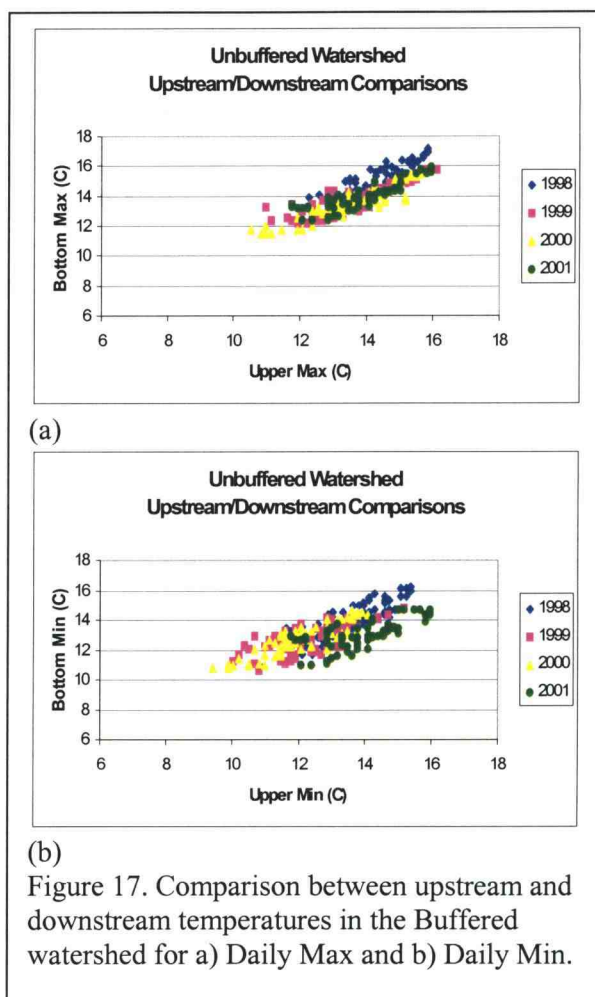


Figure 17. Comparison between upstream and downstream temperatures in the Unbuffered watershed for a) Daily Max and b) Daily Min.

## Discussion

Stream temperature in both the buffered and unbuffered streams showed little response to the 50% canopy removal and watershed burn prescribed by low severity/high frequency phase of Blue River Landscape Study. Daily, monthly, and seasonal temperature minimums, maxima, and diurnal variation showed little change after treatment. Other research has shown that summer maxima increased by 3.5 °C after partial canopy removal (7-33%) in Washington (Murray et al. 2000) and that 100% canopy removal resulted in 4.4 to 12°C increases in summer maxima (Brown and Krygier 1970, Rishel et al. 1982, Lynch et al. 1984, Johnson and Jones

2000). 100% timber removal also resulted in 1-2 °C increases in minimum stream temperatures (Brown and Krygier 1970, Lee and Samuel 1976, Rishel et al. 1982) and significant increases in diurnal temperatures range (Johnson and Jones 2000, Lee and Samuel 1976, Rishel et al. 1982, Lynch et al. 1984, Sinokrot and Stefan 1993). The largest stream temperature responses to the BRLS were 1 °C increases in daily August minimums and maxima in the buffered watershed during the first year after harvest. Compared to the post-harvest stream temperature increases reported in the literature, stream temperature responses to the BLRS were relatively minimal. Stream temperatures never exceeded 18 °C, the stream temperature standard set by the Oregon Department of Environmental Quality. The stream temperature stability in the study reaches can be attributed to the relatively little canopy reduction prescribed by the BLRS, topographic shading, and groundwater inputs in the treatment streams.

Compared to 1998 and 1999, summer seasonal minimum temperatures in the buffered stream increased by approximately 0.7 °C in 2000, the first year after canopy removal, and by approximately 0.3 °C in 2001, the first after the controlled burn and the second year after canopy removal (Figure 12, Table 2). Summer seasonal maximum temperatures increased by approximately 0.5 °C in 2000 and by approximately 0.2 °C in 2001 (Figure 12, Table 2). There was no post treatment response in diurnal variation (Figure 12) and, more importantly, no change in linear temperature relationships in the stream reach (Figure 14). These findings are consistent with research that has shown little stream temperature response to timber harvest practices that left stream buffers (Lee and Samuel 1976, Rishel et al. 1982, Lynch et al. 1984, Sugimoto et al. 1997). However, stream buffers in these studies ranged from 30 to 100 meters, while the BRLS only prescribed 15 to 20 meter buffers.



The stability of stream temperatures in the buffered watershed can be attributed to several factors. The 50% canopy removal still left a considerable number of mature upland Douglas fir and western hemlock trees in the watershed. The stream buffer, while comparatively narrow, also included riparian shrubs, bigleaf maple, western redcedar, Douglas fir, and western hemlock trees along the stream. The watershed slope is also very steep on all sides, providing abundant topographic shading. Direct solar radiation is the dominant external driver of stream temperatures (Brown 1969, Brown and Krygier 1970, Sinokrot and Stefan 1993, Johnson and Jones 2000). Dramatic increases in the amount of solar radiation received by streams after timber harvest have been shown to increase stream temperatures significantly (Brown and Krygier 1970, Rishel et al. 1982, Lynch et al. 1984, Johnson and Jones 2000). The combination of vegetative and topographic shading in the buffered watershed, as well as the stream's northeast aspect, greatly limited the post-treatment increase in solar radiation received by the stream, resulting relatively small increases in stream temperature.

Stream buffers have shown to greatly reduce the impact of timber harvest on stream temperature (Lee and Samuel 1976, Rishel et al. 1982, Lynch et al. 1984, Sugimoto et al. 1997). Surprisingly, stream temperatures in the buffered watershed of the BLRS showed a greater response to canopy removal than stream temperatures in the unbuffered watershed. This greater response is attributed to lower levels of topographic shading provided by the less steep buffered watershed when compared to the unbuffered watershed. The relative narrowness of the riparian buffer also reduced its impact on stream temperature.

The buffered stream is relatively short and spring fed. It is expected that phreatic groundwater inputs are high along the entire stream reach due to the watershed's steep slope and the characteristic hillslope hydrology of the region. Phreatic groundwater provides a cool baseline

temperature for the stream and a considerable buffer for increased heat loading (Smith and Lavis 1974, Sinkrot and Stefan 1993, Hawkins et al. 1997, Poole and Berman 2001). Steep channel slopes and alluvial deposits throughout the study reach lead to high rates of hyporheic exchange in the system, which further buffers heat fluxes (Constanz 1998, Poole and Berman 2001). Bedrock exposure in stream channel is limited to one small section at the bottom of the monitored reach. This lack of bedrock and the corresponding domination of alluvium reduces the heat loading capacity of the stream channel (Henry et al. 1994, Morrice et al. 1997).

Seasonal minimum temperatures in the unbuffered stream were elevated by approximately  $0.4^{\circ}\text{C}$  in both 2000 and 2001 compared to 1998 and 1999 (Figure 13, Table 3). The Seasonal maximum temperature increased by approximately  $0.2^{\circ}\text{C}$  in 2000 (Figure 13, Table 3). The seasonal maximum temperature was unchanged in 2001 compared to pretreatment data (Figure 13, Table 3). There was very little post treatment response in diurnal variation (Figure 13) and no significant change in linear temperature relationships in the stream reach (Figure 15). Stream temperature response to the treatments prescribed by the BLRS were relatively minor when compared to the  $3.5^{\circ}\text{C}$  temperature increase after partial canopy removal in Washington (Murray et al. 2000). However, it is important to note that partial canopy removal in the Murray study involved clearcutting patches within the watershed and leaving the remainder of the watershed intact, while the BLRS prescribed a 50% canopy removal in the entire treatment area.

The stability of stream temperatures in the unbuffered watershed can be attributed to many of the same factors that contribute to temperature stability in the buffered watershed. The 50% canopy removal left a considerable number of mature upland Douglas fir, western hemlock, western redcedar, and bigleaf maple trees. Even in absence of a stream buffer, the treatment left a considerable amount of riparian vegetation intact, which serves to reduce solar radiation impact

to the stream (Lynch et al. 1984, Sinokrot and Stefan 1993, Poole and Berman 2001). Abundant topographic shading was again provided by steep watershed slope. The combination of vegetative and topographic shading lead to relatively little change in post-treatment solar radiation received by the stream. Stream aspect trends to the east-southeast in the unbuffered watershed and does not play a significant role in the system's heat budget.

The unbuffered stream is also dominated by phreatic groundwater inputs due the stream length and proximity to the stream source. It is expected that phreatic groundwater inputs are high along the entire reach, providing a cool baseline temperature for the stream and a considerable buffer for increased heat loading (Smith and Lavis 1974, Sinokrot and Stefan 1993, Hawkins et al. 1997, Poole and Berman 2001). The combination of steep channel slopes and alluvial deposits in the study reach elevates hyporheic exchange, buffering heat inputs to the system. The unbuffered stream contains considerable amounts of bedrock exposed by the removal of alluvium from the steepest sections of channel slope. While the bedrock could undoubtedly act as a heat sink for the increased post-harvest solar radiation (Henry et al. 1994, Morrice et al. 1997), the steep slopes of the bedrock sections lead to very short residence time for the passing water, reducing heat transfer from the streambed to the channel.

In channel discharges are considerably lower in the control watershed compared to the two treatment watersheds. While the total volume of water flowing through the watershed is probably comparable to volumes of water moving through the buffered and unbuffered watersheds, it is estimated that the control watershed transports a greater percentage of water through the channel substrate, reducing in-stream flows. This reduction in channel water leads minimal pool depth, exposing temperature sensors to the atmosphere, resulting in the extreme variations in diurnal temperature documented by the bottom and lower sensors.



While the topographic shading and groundwater inputs of the study watersheds greatly reduced the impact of the BLRS on stream temperature, these watershed characteristics are probably not enough to offset the effects of complete canopy removal. Complete canopy removal would quite possibly result in the 4.4 to 12°C increase in stream temperature maxima seen in other research (Brown and Krygier 1970, Rishel et al. 1982, Lynch et al. 1984, Johnson and Jones 2000). A 50% canopy removal could also result in considerably higher stream temperature response if it were applied in an area with little groundwater inputs to buffer the increased heat loading. The impact of partial canopy removal could be further intensified by reduced watershed slopes and/or southwest trending streams. Reduced watershed and streambed slopes would not only reduce topographic shading, but also increase the channel residence of the water and lengthen the time in which the increased heat loading from canopy removal impacts the stream water. Southwest trending streams receive relatively high amounts of solar radiation, which would likely result significantly higher stream temperature responses to canopy removal.

The 50% canopy removal prescribed by low severity/high frequency phase of Blue River Landscape Study is considerably lower than the percent canopy removal prescribed by many of the current timber harvest techniques in the region and contributes greatly to the lack of response in stream temperature. However, the watershed characteristics of the study area, most notably the phreatic and hyporheic groundwater influences and topographic shading, minimize the impacts of the increased solar radiation markedly. Small order streams can be extremely variable in their response to disturbance and care should be taken to properly characterize any watershed before applying similar treatments.

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