HYDROGEOLOGIC CONTROLS ON STREAM TEMPERATURES IN HEADWATER CATCHMENTS IN RELATION TO FOREST MANAGEMENT ACTIVITIES, WILLAMETTE RIVER BASIN

Progress Report 1

By

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1.0 INTRODUCTION

Stream temperature is a critical component of aquatic habitat. In the Pacific Northwest, the sensitivity of fish species such as salmon to changes in stream temperature continues to be an important environmental management issue. This study seeks to directly assess how regional differences in geology directly influence stream temperature regimes in headwater streams within the Willamette River Basin in Oregon. We hypothesize that in the Willamette River Basin, regional patterns in geology are a dominant control of the spatial variation in water quality and quantity and thereby strongly influence sensitivity of stream temperature to land use change. By characterizing the natural controls on stream temperature variability in both headwater and higher-order streams within the Willamette River Basin, we contribute to a regional understanding of existing conditions and their sensitivity to human activities.

The Willamette River is the tenth largest river in the United States, based on annual flow. It runs from south to north before joining the Columbia River at Portland. Streamflow within the main stem Willamette River, its major tributaries including the McKenzie River, and a distributed network of small headwater basins, supports both human activities and ecosystems in the region. In particular, the stream network provides critical aquatic habitat for a range of threatened species, including salmon and steelhead trout, which are the focus of targeted restoration strategies that have cost over $3 billion dollars in the last 20 years (National Academy of Science 1996).

Within the 11,000 km^2 Willamette River Basin, sharp contrasts in climate, geology and topography are expressed along an east-west transect. Major tributaries of the Willamette River, including the McKenzie, Santiam, and Clackamas rivers, generally flow westward; the upper reaches of the McKenzie and Santiam rivers trend north-south, however, as they follow the western margin of the fault-bounded High Cascades province (Sherrod and Smith 1989; Grant 1997). Because of their orthogonal orientation to major topographic and geologic trends, the rivers cross three biogeoclimatic zones: (1) High Cascades, with elevations greater than 1200 m underlaid by glacial deposits and less than 2-million-year-old porous volcanic rocks, where most precipitation falls as snow; (2) Western Cascades, with elevations of 400 to 1200 m underlaid by 3.5- to 25-million-year-old deeply weathered but relatively impervious volcanic rocks, where precipitation falls as rain and snow; and (3) Cascades foothills and Willamette Valley, with elevations below 400 m underlaid by alluvium and greater than 25-million-year-old sedimentary and volcanic rocks, where most precipitation falls as rain (Figure 1).

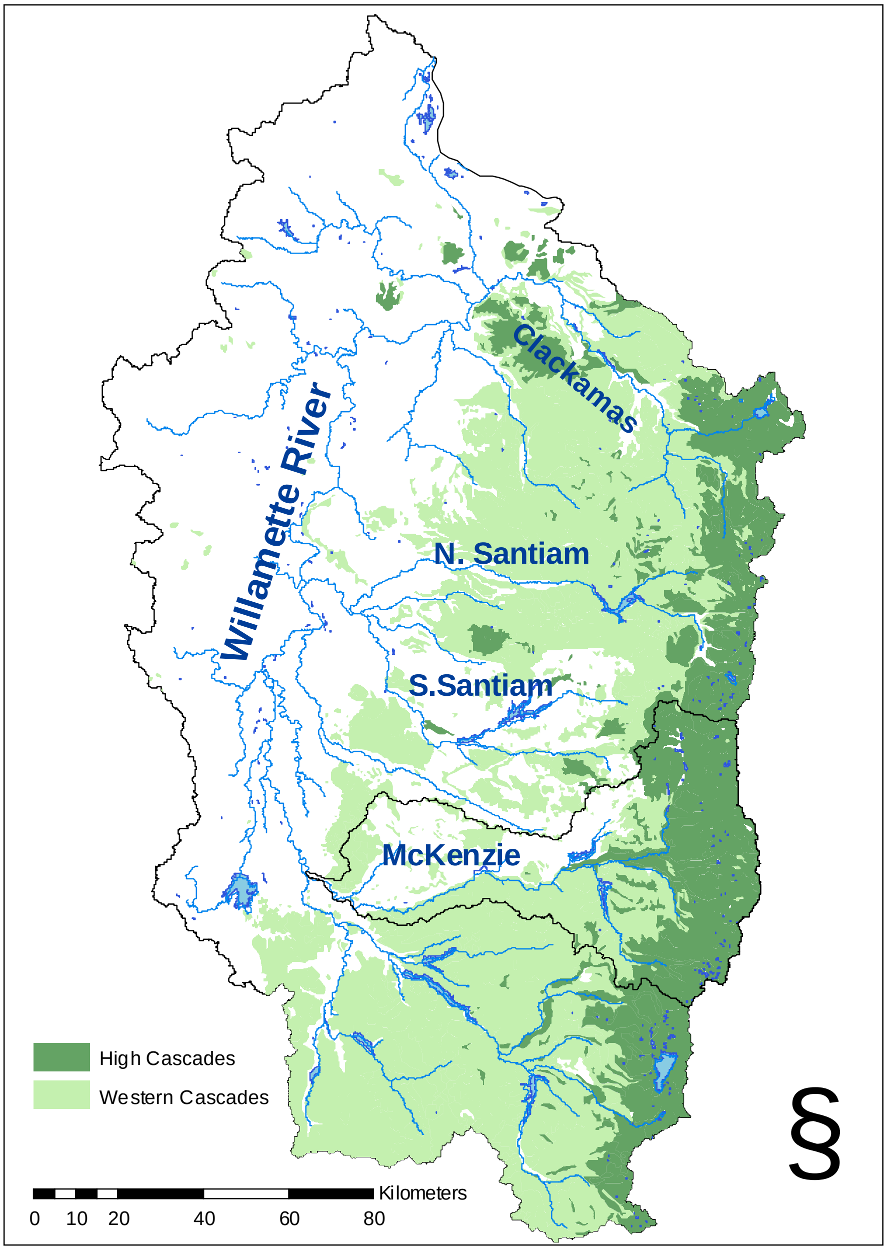


Figure 1. Willamette River Basin Showing High/Western Cascades Geology and McKenzie River Basin Outline

This broad geological setting imposes strong controls on the temperature regimes of rivers in the basin. These temperature regimes must be understood before effects of forest management on these regimes can be interpreted. For example, at the reach scale, riparian vegetation increases stream shading, thereby reducing stream temperatures. Maintaining and restoring riparian vegetation is a major focus of forest management activities and regulations on both federal and private lands. As we describe here, however, the initial magnitude and variability of stream temperature across different reaches is controlled by regional-scale factors, including climate and geology. Developing a broad regional-scale understanding of natural controls on stream temperature provides a sound basis for understanding stream temperature variation and establishing achievable temperature standards. This regional-scale framework is the focus of this study.

2.0 BACKGROUND

A variety of factors control the spatial and temporal pattern of stream temperatures in a given region. These controls can be categorized into two main classes. The first class involves processes that result in stream heating by direct energy inputs, including solar radiation, heat convection from the air, or heat conductance from the stream bed. Changes to stream temperature due to logging practices are generally associated with changes in solar radiation inputs as a function of shading and, to a lesser extent, changes in substrate temperature (Johnson and Jones 2000). A second class of controls on stream temperature involves the initial source of and additional contributions to water in the stream. The temperature of water inputs, both groundwater and tributary inflows, directly impacts stream temperature through advection. In addition, changing the volume of streamflow also alters stream sensitivity to energy inputs (Brown 1969). One of the challenges in interpreting and managing the thermal regime of headwater streams is placing them within a larger biogeoclimatic framework. Chen et al. (1998), for example, found that for the Upper Grande Ronde Watershed, Oregon, an energy balance model overestimated stream temperature in locations dominated by cool groundwater inflow.

Much of the current research on stream temperature within Oregon and other areas in the Pacific Northwest has focused on the first class of controls (radiation, convection, and conductance energy inputs) in small watersheds or stream reaches where spatial variation in groundwater input volumes or temperature are not a significant factor. Our preliminary studies have shown that the source of most of the water in the Willamette River region during the summer is from deep groundwater systems in the High Cascades (Tague and Grant in progress). An empirical analysis of US Geologic Survey (USGS) gaged streams indicates that during the summer, unit-area discharge volumes are significantly higher for High Cascades streams, and suggest a dominance of deeper groundwater flowpaths in this region (Tague and Grant in progress). The implications of these differences in hydrology for stream temperature are unknown, although Manga (1997) observed that High Cascades water is distinguished as being of uncommonly high quality, with low levels of dissolved solids and low temperatures.

Our earlier analysis of discharge patterns indicates that there may be strong within-region differences between High and Western Cascades areas in the Willamette River Basin in terms of the source of water to streams and consequently the temperature of water inflows. Regional differences in both the inflow stream temperature as well as discharge volumes will therefore determine the consequences of radiation heating for aquatic life. For example, if the temperature of stream water inputs is initially low, then additional heating due to low riparian cover will less likely result in temperatures above regulatory or ecological thresholds, whereas if initial flow volumes are low, temperatures will be more sensitive to variation in radiation inputs. Regional background temperature differences could also lead to misinterpretations of the impact of human activities. For example, naturally warmer stream flow might be interpreted as a management effect.

In this study, we develop the argument that interpreting the effects of human activities on temperature regimes of headwater streams in the Willamette River Basin requires an understanding of the underlying hydrogeologic setting. To accomplish this, our research is directed at determining the background stream temperature regime from different source areas. We use a combination of historical stream temperature data together with data collected during the summer of 2002 to develop regional regression models that illustrate differences between High and Western Cascades streams. The geographical focus of this study is the McKenzie River subbasin, which is one of the larger tributaries of the Willamette River. However, we argue that our findings will be applicable to other larger tributaries of the Willamette River Basin that include significant areas of both High and Western Cascades geologies in their drainage basins (Grant and Tague 2002).

3.0 METHODOLOGY

Hourly stream temperature data was collected during the summer of 2002 for a selection of High and Western Cascades streams. This data was analyzed to explore differences between these biogeoclimatic zones. Discharge was measured for all streams monitored as part of this project and each stream was field surveyed for evidence of groundwater spring input. We used geomorphic evidence (e.g., lack of well-defined floodplains, stable channels) as well as information from topographic maps and USDA Forest Service (USDAFS) personnel to determine the extent of spring influence. Not all spring inputs were found, however we are confident that we have identified most of the major groundwater-dominated systems. This information allowed in-depth graphical analysis of the relationships among air and stream temperatures and geographic setting. We generalized from this initial analysis using a regression-based approach to examine differences in stream temperature behavior for High and Western Cascades sites. Data for the broader analysis incorporated both previous temperature monitoring by the USDA Forest Service and data collected as part of this project. Herein we discuss methods for each of these steps in greater detail.

3.1 Classification of High and Western Cascades Geology

From a 1:500,000-scale geologic map of Oregon (Walker and MacLeod 1991) we classified rock units within the McKenzie River Basin as High or Western Cascades based on rock type and age using the following criteria: volcanic rocks greater than 8-million-years-old were classified as Western Cascades; volcanic rocks younger than 2-million-years-old were classified as High Cascades; and rocks between 2- and 8-million-years-old were placed in one of the two categories based on local topography (i.e., ridge-capping basalts) or broad regional location.

Individual watersheds and streams were identified as High or Western Cascades depending on whether the greater percentage of basin area was classified in either terrain.

3.2 Field Survey and Temperature Data Collection

The Western Cascades portion of the McKenzie River Basin has been more extensively studied than the High Cascades, in terms of both discharge and stream temperature. The greatest density of flow and temperature measurement sites are located in the H.J. Andrews Experimental Forest, a Long-Term Ecological Research (LTER) site, but USGS gage sites and other USDA Forest Service temperature sites are scattered throughout the Western Cascades region. The upper portion of the McKenzie River drains the High Cascades where temperature and stream gage sites are much fewer, although USDA Forest Service stream temperature data was available for a number of McKenzie River tributaries (Figure 2; Table 1). Preliminary field survey and discharge monitoring during summer 2001 found that several of the largest sources of water in the upper McKenzie River (e.g., Olallie Creek, Roaring River) had not been monitored (Table 1). These sites were selected for stream temperature monitoring for this project (Figure 2; Table 2). In addition we also monitored several Western Cascades streams, which represent relatively high-elevation Western Cascades sites. These sites are of particular interest in the understanding of High/Western Cascades differences in stream temperature because they reflect sites with Western Cascades geology but high-elevation (snow-dominated) climate (Figure 3). High Cascades sites tend to have greater drainage areas for the same elevation, reflecting the overall higher elevation of the High Cascades region. Western Cascades sites at elevations comparable to those of the High Cascades are typically located in headwater areas and thus have lower drainage areas. We also avoided sampling large Western Cascades streams because these tend to be those sampled by the USDA Forest Service and USGS.

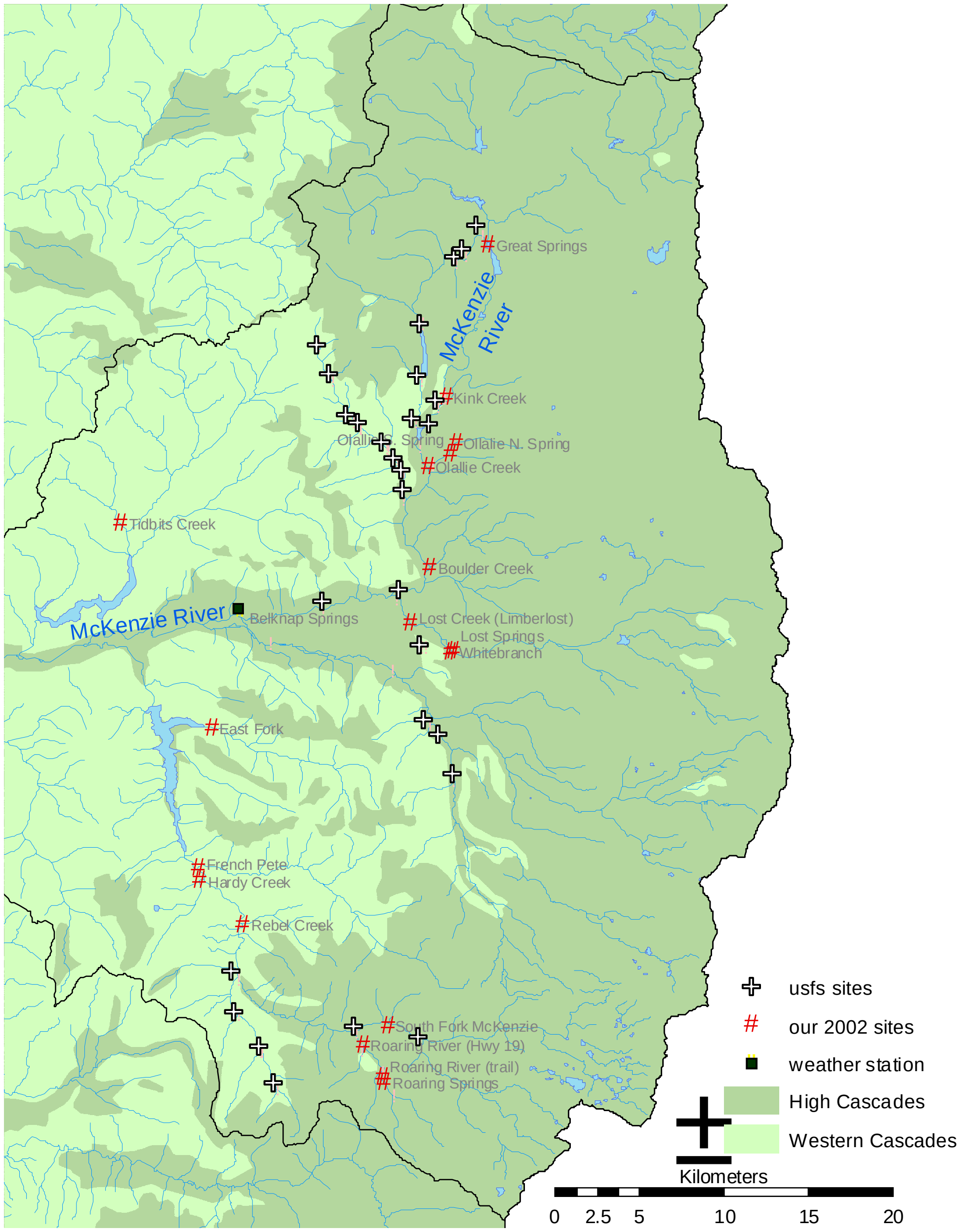


Figure 2. Location of Sites in the McKenzie River Drainage Monitored for Temperature and/or Discharge

Table 1. Unit Discharges for High and Western Cascades

	August Unit Discharge (cms/km^2)	
	2001	2002
High Cascades		
Cascade Creek	0.0495	
Elk Creek	0.0076	
McBee Creek	0.0017	
Roaring River (Hwy 19)	0.0701	0.0893
Boulder Creek	0.0003	0.0003
Twisty Creek	0.0001	
Olallie Creek	0.0636	0.1516
Kink Creek	0.0008	0.0005
Hackleman Creek	0.0013	
S Fork McKenzie River		0.0191
Roaring River (at trail)		0.1769
White Branch Creek		0.0024
Western Cascades		
E Fork S Fork McKenzie River	0.0022	0.0021
Walker Creek	0.0026	
French Pete Creek	0.0038	0.0040
Tidbits Creek		0.0046
Hardy Creek		0.0026
Rebel Creek		0.0020

Table 2. All Sites Used in This Analysis[1]

USDA Forest Service Sites	Drainage Area (km^2)	Dates of Record (July-Sept)
High Cascades Streams		
McKenzie River above Confluence with South Fork McKenzie River		
Ikenick Creek above marsh	2.647	2000
below marsh	2.8254	2000
below highway 126	14.639	2000
Kink Creek	31.5167	1998
McKenzie River above Trailbridge Reservoir	415.6622	1998-2001
Sweetwater Creek	7.0677	1998-1999
Smith River above Smith Reservoir	35.5276	1998-2001
base of Smith Reservoir	46.8571	1998-2001
above Trailbridge Reservoir	51.7528	1999-2001
McKenzie River Below Trailbridge Reservoir	481.3463	1998-2001
Olallie Creek	29.5061	1998
Lost Creek	199.413	1998
McKenzie River near Ranger Station	897.165	2000-2001
Horse Creek above Pothole Creek	142.4378	1998
above Castle Creek	160.7455	2001
Castle Creek	5.9783	2001
below Spring Creek	356.9816	2001
below Road 2638	386.5393	1998-2001
South Fork McKenzie River Drainage		
South Fork McKenzie River	125.9037	1998
Elk Creek	51.2242	1998
Roaring River upper site	6.4387	1998
McBee Creek	6.3708	1998
Moss Creek	5.4967	1998
lower site	34.2618	1998, 1999, 2001
Western Cascades Streams		
McKenzie River above Confluence with South Fork McKenzie River		
Deer Creek Drainage		
Cadenza Creek	2.184	1998-2001
below Cadenza Creek	9.7918	1998-2001
Carpenter Creek	1.7087	1998-2001
above County Creek	28.2486	1999-2001
County Creek	7.7379	1998, 2000, 2001
above Fritz Creek	39.0072	Aug-Sept 2001
Fritz Creek	6.0385	1998, 1999, 2001

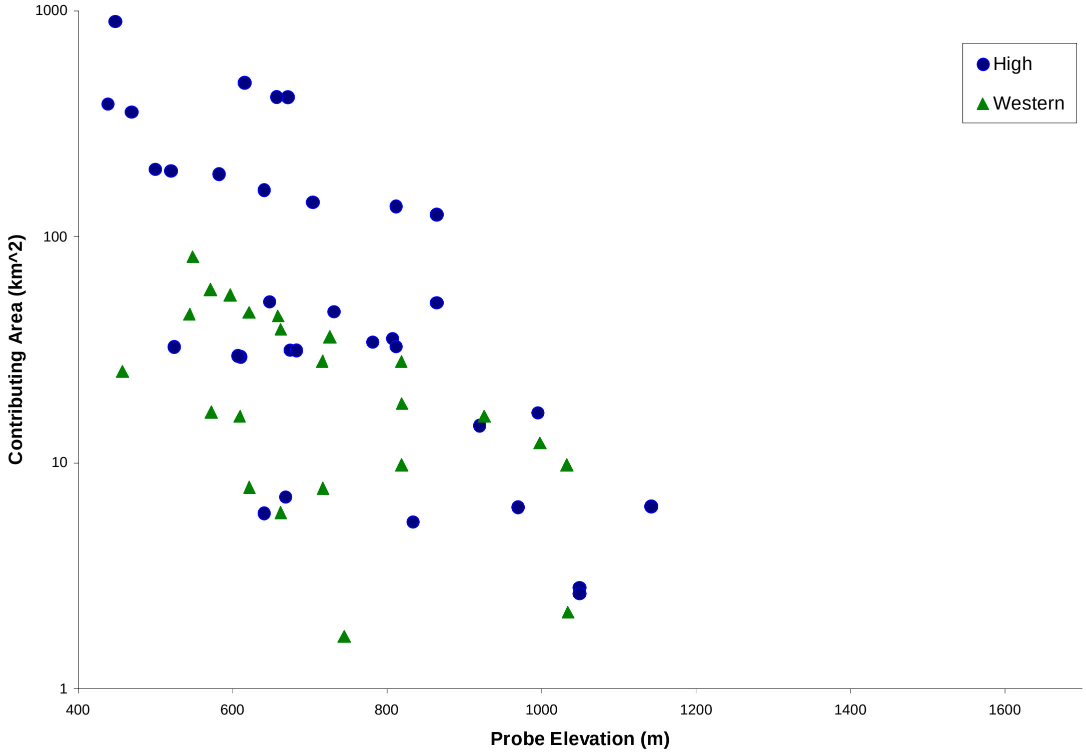
(Continued on next page. See note at end of table.)

Table 2. Continued

USDA Forest Service Sites	Drainage Area (km^2)	Dates of Record (July-Sept)
Deer Creek Drainage (continued)		
above Budworm Creek	46.4566	1998-2001
Budworm Creek	7.7867	1998-2001
below Budworm Creek	55.3458	1998-2000
mouth of Deer Creek	58.6466	1998-2001
South Fork McKenzie River Drainage		
Augusta Creek headwaters	12.2485	1998-2001
above Grasshopper Creek	18.2634	1999-2001
Grasshopper Creek	9.7993	1998, 1999
below Grasshopper Creek	28.0868	1998-2001
below Pass Creek	36.0678	1998, 2000, 2001

2002 Sites	Drainage Area (km^2)	Period of Record (2002)
High Cascades Springs		
Great Springs (Clear Lake-McKenzie River)	207.818	July 16-Sept
Tamolitch Pool (McKenzie River)	382.9829	July 16-Sept
Olallie North (Olallie Creek)	12.3506	Aug-Sept
Olallie South (Olallie Creek)	15.9341	Aug-Sept
Lost Springs	0.0002	July-Sept
Roaring Springs (Roaring River)	6.4387	Aug-Sept
High Cascades Streams		
Kink Creek	31.4577	July-Sept
Olallie Creek	29.7198	July-Sept
Boulder Creek	32.6726	July-Sept
White Branch	189.3315	July 24-Sept
Lost Creek	195.8063	July-Sept
South Fork McKenzie River	136.481	July-Sept
Roaring at Roaring River Ridge Trail	16.7002	Aug-Sept
Roaring River at Road 19	32.7838	July-Sept
Western Cascades Streams		
Rebel Creek	16.1408	July-Sept
Hardy Creek	16.7874	July-Sept
French Pete	81.5511	July-Sept
East Fork South Fork McKenzie River	45.3962	July-Sept
Tidbits Creek	25.437	July-Sept

[1] Subbasins are listed in downstream order, beginning with the McKenzie River headwaters. Within subbasins, stream reaches also are listed in downstream order.



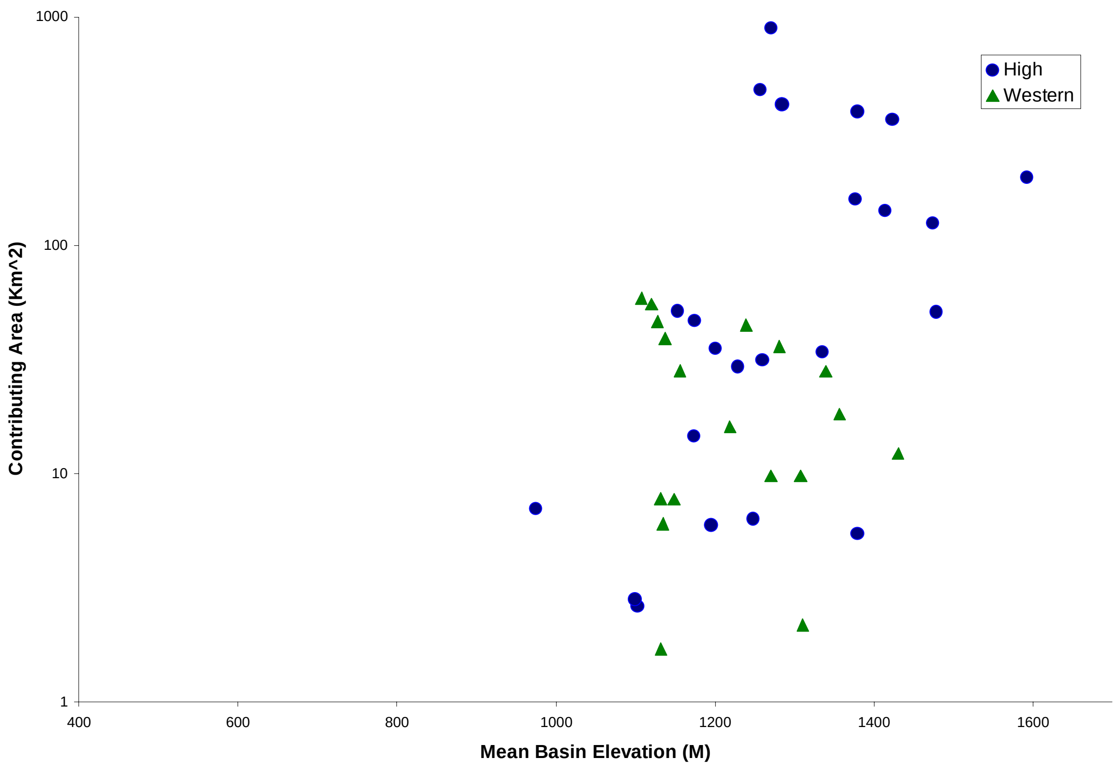
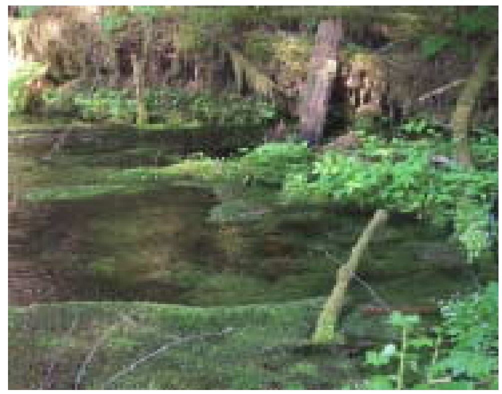


Figure 3. Contributing Area vs (top) Probe Elevation and (bottom) Mean Basin Elevation for All Sites, 1998-2002

Preliminary discharge monitoring during summer 2001 of several of these High Cascades sites found very high discharge values relative to their topographically defined contributing areas (Table 1). For each of these high-discharge sites—Olallie Creek, Roaring River, Clear Lake—we followed the stream channel to investigate the source or headwaters. For all of these streams, the stream headwaters were fed by large springs. Channel heads are typically a diffuse area of multiple springs (Figure 4). We installed temperature probes for each of these spring systems; we also installed probes longitudinally downstream to examine how temperatures changed with distance from source (Table 2). This longitudinal sampling provided information on the relative warming along each tributary and provided information on groundwater contributions in the High Cascades system. We also found that one of the McKenzie River tributaries mapped within the High Cascades region, Boulder Creek, did not show the relatively high values of summer discharge. Field exploration of this site found that this High Cascades stream appeared to be a surface-water-dominated system with no evidence of groundwater spring systems in its contributing source area.

(a) 

(b) 

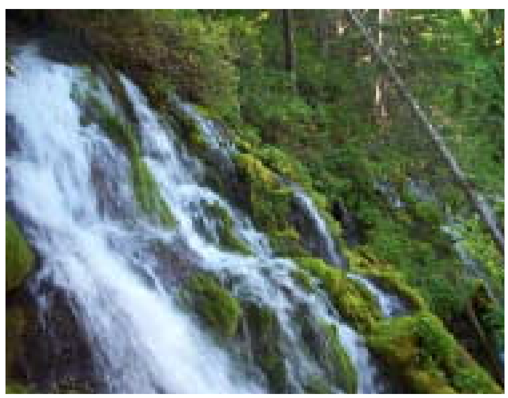
(c) 

Figure 4. Cascade Springs: (a) Tamolitch Pool, McKenzie River (large, deep spring); (b) Lost Spring, Lost Creek (quiet seep); (c) Roaring Spring, Roaring River (zone of gushing springs)

Our stream monitoring locations for both High and Western Cascades were selected in areas with relatively little or no forest harvesting activity. All of the stream temperature sites had mature forests in the riparian zone.

At all of our monitored sites both hourly stream temperature and bimonthly discharge measurements were taken. Stream temperature was monitored using HOBO® Water Temp Pro temperature probes. A wading discharge measurement was taken bimonthly using a Marsh-McBirney FloMate® velocity meter, following standard USGS procedure. For regional regression analysis, we included all available USDA Forest Service temperature monitoring sites from 1998 through 2001 as well as data collected during summer 2002 as part of this project.

3.3 Air Temperature Data

Air temperature was used to account for variation in stream heating between the different sites, but we did not measure air temperature directly. Point measurements of daily air temperature were obtained from the Belknap Springs National Climatic Data Center (NCDC) site (Figure 2). Spatial interpolation of these values was based on PRISM (Parameter-elevation Regressions on Independent Slopes Model). PRISM is a widely used tool that combines point meteorological data, surface topography, and other information to generate spatial estimates of climate variables (see http://www.ocs.orst.edu/pub/maps/Precipitation/Total/U.S./us_rast_meta.html). The PRISM model includes data from the NCDC network in its estimation of air temperature surfaces. The most recent available PRISM data set was for summer 1997. We assumed that spatial variation in summer air temperature is temporally constant, thus use of the 1997 PRISM data set for spatial interpolation was reasonable. PRISM provides a 1 km grid cell map of air temperature. To account for spatial variation of air temperature within the PRISM cell, we use a standard (6.4°C/km) elevation lapse rate for temperature and assumed that PRISM values reflect air temperature at the mean elevation within the 1 km PRISM grid cell. Thus, air temperature at a given stream site is calculated as follows:

$$T_{air}[\text{site}] = T_{air}[\text{Belknap}] + (T_{air}[\text{PRISM-site}] - T_{air}[\text{PRISM-Belknap}] + (\text{elev.PRISM-site} - \text{elev.site}) * \text{airT.lapse.rate})$$

where $T_{air}[site]$ is air temperature used for the stream monitoring site; $T_{air}[Belknap]$ is the air temperature from Belknap NCDC records; $T_{air}[PRISM\text{-}site]$ and $T_{air}[PRISM\text{-}Belknap]$ are the PRISM estimates of 1997 mean August air temperature for the grid cell containing the monitoring site and the Belknap NCDC station, respectively; *elev.site* is the elevation of the stream monitoring site; *elev.PRISM-site* is the mean elevation of the PRISM grid cell containing the stream monitoring site; and *airT.lapse.rate* is the air temperature lapse rate.

3.4 Stream Temperature Analysis

To explore controls on the spatial pattern of maximum temperature, we compared spatial variation in maximum August stream temperature (typically the warmest month) with spatial variation in mean August air temperature. Ordinary linear least squares regression analysis was used to explore the relationship between mean air temperature, drainage area, and maximum August stream temperature for monitored sites. Drainage area was used as an index of flowpath length to reflect distance (time of travel) over which the stream had been warmed from solar and atmospheric inputs. Separate regressions were developed for High and Western Cascades sites and differences were explored. For this regression analysis, temperature data recorded at spring sources were not included, since they reflect groundwater rather than stream temperatures.

To examine controls on temporal variability in stream temperature, separate regression relationships between daily stream temperature with air temperature throughout the summer period (July through September) were computed for each site. Maximum likelihood time series regression was used to account for temporal autocorrelation in daily stream temperature values. Variation in mean regression coefficients as well as standard error was then compared for the High and Western Cascades stream populations. For temporal analysis, both the air and stream temperature data sets were aggregated to 3-day moving averages. Three-day averages were selected to resolve the lag between air and stream temperature, which is typically less than a day, and to reflect the temporal resolution of summer temperature trends, which in this region tend to involve 2- to 3-day warming or cooling periods.

3.5 Longitudinal Analysis

Discovery of spring systems at the head of several of the major tributaries in the High Cascades sites confirmed the importance of groundwater contributions to these streams. To explore the role of these groundwater sources in controlling stream temperature, we examined spatial differences between spring temperatures and stream temperatures longitudinally downstream of the springs on Olallie Creek and Roaring River. On Roaring River, samples were taken at two locations downstream of the spring. These longitudinal trajectories were compared with typical Western Cascades trajectories, using daily temperature recorded at multiple points along Lower Deer and Upper and Lower Augusta Creeks.

4.0 RESULTS

4.1 2002 Stream Temperature Monitoring

Throughout the 2002 summer season daily stream temperatures for streams and spring sites illustrate that Western Cascades streams were warmer and more variable than High Cascades streams (Figure 5). Only one High Cascades stream that is not fed by groundwater springs (Boulder) does not follow this general trend. Temperatures from the groundwater springs that are the sources for most High Cascades streams showed near constant temperatures of 4 to 6°C throughout the season. These results suggest that the presence of deep groundwater spring systems rather than the shift to a snowmelt-dominated system drive the colder temperatures typical of most High Cascades streams. All of the high-discharge streams measured within the High Cascades contributing area of the McKenzie River appear to be spring fed. No evidence of spring-fed streams was found in the Western Cascades streams that we monitored.

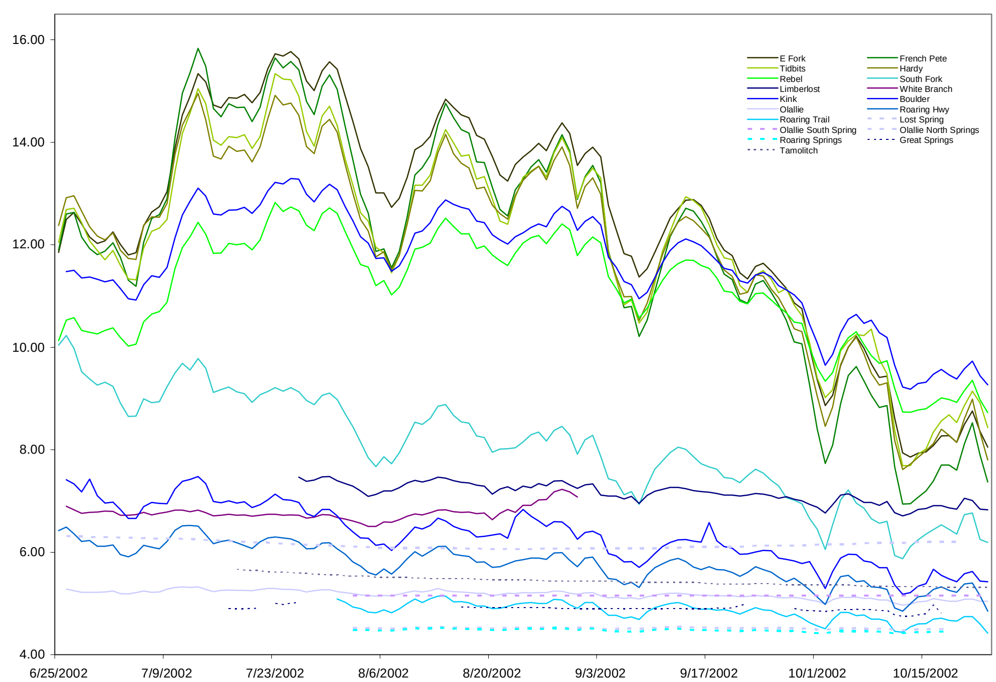


Figure 5. Average Daily Stream Temperature for Western Cascades Sites (green lines) and High Cascades Sites (blue and purple lines) Monitored in Summer 2002 (dotted lines indicate probes at springs)

In general, the relationship between air temperature and stream temperature at a given point is mediated by upstream channel length. In areas with low groundwater inputs, such as the Western Cascades, stream channel length controls the distance over which stream has been heating. In these areas, channel length is also correlated with discharge volumes and drainage area. With increasing channel length, water temperatures in streams increase. In the High Cascades system, however, this relationship is complicated by groundwater contributions. Large additions of cold temperature groundwater at the stream head can obscure correlations between water temperature and stream channel length, as well as correlations between discharge and topographically defined drainage area. The temperatures of spring-fed systems are much more constant through time and less in equilibrium with surrounding air temperature, particularly during the warmest periods when the greatest potential for warming occurs (Figure 5). The influx of cold groundwater along the stream reach and higher discharge volumes help to buffer the High Cascades streams from warming.

Longitudinal measurements of stream temperature along reaches without any significant tributary inputs show that High Cascades spring streams generally warm more slowly than Western Cascades streams (Figure 6). For Western Cascades streams, faster rates of warming tend to occur in the upper reaches (e.g., Upper versus Lower Augusta) where stream temperatures are initially cooler than air temperature. Warming rates diminish downstream as stream temperature approaches equilibrium with the air temperature.

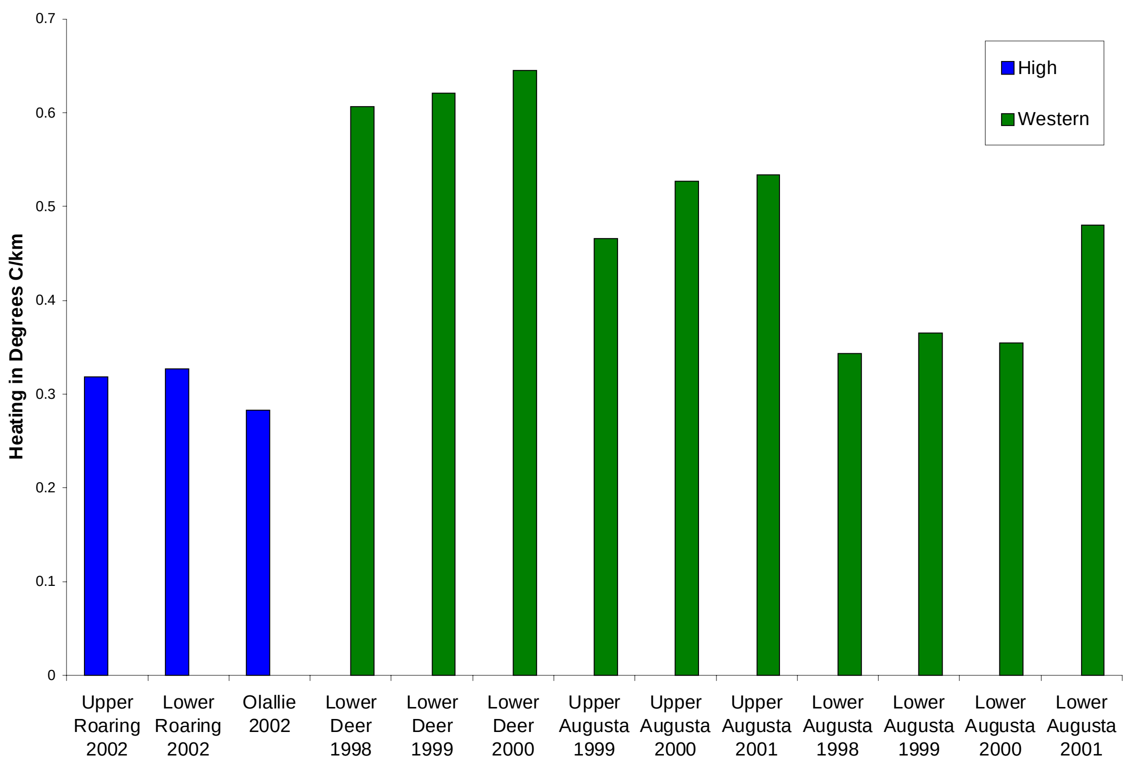


Figure 6. Longitudinal Downstream Heating for Both High and Western Cascades Stream Reaches in Degrees Centigrade per Kilometer

High Cascades streams also show much lower stream temperature variability at both the monthly and daily time step (Figure 7). For individual streams, diurnal variation in stream temperature decreases throughout the season, as the difference between air and groundwater temperatures decline

(Figure 8). For High Cascades sites variability increases with distance downstream from the spring source. Roaring River stream temperature, measured approximately 4 km from the spring source shows greater variability when compared with a site on the Olallie Creek measured only 2 km from spring head (Figure 8). Roaring River is significantly less variable in comparison with Hardy, a Western Cascades stream, which is approximately 6 km in length and has a much smaller drainage area (16 km^2) relative to Olallie Creek (29 km^2) and Roaring River (32 km^2). Greater variability of the Western Cascades stream reflects both the smaller unit and absolute discharge volumes as well as the lack of cold groundwater inputs.

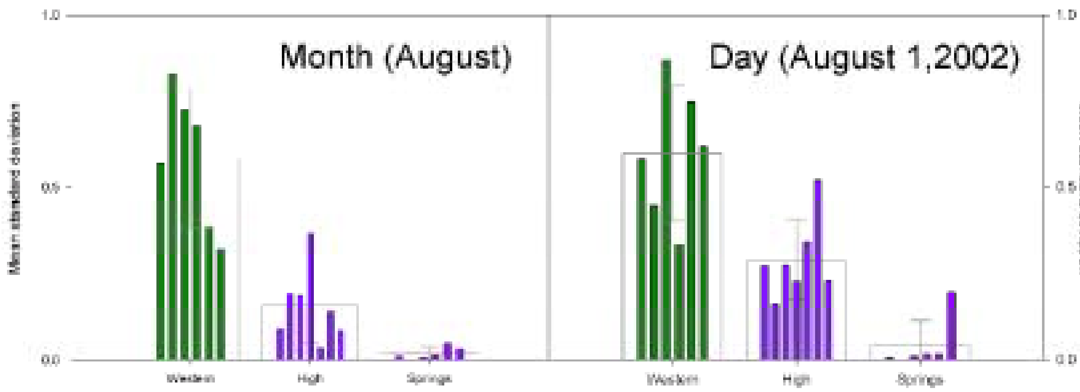


Figure 7. Mean of Standard Deviation in Daily Averages for the Month of August and Standard Deviation in Hourly Measurements for August 1, 2002, for Western Cascades (green), High Cascades (blue), and Spring Sites (purple) (aggregate mean and standard deviation shown in gray)

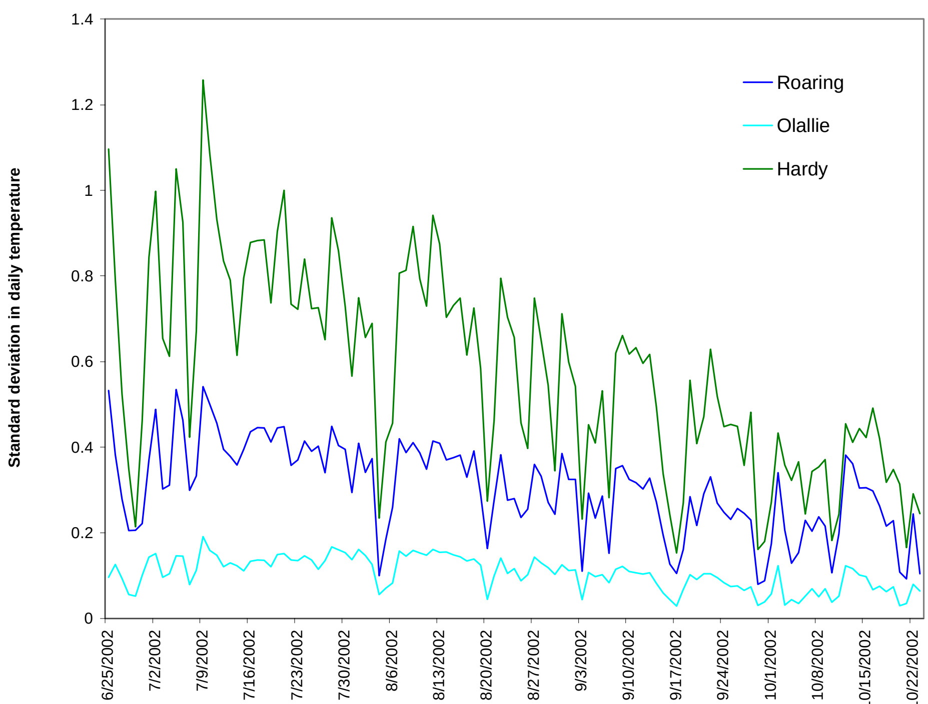


Figure 8. Standard Deviation in Average Daily Temperature for Roaring River (dark blue), Olallie Creek (light blue), and Hardy Creek (green) for Summer 2002

Finally, discharge measurements also reflect the unique behavior of High Cascades spring-fed streams and have implications for scaling stream temperature differences between the High and Western Cascades headwater streams (Table 1). High unit discharge values suggest that groundwater aquifers that support these springs may extend well beyond drainage areas as defined by surface topography. As with temperature, discharge volumes for High Cascades springs are more constant throughout the summer. In some cases, discharge actually increases over the summer, which may reflect a delayed snowmelt signal. This higher and more consistent discharge of the High Cascades streams has important implications for temperature since it means that based on drainage area these streams maintain a disproportionate percentage of the flow in the larger McKenzie River and ultimately the Willamette River. Streamflow from Roaring River, for example, contributed 1% of discharge in the entire Willamette River (based on USGS gage measurements near the outlet at Portland). Thus, colder and more consistent stream temperatures associated with High Cascades spring-fed headwater streams, play a disproportionate role in contributing to the temperature of larger tributaries (these implications will be investigated further in Part II of this project).

4.2 USDA Forest Service Stream Summary

Differences between High and Western Cascades streams also were evident in USDA Forest Service stream temperature monitoring from 1998 through 2001 suggesting that High Cascades streams are consistently colder in terms of both maximum and average stream temperatures (Figure 9). Although surface and groundwater dominated systems cannot be distinguished in this data set, the lower stream temperature associated with High Cascades streams is consistent with findings based on our stream temperature monitoring which show that many High Cascades streams are spring fed.

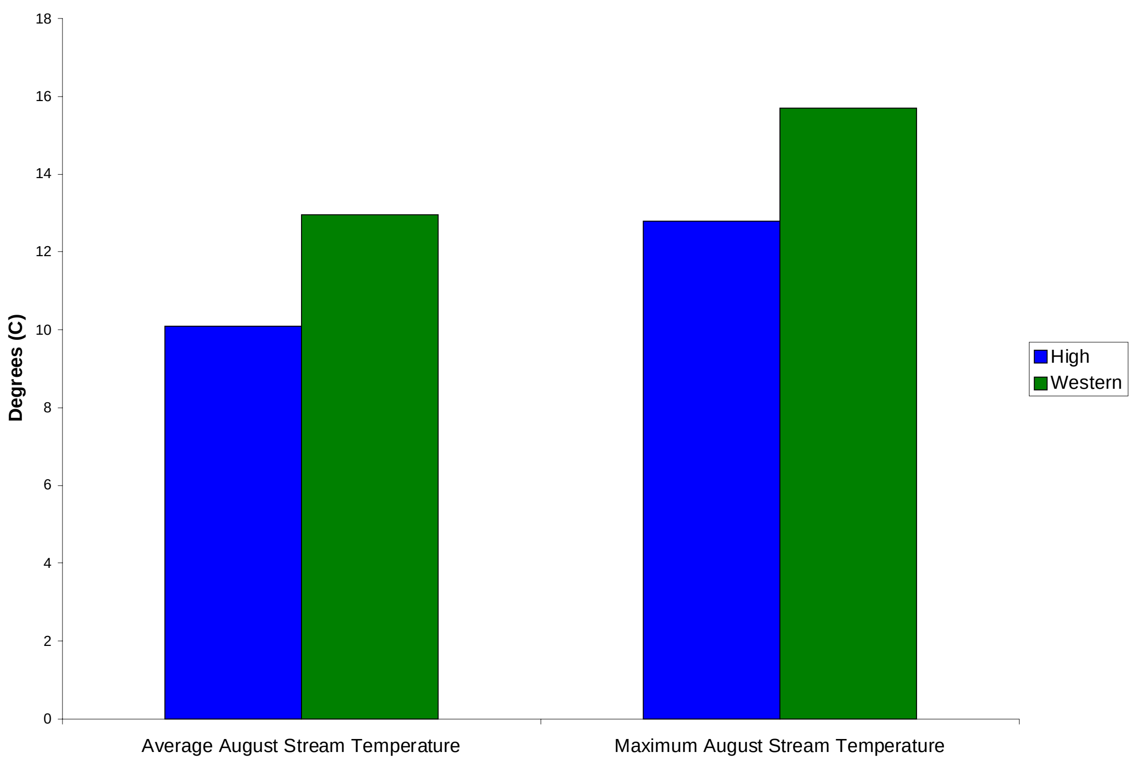


Figure 9. Average and Maximum August Stream Temperatures for All High Cascades and All Western Cascades USDAFS Sites, 1998-2001

4.3 Regression Analysis

4.3.1 *Maximum August Stream Temperature*

As expected, maximum August stream temperature for Western Cascades sites is positively and significantly correlated with both contributing area and air temperature (Figure 10; Table 3a; Table 3b). For these sites, spatial variation in maximum stream temperature can be partially explained as a function of the energy available for warming (air temperature) and the distance over which that warming is allowed to occur (as reflected by drainage area). Additional sources of variability may include stream shading characteristics, differences in drainage area–channel length relationships, differences in discharge, and variation in August air temperature. For High Cascades sites neither the relationship with air temperature nor with drainage area was statistically significant, which is consistent with the interpretation that the temperature of many High Cascades sites is dominated by groundwater spring contributions.

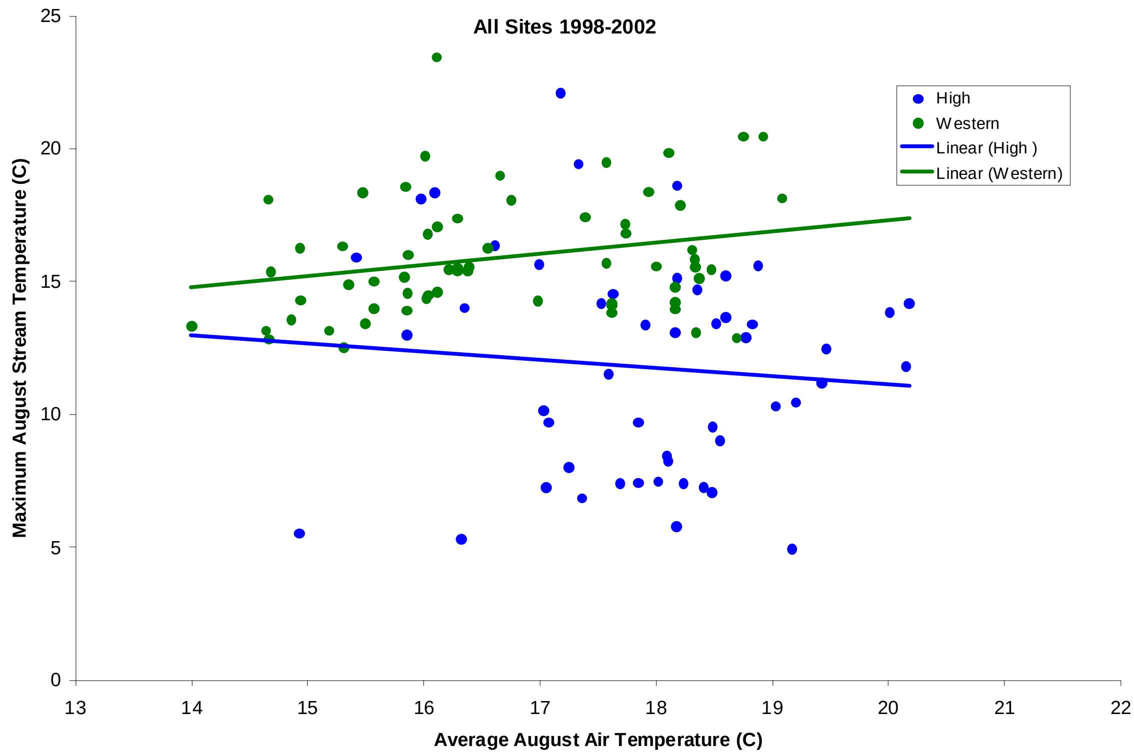


Figure 10. Maximum August Stream Temperature vs Average August Air Temperature for High and Western Cascades Sites, 1998-2002

Table 3a. Regression Results for Monthly Air (Ta)-Stream Temperature Regressions with and without Contributing Area for High and Western Cascades and All Sites

	Intercept	Ta Coefficient	Area Coefficient	R^2	p-Value
Without Area					
All	23.0938	-0.5229		0.03718	0.04075
High	17.2679	-0.306		0.007614	0.5468
Western	8.811	0.4264		0.0641	0.04527
With Area					
All	17.469692	-0.155494	-0.007374	0.1261	0.0006043
High	14.021263	-0.092507	-0.00312	0.03265	0.4584
Western	13.78293	0.05937	0.04723	0.1948	0.001503

Table 3b. Analysis of Daily Regression Results for High and Western Cascades and All Sites

	High Cascades	Western Cascades	All Sites
Mean Ta Coefficient	0.229152115	0.414355079	0.33061113
Variance of Ta Coefficients	0.037486847	0.010422425	0.031009878
Mean Standard Error	0.133061009	0.211002411	0.175759342
Mean Residual Error	0.02712677	0.049713704	4.453517478
Mean Intercept	5.046104231	3.964398254	4.453517478
Variance of Intercepts	3.628047409	4.217585676	4.209236584

4.3.2 *Daily Stream Temperature*

When air-stream temperature relationships throughout the summer are examined for individual streams, it is clear that warming of stream reaches in Western Cascades systems generally follows changes in air temperature (Figure 11a). Relationships between air and stream temperature are more pronounced at the daily rather than monthly time step. The high influx of groundwater in spring-fed sites again confounds this relationship for most High Cascades sites (Figure 11b). For sites measured as part of this project, High Cascades measurements can be classified as spring- versus surface-dominated systems (Figure 12). For surface-dominated systems, the relationship between stream and air temperature follows that of Western Cascades sites, further suggesting that groundwater rather than differences in climate are responsible for the distinctive stream-air-discharge area relationships for most High Cascades sites.

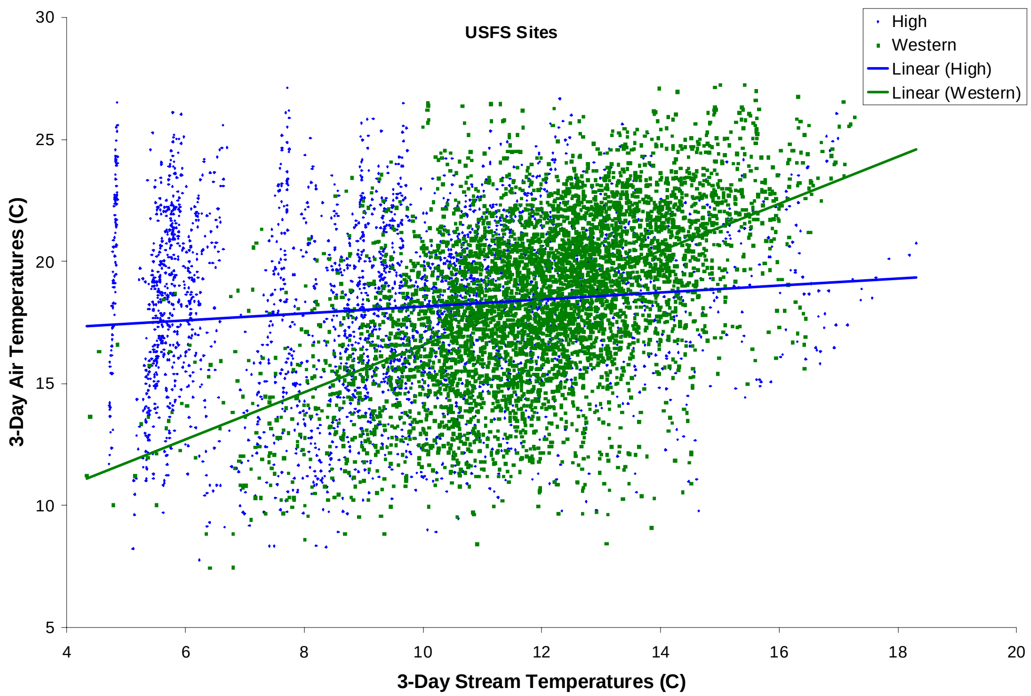


Figure 11a. 3-Day Running Averages for Air Temperature and Stream Temperature for High and Western Cascades USDAFS Sites, 1998-2001

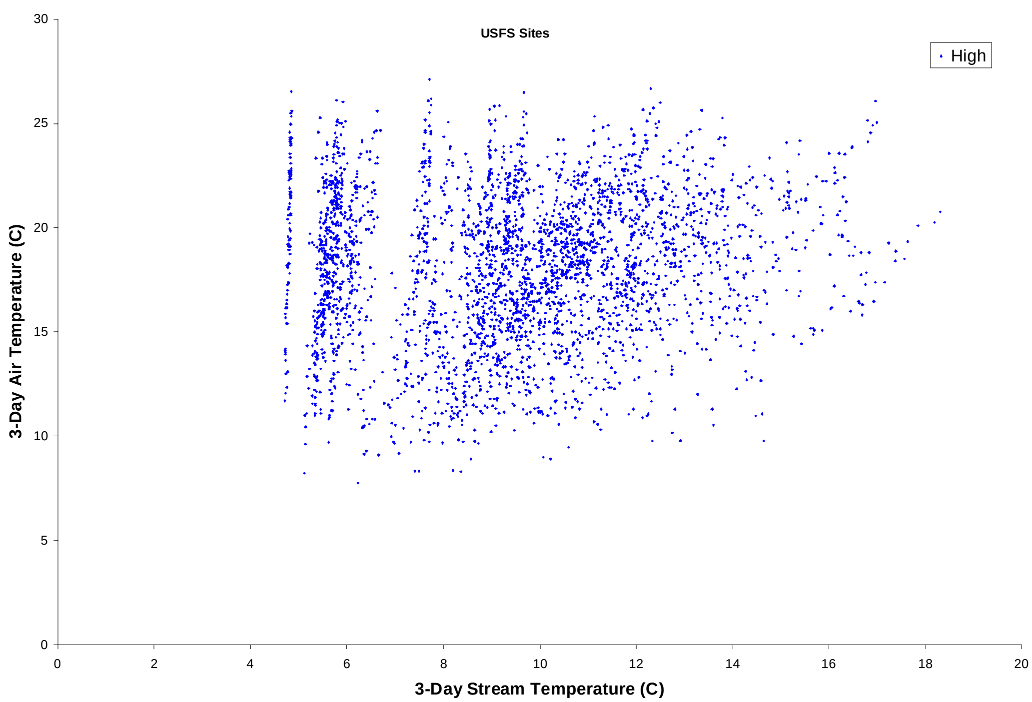


Figure 11b. 3-Day Running Averages for Air Temperature and Stream Temperature for High Cascades USDAFS Sites, 1998-2001

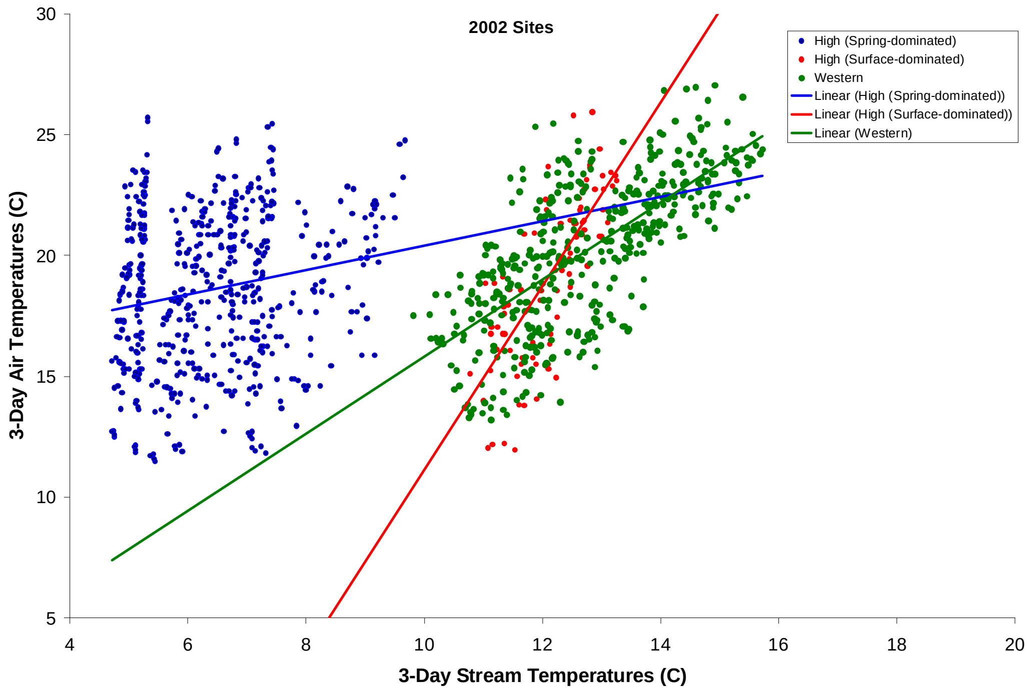


Figure 12. 3-Day Running Averages for Air Temperature and Stream Temperature for Spring-Dominated High Cascades, Surface-Dominated High Cascades, and Western Cascades Sites for 2002

All streams show a positive and statistically significant correlation between air temperature and stream temperature (Table 4). Western Cascades streams, however, show both a higher air temperature coefficient (Ta) and less spatial variation in that coefficient. Thus the relationship between air temperature and stream temperature is more sensitive and more consistent across different streams in the Western versus High Cascades (Figure 13). The relationship between the air temperature coefficient (Ta) and intercept also illustrates regional differences between High and Western streams (Figure 14). For the Western Cascades streams, warmer streams (higher intercept) are less sensitive (lower Ta coefficient) to air temperature. This may reflect spatial variation in the degree of prior (upstream) warming for each stream. For High Cascades streams, this relationship is much weaker. Further, there are a number of High Cascades streams that show both low intercepts and low Ta coefficients. Behavior in this population of High Cascades streams again suggests the role played by cold groundwater inputs, which both maintain lower stream temperatures overall and reduce the impact of atmospheric warming.

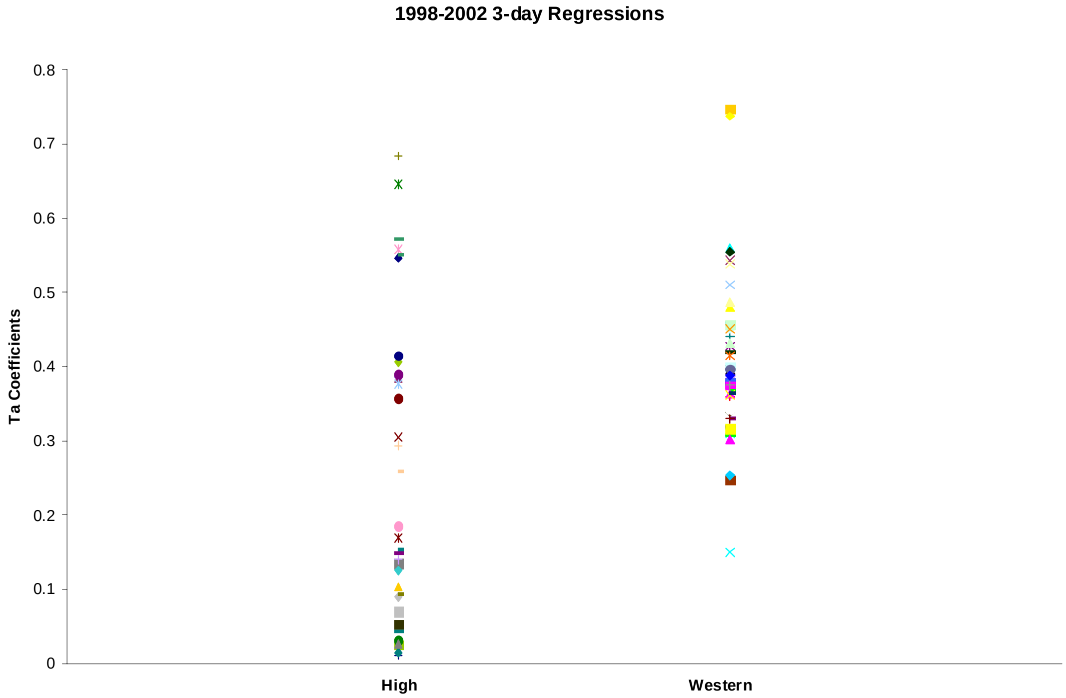


Figure 13. Comparison of Air Temperature Regression Coefficients for High and Western Cascades Sites, 1998-2002

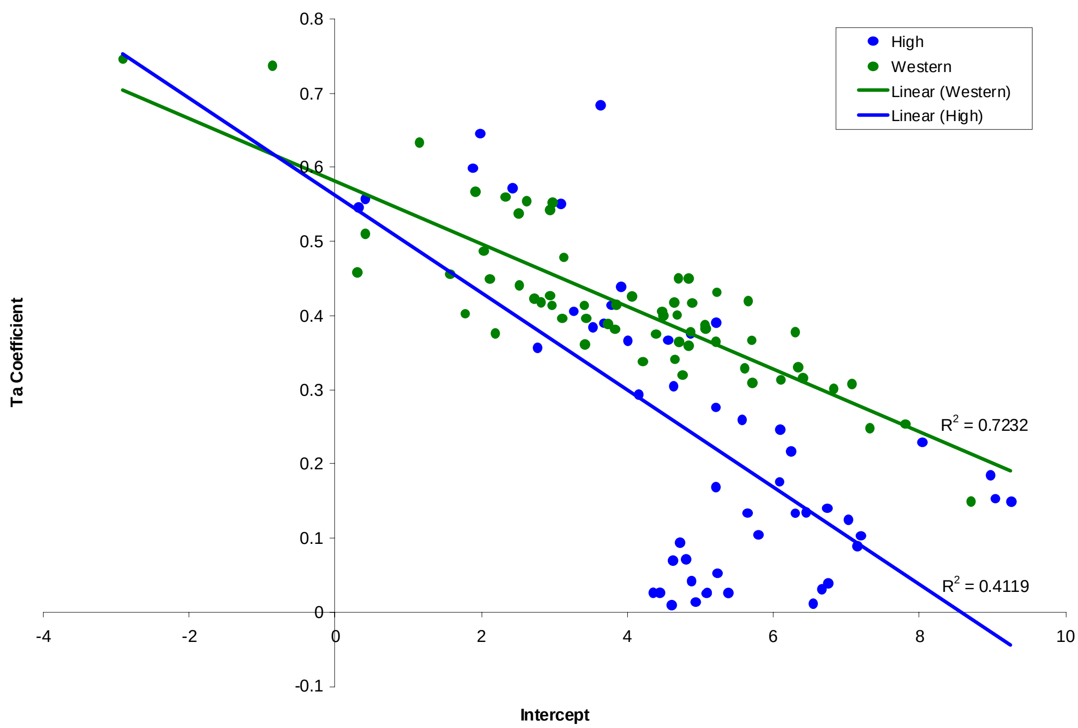


Figure 14. Ta Coefficient vs Intercept for High and Western Cascades Streams, 1998-2002

5.0 DISCUSSION AND CONCLUSIONS

Stream temperature at a particular point in time and space is a complex function of both energy inputs and their mediation by environmental factors (e.g., riparian shading, slope, aspect, channel geometry), and the input of water into the system (e.g., stream discharge, lateral groundwater and tributary inputs, hyporeic zone flow). While studies at the reach scale can incorporate field measurement of these multiple controls, regional analyses must often rely on landscape indicators of variability in one or two of the dominant controls on stream temperature. For the McKenzie River, this study suggests that the dominant control on variation in stream temperature is geology within this higher-order watershed.

Geology in the McKenzie River Basin, as well as in many of the east-west trending tributaries of the Willamette River, creates a particular hydrologic template. The younger High Cascades region, in addition to being higher in elevation, has a much less well-developed drainage network. Most precipitation, either as rain or snow, does not run off through surface channels but moves downward into deep groundwater reservoirs. Outflow from these reservoirs occurs as large, perennial springs. On the other hand, sufficient time has elapsed for the older Western Cascades landscape to develop a well-integrated surface water system. In this region, precipitation typically runs off as either surface or shallow subsurface flow (Tague and Grant in progress).

Results from this analysis illustrate that High Cascades spring-fed systems are significantly colder than shallow subsurface flow systems that drain the Western Cascades. The strength of geology as a control, as opposed to elevation-based differences in climate, is illustrated by a surface-dominated stream (Boulder Creek) in the High Cascades that shows a summer stream temperature pattern more similar to Western Cascades streams than neighboring spring-fed High Cascades streams (Figure 5). Since the majority of the streams and most of the discharge in the High Cascades region are sourced by groundwater springs; differences in High/Western Cascades stream temperatures generally correspond to differences in hydrology, one groundwater and spring dominated and the other dominated by shallow subsurface fed. Further research needed to quantify the spatial pattern and magnitude of groundwater spring drainage in the High Cascades region.

At the regional scale, we hypothesized that variation in air temperature and drainage area should account for much of the spatial and temporal variation in stream temperature. This follows other regional models where air temperature is used as a surrogate for available energy, while drainage area accounts for the length and time of travel time over which warming occurs. For the Western Cascades region, air temperature and drainage area relationships with stream temperature followed expected patterns and explained much of the temporal variation in responses for individual streams, although there was substantial variation in the strength of those relationships between streams. For the High Cascades systems these readily available measures were much less informative. The headwaters of the High Cascades systems have much greater volumes of flow, and associated drainage area/discharge relationships are also much more variable for these streams. Thus, although High Cascades streams do begin to approach air temperature values as water moves along a trajectory downstream from the spring source, spatial differences in initial headwater groundwater contributions confound predictions based on air temperature and drainage area alone. From the perspective of developing a regional scale model of stream temperature distributions, these results suggest that separate scaling methodologies will be needed for the two areas. In the High Cascades some estimate of the volume of groundwater contributions and how this varies seasonally will be required. Temperature of groundwater contributions, however, is remarkably constant between 4 and 6°C. Once groundwater discharge estimates are available, the impact of stream temperature can be readily assessed.

The process-based distinctions between High and Western Cascades systems developed here have implications for regional environmental management. Differences in the controlling mechanisms between these two systems mean that they will respond differently to environmental change. In general, differences in initial or baseline stream temperature means that the implications of warming of stream habitat will vary between the High and Western Cascades. For example, a 2°C warming from 10 to 12°C, as contrasted an increase from 5 to 7°C, may have dramatically different implications for aquatic habitat. Hence the systems will differ in their sensitivity to changes in riparian shading. Further, because the two regions are controlled by different hydrologic mechanisms, the magnitude and pattern of stream temperature response to climate change is also likely to differ between the two regions. These issues will be explored in more detail in the second part of this project, to be reported at its conclusion.

The above sections present a summary of research done during the Summer and Fall of 2002 as part of a NCASI-funded project. In addition to the temperature analysis described herein, we have undertaken background research on the development of a physically based stream temperature modeling approach. During Spring 2003, this model will be combined with the empirical results discussed above to explore how differences in groundwater temperature between High and Western Cascades mediate sensitivity to riparian shading. Part II of this project will also involve generalizing results from headwater stream analysis to larger, higher-order streams and combining this within a GIS to illustrate regional spatial variability in stream temperature throughout the Willamette River Basin.

Finally, Part II of this project will address a related hypothesis on the impact of High and Western Cascades on variability in stream turbidity. As discussed in the initial proposal, we will repeat the above analysis for stream sediment samples collected throughout fall, winter, and spring of this year. Analysis of the relationship between turbidity and geology will be done following spring 2003 water quality sample collection. Despite the lack of significant storm events this fall, we will collect a minimum of four samples, two each in winter and spring.

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