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Hydrogeologic controls on summer stream temperatures in the McKenzie River basin, Oregon

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Abstract:

Stream temperature is a complex function of energy inputs including solar radiation and latent and sensible heat transfer. In streams where groundwater inputs are significant, energy input through advection can also be an important control on stream temperature. For an individual stream reach, models of stream temperature can take advantage of direct measurement or estimation of these energy inputs for a given river channel environment. Understanding spatial patterns of stream temperature at a landscape scale requires predicting how this environment varies through space, and under different atmospheric conditions. At the landscape scale, air temperature is often used as a surrogate for the dominant controls on stream temperature. In this study we show that, in regions where groundwater inputs are key controls and the degree of groundwater input varies in space, air temperature alone is unlikely to explain within-landscape stream temperature patterns. We illustrate how a geologic template can offer insight into landscape-scale patterns of stream temperature and its predictability from air temperature relationships. We focus on variation in stream temperature within headwater streams within the McKenzie River basin in western Oregon. In this region, as in other areas of the Pacific Northwest, fish sensitivity to summer stream temperatures continues to be a pressing environmental issue. We show that, within the McKenzie, streams which are sourced from deeper groundwater reservoirs versus shallow subsurface flow systems have distinct summer temperature regimes. Groundwater streams are colder, less variable and less sensitive to air temperature variation. We use these results from the western Oregon Cascade hydroclimatic regime to illustrate a conceptual framework for developing regional-scale indicators of stream temperature variation that considers the underlying geologic controls on spatial variation, and the relative roles played by energy and water inputs. Copyright © 2007 John Wiley & Sons, Ltd.

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INTRODUCTION

The temperature of streams draining a landscape represents an integration of energy inputs from diverse sources, including solar radiation, and transfers of latent and sensible heat between the atmosphere and river channel environment. Emerging as an equally important control on stream temperature, however, is the character and extent of groundwater contributions. In many landscapes, groundwater is primarily derived from subsurface hillslope and hyporheic flows. But in landscapes dominated by volcanic or karst terrains, spring flow from large underground aquifers represents a major influx of cold water to channels and may have a significant effect on the stream temperature regimes. The actual temperature measured in a stream, therefore, reflects the interplay among solar, atmospheric and groundwater influences. Characterizing stream temperature and its geography requires understanding the relative importance of each of these factors and how they vary from landscape to landscape.

Stream temperature is a critical component of aquatic habitat. In the Pacific Northwest, the sensitivity of endangered fish species, such as salmon and bull trout, to changes in summer stream temperature continues to be an important environmental management issue, prompting regulatory and management agencies to establish temperature standards for streams and corresponding limits on land use activities that might have impacts on temperature regimes. At the reach scale, for example, riparian vegetation increases stream shading, thereby reducing stream temperatures. Because of this and other benefits, maintaining and restoring riparian vegetation is a major focus of forest management activities and regulations on both federal and private lands in the Pacific Northwest. As we describe here, however, broad-scale geological factors can strongly influence the intrinsic magnitude and variability of stream temperature at the landscape scale, so that establishing achievable temperature standards requires understanding of the underlying temperature 'template'. Furthermore, sensitivity of streams to changes in climatic or land-use forcing may vary across the landscape in response to this template.

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This study seeks to assess directly how regional differences in geology influence stream temperature regimes in headwater streams within the McKenzie River basin in western Oregon, a region dominated by both older and younger volcanic rocks. We focus specifically on summer stream temperatures, which are critical for aquatic ecosystems in this region and are linked to spatial differences in summer streamflow. This work is part of a larger study examining how the regional geological framework in western Oregon exerts a dominant control on the spatial variation in water quality and quantity. Previous work has established that summer streamflow regimes in the McKenzie vary systematically in relation to the underlying geology (Grant, 1997; Tague and Grant, 2004). Here, we examine the corresponding linkage between geological setting and the pattern of summer stream temperatures. We compare daily variations in temperature for streams in different geological terrains and explore how relationships between air temperature and stream temperature vary with hydrogeomorphic setting. These relationships are important, as air temperature often serves as a surrogate for a more complete accounting of a stream's thermal budget and is used in many empirical models that predict stream temperature in response to factors such as climatic change (Stefan and Preud'homme, 1993, Eaton and Scheller, 1996, Webb and Nobilis, 1997, Pilgrim *et al*., 1998).

GEOGRAPHIC SETTING

The McKenzie River is a tributary to the Willamette River in western Oregon (Figure 1). Within the 3470 km^2 basin, sharp contrasts in climate, geology and topography are observed along an east–west transect. The McKenzie generally flows westward, although the upper reaches of the river flow south along the fault-bounded western margin of the High Cascade province (Sherrod and Smith, 1989; Grant, 1997). The upper reaches of the McKenzie and its tributaries are within the High Cascades, a north–south-trending active volcanic arc with elevations >1200 m and underlain by glacial deposits and a thick sequence of <7-million-year-old blocky basaltic lava flows with extremely high porosities, hence water holding capacity, due to both high bulk rock permeabilities and extensive fracture networks (e.g. Saar and Manga, 1999). Springs dominate the High Cascades because the young age of the lava flows and extremely high permeabilities result in little drainage network development; consequently, virtually all precipitation infiltrates and becomes groundwater, re-emerging as springs further downslope (Jefferson *et al*., 2004, 2006). In the High Cascades, typically more than 75% of precipitation falls as snow. Further west, the river flows through the Western Cascades, an older uplifted and deeply dissected volcanic platform with elevations from 400 to 1500 m and underlain by 7–25-million-year-old deeply weathered but relatively impervious volcanic and volcaniclastic rocks. In the Western Cascades, elevations range across the typical transition between rain and snow, and watersheds within the region include both snow- and rain-dominated systems.

CONTROLS ON STREAM TEMPERATURE

The temperature of a stream is a function of energy inputs from various sources (Figure 2). Although net radiative and latent heat fluxes are often the most important controls (Hansen, 1988), groundwater inputs can play a key role in determining stream temperature. 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

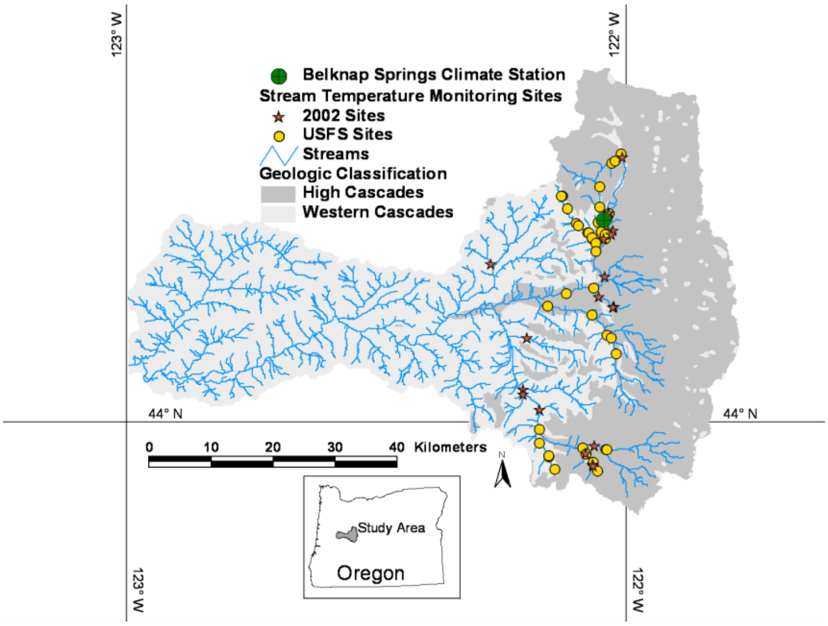

Figure 1. Stream temperature monitoring sites, located in High and Western Cascade geologic regions in the McKenzie River basin, Oregon

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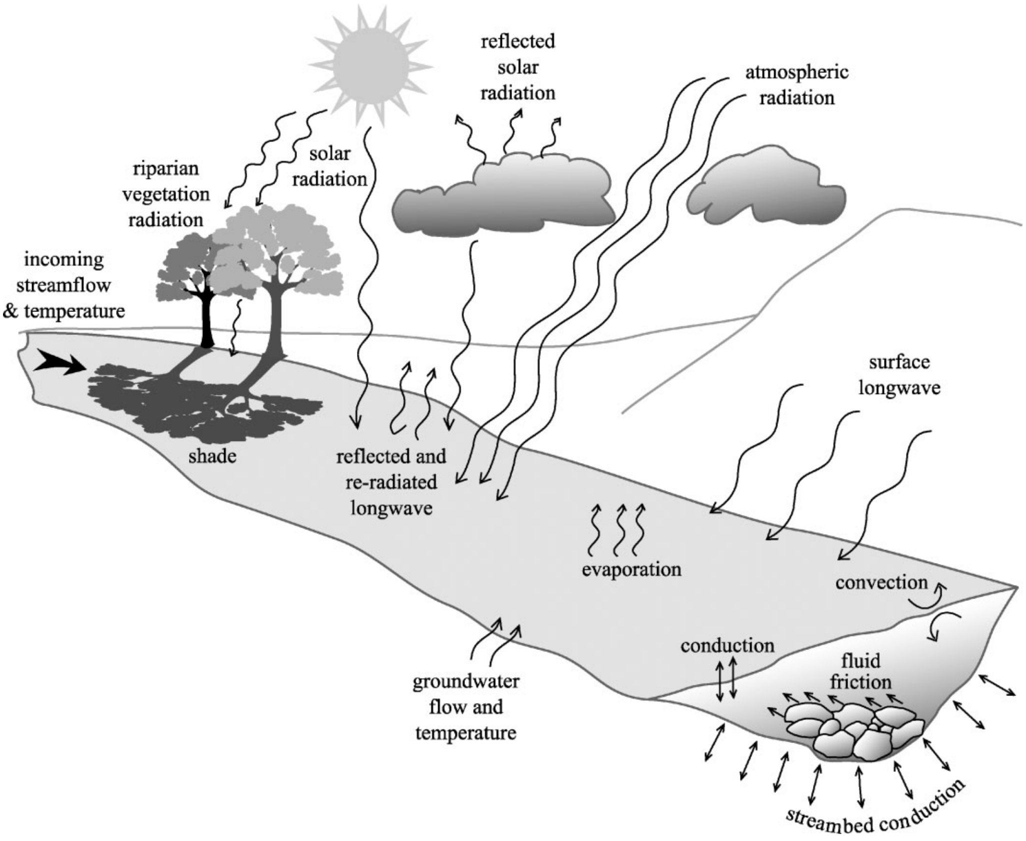

Figure 2. Energy balance inputs and outputs as controls on stream temperature

(Brown, 1969). One of the challenges in interpreting and managing the thermal regime of headwater streams is placing them within a larger biogeoclimatic framework that accounts for both groundwater inputs and radiation controls. 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 role of energy inputs on stream temperature in small watersheds or stream reaches where spatial variation in groundwater inputs or temperature is not a significant factor (Beschta and Taylor, 1988). Changes to stream temperature due to logging practices, for example, 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). But, in rivers draining the Cascade Range in Oregon, we expect that groundwater would play a major role in determining stream temperature regimes. Our previous studies have shown that, during the summer, the source of most of the water in the Willamette River system is from deep groundwater aquifers in the High Cascades (Tague and Grant, 2004). For example, over 83% of the August streamflow of the McKenzie River at the Vida US Geological Survey (USGS) gauge, a drainage area of 2400 km^2, is spring fed (Jefferson *et al.*, 2004, 2007). The flow at Vida represents, in turn, over 34% of the total mean August discharge of the Willamette River in Portland, over 275 km downstream (Moffatt *et al.*, 1990). Late-summer unit-area discharges are also significantly higher for many High Cascade as opposed to Western Cascade streams, and field surveys have found that most of these high discharge streams are sourced by large-volume springs, offering further evidence of distinctive deep groundwater flowpaths in the High Cascades (Jefferson and Grant, 2003; Grant *et al.*, 2004a,b; Jefferson *et al.*, 2004). The implications of these differences in hydrology for stream temperature have not previously been explored, although Manga (1997), in a study of spring-dominated streams on the east side of the Cascade crest, observed that High Cascade water is distinguished as being of uncommonly high quality, with low levels of dissolved solids and low temperatures.

In this study, we establish that characterizing spatial patterns and ultimately sensitivity of temperature regimes of headwater streams in the Willamette 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 air temperature–stream temperature regression models that illustrate differences between stream temperature regimes in the High and Western Cascades. We focus on the McKenzie sub-basin, where the preponderance of young volcanic rocks with extremely high permeabilities and water storage capacity in the headwaters maximally displays the contrast between High and Western Cascade lithologies. We argue, however, that our findings will be applicable to other large tributaries of the Willamette basin that include significant areas of both High and Western Cascades rocks in their drainage basins (Tague and Grant, 2004). More generally, we suggest that the ratio of water in a stream that is sourced from large-volume springs versus shallow subsurface flow represents a first-order control on stream temperatures, and that this finding should be broadly applicable to other volcanic and karst landscapes where both spring-fed and shallow subsurface flow streams coexist.

METHODOLOGY

Classification of High and Western Cascade geology

To delineate High versus Western Cascade geology, we used the same geological classification as described in Tague and Grant (2004). Briefly, we reclassified rock units from a 1 : 500 000-scale geologic map of Oregon (Walker and MacLeod, 1991) within the McKenzie basin as High or Western Cascade based on rock type and age using the following criteria. Volcanic rocks greater than 7 million years old were classified as Western Cascade, volcanic rocks younger than 2 million years old were classified as High Cascade, and rocks between 2 and 7 million years old were assigned to either category based on topographic position (i.e. ridge-capping basalts) or location. Individual watersheds and streams were identified as High or Western Cascade depending on whether greater than 50% of basin area was classified in either terrain.

Discharge and temperature data collection

We used a combination of historical temperature collected by the US Forest Service (hereafter referred to as 'USFS data') and our own field data collected in the summer of 2002 (referred to as the 2002 survey). All USFS and 2002 stream monitoring locations for both High and Western Cascades were in areas with relatively little or no forest harvesting activity, and had mature forests in their riparian zones. The USFS data consisted entirely of hourly and half-hourly stream temperature measurements collected at a total of 43 sites at a range of stream sizes throughout the McKenzie watershed that were monitored from 1 to 4 years during the period 1998–2001 (Figure 1, Table I). USFS stream temperatures were monitored using Onset® Optic StowAway® probes, each calibrated with a NIST thermometer, which have a manufacturer-reported accuracy of ±0·4 °C. On some streams (Lower Deer, Upper Augusta, Lower Augusta), multiple measurement sites distributed longitudinally permitted analysis of stream temperature changes with distance downstream.

To supplement USFS data, particularly in the High Cascades, where sampling densities were low, we installed temperature probes at an additional 19 sites in the summer of 2002 (Figure 1, Table II). These included several relatively high-elevation Western Cascade sites that are of particular interest in understanding of the High/Western Cascade differences in stream temperature because they reflect sites with Western Cascade geology but high-elevation (snow-dominated) climate. Stream temperature was monitored using HOBO® Water Temp Pro temperature probes, which have a manufacturer-reported accuracy of ±0·2 °C, at 1 h sampling intervals.

Although we relied on a broad-scale geological classification to distinguish High versus Western Cascade streams, it became apparent in the field and from the discharge data that not all streams in the High Cascades behaved similarly. Specifically, we distinguished High Cascade streams sourced from large-volume springs from those without apparent spring sources; the latter looked and behaved much more like Western Cascade streams. In the field, spring-fed streams had high-volume late-summer discharges that ran nearly bankfull, poorly defined floodplains typically supporting mature or old-growth forests, and stable woody debris accumulations, as evidenced by extensive moss blankets and nurse trees. In contrast, non-spring-fed High Cascade streams had very low late-summer streamflows, exposed cobble and boulder bars, well-developed floodplains typically colonized by alders and young conifers, and woody debris accumulations reflecting flotation and transport of individual pieces. Although not all springs were identified, mass balance calculations give confidence that we have identified most of the major spring-dominated systems in the upper reaches of the McKenzie basin underlain by High Cascade geology (Jefferson *et al.*, 2004).

These observations lead us to consider two methods of stream classification. Classification of streams based on High versus Western Cascade geology offers a method that can be readily applied using existing geologic maps, without extensive field survey. Classifying streams based on whether the source of late-summer water was spring fed (Sp) or shallow subsurface flow (Ssf) is a more process-based, hydrologic approach. This second approach is likely to be a stronger indicator of both discharge and temperature, but it requires a field survey of individual streams. Our 2002 sampling includes spring-fed and shallow subsurface-dominated High Cascade streams as well as shallow subsurface-dominated Western Cascade streams (Table II). Most High Cascade streams were spring dominated and we did not sample any spring-fed Western Cascade streams, which are uncommon and not likely to play a significant role in characterizing regional hydrologic and temperature patterns. We did not comprehensively survey the many USFS sites in the field and, thus, cannot classify them as shallow subsurface or spring fed using field criteria, but we did investigate and identify the source of one stream (Augusta Creek) that we used in the longitudinal analysis.

For several of the spring-fed streams (Upper Roaring, Lower Roaring and Ollalie) we installed temperature probes at the spring head for the summer of 2002; we also installed probes longitudinally downstream of these

Table I. USFS temperature monitoring sites

	Drainage area (km^2)	Dates of record (Jul–Sep)
High Cascade streams		
McKenzie River above confluence with South Fork McKenzie River		
Ikenick Creek		
above marsh	2·6	2000
below marsh	2·8	2000
below highway 126	14·6	2000
Kink Creek	31·5	1998
McKenzie River above Trailbridge Reservoir	415·7	1998–2001
Sweetwater Creek	7·1	1998–1999
Smith River		
above Smith Reservoir	35·5	1998–2001
base of Smith Reservoir	46·9	1998–2001
above Trailbridge Reservoir	51·8	1999–2001
McKenzie River Below Trailbridge Reservoir	481·3	1998–2001
Olallie Creek	29·5	1998
Lost Creek	199·4	1998
McKenzie River near Ranger Station	897·2	2000–2001
Cadenza Creek	2·2	1998–2001
Horse Creek		
above Pothole Creek	142·4	1998
above Castle Creek	160·7	2001
below Spring Creek	357·0	2001
below Road 2638	386·5	1998–2001
South Fork McKenzie River drainage		
South Fork McKenzie	125·9	1998
Elk Creek	51·2	1998
Augusta Creek		
headwaters	12·2	1998–2001
above Grasshopper Creek	18·3	1999–2001
below Grasshopper Creek	28·1	1998–2001
Roaring River		
upper site	6·4	1998
McBee Creek	6·4	1998
Moss Creek	5·5	1998
lower site	34·3	1998, 1999, 2001
Western Cascade streams		
McKenzie River above confluence with South Fork McKenzie River		
Castle Creek	6·0	2001
Deer Creek Drainage		
below Cadenza Creek	9·8	1998–2001
Carpenter Creek	1·7	1998–2001
above County Creek	28·2	1999–2001
County Creek	7·7	1998, 2000, 2001
above Fritz Creek	39·0	Aug–Sep 2001
Fritz Creek	6·0	1998, 1999, 2001
above Budworm Creek	46·5	1998–2001
Budworm Creek	7·8	1998–2001
below Budworm Creek	55·3	1998–2000
mouth of Deer Creek	58·6	1998–2001
South Fork McKenzie River Drainage		
Grasshopper Creek	9·8	1998, 1999
Augusta Creek below Pass Creek	36·1	1998, 2000, 2001

springs to examine how temperature changes with distance from source. This longitudinal sampling provided information on the relative warming along each tributary and provided information on groundwater contributions in the High Cascade system.

Air temperature data

Air temperature was used as a surrogate to account for variation in energy inputs to stream heating. Relationships between stream and air temperature are commonly used in regression-based models of stream temperature. Point measurements of daily air temperature were obtained from the Belknap Springs National Climatic Data Center (NCDC) site (Figure 1). Spatial interpolation of these values was based on the Parameter-elevation Regressions on Independent Slopes Model (PRISM), a widely used tool that combines point meteorologic data, surface

Table II. Sites monitored in 2002

	Drainage area (km^2)	Period of record (2002)
High Cascade springs		
Great Springs (Clear Lake–McKenzie River)	207·8	16 July–September
Tamolitch Pool (McKenzie River)	383·0	16 July–September
Olallie North (Olallie Creek)	12·4	August–September
Olallie South (Olallie Creek)	15·9	August–September
Lost Springs	0·0	July–September
Roaring Springs (Roaring River)	6·4	August–September
High Cascade Streams		
Bobby Creek	31·5	July–September
Olallie Creek	29·7	July–September
Boulder Creek	32·7	July–September
White Branch	189·3	24 July–September
Lost Creek	195·8	July–September
South Fork McKenzie	136·5	July–September
Roaring at Roaring Ridge Trail	16·7	August–September
Roaring at Road 19	32·8	July–September
Western Cascade streams		
Rebel Creek	16·1	July–September
Hardy Creek	16·8	July–September
French Pete	81·6	July–September
East Fork South Fork McKenzie	45·4	July–September
Tidbits Creek	25·4	July–September

topography and other information to generate spatial estimates of climate variables (Daly *et al.*, 1994). The most recent available PRISM data set was for summer 1997. We assume that spatial variation in summer air temperature is constant at interannual time scales; 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 1 km PRISM cell, we used a standard (6·4 °C km^{-1}) elevation lapse rate for temperature and assumed that PRISM values reflect air temperature at the mean elevation within the PRISM grid cell. Thus, air temperature at a given stream site is calculated as

$$\begin{aligned} T_{\text{air}}[\text{site}] = T_{\text{air}}[\text{Belknap}] + \{&T_{\text{air}}[\text{PRISM-site}] \\ &- T_{\text{air}}[\text{PRISM-Belkap}] + (\text{elev.PRISM-site} \\ &- \text{elev.site}) \times \text{airT.lapse.rate}\} \qquad (1) \end{aligned}$$

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-site] and T_{air}[PRISM-Belknap] are the respective PRISM estimates of 1997 mean monthly air temperature for the grid cell containing the monitoring site and the Belknap NCDC station, 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.

Spatial regime regressions

In regions with little heterogeneity in stream temperature regimes, a single regression model of air temperature against stream temperature can be used to represent the air temperature–stream temperature relationship over an area as large as a river basin (Stefan and Preud'homme, 1993). In order to test whether one air temperature/stream temperature model applies for both High Cascade and Western Cascade provinces in the McKenzie River basin, a spatial regime regression model (Anselin, 1988) was used for each year from 1998 to 2001, using the USFS data and the 2002 survey data. Spatial regime regression models were developed separately for each year to account for differences in the population of streams for which monitoring data were available.

To preserve independence, for each year we excluded multiple sites on nearby reaches in the same stream, using only the most upstream site. Additional sites (on the same stream) were added only if these sites represented a contributing area greater than 150% of that for the upstream site. The total number of sites used for each year was between 18 and 26.

The general equation for each of the yearly spatial regime regressions is given as:

$$T_{w_i} = \beta_0 + \beta_1 T_{a_i} + \beta_2 \text{geo}_i + \varepsilon_i \qquad (2)$$

where T_{w_i} and T_{a_i} are 3-day running averages of mean daily stream and air temperatures respectively and geo_i is a bivariate geology designation of '0' for sites with contributing High Cascade area less than 50% and '1' for sites with contributing High Cascade area greater than 50%. The P-value of β_2 was analysed to determine the significance of the binomial classification with the hypothesis: $H_0 : \beta_2 = 0$.

In addition to spatial regime regressions, site-specific regression relationships between daily stream temperature and air temperature throughout the summer period (July–September) were computed for each site. Variation

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in mean regression coefficients, as well as standard error, was then compared for the High and Western Cascade stream populations.

For all regression analysis, both the air and stream temperature data sets were aggregated to 3-day moving averages. The 3-day averages were selected for these regressions to minimize the fact that stream temperature lags air temperature and to remove the fact that daily variations in air temperature typically are greater than those in stream temperature.

RESULTS

We begin with a broad-brush comparison of Western and High Cascade streams and then look in detail at different stream types within these geographic regions. Mean and maximum daily stream temperatures in August are consistently greater for Western Cascade streams relative to those whose contributing area falls primarily within the High Cascade geologic region (Figure 3). Population means are statistically different at a 99% confidence level (*t*-test) for all years and for both mean and maximum August temperature. The population of streams included in the 2002 data set is the most spatially complete, as it includes a greater representation of High Cascade spring-dominated streams that were not monitored as part of the USFS data set. For the 2002 survey, maximum August stream temperatures for Western Cascade streams, measured in degrees Celsius, are almost twice those of High Cascade streams.

Average daily stream temperatures for streams and spring sites throughout the 2002 summer season illustrate that the temperature regime of Western Cascade streams is both warmer and more variable at multiple temporal scales when compared with High Cascade streams (Figures 4 and 5). Temporal variation in stream temperature for Western Cascade sites can range over 7–8 °C over the summer and early fall, and these streams consistently remain warmer than any of the spring-dominated High Cascade streams during this period (Figure 4). The two populations clearly segregate, with only one High Cascade stream (Boulder) behaving like a Western Cascade stream; field surveys showed that Boulder Creek was the only High Cascade stream not fed by groundwater springs in the 2002 data set. Temperatures from the groundwater springs that are the sources for most

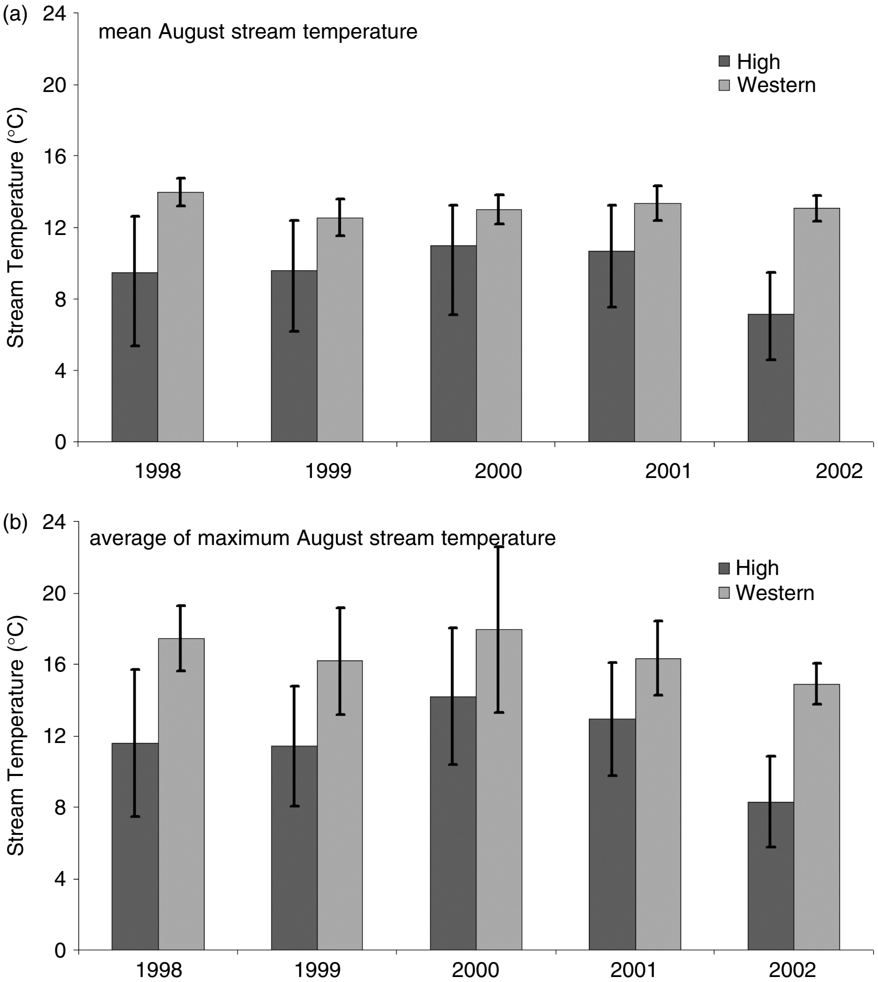

Figure 3. Average values for High and Western Cascade streams of (a) mean and (b) maximum August stream temperature, with one standard deviation confidence bounds. Note that, owing to limitations in temporal coverage of available data, the specific population of streams included in computation of average temperatures varies from year to year

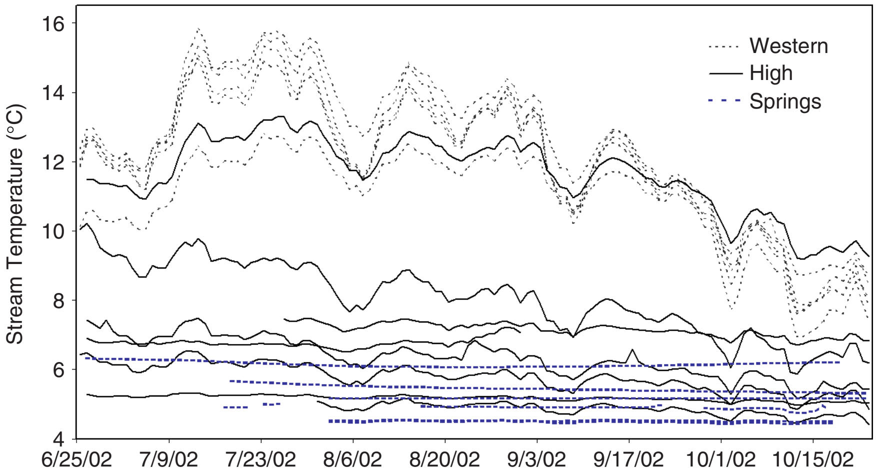

Figure 4. Average daily stream temperatures of streams monitored during 2002. Western Cascade dominated streams are shown in faint dotted lines, High Cascade streams in dark solid lines and spring systems in dark dotted lines

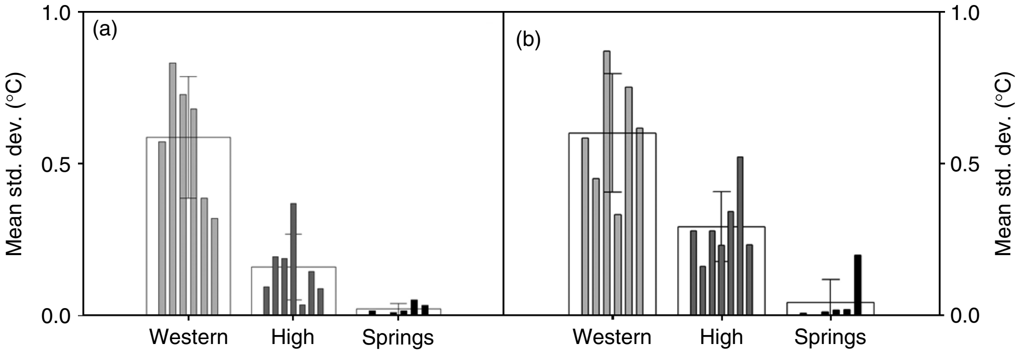

Figure 5. Temporal variation in August stream temperature for Western Cascades, High Cascades and springs shown as population mean standard deviation of (a) daily stream temperatures for August 2002 and (b) hourly stream temperatures on 1 August 2002

High Cascade streams show near-constant temperatures of 4–6 °C throughout the season (Figure 4). The contrast between Boulder Creek and other nearby High Cascade streams at similar elevations suggests that the presence of deep groundwater springs (rather than the shift to a snowmelt-dominated system) maintains the colder temperatures typical of most High Cascade streams during the summer.

During the hot, dry summer in western Oregon, there is significant temporal variation in stream temperature following both diurnal cycles of solar radiation and night-time cooling, and day-to-day trends in air temperature and cloud cover. Western Cascade streams show greater temporal variation at both daily (Figure 5a) and hourly (Figure 5b) time steps. Diurnal variation in stream temperature decreases throughout the season, following a decrease in solar radiation inputs and a decline in difference between air and groundwater temperatures (Figure 6).

For High Cascade sites, diurnal 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 Olallie measured only 2 km from the spring head (Figure 6). Stream temperatures vary much less in Roaring River, however, in contrast to Hardy, a smaller Western Cascade stream approximately 6 km long that has a much smaller drainage area (16 km^2) relative to Ollalie (29 km^2) and Roaring (32 km^2). Greater variability of the Western Cascade stream reflects both the smaller unit and absolute discharge volumes and the lack of cold groundwater inputs (Tague and Grant, 2004).

Longitudinal measurements of stream temperature along reaches without any significant tributary inputs also show that High Cascade spring streams generally warm more slowly than Western Cascade streams (Figure 7). For Western Cascade 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 more closely approaches equilibrium with its environment.

As with temperature, discharge volumes for High Cascade springs are more constant throughout the summer (Tague and Grant, 2004). This higher and more consistent discharge of the High Cascade streams has important implications for temperature, since it means that these streams maintain a disproportionate (based on drainage area) percentage of the flow in the larger McKenzie

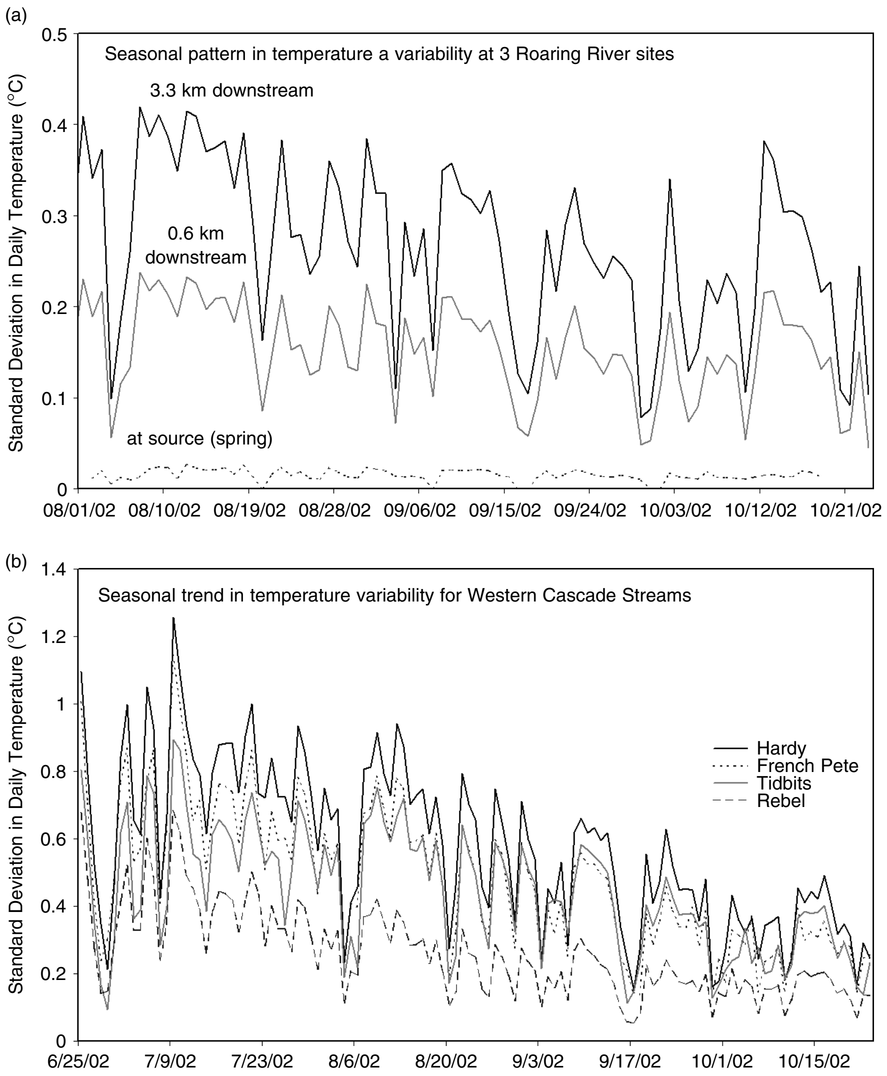

Figure 6. Daily standard deviation in hourly temperature for (a) three Roaring River (High Cascade spring-fed) sites and (b) four Western Cascade shallow subsurface-dominated streams for summer 2002

and ultimately the Willamette. Streamflow from Roaring River, for example, contributes 1% of the unregulated late-summer discharge to the entire Willamette, based on USGS gauge measurements near the outlet at Portland). Thus, the colder and more consistent stream temperatures associated with High Cascade spring-fed headwater streams play a major role in cooling larger order streams (Farrell, 2004).

Spatial regime regressions

A spatial regime regression for each year from 1998 to 2001 illustrates a consistent linear relationship between 3-day running averages of stream temperature and air temperature (Figure 8, Table III). For each year, spatial regime regressions also show that geology classification is significant at the 99% confidence level.

The scatter plots of 3-day running average stream temperatures as a function of 3-day running averages of air temperatures (Figure 8) suggest that there are two distinct populations of High Cascade streams. For each year, the coldest spring-fed High Cascade streams appear as the horizontal clusters at the bottom of the scatter plots. These streams, such as Anderson, Sweetwater, and Olallie Creeks, are influenced so little by air temperature fluctuations or other sources of heat that the distinctive temperature of their spring source is visible at all ranges of air temperatures. Note that no Western Cascade streams exhibit this insensitivity to air temperatures. Field surveys of High Cascade streams that do show a stronger

Table III. Spatial regime regression between 3-day running average of air temperature (Ta), geology (Geo) and stream temperature. Note that, owing to limitations in temporal coverage of available data, specific population of streams included in computation of average temperatures varies from year to year

Year	Intercept	Ta coefficient	Geo coefficient	Geo *P*-value
1998	8·40	0·230	−3·83	$<2 \times 10^{-16}$ [a]
1999	5·42	0·295	−2·32	$<2 \times 10^{-16}$ [a]
2000	5·76	0·351	−1·47	$<2 \times 10^{-16}$ [a]
2001	7·83	0·238	−2·25	$<2 \times 10^{-16}$ [a]

[a] 99% significance level.

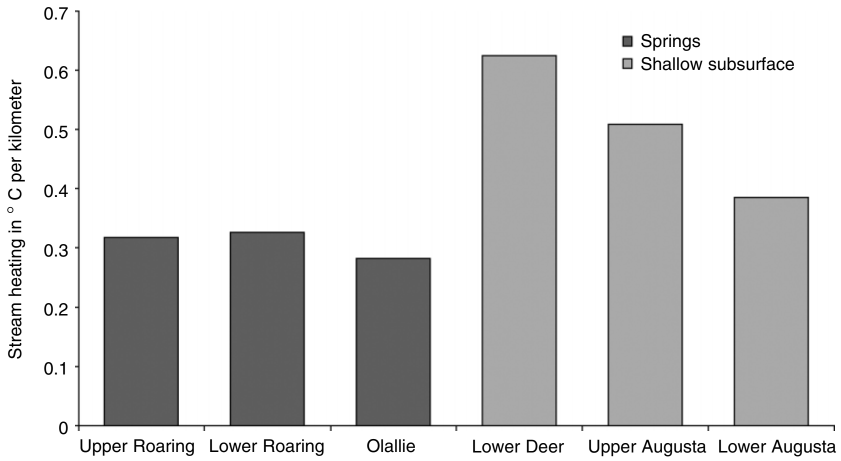

Figure 7. Longitudinal downstream heating for spring-fed and shallow subsurface-dominated stream reaches; computed as increase in degrees Celsius per kilometre stream length for average August temperatures. Spring-fed values are for 2002, and shallow subsurface values are for averages of 3 or 4 years from 1998–2001

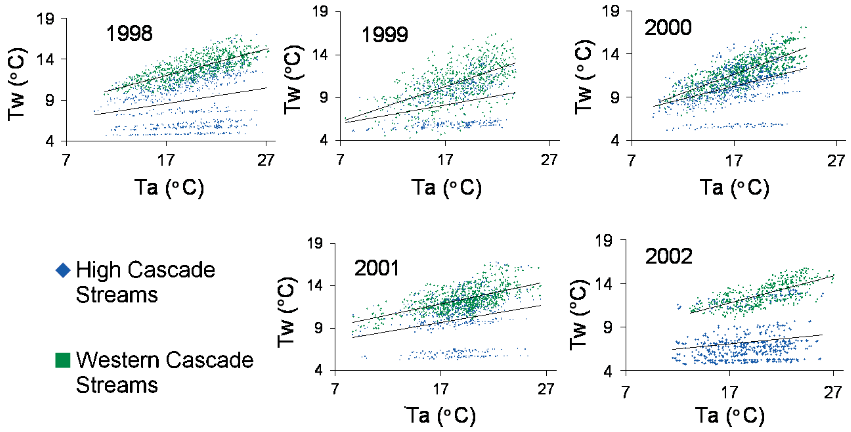

Figure 8. Air temperature (Ta)–stream temperature (Tw) relationships for High and Western Cascade streams. Stream temperatures reflect 3-day running averages for USFS sites monitored from 1998 to 2001 and our 2002 survey sites

positive relationship with air temperature confirm that they are not fed by large spring systems.

When air–stream temperature relationships are examined for individual streams, all streams show a positive and statistically significant correlation between air temperature and stream temperature (Table IV). Western Cascade streams 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 both stronger and more consistent among Western versus High Cascade streams. High Cascade streams tend to show greater spatial variation in their air temperature sensitivity (Ta coefficient). Between-stream differences in air–stream temperature relationships for High Cascade stream may reflect the greater importance of discharge and distance from spring source as controls on stream temperature for spring-fed streams. Including distance from spring source and drainage area in regression relationships with air temperature improves predictability for spring-fed streams but not for shallow subsurface flow-fed streams (Figure 9). Note that distance from source measurements is not applicable for Western Cascade stream sites. For shallow subsurface streams of the Western Cascade, however, discharge is strongly correlated with drainage area (Tague and Grant, 2004). Between-stream differences in drainage area did not improve prediction of stream temperature variability for Western Cascade streams (not shown).

Table IV. Geologic specific air–stream temperature relationships for High Cascade sites, Western Cascade sites, and all sites. All Ta coefficients are significant at $P < 0{\cdot}001$

	High Cascades	Western Cascades	All sites
Mean Ta coefficient	0·23	0·41	0·33
Minimum Ta coefficient	0·02	0·34	0·02
Maximum Ta coefficient	0·92	1·09	1·09
Variance of Ta coefficients	0·04	0·01	0·03
Mean standard error	0·13	0·21	0·18
Mean residual variance	0·03	0·05	0·04
Mean intercept	5·05	3·96	4·45

DISCUSSION AND CONCLUSIONS

This study demonstrates that a broad-scale geological classification reveals a surprising amount of information

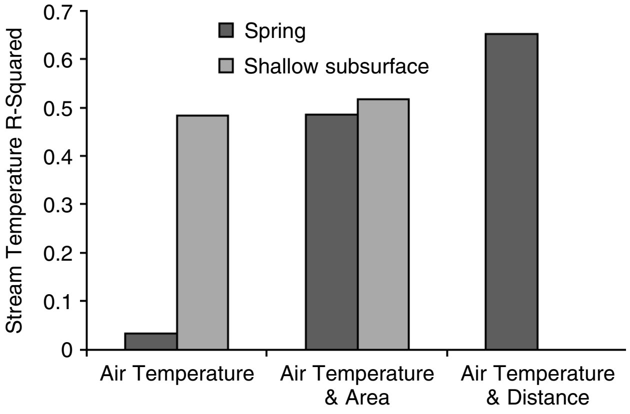

Figure 9. Stream temperature variance explained by air temperature, and by auxiliary regressions of stream temperature against air temperature and watershed area (Air Temperature & Area) and air temperature and distance from spring (Air Temperature & Distance, for spring-dominated streams only)

about stream temperature regimes. Distinguishing streams by whether they are sourced from deep groundwater reservoirs emerging as high-volume springs versus shallow subsurface flow is even more instructive, however, and provides a context for interpreting both longitudinal and spatial trends in stream temperature over a large watershed. For both large and small rivers in volcanic terrains with a range of rock ages, such as the McKenzie watershed, geologically mediated differences in hydrology are the dominant control on variation in stream temperature. Differences in both maximum and mean summer stream temperatures between High and Western Cascade regions are statistically significant. This is consistent with earlier analyses of discharge patterns that suggested strong within-region contrasts between High and Western Cascade areas (Tague and Grant, 2004). Closer examination of individual streams within these broad geologic classifications reveals that stream temperature differences more closely reflect differences between streams fed by deep groundwater and shallow subsurface flow systems. Because Western Cascade streams tend to be dominated by shallow subsurface flow and High Cascade streams tend to be dominated by deep groundwater emerging as springs, broad geologic classifications generally reflect summer stream temperature patterns. The strength of geology as a control, as opposed to elevation-based differences in climate, is illustrated by surface-water-dominated streams such as Boulder Creek in the High Cascades that show a summer stream temperature trajectory more similar to Western Cascade streams than neighbouring spring-fed High Cascade streams (Figure 6). Since the majority of the streams, and certainly most of the discharge, in the High Cascade region are sourced by groundwater springs, High Cascade/Western Cascade distinctions in stream temperature generally correspond to shallow subsurface/groundwater spring-fed differences. Future research will explore the underlying mechanisms through which geology and hydrology combine to produce differences between High and Western Cascade stream temperatures, including the role played by discharge directly and indirectly as a control on stream channel characteristics.

In the Oregon Cascades, a variety of models are used to investigate stream temperature regimes that support fish and aquatic invertebrate habitat (e.g. Rounds *et al.*, 1999; Rounds and Wood, 2001). It is clear from this study that these approaches must address critical distinctions between High and Western Cascade streams. Differences in the controlling mechanisms between these two systems mean that they will respond differently to environmental change, including local changes in riparian shading and broader regional-scale climate change. The results from this study address a key management issue: establishing stream temperature standards for water quality. State and federal resource managers are required to develop standards under the Clean Water Act, and a number of approaches have been developed, as reviewed in Sullivan *et al.* (2000). Virtually all such approaches rely on empirical and historical stream temperature records coupled with analysis of biological response to elevated temperatures. Such risk assessment approaches may take other factors controlling stream temperature into account, e.g. prevalence of riparian shading or channel geometry. However, geologically determined stream temperature regimes, as discussed here, are typically not recognized as overarching controls on stream temperature regimes, except insofar as they affect the empirical record. Geology is not even identified as a factor influencing stream temperatures in standard manuals of field and analytical procedures for stream temperature studies (e.g. Bartholow, 1989). The work presented here suggests that, to be effective, stream temperature standards and ranges need to be referenced to specific landscapes and geologies. Otherwise, standards may be set unrealistically high or low, or causative or restorative factors (changes in riparian shading) may be inaccurately identified as causes or cures for identified temperature departures.

Results from this research also have broad methodological implications for estimating spatial patterns of stream temperature at the regional scale in areas where there are contrasting hydrologic regimes (Ice *et al.*, 2004). Stream temperature at a particular point in time and space is a complex function of both energy inputs and their mediation by environmental factors (i.e. riparian shading, slope, aspect, channel geometry), and the input of water into the system (i.e. stream discharge, lateral groundwater and tributary inputs, hyporheic zone flow). Most physically based models of stream temperature do include the potential effect of groundwater inputs. However, such modelling is dependent on the quality of measurement or estimate of key inputs. *A priori* understanding of the relative importance of specific controls (e.g. latent heat flux losses, riparian shading or groundwater inputs) allows for efficient model implementation and accurate interpretation of results. Whereas 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. Air temperature is commonly used as an indicator of spatial variation in regional energy inputs, which are often the dominant source of variation within larger watersheds. If there are significant differences in the source and spatial distribution of groundwater inputs, then air temperature alone may not be a good predictor of stream temperature patterns. In these cases, landscape indicators must incorporate the combined effect of distinct discharge regimes and air temperature patterns, as a surrogate for energy inputs, on stream temperature.

In this study, the geologic setting of the Cascades generates two distinctive flow regimes: spring-dominated streams, which maintain relatively high-volume cold groundwater inputs throughout the low-flow summer season, and shallow subsurface-dominated streams with much lower volume and warmer summer flows. Partitioning the landscape into functional hydrologic units ('hydrologic landscapes') is emerging as a major new paradigm for interpreting regional differences in flow regimes (Wolock *et al.*, 2004). In the Cascade example, a geologic framework provides a relatively simple means to classify the landscape into shallow subsurface- and spring-dominated systems that are associated with distinct flow volumes and temperatures.

A conceptual model of regional-scale stream temperature patterns must consider how this geo-hydrologic template mediates stream temperature both directly and via its control on the response of the stream to energy inputs (Figure 10). At the stream source, the spring-dominated streams have both lower initial temperatures and significantly higher volumes per unit drainage area. Individual streams warm as water travels downstream until stream temperatures reach equilibrium. Lower volume streams tend to warm more quickly, since lower discharge volumes generally translate into higher width-to-depth ratios and greater radiation input per volume.

Scaling up to look at landscape spatial patterns of stream temperature requires interpretation of these difference in individual stream behaviours given a range of energy forcing conditions (represented as higher Ta coefficient in air temperature regression relationships). Because spring-dominated streams tend to warm more slowly and are farther from equilibrium with air temperature, the time/distance over which warming occurs becomes the dominant factor in distinguishing the temperature of individual stream locations. This is not the case for shallow subsurface streams, where between-stream variability is best characterized by spatial variation in air temperature. Thus, prediction of stream temperature variation within this landscape requires partitioning the landscape into two end-members: one where variation in energy forcing, as reflected in measures such as air temperature, tends to dominate, and a second where a metric characterizing time/distance over which warming occurs, such as drainage area or distance from spring source, best characterizes temperature patterns. In the first end-member, streams are likely to be closer to equilibrium with air temperature, and warm more quickly. Although these results are specific to the Cascade hydroclimatic regime, they illustrate a conceptual framework for developing regional-scale indicators of stream temperature variation that considers the underlying geologic controls on spatial variation, and the relative roles played by energy and water inputs.

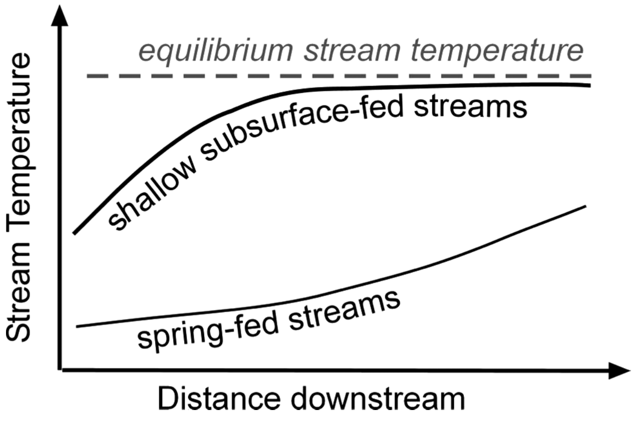

Figure 10. Conceptual model of the difference in stream temperature and rates of warming for shallow subsurface and deeper groundwater-dominated systems

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