ELEVATION, THERMAL ENVIRONMENT, AND STREAM TEMPERATURES ON HEADWATER STREAMS IN NORTHEASTERN OREGON

[1]Cynthia L. Meays*, [2]Michael M. Borman, and [3]Larry L. Larson

[1]Graduate Research Assistant*, [2]Professor, and [3]Professor,
Department of Rangeland Resources, Oregon State University;
*Currently Graduate Research Assistant, University of Victoria, British Columbia

ABSTRACT: Temperature has become an important water quality standard based on salmon and other cold-water organisms. We studied the association between temperature change with elevation and stream attributes on three headwater streams in northeastern Oregon. Two of the three streams originated from springs with very little subsurface additions through the study area. One watershed was largely burned over with very little vegetation cover. The other was an intact, forested system with substantial vegetation cover. The third stream flowed through a largely intact forest and had cold-water inputs via tributaries and subsurface flows. Temperatures were strongly associated with elevation ($p<0.0001$). Mean daily air, soil, and water temperatures averaged across all three streams during July and August 1998 and 1999 increased 1.4, 2.7, and 2.2°F, respectively, per 500 feet drop in elevation. Mean daily maximum and minimum air, soil, and water temperatures also increased with decreasing elevation ($p<0.0001$). When adjusted for exposure time, all three streams heated at similar rates. Elevation, which was associated with thermal environment, had a prominent influence on stream temperature. Exposure time to the surrounding thermal environment appeared very influential.

(KEY TERMS: stream temperature; thermal environment; elevation; exposure time; water quality; water policy/regulation)

INTRODUCTION

Stream temperature has become an important water quality attribute with implications for water policy and regulation. In Oregon, a temperature standard has been adopted by the state's Environmental Quality Commission based on what are currently thought to be optimum conditions for various physiological needs of cold-water fish such as salmon and trout (Oregon Department of Environmental Quality, 1998a). Streams not meeting the water temperature standard are placed on the water quality limited, 303(d), list. A stream can be removed from the list when there is evidence that it is violating water quality standards due to natural conditions only (Oregon Department of Environmental Quality, 1998a). A river or stream is generally listed for its entire length, mouth to headwaters, unless there is information available to divide it into segments (Oregon Department of Environmental Quality, 1998b). If we can improve our understanding of natural conditions that result in violation of the temperature standard, regulatory agencies can avoid listing stream segments that naturally exceed the temperature standard.

Brown's papers (Brown, 1969, 1970, 1972; Brown and Krygier, 1970; Brown et al., 1971) have been widely cited to support the contention that direct solar radiation is the primary source of heat loading into streams and that shade will prevent stream heating. These papers reported temperature changes associated with clearcuts along small, forested streams. A prediction equation was developed to estimate the magnitude of expected temperature change. Brown (1969, 1980) noted that this equation should be applied only to relatively short reaches of stream, less than 2000 feet, because an equilibrium temperature is eventually attained. He also noted that the predictive equation was only relevant for the special case of complete removal of shade by clearcutting; that predicting the energy input (i.e. direct solar) to a stream following a partial cut is nearly an impossible task.

Energy exchange occurs when a thermal imbalance exists, and the greater the imbalance (gradient) the greater the exchange. Energy exchange between a stream and the local environment begins with a transient period of temperature change until an equilibrium condition is achieved (Adams and Sullivan, 1989). When that occurs, stream temperature is independent of initial conditions and daily mean air and water temperatures will have converged to stabilize within 1 or 2 degrees of each other (Adams and Sullivan, 1989). Edinger et al. (1968) described this process of stream temperature change as a function of 1) temperature difference between the stream and the equilibrium temperature of the surrounding environment, and 2) exposure time. Equilibrium temperature is variable and is strongly associated with changes in the sum of the radiation, conduction, sensible heat convection, and evaporation processes that are occurring at the water-air interface.

Stream temperature patterns closely follow and lag behind air temperature patterns (Stefan and Preud'homme, 1993; McRae and Edwards, 1994; Walker and Lawson, 1977; Larson and Larson, 1997; Mosheni and Stefan, 1999). The strength of this association has led several researchers to describe local air temperature as the single most important parameter associated with daily mean stream temperature (Bartholow, 1989; Sinokrot and Stefan, 1994; Lewis et al., 2000).

Elevation has been associated with the thermal patterns of the environment and stream temperature (Ward, 1985; Meisner et al.,1988; Raphael, 1962; McRae and Edwards, 1994; Larson and Larson, 1997). Air density decreases with increasing elevation, decreasing the effect of the atmosphere (absorption and radiation of long-wave radiation) and modifying thermal patterns at the earth's surface (Hidore and Oliver, 1993). Air, ground, and ground-water temperatures are generally cooler at higher elevations.

The objective of this study was to evaluate the influence of elevation, a natural condition, on stream temperature through influence on the surrounding thermal environment, which we are defining for the purpose of this paper as air and soil temperatures.

STUDY LOCATION

BASIN CHARACTERISTICS

South Fork Burnt River in northeastern Oregon drains approximately 145 square miles, with an elevation range from approximately 7900 feet at higher spring sources to 4350 feet at the Forest Service boundary (South Fork Burnt River EIS Hydrologic Report and Recommendations for the South Fork Burnt River Analysis file, Wallowa-Whitman National Forest, November 7, 2000). Walker and Macleod (1991) map the geology of the area as 'Strawberry Volcanics – flows and flow breccia of basalt, basaltic andesite and andesite.'

Our study was conducted along three tributaries (Barney, Stevens, and Elk Creeks) to South Fork Burnt River (Figure 1) during July and August, 1998 and 1999. Average annual precipitation for the elevations included within our study area ranges from approximately 20 inches at 4500-ft elevation to approximately 37 inches at 6000-ft elevation (Daly and Taylor, 1998). The majority of precipitation occurs as snow during November through January. Spring rains occur during March through May. Early spring runoff flows reflect a fast release of precipitation stored as snow, resulting in very high, short-duration peak flows. Late summer low flows indicate limited storage ability of the headwater riparian floodplains associated with the South Fork Burnt River system (USDA Forest Service, 2001).

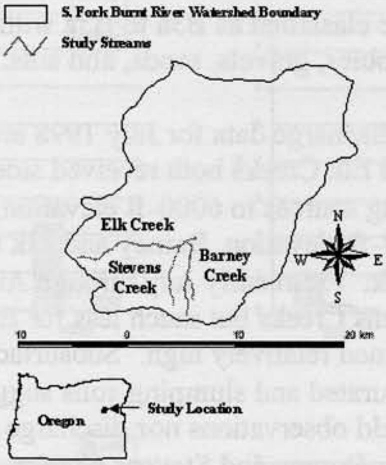

Figure 1. Streams selected for study of elevation and associated factors influencing water temperature.

STREAM CHARACTERISTICS

Barney and Stevens Creeks are adjacent drainages, with northerly aspects (Figure 1). Barney Creek drainage was burned over in 1989 leaving a large portion of the drainage with standing dead trees. Approximately three-quarters (mostly in the upper two-thirds of the watershed) of Barney Creek has approximately 36 to 40 percent cover as measured by the HemiView® camera and analysis system (data not shown). Cover represents the percent of the hemisphere above the creek surface that is obstructed by vegetation or topography. For the upper portion of Barney Creek, much of the 36 to 40 percent cover is due to surrounding topography rather than vegetation. Thus, Barney Creek, which flows north, is subject to substantial direct sunlight through most of the day, with early morning and late evening sunlight obstructed by topography. The approximately one-quarter of Barney Creek at the lower end of the watershed has intact, standing trees and has 68 to 70 percent cover. Topography continues to comprise 36 to 40 percent cover, so the remaining approximately 30 percent is due to tree canopy cover. Stevens Creek, which also flows north, has intact forest and forest understory vegetation throughout the stream course that ranges in composition from open ponderosa pine to mixed conifer forest. Stevens Creek has approximately 84 to 88 percent cover as measured by the HemiView® system (data not shown), most of which is provided by vegetation and provides shade on the creek. Elk Creek has a northeasterly aspect, is forested, and has two cool water tributaries and areas of groundwater input. Cover was not measured for Elk Creek, but based on comparisons of aerial photographs to those of Barney and Stevens Creeks, it would probably range from 75 to 85 percent, most of which is provided by vegetation. Based on field observations, exposure to direct sunlight is similar to slightly greater for Elk Creek than for Stevens Creek and substantially less than for Barney Creek. Our intention for reporting cover values is to provide a relative index of exposure to direct sunlight and is not to provide an absolute comparison.

For purposes of our study, sampling sites were located at 6000, 5500, 5000, and 4500-ft elevations. Channels for all three creeks would be classified as Rosgen A channels (Rosgen, 1996) from the spring sources to just above the 6000-ft elevation level where we began data collection. From just above 6000-ft elevation to 4500-ft elevation, where we terminated our data collection, channel types would be classified as B3a to B5a with descending elevation (Rosgen, 1996). Substrates vary among cobbles, gravels, sands, and silts.

Wetted width, depth, and discharge data for July 1998 are provided in Table 1 for comparison purposes. Barney and Elk Creeks both received side-channel inputs between 6000 and 5500-ft elevation. From spring sources to 6000-ft elevation, the three streams had similar discharges (Table 1). Below 5500-ft elevation, Barney and Elk Creeks had two to three times more discharge than Stevens Creek. From early July through August, flows decreased substantially for Barney and Stevens Creeks but much less for Elk Creek (Figure 2). The side channel input for Elk Creek remained relatively high. Subsurface inputs were not measured, however, field observations of saturated and slumping soils suggested that subsurface flows were a factor for Elk Creek. Neither field observations nor discharge measurements indicated more than minimal subsurface inputs for Barney and Stevens Creeks.

Table 1. Channel morphological characteristics based on wetted width and discharge comparisons for July 1998.

Elevation (ft)	Max. depth	Avg. depth	width	Width/depth	discharge
	------ feet ------				$ft^3\ sec^{-1}$
		Barney Creek			
6000	.43	.26	5.9	22.5	1.41
5500	.75	.52	7.9	15.0	6.00
5000	.85	.56	6.6	11.8	6.36
4500	.85	.49	4.6	9.3	6.00
		Elk Creek			
6000	.26	.23	1.6	7.1	0.71
5500	.85	.46	3.9	8.6	3.88
5000	.72	.52	4.3	8.1	4.94
4500	.39	.26	4.9	18.8	3.53
		Stevens Creek			
6000	.46	.39	2.6	6.7	2.12
5500	.59	.36	5.2	14.5	2.12
5000	.56	.33	6.6	20.0	2.47
4500	.49	.36	4.6	12.7	2.47

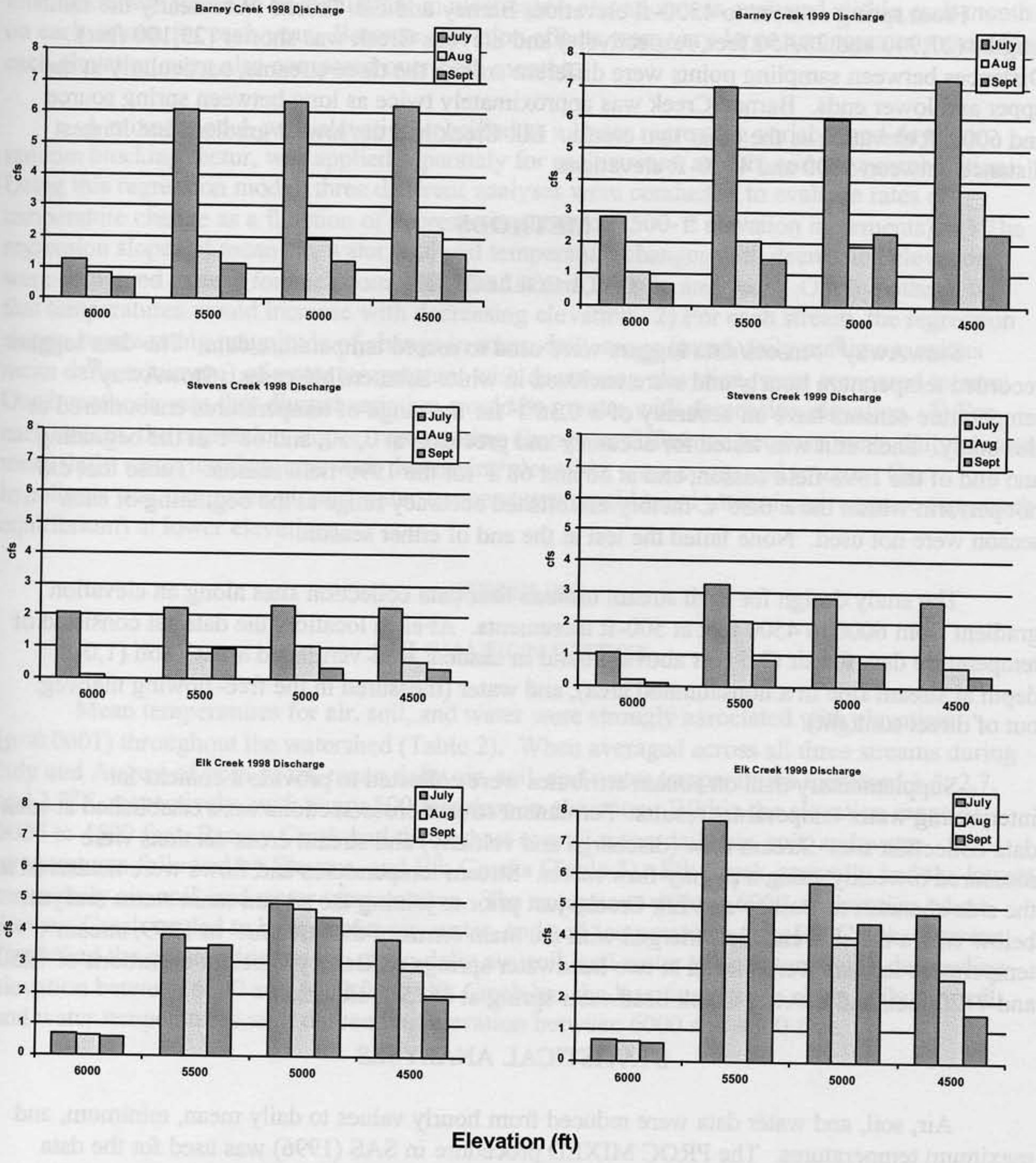

Figure 2. Stream flow discharges for Barney, Stevens, and Elk Creeks, at 6000, 5500, 5000, 4500-ft elevations, for beginning July, August, and September, 1998 and 1999.

From spring sources to 4500-ft elevation, Barney and Elk Creeks were nearly the same lengths (27,940 and 28,450 feet, respectively) and Stevens Creek was shorter (23,100 feet). Distances between sampling points were different among the three streams, particularly at the upper and lower ends. Barney Creek was approximately twice as long between spring source and 6000-ft elevation as the other two creeks. Elk Creek had the lowest gradient and longest distance between 5000 and 4500-ft elevations.

METHODS

DATA COLLECTION

StowAway® sensors/data loggers were used to record temperature data. The data loggers recorded temperature hourly and were enclosed in white submersible cases. StowAway® temperature sensors have an accuracy of ± 0.36°F for the range of temperatures encountered in this study. Each unit was tested for accuracy and precision at 0, 50, and 68°F at the beginning and end of the 1998 field season, and at 50 and 68°F for the 1999 field season. Those that did not perform within the ± 0.36°C factory established accuracy range at the beginning of each season were not used. None failed the test at the end of either season.

The study design for each stream utilized four data collection sites along an elevation gradient from 6000 to 4500 feet at 500-ft increments. At each location, the data set consisted of temperature data for air (3.5 feet above ground in shaded, well-ventilated areas), soil (1.0-ft depth at stream side in a nonsaturated area), and water (measured in the free-flowing thalweg, out of direct sunlight).

Supplementary data on stream attributes were collected to provide a context for interpreting water temperature results. Permanent stream cross-sections were established at each data collection site. Stream flow (discharge and velocity) and stream cross-sections were measured biweekly using a pygmy flow meter. Stream temperatures and flows were measured in the side channels to Barney and Elk Creeks just prior to joining the stream main stems and just below where the side channels merged with the main stems of the streams. In 1999, stream temperature loggers were placed at two headwater springs on Barney Creek at elevations of 7250 and 7120 feet, and Stevens Creek headwater spring at 6675-ft elevation.

STATISTICAL ANALYSES

Air, soil, and water data were reduced from hourly values to daily mean, minimum, and maximum temperatures. The PROC MIXED procedure in SAS (1996) was used for the data analysis of effects of the fixed factors elevation (6000, 5500, 5000, 4500 feet) and month (July, August) for each year (1998, 1999) and stream (Barney, Elk, Stevens). The mixed linear model included the main effects for elevation, month, their 2-factor interaction, and the random factor of day within month. Time series of random effects for day were found to have a strong autocorrelation. Therefore, day was a blocking factor relative to elevation effects and their possible interactions with month. Because the month effects are components of days, no statistical comparisons were made between the two months. Since the month-by-elevation interaction was found to be significant in most cases, elevation was analyzed within each month on each stream for each year. Because elevation effects were very large, temperature means for each elevation were also compared over both months.

A mixed model, with elevation specified as a linear regression variable and day as a random blocking factor, was applied separately for each stream, month, and year combination. Using this regression model, three different analyses were conducted to evaluate rates of temperature change as a function of decrease in elevation (500-ft elevation increments). 1) The regression slopes of mean air, water, and soil temperature changes with decreasing elevation were compared to zero for each combination of stream, month, and year. Our hypothesis was that temperatures would increase with decreasing elevation. 2) For each stream, the regression slopes, representing magnitude of change in mean daily range (mean daily maximum minus mean daily minimum) of water temperature with decreasing elevation, were compared to zero. Our hypothesis was that diurnal variation would be greater with decreasing elevation. 3) For each stream, the regression slopes, representing change in difference between mean daily air and mean daily water temperatures with decreasing elevation, were compared to zero. Our hypothesis was that mean air and water temperatures would trend toward convergence (approach equilibrium) at lower elevations.

RESULTS

ELEVATION EFFECT

Mean temperatures for air, soil, and water were strongly associated with elevation ($p<0.0001$) throughout the watershed (Table 2). When averaged across all three streams during July and August of both years, mean daily air, soil, and water temperatures increased 1.4, 2.7, and 2.2°F, respectively, with every 500 feet drop in elevation. Within the elevation range of 6000 to 4500 feet, Barney Creek had the highest overall mean daily air, soil, and water temperatures followed by Stevens, and Elk Creeks (Table 3). Elk Creek generally had the lowest mean daily air, soil, and water temperatures. The exceptions were at 6000-ft elevation where Stevens Creek tended to have cooler air, water, and soil temperatures than Elk Creek. Stevens Creek had the greatest increase in mean daily air, soil, and water temperatures with descending elevation between 6000 and 4500 feet. Elk Creek has the least increase in mean daily air, soil, and water temperatures with descending elevation between 6000 and 4500 feet.

Table 2. Regression slopes of mean temperature (°F) change per 500 feet drop in elevation for air, water, and soil, July and August, 1998 and 1999.

		July				August			
Year	Factor	Slope	SE	P[1]	R^2	Slope	SE	P	R^2
Barney									
1998	Air	1.4	0.11	0.0001	0.93	2.0	0.09	0.0001	0.97
	Water	2.5	0.04	0.0001	0.98	2.3	0.05	0.0001	0.97
	Soil	3.1	0.13	0.0001	0.90	2.5	0.11	0.0001	0.90
1999	Air	1.4	0.07	0.0001	0.99	1.3	0.05	0.0001	0.99
	Water	2.5	0.04	0.0001	0.99	2.5	0.04	0.0001	0.98
	Soil	2.5	0.07	0.0001	0.94	2.0	0.11	0.0001	0.83
Elk									
1998	Air	1.8	0.09	0.0001	0.95	1.4	0.07	0.0001	0.97
	Water	2.3	0.07	0.0001	0.95	1.8	0.05	0.0001	0.92
	Soil	1.1	0.05	0.0001	0.86	1.4	0.07	0.0001	0.88
1999	Air	0.9	0.05	0.0001	0.99	0.9	0.07	0.0001	0.98
	Water	1.6	0.05	0.0001	0.95	1.6	0.05	0.0001	0.92
	Soil	0.9	0.07	0.0001	0.80	1.3	0.04	0.0001	0.94
Stevens									
1998	Air	2.0	0.07	0.0001	0.97	2.2	0.09	0.0001	0.97
	Water	4.5	0.09	0.0001	0.97	4.1	0.09	0.0001	0.97
	Soil	2.9	0.18	0.0001	0.81	3.1	0.14	0.0001	0.86
1999	Air	1.8	0.04	0.0001	0.99	1.8	0.05	0.0001	0.99
	Water	3.6	0.11	0.0001	0.94	4.0	0.07	0.0001	0.97
	Soil	3.1	0.16	0.0001	0.84	3.4	0.16	0.0001	0.82

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[1] Significance level that the regression slope is different than zero.

Table 3. Monthly mean daily air, water, and soil temperatures (°F) for July and August, 1998 and 1999.

	Air				Water				Soil			
	1998		1999		1998		1999		1998		1999	
Elev (ft)	July	Aug	July	Aug	July	Aug	July	Aug	July	Aug	July	Aug
Barney												
6000	62.4	59.4	58.3	59.2	54.3	52.9	49.3	51.4	56.5	56.1	54.0	55.4
5500	65.8	62.4	59.5	60.3	56.3	54.5	51.3	53.4	60.1	58.6	56.7	57.7
5000	66.9	64.2	61.3	61.9	59.5	58.1	54.5	56.8	64.9	63.3	60.3	61.5
4500	67.3	65.1	62.2	63.0	61.5	59.4	56.5	58.5	64.9	63.1	61.0	60.8
Elk												
6000	58.5	56.1	55.0	56.1	46.2	45.7	45.0	45.3	51.3	50.4	48.6	50.0
5500	61.8	58.6	56.5	56.7	47.3	46.2	45.9	45.9	52.0	50.0	50.9	50.5
5000	62.1	58.6	57.0	56.7	49.5	48.2	47.7	47.7	52.9	52.5	51.4	52.3
4500	64.4	60.8	58.1	59.0	52.9	50.9	49.8	50.2	54.5	54.5	51.3	53.4
Stevens												
6000	59.4	55.6	54.5	55.0	45.3	45.0	43.0	44.6	52.5	51.1	47.1	49.6
5500	62.4	59.2	56.5	57.2	49.1	49.3	45.9	48.6	53.2	53.2	50.0	52.2
5000	64.4	61.5	58.5	59.4	52.7	52.3	48.6	51.8	54.7	54.1	49.8	52.5
4500	65.7	61.9	59.7	60.6	59.0	57.7	54.0	56.7	61.5	61.3	57.4	60.8

As with daily mean temperatures, mean daily maximum and minimum temperatures for air, soil, and water were associated ($p<0.0001$) with elevation (data not shown). Mean daily maximum air and water, as well as mean daily minimum water temperatures increased with descending elevation on all three streams. Mean daily minimum air temperature showed the most variation, and likely reflected localized patterns of cold air drainage flow.

STREAM COMPARISONS

Increase in the range of daily water temperatures (mean daily maximum temperature minus mean daily minimum temperature) with decreasing elevation was greatest on Stevens Creek, next greatest on Barney Creek, and least, but still significant, on Elk Creek (Table 4).

Table 4. Rate of temperature (°F) change per 500 feet drop in elevation during July and August, 1998 and 1999.

Stream	Slope[1]	SE	P[2]	R^2
------- Daily water temperature range increase[3] -------				
Elk	0.5	0.18	0.030	0.53
Barney	1.1	0.14	0.002	0.90
Stevens	2.0	0.40	0.002	0.80
- Decrease in mean daily air and water temperature difference[4] -				
Elk	NS[5]	NS	NS	NS
Barney	0.5	0.13	0.01	0.67
Stevens	1.1	0.23	0.001	0.78

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[1] Slope of the regression line with temperature difference as dependent variable and elevation as independent variable. Monthly mean maximum and mean minimum water, and mean air and water temperatures were used for these analyses.

[2] Significance level that the regression slope is different than zero.

[3] Difference between daily maximum and daily minimum temperatures at each elevation. Illustrates the rate at which the temperature range increases with decreasing elevation.

[4] Difference between mean daily air and mean daily water temperatures at each elevation. Illustrates the convergence of mean air and water temperatures with decreasing elevation.

[5] Slope not statistically different from zero.

The rate of convergence of mean daily water and air temperatures with decreasing elevation was the same as for change in water temperature range. Convergence was greatest on Stevens Creek, next on Barney Creek, and least (statistically non-significant) on Elk Creek (Table 4).

METEOROLOGICAL EFFECT

Monthly temperature differences ($p<0.05$) associated with weather patterns were evident in the data but did not demonstrate repeated trends over the two-year study. Air, water, and soil temperatures were warmer in July versus August 1998; however, in 1999 all three tended to be warmer in August versus July (Table 3). Variability in annual, monthly, and daily patterns of air mass movement and meteorological conditions are common in natural systems. That variability has an influence on water temperature that can override the progressively longer solar angle and less direct solar input through July and August.

DISCUSSION

ELEVATION EFFECT

As elevation increases, air density decreases and other parameters change as well. Decreasing air temperature and water vapor pressure reduce the influence of long-wave radiation on the thermal cycle at the earth's surface (Hidore and Oliver, 1993; Meisner et al., 1988). As a result, water temperature patterns at higher elevations are subject to more rapid thermal cycling and less warming even though higher elevations receive more direct solar radiation (Meisner et al., 1988). Waters flowing down an elevation gradient reflect these thermal characteristics and, at lower elevations, are subject to temperature equilibrium regimes that are warmer than where they originate. The adiabatic rate for air temperature change is given as a temperature increase of 1.6 to 2.7°F for every 500 feet drop in elevation (Hidore and Oliver, 1993). The exact value of the temperature change is determined by the stability of the air mass and its water vapor content. In this study, patterns of air, water, and soil temperature change (Table 3) were similar to the pattern of expected adiabatic temperature change.

STREAM COMPARISONS

Results suggest that temperature change on Elk Creek was depressed within the elevation range included in our study. Elk Creek mean water temperatures at 4500-ft elevation reached 65 and 69 percent of mean air temperatures during 1998 and 1999, respectively (Table 5). Thermal characteristics on Barney and Stevens Creeks favored temperature change toward an equilibrium with the surrounding environment. Mean water temperatures reached 83 percent of the mean air values for both creeks (Table 5). The rate of convergence between water and air temperatures was greater for Stevens than for Barney Creek. At 6000-ft elevation, the difference between water and air temperatures (temperature gradient) was greater on Stevens Creek than on Barney Creek. Flow velocity was much slower on Stevens Creek compared to Barney Creek (Table 6), thus exposure time was longer. The combination of difference in temperature gradient and exposure time likely explain the greater rate of convergence of water and air temperatures on Stevens Creek. Possible influences on the differences between Elk Creek and Barney or Stevens Creek may relate to differences in thermal exposure time (velocity x distance), discharge, and/or cool water input.

Table 5. Ratio (%) of mean, maximum, and minimum daily water to air temperatures at 6000 and 4500-ft elevations.

		1998			1999		
Stream	Elev.	Mean	Max.	Min.	Mean	Max.	Min.
		%			%		
Barney	6000	75	59	104	69	58	102
	4500	83	72	117	83	67	126
Elk	6000	55	46	76	56	43	94
	4500	65	48	120	69	49	141
Stevens	6000	52	32	89	52	32	98
	4500	83	67	127	83	67	143

Elk Creek had the least water temperature change (Table 3) and fastest average stream travel time (Table 6) between 6000 and 4500-ft elevation. Velocity and discharge influence the rate and amount of stream heating (Edinger et al., 1968; Adams and Sullivan, 1989; Ward, 1985; Raphael, 1962; and Larson and Larson, 1996). Stevens Creek had the lowest velocity and discharge of the three streams throughout the study (Table 6). The reduction in velocity and discharge through August was greater for Barney Creek than for Elk Creek (Table 6). Adams and Sullivan (1989) noted that significant cool water contributions depress the diurnal temperature range of a stream. In the case of Elk Creek, two side channels enter the mainstem at 5580-ft elevation. They were 2.7°F cooler and substantially increased mainstem flow (Figure 2). Barney Creek also had a side channel enter the mainstem (Figure 2), but the temperatures were not different than mainstem temperatures (data not shown).

Table 6. Mean velocity (6000 to 4500-ft elevations), mean travel time (6000 to 4500-ft elevations), and discharge (4500-ft elevation) for Barney, Stevens, and Elk Creeks during July and August, 1998 and 1999.

		1998		1999	
Stream	Attribute	July	August	July	August
Barney					
	Velocity (ft s^{-1})	1.94	0.62	1.28	0.79
	Time (h)	2.5	8.0	4.0	6.5
	Discharge ($ft^3 s^{-1}$)	6.00	1.41	7.42	2.12
Stevens					
	Velocity (ft s^{-1})	0.82	0.36	0.75	0.49
	Time (h)	6.0	13.5	6.5	10.0
	Discharge ($ft^3 s^{-1}$)	2.12	0.35	2.83	1.41
Elk					
	Velocity (ft s^{-1})	1.48	1.38	1.41	1.21
	Time (h)	4.0	4.5	4.5	5.0
	Discharge ($ft^3 s^{-1}$)	3.88	2.47	4.94	2.83

EXPOSURE TIME

Headwater sources generally reflect the temperature of the thermal mass from which they originate (Ward, 1985; Meisner et al., 1988; Raphael, 1962; Adams and Sullivan, 1989; McRae and Edwards, 1994). Waters entered the headwater streams of Barney and Stevens Creeks from ground sources that had mean temperatures of 37.6°F (37.4 to 38.5) and 40.3°F (38.8 to 41.7), respectively. The difference is likely that Barney Creek springs were closer to the snowmelt source. Stevens Creek spring water had been subsurface for a longer distance and duration and was thus exposed longer to the warmer soil temperature. From the spring sources, Barney Creek flowed approximately twice the distance and had twice the time of exposure to the surface thermal environment as Stevens Creek to reach 6000-ft elevation. At 6000-ft elevation, Barney Creek was warmer than Stevens Creek (Table 3). Elk Creek spring sources were not measured in this study.

Barney and Stevens Creeks are representative of streams having a spring source with minimal additional subsurface water sources downstream. Total travel time from spring source to 4500-ft elevation was nearly the same for the two streams. The longer distance and travel time from spring source to 6000-ft elevation for Barney Creek was offset by greater velocity (Table 6) and shorter distance between 6000 and 4500-ft elevation for Barney Creek versus Stevens Creek. Both streams transitioned toward thermal equilibrium and had similar temperature patterns upon reaching 4500-ft elevation. Calculation of mean temperature change between 6000 and 4500-ft elevations (Table 2) suggests that Stevens Creek was heating 2.0 and 1.1°F more than Barney Creek per 500 feet drop in elevation during 1998 and 1999. However this perspective does not reflect exposure time and flow (Table 6). Stevens Creek had between 50 and 70 percent more exposure time and contained flows that were only 25 to 66 percent of those found on Barney creek during August 1998 and 1999. Calculation of the temperature change per hour reveal that Barney, Stevens, and Elk Creek water temperatures changed 0.81, 0.95, and 1.15°F h^{-1} in August 1998 and 1.08, 1.21, and 0.97°F h^{-1} in August 1999.

CONCLUSIONS

Compared to other thermal sources, the atmosphere effect provides a strong buffer against thermal extremes at the earth's surface, transporting heat horizontally and vertically (Hidore and Oliver, 1993). The association of weather and elevation to stream temperature observed in this study represents measures of atmosphere effect. Our results suggest that atmosphere effect has a prominent influence on stream temperatures; effectively setting limits within which stream temperatures will occur. Within those limits, the thermal signature of an individual stream is defined by that stream's attributes. In this case study, exposure time (velocity x distance) appeared to be more responsible for temperature differences observed on Elk, Barney, and Stevens Creeks than were cool water inputs, discharge volume, or shade provided by trees.

Given sufficient time, streams should be expected to reach a dynamic equilibrium with mean air temperatures. As was noted on Stevens Creek, canopy cover alone was not sufficient to prevent water temperature from trending toward equilibrium with air temperature. As was noted in the case of Elk Creek, cool water inputs were not sufficient to prevent water temperature from trending toward equilibrium with air temperature.

At lower elevations, streams will generally function within a warmer thermal environment than at higher elevations, and they will have had longer exposure time. From a regulatory perspective, water temperatures should be expected to be higher at lower elevations unless some other factor influences the surrounding thermal environment.

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