

## Temperatures of Three Headwater Streams in Northeastern Oregon

### Abstract

Stream temperature is an important component of water quality for salmon and other organisms. We studied the relationship between water temperature and elevation in three headwater streams in northeastern Oregon. Two streams had very little subsurface addition. One of these watersheds was largely burned over with little vegetation cover. The other was an intact, forested system with substantial vegetation cover. The third watershed was largely intact forest with tributary and subsurface cold-water inputs. Water temperatures were strongly associated with elevation ( $P < 0.001$ ;  $R^2 = 0.92$  to  $0.99$ ). Averaged across all three streams during July and August 1998 and 1999, mean daily air temperature increased  $0.8^\circ\text{C}$ , mean daily soil temperature increased  $1.5^\circ\text{C}$ , and mean daily water temperature increased  $1.2^\circ\text{C}$  per 150 m drop in elevation, similar to the expected adiabatic lapse rate of  $0.9$  to  $1.5^\circ\text{C}$  per 150 m elevation change. Water temperature diurnal variation increased and mean water and air temperatures trended to convergence with decreasing elevation. Elevation effect was moderated by cool water inputs, discharge, and flow rate, but not vegetation cover. When adjusted for exposure time, all three streams heated at similar rates. Water temperatures should be expected to be higher at lower elevations at approximately the same magnitude as the expected adiabatic lapse rate, with some degree of modification due to discharge, rate of flow (exposure time), and cool water inputs.

### Introduction

Water temperature has been described as one of the most important of all water quality criteria (Johnson 1971, Cluis 1972, Smith and Lavis 1975, Isaak and Hubert 2001). Because physical, chemical, and biochemical parameters, as well as biological community distribution are temperature dependent, water temperature standards have been established to provide the basis for regulation and policy development.

Energy exchange occurs when a thermal imbalance exists. 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 equilibrium is achieved (Adams and Sullivan 1989). When equilibrium is reached, stream temperature is independent of initial conditions and daily mean air and water temperatures will have converged to stabilize within 1 or  $2^\circ\text{C}$  of each other (Adams and Sullivan 1989). This process of stream temperature change is a function of: 1) temperature difference between the stream and the equilibrium temperature of the surrounding environment, and 2) exposure time (Edinger et al. 1968). Equilibrium temperature is variable and is strongly associated with changes in the sum of the radiation, conduction, sensible heat

convection, and evaporation processes at the water-air interface.

Stream temperature patterns closely follow and lag behind air temperature patterns (Walker and Lawson 1977, Stefan and Preud'homme 1993, McRae and Edwards 1994, 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). Cluis (1972) effectively predicted daily stream temperature fluctuations as a function of air temperature, which he considered the one factor best integrating the different causes of water temperature fluctuations.

Elevation has been associated with the thermal patterns of the environment and stream temperature (Raphael 1962, Johnson 1971, Ward 1985, Meisner et al. 1988, 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. Isaak and Hubert (2001) suggested that mean basin elevation correlates well with stream temperatures ( $r = -0.77$ ;  $P < 0.01$ ). They suggested that basin elevation

<sup>1</sup>Author to whom correspondence should be addressed.  
E-mail: michael.borman@oregonstate.edu

should become the preferred surrogate whenever stream temperature data are unavailable. Smith and Lavis (1975) considered volume of discharge to be the most important hydrological variable influencing stream temperature. At lower levels of discharge, the prevailing water temperature is much more directly dependent on air temperature and other local environmental factors.

In this case study, we measured the response of stream temperature to decreasing elevation for three headwater streams in northeast Oregon. We tested the following specific hypotheses: 1) stream temperature increases with decreasing elevation; 2) diurnal variation of water temperature increases with decreasing elevation; and 3) mean air and water temperatures trend toward convergence at lower elevations. Differences among the three streams in vegetation cover, flow volume, and time of exposure provide an opportunity to consider the elevation/temperature relationship among three streams as a function of those differences.

## Methods

### Study Area

Barney, Stevens, and Elk Creeks are first-order tributaries to South Fork Burnt River in northeast Oregon (Figure 1). Average annual precipitation within our study area ranges from approximately 50 cm at 1370-m elevation to approximately 95 cm at 1830-m elevation (Daly and Taylor 1998). Most precipitation occurs as snow during November through January and rain during March through May. High, short-duration, early-spring peak flows reflect a fast release of precipitation stored as snow. Late summer low flows indicate limited storage ability of the headwater riparian floodplains associated with the South Fork Burnt River system.

### Stream and Drainage Characteristics

Barney and Stevens Creeks are adjacent drainages, with northerly aspects and Elk Creek is nearby with a northeasterly aspect. Channels for all three creeks were classified as Rosgen A channels (Rosgen 1996) from the spring sources to the 1830-m elevation level where we began data collection. From 1830-m elevation to 1370-m elevation, channel types are B3a to B5a with descending elevation (Rosgen 1996). Substrates vary among cobbles,

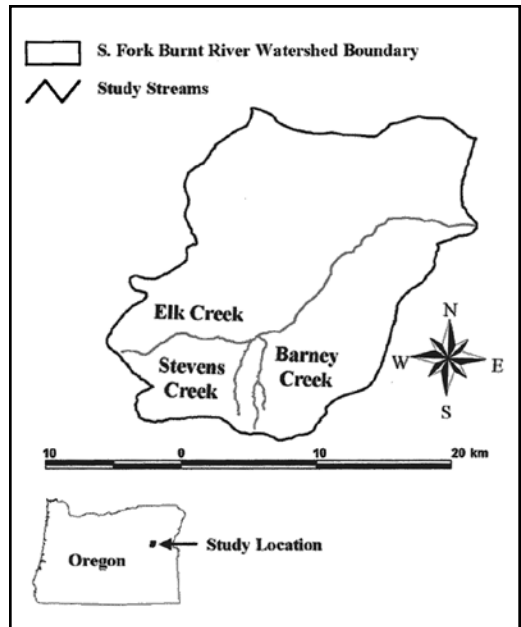


Figure 1. Barney, Elk, and Stevens Creek drainages flowing into South Fork Burnt River. Barney and Stevens Creeks flow north and Elk Creek to the northeast. Barney Creek spring sources are at 2210 and 2170-m elevation. Stevens Creek spring source is at 2035-m elevation. Elk Creek spring source is at 2000-m elevation.

gravels, sands, and silts. Channel morphological characteristics are provided in Table 1.

From spring sources to 1370-m elevation, Barney and Elk Creeks were similar lengths (8515 and 8670 m, respectively) and Stevens Creek was shorter (7040 m). Barney Creek was approximately twice as long between spring source and 1830-m elevation as the other two creeks.

Two side channels enter the Elk Creek main channel between 1830 and 1675-m elevations. They were 1.5°C cooler and substantially increased main-channel flow (Figure 2). We did not measure subsurface inputs, but based on visual observations of seepage and side-slope slumping in the upper reach, we assumed that subsurface inputs were augmenting Elk Creek discharge to some extent. A side channel augmented flow in Barney Creek (Figure 2), but the temperature was the same as the main-channel. Stevens Creek has no tributaries. Both Barney and Stevens Creeks have little apparent subsurface input.

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

| Elevation (m) | Max. depth (m) | Avg. depth (m) | Width (m) | Width/Depth ratio | Discharge m <sup>3</sup> sec <sup>-1</sup> |
|---------------|----------------|----------------|-----------|-------------------|--|
| Barney Creek  |                |                |           |                   |  |
| 1830          | 0.13           | 0.08           | 1.8       | 22.5              | 0.04                                       |
| 1675          | 0.23           | 0.16           | 2.4       | 15.0              | 0.17                                       |
| 1525          | 0.26           | 0.17           | 2.0       | 11.8              | 0.18                                       |
| 1370          | 0.26           | 0.15           | 1.4       | 9.3               | 0.17                                       |
| Elk Creek     |                |                |           |                   |  |
| 1830          | 0.08           | 0.07           | 0.5       | 7.1               | 0.02                                       |
| 1675          | 0.26           | 0.14           | 1.2       | 8.6               | 0.11                                       |
| 1525          | 0.22           | 0.16           | 1.3       | 8.1               | 0.14                                       |
| 1370          | 0.12           | 0.08           | 1.5       | 18.8              | 0.11                                       |
| Stevens Creek |                |                |           |                   |  |
| 1830          | 0.14           | 0.12           | 0.8       | 6.7               | 0.06                                       |
| 1675          | 0.18           | 0.11           | 1.6       | 14.5              | 0.06                                       |
| 1525          | 0.17           | 0.10           | 2.0       | 20.0              | 0.07                                       |
| 1370          | 0.15           | 0.11           | 1.4       | 12.7              | 0.06                                       |

### Data Collection

We measured air (1.1 m above ground in shaded, well-ventilated areas), water (in the free-flowing thalweg, out of direct sunlight), and soil (0.3-m depth near stream side in a nonsaturated area) temperatures during July and August, 1998 and 1999, at four data collection sites for each stream, along an elevation gradient from 1830 to 1370 m, at 150-m increments. Soil temperatures provided an additional index of thermal environment. They were not intended to represent a source of energy exchange with water, although that could occur at the streambed-water interface. StowAway® sensors/data loggers, enclosed in white submersible cases, recorded temperature hourly. Temperatures from 0600 to 1800 hours represented the heating period of the day. StowAway® temperature sensors have an accuracy of ± 0.2°C for the range of temperatures encountered in this study. Each unit was tested for accuracy and precision at 0, 10, and 20°C at the beginning and end of the 1998 field season, and at 10 and 20°C for the 1999 field season. All sensors performed appropriately.

Cover represents the percent of the hemisphere above the creek surface that is obstructed by vegetation or topography. We measured cover using the HemiView® camera and analysis system. Cover values are intended to provide a relative index of exposure to direct sunlight and not to provide an absolute comparison. We measured stream flows (discharge and velocity) biweekly at data collection sites 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 main channels and just below where the side channels merged with the main channels of the streams. In 1999, we placed stream temperature loggers at two headwater springs on Barney Creek at elevations of 2210 and 2170 m, and Stevens Creek headwater spring at 2035-m 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 (1830, 1675, 1525, 1370 m) and month (July, August) for each year (1998, 1999) and stream (Barney, Elk, Stevens). 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, we conducted three different analyses to evaluate rates of temperature change as a function of decrease in elevation: 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. 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

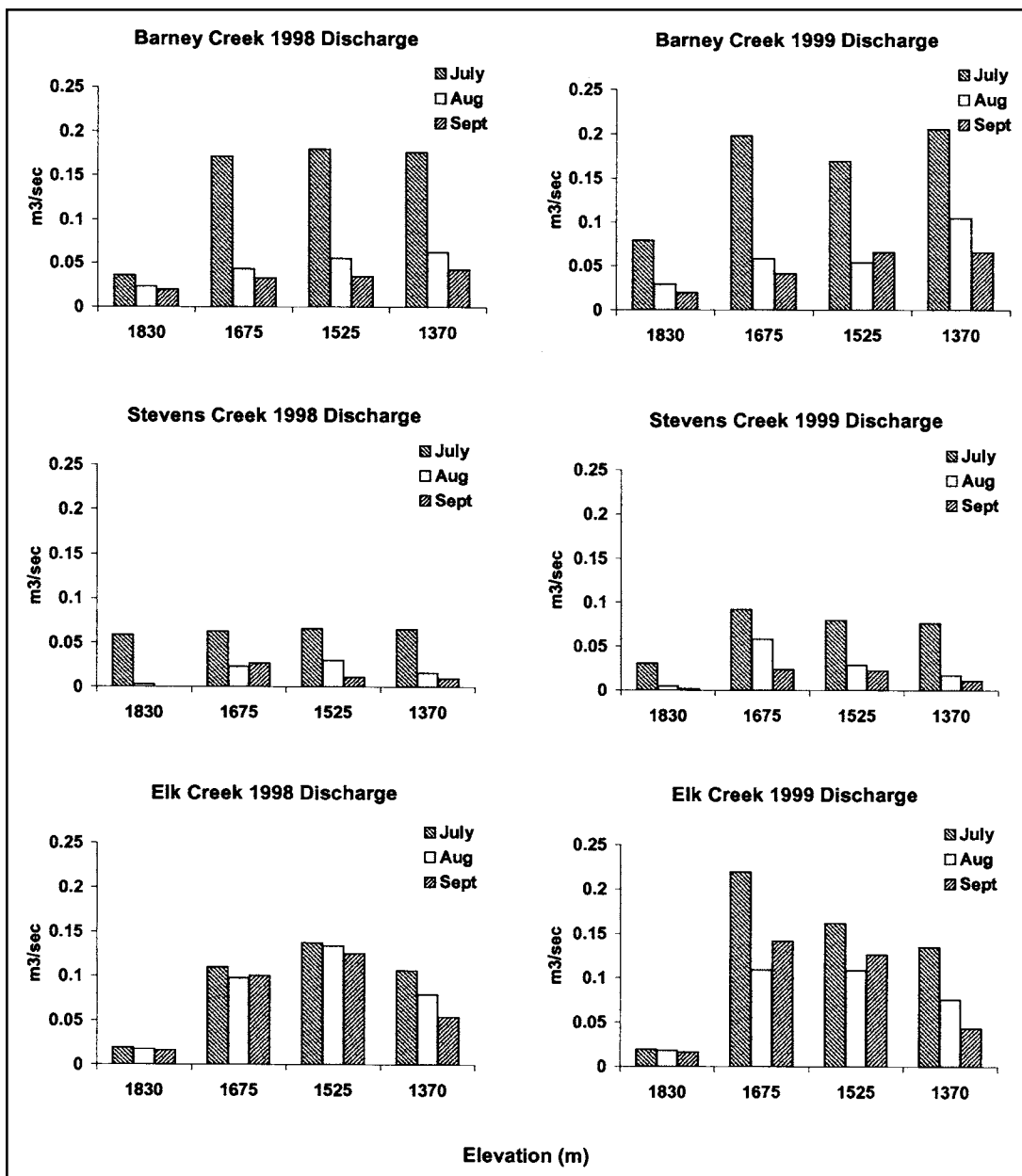


Figure 2. Stream flow discharges for Barney, Stevens, and Elk Creeks, at 1830, 1675, 1525, and 1370-m elevations, for beginning July, August, and September, 1998 and 1999.

with decreasing elevation, were compared to zero. 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. The level of significance was set at  $P = 0.05$ .

## Results

### Elevation Effect

Mean temperatures for air, soil, and water were strongly associated with elevation ( $P < 0.001$ ) throughout the watershed (Table 2). When averaged

TABLE 2. Regression slopes of mean monthly temperature (°C) change per 150 m drop in elevation for air, water, and soil, July and August, 1998 and 1999. All slopes were significantly different than 0 at  $P < 0.001$ .

| Year          | Factor | July  |                | August |                |
|---------------|--------|-------|----------------|--------|----------------|
|               |        | Slope | R <sup>2</sup> | Slope  | R <sup>2</sup> |
| Barney Creek  |        |       |                |        |                |
| 1998          | Air    | 0.8   | 0.93           | 1.1    | 0.97           |
|               | Water  | 1.4   | 0.98           | 1.3    | 0.97           |
|               | Soil   | 1.7   | 0.90           | 1.4    | 0.90           |
| 1999          | Air    | 0.8   | 0.99           | 0.7    | 0.99           |
|               | Water  | 1.4   | 0.99           | 1.4    | 0.98           |
|               | Soil   | 1.4   | 0.94           | 1.1    | 0.83           |
| Elk Creek     |        |       |                |        |                |
| 1998          | Air    | 1.0   | 0.95           | 0.8    | 0.97           |
|               | Water  | 1.3   | 0.95           | 1.0    | 0.92           |
|               | Soil   | 0.6   | 0.86           | 0.8    | 0.88           |
| 1999          | Air    | 0.5   | 0.99           | 0.5    | 0.98           |
|               | Water  | 0.9   | 0.95           | 0.9    | 0.92           |
|               | Soil   | 0.5   | 0.80           | 0.7    | 0.94           |
| Stevens Creek |        |       |                |        |                |
| 1998          | Air    | 1.1   | 0.97           | 1.2    | 0.97           |
|               | Water  | 2.5   | 0.97           | 2.3    | 0.97           |
|               | Soil   | 1.6   | 0.81           | 1.7    | 0.86           |
| 1999          | Air    | 1.0   | 0.99           | 1.0    | 0.99           |
|               | Water  | 2.0   | 0.94           | 2.2    | 0.97           |
|               | Soil   | 1.7   | 0.84           | 1.9    | 0.8            |

across all three streams during July and August of both years, mean daily air, soil, and water temperatures increased 0.8, 1.5, and 1.2°C, respectively, with every 150 m drop in elevation. Within the elevation range of 1830 to 1370 m, Barney Creek had the highest overall mean daily air, soil, and water temperatures followed by Stevens, then Elk Creek. Stevens Creek had the greatest and Elk Creek the least increase in mean daily air, soil, and water temperatures with descending elevation (Table 2).

As with daily mean temperatures, mean daily maximum and minimum temperatures for air, soil, and water were associated ( $P < 0.001$ ) with elevation. 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 cold air flow patterns.

Increase in diurnal water temperature fluctuation (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 3).

TABLE 3. Change in difference between daily maximum and minimum water temperatures (°C) per 150 m drop in elevation during July and August, 1998 and 1999.

| Stream  | Slope <sup>1</sup> | P     | R <sup>2</sup> |
|---------|--------------------|-------|----------------|
| Elk     | 0.3                | 0.03  | 0.53           |
| Barney  | 0.6                | 0.002 | 0.90           |
| Stevens | 1.1                | 0.002 | 0.80           |

<sup>1</sup>Slope of the regression line with temperature difference as dependent variable and elevation as independent variable. Monthly mean maximum and mean minimum water temperatures were used for this analysis.

The rate of convergence of mean daily water and air temperatures with decreasing elevation was greatest on Stevens Creek, next on Barney Creek, and least (statistically non-significant) on Elk Creek (Table 4). Mean water temperatures at 1370-m elevation reached 83 percent of mean air values for Barney and Stevens Creeks in both years (Table 5). Elk Creek mean water temperature reached 65 and 69 percent of mean air temperature during 1998 and 1999, respectively (Table 5).

TABLE 4. Change in mean daily air and water temperature (°C) difference per 150 m drop in elevation during July and August, 1998 and 1999.

| Stream  | Slope <sup>1</sup> | P     | R <sup>2</sup> |
|---------|--------------------|-------|----------------|
| Elk     | NS                 |       |                |
| Barney  | 0.3                | 0.01  | 0.67           |
| Stevens | 0.6                | 0.001 | 0.78           |

<sup>1</sup>Slope of the regression line with temperature difference as dependent variable and elevation as independent variable. Monthly mean air and water temperatures were used for this analysis.

### Vegetation Cover

Barney Creek has about 40 percent cover due to topography throughout its drainage. In the lower third, trees contribute an additional 30 percent cover. The upper two-thirds of Barney Creek burned in 1989. Barney Creek is subject to substantial direct sunlight through most of the day, with early morning and late evening sunlight obstructed by topography. Stevens Creek has intact forest and forest understory vegetation throughout the stream course that ranges in composition from open ponderosa pine to mixed

TABLE 5. Ratio (%) of mean, maximum, and minimum daily water to air temperatures at 1830 and 1370-m elevations.

| Stream  | Elev. | 1998 |      |      | 1999 |      |      |
|---------|-------|------|------|------|------|------|------|
|         |       | Mean | Max. | Min. | Mean | Max. | Min. |
| Barney  | 1830  | 75   | 59   | 104  | 69   | 58   | 102  |
|         | 1370  | 83   | 72   | 117  | 83   | 67   | 126  |
| Elk     | 1830  | 55   | 46   | 76   | 56   | 43   | 94   |
|         | 1370  | 65   | 48   | 120  | 69   | 49   | 141  |
| Stevens | 1830  | 52   | 32   | 89   | 52   | 32   | 98   |
|         | 1370  | 83   | 67   | 127  | 83   | 67   | 143  |

conifer forest. Stevens Creek has approximately 85 percent cover, most of which is provided by vegetation that provides shade on the creek. Elk Creek has about 80 percent cover, most of which is provided by vegetation with similar composition to Stevens Creek.

### Discharge and Time of Exposure

From spring sources to 1830-m elevation, the three streams had similar discharges (Figure 2). Barney and Elk Creeks both received side-channel inputs between 1830 and 1675-m elevation. Below 1675-m 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.

Travel time (time of exposure) from 1830-m to 1370-m elevation was greatest for Stevens Creek throughout the study (Table 6). Travel time was least for Barney Creek during July and for Elk Creek during August in both years (Table 6). When adjusted to temperature change per hour, Barney, Stevens, and Elk Creek water temperatures changed 0.45, 0.53, and 0.64°C h<sup>-1</sup> in August 1998 and 0.60, 0.67, and 0.54°C h<sup>-1</sup> in August 1999.

## Discussion

### Elevation Effect

As elevation increases, air density decreases and other parameters change as well. Decreasing air

TABLE 6. Mean velocity (1830 to 1370-m elevations), mean travel time (1830 to 1370-m elevations), and discharge (1370-m elevation) for Barney, Stevens, and Elk Creeks during July and August, 1998 and 1999.

| Stream  | Attribute                                   | 1998 |        | 1999 |        |
|---------|---|------|--------|------|--------|
|         |   | July | August | July | August |
| Barney  | Velocity (ms <sup>-1</sup> )                | 0.59 | 0.19   | 0.39 | 0.24   |
|         | Time (h)                                    | 2.5  | 8.0    | 4.0  | 6.5    |
|         | Discharge (m <sup>3</sup> s <sup>-1</sup> ) | 0.17 | 0.04   | 0.21 | 0.06   |
| Stevens | Velocity (ms <sup>-1</sup> )                | 0.25 | 0.11   | 0.23 | 0.15   |
|         | Time (h)                                    | 6.0  | 13.5   | 6.5  | 10.0   |
|         | Discharge (m <sup>3</sup> s <sup>-1</sup> ) | 0.06 | 0.01   | 0.08 | 0.04   |
| Elk     | Velocity (ms <sup>-1</sup> )                | 0.45 | 0.42   | 0.43 | 0.37   |
|         | Time (h)                                    | 4.0  | 4.5    | 4.5  | 5.0    |
|         | Discharge (m <sup>3</sup> s <sup>-1</sup> ) | 0.11 | 0.07   | 0.14 | 0.08   |

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 warmer temperature equilibrium regimes. The adiabatic rate for air temperature change is given as a temperature increase of 0.9 to 1.5°C for every 150 m drop in elevation (Hidore and Oliver 1993). Actual 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 were generally similar to the pattern of expected adiabatic temperature change. Temperature change was slightly less for Elk Creek (0.8°C) than the range of expected adiabatic lapse rate.

Initial surface water temperatures were influenced by ground water temperatures at the spring

sources of the three creeks. The distance from spring source to 1830-m elevation was less for Stevens Creek (910 m) than for Barney Creek (1800 m). Thus, at 1830-m elevation Stevens Creek was much more heavily influenced by initial ground water temperature, which resulted in a larger gradient between water and air temperature. This likely partially explains why water temperature increase and rate of convergence were greater for Stevens Creek. By the time water reached 1370-m elevation, convergence of mean air and water temperatures had progressed further on Barney and Stevens Creeks than on Elk Creek (Table 5). Substantial cold water additions via side channels and apparent subsurface inputs apparently contributed to less diurnal variation of water temperature and lower level of convergence between air and water temperatures for Elk Creek at 1370-m elevation.

#### Vegetation Cover

Vegetation cover comparisons among the three streams did not relate to water temperature responses. Stevens Creek, with the highest canopy cover, had the greatest temperature increase between 1830 and 1370-m elevations. Barney Creek, with by far the least canopy cover, was intermediate in temperature increase with decreasing elevation. The distance between spring source and 1830-m elevation was about twice as long for Barney Creek as for the other two streams, which would have provided greater exposure time and trend to equilibrium for Barney Creek by the time water reached 1830-m elevation.

#### Discharge and Time of Exposure

Our results are similar to those of Smith and Lavis (1975). They concluded that air temperatures comprised a reasonably reliable index of overall thermal behavior for a small stream under normal low-flow conditions (flows in their study were  $\leq 0.7 \text{ m}^3 \text{ s}^{-1}$  88 percent of the time). At higher flows, water temperature became less directly responsive to changes in the atmospheric environment. The authors attributed the poorer correlations at higher flows to the increased thermal capacity of the stream and to reduced travel time for stream water to pass through the drainage basin. This reduced the time during which the stream water came under either atmospheric or any other local environmental influence. Elk Creek's higher flows

appeared to be the result of cold water inputs from tributaries and from subsurface flows in the upper reach. Cooler temperatures and higher flows increased the thermal capacity and reduced time of exposure of Elk Creek, minimizing the temperature change observed in the length of creek we studied. By contrast, the initially higher temperature gradient between water and air on Stevens Creek, combined with lower discharge and slow rates of flow, established conditions that favored the convergence of water and air temperature.

#### 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). For this study, atmosphere effect is represented by the observed association of elevation to stream temperature. Our results confirm that atmosphere effect has a prominent influence on stream temperatures and effectively sets limits within which stream temperatures will occur. Within those limits, the thermal signature of an individual stream is defined by other attributes. In this case study, exposure time (velocity/distance), a function of discharge volume and rate of flow, and cool water inputs appeared to be more responsible than canopy cover for temperature differences observed on Barney, Elk, and Stevens Creeks.

The gradient between water and air temperatures drives energy exchange toward an equilibrium condition. All three creeks in this study were trending toward equilibrium. Change per increment of elevation varied among the three, but elevation effect was consistently associated with water, air, and soil temperature change and was similar to the expected adiabatic rate of change. As noted above, rate of convergence was more closely associated with time of exposure, which within the elevation range of this study, was a function of discharge and rate of flow.

Given sufficient time, streams should be expected to reach a dynamic equilibrium with mean air temperatures. As was noted on Stevens Creek, canopy cover was not sufficient to prevent water temperature from trending toward equilibrium with air temperature. Shade did not appear to be a major factor influencing stream temperature within the context of this study. In the case of

Elk Creek, even with cool water inputs water temperature trended toward equilibrium with air temperature.

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