Factors influencing stream temperatures in small streams: substrate effects and a shading experiment

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Abstract: The temperature of stream water is an important control of many in-stream processes. To better understand the processes and consequences of solar energy inputs to streams, stream temperature dynamics were examined before, during, and after experimental shading of a 150-m reach of a second-order stream in the Oregon Cascade Range. Maximum water temperatures declined significantly in the shaded reach, but minimum and mean temperatures were not modified. Heat budget calculations before shading show the dominance of solar energy as an influence of stream temperature. The influence of substrate type on stream temperature was examined separately where the water flowed first over bedrock and then through alluvial substrates. Maximum temperatures in the upstream bedrock reach were up to 8.6 °C higher and 3.4 °C lower than downstream in the alluvial reach. Better understanding of factors that influence not only maximum but minimum temperatures as well as diurnal temperature variation will highlight types of reaches in which stream temperature would be most responsive to changes in shading. Many apparent discrepancies in stream temperature literature can be explained by considering variation in the relative importance of different stream temperature drivers within and among streams and over time.

Résumé : Dans les cours d'eau, la température de l'eau est un important facteur de contrôle de plusieurs processus internes. Afin de mieux comprendre les processus reliés à l'apport d'énergie solaire dans les cours d'eau et d'en évaluer les conséquences, nous avons examiné la dynamique thermique avant, pendant et après une expérience dans laquelle nous avons ombragé expérimentalement une section de 150 m d'un ruisseau d'ordre deux dans la chaîne des monts Cascades en Oregon. Les températures maximales de l'eau ont décru significativement dans la section ombragée, mais les températures minimales et moyennes sont restées inchangées. Les calculs de bilans thermiques avant l'expérience ont montré que l'énergie solaire a une influence dominante sur la température du cours d'eau. L'effet du type de substrat sur la température du cours d'eau a pu être examiné séparément là où l'eau coule d'abord sur la roche-mère pour ensuite traverser des substrats alluviaux. Les températures maximales dans la section de roche-mère d'amont sont jusqu'à 8,6 °C supérieures et 3,4 °C inférieures à celles de la section alluviale d'aval. Une meilleure compréhension des facteurs qui influencent non seulement les températures maximales et minimales, mais aussi la variation journalière de la température, permettra d'identifier les sections dans lesquelles la température du cours d'eau est plus susceptible d'être affectée par les changements d'ombrage. Plusieurs contradictions apparentes dans la littérature scientifique concernant la température des cours d'eau peuvent s'expliquer en considérant les variations dans le temps, ainsi que dans un même cours d'eau et d'un cours d'eau à un autre, de l'importance relative des différents facteurs qui régissent la température des cours d'eau.

[Traduit par la Rédaction]

Introduction

The temperature of stream water has been a focus of study for many years because of the importance of temperature in governing in-stream processes such as metabolism, organic matter decomposition, and solubility of gases as well as the effects of temperature on stream biota. Stream temperature in many regions has increased as a result of land use practices (Beschta and Taylor 1988; Sugimoto et al. 1997), resulting in undesirable impacts on cold-water species such as salmonids (Beschta et al. 1987; Bisson et al. 1992; Li et al. 1994). Stream temperature is controlled by multiple factors (Sinokrot and Stefan 1993; Poole and Berman 2001) whose influences and magnitude can be difficult to examine independently.

There is conflicting information in the peer-reviewed literature about the relative ranking of contributing factors of stream temperature. Although incoming solar radiation is generally recognized to be the major source of thermal energy for streams (Brown and Krygier 1970; Sinokrot and Stefan 1993; Webb and Zhang 1999), some have suggested that air temperature is a major influence of stream tempera-

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ture (Smith and Lavis 1975; Sullivan and Adams 1990). The role of shade as an influence of stream temperature has been questioned (Larson and Larson 1996), and decreases in stream temperature under shade have been primarily attributed to convective heat exchanges (Larson et al. 2002) rather than to reduced incoming radiation. Strong correlations between stream temperature fluctuations and other environmental factors (Sullivan and Adams 1990; Brosofske et al. 1997) can also result in potential misidentification of causative factors (Johnson 2003).

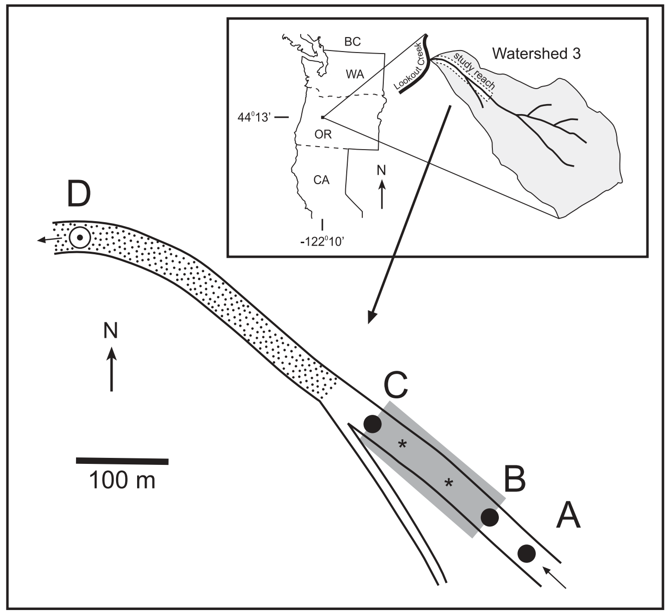
A factor that has historically been disregarded or misinterpreted as an influence of stream temperature is the type of substrate through which and over which the water flows (Brown 1969; Beschta and Weatherred 1984; Sugimoto et al. 1997). Brown (1969), for example, suggested that bedrock reaches dampened diurnal fluctuations and that gravel alluvial-type substrates had little influence on temperature dynamics. Although hyporheic or subsurface flows have been shown to exhibit dampened diurnal fluctuations compared with in-stream water (Ringler and Hall 1975; White et al. 1987; Evans and Petts 1997), hyporheic flows have been considered to be a very minor influence on in-stream temperature dynamics. However, recent studies of dynamic thermal regimes in the hyporheic zone (Malard et al. 2001), along with an improved understanding of the hyporheic zone as an important flow path of surface water (Haggerty et al. 2002; Kasahara and Wondzell 2003), now suggest that the hyporheic zone may play an important role in influencing stream temperature in alluvial reaches.

Questions also exist concerning longitudinal patterns of stream temperature and whether temperatures, once they have increased, will decrease downstream as a stream enters a shaded reach. Based on energy balance considerations, Beschta et al. (1987) suggested that streams do not “cool” when they flow through shaded reaches; others, however, have observed decreases in stream temperature within shaded reaches downstream of clearcuts (Zwieniecki and Newton 1999) or other openings (Torgerson et al. 1999).

Changes in vegetation near streams can have major impacts on stream temperature (Brown and Krygier 1970; Beschta and Taylor 1988; Johnson and Jones 2000). Streams and their riparian areas have been greatly modified across most ecosystems (Bisson et al. 1992; Sugimoto et al. 1997). Small forested streams historically have not been protected under riparian management guidelines or forest harvest best management practices; agricultural or urban streams of all sizes have had even less protection. The response of stream temperature to changes in near-stream vegetation has been shown to vary, with water temperature in some small streams dramatically increasing following disturbance and removal of riparian vegetation (Brown and Krygier 1970; Johnson and Jones 2000), while other streams show much less response (Ziewienski and Newton 1999). Understanding the mechanisms of stream temperature responses to shade and to various substrates would be valuable, especially for management or restoration activities.

To evaluate some of the competing views of influences and controls of stream temperature, I examined the influence of type of substrate, using comparison of adjacent reaches within a study stream, and the role of shade in one of these reaches, using experimental methods. Experimental manipulations are well suited to examining shading separately from the other functions of riparian vegetation that can also influence stream temperatures. Questions addressed in this paper include: Do different types of substrates influence summer stream temperatures? Do stream temperatures decrease as the water flows through a shaded reach? What is the relative magnitude of influence of air temperature versus shade on stream temperature?

Fig. 1. Location of the study reach in Watershed 3, H.J. Andrews Experimental Forest, Oregon, USA, showing upstream bedrock (open areas) and downstream alluvial (stippled areas) sections, the portion of the bedrock reach that was shaded (shaded area), and locations of sites A–C temperature sensors (●), photosynthetically active radiation sensors (*), and stream gauge and temperature sensor (⊙).



Methods

The study stream in Watershed 3 (WS 3) in the H.J. Andrews Experimental Forest, western Cascades Range, Oregon (Fig. 1), had over 1 km of its length scoured to bedrock by debris flows in 1964 and again in 1996. Downstream of the exposed bedrock, alluvial and colluvial materials scoured from upstream have been deposited, creating a 300-m-long reach with an extensive hyporheic zone (Haggerty et al. 2002; Kasahara and Wondzell 2003). All riparian vegetation along both the bedrock and alluvial reaches of the stream was removed during the debris flows and the stream is exposed to full incoming solar radiation midday during summer. Steep valley walls with coniferous trees provide topographic and vegetative shading in early morning and late afternoon. A stream gauging station is located at the downstream end of the alluvial reach and approximately 100 m upstream of the confluence of WS 3 with Lookout Creek.

To examine the effects of substrates and shading on stream temperature dynamics, water and air temperature sensors (Onset Stowaway, ±0.1 °C resolution) were deployed at multiple sites in WS 3 (Fig. 1). Before being deployed, sensors were cross-validated to account for potential differences in

Fig. 2. Photograph during shading of the bedrock reach. Shade was suspended approximately 2 m above the water surface. For scale, note the person standing at the water level on the edge of stream.

accuracy and programmed to record instantaneous temperatures at half-hour intervals. Each water temperature sensor was placed into the stream in a protective, open-ended, 5-cm-diameter white plastic tube to prevent incoming solar radiation from directly striking the sensor. Air temperature sensors were placed 1.5–2.0 m above the water surface in a half-circle white protective housing, again to block direct radiation of the sensor.

Shading experiment

Two hundred metres of the bedrock portion of WS 3 was selected for the stream shading experiment. Air and water temperatures were recorded for 3 weeks before shading, 3 weeks during shading, and 3 weeks after shading. Temperature sensors were placed at the upstream (site A) and downstream extent (site C) of the bedrock reach to be shaded (Fig. 1) and stream and air temperatures were recorded from 25 June to 26 August 1997. From 15 July through 5 August, the entire wetted channel through this study reach was shaded. Black plastic sheeting (2-mil (50.8-μm) thickness), supported by a rope suspension system, was located approximately 2 m above the water surface to block incoming solar radiation and yet to allow natural air movement beneath the plastic (Fig. 2). To quantify the influence of shade on air temperature, additional air temperature sensors were placed under the shade 1 m above the water surface at site B (upstream end of shade) and site C (downstream end of shade). Photosynthetically active radiation (PAR) sensors (CR 10 data loggers, Campbell Scientific, Inc.) measured and recorded incoming solar radiation at 15-min intervals at two locations in the center of the stream in the shaded reach from 27 July to 25 August. At each location, PAR sensors were set vertically, with one sensor located above the shade and a second sensor located below the shade and 0.2 m above the water surface.

Substrate differences

To examine the influences of substrates on stream temperature dynamics in WS 3, a temperature sensor was also deployed at the downstream end of a 300-m-long unshaded alluvial reach (Fig. 1, site D) to compare with the upstream bedrock reach. The following physical variables were measured in both the bedrock and alluvial study reaches during August 1997 and averages for each reach calculated: wetted width of the channel and water depth at three points across the channel were measured every 5 m along the length of each study reach, channel slope for each reach was measured using a laser level, potential open sky for July was calculated for each reach from Solar Pathfinder® traces made every 20 m along the channel (Solar Pathways Inc., Glenwood Springs, CO 81601, USA), percent cover provided by vegetation and topography was measured every 20 m using a spherical densiometer (Platts et al. 1987), and aspect was also noted every 20 m using a compass. Water velocity was measured in the bedrock and alluvial reaches using several methods: point measurements (Marsh-McBirney flowmeter) of cross-sectional velocities in three transects within each reach and travel time of the visible leading edge of fluorescein dye releases over three 10 m sections. These were compared with median water velocity rates calculated from multiple day solute releases in each reach (S. Wondzell, US Forest Service, Pacific Northwest Research Station, Olympia, Wash., unpublished data). Discharge was calculated from depth and flow measurements taken at the downstream end of the bedrock reach and at the gauge.

Analyses

Regression relationships of daily maximum stream temperature at sites C and A, where stream temperature at site A is the independent variable and at site C is the dependent variable, were compared for three time periods: before, during, and after shading. Sums of squares for the full model were calculated and compared with sums of squares and mean square error of partial models ("dummy variables in regressions"; Kleinbaum et al. 1998). Regression relationships were evaluated to see if lines were parallel and (or) coincident. Daily minimum and mean stream temperatures at sites A and C were similarly analyzed.

Heat budgets for the bedrock reach were calculated for the hour nearest maximum incoming solar inputs on 20 July 1997, with and without shading (Appendix A) (Monteith and Unsworth 1990; Sinokrot and Stefan 1993; Webb and Zhang 1999). Incoming solar radiation with and without shading was measured in the reach. Reflected radiation was measured with a downward facing pyranometer. Long-wave radiation without shade was calculated using published values of net flux between incoming and reflected long wave (Monteith and Unsworth 1990). During shading, the black plastic would have blocked direct incoming long-wave radiation (Oke 1987), but net long-wave fluxes during shading were assumed to continue owing to reflection and reradiation from surfaces that were not shaded (M. Unsworth, Department of Forest Science, Oregon State University, Corvallis, OR 97331, USA, personal communication). Evaporation and convection were calculated using onsite measures of wind speed, relative humidity, and air and water temperatures. Conduction was calculated using estimates of subsurface temperatures within the bedrock.

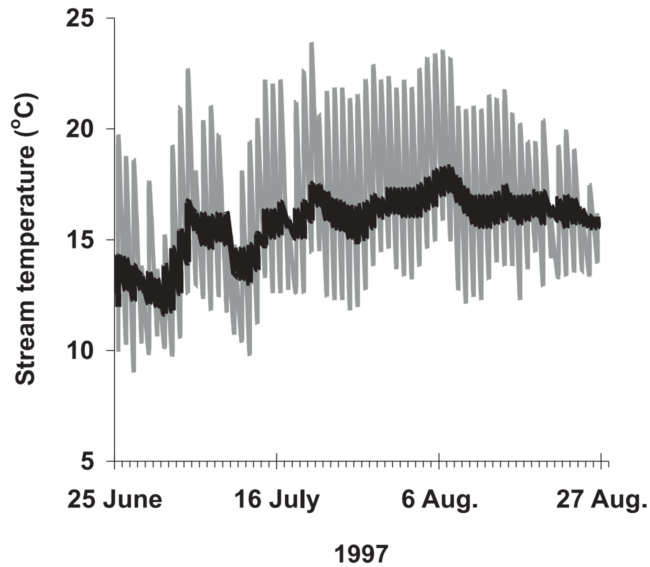
Results

Substrate influences on stream temperature

Throughout the summer, diurnal fluctuations of stream temperature in the bedrock reach were much greater than downstream in the alluvial reach (Fig. 3). Daily maximum temperatures were higher and minimum temperatures lower in the bedrock reach than downstream in the alluvial reach. Mean daily temperatures, however, were similar. Short intervals of rainy and (or) cloudy days resulted in higher maximum temperatures at site D than at site A. Stream temperatures increased through the summer, with the seasonal maximum temperature occurring on 20 July at site A in the bedrock reach and on 7 August at site D in the alluvial reach (Fig. 3).

Within each reach, temperatures changed over very short distances. As the stream flowed through the bedrock reach from site A to site C (200 m), daily maximum stream temperatures increased several degrees (Figs. 4*a* and 4*c*). In the alluvial reach, between sites C and D (350 m), daily maximum temperatures decreased by as much as 8.7 °C and minimum temperatures increased by 3.9 °C.

Fig. 3. Daily maximum and minimum stream temperatures during the summer 1997 in adjacent bedrock and alluvial reaches. Site A, in the bedrock reach (grey line), is 550 m upstream of site D at the downstream portion of the alluvial reach (black line).



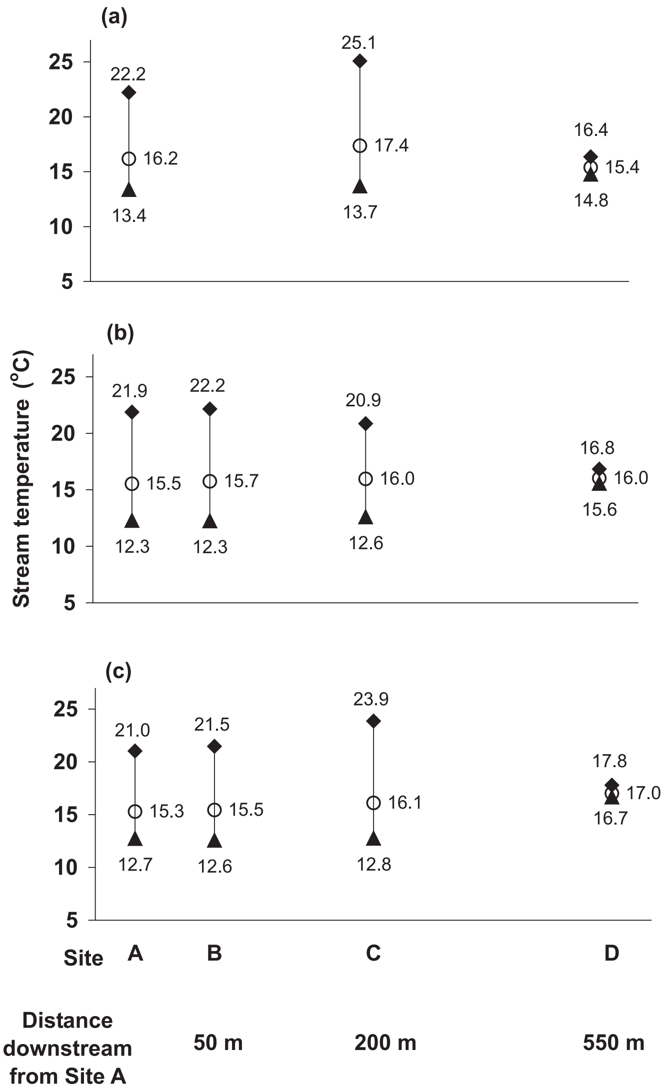
Although physical characteristics in the two reaches were generally similar (Table 1), estimates of water velocity differed dramatically, depending on the measurement method (Table 2). Average water velocity from point measurements in the two reaches were similar, but velocity calculated from dye releases or from median travel time from solute releases was very different between reaches (Table 2). Using leading edge of dye, average water velocity in the alluvial reach was two-fifths that in the bedrock reach. However, using conservative solute releases, median water velocity in the alluvial reach was 1/100th of the rate in the bedrock reach. Median retention time of water in the 200-m section of bedrock was 1.1 h but was 18 h in the 300-m alluvial reach (Table 2) (S. Wondzell, US Forest Service, Pacific Northwest Research Station, Olympia, Wash., unpublished data).

No groundwater inputs were visible in the bedrock reach. There was an increase in discharge between site C and the gauge at site D (Table 1), most of which can be accounted for by a small tributary that entered 50 m below site C. Stream temperatures just downstream of the bedrock reach and this confluence of the small tributary with WS 3 stream were within 0.1 °C of those at site C for 22 h each day and were up to 1.0–1.5 °C higher during full summer sun (noon to 1300) (S.L. Johnson, unpublished data). These increases likely occurred as the water traveled through an additional section of 50 m of bedrock and were similar to temperature increases upstream between sites A and B.

Effects of shading on stream temperatures

The experimental shading resulted in decreases in maximum water temperature at the downstream end of the shaded reach. Before and after shading, maximum water temperature was up to 3–4 °C higher at site C than at site A 200 m upstream (Fig. 4). During the shading experiment, maximum water temperature at site C was up to 1 °C lower than at site A (Fig. 5). However, the mean and minimum temperatures at

Fig. 4. Maximum (◆), minimum (▲), and mean (○) stream temperatures at sites A–D in WS 3 for 3 days representative of (*a*) before shading on 14 July, (*b*) during shading on 23 July, and (*c*) after shading on 8 August. Site A is the most upstream site and shading occurred from site B downstream to site C.



site C continued to be greater than at sites A and B (Figs. 4 and 5).

Additional temperature sensors were added at site B because the plastic shading could not be suspended over the upper 50 m of the bedrock study reach. Maximum temperatures increased in the 50 m between sites A and B (Fig. 4) and the decrease from shading would have been greater if sites B and C were compared. However, sites A and C were used for statistical analysis because of the existence of pretreatment data.

The slope of the regression of maximum daily temperatures at sites A and C during shading was significantly different from that before or after shading ($f = 9.36$, $p < 0.01$). Shading did not significantly change the slopes of the regression relationship of temperature at sites A and C for daily mean or minimum temperatures (mean: $f = 1.42$, $p > 0.05$; minimum: $f = 0.96$, $p > 0.05$). Owing to seasonal trends in stream temperature, the intercepts of regression relationships before and after shading were significantly different for maximum and minimum daily stream temperatures ($f = 20.67$, $p < 0.001$; $f = 3.73$, $p < 0.05$) but not for means ($f = 3.16$, $p > 0.05$).

Shading reduced incoming solar radiation as well as air temperature. Daily maxima of PAR under the shade were less than 1/200th of that in the sun (10 versus 2100 μmol·m^{-2}·s^{-1}). Maximum air temperatures under the shade were lower than in sun by approximately 3–4 °C (Fig. 6). Air temperatures under the shade were slightly lower at the upstream site, site B, than at site C downstream, possibly because of upstream winds during the heat of the day. Minimum air temperatures under the shade were slightly warmer than upstream or downstream (Fig. 6).

Table 1. Physical characteristics of study reaches in WS 3.

Parameter	Bedrock reach	Alluvial reach
Wetted width, average (m)	2.13	2.11
Water depth, average (m)	0.07	0.08
Water depth, maximum (m)	0.36	0.49
Discharge (L·s^{-1})	3.4	4.0
Channel gradient (m·m^{-1})	0.14	0.13
Percent open sky (Solar Pathfinder®)	40	28
Percent canopy density (densiometer)	28	38
Aspect (upstream)	70°	62°

Note: Percent open sky is the mean for July from Solar Pathfinder® data. Discharge was measured at the most downstream point in each reach on 31 July 1997. A small tributary (0.40 L·s^{-1}) entered downstream of the bedrock reach and at the top of the alluvial reach.

Heat budget using microclimatic data

An energy heat budget was constructed for midday summer conditions in the bedrock reach to quantify factors influencing stream temperature and to model the effects of the shading experiment on stream temperature. Incoming radiation and stream and air temperatures were measured on site during the shading experiment and relative humidity, wind speed, and soil temperature data were available from the H.J. Andrews Primary Meteorological Station 2 km away. However, because microclimatic conditions near streams differ from those at even nearby upland climatic stations (Brosofske et al. 1997; S.L. Johnson, unpublished data), these same variables were remeasured on site during the summer of 2001 using a portable climatic station (Campbell Scientific, Inc.) in the bedrock reach of WS 3. Comparisons of climatic data between 19–20 July 1997 and 19–20 July 2001 for the Primary Meteorological Station show that conditions between years were similar (incoming solar, $R^2 = 0.91$; wind speed, $R^2 = 0.86$; air temperature, $R^2 = 0.82$; relative humidity, $R^2 = 0.87$; $p < 0.001$ for all); therefore, incoming radiation, wind speed, relative humidity, and soil temperatures from the WS 3 microclimatic station on 20 July 2001 were used for the heat budget calculations of the shading experiment to have modeled conditions represented by the budget as close as possible to those occurring on site during the shading experiment (Appendix A).

Midday stream temperature heat budgets with and without shading differed dramatically in the amount of radiative

Table 2. Average velocity of stream water in bedrock and alluvial reaches in WS 3.

Measurement method	Bedrock reach ($m \cdot s^{-1}$) (SE)	Alluvial reach ($m \cdot s^{-1}$) (SE)
Flowmeter	0.20 (0.06)	0.15 (0.05)
Dye release, leading edge	0.10 (0.05)	0.04 (0.03)
Solute release, median velocity	0.050*	0.005*

Note: Median velocity using solute releases was calculated as reach length·(median retention time)$^{-1}$. An asterisk denotes unpublished data from S. Wondzell, US Forest Service, Pacific Northwest Research Station, Olympia, Wash.

Fig. 5. Differences in daily maximum (black line), minimum (grey line), and mean (broken line) stream temperatures between sites C and A during the summer of 1997. The shading experiment occurred 16 July through 5 August.

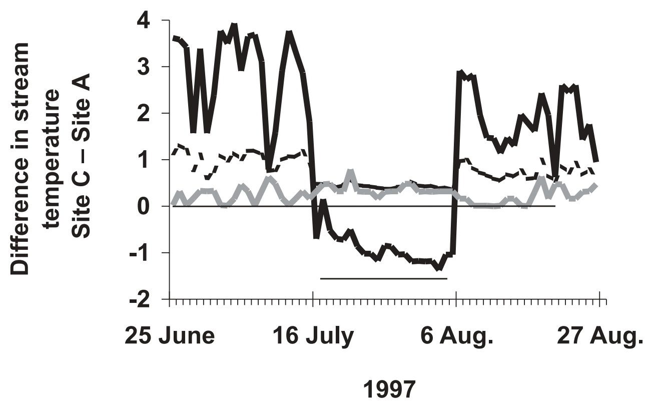


Fig. 6. Maximum (◆), minimum (▲), and mean (○) air temperatures on 23 July during the shading experiment in WS 3. Air temperature sensors were paired at sites B and C, with a sensor (Shade) located under the shade midway between the stream surface and the shade and a second sensor (Sun) located at a similar height above the stream but 1.5 m upstream or downstream of the shade.

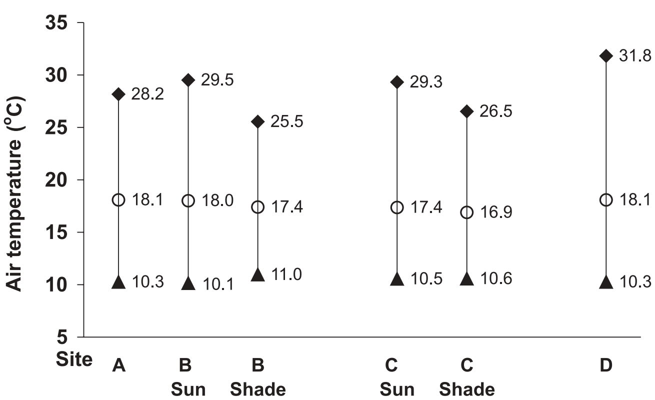
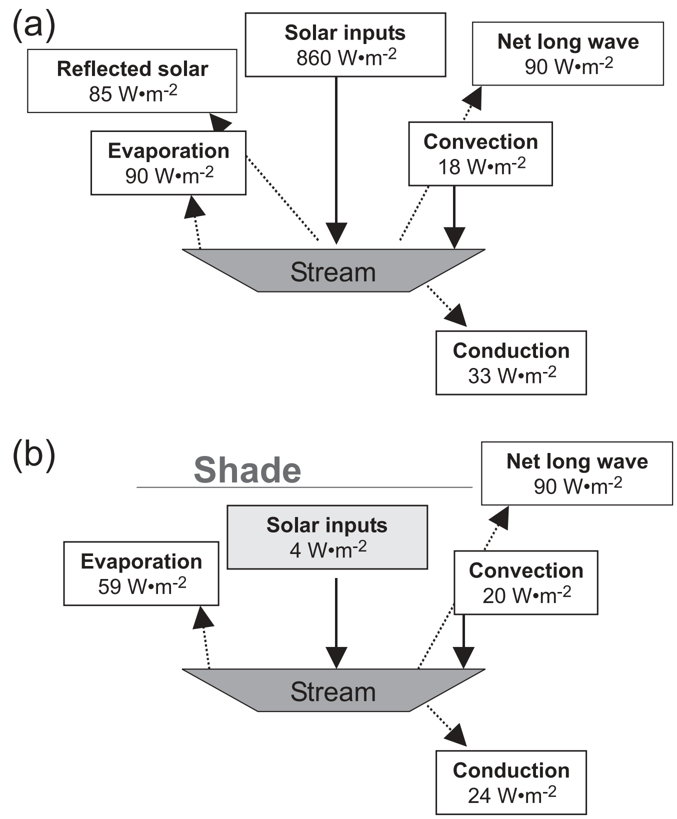


Fig. 7. Heat energy budgets for 1200, 20 July 1997, in the bedrock reach: (*a*) full sun, the sum of fluxes is 580 $W \cdot m^{-2}$ towards the stream; (*b*) under shade, the sum of fluxes is 149 $W \cdot m^{-2}$ away from the stream.



inputs (Fig. 7). Net energy fluxes without shading were dominated by solar inputs (Fig. 7*a*); the sum of these positive and negative fluxes (580 $W \cdot m^{-2}$) slightly overestimated temperature increases for the calculated volume of stream in this 150-m reach. During shading, net energy fluxes were dramatically reduced (Fig. 7*b*); the sum of fluxes under shade (–149 $W \cdot m^{-2}$) corresponds to approximately a 1 °C decrease of maximum temperature through this reach. These calculations assume that the conditions measured at the microclimatic station were representative of those throughout the reach and that one-half volume of water calculated for the reach moved through the reach during the hour.

Although solar inputs were decreased by the shading experiment, the magnitude of other fluxes showed little change during shading. However, with reduced solar inputs, the relative proportion of the total energy budget from these other fluxes greatly increased. Under shade, the largest energy fluxes were evaporation and net long-wave radiation. Evaporative fluxes result in movement of heat energy away from the stream and are greatly influenced by wind speed and relative humidity of the overlying air mass. Convective fluxes are determined by temperature differences between the water and air and, on a warm summer day when the air is warmer than the stream, result in energy moving toward the stream. Convective exchanges increased only slightly under shade as a result of slight changes in vapor pressure with decreases in air temperature. Excess heat accumulated in the immediate vicinity of the plastic but because of the movement of the air beneath the plastic, air temperatures under the shade were less than in full sun (Fig. 6). Shading did not interfere with wind above the stream; with the plastic 2 m above the channel, much air circulation was observed under the shade.

Conduction is a function of temperature differences between water and the substrates or within the substrates. Rates of exchange depend on the thermal conductivity of the bed material as well as the gradients of temperature within the substrate. Conduction was calculated using a one-dimensional heat equation, which underestimates energy fluxes (Hondzo and Stefan 1994; Evans et al. 1998), but other methods of calculating conduction require more data on subsurface temperatures (Hondzo and Stefan 1994; Evans et al. 1998). Using these standard steady-state methods and estimated temperatures of bedrock, fluxes between the water and bedrock or within the bedrock to the cooler bedrock interior accounted for a very small portion of the heat budget with or without shading.

Discussion

Effects of shading on stream temperatures

Maximum stream temperatures significantly decreased during shading of the water surface of a 150-m bedrock reach, but minimum and mean temperatures were not substantially affected. Reduced maximum temperatures in a shaded reach without a corresponding decrease in mean or minimum temperatures could occur because the distribution of daily stream temperature in the bedrock reach was unsymmetrical; mean temperatures are lower than what would be calculated by simple averages of daily maximum and minimum. Thus, short sections of shade can decrease instantaneous energy fluxes at midday, while the daily energy balance for stream temperature remains essentially unchanged.

Dissipation of a portion of the water's heat energy as the water moves downstream has been suggested to not be common (Beschta et al. 1987), but this experiment shows that it is possible to have longitudinal maximum temperatures influenced by shade. Maximum stream temperature immediately responded to the placement and the removal of shade, showing the importance of incoming radiation in controlling daily maximum stream temperatures. Using the median travel time of water in the bedrock reach of approximately 1 h allows examination of the temperature of the water entering the reach and temperature dynamics as it moves through the reach. Early in the day, water temperature, lagged by the median travel time, increased between sites B and C, while at midday under shade, temperature declined in the shaded reach (Appendix B). Although the heat budget analysis of the shaded reach during midday highlights evaporation as a possible mechanism for energy transfer away from the stream, conduction may also have contributed but was likely underestimated because of unavailability of temperature data from within the bedrock.

Minimum temperatures were not influenced by the shade. Theoretically, minimum water temperature could have been expected to either increase or decrease as the stream flowed through the shaded reach. Streams under vegetative cover can exhibit higher minimum temperature in response to reduced radiative losses of long-wave energy (Oke 1987; Monteith and Unsworth 1990); if this was a dominant mechanism during this experiment, minimum stream temperatures would have increased as a result of the shading. Alternatively, shading could have the opposite effect if results were extrapolated from studies of natural reestablishment of riparian vegetation over time, where minimum temperature decreased under shade (Brown and Krygier 1970; Johnson and Jones 2000). These potential opposing hypotheses of response of minimum stream temperature to cover over a stream suggest that more examination of the controls of minimum stream temperature is warranted.

Several factors in this experiment, such as the type of material used for shading or that shading only covered the wetted portion of the stream channel, may have not functioned in a similar manner to the influence of riparian vegetation on stream temperatures; however, these same factors allowed examination of the role of shade independent of the myriad other functions of riparian vegetation. Riparian vegetation influences streams and stream temperature through multiple pathways in addition to providing shade. Riparian vegetation influences microclimatic conditions through biological functions such as evapotranspiration and release of water vapor as well as through physical means such as decreasing wind speeds. Vegetation also provides bank stability, which can impact width to depth ratios and the exposed surface area of the stream. Accumulations of large organic matter inputs have an effect on hydraulic retention times. Although incoming radiation levels in dense natural forests can be as low as those under the experimental shade, riparian forests would have more variability of incoming light levels because of the shape and structure of the vegetation.

The lack of influence of this shading experiment on minimum and mean stream temperatures suggests that because not all stream metrics are equally responsive, each metric should be considered individually when evaluating stream temperature responses to mitigation or restoration activities. Biologically, maximum as well as minimum stream temperatures are important. Maximum temperatures have become the foci of many water quality standards because high water temperature can increase stress and metabolic rates for coldwater salmonids, increase viability of disease vectors, and potentially serve as barriers for migrating fishes (Beschta et al. 1987; Li et al. 1994). Less is known about the influences of minimum temperature or how organisms respond to diurnal fluctuations of temperature (Cox and Rutherford 2000). Concluding that downstream shading ameliorates upstream temperature increases (Zwieniecki and Newton 1999) is premature without examination of minimum and mean temperatures.

Substrate influences on stream temperatures

Substrate type can be an important influence on maximum and minimum stream temperatures, as demonstrated by the dramatic differences in maximum, minimum, and diel fluctuations between the bedrock reach and the reach with alluvial substrates and hyporheic flows. The juxtaposition of substrate types, as found in WS 3, provided a natural experiment, where the stream flows through a bedrock reach and then through an alluvial reach with extensive hyporheic exchange. The influence of substrate type on diel temperature fluctuations is very dramatic in WS 3 because of the homogeneity of each reach type and the volume of water exposed to each substrate type. Most streams have high heterogeneity of substrate conditions, which may explain why the influence of specific substrates on in-stream temperature dynamics is not broadly recognized (i.e., Clark et al. 1999).

In this study, the bedrock reach showed high maximum temperatures, low minimum temperatures, and wide diurnal fluctuations. Although Brown (1969) and Beschta and Weatherred (1984) suggested that bedrock reduces maximum temperature and dampens diurnal fluctuations by absorbing energy in the heat of the day and releasing the stored energy later, this was not observed in the bedrock reach of WS 3. The high daytime water temperatures in the bedrock reach were likely influenced by reflection of solar energy from the smooth bedrock surfaces into the shallow stream. The bedrock under the shallow stream may have been absorbing some incoming solar energy and serving as a minor heat sink but not to the extent predicted by Brown (1969). Minimum stream temperatures in the bedrock reach were much cooler than those in nearby streams (Johnson and Jones 2000); therefore, the nighttime rerelease of stored energy from daytime was not apparent in the thermograph of temperature from this reach.

As the water from the bedrock reach flowed into the alluvial reach, stream temperatures were dramatically dampened, with lower maxima and higher minima. The influence of hyporheic flow on in-stream temperature has been previously thought to be fairly localized (White et al. 1987). Dampening of subsurface diurnal water temperatures has been documented as a function of depth into subsurface gravels (Ringler and Hall 1975; Evans et al. 1998; Malcolm et al. 2002). Influences of hyporheic exchange flows on surface stream temperatures have generally been observed only at microscales, such as upwelling locations or within small side channels (White et al. 1987; Evans et al. 1998; Clark et al. 1999), creating important thermal refugia for biota.

Hyporheic flow could influence downstream temperature maxima and minima by several possible mechanisms. Reach residence time is lengthened by hyporheic flow paths (Poole and Berman 2001; Haggerty et al. 2002). Increased hydraulic retention and the large volume of subsurface storage could lead to simple mixing of warm daytime water and cooler nighttime water, thereby moderating downstream temperatures. However, while the water is in contact with the subsurface substrates, conduction would also occur, transferring heat energy from warmer to cooler surfaces. Water warmed during the daytime and flowing over cooler rocks in the subsurface would transfer heat to the substrates. During the night, cooler stream water entering the subsurface and passing over warmer rocks would absorb heat. These processes also occur on a small scale, in-stream (Brown 1969), but the magnitude of surface area of substrates within a porous hyporheic zone can greatly dwarf the exposed surface area of a stream channel. The potential influence of alluvial substrates on surface stream temperature is related to the proportion of total stream flow passing through the hyporheic zone, which, in the lower 100 m of WS 3, is the majority of stream flow (Kasahara and Wondzell 2003).

Many factors influence fluxes of energy and determine the magnitude of heat transfer between a stream and its surroundings (Brown 1969; Clark et al. 1999; Poole and Berman 2001). Ultimately, heat fluxes are influenced by the duration of time over which exchanges can occur as well as the rates controlling potential energy exchanges. In the bedrock reach, where median water velocities were high and the hydraulic retention time of water was short, dominant energy exchange processes must have been those with very high rates to result in rapid temperature increases and decreases over a short reach. Alternatively, in the alluvial reach, complex flow paths resulted in slow median water velocities and therefore long hydraulic retention times. These slow velocities led to mixing of daytime and nighttime water between and within the channel and hyporheic zone, allowing processes with lower rates of energy exchange to have a potentially significant impact on stream temperature. The duration of contact between water and its surroundings influences stream temperature energy exchanges and highlights the need for information on reach-scale hydraulic retention to understand the extent to which energy flux dynamics vary from habitat to habitat.

Addressing conflicts within the literature

Stream temperature dynamics, especially heat budgets, are complicated and the relative magnitude of different components can shift among sites with differing biotic and geophysical properties. This has led to apparently contradictory findings within the scientific literature (Beschta 1997; Beschta et al. 2003; Johnson 2003). Although some authors have suggested that shade is not an important factor for stream temperature (Larson and Larson 1996; Larson et al. 2002), maximum temperatures in this study were strongly influenced by the reduction of incoming solar radiation over even a short reach. Heat budget calculations for the bedrock reach demonstrate the importance of incoming solar radiation as a dominant factor influencing stream temperature.

The heat budgets also showed that convective or sensible heat exchanges between warm air and cooler streams comprise a relatively small portion of the total heat flux. Therefore, air temperature is apt to be a relatively weak determinant of stream temperature. While other published accounts suggest that air temperature is a dominant driver (Smith and Lavis 1975; Sullivan and Adams 1990; Larson and Larson 1996), this conclusion is based on an observed strong correlation between air and stream temperature. Rather than indicating a causal relationship, however, the correlation exists because both air and water temperature are responding to the same temporal fluctuations in solar heat inputs.

Although substrate type was recognized by Brown (1969) and more recently by others (Evans et al. 1998; Clark et al. 1999; Webb and Zhang 1999) to be a factor in heat budgets, it has not been generally envisioned as important to stream temperature dynamics (Beschta et al. 1987; Sugimoto et al. 1997). Observations of stream temperature in bedrock and alluvial reaches in WS 3, as well as other emerging research (R.D. Moore, Department of Geography and Forest Resources Management, University of British Columbia, Vancouver, BC V6T 1Z2, Canada, personal communication), show that the type of substrate can have important influences on in-stream temperatures.

Longitudinal temperature dynamics are also complex and many questions remain to be answered. Historically, stream temperature was not thought to decrease downstream once it had warmed (Beschta et al. 1987). However, recent technological advances (Hobo®, Stowaway®, Ibutton®, FLIR®) have provided methods to easily measure instantaneous temperature at many more points than previously possible. Studies with high densities of measurements sites along a stream have revealed increased complexity of longitudinal and lateral stream temperature dynamics (Clark et al. 1999; Torgerson et al. 1999; Arscott et al. 2001). Although longitudinal trends in stream temperature exist in most stream networks, local deviation from those trends can be substantial. Use of average longitudinal temperature trends (Zwieniecki and Newton 1999) is therefore inappropriate for determining whether stream temperature has "recovered" from an upstream perturbation as well as for other applications where precise, accurate estimates of predisturbance conditions are required. A better knowledge of the mechanisms of energy exchanges will help us understand interactions among the controlling factors of stream temperature and the multiple functions of shade over streams.

In conclusion, the type of substrate over which a stream flows may have implications for stream management activities and may explain some of the variability in temperature responses to riparian removal or forest harvest. Streams flowing over bedrock may be more responsive to slight changes of incoming solar radiation, while those on alluvial substrates may be buffered by longer hydraulic retention times, resulting in dampened diurnal fluctuations in stream temperatures. Although the reduction of incoming shortwave solar radiation was greater in this shading experiment than what would generally occur with patchy riparian vegetation, decreases in maximum stream temperatures were observed in a short (150 m) shaded reach. However, downstream shading of a stream does not appear to totally remediate the effects of upstream disturbances or riparian removal on stream temperatures because mean and minimum temperatures were only minimally affected.

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References

Arscott, D.B., Tockner, K., and Ward, J.V. 2001. Thermal heterogeneity along a braided floodplain river (Tagliamento River, northeastern Italy). Can. J. Fish. Aquat. Sci. **58**: 2359–2373.

Beschta, R.L. 1997. Riparian shade and stream temperature: an alternative perspective. Rangelands, **19**: 25–28.

Beschta, R.L., and Taylor, R.L. 1988. Stream temperature increases and land use in a forested Oregon watershed. Water Res. Bull. **24**: 19–25.

Beschta, R.L., and Weatherred, J. 1984. A computer model for predicting stream temperatures resulting from the management of streamside vegetation. WSDG-AD-00009. US Department of Agriculture, Forest Service, Fort Collins, Colorado.

Beschta, R.L., Bilby, R.E., Brown, G.W., Holtby, L.B., and Hofstra, T.D. 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions. *In* Streamside management: forestry and fishery interactions. *Edited by* E.O. Salo and T.W. Cundy. Institute of Forest Resources, University of Washington, Seattle, Wash. pp. 191–232.

Beschta, R.L., McIntosh, B.A., and Torgerson, C.E. 2003. Comment: perspectives on water flow and the interpretation of FLIR images. [J. Range Manag. **55**: 106–111, 2002.] J. Range Manag. **56**: 97–99.

Bisson, P.A., Quinn, T.P., Reeves, G.H., and Gregory, S.V. 1992. Best management practices, cumulative effects, and long-term trends in fish abundance in Pacific Northwest river systems. *In* Watershed management: balancing sustainability and environmental change. *Edited by* R.J. Naiman. Springer-Verlag, New York. pp. 189–232.

Brosofske, K.D., Chen, J., Naiman, R.J., and Franklin, J.F. 1997. Harvesting effects on microclimatic gradients from small streams to uplands in western Washington. Ecol. Appl. **7**: 1188–1200.

Brown, G.W. 1969. Predicting temperatures of small streams. Water Resour. Res. **5**: 68–75.

Brown, G.W., and Krygier, J.T. 1970. Effects of clear-cutting on stream temperature. Water Resour. Res. **6**: 1133–1139.

Clark, E., Webb, B.W., and Ladle, M. 1999. Microthermal gradients and ecological implications in Dorset rivers. Hydrol. Processes, **13**: 423–438.

Cox, T.J., and Rutherford, J.C. 2000. Thermal tolerances of two stream invertebrates exposed to diurnally varying temperature. N.Z. J. Mar. Freshw. Res. **34**: 203–208.

Evans, E.C., and Petts, G.E. 1997. Hyporheic temperature patterns within riffles. Hydrol. Sci. J. **42**: 199–213.

Evans, E.C., McGregor, G.R., and Petts, G.E. 1998. River energy budgets with special reference to river bed processes. Hydrol. Processes, **12**: 575–595.

Haggerty, R., Wondzell, S.M., and Johnson, M.A. 2002. Power-law residence time distribution in the hyporheic zone of a 2nd-order mountain stream. Geophys. Res. Lett. **29**: 13 (doi: 10.1029/2002GL014743).

Hondzo, M., and Stefan, H.G. 1994. Riverbed heat conduction prediction. Water Resour. Res. **30**: 1503–1513.

Johnson, S.L. 2003. Stream temperature: scaling of observations and issues for modelling. Hydrol. Processes, **17**: 497–499.

Johnson, S.L., and Jones, J.A. 2000. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. Can. J. Fish. Aquat. Sci. **57**: 30–39.

Kasahara, T., and Wondzell, S.M. 2003. Geomorphic controls on hyporheic exchange flow in mountain streams. Water Resour. Res. **39**: 1005 (doi: 10.1029/2002WR001386).

Kleinbaum, D.G., Kupper, L.L., and Muller, K.E. 1998. Applied regression analysis and other multivariable methods. 3rd ed. Duxbury Press, Boston, Mass.

Larson, L.L., and Larson, S.L. 1996. Riparian shade and stream temperature: a perspective. Rangelands, **18**: 149–152.

Larson, S.L., Larson, L.L., and Larson, P.A. 2002. Perspectives on water flow and the interpretation of FLIR images. J. Range Manag. **55**: 106–111.

Li, H.W., Lamberti, G.A., Pearsons, T.N., Tait, C.K., and Buckhouse, J.C. 1994. Cumulative effects of riparian disturbances along high desert trout streams of the John Day Basin, Oregon. Trans. Am. Fish. Soc. **123**: 627–640.

Malard, F., Alain, M., Uehleinger, A.M., and Ward, J.V. 2001. Thermal heterogeneity in the hyporheic zone of a glacial floodplain. Can. J. Fish. Aquat. Sci. **58**: 1319–1335.

Malcolm, I.A., Soulsby, C., and Youngson, A.F. 2002. Thermal regime in the hyporheic zone of two contrasting salmonid spawning streams: ecological and hydrological implications. Fish. Manag. Ecol. **9**: 1–10.

Monteith, J.L., and Unsworth, M. 1990. Principles of environmental physics. 2nd ed. Arnold Press, London, UK.

Oke, T.R. 1987. Boundary layer climates. 2nd ed. Routledge Press, London, U.K.

Poole, G.C., and Berman, C.H. 2001. An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation. Environ. Manag. **27**: 787–802.

Platts, W.S., Armour, C., Booth, G.D., Bryant, M., Bufford, J.L., Culpin, P., Jensen, S., Lienkaemper, G.W., Minshall, G.W., Monsen, S.B., Nelson, R.L., Sedell, J.R., and Tuhy, J.S. 1987. Methods for evaluating riparian habitats with applications to management. Gen. Tech. Rep. INT-221. US Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, Utah.

Ringler, N.H., and Hall, J.D. 1975. Effects of logging on water temperature and dissolved oxygen in spawning beds. Trans. Am. Fish. Soc. **104**: 111–121.

Sinokrot, B.A., and Stefan, H.G. 1993. Stream temperature dynamics: measurements and modeling. Water Resour. Res. **29**: 2299–2312.

Smith, K., and Lavis, M.E. 1975. Environmental influences on the temperature of a small upland stream. Oikos, **26**: 228–236.

Sugimoto, S., Nakamura, F., and Ito, A. 1997. Heat budget and statistical analysis of the relationship between stream temperature and riparian forest in the Toikanbetsu River Basin, northern Japan. J. For. Res. **2**: 103–107.

Sullivan, K., and Adams, T.A. 1990. The physics of forest stream heating: 2. An analysis of temperature patterns in stream environments based on physical principles and field data. Weyerheauser Tech. Rep. 004-5002.90/2. Technology Center, Tacoma, Wash.

Torgerson, C.E., Price, D.M., Li, H.W., and McIntosh, B.A. 1999. Multiscale thermal refugia and stream habitat associations of chinook salmon in northeastern Oregon. Ecol. Appl. **9**: 301–319.

Webb, B.W., and Zhang, Y. 1999. Water temperatures and heat budgets in Dorset chalk water courses. Hydrol. Processes, **13**: 309–321.

White, D.S., Elzinga, C.H., and Hendricks, S.P. 1987. Temperature patterns within the hyporheic zone of a northern Michigan river. J. North Am. Benthol. Soc. **6**: 85–91.

Zwieniecki, M., and Newton, M. 1999. Influence of streamside cover and stream features on temperature trends in forested streams of western Oregon. West. J. Appl. For. **14**: 106–112.

Appendix A. Heat budget parameters

Abbreviations, units, and sources of equations are indicated.

Incoming solar radiation ($W \cdot m^{-2}$): measured with a pyranometer on 20 July 2001; average calculated for noon to 1300. Radiation under shade calculated from average of two PAR (photosynthetically active radiation) sensors under shade for noon to 1300, 28 July 1997. Conversion: 2.35 $W \cdot m^{-2}$ = 1.0 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Oke 1987).

Reflected radiation ($W \cdot m^{-2}$): measured with downfacing pyranometer in full sun at noon, 20 July 2001.

Net long-wave radiation ($W \cdot m^{-2}$): calculated difference between incoming and reflected long-wave radiation (Monteith and Unsworth 1990).

Evaporative energy flux (H_{evap}, $W \cdot m^{-2}$): $E_v L_v \rho$ (Webb and Zhang 1999).

- E_v evaporation rate ($mm \cdot day^{-1}$) = $0.165(0.8 + U/100)(E_w - E_a)$ where U = wind speed ($km \cdot day^{-1}$) measured at noon, 20 July 2001, as 0.81 $m \cdot s^{-1}$ (E_v units converted to $m \cdot s^{-1}$ before further calculations)
- E_w saturated vapor pressure (mbar, 1 bar = 100 kPa) at T_w (Oke 1987) calculated from T_w to be 31.7 mbar in sun and 25 mbar under shade
- E_a vapor pressure (mbar) at T_a (Oke 1987) calculated from T_a to be 18.5 mbar in sun and 16 mbar under shade
- L_v latent heat of vaporization ($°C \cdot J \cdot g^{-1}$) = $2454.9 - 2.366T_a$ (Webb and Zhang 1999)
- ρ density of water ($g \cdot m^{-3}$) at 25 °C.
- T_a air temperature, 29.5 °C in sun and 26.0 °C under shade on 20 July 1997
- T_w water temperature, 25.0 °C in sun and 20.9 °C under shade on 20 July 1997

Convective energy flux (H_{conv}, $W \cdot m^{-2}$): $[(0.61P(T_w - T_a)/(E_w - E_a))/1000]H_{evap}$ (Webb and Zhang 1999).

- P atmospheric pressure, assumed to be 970 mbar

Conduction (H_{cond}, $W \cdot m^{-2}$): $K(dt/dz)$ (Brown 1969; Sinokrot and Stefan 1993).

- K thermal conductivity of substrate ($J \cdot m^{-1} \cdot s^{-1} \cdot °K^{-1}$), estimated to be 2.19 for stone (Oke 1987), and dt/dz = temperature gradient between surface of substrate, where the surface was assumed to be water temperature and substrate at 1 m depth assumed to be 10 °C

References

Brown, G.W. 1969. Predicting temperatures of small streams. Water Resour. Res. **5**: 68–75.

Monteith, J.L., and Unsworth, M. 1990. Principles of environmental physics. 2nd ed. Arnold Press, London, UK.

Oke, T.R. 1987. Boundary layer climates. 2nd ed. Routledge Press, London, UK.

Sinokrot, B.A., and Stefan, H.G. 1993. Stream temperature dynamics: measurements and modeling. Water Resour. Res. **29**: 2299–2312.

Webb, B.W., and Zhang, Y. 1999. Water temperatures and heat budgets in Dorset chalk water courses. Hydrol. Processes, **13**: 309–321.

Appendix B

Table B1. Synchronous stream temperatures at sites in WS 3 on 23 July 1997.

Time (PST)	Temperature (°C)			
	Site A	Site B	Site C	Site D
0007	14.8	14.9	15.7	16.2
0037	14.6	14.6	15.4	16.2
0107	14.3	14.4	15.2	16.0
0137	14.1	14.3	14.9	16.0
0207	14.0	14.0	14.8	16.0
0237	13.8	13.8	14.5	16.0
0307	13.7	13.6	14.3	15.9
0337	13.4	13.5	14.1	15.9
0407	13.4	13.3	14.0	15.9
0437	13.1	13.0	13.8	15.9
0507	12.9	12.9	13.5	15.7
0537	12.9	12.7	13.4	15.7
0607	12.7	12.7	13.4	15.7
0637	12.6	12.6	13.1	15.7
0707	12.4	12.4	13.1	15.6
0737	12.4	12.3	12.9	15.6
0807	12.3	12.3	12.8	15.6
0837	12.3	12.3	12.6	15.6
0907	12.4	12.3	12.6	15.6
0937	12.4	12.4	12.8	15.6
1007	12.6	12.6	12.8	15.6
1037	12.7	13.0	12.9	15.6
1107	13.1	14.1	13.2	15.7
1137	15.2	15.1	13.8	15.9
1207	17.2	17.1	14.9	16.2
1237	19.7	18.9	16.2	16.0
1307	21.9	21.0	17.6	16.0
1337	21.9	22.2	18.9	16.0
1407	21.5	22.0	20.0	16.2
1437	20.4	21.3	20.9	16.2
1507	19.4	20.5	20.9	16.2
1537	18.4	19.7	20.5	16.2
1607	18.0	19.0	20.0	16.4
1637	17.8	18.6	19.6	16.7
1707	17.6	18.4	19.2	16.8
1737	17.5	18.2	18.9	16.8
1807	17.5	18.2	18.7	16.8
1837	17.3	17.8	18.4	16.5
1907	17.2	17.8	18.3	16.5
1937	17.0	17.4	18.1	16.4
2007	16.8	17.1	17.8	16.2
2037	16.5	16.8	17.6	16.2
2107	16.4	16.5	17.5	16.2
2137	16.0	16.3	17.1	16.2
2207	15.7	16.0	16.8	16.0
2237	15.6	15.7	16.7	16.0
2307	15.2	15.4	16.3	16.0
2337	15.1	15.2	16.0	16.0

Note: Experimental shading occurs between sites B and C and flow of water is from site A to site D (Fig. 1).