THE INFLUENCE OF ENVIRONMENTAL AND PHYSICAL FACTORS ON THE THERMAL PATTERNS OF HEADWATER STREAMS

[1]Craig Carr, [2]Tamzen Stringham and [3]David Thomas

[1]Graduate Research Assistant, [2]Assistant Professor, Department of Rangeland Resources, Oregon State University; [3]Professor, Department of Statistics, Oregon State University

INTRODUCTION

Stream temperature is an important component in regulating aquatic ecosystem function and is a stream attribute over which resource management may have a significant influence. Recognizing the importance of water temperature, government regulatory agencies have legislated stream temperature standards to prevent aquatic ecosystem degradation. Understanding the parameters significant in generating stream temperature is important where resource management goals include stream temperature criteria. This study was initiated to broaden our understanding of the factors that control stream temperature. An improved understanding of the thermal processes in lotic systems will assist regulators in developing appropriate stream temperature criteria and landowners and resource managers in developing and implementing management strategies appropriate for specific stream temperature objectives.

The objectives of this study were: (1) To characterize the thermal pattern of four low discharge streams and to identify the physical and environmental factors that expressed significant and functionally viable relationships with the daily maximum stream temperature, daily minimum stream temperature and daily rate of stream heating; and (2) To characterize the differences in relationships identified through objective (1) that were observed between streams that exist in differing biogeographical settings.

SITE DESCRIPTION AND RESEARCH METHODS

Four morphologically similar streams were selected for this study (Table 1). Two streams, Bsk creek and Lsk creek, flow through big sagebrush / western juniper rangelands in southeast Oregon and two streams, Grs creek and Gdn creek, flow through ponderosa pine / Douglas fir forests in northeast Oregon. All streams were low flow streams with discharge rates variable but typically less than 0.7 ft^3/sec.

Table 1. Characteristics of each stream used in this study.

	Lsk Creek	Bsk Creek	Grs Creek	Gdn Creek
Direction of flow	N → S	N → S	NW → SE	N → S
Elevation (ft) (top to bottom)	6,000 – 5,000	6,500 – 5,000	3,600 – 2,750	3,400-3,000
Total length studied (ft)	9,250	18,000	19,652	13,000
Typical width (ft)	4.5	3.3	3.3	9
Gradient range (%)	7 – 15%	4 – 10%	3 – 5.5%	2-9%
Dominant Substrate	gravel	gravel	gravel/cobble	gravel

Each study stream was divided into sampling reaches based on qualitatively assessed similarities in streamside shade and channel morphology. Within each sampling reach data were collected that described the streams physical and environmental attributes and include air temperature, stream temperature, shade, reach elevation and reach length. Temperature data were recorded in the upstream and downstream boundaries of each sampling reach using Stowaway® XTI and Hobo® programmable thermistors (Onset Computer Corporation). The thermistors were programmed to log temperature every hour on the hour. Shade within each sampling reach was modeled using the hemiview hemispherical photography analyses system (Hemiview 2.1, Delta T Devices Ltd.). A Nikon 900 coolpix digital camera equipped with a 180° fisheye lens and mounted on a self-leveling camera mount was used to acquire the images. Elevation at the upstream and downstream boundary of each sampling reach was measured using a digital altimeter. Reach lengths were assessed using ArcInfo geographic information system by measuring between GPS located sampling reach boundaries overlaid on a digital orthophoto.

To fully address the questions of interest, one data set was created for each stream that incorporated data from the 20 hottest days of each year. Grs creek in 2001, however, was restricted to 19 days. As the focus of this study was to investigate stream temperature differences between stream sections with varying physical and environmental characteristics, the 20 hottest days data set was selected as a method to control between-day variability. This data selection method also reduced the data sets to a more manageable size. The variables used in these analyses include daily maximum stream temperature, daily minimum stream temperature, daily rate of stream heating, daily maximum air temperature, daily minimum air temperature, reach shade, reach length, mean reach elevation and reach elevation change. Whereas the daily maximum stream and air temperatures were determined by the first encounter of the hottest temperature each day, the coldest temperature recorded on the same day but prior to the expression of the maximum temperature was considered the daily minimum stream or air temperature. Daily rate of stream heating was determined as the daily maximum stream temperature minus daily minimum stream temperature divided by the time, in hours, between their occurrences. The temperature data used in these analyses were from the downstream boundary of each sampling reach. Mean reach elevation was used to characterize the elevation of each sampling reach and corresponds to the average elevation of the upper and lower reach boundary elevations. Elevation change was calculated at the difference in elevation between the upper and lower reach boundaries. Shade values were modeled based on a three month period spanning May 22 through August 21. This interval was chosen to reflect shade occurring during the hot part of the summer when stream heating is typically maximized.

DATA ANALYSIS

Analysis of variance (ANOVA) combined with least significant differences (LSD) were used to test for differences between sampling reaches for the responses of daily maximum stream temperature, daily minimum stream temperature, the daily rate of stream heating, daily maximum air temperature, daily minimum air temperature and shade. The individual effects of various physical and environmental parameters on the stream temperature responses were determined through the use of path analyses. *A posteriori* two-way ANOVA investigating the factors date and reach were performed for the responses of daily maximum stream temperature, daily minimum stream temperature, daily rate of stream heating, daily maximum air temperature and daily minimum air temperature. All analyses were performed using SAS statistical software (SAS Institute Inc. 1998).

Although path analysis is a simple extension of multiple regression it provides for the explanation of complex causal schemes by allowing the effects of independent variables on one another (Klemm 1995 and Mitchell 1993). This analysis approach was selected because path models illustrating *a priori* hypotheses combined with standardized path coefficients clearly and logically display results and allow for direct comparisons of the relative strengths of the paths posited in the model. For another example of path analyses used in stream temperature research see Isaak and Hubert (2001).

The path models used in these analyses are displayed in (Figure 1). Some variations of these models were developed in response to data irregularities, however, the basic objective of evaluating parameter significance relative to the stream temperature responses was achieved. The rationale for the hypothesized paths are outlined below.

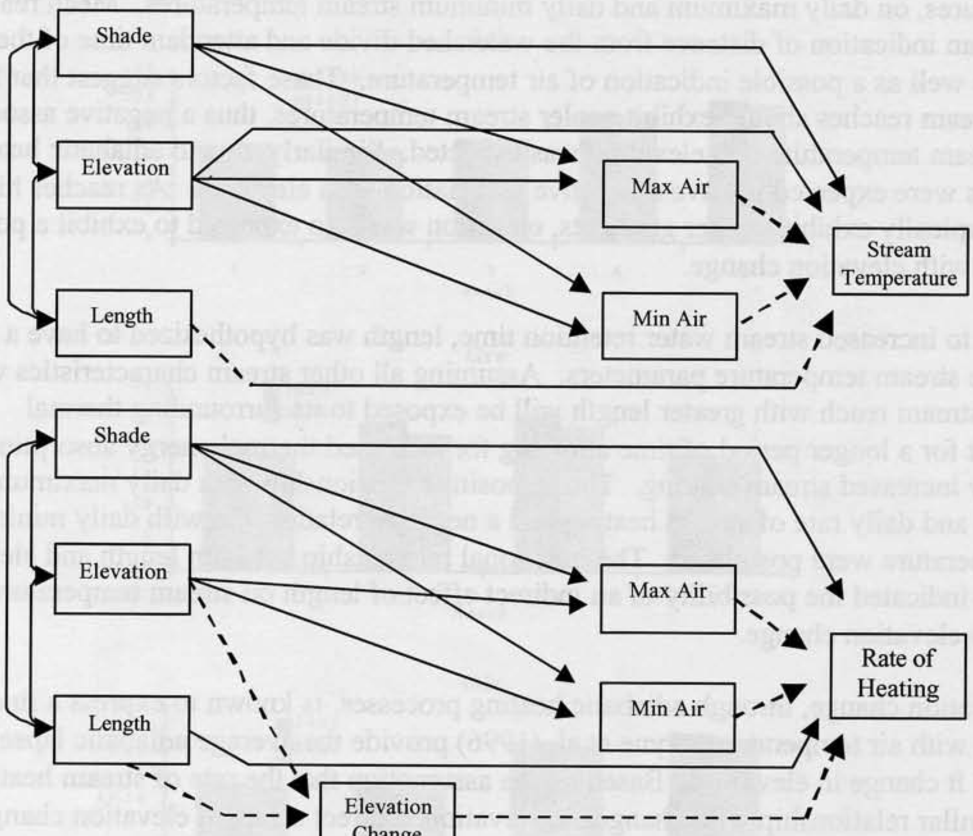


Figure 1. Diagrams representing the hypothesized path models used in the analyses of these stream temperature data. The upper model refers to both daily maximum and minimum stream temperatures while the lower model represents the rate of stream heating. Dashed lines represent paths hypothesized to be positive while solid lines represent paths hypothesized to be negative. A combination of solid and dashed indicates a path that varies between responses.

Results from some stream temperature studies have shown a strong relationship between air temperature and stream temperature. These two parameters often express similar diurnal, seasonal, and yearly temperature patterns, and many authors suggest that air temperature is a significant factor in determining stream temperatures (e.g. Smith and Lavis 1975 and St-Hilaire et al. 2000). Daily maximum and minimum air temperatures were hypothesized to exhibit a direct positive effect on the stream temperature parameters.

Several studies have identified solar radiation as an integral component of stream temperature regulation (e.g. Brown and Krygier 1967 and Brown 1969). Reduced exposure to solar radiation can decrease the amount of thermal energy available for transfer into the stream. The ability of shade to reduce stream exposure to solar energy suggested a direct negative effect of shade on the stream temperature parameters. The same argument was used to propose the path between shade and maximum and minimum daily air temperatures. This path was included to explore the indirect effect of shade on stream temperature as well as the direct effect of shade on air temperature.

Elevation was hypothesized to exhibit a direct effect and an indirect effect, mediated by air temperatures, on daily maximum and daily minimum stream temperatures. Mean reach elevation is an indication of distance from the watershed divide and attendant time of thermal exposure, as well as a possible indication of air temperature. These factors suggest that higher elevation stream reaches should exhibit cooler stream temperatures, thus a negative association between stream temperature and elevation was expected. Similarly, due to adiabatic heating, air temperatures were expected to have a negative association with elevation. As reaches higher in a watershed typically exhibit steeper gradients, elevation was also expected to exhibit a positive relationship with elevation change.

Due to increased stream water retention time, length was hypothesized to have a direct effect on the stream temperature parameters. Assuming all other stream characteristics were constant, a stream reach with greater length will be exposed to its surrounding thermal environment for a longer period of time allowing for increased thermal energy absorption or alternatively increased stream cooling. Thus a positive relationship with daily maximum stream temperature and daily rate of stream heating and a negative relationship with daily minimum stream temperature were postulated. The functional relationship between length and elevation change also indicated the possibility of an indirect effect of length on stream temperature mediated by elevation change.

Elevation change, through adiabatic heating processes, is known to express a linear relationship with air temperature. Pyne et al. (1996) provide the average adiabatic lapse rate as 3.5 °F/1000 ft change in elevation. Based on the assumption that the rate of stream heating may exhibit a similar relationship with changes in elevation, a direct effect of elevation change on the rate of stream heating was hypothesized. Because of the linear relationship between air temperature and elevation change, elevation change alone would produce a similar response in air temperature regardless of the location along the stream. Thus no paths flowing from elevation change to daily maximum and minimum air temperatures were proposed.

RESULTS AND DISCUSSION

DAILY MAXIMUM STREAM TEMPERATURE

All four streams analyzed in this study exhibited noticeable downstream heating. With the exception of those reaches in Bsk, Grs and Gdn creeks that were influenced by groundwater or subsurface flow, downstream reaches consistently experienced increases in the daily maximum stream temperature (Figure 2).

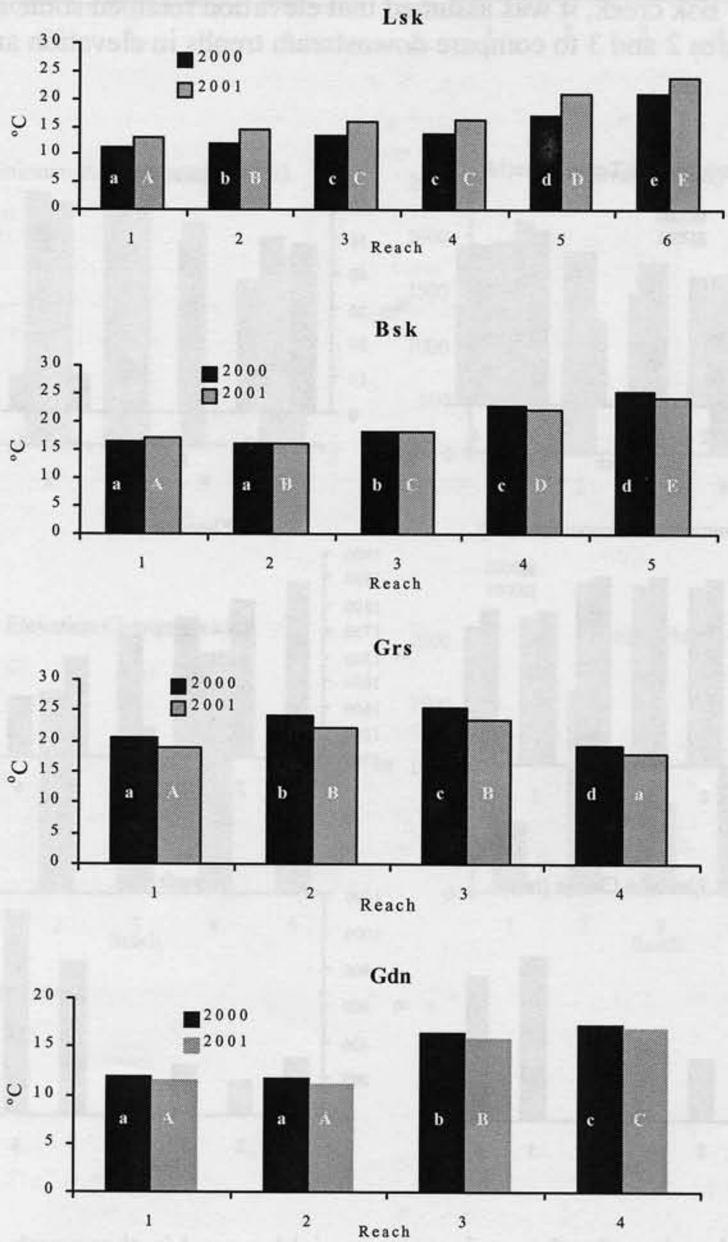


Figure 2. Mean daily maximum stream temperature for each sampling reach on each stream for 2000 and 2001. Different letter codes indicate significant differences within years (á = 0.05). Reach 1 is the highest elevation reach.

Of the factors investigated in this study, the most significant parameter with respect to relationships with daily maximum stream temperature appears to be reach elevation. Although some streams did exhibit downstream increases in daily maximum air temperature, this was not consistent over all streams (Figure 3). Moreover, when reach level variation in maximum air temperature was present and statistically accounted for, elevation still retained its strong direct effect on maximum stream temperature. Thus, the influence of elevation on daily maximum stream temperature was likely an effect of cumulative increases in thermal energy exposure in the downstream direction rather than elevationally driven climatic gradients. Although a high correlation between shade and elevation limited the statistical confidence around the importance of the elevation effect in Bsk creek, it was assumed that elevation retained some association with this response. (See Figures 2 and 3 to compare downstream trends in elevation and maximum stream temperature).

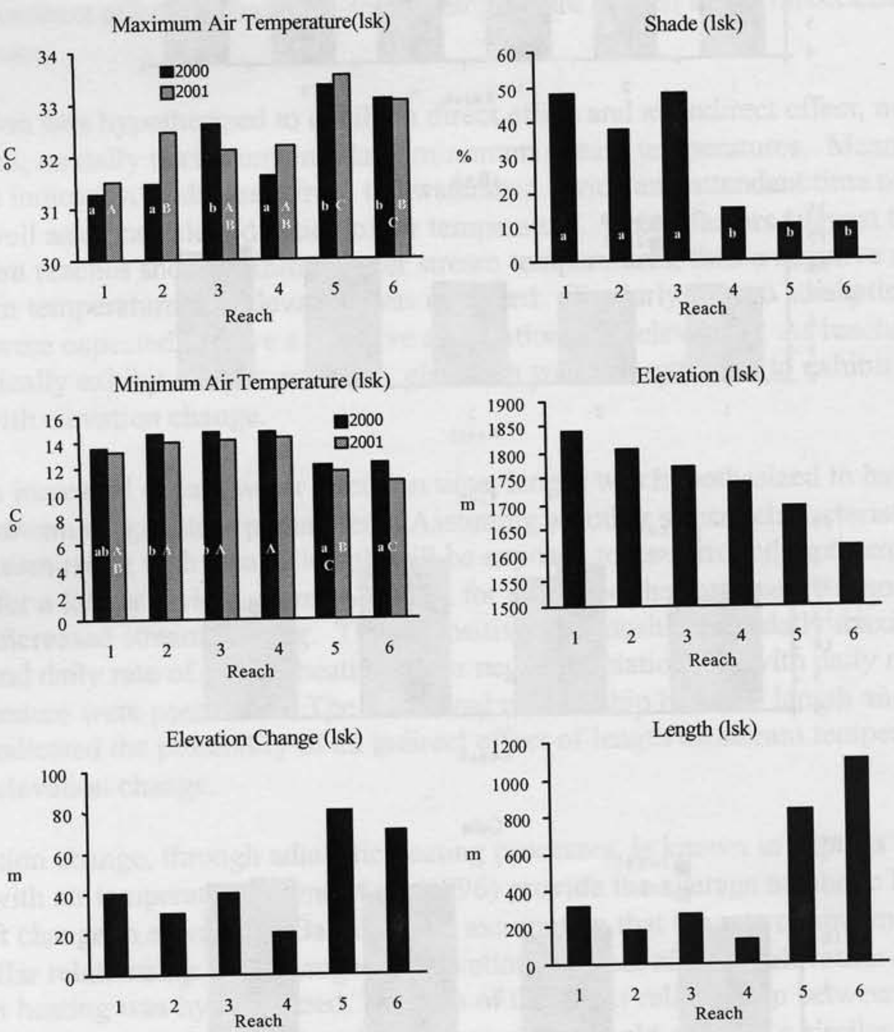


Figure 3 Sampling reach values for the explanatory variables used in these path analyses. Air temperature and shade values are reach means while elevation, elevation change and length values are constants. Different letter codes indicate significant differences within years (á = 0.05). Streams are identified on each chart. Reach 1 is the highest elevation reach.

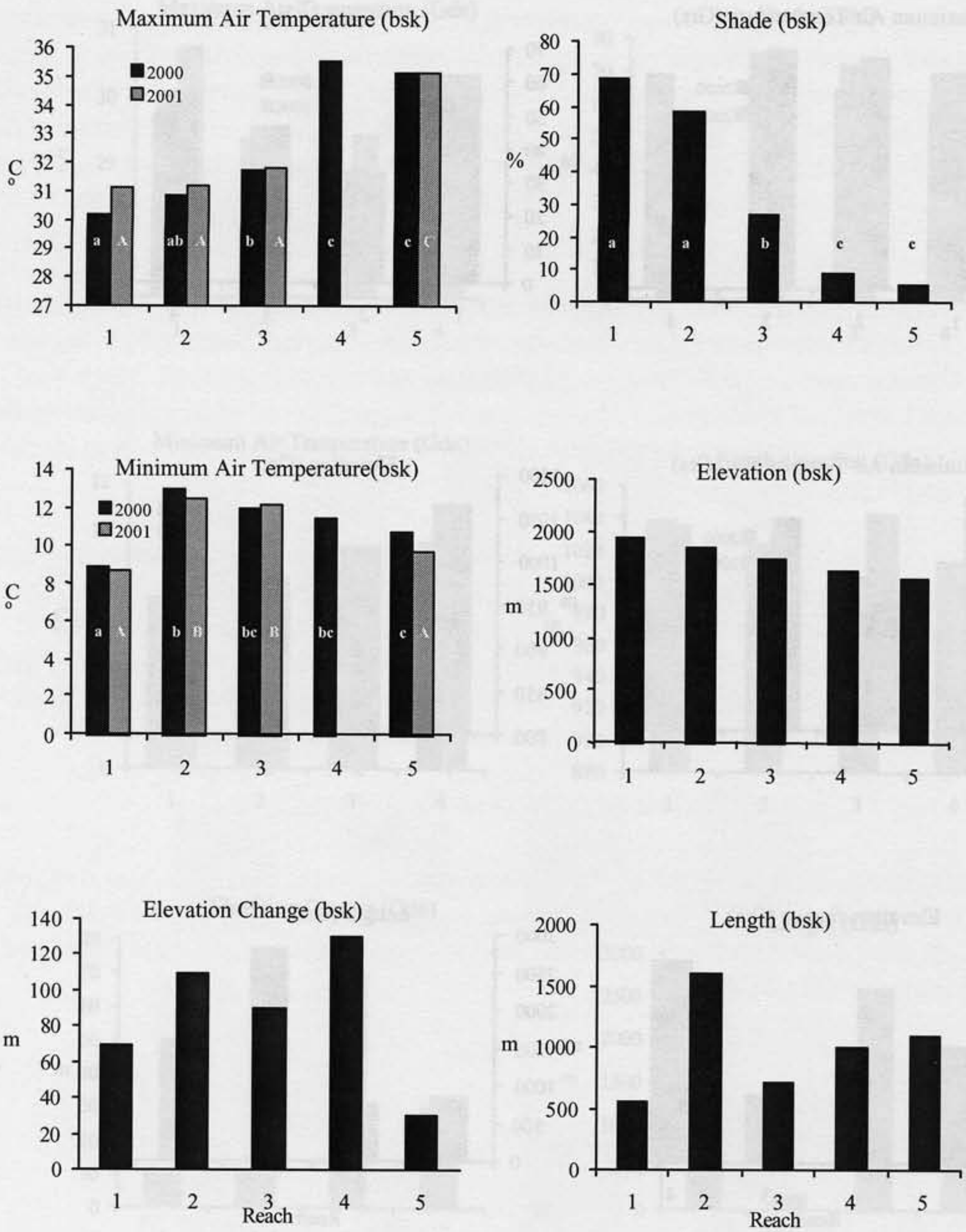
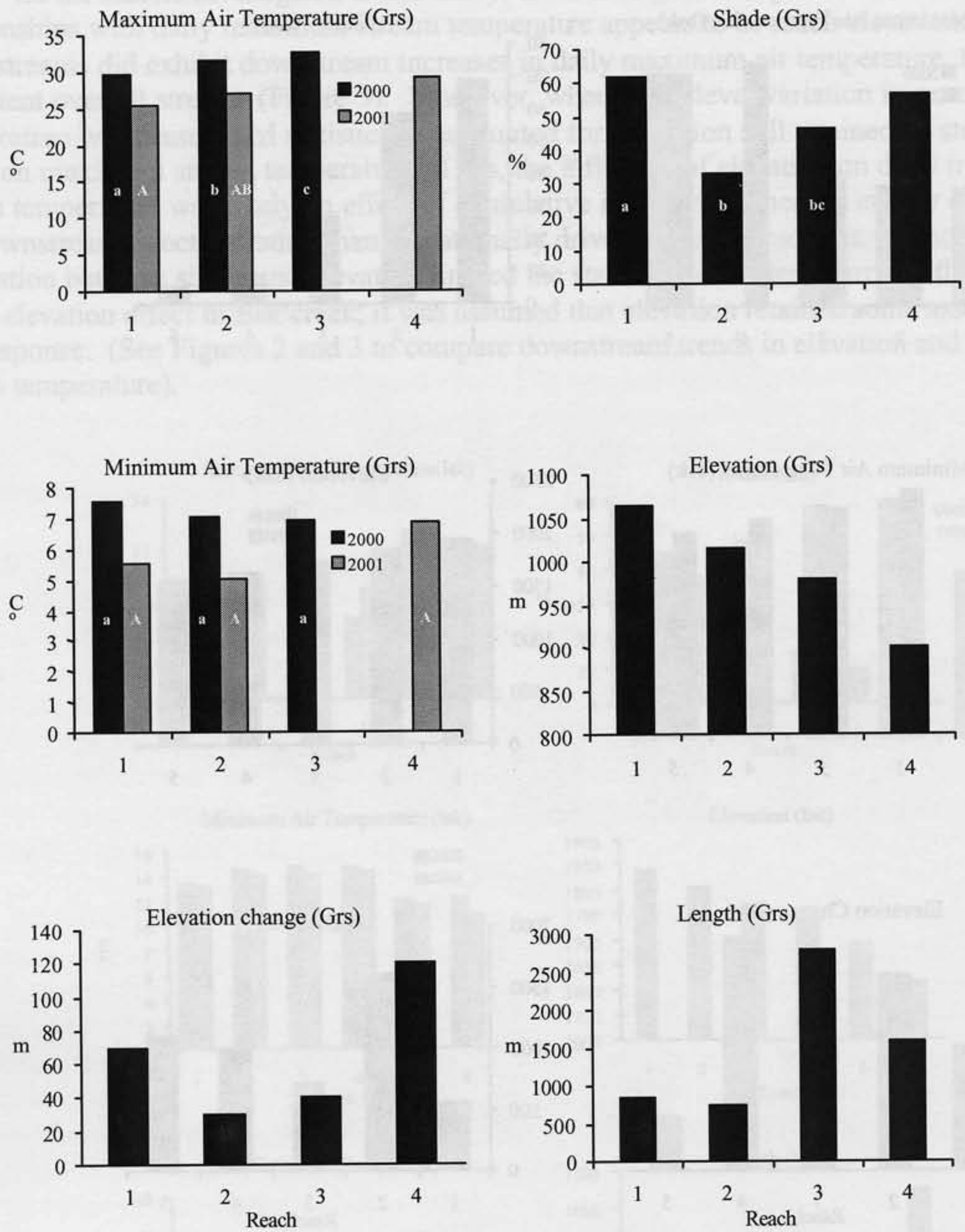


Figure 3. (Continued)



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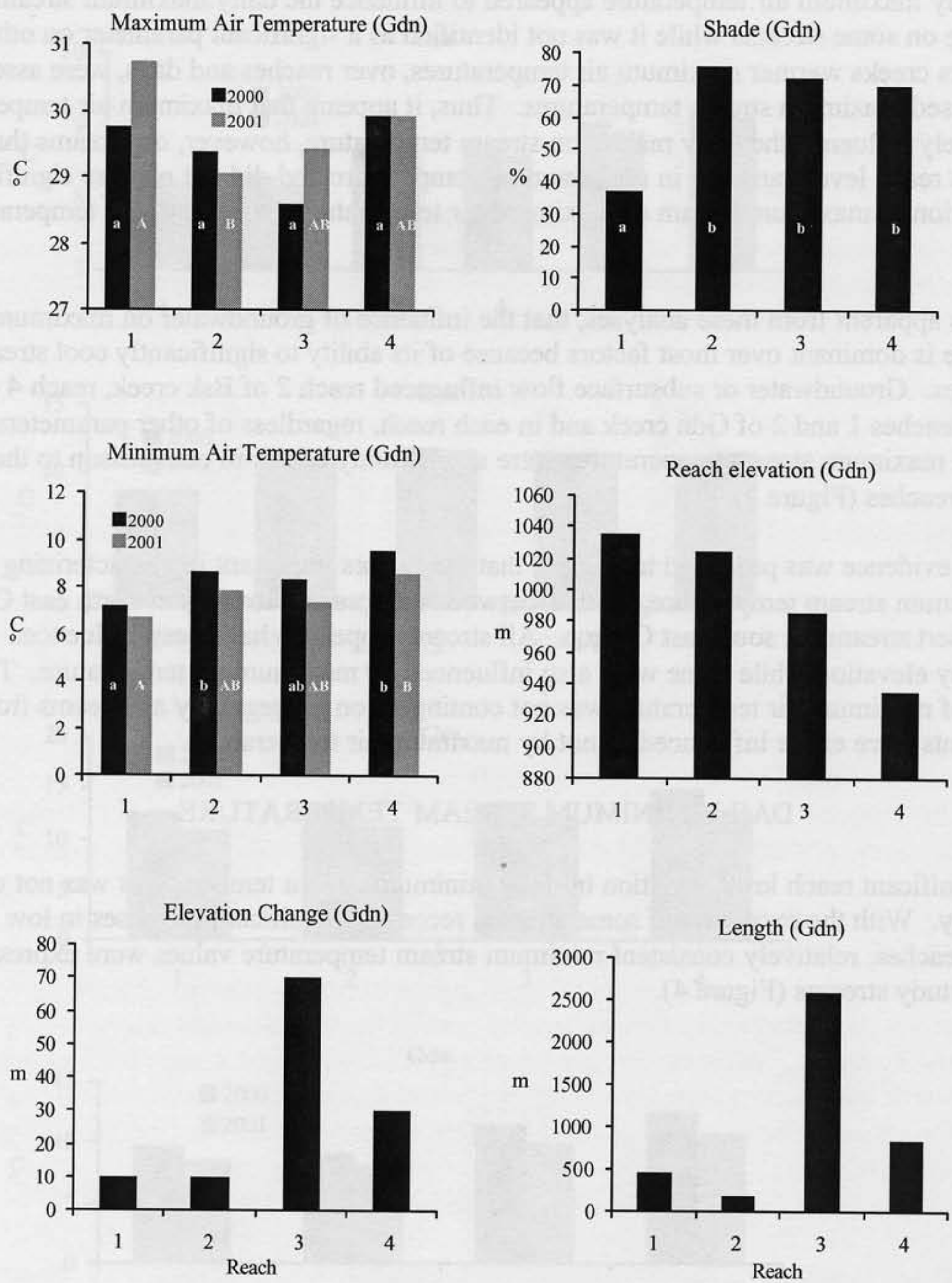

Figure 3. (Continued)

Daily maximum air temperature appeared to influence the daily maximum stream temperature on some streams while it was not identified as a significant parameter on others. In Bsk and Grs creeks warmer maximum air temperatures, over reaches and days, were associated with increased maximum stream temperatures. Thus, it appears that maximum air temperature can positively influence the daily maximum stream temperature, however, on streams that did not express reach level variation in maximum air temperature and did not express significant daily variation in maximum stream or maximum air temperatures, maximum air temperature had no effect.

It is apparent from these analyses, that the influence of groundwater on maximum stream temperature is dominant over most factors because of its ability to significantly cool stream temperatures. Groundwater or subsurface flow influenced reach 2 of Bsk creek, reach 4 of Grs creek and reaches 1 and 2 of Gdn creek and in each reach, regardless of other parameters, the mean daily maximum stream temperatures were significantly cooler in comparison to the remaining reaches (Figure 2).

No evidence was produced to suggest that the factors important in characterizing the daily maximum stream temperature differed between the forested streams in north east Oregon and the desert streams in southeast Oregon. All streams appear to have been influenced primarily by elevation while some were also influenced by maximum air temperature. The influence of maximum air temperature was not contingent on biogegraphy as streams from both environments were either influenced or not by maximum air temperature.

DAILY MINIMUM STREAM TEMPERATURE

Significant reach level variation in daily minimum stream temperatures was not observed in this study. With the exception of some streams recording significant increases in low elevation reaches, relatively consistent minimum stream temperature values were expressed within all study streams (Figure 4).

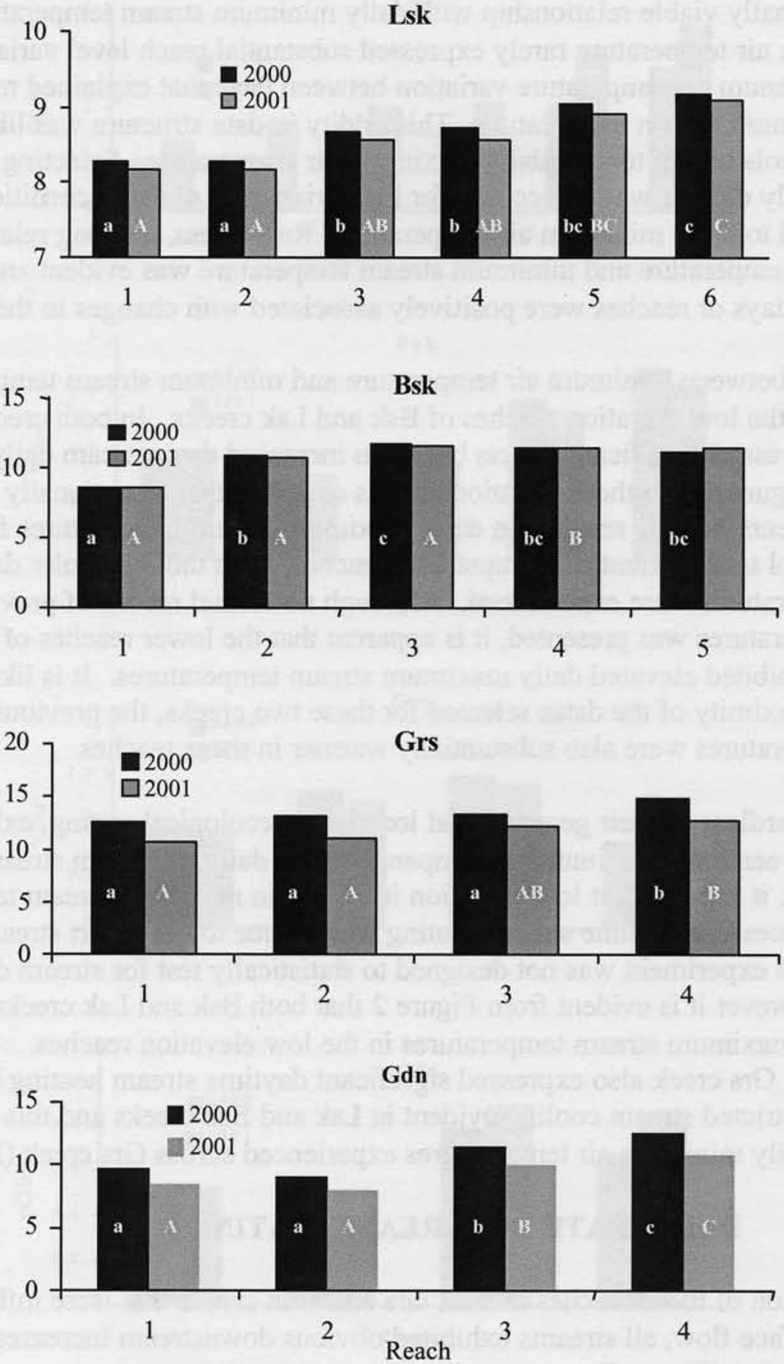

Figure 4. Mean daily minimum stream temperature for each sampling reach on each creek in 2000 and 2001. Different letter codes indicate significant differences within years (á = 0.05). Reach 1 is the highest elevation reach.

Daily minimum air temperature was consistent across all streams in expressing the most significant and functionally viable relationship with daily minimum stream temperature. Interestingly, minimum air temperature rarely expressed substantial reach level variation (Figure 3). Rather, it was minimum air temperature variation between days that explained much of the variation in daily minimum stream temperature. This oddity in data structure was likely a result of data selection protocols biased toward daily maximum air temperature. Selecting for the hottest 20 days evidently did not wholly account for the variation in climatic conditions, particularly with regard to daily minimum air temperature. Regardless, a strong relationship between minimum air temperature and minimum stream temperature was evident and changes in one parameter over days or reaches were positively associated with changes in the other.

The relationship between minimum air temperature and minimum stream temperature appeared to decay over the low elevation reaches of Bsk and Lsk creeks. In both creeks, reach defined parameters expressed significant effects based on increased downstream daily minimum stream temperatures (Figure 4). In these situations it was expected that elevationally derived increases in daytime stream heating resulted in daily maximum stream temperatures from which the stream could not cool to the extent of the upstream reaches, even though cooler daily minimum stream temperatures were experienced. Although no formal record of previous day maximum stream temperatures was presented, it is apparent that the lower reaches of these two streams consistently exhibited elevated daily maximum stream temperatures. It is likely that, based on the general proximity of the dates selected for these two creeks, the previous day maximum stream temperatures were also substantially warmer in these reaches.

All streams, regardless of their geographical location or ecological setting, exhibited a strong association between daily minimum air temperature and daily minimum stream temperature. However, it appears that low elevation increases in minimum stream temperature likely in response to excessive daytime stream heating was unique to the desert streams in southeast Oregon. This experiment was not designed to statistically test for stream differences in thermal patterns, however it is evident from Figure 2 that both Bsk and Lsk creeks experienced hot daily maximum stream temperatures in the low elevation reaches. Interestingly, however, Grs creek also expressed significant daytime stream heating but showed no indication of the restricted stream cooling evident in Lsk and Bsk creeks and this may be related to the cooler daily minimum air temperatures experienced across Grs creek (Figure 3).

DAILY RATE OF STREAM HEATING

With the exception of those reaches in Bsk, Grs and Gdn creeks that were influenced by groundwater of subsurface flow, all streams exhibited obvious downstream increases in the daily rate of stream heating (Figure 5).

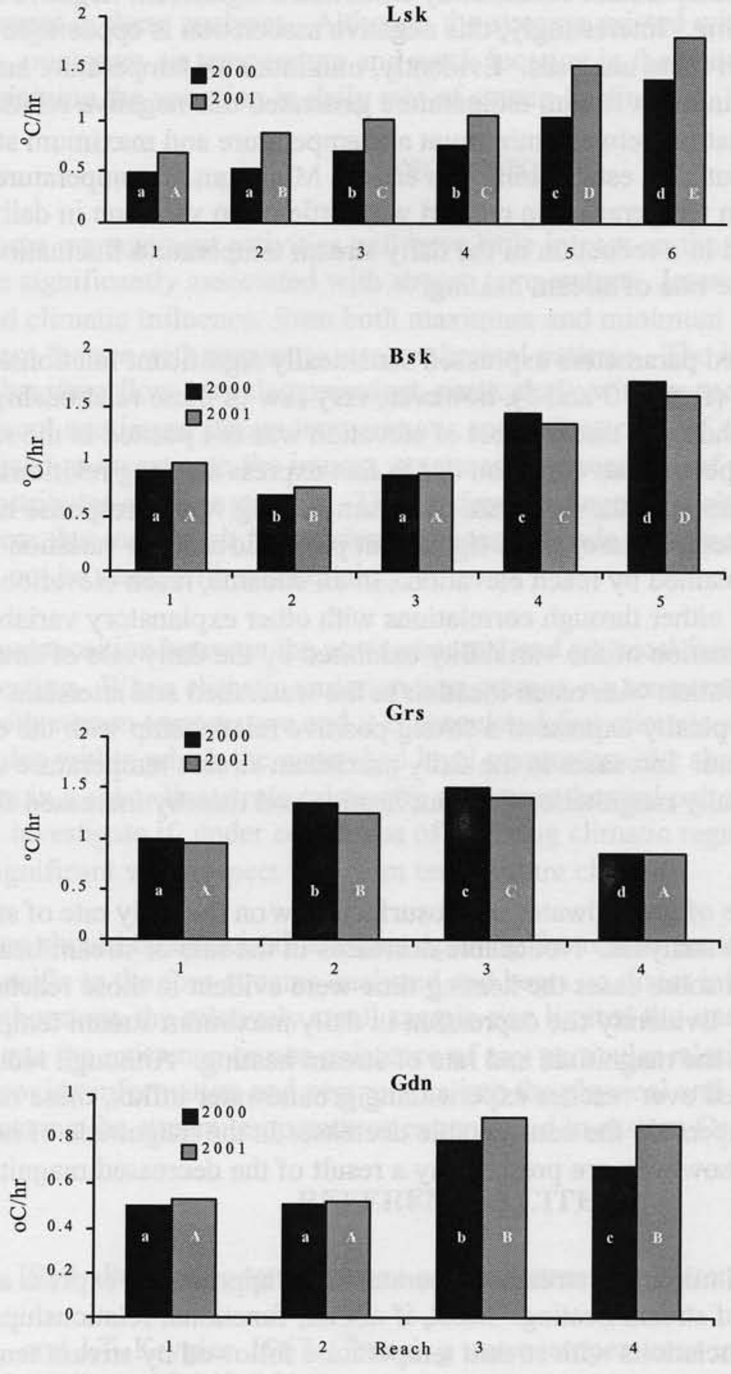

Figure 5. Mean daily rate of stream heating for each sampling reach on each stream in 2000 and 2001. Different letter codes indicate significant differences within years at the 0.05 significance level. Reach 1 is the highest elevation reach.

Daily minimum air temperature consistently exhibited a significant negative association with the rate of stream heating. Interestingly, this negative association is opposite to that hypothesized at the outset of these analyses. Evidently, minimum air temperature and its positive association with minimum stream temperature generated this negative relationship. However, the lack of association between minimum air temperature and maximum stream temperature was also influential in establishing this effect. Minimum air temperature related changes in minimum stream temperature, in concert with little or no variation in daily maximum stream temperature, resulted in a reduction in the daily stream temperature fluctuation and thus a negative association with the rate of stream heating.

Various reach defined parameters expressed statistically significant relationships with the daily rate of stream heating (figures 3 and 5), however, very few of these relationships retained any functional validity. Although a direct effect of elevation was not posited in the rate of heating analyses, it was suspected that elevation did in fact express a strong relationship with this response. Much of the variation in the daily rate of stream heating was in response to changes in the daily maximum stream temperature, and a significant proportion of the variation in maximum stream temperature was explained by reach elevation. In all streams, reach elevation was implicated in some fashion, either through correlations with other explanatory variables or indirect effects, in the explanation of the variability exhibited by the daily rate of stream heating. Elevation, through its association with reach location in the watershed and attendant time of thermal energy exposure, typically expressed a strong positive relationship with the daily maximum stream temperature. Increases in the daily maximum stream temperature subsequently generated increases in the daily magnitude of stream heating and thereby increased the daily rate of stream heating.

The strong influence of groundwater or subsurface flow on the daily rate of stream heating was evident in these analyses. Noticeable decreases in the rate of stream heating, the magnitude of heating and in some cases the heating time were evident in those reaches where subsurface flow was noted. Evidently the depression in daily maximum stream temperatures translated into reductions in the magnitude and rate of stream heating. Although reductions in the heating time were noticed over reaches experiencing groundwater influx, these reductions were not large enough to supersede the considerable decreases in the magnitude of heating. The reductions in heating time, however, are presumably a result of the decreased magnitude of stream heating.

Daily maximum and minimum stream temperature also appeared to express a significant influence on the daily rate of stream heating. Most, if not all, functional relationships were based on explanatory variable associations with stream temperature followed by stream temperature associations with the rate of stream heating. Maximum and minimum stream temperatures were not included as predictor variables in the rate of stream heating analyses and it may prove fruitful in future studies to incorporate these parameters and investigate the relevance of the indirect effects of other explanatory variables mediated by these stream temperature parameters.

Between stream differences in the parameters influencing the daily rate of stream heating were not apparent in these analyses. Although the streams existed within differing environments, minimum air temperature and reach location in the watershed were the primary factors in explaining the variation in daily rate of stream heating.

CONCLUSION

Resource management activities will have little impact on the parameters found, on these streams, to be significantly associated with stream temperature. Interestingly, location in the watershed and climatic influence, from both maximum and minimum air temperatures, emerged as the dominant factors with respect to stream thermal patterns. The influence of groundwater influx and subsurface flow was also prevalent, particularly with respect to their ability to significantly cool maximum stream temperatures and reduce rates of stream heating. This study was not designed to investigate the impact, on stream temperature, of potential changes in any of the physical attributes of these streams. Thus, inferences regarding alterations to the existing thermal patterns that may result from future changes in shade or watershed hydrology, for example, can not be made with any certainty.

The juxtaposition between the environmental and physical factors that emerged from this study is interesting. When climatic variation was present, air temperature appeared to exhibit an association with stream temperature and it is speculated that climatic regime is the primary thermal stimulus within which the watershed level parameters like shade, elevation and channel shape function in a subordinate role relative to a streams thermal pattern. Moreover, it would be interesting to investigate if, under conditions of differing climatic regimes, the watershed parameters significant with respect to stream temperature change.

Caution should be exercised when interpreting the results presented herein. This was a case study specific to the four streams analyzed and bears no direct inference to other stream systems. Furthermore, the relatively small sample size limited the statistical ability to confidently state the existence or non-existence of any particular relationship. Nevertheless, this report does provide information and perspective into the physical and environmental factors that may be influencing the stream temperatures experienced in eastern Oregon streams.

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