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A HYPOTHESIS ABOUT FACTORS THAT AFFECT MAXIMUM SUMMER STREAM TEMPERATURES ACROSS MONTANE LANDSCAPES[1]

Daniel J. Isaak and Wayne A. Hubert[2]

ABSTRACT: Temperature is an important variable structuring lotic biotas, but little is known about how montane landscapes function to determine stream temperatures. We developed an *a priori* hypothesis that was used to predict how watershed elements would interact to affect stream temperatures. The hypothesis was tested in a series of path analyses using temperature data from 26 sites on second-order to fourth-order streams across a fifth-order Rocky Mountain watershed. Based on the performance of the first hypothesis, two revised versions of the hypothesis were developed and tested that proved to be more accurate than the original hypothesis. The most plausible of the revised hypotheses accounted for 82 percent of the variation in maximum stream temperature, had a predicted data structure that did not deviate from the empirical data structure, and was the most parsimonious. The final working hypothesis suggested that stream temperature maxima were directly controlled by a large negative effect from mean basin elevation (direct effect = -0.57, $p < 0.01$) and smaller effects from riparian tree abundance (direct effect = -0.28, $p = 0.03$), and cattle density (direct effect = 0.24, $p = 0.05$). Watershed slope, valley constraint, and the abundance of grass across a watershed also affected temperature maxima, but these effects were indirect and mediated through cattle density and riparian trees. Three variables included in the *a priori* hypothesis – watershed aspect, stream width, and watershed size – had negligible effects on maximum stream temperatures and were omitted from the final working hypothesis.

(KEY TERMS: wildland and forest hydrology; path analysis; geomorphology; GIS; stream temperature; montane landscape).

INTRODUCTION

Stream temperature is an important water quality parameter that directly and indirectly affects aquatic biotas. Direct effects are evident when temperature-dependent metabolic processes lead to mortalities (Olson and Foster, 1955), determine the distributions of species (Cech *et al.,* 1990), or the rate at which growth occurs (Phinney and McIntire, 1965; Holtby, 1988). Temperature may indirectly affect aquatic biotas by moderating the outcomes of species interactions (Baltz *et al.,* 1982), changing the incidence of disease within populations (Rucker *et al.,* 1953), or altering dissolved oxygen levels, which subsequently determine the bioavailability of many heavy metals (Goldman and Horne, 1983).

Many variables can affect the temperatures of lotic waters (Ward, 1985), but the thermal regimes of small streams are affected most by ambient-air temperatures and direct insolation (Brown, 1969; Sinokrot and Stefan, 1994). In streams flowing through areas with little topographic complexity, air temperatures and insolation are not strongly dictated by the surrounding landscape and the effects of the landscape are often discounted (e.g., Cluis, 1972; Kothandaraman, 1972; Preud'homme and Stefan, 1992; Stefan and Preud'homme, 1993). A similar approach would be less useful in montane settings, where complex geomorphologies can dramatically alter air temperatures and the solar radiation that streams are exposed to – at times resulting in nearby streams with markedly different temperature regimes (Johnson, 1971; Boon and Shires, 1976).

Although studies regarding stream temperatures in montane settings have been conducted, these studies focus primarily on the pre-treatment and post-treatment effects of timber harvest (Brown and Krygier, 1970; Swift and Messer, 1971; Feller, 1981; Holtby, 1988) or on diel and seasonal patterns in stream temperatures (Beschta and Taylor, 1988; Hostetler, 1991). A limited number of observational (Johnson, 1971; Smith and Lavis, 1975; Boon and Shires, 1976) and simulation studies (Theurer *et al.,*

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1984; Chen *et al.,* 1998) have recognized linkages between stream temperatures and the surrounding landscape. However, no attempts have been made to understand how the elements of a montane watershed interact to affect stream temperatures or to assess the relative strengths of these external factors in a probabilistic setting. Our objectives were to develop a detailed hypothesis about the factors thought to affect stream temperatures in montane settings, use empirical data to test predictions generated by the hypothesis, and revise the original hypothesis to derive a more accurate and systemic understanding of how montane landscapes function to determine stream temperatures.

Stream Temperature Hypothesis

In this section, the stream temperature hypothesis is described and rationales are provided for the causal relationships among the study system variables. To facilitate accurate modeling of this system, the elements that compose the terrestrial landscape have been divided into two classes. Geomorphic characteristics are those features of watersheds that pertain to size, shape, or orientation; whereas land-surface attributes describe surficial or near surface aspects of the same land area.

A survey of the literature, combined with observations made while collecting data, suggested that stream temperatures could be directly affected by five factors: stream width, elevation, cattle density, riparian composition, and watershed aspect; and that four additional factors may indirectly affect temperatures via control of direct effectors (Figure 1). In a mechanistic sense, increases in stream width should increase stream temperatures because riparian vegetation provides less shade to wider streams (Naiman and Sedell, 1980). Stream width should in turn be affected by variables that determine the amount of precipitation a watershed receives, and stream width can be expected to increase as watershed size increases because larger land areas collect and concentrate more precipitation. Elevation is also expected to be an important determinant of streamflows in montane landscapes because the lapse rate of temperature with elevation and orographic lifting of air parcels cause greater condensation and precipitation at high elevations (Brooks *et al.,* 1991). Therefore, if all other factors are held constant, the width of a stream flowing from a high-elevation basin should be greater than the width of a stream flowing from a low-elevation basin. Elevation can also be predicted to have a direct negative effect on stream temperatures given the relationship between ambient-air temperature and stream temperature (Cluis, 1972; Stefan and Preud'homme, 1993).

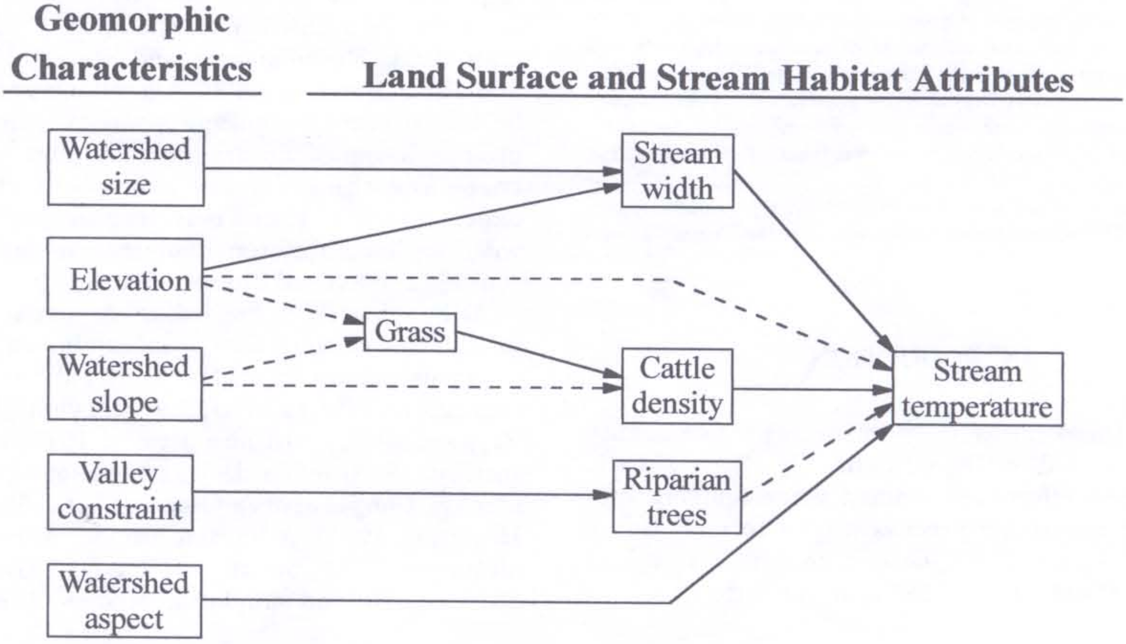

Figure 1. Hypothesis About Factors That Affect Temperatures of Small Mountain Streams. Arrows point in the direction of causality; if an arrow has a solid line, the relationship is predicted to be positive, if an arrow has a dashed line, the relationship is predicted to be negative.

Grazing by domestic cattle is a land use that is common to many montane landscapes across western North America (Council for Agricultural Science and Technology, 1974). Because cattle spend large amounts of time near streams (Roath and Krueger, 1982; Senft *et al.,* 1985), where they reduce or eliminate riparian vegetation (Platts and Nelson, 1985; Knapp and Matthews, 1996), it can be expected that greater cattle densities will result in warmer stream temperatures. Although the distribution of cattle across a landscape is somewhat arbitrary given human intervention, our field observations suggest that cattle are generally grazed in areas amenable to their preferences for gradual slopes (Mueggler, 1965; Cook, 1966) and grass forage (Odion *et al.,* 1988). The proportion of a land surface covered with grass will be controlled by factors that regulate onsite moisture levels and grass abundance is predicted to decrease as elevation increases because trees will become the dominant landcover in the cool and mesic conditions at high elevations (Running, 1984). Grass abundance is also expected to be negatively related to watershed slope because topographic shading is greater in steeper watersheds, which should result in mesic conditions and more trees.

Riparian vegetation plays an important role in regulating stream temperatures by providing shade to the stream (Brown and Krygier, 1970; Feller, 1981). Because trees provide more shade than other forms of riparian vegetation such as shrubs or grasses, stream temperatures can be predicted to be colder in those watersheds where trees make up a large proportion of the riparian vegetation. The likelihood of having trees for riparian vegetation is in turn controlled by the geomorphic character of the adjacent valley. In constrained valleys, trees should be more common because greater water-table depths and less frequent and extensive flood disturbances favor the establishment of trees over grasses and shrubs (Hawk and Zobel, 1974; Gregory *et al.,* 1991).

Watershed aspect is thought to influence stream temperatures on the premise that orientation relative to the path of the sun will alter the amount and intensity of sunlight that a stream receives (Johnson, 1971; Smith and Lavis, 1975). As such, streams within the northern hemisphere that have northerly aspects are generally believed to be coldest and those with southerly aspects, warmest. It could be argued, however, that streams with northerly and southerly aspects are oriented similarly relative to the path of the sun, but simply flow in opposite directions. If this scenario is accurate, watershed aspect would have the same effect on the temperatures of streams with northerly and southerly aspects and a different effect on streams with easterly and westerly aspects.

STUDY AREA

Data to test the stream temperature hypothesis were collected in the 2,150-km^2 Salt River watershed on the border between Idaho and Wyoming. The Salt River watershed is part of the Middle Rocky Mountain physiographic province (Fenneman, 1931) and is bordered by mountain ranges that differ markedly in morphology (Figure 2). On the east side of the watershed, the rugged Salt River Range rises to peak at elevations exceeding 3,300 m. The terrain in the Caribou and Webster ranges to the west and the Gannett Hills to the south is less rugged, and elevations do not exceed 2,800 m. Surficial geology across the watershed is most often characterized by colluvium and thin soils derived from underlying geologic materials, but bedrock outcrops are not uncommon hillslope features and extensive alluvial deposits of Quaternary age fill the main river valley and downstream portions of some mountain valleys. Bedrock geology is sometimes karstic in nature (Geological Survey of Wyoming, unpublished data), but outflows from these formations affected none of the streams included in this study. Pleistocene glaciation occurred at the highest elevations in the Salt River Range, but did not extend to valley bottoms (Oriel and Platt, 1980).

Stream characteristics differ with contrasts in mountain morphologies. Valleys in the Salt River Range are most often narrow and constrained, whereas valleys across the remainder of the watershed grade from constrained in upstream areas to unconstrained in downstream areas. Stream characteristics also differ and Salt River Range streams typically have straighter channel patterns, larger substrate sizes, and steeper slopes than other streams. Salt River Range streams have riparian floras dominated by conifers, except along unconstrained or recently disturbed reaches, where riparian zones are composed of willows (*Salix* spp.), sedges (*Carex* spp.), and grasses. Riparian vegetation adjacent to downstream reaches of other streams consists of willows, sedges, and various grass species, but changes to mixed conifer stands in headwater areas. Hydrographs of all streams are driven by snowmelt, and peak discharges occur in May and June, followed by baseflows from late July into March (U.S. Geological Survey, unpublished data) (Figure 3a).

The climate in the Salt River watershed is classified as cold with humid winters. Mean annual air temperature on the Salt River valley floor is 3.5°C and ranges from monthly averages of -9.1°C in January to 16.7°C in July (Owenby and Ezell, 1992). Precipitation is evenly distributed throughout the year and comes as snow during cooler months and as rain over the remainder of the year. Annual precipitation

Figure 2. Greyscale Hillshade of a Digital Elevation Model Depicting the Stream Drainage Network Across the Salt River Watershed. Stream temperatures were recorded at locations marked with squares in 1996 and circles in 1997. The value in each marker represents the maximum summer stream temperature in degrees Celsius.

averages 50 cm on the Salt River valley floor and increases to over 100 cm at high elevations (Othberg, 1984).

Post-settlement land use in the Salt River watershed is indicative of geomorphic constraints and land ownership status. Most of the alluvial plain in the main valley and the lower ends of alluviated mountain valleys are privately owned small grain and hay fields. The remainder of the watershed is managed by the U.S. Forest Service and grazed by domestic cattle and sheep. Sheep grazing is common at the highest elevations, whereas cattle grazing is confined to the Gannett Hills and lower elevations in the Caribou and Webster ranges. Forestry activities are virtually nonexistent, but unpaved roads have been constructed in most major drainages and are used for recreation and to tend domestic livestock.

METHODS

Continuously-recording digital thermographs (model WTA32, Onset Computer Corporation, Pocasset, Massachusetts; use of trade names does not constitute endorsement by the University of Wyoming) were used to record stream temperatures at 26 sites on second-order to fourth-order streams across the Salt River watershed (Figure 2). When selecting sites to place thermographs, a diversity of streams was sought so that the ranges of study variables encompassed as much natural variation as possible (Table 1). No sites were sampled downstream from reservoirs, major water withdrawals, and large springs where the natural thermal regimes of streams would be altered. We also avoided the Salt River in the main valley where the buffering effects of the extensive alluvial aquifers would weaken the linkage between stream temperatures and the surrounding landscape.

TABLE 1. Descriptive Statistics for Variables in a Dataset Used to Test a Hypothesis About Factors That Affect Temperatures of Small Mountain Streams.

Variable	Mean	Standard Deviation	Minimum	Maximum
MAX_TEMP*	17.0	4.7	9.5	25.0
MIN_TEMP	5.0	1.8	2.0	10.2
MEAN_TEMP	10.9	3.2	6.0	17.3
TEMP_RANG	12.0	3.8	5.6	18.0
DEG_DAYS	1697	492	934	2696
WAT_SZE	40.3	43.7	5.1	176.8
BAS_ELE	2395	210	2133	2892
STR_WID	4.2	1.6	1.3	8.0
VAL_CON	0.072	0.034	0.024	0.185
RIP_TREE	27.9%	25.3%	0.0%	92.3%
WAT_ASP90	47.0	23.0	1.0	82.5
WAT_ASP180	85.1	49.3	1.0	160.0
CAT_DENS	3.2	7.5	0.0	28.5
WAT_SLOP	17.7	4.9	11.0	27.1
GRASS	16.2%	15.0%	0.0%	45.2%

*MAX_TEMP = maximum stream temperature (C°); MIN_TEMP = minimum stream temperature (C°); MEAN_TEMP = average stream temperature (C°); TEMP_RANG = stream temperature range (C°); DEG_DAYS = degree-days (average stream temperature x 156 days); WAT_SZE = watershed size (km^2); BAS_ELE = mean basin elevation (m); STR_WID = stream width at thermograph location (m); VAL_CON = mean valley constraint (active channel width/valley floor width); RIP_TREE = proportion of the riparian zone composed of conifers; WAT_ASP90 = watershed aspect (°) coded to match the prediction that aspect has the same effect on streams with northerly and southerly aspects; WAT_ASP180 = watershed aspect (°) coded to match the prediction that streams with northerly aspects are colder than streams with southerly aspects; CAT_DENS = density of cattle within a watershed (cows/km^2); WAT_SLOP = mean watershed slope (°); and GRASS = proportion of a watershed covered by grassland and with an elevation less than 2,400 m.

Thermographs were set to record a temperature every 30 minutes and were deployed in streams by affixing each thermograph to a brick that shielded the thermograph from direct solar radiation and held it in a well-mixed pool. Thermographs were placed in streams during late June and left in place until late September, when daily temperatures began to cool. This sample period was chosen because the effects of the landscape on stream temperatures were most apparent at this time (Figure 3b) and consistent baseflows, combined with a lack of snow cover, made the placement and retrieval of thermographs practical. Most stream temperature data were collected in 1997, but temperature data for five sites were collected in 1996.

Maxima, minima, means, ranges, and total degree-days were calculated from the time series of temperatures that thermographs recorded between July 1 and September 15 (Table 1). Because of the strong correlations between maxima and the other stream temperature measures (Table 2), and because of its often-cited importance to aquatic biota (e.g., Coutant, 1977), maxima were used as the measure of stream temperature for subsequent analyses.

In conjunction with temperature data, several habitat variables were measured along reaches of stream that averaged 180 m. When time was limiting, one reach thought to be representative of the stream was sampled, but most often (19 of 26 sites), reaches were sampled at 50 m elevation intervals along the length of stream (5-30 km) that was upstream from the thermograph location. Within each reach, wetted stream width and active channel width were measured to the nearest centimeter along transects spaced at 10-m intervals and run perpendicular to the direction of streamflow. Active channel width, as defined by Grant and Swanson (1995), was the area inundated by stream flow plus the adjacent unvegetated channel shelf, gravel bars, and secondary channels. Riparian vegetation at both ends of each transect was visually classified as trees or grass/shrubs and the proportion of the riparian zone composed of trees calculated for each individual reach before a mean was calculated for the stream.

Land surface and geomorphic variables were quantified for the watershed upstream from sample reaches using a GIS. Coverages included a 30-m resolution digital elevation model (DEM), 1:24,000-scale stream hydrology and vegetation-type coverages, point coverages of thermograph and reach locations, and a polygon coverage of U.S. Forest Service grazing allotment boundaries that contained information on the number of cattle grazed. Completed coverages or data required to build them were acquired from the Caribou and Bridger-Teton National Forests, the Spatial Data and Visualization Center (2000a) at the University of Wyoming, the Idaho Department of Water Resources (2000), the Geospatial Data Center (2000), and Idaho GAP Analysis Project (2000) at the University of Idaho.

Elevation was initially quantified in two ways – as a point elevation at the thermograph location and as the mean elevation of the basin upstream from the thermograph. Basin elevation was calculated by delineating a pourpoint on the DEM at the thermograph location and using the Surface Water Modeler 1.0 extension (Spatial Data and Visualization Center, 1999b) in ArcView 3.1 [Environmental Systems Research Institute (ESRI); Redlands, California] to automatically delineate the watershed upstream from the pourpoint. Basin elevation was then calculated for the watershed using the HydroTools 1.1 extension (ESRI, Redlands, California) in ArcView 3.1. Basin elevation correlated more strongly with maximum stream temperature ($r = -0.77$; $p < 0.01$) than did a point elevation ($r = -0.52$; $p < 0.01$), which was not surprising given that the thermal capacity of water would integrate air temperatures over some distance. Because basin elevation appeared to provide a better measure of this spatially-distributed effect, basin elevation was used in subsequent analyses.

The size of the watershed upstream from each thermograph was determined using the HydroTools 1.1 extension. Cattle density was quantified by dividing the number of cattle that annually grazed a watershed by watershed size. Grass abundance was calculated as a proportion by dividing the area covered with grassland and at an elevation lower than 2,400 m by watershed area. The elevation limit was imposed because alpine meadows often exist above treeline, but sheep were grazed in these areas rather than cattle. Mean slope was calculated for each watershed from a slope coverage derived from the DEM in ArcView 3.1. Valley constraint was calculated for each reach where habitat variables were measured as the active channel width divided by the width of the adjacent valley floor. Using Grant and Swanson's (1995) definition of a valley floor as the valley width at an elevation 3 m above the streambed, valley floor width was calculated as an average from three elevation transects that were evenly spaced along the length of a reach and were interpolated from the elevation model. Once valley constraint had been calculated for individual reaches, an average was calculated for the entire stream.

Watershed aspect was measured along a line from the upstream extent of bluelines on 1:24,000-scale USGS topographic maps to the thermograph location as the number of degrees from true north. Because aspect is a circular measurement, streams with aspects differing by 180° can sometimes be considered identical, depending on how aspect is predicted to

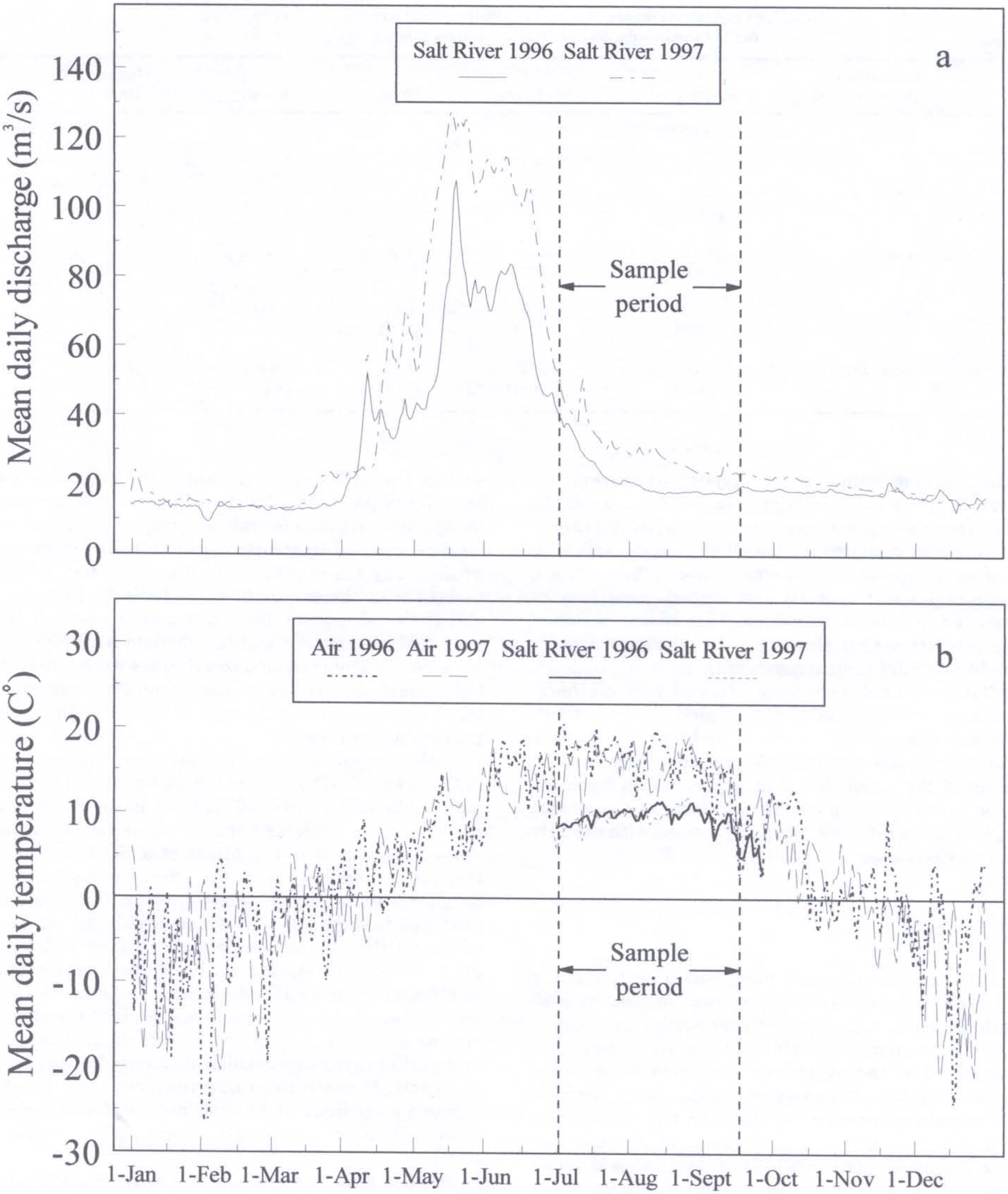

Figure 3. Mean Daily Discharge of the Salt River (a) and Mean Daily Air Temperatures and Stream Temperatures (b) in the Salt River Watershed During 1996 and 1997. Discharge data were recorded at a U.S. Geological Survey gauging station on the lower Salt River; air temperature data were recorded at a National Oceanic and Atmospheric Administration weather station in the Salt River valley, and stream temperature data were recorded at a thermograph location on the upper Salt River.

TABLE 2. Correlations Among Stream Temperature Attributes Measured at 26 Sites on Second-Order to Fourth-Order Mountain Streams (probability values are in parentheses).

Temperature Attribute	Maximum	Minimum	Mean	Range	Degree Days
Maximum	1.00 –				
Minimum	0.64 (< 0.01)	1.00 –			
Mean	0.96 (< 0.01)	0.79 (<0.01)	1.00 –		
Range	0.93 (< 0.01)	0.32 (0.11)	0.81 (< 0.01)	1.00 –	
Degree Days	0.96 (< 0.01)	0.79 (< 0.01)	1.00 (< 0.01)	0.81 (< 0.01)	1.00 –

affect stream temperature. Aspect measurements were therefore coded to eliminate this redundancy. In the first coding scheme, streams with northerly aspects were assigned the lowest values, streams with southerly aspects were assigned the highest values, and streams with easterly and westerly aspects were assigned intermediate values. This coding matched the prediction that streams with northerly aspects would be colder than streams with southerly aspects. In the second coding scheme, streams with northerly and southerly aspects were assigned the lowest values and streams with easterly and westerly aspects were assigned the highest values. This coding matched the prediction that aspect would have the same effect on streams with northerly and southerly aspects and a different effect on streams with easterly and westerly aspects.

Data Analysis

Path analysis (Wright, 1934) was used to analyze the stream temperature hypothesis. To conduct each path analysis, least-squares regressions were calculated for response variables in a manner that was structured by the hypothesis. Five regressions were required for the path analysis of the initial hypothesis – a simple regression for riparian tree abundance with valley constraint as the predictor and multiple regressions for stream width, grass, cattle density, and temperature maximum because these variables had multiple predictors (Figure 1). The amount of change in a response variable that was attributable to a predictor was estimated as a partial regression coefficient. These coefficients were standardized to facilitate comparisons of effect strengths within and among the different regressions that composed a hypothesis (unstandardized coefficients are provided in Appendix A). The overall accuracy of the hypothesis was assessed by comparing the correlation matrix predicted by the hypothesis to the correlation matrix derived from the empirical data (Table 3). Procedure CALIS (SAS Institute, 1989) was used to calculate the predicted correlations and to calculate a χ^2 measure of model fit. The predicted correlations were also plotted against observed correlations and the strength of this bivariate relationship was quantified with a simple Pearson correlation.

Path analysis also facilitated the calculation of indirect effects (IEs) of predictors on response variables. Whereas a direct effect (DE) is the effect of a predictor on a response variable when no intermediary exists, an IE is the effect of a predictor on a response variable wherein the effect passes through an intermediary. As an example, watershed size was predicted to have a DE on stream width, and stream width, a DE on stream temperature (Figure 1). If both predictions were subsequently verified, watershed size would have an IE on stream temperature that was mediated through stream width. Indirect effects are calculated by multiplying the values of standardized partial regression coefficients along the appropriate path. If more than one indirect path exists between a predictor and a response variable, the predictor's IE is the sum of all unique paths (Mitchell, 1993).

Because path analysis relies heavily on regression modeling, several assumptions regarding the distribution of residual errors apply (Neter *et al.*, 1989). Scatter plots and residual plots gave no indication that assumptions regarding linearity or homoscedasticity were untenable, but normal probability plots

TABLE 3. Correlations Among Variables in a Dataset Used to Test a Hypothesis About Factors That Affect Maximum Temperatures of Small Mountain Streams (probability values are in parentheses).

Variable	MAX_ TEMP	WAT_ SZE	BAS_ ELE	STR_ WID	VAL_ CON	RIP_ TREE	WAT_ ASP90	WAT_ ASP180	CAT_ DENS	WAT_ SLOP	GRASS
MAX_TEMP	1.00 –										
WAT_SZE	0.35 (0.08)	1.00 –									
BAS_ELE	-0.77 (< 0.01)	-0.36 (0.07)	1.00 –								
STR_WID	-0.08 (0.70)	0.73 (< 0.01)	-0.06 (0.79)	1.00 –							
VAL_CON	-0.33 (0.10)	0.12 (0.55)	0.05 (0.81)	0.056 (< 0.01)	1.00 –						
RIP_TREE	-0.72 (< 0.01)	-0.33 (0.10)	0.60 (< 0.01)	0.11 (0.61)	0.47 (0.01)	1.00 –					
WAT_ASP90	-0.22 (0.29)	0.90 (0.68)	0.05 (0.80)	0.30 (0.14)	0.12 (0.57)	0.22 (0.29)	1.00 –				
WAT_ASP180	-0.06 (0.78)	-0.28 (0.16)	0.07 (0.75)	-0.03 (0.87)	-0.12 (0.56)	0.14 (0.51)	0.39 (0.05)	1.00 –			
CAT_DENS	0.42 (0.03)	0.18 (0.37)	-0.21 (0.31)	-0.19 (0.36)	-0.29 (0.14)	-0.30 (0.14)	-0.23 (0.27)	-0.44 (0.02)	1.00 –		
WAT_SLOP	-0.82 (< 0.01)	-0.28 (0.17)	0.82 (< 0.01)	0.09 (0.67)	0.23 (0.25)	0.71 (< 0.01)	0.19 (0.35)	0.24 (0.24)	-0.44 (0.03)	1.00 –	
GRASS	0.66 (< 0.01)	0.27 (0.18)	-0.58 (< 0.01)	-0.12 (0.56)	-0.25 (0.21)	-0.64 (< 0.01)	-0.37 (0.06)	-0.44 (0.02)	0.67 (< 0.01)	-0.77 (< 0.01)	1.00 –

suggested that residuals were often distributed nonnormally. Departures from normality make significance tests based on normal distributions inaccurate, but rather than transforming variables, bootstrap procedures were used to calculate the significance of parameter estimates (SAS Institute, 1995). Linear-regression models also require that residuals be independently distributed, but temporally-correlated residuals could occur where response variables exhibited trends in time during data collection efforts (e.g., interyear differences in stream discharges or temperature patterns). To test for a time effect, sample year was added to the regressions for stream width and temperature. No time effect was apparent for stream width, but an effect did occur for maximum stream temperature so this term was retained in all temperature regressions to control for this nuisance variation.

Multicollinearity, which results from correlations among the predictors in a multiple regression, can lead to unreliable parameter estimates and significance tests when interpredictor correlations are strong. The effects of multicollinearity were monitored using standard diagnostic tests such as variance-inflation factors, condition indices, and tolerance values (SAS Institute, 1989). When problems arose, ridge regression (Neter *et al.*, 1989) was used to derive more reliable parameter estimates. Unfortunately, the unresolved problem of deriving significance tests for ridge parameter estimates ultimately led to a more conventional approach to dealing with this problem – deleting predictors with the smallest univariate correlation to the response variable until parameter estimates stabilized.

RESULTS

Results of the path analysis suggest that much of the variation in maximum stream temperatures could be explained by the predictors included in the initial hypothesis ($R^2 = 0.83$). Most explained variation was due to a large negative effect of basin elevation (DE =

-0.59, $p < 0.01$) and the smaller effects of riparian tree abundance (DE = -0.26, p = 0.06) and cattle density (DE = 0.22, p = 0.09; Hypothesis A, Figure 4). Stream width and watershed aspect, coded such that streams with northerly and southerly aspects were predicted to have similar temperatures, had small and insignificant effects on maximum stream temperatures.

For other response variables in this hypothesis, stream width had much of its variation ($R^2 = 0.58$) explained by a large positive effect of watershed size (DE = 0.81, $p < 0.01$) and a smaller effect of basin elevation (DE = 0.23, p = 0.09). Forty-six percent of the variation in cattle density was attributable to watershed slope (DE = 0.20, p = 0.05) and grass abundance (DE = 0.82, $p < 0.01$). However, multicollinearity problems rendered these estimates questionable. Ridge-regression estimates instead suggested that grass abundance had a somewhat smaller, but positive effect on cattle density (DE = 0.40) and that watershed slope had a small negative effect (DE = -0.08) rather than a positive effect. Problems with multicollinearity also arose in the regression for grass abundance, where watershed slope appeared to have a large negative effect (DE = -0.90, $p < 0.01$) and basin elevation had a small positive effect (DE = 0.16, p = 0.45). Ridge-regression estimates suggested the effect of watershed slope was smaller (DE = -0.47) and that basin elevation had a positive, rather than negative effect (DE = -0.14).

As would be expected given the number of small and insignificant effects that the initial hypothesis contained, the predicted data structure differed from the empirical data structure ($\chi^2 = 57.99$, df = 27, $p < 0.01$). Additionally, a scatterplot of the observed and predicted correlations indicated that, despite a strong univariate correlation (r = 0.89, $p < 0.01$; Figure 4), several correlation pairs plotted well away from the 1:1 line.

Based on results from the first path analysis, the hypothesis was revised. Stream width and watershed size were deleted and the coding of watershed aspect was changed to match the prediction that streams with northerly aspects would be coldest and streams with southerly aspects would be warmest (Hypothesis B, Figure 4). Multicollinearity problems were eliminated by deleting the paths from basin elevation to grass abundance and from watershed slope to cattle density. After these revisions, the effect of watershed aspect on stream temperature remained negligible, but the overall accuracy of the hypothesis improved ($\chi^2 = 32.55$, df = 18, p = 0.02).

In a final revision of the hypothesis, watershed aspect was dropped and a path was added from watershed slope to riparian tree abundance (Hypothesis C; Figure 4). The path was added on the premise that watersheds with greater slopes tend to have more confined stream channels where vegetation from adjacent hillslopes can often impinge on the stream. If steeper watersheds favor increased abundance of trees through topographic shading, the end result should be more trees in the riparian vegetation. With these revisions, the third hypothesis was simpler than its predecessors, but it explained a similar amount of variation in maximum stream temperatures (C R^2 = 0.82; A and B R^2 = 0.83). The third hypothesis also explained more of the variation in riparian tree abundance (C R^2 = 0.60; A and B R^2 = 0.22) due to the positive effects of watershed slope (DE = 0.64, $p < 0.01$) and valley constraint (DE = 0.32, p = 0.05). Additionally, all the effects included in Hypothesis C were statistically significant, of at least moderate magnitude, and in a direction (positive or negative) that agreed with *a priori* predictions. The accuracy of Hypothesis C was good as the predicted data structure did not differ from the empirical data structure ($\chi^2 = 9.97$, df = 14, p = 0.76) and the correlation between observed and predicted correlations was strong (r = 0.99, $p < 0.01$; Figure 4). Finally, a regression-line plot of the predicted maxima versus observed maxima from the final regression model for stream temperature revealed no large outliers (Figure 5).

Because Hypothesis C provided a plausible representation of the study system, we proceeded with a more detailed interpretation. Stream temperature maxima were controlled by a large effect from mean basin elevation (DE = -0.57, $p < 0.01$) and smaller effects from riparian tree abundance (DE = -0.28, p = 0.03), and cattle density (DE = 0.24, p = 0.05). Valley constraint, watershed slope, and grass abundance also had effects on temperature maxima, but these effects were indirect and mediated through cattle density and riparian trees. Indirect effects were calculated by multiplying the standardized partial regression coefficients along the appropriate path, so for valley constraint, the IE was 0.32 (constraint effect on trees) x -0.28 (tree effect on temperature) = -0.09. Watershed slope also had a negative IE on temperature maxima (-0.30), part of which was mediated through riparian trees (0.64 x -0.28 = -0.18) and part was due to the grass/cattle/temperature path (-0.77 x 0.67 x 0.24 = -0.12). The IE of grass abundance on temperature maxima was positive and mediated through cattle density (0.67 x 0.24 = 0.16).

DISCUSSION

Few studies have linked the temperature attributes of small mountain streams to the surrounding landscape. In earlier studies that attempted this goal (Johnson 1971; Smith and Lavis 1975), the small

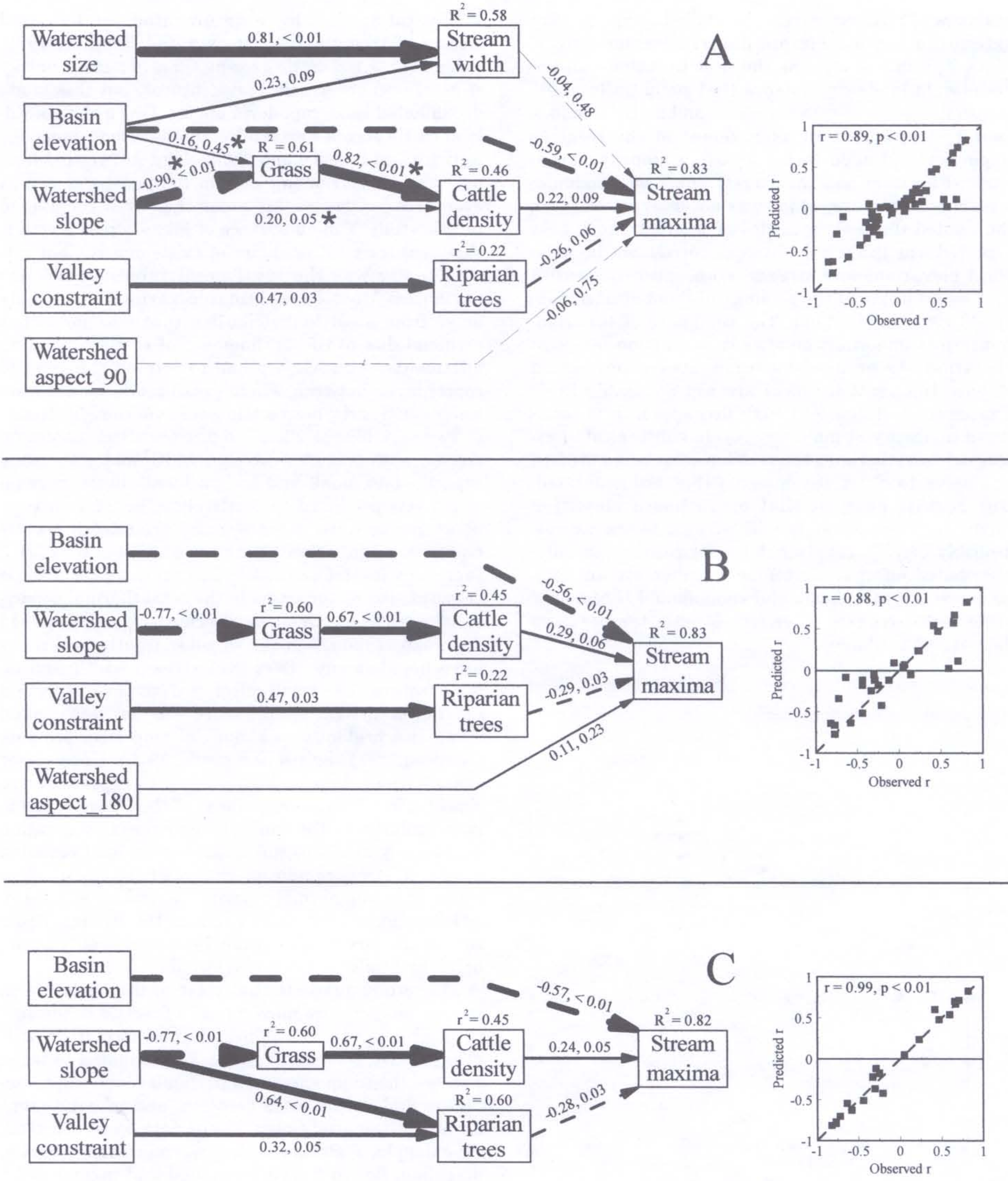

Figure 4. Path Diagrams for Three Versions of a Hypothesis About Factors That Affect Maximum Temperatures of Small Mountain Streams. Arrows point in the direction of causality; if an arrow has a solid line, the relationship is positive, if an arrow has a dashed line, the relationship is negative. The width of an arrow is proportional to the strength of the effect that a predictor has on a response variable. Numbers next to arrows are standardized partial regression coefficients and probability values. Asterisks denote effects that were uninterpretable due to problems with multicollinearity.

numbers of streams studied precluded analyses from extending beyond simple descriptive measures. Therefore, this study was the first to include all the broadscale landscape factors that potentially affect stream temperatures in the same probabilistic model. Doing so provided an assessment of the relative importance of each factor across a montane landscape. Elevation had the largest effect on maximum stream temperature, which was not unexpected given the limited thermal capacities of small streams. Less expected was the relatively weak correlation between point elevations and stream temperatures, a result that was similar to the findings of Sloat *et al.* (1999) for 33 sites in Montana. The weakness of this relationship is important because it is common for point elevations to be used as surrogates when actual stream temperature data are not available (e.g., Fausch *et al.,* 1988). Although this approach is sometimes necessary, it may incorporate substantial unexplained variation into the relationships being studied and serve to cloud any insights that are generated. Our results suggest that mean basin elevation correlates more strongly with stream temperatures, probably because it better characterizes the spatially-distributed effect of air temperature on stream temperature. As such, basin elevation should become the preferred surrogate whenever stream temperature data are unavailable.

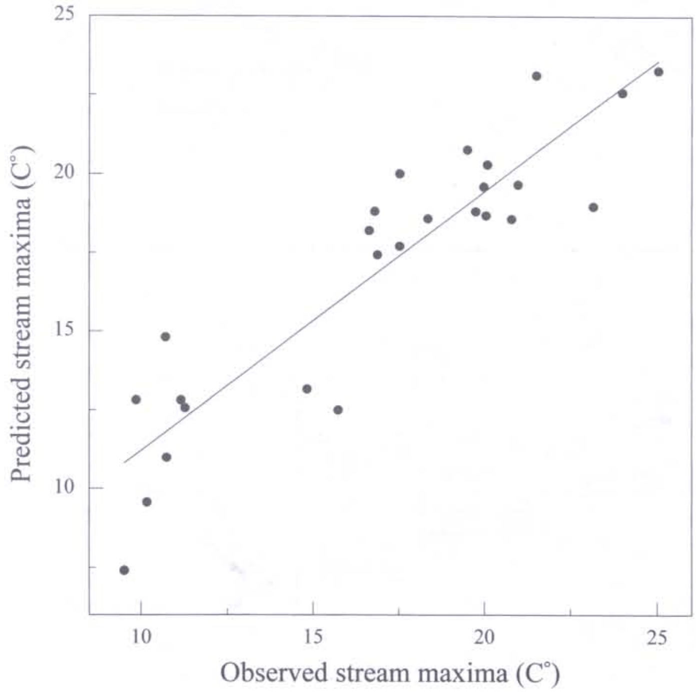

Figure 5. A Regression-Line Plot of the Predicted Maxima From the Final Regression Model for Maximum Stream Temperature Versus Observed Maxima.

Several studies have documented the localized effects of tree shading (Brown and Krygier, 1970; Feller, 1981) and cattle grazing (Li *et al.,* 1994; Belsky *et al.,* 1999) on stream temperatures, but this study documented landscape-level effects. Given the ubiquity of cattle across western North America (Council for Agricultural Science and Technology, 1974), this land use may be increasing stream temperatures across even broader geographic areas than that considered in this study. The abundance of grass across a watershed was a useful predictor of cattle density, but cattle density was the least predictable of response variables. Most unexplainable variation probably arose from a cattle distribution that was somewhat artificial due to the confinement of cattle to grazing allotments. As such, we had to rely on the general concordance between where grazing allotments were established and where cattle would volitionally occur.

Two variables predicted to directly affect maximum stream temperature – stream width and watershed aspect – had small and insignificant effects. Stream width was predicted to positively affect stream temperatures because wider streams are shaded less by riparian vegetation (Naiman and Sedell. 1980). Increases in stream width, however, would also be accompanied by increases in the total thermal capacity of a stream. Greater thermal capacity would decrease responsiveness to solar inputs and must have negated any effect that stream width had on temperature. The small effect of watershed aspect on maximum stream temperature was not unexpected given the previous weakness of empirical support (Johnson, 1971; Smith and Lavis, 1975). Upon closer examination, there is little reason to expect a large aspect effect because regardless of the stream's orientation relative to the sun, it is the riparian vegetation that largely mediates the amount of sunlight reaching a stream. An exception might be where steep valley walls often superceded riparian control of solar insolation and provided direct shade to the stream. These conditions, however, are probably common only at the upper extremity of perennial streamflow.

This study suggests that most of the variation in stream temperature maxima are a function of the surrounding landscape. Unexplained variation will always exist, however, and can be attributed to three sources: the uniqueness of a particular landscape, factors excluded from consideration, and measurement errors. In the study area where data were collected, for example, a stream with a warmer than expected maximum flowed from a watershed that had burned a decade earlier and riparian vegetation had yet to return to prefire conditions. Another stream that was warmer than expected had an unusual combination of a high basin elevation and an unconstrained valley floor, which resulted in much of the riparian zone lacking trees. Microscale factors not included in this study, such as turbulent-flow characteristics or the dam-building activities of beavers, also have the potential to affect temperatures by altering how streams adjust to ambient-air temperatures and solar influxes. Additionally, the many springs and seeps that contribute coldwater inflows over the course of a stream (Bilby, 1984) can produce localized depressions in stream temperatures (Torgersen *et al.,* 1999) that are difficult to incorporate into a broadscale study design. A last source of unexplained variation is simply due to measurement errors associated with the variables used to predict stream temperature. Time constraints occasionally precluded the sampling of more than one reach upstream from a thermograph. If the selected reach was not representative of the entire stream, the estimate of riparian tree abundance for that stream would have also been inaccurate. Similarly, differences among years in the number of cattle grazed on each allotment or a lack of data for several privately-owned sections of land that were upstream from thermograph locations could have resulted in measurement errors.

Management Implications

Much of the variation in temperature maxima appears to be controlled, either directly or indirectly, by geomorphic characteristics that are beyond the influence of normal management activities. As a result, managers attempting to effect change in the thermal regimes of small mountain streams must focus efforts on land uses that alter the integrity of the riparian corridor. These efforts could entail changing the densities of cattle grazed in allotments, altering cattle distributions, or adjusting the number of near stream anthropogenic disturbances involving timber harvest or road crossings.

Stream temperature maxima were modeled in this study because many previous works cite the ecological importance of this temperature attribute (Coutant, 1977). However, maxima were strongly correlated with several other temperature attributes. This knowledge, combined with linkages to broadscale variables, suggests that much can be inferred about the thermal regimes and probable productivities of small mountain streams across wide geographic areas. For example, mean basin elevations could be calculated for a series of streams where temperature data were unavailable and used to rank the thermal regimes of these streams. If more detailed insight was desired, estimates of cattle density or riparian composition could be incorporated into the ranking system. Such an approach seems most practical for managers working with extensive mountainous landscapes where the remoteness of many areas precludes easy acquisition of stream temperature data.

Utility of Path Analysis

This study was greatly facilitated by path analysis, which despite being closely allied with regression modeling, offers several advantages that allow researchers to draw novel inferences. First, many study systems are inherently complex and characterized by chains of causality and interdependence (Christensen *et al.,* 1996). As such, factors that seem to have little direct relevance to a response variable may exert control of that variable through an intermediary. Because conventional regression models have no provisions for dealing with this situation, the result is either that such insights are missed entirely or are erroneously portrayed via a direct effect of a predictor on a response variable. Path analysis, by contrast, has an inherent capacity to deal with this complexity through the interlinkage of regression models. Second, path diagrams present the results of a path analysis in a data rich, but intuitive format that makes it easy to understand the evolution of a hypothesis, the types of effects that predictors have on response variables, and the relative importance of each predictor. Third, advances in covariance structure analysis (Bollen and Long, 1993) have made it possible to compare a predicted data structure to an empirical data structure, thereby providing an assessment of the overall accuracy of a hypothesis and facilitating comparisons among competing hypotheses. Last, because path analysis is a causal-modeling technique, it requires that a very detailed and very explicit hypothesis be developed before the analysis is conducted. Researchers are thus forced to develop a deep level of familiarity with a study system and to include a plausible mechanism with each path included in a hypothesis. This step makes all aspects of the thinking associated with a hypothesis clear and discourages blind data snooping and the weak post-hoc explanations that often result.

Despite the opportunities that path analysis offers for a more rigorous application of the scientific method, and that it has become a staple technique in the social science and evolutionary genetics fields [see introductory sections in Klem (1995) and Petraitis *et al.* (1996)], path analysis has rarely been used within the aquatic sciences. As aquatic systems are not inherently simpler than study systems in other fields, there seems to be no logical reason for this situation. The only limitation of path analysis relative to conventional regression modeling is that a body of knowledge sufficient to develop a comprehensive *a priori* hypothesis must exist. Whether this requirement is met can only be judged by researchers with expertise in a particular field, but path analysis would seem to be a technique that interested researchers could easily apply given excellent introductory articles (Mitchell, 1993; Klem, 1995) and widespread familiarity with regression modeling.

CONCLUSION

A hypothesis that predicted how geomorphic and land-surface features would interact to affect stream temperature was developed and tested. The next step in the scientific process might involve conducting a series of critical experiments to more rigorously test the specific predictions stemming from the final working hypothesis (e.g., Wootton, 1994). Due to the nature of montane landscapes, however, many of these predictions either cannot be tested with manipulative experiments (those predictions involving geomorphic variables) or have already been confirmed (those predictions involving riparian composition) (e.g., Brown and Krygier, 1970; Feller, 1982). One of the most important contributions of this study, therefore, was that it facilitated an assessment of the relative importance of the broadscale factors that were thought to affect maximum stream temperatures. Additionally, the integration of these factors into a broader hypothetical framework provides a systemic understanding of how a landscape functions to affect the thermal regimes of small mountain streams. Although the hypothesis may have some broader utility, it has only been tested with data from one study area and caution must be exercised in the generality of interpretation until replicate tests can be conducted elsewhere.

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APPENDIX A

Summary of Regression Equations With Unstandardized Coefficients Used in Three Versions of a Hypothesis About Variables That Affect Maximum Summer Temperatures of Small Mountain Streams.

Hypothesis Version	Response Variable	Parameter	Partial Regression Coefficient	95 Percent CI	P-Value
A	MAX_TEMP	BAS_ELE	-1.32×10^{-2}	-0.0210, -0.0050	< 0.01
		CAT_DENS	0.137	-0.035, 0.416	0.09
		RIP_TREE	-4.83	-10.1, 0.2	0.06
		STR_WID	-0.127	-0.902, 0.390	0.48
		WAT_ASP90	-1.15×10^{-2}	-0.0510, 0.0420	0.75
		YEAR	-3.60	-6.48, -1.34	< 0.01
		Intercept	399	174, 677	< 0.01
	RIP_TREE	VAL_CON	3.47	0.29, 5.78	0.03
		Intercept	2.77×10^{-2}	-0.134, 0.262	0.82
	STR_WID	WAT_SZE	3.01×10^{-2}	0.0209, 0.0446	< 0.01
		BAS_ELE	1.80×10^{-3}	-0.0002, 0.0044	0.09
		Intercept	-1.35	-7.56, 3.82	0.66
	CAT_DENS	WAT_SLOP	0.306	0.005, 0.824	0.05
		GRASS	41.1	15.9, 75.8	< 0.01
		Intercept	-8.85	-22.0, -2.1	0.02
	GRASS	WAT_SLOP	-2.77×10^{-2}	-0.0405, -0.0131	< 0.01
		BAS_ELE	1.00×10^{-4}	-0.0002, 0.0005	0.45
		Intercept	0.385	-0.255, 0.871	0.22
B	MAX_TEMP	BAS_ELE	-1.26×10^{-2}	-0.0200, -0.0060	< 0.01
		CAT_DENS	0.179	-0.027, 0.318	0.06
		RIP_TREE	-5.34	-10.3, -0.9	0.03
		WAT_ASP180	1.08×10^{-2}	-0.0070, 0.0320	0.23
		YEAR	-3.45	-5.85, -1.64	< 0.01
		Intercept	381	197, 607	< 0.01
	RIP_TREE	Same as above			
	CAT_DENS	GRASS	33.3	12.5, 58.4	< 0.01
		Intercept	-2.18	-5.11, -0.54	< 0.01
	GRASS	WAT_SLOP	-2.38×10^{-2}	-0.0299, -0.0171	< 0.01
		Intercept	0.583	0.428, 0.714	< 0.01
C	MAX_TEMP	BAS_ELE	-1.28×10^{-2}	-0.0190, -0.0050	< 0.01
		CAT_DENS	0.148	-0.002, 0.273	0.05
		RIP_TREE	-5.23	-10.1, -0.7	0.03
		YEAR	-3.57	-5.77, -1.75	< 0.01
		Intercept	395	214, 599	< 0.01
	RIP_TREE	WAT_SLOP	3.29×10^{-2}	0.0148, 0.0485	< 0.01
		VAL_CON	2.38	0.04, 3.77	0.05
		Intercept	-0.475	-0.749, -0.147	< 0.01
	CAT_DENS	Same as above			