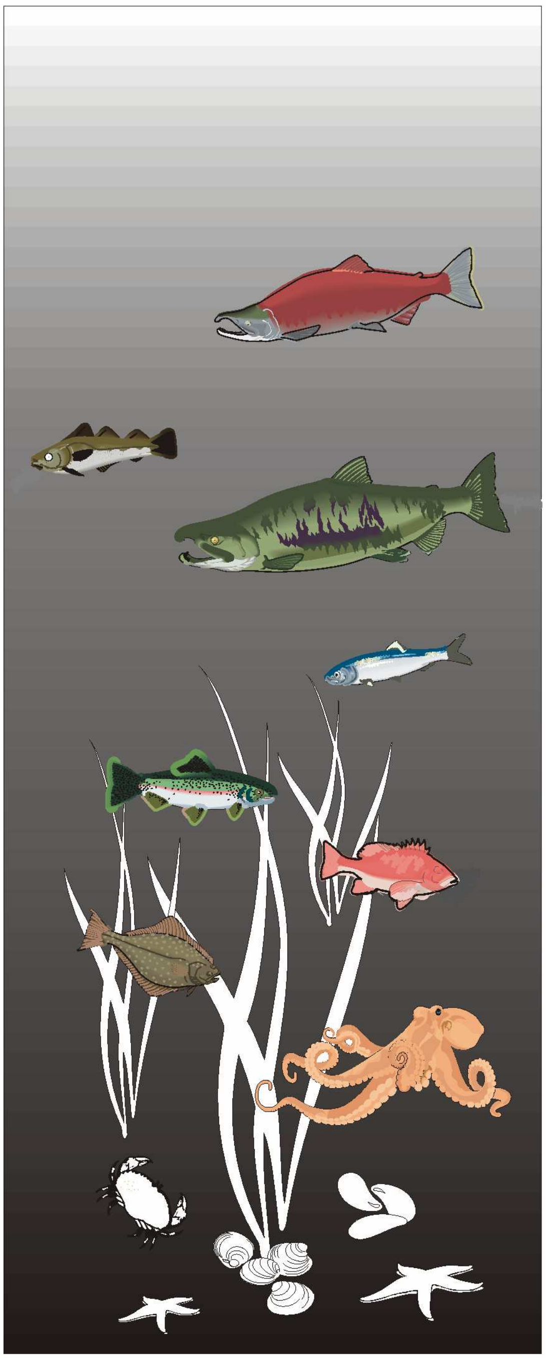
Northwest Fishery Resource Bulletin



A Comparison of Summer Stream Temperatures in Unmanaged and Managed Sub-basins of Washington's Western Olympic Peninsula

By

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and

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Northwest Indian Fisheries Commission

Project Report Series No. 4

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Project Report Series

The Northwest Fishery Resource Bulletin presents the results of investigations carried out by the Washington Dept. of Fish and Wildlife, Western Washington Treaty Tribes, and/or the Northwest Indian Fisheries Commission that are deemed of sufficient interest to be made available to the scientific community and the public.

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October 1995

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ABSTRACT

A study was conducted to evaluate the effects of timber harvest on summer stream temperatures in the temperate rain forests of the Olympic Peninsula, Washington. Temperatures of 11 streams in unmanaged (unlogged) sub-basins and 15 streams in managed (logged) sub-basins were monitored continuously from July 9 through August 16, 1992. Thirteen variables describing either the sub-basin, or the reach of stream where monitoring occurred, were measured at each study site. Independent variables measured included: sub-basin size, proportion of sub-basin classified as late seral stage forest, stream elevation, stream gradient, amount of shade in the temperature reach, and summer discharge. Five water temperature variables and four air temperature variables were used to characterize the temperatures at each site. These dependent variables included: mean hourly water and air temperature, mean daily high water and air temperature, and mean daily low water and air temperature.

No significant differences in mean air temperatures were found between the monitoring sites in unmanaged and managed sub-basins. Significant differences were found, however, between group means of all five variables used to characterize the water temperatures of the study sites. For all water temperature variables, the managed group had significantly warmer mean temperatures than the unmanaged group. These significant differences between group means persisted even when the effects of environmental variables that may influence water temperatures, such as stream elevation and amount of shade in the temperature reach, were removed. Only after controlling for the differences between the unmanaged and managed groups in the proportion of each sub-basin classified as late seral stage forest did the differences in mean stream temperatures become non-significant. The proportion of sub-basin classified as late seral stage forest was also the best single variable for predicting mean average hourly and mean daily maximum water temperatures at both unmanaged and managed sites.

We feel that the proportion of sub-basin classified as late seral stage forest is an indicator of the cumulative effects of logging activities within a sub-basin. A cumulative effect could explain the linear relationship between this variable and the stream temperature variables. Managed sites with high values (65-90%) of stream shade generally had warmer mean water temperatures than unmanaged sites with similar stream shade values. Similarly, managed sites at low elevations (< 100 m) had higher mean water temperatures than unmanaged sites at similar or greater elevations. We feel this demonstrates that managing for stream temperature at the reach level will not be successful unless logging activity throughout a sub-basin is considered.

Maximum temperatures in the streams draining managed sub-basins exceeded the Washington State water temperature criterion of 16.0° C ten times more often, on average, than the streams in unmanaged sub-basins during the monitoring period. Since the managed sites of this study are representative of low-elevation (less than 260 m above sea level), managed sites in the area, it is reasonable to assume the majority of the low-elevation, managed stream channels on the Western Olympic Peninsula are not in compliance with the provisions of the Clean Water Act or Washington State Administrative Code.

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INTRODUCTION

Laboratory experiments have demonstrated that juvenile Pacific salmon (*Oncorhynchus spp.*) have a preferred temperature range of 12°-14° C regardless of their acclimation temperature (Brett 1952). Field observations have shown that water temperature is one of the most important environmental factors affecting micro-habitat choice by salmonids in lakes and streams (Ferguson 1958; Baltz et al. 1987). Stream temperatures in the 20° C to 25° C range can cause severe stress and possible death in salmonids depending on the acclimation regime and duration of exposure (MacDonald et al. 1991).

The U. S. Environmental Protection Agency (EPA) has developed national standards for managing cold-water fish (EPA 1986) in order to provide for successful spawning, egg incubation, fry rearing, and normal species diversity. These standards include criteria that specify a maximum temperature for short-term exposures that is time dependent and species specific and an upper limit on the average weekly temperature which should not exceed more than one-third of the difference between the optimum and the lethal temperature for sensitive species. Each state is allowed to set its own water quality standards as long as they meet the criteria outlined by the EPA. Currently, Washington State has established water quality standards for surface waters of the state (WAC 1992) in order to protect "beneficial uses", which include fish. All of the streams that were monitored in this study are classified as Class AA (extraordinary) under standards of the State of Washington and have a maximum allowable temperature of 16.0° C. Washington State currently does not have a standard for the average weekly water temperature.

This is the first study in Washington State to evaluate the effects of timber harvest on stream temperatures within the temperate rain forests of the Olympic Peninsula. The Hoh Tribe monitored stream temperatures in **managed** (logged) and **unmanaged** (unlogged) sub-basins for two consecutive months during the summer of 1992. Of primary interest was the frequency that water temperatures of managed and unmanaged streams exceeded the Class AA standard of 16°C.

<u>Study Objectives</u>

The five primary objectives of this study were:

1. Measure the water and air temperature regimes of streams draining unmanaged and managed sub-basins.

2. Characterize the age and species composition of each study site's riparian vegetation.

3. Compare the water and air temperature (dependent) variables for streams in unmanaged and managed sub-basins. If there is a significant difference between the two groups, determine if it can be related to differences between the groups in one or more of the independent variables measured.

4. Determine if there are significant relationships between the independent variables (basin or channel morphology, stream hydrology, stream shade, etc.) and dependent variables (mean water and air temperatures).

5. Determine if there is a difference between unmanaged and managed sub-basins in the frequency that the Class AA standard is exceeded and if any independent variables explain the patterns observed.

Study Area

The 28 streams sampled for this study were all located on the western slope of Washington's Olympic Peninsula (Figure 1) where annual rainfall often exceeds 3,550 mm. The western Olympic Peninsula is part of the coastal forest zone (Lyons 1956) where forests are dominated by Sitka spruce (*Picea sitchensis*), Douglas-fir (*Pseudotsuga menziesii*), Western red-cedar (*Thuja plicata*), Western hemlock (*Tsuga heterophylla*), broadleaf maple (*Acer macrophyllum*) and red alder (*Alnus rubra*). The rock formations in the study area are primarily marine sandstones, shales, siltstones, and conglomerates (Tabor and Cady 1978).

Individual study sites were located on tributaries to the Hoh, Queets, Bogachiel, and Kalaloch Rivers (Figure 1). All unmanaged sites were within the boundaries of Olympic National Park. There are five species of Pacific salmon and three species of trout that inhabit waters in the study area: coho salmon (*O. kisutch*), chinook salmon (*O. tshawytscha*), pink salmon (*O. gorbuscha*), sockeye salmon (*O. nerka*), chum salmon (*O. keta*), steelhead trout (*O. mykiss*), dolly varden trout (*Salvelinus malma*), and cutthroat trout (*O. clarki*).

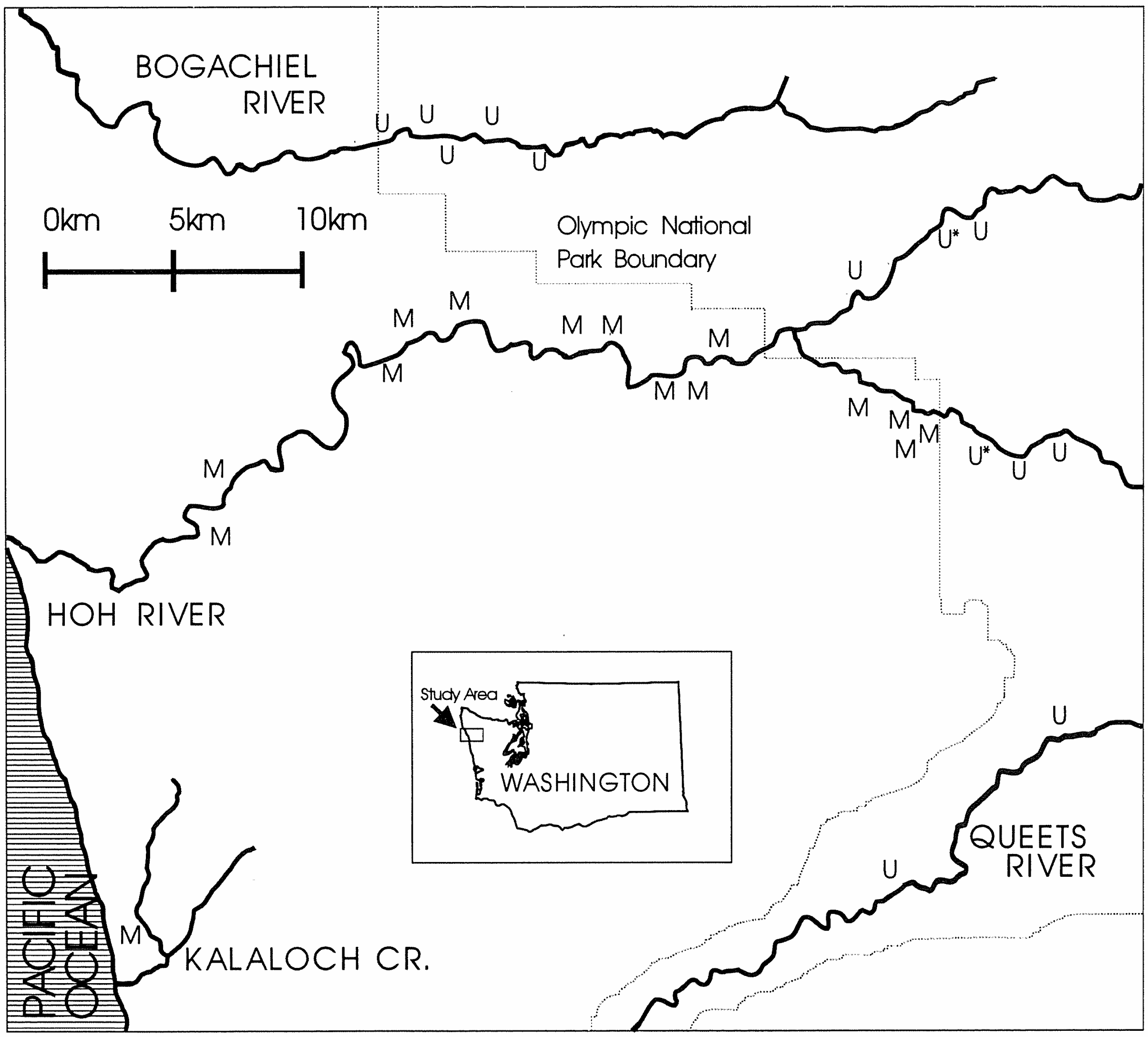

Figure 1. Map of the study area showing the location of the 28 sites monitored for stream temperatures. **U** indicates an unmanaged site and **M** indicates a managed site: an * indicates a site was not used in the data analyses.

METHODS

Temperature data were collected at 13 streams in unmanaged sub-basins and 15 streams in managed sub-basins. Water temperatures were monitored with continuously recording digital thermographs from June 20 through September 15, 1992. Air temperatures at six of the unmanaged sites and 12 of the managed sites were recorded, also. Physical measurements were made at each study site to characterize channel morphology, stream shade, and stream discharge. Other variables, such as basin size, elevation, channel gradient, and channel length, were obtained from 15° U. S. Geologic Survey (USGS) topographic maps. All physical measurements were recorded in metric units: water and air temperatures were recorded in degrees centigrade (°C).

Study Site Definition and Classification

Each study site consisted of a 600-m length of stream, termed a temperature reach, which was encompassed by a distinct sub-basin (Figure 2). A study site was classified as unmanaged if less than 15% of the mature forest in the sub-basin had been logged and no harvest activity had occurred within the riparian corridor of the temperature reach. Conversely, a study site was classified as managed if 15% or more of the mature forest had been harvested within the sub-basin or harvest activity had occurred within the riparian corridor of the temperature reach.

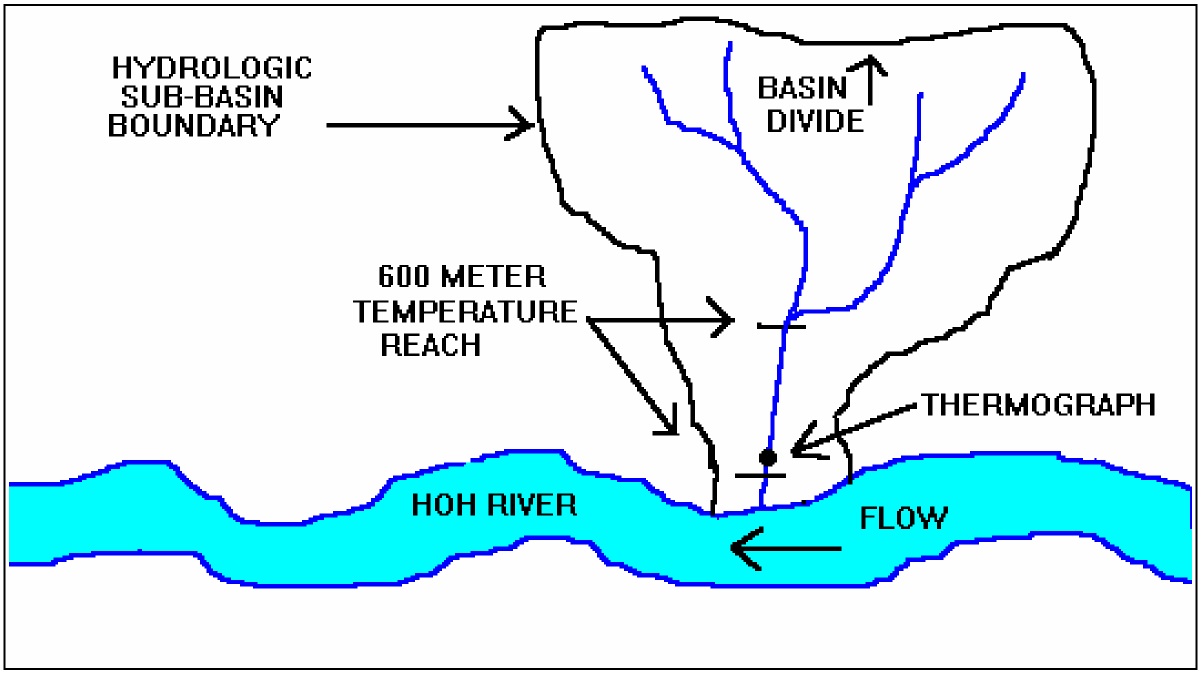

Figure 2. Example of a study site with the temperature reach and sub-basin hydrologic boundaries illustrated.

Study Site Selection:

Each study site had unique physical features that made comparison with other sites difficult. However, to reduce site variability and improve comparative analyses, only sites that met the following criteria were selected for this study: (1) the elevation at the downstream end of the study site was less than 300 m; (2) the sub-basin encompassing the site was smaller than 31 km^2; and (3) the study stream was classified as a AA water (WAC 173-201A-130).

Temperature Monitoring Methods

The thermographs used in this study had several different components; a weather proof box, a data logger, extension cables, and one or more temperature probes or thermistors (Figure 3). Two different types of thermographs were used in this study, Ryan Tempmentors™ and Unidata data loggers. The Ryan thermographs were equipped with one thermistor located at the end of an 8-m extension cable and were programmed to take one water temperature measurement every hour. In contrast, the Unidata loggers were equipped with two thermistors located at the ends of two 10-m extension cables and were used to measure water and air temperatures simultaneously. In addition, the Unidata loggers scanned temperature every five seconds and stored the hourly minimum, maximum, and average readings. All thermistors were checked for accuracy by submersion in an ice bath solution with a calibration thermometer prior to deployment. Any thermistor that was not within ±0.5° C of the true water temperature was discarded. A post-season calibration after the field season was conducted using similar methods.

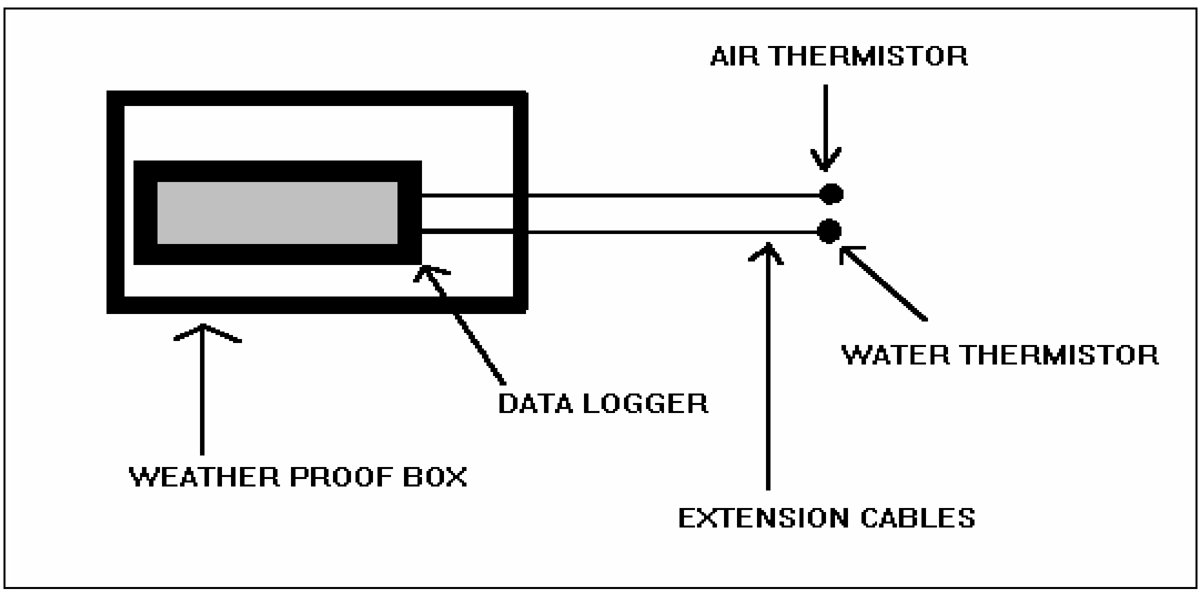

Figure 3. Diagram of the various components of a thermograph: weather-proof box, data logger, extension cables, and thermistors.

Thermographs were placed outside the ordinary high water line in weather-proof containers with only the thermistor in the water (Figure 4). Keeping the thermograph's data logger outside the ordinary high water line reduces the chance of damage during high flows. Thermistors were placed in the first perennial pool encountered - going upstream - within a site's temperature reach. Pools were selected instead of glides because summer low flows can cause glides to dry up and salmonids often prefer to rear in pool habitat (Bisson et al. 1987; Beschta and Platts 1986). Thermistors were placed in a shaded location of the pool with good water circulation. To keep the thermistor out of the influence of cooler groundwater (Bilby 1984), rock cairns were built and thermistors placed off the bottom (Figure 4).

Air temperature thermistors were placed between one and three meters outside the ordinary high water line (edge of channel), usually in a tree or bush (Figure 4). Care was taken that the thermistor was well shaded from direct sunlight.

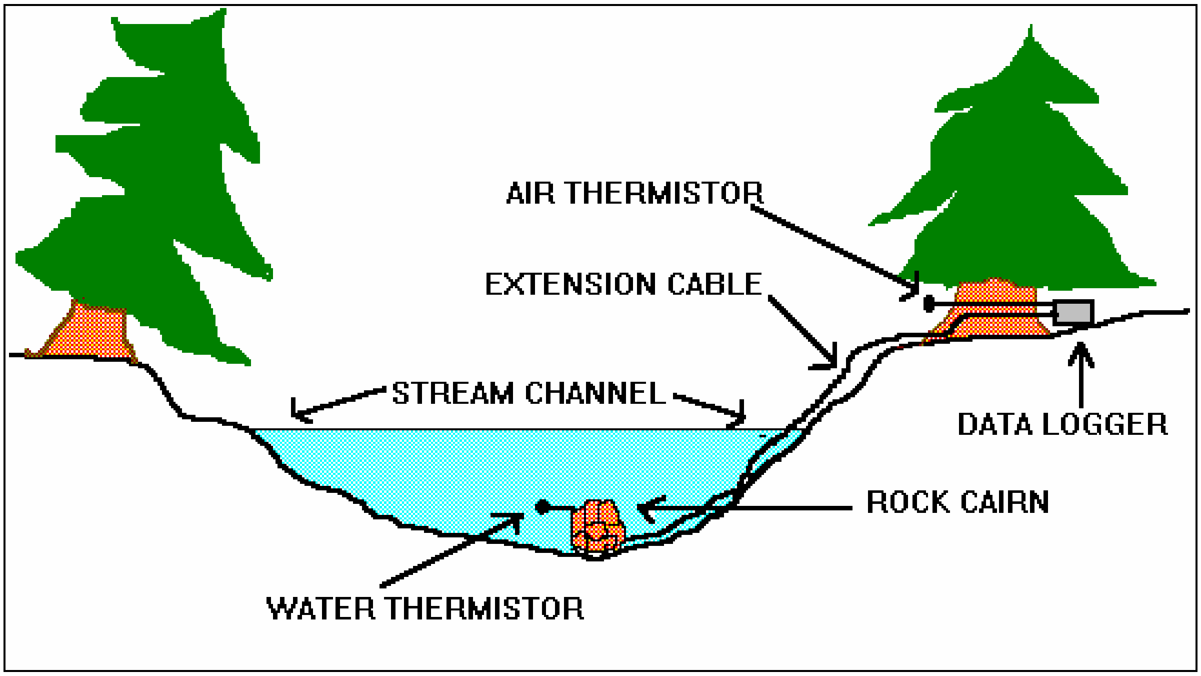

Figure 4. A cross section of a study site showing the location of the thermistors and the data logger.

Riparian Classification

The age and species composition of the dominant riparian vegetation was estimated for each temperature reach by visual assessment. Age was broadly classified as either young (< 25 years), second-growth (25 to 70 years), or mature (> 70 years). Each reach was divided into 20 sections (each 30 m in length) and the average age of trees along the stream bank was estimated for each section. The observations were made from the middle of the wetted channel and recorded separately for each bank. Thus, each temperature reach had a total of 40 visual estimates of the age of the riparian canopy. The percentage that each age group comprised of these 40 observations was used to describe the age composition.

The species composition of each temperature reach was estimated similarly to age composition. Within each 30-m section, the dominant riparian species along each bank was classified as deciduous, coniferous, or mixed. The percentage that each species category comprised of these 40 observations was used to describe species composition.

These visual methods are strictly a qualitative assessment and are not intended to provide precise data. We believe they provide a general assessment of the age and species composition of each study site's riparian zone. It is impossible to visually estimate the exact age of a tree, but we believe that we were within ±10 years of the true age. However, this inability to estimate the true age of a tree can lead to inaccuracies between the three age classes. Therefore, the results from the age and species composition surveys are not used in any of the statistical analyses but are presented for informational purposes only.

Variable Definitions

Twenty-two variables (excluding age or species compositions) were measured for this study. Each variable was classified as either an independent (physical) variable or a dependent (temperature) variable. All of the independent variables examined described either channel morphology or characteristics of the sub-basins. The dependent variables were all components of a study site's temperature regime and included average, minimum, and maximum temperatures. Abbreviations were assigned to each variable to simplify references.

Independent Variables:

The 13 independent variables examined in this study and the methods used to quantify them are described below. The abbreviation for each variable is in parentheses after its name.

Basin size (BASIZE) was obtained from USGS 15° topographic maps using a digital planimeter and represents the total hydrologic catchment area (km^2) above each thermograph.

Elevation (ELEV) refers to the elevation in meters of the thermograph within each study site and was obtained from USGS 15° topographic maps.

Gradient (GRADE) was determined from USGS 15° topographic maps and is the average gradient of a temperature reach.

Channel length (CLENGTH) is the total length in meters of the stream channel as measured from a study site's thermograph to the sub-basin divide. CLENGTH was obtained from USGS 15° topographic maps.

Stream shade (SHADE) was measured every 30 m within a temperature reach using a spherical densiometer (Lemmon 1957). At each 30-m station, stream shade was measured by standing in the middle of the channel and measurements were taken in four directions and averaged (Figure 5). Thus, each study site had twenty average stream shade values which were then averaged for the entire temperature reach.

Summer discharge (LOWFLOW) measurements were made during the last week of July when streams typically experience their minimum flows. A Marsh-McBirney flow meter was used to measure discharge in m^3/sec (cms) using conventional methods (Schuett-Hames et al. 1992). All summer lowflow measurements were made at the first suitable riffle above the thermograph.

Mature forest (CLASS-1) is the proportion of forest within a study site's sub-basin that is classified as late seral stage. This information was obtained from the Olympic Region Geographic Information System (GIS) at the Washington State Department of Natural Resources (DNR). In the classification system used by the DNR, late seral stage forests (Class 1 forests) are defined as having more than 10% crown closure in trees greater than 53 cm diameter at breast height, more than 70% total crown closure, and less than 75% of the crown in hardwoods or shrubs (WSDNR 1993). The classification of forest lands as Class 1 was based upon LandSAT Thematic Mapper images taken in 1988. The methods used for the classification are described in Congalton et al. (1993). Any harvest that occured between 1988 and 1992 was accounted for in the DNR GIS database. It is important to note that this variable was not used in the classification of the stream sites to the unmanaged and managed groups.

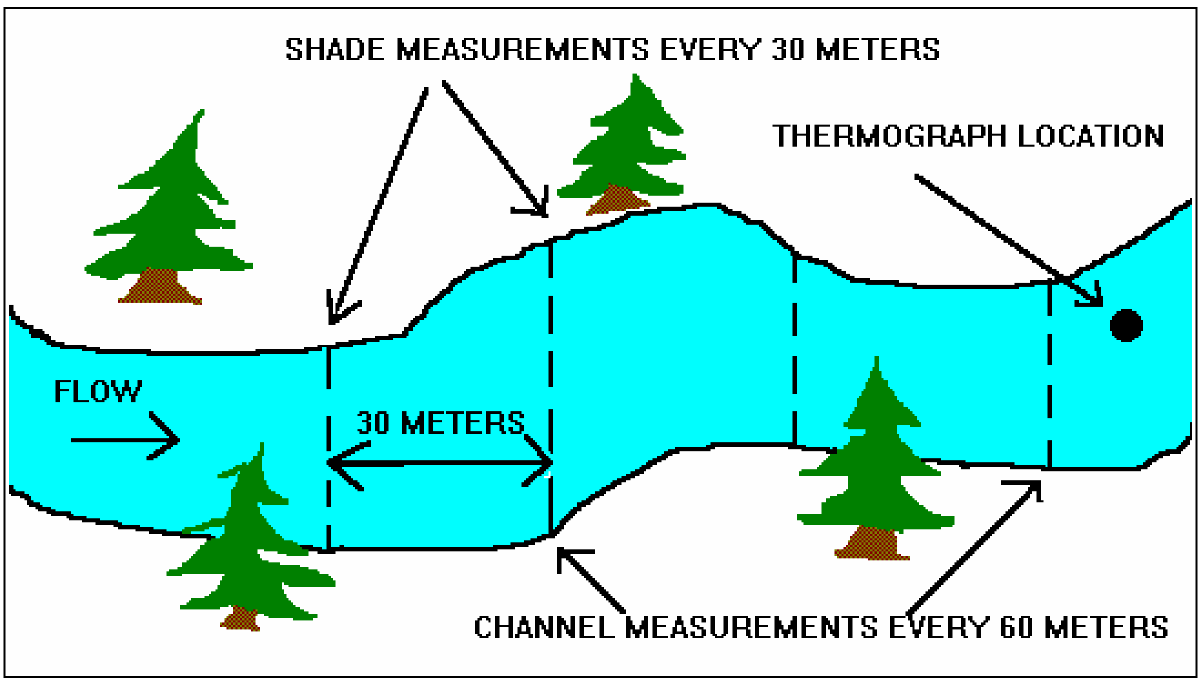

Figure 5. A portion of a study site's temperature reach illustrating the location and frequency of stream shade and channel measurements.

Bankfull width (BFWIDTH) was measured at 60-m intervals along the temperature reach (Figure 5) by stretching a measuring tape taunt across the stream at the bankfull height of the channel (Figure 6). Ten bankfull width measurements were made in each temperature reach and averaged.

Bankfull depth (BFDEPTH) was measured at every 60-m station, also. The bankfull width portion of the channel was divided into eight, evenly-spaced segments and the bankfull depth (Figure 6) measured at each segment with a stadia rod. The average of these eight measurements was used as the depth for the station. Bankfull depth measurements were made at ten stations in each temperature reach and averaged.

The **wetted width** (WETWIDTH) and **wetted depth** (WETDEPTH) measurements were made at the same stations as the bankfull width and depth measurements (Figure 6) except wetted measurements were made in late July when streams were near their minimum discharge. A measuring tape was stretched perpendicular to the wetted portion of the channel and the width measured directly (Figure 6). The wetted depth at a station was determined by dividing the wetted portion of the channel into eight, evenly-spaced segments, measuring the wetted depth at each segment with a stadia rod, and averaging the eight measurements. Wetted width and depth measurements were made at ten stations in each temperature reach and averaged.

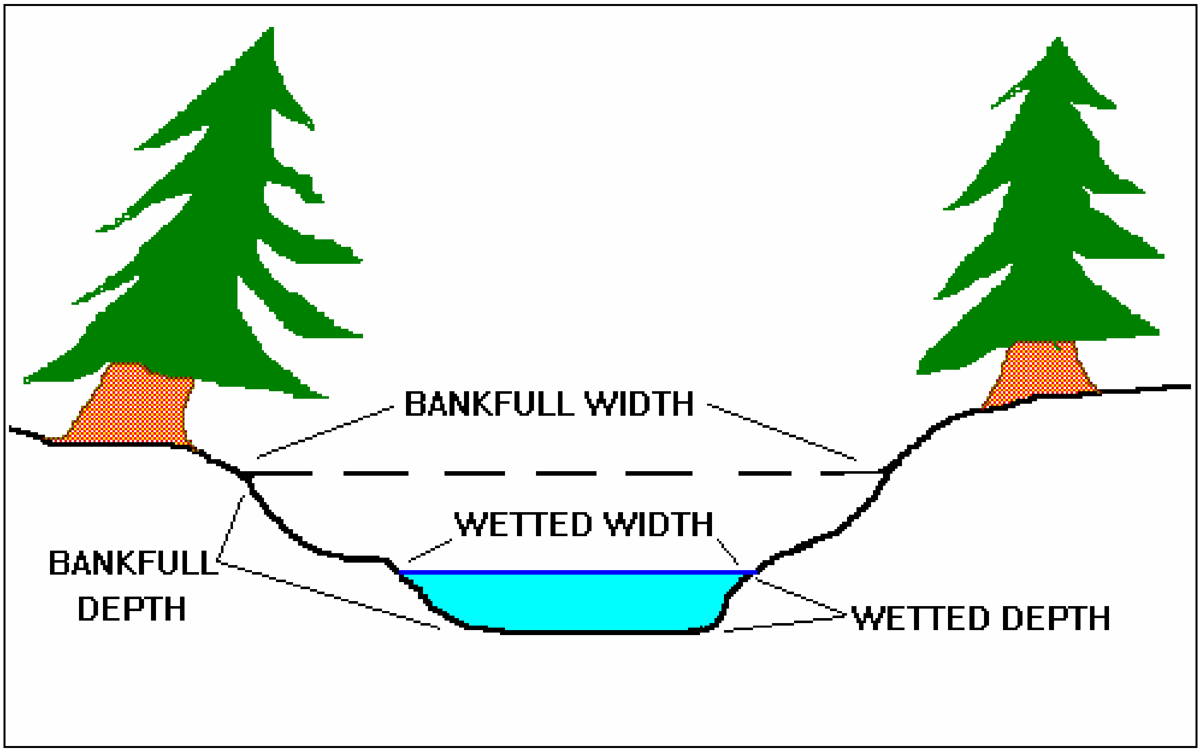

Figure 6. A cross section of a study site showing some of the variables describing channel morphology.

Bankfull width to depth ratio (BFW/D) was calculated for each temperature reach by dividing the average bankfull width by the average bankfull depth.

The **wetted width to depth ratio** (WETW/D) was calculated for each temperature reach by dividing the average wetted width by the average wetted depth.

Dependent Variables:

The nine dependent variables examined in the study are defined below. The abbreviation used for each variable is in parentheses after its name. Only temperature data from July 9 through August 16 were used in the analyses because of thermograph malfunctions at one or more sample sites during other time periods. This will be referred to as the analysis period.

Mean hourly water temperature (XAVEH2O) is the mean of the 936 (24 hourly temperatures per day x 39 days) hourly water temperatures recorded during the analysis period.

Median hourly water temperature (XMEDH2O) is the median temperature value for the 936 hourly water temperatures recorded during the analysis period.

Mean daily low water temperature (XMINH2O) is the mean of the 39 daily minimum water temperatures recorded during the analysis period.

Mean daily high water temperature (XMAXH2O) is the mean of the 39 daily maximum water temperatures recorded during the analysis period.

Number of days where the maximum daily water temperature exceeded 16.0^{O}C (N>16.0) is the number of days during the analysis period that a study site's maximum daily water temperature exceeded Washington State's water quality temperature criterion for Class AA waters of 16.0° C.

Mean hourly air temperature (XAVEAIR) is the mean of the 936 hourly air temperatures recorded during the analysis period.

Median hourly air temperature (XMEDAIR) is the median temperature value for the 936 hourly air temperatures recorded during the analysis period.

Mean daily low air temperature (XMINAIR) is the mean of the 39 daily minimum air temperatures recorded during the analysis period.

Mean daily high air temperature (XMAXAIR) is the mean of the 39 daily maximum air temperatures recorded during the analysis period.

Statistical Analyses

There are two distinct sections to the statistical analyses conducted. The first section is a summary of the independent and dependent variable data by group: unmanaged or managed. Included are tests of normality of the data for each variable, by group, and a comparison of the unmanaged and managed groups for each variable. The second section of the analyses examines the relationships among the dependent and independent variables. These analyses focus on the relationships between important dependent water temperature variables and the independent variables.

Descriptive Statistics and Comparison of Groups:

At the end of the field season all temperature data were transferred from the thermographs to desktop computers for analysis. Basic descriptive statistics (mean, standard error, and coefficient of variation) were calculated for each of the independent and dependent variables by group: unmanaged or managed. Many of the parametric analyses conducted require the assumption of normally distributed variables. The Kolmogorov goodness-of-fit statistic (Conover 1980) was used to test the hypothesis that the data were not significantly different from a normal distribution. These tests were conducted for each variable by group.

Another assumption necessary for the parametric tests which compared the means of the two groups was that the groups have homogeneous variances. This assumption was tested using a variance-ratio test based upon the F statistic (Zar 1974). When the hypothesis of homogeneous variances was not accepted, data transformations were used to equalize group variances when possible.

For each variable, the means for the groups were compared using a t-test (Zar 1974) and its nonparametric equivalent the Mann-Whitney (MW) test (Conover 1980). The Kolmogorov-Smirnov (KS) two-sample test was used to compare group distribution functions (Conover 1980). Frequency histograms were produced to visually compare the distributions of both independent and dependent variables between the two groups.

There were significant differences between the unmanaged and managed groups for some of the independent variables and dependent, water temperature variables. A significant difference between the groups for a dependent variable could be due to differences between the groups in an independent variable, if that variable has a significant influence on water temperature. Analysis of variance with a covariate (Searle 1987) was used to address this problem. Analysis of variance with a covariate (ANOVAWC) is used to test for differences between group means for a dependent variable controlling for the effect of a concomitant variable (usually called a covariate). The covariate must be a continuous variable whose effects are linear. The effect of the covariate is controlled for by adjusting the means of the dependent (response) variable to account for the difference between the two groups in the covariate (Kleinbaum and Kupper 1978). Therefore, the possible confounding effects on the dependent variable, due to differences in the distributions of the covariate for the two groups, are removed. ANOVAWC was used to test for a difference between group means of the water temperature variables using the independent variables which had significant differences between group means, or variables identified as important by previous research, as covariates.

Relationships Among Independent and Dependent Variables:

The examination of relationships among independent and dependent variables began by estimating the correlation among all possible variable pairs (for all independent [***X***] and dependent [***Y***] variables) using data for the unmanaged and managed groups combined. Both Pearson's correlation coefficient and Spearman's (nonparametric) correlation coefficient were calculated (Conover 1980). The significance of each coefficient was determined using standard statistical tables based on the value of the coefficient and sample size. Correlations were classified as either: non-significant (NS) when $P > 0.05$; significant (denoted by *) when $0.01 > P \leq 0.05$; or highly significant (denoted by **) when $P \leq 0.01$.

In addition to using the correlation coefficient to determine if there was a significant relationship between an independent and dependent variable pair, analysis of covariance (ANCOVA) was used to examine the relationship between three of the dependent water temperature variables judged to be most important and the independent variables. Analysis of covariance was used to determine if the relationship between each independent-dependent (***XY***) variable pair was the same for the unmanaged and managed groups. If the relationship of the dependent variable to the independent variables was different for the managed group compared to the unmanaged group, then a simple correlation coefficient may not accurately reflect the significance of the relationship between the variables. Analysis of covariance was used to determine if the relationship between the ***XY*** variables was the same for the two groups. The analyses followed procedures described in Kleinbaum and Kupper (1978). The combined (unmanaged and managed) data were fit to the multiple regression model:

$$Y = \beta_0 + \beta_1 X + \beta_2 Z + \beta_3 XZ + \varepsilon$$

where ***Y*** and ***X*** are the dependent and independent variables, respectively. ***Z*** is a dummy variable denoting group membership: ***Z*** = 0 if unmanaged or 1 if managed. The β_i are regression coefficients and ε is the error term. This model was then used to test the two hypotheses of interest:

I. The regression lines for the groups are parallel, i.e., H_o: $\beta_3 = 0$. Thus, for a given change in the independent variable the two groups have a similar response in the dependent variable, and

II. The two lines are coincident, i.e., H_o: $\beta_2 = \beta_3 = 0$. If this hypothesis is not rejected, then the relationship between the dependent and independent variables is the same for the two groups and is represented by the usual regression model: $\boldsymbol{Y = \beta_0 + \beta_1 X + \varepsilon}$.

If both of these hypotheses are not rejected, then the relationship between the dependent and independent variables examined is not significantly different for the unmanaged and managed groups and a single regression line can be used to describe the relationship.

The best linear relationship between the independent variables and the three dependent variables examined (XAVEH2O, XMAXH2O, and N>16.0) was determined by simple regression analysis using least squares (Zar 1974). Based upon the results of the ANCOVA, either a single regression line for the unmanaged and managed data combined or separate regression lines for each group were calculated. The coefficient of determination, R^2, for each regression line was estimated. The coefficient of determination is the proportion of the total variation in the dependent variable (***Y***) explained by the fitted regression line (Draper and Smith 1981). $R^2 = 0.50$[1] was selected as the minimum value we considered useful for a regression equation to be used for predictive purposes.

The final examination of the relationship between the dependent and independent variables explored the use of multiple independent variables in the regression equations (as opposed to the single independent variable regression analysis above). The stepwise regression procedure in SPSS (Norusis 1988) with the significance levels of the F-to-enter and F-to-remove values set at 0.05 was used. Two analyses were run for each of the dependent variables examined (XAVEH2O, XMAXH2O, and N>16.0). For the first model, all 13 independent variables were submitted to the procedure; for the second model the CLASS-1 independent variable was removed from the variables submitted. The adjusted R^2 (Draper and Smith 1981) was used to examine the increase in the goodness of fit of the model for each independent variable entered into the regression equation. The adjusted R^2 was used to compare models because it accounts for differences in sample sizes and degrees of freedom in the models. Five types of plots were used to examine the models for linearity and homogeneity of variances: (1) a case-wise plot of studentized residuals (Draper and Smith 1981); (2) plots of standardized residuals versus predicted values; (3) plots of residuals versus the independent variables in the model; (4) normal probability plots; and (5) partial regression plots (Norusis 1988). The presence of multicollinearity among the independent variables in the model was monitored using the TOLERANCE criterion of SPSS (Norusis 1988).

Two evaluation statistics are used to compare the performance of the two regression models (one with CLASS-1 and one without CLASS-1). The two statistics are the mean percent error (MPE) and the mean square error (MSE). MPE is a measure of model bias while MSE is a measure of model accuracy (Abraham and Ledolter 1983). They are defined as:

$$MPE = \frac{100}{n} \sum_{i=1}^{n} \frac{(observed_i - predicted_i)}{observed_i}$$

[1] With $R^2 = 0.50$, the fitted regression line explains 50% of the variation in the ***Y*** variable.

and

$$MSE = \frac{\sum_{i=1}^{n} (observed_i - predicted_i)^2}{n}$$

where ***n*** is the number of observations in the regression model and ***observed*** and ***predicted*** refer to the independent (***Y***) variable.

RESULTS

As noted previously, due to periodic malfunctions of some thermographs data analyses were restricted to the 39-day period from July 9 through August 16. Streams in the Pacific Northwest usually experience peak water temperatures during this period (Levno and Rothacher 1967; Beschta and Taylor 1988; Holtby 1988). Although 28 streams were sampled concurrently, data from only 26 streams were used in the analyses. The data from two unmanaged streams were omitted from the analyses because of extended thermograph malfunctions during the analysis period. Therefore, data from 11 streams draining unmanaged sub-basins and 15 streams draining managed sub-basins were used in the analyses. The thermographs on these 26 streams recorded water temperatures continuously throughout the analysis period (July 9 through August 16).

The results are presented in three sections. The first section summarizes the results of the riparian classification surveys. The second section summarizes the independent and dependent variable data and includes a comparison of the unmanaged and managed groups for each of the variables. The third section examines the relationships among the independent and dependent variables.

Summary of Riparian Classification

Based upon the visual assessments, the species composition of the managed sites, on average, consisted of nearly three times as many stands of deciduous trees than the unmanaged sites (Table 1). In comparison, the temperature reaches of unmanaged sites, on average, had approximately twice as many stands of coniferous trees than the managed sites. The percentages of mixed stands (coniferous and deciduous mixed) were about equal for the unmanaged and managed groups. In general, the majority of deciduous trees were alder: several sites had large numbers of broadleaf maples.

The age composition surveys estimated that the mean composition of the riparian zone for unmanaged sites was about 79% mature forest compared to only 23% mature forest for managed sites. The riparian zones of unmanaged sites averaged 8% young forest and 13% second growth. In comparison, the managed sites averaged 44% percent young forest and 33% second growth (Table 1).

Descriptive Statistics and Comparison of Groups

Basic descriptive statistics were compiled for the independent and dependent variables for each of the 26 study sites. The mean, standard error, and coefficient of variation for each variable for all unmanaged sites combined and all managed sites combined were then calculated. The groups were compared using the statistics described in the Methods section.

Table 1. Estimated percent species composition and percent age composition of the riparian zone adjacent to each temperature reach.

		Estimated Percent Species Composition			Estimated Percent Age Composition		
Site Name	M/U[a]	Deciduous	Coniferous	Mixed	Young	2nd Growth	Mature
TWIN	U	37.5%	25.0%	37.5%	20.0%	7.5%	72.5%
CAMP	U	0.0%	95.0%	5.0%	0.0%	0.0%	100.0%
MATSON	U	0.0%	77.5%	22.5%	0.0%	0.0%	100.0%
JACKSON	U	5.0%	52.5%	42.5%	2.5%	5.0%	92.5%
OLLALIE	U	5.0%	15.0%	80.0%	0.0%	0.0%	100.0%
HADES	U	0.0%	100.0%	0.0%	0.0%	0.0%	100.0%
INDIAN	U	0.0%	95.0%	5.0%	0.0%	0.0%	100.0%
MOSQUITO	U	7.5%	60.0%	32.5%	37.5%	5.0%	57.5%
KACKWA	U	15.0%	52.5%	32.5%	10.0%	37.5%	52.5%
COAL	U	22.5%	40.0%	37.5%	2.5%	40.0%	57.5%
HARLOW	U	72.5%	0.0%	27.5%	17.5%	50.0%	32.5%
Mean		15.0%	55.7%	29.3%	8.2%	13.2%	78.6%
ROCK	M	20.0%	17.5%	62.5%	25.0%	10.0%	65.0%
MAPLE	M	85.0%	0.0%	15.0%	80.0%	20.0%	0.0%
WINFIELD	M	77.5%	0.0%	22.5%	12.5%	87.5%	0.0%
NOLAN	M	55.0%	5.0%	40.0%	7.5%	87.5%	5.0%
FISHER	M	25.0%	55.0%	20.0%	82.5%	0.0%	17.5%
HOOT	M	2.5%	95.0%	2.5%	12.5%	5.0%	82.5%
OWL	M	20.0%	12.5%	67.5%	12.5%	70.0%	17.5%
LINE	M	25.0%	55.0%	20.0%	75.0%	0.0%	25.0%
ALDER	M	2.5%	70.0%	27.5%	10.0%	2.5%	87.5%
CANYON	M	40.0%	7.5%	52.5%	20.0%	75.0%	5.0%
ANDERSON	M	57.5%	0.0%	42.5%	57.5%	42.5%	0.0%
TOWER	M	90.0%	2.5%	7.5%	80.0%	10.0%	10.0%
WILLOUGHBY	M	100.0%	0.0%	0.0%	97.5%	0.0%	2.5%
SPLIT	M	27.7%	60.2%	12.1%	67.5%	0.0%	32.5%
KALALOCH	M	30.0%	0.0%	70.0%	15.0%	85.0%	0.0%
Mean		43.8%	25.3%	30.8%	43.7%	33.0%	23.3%

[a] M/U = U for unmanaged sub-basins and M for managed sub-basins.

Basin and Channel Morphology Data:

The independent variables describing sub-basin and channel morphologic features are listed for each of the 26 study sites in Appendix Table 1. The mean, standard error, and coefficient of variation of each variable, by group, are presented in Appendix Table 1, also. Because of logistical problems, summer discharge (LOWFLOW) was not measured at Coal Creek and summer discharge, wetted width, and wetted depth were not measured at Harlow Creek. These are both unmanaged streams.

Water and Air Temperature Data:

The water and air temperature data (the dependent variables) collected at each site during the 1992 field season are summarized in Appendix Table 2. The mean, standard error, and coefficient of variation of each variable, by group, are presented in Appendix Table 2, also.

Comparison of Unmanaged and Managed Groups:

The mean, standard error, and coefficient of variation for each independent variable, by group, are summarized in Table 2. All the Kolmogorov tests comparing the cumulative distributions of each independent variable, for a group, to the normal distribution were not rejected (all $P > 0.25$). Therefore, the assumption of a normal distribution for the independent variable data appears reasonable. However, the assumption of equal group variances was rejected using the F test for the BASIZE, SHADE, and CLASS-1 variables (Table 2). Different transformations were examined for each of these variables. The natural logarithm of BASIZE, squared value of SHADE, and arcsine transformation (Zar 1974) of the CLASS-1 variable resulted in significance levels greater than 0.05 for the variance-ratio test.

For the independent variables, only the CLASS-1 variable has a significant difference ($P < 0.01$) between the groups for all four of the tests used to compare the unmanaged and managed groups. With the exception of the MW test of the ELEV variable, the tests comparing the locations or distributions of the two groups (the t, MW, and KS tests) all had *P* values greater than 0.10 for the other independent variables.

Histograms comparing the distributions of nine of the thirteen independent variables, by group, are shown in Figure 7. The two groups have relatively similar frequency distributions for the variables displayed except for ELEV and CLASS-1. BFW/D and WETW/D are not shown since they are a function of the bankfull width and bankfull depth variables and the wetted width and wetted depth variables, respectively. WETDEPTH and CLENGTH are not displayed either because of space considerations. The distributions of these four variables are very similar for the unmanaged and managed groups.

Table 2. Comparison of unmanaged and managed group means for the independent variables and the significance of the tests comparing the two groups.

Independent	Unmanaged Group				Managed Group				Significance of hypothesis tests[b]			
Variable	Mean	St. Err.	N[a]	CV	Mean	St. Err.	N	CV	F	KS	t	MW
BASIZE	7.0	1.67	11	23.8%	11.3	2.74	15	24.3%	**0.045**	0.758	0.584[c]	0.697
ELEV	154.1	15.58	11	10.1%	114.5	19.02	15	16.6%	0.263	0.101	0.120	0.058
GRADE	7.3	1.43	11	19.6%	7.8	2.28	15	29.1%	0.054	0.758	0.843	0.467
CLENGTH	4,922	629.2	11	12.8%	5,618	856.7	15	15.2%	0.145	0.579	0.519	0.938
SHADE	71.9	2.32	11	3.2%	64.9	4.91	15	7.6%	**0.007**	0.758	0.250[c]	0.483
LOWFLOW	0.060	0.021	9	35.0%	0.082	0.025	15	30.5%	0.252	0.648	0.511	0.399
CLASS-1	89.3	4.09	11	4.6%	29.1	6.64	15	22.8%	**0.048**	**0.000**	**0.000**[c]	**0.000**
BFWIDTH	10.2	1.03	11	10.1%	12.4	1.33	15	10.7%	0.192	0.850	0.197	0.324
BFDEPTH	0.587	0.060	11	10.2%	0.498	0.029	15	5.8%	0.052	0.733	0.200	0.284
BFW/D	19.2	3.05	11	15.9%	25.7	2.66	15	10.4%	0.977	0.217	0.124	0.102
WETWIDTH	4.18	0.491	10	11.8%	4.97	0.713	15	14.4%	0.088	0.970	0.370	0.760
WETDEPTH	0.156	0.025	10	16.0%	0.154	0.014	15	9.1%	0.207	0.996	0.945	0.889
WETW/D	30.4	4.51	10	14.9%	32.1	2.99	15	9.3%	0.467	0.787	0.763	0.542

[a] Sample size.

[b] F = F-test of equality of group variances.
KS = Kolmogorov-Smirnov nonparametric test of equality of cumulative distributions.
t = t-test of equality of group means.
MW = Mann-Whitney nonparametric test of equality of group means.

[c] Test conducted on transformed variable.

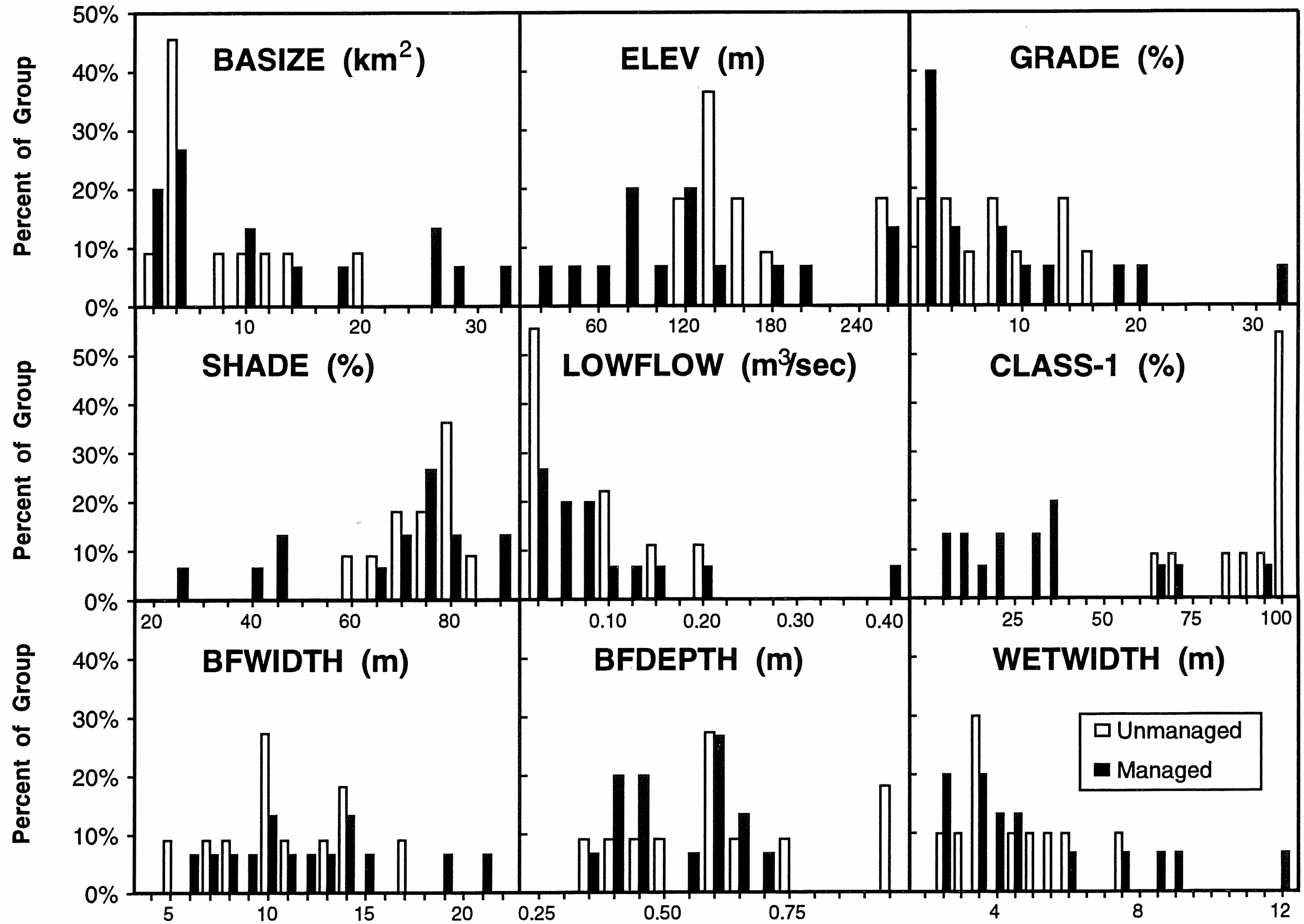

Figure 7. Frequency histograms comparing the distributions of data in the unmanaged and managed groups for nine of the thirteen independent variables.

The mean, standard error, and coefficient of variation for each dependent temperature variable, by group, are summarized in Table 3. All the Kolmogorov tests comparing the cumulative distributions of each dependent variable, for a group, to the normal distribution were not rejected (all $P > 0.18$). The assumption of a normal distribution for the dependent variable data appears reasonable, also. The assumption of equal group variances was rejected using the F test only for the N>16.0 variable (Table 3). The square root of the N>16.0 values (plus 0.5) increased the significance level to 0.044 for the variance-ratio test.

All the tests comparing the locations or distributions of the two groups (the t, MW, and KS tests) had *P* values less than 0.01 for the dependent water temperature variables. In contrast, none of these tests were significant for the four dependent air temperature variables (all $P > 0.44$).

Histograms comparing the distributions of the dependent temperature variables, by group, are shown in Figure 8. Generally, the water temperature data from unmanaged sites are concentrated to the left of the data from managed sites (are cooler) for all four water temperature variables (XAVEH2O, XMEDH2O, XMINH2O, and XMAXH2O). Only four of the 11 streams in unmanaged sub-basins exceeded the 16.0° C temperature standard established for Class AA waters in Washington during the 39-day monitoring period (variable N>16.0). The maximum number of days that the standard was exceeded at an unmanaged site was 11. In contrast, 14 of the 15 managed sites (93%) exceed the 16.0° C temperature standard on at least one day during the monitoring period. Nine of the 15 managed sites (60%) exceeded the standard for 15 or more days during the monitoring period. The distributions of the four air temperature variables are very similar for the unmanaged and managed groups.

ANOVA with a Covariate for the Water Temperature Variables:

The only independent variable which had a significant difference between the unmanaged and managed groups was the CLASS-1 variable. The ELEV and SHADE variables were included in the ANOVAWC analyses conducted even though there were not significant differences between the unmanaged and managed groups for these variables. ELEV and SHADE were included because: (1) elevation and stream shading were found by Sullivan et al. (1990) to be important variables affecting stream temperatures in Washington State and (2) the distributions of the ELEV and SHADE variable for the unmanaged and managed groups, although not significantly different statistically, were still dissimilar (Figure 7).

The ANOVAWC was performed using the ELEV, SHADE, and CLASS-1 variables as single covariates, with all possible two-variable combinations of the three variables as covariates, and with all three variables as covariates. These analyses were limited to the XAVEH2O, XMAXH2O, and N>16.0 dependent variables. The XMINH2O variable was not included in these analyses because it is not of as great concern with respect to water quality standards. The XMEDH2O variable was omitted from further analysis because it was very similar to the XAVEH2O variable in its mean value, variance, and distribution.

Table 3. Comparison of unmanaged and managed group means for the dependent variables and the significance of the tests comparing the two groups.

Dependent	Unmanaged Group				Managed Group				Significance of hypothesis tests[b]			
Variable	Mean	St. Err.	N[a]	CV	Mean	St. Err.	N	CV	F	KS	t	MW
Water Temperature Variables												
XAVEH2O	12.8	0.39	11	3.1%	14.7	0.31	15	2.1%	0.739	**0.000**	**0.001**	**0.000**
XMEDH2O	12.7	0.41	11	3.2%	14.6	0.30	15	2.1%	0.569	**0.000**	**0.001**	**0.000**
XMINH2O	12.2	0.38	11	3.1%	13.7	0.23	15	1.7%	0.229	**0.003**	**0.003**	**0.001**
XMAXH2O	13.6	0.41	11	3.0%	16.0	0.43	15	2.7%	0.492	**0.000**	**0.000**	**0.000**
N>16.0	1.8	1.07	11	58.8%	18.3	3.27	15	17.9%	**0.000**	**0.003**	**0.000**[c]	**0.001**
Air Temperature Variables												
XAVEAIR	16.0	0.21	6	1.3%	15.9	0.19	12	1.2%	0.663	0.767	0.729	0.778
XMEDAIR	14.9	0.17	6	1.1%	15.0	0.17	12	1.1%	0.458	1.000	0.760	0.962
XMINAIR	12.2	0.16	6	1.3%	12.2	0.22	12	1.8%	0.140	0.964	0.881	1.000
XMAXAIR	21.0	0.41	6	1.9%	20.6	0.34	12	1.7%	0.737	0.964	0.449	0.542

[a] Sample size.

[b] F = F-test of equality of group variances.
KS = Kolmogorov-Smirnov nonparametric test of equality of cumulative distributions.
t = t-test of equality of group means.
MW = Mann-Whitney nonparametric test of equality of group means.

[c] Test conducted on transformed variable.

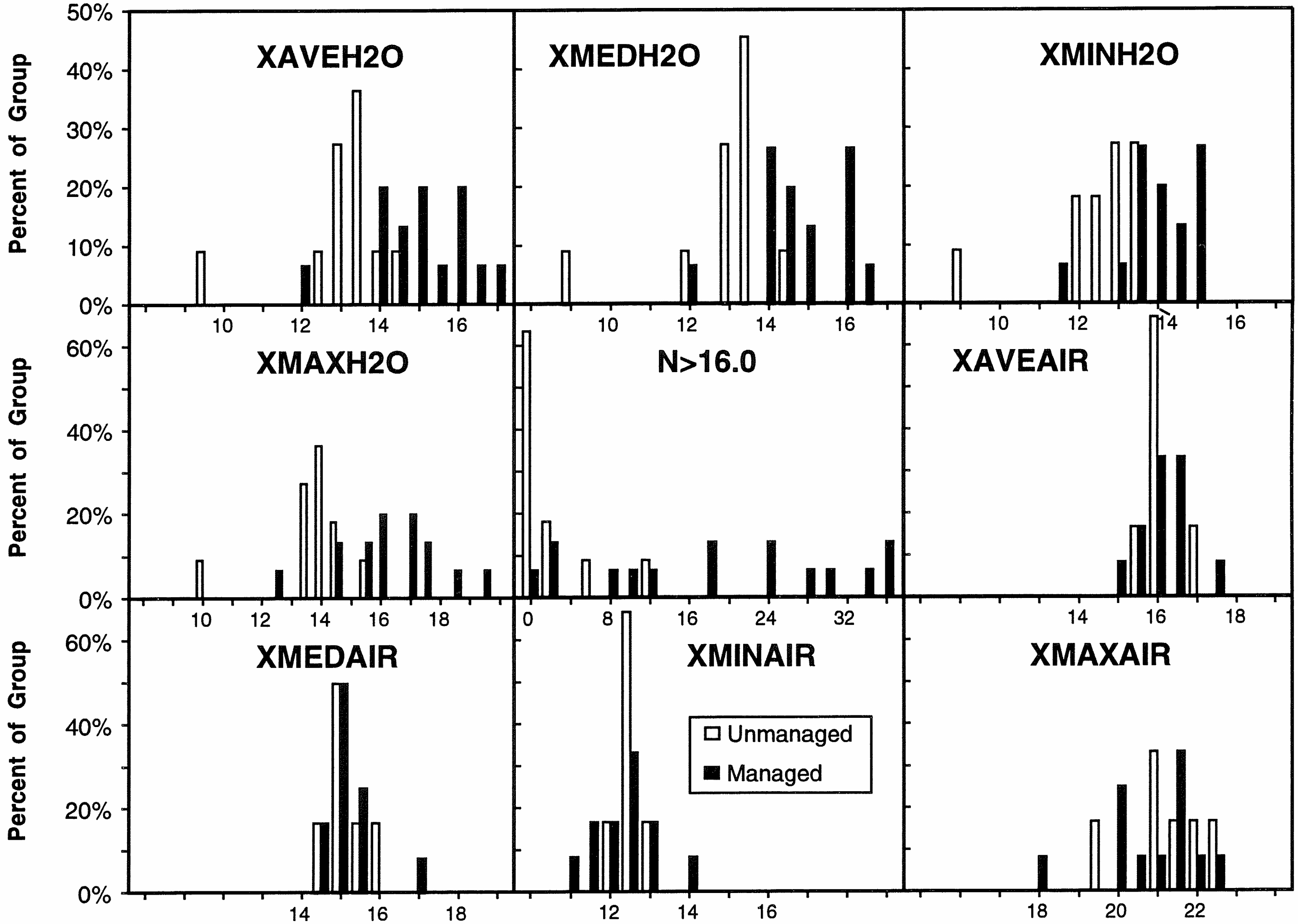

Figure 8. Frequency histograms comparing the distributions of data in the unmanaged and managed groups for the dependent variables. All temperatures reported in ^{o}C.

CLASS-1 was significant as a single covariate for all three of the dependent variable models examined (Table 4). The results that are important to focus on in Table 4 are significant covariates ($P < 0.05$) combined with a non-significant ($P > 0.05$) result for the test of group means. Together these indicate that when the differences between the unmanaged and managed groups for the covariate(s) are controlled, the difference between the group means in the dependent (water temperature) variable is no longer significant. When the effects of differences between groups for the CLASS-1 variable are controlled, the differences between the unmanaged and managed groups for the three water temperature variables are no longer significant (all $P \geq 0.70$). The only other single covariate that was significant was SHADE for the N>16.0 model. However, when the effects of differences between groups for the SHADE variable are controlled the difference in N>16.0 between the two groups remains significant.

For the two-covariate models, ELEV and SHADE were significant covariates for the XMAXH2O and N>16.0 models, but the difference between group means for these two dependent variables remained significant for these models. The CLASS-1 covariate was consistently the only significant covariate in the ELEV\CLASS-1 and SHADE\CLASS-1 models. This indicates that the addition of the other covariates (ELEV or SHADE) did not significantly improve the models compared to the models with only the CLASS-1 covariate.

For the three-covariate model for XAVEH2O, none of the covariates were significant. Only the SHADE covariate was significant for the three-covariate, XMAXH2O model. The ELEV and SHADE variables were significant covariates for the N>16.0 models. CLASS-1 was not a significant covariate in these three-variable models. The CLASS-1 variable was present in all models for which the hypothesis of equal group means for the unmanaged and managed groups was not rejected.

Relationships Among Independent and Dependent Variables

The parametric (Pearson's) and nonparametric (Spearman's) correlation coefficients, and the significance of each, among all possible variable pairs are summarized in Appendix Table 3. For the correlations among independent (independent-independent) variable pairs, the ELEV, SHADE, and CLASS-1 variables are focused on since these variables have been identified as important independent variables in the previous analyses. The ELEV variable has significant ($P \leq 0.05$) correlations with BASIZE, GRADE, CLENGTH, SHADE, BFWIDTH, and BFW/D (both Pearson's and Spearman's coefficients) and CLASS-1 (Pearson's only). SHADE has a significant correlation ($P \leq 0.05$) only with ELEV (both correlations) and BFDEPTH (Spearman's only). CLASS-1 has a significant correlation ($P \leq 0.05$) only with ELEV (Spearman's only).

The independent-dependent variable correlations with the water temperature variables are of primary interest. Only the ELEV, SHADE, CLASS-1, and BFW/D variables have significant correlations with more than one of the dependent, water temperature variables. These correlations are ≥ 0.50 only for the ELEV, SHADE, and CLASS-1 variables. The strongest correlations are between the water temperature variables and the CLASS-1 variable (correlations all greater than -0.60). Figure 9 shows the relationships between these three independent variables and the XAVEH2O, XMAXH2O, and N>16.0 dependent variables.

Table 4. Results of the analysis-of-variance tests conducted on the XAVEH2O, XMAXH2O, and N>16.0 dependent variables to compare the unmanaged and managed groups using CLASS-1, ELEV, and SHADE as covariates.

	XAVEH2O		**XMAXH2O**		**N>16.0**	
Covariates	Significance Levels		Significance Levels		Significance Levels	
Examined	Covar.[a]	Means[b]	Covar.	Means	Covar.	Means
ELEV (A)	0.320	0.002	0.416	0.002	0.521	0.001
SHADE (B)	0.399	0.002	0.096	0.001	**0.018**	0.001
CLASS-1 (C)	**0.014**	**0.753**	**0.014**	**0.708**	**0.009**	**0.702**
A, B	0.111	0.026	**0.012**	0.029	**0.001**	0.019
ELEV	0.057		**0.015**		**0.003**	
SHADE	0.067		**0.005**		**0.000**	
A, C	**0.040**	**0.788**	**0.045**	**0.736**	**0.035**	**0.723**
ELEV	0.463		0.595		0.745	
CLASS-1	**0.020**		**0.020**		**0.013**	
B, C	0.051	**0.742**	**0.026**	**0.629**	**0.006**	**0.558**
SHADE	0.806		0.242		0.054	
CLASS-1	**0.023**		**0.034**		**0.028**	
A, B, C	0.063	**0.736**	**0.014**	**0.604**	**0.001**	**0.506**
ELEV	0.234		0.069		**0.018**	
SHADE	0.328		**0.037**		**0.003**	
CLASS-1	0.090		0.167		0.176	

[a] Covar. is the significance of the test of the covariate(s) to the ANOVA model, including both the combined effects for models having more than one covariate and for the single effects of each covariate.

[b] Means is the significance of the test of equal group means controlling for the differences between the groups in the covariate(s).

There were no significant correlations between the mean air temperature and mean water temperature (dependent-dependent) variable pairs. On a daily time scale, air and water temperatures were significantly correlated.

Single Variable Regression Analysis:

The results of the ANCOVA for the XAVEH2O, XMAXH2O, and N>16.0 dependent variables are summarized in Table 5. The hypothesis of parallel slopes for the unmanaged and managed groups (hypothesis I) was not rejected for all independent-dependent variable pairs except SHADE-XAVEH2O and WETW/D-XAVEH2O. The hypothesis of coincident lines (hypothesis II) was rejected for every independent variable except CLASS-1. Therefore, the relationship between the independent and dependent variables is different for the unmanaged and managed groups and a common regression line for the combined groups is not appropriate for all independent variables except CLASS-1. Both hypotheses were not rejected for the CLASS-1 variable and the three dependent variables examined. This indicates that a single regression equation can be used to explain the relationship between the CLASS-1 variable and these dependent variables using data for the groups combined. All other independent-dependent variable relationships, however, require separate regression equations for each group.

Table 6 summarizes the R^2 values and significance levels for the least-squares regression lines. The CLASS-1 variable explained more than 50% of the variability in each of the three dependent variables examined (XAVEH2O, XMAXH2O, and N>16.0). These were the only regressions where it was appropriate to combine the data from the unmanaged and managed groups. The only other independent variable with a significant relationship ($P < 0.05$) and an $R^2 > 0.50$ was the WETW/D variable with the XAVEH2O and XMAXH2O variables, but only for the unmanaged group. Other than the CLASS-1 variable, there were no independent variables which explained more than 29% of the variation of the dependent water temperature variables for the managed group.

The cumulative distributions of the CLASS-1, XAVEH2O, XMAXH2O, and N>16.0 variables (for the unmanaged and managed data combined) were not significantly different from the normal distribution (P = 0.46, 0.95, 0.87, and 0.13, respectively). Therefore, the combined data from these variables was used in linear regression analyses. The regression lines for the three dependent variables and the CLASS-1 variable are shown in Figure 10. The data for the XAVEH2O and XMAXH2O variables are more tightly clustered around the regression line than the data for the N>16.0 variable. There is considerable scatter of the data around the regression line for the N>16.0 variable.

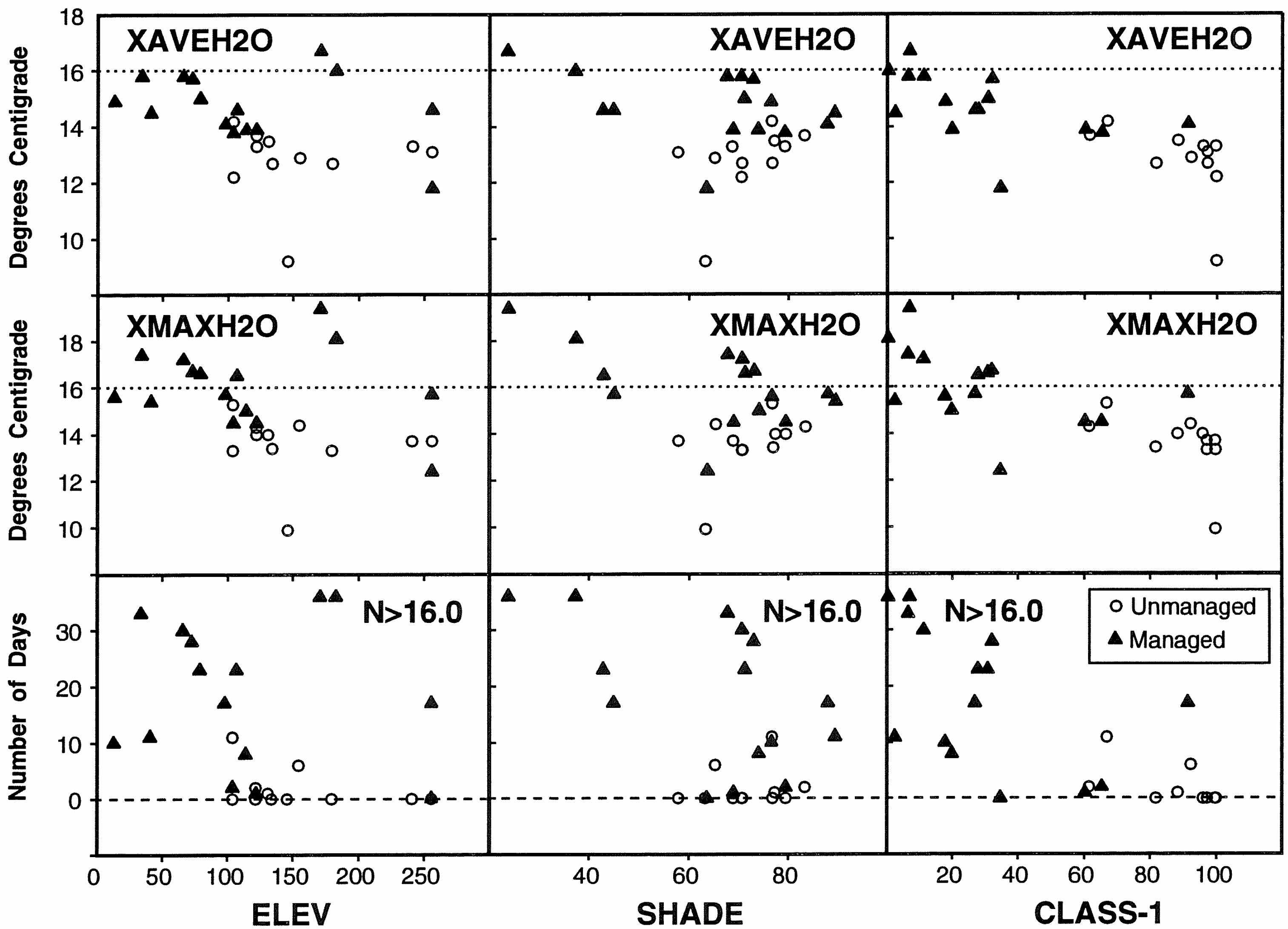

Figure 9. Plots showing the relationship between the XAVEH2O, XMAXH2O, and N>16.0 dependent variables and the ELEV, SHADE, and CLASS-1 independent variables.

Table 5. Results of the analysis-of-covariance conducted on the XAVEH2O, XMAXH2O, and N>16.0 dependent variables and all independent variables to determine if a single regression line was appropriate to describe the relationship between the dependent and independent variables.

Independent Variable	XAVEH2O Significance Levels		XMAXH2O Significance Levels		N>16.0 Significance Levels	
	H_o: I[a]	H_o: II[b]	H_o: I	H_o: II	H_o: I	H_o: II
BASIZE	0.322	**0.004**	0.614	**0.005**	0.720	**0.004**
ELEV	0.553	**0.009**	0.863	**0.008**	0.953	**0.005**
GRADE	0.095	**0.001**	0.414	**0.002**	0.841	**0.002**
CLENGTH	0.484	**0.004**	0.769	**0.004**	0.683	**0.003**
SHADE	**0.042**	**0.001**	0.051	**0.001**	0.292	**0.002**
LOWFLOW	0.329	**0.008**	0.372	**0.005**	0.636	**0.006**
CLASS-1	0.391	0.652	0.596	0.808	0.669	0.848
BFWIDTH	0.074	**0.002**	0.207	**0.003**	0.395	**0.003**
BFDEPTH	0.773	**0.003**	0.485	**0.002**	0.316	**0.002**
BFW/D	0.120	**0.002**	0.381	**0.004**	0.639	**0.006**
WETWIDTH	0.253	**0.004**	0.287	**0.003**	0.651	**0.004**
WETDEPTH	0.647	**0.004**	0.502	**0.002**	0.473	**0.002**
WETW/D	**0.028**	**0.017**	0.084	**0.001**	0.519	**0.003**

[a] H_o: I is the test for parallel slopes for the two groups.

[b] H_o: II is the test for coincident lines (equal slope and intercept) for the two groups.

Table 6. Summary of the linear regressions between the XAVEH2O, XMAXH2O, and N>16.0 variables and all independent variables, for the unmanaged or managed groups, or the groups combined when appropriate.

Independent Variable	XAVEH2O				XMAXH2O				N>16.0			
	Unmanaged		Managed		Unmanaged		Managed		Unmanaged		Managed	
	R^2	Sig.[a]	R^2	Sig.	R^2	Sig.	R^2	Sig.	R^2	Sig.	R^2	Sig.
BASIZE	0.04	0.559	0.08	0.295	0.01	0.827	0.04	0.462	0.01	0.727	0.06	0.360
ELEV	0.00	0.995	0.11	0.230	0.01	0.773	0.04	0.476	0.12	0.298	0.01	0.690
GRADE	0.15	0.234	0.12	0.209	0.04	0.558	0.04	0.451	0.18	0.197	0.01	0.689
CLENGTH	0.01	0.787	0.07	0.330	0.00	0.911	0.04	0.454	0.03	0.606	0.07	0.341
SHADE	0.24	0.125	0.17	0.130	0.20	0.174	**0.29**	**0.039**	0.02	0.646	**0.27**	**0.046**
LOWFLOW	0.12	0.365	0.01	0.913	0.12	0.355	0.01	0.800	0.14	0.318	0.01	0.772
CLASS-1	**0.53**	**0.000**	**same**		**0.54**	**0.000**	**same**		**0.57**	**0.000**	**same**	
BFWIDTH	0.13	0.281	0.19	0.107	0.06	0.478	0.13	0.189	0.01	0.799	0.16	0.143
BFDEPTH	0.02	0.667	0.04	0.495	0.01	0.834	0.06	0.373	0.03	0.609	0.06	0.398
BFW/D	0.12	0.287	0.09	0.273	0.04	0.570	0.04	0.483	0.04	0.537	0.05	0.434
WETWIDTH	0.10	0.371	0.03	0.541	0.13	0.301	0.02	0.618	0.07	0.463	0.01	0.668
WETDEPTH	0.08	0.436	0.15	0.148	0.05	0.531	0.12	0.197	0.01	0.747	0.04	0.499
WETW/D	**0.66**	**0.004**	0.01	0.800	**0.63**	**0.006**	0.01	0.799	0.04	0.603	0.03	0.559

[a] Sig. = significance of the overall regression (i.e., the significance of the slope).

[b] same = same as unmanaged group. This means that only a single regression line is needed for the combined (unmanaged and managed) data.

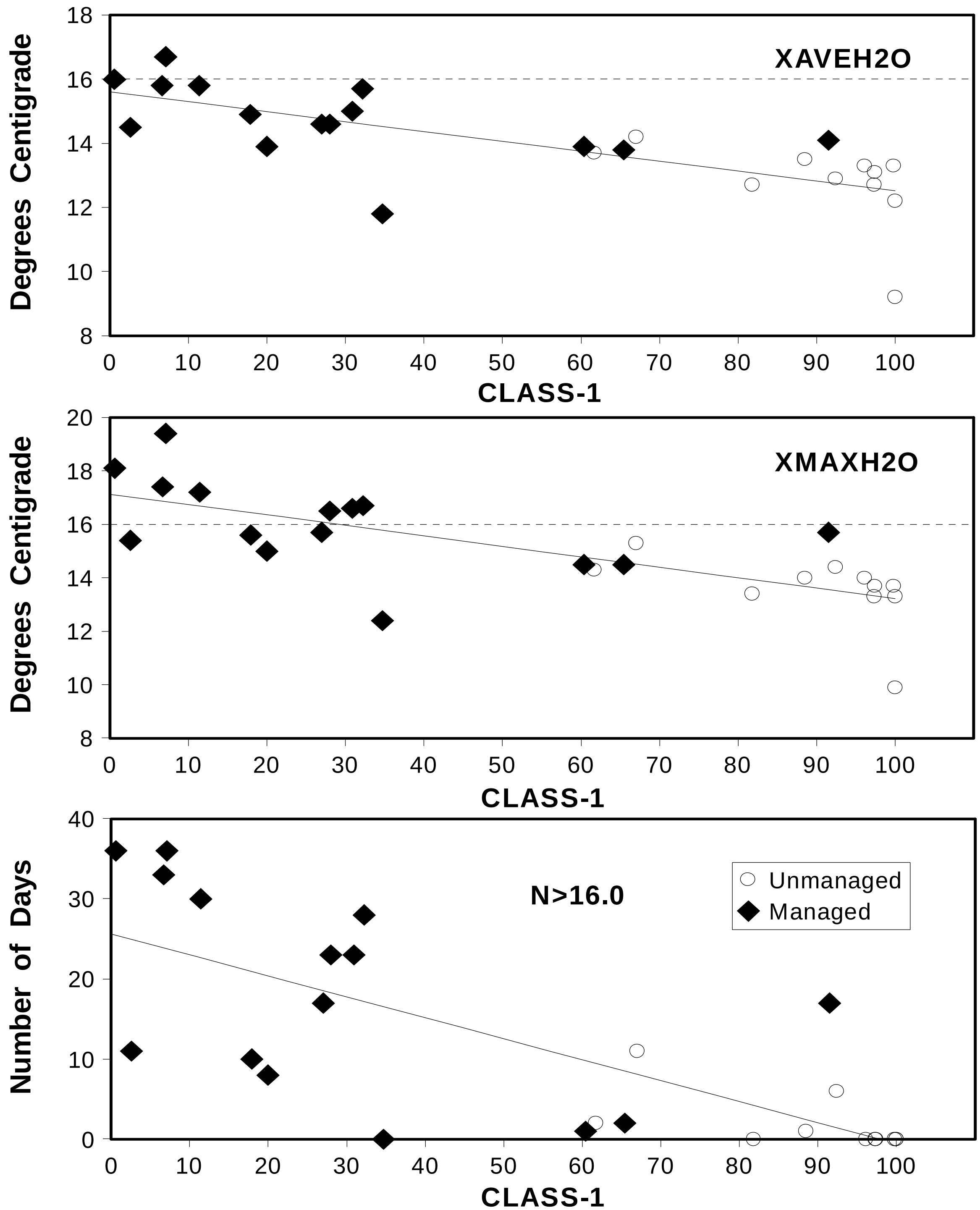

Figure 10. Regression lines for the relationships between the CLASS-1 independent variable and the XAVEH2O, XMAXH2O, and N>16.0 dependent variables.

Stepwise Regression Analysis:

XAVEH2O. When the CLASS-1 variable was included in the stepwise regression (Model I) for the XAVEH2O variable, both it and the WETW/D variable entered into the model. When the CLASS-1 variable was not included in the stepwise procedure (Model II), none of the remaining independent variables had an F-to-enter value with a significance level less than the 0.05 entry criterion. The adjusted R^2 for the two-variable, CLASS-1 model was 0.58. Both regression coefficients for this model were significant ($P < 0.04$) as was the intercept (Table 7). None of the residual plots indicated any gross departures from linearity or heterogeneity of variances. Plots of predicted values for XAVEH2O versus standardized residuals for Model I are shown in Figure 11. The model evaluation statistics for Model I are presented in Table 10.

XMAXH2O. When the CLASS-1 variable was included in the stepwise regression (Model I) for the XMAXH2O variable it was the only independent variable entered into the model. When the CLASS-1 variable was not included in the stepwise procedure (Model II), three of the independent variables were entered into the model. The variables entered were (in order of entry): SHADE, ELEV, and WETW/D. The adjusted R^2 for the CLASS-1 model was 0.52 compared to 0.64 for the three-variable model (Table 8). All three regression coefficients for the three variables in Model II were significant ($P < 0.01$) as was the intercept (Table 8). None of the residual plots indicated any gross departures from linearity or heterogeneity of variances. Plots of predicted values for XAVEH2O versus standardized residuals for models I and II are shown in Figure 11. Model II had a smaller MPE and MSE than Model I. Model I fits the unmanaged data better (has a smaller MSE) than Model II. Conversely, Model II fits the managed data better than Model I.

N>16.0. When the CLASS-1 variable was included in the stepwise regression (Model I) for the N>16.0 variable, it was the only independent variable entered into the model. When the CLASS-1 variable was not included in the stepwise procedure (Model II), two of the independent variables were entered into the model. The variables entered were (in order of entry): SHADE and ELEV. The adjusted R^2 for the CLASS-1 model was 0.55 compared to 0.58 for the two-variable model (Table 9). Both regression coefficients for the two variables in Model II were significant ($P < 0.01$) as was the intercept (Table 9). None of the residual plots indicated any gross departures from linearity. In contrast to the previous analyses, the residual plots for the N>16.0 variable indicate some heterogeneity of variances (Figure 11). The residuals for larger values of N>16.0 tend to have a greater dispersion than the smaller values. Model II has a slightly smaller MSE than Model I. The MPE statistic could not be calculated because of the presence of observations with a zero value in both groups. Similarly to the XMAXH2O analysis, Model I fits the unmanaged data better than Model II while Model II fits the managed data better than Model I.

Table 7. Results of the stepwise linear regressions for the XAVEH2O variable. All 13 independent variables were submitted to Model I while the CLASS-1 variable was omitted from the independent variables submitted to Model II.

Model	Adj. R^2	Regression Parameter	Estimated Coefficient	Significance of Parameter
Model I				
CLASS-1	0.512	Regression		**0.000**
		CLASS-1	-0.0309	**0.000**
		Intercept	15.6051	**0.000**
CLASS-1, WETW/D	0.581	Regression		**0.000**
		CLASS-1	-0.0318	**0.000**
		WETW/D	-0.0370	**0.036**
		Intercept	16.8163	**0.000**
No more variables entered				
Model II				
No variables entered				

Table 8. Results of the stepwise linear regressions for the XMAXH2O variable. All 13 independent variables were submitted to Model I while the CLASS-1 variable was omitted from the independent variables submitted to Model II.

Model	Adj. R^2	Regression Parameter	Estimated Coefficient	Significance of Parameter
Model I				
CLASS-1	0.520	Regression		**0.000**
		CLASS-1	-0.0391	**0.000**
		Intercept	17.1346	**0.000**
No more variables entered				
Model II				
SHADE	0.127	Regression		**0.041**
		SHADE	-0.0512	**0.041**
		Intercept	18.4753	**0.000**
SHADE, ELEV	0.456	Regression		**0.004**
		SHADE	-0.0919	**0.003**
		ELEV	-0.0194	**0.007**
		Intercept	23.7815	**0.000**
SHADE, ELEV, WETW/D	0.636	Regression		**0.000**
		SHADE	-0.1116	**0.000**
		ELEV	-0.0236	**0.000**
		WETW/D	-0.0726	**0.002**
		Intercept	27.9460	**0.000**
No more variables entered				

Table 9. Results of the stepwise linear regressions for the N>16.0 variable. All 13 independent variables were submitted to Model I while the CLASS-1 variable was omitted from the independent variables submitted to Model II.

Model	Adj. R^2	Regression Parameter	Estimated Coefficient	Significance of Parameter
Model I				
CLASS-1	0.551	Regression		**0.000**
		CLASS-1	-0.2617	**0.000**
		Intercept	25.6226	**0.000**
No more variables entered				
Model II				
SHADE	0.215	Regression		**0.010**
		SHADE	-0.4113	**0.010**
		Intercept	39.2555	**0.001**
SHADE, ELEV	0.579	Regression		**0.000**
		SHADE	-0.6874	**0.000**
		ELEV	-0.1320	**0.001**
		Intercept	75.3098	**0.000**
No more variables entered				

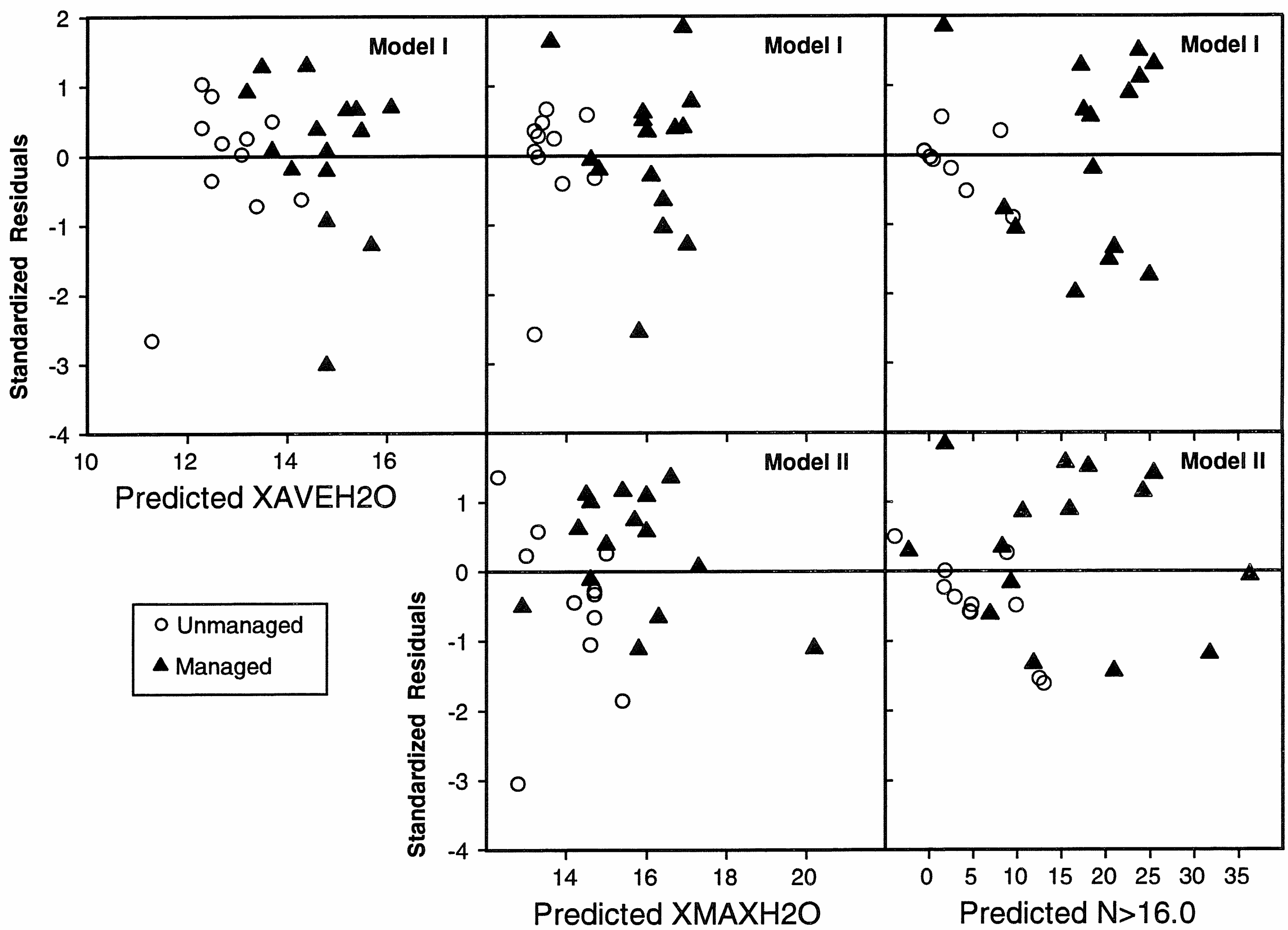

Figure 11. Plots of predicted values versus standardized residuals for regression models I and II using the XAVEH2O, XMAXH2O, and N>16.0 dependent variables.

Table 10. Summary of the mean percent error (MPE) and mean square error (MSE) statistics used to compare regressions models I and II for the XAVEH2O, XMAXH2O, and N>16.0 dependent variables.

Dependent Variable	Model	MPE			MSE		
		Unmanaged	Managed	Total	Unmanaged	Managed	Total
XAVEH2O	I	-1.1%	-0.1%	-0.5%	0.68	1.09	0.92
	II						
XMAXH2O	I	-1.5%	-0.4%	-0.9%	1.24	2.05	1.71
	II	-4.5%	2.1%	-0.7%	1.65	0.87	1.20
N>16.0	I	NA[a]	NA	NA	9.65	111.02	68.14
	II	NA	NA	NA	38.84	77.45	61.11

[a] MPE statistic cannot be calculated because of observations with a value of zero.

DISCUSSION

There were five objectives for this study identified in the INTRODUCTION. Of these, the first two: (1) measure the water and air temperature regimes of streams draining unmanaged and managed sub-basins; and (2) characterize the age and species composition of the riparian vegetation at each study site, were accomplished and are documented in the RESULTS and in appendix tables. The remaining three objectives require further discussion in order to reach conclusions.

<u>Objective 3:</u> <u>Compare water and air temperatures of streams in unmanaged and managed sub-basins</u>

No significant differences in mean air temperatures were found between the unmanaged and managed groups. The largest difference between the two groups for a mean air temperature variable was 0.04° C for XMAXAIR. However, the 18 air temperature probes used in the study were all placed in 100% shaded locations in the riparian zones of the temperature reaches. The air temperatures in other parts of each sub-basin, and for the sub-basins as a whole, were not measured and might be different for the two groups.

Significant differences were found between the group means of all five variables used to characterize the water temperatures of the study sites. For all water temperature variables, the managed group had significantly ($P < 0.05$) **warmer** temperatures than the unmanaged group. These significant differences between group means persisted even when the influences of environmental variables that may affect water temperatures, such as stream elevation and amount of shade in the temperature reach, were removed.

None of the unmanaged sites had mean daily high water temperatures (XMAXH2O) or mean daily water temperatures (XAVEH2O) that exceeded the 16.0° C standard established for Class AA waters in Washington. However, 7 of the 15 managed sites had mean daily high water temperature ≥ 16.0° C and one managed site had an average daily water temperature in excess of 16.0° C. On average, the unmanaged sites had peak stream temperatures in excess of 16.0° C during 1.8 days of the 39-day monitoring period (range 0 to 11). In contrast, the managed sites had peak stream temperatures in excess of 16.0° C an average of 18.3 days during the 39-day monitoring period (range 0 to 36).

We believe these data present convincing evidence that the stream temperatures of the managed group were significantly warmer than the unmanaged group and this difference was due primarily to the effects of logging in the managed sub-basins. Similar results have been demonstrated previously by Gray and Edington (1969), Brown and Krygier (1970), Beschta and Taylor (1988), and Holtby (1988). The ANOVAWC demonstrated that even after the influences of SHADE and ELEV were controlled for concurrently, the stream temperatures of the managed group remained significantly warmer than the unmanaged group. Only after controlling for the differences in the CLASS-1 variable did the difference in mean stream temperatures between the two groups become non-significant. This is very important because it demonstrates that **managing for stream temperature at the reach level will not be successful unless logging activity throughout a basin is considered**.

The difference in stream temperatures between the unmanaged and managed groups was demonstrated to be directly related to the CLASS-1 independent variable. The CLASS-1 variable is the percentage of forest within a study site's sub-basin that is classified as late seral stage. The CLASS-1 variable is largely a reflection of the degree of logging that has occurred in a sub-basin, although fire and windthrow are factors, also. For unmanaged sites the CLASS-1 variable ranged from 62% to 100% (mean = 89%) while for managed sites this variable ranged from 0.6% to 92% (mean = 29%). Variables identified as important influences on stream temperature relationships in an earlier study of streams in Washington State by Sullivan et al. (1990), stream elevation and amount of stream shading, did not explain the differences in stream temperatures observed in this study. This may be due to the relatively low elevations of the sites in this study (range from 13 m to 256 m).

Objective 4: Determine if significant relationships between the independent and dependent variables exist

The variable which best explained the differences in mean temperatures between the unmanaged and managed sites (CLASS-1) was also the best single variable to predict the three stream temperature variables examined: XAVEH2O, XMAXH2O, and N>16.0. CLASS-1 was the only independent variable for which a single regression line was appropriate for combined data from the two groups. Analysis-of-covariance indicated that separate regression equations were required for each group (unmanaged and managed) for all other independent variables examined. Generally, the slopes of the linear regressions were not significantly different between the groups but the intercepts for each group were significantly different for the other independent variables. The linear relationship between the CLASS-1 variable and the XAVEH2O and XMAXH2O dependent variables was very good and data from both unmanaged and managed sites are clustered near the line (Figure 10). Although the R^2 for the regression with the N>16.0 variable was comparable to that for the previous models, there was considerably more variation of the data around the regression line (Figure 10). For the N>16.0 variable, this model may not be adequate for predictive purposes.

The N>16.0 variable can be thought of as a dichotomous variable, either the stream temperature exceeds 16.0° C on a given day or it doesn't. We suggest that logit models (Agresti 1990) be examined for predictive purposes with this variable. The independent variables examined for the logit analysis could include those examined for this study plus one or more daily air temperature variables. Although no significant correlations between the mean air temperature variables and the mean water temperature variables were found in this study, on a daily scale air temperatures are more influential on water temperatures.

We feel that the CLASS-1 variable represents a surrogate for the **cumulative effects of logging activities** within a sub-basin. A cumulative effect would help explain the linear relationship between CLASS-1 and the stream temperature variables (Figure 10). The visual assessment of the riparian habitat conducted for this study indicated that harvest activities have altered stream shade by reducing the age of the riparian canopy and increasing the amount of deciduous vegetation adjacent to stream channels. In addition, harvest activities have substantially decreased the average age of the forest within the entire study area (Table 1). All of these factors are probably correlated to some degree with the CLASS-1 variable. Therefore, as the amount of late seral stage forest decreases in a sub-basin, the more impact all of these factors have on stream temperature. Other evidence of a cumulative effect can be seen in Figure 9. Sullivan et al. (1990) found high SHADE values and higher elevations to be associated with lower stream temperatures. In Figure 9, managed sites with high values (65-90%) for SHADE generally have warmer mean water temperatures (XAVEH2O and XMAXH2O) than unmanaged sites with similar SHADE values. Similarly, managed sites at low elevations (ELEV < 100 m) have higher mean values for XAVEH2O and XMAXH2O than unmanaged sites at similar or greater elevations. Studies in Oregon (Beschta and Taylor 1988) and British Columbia (Holtby 1988) have found significant relationships between the percentage of a watershed harvested and the maximum stream temperatures during the summer.

<u>Objective 5:</u> <u>Determine if study sites exceed stream temperature criteria for class AA waters</u>

Currently, only a single occurrence of a stream temperature above the 16.0° C standard is required for a stream to violate the State of Washington's water quality standards (WAC 173-201A). Using this criterion, four of the unmanaged sites exceeded the standard for Class AA waters. Apparently, it is not uncommon for streams in the study area which are not impacted by logging activities to naturally exceed the standard. Therefore, the utility of the current standard is in question. Water temperature standards which recognize that stream temperatures sometimes naturally exceed the 16.0° C temperature criterion are needed. For example, the criterion could be established as a maximum allowable number of days stream temperatures exceed 16.0° C during any consecutive 30-day or 60-day period. The maximum allowable number of days could be established by long-term (5 to 10 year) studies monitoring streams that have not been impacted by logging. For the coastal streams in this study, the N>16.0 variable was highly correlated with other stream temperature variables. Therefore, managing for the N>16.0 variable would probably control the XAVEH2O and XMAXH2O variables.

CONCLUSIONS

The managed (logged) creeks in this study, on average, exceeded the Washington State maximum water temperature criterion of 16.0° C ten times more often than the unmanaged creeks during the period July 9 through August 16, 1992. Since the managed sites of this study are representative of low-elevation (less than 260 m above sea level) managed sites in the area, it is reasonable to assume the majority of the low-elevation, managed stream channels on the Western Olympic Peninsula are not in compliance with the provisions of the Clean Water Act or Washington State Administrative Code. The Washington State standard specifying a single occurrence of a stream temperature greater than 16.0° C is probably too restrictive since the temperatures of unmanaged streams were found to exceed this criterion on some occasions. A more liberal standard defined as the maximum allowable number of days that water temperatures can exceed 16.0° C during a 30-day or 60-day period would provide a more realistic regulation.

The proportion of a sub-basin classified as late seral stage forest was the single, most influential independent variable for explaining the stream temperatures measured at the study sites. Environmental factors such as stream elevation and amount of stream shading did not influence stream temperatures to the degree that the proportion of the sub-basin classified as mature forest. We feel this provides strong evidence that stream temperatures cannot be successfully managed at the reach level unless basin-wide harvest activities are carefully considered.

We recommend that stream temperature studies similar to this one be repeated to verify the importance of the CLASS-1 variable. Although SHADE and ELEV were not as important to the stream temperatures relationships in this study as the CLASS-1 variable, they may still be important variables. The sample sizes for this study were relatively small, so the tests used to compare group means and the regressions conducted generally had low power (< 0.50). With an increased number of study sites, these variables might become more influential. Other factors not investigated in this study that might have an effect on stream temperatures are residual pool depths, amount of large woody debris, riparian width and height, thermal insulation of alders versus conifers, ground water influence, and relative humidity.

ACKNOWLEDGEMENTS

The authors would like to express gratitude to the following people for assisting in data collection and synthesis, consultation, and encouragement: Stacy Rosales, Monty Arthur, Jim Jorgensen, Rosetta Leitka, Jerry Horejsi, Paul Conrecode, and Ed Rashin. Dave Johnson, Washington Department of Natural Resources, supplied the information from the Olympic Region geographic information system. Dave Schuett-Hames, Northwest Indian Fisheries Commission; Dr. Marianna Alexandersdottir, Washington Department of Fish and Wildlife; and Mike McHenry, Lower Elwha S'Klallam Tribe, reviewed drafts of this report and provided many helpful comments.

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APPENDIX TABLES

Appendix Table 1. List of values for all independent variables for the 1992 field season. The variables are defined in the Methods section of the report.

Site Name	M/U[a]	BASIZE	ELEV	GRADE	CLENGTH	SHADE	LOWFLOW	CLASS-1	BFWID	BFDEP	BFW/D	WETWID	WETDEP	WETW/D
TWIN	U	7.51	146	2.0	4,390	63.4	0.08	100.0	12.16	0.43	28.28	5.09	0.08	63.63
CAMP	U	10.88	256	10.0	5,976	58.0	0.14	97.4	13.05	0.91	14.34	5.95	0.34	17.50
MATSON	U	3.11	241	14.4	3,476	68.9	0.01	99.8	10.09	0.58	17.40	4.15	0.13	31.92
JACKSON	U	13.73	180	8.0	7,104	70.8	0.18	97.3	13.78	0.73	18.88	7.23	0.19	38.05
OLLALIE	U	3.11	122	3.4	3,628	79.5	0.02	96.1	7.56	0.30	25.20	3.14	0.08	39.25
HADES	U	8.03	134	8.0	6,098	77.0	0.08	81.8	9.21	0.91	10.12	4.60	0.21	21.90
INDIAN	U	1.81	131	12.5	3,201	77.4	0.01	88.5	6.19	0.49	12.63	3.05	0.15	20.33
MOSQUITO	U	2.33	122	13.1	2,896	83.5	0.01	61.7	4.94	0.55	8.98	2.41	0.16	15.06
KACKWA	U	3.89	104	2.5	4,024	76.8	0.01	67.0	9.09	0.61	14.90	3.45	0.13	26.54
COAL	U	3.89	104	4.9	3,659	70.7		100.0	9.51	0.58	16.40	2.68	0.09	29.78
HARLOW	U	19.17	155	1.5	9,695	65.4		92.4	16.31	0.37	44.08			
Sample Size		11	11	11	11	11	9	11	11	11	11	10	10	10
Mean		7.04	154	7.3	4,922	71.9	0.06	89.3	10.17	0.59	19.20	4.18	0.16	30.40
Standard Error		1.67	15.6	1.4	629	2.3	0.02	4.1	1.03	0.06	3.05	0.49	0.02	4.51
Coef. of Var.		23.8%	10.1%	19.6%	12.8%	3.2%	35.0%	4.6%	10.1%	10.2%	15.9%	11.8%	16.0%	14.9%
ROCK	M	2.59	98	8.0	3,140	88.1	0.01	91.5	6.34	0.37	17.14	2.20	0.12	18.33
MAPLE	M	16.84	114	2.0	8,689	74.1	0.14	20.0	14.66	0.34	43.12	7.07	0.19	37.21
WINFIELD	M	30.83	66	1.0	10,061	70.7	0.19	11.4	20.98	0.64	32.78	8.05	0.23	35.00
NOLAN	M	26.43	34	1.1	10,366	67.8	0.08	6.7	22.90	0.55	41.64	5.91	0.19	31.11
FISHER	M	1.30	183	20.0	2,439	37.4	0.01	0.6	8.96	0.43	20.84	2.32	0.06	38.67
HOOT	M	1.55	256	31.1	2,073	63.7	0.02	34.7	5.61	0.55	10.20	2.32	0.09	25.78
OWL	M	24.36	107	1.1	11,281	42.9	0.38	28.0	18.51	0.64	28.92	11.59	0.18	64.39
LINE	M	2.59	256	12.0	2,531	45.0	0.04	27.0	7.44	0.58	12.83	3.72	0.12	31.00
ALDER	M	12.44	73	1.8	7,622	73.1	0.03	32.2	13.57	0.37	36.68	4.45	0.12	37.08
CANYON	M	3.11	122	6.1	3,963	69.0	0.06	60.4	11.34	0.43	26.37	3.29	0.15	21.93
ANDERSON	M	8.81	41	3.3	3,506	89.6	0.04	2.6	10.82	0.37	29.24	4.15	0.15	27.67
TOWER	M	3.63	104	8.9	3,354	79.5	0.05	65.4	9.42	0.58	16.24	3.29	0.12	27.42
WILLOUGHBY	M	8.03	79	3.8	4,573	71.3	0.06	30.9	12.01	0.43	27.93	3.93	0.12	32.75
SPLIT	M	1.81	171	16.9	2,652	23.9	0.02	7.1	9.51	0.67	14.19	3.41	0.24	14.21
KALALOCH	M	24.87	13	0.5	8,018	76.7	0.10	17.9	13.93	0.52	26.79	8.81	0.23	38.30
Sample Size		15	15	15	15	15	15	15	15	15	15	15	15	15
Mean		11.28	115	7.8	5,618	64.9	0.08	29.1	12.40	0.50	25.66	4.97	0.15	32.06
Standard Error		2.74	19.0	2.3	857	4.9	0.02	6.6	1.33	0.03	2.66	0.71	0.01	2.99
Coef. of Var.		24.3%	16.6%	29.1%	15.2%	7.6%	30.5%	22.8%	10.7%	5.8%	10.4%	14.4%	9.1%	9.3%

[a] M/U = U for unmanaged sub-basins and M for managed sub-basins.

Appendix Table 2. List of values for all dependent variables for the 1992 field season. The variables are defined in the Methods section of the report. All temperatures are in ^{O}C.

Site Name	M/U[a]	XAVEH2O	XMEDH2O	XMINH2O	XMAXH2O	N>16.0	XAVEAIR	XMEDAIR	XMINAIR	XMAXAIR
TWIN	U	9.2	9.0	8.8	9.9	0	15.9	14.6	11.7	21.4
CAMP	U	13.1	13.1	12.5	13.7	0	15.3	14.4	12.3	19.4
MATSON	U	13.3	13.3	12.9	13.7	0	15.8	14.9	12.1	20.7
JACKSON	U	12.7	12.6	12.1	13.3	0	15.9	15.1	12.2	20.6
OLLALIE	U	13.3	13.2	12.7	14.0	0				
HADES	U	12.7	12.6	12.1	13.4	0				
INDIAN	U	13.5	13.4	13.1	14.0	1				
MOSQUITO	U	13.7	13.5	13.1	14.3	2				
KACKWA	U	14.2	14.2	13.5	15.3	11	16.0	14.9	12.3	22.0
COAL	U	12.2	11.9	11.5	13.3	0	16.9	15.6	12.9	22.0
HARLOW	U	12.9	12.8	12.0	14.4	6				
Sample Size		11	11	11	11	11	6	6	6	6
Mean		12.8	12.7	12.2	13.6	1.8	16.0	14.9	12.2	21.0
Standard Error		0.4	0.4	0.4	0.4	1.1	0.2	0.2	0.2	0.4
Coef. of Variation		3.1%	3.2%	3.1%	3.0%	58.8%	1.3%	1.1%	1.3%	1.9%
ROCK	M	14.1	13.9	13.1	15.7	17	16.3	14.9	12.3	22.2
MAPLE	M	13.9	13.7	13.0	15.0	8	15.7	14.4	11.4	21.0
WINFIELD	M	15.8	15.6	14.7	17.2	30	15.7	14.9	12.4	19.7
NOLAN	M	15.8	15.6	14.7	17.4	33	15.5	14.9	11.9	19.5
FISHER	M	16.0	15.8	14.2	18.1	36	16.2	15.1	12.3	21.1
HOOT	M	11.8	11.6	11.3	12.4	0				
OWL	M	14.6	14.4	13.4	16.5	23	17.2	16.6	14.0	21.2
LINE	M	14.6	14.4	13.8	15.7	17	15.9	14.6	11.9	21.3
ALDER	M	15.7	15.6	14.7	16.7	28	15.7	14.9	12.4	21.7
CANYON	M	13.9	13.9	13.4	14.5	1	16.3	15.3	12.7	21.4
ANDERSON	M	14.5	14.4	13.7	15.4	11	15.2	14.4	11.5	20.0
TOWER	M	13.8	13.7	13.2	14.5	2	16.1	15.3	12.7	20.2
WILLOUGHBY	M	15.0	14.8	14.0	16.6	23				
SPLIT	M	16.7	16.2	14.5	19.4	36				
KALALOCH	M	14.9	14.9	14.3	15.6	10	14.6	14.6	11.0	17.9
Sample Size		15	15	15	15	15	12	12	12	12
Mean		14.8	14.6	13.7	16.1	18.3	15.9	15.0	12.2	20.6
Standard Error		0.3	0.3	0.2	0.4	3.3	0.2	0.2	0.2	0.3
Coef. of Variation		2.1%	2.0%	1.7%	2.7%	17.9%	1.2%	1.1%	1.8%	1.7%

[a] M/U = U for unmanaged sub-basins and M for managed sub-basins.

Appendix Table 3. Pearson's correlation coefficient (r) and Spearman's correlation coefficient (ρ) for all independent and dependent variable pairs[a].

Variable	BASIZE		ELEV		GRADE		CLENGTH	
	r	ρ	r	ρ	r	ρ	r	ρ
Independent Variables								
BASIZE	-	-	**-0.48***	**-0.52****	**-0.61****	**-0.86****	**0.95****	**0.95****
ELEV	**-0.48***	**-0.52****	-	-	**0.70****	**0.70****	**-0.41***	**-0.45****
GRADE	**-0.61****	**-0.86****	**0.70****	**0.70****	-	-	**-0.64****	**-0.86****
CLENGTH	**0.95****	**0.95****	**-0.41***	**-0.45****	**-0.64****	**-0.86****	-	-
SHADE	0.02	0.02	**-0.48***	**-0.53****	-0.35	-0.13	-0.01	-0.04
LOWFLOW	**0.72****	**0.82****	-0.13	-0.20	**-0.41***	**-0.60****	**0.79****	**0.79****
CLASS-1	-0.35	-0.12	0.32	**0.36***	-0.03	0.15	-0.20	-0.03
BFWIDTH	**0.92****	**0.90****	**-0.40***	**-0.36***	**-0.61****	**-0.76****	**0.91****	**0.89****
BFDEPTH	0.09	0.08	0.35	0.29	0.20	0.23	0.10	0.06
BFW/D	**0.69****	**0.70****	**-0.50****	**-0.50****	**-0.66****	**-0.78****	**0.72****	**0.69****
WETWIDTH	**0.87****	**0.88****	-0.27	-0.23	**-0.53****	**-0.66****	**0.88****	**0.85****
WETDEPTH	**0.51****	**0.51****	-0.02	-0.13	-0.18	-0.21	**0.50***	**0.49****
WETW/D	**0.44***	**0.45***	-0.15	-0.18	**-0.41***	**-0.55****	**0.47***	**0.46****
Dependent Variables								
XAVEH2O	0.26	0.13	-0.34	**-0.45****	-0.07	-0.22	0.19	0.08
XMEDH2O	0.26	0.12	-0.35	**-0.46****	-0.09	-0.21	0.20	0.08
XMINH2O	0.27	0.17	-0.38	**-0.53****	-0.12	-0.25	0.20	0.11
XMAXH2O	0.26	0.15	-0.31	**-0.45***	-0.06	-0.25	0.20	0.12
N>16.0	0.33	0.14	-0.29	**-0.43***	-0.08	-0.25	0.27	0.10
XAVEAIR	-0.29	**-0.53***	0.18	0.29	0.15	0.31	-0.11	-0.34
XMEDAIR	0.09	-0.18	-0.09	0.01	-0.05	0.09	0.23	-0.06
XMINAIR	-0.06	-0.16	0.12	0.06	0.07	0.09	0.12	-0.03
XMAXAIR	**-0.60****	**-0.55****	0.24	0.16	0.16	0.17	-0.41	-0.36

[a] Significance levels: * = $0.01 < P \leq 0.05$; ** = $P \leq 0.01$ (both two-tailed tests).

Appendix Table 3. Pearson's correlation coefficient (r) and Spearman's correlation coefficient (ρ) for all independent and dependent variable pairs[a] (continued).

Variable	SHADE		LOWFLOW		CLASS-1		BFWIDTH	
	r	ρ	r	ρ	r	ρ	r	ρ
Independent Variables								
BASIZE	0.02	0.02	**0.72****	**0.82****	-0.35	-0.12	**0.92****	**0.90****
ELEV	**-0.48***	**-0.53****	-0.13	-0.20	0.32	**0.36***	**-0.40***	**-0.36***
GRADE	-0.35	-0.13	**-0.41***	**-0.60****	-0.03	0.15	**-0.61****	**-0.76****
CLENGTH	-0.01	-0.04	**0.79****	**0.79****	-0.20	-0.03	**0.91****	**0.89****
SHADE	-	-	-0.23	-0.26	0.34	0.13	-0.13	-0.29
LOWFLOW	-0.23	-0.26	-	-	-0.13	-0.12	**0.68****	**0.82****
CLASS-1	0.34	0.13	-0.13	-0.12	-	-	-0.33	-0.19
BFWIDTH	-0.13	-0.29	**0.68****	**0.82****	-0.33	-0.19	-	-
BFDEPTH	-0.26	**-0.33***	0.34	0.31	0.16	0.11	0.08	0.05
BFW/D	0.07	-0.08	0.36	**0.49****	-0.32	-0.27	**0.77****	**0.80****
WETWIDTH	-0.15	-0.21	**0.91****	**0.86****	-0.25	-0.16	**0.78****	**0.87****
WETDEPTH	-0.13	-0.04	**0.45***	**0.53****	-0.11	-0.25	**0.44***	**0.49****
WETW/D	-0.19	-0.21	**0.57****	**0.40***	-0.08	-0.12	**0.46***	**0.51****
Dependent Variables								
XAVEH2O	-0.28	-0.13	0.01	-0.01	**-0.73****	**-0.83****	0.27	0.23
XMEDH2O	-0.25	-0.12	0.01	-0.02	**-0.71****	**-0.83****	0.28	0.23
XMINH2O	-0.12	-0.03	-0.02	-0.01	**-0.68****	**-0.79****	0.26	0.24
XMAXH2O	**-0.40***	-0.15	0.05	-0.02	**-0.73****	**-0.80****	0.30	0.26
N>16.0	**-0.50****	-0.19	0.11	-0.04	**-0.75****	**-0.80****	**0.42***	0.25
XAVEAIR	-0.35	-0.20	0.33	-0.21	0.28	0.35	-0.16	**-0.46***
XMEDAIR	-0.35	-0.17	**0.58***	-0.01	0.06	0.17	0.16	-0.09
XMINAIR	-0.36	-0.16	**0.49***	0.03	0.20	0.25	0.08	-0.12
XMAXAIR	-0.09	0.05	-0.21	**-0.51***	0.35	**0.41***	**-0.49***	**-0.55****

[a] Significance levels: * = $0.01 < P \leq 0.05$; ** = $P \leq 0.01$ (both two-tailed tests).

Appendix Table 3. Pearson's correlation coefficient (r) and Spearman's correlation coefficient (ρ) for all independent and dependent variable pairs[a] (continued).

Variable	BFDEPTH		BFW/D		WETWIDTH		WETDEPTH	
	r	ρ	r	ρ	r	ρ	r	ρ
Independent Variables								
BASIZE	0.09	0.08	**0.69****	**0.70****	**0.87****	**0.88****	**0.51****	**0.51****
ELEV	0.35	0.29	**-0.50****	**-0.50****	-0.27	-0.23	-0.02	-0.13
GRADE	0.20	0.23	**-0.66****	**-0.78****	**-0.53****	**-0.66****	-0.18	-0.21
CLENGTH	0.10	0.06	**0.72****	**0.69****	**0.88****	**0.85****	**0.50***	**0.49****
SHADE	-0.26	**-0.33***	0.07	-0.08	-0.15	-0.21	-0.13	-0.04
LOWFLOW	0.34	0.31	0.36	**0.49****	**0.91****	**0.86****	**0.45***	**0.53****
CLASS-1	0.16	0.11	-0.32	-0.27	-0.25	-0.16	-0.11	-0.25
BFWIDTH	0.08	0.05	**0.77****	**0.80****	**0.78****	**0.87****	**0.44***	**0.49****
BFDEPTH	-	-	**-0.52****	**-0.50****	0.27	0.31	**0.64****	**0.53****
BFW/D	**-0.52****	**-0.50****	-	-	**0.50***	**0.55****	0.04	0.03
WETWIDTH	0.27	0.31	**0.50***	**0.55****	-	-	**0.54****	**0.62****
WETDEPTH	**0.64****	**0.53****	0.04	0.03	**0.54****	**0.62****	-	-
WETW/D	-0.23	-0.28	**0.51****	**0.68****	**0.59****	**0.47****	-0.28	-0.28
Dependent Variables								
XAVEH2O	-0.06	-0.07	0.21	0.31	0.12	0.15	0.25	0.22
XMEDH2O	-0.06	-0.07	0.21	0.31	0.13	0.15	0.26	0.22
XMINH2O	-0.06	-0.03	0.19	0.28	0.13	0.18	0.27	0.24
XMAXH2O	-0.07	-0.12	0.24	**0.37***	0.13	0.10	0.21	0.18
N>16.0	-0.12	-0.12	0.34	**0.37***	0.17	0.07	0.07	0.13
XAVEAIR	0.01	0.10	-0.23	-0.35	-0.12	**-0.51***	**-0.48***	**-0.58****
XMEDAIR	0.16	0.29	-0.09	-0.13	0.26	-0.27	-0.22	-0.31
XMINAIR	0.31	0.36	-0.22	-0.23	0.10	-0.27	-0.11	-0.22
XMAXAIR	-0.33	-0.29	-0.22	-0.22	**-0.49***	**-0.59****	**-0.67****	**-0.71****

[a] Significance levels: * = 0.01 < $P \leq 0.05$; ** is $P \leq 0.01$ (both two-tailed tests).

Appendix Table 3. Pearson's correlation coefficient (r) and Spearman's correlation coefficient (ρ) for all independent and dependent variable pairs[a] (continued).

Variable	WETW/D		XAVEH2O		XMEDH2O		XMINH2O	
	r	ρ	r	ρ	r	ρ	r	ρ
Independent Variables								
BASIZE	**0.44***	**0.45***	0.26	0.13	0.26	0.12	0.27	0.17
ELEV	-0.15	-0.18	-0.34	**-0.45****	-0.35	**-0.46****	-0.38	**-0.53****
GRADE	**-0.41***	**-0.55****	-0.07	-0.22	-0.09	-0.21	-0.12	-0.25
CLENGTH	**0.47***	**0.46****	0.19	0.08	0.20	0.08	0.20	0.11
SHADE	-0.19	-0.21	-0.28	-0.13	-0.25	-0.12	-0.12	-0.03
LOWFLOW	**0.57****	**0.40***	0.01	-0.01	0.01	-0.02	-0.02	-0.01
CLASS-1	-0.08	-0.12	**-0.73****	**-0.83****	**-0.71****	**-0.83****	**-0.68****	**-0.79****
BFWIDTH	**0.46***	**0.51****	0.27	0.23	0.28	0.23	0.26	0.24
BFDEPTH	-0.23	-0.28	-0.06	-0.07	-0.06	-0.07	-0.06	-0.03
BFW/D	**0.51****	**0.68****	0.21	0.31	0.21	0.31	0.19	0.28
WETWIDTH	**0.59****	**0.47****	0.12	0.15	0.13	0.15	0.13	0.18
WETDEPTH	-0.28	-0.28	0.25	0.22	0.26	0.22	0.27	0.24
WETW/D	-	-	-0.23	0.12	-0.24	0.11	-0.28	0.08
Dependent Variables								
XAVEH2O	-0.23	0.12	-	-	**0.99****	**0.99****	**0.97****	**0.97****
XMEDH2O	-0.24	0.11	**0.99****	**0.99****	-	-	**0.98****	**0.98****
XMINH2O	-0.28	0.08	**0.97****	**0.97****	**0.98****	**0.98****	-	-
XMAXH2O	-0.16	0.09	**0.97****	**0.98****	**0.96****	**0.97****	**0.90****	**0.92****
N>16.0	0.11	0.09	**0.82****	**0.94****	**0.79****	**0.93****	**0.71****	**0.87****
XAVEAIR	0.25	-0.03	-0.17	-0.22	-0.20	-0.23	-0.25	-0.34
XMEDAIR	0.38	0.09	0.07	-0.01	0.05	0.01	0.02	-0.06
XMINAIR	0.17	-0.21	0.05	-0.03	0.04	-0.01	0.01	-0.04
XMAXAIR	0.05	-0.12	-0.25	-0.21	-0.27	-0.20	-0.31	-0.25

[a] Significance levels: * = $0.01 < P \le 0.05$; ** = $P \le 0.01$ (both two-tailed tests).

Appendix Table 3. Pearson's correlation coefficient (r) and Spearman's correlation coefficient (ρ) for all independent and dependent variable pairs[a] (continued).

Variable	XMAXH2O		N>16.0		XAVEAIR		XMEDAIR	
	r	ρ	r	ρ	r	ρ	r	ρ
Independent Variables								
BASIZE	0.26	0.15	0.33	0.14	-0.29	**-0.53***	0.09	-0.18
ELEV	-0.31	**-0.45***	-0.29	**-0.43***	0.18	0.29	-0.09	0.01
GRADE	-0.06	-0.25	-0.08	-0.25	0.15	0.31	-0.05	0.09
CLENGTH	0.20	0.12	0.27	0.10	-0.11	-0.34	0.23	-0.06
SHADE	**-0.40***	-0.15	**-0.50****	-0.19	-0.35	-0.20	-0.35	-0.17
LOWFLOW	0.05	-0.02	0.11	-0.04	0.33	-0.21	**0.58***	-0.01
CLASS-1	**-0.73****	**-0.80****	**-0.75****	**-0.80****	0.28	0.35	0.06	0.17
BFWIDTH	0.30	0.26	**0.42***	0.25	-0.16	**-0.46***	0.16	-0.09
BFDEPTH	-0.07	-0.12	-0.12	-0.12	0.01	0.10	0.16	0.29
BFW/D	0.24	**0.37***	0.34	**0.37***	-0.23	-0.35	-0.09	-0.13
WETWIDTH	0.13	0.10	0.17	0.07	-0.12	**-0.51***	0.26	-0.27
WETDEPTH	0.21	0.18	0.07	0.13	**-0.48***	**-0.58****	-0.22	-0.31
WETW/D	-0.16	0.09	0.11	0.09	0.25	-0.03	0.38	0.09
Dependent Variables								
XAVEH2O	**0.97****	**0.98****	**0.82****	**0.94****	-0.17	-0.22	0.07	-0.01
XMEDH2O	**0.96****	**0.97****	**0.79****	**0.93****	-0.20	-0.23	0.05	0.01
XMINH2O	**0.90****	**0.92****	**0.71****	**0.87****	-0.25	-0.34	0.02	-0.06
XMAXH2O	-	-	**0.90****	**0.98****	-0.04	-0.10	0.16	0.04
N>16.0	**0.90****	**0.98****	-	-	0.02	-0.03	0.13	0.07
XAVEAIR	-0.04	-0.10	0.02	-0.03	-	-	**0.82****	**0.79****
XMEDAIR	0.16	0.04	0.13	0.07	**0.82****	**0.79****	-	-
XMINAIR	0.13	0.06	0.10	0.08	**0.85****	**0.69****	**0.89****	**0.80****
XMAXAIR	-0.15	-0.10	-0.03	-0.01	**0.74****	**0.71****	0.32	0.34

[a] Significance levels: * = $0.01 < P \leq 0.05$; ** = *P* £ 0.01 (both two-tailed tests).

Appendix Table 3. Pearson's correlation coefficient (r) and Spearman's correlation coefficient (ρ) for all independent and dependent variable pairs[a] (continued).

Variable	XMINAIR		XMAXAIR	
	r	ρ	r	ρ
Independent Variables				
BASIZE	-0.06	-0.16	**-0.60****	**-0.55****
ELEV	0.12	0.06	0.24	0.16
GRADE	0.07	0.09	0.16	0.17
CLENGTH	0.12	-0.03	-0.41	-0.36
SHADE	-0.36	-0.16	-0.09	0.05
LOWFLOW	**0.49***	0.03	-0.21	**-0.51***
CLASS-1	0.20	0.25	0.35	**0.41***
BFWIDTH	0.08	-0.12	**-0.49***	**-0.55****
BFDEPTH	0.31	0.36	-0.33	-0.29
BFW/D	-0.22	-0.23	-0.22	-0.22
WETWIDTH	0.10	-0.27	**-0.49***	**-0.59****
WETDEPTH	-0.11	-0.22	**-0.67****	**-0.71****
WETW/D	0.17	-0.21	0.05	-0.12
Dependent Variables				
XAVEH2O	0.05	-0.03	-0.25	-0.21
XMEDH2O	0.04	-0.01	-0.27	-0.20
XMINH2O	0.01	-0.04	-0.31	-0.25
XMAXH2O	0.13	0.06	-0.15	-0.10
N>16.0	0.10	0.08	-0.03	-0.01
XAVEAIR	**0.85****	**0.69****	**0.74****	**0.71****
XMEDAIR	**0.89****	**0.80****	0.32	0.34
XMINAIR	-	-	0.44	0.38
XMAXAIR	0.44	0.38	-	-

[a] Significance levels: * = $0.01 < P \leq 0.05$; ** = $P \leq 0.01$ (both two-tailed tests).