The ecoprovincial average diurnal fluctuations for each watershed area class were strikingly similar. Class 6 did not have sites represented in the CSP and class 1 had no sites in the SSP, so no comparisons could be made. Class 3 showed the largest difference between the CSP and SSP, with the former having a mean diurnal flux of 3.1°C and the latter being 4.2°C. Class 4 had mean diurnal fluxes of 4.3°C and 4.5°C for the CSP and SSP, respectively. The CSP class 5 had a mean diurnal flux of 3.4°C and the SSP was 4.0°C.

Distance from Watershed Divide and Stream Temperature Across the Region

The relationship between temperature and distance from the watershed divide was similar to that observed for watershed area. This similarity was expected given the strong correlation between watershed area and distance from the watershed divide shown in Figure 7.3.

Daily Maximum and Distance from Divide

Figure 7.11-A presents the relationship between the highest 1998 daily maximum stream temperature (XY1DX) and the $\log_{10}$ of the distance from the watershed divide. Divide distances were grouped into classes and XY1DX class averages were plotted in bar chart form (Figure 7.11-B). The XY1DX increased from the 18.2°C in the 1000 to 10,000 m distance from divide class (class 1) to 27.3°C in class 4. Class 5 and 6 divide distance sites exhibited about a 2°C decrease from the class 4 average XY1DX.

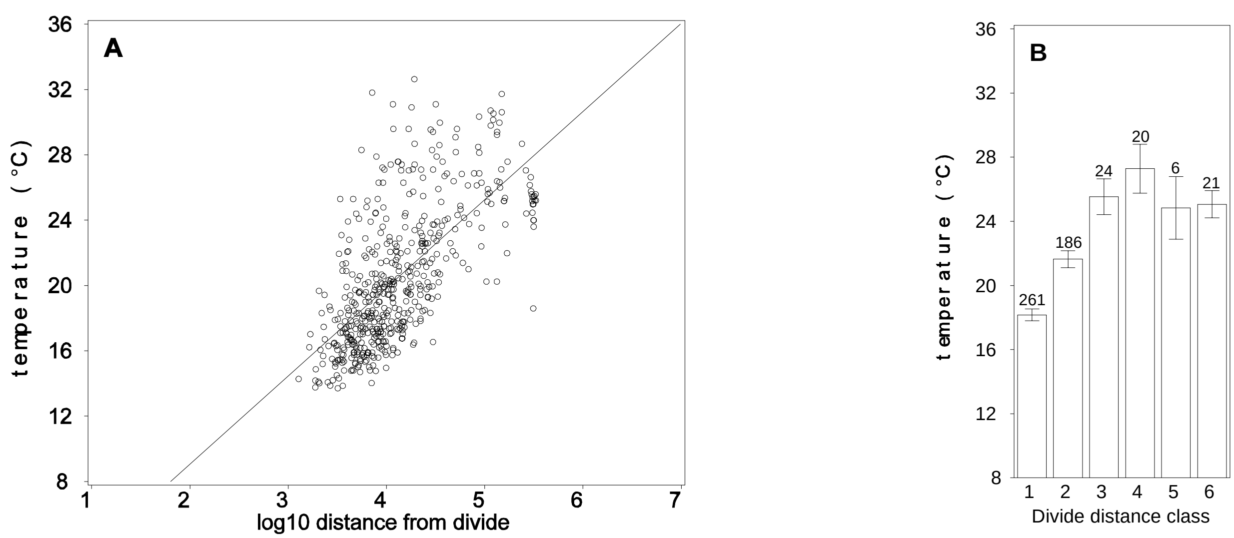
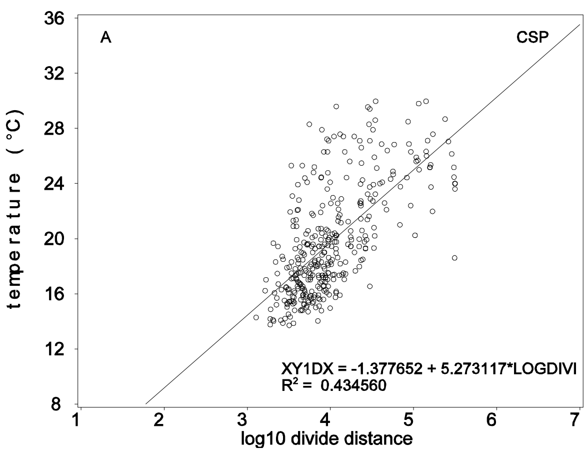
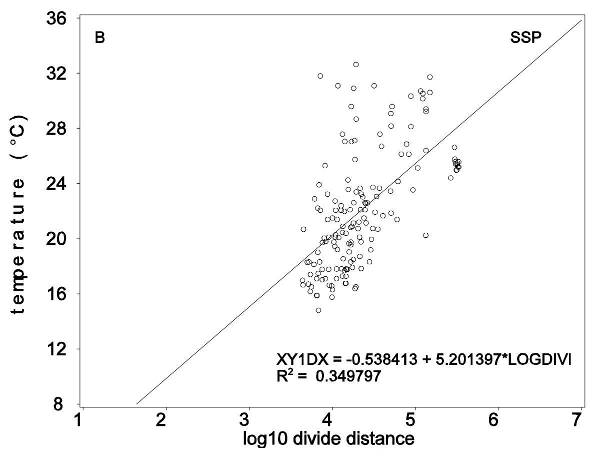


Figure 7.11. Relationship between the highest 1998 daily maximum stream temperature (XY1DX) and log distance from the watershed divide (logdivi). Scatter plot (A) with linear regression equation: XY1DX = -1.727626 + 5.396833*logdivi, R^2 = 0.441697. Bar chart (B) with divide distance classes: (1) 1000 - 10,000 m, (2) 10,001 - 50,000 m, (3) 50,001 - 100,000 m, (4) 100,001 - 150,000 m, (5) 150,001 - 200,000 m, and (6) greater than 200,000 m. Error bars represent ± 2 standard deviations. Above each error bar is the number of sites in the class.

Similar to the watershed area relationships, 1998 stream temperature monitoring sites were separated into two ecoprovinces. The CSP and SSP XY1DX values showed a bell-shaped (normal) distribution. No sites fell into class 5 in the SSP. For equivalent divide distance classes the average XY1DX was about 1°C higher in the SSP than in the CSP. The CSP XY1DX values (Figure 7.12-A) were more tightly clustered around the regression line than those for the SSP (Figure 7.12-B). The greater fit is expressed by the higher R^2 value for the CSP. The potential influence of air temperature is manifested in the distribution of the XY1DX values versus divide distance classes (Figure 7.11-C). Streams originating in the upper reaches of the watershed (class 1 divide distance) start out at approximately ground water temperature. As water moves down through the watershed, it tends to come into equilibrium with air temperature. The sites in the class 2 - 4 divide distances are exposed to warmer air temperatures in the SSP and the interior portions of the CSP. As SSP and CSP mainstems approach the coast and enter the ZCI, air temperatures decrease. Water temperature is coming into a new equilibrium with the lower air temperatures, as expressed by the decreasing XY1DX values in both the CSP and SSP for classes 5 and 6 divide distances (Figures 7.12-A and 7.12-B).





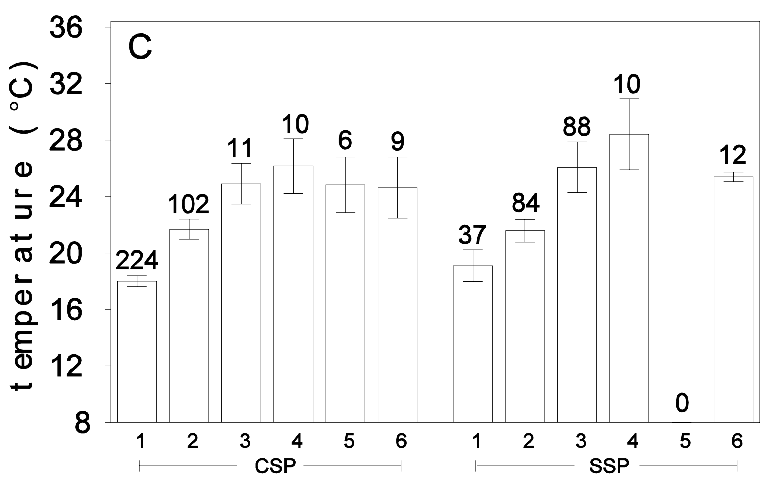


Figure 7.12. Highest 1998 daily maximum temperature (XY1DX) versus $\log_{10}$ distance from watershed divide for the (A) CSP and (B) SSP ecoprovinces. Bar chart (C) shows average of highest daily maximum temperature by divide distance classes: (1) 1000 - 10,000 m, (2) 10,001 - 50,000 m, (3) 50,001 - 100,000 m, (4) 100,001 - 150,000 m, (5) 150,001 - 200,000 m, and (6) greater than 200,000 m. Error bars represent ± 2 standard deviations. Above each error bar is the number of sites in the class.

To illustrate the change in air temperature as water masses approach the coast, the August PRISM-derived monthly average maximum air temperature was determined for each stream temperature monitoring site based on its location (UTM X- and Y-coordinates). Figure 7.13 shows the air temperature at each stream temperature monitoring site as a function of distance from the coast. The graph does not provide information on year-to-year variation in air temperatures, but does show the spatial variation in the CSP. The 30-year August monthly average maximum air temperature increases by approximately 15°C from zero to 60 km (37 mi) from the coast.

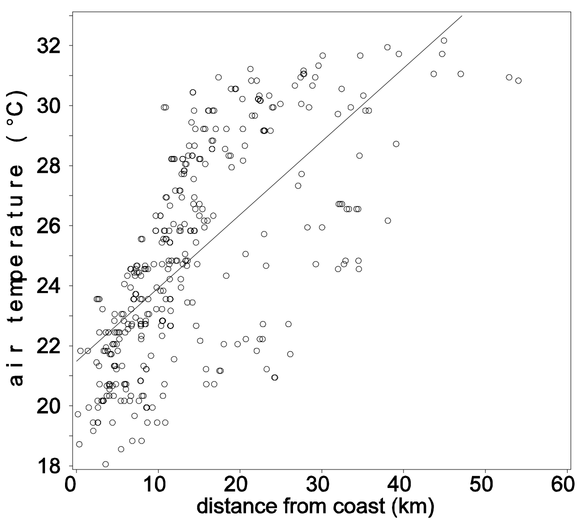


Figure 7.13. PRISM-derived air temperatures at each stream temperature monitoring site located in the CSP as a function of distance from the coast. Air temperature is the August 30-yr long-term monthly average maximum.

Seven-Day Moving Averages and Distance from Divide

Relationships between XYA7DA and XYA7DX versus distance from watershed divide are shown in Table 7.2. Similar to the watershed area relationships, the CSP sites showed a slightly higher R^2 value than the SSP sites for both temperature metrics with respect to distance from watershed divide.

Diurnal Fluctuation and Distance from Divide

The variation in diurnal stream temperature fluctuation in relation to distance from watershed divide was similar to that observed for watershed area (Figure 7.8). The distribution was not linear but suggestive of the bell-shaped curve shown in Figure 7.9. There was great variation in diurnal fluctuation values at any given divide distance, ranging from near zero to 13°C.

The CSP exhibited a smaller range in diurnal flux values than the SSP. The highest diurnal flux values were observed in the SSP at divide distances between 10 km and 30 km. The CSP had a greater proportion of sites with diurnal fluxes less than 2°C.

The scatter seen in the stream temperature values at different watershed areas and divide distances is not unexpected, given an understanding of the air temperature regimes experienced across basins in Northern California. Each basin has its own unique air temperature characteristics. Stratifying sites by ecoprovinces showed a slight reduction in the scatter. Examination of individual basins or HUCs shows an even greater reduction in the scatter. A much clearer picture emerges.

Watershed Position within Hydrologic Units

Spatial trends in water temperature were examined by USGS cataloging units (HUCs). Cataloging units are often referred to as fourth field watersheds, but more appropriately are geographic areas representing part or all of a surface drainage area, a combination of drainage areas, or a distinct hydrologic feature (Seaber et al., 1987). The term subbasin is suggested as a substitute for cataloging unit since this term has no common use or meaning and should be avoided (McCammon, 1994). Subbasins within the California coho salmon ESUs range from 40,000 ha to 533,000 ha with an average of 230,000 ha. For clarity the term

Table 7.2. Linear Regression Equations for Relationship between 1998 XYA7DA[1] and XYA7DX[2] versus Log_{10} Distance from Watershed Divide, Combined and by Ecoprovince.

Variable	Ecoprovince	No. of Sites	Slope	Intercept	R^2
XYA7DA	combined	518	4.85887	-2.12888	0.57558
XYA7DA	CSP	362	4.36730	-0.29115	0.55200
XYA7DA	SSP	156	5.57786	-4.94992	0.54158
XYA7DX	combined	518	5.26481	-1.87331	0.45409
XYA7DX	CSP	362	5.06076	-1.23044	0.44574
XYA7DX	SSP	156	5.16197	-1.01943	0.36062

[1]XYA7DA = 7-day moving average of the daily average.
[2]XYA7DX = 7-day moving average of the daily maximum.

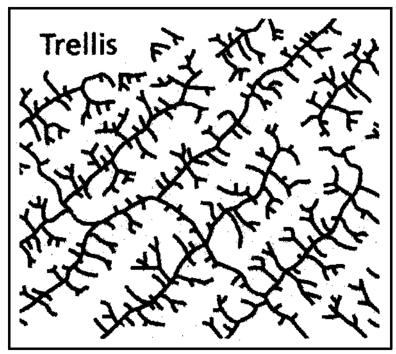
HUC is used to refer to the USGS subbasin. See Figure 4.9 in Chapter 4 for a spatial display of the HUCs that comprise the range of the coho salmon in Northern California. Watershed position within each HUC, as represented by watershed area and distance from watershed divide, was assessed for each of the temperature metrics presented in the previous sections of this chapter. These analyses were limited to 1998, the most data-rich year.

Watershed Area and Stream Temperature in Hydrologic Units

Stream temperature monitoring sites were aggregated by HUC. The highest daily maximum, seven-day moving average of both the daily average and daily maximum, lowest daily minimum, and diurnal fluctuation were plotted versus log_{10} watershed area by HUC. These graphs can be found in Appendix D. The following discussion on the relationship between stream temperature and distance from the watershed divide also apply to graphs of temperature-watershed area relationships found in Appendix D.

Distance from Watershed Divide and Stream Temperature in Hydrologic Units

Although there is strong correlation between watershed area and distance from watershed divide (Figure 7.3), the relationship between the two can depend upon the hydrologic configuration of a drainage, e.g., whether it is dendritic or trellis (Figure 7.14).



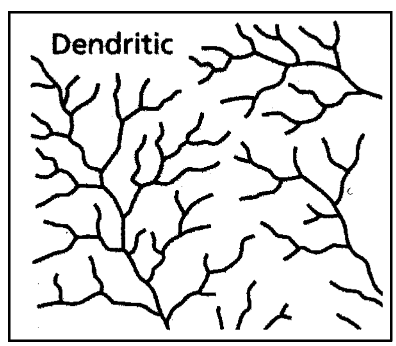


Figure 7.14. Two examples of watershed drainage patterns common in Northern California hydrologic units, dendritic and trellis. Patterns are determined by topography and geologic structure. Modified after FISRWG (1998).

In round types of HUCs a dendritic drainage pattern is common. In more elongated HUCs, a trellis drainage pattern is more the norm. In a dendritic type of HUC, for a unit increase in distance from divide, the watershed area would be greater than for the same divide distance unit increase in a trellis HUC. Given these potential differences we felt it was not redundant to examine in greater detail the variation in each of the temperature metrics as a function of distance from watershed divide.

Daily Maximum and Distance from Watershed Divide by HUC

What is most striking is the consistent increase in the highest daily maximum (XY1DX) stream temperature with increasing watershed area and distance from the watershed divide in all HUCs (Figure 7.15). Even in HUCs with large numbers of data points, each point representing a different tributary, the increase was consistent. Both tributaries (open circles) and mainstems (crosses) showed an increase in XY1DX with increasing distance from the divide and watershed area. It was disappointing that few temperature records were available on mainstems at lower watershed areas divide distances. Most of the mainstem temperatures were measured far down in the drainage, often near the point where the river drains to the ocean.

The Klamath River sites located at the highest watershed areas appeared to have lower temperatures than other sites in Figure 7.5-B. However, looking at these sites in the context of their basin, they fall in alignment with the general increasing trend for the basin (Figure 7.15-L). The Lower Eel HUC (Figure 7.15-E) clearly shows a decrease in mainstem temperatures at the highest divide distances. This is most likely due to the cooling influence of air temperatures as the water nears the coast. Other mainstem rivers in the Lower Eel HUC exhibited decreases with increasing divide distance, namely the North Fork Eel and the Van Duzen River.

A similar decrease in water temperature at the highest divide distance was noted in the Mad-Redwood HUC (Figure 7.15-B). Both Mad River and Redwood Creek showed a decrease in XY1DX with increasing divide distance. Mad River XY1DX values decreased by about 4°C over a 10 km distance. Redwood Creek decreased by about 7°C over a 40 km distance. The decrease is quite striking, considering the thermal inertia of these systems. Again, the cooling influence of coastal air temperatures is believed to be responsible for the decrease in XY1DX at the higher divide distances. Two sites on the Little River showed an increase with increasing divide distance. However, no sites were located on the Little River near its outlet into the Pacific Ocean near Trinidad, CA to verify the cooling influence of coastal air temperature on water temperature in this river.

In the Big-Navarro-Garcia HUC (Figure 7.15-H) a cluster of mainstem sites are seen at the highest divide distances. These sites include the Big, Garcia, Ten Mile, and Noyo Rivers, all making up the major drainages in the HUC. Although too few sites were located in any one of the four rivers to clearly discern a similar cooling trend at the highest divide distance, the four sites on the Garcia River seem to exhibit this behavior. There was approximately a 5°C decrease in the XY1DX from the next-to-highest to highest divide distance. The trio of points in both lower parts of the Big and Noyo Rivers also seem to show a decrease in XY1DX values from the next-to-highest to highest divide distance, although not as large as that observed in the Garcia River. The clustering of the four rivers' sites into four distinct groups indicate that they may be integrating the thermal regimes within their respective basins, which includes differing air temperature regimes and land use patterns.

The reported upper lethal incipient temperature (ULIT) for juvenile coho salmon is 26°C (Brett, 1952). Subtracting a two-degree safety margin from the ULIT as recommended by Coutant (1972) gives us a potential reference value of 24°C to compare XY1DX values against. Comparing XY1DX values to the 24°C acute reference value shows that no tributary sites in the Mad-Redwood exceeded this value (Figure 7.15-B). It is not until greater distances from the watershed divide are reached on the mainstem Mad River and Redwood Creek do temperatures exceed 24°C.

In both the Upper Eel (Figure 7.15-C) and Middle Fork Eel (Figure 7.15-D) HUCs XY1DX values exceeded 24°C at divide distances less than those observed in the Mad-Redwood HUC. More tributary XY1DX values were observed above 24°C in the Upper and Middle Fork Eel HUCs. The divide

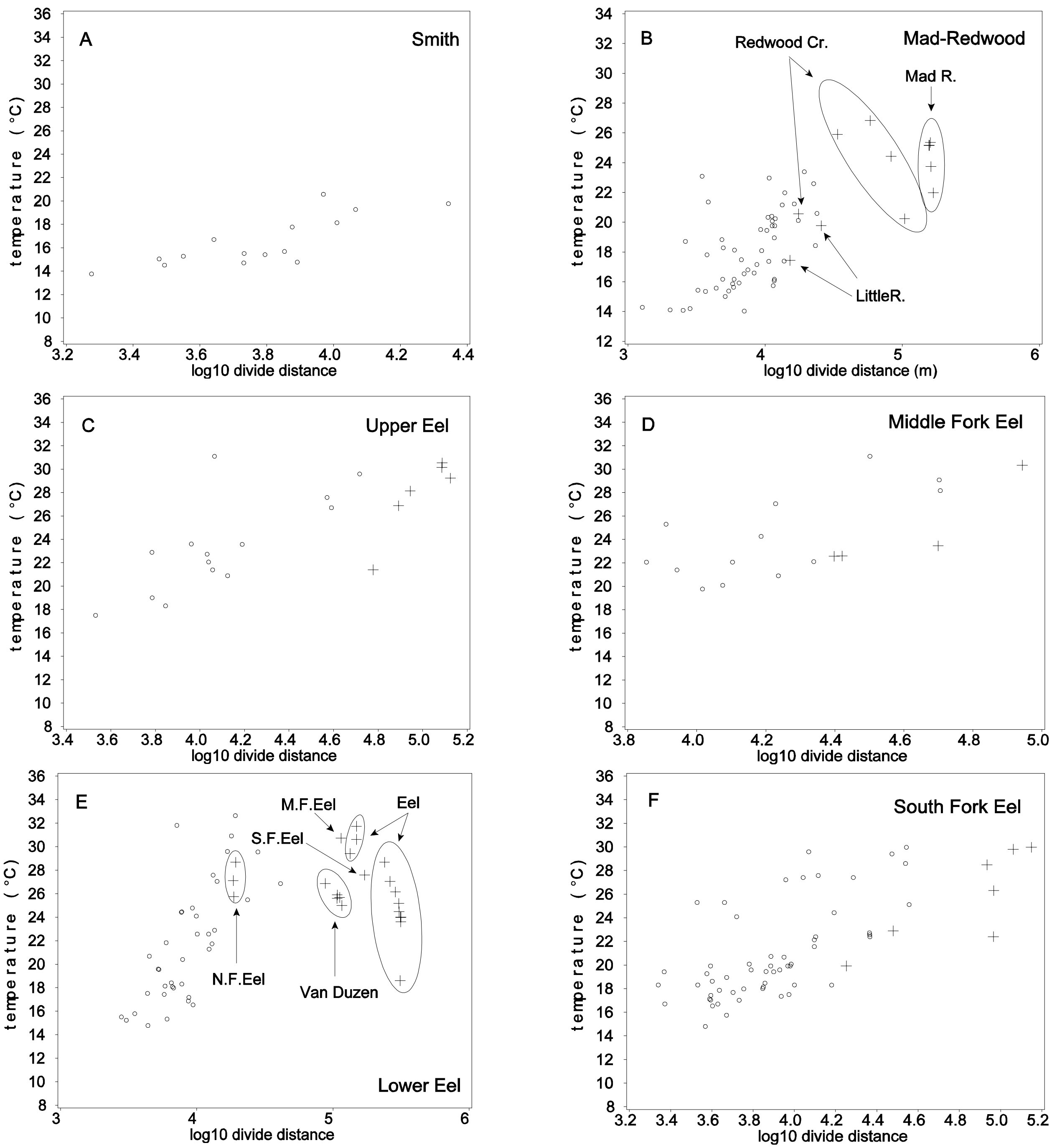


Figure 7.15. The 1998 highest daily maximum stream temperature (XY1DX) versus $\log_{10}$ distance from watershed divide (meters) for HUCs comprising the range of the coho salmon in Northern California. Circles represent tributaries and crosses represent mainstems.

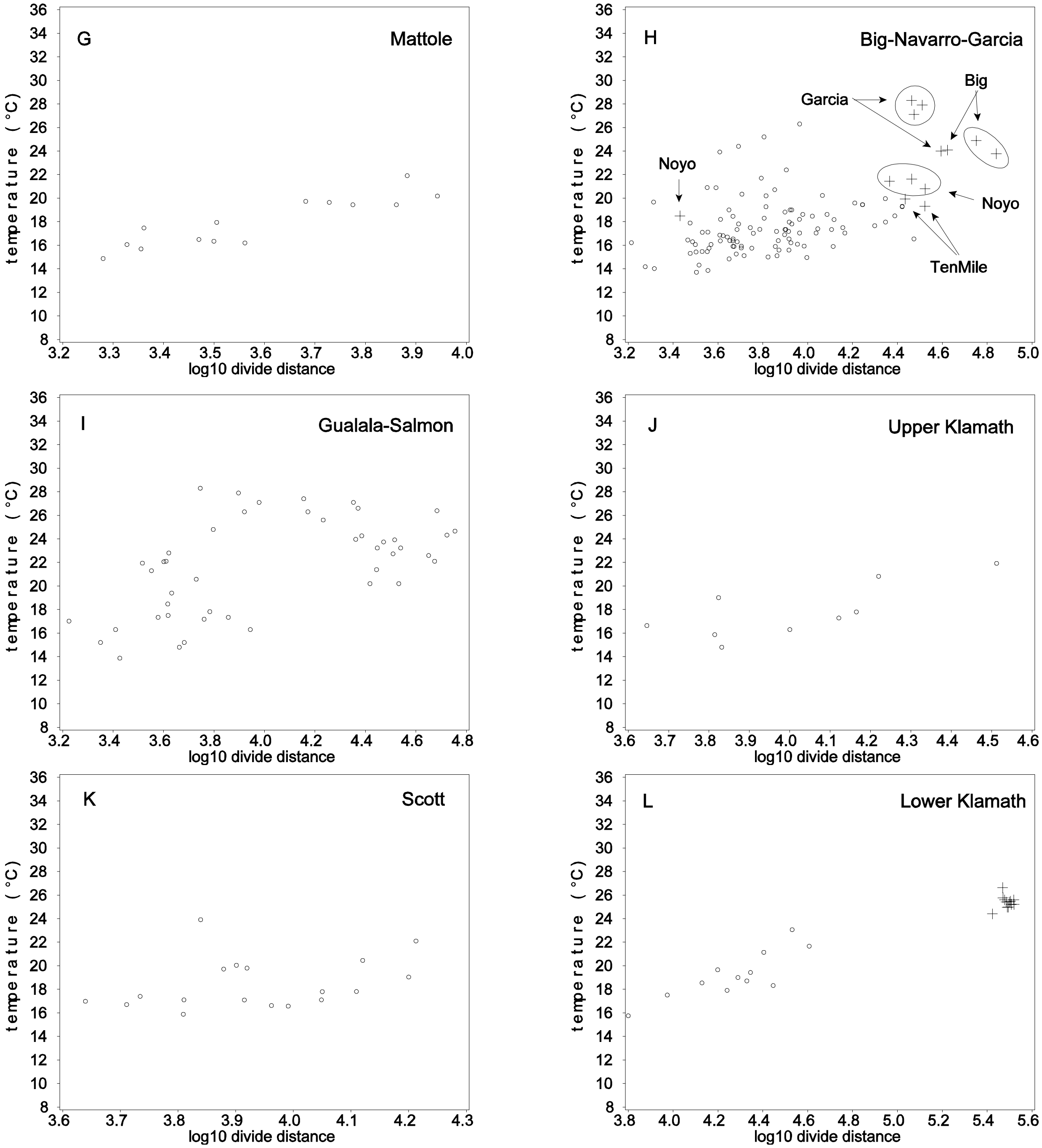


Figure 7.15. (continued)

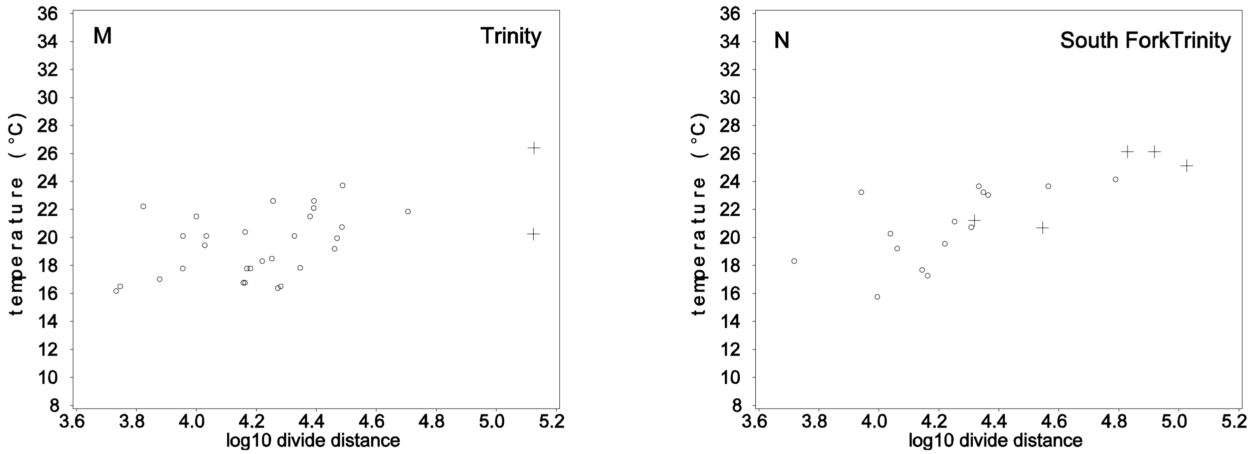


Figure 7.15. (continued)

distance at which XY1DX values begin to exceed 24°C in the Lower Eel HUC was approximately 10 km (Figure 7.15-E). Not all tributaries exceeded this reference value at 10 km or greater ($\log_{10} = 4$ for 10,000 m divide distance) from the watershed divide. The PRISM 30-year average air temperature in the three Eel HUCs are 1°C to 1.5°C higher than in the Mad-Redwood HUC (see Chapter 4, Table 4.2). The XY1DX values dropped in the Van Duzen River by about 2°C over an increase in divide distance of about 100 km. The mainstem Eel River exhibited a 14°C decrease in XY1DX over about a 150 km increase in divide distance. The mainstem Eel River drainage, from Lake Pillsbury to the ocean is examined in greater detail in a subsequent section.

Some HUCs had no sites or only one site with XY1DX values above 24°C (Smith, Mattole, Upper Klamath, Scott). The Smith and Mattole HUCs have the lowest August average air temperatures (based on 30-year PRISM average air temperatures, see Chapter 4, Table 4.3). The Scott HUC, a relatively warm HUC, had only one tributary site with a XY1DX value that exceeded 24°C (Figure 7.15-K) at a divide distance of about 8 km. The Gualala-Salmon is one of the coolest HUCs in terms of air temperature, yet had several tributary sites that had XY1DX values in excess of 24°C at divide distances between 5 km and 25 km. The majority of sites that exceeded 24°C in the Big-Navarro-Garcia HUC (Figure 7.15-H) were on the mainstems of the Garcia and Big Rivers at over 25 km from the watershed divide. The Lower Klamath HUC (Figure 7.15-L) had XY1DX values over 24°C in the mainstem Klamath at distances over 600 km from the watershed divide. In the Trinity and South Fork Trinity HUCs, sites that exceeded 24°C were mostly mainstem sites (Figures 7.15-M & N).

The upstream extent of XY1DX values exceeding 24°C seems to be greater in those HUCs with higher average air temperatures.

Seven-Day Moving Averages and Distance from the Watershed Divide by HUC

Seven-day moving average statistics are often compared to **M**aximum **W**eekly **A**verage **T**emperature (MWAT) thresholds. MWAT thresholds have often been assumed to be protective of certain species and life stages (McCullough, 1999). MWAT can either be calculated as 1) the temperature halfway between the optimal growth temperature (OT) and the temperature at which there is zero net growth, or 2) a third of the difference between the UILT and the optimum temperature (Brungs and Jones, 1977; Ferraro et al., 1978; Armour, 1991). The second method is the one most commonly used in California and other states in the Pacific Northwest, primarily because the data are more readily available to perform the calculation. Using the second method for calculating MWAT:

$$MWAT = OT + \frac{(UILT - OT)}{3}$$

and values for OT and UILT of 14.8°C and 26°C, respectively (Brett, 1952), a value of 18.3°C is calculated for an MWAT threshold.

Using 18.3°C as a reference value, XY7DA and XYA7DX values were assessed for each HUC in relation to distance from watershed divide. Figure 7.16 presents plots of the relationship between XYA7DA and divide distance by HUC.

The distribution of points on each graph was very similar to the plots of XY1DX versus $\log_{10}$ divide distance (Figure 7.15). Sites on the mainstem Mad River and Redwood Creek (Figure 7.16-B), as well as those on the North Fork Eel, Van Duzen, and Eel Rivers (Figure 7.16-E), showed the characteristic decrease in water temperature with increasing divide distance, suggestive of the cooling effects of coastal air temperatures. Again, the four rivers that comprise the Big-Navarro-Garcia HUC were clustered into four distinct groups (Figure 7.16-H).

The sites in the Smith HUC had no XYA7DA values over 18.3°C (Figure 7.16-A). The Smith HUC is the coolest HUC in terms of air temperature (see Chapter 4, Table 4.2). The Mad-Redwood HUC had several tributary and mainstem sites with XYA7DA values over 18.3°C, most of which occurred at divide distances greater than 10 km (Figure 7.16-B). The mainstems of Redwood Creek and Mad River showed the same decrease in XYA7DA values at the higher divide distances as did XY1DX. We postulate that the decrease is due to cooler air temperatures in the zone of coastal influence.

The four Eel River HUCs, i.e., Upper, Middle Fork, Lower, and South Fork, exhibited a preponderance of sites with XYA7DA values exceeding 18.3°C (Figures 7.16-C through F). In the Lower and South Fork Eel HUCs, some sites below 18.3°C were observed extending as far down from the watershed divide as 16 km. Although mainstem sites on the Eel River exhibited a decrease in XYA7DA with increasing divide distance, the only mainstem temperature that did not exceed 18.3°C was the last site on the Eel River just before it drains to the Pacific Ocean (Figure 7.16-E). Many of the tributaries in the four Eel River HUCs have their origins in very warm interior portions of the drainage. Air temperatures reach 100°C and higher during the summer months.

Very few of the sites in the four Eel River HUCs for which water temperature data were available were accompanied by canopy closure data. In the Upper Eel HUC, three sites with canopy closure values greater than 70% had XYA7DA values less than 18.3°C, while seven sites with canopy closure values greater than 70% had XYA7DA values greater than 18.3°C. In the Middle Fork Eel HUC two sites with canopy greater than 70% were below the reference while three were above. In the Lower Eel HUC, 12 sites with canopy greater than 70% had XYA7DA values less than 18.3°C and five were above the reference value. In the South Fork Eel HUC, 23 sites with canopy greater than 70% were below 18.3°C while six were above. Canopy will be discussed in greater detail in Chapter 9.

The Mattole HUC, a cool HUC with respect to air temperature, did not have any sites with XYA7DA values over 18.3°C (Figure 7.16-G). Also, the Scott (Figure 7.16-K) and Upper Klamath (Figure 7.16-J) HUCs had no sites with XYA7DA values over 18.3°C. In the Big-Navarro-Garcia HUC (Figure 7.16-H), three tributary sites had XYA7DA values that exceeded the reference value. The most upstream site on the Noyo River was below the reference value, while three Noyo River sites at the highest divide distances were slightly above the reference value. The XYA7DA values for sites at the highest values for divide distance in the Big and Garcia Rivers were all above 18.3°C. The two sites on Ten Mile River were below the reference value.

Examination of the relationship between XYA7DX and distance from the watershed divide for each HUC revealed a very similar distribution of data points as XYA7DA. Since XYA7DX is based on daily maxima rather than daily averages, values were

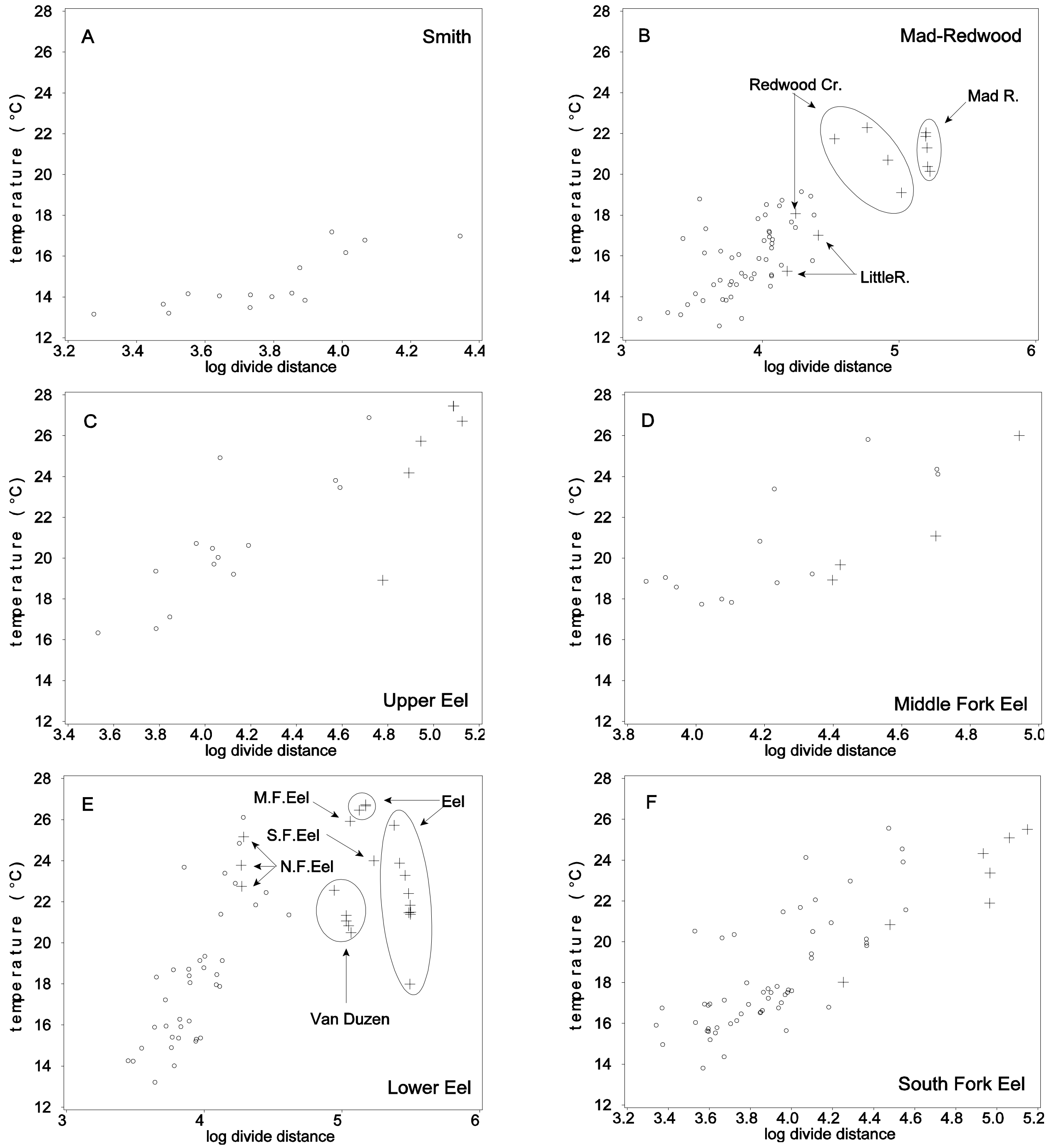


Figure 7.16. The highest 1998 seven-day moving average of the daily average stream temperature (XYA7DA) versus $\log_{10}$ distance from watershed divide (meters) for HUCs comprising the range of the coho salmon in Northern California. Circles represent tributaries and crosses represent mainstems.

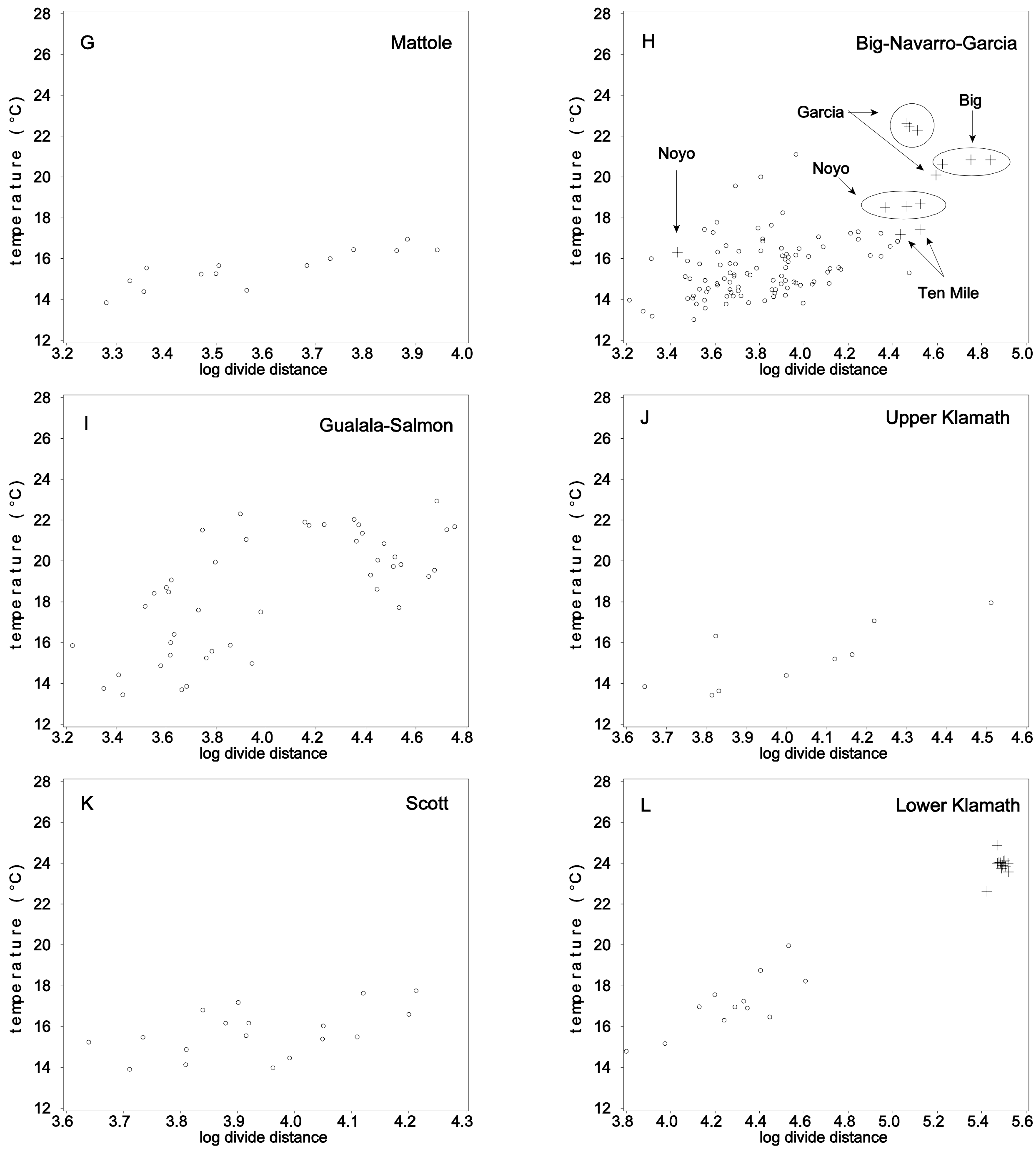


Figure 7.16. (continued)

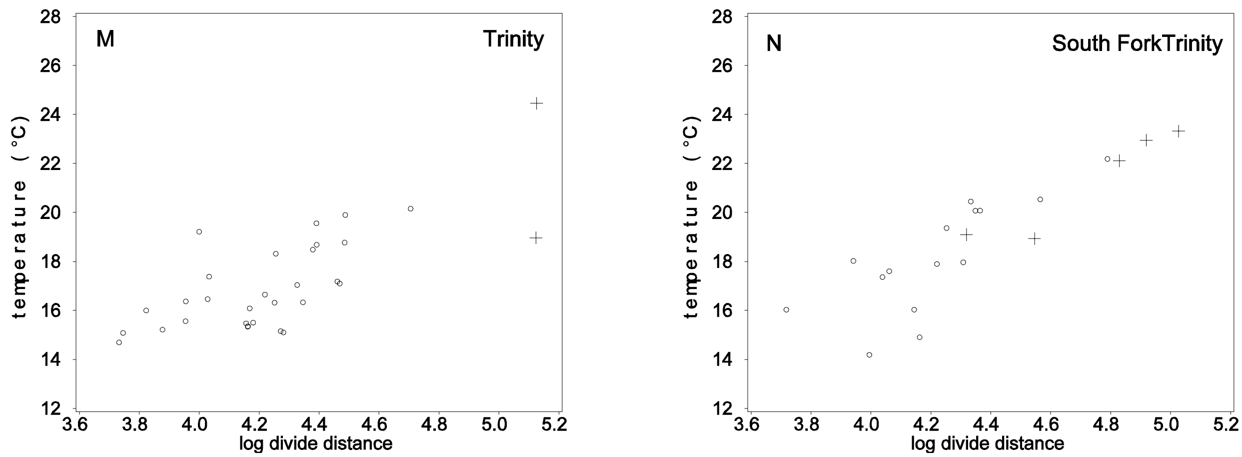


Figure 7.16. (continued)

higher and more sites exceeded the 18.3°C MWAT reference value. Even those HUCs that did not have any XYA7DA values above 18.3°C had XYA7DX values over the reference value. The distance from watershed divide where sites began to exceed 18.3°C decreased for XYA7DX values. Graphs of XYA7DX versus distance from the watershed divide can be found in Appendix D.

Sullivan et al. (1990) and Adams and Sullivan (1990) found that water temperatures seem to level off at some equilibrium temperature that is approximately equal to the average air temperature for the basin. It is not clear how or where average basin air temperatures were determined in their studies. A general trend was observed across HUCs in stream temperature metric values in that HUCs with higher monthly average air temperatures (Chapter 4, Table 4.2) attained higher stream temperatures. The Smith and Mattole HUCs exhibited lower XY1DX, XYA7DA, and XYA7DX values than other HUCs and are the coolest in terms of air temperature. The PRISM 30-year long-term average air temperatures for August in the Smith and Mattole HUCs are 17.1°C and 16.1°C, respectively (see Chapter 4, Table 4.2). Both the Smith and Mattole HUCs are largely coastal HUCs, with minimal area extending into the warmer interior sections of the region. Those coastal HUCs that are oriented with large areal portions in the interior and HUCs that are entirely inland generally have higher 30-year average air temperatures and exhibited higher stream temperatures.

The MWAT metric is an extrapolation of laboratory studies that may or may not be representative of actual field conditions. Some well-designed stream temperature monitoring studies that are coupled with fish presence/absence and/or abundance surveys are needed to validate both chronic and acute thermal stress thresholds. Essig (1998) found that state temperature criteria were exceeded at over 50% of the 98 Idaho stream locations where salmonid spawning was observed. At the same sites where exceedance of temperature criteria was noted, rearing was observed in the following year.

Diurnal Fluctuation and Distance from Watershed Divide by HUC

The diurnal fluctuation of stream temperature with respect to distance from the watershed divide was examined. Figure 7.17 shows that diurnal flux did not follow a linear trend with $\log_{10}$ divide distance (or watershed area - see graphs in Appendix D). HUCs that had sites representing a wide range in divide distances exhibited more of a bell-shaped distribution (see Figure 7.9) than HUCs that had sites at only lower or higher divide distances. Only a portion of the curve may be expressed in those HUCs that do not have sites along the entire continuum of divide distances. The lack of sites at higher values of

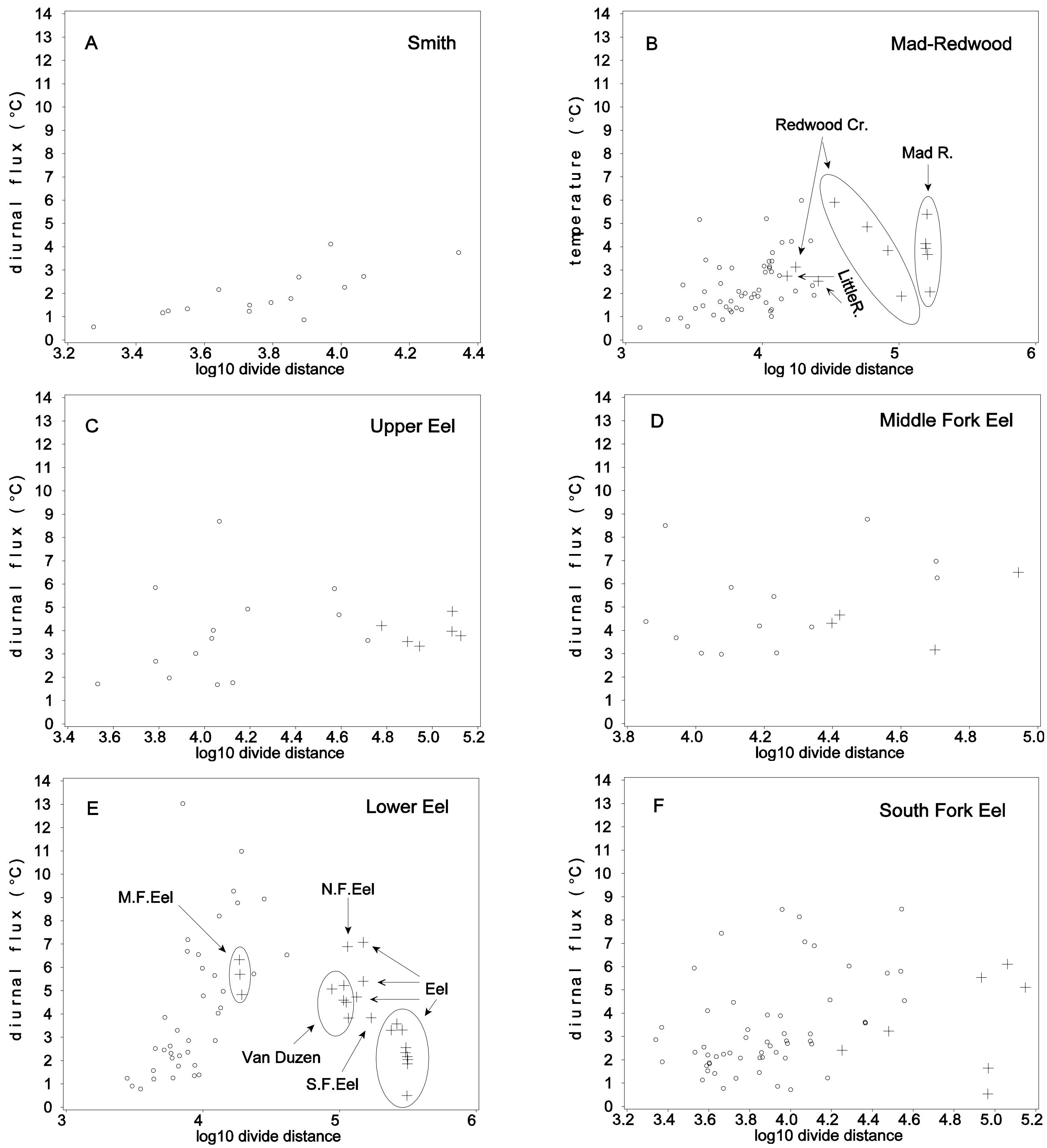


Figure 7.17. The average 1998 diurnal stream temperature fluctuation versus $\log_{10}$ distance from watershed divide (meters) for HUCs comprising the range of the coho salmon in Northern California. Circles represent tributaries and crosses represent mainstems.

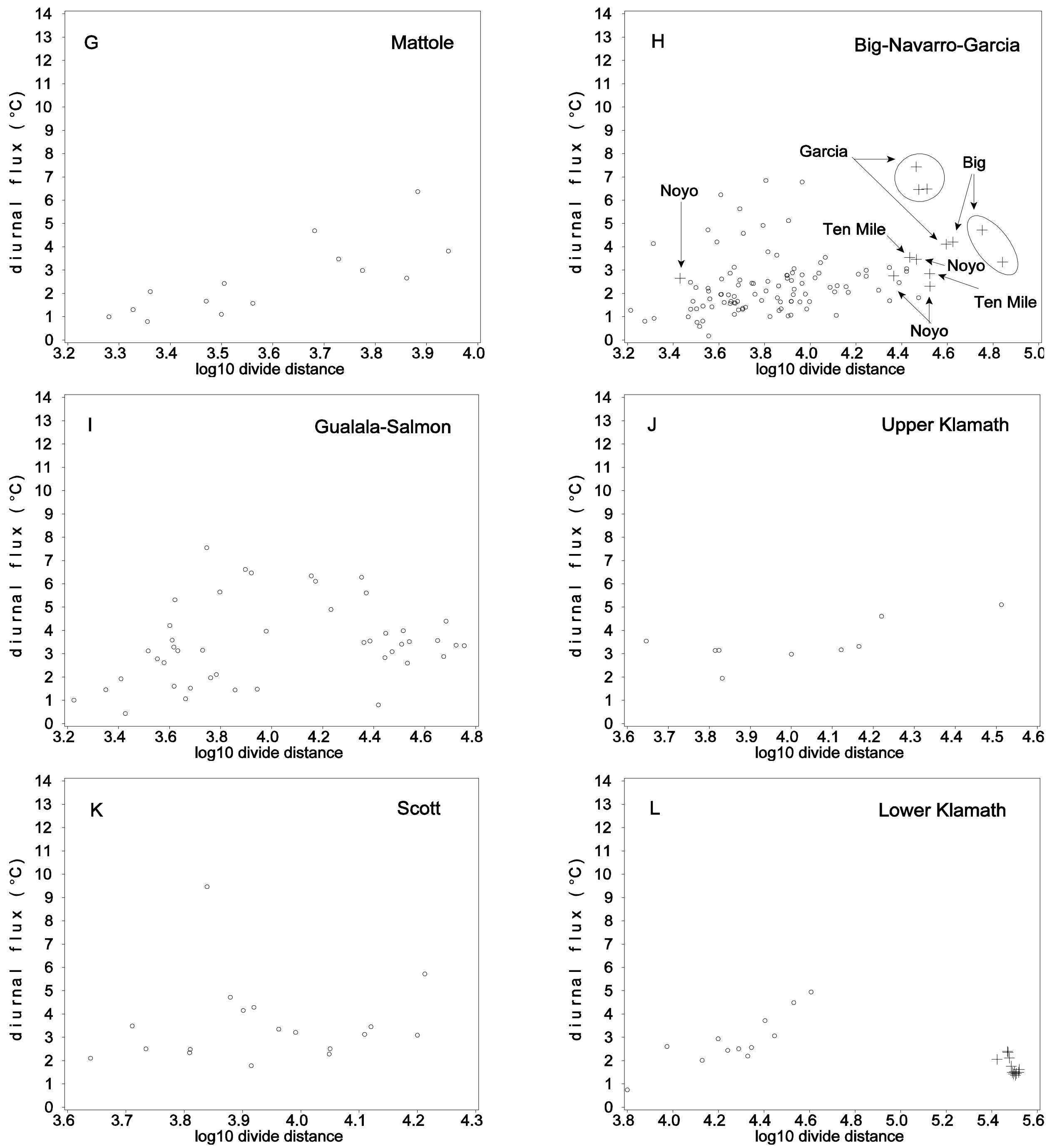
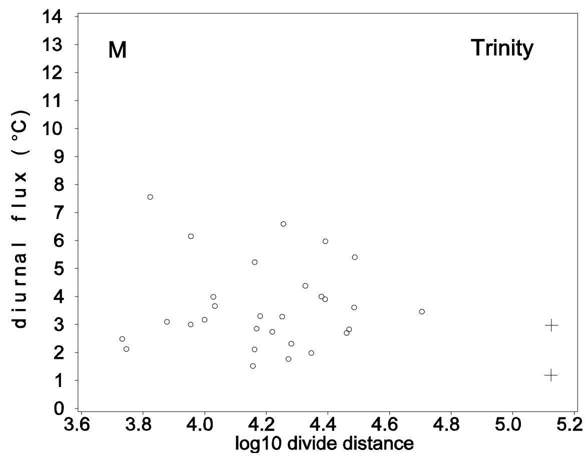


Figure 7.17. (continued)



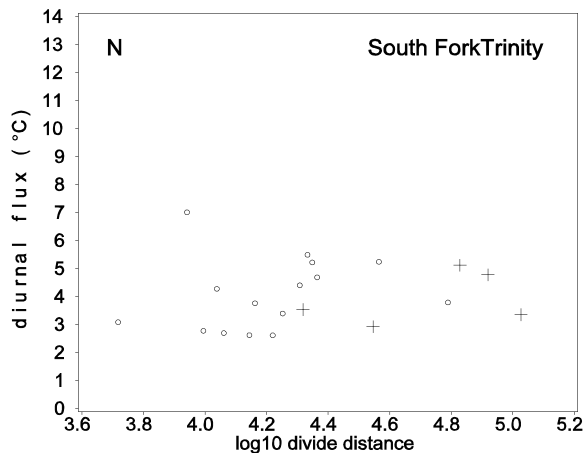


Figure 7.17. (continued)

watershed area may be because the HUC is smaller and simply does not have divide distances any higher than those observed or no sites were available at the greatest divide distances that exist in the HUC. It must also be borne in mind that some HUCs are not complete hydrologic units with respect to a mainstem river. For example, the mainstem Eel River is broken up into three HUCs, the Upper, Middle, and Lower.

Thus, the largest divide distance for the mainstem Eel River is not found until one examines the Lower Eel HUC. For HUCs with sites lacking at the lower divide distances, small order streams were not adequately sampled. Examination of only a portion of the curve may account for the observed decrease in diurnal fluctuation with increasing divide distance reported by Sullivan et al. (1990).

The Lower Eel HUC (Figure 7.17-E) exhibited the greatest diurnal fluctuation, with the highest being about 13°C at a watershed area of approximately 1300 ha and about 10 km from the divide. The decrease in mainstem diurnal fluctuation is most likely due to the arrival of mainstem water at the coast and the thermal inertia of the larger volume of water. Air temperatures near the coast are characterized by lower daily maxima and higher daily minima. The smaller diurnal fluctuation in air temperature is manifested in a smaller diurnal fluctuation in water temperature.

In general, HUCs with the highest PRISM 30-year average air temperatures showed the greatest diurnal fluctuations. Conversely, HUCs with the lowest air temperatures exhibited the lowest diurnal fluctuations. It must be considered, however, that not all tributaries or mainstems in every HUC are represented. Obviously, only data that were submitted to the FSP for this regional assessment can be included in the analyses.

Sum Degrees and Sum Degree Hours

While the previously presented stream temperature metrics reveal a great deal about the thermal behavior of sites with respect to their watershed position and other landscape and site-specific attributes, another set of metrics was developed to evaluate cumulative exposure to elevated temperatures. These elevated temperatures are transient in nature and are closer to the upper lethal incipient temperature. Temperatures near the upper lethal incipient temperature present acute thermal stress to coho salmon and other aquatic organisms.

Considering the highest daily maximum or highest seven-day moving average of both the daily average and daily maximum for a site sheds no light on whether the highest observed daily or weekly temperature was transient or persisted at or above the acute threshold for long periods (duration). Moreover, the highest daily and weekly metrics do not provide any information on the magnitude of temperatures above an acute thermal stress value. That is, was the highest daily or weekly metric simply a blip on the radar screen while the remainder of temperatures were below, at, or barely above an acute threshold? Alternatively, were the temperatures elevated significantly above the acute threshold for long periods of time, e.g., several hours (consecutive or nonconsecutive) for many days at a time (consecutive or nonconsecutive)? Although we do not normally think of temperature in terms of concentration, it is useful to do so in this case. If we consider the magnitude of temperature as concentration then we could consider the dose to be concentration multiplied by time.

Sites used for these analyses had continuous, uninterrupted observations for a 30-day period in 1998, from July 21 through August 19. Figure 7.18 illustrates the concept of sum degrees and sum degree hours for seven hypothetical temperature observations. This illustration helps to demonstrate how sampling intervals (hourly or some other interval) were allocated into areas above the acute thermal reference value. Different sampling frequencies do not affect the calculation, since the area above the reference value is calculated geometrically and not arithmetically.

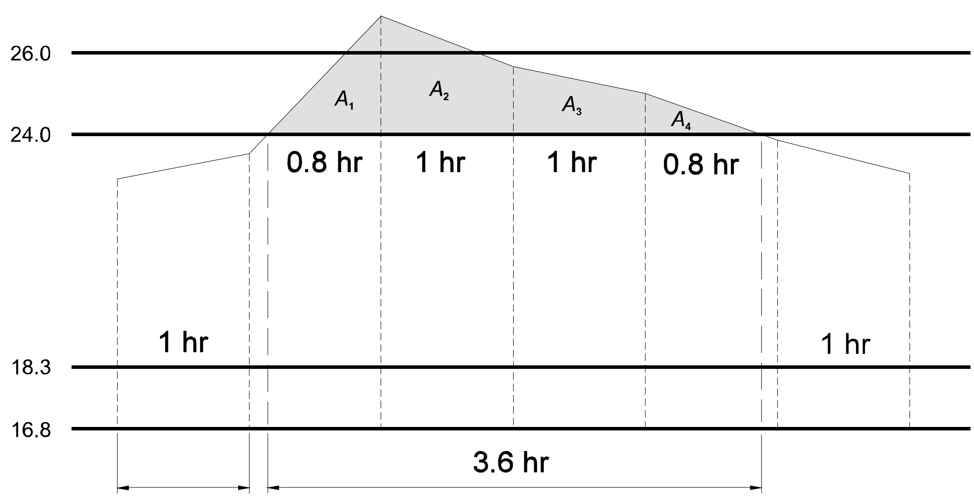


Figure 7.18. Graphical representation of seven hypothetical temperature observations with four acute thermal stress reference values (solid heavy lines). Short vertical dashed lines represent sampling intervals and long vertical dashed lines represent the total time (sum degree hours) above the 24°C threshold. $\sum(A_1, A_2, A_3, A_4)$ represents the area under the curve above 24°C (sum degrees).

To obtain better estimates of these metrics, relatively simple geometric calculations were performed. By considering the portion of each sampling interval above the threshold as an area (A_1, A_2, A_3, A_4), the sum of these areas represents the sum degrees above the threshold (shaded portion in Figure 7.25). The sum degree hours above the threshold (3.6 hr) was determined by summation of the total time spent above the threshold. Figure 7.18 may represent only one excursion of stream temperature above an acute reference value at a particular site. Such excursions may occur on more than one occasion, in which case the total hours and all the areas above the reference value are summed for the entire July 21 to August 19 sampling window to determine sum degree hours and sum degrees, respectively.

In this example, the 24°C reference value was exceeded in the second 1-hr sampling interval for eight-tenths of an hour as was the fifth 1-hr interval. Note that only a portion of the second and fifth 1-hour interval exceeded the temperature threshold (Figure 7.18). Allocating the entire 1-hr sampling interval as being above the threshold would tend to overestimate (or underestimate) the total amount of time spent (sum degree hours) above the threshold (3.6 hr), as well as give an imprecise estimate of sum degrees.

Sum degrees are comparable to degree days as a means of quantifying cumulative warmth in a season or year at a given location. It is a measure that takes into account both magnitude and duration of departure from a chosen threshold temperature. Degree days originated as a means to predict residential heating and cooling needs. They are also used in agriculture to predict an area's suitability for growing certain crops or the day of maturation of a crop in a given year (Trewartha, 1968). The degree day concept provides a single quantity that is better at characterizing the warmth at a given site than is annual average temperature (Essig, 1998). The metric has not been commonly applied to stream temperature monitoring and assessment.

Figure 7.19 shows the relationship between divide distance and sum degrees over 24°C (SUMDEG24) by HUC. For brevity, plots of watershed area versus SUMDEG24 are not shown. These plots were similar to those shown in Figure 7.19. A fixed range on the y-axis was not possible due to the large distribution in sum degree values. As expected, those sites that did not have daily maxima over 24°C obviously had zero values for SUMDEG24. HUCs with sites having all SUMDEG24 values of zero were the Smith, Mattole, Upper Klamath, and Scott.

In the Mad-Redwood HUC only the mainstem sites in the lower portions of Redwood Creek and Mad River exhibited SUMDEG24 values greater than zero. In the Eel HUCs (i.e., Upper, Middle, Lower, and South Fork), both tributary and mainstem sites were observed with SUMDEG24 values greater than zero. The Eel HUCs exhibited the highest SUMDEG24 values of all the HUCs in the range of the coho for which temperature data were available. The occurrence of high SUMDEG24 values was seen at sites within a few kilometers of the watershed divide.

One problem with the use of sum degrees is the lack of published reference or threshold values for determining what values for this metric can be considered to be potentially injurious to juvenile coho or other species and life stages. Inasmuch as the derivation of the sum degree metric has imbedded in it an acute thermal stress reference value (i.e., 24°C), it would stand to reason that any values greater than zero would suggest the potential for acute thermal stress. The metric does allow for relative comparisons between sites.

Hydrologic Unit Case Studies

Examination of stream temperature metrics with respect to watershed area and distance from the watershed divide revealed a great deal about the thermal regimes in each hydrologic unit. However, watershed area and divide distance do not always coincide with the relative position (topology) of tributary and mainstem sites. A tributary with a large watershed area or divide distance may enter the mainstem upstream from another tributary site with a

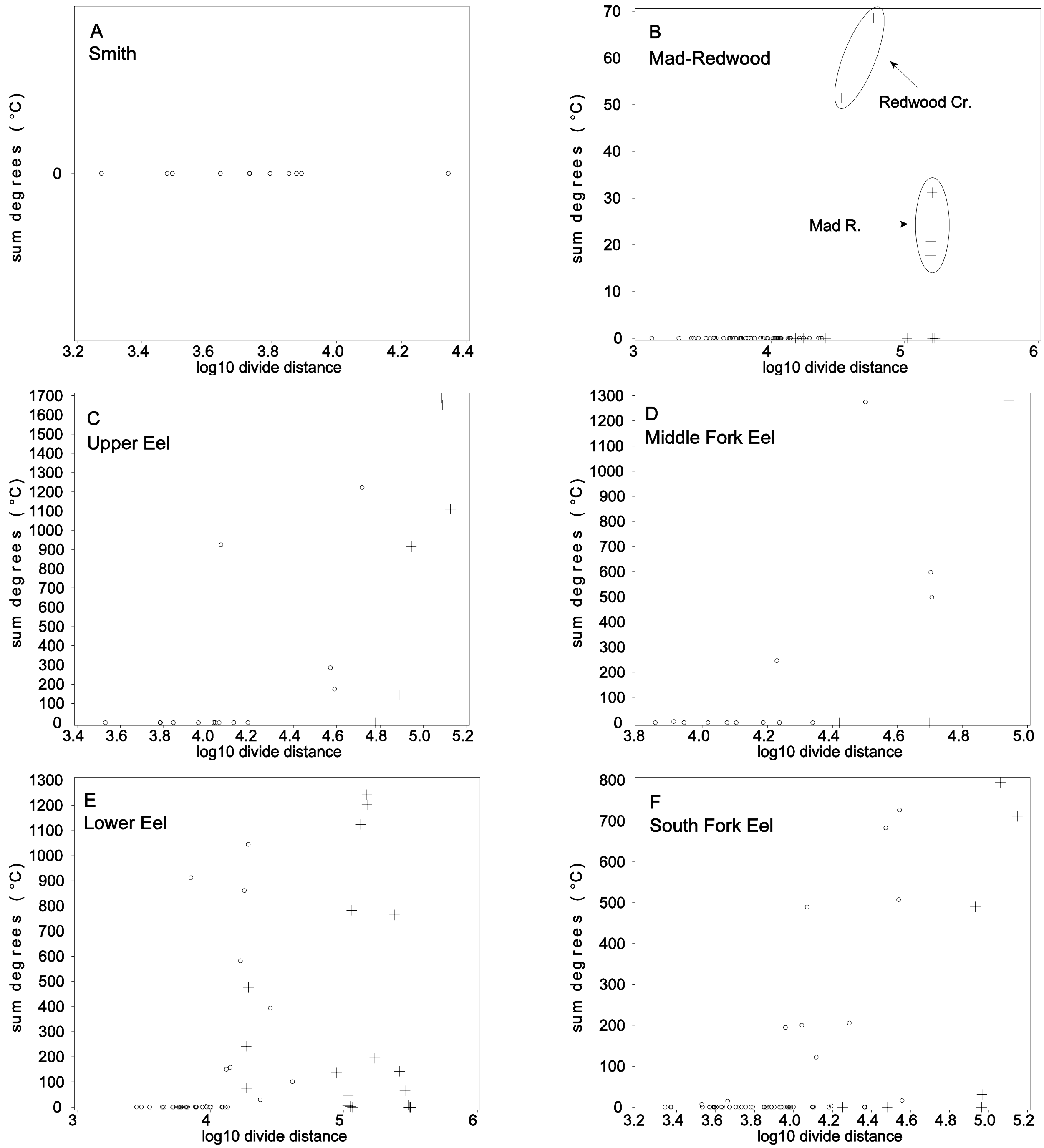


Figure 7.19. Sum degrees over 24°C versus $\log_{10}$ divide distance (meters) for HUCs that comprise the range of coho salmon in Northern California. Circles are tributary sites and crosses are mainstem sites.

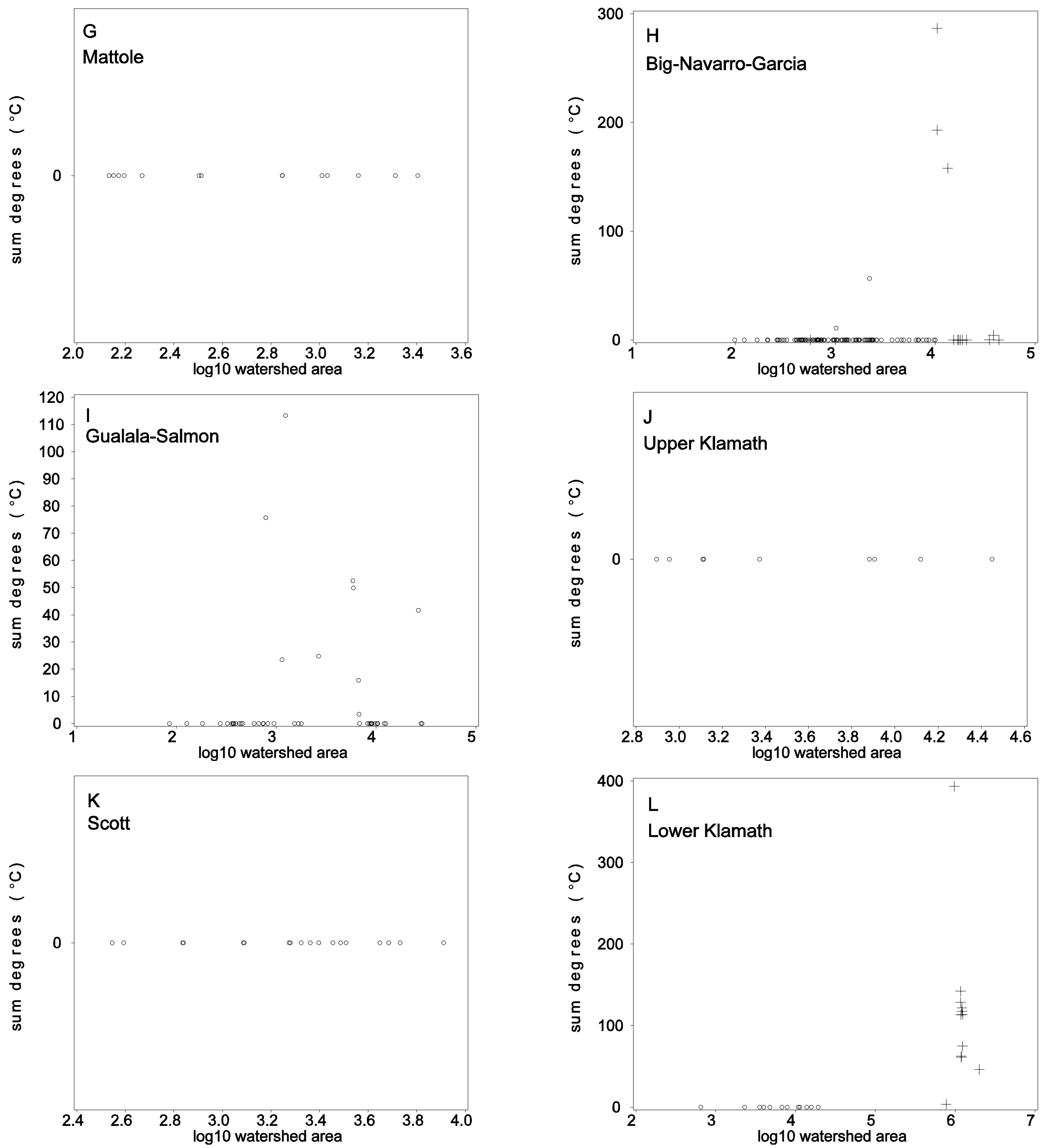


Figure 7.19. (continued)

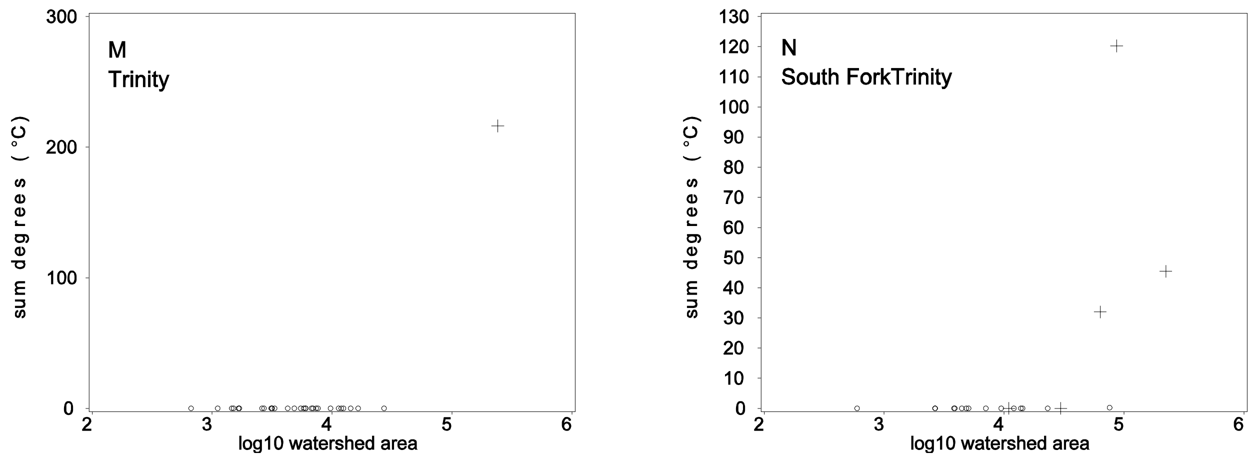


Figure 7.19. (continued)

smaller watershed area or divide distance. To develop a better understanding of stream hierarchical thermal regimes and the potential cumulative effects of tributary temperatures on mainstem temperatures, tree graphs and stream network diagrams were developed for three basins that had a relatively large number of sites on both tributaries and mainstems.

The daily maximum and diurnal fluctuation on the warmest day in 1997 and the sum degrees and total time above 24°C for day of year 201 to 230 were calculated for sites in the mainstem Eel River and Gualala River drainages. The same metrics were calculated for the warmest day in 1998 in the Ten Mile River drainage. While 1998 data were used in previous sections, 1997 had a better distribution of sites on both tributaries and the mainstems in the Eel and Gualala River drainages for the conduct of a hierarchical stream temperature assessment.

Mainstem Eel Drainage from Lake Pillsbury to the Pacific Ocean

There were 35 sites in the Eel River drainage located on the mainstem and on tributaries nearest the confluence with the mainstem from Lake Pillsbury to the Pacific Ocean. This represents a distance of approximately 320 km along the mainstem Eel River. All tributary monitoring sites nearest the mainstem confluence were within 6000 m of the mainstem, with most being less than 1000 m from the mainstem. The database was queried for the day in 1997 on which the most sites in the drainage had their highest daily maximum temperature, which was 08 August. The daily maximum temperature on 08 August 1997 was plotted against $\log_{10}$ watershed area and $\log_{10}$ distance from watershed divide (Figure 7.20). The distribution of daily maximum temperatures are not unlike those observed for the Upper, Middle, and Lower Eel HUCs in 1998 (Figures 7.16-C, D and E).

The characteristic increase in stream temperature with increasing watershed area and divide distance is evident in Figure 7.20. Similar to the 1998 XY1DX values for the Lower Eel HUC (Figure 7.15-E and 7.16-E), the 08 August 1997 daily maximum temperatures in the mainstem Eel River show a decrease at the highest watershed areas and divide distances.

The daily maximum and diurnal fluctuation are displayed on the tree graph shown in Figure 7.21. The daily maximum below Lake Pillsbury was 19.1°C (divide distance = 54 km) with a diurnal fluctuation of 1.6°C. The low diurnal fluctuation is most likely due to the stable temperature of hypolimnetic waters discharged from the bottom of the reservoir through Scott Dam. In about 16 km

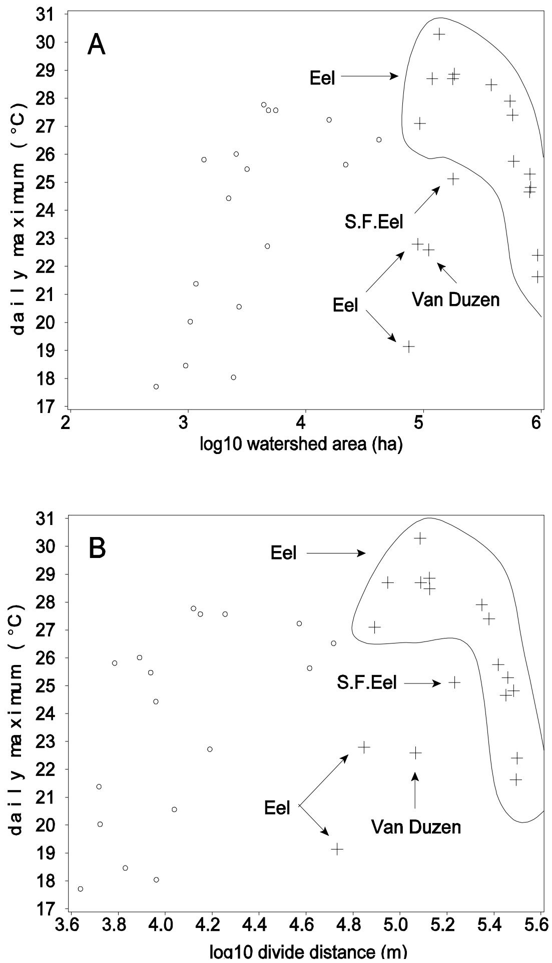


Figure 7.20. Daily maximum stream temperature measured on 08 August 1997 at 35 sites in the mainstem Eel River drainage from Lake Pillsbury to the Pacific Ocean. (A) Daily maximum versus log10 watershed area and (B) daily maximum versus log10 distance from the watershed divide. Circles are tributary sites and crosses are mainstem sites.

(divide distance = 75 km) the Eel River daily maximum increased by 3.6°C. Between mainstem divide distances of 54 km and 75 km three warmer tributaries enter the mainstem, Benmore (25.8°C), Soda (20.6°C), and Bucknell (22.7°C) Creeks (Figure 7.21). The entrance of three tributaries with warmer temperatures could partially contribute to the increase in Eel River temperatures 20 km below the dam.

Daily maximum air temperatures in this portion of the Eel River drainage are near 40°C in August. Water temperatures in the Eel could be coming into equilibrium with warmer air temperatures. Sullivan et al. (1990) state that tributaries had more of an observed cooling or warming effect on mainstem temperatures in the upper reaches of a basin. However, below Lake Pillsbury, the Eel River is already a rather sizable river. The 30-year mean August discharge below Scott Dam is 182 cfs (USGS, 1994). Tributaries would need to contribute a large proportion of the combined flow to alter the mainstem temperature. However, based on the watershed areas of the three tributaries (Benmore = 1360 ha, Soda = 2705 ha, Bucknell = 4710 ha) their total relative contribution to the flow of the Eel River (watershed area = 74,956 ha below the dam) is less than 10%. Caution should be exercised, considering that the Eel River flow is highly regulated. Watershed area may not be a very good surrogate under such regulated flow conditions.

The river continues to warm up to a divide distance of 88 km, where the daily maximum water temperature reached 28.6°C (Figure 7.21).

Outlet Creek is a large tributary that enters the Eel River at about 122 km from the mainstem watershed divide. Outlet Creek entered the mainstem with a daily maximum temperature of 26.5°C. The Eel River daily maximum temperature above the confluence with Outlook Creek was 30.2°C (Figure 7.21). A simple calculation on the expected cooling effects of Outlet Creek on the mainstem Eel River can be made by assuming that Outlet Creek is approximately 31% of the water volume and the mainstem is 69%, based on their respective watershed areas, 41,808 ha and 135,980 ha. Using a mixing equation developed by Brown et al. (1972):

$$\text{temperature} = (p_1 \times T_1) + (p_2 \times T_2) + \ldots (p_n \times T_n)$$

where p_n is the proportion of combined flow contributed by each of n streams and T_n = temperature of stream n, the predicted mainstem temperature below the confluence with Outlook Creek can be calculated as, temperature = (0.31 x 26.5°C) + (0.69 x 30.2) = 29.1°C.

The predicted temperature was within 0.2°C of the observed temperature of 28.9°C. Thus, it appears that given sufficient flow (watershed area ratios being used as a surrogate for relative flow ratios), a cooling effect was realized. The downstream distance of the cooling influence cannot be ascertained from the distribution of sites in the Eel Drainage.

While fairly good agreement was noted for observed and predicted values using Brown's equation, this was for a single temperature metric (XY1DX) and represents the highest daily maximum temperature on a single day. We examined the predictive ability of the equation for a one-week time period to determine whether there was good agreement over several diurnal cycles. Figure 7.34 shows observed tributary, upstream, downstream temperatures and the predicted downstream temperature for Tomki Creek's confluence with the mainstem Eel River. The day of the highest daily maximum was bracketed by three days on either side to examine diurnal fluctuations in observed versus predicted temperatures over the course of a week. The observed and predicted downstream stream temperatures showed good overlap over the entire one week period. Other system confluences also showed good agreement between the observed and predicted downstream stream temperatures (see Appendix D).

The Middle Fork Eel River enters the main fork of the Eel River at about 130 km from the mainstem watershed divide (Figure 7.21). Unfortunately, no temperature sites were available on the Middle Fork that were close enough to the confluence with the Eel River to be representative of incoming water temperatures.

Reference to Figures 7.16-D and 7.16-E shows that the Middle Fork Eel had XY1DX values between 28°C and 30°C at sites with the highest divide distances. These sites were still 10 to 20 km from the confluence with the Eel River. However, given the stability of water temperatures in large mainstems, the Middle Fork temperatures may be quite close to the water temperature at its confluence with the mainstem Eel. Above the Middle Fork the mainstem Eel had a daily maximum of 28.9°C. Just below the confluence, the mainstem Eel daily maximum temperature was 28.5°C. It appears that the Middle Fork Eel was at a temperature very similar to the main Eel River. Very little change in the mainstem Eel temperature was observed below the confluence with the Middle Fork.

The remaining tributaries that enter the Eel River below the Middle Fork are small in watershed area and have daily maxima very close to mainstem daily maximum temperatures. Their influence on mainstem temperatures appears to be negligible. From the confluence with North Dobbyn Creek and continuing downstream, the daily maxima begin to decrease (Figure 7.21). The South Fork Eel River enters the main Eel River at ~262 km from the main Eel's watershed divide. The South Fork has about a third of the watershed area as the main Eel at this point. The two rivers have daily maxima within 0.7°C of each other.

At about 312 km from the watershed divide on the main Eel River the Van Duzen enters the Eel with a daily maximum of 22.6°C. The Van Duzen has a watershed area of 110,778 ha compared to the Eel River's watershed area of 814,997 ha. The Van Duzen was estimated to be about 13% of the flow of the mainstem Eel. Using Brown's equation the predicted Eel River temperature below the Van Duzen was 24.5°C, compared to an observed temperature of 21.6°C. Although Strongs Creek with its cooler water entered the Eel River about 5 km downstream from the Van Duzen, its watershed area was less than 1% of the Eel's. The decrease in Eel River temperatures, beginning at North Dobbyn Creek and continuing to the Pacific Ocean, are believed to be due to the influence of cooler coastal air temperatures.

While the predicted temperature of the Eel River below Outlet Creek was surprisingly close to the observed value, caution should be used in applying watershed area as a surrogate for flow in these types of calculations. This is especially prudent in systems that are strongly influenced by flow regulation, and

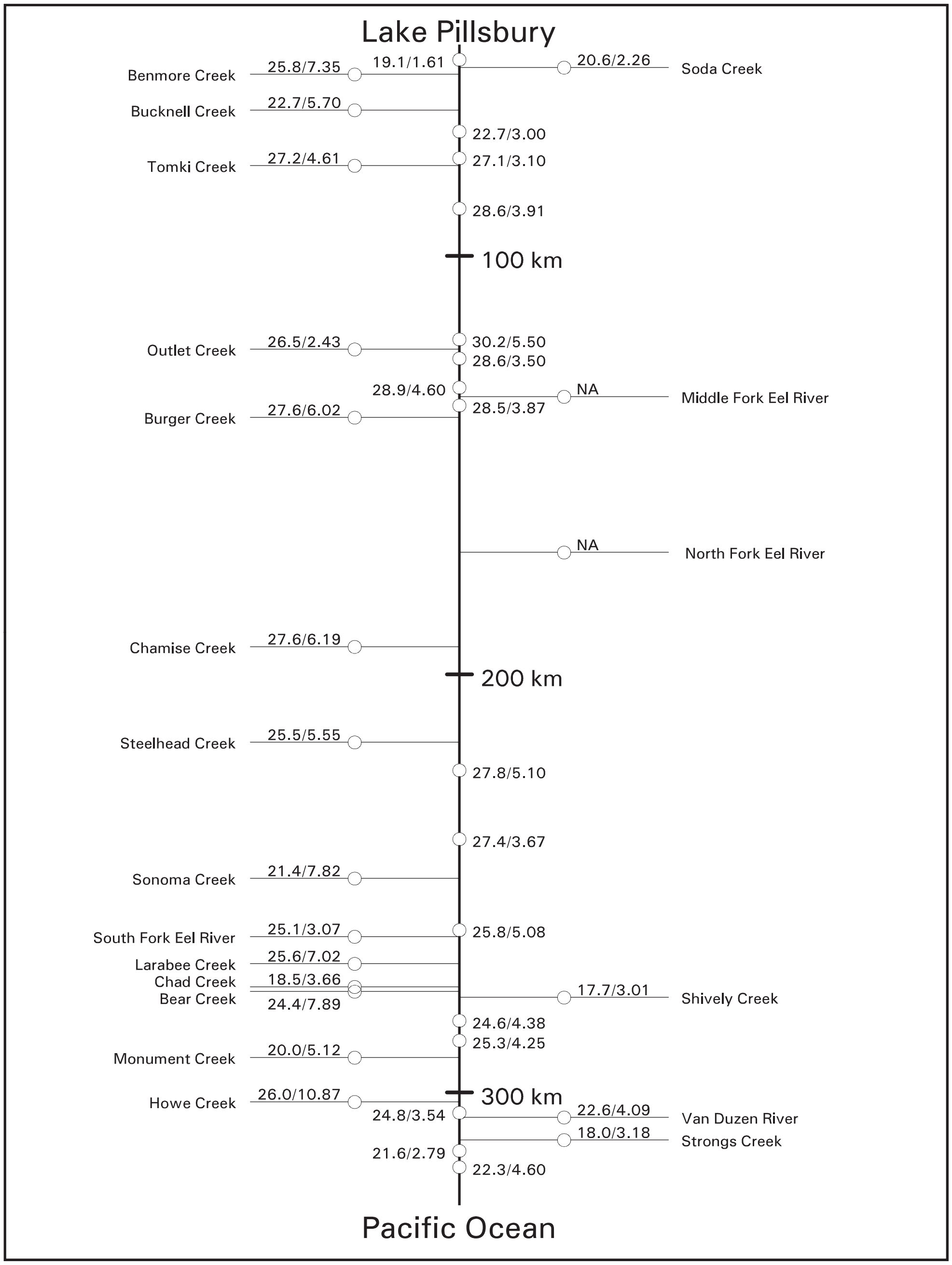


Figure 7.21. Tree graph of tributary and mainstem Eel River daily maximum stream temperatures (°C) (left number) and diurnal fluctuation (°C) (right number) measured on August 8, 1997. Monitoring sites and tributary confluence locations are to scale. Tributary monitoring site locations are not to scale. Divide distances are shown in 100-km increments. Tributary sites varied from 105 m to 5600 m from the mainstem.

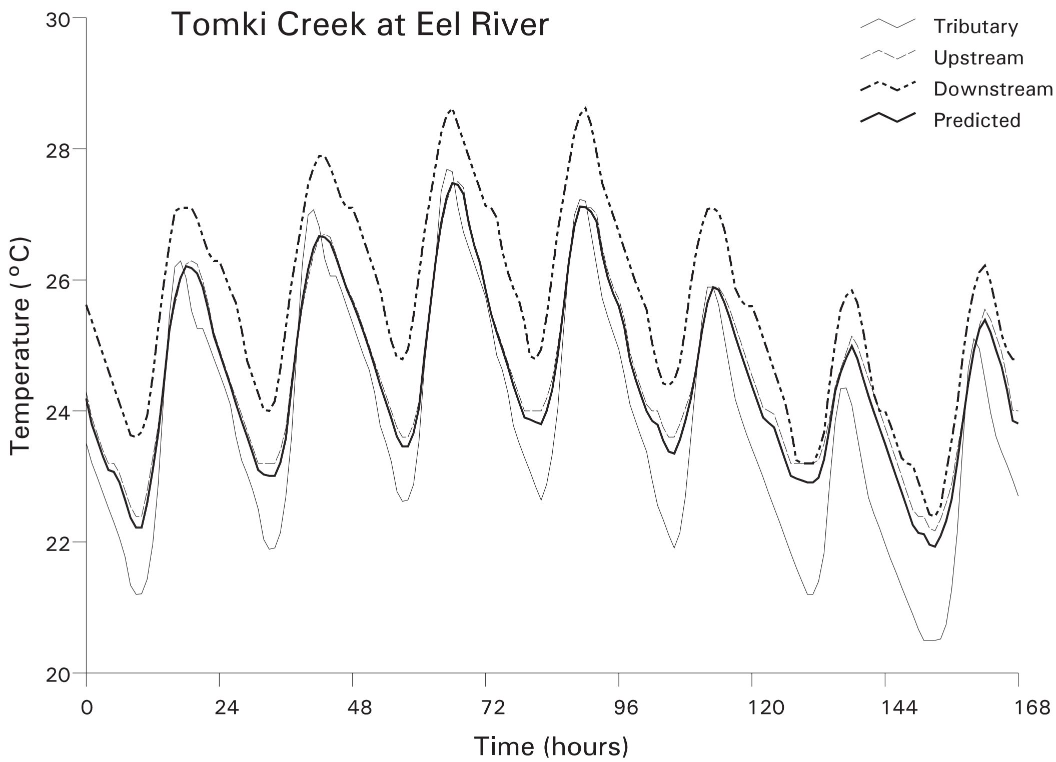


Figure 7.22. Diurnal trends in water temperatures for Tomki Creek, above the confluence on the Eel River, below the confluence on the Eel River, and the predicted (Brown's equation) temperature below the confluence. Temperatures were measured during the week of August 8, 1997.

reach very low summer baseflows, such as the Eel River system.

The diurnal fluctuations observed in the Eel River drainage appear to vary with the magnitude of the daily maximum and the watershed area of the tributary and mainstem. In general, the smaller the watershed area of a tributary, the higher the diurnal fluctuation. Canopy closure also plays a significant role in the level of daily maximum water temperature attained and the diel variation (Bartholow, 1989; Sullivan et al., 1990). Canopy effects on the highest daily maximum were presented in Chapter 5. Additional discussion is presented in Chapter 9.

Examination of the sum degrees over 24°C (SUMDEG24) and the total time spent above 24°C (SUMT24) provides some interesting insights and contrasts to the thermal regime that was developed previously for the Eel River drainage using the daily maximum temperature. Figure 7.23 shows the same tree graph with SUMDEG24 (number to left of slash) and SUMT24 (number to right of slash) values calculated for each site. The mainstem Eel River sites exhibited many of the highest SUMDEG24 values and corresponding SUMT24 values. Benmore and Larabee Creeks had comparable daily maxima (~26°C), however Benmore had a SUMDEG24 of 28°C for 45 total hours above 24°C, while Larabee had a SUMDEG24 value of 148°C for 135 total hours (Figure 7.23). The differences in SUMDEG24 and SUMT24 for these two streams that exhibited comparable daily maxima and seven-day moving averages illustrate the potential utility of these two acute thermal stress metrics.

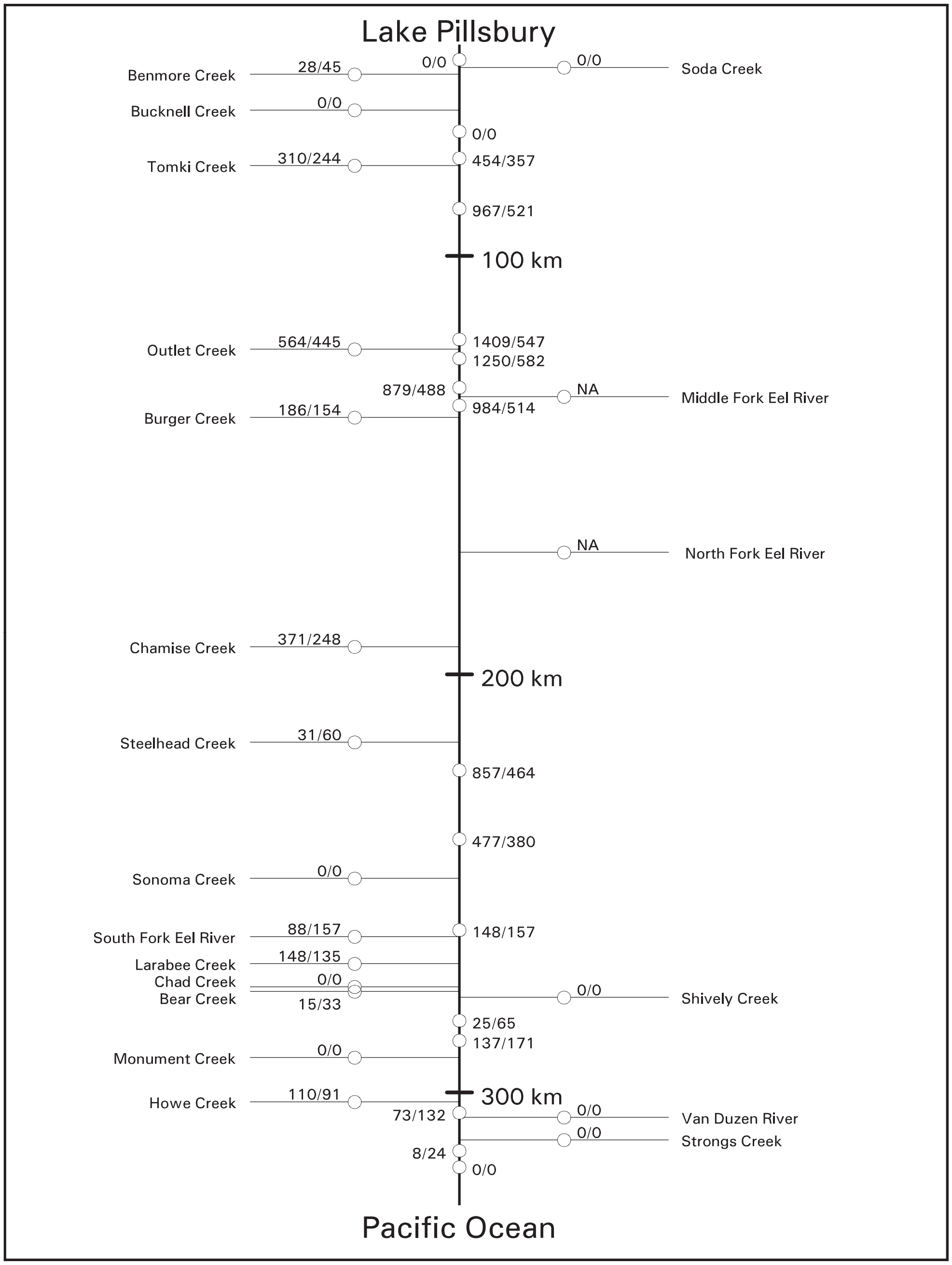


Figure 7.23. Tree graph of tributary and mainstem Eel River sum degrees (left number) and total time (hrs) (right number) over 24°C measured on August 8, 1997. Monitoring sites and tributary confluence locations are to scale. Divide distances are shown in 100-km increments. Tributary sites varied from 105 m to 5600 m from the mainstem.

Daily maxima for North Dobbyn Creek and the Eel River near its confluence were both 27.8°C. North Dobbyn exhibited a diurnal fluctuation 5°C greater than the Eel River. However, the SUMDEG24 value for the Eel River site was nearly four times greater than the North Dobbyn site and temperatures above 24°C lasted nearly 3 times longer (Figure 7.23).

Two sites on the main Eel River, one at approximately 89 km divide distance (i.e., the site below Tomki Creek) and the other site at 122 km divide distance (i.e., the site below Outlet Creek) had daily maxima of ~29°C (Figure 7.21). The SUMDEG24 for the upstream site was 967°C (SUMT24 = 547 hr) and the SUMDEG24 for the downstream site was 1250°C (SUMT24 = 582 hr) (Figure 7.23). In this case, the amount of time each site spent above 24°C was quite similar, however the downstream site had higher temperatures above 24°C than the upstream site, that is it had more cumulative warmth.

Gualala River Drainage

The year with the greatest number of sites on both receiving waters and tributaries in the Gualala River drainage was 1997. There were 39 sites available for analysis, 16 on tributaries and 23 on receiving waters. The warmest day for the majority of sites was found to be July 8, 1997. Daily maximum and diurnal fluctuations for this day were used to examine hierarchical stream temperature relationships. The 39 sites had continuous, uninterrupted temperature data between July 21 and August 19 for the calculation of the SUMDEG24 and SUMT24 acute thermal stress metrics.

Figure 7.24 depicts the hydrological distribution of daily maximum and diurnal fluctuation values in the Gualala River drainage. The shaded area on the graph is an estimate of the areal distribution of the (ZCI) for the month of July, based on PRISM 30-year average maximum air temperatures. Chapter 4 provides a more detailed description of the derivation of the ZCI.

In general, there was a decrease in daily maxima as water entered the ZCI. Beginning with the northernmost drainage, the North Fork of the Gualala River, a daily maximum of 25.9°C was observed outside of the ZCI (Figure 7.24). A warmer tributary enters the North Fork with a daily maximum of 27.1°C. The entrance of this warmer tributary did not seem to greatly influence the North Fork temperature, for the next daily maximum below the tributary was 25.2°C. About 2 km downstream another site on the North Fork recorded a daily maximum of 26.9°C, followed by a site another 2 km downstream with a daily maximum of 23.8°C. Below this point, a tributary (Dry Creek) enters the North Fork from the north. This tributary showed a decrease in daily maxima from 20.5°C to 16.1°C as it approached the ZCI (Figure 7.24). Other factors may contribute to the 4°C decrease in stream temperature over about a two kilometer distance, e.g., changes in riparian vegetation, habitat type where sensor was placed, etc.

The North Fork daily maximum dropped 2.4°C at the point where it entered the ZCI to a daily maximum of 21.1°C (Figure 7.24). We applied the Brown's equation to evaluate the predicted effect of the cooler Dry Creek tributary water on the North Fork temperature. The tributary site has a watershed area of 1677 ha and the site on the North Fork upstream of Dry Creek has a watershed area of 6840. Solving the equation below:

Predicted temperature = (0.245 x 16.1°C) + (0.755 x 23.8°C) = 21.9°C (observed = 21.1°C).

The upstream and downstream North Fork sites were about 2 km from the confluence with Dry Creek. The slightly cooler observed daily maximum value of 21.1°C compared to the predicted 21.9°C may be due to the onset of the ZCI or that the true discharge of Dry Creek was significantly larger or the North Fork's discharge was lower than predicted based on their respective watershed areas.

The generally accepted pattern is that of an increase in water temperature as water travels from headwaters to downstream reaches. The Little North Fork, which lies entirely within the ZCI, seems to exhibit this pattern, with temperature increasing with increasing distance from the watershed divide. The Little North Fork temperature increased about 4°C before merging with the North Fork (Figure 7.24). The South Fork had a daily maximum of 23.7°C at

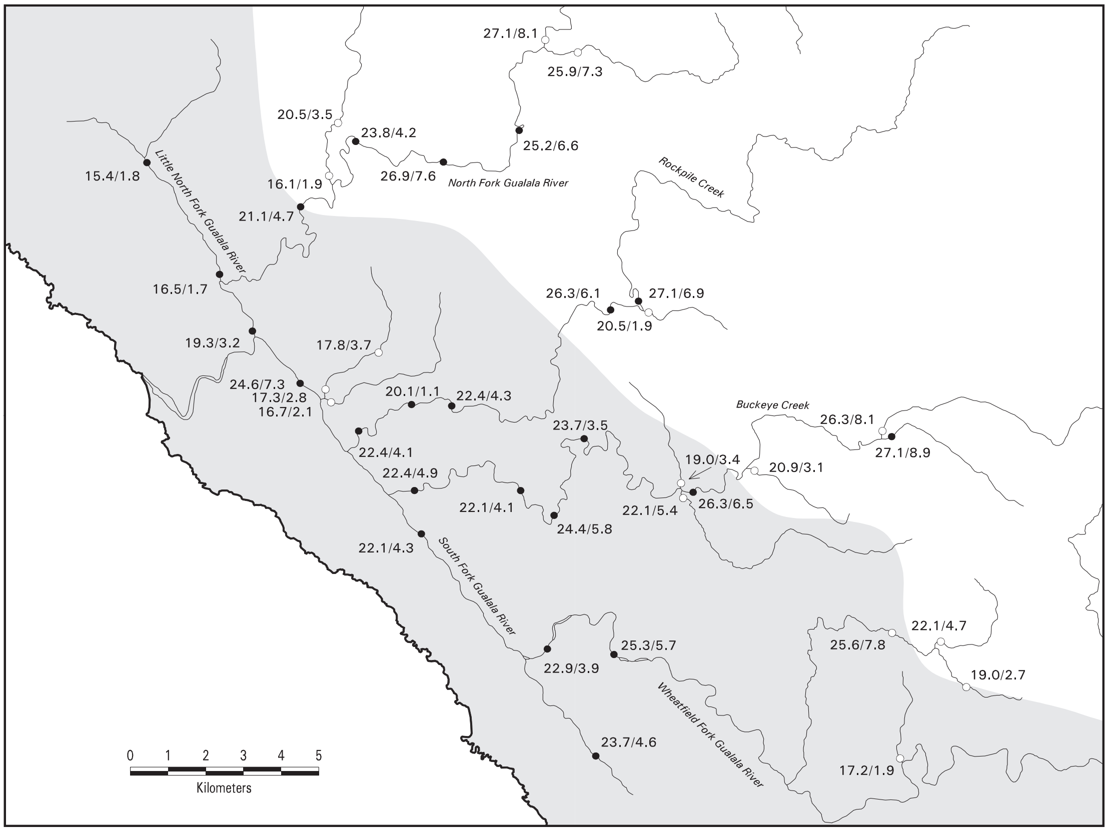


Figure 7.24. Stream network of tributaries and receiving waters in the Gualala River drainage showing the daily maximum stream temperatures (°C) (number on left side) and diurnal fluctuations (°C) (number on right side) on July 8, 1997. Receiving water (solid circles) and tributary (open circles) monitoring site locations are to scale. Shaded area represents an estimate of the areal distribution of the zone of coastal influence, our best approximation of the fog zone.

the most upstream site, with about a 1°C decrease at a site 17 km downstream. The last site before its confluence with the North Fork had a daily maximum of 24.6°C.

Rockpile Creek has a fairly large drainage area that feeds into the South Fork. Its most upstream site had a daily maximum of 27.1°C. A small tributary (Horsethief Canyon) enters Rockpile Creek with a daily maximum of 20.5°C, about 7°C cooler than Rockpile Creek (Figure 7.24). The watershed area at the Horsethief Canyon site is 667 ha and the site just upstream on Rockpile Creek is 5917 ha. The ratio of the two watershed areas indicates that Horsethief Canyon contributes approximately 11% of the flow at its confluence with Rockpile Creek. The predicted downstream temperature was 26.3°C, in complete agreement with the observed daily maximum temperature in Rockpile Creek.

Sites on both the South Fork and Little North Fork, both watercourses residing entirely within the zone of coastal influence, showed an increase in diurnal fluctuation with increasing distance from the watershed divide (Figure 7.24). Mainstems (North Fork, Rockpile, and Buckeye) that originate outside the zone of coastal influence (ZCI) and flow westerly

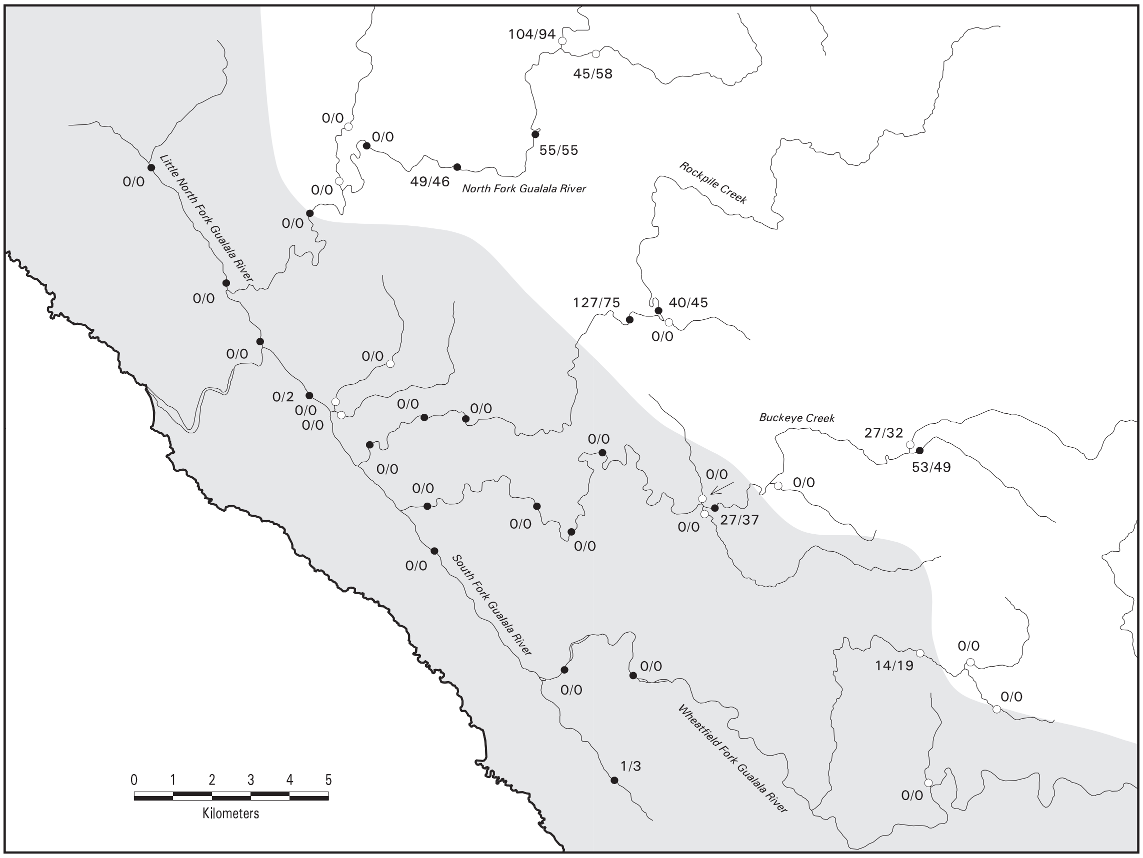


Figure 7.25. Stream network diagram of tributaries and receiving waters in the Gualala River drainage showing the sum degrees above 24°C (SUMDEG24) and the total time spent above 24°C (SUMT24). SUMDEG24 (number on left side) and SUMT24 (number on right side) were calculated from uninterrupted monitoring data collected between July 21 to August 19, 1997. Receiving water (solid circles) and tributary (open circles) monitoring site locations are to scale. Shaded area represents an estimate of the areal distribution of the zone of coastal influence, our best approximation of the fog zone.

into the ZCI exhibited a general decrease in diurnal fluctuation. The change in diurnal fluctuation coincided with the relative magnitude of the daily maximum stream temperature.

Sites outside of the ZCI were predominantly the ones that showed values greater than zero for SUMDEG24 and SUMT24 (Figure 7.25). Only two sites within the ZCI had greater than zero values for these two acute thermal stress metrics. The site with the highest values for SUMDEG24 and SUMT24 was on a tributary to the North Fork, with values of 113°C and 127 hr, respectively. A site within the ZCI on Wheatfield Fork had values of 42°C and 75 hr.

Ten Mile River Drainage

The warmest day in 1998 for the majority of sites in the Ten Mile River drainage was August 4th. Daily maxima and diurnal fluctuations for this day were used to evaluate the hierarchical thermal regimes in the drainage. There were 31 sites that had complete data for the time period July 21 to August 19. SUMDEG24 and SUMT24 were calculated for data in this 30-day window. There were 13 sites on tributaries and 18 on tributary receiving waters.

The three forks of Ten Mile River did not show significant decreases in daily maximum temperatures upon entering the ZCI (Figure 7.26). The North Fork Ten Mile River started with a daily maximum of 20.7°C at 7 km from the watershed divide. Five kilometers downstream on the North Fork, a sensor recorded a daily maximum of 18.3°C. Proceeding downstream approximately 5 km a daily maximum of 19.5°C was recorded. At 22.2 km from the watershed divide the daily maximum was 20.0°C. The last site on the North Fork had a daily maximum of 19.3°C. Thus, the North Fork realized only about a 1°C decrease upon entering the ZCI, even with two cooler tributaries entering the mainstem in the ZCI. The Little North Fork enters from the north and has a watershed area of 1990 ha. It had a daily maximum of 16.2°C (Figure 7.26). The watershed area of the North Fork site upstream from the Little North Fork has a watershed area of 7527 ha. The predicted temperature of the combined flows is 18.9°C, compared to an observed downstream daily maximum of 19.3°C. Thus, the lower water temperature of the Little North Fork seems to account for the decrease in the North Fork temperature.

The Middle Fork begins with a daily maximum of 16.4°C outside the ZCI and begins to increase in temperature as it flows towards the coast. The temperature remained near 19°C, except at one site at a divide distance near 22 km, where the daily maximum dropped about 3°C (Figure 7.26). The temperature stayed fairly constant through the ZCI despite the entrance of four cooler tributaries. The relative watershed areas of the tributaries compared to the mainstem Middle Fork would suggest that they would have a minor influence on the mainstem water temperature. There may be other warmer tributaries entering the Middle Fork for which no temperature data were available. There were no sites spatially situated in the Middle Fork to apply Brown's equation to determine tributary cooling effects.

The South Fork Ten Mile River started out with a daily maximum temperature similar to the Middle Fork, i.e., 16.5°C. Daily maxima increased in a downstream direction and remained between 18.5°C and 20.2°C until reaching about 30 km from the watershed divide, where the daily maximum was 16.5°C. A cool tributary entered the South Fork from the south at about 20 km from the watershed divide and its watershed area was 1019 ha. It had a daily maximum temperature of 15.9°C. The site upstream on the South Fork had a daily maximum of 19.5°C with a watershed area of 4817 ha. The predicted temperature after mixing was 18.7°C, compared to an observed temperature of 18.5°C at about 25 km from the divide.

The cooling influence of the ZCI did not appear to act on the forks of the Ten Mile River as significantly as that observed in the Eel River drainage. The Eel is a much longer system and resides for a longer distance, and hence a longer period of time, in the ZCI than the Ten Mile River system. There may have been insufficient time for water in the Ten Mile River drainage to come into equilibrium with cooler coastal air temperatures.

The diurnal fluctuation of water temperatures in the Ten Mile drainage were small in comparison to the Eel drainage network. The coolest tributaries with small watershed areas exhibited the lowest diurnal fluctuations, ranging from 0.6°C to 3.9°C. Diurnal fluctuations on the mainstems ranged from 1.4°C at the uppermost site on the South Fork to 4.2°C on the North Fork. We evaluated the application of the Brown's equation to diurnal fluctuations and found very good predictive capabilities. On the tributary of the South Fork discussed previously, the predicted diurnal fluctuation was 2.9°C compared to an observed fluctuation of 3.0°C. On the tributary entering the North Fork the predicted diurnal fluctuation was 3.5°C, in complete agreement with the observed value. Thus, cooler tributaries appear to not only decrease the receiving water temperature in an amount proportional to its flow, but also

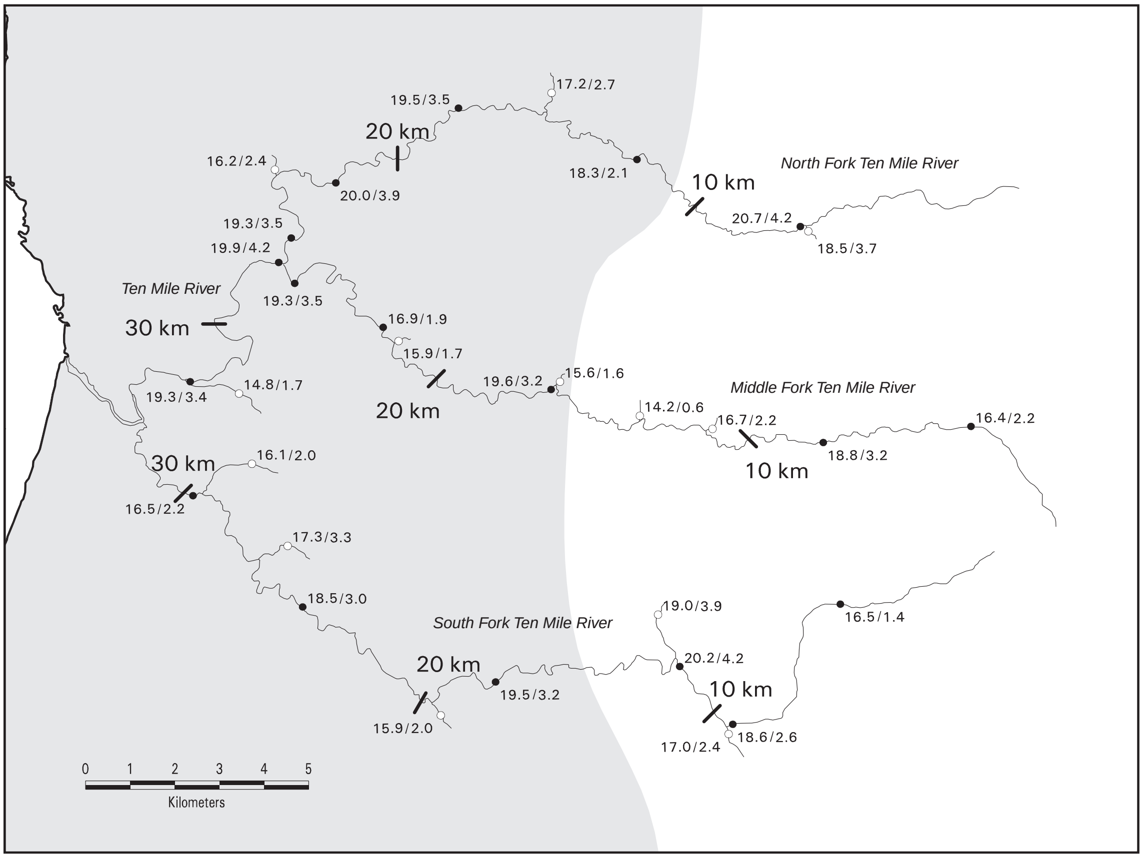


Figure 7.26. Stream network of tributaries and receiving waters in the Ten Mile River drainage showing the daily maximum stream temperatures (°C) (number on left side) and diurnal fluctuations (°C) (number on right side) on July 8, 1998. Receiving water (solid circles) and tributary (open circles) monitoring site locations are to scale. Shaded area represents an estimate of the areal distribution of the zone of coastal influence, our best approximation of the fog zone.

attenuate the diurnal fluctuation of the receiving water.

Examination of the daily maxima and diurnal fluctuations in the Ten Mile drainage revealed that water temperatures were fairly moderate compared to other HUCs. The SUMDEG24 and SUMT24 provide additional evidence that water temperatures were not greatly elevated, in that no values for either acute thermal stress metric had values greater than zero. Nearly half of the drainage network falls within the ZCI, which may partially account for the observed temperatures.

Potential Downstream Influence of Tributaries on Mainstem Temperatures

The downstream distance the cooling or warming influence of tributaries has on receiving waters has been a matter of speculation and debate for many years (Caldwell et al., 1991; Zwieniecki and Newton, 1999). To adequately address such a question, a sampling design needs to be developed specifically to address this issue. The data used in this regional assessment were not collected with any underlying sampling design specifically geared towards answering this question. However, Brown's equation can be used to make an initial examination of this issue with the available data. Many environmental factors will influence the distance a cooling or warming effect will linger downstream, e.g, canopy, depth, flow, gradient, air temperature, groundwater influx, fog zone.

The observed and predicted daily maximum temperatures below various tributaries in the three case study drainages are presented in Table 7.3. The analyses can provide information on the minimum distance receiving water temperatures may have water temperatures near the predicted value after mixing with a cooler or warmer tributary. However, the maximum distance cannot be determined with existing data.

At a distance 10 km below the confluence with Tomki Creek the Eel River exhibited a temperature about 1°C warmer than the predicted value (Table 7.3). At some distance less than 10 km downstream of the confluence the mainstem temperature began to come into equilibrium with riparian and climatic conditions. Two tenths of a kilometer below Outlet Creek the Eel River was 0.4°C below the predicted value. At 10.4 km downstream the Eel was at 28.5°C, within 0.5°C of the predicted value. The Eel River about 6 km below the confluence with the Van Duzen was about 3°C cooler than predicted. The fog zone could account for this discrepancy between observed and predicted values. In the Gualala River drainage, receiving water temperatures were within ~1°C of the predicted value at up to about 5 km downstream from the confluence with cooler tributary temperatures. In the Ten Mile drainage, receiving water temperatures were within 0.5°C of the predicted at distances up to about 5 km downstream of the confluence.

These analyses seem to indicate that the extent of the influence of cooler tributaries on receiving water temperatures is at least partially dependent on the ratio of mixing volumes. The closer the ratio was to 1:1, the closer the observed values were to the predicted and the further downstream the agreement between observed and predicted was realized. That is, the greater the tributary's contribution to the mainstem flow, the greater and longer lasting is the influence of cooler tributary waters on mainstem temperatures. Zwieniecki and Newton (1999) found that slightly warmer stream temperatures within a clearcut area with a buffer zone returned to the predicted trend line temperature at a distance of 150 m. The streams they evaluated were much smaller in size than those examined in Table 7.3. Caldwell et al. (1991) examined Type 4 and 5 stream temperatures in Washington state, and their influence on Type 3 streams. Type 4 and 5 streams are defined by Washington state forest practice rules as small headwater streams that do not support significant fish populations. These would be similar to California's Class 2 and 3 streams. Washington's Type 1-3 streams include, by definition, all large streams and shorelines of the state. Any stream with a late-summer base flow of greater than 0.009 cms (0.3 cfs), and any stream that supports a significant fish population, is classified as Type 1, 2, or 3. The tributaries and receiving waters assessed in Table 7.3 are all Class 1 streams by California forest practice rules definition. Thus, direct comparisons may not be totally appropriate. Caldwell et al. (1991) found that small headwater streams of Type 4 did not have an influence on Type 1-3 streams if their confluence was more than about 7 km (4.5 mi) from the receiving water's distance from watershed divide. The authors used divide distance as a surrogate for stream size and drainage area.

Table 7.3. Comparison of Predicted and Observed Mainstem Temperatures below Tributaries in the Eel, Gualala, and Ten Mile River Drainages.

tributary/mainstem	mainstem:trib. flow ratio	upstream mainstem temp. (°C)	trib. temp. (°C)	predicted downstream mainstem temp. (°C)	observed downstream mainstem temp. (°C)	downstream distance from trib. (km)
Eel River Drainage						
Tomki/Eel	6:1	27.1	27.2	27.1	28.6	10.2
Outlet/Eel	3.2:1	30.2	26.5	29.0	28.6	0.2
					28.5	10.7
Van Duzen/Eel	7.7:1	24.8	22.6	24.5	21.6	5.9
Gualala River Drainage						
Horsethief/Rockpile	9:1	27.1	20.5	26.3	26.3	0.9
Dry/NF Gualala	4:1	23.8	16.1	21.9	21.1	1.1
Wheatfield/SF	2.4:1	23.7	22.9	23.2	22.1	4.6
Franchini-Grass-hopper/Buckeye	6.7:1	26.3	19.0/22.1	25.3	23.7	5.7
Ten Mile River Drainage						
Little Fork NF/NF	3.8:1	20.0	16.2	18.9	19.3	2.4
Church/SF	4.8:1	19.5	15.9	18.7	18.5	4.7

Note: All temperatures are daily maxima. Eel River drainage temperatures measured on August 16, 1997, Gualala River drainage temperatures measured on July 8, 1997, and Ten Mile drainage temperatures measured on August 4, 1998.

The results of a preliminary analysis of a small data set (Table 7.3) suggest that the distance from the divide at which a tributary may have an influence on the receiving stream's temperature is a function of the ratio of flows (or watershed areas being used as a surrogate for flow). The distance downstream the influence lasts is dependent upon the ratio, as well as the characteristics of the receiving water environment and climatic conditions.

Graphs of predicted and observed stream temperatures over a one-week period for each of the sites in Table 7.3 can be found in Appendix D.

Summary

At the ecoprovincial scale watershed position, as represented by watershed area and distance from the watershed divide, played an important role in explaining spatial trends in stream temperature. Stream temperature generally increased with increasing stream size (higher watershed area) and distance from the watershed divide. Stream temperature decreased at the highest divide distances at many mainstem sites. The decrease was attributed to the cooling influence of coastal air temperatures. At a given divide distance daily maximum and daily minimum stream temperatures in the Coastal Steppe Province were less variable than in the Sierran

Steppe Province. Just as the maritime climate tends to moderate air temperature in the CSP, it appears to have a similar effect on stream temperatures.

What is most striking is the consistent increase in the highest daily maximum (XY1DX) stream temperature with increasing distance from the watershed divide in all HUCs that comprise the range of the coho salmon in Northern California. Even in HUCs with large numbers of data points, each point representing a different tributary or mainstem, the increase was consistent. The site's location in the HUC played a large role in explaining stream temperature at any given location.

Stream temperatures in some HUCs showed steeper increases than others. As shown in Chapter 4 and 5 air temperature regimes vary greatly between and within HUCs. In coastal HUCs with large areal portions laying in the interior (e.g., Mad, the four Eel HUCs, and the Big-Navarro-Garcia) air temperature in the interior can be 10° to 15°C warmer than near the coast. Low order streams in these HUCs originate in areas of high air temperatures (~100°F). These coastal-interior oriented HUCs were predominantly the ones showing the steepest rate of stream temperature increase with increasing divide distance.

Coastal HUCs (e.g., Mattole, Smith) showed more moderate longitudinal increases in stream temperature. Streams in coastal-interior HUCs that lie completely within the zone of coastal influence also showed a moderate longitudinal increase in stream temperature. Streams that originate outside of the ZCI and flow into the ZCI often showed a decrease in water temperature.

Sum degree is comparable to degree days as a means of quantifying cumulative warmth in a season or year at a given location. It is a measure that takes into account both magnitude and duration of departure from a chosen threshold temperature. At some sites where traditional temperature metrics, such as the highest daily maximum or highest seven-day moving average, did not exceed acute or chronic thermal threshold values, sum degree was higher than at sites where traditional metrics did not exceed thresholds. While there is little documented use of sum degree or degree day in assessing thermal stress on aquatic biota, it is hoped that the use of this metric will increase. Development of sum degree thresholds is needed to lend biological relevance to this metric. Reanalysis of existing stream temperature data where fish presence/absence and/or abundance data were also collected, such as the work of Essig (1998) on streams in Idaho, would be useful for establishing sum degree thresholds.

Application of Brown's mixing equation revealed very good predictions in receiving water temperature change below the confluence with a warmer or cooler tributary. The closer the downstream mainstem site was to the confluence, the better the agreement between observed and predicted water temperature. With increasing distance below a confluence, the mainstem is probably beginning to adjust to new equilibrium conditions of air temperature, groundwater influx, canopy, and other riparian conditions. The downstream extent to which a tributary influences mainstem temperatures could not be determined from our meta-analysis. The downstream influence appears to be a function of discharge ratio (watershed area used as a surrogate for discharge).

While the predicted temperature of the Eel River below Outlet Creek was surprisingly close to the observed value, caution should be used in applying watershed area as a surrogate for flow in these types of calculations. This is especially prudent in systems that are strongly influenced by flow regulation, and reach very low summer baseflows, such as the Eel River system.

When establishing stream temperature goals for maintenance of certain beneficial uses, watershed position is an important consideration. A natural gradient in stream temperature occurs from the headwaters to the lower reaches. This natural gradient produces discrete zones with temperature regimes suitable for distinctly different fish communities and activities (Armour, 1991). Stream temperature standards should be developed with an understanding of the natural temperature regimes in HUCs throughout the range of the coho salmon in Northern California.

Chapter 8

INFLUENCE OF SITE-SPECIFIC ATTRIBUTES ON STREAM TEMPERATURES

Introduction

In Chapters 6 and 7, trends in stream temperatures observable at broad regional scales were investigated. An appreciation of the climatic regimes that are imposed upon streams across Northern California is useful to gain a better understanding of status and trends in water temperature at smaller spatial scales (e.g., watersheds, streams, reaches). Such an appreciation enables one to place watersheds and streams in the context of the "big picture."

This chapter zooms in to a finer spatial scale to examine the influence of various site-specific attributes on stream temperature. These attributes were unfortunately limiting in terms of sample size. For years prior to 1998, values for many site-specific attributes that required measurement in the field were missing for many sites. Therefore, temperature and site-specific attribute data for 1998 were primarily used in this chapter. The site-specific attributes examined in this chapter are channel orientation, gradient, habitat type, and bankfull width.

Channel orientation seems to have an influence, although not a significant influence, on daily maximum stream temperatures. The daily maximum temperature near the solar equinox was greater in the east-west (EW) channel orientation than the north-south (NS). While it was expected that a greater channel orientation signal would be apparent in the 0-24% canopy class, the greatest differences between EW and NS daily maximum temperature was observed in the intermediate canopy classes (25-49% and 50-74%). Observed trends may simply be an artifact of site location and lack of a sampling design specifically developed to address the channel orientation issue.

Stream temperatures generally decreased with increasing channel gradient. This is most likely because sites with higher gradients are generally closer to the headwaters. Riffle and run sites had average stream temperatures only slightly higher than shallow pool sites. Deep pool sites exhibited the highest average daily maximum stream temperatures. The geographic distribution of all habitat types was not uniform in 1998. A large number of deep pool sites were located in the southern portion of the SONCC ESU where air temperatures are warmer than the northern portion of the ESU. Additionally, most of the deep pool sites were located in large systems, such as the lower Eel River, where the stream is potentially too wide for stream-side vegetation to provide adequate canopy. Canopy closure was less than 20% in 36 out of the 41 deep pool sites. The disproportionate geographical distribution of deep pool sites and the low canopy associated with these sites could account for their higher daily maximum stream temperature average. Stream temperatures generally showed an increasing trend with increasing bankfull width. The sample size was too limited to draw definitive conclusions. As bankfull width increases, effective stream-side shading is reduced. Moreover, sites are usually at greater watershed areas and divide distances at higher bankfull widths.

Influence of Channel Orientation on Stream Temperatures

Streams with generally north-to-south or south-to-north flows have relatively shorter periods of direct overhead solar radiation than do east-to-west or west-to-east flowing streams (Sullivan et al., 1990). Arguments for both EW and NS having higher stream temperatures have been made. Given the east-to-west solar path and the solar zenith during the summer months, riparian vegetation along E-W or WE flowing streams might contribute greater shade than NS or SN flowing streams. Topographic relief, if higher than the solar zenith angle, could also provide shade in EW/WE streams. Direct sun would only intercept EW stream surfaces in the early morning and late afternoon, a time when solar heat energy is near a minimum. The alternative argument that EW streams may have higher stream temperatures is that NS oriented streams have relatively short periods of direct overhead solar radiation (Sullivan et al., 1990). Therefore, riparian shade might be less important on NS oriented streams than along EW oriented streams. Both are valid arguments, which leads to the formulation of the null hypothesis, that water temperatures in streams with NS or EW orientations are not significantly different.

The relationship between channel orientation and the highest seven-day moving average of the daily average (XYA7DA) and daily maximum (XYA7DX) and the highest daily maximum (XY1DX) was investigated. Channel orientation was derived in GIS for each site by measuring the downstream bearing of the channel over a distance of approximately 600 meters upstream from the temperature sensor location to the nearest degree. Six hundred meters is our best estimate of the length of a thermal reach that could be applied across all streams. This may be an overestimate or underestimate of the length of a thermal reach at some sites, depending on the size and flow of the particular stream.

Distribution of Channel Orientations

The distribution of channel orientations for sites monitored in 1998 is presented in Figure 8.1. Similar distribution graphs of channel orientation for data collected in 1990 through 1997 can be found in Appendix E. Orientations were grouped into 30-degree classes starting at 345°. Orientations from 345° to 15° (a thirty-degree class) are shown on the graph as a vertical bar between the x-axis origin at 345° and 15°. Orientations from 15° to 45° are represented by the vertical bar between 15° and 45°, and so forth for the other 30-degree classes. The cumulative proportion of sites in each channel orientation class is overlaid on the graph.

With an understanding of the hydrology and basin characteristics of Northern California it is not surprising to find that there were fewer streams in the 0° to 90° and 90° to 180° orientation classes (Figure 8.1). These classes represent streams that flow in a northeasterly to easterly or southeasterly to southerly direction. Many of the Northern California basins and watersheds within basins have northwesterly and southwesterly orientations. However, streams can meander or follow tortuous geologic formations over some portions of their total length in a NE, E, or SE direction.

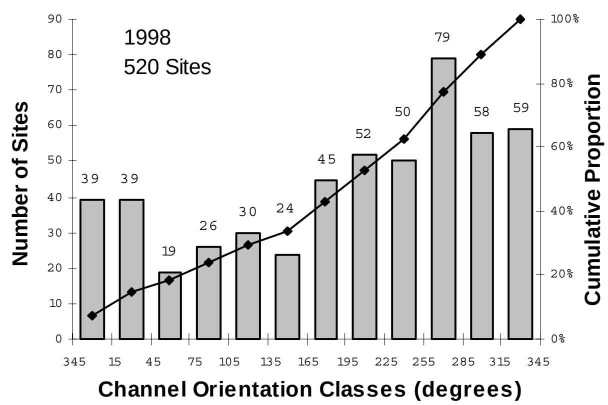


Figure 8.1. Distribution of stream temperature monitoring sites by channel orientation classes. Orientation was derived in GIS at a point ~600 meters upstream from the stream temperature monitoring site. Orientation is in a downstream direction.

Polar Plots of Stream Temperature

Figure 8.2 is a presentation of polar plots showing the highest daily maximum temperature (XY1DX) for each site by year, plotted with respect to channel

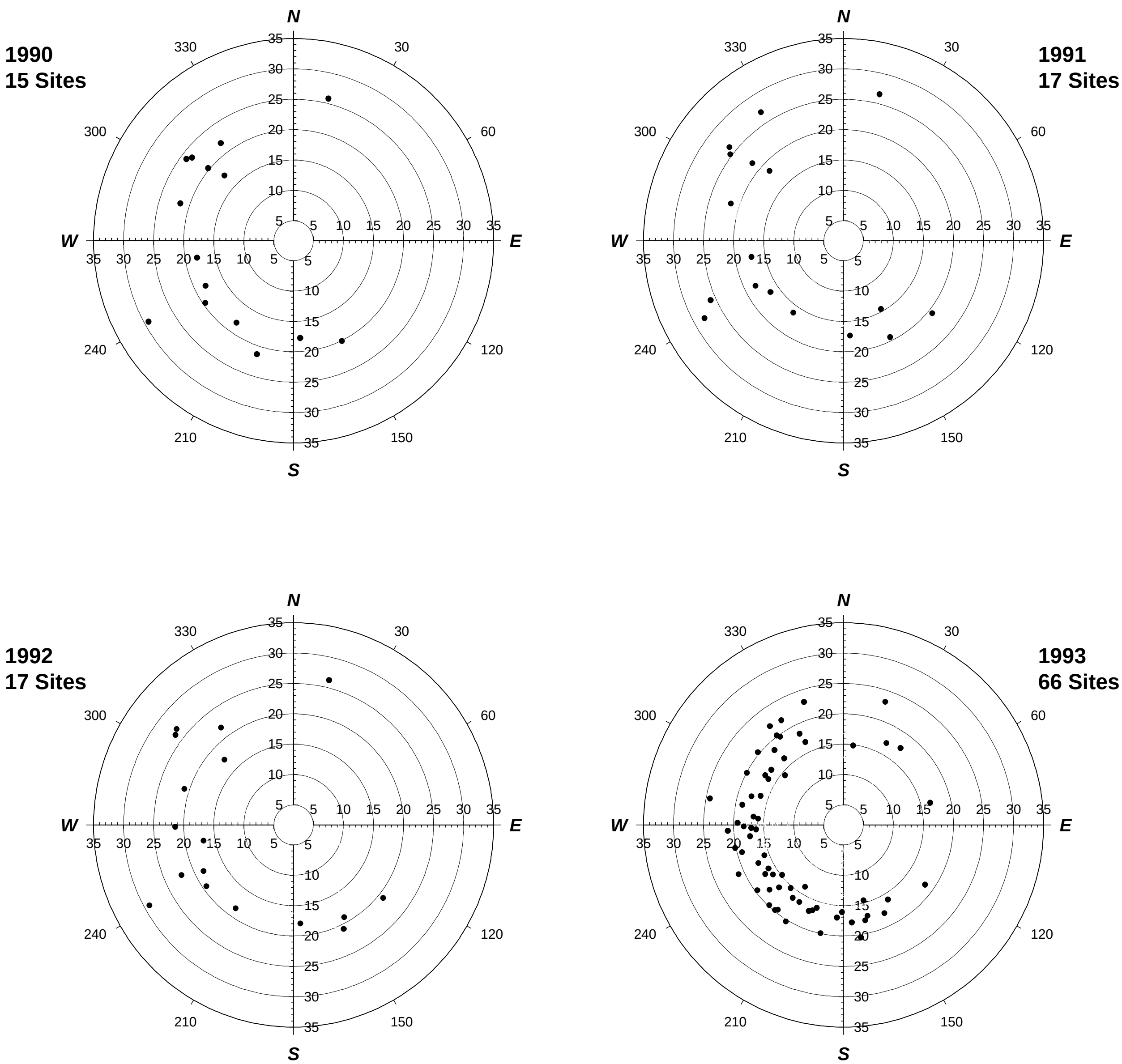


Figure 8.2. Highest daily maximum stream temperature (°C) with respect to channel orientation (degrees) for years 1990 - 1998. Orientation was derived in GIS over the reach ~600 meters upstream from the stream temperature monitoring location. Orientation was determined in a downstream direction along the 600-m reach.

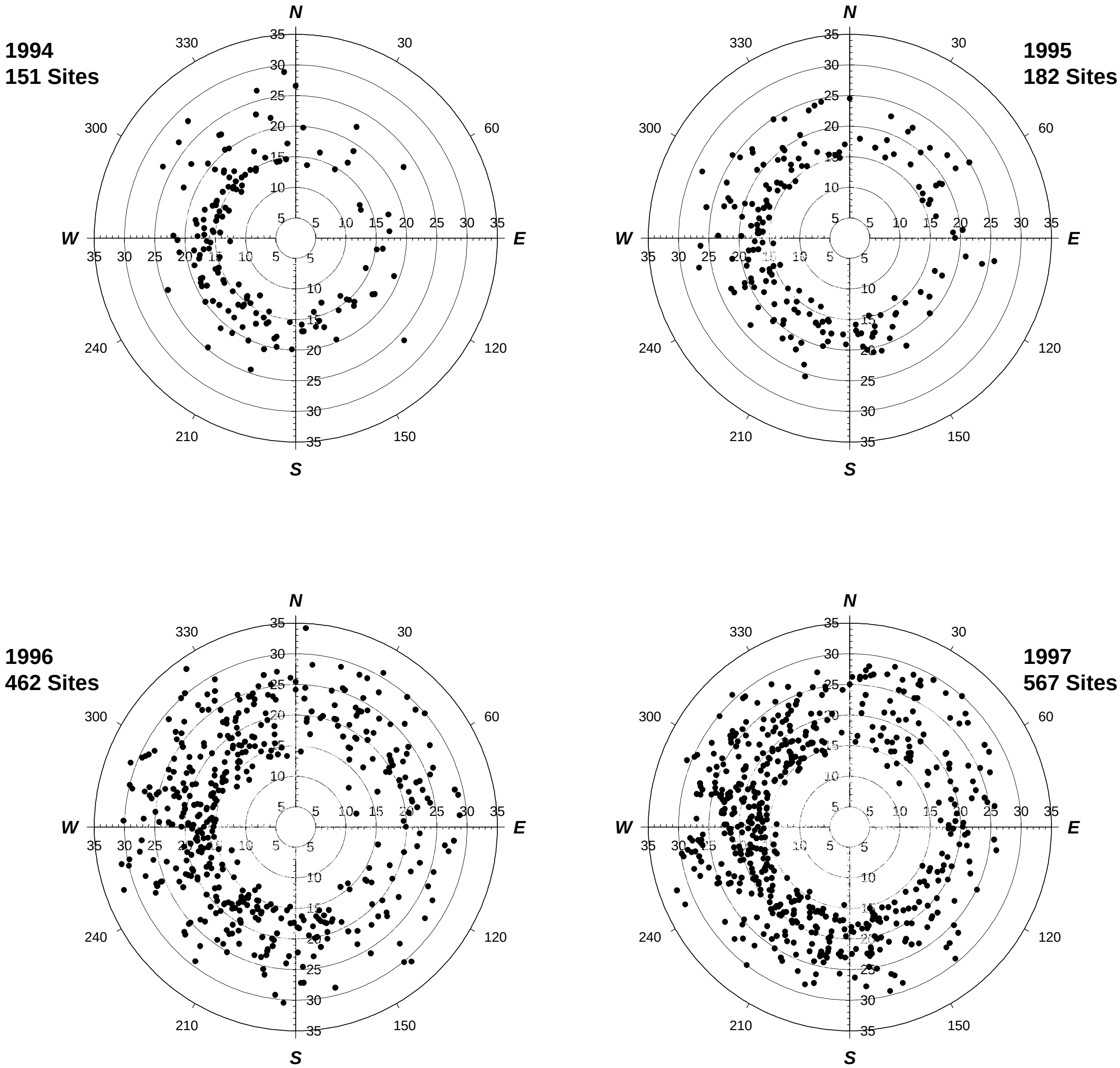


Figure 8.2. (continued)

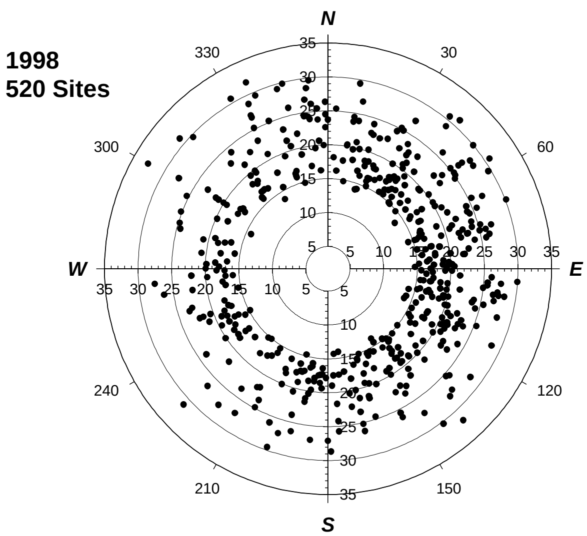


Figure 8.2. (continued)

orientation. The temporal window from July 21 to August 19 was imposed upon the data to ensure that the highest temperature values were indeed the "true" highest. Sites with no more than five missing daily records within the one-month temporal window were used in the analyses.

Visual examination of the polar plots in Figure 8.2 did not reveal any obvious trends. The polar plots can be visually misleading by virtue of the distribution of channel orientations. There were more data points in those sectors that had a greater occurrence of sites with a given channel orientation. Careful inspection of the polar plots does not indicate a preponderance of higher XY1DX values in any particular sector. Similar polar plots for the XYA7DA are presented in Appendix E.

Further graphical and statistical treatments of the data were performed and are presented in the following sections.

Graphical and Statistical Analyses by Orientation Classes

Channel orientations were grouped into two classes, north-south or south-north (**NS**) and east-west or west-east (**EW**):

NS

$330 \leq \text{orientation} \leq 30$

OR

$210 \geq \text{orientation} \geq 150$

EW

$120 \geq \text{orientation} \geq 60$

OR

$240 \leq \text{orientation} \leq 300$

A thirty-degree range on either side of the major compass points (N, S, E, and W) was chosen for orientation classes to remove orientations that fell between NS and EW (Figure 8.3).

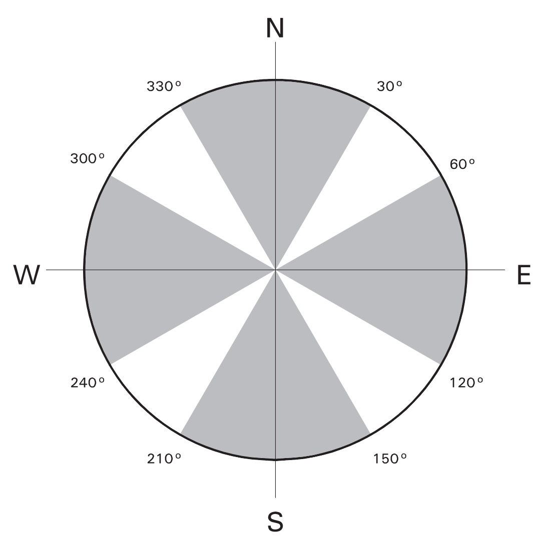


Figure 8.3. North-South and East-West channel orientation classes used to assess the influence of channel orientation on stream temperatures. Shaded area represents 30 degrees on either side of cardinal directions.

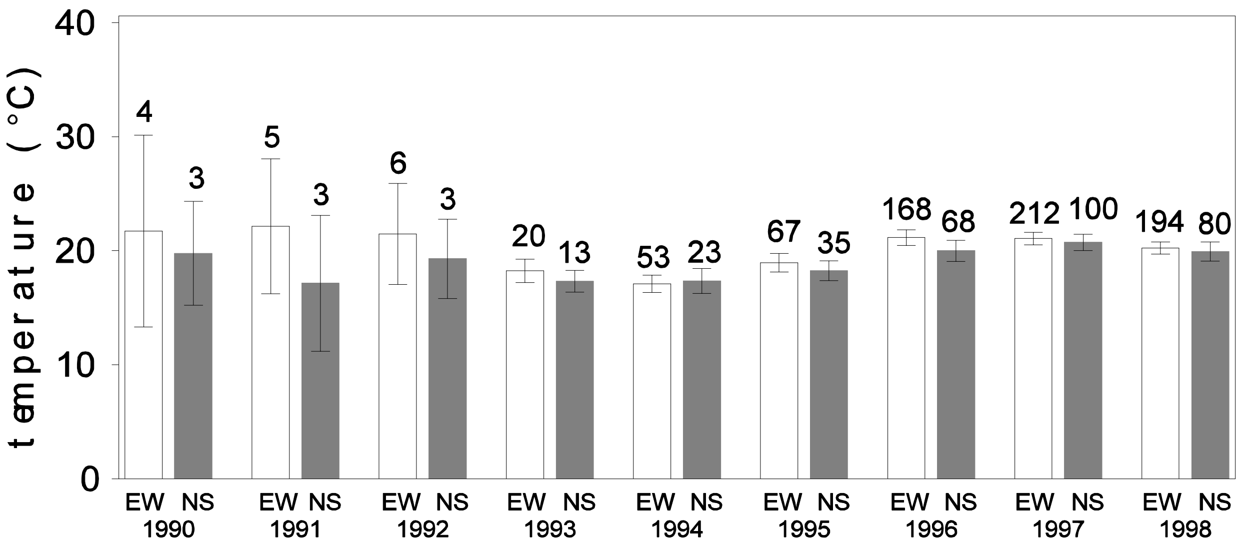


Figure 8.4. Average of the highest daily maximum stream temperature by orientation class and year. EW = streams with orientations flowing east-west or west-east; NS = streams with orientations flowing north-south or south-north. Error bars represent two standard deviations. Number of sites in each orientation class is shown above the error bars.

These borderline orientations would include channel orientations such as NNE, NSE, SSW, and NNW. These borderline orientations could possibly obscure any discernable trends in stream temperature with respect to channel orientation.

Figure 8.4 shows the class average XY1DX by orientation class and year. The error bars represent plus or minus two standard deviations. The EW group exhibited higher average temperatures compared to the NS group for each yearly comparison. The differences between EW and NS average temperatures lessened in 1997 and 1998, probably due to a greater sample size with greater representation of streams in each of the channel orientation classes. Error bars overlapped between orientation classes within each yearly comparison. No significant difference was discernable between the NS and EW orientation classes in any of the nine years as exhibited by the overlap in error bars. Comparisons should be made between orientation classes within a given year **only**, since different sites were monitored in each year.

An analysis of variance (ANOVA) was performed using the PROC GLM procedure in SAS (1985), the preferred procedure for unbalanced designs. Both *orientation class* and *year* were used as independent variables in the model, with an interaction term included (Table 8.1).

Table 8.1. ANOVA Results of Highest Daily Maximum Stream Temperature Versus Channel Orientation and Year and the Interaction Term.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	508.95415	169.65138	11.23	<0.0001
orientation class	1	14.1398854	14.1398854	0.94	0.3335
year	1	411.6886690	411.6886690	27.26	<0.0001
year*orientation class	1	14.0875693	14.0875693	0.93	0.3344

Results of ANOVA shown in Table 8.1 indicate that the model was significant, with a probability of <0.0001. However, the largest source of variability in XY1DX was explained by the *year* model term. Significant differences in the XY1DX across years was expected due to the different sites that were monitored across years. The *orientation class* and *year*orientation class* terms in the model were not significant. Similar statistics performed on the highest seven-day moving average of the daily average and the highest seven-day moving average of the daily maximum returned similar results. Also, scientific curiosity led to the examination of the lowest daily minimum temperature metric with respect to channel orientation. No significant relationship was found.

These findings are consistent with other researchers (Swift and Messer, 1971; Sullivan et al., 1990) who found that channel orientation did not account for differences in stream temperatures. Sullivan et al. (1990) found that in streams flowing easterly or westerly, there appeared to be a slightly lower maximum and mean stream temperature and diurnal fluctuation. Unfortunately, in the Timber, Fish, and Wildlife Study (Sullivan, 1990) there were relatively few streams that flowed EW or WE, and those that did were partially shaded, making comparisons tenuous. Although the relationship between channel orientation and stream temperature is not strong, some states' forest practice guidelines have in the past conditioned buffer-strip shade requirements based on channel orientation.

Channel Orientation and Canopy

The interaction between channel orientation and canopy was examined for streams in Northern California. The streams used in the examination of the influence of channel orientation on stream temperature consisted of a diversity of channel widths and canopy closure values. Sites with non-null canopy values were used to examine the relationship between stream temperature versus channel orientation and canopy. The year with the least number of null values for canopy was 1998. The same channel orientation classes (NS and EW) and canopy classes (0-24%, 25-49%, 50-74%, and 75-100%) were used to group stream temperature sites. At lower canopy classes, higher XY1DX values were observed. Within canopy classes there was no significant difference between average XY1DX values observed in each channel orientation class. Table 8.2 shows ANOVA results for the comparison. *Canopy class* was a significant model term explaining the variability in the highest daily maximum stream temperature. *Channel orientation* was not significant singly or in its interaction with the *canopy class* term.

The highest 1998 daily maximum temperature at each site usually occurred during the last two weeks in July and first two weeks in August. This was true for all years in our data set. The sun azimuth is lower during this time of year than near the time of the summer equinox. The influence of channel orientation and canopy on stream temperature may be more pronounced near the solar equinox. The daily maximum stream temperature observed at each site on June 26, 1998 and the highest 1998 daily maximum were compared. Not all sites with XY1DX values had stream temperature data for 26 June 1998. Therefore, to make valid comparisons, the same sites must be compared. Only XY1DX values for sites that had valid 26 June daily maxima were used in the comparison. Figure 8.5 indicates that there was a larger difference between EW and NS 26 June daily maxima in the two intermediate canopy groups

Table 8.2. ANOVA Results of Highest Daily Maximum Stream Temperature (XY1DX) Versus Channel Orientation and Canopy Classes and the Interaction Term.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	1133.584474	161.940693	16.28	<0.0001
orientation class	1	6.5332162	6.5332162	0.66	0.4186
canopy class	3	935.2782947	311.7594316	31.35	<0.0001
orientation*canopy	3	65.5386644	21.8462215	2.20	0.0898

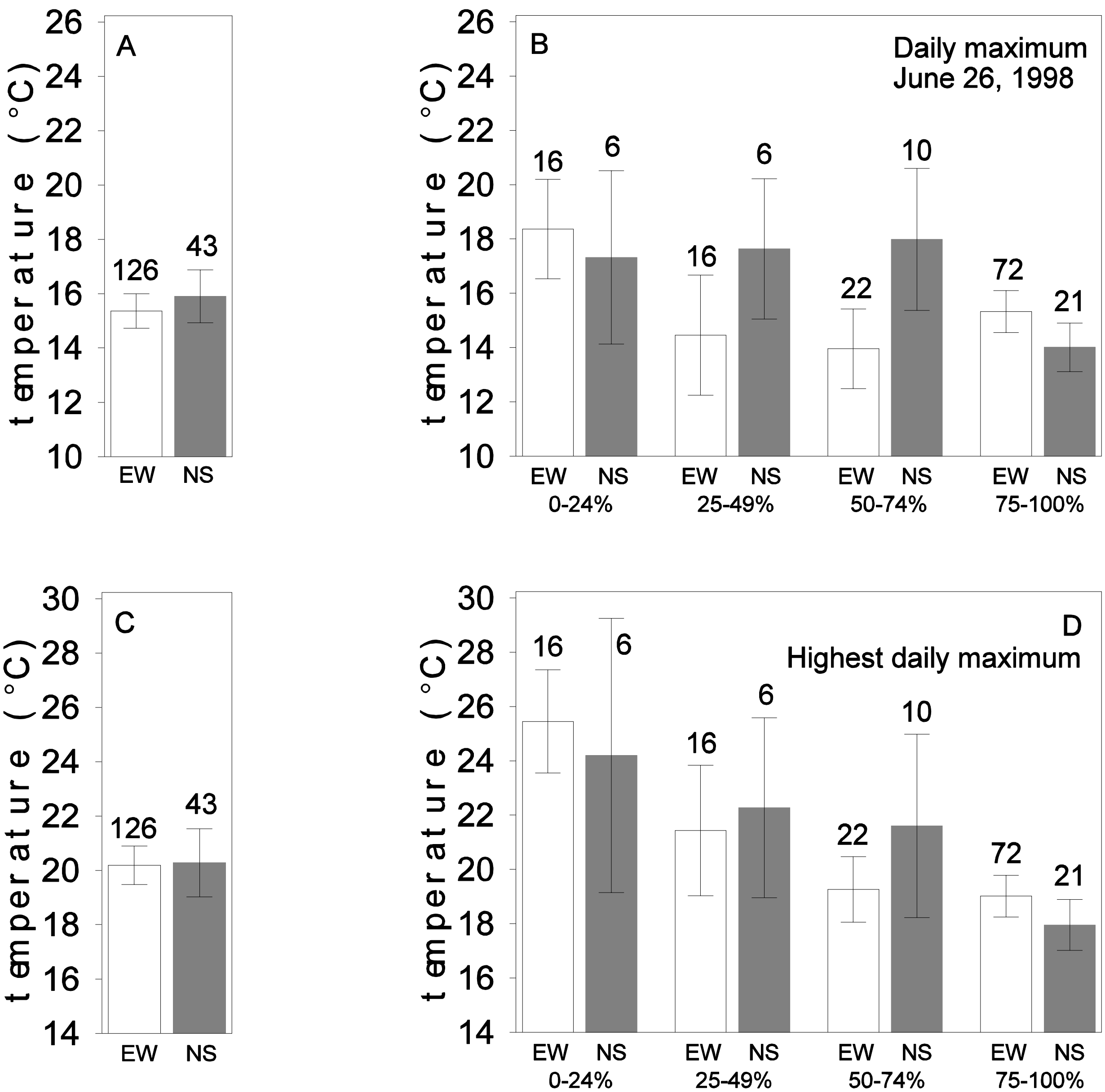


Figure 8.5. Comparison of the daily maximum stream temperature measured on 26 June 1998 and the highest 1998 daily maximum by orientation class and canopy class. (A) 26 June daily maximum by orientation class, (B) 26 June daily maximum by orientation class and canopy class, (C) highest 1998 daily maximum by orientation class, and (D) highest 1998 daily maximum by orientation class and canopy class. EW = streams with orientations flowing east-west or west-east; NS = streams with orientations flowing north-south or south-north. Number above error bar is the number of sites in the orientation class.

(Figure 8.5-B) compared to the XY1DX values that occur later in the year (Figure 8.5-D). While there seems to be a stronger channel orientation signal in the 26 June daily maximum stream temperatures, the reason the signal only appears in the 25-49% and 50-74% canopy classes is unclear. Topographic shading may account for the lower daily maxima observed in the NS orientation group at the lowest and highest canopy classes. Moreover, differences in canopy measurement procedures and varying channel lengths along which canopy was measured upstream from the stream temperature sensor may partially explain the results. A study specifically designed to address the channel orientation issue is warranted.

Streams with wide channels have a reduced shading effectiveness from stream-side vegetation because of the distance of the canopy from the stream. Streams with such wide channels would most likely show very little correlation between stream temperature and channel orientation. Out of 548 sites with 1998 stream temperature data, 365 had non-null canopy values. Of these 365 sites, 203 fell within one of the four orientation quadrants (Figure 8.3). Of these 203 sites used to assess the relationship between canopy and channel orientation, the five smallest watershed areas (21, 85, 93, 142, and 149 hectares) in the data set all had canopy values greater than 90%. Of the 203 sites, the five largest watershed areas had canopy values of 50, 0, 0, 1, and 0%. The 50% value may be anomalous. Some investigators placed temperature probes in side channels of lower mainstem rivers to characterize the extent of thermal refugia. Side-channel canopy values could potentially be higher than wider, mainstem channels.

To assess the interaction between canopy and channel orientation on water temperature in streams of similar size, an arbitrary watershed area of ≤18,000 ha was used to subset the 1998 data. Using the relationship between drainage area and bankfull width shown in Figure 8.6, a drainage area of approximately 18,000 hectares (~70 square miles) corresponds to a bankfull width of ~12 m (~40 ft). This watershed area and corresponding bankfull width would potentially be capable of providing riparian shade given adequate canopy retention. The distance where streams may become too wide for stream-side vegetation to provide adequate shading is empirically developed using FSP data in Chapter 9 - Canopy.

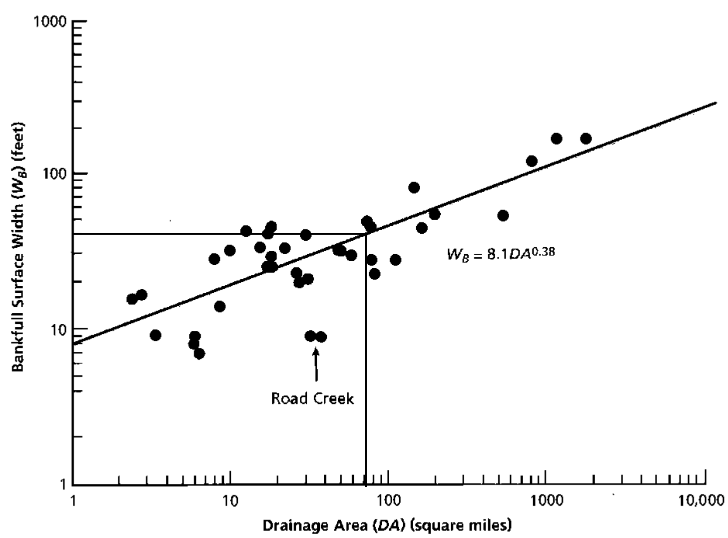


Figure 8.6. Bankfull surface width versus drainage area - Upper Salmon River, Idaho. Local variations in bankfull width may be significant. Road Creek widths are narrower because of lower precipitation. Taken from FISRWG (1998).

The relationship between XY1DX, channel orientation, and canopy class was examined for sites with watershed areas less than or equal to 18,000 ha. ANOVA revealed that no significant difference in XY1DX existed between channel orientation within each canopy class. However, there was a significant difference in XY1DX between canopy classes.

Sullivan et al. (1990) found that EW oriented streams had slightly lower diurnal fluctuations than NS oriented streams. This relationship was examined for the average diurnal fluctuation for the time period between July 21 and August 19, 1998, for 243 FSP sites. Diurnal fluctuation values (daily maximum - daily minimum) for 274 FSP sites and 243 FSP sites with watershed areas less than or equal to 18,000 ha (~70 sq mi) did not reveal any significant differences between channel orientation classes (Figure 8.7).

Canopy/channel orientation interaction and average 1998 diurnal stream temperature fluctuation was examined for FSP sites with watershed areas less than or equal to 18,000 ha. The results are presented in Figure 8.8. Similar to the comparison of XY1DX (Figure 8.5), there was no significant difference in the diurnal fluctuation between each channel orientation class within a given canopy class (Figure 8.8).

There appears to be a slightly higher diurnal fluctuation in the EW orientation group for the 0-24%, 25-49%, and 75-100% canopy classes, although the differences were not significantly different from the NS orientation group. Greater sample size is required in the lower canopy classes in each of the channel orientation classes to definitively determine whether a difference actually exists.

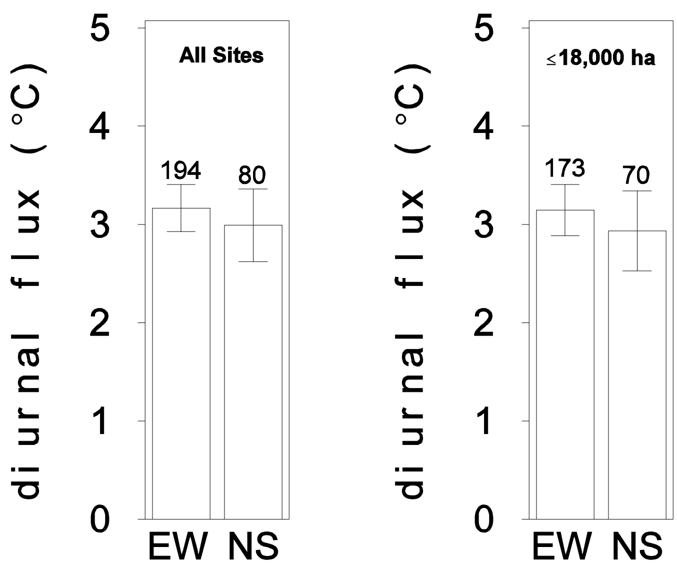


Figure 8.7. Comparison of average diurnal fluctuation by channel orientation class. Diurnal fluctuation averaged for July 21 through August 19, 1998. All sites (A) and sites with watershed area less than or equal to 18,000 ha (B).

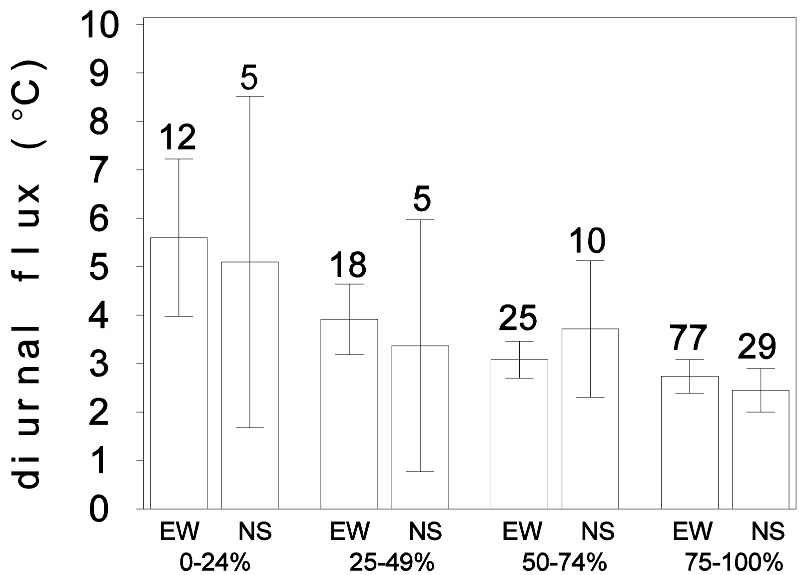


Figure 8.8. Average 1998 diurnal temperature fluctuation by orientation class and canopy class for 181 sites with watershed area less than or equal to 18,000 hectares (~70 sq. mi.). EW = streams with east-west or west-east orientations; NS = streams with north-south or south-north orientations. Error bars represent two standard deviations. Number of sites in each orientation class is shown above the error bars.

Influence of Channel Gradient on Stream Temperatures

Channel gradient is an important factor influencing stream temperature. Gradient may be correlated with other variables such as flow, bankfull width, elevation, distance from watershed divide, and channel type. While gradient is correlated with other variables, it may be more responsive to more localized channel characteristics that are not discernable with other independent variables. Gradient may serve as a surrogate for flow, and hence its significance and inclusion in the empirical models described in Chapter 10. Very few flow measurements were collected by FSP cooperators, too few to be used in a regional assessment.

Channel gradient is determined by measuring the change in vertical distance over a given horizontal distance. Gradient may be expressed in m/km, ft/mi, or percentages. Channel gradient was a GIS-derived variable in FSP's stream temperature assessment.

The average gradient along a 600-m reach upstream from the stream monitoring point was determined using an Avenue script macro program executed in Arc View. A 30-m digital elevation model was used with digital raster graph images of 1:24,000 USGS quadrangles. A more detailed description of the procedure can be found in Chapter 2 - Methods. The avenue script code can be found in Appendix A.

Figure 8.9 shows the distribution of channel gradients for streams where temperature was monitored in 1998. There were 60 sites with gradients of zero. There were 23 sites that had negative values due to their low gradients and the inability to determine these low gradient streams with existing digital elevation models. Gradients ranged from zero (including negative gradient values) to 24%, with about 80% of the sites having gradients between zero and 5%. Thus, a large majority of temperatures was measured at sites with gradients potentially suitable for coho salmon.

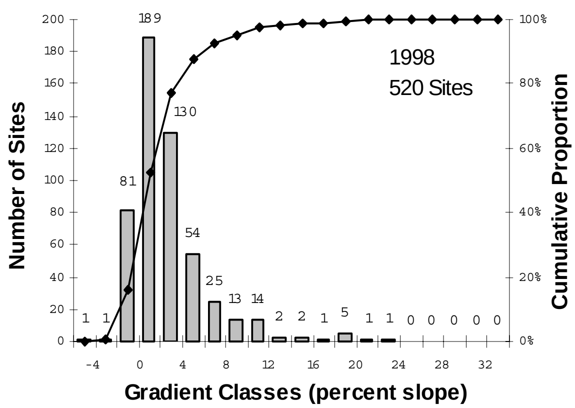


Figure 8.9. Distribution of 1998 stream temperature monitoring sites by channel gradient classes. Gradient was derived in GIS along a ~600-m reach upstream from the stream temperature monitoring site.

Variation in the highest 1998 daily maximum stream temperature (XY1DX) with channel gradient is presented in Figure 8.10. There was a decreasing trend in XY1DX with increasing gradient. This trend may have several underlying mechanisms. As gradient increases, the distance from the watershed divide and drainage area decreases. Stream temperatures are expected to be cooler closer to the headwaters. Streams become narrower at higher gradients, thereby making riparian vegetation more effective in providing shade.

The average XY1DX for all channel gradient classes (Figure 8.10-A) was less than 26°C, the upper lethal incipient threshold for juvenile coho salmon. Subtracting a two-degree safety margin from the upper lethal incipient threshold, as suggested by Coutant (1972), offers another reference temperature which to compare stream temperatures against. None of the channel-gradient-class XY1DX averages exceeded the safety-margin reference value (Figure 8.10-B). However, examination of the scatter plot shows that at many sites, both the 26°C and 24°C reference values were exceeded. At channel gradients greater than approximately 10%, temperatures did not exceed the lower reference value. However, channel gradients greater than 10% are probably too steep to serve as potentially suitable habitat for juvenile coho. Steelhead trout can be found in high-velocity/high-gradient streams (Barnhart, 1986).

Analysis of variance using the PROC GLM procedure in SAS (SAS, 1985) revealed that for 518 sites in 1998, channel gradient explained about 10% of the variability in XY1DX, XYA7DA, and XYA7DX. All three models had significant F values. Channel-gradient class averages for the three temperature metrics were significantly different at the 0.0001 level. Channel gradient was considered an important variable for inclusion in the empirical models presented in Chapter 10. The four gradient classes were used as categorical variables in the models.

Influence of Habitat Type on Stream Temperatures

While the Forest Science Project Stream Temperature Protocol (Appendix A) calls for placement of temperature sensors in well-mixed habitats, e.g., riffles and runs, many data contributors placed their sensors in pools. There was no overriding sampling design. Each organization had their own objectives for monitoring temperature, which often included characterization of the extent of cold water refugia.

Figure 8.11 presents the distribution of sites monitored in 1998 by habitat type. Out of 518 sites for which complete, uninterrupted temperature data were available between July 21 and August 19, 466 sites had non-null habitat type values. About 50% of the sites were in either riffles or runs. The remaining 50% were in shallow pools, medium-depth pools, or deep pools.

Figure 8.12 shows the average XY1DX for each habitat type. Riffle and run sites had average XY1DX values only slightly higher than SPOOL sites. DPOOL sites exhibited the highest average XY1DX. The geographic distribution of all habitat types was not uniform in 1998. A large number of DPOOL sites were located in the southern portion of the SONCC ESU where air temperatures are warmer than the northern portion of the ESU. Additionally, most of the DPOOL sites were located in large systems, such as the lower Eel River, where the

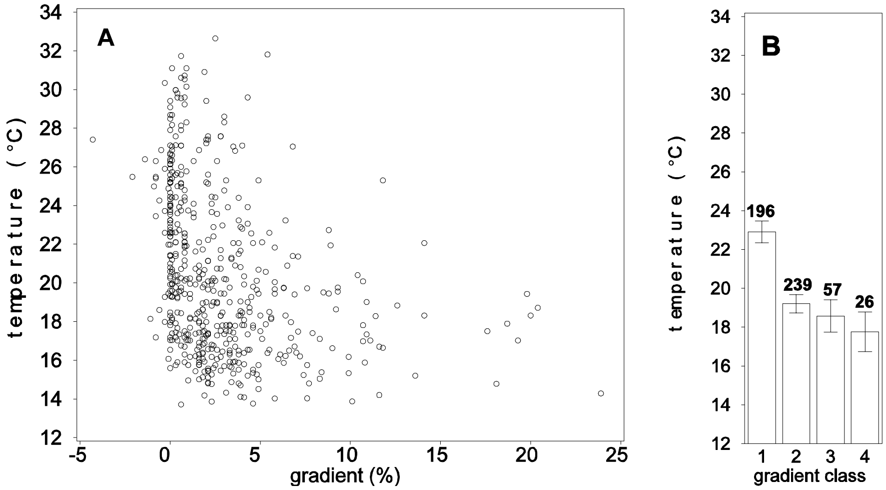
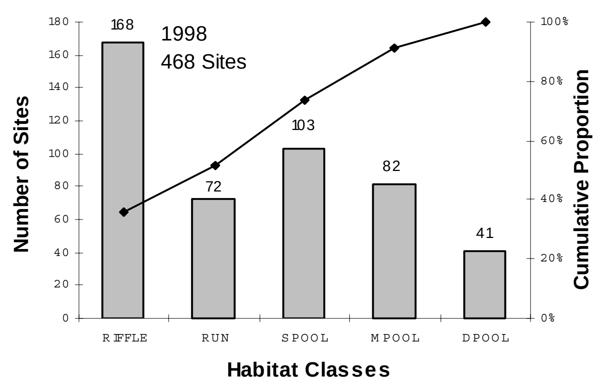


Figure 8.10. Variation in the highest 1998 daily maximum stream temperature (XY1DX) with channel gradient. Scatter plot (A) and bar chart (B). Gradient classes are 1 = <1%, 2 = 1% to <5%, 3 = 5% to <10%, and 4 = >10%. Gradient was derived in GIS along a ~600-m reach upstream from the stream temperature monitoring site.

Figure 8.11. Distribution of 1998 stream temperature monitoring sites by habitat type. Plotted line is the cumulative proportion. SPOOL = shallow pool less than 2 ft in depth, MPOOL = medium-depth pool 2 to 4 ft in depth, DPOOL = deep pool greater than 4 ft in depth or pools suspected of maintaining thermal stratification.



stream is too wide for streamside vegetation to provide adequate canopy. Canopy closure was less than 20% in 36 out of the 41 DPOOL sites. The disproportionate geographical distribution of DPOOL sites and the low canopy associated with these sites could account for their higher XY1DX average.

Comparing temperatures in different habitat types across broad geographic areas may be inappropriate, as shown in Figure 8.12, unless the sites are placed in proper geographic context. In any given stream, deep pools are expected to be cooler than riffles or runs from the same stream. A misleading view of stream temperatures can result by having a preponderance of deep pools in a restricted (warmer) geographic area and in predominantly large stream systems. The habitat types used in this assessment are relative terms. A deep pool in a low-order stream may be similar, at least in terms of depth, to a riffle or run in a high-order stream.

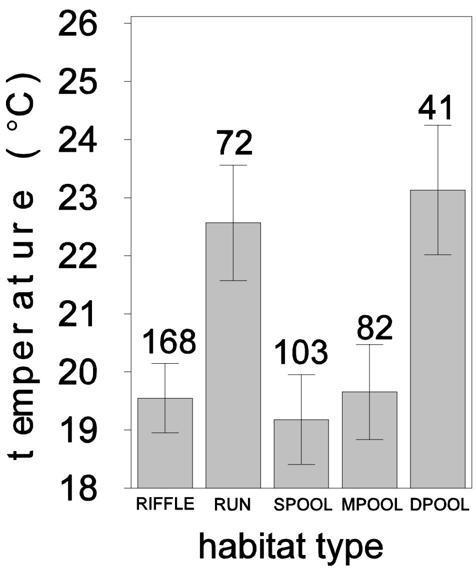


Figure 8.12. Average of the highest 1998 daily maximum stream temperature by habitat type. Habitat types are defined in Figure 8.11 caption. Error bars represent ±2 standard deviations. Number of sites in each habitat type are shown above error bar.

Influence of Bankfull Width on Stream Temperatures

The number of sites for which bankfull width was provided was somewhat limited. In 1998 there were 176 sites for which bankfull width was available. The frequency distribution of 1998 bankfull width values is shown in Figure 8.13-A. Approximately 90% of the sites had bankfull widths less than 32 m. This is the width at which canopy is estimated to become too wide for riparian vegetation to effectively shade streams (See Chapter 9). Figure 8.13-B shows a general increase in stream temperature with bankfull width. Bankfull width is correlated with divide distance and watershed area.

Bankfull width is an important variable in all of the process-based models compared by Sullivan et al. (1990). In empirical models developed by Sullivan et al. (1990) for 36 sites in Washington, bankfull width was highly significant in explaining the variability in stream temperature. In the present study, about 44% of the variability in the highest daily maximum stream temperature was predicted by $\log_{10}$ bankfull width. However, this was based on a small sample size. There is a strong correlation between bankfull width and discharge (Bartholow, 1989). All the heat flux processes in the SSTEMP model, and other process-based models, occur at the air-water or water-ground interface, both interfaces being functions of stream width. Bankfull width is negatively correlated with canopy closure. As streams widen, the ability of riparian vegetation to provide effective shading is diminished. The interplay between bankfull width and canopy is discussed in Chapter 9.

Interactions

The variables discussed in this chapter are strongly correlated with other stream characteristics, such as canopy, divide distance, watershed area, and elevation. Table 8.3 presents a Pearson correlation matrix for three site-specific attributes (channel orientation, channel gradient, and bankfull width) examined in this chapter, canopy (discussed in Chapter 9), and three watershed variables (divide distance, watershed area, and elevation).

The site-specific variables presented here may integrate a cadre of factors that influence stream temperature. However, many of the correlating variables are easier to estimate. Most of the correlating variables were derived in GIS. However, in predicting stream temperatures using variables that correlate well with certain site-specific attributes one loses some amount of site-specific information. In our study, we gain significant numbers of observations by using correlated variables rather than site-specific attributes. Table 8.3 shows the large decrease in sample size when bankfull width (176 sites) or canopy (376 sites) is used in a comparison. Using both bankfull width and canopy in a model would limit the sample size to 161 sites.

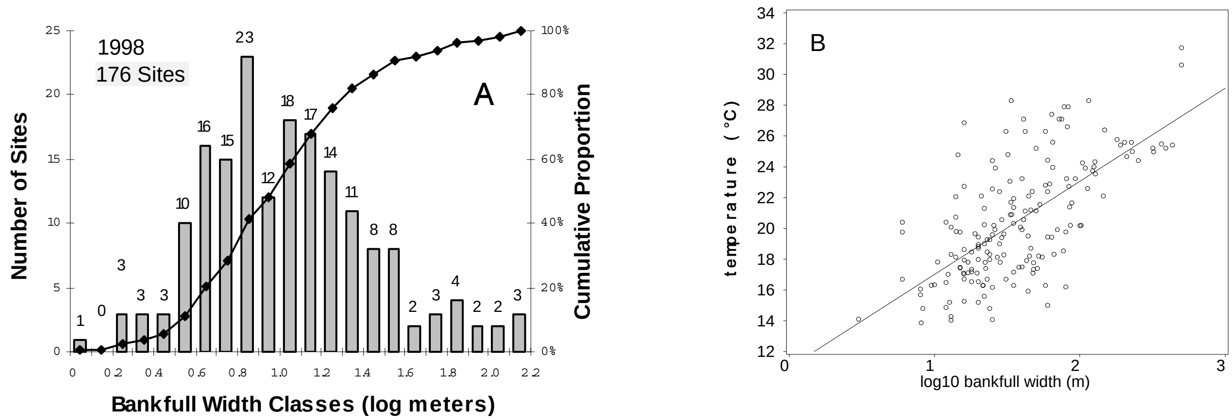


Figure 8.13. Frequency distribution (A) of 176 stream temperature monitoring sites measured in 1998 with non-null bankfull widths. Plotted line is the cumulative proportion. Plot B shows the highest daily maximum temperature versus $\log_{10}$ bankfull width in meters. Regression equation is: XY1DX = 10.9007 + 6.1034*LOGBF, $R^2 = 0.4366$.

Table 8.3. Pearson Correlation Coefficients for Various Site-Specific and Watershed-Level Attributes for 1998 Stream Temperature Data Set.

	canopy closure	**channel gradient**	**$\log_{10}$ divide distance**	**$\log_{10}$ watershed area**	**elevation**
$\log_{10}$ bankfull width	-0.6051 <0.0001 161	-0.40051 <0.0001 176	0.80727 <0.0001 176	0.80482 <0.0001 176	-0.23104 0.0020 176
canopy closure		0.30484 <0.0001 376	-0.68279 <0.0001 376	-0.69808 <0.0001 376	-0.05772 0.2643 376
channel gradient			-0.49288 <0.0001 518	-0.49659 <0.0001 518	0.25243 <0.0001 518
$\log_{10}$ divide distance				0.98683 <0.0001 518	-0.10064 <0.0220 518
$\log_{10}$ watershed area					-0.06548 0.1366 518

NOTE: Top number is Pearson correlation coefficient, middle number is probability of correlation due to random chance, and bottom number is number of sites.

Summary

Channel Orientation

Graphical and statistical evaluations of the relationship between XY1DX and channel orientation did not show any significant differences between channel orientation classes. Averages for XY1DX were slightly higher in the EW orientation class, although they were not significantly different from the NS orientation class.

Examination of canopy closure in relation to channel orientation did not show any significant differences between channel orientation class within each canopy class. That is, the interaction between canopy and channel orientation was not significant. However, there were significant differences in stream temperatures across canopy classes, with the lower canopy values showing higher average values for the highest daily maximum stream temperature. Other temperature metrics, i.e., XYA7DA and XYA7DX showed similar trends with respect to channel orientation and canopy closure. The influence of canopy of stream temperature is explored in depth in Chapter 9.

Diurnal fluctuation was compared at each channel orientation for all sites combined and sites with watershed area less than or equal to 18,000 ha. No significant differences were determined. The interactive effects of channel orientation and canopy on diurnal fluctuation was not significant. Similar to the XY1DX, diurnal fluctuation in each canopy closure class showed significant differences, with the lower canopy classes showing higher diurnal fluctuations.

Given all the other factors that have been shown to influence stream temperatures (e.g., canopy, air temperature), channel orientation appears to play a minor role. Due to a lack of significance in the interaction between canopy class and channel orientation, special canopy retention levels for certain channel orientations may not be warranted. Canopy was shown to be significant in influencing stream temperatures. The relationship between canopy and stream temperature is explored in greater depth in Chapter 9.

All sites in our regional stream temperature analysis contained non-missing values for channel orientation due to our ability to derive this attribute in GIS. Out of 548 sites with water temperature data available for regional analyses in 1998, 365 had non-null canopy values, and of these 203 fell in one of the four channel orientation quadrants (Figure 8.3). There was an even greater paucity of canopy data in years prior to 1998. These data voids are a great impediment to our ability to discern regional status and trends in stream temperatures and the factors that control them. A statistically valid sampling design coupled with canopy measurements collected using a consistent protocol is needed to better address the interaction between channel orientation, canopy, and stream temperature.

Channel Gradient

There was a decreasing trend in XY1DX with increasing gradient. This trend may have several underlying mechanisms. As gradient increases, the distance from the watershed divide and drainage area decreases. Stream temperatures are expected to be cooler closer to the headwaters. Streams become narrower at higher gradients, thereby making riparian vegetation more effective in providing shade.

None of the channel-gradient-class XY1DX averages exceeded the 24°C reference value (Figure 8.10-B). However, examination of the scatter plot shows that at many sites, both the 26°C and 24°C reference values were exceeded. At channel gradients greater than approximately 10%, temperatures did not exceed the lower reference value. However, channel gradients greater than 10% are probably too steep to serve as potentially suitable habitat for juvenile coho.

Analysis of variance using the PROC GLM procedure in SAS (SAS, 1985) revealed that for 518 sites in 1998, channel gradient explained about 10% of the variability in the XY1DX, XYA7DA, and XYA7DX temperature metrics. All three models had significant F values. Channel-gradient class averages for the three temperature metrics were significantly different at the 0.0001 level.

Habitat Type

Riffle and run sites had average XY1DX values only slightly higher than SPOOL sites. DPOOL sites exhibited the highest average XY1DX. Comparing temperatures in different habitat types across broad geographic areas may be inappropriate, unless the sites are placed in proper geographic context. In any given stream, deep pools are expected to be cooler than riffles or runs from the same stream. A misleading view of stream temperatures can result by having a preponderance of deep pools in a restricted (warmer) geographic area and in predominantly large stream systems. The habitat types used in this assessment are relative terms. A deep pool in a low-order stream may be similar, at least in terms of depth, to a riffle or run in a high-order stream.

Bankfull Width

Bankfull width is an important variable in many process-based models. In 1998 there were 176 sites for which bankfull width was available. Approximately 90% of the sites had bankfull widths less than 32 m. In the present study, about 44% of the variability in the highest daily maximum stream temperature was predicted by $\log_{10}$ bankfull width. Bankfull width is negatively correlated with canopy closure. As streams widen, the ability of riparian vegetation to provide effective shading is diminished. The interplay between bankfull width and canopy is discussed in Chapter 9.

Chapter 10

EMPIRICAL MODELING OF REGIONAL STREAM TEMPERATURES

Introduction

This chapter is a culmination of empirical meta-analyses of stream temperatures and various landscape-level and site-specific variables presented throughout previous chapters. It has been illustrated throughout this report that variation in stream temperature is not well explained by any single independent variable, particularly in regional analysis. Many factors influence the thermal regime of running waters. In this chapter, various models are developed that serve to show the interaction of various independent variables that operate at different spatial scales.

Process-Oriented Versus Empirical Models

Many factors act singly and interactively to influence stream temperatures. It is difficult to evaluate the effects of one variable in the absence of other factors. One of the values of process-based models, such as SSTEMP, SNTEMP, and TEMP86, is the ability to vary the factor of interest while keeping all other factors constant (Bartholow, 1989; Sullivan et al., 1990). Such models are better suited to exploration of system changes and alternative aquatic/riparian management scenarios, but at the cost of more intensive data collection, data entry, and manual calibration (Bartholow, 1989). Conversely, one of the advantages of empirical models is the ability to identify streams where temperatures are likely to be affected by climatic and land management constraints (Sullivan et al., 1990). Purely statistical models lend themselves well to temperature prediction when the stream geometry and hydrologic conditions are not expected to change dramatically and long periods of record are available (Bartholow, 1989). However, empirical models are only representative of the geographic location from which the data were collected. Extrapolation outside the area is tenuous.

Applying process-based models to large stream networks has not proven very successful in the past (Sullivan et al., 1990). Acquisition and management of auxiliary data sets to run many process-based stream temperature models at basin-wide scales has been overwhelming to all but the most well-staffed and well-funded organizations. More recent modeling efforts with greater reliance on remotely sensed data and GIS have shown some promise, such as the Hydrologic Simulation Program in Fortran (HSPF) (Bicknell et al., 1997; Chen et al.1998a, 1998b).

Empirical modeling was undertaken in the present study due to a number of constraints that prevented development of a new process-based model or use of an existing one. Intensive data requirements and a small staff were the major reasons for opting for development of empirical models. The level of complexity of empirical models can range from very complex to quite simple. Complex models are good for hypothesis testing, whereas simple models are good for forecasting. If the model is intended to determine uncertainty in risk assessment or to do decision analysis, the level of model complexity is less clear (Bartholow, 1989). The nature of this type of meta-analysis, that is, using data collected with multiple field protocols with varying levels of data quality, limits the analysis to hypothesis formulation. That is, models were developed to propose hypotheses that will then require testing with data collected using a probabilistic sampling design to select sites that should be monitored using a consistent field protocol.

Hypothesis Formulation

Two of the major factors that control stream water temperature are air temperature and solar radiation. Higher air temperatures and higher solar radiation exposure result in higher water temperature. The position of a site within a watershed is also important in explaining the temperature profile for that location. Sites lower in a watershed tend to have greater water volume, wider channel width (resulting in less effective shade), and generally have had more time to equilibrate with air temperature. The wider the channel, the less effective is stream-side vegetation at shading a stream from solar radiation, and air temperature becomes a more important factor controlling stream temperature at site locations further down in the watershed (Sullivan et al., 1990). Larger volumes of water are slower to respond to changes in both air temperature and solar radiation exposure due to thermal inertia. Some data providers placed probes in pools and, given the possibility of thermal stratification, pools may be cooler than runs or riffles in the same general location. Thus, habitat type may be an important factor influencing water temperature at the sensor. Stream temperature at a particular location may be estimated as a function of air temperature, solar radiation exposure, watershed position, stream size, and habitat type.

Air Temperature

Data from few water temperature sites were submitted with corresponding air temperature data. As a consequence, air temperature data from 72 remote air temperature stations were matched up with each water site (see chapter 5). The remote air temperature station data were summarized by month, which was then matched with daily and weekly water temperature metrics. Daily maximum and seven-day moving average temperature metrics were focused on because of their common usage in assessing stream temperature regimes. With fewer remote air temperature sites available to match up with water sites, a single remote air temperature station may be matched up with many water sites. For example, one air site that had a 1998 July and August average maximum air temperature of 32.45°C was matched up with thirty-one 1998 water sites. The highest 1998 seven-day moving average of the daily maximum water temperature at these 31 sites ranged from 15.5°C to 25.4°C, with a mean of 20.3°C. Water sites were assigned air temperature metrics that were not necessarily well correlated with local air temperature at the water sites (see chapter 5). In an attempt to find better air temperature surrogates for each water site, monthly PRISM estimated air temperature values for the four-km grid cells that contained the water site (see Chapter 4) were evaluated. However, the PRISM data is a 30-year long-term average for each month. As a result, there is no difference in estimated air temperature at each location for different years. Additionally, similar to remote air station data, only monthly data where available.

Some locational information was explored as possible air temperature surrogates. Air temperature tends to cool in a northward direction. The UTM Y-coordinate (UTMY) at each water temperature site may function as a surrogate for the north-south air temperature gradient. Sites located at greater distances from the coast (COASTDIS), or further east, easting estimated by the UTM X-coordinate (UTMX), tend to have warmer air temperatures. Higher elevations, estimated by the UTM Z-coordinate (UTMZ), tend to have cooler air temperatures, excluding sites within the zone of coastal influence (ZCI). Air temperatures within the ZCI (FOG08 = 1) are cooler than air temperatures outside the ZCI (FOG08 = 0). Since the ZCI was derived from PRISM data, there are no between-year differences that can be modeled using purely locational information as surrogates for air temperature.

Direct Solar Insolation

Canopy closure was the only variable available that could be used as a surrogate for direct solar insolation, although channel orientation and topographical shading may also influence the amount of solar radiation reaching the stream. Topographic shading was not available for this regional assessment. Canopy data were collected with different protocols, some of which may not adequately characterize the canopy closure for an entire thermal reach (see Chapter 9). Thus, there is substantial measurement error in the canopy closure estimates. Moreover, the canopy closure value may not be indicative of the effective shade provided at a given site. Out of 520 sites monitored in 1998, 376 sites had non-null values for canopy closure.

Watershed Position

The further the distance a water temperature site is from the watershed divide and the larger the watershed area above the site, the warmer the expected water temperature for the site. The further a water site is from the watershed divide, the greater is the travel time with the potential for longer exposure to both solar radiation and different air temperature regimes. The longitudinal increase in water temperature as water travels down the stream does not account for localized decreases in water temperature as streams enter areas with different riparian conditions or as they enter the zone of coastal influence. Generally, the larger the watershed area above a stream site the larger the stream. Watershed area was used as a surrogate for stream size. The relationship between distance from watershed divide (DIVIDIS) and watershed area (WAAREA) and several stream temperature metrics were found to be non-linear. The logs of both DIVIDIS (LOGDIVI) and WAAREA (LOGWA) linearized these relationships. Stream gradient measured along a 600-meter reach above the site was also modeled because gradient is highly correlated with watershed position. Stream sites closer to the headwaters tend to have steeper gradients than those lower in the watershed. However, the gradient was approximated in GIS using a 30-meter digital elevation model. Because of uncertainty in the error, gradient was classified into four categories: 1) flat = <1% slope, 2) sloped = 1% to <5%, 3) steep = 5% to <10%, and 4) very steep =>10%. The categorical form of gradient was used in model development.

Stream Size

Bankfull width and depth were requested for all stream temperature sites. However, only 158 bankfull widths and 58 bankfull depths were submitted with canopy and habitat values for the 520 water temperature data sets submitted for 1998. No sites had bankfull width or bankfull depth data for 1997. Bankfull depth and bankfull width were largely excluded from modeling because of the large number of sites with null values. WAAREA and DIVIDIS, and their logs, were considered fairly good surrogates for stream size (See Chapter 9).

Habitat Type

A number of sites for which stream temperature data were submitted were intended for studies to characterize the extent of thermal refugia. About 50% of the 1998 sites had temperature sensors placed in pools, with the other 50% placed in riffles or runs. An analysis of the data indicated that deep pools, medium pools, and shallow pools could be combined into one group (POOL) and that runs and riffles could be combined into another group (RIFFLE_RUN).

Minimum Data Requirements

In addition to the GIS-derived variables that were available for nearly all sites, a site also had to have a reported canopy value and habitat type to be used in model fitting. Inclusion of habitat type in the list of required variables resulted in the loss of nine 1998 sites and four 1997 sites from the data set, after sites with missing canopy values were removed. Table 10.1 shows the number of sites for the coastal and interior ecoprovince, and both ecoprovinces combined, after various data requirements were imposed on the data. Data from 1997 are included in the table because data from this year were used in 1998 model validation analyses.

Models

Three temperature metrics were fit to empirical models: (1) the highest seven-day moving average of the daily average (XYA7DA), (2) the highest seven-day moving average of the daily maximum (XYA7DX), and (3) the highest daily maximum stream temperature (XY1DX). Models for the three stream temperature metrics were developed for two geographic areas, the coastal ecoprovince and the interior ecoprovince, plus a model for both

Table 10.1. Number of Sites for 1997 and 1998 by Ecoprovince with Non-null Canopy and Habitat Type Data (Minimum Requirement to Be Included for Modeling) Provided with the Water Temperature Data, Followed by the Number of Sites with Non-null Bankfull Widths (BFWIDTH) and Bankfull Depths (BFDEPTH).

		Ecoprovince		
Year	Independent Variables Available	**Coastal**	**Interior**	**Combined**
1997	all GIS-derived variables, canopy, and habitat	100	48	148
1998	all GIS-derived variables, canopy, and habitat	255	110	365
1997	with BFWIDTH	0	0	0
1998	with BFWIDTH	121	37	158
1997	with BFDEPTH	0	0	0
1998	with BFDEPTH	28	30	58

ecoprovinces combined. A total of nine models were developed.

While the average of combined July-August monthly air temperatures were used to model daily and weekly water temperature metrics, we found there to be good correlation between the monthly water temperatures and the daily and weekly water temperature metrics. Sullivan et al. (1990) also noted an unexpectedly close agreement between their 30-day water temperature criterion and the more commonly applied one-day and seven-day temperature metrics found in Washington’s water quality standards and forest practice rules.

It was expected that the best models would indicate that stream temperature was a function of air temperature, direct solar radiation, and a few physical stream characteristics. Canopy closure was used as a surrogate for incoming solar insolation, although channel orientation and topographic shading may also be influential in the amount of solar radiation reaching a stream. Physical characteristics such as channel gradient, bankfull width, bankfull depth, whether the stream is in or out of the ZCI, and if the stream is in or out of the California Coastal Steppe Ecological Subregion (i.e., coastal ecoprovince) may influence stream heating processes. Groundwater temperature is believed to be the initial temperature at which water enters the stream (Allan, 1995; Sullivan et al., 1990). Groundwater temperature, estimated from PRISM long-term air temperature data, was also investigated as a possible explanatory variable. Some data providers placed temperature probes in deep pools in an attempt to describe the extent of thermal refugia. Habitat type was investigated to determine whether this categorical variable had an effect. A lack of stream-side air temperature data collected near the water temperature site may have been the largest impediment to developing good stream-temperature prediction models.

Relatively few water temperature sites had corresponding air temperature data. This necessitated using a number of alternatives to estimate air temperature at the stream site. Other studies have found that remote air stations can serve as a reasonable index of near-stream air temperature (Moore, 1967; Sullivan et al. 1990.) However, these studies relate air temperature at one station in a single watershed. Air temperature at a single remote location may be highly correlated with air temperature at a site in a distant watershed. However, the regional modeling described in this study attempted to fit data over a large geographic area. Single remote air temperature stations were related to many water temperature stations. Many different remote air temperature stations were used across the landscape. The result was a poor relationship between remote air temperature and air temperature at the water site when the relationship was examined across all water sites at the regional scale.

Model Selection Methods

Since the data, as a whole, were collected without a central assessment question and numerous protocols were used for measuring stream temperature and various site-specific attributes, serious model fitting assumptions are violated. Noting that the selected models are only ***working hypotheses***, the process of "data dredging" was utilized. "Data dredging" explores the data set without an *a priori* model, searching for a good fitting model. This procedure has a tendency to over fit the data where unrelated variables are included in selected models exclusively due to chance (Burnham and Anderson, 1998).

As previously stated, 1998 was the most data-rich year and was used for model fitting. There were several sites from 1997 that were suitable for model validation. The first step used a backward elimination stepwise approach with one forward step on the variables listed in Table 10.2.

Table 10.2. List of Variables Used to Start the *Backward Selection with One Forward Step* Modeling Procedure.

Variable	Description
ECO263	Used only in combined ecoprovince model, ECO263 = 1 if in the coastal ecoprovince, otherwise ECO263 = 0.
COASTDIS	Shortest distance from the site to the coast (km)
UTMX.10E4	UTMX coordinate divided by 10,000 (east-west position measurement)
UTMY.10E5	UTMY coordinate divided by 100,000 (north-south position measurement)
UTMZ	Elevation of the site (meters)
CANOPY	Reported Canopy Closure (percent)
MO.MAX3	Average of combined July and August average daily maximum for the nearest remote air station (12-dimensional Euclidian distance) (°C)
MO.MIN3	Average of combined July and August average daily minimum for the nearest remote air station (12-dimensional Euclidian distance) (°C)
MO.AVG3	Average of combined July and August average daily average for the nearest remote air station (12-dimensional Euclidian distance) (°C)
LOGDIVI	Log (base 10) of the GIS estimated distance from site to watershed divide (km)
LOGWA	Log (base 10) of the GIS estimated watershed area above site (hectares)
POOL	if HABITAT = shallow, medium, or deep pool, POOL = 1 if HABITAT = run or riffle, POOL = 0 if HABITAT not reported, POOL = missing value
GRAD2	Gradient Classification: flat = < 1% slope, sloped = 1% to <5%, steep = 5% to <10%, very steep = >10%
FOG08	if site is in the zone of coastal influence defined for August, then FOG08=1 if site is out of the zone of coastal influence defined for August, then FOG08=0
P.MO.MAX	Average of PMAX07 and PMAX08 (PRISM estimated July and August, respectively, maximum air temperatures for the area containing the site (°C)
BFWIDTH	Bankfull width (meters)
BFDEPTH	Bankfull depth (meters)
CANOPY.LOGDIVI	Interaction between CANOPY and LOGDIVI
CANOPY.LOGWA	Interaction between CANOPY and LOGWA
UTMX.UTMY	Interaction between UTMX and UTMY
UTMZ.COASTDIS	Interaction between UTMZ and COASTDIS
LOGDIVI.LOGWA	interaction between LOGDIVI and LOGWA

Preliminary Modeling

At the outset of modeling, there was considerable discussion as to what method was most appropriate: a classical approach using backward selection or the information theory method of Akaike's Information Criterion (AIC; Burnham and Anderson, 1998). While investigating which was more appropriate, a large number of models were developed and AIC scores compared. With the large number of competing models examined, it became obvious there was a high probability that the *best* model (i.e., the one with the lowest AIC score) may include variables by chance and not due to real relationships. Many models had similar AIC scores, and given the chance that some might be slightly better due to chance, it was not readily apparent which models were best. However, a number of variables were always in models with higher, less desirable, AIC scores. These variables (Table 10.3) were not considered in the backward elimination with one forward step procedure discussed below.

Backward Selection

With the assistance of S-PLUS programs, nine models were selected (for three temperature metrics and three geographical extents) using a backward selection approach with one forward step. The backward steps stopped when the probability for the smallest partial $\boldsymbol{F}$ statistic was less than $0.05/k$ where k is the number of variables at the start of the procedure. The partial F-statistic is the F-statistic for each variable as if that variable was the last one to enter the model (Stevens, 1986). The one forward step tested all the removed variables, one at a time, by adding them back into the model to see if the partial $\boldsymbol{F}$ statistic for any of the removed variables became significant ($p < 0.05/k$) by the removal of any of the other variables. Two variables were exceptions to the rules for removal, BFWIDTH and BFDEPTH. The data set that had non-missing values for BFWIDTH and BFDEPTH was small and the sites with non-null values were poorly distributed spatially. These data were provided by only a few organizations and were not representative of the region. Thus, BFWIDTH and BFDEPTH were the first two variables removed from the models.

Interactive terms were entered into the model during the automated S-PLUS process as separate variables. For example, the CANOPY-LOGDIVI interaction term was the product of the CANOPY and LOGDIVI terms. The newly created variable was called CAN.LOGDIV. The new variable was then used in model development. During the backwards procedure if a primary variable of a retained interactive term was dropped from the final model, a new backwards procedure was performed using the selected model and all the dropped primary terms. If the interactive term did not meet the partial $\boldsymbol{F}$ statistic threshold, it was omitted, favoring the primary terms.

Table 10.3. Variables Found to be Poor Predictors of Stream Temperature and Subsequently Removed from Model Development.

Variable	Description
WAAREA	GIS estimated watershed area above site (ha)
DIVIDIST	GIS estimated distance from site to watershed divide (km)
PMAX07	PRISM estimated July maximum air temperature (°C)
PMAX08	PRISM estimated August maximum air temperature (°C)
PMEAN.ANN.AIR	PRISM estimated mean annual air temperature (°C)
SINUOSITY	A measure of curvature along a 600-m reach above the water site
CAZMUTH	Channel orientation (north-south, east-west) along a 600-m reach above the water site
CANOPY.DIVIDIST	Interaction between canopy closure and DIVIDIST
CANOPY.WAAREA	Interaction between canopy closure and WAAREA
DIVIDIST.WAAREA	Interaction between DIVIDIST and WAAREA

Alternative Model Selection and Model Comparisons

Upon examination of the models suggested by the backward selection procedure, alternative models were proposed in an educated search for better air temperature surrogates. One alternative model for each primary model from the backward selection procedure was suggested. The Forest Science Project staff used knowledge gleaned from the analyses reported in preceding chapters, literature reviews, and preliminary model building processes to formulate alternative models. The two models constructed for each of the three 1998 temperature metrics, the backward selected S-PLUS model and its alternative, were compared to each other using their AIC scores. Finally, both models fit to 1998 data were cross validated using 1997 data.

The 1997 data used for model validation were separated into two groups: those that were at the same location as 1998 sites (matched sites) and those that were at different locations than 1998 sites (unmatched sites). A W-statistic, a residual-like statistic, similar to that used by Sullivan et al. (1990) was calculated and averaged for matched, unmatched, and all 1997 sites combined:

$$\overline{W}_{97\cdot j} = \frac{\sum(\hat{y}_{i_{97\cdot j\cdot 98}} - y_{i_{97\cdot j}})}{n_{97\cdot j}}$$

where

j is the group (all, matched, or unmatched sites)

$\hat{y}_{i_{97\cdot j\cdot 98}}$ is the temperature estimate for the i^{th} 1997 data point estimated by the curve fit to 1998 data;

$y_{i_{97\cdot j}}$ is the measured temperature metric for the i^{th} 1997 observation from group j; and

$n_{97\cdot j}$ is the number of observations for group j in 1997.

The average W-statistic is the average error for the fit of the validation data set. If the model fit with the 1998 is good, the average W-statistic for the 1997 estimates should be near zero.

The standard deviation for the W-statistic was calculated as:

$$St.Dev\left(W_{97\cdot j}\right) = \sqrt{\frac{\sum\left[(\hat{y}_{i_{97\cdot j\cdot 98}} - y_{i_{97\cdot j}}) - \overline{W}_{97\cdot j}\right]^2}{n_{97\cdot j} - 1}}$$

Note that the above standard deviation is not suitable for constructing confidence intervals about the average W-statistic. To construct confidence intervals about the average W-statistic, the standard error is required, which can be estimated by 1) squaring the reported standard deviation, 2) multiplying by (n-1), 3) dividing by (n-k-1) where k is the number of covariates used in the model, and 4) taking the square root of the result.

Consistency for all groups was calculated as the proportion of estimates within 2°C of the observed temperature metric.

Results

Backward Selection

In all models, air temperature (or at least surrogates of air temperature), canopy closure, and the log of distance from watershed divide and/or watershed area all were important components influencing water temperature. Additionally, the models selected for the same geographic area in the backward selection procedure for XY1DX and XYA7DX selected the same set of variables, while XYA7DA selected a different subset of variables. Note that when referring to the *backward selection procedure* the one forward step is included in addition to the repeated procedure for removed dependent variables (covariates) that were retained in interactive terms. For the combined coastal and interior ecoprovince XY1DX and XYA7DX models, the most important covariates selected by the backward selection procedure were ecoprovince, canopy closure, the log of distance from watershed divide, the log of watershed area, habitat type (factored as being in or not in a pool), in or out of the ZCI, UTMX, UTMY, and the interaction between the log watershed area and log distance from divide (Table 10.4).

The most important covariates in the XYA7DA model for the combined ecoprovince data set were elevation, canopy closure, the log of distance from watershed divide, the log of watershed area, in or out of the zone of coastal influence, shortest distance from the coast, UTMX, the canopy and log divide distance interaction, and the elevation and coast distance interaction (Table 10.5). For this model, however, the log of distance from watershed divide, and the shortest distance from the coast did not meet the partial ***F*** statistic threshold, but interaction terms containing those variables remained significant. The single terms were left in the model to assist in interpreting the role of those variables in influencing the highest seven-day moving average of the daily average stream temperature.

Table 10.4. Linear Regression Results for the Dependent Variables XY1DX and XYA7DX in the Combined Interior and Coastal Ecoprovince Data Sets.

	Dependent Variable							
	XY1DX				XYA7DX			
Independent Variable	**Value**	**Std. Error**	**t value**	**Pr(>|t|)**	**Value**	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	96.929	11.347	8.542	>0.0001	96.383	10.822	8.907	>0.0001
ECO263	-1.778	0.522	-3.406	0.0007	-1.952	0.498	-3.922	0.0001
CANOPY	-3.824	0.524	-7.298	>0.0001	-3.628	0.500	-7.260	>0.0001
LOGDIVI	6.246	1.683	3.711	0.0002	6.400	1.605	3.987	0.0001
LOGWA	4.895	1.163	4.207	>0.0001	4.431	1.110	3.994	0.0001
POOL	-1.051	0.267	-3.935	0.0001	-0.960	0.255	-3.772	0.0002
FOG08	-2.641	0.318	-8.296	>0.0001	-2.507	0.304	-8.257	>0.0001
UTMY.10E5	-1.890	0.183	-10.316	>0.0001	-1.895	0.175	-10.844	>0.0001
UTMX.10E4	-0.352	0.068	-5.158	>0.0001	-0.346	0.065	-5.325	>0.0001
LOGDIVI.LOGWA	-0.963	0.190	-5.065	>0.0001	-0.915	0.181	-5.045	>0.0001

Model Performance		
Statistic	**XY1DX**	**XYA7DX**
Multiple R^2	0.6816	0.6900
Sample size	365	365
Model F-stat	84.43	87.81
df - numerator	9	9
df - denominator	355	355
p(F)	>0.0001	>0.0001

Note: Provided in the upper portion of the table are the coefficient values with their standard error, t-statistic, and the probability that the coefficient value is not different from zero. Model statistics are shown in the lower portion of the table.

Table 10.5. Linear Regression Results for the Dependent Variable XYA7DA in the Combined Interior and Coastal Ecoprovince Data Sets.

	Dependent Variable			
	XYA7DA			
Independent Variable	**Value**	**Standard Error**	**t value**	**Pr(>|t|)**
(Intercept)	-2.319	2.877	-0.806	0.4207
UTMZ	0.005	0.001	6.693	>0.0001
CANOPY	-6.365	1.169	-5.448	>0.0001
LOGDIVI	2.860	1.029	2.780	0.0057
LOGWA	0.068	0.634	0.107	0.9145
FOG08	-1.576	0.257	-6.128	>0.0001
COAST.KM	-0.003	0.009	-0.291	0.7713
UTMX.10E4	0.235	0.046	5.141	>0.0001
CAN.LOGWA	1.179	0.312	3.777	0.0002
UTMZ.COASTKM	0.000	0.000	-7.384	>0.0001

	Model Performance
Statistic	**XYA7DA**
Multiple R^2	0.7448
Sample size	374
Model F-stat	118.1
Degrees of freedom - numerator	9
Degrees of freedom - denominator	364
p(F)	>0.0001

NOTE: Provided in the upper portion of the table are the coefficient values with their standard error, t-statistic, and the probability that the coefficient value is not different from zero. Model statistics are shown in the lower portion of the table.

For the XY1DX and XYA7DX interior ecoprovince models, canopy closure, the log of distance from watershed divide, UTMX, UTMY, and the interaction between UTMX and UTMY where all variables selected in the backward procedure (Table 10.6). The XYA7DA model for the interior ecoprovince used the same covariates as the other two models, with the addition of elevation and distance to the coast (Table 10.7).

The XY1DX and XYA7DX coastal ecoprovince models included the variables canopy, log divide distance, log watershed area, habitat type (POOL or RIFFLE_RUN), within or outside ZCI, UTMX, and the interaction between the log watershed area and log divide distance (Table 10.8). From the list of variables for XY1DX and XYA7DX coastal ecoprovince models, the XYA7DA coastal ecoprovince model removed the log of watershed area and the interaction between the logs of watershed area and divide distance, and replaced UTMX with UTMY (Table 10.9).

Table 10.6. Linear Regression Results for the Dependant Variables XY1DX and XYA7DX in the Interior Ecoprovince Data Set.

	Dependant Variable							
	XY1DX				XYA7DX			
Independent Variable	**Value**	**Std. Error**	**t value**	**Pr(>|t|)**	**Value**	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	1581.337	256.396	6.168	>0.0001	1492.37	252.380	5.913	>0.0001
CANOPY	-4.447	0.829	-5.364	>0.0001	-4.083	0.816	-5.003	>0.0001
LOGDIVI	2.348	0.542	4.334	>0.0001	2.389	0.533	4.482	>0.0001
UTMY.10E5	-34.342	5.655	-6.073	>0.0001	-32.385	5.567	-5.818	>0.0001
UTMX.10E4	-29.557	5.244	-5.637	>0.0001	-27.813	5.162	-5.388	>0.0001
UTMY10E5.UTMX10E4	0.647	0.116	5.596	>0.0001	0.608	0.114	5.343	>0.0001

	Model Performance	
Statistic	**XY1DX**	**XYA7DX**
Multiple R^2	0.7530	0.7495
sample size	112	112
Model F-stat	64.61	63.43
df - numerator	5	5
df - denominator	106	106
p(F)	>0.0001	>0.0001

NOTE: Provided in the upper portion of the table are the coefficient values with their standard error, t-statistic, and the probability that the coefficient value is not different from zero. Model statistics are shown in the lower portion of the table.

Table 10.7. Linear Regression Results for the Dependant Variable XYA7DA in the Interior Ecoprovince Data Set.

	Dependant Variable			
	XYA7DA			
Independent Variable	**Value**	**Standard Error**	**t value**	**Pr(>|t|)**
(Intercept)	1055.258	157.941	6.681	>0.0001
UTMZ	-0.002	0.001	-3.140	0.0022
CANOPY	-2.484	0.532	-4.666	>0.0001
LOGDIVI	2.783	0.402	6.928	>0.0001
COAST.KM	-0.069	0.022	-3.169	0.0020
UTMY.10E5	-23.610	3.461	-6.822	>0.0001
UTMX.10E4	-20.044	3.211	-6.243	>0.0001
UTMY10E5.UTMX10E4	0.455	0.071	6.463	>0.0001

	Model Performance
Statistic	**XYA7DA**
Multiple R^2	0.8731
sample size	112
Model F-statistic	102.2
degrees of freedom - numerator	7
degrees of freedom - denominator	104
p(F)	>0.0001

Note: Provided in the upper portion of the table are the coefficient values with their standard error, t-statistic, and the probability that the coefficient value is not different from zero. Model statistics are shown in the lower portion of the table.

Table 10.8. Linear Regression Results for the Dependant Variables XY1DX and XYA7DX in the Coastal Ecoprovince Data Set.

	Dependant Variable							
	XY1DX				XYA7DX			
Independent Variable	**Value**	**Std. Error**	**t value**	**Pr(>|t|)**	**Value**	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	-16.836	5.494	-3.065	0.0024	-18.598	5.174	-3.595	0.0004
CANOPY	-4.108	0.608	-6.753	>0.0001	-3.988	0.573	-6.962	>0.0001
LOGDIVI	7.424	1.934	3.839	0.0002	7.619	1.821	4.183	>0.0001
LOGWA	4.965	1.373	3.616	0.0004	4.659	1.293	3.603	0.0004
POOL	-1.278	0.287	-4.451	>0.0001	-1.206	0.270	-4.461	>0.0001
FOG08	-1.949	0.306	-6.378	>0.0001	-1.774	0.288	-6.164	>0.0001
UTMX.10E4	0.232	0.065	3.551	0.0005	0.252	0.062	4.097	0.0001
LOGDIVI.LOGWA	-1.095	0.253	-4.335	>0.0001	-1.080	0.238	-4.542	>0.0001

	Model Performance	
Statistic	**XY1DX**	**XYA7DX**
Multiple R^2	0.6819	0.6917
sample size	255	255
Model F-stat	75.64	79.18
df - numerator	7	7
df - denominator	247	247
p(F)	>0.0001	>0.0001

Note: Provided in the upper portion of the table are the coefficient values with their standard error, t-statistic, and the probability that the coefficient value is not different from zero. Model statistics are shown in the lower portion of the table.

Table 10.9. Linear Regression Results for the Dependant Variable XYA7DA in the Coastal Ecoprovince Data Set.

	Dependant Variable			
	XYA7DA			
Independent Variable	**Value**	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	34.399	4.854	7.086	>0.0001
CANOPY	-1.909	0.388	-4.918	>0.0001
LOGDIVI	3.769	0.239	15.765	>0.0001
POOL	-0.881	0.187	-4.703	>0.0001
FOG08	-1.712	0.185	-9.259	>0.0001
UTMY.10E5	-0.669	0.109	-6.118	>0.0001

	Model Performance
Statistic	**XYA7DA**
Multiple R^2	0.7588
sample size	255
Model F-stat	156.7
degrees of freedom - numerator	5
degrees of freedom - denominator	249
p(F)	>0.0001

Note: Provided in the upper portion of the table are the coefficient values with their standard error, t-statistic, and the probability that the coefficient value is not different from zero. Model statistics are shown in the bottom portion the table.

Alternative Model Selection and Model Comparisons

Combined Ecoprovinces

Most of the suggested alternative models contained various air temperature metrics. Backward selection XY1DX and XYA7DX models for combined ecoprovinces contained the covariates ecoprovince, canopy closure, the log of distance from watershed divide, the log of watershed area, habitat type, in or out of the zone of coastal influence, UTMX, UTMY, and the interaction between the logs of watershed area and distance from divide. The alternative models used the PRISM estimated 30-year August average maximum air temperature (PMAX08) in place of UTMY and UTMX and removed the interaction term between the log of divide distance and the log of watershed area.

The alternative model was compared to the primary model (the model selected by the backward selection procedure) for XY1DX and XYA7DX (Table 10.10). For both stream temperature metrics the primary model had better AIC scores and higher R^2 values for the 1998 data. Generally, the mean W-statistic for all 1997 sites favored the alternative model (Table 10.10).

For XY1DX, the mean W-statistic for the 1997 matched and unmatched groups favored the primary model, but the statistics for the groupings in the alternative models had opposite signs resulting in an average W-statistic that favored the alternate model. Consistency values, that is the proportion of sites that had estimates within 2°C of the observed value, for the 1997 all-sites-combined validation comparisons favored the alternative XY1DX and XYA7DX models.

For the combined ecoprovince XYA7DA model, a similar change in variables was made in the alternative model. Air temperature surrogate variables (distance from coast, UTMX, elevation, and the elevation and coast distance interaction) were replaced with the same PRISM estimated 30-year August average maximum air temperature metric (PMAX08). The results of model comparisons were more complicated than previous comparisons. While the AIC score and the 1998 R^2 still favored the primary model, the 1997 W-statistics mostly favored the primary model as well. An exception was noted for the unmatched 1997 sites, with slightly lower mean W-statistics and higher consistency values for the alternative model.

Interior Ecoprovince

For the interior ecoprovince XY1DX, XYA7DX, and XYA7DA models, P.MO.MAX replaced UTMX, UTMY, and the UTMX-UTMY interaction as the air temperature surrogate for the alternative models (Table 10.11). Additionally, all alternative models used the canopy closure - log divide distance interaction term, which was not selected for any of the primary models. For all model comparisons, the primary model out performed the alternative model (Table 10.11). Though mixed, the W-statistics mostly favored the primary models. Still, the AIC score and R^2 values showed that the primary models were much better, but the cross validation statistics using the 1997 data indicated that the primary models were only marginally better.

Coastal Ecoprovince

The alternative models for XY1DX and XYA7DX in the coastal ecoprovince used PMAX08 and distance from coast as air temperature surrogates in place of UTMX used by the primary models (Table 10.12). The AIC score and the R^2 values were better for the primary model. However, the alternative models generally fit the 1997 data better (Table 10.12). The only exception was the W-statistics for the primary XY1DX models were slightly better than those for the alternative models. The alternative model for XYA7DA in the coastal ecoprovince similarly used PMAX08 and distance from coast as air temperature surrogates in place of UTMY (Table 10.12). Like the other models, the AIC and R^2 values were better for the primary XYA7DA model, while the 1997 data were better fit by the alternative model as indicated by lower W-statistics.

Table 10.10. Comparison of Combined-Ecoprovince Models Produced in the Backward Selection Procedure (Primary Columns) and an Alternative Model for XY1DX, XYA7DX, and XYA7DA.

	Dependent Variable Model					
	XY1DX		XYA7DX		XYA7DA	
Independent Variable	**Primary**	**Alternative**	**Primary**	**Alternative**	**Primary**	**Alternative**
(Intercept)	96.929	5.259	96.383	3.733	-2.319	1.629
COASTDIS	0	0	0	0	-0.003	0
UTMX.10E4	-0.352	0	-0.346	0	0.235	0
UTMY.10E5	-1.890	0	-1.895	0	0	0
UTMZ	0	0	0	0	0.005	0
CANOPY	-3.824	-4.148	-3.628	-3.958	-6.365	-4.914
LOGDIVI	6.246	2.674	6.400	3.060	2.860	4.069
LOGWA	4.895	0.348	4.431	0.071	0.068	-0.604
POOL	-1.051	-0.386	-0.960	-0.295	0	0
FOG08	-2.641	-1.252	-2.507	-1.107	-1.576	-0.687
PMAX08	0	0.191	0	0.195	0	0.125
ECO263	-1.778	1.785	-1.952	1.616	0	0
CANOPY.LOGWA	0	0	0	0	1.179	0.870
UTMZ.COASTDIS	0	0	0	0	-9.3E-5	0
LOGDIVI.LOGWA	-0.963	0	-0.915	0	0	0

Statistic	**Model Performance**					
AIC	645.1271	756.1424	610.5244	729.2842	380.6189	492.7467
R^2_{98}	0.6816	0.5636	0.6900	0.5661	0.7518	0.6570
$Consistency_{98}$	0.6274	0.5699	0.6685	0.5726	0.8137	0.7096
n_{98}	365	365	365	365	365	365
$W_{97\text{-ALL}}$	0.2562	-0.0839	0.3514	0.0102	0.4804	-0.1589
St Dev.($W_{97\text{-ALL}}$)	2.2872	2.1141	2.1664	2.0401	1.4148	1.5248
$Consistency_{97\text{-ALL}}$	0.6486	0.6892	0.6757	0.6959	0.8514	0.8378
$n_{97\text{-ALL}}$	148	148	148	148	148	148
$W_{97\text{-match}}$	0.1706	-0.3562	0.2639	-0.2610	0.4404	-0.3678
St Dev.($W_{97\text{-match}}$)	2.0492	1.8879	1.9163	1.8021	1.1871	1.4175
$Consistency_{97\text{-match}}$	0.6701	0.7010	0.7010	0.7216	0.9072	0.8454
$n_{97\text{-match}}$	97	97	97	97	97	97
$W_{97\text{-unmatch}}$	0.4190	0.4339	0.5180	0.5262	0.5564	0.2383
St Dev.($W_{97\text{-unmatch}}$)	2.6975	2.4248	2.5892	2.3635	1.7806	1.6529
$Consistency_{97\text{-unmatch}}$	0.6078	0.6667	0.6275	0.6471	0.7451	0.8235
$n_{97\text{-unmatch}}$	51	51	51	51	51	51

Note: Column values are coefficients for independent variable. A zero value indicates the variable was not used in that model. The lower portion of the table presents comparative model performance statistics. Comparisons should only be made between primary and alternative models within the same dependent variable. Lower AIC values indicate a *better* model. R^2 values are reported for the 1998 sample. 1997 data are grouped as: (1) all sites combined (ALL), (2) 1997 sites at the same location as 1998 sites (match), and (3) 1997 sites at different locations than 1998 sites (unmatch). W-statistic is the average error for the validation data set. Consistency is the proportion of sites with estimates within 2°C of the observed value.

Table 10.11. Comparison of Interior Ecoprovince Models Produced in the Backward Selection Procedure (Primary Columns) and an Alternative Suggestion for XY1DX, XYA7DX, and XYA7DA.

	Dependent Variable Model					
	XY1DX		XYA7DX		XYA7DA	
Independent Variable	**Primary**	**Alternative**	**Primary**	**Alternative**	**Primary**	**Alternative**
(Intercept)	1581.337	1.327	1492.37	-0.471	1055.258	-1.235
COASTDIS	0	0	0	0	-0.069	-0.052
UTMX.10E4	-29.557	0	-27.812	0	-20.044	0
UTMY.10E5	-34.342	0	-32.384	0	-23.610	0
UTMZ	0	0	0	0	-0.002	0.002
CANOPY	-4.447	-22.082	-4.083	-21.683	-2.484	-12.570
LOGDIVI	2.347	1.021	2.389	1.071	2.783	2.226
P.MO.MAX	0	0.592	0	0.615	0	0.461
CANOPY.LOGDIVI	0	4.279	0	4.272	0	2.627
UTMX.UTMY	0.647	0	0.608	0	0.455	0

Statistic	**Model Performance**					
AIC	190.5035	273.4447	187.1549	266.5003	84.5871	181.6462
R^2_{98}	0.7533	0.4661	0.7497	0.4756	0.8722	0.6854
$Consistency_{98}$	0.700	0.4909	0.7182	0.4909	0.9091	0.6545
n_{98}	110	110	110	110	110	110
$W_{97\text{-}ALL}$	0.287	-0.5936	0.3008	-0.5832	0.6218	0.5293
St Dev.($W_{97\text{-}ALL}$)	2.0027	2.3263	1.8848	2.2817	1.2864	1.6245
$Consistency_{97\text{-}ALL}$	0.687	0.6875	0.7500	0.6875	0.8542	0.8125
$n_{97\text{-}ALL}$	48	48	48	48	48	48
$W_{97\text{-}match}$	0.661	-0.7013	0.6548	-0.6981	0.6901	0.4242
St Dev.($W_{97\text{-}match}$)	1.8045	1.8077	1.6967	1.7212	1.0958	1.3717
$Consistency_{97\text{-}match}$	0.666	0.7222	0.7222	0.7222	0.8889	0.8333
$n_{97\text{-}match}$	36	36	36	36	36	36
$W_{97\text{-}unmatch}$	-	-0.2703	-0.7612	-0.2385	0.4168	0.8444
St Dev.($W_{97\text{-}unmatch}$)	2.2219	3.5458	2.0924	3.5560	1.7857	2.2680
$Consistency_{97\text{-}unmatch}$	0.750	0.5833	0.8333	0.5833	0.7500	0.7500
$n_{97\text{-}unmatch}$	12	12	12	12	12	12

Note: Column values are coefficients for independent variables. A zero value indicates the variable was not used in that model. The lower portion of the table presents comparative model performance statistics. Comparisons should only be made between primary and alternative models within the same dependent variable. Lower AIC values indicate a *better* model. R^2 values are reported for the 1998 sample. 1997 data are grouped as: (1) all sites combined (ALL), (2) 1997 sites at the same location as 1998 sites (match), and (3) 1997 sites at different locations than 1998 sites (unmatch). W-statistic is the average error for the validation data set. Consistency is the proportion of sites with estimates within 2°C of the observed value.

Table 10.12. Comparison of Coastal Ecoprovince Models Produced using the Backward Selection Procedure (Primary Columns) and an Alternative Model for XY1DX, XYA7DX, and XYA7DA.

	Dependent Variable Model					
	XY1DX		XYA7DX		XYA7DA	
Independent Variable	**Primary**	**Alternative**	**Primary**	**Alternative**	**Primary**	**Alternative**
(Intercept)	-16.836	-12.316	-18.598	-13.370	34.399	2.006
COASTDIS	0	-0.005	0	-0.011	0	-0.022
UTMX.10E4	0.232	0	0.252	0	0	0
UTMY.10E5	0	0	0	0	-0.669	0
CANOPY	-4.108	-4.228	-3.988	-4.109	-1.909	-2.070
LOGDIVI	7.424	8.937	7.619	9.189	3.769	3.739
LOGWA	4.965	5.097	4.659	4.883	0	0
POOL	-1.278	-1.138	-1.206	-1.055	-0.880	-0.630
FOG08	-1.949	-2.023	-1.774	-1.947	-1.712	-1.354
PMAX08	0	0.060	0	0.060	0	0.127
LOGDIVI.LOGWA	-1.095	-1.254	-1.080	-1.257	0	0

Statistic	**Model Performance**					
AIC	411.9348	425.9549	381.3281	399.2745	188.8292	219.4279
R^2_{98}	0.6819	0.6665	0.6917	0.6719	0.7588	0.7302
$Consistency_{98}$	0.686	0.6745	0.7059	0.7176	0.8745	0.8353
n_{98}	255	255	255	255	255	255
$W_{97\text{-}ALL}$	0.112	-0.1144	0.2664	0.0164	0.1746	0.0822
St Dev.($W_{97\text{-}ALL}$)	2.1272	2.0059	1.9826	1.8862	1.2710	1.1874
$Consistency_{97\text{-}ALL}$	0.760	0.7200	0.7700	0.7600	0.9100	0.9100
$n_{97\text{-}ALL}$	100	100	100	100	100	100
$W_{97\text{-}match}$	0.017	-0.1852	0.1931	-0.0333	0.1304	0.0492
St Dev.($W_{97\text{-}match}$)	1.8971	1.7928	1.7276	1.6391	1.0448	1.0393
$Consistency_{97\text{-}match}$	0.819	0.7869	0.8361	0.8197	0.9344	0.9344
$n_{97\text{-}match}$	61	61	61	61	61	61
$W_{97\text{-}unmatch}$	0.259	-0.0038	0.3811	0.0942	0.2436	0.1338
St Dev.($W_{97\text{-}unmatch}$)	2.4637	2.3209	2.3463	2.2397	1.5739	1.4010
$Consistency_{97\text{-}unmatch}$	0.666	0.6154	0.6667	0.6667	0.8718	0.8718
$n_{97\text{-}unmatch}$	39	39	39	39	39	39

Note: Column values are coefficients on independent variable. A zero value indicates the variable was not used in that model. The lower portion of the table presents comparative model performance statistics. Comparisons should only be made between primary and alternative models within the same dependent variable. Lower AIC values indicate a *better* model. R^2 values are reported for the 1998 sample. 1997 data are grouped as: (1) all sites combined (ALL), (2) 1997 sites at the same location as 1998 sites (match), and (3) 1997 sites at different locations than 1998 sites (unmatch). W-statistic is the average error for the validation data set. Consistency is the proportion of sites with estimates within 2°C of the observed value.

Discussion

All of the models indicate that canopy closure, air temperature, and watershed position have important influences on stream temperature. However, there are other variables not adequately investigated that may be important factors in stream temperature but were not addressed because of data gaps: bankfull depth, bankfull width, and basin to name a few.

Additionally, the lack of air temperature data at the stream site made it necessary to investigate the effects of air temperature through the use of surrogates. Air temperature probably plays a greater role in influencing water temperature than these models seem to indicate. Likewise, canopy closure data were collected with a variety of methods with different levels of accuracy; which leads to a similar problem with the canopy data as seen with the air data. With the error introduced into the canopy values by the collection methods, canopy should also have a much greater influence on water temperature than the models indicate.

Cross validation results indicated some possible model over fitting. Although model statistics indicated that all the primary models performed much better, mixed results from model validation procedures suggest the possibility that the some selected covariates in the primary models may fit the data well due to chance. Observed coefficients for some of the covariates may not be indicative of real relationships between dependent and independent variables.

Similarity Between XY1DX and XYA7DX

XY1DX, the highest maximum stream temperature for the year, and XYA7DX, the highest seven-day moving average of the daily maximum stream temperature, both measures of daily maxima, had similar models for all three geographic areas (Tables 10.4, 10.6, and 10.8). Both dependent variables used the same list of covariates in the same ecoprovince models. Although not identical, the coefficients for the coincident covariates in each model were similar and always of the same sign. An increase in the value of a covariate that results in an increase in water temperature for one dependant variable resulted in an increase in water temperature for the other dependant variable as well. In contrast, XYA7DA is the highest seven-day moving average of the daily average stream temperature, which is a measure of daily average and not daily maximum. XYA7DA models had a different list of covariates compared to the XY1DX and XYA7DX models for all geographic areas.

The similarities are not surprising given the relationships that exist between the dependant variables. The fit of XY1DX versus XYA7DX had an R^2 values of 0.995, while the R^2 of XYA7DA versus XY1DX and XYA7DX were still high, at 0.922 and 0.934, respectively. There was sufficient difference in the variation of each of the three temperature metrics to result in the selection of a different set of variables. Sullivan et al. (1990) believe that average water temperature may be more a function of average air temperature, whereas temperature metrics dealing with daily maxima are more related to solar heat input. Differences in the set of covariates chosen for the daily maxima type stream temperature metrics and the daily average metrics may be indicative of different heating processes.

Air Temperature

All selected models used surrogates for air temperature. Unfortunately, for the primary models, these surrogates were always related to geographic or topographic position. Latitude, longitude, distance from coast, ecoprovince, and zone of coastal influence all were selected covariates in the models. Not one air temperature metric went into any primary model. Remote air temperature data may work better than the surrogates listed above when modeling temperature for basins. If all the sites are within an ecoprovince with a small range in latitude and longitude, the other covariates might not be as significant (given a smaller range in values) and the remote air station might provided the better relationship. Without having a direct estimate of air temperature in the model, it is difficult to see the relationship between water temperature and air temperature. In chapter 5, a positive correlation between water temperature and air temperature was established.

The interior ecoprovince models (Table 10.6 and 10.7) illustrate the challenge in interpreting the effect of air temperature on water temperature. The further east the site (increasing UTMX) the cooler the water temperature. It is expected that moving eastward would result in an increase in air temperature. However, in the interior-ecoprovince portion of the coho salmon range there is a relationship between UTMX (easting) and elevation. Generally, at stream temperature sites within the interior ecoprovince, elevation increases in a west-to-east direction. Additionally, in the interior ecoprovince, there is a negative correlation between elevation and air temperature (adiabatic cooling). Thus, the further east a site is located, the cooler the air temperature. To further confound the analysis, elevation also entered the XYA7DA interior ecoprovince model as well. Potentially, there is an interactive relationship between elevation and UTMX.

Ecoprovince and the zone of coastal influence are examples of similar air temperature surrogates that entered the models. For the combined ecoprovince models, ecoprovince was factored as in or out (1 or 0) of the coastal ecoprovince. At the same time, the sites were factored as in or out of the zone of coastal influence. Although not the same, the zone of coastal influence is close to the same geographic area as the coastal ecoprovince. There were no sites that were in the interior ecoprovince and the zone of coastal influence, although the zone of coastal influence does enter the interior ecoprovince. Conversely, there were coastal ecoprovince sites that were out of the zone of coastal influence. For the XY1DX and XYA7DX models, both ecoprovince and zone of coastal influence were important factors. XY1DX and XYA7DX estimates were cooler in the coastal ecoprovince and in the zone of coastal influence. The XYA7DA model did not select ecoprovince as a factor, but the zone of coastal influence was significant with sites in the ZCI being cooler. Moreover, in the coastal ecoprovince models, all three dependent variables selected the zone of coastal influence as a significant factor.

Lack of time-step correspondence between air and water temperature metrics was a potential reason for mediocre water temperature prediction capabilities. Models were fit to stream temperature data on daily or weekly statistics. The weekly data were seven-day moving averages. While both the daily maximum and the seven-day moving averages change from day to day, the highest daily maximum and highest seven-day moving average for the year was used in model development. Most XY1DX, XYA7DX, and XYA7DA values occurred in late July and early August (see March 1998 FSP Technical Note in Appendix A).

Air temperatures used in model development were calendar monthly averages. Most of the air temperature data used in modeling were available only as monthly summaries. The time scales for air and water temperature metrics used in modeling were obviously mismatched. However, we were interested in modeling stream temperature metrics that are in common usage in California and the Pacific Northwest. Sullivan et al. (1990) found unexpectedly good agreement between the commonly used temperature metrics and monthly water temperatures.

Since the highest daily maxima and seven-day moving averages occur predominantly in July and August we chose to use the combined July-August average air temperature in model development. During preliminary modeling exercises, AIC scores almost always favored the combined July and August average maximum air temperature metric over the single July or August values. Thus, for the backward selection procedures, only the July and August average maximum air temperature metric was used. However, the relationship between PMAX08 (an August maximum air temperature metric) and P.MO.MAX (a July and August average maximum air temperature metric) was very high ($R^2 = 0.999$ for linear fit). Thus, there was little difference if PMAX08 or P.MO.MAX was used in the models.

Solar Radiation Exposure

Canopy closure was the single most important variable investigated with respect to solar radiation exposure, although ecoprovince and ZCI also play a role in the amount of solar radiation reaching the stream surface. The coastal ecoprovince and the ZCI generally will have more solar radiation filtered out by fog and clouds than areas outside of the ZCI and in the interior ecoprovince.

Every fitted model included canopy as a covariate, and in every model, there was an inverse relationship between canopy closure and water temperature. However, without a sound sampling design and without canopy data collected using consistent protocols that measure effective shade, the level of analysis required to answer questions like, "how much canopy needs to be retained to keep the water at *x* degrees under condition *y*?" cannot reliably be answered. Given the caveat that this modeling effort was exploratory in nature and that numbers presented lack any level of confidence, the primary XYA7DA interior ecoprovince model suggests that there was a positive interaction between canopy and the log of the watershed area. This poses an interesting conundrum that warrants further investigation. Just how do watershed area and canopy closure interact. Below, the terms that involve canopy were put into an inequality that indicates that there is a cooling effect on stream temperature:

$$1.2(CANOPY * LOGWA) - 6.4(CANOPY) < 0$$

The above statement is true only when:

$$LOGWA < \frac{6.4(CANOPY)}{1.2(CANOPY)} ,$$

or, canceling *CANOPY*, when *LOGWA* is less than 5.33 or about 215,000 ha. Once the log of watershed area exceeds 215,000 ha, canopy has a warming effect on stream temperature. This, however, should not be surprising since sites in our region-wide study area did not exhibit canopy levels above 30% at watershed areas greater than about 63,000 ha (see Chapter 9). With increasing watershed area and divide distance canopy is expected to decrease due to channel widening, rendering adjacent stream-side vegetation ineffective at providing shade to stream surfaces. Concomitantly, there is generally a longitudinal warming in stream temperature with increasing distance from the watershed divide and increasing watershed area.

Watershed Position

Watershed position, as expressed as either the log of distance from the watershed divide, the log of watershed area, or both, entered every model. In all cases, as the watershed area or distance from divide increased, there was an increase in steam temperature. However, the models for XY1DX and XYA7DX in the coastal and the combined ecoprovinces included an interactive term between log watershed area and log distance from divide that had a negative coefficient. Analyses similar to that for the canopy closure log watershed area interaction might reveal situations where certain combinations of watershed area and distance from divide might have a cooling effect. Such a phenomenon is not unreasonable since it was shown earlier that warm rivers flowing out of warm interior portions of watersheds exhibited a cooling down upon entering the zone of coastal influence.

Habitat Type

FSP had requested that temperature probes be placed in riffles were the water is well mixed. However, a number of temperature probes were placed in pools, some of which were designed to characterize the extent of cool thermal refugia. Since many pool probes were intentionally placed to measure water that is cooler than that found in the well-mixed riffles, habitat type was used as a factor for consideration in the models. The habitat type factor grouped shallow pools, medium pools, and deep pools together in one group and runs and riffles into the other. Habitat type was found to be a significant factor in the coastal and combined ecoprovince models, where, as expected, pools were cooler than runs and riffles. The result that habitat types were not significant in the interior but were on the coast might not be a real response, but may be due to differences in sampling methods. The probes that were known to be placed in pools for describing cool thermal refugia were all in the coastal ecoprovince. Thus, it was expected that these sites would be cooler. For pool sites in the interior ecoprovince, the purpose for placement in pool habitat was largely unknown. Additionally, fewer probes were placed in pools in the interior, making comparisons difficult. There was over 50% pool placement of probes in the coastal ecoprovince and only about 30% pool placement in the interior.

The placement of temperature probes into pools adds additional unnecessary complexity to an already complex relationship. The relationship between water temperature and the covariates that control water temperature is difficult to model. Collecting data in pools as well brings into the model a relationship between the mixed water of the riffles and water that may or may not stratify in pools. If water temperatures were measured only in well- mixed riffles, then the water temperature models would have less variability, making interpretation much easier and more reliable.

Stream size

As stated in the watershed position section, there was a relationship between watershed area and distance from watershed divide with respect to stream temperature. Stream size is also related to watershed area and distance from divide, thus those variables might serve a surrogacy role for stream size in the model.

Bankfull width and bankfull depth were left in the backward selection procedure only to illustrate their possible importance. In preliminary modeling exercises, when either or both covariates entered the model a good AIC score with a high R^2 value was observed. However, model improvement may be because of the relatively small geographic area represented by sites with non-null bankfull data. Whether the good fits were due to an actual relationship between water temperature versus bankfull width and depth or whether due to the limited number of basins entered into the models is unknown. However, given the significance of bankfull width in several physical-based temperature models (Bartholow, 1989; Sullivan et al., 1990), it is believed that the observed importance of this variable in the present study is real and not an artifact of limited areal extent. In the future, bankfull width and bankfull depth should be recorded and investigated for the potential effects on stream temperature.

Basin

During preliminary model exploration, BASIN was one of the most important covariates. However, many basins had no stream temperature sites, others had a few, and some basins dominated the data set. One of the fitted models indicated that the Smith River basin was the hottest basin, when factoring out other effects in the model. The Smith River basin had only four stream temperature sites, making more in-depth investigation of such a small number of sites feasible. All four sites had high canopy values, were close to the coast, were located in the northern portion of the study area, and were close to the watershed divide. All of these factors would result in an lower estimated water temperature without taking basin into account. These four sites were all small coastal streams. None were mainstem or interior ecoprovince sites. These points were not representative of the Smith River basin as a whole. Given this problem and the large number of basins without any sites, BASIN was dropped from the analysis.

This underscores the effects of a lack of sampling design on the error structure of the data and the resulting models.

Summary

Researchers have had a great deal of success modeling stream temperature at basin and smaller scales. However, if the desire is to model stream temperature at a coho salmon ESU scale, many complications not seen at the smaller scale arise. Namely, remote air data coupled with surrogates, such as elevation, may work well for developing a basin-scale model, but at a regional scale, a better estimate of the local air temperature is required. Additionally, these analyses were confounded by the fact that there was no sampling design in place. Basins rich in data, like the Eel River, were over represented as compared to a basin like the Smith River, where only four sites were found. Without a sampling design to guide placement of stream temperature sensors it is difficult to know exactly what geographic area these models describe.

All the fitted models indicated that air temperature, solar radiation, and watershed position were important covariates. Positional covariates entered all the models. While these were viewed as air temperature surrogates, this underscores the fact that location is an important factor in stream temperature profiles. For example, two sites that appear to be identical with respect to habitat, riparian condition, shading, watershed area, and flow rate, but are in different basins will more than likely have different temperature profiles. Stream temperature “target” values that may be easily achieved in some areas might be impossible in others.

Although models were presented and statements made as to what independent variables influence water temperature, the lack of a sampling design makes in-depth analyses tenuous. Questions regarding each covariate’s contribution to explaining variation in stream temperature requires data collected with a sampling design suited for developing explanatory models. Such a design would require a sampling frame, constructed from a well-defined sampling universe. Then, a random probability sample of some type must be drawn from the sampling frame. Finally, air temperature, canopy, and stream-size data collection, and stream temperature sensor placement must all adhere to consistent protocols and all collected values must be submitted. Note, the explanatory model would not work well to predict stream temperatures. The explanatory model will require local air temperatures and good canopy data that will be expensive to collect at a large scale. If a predictive model is desired, then a higher sampling rate applied over a smaller spatial scale, without collection of local air temperature, would be more cost effective. Nonetheless, a sampling design with a random probability sample is still required.

Chapter 11

HISTORICAL PERSPECTIVES

Introduction

The advent of digital continuous monitoring devices for stream temperature is a quite recent event. Continuous thermographs have been available since 1951 (Blodgett, 1970). There are reports dating back fifty years or more that contain synoptic hand-held thermometer temperature data reported for select stream and river locations across Northern California. Comparison of a single stream temperature datum point recorded at some arbitrary time of day at some arbitrary location on a stream in the past to more recent continuously monitored stream temperature data is difficult. It may lead to erroneous conclusions or no conclusions at all.

Matching up the location of the historical data or datum to more recent data can often be laborious detective work, attempting to identify the location of a crime scene for a crime committed several decades ago. Usually the location information is very sketchy. Locations may be referenced to some landmark (bridge, road, pool) that no longer exists or to a stream or confluence whose name has changed.

Recent FSP data contributor sites up to 2000 m from the historical site location were used in comparisons. However, for status assessment and regional trend analyses of FSP sites presented in Chapters 3 - 9, ten meters was the largest distance separating two sites that were considered to be the same site across multiple years. There was only one historical site that was approximately 10 m from a contemporary FSP site. If the more stringent standard for defining a unique site location was used for the historical comparisons, there would be only one historical comparison. Thus, some concessions were made in order to increase the number of matched sites for historical comparison purposes. Many of the historical sites were located on mainstem rivers, which are believed to have less longitudinal temperature variability over long (thousands of meters) distances. Less longitudinal variability allows comparisons of historical and contemporary sites that are not collocated.

Most of the historical data comes from larger streams where air temperature is most likely the major factor influencing water temperature. Thus, this analysis does little to address any stream temperature changes that have occurred since the 1950's in smaller streams, where most coho salmon rearing takes place and where land management practices may have a greater influence on thermal regimes and the extent of potentially suitable habitat. This historical analysis is on a site-by-site basis and not a regional assessment of trends in stream temperatures across the range of coho salmon in Northern California.

We found that stream temperatures at many sites have been fairly similar over two or more decades. Much of the variability that was observed could be attributable to year-to-year changes in air temperatures. On smaller streams, changes from historical stream temperature levels may be related to changes in certain site factors. However, no historical site attribute data, and in some cases no contemporary site attribute data, were available for which to relate changes in water temperature.

Sources of Historical Stream Temperature Information

Various reports from the Bureau of Fish Conservation, California Division of Fish and Game can be found in the government documents section of the library. Many of these reports contain max-min or single grab sample water temperatures, often accompanied by synoptic air temperatures measured at approximately the same time and place.

The U.S. Environmental Protection Agency (EPA) maintains a database of water quality information. The database, known as STORET, is a computerized data base utility maintained by the EPA for the STOrage and RETrieval of chemical, physical, and biological data pertaining to the quality of the waterways within and contiguous to the United States. A data request for all stream temperature data available in STORET for the HUCs comprising the range of the coho salmon in Northern California was submitted to the U.S. EPA. The data were received within two days of the request. The stream temperature monitoring point locations were displayed in GIS and compared to FSP's point coverage. It was found that 1996-1997 data from a large federally funded water temperature monitoring study in the Eel River Basin were submitted to the U.S. EPA for inclusion in STORET with their original site coordinates. On average, these points were 993 m from their true locations with a maximum of 63 km (See Chapter 2, Spatial Accuracy Assessment). This raises some concerns as to the spatial accuracy of other stream temperature data found in STORET. The quality of data in STORET, both for the numeric values of the parameter of interest and for the spatial location where the parameter was measured, is entirely up to the discretion of the data contributor. Also, the received data set had data from hand held thermometers, digital continuous monitoring devices, and thermographs, with no indication of which collection method was used for the site. Many sites had only one record, listed with a date; it was unknown whether these particular points were grab samples or daily maxima. Because of the uncertainty surrounding these data, STORET data were not used in historical comparisons.

The USGS has recorded water temperature at many of their stream gaging stations. The sites are located primarily on mainstem tributaries, usually fourth order or greater. A very good source of temperature data that was used in this chapter was a stream temperature summary report prepared by Blodgett (1970) who summarized USGS water temperature data in tabular format. Both periodic and continuous temperature data were reported. The data for some locations date back to the early 1950's. USGS has also published water temperature data in annual ***Water Resources Data for California*** reports (USGS, 1975, 1976, 1977, 1978, 1979, 1980). One of the impediments in using USGS stream temperature data as an assessment tool for historical status and trends is that the locations of gaging stations are mostly on large, mainstem portions of Northern California rivers. Water temperatures in these large, wide-channeled watercourses will be more a function of air temperature, as was discussed in Chapter 5. The effects of flow control on water temperature of many Northern California rivers was noted by Blodgett (1970) throughout his report.

The Pacific Gas and Electric Company (PG&E) of California conducted a water monitoring program in association with the Potter Valley Project (PG&E, 1996). Water temperature was monitored at 16 locations from 1980 through 1995. The Forest Science Project acquired these data in already summarized format: daily minimum, average, and maximum values. The Forest Science Project located six FSP sites that were within an estimated 1100 m of PG&E sites for comparisons. However, the exact location of the PG&E sites remains unknown and the true distances between the FSP site and the PG&E site may actually be less than or greater than 1100 m.

Summary of Administrative Reports

1951 Inland Fisheries Administrative Report

Stream temperature data collected in 1950 were found for a site located on the Eel River at Fernbridge, CA (Murphy and DeWitt, 1951). Data were reportedly collected with a thermograph of unknown make and model. Daily maxima and minima were reported for June through September, 1950. A Forest Science Project data contributor deployed a continuous stream temperature sensor near Fernbridge in 1997. Data collection began on July 23, 1997 and ended on September 30, 1997. A comparison of the 1950 and 1997 daily maxima and minima for this location is shown in Figure 11.1. The daily maxima in August ranged from 18.3° to 22.2°C in 1950 and from 19.4° to 22.4°C in 1997. The August daily minima ranged from 17.2° to 21.1°C in 1950 and from 19.0° to 20.9°C in 1997.

There was no information in the Murphy and DeWitt (1951) report on the exact placement of the thermograph, e.g., whether it was placed in a pool or riffle, whether the sensor was shaded from direct sunlight, or whether the sensor was placed in the thalweg. The drainage area at this location is approximately two million acres. Such a large drainage area value would suggest that the Eel River at this location is quite wide with little or no stream-side shading. This hypothesis is supported by first-hand knowledge of the Eel River at this location and by the canopy closure value reported to the Forest Science Project at the Fernbridge site in 1997 (5%).

Monthly average air temperatures were obtained for a NOAA weather station located in Scotia, CA, approximately 17 km (~11 mi) from Fernbridge. The monthly average maxima and minima air temperatures are shown in Figure 11.2. Examination of monthly average air temperatures for the months of July, August, and September revealed that in 1997 these months were warmer than in 1950. Warmer air temperatures may account for the higher daily maxima and minima water temperatures observed in 1997 compared to 1950.

From the same report prepared by Murphy and DeWitt (1951) air and water temperature data were presented for various locations on the Eel River and at the mouth of the Van Duzen River at its confluence with the Eel River. Table 11.1 presents these data as they appeared in the 1951 report. There was no information in regards to canopy closure, flow rates, or other site-specific attributes.

Water temperature exceeded air temperature in most instances. On June 25, 1950, the weather was noted to be clear and warm. The water temperature in the Van Duzen River exceeded the air temperature at 6:00 PM by 7.2°C (13°F) on this particular day in 1950. Water at these locations originated in more interior portions of the basin, where air temperatures can be much warmer than more coastal areas (see Chapter 4). On July 8 and August 20, 1950, both days reported as clear and warm, the water temperature was 23.3°C around 1 pm. This may represent the maximum equilibrium stream temperature at this location on the Van Duzen River. On August 8, 1997 the daily maximum stream temperature was 22.6°C near the same location (see Figure 7.21). The stream temperatures recorded 47 years apart are quite similar, suggesting that this temperature value may be near the equilibrium temperature for this location on the Van Duzen.

Table 11.1 is a good example of the lack of locational information found with most historical temperature data. With better site location information more recent FSP stream temperatures could quite possibly have been collected at a site in close proximity to the 1950 sites. Not all locational information in historical sources is undetailed, as can be seen in the next Administrative Report by Blea (1938).

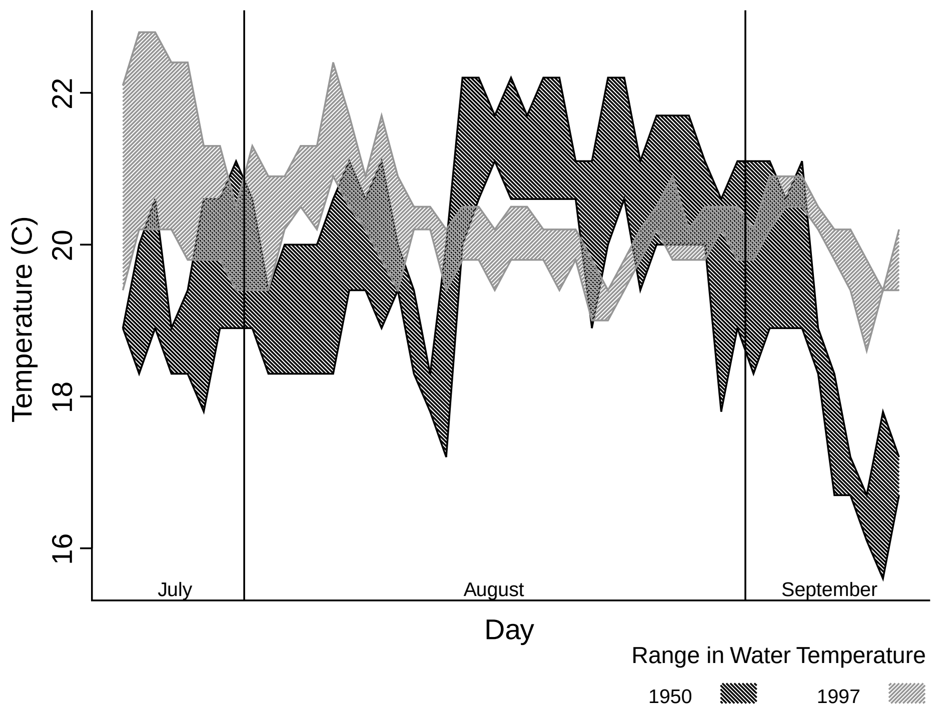


Figure 11.1. Comparison of daily maxima and minima Eel River water temperatures (°C) measured at Fernbridge, CA in 1950 and 1997 from mid-July through mid-September.

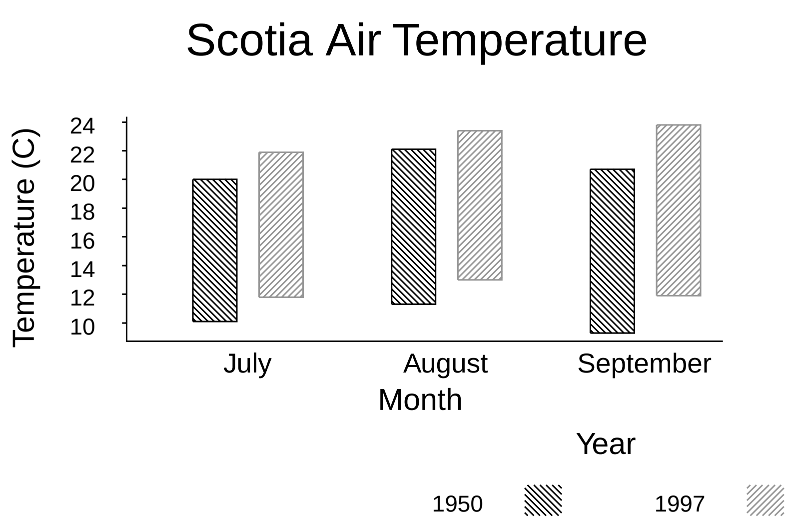


Figure 11.2. Comparison of air temperature for July, August, and September at Scotia, CA in 1950 and 1997. The tops of the bars indicate the average monthly maxima, while the bottoms represent average monthly minima.

Table 11.1. Hand-held Air and Water Temperatures Collected at Various Times and Locations During the Summer of 1950 in the Lower Eel Basin (Taken from Murphy and DeWitt, 1951).

			Temperature (°C)		
Date	**Time**	**Place**	**Air**	**Water**	**Remarks**
June 10	9:35 AM	Eel River VD	16.1	17.2	Cloudy, cool
" "	9:45 AM	Van Duzen R.	16.1	16.1	" "
" "	11:45 AM	Weott Bay	13.3	15.0	In backwater of Bay
" "	12:05 PM	Salt R. Bridge	13.3	14.4	Flow 100 g.p.m. (rough)
" "	12:45 PM	Singley Pool	13.3	20.6	Water clear, green
June 11	11:30 AM	Van Duzen R.	16.7	15.0	Cloudy, mild
" "	1:30 PM	Singley Pool	14.4	16.7	Cloudy, cool
June 12	10:00 AM	Singley Pool	12.2	16.1	Cloudy, cool
" "	4:00 PM	Van Duzen R.	13.9	15.6	Cloudy, cool, water not too clear
" "	5:00 PM	Singley Pool	12.2	15.0	Cloudy, cool
June 13	6:20 PM	Van Duzen R.	12.2	13.9	Cloudy, cool, water muddy
June 17	10:00 AM	Van Duzen R.	14.4	14.4	Cloudy, warm
" "	11:30 AM	Fernbridge	13.3	15.6	Cloudy, warm
June 19	9:00 AM	Van Duzen R.	13.9	13.9	Cloudy, mild
June 20	4:15 PM	Van Duzen R.	14.4	15.6	Cloudy, cool, windy
" "	5:00 PM	Fernbridge	13.9	17.2	" " "
June 22	2:30 PM	Van Duzen R.	14.4	17.8	Partly cloudy, cool
June 24	10:40 AM	Van Duzen R.	15.6	16.7	Partly cloudy, mild
June 25	6:00 PM	Van Duzen R.	13.9	21.1	Clear, mild
June 28	10:20 AM	Van Duzen R.	18.9	19.4	Clear, warm
" "	2:30 PM	Dungan Pool	18.3	20.6	" "
June 29	10:30 AM	Van Duzen R.	15.6	18.9	" "
July 2	1:00 PM	Van Duzen R.	20.0	21.7	" "
July 3	11:30 AM	Dungan Pool	18.3	18.9	" "
" "	12:30 PM	Van Duzen R.	15.6	20.0	" "
July 8	1:00 PM	Van Duzen R.	21.7	23.3	" "
July 9	9:30 AM	Van Duzen R.	12.8	16.7	Cloudy, cool, misty
July 15	12:00 PM	Van Duzen R.	18.3	22.2	Clear, warm
July 23	10:30 AM	Van Duzen R.	15.6	17.8	Cloudy, mild
July 29	10:00 AM	Van Duzen R.	15.6	18.3	Clear, warm
July 31	12:00 PM	Van Duzen R.	19.4	22.8	" "
Aug. 5	3:30 PM	Dungan Pool	18.3	19.4	Clear, warm, breezy
Aug. 6	2:00 PM	Van Duzen R.	18.3	22.2	" " "
Aug. 20	1:30 PM	Van Duzen R.	18.9	23.3	" " "

1938 Inland Fisheries Administrative Report

In 1938 large steelhead trout mortality was reported on the South and Middle Forks of the Eel River. J.H. Blea of the California Division Fish and Game, Inland Fisheries Branch investigated the problem. He prepared a detailed report that appeared in the Administrative Records of the Inland Fisheries Branch in 1938 (Blea, 1938). Blea collected several air and water temperature readings with a hand-held thermometer at numerous locations in the South Fork and Middle Fork Eel Rivers and in various tributaries. Most of the tributary water temperatures were collected near the confluence with the river. At some tributary locations he also recorded the water temperature of the mainstem above and/or below the tributary. Blea also made observations of the number of steelhead trout and any mortalities or obvious signs of a diseased condition.

Upon arriving at the scene Blea learned that three weeks prior to 21 July 1938 the weather had been hot, and became even hotter over the next three days. Air temperatures in Garberville reached 44°C (112°F). He described both the South Fork and Middle Forks of the Eel River in the area of his investigation as:

> *. . . unusually exposed to the sun for distances of seventy-five miles or more. The broad river beds offer no shade to the relatively small flow of water which moves slowly along, alternately through large pools and wide, shallow riffles.*

Blea stated that despite the heavy winter rainfall the rivers were low because there had not been the usual spring rains. Blodgett (1970) states that flow regulation of the Eel River began in December of 1921, the time at which the Scott Dam went into operation. Construction of the Cape Horn Dam in 1908 may also have influenced flow regimes on the Eel River in 1938. Blea speculated that water temperatures had probably reached 80°F to 85°F (27° to 29°C) throughout much of the area where fish exhibited a high incidence of "disease". "These temperatures are very near the lethal limit for trout and this factor coupled with the consequently low oxygen content apparently reduced resistance of the fish to the diseases."

The Blea report is about the only historical report, other than USGS reports, that could be uncovered that had adequate location information for both tributary and mainstem sites that enabled us to compare more recent FSP water temperature data. Table 11.2 is a summary of air and water temperature measurements taken by Blea at various locations on the South and Middle Forks of the Eel River and tributaries entering the mainstems. More contemporary recordings of water and air temperature are included in the table for historical comparison purposes. Hourly air temperature recordings were not available for the nearest NOAA air station located at Richardson Grove State Park, therefore monthly averages are presented in Table 11.2.

On the Middle Fork of the Eel River at Fort Seward the water temperature reported by Blea was 23.9°C (75°F) at 9:30 am on 27 July 1938 (Table 11.2). A Forest Science Project site located near the same location (~1500 m upstream), as best as can be determined from the 1938 site location description, was found to have a water temperature of 24.4°C (75.9°F) at 9:47 am on 27 July 1997. It is highly unlikely that the 17-minute difference in the time of day the two readings were taken might account for the 0.5°C (0.9°F) difference in the water temperatures. A comparison of present-day water temperatures to synoptic grab sample water temperatures can be considered qualitative at best. Nevertheless, the similarity is striking.

Dean Creek is a tributary to the South Fork Eel and exhibited a water temperature of 19.4°C at 8:00 am on 31 July 1938 (Table 11.2). On the same day in 1996 at about the same time of day, the water temperature was 22.0°C. The July monthly average air temperatures indicated that July 1996 was warmer than July 1938. However, the monthly average air temperature for July 1997 was the same as 1996, but the water temperature was lower than the 1938 value.

Table 11.2. Hand-Held Air and Water Temperatures Collected at Various Times and Locations During the Summer of 1938 in the South Fork and Mainstem Eel River and Various Tributaries (Blea, 1938) in Comparison to More Contemporary Forest Science Project Data.

date	time	location	Water and Air Temperature (°C)														Dist (m)	Dir
			1938		1993		1994		1995		1996		1997		1998			
			H20	Air	H20	Air	H20	Air	H20	Air	H20	Air	H20	Air	H20	Air		
South Fork Eel River and Tributaries																		
7/31	8:00 AM	Dean Cr.	19.4	20.9							22.0	21.9	19.0	21.9			312	UP
7/26	8:30 AM	Redwood Cr.	18.3	20.9							21.1	21.9					1922	UP
7/28	8:30 AM	Sprowl Cr. at mouth	17.2	20.9							17.7	21.9	16.5	21.9			153	UP
7/25	10:30 AM	Six mi. above Benbow Dam	23.9	20.9											23.8	19.7	1463	UP
7/30	9:00 AM	Indian Cr. @ SF Eel	17.2	20.9									18.7	21.9			46	UP
7/30	12:00 PM	Indian Cr. two miles from Eel	19.4	20.9	19.0	19.6	21.1	20.1	20.4	21.3	21.7	21.9					747	UP
8/01	2:00 PM	Indian Cr. @ SF Eel	23.9	20.0									21.7	23.4			46	UP
7/25	1:00 PM	Red Mountain Cr. @ SF Eel	20.0	20.9							23.5	21.9	24.6	21.9	24.0	19.7	101	UP
7/31	6:30 PM	Rattlesnake Cr. @ SF Eel	23.3	20.9							26.1	21.9	25.2	21.9	23.2	19.7	164	UP
7/31	6:30 PM	SF Eel above Rattlesnake Cr.	23.9	20.9							26.7	21.9	26.0	21.9			351	UP
8/01	5:30 PM	Elder Cr. @ SF Eel	16.7	20.0							19.0	21.6	17.7	23.4	18.0	20.9	132	UP
8/01	5:30 PM	SF Eel above Elder Cr.	21.1	20.0									19.9	23.4	20.2	20.9	99	UP
8/01	5:00 PM	Dutch Charlie Cr. @ SF Eel	15.6	20.0							19.3	21.6	18.6	23.4			310	UP
8/01	4:00 PM	Redwood Cr. @ SF Eel	16.1	20.0							16.1	21.6					10	UP
Mainstem Eel River and Tributaries																		
7/26	1:00 PM	SF Eel @ Mainstem Eel	21.1	20.9							23.7	21.9	23.9	21.9	25.1	19.7	261	UP
7/29	12:00 PM	S. Dobbyn Cr. @ road xing	21.1	20.9									20.8	21.9	20.3	19.7	69	UP
7/27	9:30 AM	Eel @ Ft. Seward	23.9	20.9									24.8	21.9			1464	UP
7/27	9:30 AM	Eel @ Fort Seward	27.0	20.9									24.8	21.9			1160	UP
7/30	5:30 PM	MF Eel near Dos Rios	26.7	20.9							28.5	21.9	27.0	21.9	25.3	19.7	187	UP
7/30	5:30 PM	Eel @ Mf Eel near Dos Rios	25	20.9											24.3	19.7	37	UP
Other Points																		
7/26	3:00 PM	Little Van Duzen @ road xing	21.7	20.9							25.4	21.9	24.5	21.9	24.4	19.7	65	DN
7/29	1:30 PM	Larabee Cr. @ road xing (road fr Blocksburg to Bridgeville)	21.1	20.9							21.8	21.9	17.6	21.9	20.0	19.7	26	DN

NOTE: All air temperature data are monthly averages recorded at a NOAA station in Richardson Grove State Park. Distance up (UP) or downstream (DN) from FSP site is shown in last two columns.

Redwood Creek exhibited a water temperature of 18.3°C at 8:30 am on 26 July 1938. On the same day and time in 1996 the water temperature was 21.1°C at a FSP site located about 1900 m upstream from the Blea 1938 site. The monthly average air temperatures for July and August 1996 indicate it was a warmer year than 1938, which may partly account for the higher water temperatures observed in 1996.

Sprowl Creek at its confluence with the South Fork Eel showed very similar water temperatures at nearly a 60-year sampling interval. In fact, in 1997, while air temperatures were higher than 1938's, water temperature in Sprowl Creek was lower.

Out of the 21 comparisons of historical and contemporary water temperatures presented in Table 11.2, eight showed relatively little change, 10 showed an increase, and three showed a decrease in water temperature. It is difficult to determine whether some of the observed increases were due to differences in climate, riparian conditions, flow, or all the above. The observed decrease in water temperature at Indian Creek was in the presence of monthly average air temperatures about 3°C higher in 1997 compared to 1938.

Potter Valley Project

A stream temperature monitoring study was performed in conjunction with the Potter Valley Project by Pacific Gas and Electric (PG&E) of California (PG&E, 1996). Daily water temperature summary statistics (i.e., daily minimum, average, and maximum) were obtained from PG&E. Data were collected at various locations along the mainstem Eel River above Pillsbury Lake to Fort Seward, CA. Two tributaries were also monitored, Tomki Creek which enters the mainstem below the Cape Horn Dam and Outlet Creek which enters the mainstem upstream from Dos Rios, CA. Figure 11.3 shows the approximate location of the monitoring sites. Water temperature data were collected from 1980 to 1995, although all locations did not have all years for their data records. Some stations had continuous data spanning the entire year, while others ended in early July for most years.

The only site location information provided with the PG&E data was an 8 by 10 inch map with a mark for each site labeled with a location name (e.g. Eel River Below Scott Dam). The marks covered nearly 1 km of stream. The sites were placed into a GIS coverage by visual estimation of the marks' center on the map and placed on the blue-line stream using a digital raster graph topographic map in ArcView. The spatial accuracy of this method was poor. After placement, it became apparent that two PG&E sites were at the same location as two USGS sites (Eel River Below Scott Dam and Eel River Above Van Arsdale Reservoir). These two sites had differences between the estimated PG&E location and the USGS location of approximately 270 m and 1270 m, respectively. Table 11.3 shows the estimated distance from the PG&E site to the corresponding USGS and FSP sites. Since the location of the PG&E sites were rather imprecise, these distances are presented to demonstrate that the sites are probably in the general vicinity of each other, with the caveat that comparisons may not be entirely appropriate, particularly for the two tributary sites. Longitudinal variability in water temperatures for larger mainstem rivers is considered to be much smaller than tributaries. Thus, some leeway is afforded in terms of spatial accuracy.

The PG&E, USGS, and FSP sites listed in Table 11.3 were combined on a single chart to develop a historical view of stream temperatures at each location. Monthly average water temperatures were calculated from the continuous data for FSP sites and from daily averages for the PG&E data. USGS data are reported as monthly average values in the Blodgett report (1970) and the various USGS ***Water Resources Data for California*** reports. If a month was missing more than five days of data, the average was not presented on the graph. Each bar on the chart represents monthly averages for June, July, August, or September. The vertical lines represent the range in daily minimum and maximum temperatures for each month.

Data charts are presented in a downstream direction, with the most upstream site presented first and tributaries to mainstems presented last. Typically, the hottest two months of each year were presented in

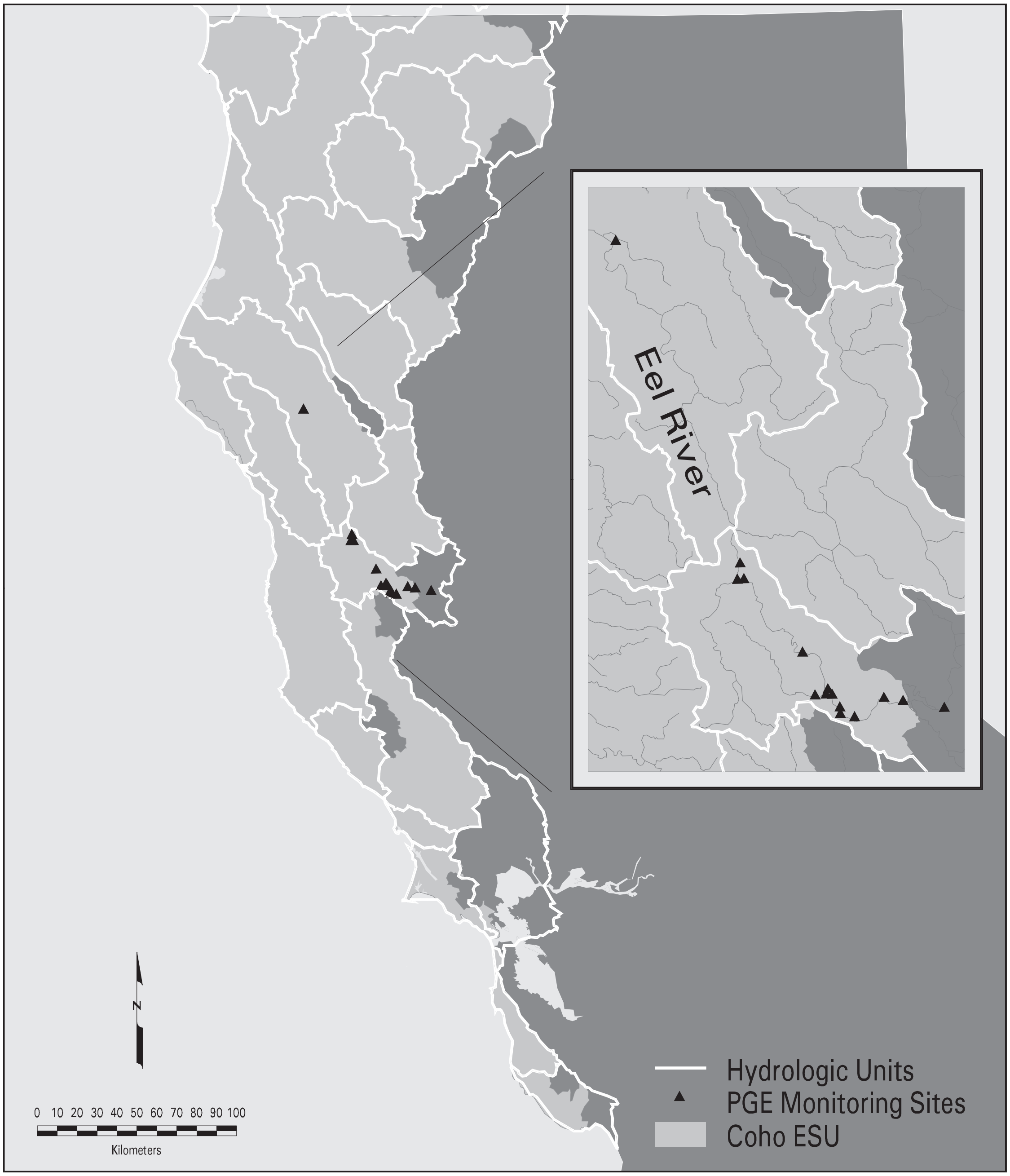


Figure 11.3. Location of PG&E Potter Valley Project stream temperature monitoring sites.

Table 11.3. The Estimated Distance from the PG&E Site to the Corresponding USGS and FSP Sites.

Site Location	Distance to FSP Site (m)	Distance to USGS Site (m)
Eel River Below Scott Dam	+350	+270
Eel River Above Van Arsdale Reservoir	-1030	-1270
Eel River Near Dos Rios	-620	-530
Eel River at Fort Seward	+720	0
Tomki Creek Near Eel River	-730	N/A
Outlet Creek Near Longvale	-620	N/A

NOTE: Positive values are upstream of the PG&E site, while negative numbers are downstream. The location of the PG&E sites are imprecise, thus the distances listed are only approximations to illustrate that the compared sites are probably in the same general vicinity.

the bar charts, i.e., July and August. More than one month may be shown on the graph because of the large number of months in various years with missing values for one or more months. Presenting multiple months increases the likelihood that a historical comparison can be made for at least one of the months across multiple years. The site below Scott Dam showed its highest stream temperatures in September; thus August and September were presented for the below-Scott-Dam site. Many PG&E sites did not have August data and some did not have July data. June data were presented for any site that did not have August data.

Figure 11.4 shows the monthly average water temperatures for the site situated below Scott Dam near Potter Valley, CA. Eel River water temperatures below Scott Dam do not seem to have changed appreciably over the last 33 years, with 1995 being one of the coldest years on record. Most years for this site show an increase in water temperature from June through September, which sets this site apart from almost all of the 1090 sites examined in the FSP regional assessment. Water temperatures at most other sites were hottest in July and August, while June and September were cooler. The steady increase from June through September is evident in the data collected by three different organizations over a 33-year time span, with 1977 being the only year on record where August had a higher monthly average than September. It would suffice to say that this trend is real, and not an artifact. The observed trend in water temperatures at this site is elaborated upon later in this chapter (USGS Continuous Data).

Figure 11.5 shows historical water temperature trends on the Eel River above Van Arsdale Reservoir, near Potter Valley, CA. The watershed area at this location was about 75,000 ha (290 sq mi) and the distance from the watershed divide was about 55 km (30 mi). Temperatures show the locally normal pattern for years where all four months of data were available, hottest in July and August. The temperatures varied between 16°C and 20°C for most months and most years. Water temperatures in 1992 and 1993 were some of the lowest July monthly averages for the 12 records spanning over 34 years. The August 1997 monthly average was the only one to exceed 20°C, however, most years did not have August data.

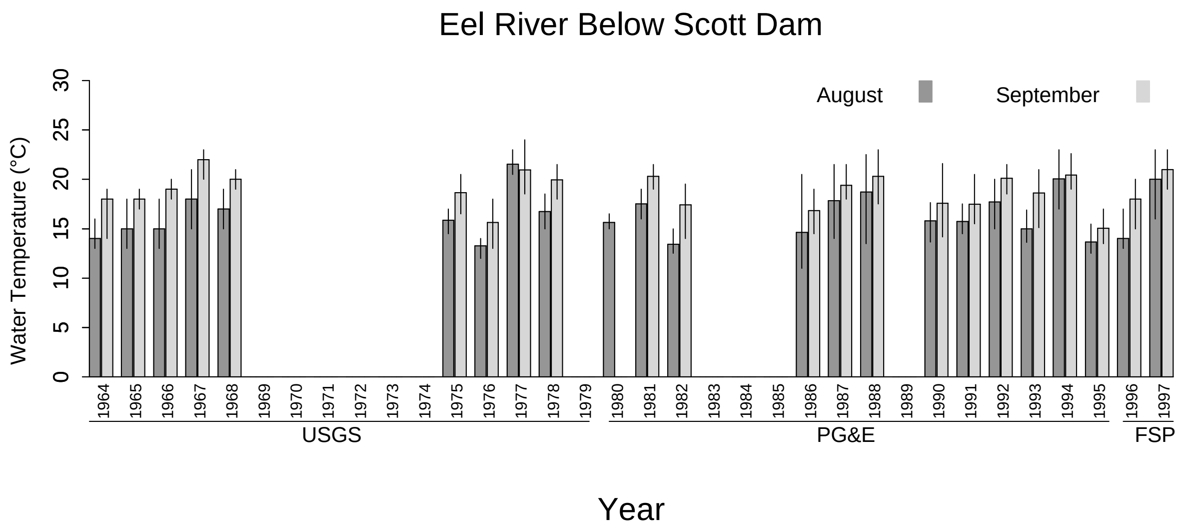


Figure 11.4. Comparison of historical USGS and PG&E monthly average stream temperature data with more recent Forest Science Project data during August and September. The site was located on the Eel River below Scott Dam, near Potter Valley, CA. Vertical lines represent the range in daily minimum and maximum temperatures for each month.

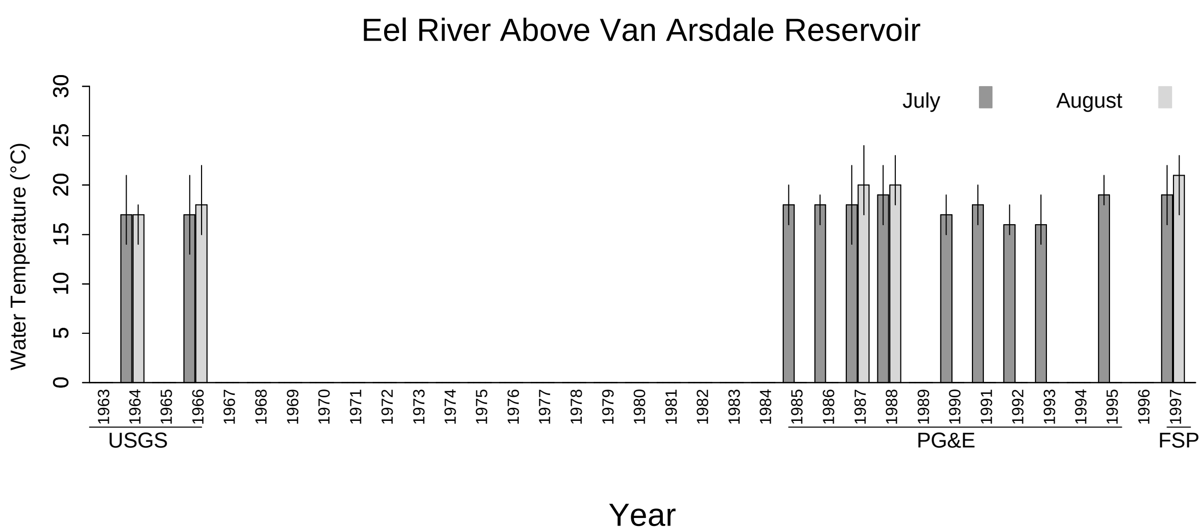


Figure 11.5. Comparison of historical USGS and PG&E monthly average stream temperature data with more recent Forest Science Project data during July and August. The site was located on the Eel River above Van Arsdale Reservoir. Vertical lines represent the range in daily minimum and maximum temperatures for each month.

Figure 11.6 presents a comparison of water temperatures at a site located on the Eel River near Dos Rios, CA. The watershed area at this location was about 136,000 ha (525 sq mi) and the distance from the watershed divide was 120 km (75 mi). The Eel River is quite wide near Dos Rios, with riparian vegetation too far from much of the stream to provide any appreciable shading. Most years of data collected for the PG&E site had data for only June and only three years of August data. The only year when August monthly average temperature (26°C) was higher than the July monthly average temperature (25°C) was 1966. June replaced August for the comparison since doing so greatly increased the number of years that could be examined. July monthly average water temperatures were near or above 25°C for most years in the long-term record. June 1993 was the lowest monthly average in the record, at about 18°C.

Figure 11.7 shows long-term monthly average water temperatures at a location on the Eel River at Fort Seward, CA. The watershed area at this location was about 544,000 ha (2100 sq mi) and the distance from the watershed divide was 225 km (140 mi). The channel is quite wide and aggraded at this location. The stream is mostly unshaded with vegetation offering minimal shading on the outside edges of bends. The canopy closure value submitted by a FSP cooperator in 1998 was 5%. The PG&E sites had enough data for only the month of June, thus June is the only month with data presented. No obvious increase in temperature can be detected.

Figure 11.8 presents a comparison of historical and more recent water temperatures at a site on Outlet Creek near Longvale, CA. The watershed area was 41,800 ha (160 sq mi) and the distance from divide was 50 km (30 mi). Unfortunately, only June monthly averages were available for the USGS and PG&E portions of the record. Thus, we are somewhat limited in our ability to discern any trends over time. Again, no obvious increase in temperature can be detected. June 1968 monthly average water temperature was slightly below 20°C. In 1985 the June monthly average was about 24°C, and in 1996 through 1998 was about 22°C.

Figure 11.9 compares monthly average temperatures on Tomki Creek near the Eel River over a 16-year period. The watershed area at this location was 15,800 ha (60 sq mi) and the distance from watershed divide was 35 km (25 mi). There was a gradual increase in monthly average temperatures from 1982 to 1988, followed by a return to 1982 levels in the 1990's. No data were available in 1990. In 1991, temperatures again reached levels seen in 1989. Water temperatures in 1996-1998 were at levels similar to those in 1986. The monthly average water temperatures fluctuated between 17°C and 25°C over the 16-year time period. There was no discernable increasing or decreasing trend.

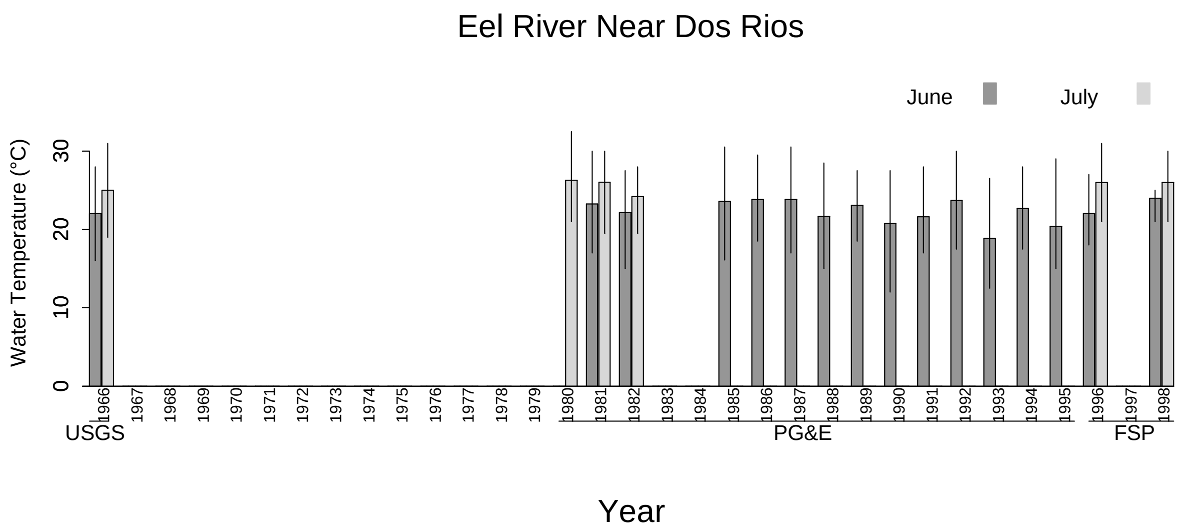


Figure 11.6. Comparison of historical USGS and PG&E monthly average stream temperature data with more recent Forest Science Project data during June and July. Location is on the Eel River near Dos Rios, CA. Vertical lines represent the range in daily minimum and maximum temperatures for each month.

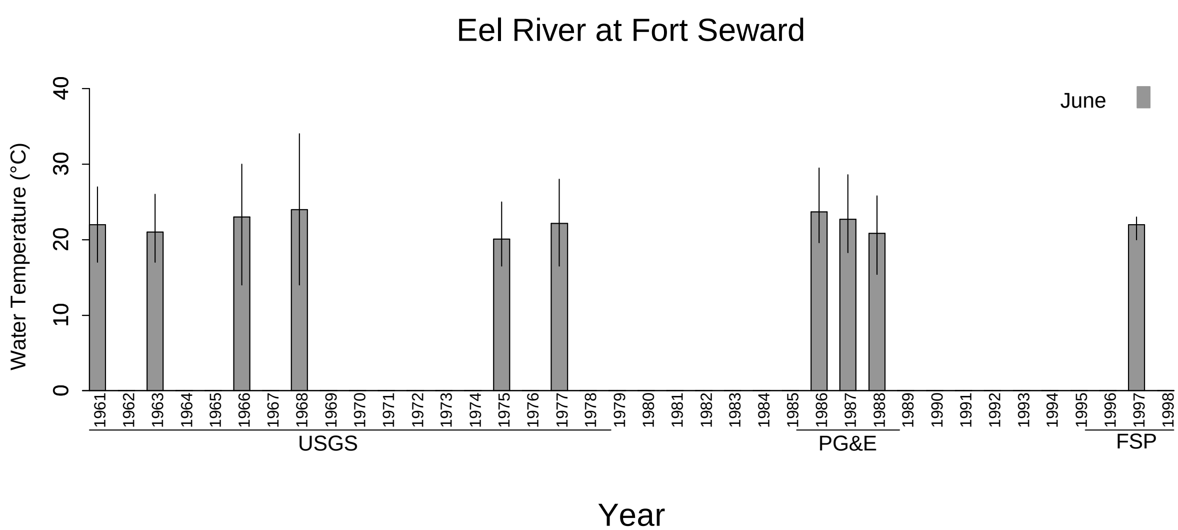


Figure 11.7. Comparison of historical USGS and PG&E monthly average stream temperature data with more recent Forest Science Project data during the month of June on the Eel River at Fort Seward, CA. Vertical lines represent the range in daily minimum and maximum temperatures for each month.

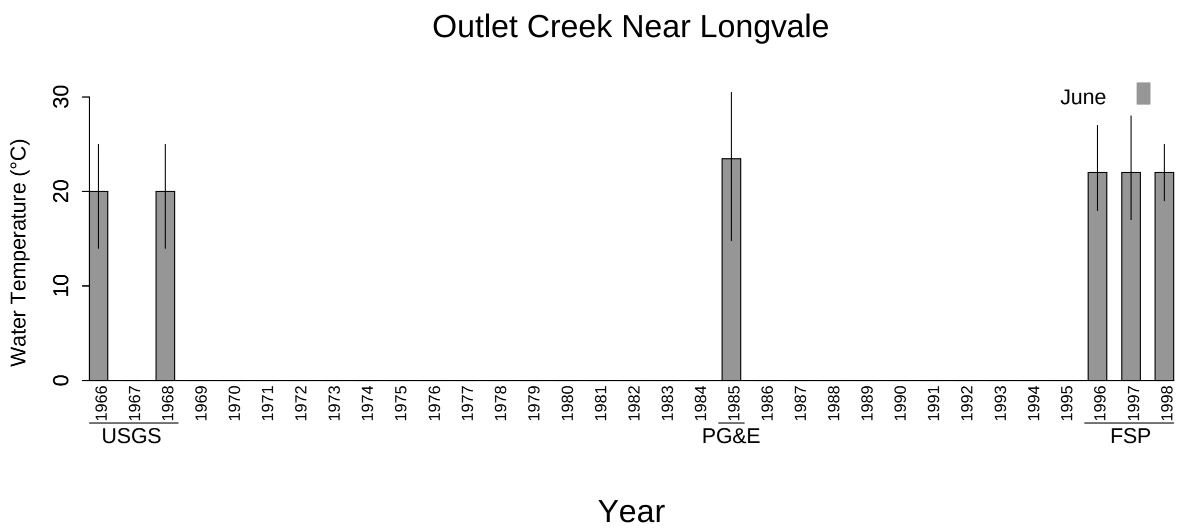


Figure 11.8. Comparison of historical USGS and PG&E monthly average stream temperature data with more recent Forest Science Project data during June for the site at Outlet Creek near the Longvale, CA. Vertical lines represent the range in temperatures for each month.

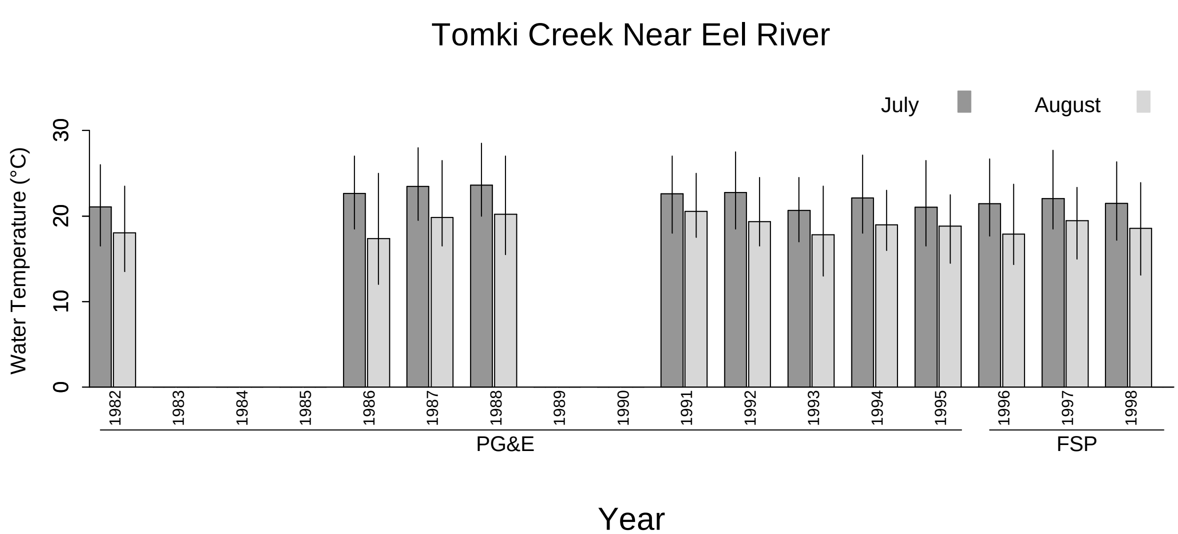


Figure 11.9. Comparison of historical PG&E monthly average stream temperature data with more recent Forest Science Project data during July and August at Tomki Creek near the Eel River. Vertical lines represent the range in temperatures for each month.

United States Geological Survey Gaging Stations - The Blodgett Report

A summary of stream temperature data collected from 1950 through 1969 at various locations throughout Northern California was prepared by Blodgett (1970). Stream temperatures were measured at USGS gaging stations using continuous sensors, hand-held thermometers, or both. Published in the report are temperature data obtained systematically either once or twice per day or by thermograph. Some periodic temperature observations (those obtained infrequently), as well as most of the thermograph and periodic records collected by other agencies, were also published in the report and do not appear in any other compilation. Latitude and longitude were reported for each station to the nearest second. Coordinates were entered into a GIS database. Generally, there were noticeable discrepancies in the location placement; sites usually did not fall on a blue-line stream on a USGS topographic map. If the coordinate-based placement of a USGS monitoring site was near a monumented USGS symbol on a DRG, the coordinates for the site were changed to place the site in the center of the stream adjacent to the USGS monitoring site marked on the DRG. There still is some error in the location placement of the USGS sites, but the placement of the USGS sites is without doubt closer to their true location than the PG&E sites. USGS sites that did not fall near the named stream indicated for that site were not used in the analysis. However, this lack of coordinate placement and stream name matching seldom occurred with USGS sites. In general, the location information contained in the Blodgett (1970) and other USGS reports was superlative. Figure 11.10 shows a map of USGS stream temperature monitoring locations found in the Blodgett report, with a dark triangle denoting those sites with matching FSP sites.

Figure 11.11 illustrates the location of continuous temperature sensors at USGS gaging stations circa 1970. There may be a concern as to the representativeness of water temperature measurements collected at gaging stations. Jones (1965) examined the relationship between the average water temperature of the stream and the temperature collected at the thermograph probe. Results showed that for 24 gaging stations with temperature monitors on streams in California compared to 180 temperature transects (cross sections surveyed with hand-held thermometers at different flow conditions) there were only 11 instances when the sensor reading differed from the average stream temperature by more than 1°F (0.556°C).

The USGS defines three stream temperature categories: true stream temperature (TST), temperature near the sensor (TNS), and the temperature recorded (TRC) (Stevens et al., 1975). The TST is defined as an instantaneous measurement obtained with a calibrated, full-immersion thermometer held in a shaded location in the stream's main flow away from the influence of tributaries or groundwater influx. The actual water temperature around the sensor (TRC) reflects its location in the channel cross section and may be quite different from TST. The TRC is the temperature value that is actually recorded and is a function of how well the thermometer or sensor is calibrated. If the device is calibrated correctly then TRC and TNS should be equal. The differences between TST and TNS remain, and will vary with each stream as well as diurnally and seasonally (Stevens et al., 1975). Moore (1967) as cited in Essig (1998) found about a 2°C difference in temperature across the Middle Fork of the Willamette River near Dexter, OR. He noted that in all instances the difference between TST and TNS could be accounted for by "one or two observations of comparatively high temperatures near the bank where the flow is extremely sluggish." As Essig (1998) points out, this is the location where many stream temperature probes are placed, especially in wide streams, due to logistical and safety reasons. The differences between TST and TNS are simply not known in most cases. This holds true not only for historical data, but for all contemporary stream monitoring activities as well. Given the unknown differences between TST and TNS great caution should be applied when interpreting any stream temperature data, particularly in a regulatory context (Essig, 1998). In this chapter, and in preceding chapters, stream temperatures are used in a relative sense, to explore historical trends and associations between temperature and various landscape-level and site-specific attributes.

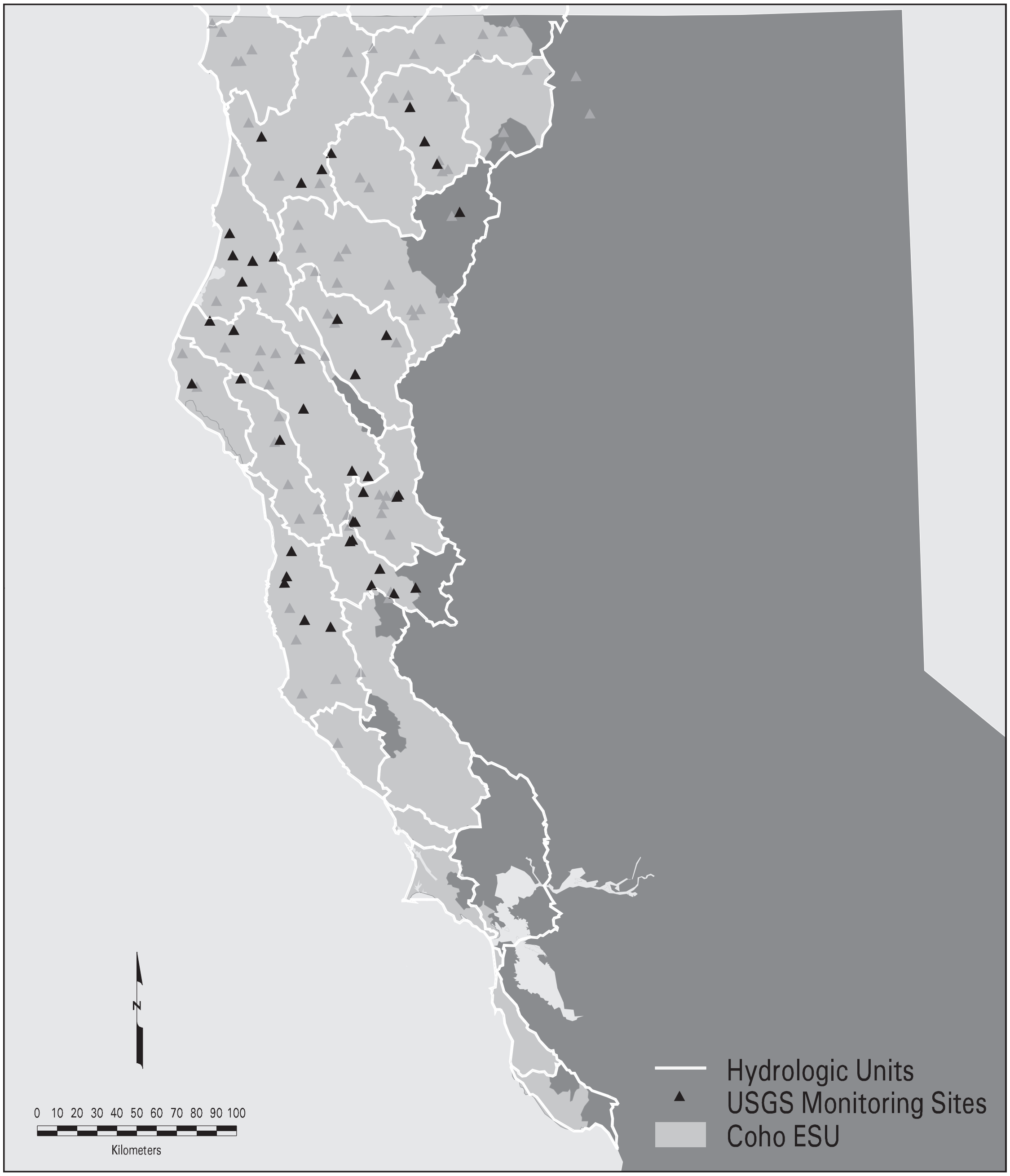


Figure 11.10. Location of USGS sites that were compared to more recent FSP stream temperature monitoring sites. Dark triangles (46 sites) represent USGS-FSP comparisons. Lighter triangles represent USGS sites with historical data available but no matching FSP site.

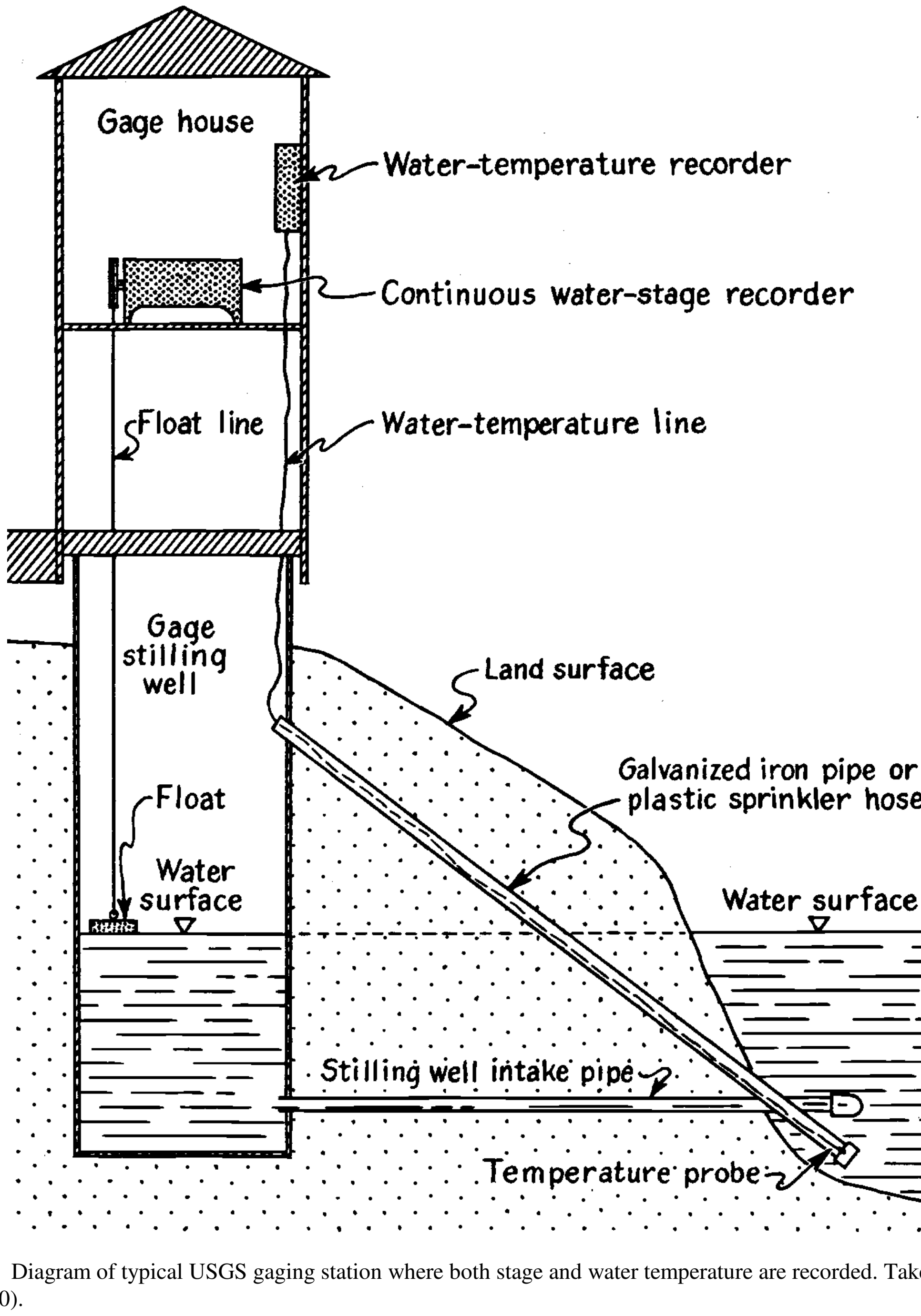


Figure 11.11. Diagram of typical USGS gaging station where both stage and water temperature are recorded. Taken from Blodgett (1970).

USGS Periodic Data

Periodic water temperature data were collected on an irregular basis and less frequently than continuous data. Periodic observations were obtained by holding a thermometer in the stream and reading it while the bulb was immersed. Periodic data were reported as the maximum value and date of occurrence of the maximum value at each site. Periodic data were only used in historical comparisons when no continuous temperature data were available. Below is an example of the way in which periodic data for maximum temperature were reported in the Blodgett report (1970) and other USGS reports.

<u>EXTREMES.</u> – PERIODIC DATA:
MAXIMUM = 29 DEG. C,
JULY 23, 1958, JULY 10, 1968

In this example, the values shown on the bar chart for this site would be 29°C for 1958 and 1968. The annual highest daily maximum temperature from the corresponding FSP site was graphed for each year that the FSP site was monitored. The periodic maximum, however, is a biased estimate for the maximum temperature for the period of record. A total of 12 July temperatures and 12 August temperatures (the hottest months of the year) were measured from 1958 through 1968. Even if the temperatures recorded were the maximum temperatures for the days of record, the true maximum temperature reached from 1958 through 1968 probably was not captured. Thus, the true maximum temperature for any periodic record could possibly be greater than the listed maximum value.

Additionally, the way in which the maximum temperature for the period of record was reported does not provide temperature values for years that did not have the highest value. That is, if periodic data were collected for years 1958 through 1968, only the maximum over this entire 11-year period was reported. If 1959 had the highest value out of all years, for example, 24°C, only the 1959 value would be shown in the data summary. If all other years had 23°C, their values were not reported.

The comparisons made in this section are on a site-by-site basis. They are not necessarily reflective of the larger ESU regional analysis. Any historical periodic data that had a nearby FSP site were included in the analysis. A discussion of site-specific attributes (e.g., canopy closure) was included to offer possible insight into historical stream temperature patterns. Canopy data were considered if such data existed for an FSP site and if watershed area or divide distance indicated the stream was not too wide for stream-side vegetation to provide shade.

Air temperature data were acquired for each date the daily maximum water temperature was reported. The "nearest" air temperature site, located using the 12-dimensional Euclidian distance algorithm described in Chapter 5, was compared to the water temperature site.

Sites are grouped by the USGS basin names as they appeared in the Blodgett (1970) report.

Summary of USGS Periodic Data

Trends in stream temperature varied from historic to contemporary times. There were a total of eight sites that appeared to have lower maximum stream temperatures in the 1990's than in the historic periodic record. Three of the eight sites had temperatures that were sightly less (~1°-2°C) than past temperatures and probably have similar temperature patterns today as they did historically. Those sites were:

(1) Little River near Crannell;
(2) Sugar Creek near Callahan in the Klamath River Basin; and
(3) Shackleford Creek near Mugginsville in the Klamath Basin.

Five of the eight sites had a 4°C or greater decrease in stream temperature for more recent stream temperatures compared to historic records. The sites that were cooler in more recent times were:

(1) Jacoby Creek near Freshwater
(2) Etna Creek near Etna in the Klamath Basin
(3) Big Creek near Hayfork in the Klamath Basin
(4) Albion River near Comtche
(5) South Fork Big River near Comtche

These sites all have relatively small watershed areas. The Little River site had the largest at 10,500 ha. Channel width at this watershed area size could still allow for stream-side vegetation to have an influence on stream temperature. Additionally, it is quite possible that the observed changes in water temperature from past to present times may be due to differences in the locations of the sites. The largest difference between contemporary and historic site placement was Etna Creek, where the FSP site was over 2 km upstream from the USGS site. It is also likely that an increase in canopy closure for some of these sites may have contributed to the cooling of more recent stream temperatures.

There was a total of four sites that showed little change in maximum stream temperatures from the historic record. With one exception, the maximum temperatures measured in the 1990's were within one degree of the periodic historic record. Those sites were:

(1) North Fork Mad River near Korbel
(2) Bluff Creek near Weitchpec
(3) Pudding Creek near Fort Bragg
(4) East Branch of South Fork Eel River near Garberville

Pudding Creek had two years of maximum temperatures that where 2°C greater than the historic record. However, the FSP site was ~1.3 km downstream of the USGS site. Moreover, the FSP site's watershed area was only 3681 ha, indicative of a relatively small stream. In such a small stream the downstream distance of the FSP site from the USGS site is more than adequate to explain the 2°C increase, due to natural longitudinal warming trends.

There were four sites that indicated stream temperature increases in more contemporary times. All four sites had at least a 4°C increase in water temperature for more recent years compared to the historical record. The sites were:

(1) Redwood Creek near Blue Lake
(2) South Fork Trinity River at Forest Glen in the Klamath Basin
(3) Mill Creek below Alder Creek near Covelo in the Eel River Basin
(4) Hulls Creek near Covelo in the Eel River Basin

The South Fork Trinity River site at Forest Glen has a relatively large watershed area (54,000 ha) and divide distance (50 km) compared to the other sites in the historical periodic record. The water temperature at this site should not be as susceptible to changes in canopy since the channel is quite wide. Yet, there was a large jump in stream temperature maxima from 1993 (20°C) to 1994 (27°C). Mill Creek and Hulls Creek both had smaller watershed areas and reductions in canopy could be responsible for increased stream temperature. All sites that exhibited an increase in maximum stream temperature lacked canopy data.

Periodic Data By Basin

Differences in air temperature can also account for a large proportion of the historical variability in stream temperatures at some sites. The influence of air temperature and other environmental factors on historical trends in stream temperature will be explored in more depth in the following section.

Mad River Basin

At a site located on the North Fork of the Mad River near Korbel, CA the periodic maximum water temperature in 1959 was 22°C, with a maximum air temperature on that day of 17.8°C (Figure 11.12). Nearly forty years later, at a FSP site located about 1700 m downstream from the USGS site, the highest daily maximum water temperature was 23°C, with an average daily maximum air temperature of 18.9°C. The air temperature value is the daily maximum air temperature for the date on which the maximum water temperature was reported. The 1998 site had a slightly higher water temperature than the periodic record, but the air temperature was slightly higher as well. The FSP site further downstream from the USGS site had a watershed area of 10,850 ha. The canopy closure value for the site was reported to be 5% in 1998. Given the distance traveled from the upstream USGS site to the downstream FSP site, the higher air temperature on the more contemporary date, and the open canopy, it is expected that the FSP site would be warmer than the USGS site.

Little River Basin (Humboldt County)

One USGS site in the Little River Basin (Humboldt County) was suitable for historical water temperature comparison. On the Little River near Crannell, CA the periodic maximum water temperature was reported to be 22°C in 1959 (Figure 11.13). The daily maximum air temperature was 14.4°C on the day of occurrence of the highest periodic maximum water temperature in 1959. In 1998 the highest daily maximum water temperature observed at a site located 110 m downstream from the USGS site was 20°C, with a daily maximum air temperature of 19.4°C. In spite of the much warmer air temperature in 1998, the 1998 maximum water temperature record was cooler. These sites were close enough together and the watershed area large enough (10,500 ha) that differences in temperature due to differences in site location should be minimal. No canopy data were available for this site.

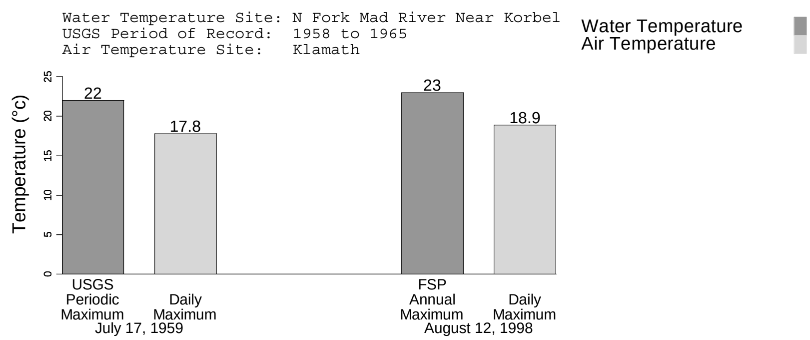


Figure 11.12. Comparison of yearly maximum stream temperatures at a historical USGS site and a more recent FSP site located on the North Fork of the Mad River near Korbel, CA in the Mad River Basin. The FSP site was located 1700 m downstream from the USGS site.

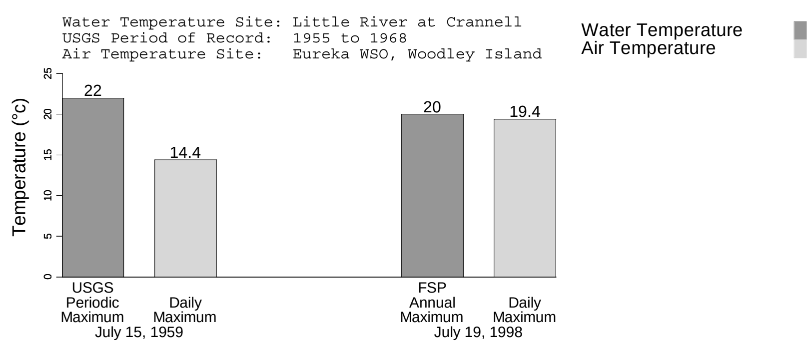


Figure 11.13. Comparison of yearly maximum stream temperatures at a historical USGS site and a more recent Forest Science Project site located in the Little River near Crannell, CA. The FSP site was located 110 m downstream from the USGS site.

Redwood Creek Basin

One Redwood Creek Basin USGS site was suitable for historical comparison. The USGS references this site as Redwood Creek near Blue Lake, CA. After placement of the site on a DRG, a better reference would be Redwood Creek near Highway 299 bridge. In 1953 and 1958 the periodic maximum water temperature at the Redwood Creek USGS site was 22°C (Figure 11.14). The daily maximum air temperature matched with the corresponding maximum periodic water temperature was 35.6°C in 1953 and 37.8°C in 1958. In 1997 and 1998, at a FSP site located about 30 m upstream from the USGS site, the highest daily maximum stream temperatures were 27°C and 26°C, respectively. The daily maximum air temperature was 40°C in 1997 and 38.3°C in 1998. The annual maximum temperatures measured in Redwood Creek near Highway 299 were higher than those measured for the periodic record. There were only four July records and two August records in the eight year historical periodic record. The probability is low that the true maximum water temperature for the historical period of record was captured.

Jacoby Creek Basin

One USGS site in the Jacoby Creek Basin in Humboldt County was suitable for historical water temperature comparison. The periodic maximum water temperature at a USGS site located on Jacoby Creek near Freshwater, CA was reported to be 21°C in 1959, with a corresponding daily maximum air temperature of 13.9°C (Figure 11.15). The proximity of this site to the coast is reflected by the low air temperature value. In 1994, a FSP cooperator deployed a sensor approximately 1060 m downstream from the USGS site. The highest daily maximum water temperature in 1994 was 15°C, with a daily maximum air temperature of 16.7°C on the day the highest water temperature occurred. The site was located close to the headwaters, with a watershed area of 1760 ha and distance from the watershed divide of 15 km. The 6°C decrease in the maximum water temperature in 1994 may be related to increased canopy along the upstream reaches of the stream. The FSP data contributor did not provide canopy information for this site.

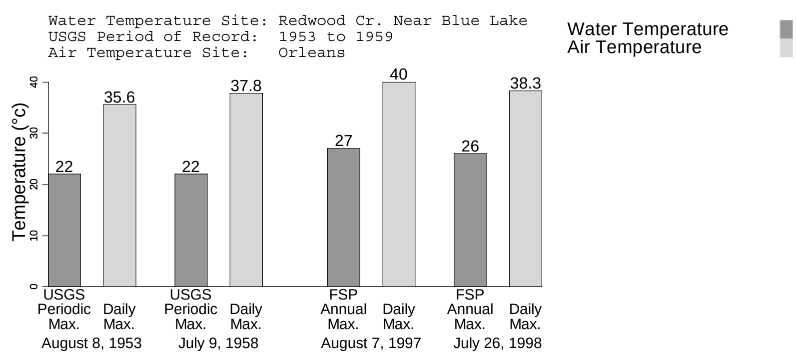


Figure 11.14. Comparison of yearly maximum stream temperatures at a historical USGS site and a more recent Forest Science Project site located in Redwood Creek near Blue Lake. The FSP site was located 30 m upstream from the USGS site.

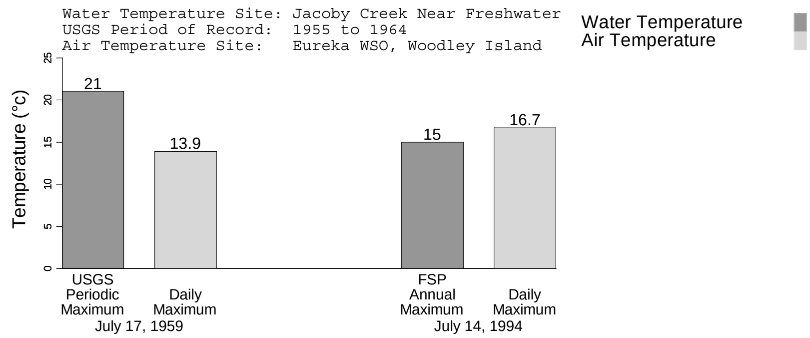


Figure 11.15. Comparison of maximum stream temperatures at a historical USGS site and a more recent FSP site on Jacoby Creek near Freshwater, CA. The FSP site was located 1060 m downstream from USGS site.

Klamath River Basin

Six periodic USGS sites in the Klamath Basin had FSP sites in relatively close proximity for historical water temperature comparison purposes. Comparisons of historical USGS water temperature data to more recent FSP data are shown in Figure 11.16.

The periodic maximum water temperatures reported for Sugar Creek near Callahan, CA for 1958 and 1959 were both 20°C, with maximum air temperatures of 38.9°C and 33.3°C, respectively (Figure 11.16-A). In 1998 the daily maximum air temperature was about the same as 1958, however, the highest daily maximum water temperature at a FSP site located 30 m upstream from the USGS site was 18°C. The water temperature was cooler in 1998 than the historic periodic maximum. The watershed area for this site was small (3065 ha) and had a reported canopy value of 5% in 1998. The decrease in maximum stream temperature may be due to an increase in canopy closure upstream from the water site.

Etna Creek near Etna, CA had a reported periodic maximum water temperature of 21°C in 1959. The daily maximum air temperature on the same day in 1959 was 33.3°C (Figure 11.16-B). In 1998 the highest daily maximum temperature observed at a FSP site located 2200 m upstream from the USGS site was 17°C, with a daily maximum air temperature on that day of 37.8°C. The 1998 water temperature was considerably lower than the historic periodic maximum. The relatively large decline in temperature at this site may be due to an increase in canopy or to a difference in site location. The site’s watershed area was small (4450 ha) and had a listed canopy closure of 5% in 1998. At this size of a watershed, changes in canopy can have a significant effect. However, the FSP site was 2200 m upstream from the USGS site and the FSP site was only 11 km from the watershed divide. The extra distance from the FSP site to the USGS site is sufficient for significant increases in water temperature.

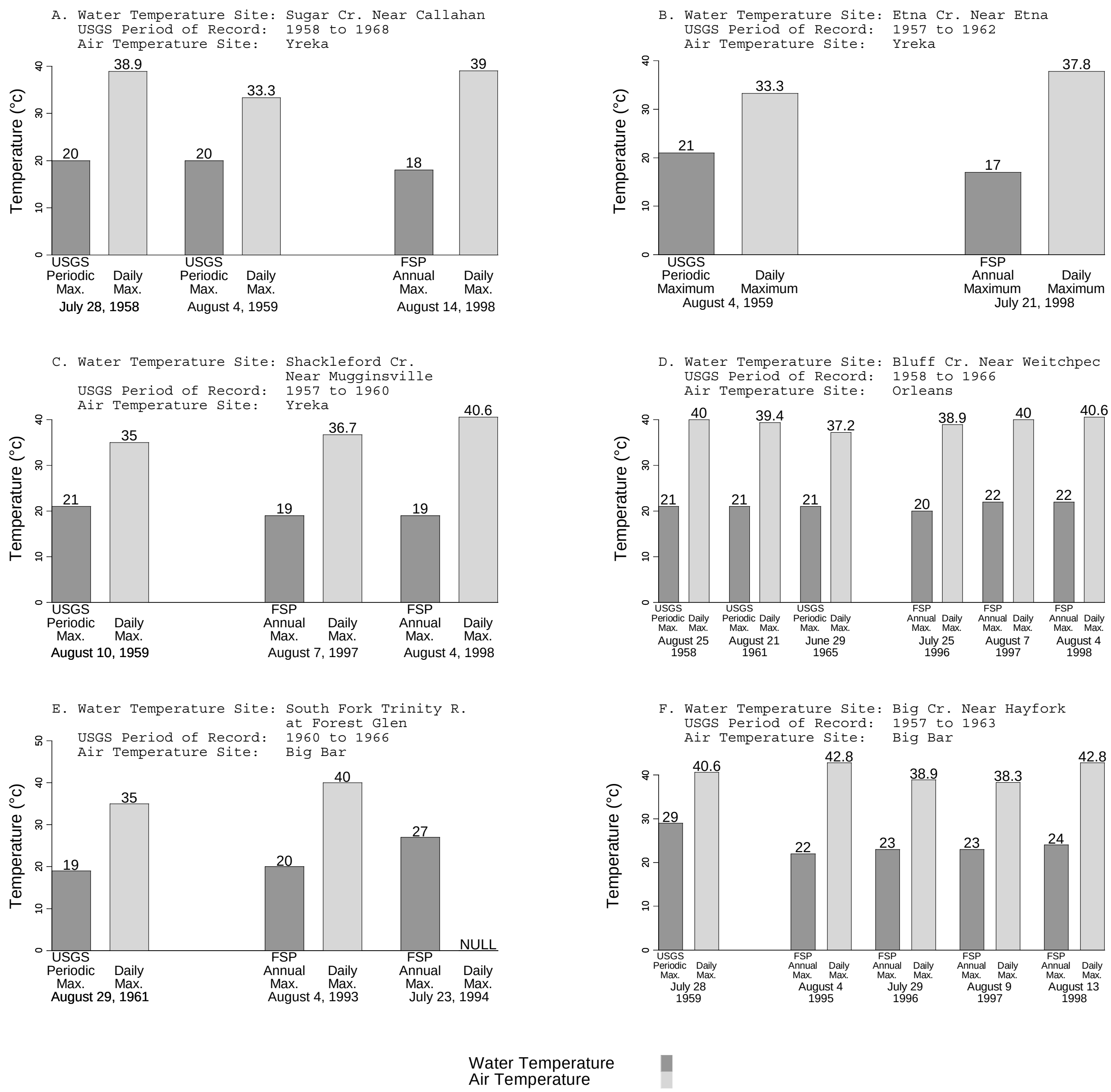


Figure 11.16. Comparison of maximum stream temperatures at historical periodic USGS sites and more recent continuous FSP sites located in the Klamath River Basin. The nearby FSP site was located A) 30 m upstream, B) 2200 m upstream, C) 1320 m upstream, D) 1420 m downstream, E) 740 m downstream, and F) 110 m downstream from the USGS site.

Shackleford Creek near Mugginsville, CA had a reported periodic maximum water temperature of 21°C in 1959, with a daily maximum air temperature of 35.0°C (Figure 11.16-C). The nearby FSP stream temperature monitoring site was located about 1320 m upstream from the USGS site. In 1997 and 1998, the highest daily maximum temperature in both years was 19°C. The maximum air temperatures were 36.7°C and 40.6°C, respectively. The more recent water temperatures were cooler than the historic periodic maximum. The Shackleford site also had a small watershed area (4800 ha) and stream temperatures at the site may be significantly influenced by canopy closure. Additionally, 1320 m downstream distance in a stream of this size is sufficient to account for the observed 2°C increase in water temperature at the historic site over the contemporary upstream temperatures.

Bluff Creek near Weitchpec, CA had reported periodic maximum water temperatures in 1958, 1961, and 1965 that were 21°C (Figure 11.16-D). The respective maximum air temperature was 40.0°C, 39.4°C, and 37.2°C on the day of occurrence for each of the periodic maximum water temperatures. A FSP site located approximately 1420 m downstream from the USGS site collected data for three consecutive years, 1996, 1997, and 1998. The highest daily maximum temperature was 20°C in 1996 and 22°C in 1997 and 1998. The average daily maximum air temperatures on the days the highest daily maximum water temperatures occurred were 38.9°C, 40.0°C, and 40.6°C, respectively. The stability in water temperature across the years is remarkable, with only a two-degree range. The site had a reported canopy value of less than 5% in 1998. The low canopy value may be due in part to the site's watershed position, being approximately 40 km from the watershed divide and having a drainage area of about 19,000 ha. The channel at this location may be too wide for canopy to provide much shade.

At a location on the South Fork of the Trinity River at Forest Glen, CA the reported periodic maximum water temperature for 1961 was 19°C, with a corresponding daily maximum air temperature of 35.0°C (Figure 11.16-E). At a FSP site located 740 m downstream from the USGS site, the highest 1993 daily maximum water temperature was 20°C, with a daily maximum air temperature of 40.0°C (104°F). In the following year, the highest daily maximum water temperature increased by 7°C. Unfortunately, no air temperature data were available on that day in 1994. The watershed area at this location was roughly 54,000 ha with a distance from the watershed divide of about 50 km. Although the water temperature in 1993 was similar to the historic periodic maximum, the 1994 water temperature was much warmer. On inspection of the records, 1994 was much hotter than 1993 for most of the summer. The 1994 record did not start until July 19, missing a significant portion of the summer. No reasonable explanation for the increase in temperature could be reached.

A USGS gaging station located on Big Creek near Hayfork, CA had a reported periodic maximum water temperature of 29°C in 1959 (Figure 11.16-F). This particular site is located in a very warm area. The daily maximum air temperatures in 1959 and in 1995 through 1998 were consistently near 40°C (104°F) on the days the highest maximum water temperatures were observed. A FSP site was located 110 m downstream from the USGS site. Despite the high air temperatures in 1995 through 1998 the highest daily maximum water temperature in these years was about 6°C lower than the periodic maximum water temperature reported in 1959. The watershed area at this location was about 7050 ha and the distance from the watershed divide was 22 km. The stream corridor is most likely capable of supporting shade-producing riparian vegetation. The decrease in daily maximum water temperatures may be due, in part, to increased shading upstream from this section of Big Creek. Unfortunately no canopy data were reported for this location.

Albion River Basin

Comparison of maximum water temperature was possible at one site located on the Albion River near Comtche, CA. A FSP site was located 1070 m upstream from the USGS site in 1996 and 1997. The periodic maximum water temperature reported in 1967 was 20°C, with a corresponding daily maximum air temperature of 34.4°C (Figure 11.17). In 1996 the highest daily maximum water temperature was 18°C, with a corresponding daily maximum air temperature of 38.3°C. In 1997 the air temperature was about 12°C lower than in 1996, with a 1°C decrease in the highest daily maximum water temperature. This site is located near the headwaters of the Albion River. The drainage area is 3530 ha (13 sq mi) and the distance from the watershed divide is 9 km (~6 mi). Water temperatures at this location are probably more responsive to changes in incoming solar radiation than to changes in air temperature, although these two sources of heat input are obviously related. Water temperatures at distances close to the headwaters are believed to be similar to groundwater temperatures (Sullivan et al., 1990). Sullivan et al. (1990) found that primary heat input into small headwater streams is via direct solar radiation input. Unfortunately, no canopy data were provided by the FSP data contributor. The maximum water temperatures in 1996 and 1997 were slightly cooler than the maximum historical periodic record. The FSP site, however, is 1.1 km upstream of the USGS site; the difference in temperature may be due to the difference in site location.

Big River Basin

There was one site in the Big River Basin that was suitable for historical comparisons. A USGS site located on the South Fork Big River near Comtche, CA had a reported periodic maximum water temperature of 26°C in 1961, with an daily maximum air temperature of 40.0°C (Figure 11.18). In 1997 the highest daily maximum water temperature at a FSP site located 490 m upstream from the USGS site was 22°C, with a corresponding daily maximum air temperature of 40.6°C. The watershed area (4289 ha) and distance from the watershed divide (14 km) indicate that the site was located near the headwaters. Despite similar daily maximum air temperatures in the two years, the daily maximum water temperature was 4°C lower in 1997 than in 1961. No canopy data were provided by the FSP data contributor, so no conclusions can be drawn. However, we cannot rule out the possibility that an increase in canopy in 1997 may be partly responsible for the lower daily maximum water temperature. Although this site has a small drainage area and the FSP site is upstream of the USGS site, the approximately 500 m is probably not enough distance to account for an increase in water temperature of 4°C.

Pudding Creek Basin

In the Pudding Creek Basin in Mendocino County, one site was suitable for historical water temperature comparisons. On Pudding Creek near Fort Bragg, CA the reported 1965 periodic maximum water temperature was 16°C, with a daily maximum air temperature of 37.2°C on the day the periodic maximum occurred (Figure 11.19). At a FSP site located 1320 m downstream from the USGS site the highest daily maximum water temperature for 1993 through 1998 varied by no more than 2°C from the 1965 periodic maximum water temperature. The daily maximum air temperatures in 1993-1998 ranged from 29 to 37°C. The site on Pudding Creek was located close to the headwaters, with a watershed area of 3681 ha and distance from watershed divide of 15 km. At such a watershed position water temperatures would be expected to be below air temperature. Air temperature has little effect near the headwaters, where direct solar radiation and groundwater temperature have greater influence on stream temperature (Sullivan et al., 1990). The FSP site is further downstream from the USGS site, which could account for the small increase in stream temperature experienced by the more recent records.

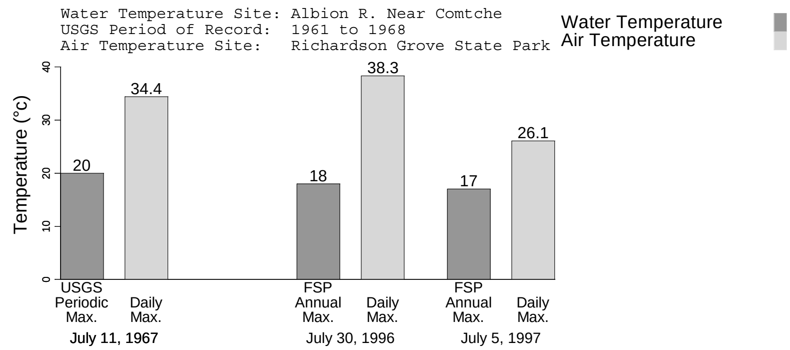


Figure 11.17. Comparison of maximum stream temperatures at historical USGS sites and more recent Forest Science Project sites located in the Albion River Basin. Nearest FSP site was located 1070 m upstream from the USGS site.

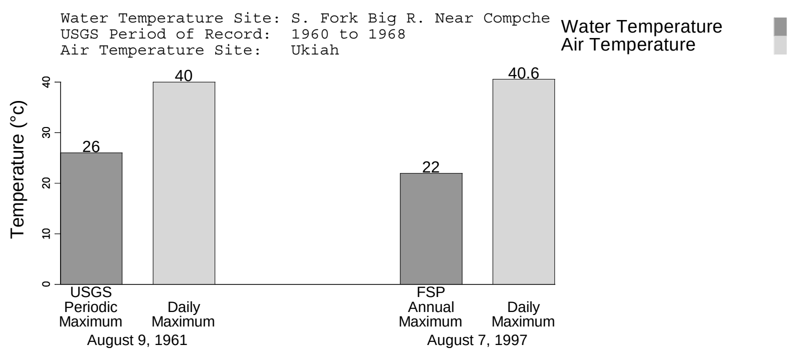


Figure 11.18. Comparison of maximum stream temperatures at a historical USGS periodic site and a more recent Forest Science Project site located on the South Fork of the Big River near Comtche, CA. The FSP site was located 490 m upstream from the USGS site.

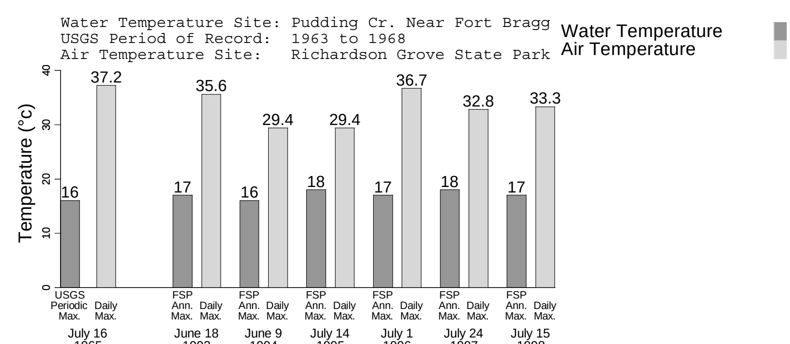


Figure 11.19. Comparison of maximum stream temperatures at a historical USGS site and a more recent Forest Science Project site located on Pudding Creek near Fort Bragg, CA. The nearest FSP site was located 1320 m downstream from the USGS site.

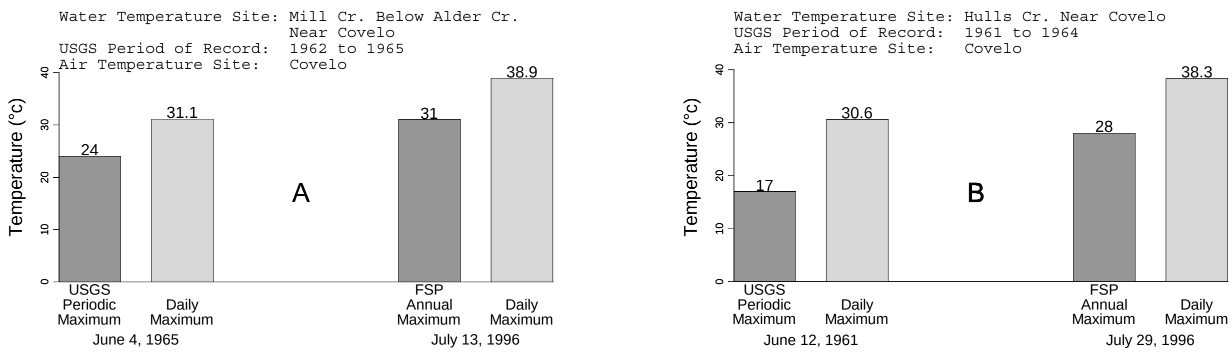
Eel River Basin

There were three USGS sites in the Eel River Basin with periodic water temperature data suitable for comparison to more recent FSP water temperature data acquisitions. Comparisons are shown in Figure 11.20.

A USGS site located on Mill Creek below Alder Creek near Covelo, CA had a reported periodic maximum water temperature of 24°C in 1965, with a corresponding daily maximum air temperature of 31.1°C (Figure 11.20-A). A FSP site was located 1330 m downstream from the USGS site monitored water temperature in 1996. The highest daily maximum water temperature was 31°C in 1996, a 7°C increase above the 1965 periodic maximum water temperature. However, the maximum air temperature was 8°C higher in 1996. The watershed area at the Mill Creek site was 4493 ha and the distance from the watershed divide was 14 km. Channel width at this watershed position should be capable of providing riparian shade. While the site is located fairly close to the headwaters, the water temperature at the site may have responded to the higher air temperature in 1996. If the site lacked stream-side vegetation, increased solar radiation could be responsible for the elevated daily maximum water temperature observed in 1996. No canopy data were provided by the FSP data contributor. It must also be kept in mind that with only a total of 12 periodic records taken for four years, the periodic maximum temperature is probably not the maximum daily water temperature for the periodic record period. Also, the 1330 m downstream location of the FSP site may contribute to higher stream temperatures than occurred at the USGS site.

On Hulls Creek near Covelo, CA the reported periodic maximum temperature in 1961 was 17°C, with a daily maximum air temperature of 30.6°C on the day the periodic maximum water temperature occurred (Figure 11.20-B). At approximately 470 m downstream from the USGS site, an FSP site measured a highest daily maximum water temperature of 28°C in 1996. The corresponding daily maximum air temperature was 38.3°C. Similar to the Mill Creek site, the water temperature increased with a substantial increase in air temperature. Also similar to the Mill Creek site, only 18 periodic records were taken over four years; thus, the periodic maximum temperature may not be the true maximum daily water temperature for the periodic record period. The watershed area at the Hulls Creek site was 6840 ha and the distance from the watershed divide was 17 km. The downstream distance of 470 m for the FSP site is not of sufficient distance to account for an 11°C difference between the stream temperature records. The channel width at this watershed position is most likely capable of providing stream side shade, although no canopy information was provided by the FSP data contributor.

A USGS site located on the East Branch of the South Fork of the Eel River near Garberville, CA had a reported periodic maximum water temperature of 28°C in 1967 (Figure 11.20-C). The daily maximum air temperature on that day was 27.2°C. At about 880 m downstream from the USGS site a FSP site had a highest daily maximum temperature of 29°C in 1996. The air temperature maximum for the day of the highest daily maximum water temperature was 11°C higher in 1996 than it was in 1967. The watershed area at this site was 1169 ha and the distance from the watershed divide was 5 km. The channel width at this watershed position should be narrow enough to allow stream side vegetation, if present, to provide shade. The periodic historical maximum is similar to the maximum stream temperature seen in 1996.



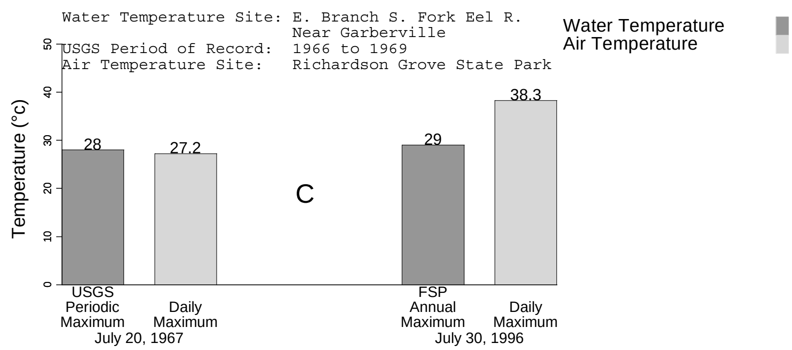


Figure 11.20. Comparison of maximum stream temperatures at historical USGS sites and more recent Forest Science Project sites in the Eel River Basin. Nearest FSP site was located (A) 1330 m downstream, (B) 470 m downstream, and (C) 880 m downstream from the USGS site.

Summary of USGS Continuous Data

Water temperature data from USGS gaging stations (Blodgett, 1970) equipped with continuous monitors were scanned from the hardcopy report using a flatbed scanner. The images were converted to characters using optical character recognition software. The data were verified against the hardcopy report. Corrections were made where necessary. The continuous data were entered into a Microsoft Access database for comparison to more recent FSP stream temperature data. The USGS continuous data were reported as monthly minima, means, and maxima. The stream temperature data from FSP sites located in close proximity to USGS continuous monitoring sites were aggregated to monthly minima, means, and maxima for direct comparisons to the USGS data.

Historical data comparisons were grouped by basin names as they appeared in the USGS report (Blodgett, 1970) and by sites that shared the same air temperature site. Basins are presented with the northernmost basin first. Each site is represented in a bar chart with the height of the bar indicating the monthly average temperature and vertical lines representing the range in temperatures for each month. July and August are usually the hottest months for the year and are the only months presented in the figures, with exceptions where noted.

Klamath River Basin

Four USGS sites with continuous monitoring data were located in the proximity of FSP sites in the Klamath River Basin. Figures 11.21, 11.22, and 11.23 show the temporal trends in water and air temperature at the four sites. The bars represent the monthly average water and air temperature value and the vertical lines represent the range in the monthly minimum and maximum temperature values.

A USGS site located on the Salmon River at Somes Bar had continuous water temperature data for 1966, 1968 and 1975 through 1978 (Figure 11.21-A). A FSP site was located about 70 m downstream from the USGS site. August 1966 was the warmest month in the 32-yr record, having both the highest monthly maximum (30.0 °C) and highest monthly average (22°C). The monthly average water temperature for more recent data (1997 and 1998) was slightly warmer (21.0°C) than most other years. However, it should be noted that the July and August monthly minima in 1997 and 1998 were higher, while the monthly maxima were quite similar to earlier years. Higher monthly minima would account for the higher monthly averages. August 1966 and 1977 monthly average air temperatures measured in Orleans at a distance of 9.8 km from the water monitoring location were the warmest August averages for the record. Summarily, there was not a noticeable change in stream temperature in the Salmon River at Somes Bar over the 32-year record.

The watershed area at the Salmon River site was 194,255 ha (~750 sq mi) and the distance from the watershed divide was approximately 93 km (~58 mi). The channel width at this watershed position was probably quite wide. The canopy value of zero at this site provided by an FSP data contributor provides additional evidence that the stream may be too wide for riparian vegetation to provide shading. Thus, localized changes in the vegetation will have little effect on stream temperature.

A USGS site was located on the Klamath River at Orleans, CA. The river is wide at this location, with a watershed area of about one million ha (nearly 4000 sq mi) and a distance from watershed divide of 306 km (190 mi). The canopy reported in 1998 at a FSP site located 470 m downstream from the USGS site was zero. All July and August monthly average temperatures throughout the record remained between 20°C to 25°C (Figure 11.21-B). The air site, located in Orleans, was 0.4 km from the USGS site. The monthly average air temperatures in July and August were also in the 20 to 25°C range (Figure 11.21-C). There were no detectable trends in stream temperature as a function of time.

A USGS site was located on Hayfork Creek near Hyampom, CA. The watershed area is 99,932 ha (386 sq mi) and the distance from watershed divide was 85 km (53 mi) at this location on Hayfork Creek. No canopy values were reported in 1990-1992 or 1998 at a FSP site located 470 m downstream from the USGS site. July and August monthly averages ranged from 19 to 25°C (Figure 11.22, top). In 1961, the site experienced the warmest monthly average water temperatures (25°C and 24°C for July and August, respectively). Unfortunately, air temperature data (collected at Big Bar at a distance of 21.9 km) for August 1991 and 1992 and July 1990 were not available, so a complete picture of air temperature trends is not possible. For the months with available data, it appears that 1990-1992 were warmer than similar months in 1961-1967 (Figure 11.22, bottom). Temperatures do not appear to be changing through time at this site.

A USGS site was located on Blue Creek near Klamath, CA. Water temperatures in the 1960's were very similar to those observed in 1994 and 1995 at a FSP site located 1800 m downstream from the USGS site. Average monthly water temperatures ranged from 16°C to 18°C for all years (Figure 11.23, top). Air temperature (measured at Prairie Creek State Park near Orick, 13.7 km from the water temperature site) was moderate, due to the close proximity to the coast (Figure 11.23, bottom). Thus, Blue Creek water temperatures may be more moderated by cooler coastal air temperatures than more interior Klamath Basin sites. The watershed area at this site was 31,415 ha (121 sq mi) and the distance from the watershed divide was 39 km (24 mi). This is a small enough watershed that the stream temperature may be influenced by canopy; however, no canopy data for the site was reported.

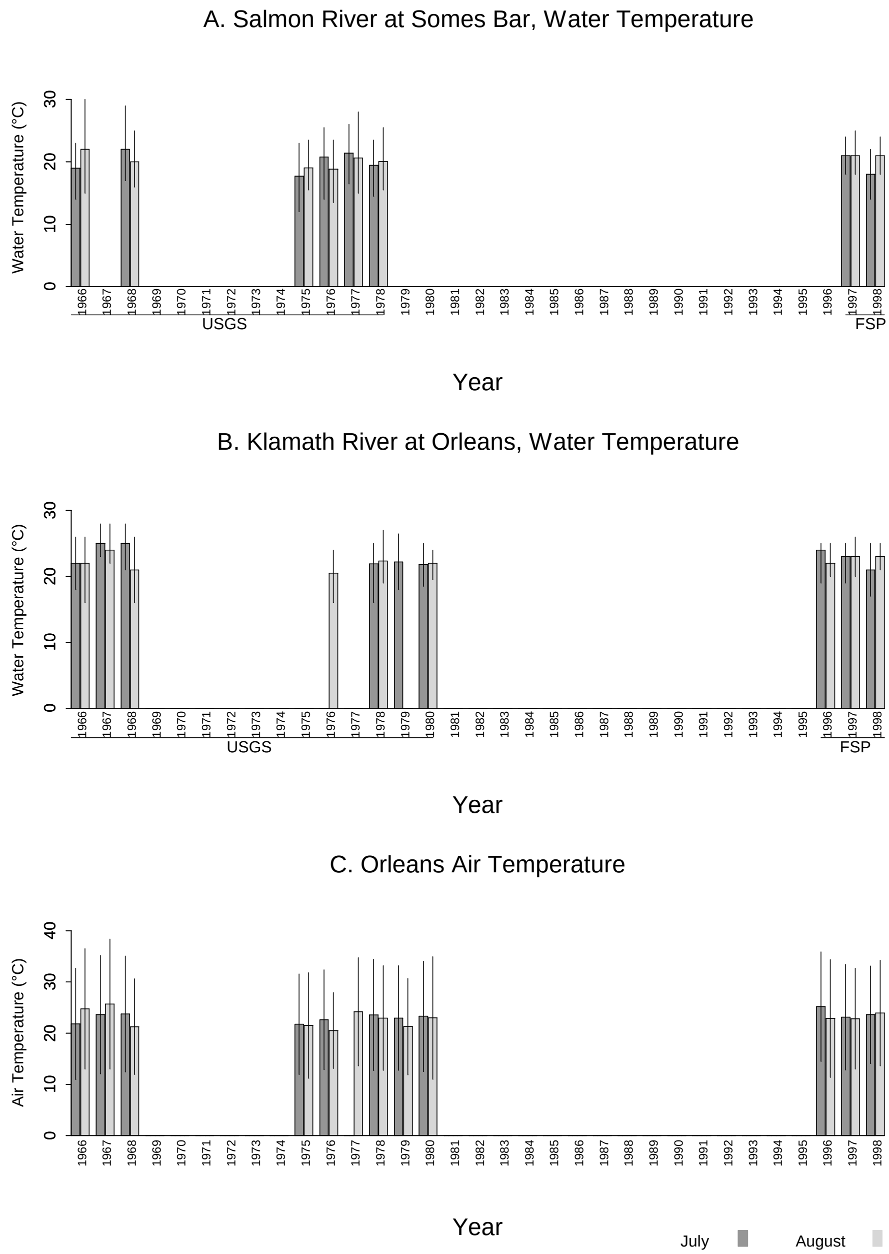


Figure 11.21. Comparison of historical USGS monthly average stream temperature and more recent FSP data for Klamath River Basin sites. Nearby FSP site on the Salmon River (A) was 70 m downstream from the USGS site and on the Klamath River (B) was 470 m downstream. NOAA air temperature site (C) in Orleans was 0.4 km from USGS site. Vertical lines represent the range in temperatures for each month.

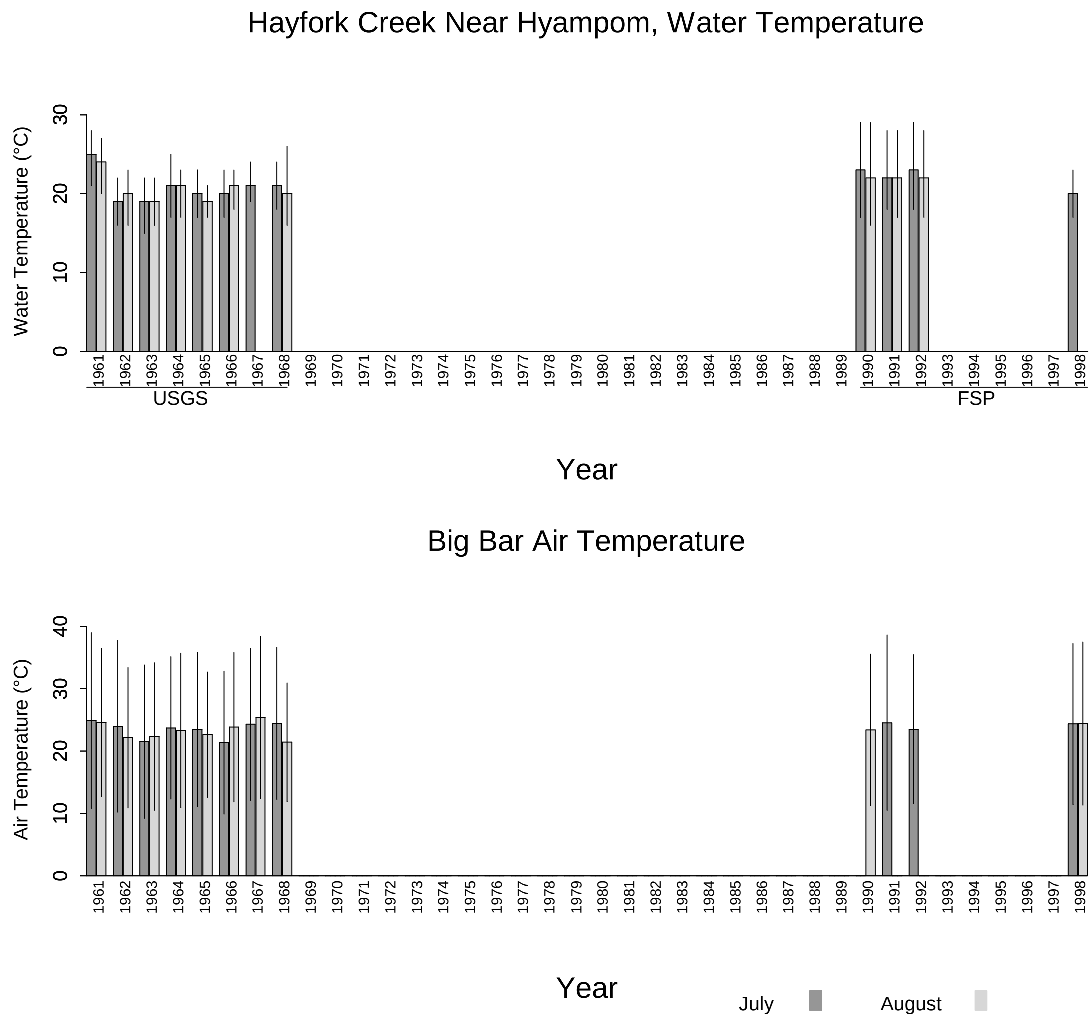


Figure 11.22. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for two sites located in the Klamath River Basin. Nearest FSP site on Hayfork Creek (top) was 1500 m downstream from USGS site. Air temperature was measured at NOAA station at (bottom) Big Bar, CA. Vertical lines represent the range in temperatures for each month.

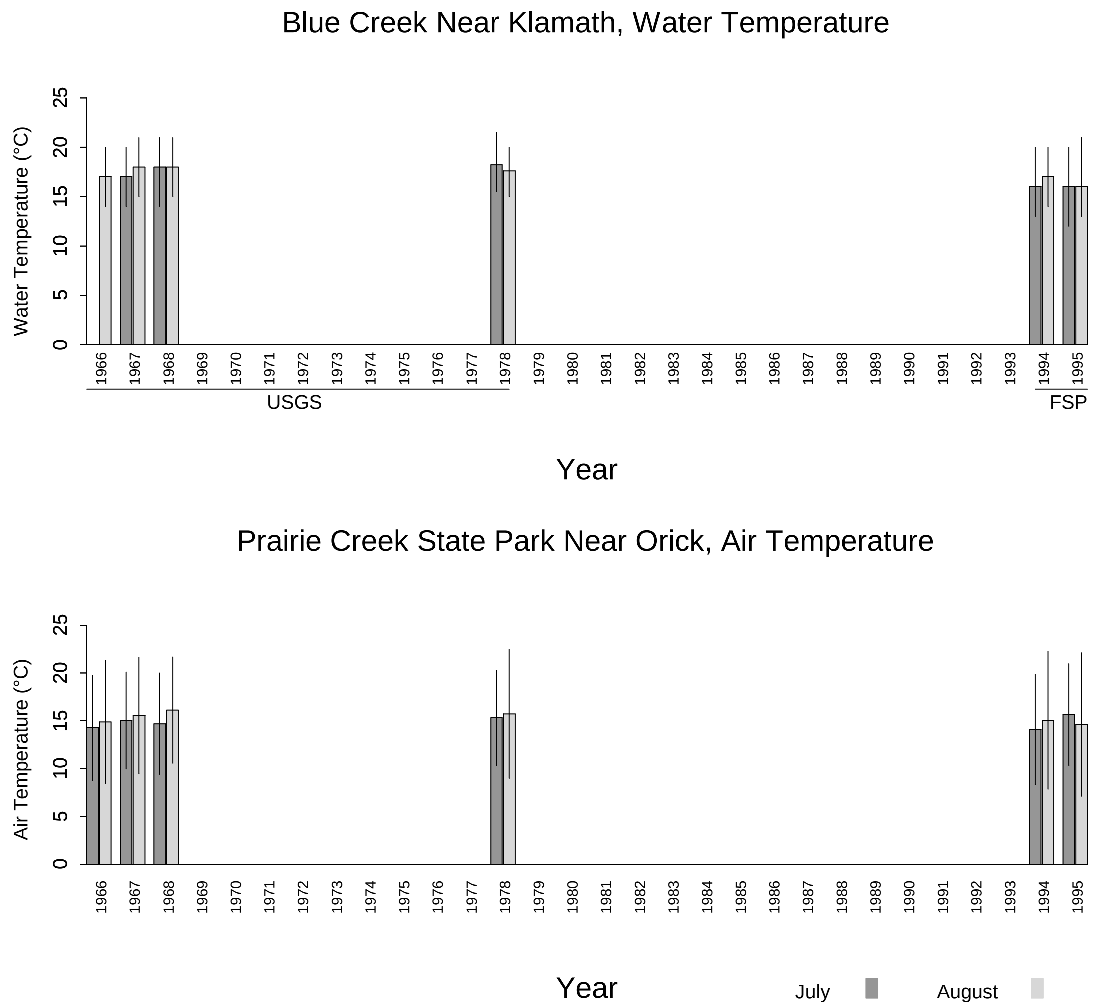


Figure 11.23. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for a site located in the Klamath River Basin. Nearby FSP site on Blue Creek (top) was 1800 m downstream of the USGS site. Air temperature (bottom) was measured at NOAA station at Prairie Creek State Park near Orick, CA. Vertical lines represent the range in temperatures for each month.

Mad River Basin

In the Mad River Basin only one USGS site with continuous water temperature data was in close proximity to a more recent FSP site. This site was located on the Mad River near Arcata, CA. The nearest FSP site was located 1660 m downstream from the USGS site. The FSP site was operated only in 1998. The watershed area at this location on the Mad River was 125,504 ha (484 sq mi) and the distance from the watershed divide was 169 km (105 mi). The reported canopy cover at this site in 1998 was 5%. The monthly average water temperatures for July and August 1998 at the FSP site were 19°C and at the USGS site ranged from 18°C to 22°C. Figure 11.24 shows the monthly and yearly temporal trends in air temperature for the nearest air site located at the National Weather Service Office (WSO) on Woodley Island, Eureka, CA. Monthly water temperatures on the Mad River near Arcata do not seem to indicate either a warming or cooling trend over about the last 37 years.

Eel River Basin

There were twelve USGS continuous water temperature monitoring sites in the Eel River Basin that had more recent FSP sites in close proximity for historical comparison purposes. Sites are grouped together with their nearest air temperature station.

Figure 11.25 shows a comparison between three matched pairs of USGS and FSP sites in the Eel River Basin. A USGS site on the Eel River below Scott Dam exhibited monthly average water temperatures below 20°C for most months. Monthly average temperatures gradually increased from June to September. September proved to be the month with the highest monthly average water temperature for both the USGS and a FSP site located 80 m upstream.

Impoundment of a river alters the thermal regime, even in large rivers (Allan, 1995). If the flow through the reservoir is slow, the reservoir will undergo thermal stratification typical of lakes (Wetzel, 1983). During the summer, reservoir surface water will be warmer than is typical for river water, and deep water will be quite cool, often between 6°C and 10°C. A dam that releases surface water from its impoundment will usually increase the annual temperature range immediately downstream, whereas a deep release dam will lessen annual variation. Scott Dam is a deep release dam. The USGS and FSP sites were approximately 1000 m below the dam. If air temperature and solar radiation were the primary heat sources at this location, one would expect to see the highest monthly average water temperatures in July and August like the majority of other FSP sites. Another mechanism must be responsible for the continual increase in water temperature until the highest monthly average is attained in September. The delayed peak in water temperatures is most likely a result of the break up of the reservoir's thermocline as fall approaches, with warmer surface water mixing with deeper cool water. Also, the reservoir may be drawn down enough that warmer surface water is being released through the dam.

The watershed area at the below-Scott-Dam location was 74,956 ha (289 sq mi) and the distance from the watershed divide was 54 km (34 mi). No canopy data were submitted by FSP cooperators for this site, but given the site's watershed position, it is probably less than 5% and not affected by land management practices. While 1997 was one of the warmer years on record, it was not outside the range of the historical record and 1996 was more similar to earlier years (Figure 11.25-A). The August average water temperature ranged from 14°C to 22°C with maximum values ranging between 16°C and 23°C. Average August water temperature was 20°C in 1997 (over 1°C cooler than the 1977 record) and maximum August water temperature was 23°C in both 1977 and 1997. The September average water temperature ranged from 16°C to 22°C with maximum values ranging between 18°C and 24°C. Average September water temperature was 21°C in 1997 (almost the same as the 1977 record) and maximum September water temperature was 23°C in both 1967 and 1997(1°C cooler than the 1977 record). There was no discernible historical trend in water temperature at this site.

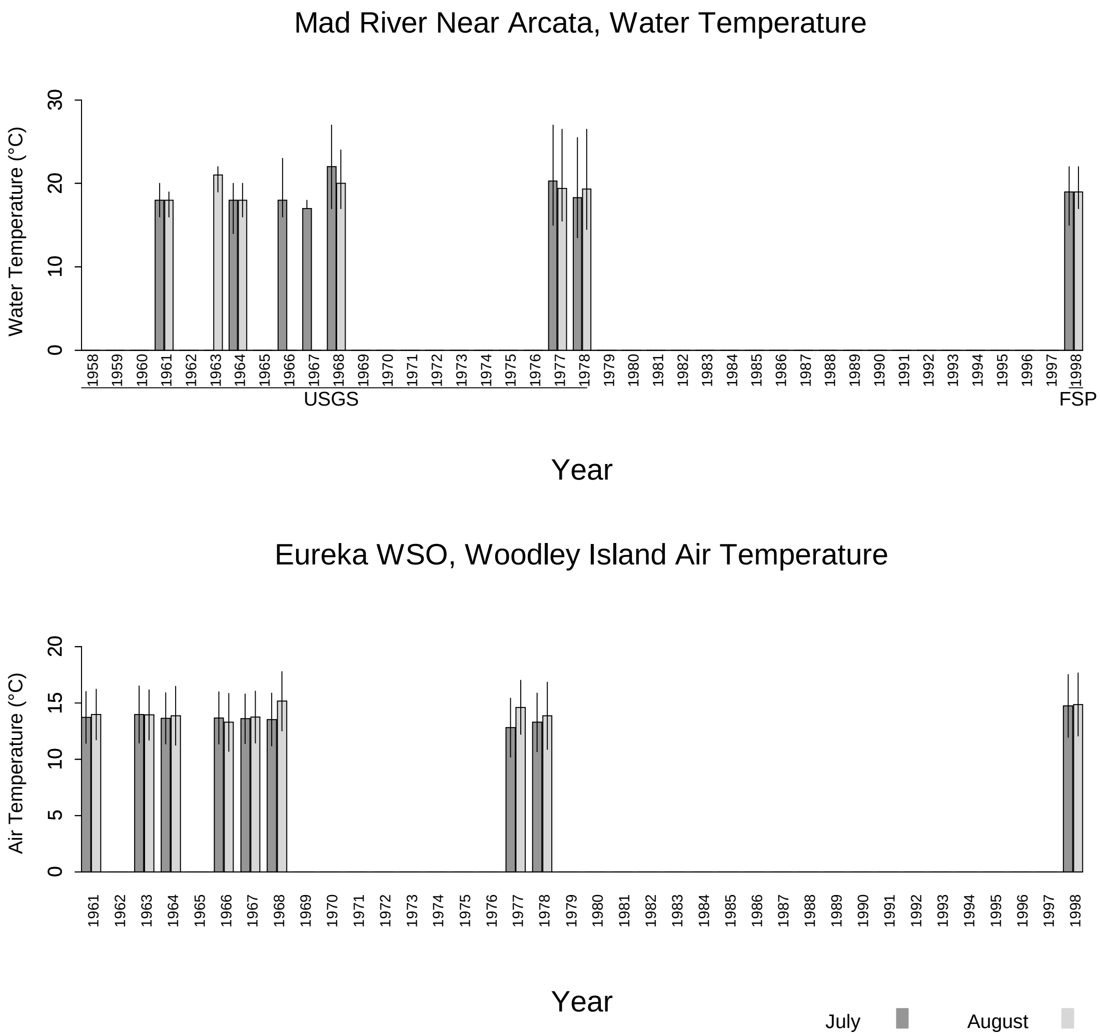


Figure 11.24. Comparison of (top) historical USGS monthly average stream temperature data in the Mad River near Arcata, CA and more recent Forest Science Project data for a site located 1660 m downstream from the USGS site, and (bottom) monthly average air temperature from nearest air site in Eureka, CA. Vertical lines represent the range in temperatures for each month.

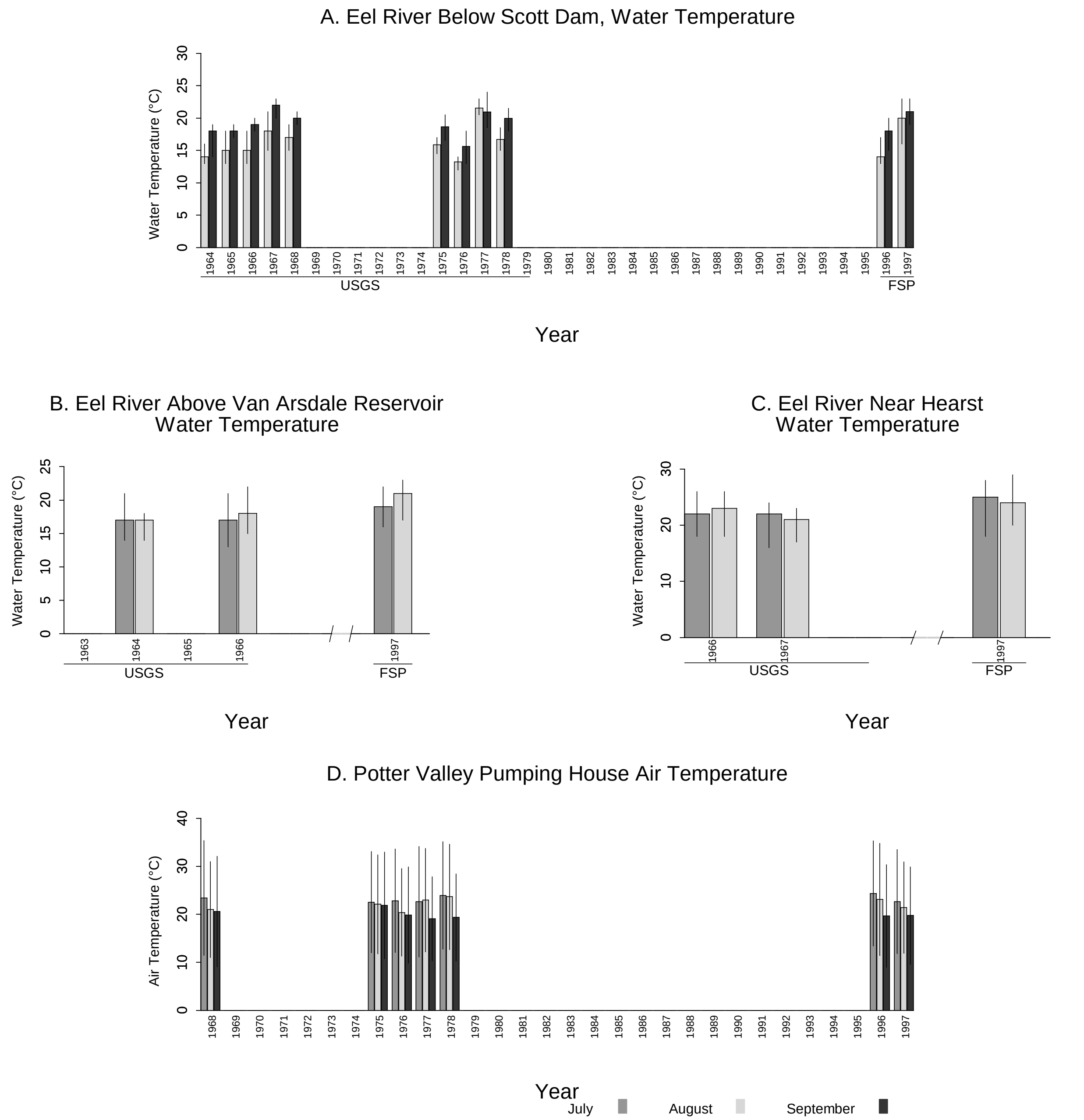


Figure 11.25. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for a site located in the Eel River Basin. Nearby FSP sites were (A) 80 m upstream, (B) 240 m upstream, and (C) 350 m upstream from the USGS site. Air temperature (D) was measured at the Potter Valley Pumping House. Vertical lines represent the range in temperatures for each month.

A USGS site located above Van Arsdale Reservoir had a matching FSP site located 240 m upstream from the USGS site. The watershed area at this location was 89,343 ha (345 sq mi) and the distance from the watershed divide was 70 km (43 mi). No canopy data were submitted by FSP cooperators for this site, but given the site's watershed position, it is probably less than 5% and not affected by land management practices. Monthly average water temperatures were very stable in 1963, 1964, and 1966. Water temperatures varied between 16°C and 18°C (Figure 11.25-B). Monthly average water temperatures measured in 1997 at a FSP site located 240 m upstream from the USGS site were about 3°C higher than those in 1963, 1964, and 1966. Air temperatures measured at an air monitoring station at the Potter Valley Pumping House were incomplete. Only 1968 air temperature data were available, thus analysis with air temperature is not possible. Just as at the site below Scott Dam, this site had warmer water temperature in 1997 than in earlier years. Unlike the Scott Dam site, no data were available in the 1970's.

Three years of data are compared in Figure 11.25-C for a site located on the Eel River near Hearst, CA. The watershed area at this location was 118,897 ha (459 sq mi) and the distance from the watershed divide was 89 km (55 mi). No canopy data were submitted by FSP cooperators for this site, but given the site's watershed position, it is probably less than 5% and not affected by land management practices. The August monthly average water temperature in 1966 was higher than in 1967, while for July, both years were the same. Monthly average water temperatures in 1997, measured at a FSP site located 350 m upstream from the USGS site were higher than values in 1966 and 1967. Air temperatures in 1997 (Figure 11.25-D) did not appear to be warmer than other years. The data for the Hearst site was similar to the site above the Van Arsdale Reservoir. The site had recent data for only 1997, and, as seen at the site below Scott Dam, 1997 was the warmest year in the record.

Figures 11.26 and 11.27 show comparisons for six USGS and FSP matched site pairs that were within 20 km of Covelo, CA. All six matched water sites use the air temperature data collected at Covelo as an index for the air temperature.

A USGS water temperature site in the Eel River near Dos Rios in 1966 had FSP cooperator recorded stream temperature data 70 m downstream in 1996 and 1998. The USGS site was approximately 19.2 km from the Covelo air temperature site. The July 1966 average water temperature was 1°C cooler than both the July 1996 and 1998 records (Figure 11.26-A). The August 1966 average water temperature was 1°C warmer than August 1998 and 2°C warmer than August 1996. Monthly maximum temperatures were all between 29°C and 31°C. Monthly average air temperature was also quite similar, ranging from 21.7°C to 24.6°C. The records indicate that there was not a substantial difference at this site between the historical record and the two more recent records.

USGS and an FSP cooperator both collected one year of data at a site on the Middle Fork of the Eel River below Cable Creek. The FSP site, operated in 1998, was 300 m downstream of the USGS site, operated in 1959. The USGS site was 11.1 km from the Covelo air temperature site. The sites were similar between the two years with 1959 having a 1°C warmer July monthly average and a 1°C cooler August monthly average (Figure 11.26-B). The monthly maximum water temperatures were also similar to 1959, having a 3°C higher July maximum and a 3°C cooler August maximum. The air temperature was slightly higher in July 1959 compared to the other months, but both years of August air temperatures were similar. This site had a drainage area (~193,000 ha) strongly suggesting that canopy had little influence on stream temperature. In 1998, the FSP cooperator reported a canopy closure of 5%.

At a site in the Middle Fork of the Eel River above Black Butte River, USGS collected stream temperature data in 1959, 1966, and 1968. At a site 1400 m downstream, an FSP cooperator collected stream temperature data in 1996 and 1997. The USGS site was 16.3 km from the Covelo air temperature site. Average monthly stream temperatures for July and August ranged from 21°C to 23°C and the monthly maxima ranged from 26°C to 29°C (Figure 11.26-C) across all years in the record. With a 1400-meter difference between site

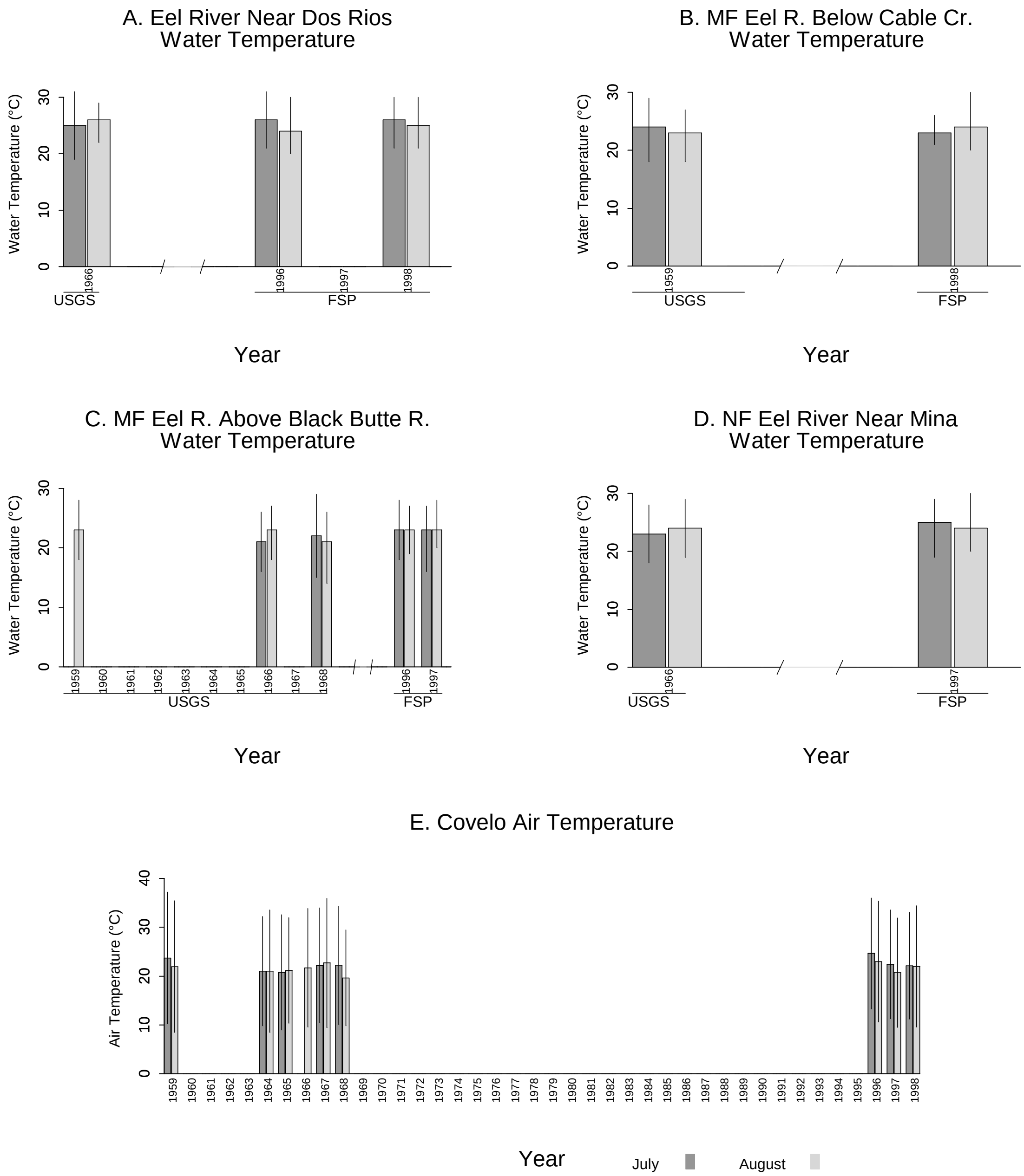


Figure 11.26. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for four sites located in the Eel River Basin. Nearest FSP site was A) 70 m downstream, B) 300 m downstream, C) 1400 m downstream, and D) 360 m upstream from the USGS site. Air temperature (E) was measured at a NOAA site located in Covelo, CA. Vertical lines represent the range in temperatures for each month.

location, these differences may be due solely to location differences. Thus, there is no detectable difference in temperatures for this site.

The USGS collected water temperature data in the North Fork of the Eel River near Mina in 1959. A FSP cooperator recorded stream temperature 360 m upstream from the USGS site in 1998. The USGS site was 19.0 km from the Covelo air temperature site. The July monthly average water temperature for 1966 was 2°C cooler than the 1998 record (Figure 11.26-D). The August monthly average water temperature for both 1996 and 1998 was 24°C. The July and August monthly maxima for 1996 were 1°C cooler than those for 1998. There was not an air temperature record for July 1966, but August 1966 average air temperature was warmer than the 1998 record. A change in stream temperature at this site could not be perceived.

The USGS collected water temperature data in Black Butte River near Covelo from 1964 through 1968. An FSP cooperator collected water temperature data for 1996 through 1998 at a site 180 m downstream of the USGS site. The Covelo air temperature station was 15 km from the USGS site. For the 1996 through 1998 records, the July average stream temperature ranged from 22°C to 24°C, while the 1964 through 1968 July records ranged from 20°C to 25°C (Figure 11.27-A). For the 1996 through 1998 records, the August average stream temperature was 23°C for all three years, while the 1964 through 1968 August records ranged from 21°C to 25°C. Similarly, the monthly maximum temperatures for 1996 through 1998 also fell within the range of the 1964 through 1968 record.

At a site on the Middle Fork of the Eel River near Dos Rios, USGS collected water temperature data for thirteen separate nonconsecutive years from 1958 through 1980. A FSP cooperator collected data in 1998 at a site 610 m downstream from the USGS site. The USGS site was 10.7 km from the Covelo air temperature site. July average water temperature for the recorded years from 1958 through 1968 ranged from 23°C to 27°C and for 1976 through 1980 ranged from 23°C to 25°C (Figure 11.27-B). The 1998 July average stream temperature was 24°C. The earliest three years (1958, 1959, and 1961) had the warmest July water temperatures. For most years August was slightly (1°C to 2°C) cooler. August average water temperature for the years from 1958 through 1968 ranged from 24°C to 26°C and for 1976 through 1980 ranged from 23°C to 25°C. The 1998 July average stream temperature was 24°C. Again, the earliest three years had the warmest July water temperatures. The warmest water temperature records, 1958, 1959, and 1961, also had the warmest air temperatures. Canopy for this site was reported at 5% by a FSP data contributor for 1998. This site had a relatively large drainage area (193,000 ha), indicating that the channel is quite wide. Canopy probably has not played a role historically in influencing stream temperature at this site.

Figure 11.28 shows the comparison for a USGS site and a FSP matched site on the Eel River at Fort Seward. The sites use the air temperature data collected at Richardson's Grove State Park as an index for the air temperature at the water temperature sites. The FSP site on the Eel River at Fort Seward was 730 m upstream of the USGS site. July and August monthly average water temperatures for 1961 to 1964 were 22°C to 23°C, respectively. In 1966 and 1968, the July average water temperatures were 25°C and 26°C, respectively. The August 1966 average water temperature was 26°C. The July 1975, 1977, and 1997 average water temperatures were all close to 24°C. The August 1975, 1978, 1997, and 1998 average water temperatures were all approximately 24°C, while the August 1977 average was about 25°C. More recent data collected at the site indicated that there was no notable increase in stream temperature over time.

The USGS collected water temperature data in the Eel River at Fernbridge in 1957 and 1958. A FSP cooperator collected water temperature data at a site 230 m downstream. The matched pair uses the air temperature data collected about 16 km away at Scotia as an index for the air temperature. The July average water temperature for 1957, 1958, and 1997 and all four years for August was 20°C (Figure 11.29). The August 1998 average water temperature was 21°C. The maximum monthly stream temperature ranged from 22°C to 23°C, except for August 1998 which was 24°C. The water temperatures at this site were similar, while the air

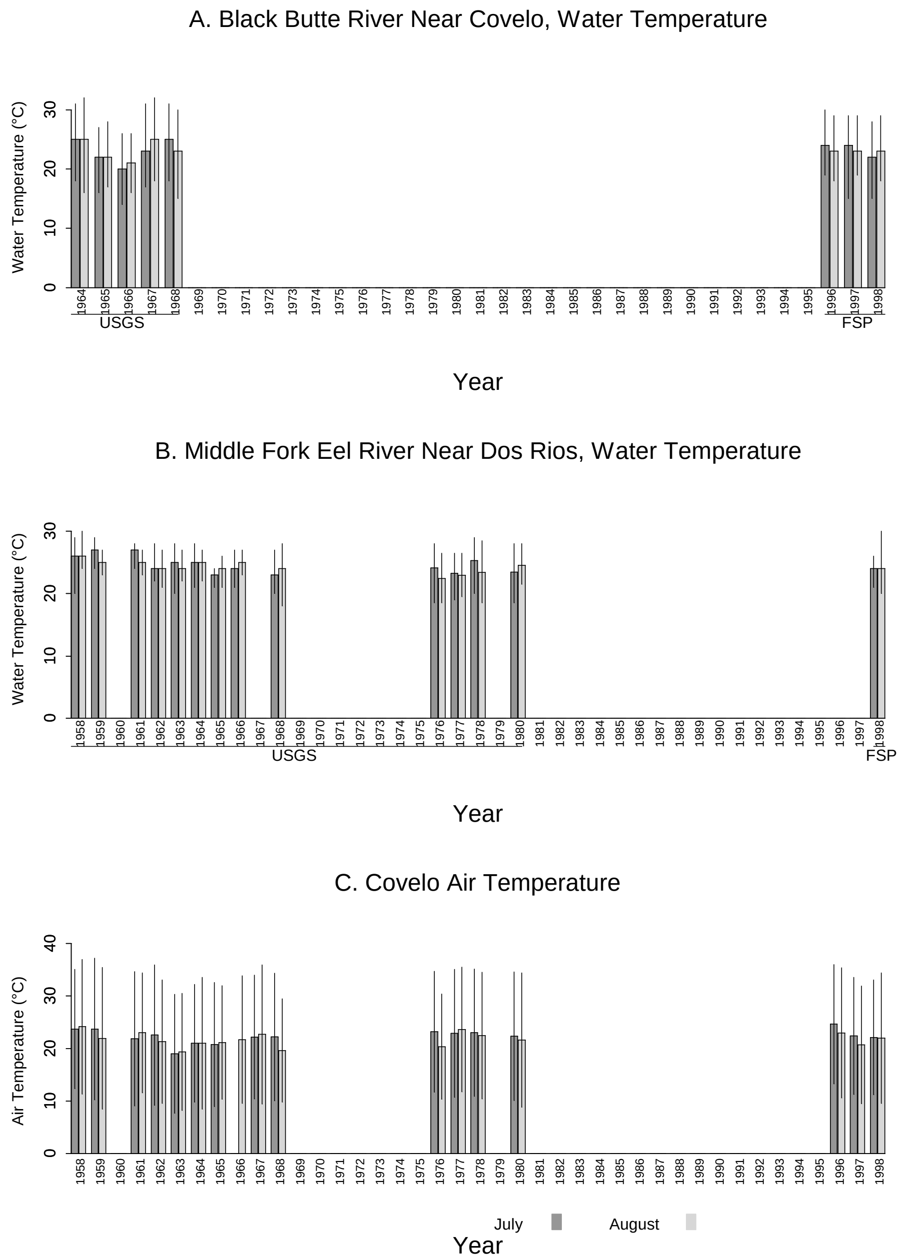


Figure 11.27. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for two sites located in the Eel River Basin. Nearby FSP site was A) 180 m downstream, and B) 610 m downstream from the USGS site. Air temperature (C) was measured at a NOAA site located in Covelo, CA. Vertical lines represent the range in temperatures for each month.

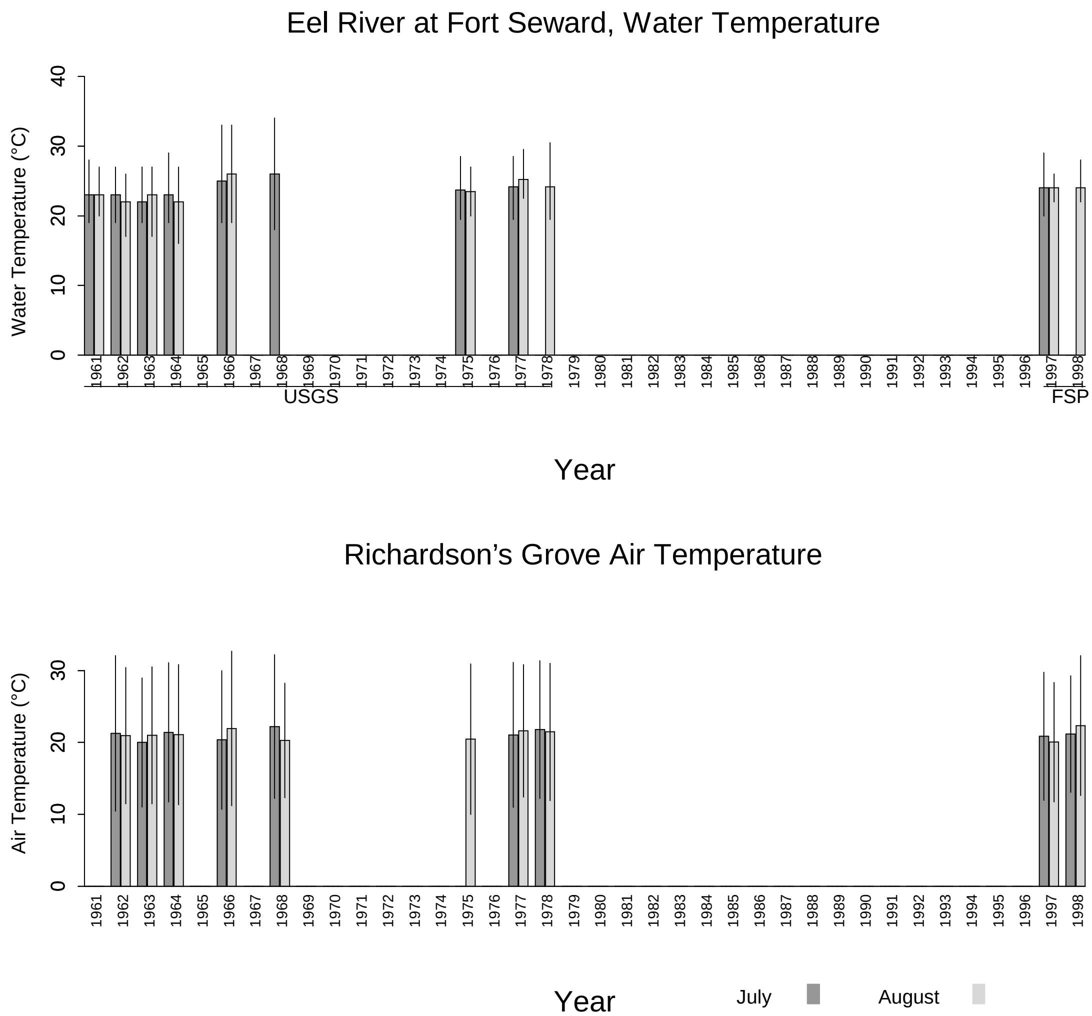


Figure 11.28. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for a site located on the Eel River at Fork Seward (top). From the USGS site, the nearby FSP site was 730 m upstream. Air temperature (bottom) was measured at Richardson's Grove State Park. Vertical lines represent the range in temperatures for each month.

temperature was somewhat variable (a range for average monthly air temperature of 15.9°C to 17.7°C).

Water temperature data were collected by the USGS from 1961 to 1964 at the South Fork of the Van Duzen River near Bridgeville (South Fork of the Van Duzen is usually referred to as the Little Van Duzen River). A FSP cooperator collected water temperature data in 1996 through 1998 at a site 70 m downstream from the USGS site. However, the 1996 data has not been presented in the figure; the monthly maxima were much higher than the other monthly maxima, and the monthly minima were much lower than the other monthly minima. It is believed that the data provided in 1996 for this site either had a

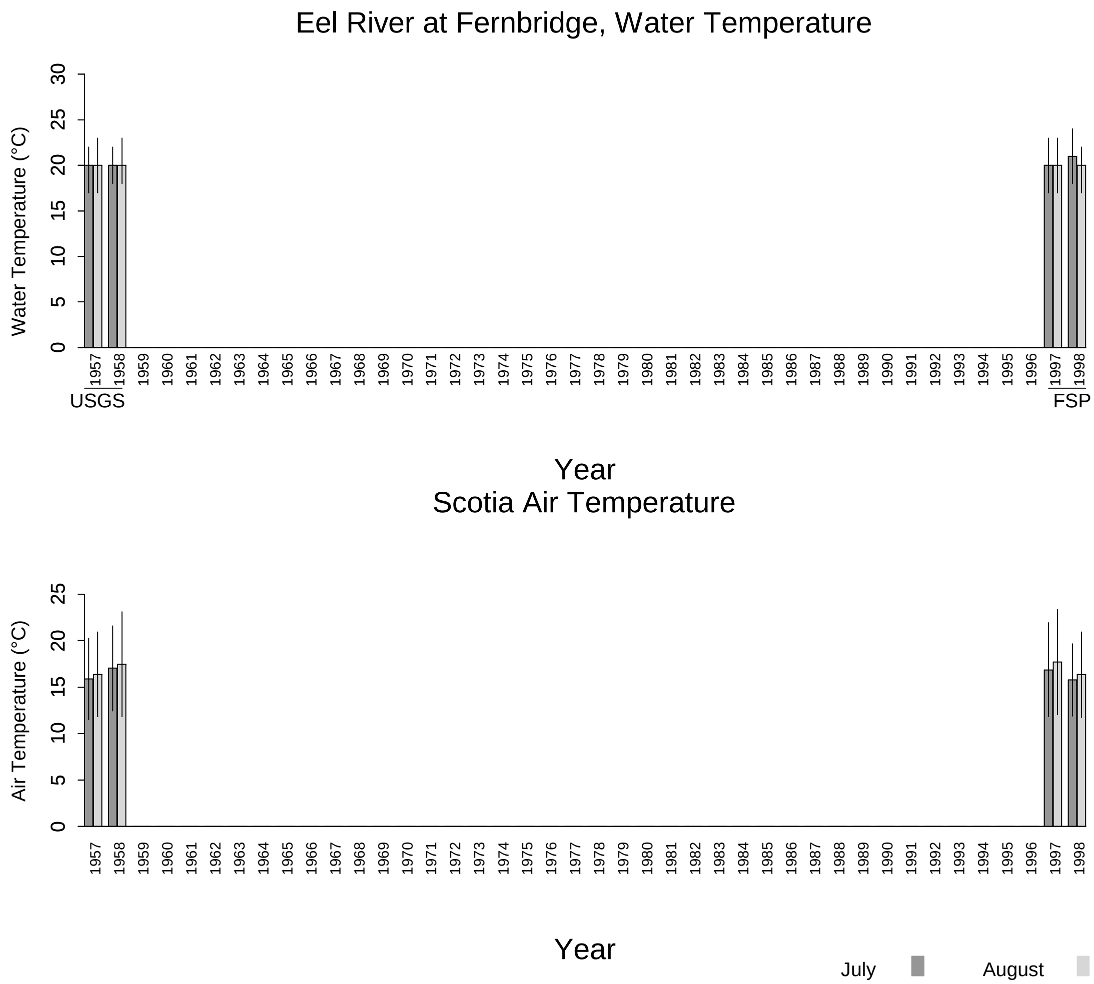


Figure 11.29. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for a site located in the Eel River Basin(top). From the USGS site, the nearby FSP site was 230 m downstream. Air temperature (bottom) measured at a NOAA site located in Scotia, CA. Vertical lines represent the range in temperatures for each month.

dewatered temperature sensor and measured air temperature or came from another location. The USGS site was 69 km from the air temperature station at the Weaverville Ranger Station. The July 1961 to 1964 monthly average stream temperature ranged from 19°C to 21°C, while the 1997 and 1998 averages were both 20°C (Figure 11.30). The August 1961 to 1964 monthly average stream temperature ranged from 18°C to 21°C, while the 1997 and 1998 averages were both 19°C. The monthly average water temperature maxima for 1997 and 1998 also fell within the range of the 1961 to 1964 records. Monthly average air temperatures were also fairly consistent for the record, ranging from 19°C to 23°C. There does not seem to be much change in historical water temperatures at this site.

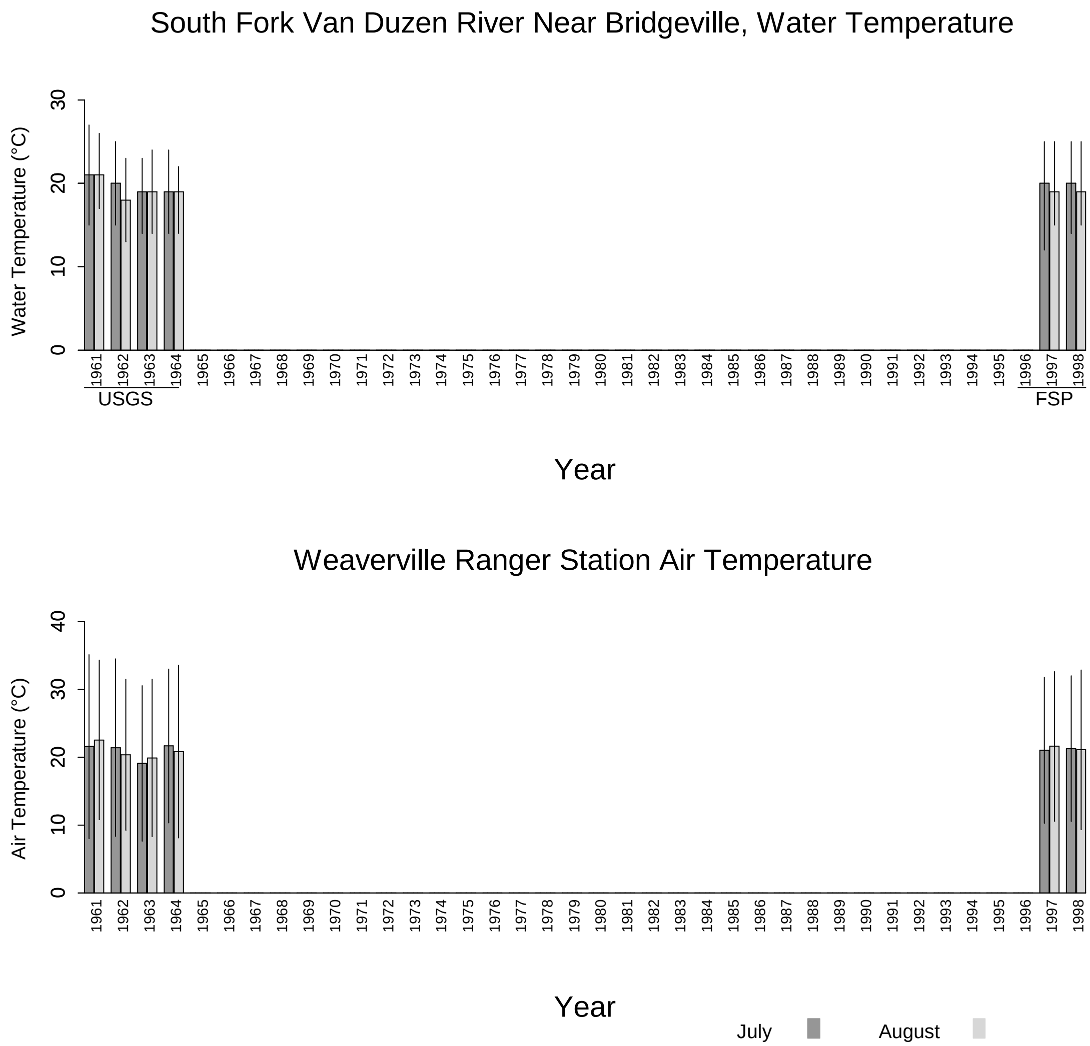


Figure 11.30. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for a site located in the Little Van Duzen River (South Fork, Van Duzen River) of the Eel River Basin (top). From the USGS site, the nearby FSP site was 70 m downstream. Air temperature (bottom) measured at the Weaverville Ranger Station. Vertical lines represent the range in temperatures for each month.

Ten Mile River Basin

One USGS site was located in the Ten Mile River Basin that had a matching FSP site. The site was located on the Middle Fork of Ten Mile River near Fort Bragg, CA. USGS collected data from 1965 through 1968 while the FSP cooperator collected data from 1993 through 1998. The USGS site was 11 km from the air temperature station near Fort Bragg. The watershed area at this location was 8621 ha (33 sq mi) and the distance from the watershed divide was 26 km (16 mi). Canopy closure reported in 1998 was ~30%. All years of data were similar, with 1967 having the warmest monthly average water temperatures (Figure 11.31). The July monthly average water temperature ranged from 15°C to 18°C, and August monthly average water temperature ranged from 15°C to 17°C. There does not appear to be any trend in stream temperature at this site.

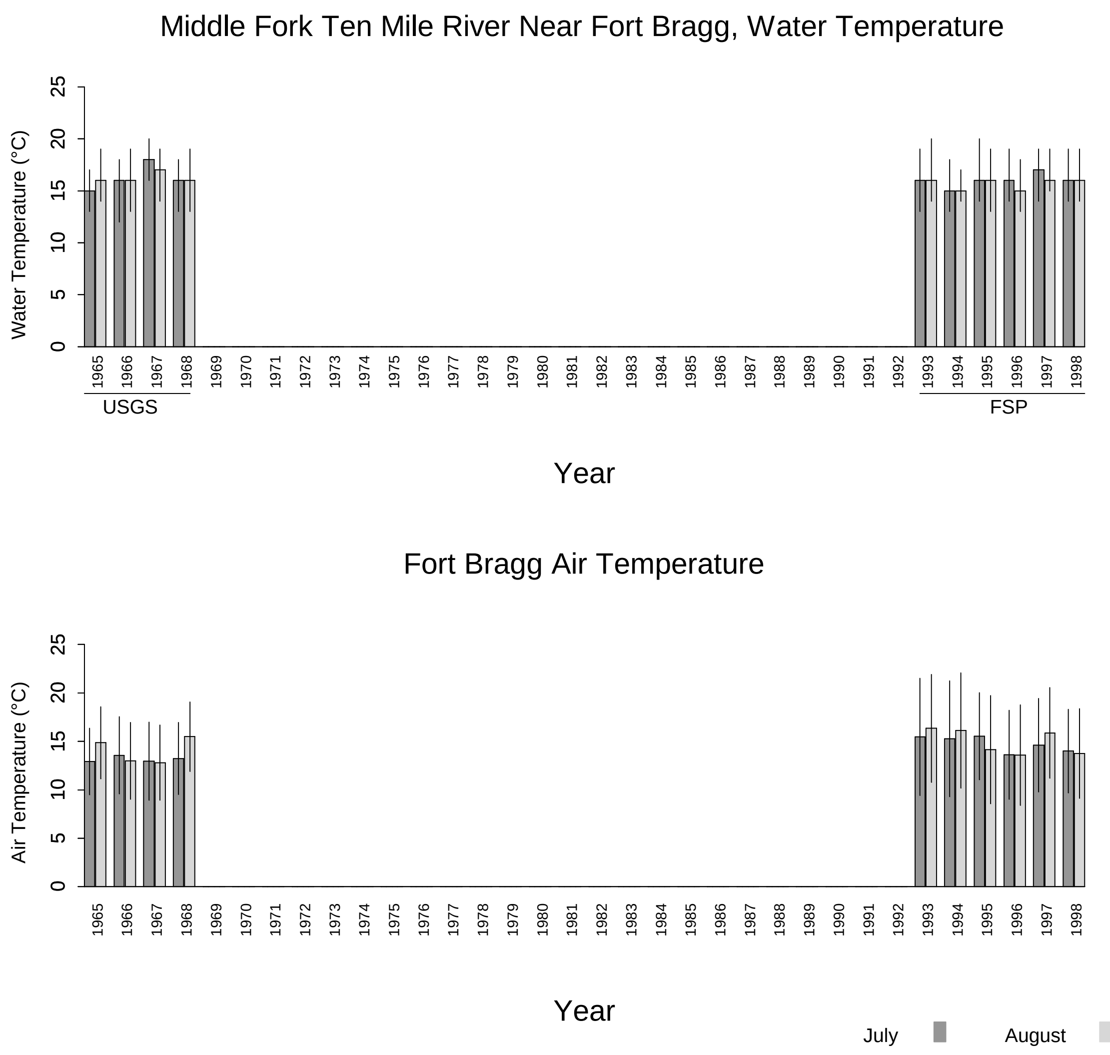


Figure 11.31. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for a site located on the Middle Fork of Ten Mile River (top). Nearest FSP site is 1070 m downstream. Vertical lines represent the range in monthly minima and maxima. Air temperature (bottom) measured at a NOAA site located in Fort Bragg, CA.

Summary

Historical trends in water temperature appeared to be largely a function of air temperature. This relationship is probably due to the fact that most USGS stream temperature monitoring sites are located on large, mainstem rivers. Monthly average air and water temperatures from matched USGS-FSP sites were plotted in Figure 11.32. Air temperature sites were selected using a 12-dimensional Euclidian distance model. There is a definite positive correlation between historical air and water temperatures.

At some sites, contemporary water temperatures have shown appreciable increases or decreases from historical levels. Most of these sites were on tributaries, where local site factors may partially account for the observed trends. Large storm events that occurred in the historical record, such as the 1964 flood, may have left a legacy of altered riparian and channel conditions that could be related to some of the observed increases in contemporary stream temperatures from historical levels. Recovery of riparian vegetation from catastrophic natural disturbances and past timber harvesting practices are perhaps involved in the observed decrease in recent stream temperatures from levels seen in the 1950's and 1960's at some of the tributary sites.

The large database developed by the Forest Science Project and other organizations throughout the state should be maintained to serve as historical data for future stream temperature monitoring efforts. Purposive monitoring designs must be developed to capitalize on the existing network of stream temperature monitoring sites. More site-specific attribute data should be collected using consistent protocols so that trends in stream temperature can be interpreted more concisely. Site-specific data should also include local air temperature. These data are essential for gaging the effectiveness of current and future forest practice rules and other land management prescriptions.

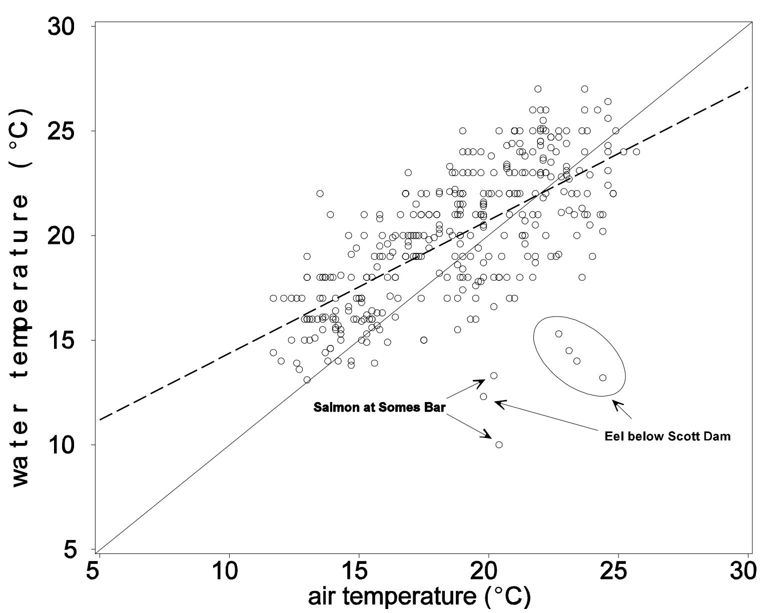


Figure 11.32. Monthly average air versus water temperature for all USGS - FSP matched sites for June, July, August, and September, wherever available. Regression equation (dashed line) is: water temperature = 7.995398 + 0.63657*(air temperature), R^2 = 0.4436. Solid line is one-to-one correspondence. Data spans 1957 through 1998. Two outlier sites are noted, the Eel River below Scott Dam and the Salmon River at Somes Bar.

Chapter 12

CONCLUSIONS AND RECOMMENDATIONS

The Forest Science Project's Regional Stream Temperature Assessment was an assessment using existing data, i.e., a meta analysis. As such, there was no sampling design in place to dictate (1) where stream temperature sensors should be located in the stream network, (2) what habitat type (e.g., pool versus riffle) sensors should be submerged, (3) what sampling frequency should be employed, or (4) what sampling window should be targeted. Each data contributor had their own objectives for stream temperature monitoring. These diverse objectives can be grouped into three broad categories:

- Pre- and post-timber harvest plan monitoring
- Thermal reach monitoring
- Characterization of thermal refugia

The data collected reflected a broad spectrum of climatic, hydrological, topographical, and ecophysiographical conditions. As a consequence, an array of sites reflecting a range of riparian conditions across the region allowed for post-stratification of variables by hierarchical spatial scales for statistical analyses. The area of interest (AOI) for the regional assessment was defined as the range of the coho salmon in Northern California, the largest spatial scale assessed.

Stream temperature data from over 1200 sites in Northern California were acquired, with 1090 sites meeting various physical, spatial, and temporal criteria defined for the regional assessment. An information management infrastructure was developed to process and analyze over six million stream temperature records and a myriad of other site-specific and geographic attributes. The most data-rich year was 1998, with more sites having both water temperature data and site-specific attribute data. It was the year that was used for most of the analyses presented in this report.

Methods (Chapter 2)

A large amount of stream temperature and ancillary data were acquired, processed, and synthesized for the regional assessment.

Conclusions

Considerable time and effort was invested in the development of stream temperature data processing procedures. Much of the process has been automated. However, detection of ambient air spikes and other anomalous readings still required manual inspection of each and every thermograph.

The salient features of stream temperature protocols developed by various state and federal organizations in Oregon, Washington, and California were combined to arrive at the peer-reviewed protocol found in Appendix A. Many organizations in California and the Pacific Northwest have adopted the Forest Science Project stream temperature protocol, in part or in its entirety.

Regional assessments of temperature sensor data in a geographic context require location information with a known level of spatial error. Moreover, the coordinate values of the sensors should be of the same or better quality than the base data used in the spatial analyses. The importance of positional accuracy became more evident as our regional analyses progressed. The early determination that many of the coordinates provided by data contributors were kilometers from their true location and the initial results from these misplaced sensors convinced us that a successful regional study relies heavily on known probe placement. There seems to exist all too often a lack of appreciation of the importance of place in modern ecological research. The likely result is a misunderstanding of the relationships between location and response. For this reason all stream temperature probe coordinates were validated and in many cases upgraded by confirming the location with the person responsible for probe installation.

Once the precise location of each monitoring site was determined on the 1:24,000 base data, it was apparent that many sites were not associated with a blue line stream on the 1:100,000 hydrography layer developed from EPA Reach File 3 by Teale Data Center. This was due, in part, to the alignment differences between the layers of differing scale and also because many streams with temperature sensors were not illustrated on the 1:100,000 level data. At the time, this was the only readily available hydrography layer encompassing the region-wide study area. Recently, the 1:000,000 scale National Hydrography Dataset (NHD) has become widely available. This is a significantly enhanced river layer that includes many features necessary for network modeling. Unfortunately, the lack of resolution in 1:100,000 scale hydrography data required that we use many manual procedures to acquire the GIS attributes used in this assessment. Development of framework 1:24,000 scale hydrography is critical to future monitoring and research efforts. Cumulative watershed or basin assessment of stream temperature requires a channel-routed, topologically accurate stream network to enable one to model the transport of water masses in a GIS environment. While there are various 1:24,000 stream coverages available for select watersheds in California, a 1:24,000 seamless stream coverage does not exist for the region-wide study area. The USGS and EPA are taking the steps to begin development of the NHD at 1:24,000, but without support from data contributors outside their agencies this will be a long and arduous task. To this end the Forest Science Project recently completed a 1:24,000 stream coverage for the Van Duzen River sub-basin following protocols developed by the Interorganizational Resource Information Coordinating Council (IRICC) that supports the Northwest Forest Plan.

Digital Elevation Model (DEM) data of 30-meter resolution were compiled, edge-matched and validated for the entire study area. Watershed area, distance to divide, probe separation distance, and gradient were all calculated directly or indirectly from the underlying elevation model. Prior to compilation by FSP staff, no seamless elevation data existed for the study area. This data set required a substantial investment of time, but payed large dividends during analyses. Recently, the USGS announced the completion of the National Elevation Dataset (NED). A 30-meter raster dataset stored in the latitude-longitude coordinate system and tiled by 1 degree blocks. While not available throughout the study area, newly created 10-meter DEMs show promise in enhancing the ability to derive useful information for regional ecological assessments. On the horizon are Light Detection and Ranging (LIDAR) DEMs of 1 to 3-meter resolution having horizontal and vertical accuracies of 2 and 1.5 decimeters respectively. This product will give GIS analysts the ability to accurately map existing channels to the headwaters. Captured simultaneously and co-registered with ground elevation data are vegetation heights. From these data the riparian corridor including fine scale gradient, topographic shading, above-water channel morphology, and to some degree riparian vegetation characteristics can be evaluated.

Recommendations

Adherence to a standardized protocol to collect stream temperature data across the entire region would greatly facilitate regional assessments. Careful attention to positional accuracy is needed to topologically place stream temperatures in proper geographic and watershed context. A seamless, channel-routed 1:24:000 stream coverage should be developed to allow better modeling of temperature transport for cumulative effects assessment.

Although much was learned from this meta analysis, many relationships were blurred by the lack of a sampling design. In future work, clear and concise monitoring and assessment questions should be formulated and a sampling design constructed to address these questions.

Regional Trends in Air Temperature (Chapter 4)

Air temperature is considered to be one of the most important factors influencing stream temperatures. As such, it was important to develop a better understanding of air temperature regimes across the range of coho salmon in Northern California.

Conclusions

Northern California can be characterized as being climatically diverse, with cool coastal areas and warm interior regions. A widely accepted concept is that air temperature decreases with increasing elevation due to adiabatic cooling processes. In Northern Coastal California, air temperature was found to be more a function of distance from the coast. In the coastal areas, air temperature was actually found to increase with increasing elevation during the summer months. In fall and winter, air temperature trends follow normal adiabatic cooling patterns in both the coastal and interior portions of the study area. In the warmer interior portion of the AOI, summer air temperatures followed the more traditional adiabatic tendency. Stream temperature modelers should be cognizant of the inverse relationship between air temperature and elevation in the coastal area in the summer months. Elevation should not be used as a surrogate for air temperature until the inland extent of the maritime influence has been determined.

Using 30-year PRISM air temperature data HUC-level air temperature regimes were developed. In HUCs that are oriented such that a portion lies on the coast and a portion lies in the interior, air temperature gradients up to 15°C from the headwaters to the coast are realized. Headwater streams that originate in the warm interior portions of these HUCs may tend to attain higher temperatures at short distances from the watershed divide. Using PRISM data, the zone of coastal influence was delineated.

Recommendations

PRISM data should be acquired for individual years to provide better year-to-year discernment in air temperature trends at 4-km or finer spatial resolution (1- or 2-km). Acquisition of finer temporal and spatial air temperature data will improve our ability to model trends in water temperature.

Inasmuch as air temperature greatly influences stream temperature, air temperature regimes in Northern California should be taken into account when setting stream temperature target values.

Air-Water Temperature Relationships (Chapter 5)

The relationship between macro- (remote) air and micro- (local) air temperatures was examined in this chapter.

Conclusions

Some local, stream-side air temperature stations correlated better than others with remote air temperatures. After final matching of water temperature sites with nearest 12-dimensional Euclidian distance remote sites, the distance from the stream site did not seem to play a role in how well the matched remote air temperature coincided with stream-side air temperature. Microclimate most likely plays an important role in how well remote air temperature correlates with localized air temperature.

Stream temperature showed a slight to moderate relationship with remote air temperature. Having such a small number of remote air temperature sites to match up with a large number of stream temperature sites contributed to the large variability in the relationship. When using only a small number of remote air temperature sites, caution should be exercised when making broad generalizations about climatic conditions from one year to the next to explain trends in stream temperatures.

At ten sites where air temperature was monitored at stream-side, much better correlations between local air and water temperature were observed, as expected and documented in other studies.

Out of 1090 sites, there were 154 sites that were monitored over three consecutive years (1996 - 1998). Daytime stream temperature metrics (highest daily maximum, seven-day moving average of the daily average, and seven-day moving average of the daily maximum) showed very little change across the three-year period. Daily minimum stream temperature showed a significant difference, with lowest daily minima occurring in 1996, the year with the lowest daily minimum air temperatures.

Our ability to discern trends in stream temperatures with year-to-year variations in air temperature were hampered by the limited number of remote air temperature sites with which to match up with water temperature sites.

Recommendations

To determine the influence of air temperature on streams with varying levels of canopy and at various watershed positions, a sampling design is needed to specifically address this issue. More stream-side collection of air temperature is needed. A complete suite of site-specific attributes should be collected at each water temperature site, using consistent protocols.

More sensors should be kept in the same location for a greater number of consecutive years to improve trend detection capabilities. The location of trend-detection sensors should cover a range of watershed positions and riparians conditions. A well-defined sampling design coupled with a consistent stream temperature protocol should dictate sensor placement.

Geographic Position and Stream Temperatures (Chapter 6)

This chapter examined the influence of broad-scale geographic position on stream temperatures. These factors included distance from the coast, ecoprovince, zone of coastal influence, north-south distribution (latitude), and elevation. Do local site factors completely control water temperatures or can some regional scale patterns be observed? The environmental variable that exerts its influence across all of these geographic factors is predominantly air temperature.

Conclusions

All of the geographic independent variables examined can serve as surrogates for air temperature. However, as described in Chapter 5, for the data set that was available, stream temperatures correlated better with microair temperatures. Micro- and macro-air temperatures were found to not always correlate very well. While macroair temperatures will have an influence on microair temperature, site-specific factors will affect the degree of correlation between the two. Thus, geographic trends in water temperature will be obscured by localized effects on microair temperatures. This was manifested by the large variability seen in stream temperatures with various geographic position variables. The zone of coastal influence was perhaps the most useful geographic factor for explaining the variation in stream temperatures at the regional scale. ZCI was perhaps more effective than ecoprovince in explaining the variability in stream temperature. Separation of stream temperature sites by whether they fell inside or outside of the zone of coastal influence showed significant differences. For all sites combined, and at given divide distances, stream temperatures inside the ZCI were significantly cooler than those outside the ZCI.

Recommendations

In the formulation of stream temperature targets, whether narrative or numeric, ecoprovince and ZCI should be considered. The temperature that a stream can reasonably attain is dependent upon its location with respect to ecoprovince and ZCI. Air temperature may be the discriminating factor that operates at these two broad geographic delineations. The fog layer associated with the ZCI can decrease both air and water temperatures, by its attenuation of incoming solar radiation. The spatial extent of the ZCI varies daily, seasonally, and yearly. PRISM data for individual years should be acquired to map the areal extent of the ZCI at different temporal resolutions.

Watershed Position and Stream Temperature (Chapter 7)

Water temperature has a tendency to increase with increasing distance from the watershed divide and with increasing drainage area. This simple picture of stream temperature change over downstream distance can be altered by local conditions. Riparian shading can vary along the length of a stream course due to natural or human-induced causes. Air temperature regimes can change from the headwaters to the mouth, not always in an increasing manner, as shown in Chapter 4. In Northern Coastal California air temperatures may decrease by as much as 15°C by the time a parcel of water reaches the ocean after its journey from the headwaters, due to oceanic control on air temperatures near the coast.

Conclusions

Stream temperature was highly dependent upon watershed position, both in terms of watershed area and distance from the watershed divide. Each of the eighteen hydrologic units (HUC) that comprise the range of the coho salmon showed an increase in stream temperature with an increase in watershed area and distance from the watershed divide. The rate of downstream increase in stream temperature appeared to vary with HUC location, i.e., whether the HUC was completely coastal, partly coastal and partly interior, or completely interior.

The traditional temperature metrics used to assess thermal impacts in streams (e.g., the highest seven-day moving average of the daily average or maximum, the highest daily maximum) may not adequately portray the thermal *dose* experienced by aquatic biota. Dose is determined by concentration multiplied by duration.

Stream network diagrams showed that streams can exhibit a decrease in stream temperature as the stream transitions from outside to inside the ZCI.

Recommendations

HUC location should be considered in setting realistically attainable stream temperature targets. When establishing stream temperature goals for maintenance of certain beneficial uses, watershed position within each HUC is an important consideration. A natural gradient in stream temperature occurs from the headwaters to the lower reaches. This natural gradient produces discrete zones with temperature regimes suitable for distinctly different fish communities and activities (Armour, 1991). Stream temperature standards should be developed with an understanding of the natural temperature regimes in HUCs throughout the range of the coho salmon in Northern California.

Using a sound sampling design, longitudinal stream temperature trend lines should be developed for each HUC. Sites with effective solar intercepting shade should be used to develop these trend lines. Stream temperatures at various sites in a HUC can be plotted and departures from the trend line can be assessed temporally and spatially.

Temperature metrics that embody the concept of dose, such as sum degrees or mean degree day, should be assessed with respect to their power in explaining presence/absence and abundance of salmonids. To develop linkages between these alternative thermal stress metrics and fish response, integrated temperature and fish monitoring is required. Too often fish surveys and temperature monitoring are conducted in different locations in a stream. Greater effort should be made to integrate all aspects of temperature and habitat characterization. Habitat typing data are often collected in stream reaches that are different from fish survey and temperature monitoring.

Site-Specific Attributes and Stream Temperature (Chapter 8)

The site-specific attributes examined in this chapter are channel orientation, gradient, habitat type, and bankfull width.

Conclusions

All sites in our regional stream temperature analysis contained non-missing values for channel orientation due to our ability to derive this attribute in GIS. Out of 548 sites with water temperature data available for regional analyses in 1998, only 365 of these were accompanied by canopy data. There was an even greater paucity of canopy data in years prior to 1998. These data voids are a great impediment to our ability to discern regional status and trends in stream temperatures and the factors that control them. A statistically valid sampling design coupled with canopy measurements collected using a consistent protocol is needed to better address the interaction between channel orientation, canopy, and stream temperature.

Comparing temperatures in different habitat types across broad geographic areas may be inappropriate, unless the sites are placed in proper geographic context. In any given stream, deep pools are expected to be cooler than riffles or runs from the same stream. A misleading view of stream temperatures can result by having a preponderance of deep pools in a restricted (warmer) geographic area and in predominantly large stream systems. The habitat types used in this assessment are relative terms. A deep pool in a low-order stream may be similar, at least in terms of depth, to a riffle or run in a high-order stream.

Bankfull width is an important variable in many process-based models. In 1998 there were 176 sites for which bankfull width was available.

The power of this regional assessment would have been greatly increased if more site-specific attribute data were collected at each stream temperature site. Bankfull width was available at very few sites, but was found to be highly significant in explaining trends in stream temperature. GIS-derived attributes (e.g., divide distance and watershed area) were used as surrogates for stream size, with fairly good success. However, localized variability in channel characteristics and flow rates can introduce errors in modeling the relationship between stream temperature and stream-size surrogates.

Recommendations

In future regional assessments a greater effort should be made to collect important site-specific attribute data that are known to be highly influential in controlling stream temperature. The use of consistent protocols and a sampling design developed to address well-articulated and agreed upon monitoring and assessment questions is critical.

Canopy (Chapter 9)

A diversity of methodologies were used by organizations who submitted canopy data to the Forest Science Project. Despite this diversity, some useful relationships were found in the data.

Conclusions

The amount of canopy appears to diminish with increasing distance from the watershed divide. A theoretical maximum divide distance was found to be approximately 70 km. At this distance, streams may potentially be too wide for stream-side vegetation to provide adequate stream shading. This distance is a theoretical maximum and will vary from watershed to watershed, HUC to HUC, and basin to basin. This distance may have also been influenced by past natural catastrophic events (e.g., the 1964 flood) and historical land management practices. For three temperature metrics commonly used to assess thermal regimes in streams, canopy was found to be highly correlated with stream temperature.

Recommendations

Development and adherence to a canopy measurement protocol that clearly relates to interception of incoming solar radiation is needed. Effective shade is the operative variable that influences stream temperature. Effective shade should be measured along a certain distance (thermal reach) upstream from the stream temperature monitoring device. Research should be undertaken to develop methods for estimating effective canopy cover using remote sensing imagery or hemispherical photography. Methods that require less subjectivity should be preferred.

Empirical Modeling (Chapter 10)

The chapter is a culmination of empirical meta-analyses of stream temperatures and various landscape-level and site-specific variables presented throughout previous chapters. It has been illustrated throughout this report that variation in stream temperature is not well explained by any single independent variable, particularly in regional analysis. Many factors influence the thermal regime of running waters. In this chapter, various models were developed that serve to show the interaction of various independent variables that operate at different spatial scales.

Conclusions

Geographic position played a major role in explaining variability in steam temperature at the regional scale. Geographic variables are believed to largely serve as surrogates for air temperature. None of the air temperature metrics based on data collected at remote air temperature sites were useful in explaining stream temperature variation. In alternative models where geographic variables such as UTMX and UTMY were excluded from the model, PRISM 30-year August average maximum air temperature was found to be somewhat useful in predicting stream temperature. However, using either geographic variables or PRISM 30-year long-term average air temperature, the ability to detect year-to-year changes in water temperature due to changing air temperatures is lost.

Researchers have had a great deal of success modeling stream temperature at basin and smaller scales. However, if the desire is to model stream temperature at a coho salmon ESU scale, many complications not seen at the smaller scale arise. Namely, remote air data coupled with surrogates, such as elevation, may work well for developing a basin-scale model, but at a regional scale, a better estimate of the local air temperature is required.

Canopy and habitat type were important site-specific attributes that helped explain variation in stream temperature. The logs of divide distance and watershed position were retained in backward elimination model development. These variables relate to watershed position and serve as surrogates for stream size (e.g., bankfull width).

Whether a site was in or out of the zone of coastal influence helped explain spatial trends in stream temperature. Inasmuch as ZCI was derived from 30-year long-term PRISM air temperature data, annual variability in the areal extent of the ZCI is not captured.

In the combined eocprovince model, whether the site was located in the coastal or interior ecoprovince had some explanatory power in stream temperature. Differences in air temperature regimes probably account for the discriminatory power associated with ecoprovince.

All the fitted models indicated that air temperature, solar radiation, and watershed position were important covariates. Positional covariates entered all the models. While these were viewed as air temperature surrogates, this underscores the fact that location is an important factor in stream temperature profiles. For example, two sites that appear to be identical with respect to habitat, riparian condition, shading, watershed area, and flow rate, but are in different basins will more than likely have different temperature profiles. Stream temperature “target” values that may be easily achieved in some areas might be impossible in others.

Recommendations

The placement of temperature probes into pools added additional unnecessary complexity to an already complex relationship. If water temperatures were measured only in well- mixed riffles, then water temperature models would have less variability, making interpretation much easier and more reliable. We are, however, grateful that so many organizations were willing to provide data, regardless of habitat type. Without their generous contributions of both time and data, this assessment would not have been possible. In future regional assessments there should be greater adherence to the Forest Science Project’s stream temperature protocol that stipulates placement of probes in well-mixed riffles.

In preliminary modeling exercises, when either or both bankfull width or depth covariates entered the model a good AIC score with a high R^2 value was observed. However, there was a paucity of data for these variables. Given the importance of stream size in many physical-based stream temperature models, greater effort should be made to measure these very important site-specific attributes.

Although models were presented and statements made as to what variables influence water temperature, the lack of a sampling design made in-depth analyses tenuous. Questions regarding each covariate's contribution to explaining variation in stream temperature requires data collected with a sampling design suited for developing explanatory models. Such a design would require a sampling frame, constructed from a well-defined sampling universe. Then, a random probability sample of some type must be drawn from the sampling frame. Finally, air temperature, canopy, and stream-size data collection, and stream temperature sensor placement must all adhere to consistent protocols and all collected values must be submitted.

Historical Perspectives (Chapter 11)

Most of the historical data came from larger streams where air temperature is most likely the major factor influencing water temperature. Thus, this analysis does little to address stream temperature changes that may have occurred since the 1950's in smaller streams, where most coho salmon rearing takes place and where land management practices may have a greater influence on thermal regimes and the extent of potentially suitable habitat. This historical analysis was on a site-by-site basis and not a regional assessment of trends in stream temperatures across the range of coho salmon in Northern California.

Conclusions

At some sites, contemporary water temperatures have shown appreciable increases or decreases from historical levels. Most of these sites were on tributaries, where local site factors may partially account for the observed trends. Large storm events that occurred in the historical record, such as the 1964 flood, may have left a legacy of altered riparian and channel conditions that could be related to some of the observed increases in contemporary stream temperatures from historical levels. Recovery of riparian vegetation from catastrophic natural disturbances and past timber harvesting practices are perhaps involved in the observed decrease in recent stream temperatures from levels seen in the 1950's and 1960's at some of the tributary sites.

An interesting commentary on the effects of the 1964 flood was noted in the USGS historical data in that many gaging stations did not have stream temperature data for 1965. Although the lack of data at many gaging stations following 1964 may have been a coincidence, it may more likely be a result of the widespread devastation that resulted from the flooding of many streams and rivers throughout Northern California.

Recommendations

The large database developed by the Forest Science Project and other organizations throughout the state should be maintained to serve as historical data for future stream temperature monitoring efforts. Purposive monitoring designs must be developed to capitalize on the existing network of stream temperature monitoring sites. More site-specific attribute data should be collected using consistent protocols so that trends in stream temperature can be interpreted more concisely. Site-specific data should also include local air temperature. These data are essential for gaging the effectiveness of current and future forest practice rules and other land management prescriptions.

A sad commentary is that as we worked through USGS water resource summary reports from the 1970's and 1980's, many gaging stations that had once gathered stream temperature data in the 1960's began to go offline in the following two decades. The loss of more and more gaging stations due to budgetary constraints will greatly hinder research in many ecological and physical science disciplines. It is hoped that the value of maintaining a network of strategically located gages throughout drainages in Northern California will be realized and that more stations will be brought back online.

Regional Assessment of Stream Temperatures Across Northern California and Their Relationship to Various Landscape-Level and Site-Specific Attributes

T.E. Lewis

D.W. Lamphear

D.R. McCanne

A.S. Webb

J.P. Krieter

W.D. Conroy

Forest Science Project
Humboldt State University Foundation, Arcata, CA
(707) 825-7350

Forest Canopy Measurements In Watercourse and Lake Protection Zones: A Literature Review

By

Marty Berbach, Pete Cafferata, Tim Robards, and Brad Valentine
California Department of Forestry and Fire Protection
Sacramento[1]

Final Report
June 1999

[1] Correspondence regarding this paper should be sent to: California Department of Forestry and Fire Protection, P.O. Box 944246, Sacramento, CA 94244-2460

Table of Contents

I. Introduction

On September 12, 1997, the Forest Management Committee of the California Department of Forestry and Fire Protection (CDF), requested recommendations on how to measure canopy cover in a statistically valid manner. The purpose of this report is to present a full and comprehensive discussion of terminology and definitions, literature review and citations. Initially, the intended audience is CDF Forest Practice Inspectors, with the goal of assisting them in enforcing Timber Harvesting Plan (THP) canopy mitigation measures. This paper applies to the enforcement of the Forest Practice Rules (FPRs) where percent canopy retained is an issue.

This paper is a companion to the study Robards et al. (1999) conducted comparing the techniques and efficiencies of various methods discussed here, which led to the development of specific protocols for measuring canopy in enforcement cases (Robards 1999). The subject matter in this paper could also be applied to any monitoring program that looks at forest canopy standards, its effectiveness in providing shade and protecting stream temperature. However, the scope of this paper does not include a thorough discussion of all variables that influence stream temperature.

We present this review focusing on the Watercourse and Lake Protection Zones (WLPZs) as applied in the FPRs. However, we note that this one specific application is simply a narrow in scope. We hope that the tools and concepts we discuss will be useful for any application that needs to measure canopy cover or shade, whether it be related to aquatic or upland resources.

Acknowledgments

Jerry Ahlstrom, Gary Brittner, Nancy Drinkard, Fred Jansen, John Marshall, John Munn, Ken Nielson, Chuck Schoendienst, Dave Soho, and Dan Walters provided useful comments and suggestions on this document.

II. Discussion of key and overlapping terms

We thought it would be valuable to define and discuss the variations of the terms "canopy" and "shade", their synonyms, and the methods used for their measurement. We have attempted to be exhaustive. While this may seem to be unnecessary, we believe that a full discussion and understanding of the terms is important to understand the best means to manage and measure canopy and shade in ways that are both enforceable and meaningful.

2.1 Canopy

There are many synonymous, overlapping, and different definitions of the term "canopy". While many definitions may seem unnecessary or redundant (and are in many cases), these often are due to the specific use to which the definition is applied. Some authors have applied terms so loosely as to add confusion to the issue. This section will attempt to present and define all of the variations on the term "canopy" and related terms and to identify conceptual overlap and differences between them. Hopefully this will help clarify any potential misuse and confusion of terms.

"Canopy" Closure Terms and Synonyms

Garrison et al. (1997) uses the terms **canopy cover, canopy closure** and **crown closure** synonymously. **Canopy closure** is the term used in the California Wildlife Habitats Relationship (CWHR) system for tree and shrub dominance classification (Mayer and Laudenslayer 1988).

Platts et al. (1987) define canopy closure as the area of the sky over the selected site bracketed by obscuring vegetation (see **canopy density** below). This definition does not account for the density of the vegetation within the area bracketed, but rather can be considered an outline of a plant's branches and foliage. Canopy closure can be considered constant within and across seasons if fast-growing vegetation is not dominant. Being an outline of the vegetation, canopy closure is not sensitive to whether or not a plant is deciduous.

Barbour et al. (1987) define **canopy coverage** as the percentage of ground covered by the canopy. Bunnell and Vales (1990) use the term **mean crown completeness** as a synonym.

Other terms included which, in context, may be synonymous with canopy are closure **forest canopy**, **crown canopy**, and **tree canopy**. Subsets of canopy closure by species and/or structure can be useful for different purposes (e.g., conifer or shrub canopy closure).

For the CWHR system, the cover of the overstory trees contributing to the canopy is measured. This can be done from ground or remote sensing information (Garrison et al. 1997). Overlapping canopies are not counted, therefore the maximum canopy closure value possible is 100 percent.

Canopy Density

Canopy density is defined as the amount of the sky blocked by vegetation (see **canopy closure**). Canopy density can change drastically if canopy vegetation is deciduous and/or fast growing, whereas canopy closure can be constant if fast-growing vegetation is not dominant (Platts et al. 1987). Multiple layers of foliage, deep crowns, and interlocking tree branches can enhance canopy density. Its value can exceed 100 percent. As for closure, structural or species subsets can be considered.

Canopy Volume

Canopy volume is an indirect measure of **foliage volume**, and is calculated by separate equations from geometry that approximate conifer and hardwood shapes. This is a means of measuring indirectly the foliage available for consumption by wildlife or as substrates for insects and other prey (Morrison et al. 1992, Biging and Wensel 1990).

Angular Canopy Density

Angular canopy density is the term used by Brazier and Brown (1973) to measure vegetation along the path of the incoming solar radiation rather than along a vertical view of the sky. This is measured at the angle at which vegetation effectively blocks summer (or any user-desired season) sun (Kondolf et al. 1996). Angular canopy density can be measured at one point in time (usually mid-day with a one-foot square plane mirror marked with a three inch grid) and recorded as percent shade/sun; or can be measured along the entire sun's arc with the use of a **Solar Pathfinder®** (see below) and recorded as percent solar insolation (heat). Also see **shade** below.

Shade "Canopy"

The term **shade canopy** can be considered either redundant in that canopy creates shade, or a misuse of the terms because shade and canopy is related but distinct physical properties that are measured differently. Relative to other directions, vegetation or other obstructions to the south provide the most valuable shade when measured as the greatest obstruction of direct solar heating. Objects to the east and the west can also shade a point from direct sun light. Objects on the northern half of a circle around a sample point do not provide direct shade, but may intercept reflective and re-radiated solar energy. See **shade**, **Solar Pathfinder®**, and **WLPZ vs. Riparian Zone** below.

Crown Diameter

Crown diameter is one of two variables used to determine CWHR size class, with stem diameter as the other. Crown diameter assumes a regular geometric outline (e.g., circular) of the tree's foliage. Gaps in the outline or foliage density are not considered. Crown diameter can be used for determining tree size with the use of remote sensing data, such as satellite imagery or aerial photography (Garrison et al. 1997). Caution should be exercised because crown diameter inherently over-predicts crown canopy closure as each tree is represented without overlapping crown.

Crown diameter can be measured with the use of mirror devices to view directly upward while walking along the ground, but are not commercially available. A clinometer can be used but is also awkward. Crown diameter is best measured with the use of low level aerial photographs where it can be determined more quickly with accuracy that is comparable to ground-based measures (Wenger 1984). Crown diameter or radius can also be measured as a part of an inventory.

Live Crown

The first live branch is often taken as the lower limit of the crown (Wenger 1984). The CACTOS/CRYPTOS definition requires a "balanced" crown measurement (Biging and Wensel 1990).

Live Crown Ratio (or Percent Live Crown)

Live crown ratio is the ratio of the living crown to total height (Wenger 1984). For trees with similar height, the one with a higher live crown ratio will have greater canopy density and can cast a larger shadow than would a tree with a low live crown ratio. Live-crown ratio is important in assessing shade values. For instance, two trees with the same crown diameter contribute equally to canopy closure; but the tree with the greater live-crown ratio will cast a far greater shadow. This is because the sun's rays enter at an angle away from vertical. Timber falling and yarding can reduce the live crown ratio of retained trees.

Multistoried or Multilayered Canopy

Multistoried and **multilayered** are synonymous terms. Stands with two or more canopy layers are considered to be uneven-structured (Garrison et al. 1997). Both terms imply that the layers are distinct (i.e., there is a gap between them). Under the CWHR classification system, only CWHR 6 has multi-layered tree canopies (greater than 24 inches diameter at breast height (dbh) trees over 6-11 inches dbh trees and/or 11-24 inches dbh trees) with a **total tree canopy** that exceeds 60 percent (Mayer and Laudenslayer 1988). Multi-storied stands generally should be similar or better than single-tiered stands at intercepting sunrays at low angles.

Understory Canopy

Understory canopy is the canopy of vegetation (suppressed trees, shrubs) under dominant and predominant trees of a multistoried or multilayered stand. See **low shade**.

Overstory Canopy (or Density)

Overstory canopy is the canopy of the dominant and predominant trees of a stand. See **high shade**.

Total Canopy

The term **total canopy** is used where there are **multilayered** or **multistoried canopies** (see Mayer and Laudenslayer 1988). It is the summation of canopy at each layer, with a total maximum of 100 percent. It is synonymous with canopy cover.

Riparian Canopy Opening

Riparian canopy opening refers to the gap between the canopy of the riparian vegetation on opposite banks of a stream or river. Often the canopies of small streams are like those away from the stream and hence have no riparian canopy opening in their undisturbed state. In steep, narrow, V-shaped valleys, considerable shading can result from topography and the dominant upslope species rather than riparian vegetation. In lower-gradient (especially those with unconfined channels with flood plains) and higher-order streams, the stream channel by definition is wider and often there is naturally an opening between the parallel stands on opposite banks (Anon. 1996).

Use of "Canopy" Terms in Forest Practice Rules

The FPRs define **canopy** as the more or less continuous cover of branches and foliage formed collectively by the crowns of adjacent trees and other woody species (' 895.1). The clause "more or less continuous" is confusing in that it suggests that below some (unknown) level, the foliage and branches of trees are not continuous enough to be canopy. **Shade** is not defined in the FPRs. Throughout the FPRs the term **canopy** is used 54 times. Usage includes: **canopy closure** (15 times), **canopy layers** (10 times), **multistoried canopy** (four times), **forest canopy** (three times), **streamside canopy** (two times), **multilayered canopy** (two times), **shade canopy** (two times), **crown canopy** (two times), **overstory canopy** (two times), **understory canopy** (one time), **total canopy** (one time), and **vegetative canopy** (one time). The various uses of these terms are not defined in the FPRs. It would be useful for these terms and definitions to be standardized in the FPRs.

In order to protect the beneficial uses of water, the FPRs mandate that canopy be retained after harvest. The standard FPRs require retaining a given percentage of the canopy. Historically, agencies and the public have asserted that the FPRs allowed greater reductions through multiple harvest entries, e.g., 50 percent of 50 percent of 50 percent. Even with regrowth between entries, the percentage against which a subsequent harvest was measured was a moving target. However, that changed when CDF (Wilson 1993) reported the policy that the standard is based on total possible canopy, not that which is presently available. Thus, 100 percent canopy would be a stand in which there are not gaps between the trees crowns. FPR §916.3(f) clearly states that where less than 50 percent canopy exists, only sanitation salvage is allowed.

2.2 Shade

The American Heritage Dictionary (Morris 1976) defines shade as "light diminished in intensity as a result of the interception of the rays; comparative darkness or obscurity." Bartholow (1989) defined two forms of shading: 1) riparian vegetative shade, and 2) topographic shade from valley walls, cliffs, and streambanks. Both forms result in the interception of the daily solar radiation from the surface of interest.

Oliver and Larson (1990) describe two different kinds of shade and their different properties: 1) **low shade** is created by objects such as shrubs and short trees close to the surface being shaded. Most of this kind of shade is discontinuous, distinctly either full sun or shade, with flecks of sunlight passing through. 2) Objects far removed from the surface being shaded and generally in a different stratum cast **high shade**. Sunlight diffuses into the shaded area as it passes an object for the second type of shade, and the shade appears to diffuse outward. The boundary between lighted and shaded areas becomes less distinct, and a broad area of intermediate light intensity develops. The more distant the shade, the shorter the duration which it will cast shade on any given point. McGurk (1989) refers to these two types of shading as direct and indirect (diffuse) shading.

Geler-Hayes et al. (1995) describe that in the Northern Hemisphere, a tree casts its longest shadow on the winter solstice (Dec. 21) and its shortest shadow on the summer solstice (June 21). From summer to winter solstice shadows lengthen, and from winter to summer solstice shadows become shorter. A tree casts its shortest angle at solar noon, a point when the sun reaches its highest angle of azimuth 180E and produces a shadow that points toward azimuth 0E. Solar noon occurs the same time every day with small deviations. Because shadows fall due north at solar noon, aspects at a corresponding angle east or west of north are mirror images and produce the same length shadow. However, at any one time, shadow lengths on corresponding aspects do not correlate except on north and south aspects. For example, two hours before solar noon, the shadow lengths on an east aspect will be shorter than the shadow lengths on a west aspect.

The length of a shadow is a function of the height of the vegetation, terrain slope, and the angle of the sun's rays or zenith angle. The length of the shadow can be calculated by multiplying the vegetation height by the tangent of the zenith angle. The zenith angle varies by time of day. The actual distance the shadow is projected over a stream channel, or effective shadow length, is a function of the shadow length, tree-to-channel distance, azimuth of the sun, and channel orientation (Park and Hawkins undated). Whether a shadow affects the water is also a function of channel width and the location of the stream-flow within the channel.

For conservation of cold-water fish habitat, the best time to measure stream shading is for the maximum stream temperature period, usually July through September. (See **Solar Pathfinder®** and **angular canopy density**).

2.3 WLPZ vs. Riparian Zone

The FPRs define Watercourse and Lake Protection Zone (WLPZ) as "a strip of land, along both sides of a watercourse or around the circumference of a lake or spring, where additional practices may be required for protection of the quality and beneficial uses of water, fish and riparian wildlife habitat, other forest resources and for controlling erosion" ('895.1). The minimum width and percent canopy retained are based on the FPR under '916.5 (936.5, 956.5).

The terms "riparian zone", "riparian area", "riparian vegetation" and "riparian ecosystem" are defined differently by various agencies, organizations, and individuals. A single definition has not emerged to become the standard (Melton et al. 1984, Kondolf et al. 1996). Melton et al. (1984) defined riparian ecosystems as those characterized by the presence of trees, shrubs or herbaceous vegetation that require free or unbound water, or conditions that are more moist than those of surrounding areas. Riparian vegetation is vegetation associated with rivers, streams, and other aquatic systems. The term "riparian vegetation" has been variously defined as vegetation occurring only on river and stream banks, to more inclusive definitions that encompass flood plain and terrace vegetation. Kondolf et al. (1996) defined obligate riparian vegetation as found only in riparian areas, dependent on a high water table, tolerance to inundation and soil anoxia, tolerant to physical damage from floods, tolerant to burial by sediment, and able to colonize and grow in substrates with few soil nutrients. The ecological importance of riparian areas is widely recognized (Cummins 1974, Melton et al. 1984, Knopf et al. 1988, Gregory et al. 1991, Naiman et al. 1993, Kondolf et al. 1996).

2.4 Common Field Tools

Solar Pathfinder®

The **Solar Pathfinder®** is a device used primarily to measure shade or solar radiation. It was designed for use in the solar heating industry. The Solar Pathfinder® consists of a transparent spherical dome, which reflects a panorama of the site, including shadow-casting objects. A sun path diagram, viewed through the dome, depicts the sun's path every hour of an average day for every month of the year. Therefore, information on the level of shade during the maximum stream temperature period (or any other month) can be gathered at any time of the year (Amaranthus 1983, Cafferata 1990a).

To use the Solar Pathfinder®, a latitude-appropriate insert must be placed below the reflecting dome. It is set up on a mini-tripod, commonly in the middle of a stream (or the sample point), oriented to the south, and leveled. All the vegetation and topography shading the instrument are reflected instantly and clearly on the instrument's transparent plastic dome. The average daily total solar radiation at a given point for a given month is calculated simply by summing the site radiation percentages for the shaded area on the sun path diagram. Because stream temperature in much of California usually peaks in mid to late summer, the arcs for July through September should be used and based on local information. In any case, the month(s) for which shade was estimated must be reported (Amaranthus 1983, Cafferata 1990a).

The most commonly used insert for the Solar Pathfinder® breaks an average day for each month down into ½ hour increments for the period between sunrise and sunset. Printed in each increment is the percent of the energy available during that period. The sun angle, distance, and atmosphere through which light must pass early in the morning or late in the afternoon differs from mid-day. Thus, the value of energy available is greater during a ½ hour interval at noon than it is during the same time duration at another time of the day. This insert measures the percent of solar radiation available or shaded, not the percent of light. An insert on which each ½ hour time interval had equal values would measure the percent of light available or shaded. Statistically, a single reading of a Solar Pathfinder® yields a value ranging from 0-100 percent. Depending on sampling strategy, the sample size will at best be n=one for a single reading.

The Solar Pathfinder® is commonly used as an assessment tool to predict changes in water temperature, and is not commonly used as an enforcement tool. Solar Pathfinders are currently being used in the San Mateo-Santa Cruz Ranger Unit. Among its advantages, it can identify trees that shade a given sampling point, allowing specific identification of important retention trees. Also, after a very brief training period, user-variation is low (B. Valentine, pers. observ.). It is the best device available to predict changes in stream temperature following harvesting (Cafferata 1990b).

As true for any tool, multiple settings are necessary for an accurate assessment of an entire watercourse. A disadvantage of the Solar Pathfinder® is that it does not measure understory vs. overstory canopy. Other disadvantages include slightly more time required to use the device (but similar to a spherical densiometer), must be used along streambank with deep or fast flowing water, and it is relatively bulky and fragile. (Also see **angular canopy density**, **shade "canopy"**, and **shade**).

Canopy Densitometer ("Sighting Tube")

The sighting tube most commonly used by CDF to measure canopy cover is the GRS Densitometer™. Forest staff at LaTour Demonstration State Forest has found the canopy densitometer to be an excellent and quick tool that is also relatively inexpensive (D. Walters, pers. comm.).

The documentation that comes with the Densitometer suggests line-point sampling with points evenly spaced along each transect. Points can also be collected in clusters. For example, a 25-point grid within a tenth acre CWHR plot works well. Note that the standard error calculation is different for the two methods.

An advantage of the sighting tube is that it can be used to measure understory cover, exposed soil, herbaceous cover, woody debris, etc. by pointing the instrument down. Also, the composition of multiple canopy layers may be determined from the overstory. The added advantage to this method is the ability to record diameters/species/crown position for "hit" trees and to invert the tube and record all vegetative cover. Care must be taken to not let understory vegetation prohibit the proper location of a sample point (Anon. 1995).

A single reading of a vertical sighting tube yields a binomial, either 0 (vegetation not at the crosshairs) or 1 (vegetation present at the crosshairs). Depending on sampling strategy, the sample size will at best be n=one for a single reading. Anon. (1995) used a sighting tube with line-point transect sampling to provide an estimate of canopy cover for trees or other vegetation. Multiple points might still yield a sample size of one if the points are not independent (a risk that should be evaluated when using the clustering approach described under CWHR).

One drawback with the use of the canopy densitometer is in the middle of a watercourse or along a watercourse edge, where it will only measure the riparian canopy opening and not measure the total canopy of the WLPZ. Another drawback is that for measuring canopy in redwood trees taller than 150 feet, the sighting dot in the densitometer becomes too large (M. Jameson, pers. comm.). The first problem is resolvable by proper definition of the sampling universe.

Cook et al. (1995) refers to a similar instrument as a **moosehorn**; Bunnell and Vales (1990) referred to a similar instrument as a **Gimbal sight**.

Spherical Densiometer

Another common instrument for measuring canopy cover is the **spherical densiometer**. There are two different versions of the spherical densiometer: **convex** (model A) and **concave** (model B). Both estimate the relative area of crown coverage from an inverse conically shaped field of view aligned along a vertical line that is reflected on to the mirrors. Model A has an estimating grid scratched on the surface of the convex mirror. Model B has the estimating grid superimposed between the eye and the surface of the concave mirror. In each model, the mirror is set into a wooden carrying case with a hinged lid and small bubble level (Lemmon 1956, 1957). Recommended protocols have changed since Lemmon's publication in which he recommended two approaches: count the number of squares occupied by vegetation, or, count the number of imaginary points spaced four per square. In both, a single reading is the summation of counts taken in four cardinal directions from the sample point adjusted by a factor to achieve a maximum total of 100 percent. Strickler (1959) modified the instrument by limiting the readings to only a portion of the densiometer's surface. He did this to avoid lateral overlap in the area sampled by the four-direction technique. The California Department of Fish & Game (Flossi et al. 1998) adopted this technique for stream orders one through four. They recommend taking the reading at the center of each habitat unit in four directions, parallel and perpendicular to stream flow. Because the correction factor is rounded to the nearest 1/10, the method yields a slight overestimate to which a second correction can be applied.

Sample size is determined by the variation of the stand, but the number of sample points needed is much smaller than the sighting tube because its variation is less. A single reading of a spherical densiometer yields a value ranging from 0-100 percent. Depending on sampling strategy, the sample size will at best be n=one for a single reading. Because readings taken in four cardinal directions from a single sample point may not be independent, these four readings should be considered as one sample. By limiting the reflective surface from which canopy is recorded to that near-vertical, this technique would approximate the results from a vertical sighting tube.

Hemispherical Photography

Another tool that has been available for several years but is less commonly used is hemispherical photography. This technique utilizes ultra wide-angle lenses ("fish-eye" lens) of 7.5 mm focal length or 180° field of view and has recently been combined with computer image analysis techniques (Evens and Coombe 1958, Chan et al. 1986, Weiss et al. 1991, Frazer et al. 1997). Robards et al. (1999) did not use this method in comparing techniques.

A disadvantage of this technique is that it is subject to the same biases as the spherical densiometer with their conical field of view. Hemispherical lenses and spherical mirrors do not have a vertical orientation. Also, the camera would have to be carefully leveled to get a true vertical projection. On the positive side, this technique does provide a permanent record, and the use of a digital camera provides a basis for computer calculations (Chan et al. 1986).

2.5 Crown Predictive Equations

Mathematical models describe crown attributes from easily obtained and commonly measured variables such as dbh, total height, and crown ratio (Biging and Wensel 1990; Warbington and Levitan, unk.). Crown models are useful for long term strategic planning such as Sustained Yield Plans (SYPs) because they allow habitat conditions to be quantified. Computer programs (crosswalks) that translate tree list inventory data into crown closure classifications such as is used in CWHR accomplish this. However, at a specific site there is *probably* too much variability in the models to make an accurate crown closure classification solely based on models.

2.6 Remote Sensing

Aerial Photography

Aerial photography interpretation is a common tool for forest mapping. To obtain a quantitative estimate of the percent cover, one needs a strong contrast in the appearance (brightness tone or color) of overstory, understory vegetation and non-vegetation. Typically, a dot grid is used to determine the crown closure. The resolution of the photography needs to be good enough to resolve gaps in the forest. Microgaps cannot be resolved without high-resolution film taken at low altitudes (Paris and Lynn 1990). Congalton and Biging (1992) found photo interpretation to be very subjective in delineating stand boundaries and in determining canopy closure. Conceptually, aerial photos should be useful in measuring canopy near their centers because of vertical view. At their margins, parallax renders them useless for measuring canopy.

Satellite Imagery

Satellite thematic mapping imagery data can be used to classify forest cover, such as what was done for the Timberland Task Force (Wheeler et al. 1993). However, the minimum mapping unit must be at the appropriate scale to measure the canopy coverage of interest. Poor resolution or classification errors are common problems and in some cases may be more difficult to overcome than those with aerial photography interpretation. Satellite imagery for the purpose of riparian canopy analysis probably is not an appropriate use of the technology. With shrinking resolutions (i.e., smaller pixel dimensions) this may be a possibility in the future.

2.7 Accuracy & Precision

Accuracy can be thought of as how close an estimate of a parameter is to the true value and precision as the variability around an estimate. Accuracy can be diminished by bias (a structural error of the tool used or of the sampling scheme) which forces estimates to be erroneous. Reasonable levels of precision are related to developing a sampling scheme that assures an adequate number of representative samples. The literature and experience indicates that the information holds for crown closure estimates as they relate to vertical canopy closure (Table 1).

Table 1. Accuracy and Precision of Various Methods that Measure or Estimate Canopy Cover

Method or Instrument	**Accuracy**	**Precision**
Sighting tube	Shown to be accurate (see Robards et al. 1999).	Shown to be precise if adequate samples are taken.
Spherical densiometer	Studies indicate significant bias, with the bias decreasing at very low or very high canopy values (see Robards et al. 1999).	Shown to be precise if adequate samples are taken, but precision altered by bias.
Crown predictive equations	Unknown, no known study to quantify bias.	Measurement error and inherent model variability compounded by assumptions of crown overlap.
Aerial photography	Can be accurate if done correctly, photographs of reasonable scale, and parallax corrected.	Depends on the scale.

2.8 Summary

To improve clarity, we recommend that "canopy", when used as a noun, be defined as the foliage, branches, and trunks of vegetation that block a view of the sky along a vertical projection. All other uses of the word should be as an adjective, and the nouns it qualifies be used with care. Canopy closure then becomes a two-dimensional quantification of how much vegetative material is directly above an area. It could be measured directly as vegetative material area per unit of ground on a horizontal plane. The proportion of all vertical views (samples) that intercept vegetation could be used for estimation.

To improve clarity, we recommend that "shade" only be used as a noun and not as an adjective. It should be defined as any vegetative, topographic, or structural object that casts a shadow to a user-defined location at a user-defined time of day and year.

Percent canopy closure is a FPR mandated constraint on timber harvest and thus is clearly a part of enforcement or implementation evaluation. As stated above, canopy closure is measured by an intercept from a vertical projection. On the other hand, shade is not an enforceable standard explicitly stated in the FPRs, but it may be a requirement in a particular THP if that requirement is made part of the plan. Because at our latitude the sun is never directly above, a vertical projection will never measure shade. Shade is best measured at the solar angle, or along the solar arc. Measuring shade could be part of monitoring the effectiveness of a canopy closure standard and is used to predict stream temperature changes.

A forest's canopies provides much more than simply shade to protect aquatic systems. In addition, it moderates weather conditions such as wind speed and humidity, insolates the stream against cooling by re-radiation at night, intercepts solar energy re-radiated from other near-stream surfaces, lowers brightness levels, and provides organic materials to streams. Thus concern only for shade is inadequate to provide properly functionin aquatic habitat.

III. Literature Review: Riparian Functions and Methods

3.1 Relationship of Tree Canopy and Shade on Water Temperature and Other Riparian Functions

The relationship of tree canopy, shading and water temperature is well known. Interception of the sun's rays by riparian vegetation strongly influences stream temperatures (Platts et al. 1987). Solar radiation is the greatest source of energy for raising stream temperatures (Amaranthus undated). For a given net input of solar radiation, change in temperature is directly proportional to surface area and inversely proportional to discharge. Conductive heat transfer to channel bedrock, as well as evaporative and convective heat transfers are of only minor concern (Cafferata 1990a). In winter, solar radiation levels at the stream surface are usually low, regardless of canopy cover, because days are shorter, the sun is at lower angles and there is more cloudy weather. During the summer, shading effects of the forest canopy become significant due to higher sun angles and increased solar radiation, longer days, clear weather, and low stream discharge (Beschta et al. 1987). Anadromous and resident salmonid fish species are the primary beneficial uses that are affected by increased water temperature due to solar radiation. Shade limits increased warming during day, canopy limits excessive cooling at night (especially important in winter at higher elevations). Thus, both shade and canopy together control the amplitude of daily temperature fluctuations.

3.2 Methods That Measure Tree Canopy

The description and use of the spherical densiometer, sighting tube, crown predictive equations, and aerial photos have been discussed in sections 2.4 through 2.6, including the advantages and disadvantages of each tool.

Spatial scale is a critical issue. One starting point is the FPRs, which state that conformance is to be determined on the evaluation of no less than a 200 foot lineal segment of each watercourse or lake ('916.4(b)(2), 936.4(b)(2), 956.4(b)(2)). For enforcement purposes, the inspector could apply the measurement scheme to that (the) 200 foot, contiguous stream segment(s) where the retained canopy is suspected to be substandard.

Because prevention of excessive solar heating is one of the primary functions of streamside canopy, measurements should be timed to represent the conditions during the months of greatest solar radiation and when tree leaf surface is greatest. Where and when deciduous plants are dormant, canopy cover can still be estimated by using the drip line. Alternatively, the location could be revisited during the summer period.

In addition to the tools' inherent strengths and weaknesses, a sampling protocol should 1) clearly identify the "sampling universe" and 2) explicitly address repesentativeness of samples. Perhaps the best way to assure representative samples is using a random or as necessary stratified random sample. This could be done based on a random starting location along the watercourse and a random distance perpendicular from the centerline. An alternative is a systematic sample, where a reading is recorded every *x* feet along transects aligned every *y* feet perpendicular to the centerline. It is important to assure that systematic samples don't harmonize with any natural cycles in canopy; i.e., samples every 60 feet in a fully stocked stand with 30 feet radius trees might erroneously report very high or very low canopy closure if the samples always fall on a cyclic opening or closing. We assume that in most cases, if sampling intensity is high enough the choice of random or systematic sampling will not affect the interpretation of the results.

Robards et al. (1999) compares and efficiency of techniques for measuring overstory canopy. That study does not recommend specific protocols for measuring canopy, but compares the use of the spherical densiometer, sighting tube, and ocular estimates at Jackson Demonstration State Forest. Robards (1999) developed a specific sampling protocol for potential enforcement actions for use on preharvest inspections.

3.3 Methods That Measure Instream Solar Radiation (or Shading)

The description and use of the Solar Pathfinder® has been discussed in section 2.4, including the advantages and disadvantages of the tool.

Spatial scale could be addressed the same as discussed in section 3.2, i.e., determined on the evaluation of no less than a 200 foot lineal segment of each watercourse or lake ('916.4(b)(2), 936.4(b)(2), 956.4(b)(2). Cafferata (1990a) suggested placing station at two chain (66 feet) intervals to obtain average shading before and after harvesting.

As for canopy cover, the careful definition of the sampling universe is important in developing a meaningful protocol. The extent of shade is a function of tree height, season, and crown ratio; thus these factors are determinants in delimiting the sampling area. The exact timing of seasonal extremes vary with different watershed. Beschta et al. (1987) reported that the timing of summer maximum temperature for three streams follows, by one to two months, the timing of maximum solar radiation. Because mid to late summer is the time when stream temperatures peak, the angle of the sun's rays (zenith angle) for the months of either July or August coupled with the site-potential tree height determine the area shaded by vegetation to the south. However, any month's zenith angle could be used based upon local information, as long as the month is disclosed in any resulting documents. Obviously, all of the water surfaces within that distance must be part of the sampling universe. Since mean water temperature is also controlled by air temperature, reduction of shade in the adjacent WLPZ can also influence water temperature. Thus, sampling could continue into the WLPZ on the south bank. Because the location of the low-flow channel can migrate between years, and because sunlight striking the exposed active channel will heat adjacent air and thus influence water temperature, all portions of the active channel within that distance must be included also. Shade readings into the northerly WLPZ would provide considerably less air/water temperature information important to stream warming.

Also as described under canopy closure, random or stratified random sampling is probably statistically the best sampling approach. However, systematic sampling will likely be a more efficient design. Again, care must be exercised in avoiding inherent repeating forest patterns.

IV. References

Amaranthus, M., H. Jubas, and D. Arthur. 1988. Stream shading, summer streamflow and maximum water temperature following intense wildfire in headwater streams. Symposium on Fire and Watershed Management, October 26-28, 1988, Sacramento, CA.

Amaranthus, M. undated. Stream temperatures in the Pacific Northwest. Critical factors and prediction method. Unpubl. report.

Amaranthus, M. 1983. Quantitative assessment and monitoring of effective streamside shade using the Solar Pathfinder®. Unpubl. report. Siskiyou National Forest. 3 pages.

Anonymous. 1995. The GRS Densitometer. GRS Resource Solutions. Unpubl. document. Unpaginated.

Anonymous. 1997. In-stream Monitoring Handbook. A guide for project development, implementation, and assessment. Calif. Dept. of Fish and Game, final report submitted to Calif. Dept. of Forestry and Fire Protection. 175 pages.

Barbour, M. G., J. H. Burk, and W. D. Pitts. 1987. Terrestrial Plant Ecology. Second Edition. The Benjamin/Cummings Publishing Co., Inc. 634 pages.

Bartholow, J.M. 1989. Stream temperature investigations: field and analytic methods. Instream Flow Information Paper No. 13. US Fish Wildl. Serv. Biol. Rep. 89(17). 139 pages.

Beschta, R. L., R. E. Bilby, G. W. Brown, L. B. Holtby, and T. D. Hofstra. 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions. Pages 330-372 In: Salo, E. O. and T. W. Cundy, eds., Forestry and Fisheries Interactions. Contribution No. 57, Institute of Forestry Resources, Univ. of Washington, Seattle.

Biging, G. S., and L. C. Wensel. 1990. Estimation of crown form for six conifer species of northern California. Can. J. For. Res. 20:1137-1142.

Boswell, B. 1997. Experimental methods to reduce windthrow in a streamside buffer. Forest Engineering Research Institute of Canada. FERIC Special Report No. SR-118. Vancouver, B. C. 22 pages.

Brazier, J. R., and G. W. Brown. 1973. Buffer strips for stream temperature control. Forest Research Laboratory, School of Forestry, Oregon State Univ. Research Paper 15. 9 pages.

Bunnell, F. L., and D. J. Vales. 1990. Comparison of methods for estimating forest overstory cover: differences among techniques. Can. J. For. Res. 20:101-107.

Cade, B. S. 1997. Comparison of tree basal area and canopy cover in habitat models: Subalpine forest. J. Wildl. Manage. 61(2):326-335

Cafferata, P. 1990a. Watercourse temperature evaluation guide. Calif. Dept. of Forestry and Fire Protection. Unpubl. Report, 13 pages.

Cafferata, P. 1990b. Temperature regimes of small streams along the Mendocino coast. JDSF Newsletter, Fort Bragg, CA No. 39. Calif. Dept. of Forestry and Fire Protection. 4 pages.

Chan, S. S., R. W. McCreight, J. D. Walstad, and T. A. Spies. 1986. Evaluating forest vegetative cover with computerized analysis of fisheye photographs. Forest Sci. 32(4):1085-1091.

Cobb, J. J. 1988. Influences of streamside shade in controlling maximum water temperatures. M. S. thesis, Humboldt State Univ. Arcata, CA. 103 pages.

Congalton, R. G., and G. R. Biging. 1992. How to validate stand maps. Proceedings of Stand Inventory Techniques 92 Conference, Am. Soc. for Photo & Remote Sensing, Bethesda. 11 pages.

Cook, J.G., T. W. Stutzman, C. W. Bowers, K. A Brenner, and L. L. Irwin. 1995. Spherical densiometers produce biased estimates of forest canopy cover. Wildl. Soc. Bull. 23(4):711-717.

Cummins, K. W. 1974. Structure and function of stream ecosystems. BioScience 24:631-641.

Dent, L.F., and J.B.S. Walsh. 1997. Effectiveness of riparian management areas and hardwood conversions in maintaining stream temperature. OR Dep. For., For Pract. Tech. Rep. No. 3. 34p + Apendices.

Evens, G. C., and D. E. Coombe. 1958. Hemispherical and woodland canopy photography and the light climate. J. Ecology 47:103-113.

Flossi, G., S. Downie, J. Hopelain, M. Bird, R. Coey, and B. Collins. 1998. California Salmonid Stream Habitat Restoration Manual. Third Ed. Calif. Dept. of Fish and Game, Sacramento, CA.

Frazier, G. W., J. A. Trofymow, and K. P. Lertzman. 1997. A method for estimating canopy openness, effective leaf area index, and photosynthetically active photon flux density using hemispherical photography and computerized image analysis techniques. Information Report BC-X-373, Pacific Forestry Centre, Victoria, B.C. Canadian Forest Service. 73 pages.

Ganey, J.L., and W.M. Block. 1994. A comparison of two techniques for measuring canopy closure. Western J. Applied Forestry 9(1):21-23.

Garrison, B. A., K. W. Hunting, and K. J. Sernka. 1996. Training Manual for the California Wildlife Habitat Relationships System. CWHR Database Version 5.2. Fifth ed. Calif.

Dept. of Fish and Game, Wildlife Management Division, Sacramento. 58 pages + appendices.

Geier-Hayes, K., M. A. Hayes, D. D. Basford. 1995. Determining individual tree shade length: a guide for silviculturists. Gen. Tech. Rep. INT-GTR-324. Ogden, UT: USDA Forest Service, Intermountain Research Station. 59pp.

Graves,B., and P.L. Dittberner. 1986. Variables for monitoring aquatic and terrestrial environments. US Fish & Wildl. Sev. Biol. Rep. 86(5):55.

Gregory, S. V., F. J. Swanson, W. A. McKee, and K. W. Cummins. 1991. An ecosystem perspective to riparian zones. BioScience 41:540-551.

Hayes,R.L., C. Summers, and W. Seitz. 1981. Estimating Wildlife Habitat Variables. USDI Fish & Wildlife Service. FWS/OBS-81/47. 111 pages.

Hill, T. B. Undated. Forest biometrics from space. Geographic Resource Solutions, Arcata. Unpubl. 13 pages.

Knopf, F. L., R. R. Johnson, T. Rich, F. B. Samson, and R. C. Szaro. 1988. Conservation of riparian ecosystems in the United States. Wilson Bull. 100(2):272-284.

Kondolf, G. M., R. Kattelman, M. Embury, and D. C. Erman. 1996. Status of riparian habitat. Pages 1009-1030 In: Sierra Nevada Ecosystem Project: Final Report to Congress, vol. II, Assessments and scientific basis for management options. Davis: Univ. of California, Centers for Water and Wildland Resources. 1528 pages.

Lafferty, B. Undated. A procedure for evaluating buffer strips for stream temperature protection under the Forest Practices Act. Roseburg. Unpubl. report. 7 pages.

Lemmon, P.E. 1956. A spherical densiometer for estimating forest overstory density. Forest Sci. 2(1):314-320.

Lemmon, P.E. 1957. A new instrument for measuring for estimating forest overstory density. J. Forestry 55(9):667-669.

Mayer, K.E., and W. F. Laudenslayer. 1988. A guide to wildlife habitats of california. Calif. Dept. of Forestry and Fire Protection, Sacramento. 166 pages.

McGurk, B. J. 1989. Predicting stream temperature after riparian vegetation removal. USDA Forest Service Gen. Tech. Rep. PSW-110. Pages 157-164.

Melton, B. L., R. L. Hoover, R. L. Moore, and D. J. Pfankuch. 1984. Aquatic and Riparian Wildlife. Pages 261-301 in: Managing Forested Lands for Wildlife.

Morris, W., ed. 1976, The American Heritage Dictionary. Houghton Mifflin Company. Unpaginated.

Morrison, M. L., B.G. Marcot, and W.R. Mannan. 1992. Wildlife-Habitat Relationships. Univ. of Wisconsin Press. 343 pages.

Naiman, R. J., and H. Decamps, and M. Pollock. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications 3(2):209-212.

Platts, W.S., et al. 1987. Methods for evaluating riparian habitats with applications to management. USDA For. Serv. Gen. Tech. Rep. INT-221. 177 pages.

Paris, J.F., and K. Lynn. 1990. Techniques for estimation of canopy shading watercourses. Final Report to the Trustees of the California State University, Fresno. Geo IPS Report TR-90-02. Geographic Information Processing Systems, Fresno. 13 pages + attachments.

Park, C. S. and J. Hawkins. Undated. SHADOW. Stream shade management program. Unpubl. report. 11 pages.

Quigley, T.M. 1981. Estimating contribution of overstory vegetation to stream surface shade. Wildl. Soc. Bull. 9(10:22-27.

Rae, S. P. 1995. Board of Forestry Pilot Monitoring Program: In-Stream Component. Final Report. Vol. I. Project Planning, implementation, and results. Unpubl. report. 49 pages.

Robards, T. 1999. Instructions for WLPZ canopy/surface cover compliance sampling under Forest Practice Rules. Calif. Dept. of Forestry and Fire Protection – Forest Practices, Sacramento, CA. 2 pages.

Robards, T., M. Berbach, P. Cafferata, and B. Valentine. 1999. A comparison and efficiency of techniques for measuring overstory canopy in watercourse and lake protection zones for use by CDF inspectors. Draft Calif. Forestry Note. Calif. Dept. of Forestry and Fire Protection, Sacramento, CA 15 pages.

Strickler, G. S. 1959. Use of the densiometer to estimate density of forest canopy on permanent sample plots. USDA Forest Service Res. Note PNW 180. 5 pages.

Stumpf, K.A. 1993. The estimation of forest vegetation cover descriptions using a vertical densiometer. Paper presented at Inventory and Biometrics Working Group of SAF National Convention. Indianapolis IN. Unpaginated.

Vora, R.S. 1988. A comparison of the spherical densiometer and ocular methods of estimating canopy cover. Great Basin Naturalist 48(2):224-227.

Wenger, K., ed. 1984. Forestry Handbook. John Wiley & Sons. 1335 pages.

Wheeler, D. P., et al. The report of the California Timberland Task Force. The Resources Agency, Sacramento. 78 pages.

Weiss, S. B., P. M. Rich, D. D. Murphy, W. H. Calvert, and P. R. Ehrlich. 1991. Forest canopy structure at overwintering monarch butterfly sites: measurements with hemispherical photography. Conservation Biology 5(2):165-175.

Wilson, R. 1993. Important THP and exemption information. Memorandum dated November 15 from the Director, Calif. Dept. of Forestry and Fire Protection to "All Registered Professional Foresters, Licensed Timber Operators, and Other Interested Parties."

CHAPTER SIX

Stream Temperature and Aquatic Habitat: Fisheries and Forestry Interactions

ROBERT L. BESCHTA, ROBERT E. BILBY, GEORGE W. BROWN, L. BLAIR HOLTBY, and TERRY D. HOFSTRA

ABSTRACT The temperature of water entering a forest stream system typically resembles that of the watershed's subsoil environment. As this water continues to flow down the stream system, seasonal and diurnal water temperatures are strongly influenced by solar radiation. Pronounced differences in stream temperature patterns are evident for streams draining watersheds throughout the Pacific Northwest. Seasonal and diurnal patterns of stream temperature influence a wide range of responses by instream biota. Furthermore, logging activities can initiate pronounced temperature changes by the removal of forest vegetation along channels. Buffer strips of forest vegetation are an effective means of minimizing stream temperature impacts associated with logging. Although direct mortality of fish is probably not a major concern throughout the Pacific Northwest when stream temperatures are altered by management activities, temperature changes can influence rates of egg development, rearing success, species competition, and other factors.

The temperature of water in forest streams is an important factor regulating aquatic life. But until the 1960s, the impact of harvesting on the temperature of forest streams was seldom considered or reported in the literature. Whereas fisheries studies focused on the toxicological effects of high temperature in the laboratory, most watershed studies were concerned with changes in runoff and sediment.

The situation changed dramatically in the early 1960s, especially in the Pacific Northwest. Scientists observed changes in the migration of anadromous fish in the Columbia River because of increases in temperature below dams and the outfall of the Hanford thermonuclear reactor. Conversely, the beneficial impact of dams in reducing water temperature became an issue on the Rogue River in Oregon. Research on the energy balance of large rivers began to provide information about how their temperature was affected by the macro- and microclimatic factors, storage and release from reservoirs, and localized heat inputs.

The Alsea Watershed Study in western Oregon, which began in 1958, was the first detailed study of effects of timber harvesting on the temperature of small, forest streams. Temperature changes were monitored before and after harvesting, and research on energy balance components provided a basis for understanding why temperature changes occurred. In the late 1960s, high postlogging stream temperatures were a central issue in a harvesting-fisheries controversy over the North Umpqua River in Oregon. This controversy, along with others, was part of a developing environmental awareness and involvement by the public, administrators, and legislators. These concerns also led to major changes in national policy for the USDI Bureau of Land Management and USDA Forest Service and were instrumental in the development of forest practices acts, on a state-by-state basis, for the Pacific Northwest in the early 1970s. These forest practices acts identify management activities intended to prevent significant temperature changes in fish-bearing streams.

The objectives of this paper are to characterize stream temperature regimes in forested ecosystems, to indicate the underlying physical mechanisms of temperature change resulting from the removal of forest canopies over streams, and to identify the various processes by which temperature changes following logging can affect aquatic communities and the production of fish.

STREAM TEMPERATURES AND FORESTED ECOSYSTEMS

The temperature of moisture arriving at a channel is dependent on many factors. In high mountain catchments of the Pacific Northwest, much of the annual precipitation occurs as snowfall, which accumulates on a watershed until sufficient energy is available for snowmelt. Most snowmelt typically occurs during the spring months. However, at lower elevations snowfall accumulations may be relatively transient, and rapid snowmelt can occur during rain-on-snow events. Typically, meltwater (at 0°C) and rainfall (at $\geq$ 0°C) infiltrate forest soils and then move laterally through relatively porous soils and subsoils toward topographic depressions and stream channels. The pathways by which subsurface flow reaches a channel are highly variable, but when such water eventually enters a defined channel and becomes streamflow, its temperature generally reflects that of the watershed's subsoil environment.

As water flows downstream, its temperature will continue to change as a result of several factors that make up the heat balance of water. The net rate of gain or loss by a stream as it moves through a forest is the algebraic sum of net radiation, evaporation, convection, conduction, and advection (Brown 1983). Net radiation is generally dominated by the amount of direct-beam solar radiation that reaches a stream's surface. Heat gain or loss from evaporation and convection depends on the vapor pressure and temperature gradients, respectively, between the water surface and the air immediately above the surface. Wind speed at the air-water interface is also an important controlling variable. Conduction of heat between the water in the stream and the streambed depends on the type of material that makes up the bed. Bedrock channels are more efficient than gravel-bed channels at conducting heat. Advection is the result of heat exchange as tributaries or groundwater of different temperature mixes with the main streamflow, and can either increase or decrease stream temperature.

Channel characteristics and morphology also influence the amount of heat gain or loss of a stream. The surface area over which energy transfers take place is important: wide streams receive more energy than narrow ones. Discharge is another significant variable: for the same surface area and energy input, the temperature change expected of a high-discharge stream will be less than that of a low-discharge stream. In other words, for a given rate of net input, the change in temperature of a stream is directly proportional to surface area and inversely proportional to discharge.

How do these factors combine to produce temperature patterns for coastal streams in the Pacific Northwest? In winter, solar radiation levels at the stream surface are typically low, regardless of canopy cover. This is the result of a combination of factors affecting the availability of direct-beam solar radiation: short days, low sun angles (this maximizes reflection at the water surface and the shading effects of streamside vegetation and topography), and cloudy weather. During the summer months, when solar radiation levels are greatly increased (higher sun angles, longer days, and clear skies) and stream discharge is low, shading effects of the forest canopy become significant. The seasonal progression of potential direct solar radiation (for clear weather conditions) is shown in Figure 1. Although some losses occur as solar energy is routed through the atmosphere, much of the incoming solar radiation is intercepted by the canopy of streamside vegetation. Net radiation underneath a continuous canopy may be only 15% or less than that of an unshaded stream (Brown 1983) during daytime conditions. Throughout the year, evaoporative and convective transfers of energy are typically low for forested streams, because vapor pressure and temperature gradients close to the water surface are small and wind speeds are usually low. Likewise, conductive heat transfers are usually insignificant (Brown 1969). Because water has a relatively high specific heat, seasonal and daily temperature changes of forested streams are relatively small and gradual.

Seasonal temperature patterns for three small forested streams in the Pacific Northwest are shown in Figure 2. As expected, the watersheds show maximum temperatures occurring in summer and minimums in winter. However, the exact timing and magnitude of seasonal extremes vary. Porcupine Creek, the farthest north of the three, has the greatest range in monthly stream temperatures (nearly 13°C). The timing of summer maximum temperature for these streams follows, by one to two months, the timing of maximum solar radiation (Figure 1). An exception to the cyclical pattern of seasonal temperatures, shown in Figure 2, occurs in streams fed by large springs or groundwater sources. These systems often display a nearly uniform temperature year round, being cooler than other streams in summer and warmer in winter (Minkley 1963).

Characterizing the extent of natural or climatic variability in stream temperatures is an important preliminary step in attempting to document the effects that temperature changes related to logging may have on aquatic communities. If, after logging, stream temperatures lie within the bounds of natural variability, then any effects related to temperature change might be difficult to detect. Furthermore, even if

Channel characteristics and morphology also influence the amount of heat gain or loss of a stream. The surface area over which energy transfers take place is important: wide streams receive more energy than narrow ones. Discharge is another significant variable: for the same surface area and energy input, the temperature change expected of a high-discharge stream will be less than that of a low-discharge stream. In other words, for a given rate of net input, the change in temperature of a stream is directly proportional to surface area and inversely proportional to discharge.

How do these factors combine to produce temperature patterns for coastal streams in the Pacific Northwest? In winter, solar radiation levels at the stream surface are typically low, regardless of canopy cover. This is the result of a combination of factors affecting the availability of direct-beam solar radiation: short days, low sun angles (this maximizes reflection at the water surface and the shading effects of streamside vegetation and topography), and cloudy weather. During the summer months, when solar radiation levels are greatly increased (higher sun angles, longer days, and clear skies) and stream discharge is low, shading effects of the forest canopy become significant. The seasonal progression of potential direct solar radiation (for clear weather conditions) is shown in Figure 1. Although some losses occur as solar energy is routed through the atmosphere, much of the incoming solar radiation is intercepted by the canopy of streamside vegetation. Net radiation underneath a continuous canopy may be only 15% or less than that of an unshaded stream (Brown 1983) during daytime conditions. Throughout the year, evaoporative and convective transfers of energy are typically low for forested streams, because vapor pressure and temperature gradients close to the water surface are small and wind speeds are usually low. Likewise, conductive heat transfers are usually insignificant (Brown 1969). Because water has a relatively high specific heat, seasonal and daily temperature changes of forested streams are relatively small and gradual.

Seasonal temperature patterns for three small forested streams in the Pacific Northwest are shown in Figure 2. As expected, the watersheds show maximum temperatures occurring in summer and minimums in winter. However, the exact timing and magnitude of seasonal extremes vary. Porcupine Creek, the farthest north of the three, has the greatest range in monthly stream temperatures (nearly 13°C). The timing of summer maximum temperature for these streams follows, by one to two months, the timing of maximum solar radiation (Figure 1). An exception to the cyclical pattern of seasonal temperatures, shown in Figure 2, occurs in streams fed by large springs or groundwater sources. These systems often display a nearly uniform temperature year round, being cooler than other streams in summer and warmer in winter (Minkley 1963).

Characterizing the extent of natural or climatic variability in stream temperatures is an important preliminary step in attempting to document the effects that temperature changes related to logging may have on aquatic communities. If, after logging, stream temperatures lie within the bounds of natural variability, then any effects related to temperature change might be difficult to detect. Furthermore, even if

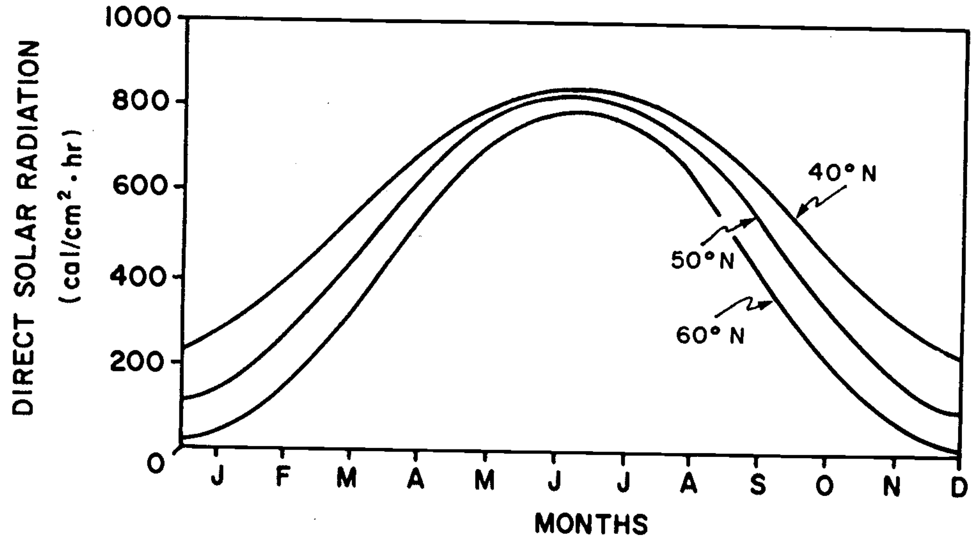


Figure 1. Seasonal pattern of potential direct-beam solar radiation at a stream surface during clear weather (assumed atmospheric transmission coefficient = 0.9) for selected latitudes (Buffo et al. 1972).

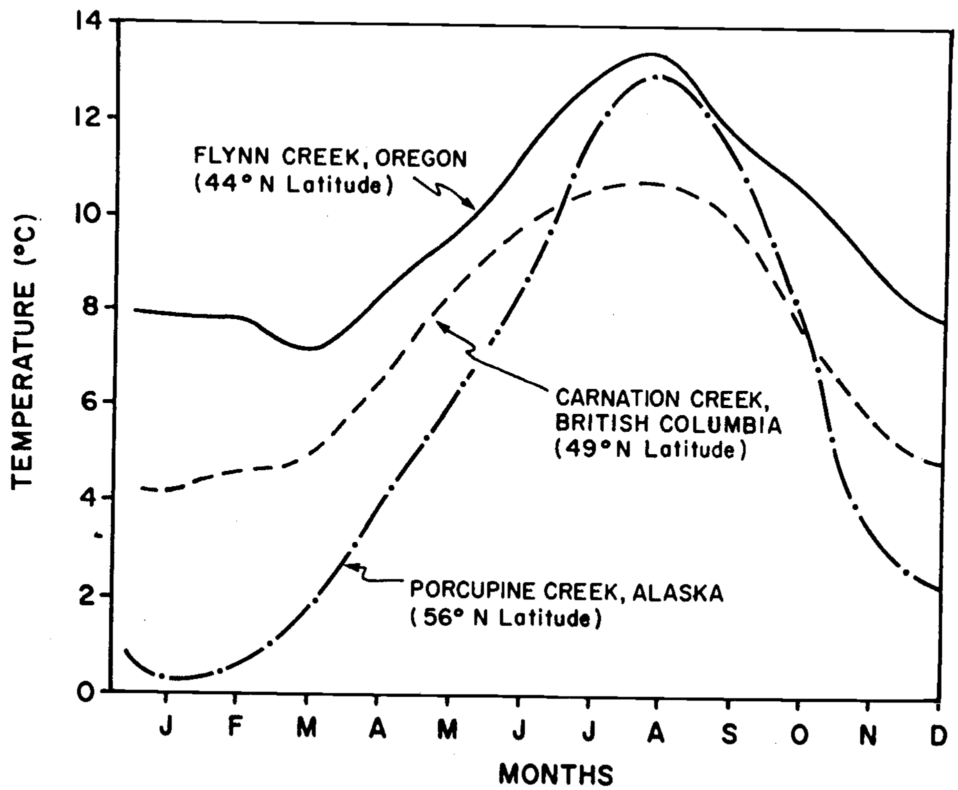


Figure 2. Seasonal temperature patterns for three coastal streams in the Pacific Northwest.

measurable, such effects might be relatively unimportant if they would be expected to result from climatic variability anyway.

The variation in monthly temperature between years can be as much as 4°C during the winter months (December-March) for Porcupine Creek in southeastern Alaska, but year-to-year variations in monthly temperature are generally less than 2°C for other times of the year (Koski 1984). Monthly temperature fluctuations between years generally remain lower than 2°C, regardless of season, at Flynn Creek in the Oregon Coast Range.

Superimposed on the seasonal progression of stream temperatures is a diurnal pattern. Generally, changes in water temperature over the course of a day tend to be greatest during summer, in part because of the relatively low volumes of water flowing in streams at that time of year. Peak daily temperatures are usually achieved during the late afternoon, and minimums just before dawn. Even in midsummer, when large diurnal changes in direct solar radiation occur above the forest canopy, the shading effects of the forest vegetation greatly moderate and reduce the energy exchanges at the stream surface. For example, diurnal temperature variations near the mouth of Carnation Creek (Vancouver Island, British Columbia) average approximately 1.3°C for the months of June, July, and August; maximum diurnal variations for these same months are less than 2.4°C (Holtby and Newcombe 1982). Diurnal variations for a well-shaded coastal Oregon stream were less than 1°C, even during the day of the annual maximum (Brown and Krygier 1970). Streams bordered with relatively low densities of forest vegetation or which have a significant number of natural openings along the channel would be expected to have higher diurnal variations.

A time series of monthly average water temperatures extending from 1923 to 1975 has been reconstructed for Carnation Creek, B.C., using fifty-two years of air temperature records from a nearby permanent weather station (Estevan Point, B.C.) and a regression of air and stream temperatures for the period 1971 to 1984. A temperature record of this duration provides an estimate of the extent to which climatic variability has influenced undisturbed stream temperatures in that region. Historical variability in Carnation Creek stream temperatures has been relatively small. For all months of the year, the average monthly temperature lies within 1°C of the long-term monthly median at least 50% of the time.

Forest streams change temperature in space as well as time, again in response to energy transfers. As stream order increases, so usually does stream width, stream discharge, and the number of tributaries. As width increases, surface area exposed to solar radiation usually increases, because riparian vegetation may shade less and less of the stream surface. On the other hand, discharge also increases in a downstream direction. The balance between these factors ultimately determines the rate of temperature change downstream, especially in summer. For instance, in the tributaries of Carnation Creek, B.C., diurnal ranges during the summer increase in proportion to drainage area and stream width (both correlates of stream surface area), indicating the overriding importance of direct solar radiation during periods of low discharge indicating the temperature regimes of small streams. During the winter there is no relation between stream surface area and diurnal range; and other factors, principally discharge and elevation, become important determinants of diurnal variation. In large rivers, diurnal temperature fluctuations are generally dampened because of the relatively large volumes of water contained by these systems (Hynes 1970).

Where tributaries join, or enter a main stream, the mixed temperature is the simple resultant of their individual temperatures, weighted by their respective discharges (Brown 1983). Thus a small tributary will produce little change in the temperature of a larger stream unless the small stream's temperature is greatly different. Hence, as stream order increases, the impact on temperature of tributaries entering the main channel generally decreases.

Because much of their flow is derived from forested headwater catchments, rivers in the Pacific Northwest exhibit seasonal temperature patterns similar to those of small forest streams. In Figure 3, average monthly temperatures are illustrated for three rivers across Oregon. Winter temperatures for the Nestucca River in the Oregon Coast Range are similar to those for the smaller Flynn Creek watershed shown in Figure 2. This similarity is primarily a consequence of the combined low net radiation inputs and high streamflows common at that time of year. In summer, monthly temperatures for the Nestucca River average approximately 18°C, or nearly 5 to 6°C warmer than those for the smaller Flynn Creek watershed. These downstream increases in monthly water temperatures during the summer occur primarily from net radiation inputs to the water as it flows through increasingly wider reaches of the stream system. In addition, flows are low at this time of year and serve to magnify the effects of energy inputs.

Winter temperatures for the Nestucca River in the Oregon Coast Range tend to be higher than for Fall Creek and the Umatilla River, located farther east (Figure 3). Fall Creek drains a portion of the western Cascades; the Umatilla River has its headwaters in the Wallowa Mountains of eastern Oregon.

The range of temperatures experienced in coastal streams is relatively low because of the maritime influence of the Pacific Ocean on the coastal climate. Lower winter temperatures occur for rivers draining the Cascades and mountain ranges farther east, where cold water temperatures associated with rainfall or snowmelt and cold nighttime air temperatures (which promote radiational cooling of stream water) are conducive to lower stream temperatures. Monthly temperatures in January for the Umatilla River in eastern Oregon average more than 3°C lower than those of the Nestucca River in the Oregon Coast Range. Downstream changes in water temperature, as water moves from headwater channels toward the mouth of a river system, are also described by Theurer et al. (1985).

Even though general temperature patterns are evident in forest streams, local anomalies may occur. Thermal stratification, while common in lakes, is generally precluded in streams, because of constant

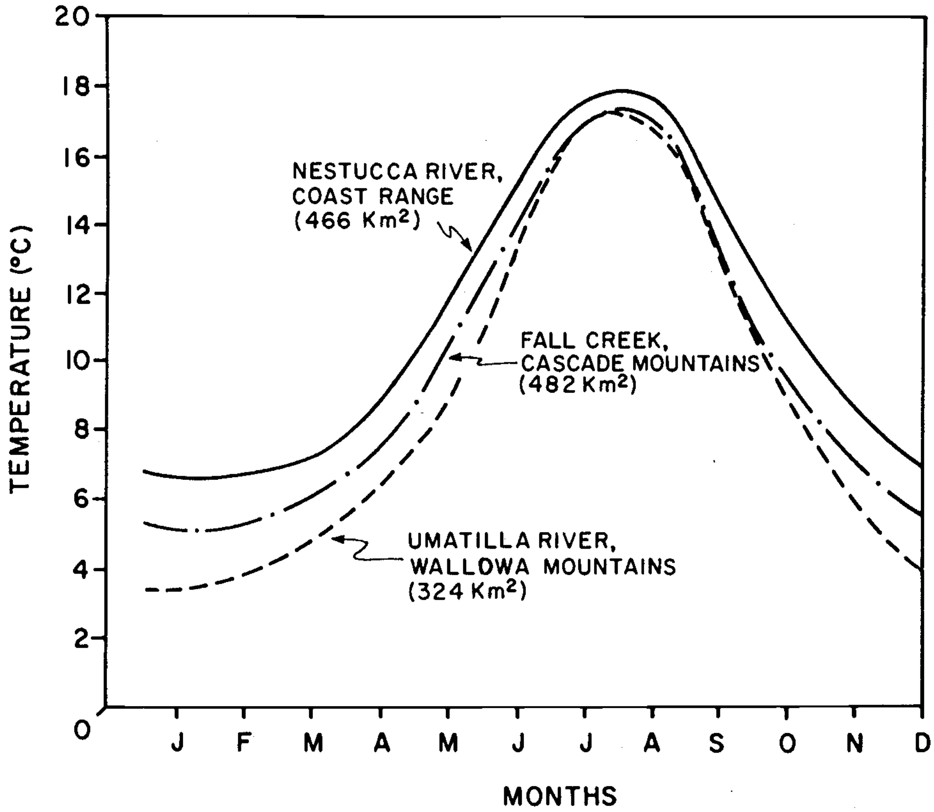


Figure 3. Seasonal temperature patterns for three rivers in Oregon (1965-71).

turbulence of flowing water. However, several studies have shown that water near the bottom of pools is sometimes 5 to 10°C cooler than water near the surface (Keller and Hofstra 1982, Bilby 1984, Keller et al., in press). Cool-water sources usually result from a tributary stream, groundwater, or an upwelling of stream water that has been cooled by flowing through the streambed (Figure 4). The occurrence of these sources seems to be rare, accounting for only 1.6% of the stream surface area of a western Washington stream (Bilby 1984). Where relatively cool water enters a channel, fish and other organisms may find local thermal environments more favorable than surface water temperatures would indicate (Gibson 1966, Keller and Hofstra 1982); however, reduced dissolved oxygen levels associated with cool-water sources may limit their immediate usefulness to instream biota (Figure 5). The occurrence of such phenomena serves as a reminder that generalizations about the thermal environments of forest streams may be misleading.

In summary, the seasonal cycles in the temperatures of streams draining forested watersheds in the Pacific Northwest can be defined on temporal and spatial scales. There are clear seasonal patterns, with low levels of between-year variability. Diurnal variations also follow a predictable pattern and are generally very small. Spatially, there are regular, predictable effects of such variables as latitude, proximity to the ocean, and stream order. Particularly during summer months, however, there appears to be a significant amount of fine-scale heterogeneity

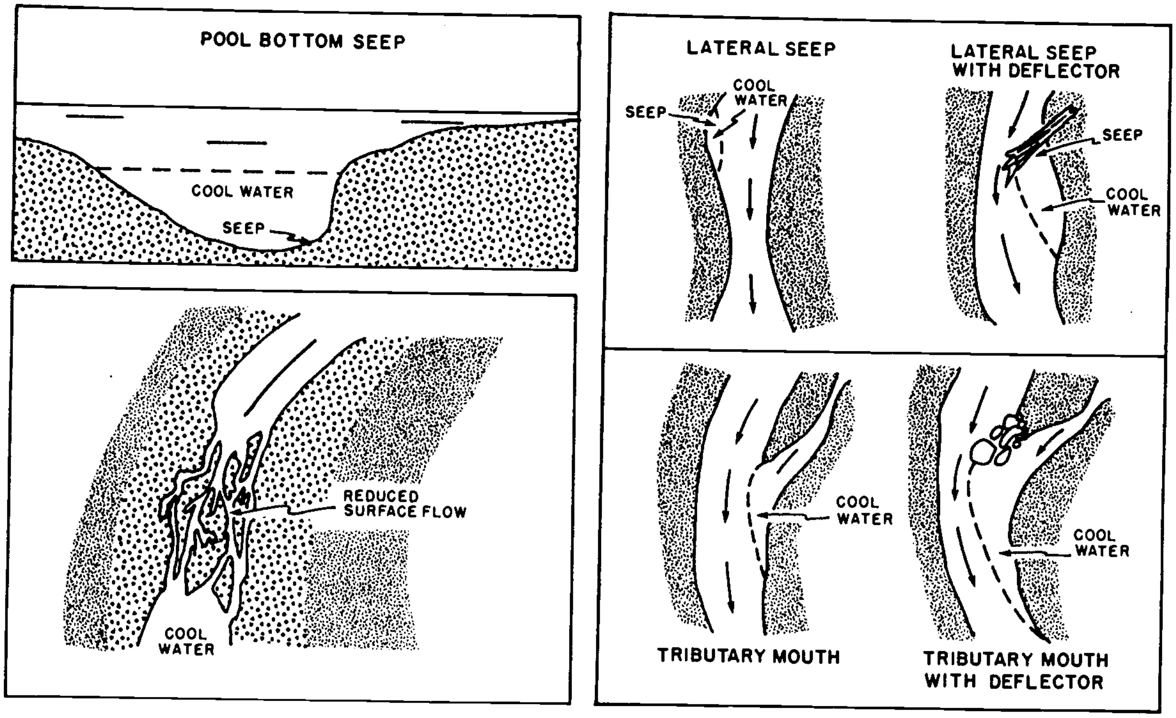


Figure 4. Examples of cool-water sources in mountain streams (from Bilby 1984).

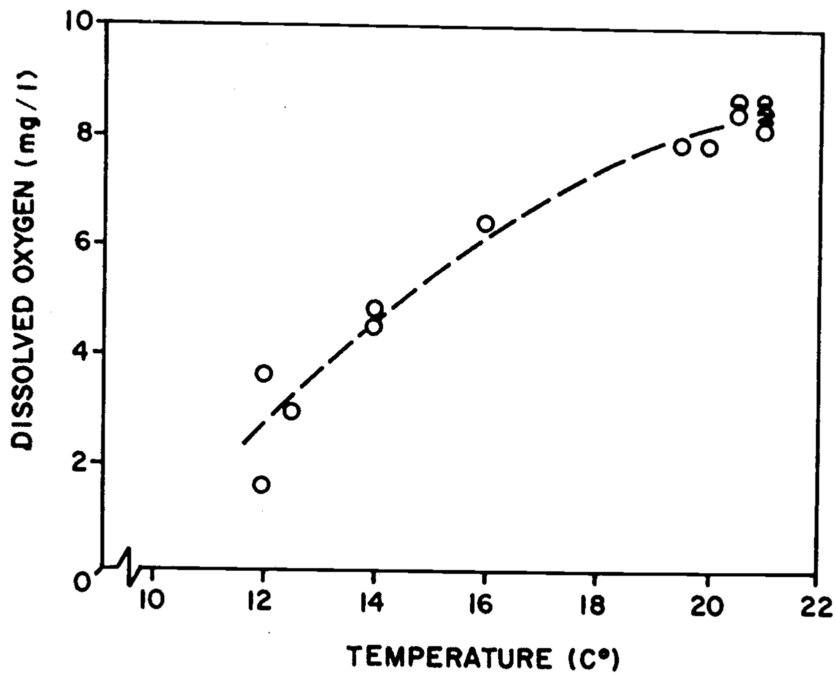


Figure 5. Relation between stream temperature and dissolved oxygen associated with a cool-water source in Redwood Creek, California (from Keller and Hofstra 1982).

in the thermal environment of streams brought about by variations in exposure to solar radiation, flow, channel widths, and the occurrence of cool-water upwelling. Nevertheless, the general temperature patterns represent a characteristic of the aquatic habitat that fish and other organisms must withstand and, perhaps more important, to which they have adapted their life strategies.

EFFECTS OF CANOPY COVER ON STREAM TEMPERATURES

Most stream temperature concerns in forest ecosystems have focused on summertime increases associated with forest harvesting. The energy balance components described earlier also operate for streams from which the canopy is removed. Again, the principal source of energy for heating small streams during summer conditions is incoming solar energy striking the water surface. The more canopy removed, the greater is the exposure of the stream to this heat source. Most of this incoming energy is stored in the stream, and its temperature rises accordingly.

Compared with solar radiation inputs, energy transfers involving convection or evaporation are of much less importance to the thermal regime of exposed mountain streams. Both require wind movement at the stream surface to be effective, in addition to temperature and vapor pressure gradients. Because of normally low wind velocities immediately above the water surface, neither process plays a significant role in controlling the temperature of an exposed stream (Brown 1983). Furthermore, these two processes tend to counterbalance each other. For example, if relatively warm air is present over a stream surface, the heat gain to the stream by convection will tend to be offset by heat loss through evaporation. This is important for several reasons. First, high air temperatures do not cause stream temperature to increase following canopy removal even though daily maximum air temperatures are usually at their highest during clear sunny weather, just as temperatures of streams are. However, the two variables are often highly correlated. Second, once a stream's temperature is increased, the heat is not readily dissipated to the atmosphere as it flows through a shaded reach. Hence, additional energy inputs to small streams can have an additive effect on downstream temperatures.

The net rate of heat exchange (N_h) per unit area of stream surface is shown in the following equation:

$$N_h = N_r + E + H + C \qquad (1)$$

where N_r = net radiation
E = evaporation
H = convection
C = conduction

Although the net radiation term comprises both short- and long-wave components, the shortwave or incoming solar radiation portion is by far the most important factor that changes as a result of canopy reductions, particularly during the summer.

Seasonal and diurnal temperature patterns of exposed streams differ markedly from those of shaded, forest streams. For a channel with a forest canopy shading the water surface, the individual terms on the right-hand side of equation (1) remain relatively small over a 24-hour period, even in midsummer. Hence diurnal temperature fluctuations are also small. However, should the canopy be removed through harvesting activities or natural causes, the net heat gain or loss may be significantly altered.

During winter months, exposed streams may experience lower temperatures when there is no canopy to inhibit energy losses by evaporation, convection, or long-wave radiation from the stream. Long-wave losses are greatest when clear skies prevail, particularly at night. While this phenomenon is not important in coastal streams of Oregon and Washington, where nighttime cloud cover and relatively warm air temperatures are common, it may be important for streams at high elevations in the Cascades and streams farther east, or at northerly latitudes where snow accumulations are insufficient to cover and insulate the channel from energy losses. Because most research studies in the Pacific Northwest have concentrated on evaluating changes in summer stream temperatures, less is known about winter temperature changes, if any, as a result of reductions in canopy cover.

Studies in deciduous forest types of the eastern United States have found relatively small changes in winter stream temperatures due to forest harvesting. In Pennsylvania, changes in winter maximum temperatures ranged from -0.7 to +0.9°C; changes in winter minimums ranged from -1.4 to +1.0°C (Table 1). In West Virginia, complete removal of riparian trees lowered winter stream temperature minimums approximately 2°C (Lee and Samuel 1976). In New Jersey, dormant season stream temperatures remained unchanged following herbicide application to riparian forest vegetation. Results from studies of coastal streams in the Pacific Northwest (Brown and Krygier 1970, Holtby and Newcombe 1982) show little change in winter temperatures following canopy reductions from logging.

During the summer, the amount of direct solar radiation available to a stream whose canopy has been removed is substantial (Figure 6), hence exposed streams may experience large diurnal fluctuations. The extent to which the incoming solar energy increases the temperature of an exposed stream further depends on the surface area of the exposed reach and the stream discharge. Streams with small discharges and large exposed areas inevitably experience the greatest temperature increases (Sheridan and Bloom 1975).

Research associated with a variety of forest types and geographic locations has identified the magnitude of temperature increases to be expected from canopy removal. For summertime conditions in the eastern United States, increases in average maximum temperatures following reductions or removal of forest canopy have generally ranged from 3 to 10°C (Table 1). Minimum temperatures in summer either remained unchanged or were generally limited to increases of less than 1°C.

Table 1. Summary of temperature changes associated with forest management activities and experimental treatments on forest watersheds, eastern United States.

Location	Treatment	Stream Temperature Variables	Temperature Change (°C)	Reference
Georgia	Clearcut with partial buffer strip	Average June-July maximum	+6.7	Hewlett and Fortson (1982)
Maryland	Riparian harvest up to 40 m from channels	Average summer maximum Average summer minimum	+4.4 to 7.6 +0.6 to 1.1	Corbett and Spencer (1975)
New Jersey	Riparian herbicide application	Average summer maximum Average summer minimum Dormant season	+3.3 Unchanged Unchanged	Corbett and Heilman (1975)
North Carolina	Deadened cove vegetation	Average summer maximum	+2.2 to 2.8	Swift and Messer (1971)
	Complete clearcut	Average summer maximum	+2.8 to 3.3	Swift and Messer (1971)
	Understory cut	Average summer maximum	0 to 0.3	
Pennsylvania	Riparian harvest (lower third of slope)	Average summer maximum Average summer minimum	+3.9 Unchanged	Lynch et al. (1975)
	Clearcut with herbicide treatment	Average June-July maximum Average June-July minimum	+10 to 10.5 +1.7 to 1.8	Rishel et al. (1982)
		Average Dec.-Feb. maximum Average Dec.-Feb. minimum	-0.5 to +0.9 -1.4 to +0.2	Rishel et al. (1982)
	Commercial clearcut with buffer strip	Average June-July maximum Average June-July minimum	+0.6 to 1.6 0 to 0.6	Rishel et al. (1982)
		Average Dec.-Feb. maximum Average Dec.-Feb. minimum	-0.7 to +0.9 -0.5 to +1.0	Rishel et al. (1982)
West Virginia	Clearcut	Average summer maximum	+4.4	Kochenderfer and Aubertin (1975)

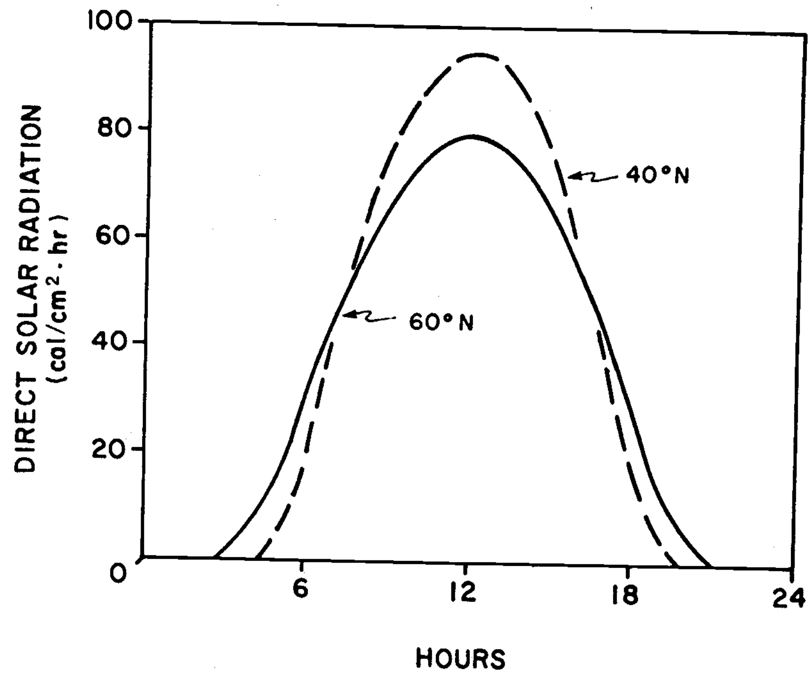


Figure 6. Daily pattern of potential direct-beam solar radiation at a stream surface during clear weather (assumed atmospheric transmission coefficient = 0.9) on June 22, for selected latitudes (Buffo et al. 1972).

For the Pacific Northwest, watershed studies in the Coast Range and the Cascade Mountains of Oregon have shown increases in mean monthly maximum temperatures of about 3 to 8°C (Table 2) following clearcut harvesting. Burning may add another 1°C increase. At Carnation Creek on Vancouver Island, British Columbia, Holtby and Newcombe (1982) found that summer temperature increases due to logging were proportional to the basin area logged. They predicted a 7°C increase in mean summertime water temperature if the entire watershed was clearcut. Studies in the Pacific Northwest also show that the minimum temperatures in summer are much less altered by canopy removal and are generally limited to increases of less than 1 or 2°C.

Concern over altered temperatures after logging streamside vegetation usually focuses on the inevitable increases in maximum temperatures observed during the summer. This focus is very much a result of the toxicological perspective on temperature changes that is prevalent in fisheries research. However, in the majority of cases in the Pacific Northwest, stream temperatures in deforested watersheds, while invariably warmer than they were in the forested state, do not approach the tolerance limits of the resident fish species.

Holtby (1986) compared temperature changes over three biologically interesting periods at Carnation Creek: (1) the winter (October through February), (2) the spring (April and May), and (3) the summer (May through September). Logging-related increases in temperature (as indexed by thermal summations), from 1977 to 1984, averaged 15% (range

Table 2. Summary of summer temperature changes associated with forest management activities on forest watersheds, Pacific Northwest.

Location	Treatment	Stream Temperature Variables	Temperature Change (°C)	Reference
Alaska (Southeast)	Clearcut and natural openings	Δ Temperature per 100 m of channel	0.1 to 1.1°C/100 m Average = 0.7°C/100 m	Meehan (1970)
British Columbia (Vancouver Island)	Logged (Tributary H)	Average June-August diurnal temperature range	0.5° to 1.8°C increase over pre-treatment levels	Holtby and Newcombe (1982)
	Logged and burned (Tributary J)	Average June-August diurnal temperature range	0.7° to 3.2°C increase over pre-treatment levels	Holtby and Newcombe (1982)
Oregon (Cascades)	Clearcut	Average June-August maximum	4.4 to 6.7°C	Levno and Rothacher (1967)
	Clearcut and burning	Average June-August maximum	6.7 to 7.8°C	Levno and Rothacher (1969)
Oregon (Coast Range)	Clearcut	Average July-Sept. maximum	2.8 to 7.8°C	Brown and Krygier (1967)
	Clearcut and burning	Average July-August maximum	9 to 10°C	Brown and Krygier (1970)
Oregon (Cascades)	Mixed clearcut and forested reaches	Δ Temperature per 100 m of channel	0 to 0.7°C/100 m	Brown et al. (1971)
	Tractor striped area	Δ Temperature per 100 m of channel	15.8°C/100 m	Brown et al. (1971)

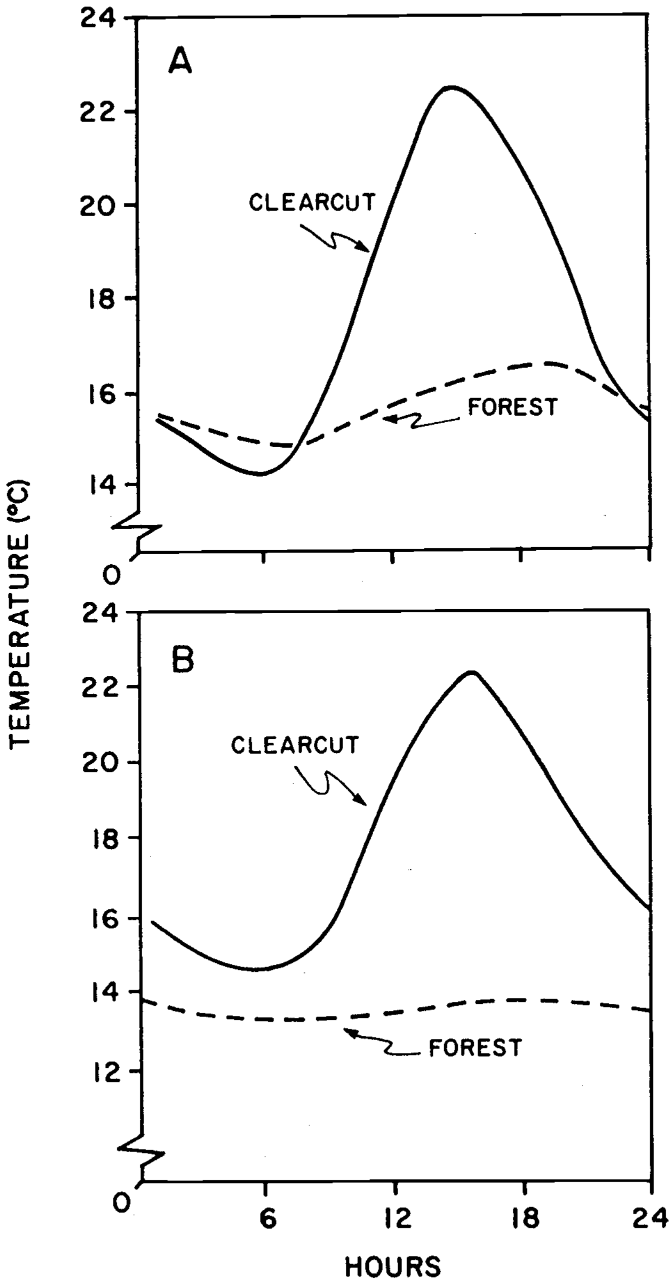


Figure 7. Summertime stream temperatures during clear weather in (A) West Virginia (from Lee 1980), and (B) Coast Range of Oregon (from Brown and Krygier 1967).

of 2 to 32%) during the winter, 27% (range of 18 to 36%) during the spring, and 37% (range of 16 to 56%) during the summer.

The increased exposure of small headwater streams draining clearcuts to incoming solar radiation leads to substantial increases in diurnal fluctuations (Figure 7). In some situations, the diurnal range in midsummer can increase by more than 15°C if the overstory shade is completely removed (Brown and Krygier 1970, Moring 1975a). In other situations, increases in diurnal ranges have been considerably less. Increases in average diurnal ranges during summer after complete clearcutting along tributaries to Carnation Creek were less than 3°C (Holtby 1986). In the main creek, average diurnal range increased approximately 1°C during the summer. Increased diurnal ranges during most of the winter months were detectable but nevertheless were considerably smaller.

Because direct-beam solar radiation is the primary factor influencing temperature change in summer, the effect of partial canopy removal is directly proportional to the reduction in canopy providing shade to the stream. What this signifies is that leaving buffer strips represents an effective means of preventing temperature change for many mountain streams.

The importance of a buffer strip for preventing increases in stream temperature can be determined by measuring its angular canopy density (ACD). Whereas canopy density is usually expressed as a vertical projection of the canopy onto a horizontal surface, ACD is a projection of the canopy measured at the angle above the horizon at which direct-beam solar radiation passes through the canopy. This angle is determined by the position of the sun above the horizon during that portion of the day (usually between 10 a.m. and 2 p.m. in mid to late summer) during which solar heating of a stream is most significant. Thus ACD can provide a direct estimate of the shading effects of streamside vegetation. Although it is possible for natural forest vegetation to have ACDs of 100%, indicating complete shading from incoming solar radiation, the ACD of old-growth stands in western Oregon generally falls between 80 and 90% (Brazier and Brown 1973, Steinblums et al. 1984). In northern California, Erman et al. (1977) found ACDs to average 75% along undisturbed streams.

The relative degree of shading provided by a buffer strip depends on a range of factors (e.g., species composition, age of stand, density of vegetation). Although buffer-strip width is also important, by itself it is not generally a good predictor of shade protection. Figure 8 illustrates the variability of ACD associated with buffer-strip width for forest stands in the Coast Range and Cascade Mountains of Oregon. Buffer strips with widths of 30 m or more generally provide the same level of shading as that of an old-growth stand.

How can we predict the effect of complete removal of riparian vegetation, partial removal, or a buffer strip on the daily temperature pattern of a stream? The answer is relatively simple: by determining the change in energy available to the stream surface. In summer this means determining how much additional surface will be exposed to direct sunlight during clear weather. This task is comparatively easy when attempting to predict the effect of completely exposing a stream reach that was fully shaded. It is more difficult to predict the change in exposed surface area that will occur following partial removal of the canopy.

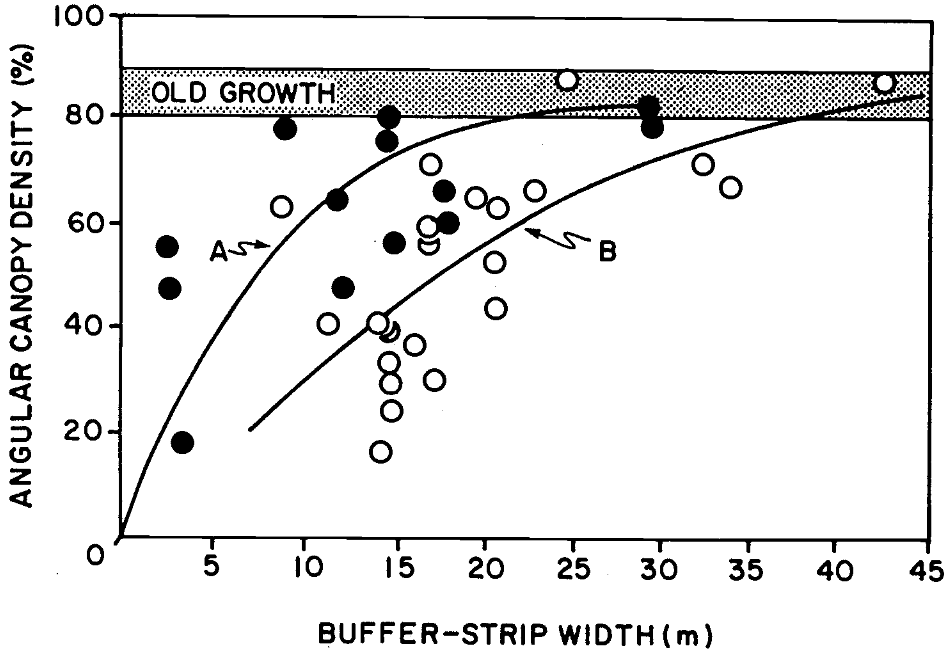


Figure 8. Relation between angular canopy density (ACD) and bufferstrip width in western Oregon. Data for (A) from Brazier and Brown (1973); data for (B) from Steinblums et al. (1984).

Once the surface area A exposed to direct-beam radiation is estimated, the increase in net energy N_h (mostly shortwave solar radiation) can be readily determined from tables and combined with an estimate of stream discharge Q to predict the temperature increase ΔT produced by harvesting:

$$\Delta T = \frac{N_h \times A}{Q} \times 0.000167 \qquad (2)$$

where N_h = net rate of heat added to the stream ($cal/cm^2 \cdot min$)

A = surface area of stream exposed to incoming solar radiation (m^2)

Q = streamflow (m^3/sec)

A detailed description of this predictive technique and the methods for laying out buffer strips to ensure temperature control are given by Currier and Hughes (1980) and Brown (1983).

Equation (2) works well for predicting temperature increases from harvest along short reaches of stream where incident solar radiation is the major contributor to the energy balance. On reaches greater than 1,000 meters, evaporative and conductive energy transfers begin to become significant dissipators of energy and must be accounted for in the prediction. Similarly, the temperature and inflow rate of groundwater must be quantified. These variables add a great deal of complexity to the prediction (Beschta 1984), making it no longer a simple, easy-to-apply technique. From a practical standpoint, this situation also means that streams exposed over long reaches will not continue heating indefinitely (e.g., Theurer et al. 1985). They will eventually reach an equilibrium temperature as evaporation, convection, conduction, and groundwater inflow balance the incoming radiation load.

What happens to temperature when streams flow from a fully exposed reach into a shaded reach? Will they cool down just as they warmed in the sun? Probably not unless cooler water from a tributary or from subsurface seepage enters the channel. Even though the direct solar radiation may be greatly reduced in the shady reach, it is still greater than long-wave radiation losses from the warm water and is likely to be greater than energy losses from evaporation, convection, or conduction. Thus the water temperature will remain relatively unchanged in the shaded reach unless it mixes with other cooler water within the reach. Management strategies to prevent excessive temperature increases by alternating shaded with unshaded reaches will be effective only if cooler inflows occur within the shaded reaches. Where cooler inflows do not occur, temperature increases from each exposed reach will not decrease appreciably through the shaded reaches, and the result is a "stair-step" temperature increase in the downstream direction (Brown et al. 1971).

Because heat added to a stream is not readily dissipated, temperature increases in small headwater streams can increase the temperature regimes of downstream reaches. The magnitude of downstream effect depends on the relative increase in temperature and amount of streamflow from the exposed tributaries. The mixing of any heated water, from exposed headwater streams, with cooler subsurface seepage or at tributary junctions will moderate the pronounced diurnal temperature increases experienced in an exposed headwater stream. Nevertheless, where extensive reaches of channel have become exposed either as a result of clearcut logging without buffer strips or from sluiced channels due to mass soil failures and debris torrents, a cumulative effect on the downstream thermal regime should be expected. Unpublished data (Beschta and Taylor 1986) for Salmon Creek, a 325 square kilometer drainage in the Oregon Cascades, shows such a cumulative effect. A thirty-year trend of increasing summer stream temperatures has been measured during a period of extensive logging and roading throughout the basin. During the summer, maximum stream temperatures at the mouth of this drainage have increased from 16°C in the mid-1950s to 22°C in the late 1970s; minimum temperatures in summer increased approximately 2°C (from 12 to 14°C) during this same period.

Increased temperatures have also been observed in the Middle Santiam River of the Oregon Cascades as the basin was logged. Logging activities in this basin have been largely limited to areas along the lower 11 km of the river, with areas farther upstream essentially undisturbed. Thus temperature changes downstream of the logged area can be referenced against temperatures of the undisturbed section. Average daily maximum temperatures for the period May to October increased approximately 1°C from 1972 to 1982, apparently as a result

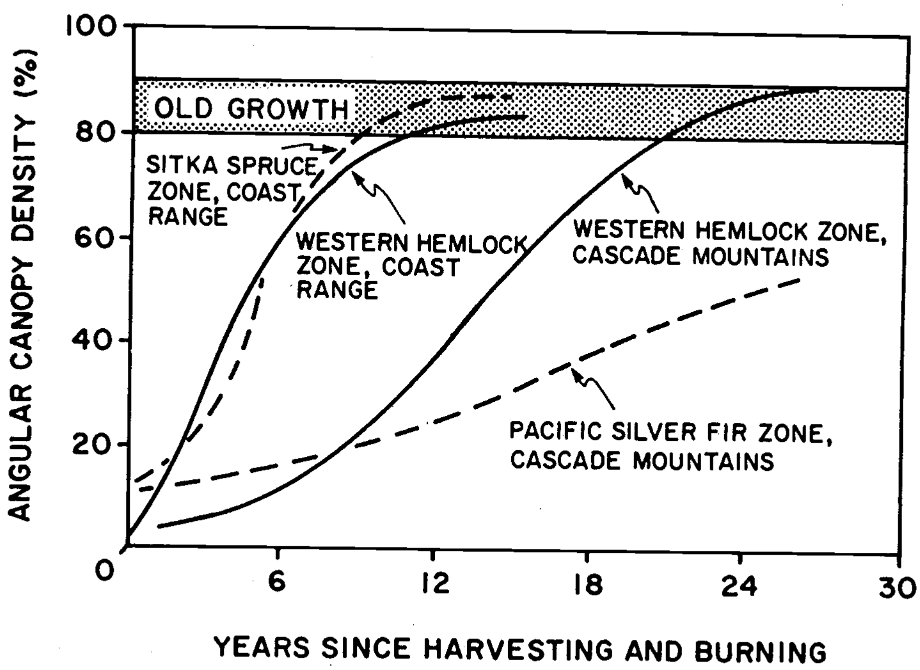


Figure 9. Relation between angular canopy density (ACD) and stand age for vegetation zones in western Oregon (Summers 1983).

of harvest (K. Sullivan, Weyerhaeuser Company, Tacoma, pers. comm.).

When temperature increases are produced by complete or partial exposure of a stream, they will subsequently decline as riparian vegetation returns. The rate of shade recovery depends on streamside conditions and vegetation. Sites in moist coastal ecosystems of the Pacific Northwest recover more rapidly than those in more arid ecosystems; sites at lower elevations more rapidly than those at higher elevations. In western Oregon, Summers (1983) examined sites with small streams that had been clearcut and burned at various times in the past to evaluate the recovery of shade (Figure 9). On the average, 50% of a stream was shaded within about five years of harvesting and burning in the Coast Range, within fifteen years from lower elevations of the Cascades (Western Hemlock Zone), and within twenty-five years for the higher elevations of the Cascades (Pacific Silver Fir Zone). Whereas small streams may be quickly overtopped by brush and effectively shaded from direct-beam solar radiation, larger streams, which require the canopies of tall conifers for shade protection, require longer periods.

Several alternatives are generally available to forest managers to prevent excessive temperature changes in order to avoid potential conflicts with fisheries interests, water quality changes, or other concerns. Where no change in temperature is permitted, a buffer strip is the obvious solution. But where some change in temperature is acceptable following logging, small clearcuts along streams, partial cuts or partial cuts within buffer strips (leaving only that vegetation that provides shade during a critical time of the year), scheduling of cutting activity over time in a drainage, or some combination of these methods can provide a desired level of temperature protection.

THERMAL EFFECTS ON THE STREAM ECOSYSTEM

Research on the effects of thermal alterations on fish communities falls into three general areas that serve as foci for our discussion: (1) trophic effects (effects of thermal alteration on other components of the community that affect fish), (2) thermal tolerances and preferences of fishes, and (3) fish metabolism, development, and activity.

Trophic Effects

Water temperature changes in mountain streams may not only influence fish populations and productivity but also that of the microbial community, algae, and invertebrates. These latter biotic components form the energy base for fish communities, and changes in these compoents can potentially be translated into impacts on fish through a change in available food. The energy base for stream biota comes primarily from two sources: algal production and terrestrial sources of organic matter (needles, leaves, twigs, etc.) (Fisher and Likens 1973). In most forest streams, the largest proportion of available energy is from terrestrial organic inputs. The nutritional value of this organic matter to animals that ingest it is due largely to an encrusting layer of microorganisms that develops after entry into the stream (Kaushik and Hynes 1971). With increased temperatures, these microflora develop more rapidly and utilize available organic matter at a higher rate (Suberkropp et al. 1975). Rapid decomposition of organic material may promote increased invertebrate production more quickly than in cooler streams, thus leading to additional fish food at an earlier time. However, the organic matter would thus be consumed over a shorter period, so this effect may be transitory.

Where streamside vegetation has been removed, light availability and stream temperatures typically increase. Although Murphy et al. (1981) demonstrated increased stream primary production mainly from increased light availability after canopy removal, it is difficult to separate the influence of light and temperature. Light limitation of aquatic plant production has been demonstrated in several Pacific Northwest streams (Stockner and Shortreed 1978, Rounick and Gregory 1981, Walter 1984). Both increased light and temperature generally cause higher production of stream algae and, in many cases, a change in species composition. Phinney and McIntire (1965) examined the influence of both light and temperature on production of a natural assemblage of periphyton in an artificial stream channel. They found that algae production was higher at 18°C than it was at 8-10°C for all tested light levels. However, the influence of increased light on algae growth in the two channels differed. At 18°C, algal production increased with light intensity up to an intermediate level and decreased at higher illumination. In the cooler channel, algal productivity increased up to the highest light level tested. Kevern and Ball (1965) and Bisson and Davis (1976) also noted a marked increase in periphyton production in heated stream channels compared with channels exposed to similar light regimes at lower temperatures. In contrast, Stockner and Shortreed (1978) conclude that nutrients and light are important regulators of algal growth in Carnation Creek, B.C., but that temperature does not have an important regulatory effect.

Changes in the taxonomic composition of the algal community in a stream following exposure to direct sunlight have been noted in several studies. In a spring-fed stream where temperature was constant (7°C), but light was experimentally varied through shade manipulation, Busch (1978) found that increased light both altered the species of algae present and caused an increase in algal biomass and invertebrate production. Warren et al. (1960) noted that in Oregon streams filamentous green algae dominated where at least 3% of full sunlight reached the substrate. In shaded stretches, diatoms predominated. Temperature also probably plays a role in this shift from a flora dominated by diatoms to one of green algae. Bisson and Davis (1976) noted a heavy growth of filamentous green algae in their heated channel. Their control channel had far less of this type of algae despite being exposed to similar light levels. The heavy growth of filamentous algae in the heated stream trapped considerable amounts of fine sediment, resulting in a shift in the invertebrate community to one dominated by oligochaete worms. These worms were rarely consumed by fish during this experiment. However, the general significance of such shifts in algal community composition on fish production in mountain streams is not well understood.

The influence of the changes in the energy base on higher tropic levels of the stream after canopy removal is difficult to interpret (Lee and Samuel 1976). Higher production levels of both microorganisms and algae suggest corresponding increases at higher levels of the food chain. However, the faster processing rate of organic matter by microbes coupled with a decrease in the input of leaves, needles, and other organic materials after clearcutting may lead to a scarcity of this material at certain times of the year. For example, Fisher and Likens (1973) found that under natural forested conditions, organic matter of leaf and twig size persisted in a small New England stream for about a year. With the more rapid processing at higher temperature, the residence time of this material in the stream should decrease. Since most terrestrial organic matter enters the stream as a pulse in autumn, an increased rate of processing could reduce summer stocks of this material, hence lowering food supplies for invertebrates dependent on this material. Thus when streams become exposed following removal of riparian vegetation, a short-term increase (from logging slash) followed by a longer term decrease in the availability of terrestrial organic matter may occur. The effect on the invertebrate populations and the extent to which it is offset by greater algal productivity are not known.

Nevertheless, despite the potential for deleterious effects, invertebrate standing crops in headwater streams that drain clearcuts are generally greater than those either in old-growth forests or in second-growth deciduous forests (Hughs 1966, Newbold et al. 1980, Smith 1980, Murphy and Hall 1981, Murphy et al. 1981). It would appear that the possible deleterious effects of removing riparian vegetation are outweighed by the increased primary production resulting from increased temperatures, light levels, and nutrients.

Invertebrates may be directly influenced by temperature increases, apart from the influence of their food supply. At higher temperatures, invertebrates feed more actively and, as a result, exhibit elevated growth rates (Cummins et al. 1973).

Temperature increases have at times been related to noticeable decreases in invertebrate production. Minshall (1968), studying a spring-fed brook in Kentucky, found a large decrease in both species diversity and numbers of individuals when stream temperature was elevated in a clearcut. However, spring-fed streams, in general, tend to have a constant, cold temperature year round and hence a fauna specialized for these unusual circumstances. This type of system may be especially sensitive to elevated temperatures.

Higher stream temperatures can also cause accelerated development of aquatic insect larvae, leading to early adult emergence (Nebeker 1971a, 1971b, Moore 1980). Salmonid fishes prey heavily on emerging adults, and accelerated insect development may benefit fish by making more food available earlier in the year. However, for most trouts (Salmo spp.) the emergence of fry from spawning gravel and the onset of active feeding coincides with spring and early summer hatches of aquatic insects.

Bisson and Davis (1976), working with two experimental stream channels, one heated about 4°C over the other, reported a reduction in the number of taxa in the heated channel. They also reported that nearly all the species represented in the channels produced higher biomasses in the control stream. There were exceptions to this rule, however, the most notable being a species of oligochaete worm and a snail, both of which exhibited increased production in the channel. Neither species was eaten by the juvenile chinook salmon in the channels, and as a result the increased production was of no benefit to the fish.

Sherberger et al. (1977) indicate that a temperature of at least 28°C was needed to influence mortality in Isonychia, a mayfly, while Hydropsyche, a caddisfly, withstood brief exposures up to temperatures of 26.5°C. Temperatures below the lethal limit did not have an effect on survival. At least in the case of these two invertebrates, lethal levels are above that needed to severely affect salmonids. Thus increased temperatures would probably eliminate the fish before their food resource was affected.

Some invertebrates are able to avoid high summer temperatures, such as those created by canopy removal, by adjusting their life cycle to spend the stressful period in a resistant, resting stage. Macan (1961) demonstrated that the mayfly, Rithrogena semicolorata, emerged earlier in the year in a warm stream than normally seen in cooler waters. The eggs deposited by the adults in spring in the warmed stream remained dormant for a longer period than those in cooler streams, hatching only when water temperatures decreased in autumn. Many invertebrates, however, such as those that spend one or more years in a larval form, would not generally be able to avoid temperature extremes by using this tactic.

Increased temperatures have been implicated in several studies as leading to increased entry of invertebrates into the drift (Pearson and Franklin 1968, Waters 1968, Bisson and Davis 1976). However, other investigators have not found this phenomenon (Bishop and Hynes 1969, Wojtalik and Waters 1970, Reisen and Prins 1972). The drift reaction of various invertebrates is probably species specific, which would account for the discrepancies noted in these studies. Increased drift rate would make more food available for fish, since drift forms the major food source for salmonids.

The influence of elevated temperatures on salmonid production of natural systems is difficult to delineate because of the variety of other factors concurrently affected. However, more abundant invertebrates have been observed in streams draining clearcuts (e.g., Murphy et al. 1981). Increased algal productivity leading to higher invertebrate production, and consequently to elevated food availability for fish, has been hypothesized as a cause of the frequent observation of increased salmonid production in streams exposed to sunlight (Murphy and Hall 1981, Weber 1981, Hawkins et al. 1983, Bisson and Sedell 1984). The consistency of these observations has led to general acceptance of the hypothesis that salmonid abundance is greater in streams draining clearcuts because there is more available food. Consequently, it is also generally accepted that an understanding of the effects of logging on the entire stream ecosystem is essential if we are to make progress in understanding the narrower problem of logging impacts on fish production.

Thermal Tolerances and Preferences of Fishes

The systematic study of the thermal tolerances and preferences of fishes began in the last century (see Brett 1970). Our understanding has slowly broadened from the concept of a single end point (e.g., a single upper lethal temperature) to a two or three factor concept (the zone of thermal tolerance of Fry 1964, where lethal temperatures are modified by acclimation temperature and exposure) and finally to a multifactorial concept where a multidimensional zone of thermal tolerance is defined by many interacting environmental factors (Brett 1970). Such studies are of necessity conducted under the tightly controlled conditions of the laboratory. The relevant objective of this work is to define for a particular species the boundaries of the thermal habitat. It may then be inferred that any land use activity that drives temperatures outside these boundaries will have deleterious and possibly lethal consequences.

Have any generalities relevant to our general topic emerged from this work? Apparently salmonids are tolerant of the extremes in temperature they are likely to encounter over their life spans and geographic ranges. In particular, the life stages of salmonid species that rear in freshwater seem especially tolerant of extreme high temperatures (extreme in the sense that most species can tolerate temperatures that are many degrees higher than any they are likely to encounter).

Because fish are cold-blooded, or poikilothermic, the temperature of their external environment dictates their internal temperature, which in turn regulates metabolic rate. Thus changes in water temperature directly influence the physiology and activity of fish. Furthermore, the relative sensitivity of fish to temperature changes depends, to a great extent, on their stage of development.

Early studies evaluated the effects of elevated temperatures on the survival of salmon eggs. For example, Combs and Burrows (1957) examined the influence of various temperatures on the survival of chinook salmon eggs. They found the upper lethal limit to be between 14 and 15.5°C. Similarly, Seymour (1959) reported that chinook eggs would not survive to the stage of vertebral development at temperatures in excess of 16.5°C. Sockeye salmon eggs appear to be even more susceptible to elevated temperatures, as Combs (1965) set the lethal level for development of this species at 13.5°C. Even in cases where temperature elevation is not sufficient to cause direct egg mortality, morphological characteristics of the fish can be altered as a result of high temperature during embryonic development (Orska 1963). Although laboratory studies provide an upper bound on temperature tolerance of eggs and embryos exposed to constant temperatures, the temperature environment in redds may be quite different.

Spawning and egg development in salmonids occurs during the autumn, winter, and spring. In coastal Oregon, Ringler and Hall (1975) found intragravel water temperatures during the time of coho salmon egg incubation in a stream draining a clearcut watershed to be well below those reported to cause developmental abnormalities. In the case of some races of spring-spawning salmonids, egg development may continue into late spring when the possibility of coincident low stream flow and sunny days could produce water temperatures detrimental to the development of the eggs. The extent to which this occurs is unknown. In addition to the influence elevated temperatures may have on egg development, depressed temperatures have been seen to lengthen incubation periods or increase freezing mortalities (Alderdice and Velsen 1978, Reiser and Wesche 1979, Reiser and White 1981). However, the effect removal of streamside vegetation has on minimum stream and intergravel temperatures in winter has generally received little attention (Needham and Jones 1959, Sheridan 1961).

Lethal threshold temperatures for Pacific salmon and steelhead trout have been identified for laboratory conditions (Figure 10), where the fish are held at a given temperature for long periods of time. This situation does not exist under natural conditions (even where temperatures have been elevated because of the removal of streamside vegetation), hence the direct application of laboratory temperature limits to field conditions is tenuous. Streams flowing through clearcut areas may display sizable fluctuations of water temperature over the period of a day, and maximum temperatures may exceed the reported lethal threshold temperatures for a brief time. However, these streams may

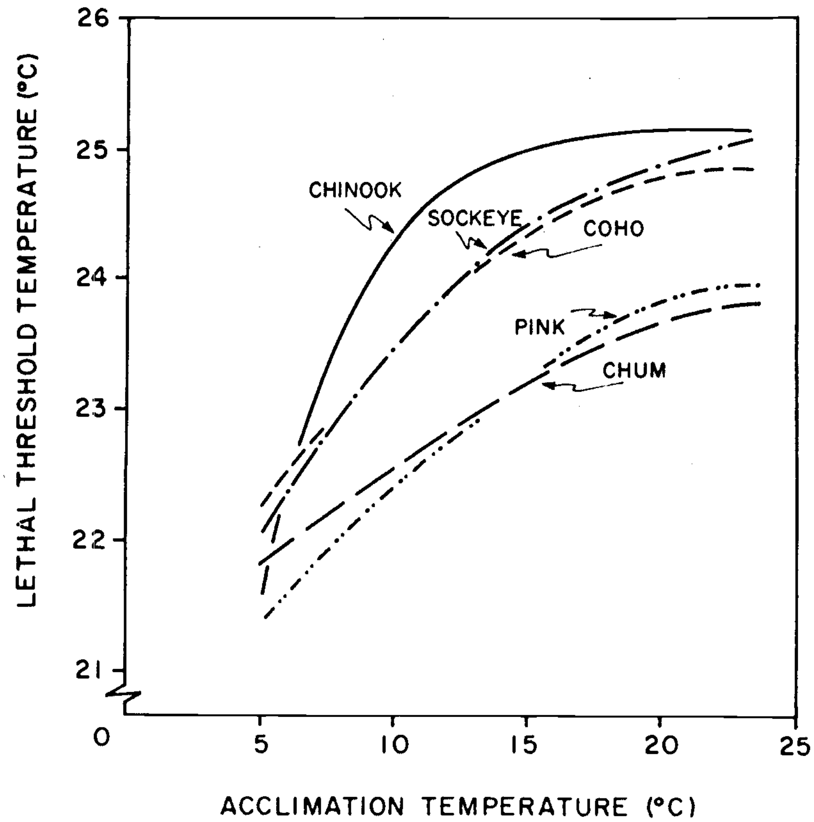


Figure 10. Lethal threshold temperatures for juvenile salmonids (from EPA 1973): chum salmon (Oncorhynchus keta), pink salmon (O. gorbuscha), coho salmon (O. kisutch), sockeye salmon (O. nerka), and chinook salmon (O. tshawytscha).

contain sizable populations of salmonids (Bisson et al. 1985). Apparently fish are able to withstand periodic, short-term exposures to fairly high temperatures with minimal detrimental impact.

The temperature levels preferred by rearing juvenile salmonids have also been evaluated in a number of laboratory studies. Brett (1952) found that the range of greatest preference by all species of Pacific salmon was from 12 to 14°C for acclimation temperatures ranging from 5 to 24°C. Brett (1952) also noted a definite avoidance of water over 15°C. Mantelman (1960) observed that juvenile rainbow trout were most commonly found in water ranging from 13 to 19°C and actively avoid water in excess of 22°C. These preferred temperatures may be exceeded in streams draining clearcut watersheds (Brown and Krygier 1970, Sheridan and Bloom 1975).

Elevated temperatures can also influence salmonid behavior. Upstream movement of adult sockeye salmon and steelhead trout was curtailed in the Columbia River when water temperatures reached 21°C (Lantz 1971). At these times the migrating fish congregated in the mouths of cooler tributaries until water temperatures decreased. Keenleyside and Hoar (1954) reported that both chum and coho salmon fry exhibited progressively increased rates of downstream migration as water temperature increased. Temperature preferences of fish have been the target of many studies; these have been summarized by Coutant (1977) and Jobling (1981).

For the coho salmon of Carnation Creek there is no evidence that increased summer temperatures (several degrees outside of their probable historical limits) and increased diurnal fluctuations affected fish distributions, at least on a macroscale. The availability of small-scale cover ("fine logging debris") was the important factor in determining the abundance of fry in stream sections whose banks had been completely clearcut, not the increases in stream temperatures in those sections (Scrivener and Andersen 1984).

Larkin (1956) noted that, as a rule, freshwater fish are adaptable to a wide range of environmental conditions and that the outcome of competitive interactions may vary depending on these conditions. A species that is dominant under one set of conditions may not necessarily prevail when conditions differ. Two recent studies have examined the influence of water temperature on interspecific interactions between fish. Reeves (1985) showed that the outcome of interactions between juvenile steelhead trout (age 1+) and the redside shiner (Richardsonius balteatus) was mediated by water temperatures. Water temperatures and the presence of the other species influenced production and activity in laboratory streams and distribution in the field and laboratory. Trout dominated in cool water (12 to 15°C) and shiners in warm water (19 to 22°). Baltz et al. (1982) found that competition between two species of nongame fish was affected by water temperature: one species dominated in cool water and the other in warm. Alteration of the temperature regime may influence not only growth and survival of a given species but also the structure of the fish community.

The development of thermal tolerance criteria in laboratory studies seems to have been markedly unsuccessful in helping understand the effects of logging on fish communities in the Pacific Northwest. To our knowledge, there are no records of elevated temperatures following shade removal that have led to extensive fish kills. An exception is the fish kill observed following a hot slash fire in Needle Branch, Oregon, during the Alsea Watershed Study (J. D. Hall, Oregon State University, Corvallis, pers. comm.). In fact, there is a general tendency for salmonid biomass to be higher in streams draining clearcuts (Burns 1972, Smith 1980, Martin et al. 1981, Murphy and Hall 1981, Holtby and Hartman 1982, Hawkins et al. 1983, Bisson and Sedell 1984, Scrivener and Andersen 1984). While such increases may have been due to many factors, the generality of the observation suggests that temperature increases resulting from clearcut logging do not, by themselves, have significant deleterious effects on salmonid abundance. One reason is that stream temperatures throughout the region seldom exceed, for extended periods, the tolerance limits of the resident salmonid species. The fish themselves also appear to be behaviorally "plastic" and can act to reduce either or both the temperatures they are exposed to and the duration of the exposure. For instance, salmonids appear to seek out cool water regions in streams where temperatures approach and exceed tolerance limits (Gibson 1966, Kaya et al. 1977). Even in studies where elevated summer temperatures, resulting from streamside disturbance, appear to have precluded salmonids, strong arguments can be made that the temperature effects were indirect. For example, Barton et al. (1985) concluded that the suitability of streams in southern Ontario for trout was characterized by maximum summer temperatures. While the effects of temperatures could have been direct, the authors suggest that elevated temperatures over several decades allowed the successful invasion of warm water competitors of the salmonids, possibly resulting in their competitive exclusion.

Although salmonid populations may respond favorably to opening of the riparian canopy, increased water temperatures, or both, resulting from management activities in these streams, the cumulative effect of these changes on other areas of the watershed has received little or no consideration in the Pacific Northwest. Water temperature in mid-order streams lower in a watershed depends largely on the temperature of water entering from upstream. Mid-order streams are important rearing areas for juvenile anadromous salmonids, especially chinook salmon and >1+ steelhead trout. They also have a more diverse fish community than lower order streams do (Vannote et al. 1980). Changes in environmental conditions may result in a decrease in available habitat for salmonids and alter the outcome of interactions between salmonids and potential competitors. Environmental changes less favorable to salmonids, such as increased water temperature in higher order streams, could offset any increase in abundance or production of anadromous salmonids that might occur from opening the canopy along lower order streams, or could even result in an overall decrease in population.

Temperature Effects on Fish Metabolism, Development, and Activity

The second general approach that has been used to study the effects of thermal change of stream fishes considers the effects of temperatures on metabolism, development, and activity. Within the bounds of thermal tolerance for any species, temperature is an important modifier of metabolism which then acts through numerous pathways to affect development, growth, activity, and reproduction or, more generally, survival and success (Brett 1958, Brett 1970, Lantz 1971). This rather broad field has been reviewed extensively (e.g., Fry 1967, Warren and Davis 1967, Brett 1970).

Except when fish are starving, the response of growth and activity to increasing temperatures is enhancement up to some optimum temperature and them diminution as the optimum is exceeded. In general, the optimal temperatures for growth and activity are similar to those likely to be encountered at a particular stage of the fish. It is also generally the case that the optima are rather broad, especially for species and life stages where the temperatures encountered are wide ranging.

Laboratory studies with salmon and trout at constant temperature levels have generally shown decreased growth with higher temperatures when food was limiting. A fish will not grow until metabolic energy requirements are first met (Warren and Davis 1967), and the metabolic rate increases with temperature. Dwyer and Kramer (1975) examined the metabolic rate of cutthroat trout at several temperatures. They measured the lowest metabolic rate at 5°C and the highest at 15°C with a decrease in rate at 20 to 24°C. Normally, metabolic rate would be expected to continue to increase as a function of temperature; however, in this experiment the trout held at 20 and 24°C fed very little, and it is likely that the decrease in metabolic rate was brought on by starvation. Wurtsbaugh and Davis (1977) found that maintenance food levels (the amount needed to maintain constant body weight) for rainbow trout were 2.7% of body weight per day at 6.9°C and 7.5% at 22.5°C. Averett (1968) found that juvenile coho salmon required twice the amount of food to grow at 17°C than at 5°C. In many salmonids, however, the dimunution in growth and swimming performance with increasing temperature occurs primarily at temperatures near the lethal thresholds (e.g., Brett 1967, Brett et al. 1969).

Wurtsbaugh and Davis (1977) indicated that if steelhead trout were fed limited amounts of food, growth decreased at higher temperatures. The difference in productivity lessened, however, if the ration was increased. Similarly, the production of coho salmon has been shown to decrease at higher temperatures under conditions of limited food (Iversen 1972). The decreased production in Iversen's (1972) study was attributed to both increased metabolic rate and a reduction in food availability due to a decrease in the invertebrate population in the artificial stream channel in which the experiment was conducted. Bisson and Davis (1976) also reported a decrease in fish production with increased temperature for juvenile chinook salmon. They subjected artificial stream channels to diurnal and annual temperature cycles with one of the channels heated and maintained at a temperature approximately 4°C higher than the control. Production in the cooler channel exceeded that in the heated channel by 100% the first year of the experiment and 30% by the second year. The decreased production in the heated channel was attributed to increased metabolic requirements and reduced food levels.

Fish productivity at elevated temperatures could probably be maintained, provided the food supply increased enough to compensate for increased metabolic requirements. In a study in which water temperature in artificial streams varied daily, production of juvenile steelhead trout (>1+) was two and one half times greater in cooler water (12 to 15°C) than in warmer (19 to 22°C) water (Reeves 1985). One reason for these differences was that fish in the cooler water were able to maintain territories in areas of higher food concentration, which were in areas of greater water turbulence.

Nearly all these studies on the influence of temperature on fish production were conducted in artificial streams. More recent studies of natural streams have not always corroborated the results from artificial channels. Martin et al. (1981) compared a population of cutthroat trout inhabiting a shaded section of stream with fish in a section of stream exposed to direct sunlight. They could find no difference in trout biomass or density between the two sections, although the exposed section had a daily maximum temperature that averaged 2°C higher than the shaded section. However, in a final analysis of the data set, Martin (1985) concluded that in the canopy area with no temperature change, density increased. In the open area where temperature increased, growth increased but density did not. Some studies of salmonid populations in streams exposed to sunlight have reported increases in production. For example, Murphy and Hall (1981) reported higher salmonid biomass in streams exposed to sunlight than in streams flowing through old-growth forest in Oregon. The temperature increases in the exposed streams were slight, ranging from 0.1 to 1°C, thus the fish biomass increase is probably attributable to factors other than increased temperature. Bisson and Sedell (1984) also reported higher salmonid biomass in streams draining clearcut areas than in shaded systems in southwestern Washington, but these authors did not monitor stream temperatures.

While the growth efficiency of salmonids is theoretically highest at low temperatures, activity of fish in cold water is at a minimum and feeding rates are correspondingly depressed. Thus optimum growth usually occurs at some intermediate temperature where activity levels are high enough to ensure active feeding, and metabolic conversion efficiencies are also relatively high. "Optimum" stream temperatures for various stages of development and species of fish are shown in Table 3.

The relation between increases in diurnal variations and growth rate is unknown. For some species, increases in diurnal variation might be beneficial. Biette and Green (1980) have demonstrated for sockeye salmon that temperature fluctuations, resulting from diurnal migrations throughout the thermoclines of stratified lakes, are associated with growth increases at low, and therefore realistic, ration levels. In contrast, Edwards et al. (1979) have shown for brown trout that increases in diurnal temperature fluctuations with constant mean temperatures result in diminution in growth. As noted earlier, streams often contain pockets of water cooler than the ambient stream (Keller and Hofstra 1982, Bilby 1984). These areas have been seen to be used by salmonids during times of stressful temperatures (Gibson 1966, Kaya et al. 1977), and may in part be responsible for the presence of salmon and trout in streams that occasionally attain very high temperatures (Bisson et al. 1985). However, the potential for this mechanism to assist in reducing thermal impacts to fish may be limited by the relative scarcity and, potentially, low oxygen concentration of cool-water areas (Bilby 1984).

Temperature is known to affect other physiological processes. For instance, as temperatures increase, diseases often become more virulent. The higher susceptibility to disease is brought on by a combination of higher metabolic rates and elevated levels of physiological stress. Ordal and Pacha (1963) and Parker and Krenkel (1969) report that a large number of common diseases of salmonids, including kidney disease, furunculosis, vibrosis, and columnaris, become more virulent as temperature increases. Nakatani (1969) found that columnaris became well established in salmonids at temperatures of 17 to 18°C under crowded conditions. When temperatures reached 21°C, the disease killed most of the infected individuals. Chinook and coho salmon and steelhead trout, infected with furunculosis, a bacterial infection, were held at temperatures ranging from 3.9 to 20.5°C (Groberg et al. 1978). At temperatures below 10°C, mortality of the fish ranged from 2 to 26% of

Table 3. Water temperature criteria, in degrees Celsius, for fish in western North America.

Species	Upstream Migration	Spawning	Incubation	Juvenile Rearing: Preferred	Juvenile Rearing: Optimum	Juvenile Rearing: Upper Lethal
Chinook	---	5.6-13.9	5.0-14.4	7.3-14.6	12.2	25.2
Fall	10.6-19.4	---	---	---	---	---
Spring	3.3-13.3	---	---	---	---	---
Summer	13.9-20.0	---	---	---	---	---
Chum	8.3-15.6	7.2-12.8	4.4-13.3	11.2-14.6	13.5	25.8
Coho	7.2-15.6	4.4- 9.4	4.4-13.3	11.8-14.6	---	25.8
Pink	7.2-15.6	7.2-12.8	4.4-13.3	5.6-14.6	10.1	25.8
Sockeye	7.2-15.6	10.6-12.2	4.4-13.3	11.2-14.6	15.0	24.6
Steelhead	---	3.9- 9.4	---	7.3-14.6	10.0	24.1
Kokanee	---	5.0-12.8	---	---	---	---
Rainbow	---	2.2-20.0	---	---	---	---
Cutthroat	---	6.1-17.2	---	9.5-12.9	---	23.0
Brown	---	7.2-12.8	---	3.9-21.3	---	24.1

Source: Adapted from Reiser and Bjornn 1979.

the infected fish. However, at 20.5°C, 93 to 100% of the infected fish died within two to three days. These investigations were conducted under conditions of constant temperature and high population densities. As with much of the temperature research, it is difficult to transfer work done in a controlled environment to a situation in the field. The virulence of various fish diseases under conditions of varying temperatures and relatively low population densities has seldom been examined.

An exception to the general rule of increased disease virulence with increased temperature was noted by Bisson and Davis (1976). They found a reduced infection rate of juvenile chinook salmon by the trematode parasite (Nanophyetus salmicola) for fish held in water 4°C warmer than a control. This seems to represent an instance where the infecting organism is less tolerant of temperature elevation than the host.

It is generally accepted that the temperature regime is one habitat component to which fish populations are locally adapted (Ricker 1972). For instance, Leggett and Carscadden (1978) demonstrated for the anadromous American shad (*Alosa sapidissima*) that the principal factor determining interpopulation differences in reproduction strategies was the variability in thermal regimes of the natal streams. Since developmental and metabolic rates in fish are highly dependent on temperature, variations in temperature lead to variation in the timing of such life history events as emergence and migrations. In lakes of the Fraser River drainage, interannual variations in sockeye salmon smolt sizes that are not accounted for by density appear determined by the length of the growing season, which, in turn, is determined by temperatures around the time of emergence (Goodlad et al. 1974).

Temperature variations around the time of smolt migration have been shown to be the principal source of interannual variability of Atlantic smolt migration timing in Norway (Jonsson and Ruud-Hansen 1985). Thedinga and Koski (1984) have shown, in their studies of the coho salmon of Porcupine Creek, Alaska, that variations in the timing of smolt outmigrations can have deleterious impacts on marine survival.

Since the timing of life history events is an adaptation to local conditions, it can be expected that changes in those environmental conditions, such as changes in temperature regimes caused by logging, may reduce the fitness of affected populations, with deleterious consequences to production (Leggett and Carscadden 1978). The possible effects of altering events such as fry emergence and smolt and adult migration have been mentioned in the context of logging effects (Narver 1972, Moring 1975b, Holtby and Newcombe 1982, Hartman et al. 1984), but with the exception of research at Carnation Creek, B.C., there has been little systematic study.

In a recently completed study, Holtby (1986) attempted to assess the effects of temperature on the timing of life history events of a population of coho salmon in a small coastal stream (Carnation Creek). Temperature-related impacts on this fish population were seen to bring about a series of changes: (1) logging-related (58%) and climate-related (42%) increases in late winter temperatures accelerated fry emergence (Holtby and Newcombe 1982, Tschaplinski and Hartman 1983); (2) increased length of growing season, resulting from earlier emergence, led to increased fry size entering their first winter (Hartman et al. 1984); (3) increased fry size led to higher overwinter survival (Holtby and Hartman 1982); (4) higher overwinter survival and size led to increased numbers and sizes of 1+ smolts; and (5) seaward migration of the smolts in spring was accelerated by seven to ten days.

The impacts of temperature increase on the freshwater phases of the coho population generally suggest increased production of smolts. However, earlier release to the sea of hatchery-stock coho smolts has been linked to decreased marine survival (Bilton et al. 1982). Therefore, the benefits that resulted from changes in smolt size and numbers following logging (Figure 11) may be substantially or wholly offset by increased saltwater mortality attributable to earlier migration.

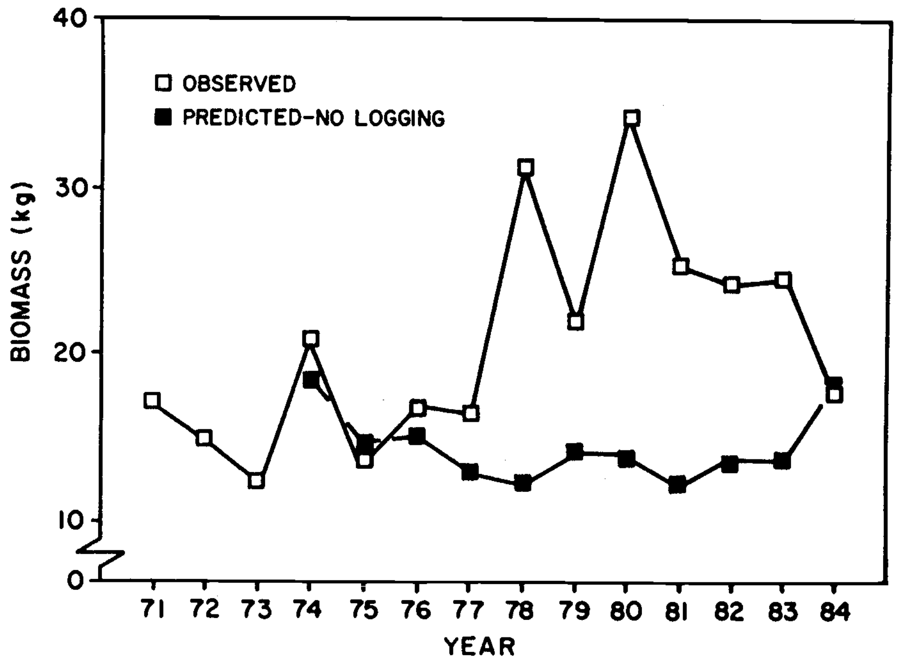


Figure 11. The combined weight of coho salmon smolts produced by Carnation Creek, B.C. Logging began in the winter of 1975-76 and was largely complete in those areas of the watershed immediately surrounding anadromous salmon habitat by the summer of 1979. The line of predicted smolt output assumes that temperature changes associated with logging did not occur (Holtby 1986).

Several important points emerge from the studies at Carnation Creek, B.C. First, the alteration in the timing of life history events due to temperature changes may significantly affect fish production. Second, temperature effects are not necessarily confined to the stream, but ultimately may affect returns of adults to the stream. Third, the temperature changes that resulted in effects on fish production were relatively small and clearly not life threatening changes that occurred in the winter and spring. The much larger thermal effects of logging that were observed during the summer had no detectable effects on coho smolt production.

SUMMARY AND CONCLUSIONS

Stream temperatures in forested watersheds in the Pacific Northwest can be characterized as (1) predictable along such various spatial scales as latitude, elevation, and stream order, (2) predictable on temporal scales such as season and day, and (3) of low variability both between years and within days. It has been repeatedly demonstrated that removal of riparian vegetation alters stream temperature regimes. In coastal streams, where prolonged periods of below zero temperatures are rare, removal of riparian vegetation invariably results in increased mean and maximum stream temperatures and increased diurnal ranges. Over a sufficiently long period, effects of streamside logging on thermal regimes can be detected throughout the year, and not just in the summer as is the general perception. In regions where winter temperatures are below freezing, the removal of riparian vegetation may result in the depression of stream temperatures and greater periods of freeze-up, but such situations have been little studied.

For a given stream, the magnitude of the temperature increase after streamside logging is proportional to the increase in exposure of the stream to incoming solar radiation, or, conversely, to the amount of shade reduction. Thus buffer strips (composed of vegetation not susceptible to blow down) are an effective means of providing shade and preventing temperature changes. The exact configuration and width of such buffer strips can be highly variable and site specific. In western Oregon, it appears that buffer strips 30 m or more in width along small streams provide approximately the same level of shading as an old-growth forest. More important, an understanding of the energy transfer influencing stream temperature permits the dimensions of streamside logging to be controlled to produce the desired effects on stream temperatures, ranging upward from no effects at all.

There are many reasons why the observed logging-related temperature increases have not had significant deleterious effects on resident salmonids. Among these are (1) the wide thermal tolerances of the freshwater forms of most of the resident salmonid species, (2) the natural diurnal cycling of stream temperatures, which limits exposure to maximum temperatures, (3) the occurrence of localized cool-water sources, which fish seem readily able to locate and utilize, (4) the inability to extrapolate tolerance limits determined under homogeneous laboratory conditions to the spatially and temporally complex thermal environments of streams, and (5) the ability of fish to migrate to other locations or to curtail activities temporarily when temperatures become stressful. Although increased summer temperatures remain a concern to fisheries managers, it appears that fish are generally able to tolerate such increases without major adverse impacts on growth or mortality.

Because of the extensive geographical range of salmonids, the effects of temperature on these fish should be viewed in a regional context. In at least some regions of the Pacific Northwest, concern over the lethal effects of elevated summer temperatures in small streams draining deforested watersheds is unwarranted. This is certainly the case in the low elevation, coastal streams of British Columbia and Washington. However, in other regions of the Pacific Northwest, increased temperatures from logging may remain a significant concern. For example, in southern areas (southern Oregon and northern California) and areas east of the Cascade Mountains, increased temperatures due to logging may have a greater impact on fish populations than in areas of cooler climate, because of ambient water temperatures. Unfortunately, for most of these areas little information is available that might demonstrate the influences increased water temperatures have on fish populations.

Temperature is clearly an important component of the habitat of many stream organisms, including the fish, and most organisms respond to the changes in stream temperatures caused by streamside logging. But because temperature is only one of several closely interconnected physical factors that are affected simultaneously by streamside logging, it is questionable whether our understanding of the impacts of logging on fish production can be increased by trying to study the effects of temperature in isolation.

Increased temperatures following logging, together with increased light levels and increased nutrient concentrations, often lead to general increases in productivity in the trophic levels that form the basis of fish production. Increased temperatures, light, and nutrients all play a role. Temperature directly affects development rates of fish; in some systems, the temperature increases lead to earlier emergence, longer growing seasons, and increased survivals at critical times in the life histories of fish. Increased temperatures also directly affect metabolism and activity levels of fish.

The apparent generality of enhanced fish production after streamside logging could be an artifact of geographically limited data or a "coastal rain-forest" perspective. For instance, there is relatively little known about the effects of logging on stream temperatures and fish production in areas where streams freeze in the winter. In such regions, production "bottlenecks" might occur during the winter period of low flows and freezing temperatures. Slight changes in stream exposure might cause decreased stream temperatures, and, coupled with other physical effects of logging such as channelization and decreased pool depths, could conceivably decrease winter habitat for fish and decrease production (Bustard 1985). Under such circumstances, enhanced summer production would be essentially nullified by worsened winter conditions.

The same streamside activities that lead to changes in temperature and light levels precipitate other changes in the stream (Bisson et al., Everest et al., Swanson et al., and Sullivan et al., in this volume). Streamside logging has often been associated with changes in sedimentation, bank stability, channel morphology, large woody debris, and other factors that ultimately alter the productive capacity of a stream for fish. Where sources of large organic debris have been removed, the effects of streamside logging on the physical configuration of the stream can extend for decades.

There are many promising areas for research on the impacts of streamside management on fisheries. There is a great need to develop empirical predictors of the productivity gains to be had from controlled streamside disturbance (In what situations should the streamside be left unaltered? If there are productivity gains to be had, how can streamsides be managed to maximize those benefits?). A great deal has yet to be learned about the processes governing the productivity of salmonids in the diverse stream types and climatic zones in the region. This knowledge is essential if the riparian zone is to be successfully managed. A technological challenge lies in the development of techniques that maximize the beneficial effects while minimizing or mitigating deleterious impacts.

Considering the productivity gains that may be had by judicious streamside treatments, it seems to us an overly conservative view to eliminate all forest management activity in the riparian zone. However, much remains to be discovered before managers can abandon their cautious stance on streamside logging. Therein lie the challenges for joint fisheries-forestry research.

ACKNOWLEDGMENTS

Review comments by G. H. Reeves, P. A. Bisson, and J. D. Hall, while the manuscript was at various stages of development, are greatly appreciated.

LITERATURE CITED

Alderdice, D. F., and F. P. J. Velsen. 1978. Relation between temperature and incubation time for eggs of chinook salmon (Oncorhynchus tshawytscha). J. Fish. Res. Board Can. 35:69-75.

Averett, R. C. 1968. Influence of temperature on energy and material utilization by juvenile coho salmon. Ph.D. thesis, Oregon State University, Corvallis.74 p.

Baltz, D. M., P. B. Moyle, and N. J. Knight. 1982. Competitive interactions between benthic stream fishes, riffle sculpin, Cottus gulosus, and speckled dace Rhinichthys osculus. Can. J. Fish. Aquat. Sci. 39:1502-1511.

Barton, D. R., W. D. Taylor, and R. M. Biette. 1985. Dimensions of riparian buffer strips required to maintain trout habitat in southern Ontario streams. North Am. J. Fish. Manage. 5:364-378.

Beschta, R. L. 1984. TEMP-84: A computer model for predicting stream temperatures from the management of streamside vegetation. USDA For. Serv. WSDG Rep. 9. Watershed Systems Development Group, Fort Collins, Colorado. 76 p.

Beschta, R. L., and R. Lynn Taylor. 1986. Increased stream temperatures of Salmon Creek, Oregon: An example of cumulative effects? Unpublished report. Department of Forest Engineering, Oregon State University, Corvallis. 20 p.

Biette, R. M., and G. H. Green. 1980. Growth of underyearling sockeye salmon (Oncorhynchus nerka) under constant and cyclic temperatures in relation to live zooplankton ration size. Can. J. Fish. Aquat. Sci. 37:203-210.

Bilby, R. E. 1984. Characteristics and frequency of cool-water areas in a western Washington stream. J. Freshw. Ecol. 2:593-602.

Bilton, H. T., D. F. Alderdice, and J. T. Schnute. 1982. Influence of time and size at release of juvenile coho salmon (Oncorhynchus kisutch) on returns at maturity. Can. J. Fish. Aquat. Sci. 39:426-447.

Bishop, J. E., and H. B. N. Hynes. 1969. Downstream drift of the invertebrate fauna in a stream ecosystem. Arch. Hydrobiol. 66:56-90.

Bisson, P. A., and G. E. Davis. 1976. Production of juvenile chinook salmon, Oncorhynchus tshawytscha, in a heated stream. NOAA Fishery Bull. 74:763-774.

Bisson, P. A., J. L. Nielsen, and J. W. Ward. 1985. Experimental release of coho salmon (Oncorhynchus kisutch) into a stream impacted by Mount St. Helens volcano. In Proceedings, Western Association of Fish and Wildlife Agencies, p. 422-435. Victoria, B.C.

Bisson, P. A., and J. R. Sedell. 1984. Salmonid populations in streams in clearcut vs. old-growth forests of western Washington. In W. R. Meehan, T. R. Merrell, Jr., and T. A. Hanley (eds.) Fish and wildlife relationships in old-growth forests: Proceedings of a symposium, p. 121-129. American Institute of Fishery Research Biologists.

Brazier, J. R., and G. W. Brown. 1973. Buffer strips for stream temperature control. Res. Pap. 15. Forest Research Laboratory, Oregon State University.9 p.

Brett, J. R. 1952. Temperature tolerances in young Pacific salmon, Oncorhynchus. J. Fish. Res. Board Can. 9:268-323.

_________. 1958. Implications and assessments of environmental stress. In P. A. Larkin (ed.) The Investigation of Fish-Power Problems Proceedings, p. 69-83. H. R. MacMillan Lectures in Fisheries. University of British Columbia, Vancouver.

_________. 1967. Swimming performance of sockeye salmon (Oncorhynchus nerka) in relation to fatigue, time and temperature. J. Fish. Res. Board Can. 24:1731-1741.

________. 1970. Temperature: Fishes. In O. Kinne (ed.) Marine Ecology, 1:513-560. Environmental factors, Part 1. Wiley-Interscience, London.

Brett, J. R., J. E. Shelbourn, and C. T. Shoop. 1969. Growth rate and body composition of fingerling sockeye salmon, Oncorhynchus nerka, in relation to temperature and ration size. J. Fish. Res. Board Can. 26:2363-2394.

Brown, G. W. 1969. Predicting temperatures of small streams. Water Resour. Res. 5(1):68-75.

________. 1983. Forestry and water quality. Oregon State University Bookstore, Inc., Corvallis. 142 p.

Brown, G. W., and J. T. Krygier. 1967. Changing water temperatures in small mountain streams. J. Soil Water Conserv. 22(6):242-244.

________. 1970. Effects of clearcutting on stream temperature. Water Resour. Res. 6(4):1133-1139.

Brown, G. W., G. W. Swank, and J. Rothacher. 1971. Water temperature in the Steamboat drainage. USDA For. Serv. Res. Pap. PNW-119. Pac. Northwest For. and Range Exp. Stn., Portland, Oregon. 17 p.

Buffo, J., L. J. Fritschen, and J. L. Murphy. 1972. Direct solar radiation on various slopes from 0 to 60 degrees north latitude. USDA For. Serv. Res. Pap. PNW-142. Pac. Northwest For. and Range Exp. Stn., Portland, Oregon. 74 p.

Burns, J. W. 1972. Some effects of logging and associated road construction on northern California streams. Trans. Am. Fish. Soc. 101:1-17.

Busch, D. E. 1978. Successional changes associated with benthic assemblages in experimental streams. Ph.D. thesis, Oregon State University, Corvallis.91 p.

Bustard, D. R. 1985. Some differences between coastal and interior streams and the implications to juvenile fish production. In J. Paterson (ed.) Habitat Improvement Workshop, Whistler, B.C. Can. Tech. Rep. Fish. Aquat. Sci. In press.

Combs, B. D. 1965. Effects of temperature on the development of salmon eggs. Prog. Fish-Cult. 27:134-137.

Combs, B. D., and R. E. Burrows. 1957. Threshold temperatures for the normal development of chinook salmon eggs. Prog. Fish-Cult. 19:3-6.

Corbett, E. S., and J. M. Heilman. 1975. Effects of management practices on water quality and quantity: The Newark, New Jersey, Municipal Watersheds. In Proceedings of a Symposium on Municipal Watershed Management, p. 47-57. USDA For. Serv. Gen. Tech. Rep. NE-13. Northeastern For. Exp. Stn., Broomall, Pennsylvania.

Corbett, E. S., and W. Spencer. 1975. Effects of management practices on water quality and quantity: Baltimore, Maryland, Municipal Watersheds. In Proceedings of Symposium on Municipal Watershed Management, p. 25-31. USDA For. Serv. Gen. Tech. Rep. NE-13. Northeastern For. Exp. Stn., Broomall, Pennsylvania.

Coutant, C. C. 1977. Compilation of temperature preference data. J. Fish. Res. Board Can. 34:739-745.

Cummins, K. W., R. C. Petersen, F. O. Howard, J. C. Wuycheck, and V. I. Holt. 1973. The utilization of leaf litter by stream detritivores. Ecology 54:336-345.

Currier, J. B., and D. Hughes. 1980. Temperature. In An approach to water resources evaluation on nonpoint silvicultural sources. EPA-600/8-80-12. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, Georgia.

Dwyer, W. P., and R. H. Kramer. 1975. The influence of temperature on scope for activity in cutthroat trout, Salmo clarki. Trans. Am. Fish. Soc. 104:552-554.

Edwards, R. W., J. W. Densen, and P. A. Russell. 1979. An assessment of the importance of temperature as a factor controlling the growth rate of brown trout in streams. J. Anim. Ecol. 48:501-507.

Erman, D. C., J. D. Newbold, and K. B. Roby. 1977. Evaluation of streamside bufferstrips for protecting aquatic organisms. Contribution 165. California Water Resources Center, University of California, Davis. 48 p.

Fisher, S. G., and G. E. Likens. 1973. Energy flow in Bear Brook, New Hampshire: An integrative approach to ecosystem metabolism. Ecol. Monogr. 43:421-439.

Fry, F. E. J. 1964. Animals in aquatic environments: Fishes. In D. B. Dill, E. F. Adolph, and C. G. Wilber (eds.) Handbook of physiology. Sec. 4: Adaptation to the environment, p. 715-728. American Physiological Society, Washington, D.C.

_________. 1967. Responses of vertebrate poikilotherms to temperature. In A. H. Rose (ed.) Thermobiology, p. 375-409. Academic Press, London.

Gibson, R. J. 1966. Some factors influencing the distribution of brook trout and young Atlantic salmon. J. Fish. Res. Board Can. 23:1977-1980.

Goodlad, J. C., T. W. Gjernes, and E. L. Brannon. 1974. Factors affecting sockeye salmon (Oncorhynchus nerka) growth in four lakes of the Fraser River System. J. Fish. Res. Board Can. 31:871-892.

Groberg, W. J., Jr., R. H. McCoy, K. S. Pilcher, and J. L. Fryer. 1978. Relation of water temperature to infections of coho salmon (Oncorhynchus kisutch), chinook salmon (O. tshawytsch) and steelhead trout (Salmo gairdneri) with Aernomora salmonicida and A. hydrophila. J. Fish. Res. Board Can. 35:1-7.

Hartman, G. F., L. B. Holtby, and J. C. Scrivener. 1984. Some effects of natural and logging-related winter stream temperature changes on the early life history of coho salmon (Oncorhynchus kisutch) in Carnation Creek, British Columbia. In W. R. Meehan, T. R. Merrell, Jr., and T. A. Hanley (eds.) Fish and wildlife relationships in old-growth forests: Proceedings of a symposium, p. 141-149. American Institute of Fishery Research Biologists.

Hawkins, C. P., M. L. Murphy, N. H. Anderson, and M. A. Wilzbach. 1983. Density of fish and salamanders in relation to riparian canopy and physical habitat in streams of the northwestern United States. Can. J. Fish. Aquat. Sci. 40:1173-1185.

Hewlett, J. D., and J. C. Fortson. 1982. Stream temperature under an inadequate buffer strip in the southeast Piedmont. Water Resour. Bull. 18(6):983-988.

Holtby, L. B. 1986. Some effects of logging related stream temperature changes on the population dynamics of coho salmon (Oncorhynchus kisutch) of Carnation Creek, British Columbia. Unpublished manuscript.

Holtby, L. B., and G. F. Hartman. 1982. The population dynamics of coho salmon (Oncorhynchus kisutch) in a west coast rain forest stream subjected to logging. In G. F. Hartman (ed.) Proceedings of the Carnation Creek Workshop: A ten-year review, p. 308-347. Pacific Biological Station, Nanaimo, B.C.

Holtby, L. B., and C. P. Newcombe. 1982. A preliminary analysis of logging related temperature changes in Carnation

Creek, British Columbia. In G. F. Hartman (ed.) Proceedings of the Carnation Creek Workshop: A ten-year review, p. 81-99. Pacific Biological Station, Nanaimo, B.C.

Hughs, D. A. 1966. Mountain streams of the Barberton area, eastern Transvaal. Part 2: The effect of vegetational shading and direct illumination on the distribution of stream fauna. Hydrobiologia 27:439-459.

Hynes, H. B. N. 1970. The ecology of running waters. University of Toronto Press, Toronto. 555 p.

Iverson, R. A. 1972. Effects of elevated temperatures on juvenile coho salmon and benthic invertebrates in model stream communities. Ph.D. thesis, Oregon State University, Corvallis. 98 p.

Jobling, M. 1981. Temperature tolerance and the final preferendum: Rapid methods for the assessment of optimum growth temperatures. J. Fish. Biol. 19:439-455.

Jonsson, B., and J. Rudd-Hansen. 1985. Water temperature as the primary influence on timing of seaward migrations of Atlantic salmon (Salmo salar) smolts. Can. J. Fish. Aquat. Sci. 42:593-595.

Kaushik, N. K., and H. B. N. Hynes. 1971. The fate of the dead leaves that fall into streams. Arch. Hydrobiol. 68:465-515.

Kaya, C. M., L. R. Kaeding, and D. E. Burkhalter. 1977. Use of a coldwater refuge by rainbow and brown trout in a geothermally heated stream. Prog. Fish-Cult. 39:37-39.

Keenleyside, M. H. A., and W. S. Hoar. 1954. Effects of temperature on the response of young salmon to water currents. Behavior 7:77-87.

Keller, E. A., and T. Hofstra. 1982. Summer "cold pools" in Redwood Creek near Orick, California. In C. Van Riper III, L. D. Whittig, and M. L. Murphy (eds.) Proceedings of the First Biennial Conference of Scientific Research in California's National Parks, University of California, Davis.

Keller, E. A., T. D. Hofstra, and C. Moses. In press. Summer "cold pools" in Redwood Creek near Orick, California. In K. M. Nolan, H. Kelsey, and D. C. Marron (eds.) Geomorphic processes and aquatic habitat in the Redwood Creek basin, northwestern California. U.S. Geological Survey Prof. Pap.

Kevern, N. R., and R. C. Ball. 1965. Primary productivity and energy relationships in artificial streams. Limnol. Oceanogr. 10:74-87.

Kochenderfer, J. N., and G. M. Aubertin. 1975. Effects of management practices on water quality and quantity: Fernow Experimental Forest, West Virginia. In Proceedings of Symposium on Municipal Watershed Management, p. 14-24. USDA For. Serv. Gen. Tech. Rep. NE-13. Northeastern For. Exp. Stn., Broomall, Pennsylvania.

Koski, K V. 1984. A stream ecosystem in an old-growth forest in southeast Alaska. Part 1: Description and characteristics of Porcupine Creek, Etolin Island. In W. R. Meehan, T. R. Merrell, Jr., and T. A. Hanley (eds.) Fish and wildlife relationships in old-growth forests: Proceedings of a symposium, p. 47-55. American Institute of Fishery Research Biologists.

Lantz, R. L. 1971. Influence of water temperature on fish survival, growth, and behavior. In J. T. Krygier and J. D. Hall (eds.) Forest land uses and stream environment: Proceedings of a symposium, p. 182-193. Oregon State University, Corvallis.

Larkin, P. A. 1956. Interspecific competition and population control in freshwater fish. J. Fish. Res. Board Can. 13:327-342.

Lee, R. 1980. Forest hydrology. Columbia University Press, New York. 349 p.

Lee, R., and D. E. Samuel. 1976. Some thermal and biological effects of forest cutting in West Virginia. J. Environ. Qual. 5(4):362-366.

Leggett, W. C., and J. E. Carscadden. 1978. Latitudinal variation in reproductive characteristics of American shad (Alosa sapidissima): Evidence of population specific life history strategies in fish. J. Fish. Res. Board Can. 35:1469-1478.

Levno, A., and J. Rothacher. 1967. Increases in maximum stream temperatures after logging old growth Douglas-fir watersheds. USDA For. Serv. Res. Note PNW-65. Pac. Northwest For. and Range Exp. Stn., Portland, Oregon. 12 p.

_________. 1969. Increases in maximum stream temperatures after slash burning in a small experimental watershed. USDA For. Serv. Res. Note PNW-110. Pac. Northwest For. and Range Exp. Stn., Portland, Oregon. 7 p.

Lynch, J. A., W. E. Sopper, E. S. Corbett, and D. W. Aurand. 1975. Effects of management practices on water quality and quantity: The Penn State Experimental Watersheds. In Proceedings of Symposium on Municipal Watershed Management, p. 32-46. USDA For. Serv. Gen. Tech. Rep. NE-13. Northeastern For. Exp. Stn., Broomall, Pennsylvania.

Macan, T. T. 1961. Factors that limit the range of fresh water animals. Bio. Rev. 36:151-198.

Mantelman, I. I. 1960. Distribution of the young of certain species of fish in temperature gradients. Transl. Ser. 257. J. Fish. Res. Board Can. 67 p.

Martin, D. J. 1985. Production of cutthroat trout Salmo clarki in relation to riparian vegetation in Bear Creek, Washington. Ph.D. thesis, University of Washington, Seattle.

Martin, D. J., E. O. Salo, S. T. White, J. A. June, W. J. Foris, and G. L. Lucchetti. 1981. The impact of managed streamside timber removal on cutthroat trout and the stream ecosystem. Part 1: Summary. FRI-UW-8107. Fisheries Research Institute, University of Washington, Seattle.

Meehan, W. R. 1970. Some effects of shade cover on stream temperature in southeast Alaska. USDA For. Serv. Res. Note PNW-113. Pac. Northwest For. and Range Exp. Stn., Portland, Oregon. 9 p.

Minkley, W. L. 1963. The ecology of spring streams, Doe Run, Meade County, Kentucky. Wild. Monogr. 2. 124 p.

Minshall, G. W. 1968. Community dynamics of the benthic fauna in a woodland springbrook. Hydrobiologia 32:305-337.

Moore, J. W. 1980. Factors influencing the composition, structure and density of a population of benthic invertebrates. Arch. Hydrobiol. 88:202-218.

Moring, J. R. 1975a. The Alsea Watershed Study: Effects of logging on the aquatic resources of three headwater streams of the Alsea River, Oregon. Part 2: Changes in environmental conditions. Fish. Res. Rep. 9. Oregon Department of Fish and Wildlife, Corvallis. 39 p.

_________. 1975b. The Alsea Watershed Study: Effects of three headwater streams of the Alsea River, Oregon. Part 3: Discussion and recommendations. Fish. Res. Rep. 9. Oregon Department of Fish and Wildlife, Corvallis. 24 p.

Murphy, M. L., and J. D. Hall. 1981. Varied effects of clear-cut logging on predators and their habitat in small streams of the Cascade Mountains, Oregon. Can. J. Fish. Aquat. Sci. 38:137-145.

Murphy, M. L., C. P. Hawkins, and N. H. Anderson. 1981. Effects of canopy modification and accumulated sediment on stream communities. Trans. Am. Fish. Soc. 110:469-478.

Nakatani, R. E. 1969. Effects of heated discharge on anadromous fish. In P. A. Krenkel and F. L. Parker (eds.) Biological aspects on thermal pollution, Vanderbilt University Press, Nashville, Tennessee.

Narver, D. W. 1972. A survey of some possible effects of logging on two eastern Vancouver Island streams. Fish. Res. Board Can. Tech. Rep. 323. 55 p.

Nebeker, A. V. 1971a. Effect of water temperatures on nymphal feeding rate, emergence and adult longevity of the stonefly, Pteronarcyla dorsata. J. Kansas Entomol. Soc. 44:21-26.

_________. 1971b. Effect of temperature at different altitudes on the emergence of aquatic insects from a single stream. J. Kansas Entomol. Soc. 44:26-35.

Needham, P. R., and A. C. Jones. 1959. Flow, temperature, solar radiation, and ice in relation to activities of fishes in Sagehen Creek, California. Ecology 40(3):465-474.

Newbold, J. D., D. C. Erman, and K. B. Roby. 1980. Effects of logging on macroinvertebrates in streams with and without buffer strips. Can. J. Fish. Aquat. Sci. 37:1076-1085.

Ordal, E., and R. E. Pacha. 1963. The effects of temperatures on disease in fish. In Water temperature: Influences, effects and control. Proceedings, Twelfth Pacific Northwest Symposium on Water Pollution Research. U.S. Public Health Service, Pacific Northwest Water Laboratory, Corvallis, Oregon.

Orska, J. 1963. The influence of temperature on the development of meristic characters of the skeleton in salmonidae. Part 2: Variations in dorsal and anal fin ray counts correlated with temperature during development of Salmo irideus. Transl., Bio. Abstr. 47(6): Abstr. 28237. 1966.

Parker, F. L., and P. A. Krenkel. 1969. Thermal pollution: Status of the art. Rep. 3. Department of Environmental and Water Resources Engineering. Vanderbilt University Press, Nashville, Tennessee.

Pearson, W. D., and D. R. Franklin. 1968. Some factors affecting drift rates of Baetis and Simuliidae in a large river. Ecology 49:75-81.

Phinney, H. K., and C. D. McIntire. 1965. Effect of temperature on metabolism of periphyton communities developed in laboratory streams. Limnol. Oceanogr. 10:341-344.

Reeves, G. H. 1985. Interaction and behavior of the redside shiner (Richardsonius balteatus) and the steelhead trout (Salmo gairdneri) in western Oregon: The influence of water temperature. Ph.D. thesis, Oregon State University, Corvallis. 101 p.

Reisen, W. K., and R. Prins. 1972. Some ecological relationships of the invertebrate drift in Praters Creek, Pitkene County, South Carolina. Ecology 53:876-884.

Reiser, D. W., and T. C. Bjornn. 1979. Influence of forest and rangeland management on anadromous fish habitat in western United States and Canada. Part 1: Habitat requirements of anadromous salmonids. USDA For. Serv. Gen. Tech. Rep. PNW-96. Pac. Northwest For. and Range Exp. Stn., Portland, Oregon. 54 p.

Reiser, D. W., and T. A. Wesche. 1979. In situ freezing as a cause of mortality in brown trout eggs. Prog. Fish-Cult. 41(2):58-60.

Reiser, D. W., and R. G. White. 1981. Incubation of steelhead trout and spring chinook salmon eggs in a moist environment. Prog. Fish-Cult. 43(3):131-134.

Ricker, W. E. 1972. Hereditary and environmental factors affecting certain salmonid populations. In R. C. Simon and P. A. Larking (eds.) The stock concept in Pacific salmon, p. 19-160. H. R. MacMillan Lectures in Fisheries. University of British Columbia, Vancouver.

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

Rishel, G. B., J. A. Lynch, and E. S. Corbett. 1982. Seasonal stream temperature changes following forest harvesting. J. Environ. Qual. 11(1):112-116.

Rounick, J. S., and S. V. Gregory. 1981. Temporal changes in periphyton standing crop during an unusually dry winter in streams of the western Cascades, Oregon. Hydrobiologia 83:197-205.

Scrivener, J. C., and B. C. Andersen. 1984. Logging impacts and some mechanisms that determine the size of spring and summer populations of coho salmon fry (Oncorhynchus kisutch) in Carnation Creek, British Columbia. Can. J. Fish. Aquat. Sci. 41:1097-1105.

Seymour, A. H. 1959. Effects of temperature upon formation of vertebrae and fin rays in young chinook salmon. Trans. Am. Fish. Soc. 88:58-69.

Sherberger, F. F., E. F. Benfield, K. L. Dickson, and J. Cairns, Jr. 1977. Effects of thermal shocks on drifting aquatic insects: A laboratory simulation. J. Fish. Res. Board Can. 34:529-536.

Sheridan, W. L. 1961. Temperature relationships in pink salmon stream in Alaska. Ecology 42(1):91-98.

Sheridan, W. L., and A. M. Bloom. 1975. Effects of canopy removal on temperature of some small streams in southeast Alaska. USDA For. Serv. Alaska Region, Juneau. 19 p.

Smith, B. D. 1980. The effects of afforestation on the trout of a small stream in southern Scotland. Fish. Manage. 11:39-58.

Steinblums, I., H. A. Froehlich, and J. K. Lyons. 1984. Designing stable buffer strips for stream protection. J. For. 82(1):49-52.

Stockner, J. G., and K. R. S. Shortreed. 1978. Enhancement of autotrophic production by nutrient addition in a coastal rainforest stream on Vancouver Island. J. Fish. Res. Board Can. 35:28-34.

Suberkropp, K., M. J. Klug, and K. W. Cummins. 1975. Community processing of leaf litter in woodland streams. Verh. Int. Ver. Limnol. 19:1653-1658.

Summers, R. P. 1983. Trends in riparian vegetation regrowth following timber harvesting in western Oregon watersheds. M.S. thesis, Oregon State University, Corvallis. 151 p.

Swift, L. W., and J. B. Messer. 1971. Forest cuttings raise temperatures of small streams in the southern Appalachians. J. Soil Water Conserv. 26(3):111-116.

__________. 1973. Lower water temperatures within a streamside buffer strip. USDA For. Serv. Res. Note SE-193. Southeastern For. Exp. Stn., Asheville, North Carolina. 7 p.

Thedinga, J. F., and K V. Koski. 1984. A stream ecosystem in an old-growth forest in southeast Alaska. Part 6: The production of coho salmon, Oncorhynchus kisutch, smolts and adults from Porcupine Creek. In W. R. Meehan, T. R. Merrell, Jr., and T. A. Hanley (eds.) Fish and wildlife relationships in old-growth forests: Proceedings of a symposium, p. 99-108. American Institute of Fishery Research Biologists.

Theurer, F. D., I. Lines, and T. Nelson. 1985. Interaction between riparian vegetation, water temperature, and salmonid habitat in the Tucannon River. Water Resour. Bull. 21:53-64.

Tschaplinski, P. J., and G. F. Hartman. 1983. Winter distribution of juvenile coho salmon (Oncorhynchus kisutch) before and after logging in Carnation Creek, British Columbia, and some implications for overwinter survival. Can. J. Fish. Aquat. Sci. 40:452-461.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37:130-137.

Walter, R. A. 1984. A stream ecosystem in an old-growth forest in southeast Alaska. Part 2: Structure and dynamics of the periphyton community. In W. R. Meehan, T. R. Merrell, Jr., and T. A. Hanley (eds.) Fish and wildlife relationships in old-growth forests: Proceedings of a symposium, p. 57-69. American Institute of Fishery Research Biologists.

Warren, C. E., and G. E. Davis. 1967. Laboratory studies on the feeding, bioenergetics, and growth of fish. In S. D. Gerking (ed.) The biological basis of freshwater fish production. Blackwell Science Publ., Oxford, England.

Warren, C. E., J. H. Wales, G. E. Davis, and P. Doudoroff. 1960. Progress report: Ecological studies of an experimental stream. Mimeographed report. Oregon State College, Corvallis.

Waters, T. F. 1968. Diurnal periodicity in the drift of a day-active stream invertebrate. Ecology 49:152-153.

Weber, P. K. 1981. Comparisons of the lower trophic levels of small stream communities in forest and clearcut sites, southeast Alaska. Ph.D. thesis, University of Washington, Seattle.

Wojtalik, T. A., and T. F. Waters. 1970. Some effects of heated water on the drift of two species of stream invertebrate. Trans. Am. Fish. Soc. 99:782-788.

Wurtsbaugh, W. A., and G. E. Davis. 1977. Effects of temperature and ration level on the growth and food conversion efficiency of Salmo gairdneri Richardson. J. Fish. Biol. 11:87-98.

Buffer Strips for Stream Temperature Control

by Jon R. Brazier
George W. Brown

April 1973
Research Paper 15

Forest Research Laboratory
School of Forestry
Oregon State University
Corvallis, Oregon

BUFFER STRIPS FOR STREAM TEMPERATURE CONTROL

Jon R. Brazier
U.S. Forest Service, Region 6
Portland, Oregon

George W. Brown
Associate Professor of Forest Hydrology
Oregon State University

Research Paper 15
April 1973

Paper 865
Forest Research Laboratory
School of Forestry
Oregon State University
Corvallis, Oregon 97331

SUMMARY

During clearcut logging, complete removal of the forest canopy and the shade it provides to small streams can cause large increases in water temperature. Such increases in temperature can be prevented if buffer strips of vegetation are left along the stream to provide shade. The purposes of this paper are to define the characteristics of buffer strips that are important in regulating the temperature of small streams and to describe a method of designing buffer strips that will insure no change in stream temperature as a result of logging and, at the same time, minimize the amount of commercial timber left in the strip.

Commercial timber volume alone is not an important criterion for temperature control. Further, the width of the buffer strip is also not an important criterion. For the small streams studied as part of this research, the maximum shading ability of the average buffer strip was reached within a width of 80 feet. Specifying standard 100- to 200-foot buffer strips for all streams generally will include more timber than necessary. The canopy density along the path of incoming solar radiation best describes the ability of the buffer strip to control stream temperature. An estimate of this value can be obtained easily by foresters laying out buffer strips in the field and will insure proper design of the buffer strip for control of stream temperature.

ACKNOWLEDGMENTS

This research was sponsored by the Environmental Protection Agency under grant 16130 FOK and Oregon State University.

The authors are indebted to Richard Marlega and Claude McLean of the U.S. Forest Service for their help in developing management guidelines and collecting data.

BUFFER STRIPS FOR STREAM TEMPERATURE CONTROL

Jon R. Brazier
George W. Brown

INTRODUCTION

The purposes of this research paper are to define the characteristics of buffer strips that are important in regulating the temperature of small streams and to describe a method of designing buffer strips that will insure no change in temperature and, at the same time, minimize the amount of commercial timber left in the strip to provide the necessary shade.

Research shows that clearcut logging can increase significantly the temperature of small streams (5, 9, 11). Temperature increases from 6 to as much as 28 degrees F have been reported. The magnitude of the increase is dependent upon stream characteristics such as discharge or flow, surface area exposed to sunlight, and amount of radiation received from the sun. Brown (3) showed that heat received by a stream exposed by clearcutting may be from five to six times that received when the stream was shaded.

Changes in temperature may influence fish habitat in several ways. As temperature increases, the ability of stream water to hold dissolved oxygen declines. Aquatic pathogens also may find warmer water more conducive to development. At extremely high temperatures, fish may be unable to survive because their lethal limit has been reached. High temperature of the water also may influence the metabolic processes of fish and, although it may not cause direct mortality, it may adversely affect growth, development, and body condition. Finally, water temperature may alter the species composition of a stream as temperatures shift from the optimum range for one species to the optimum range for another. The impact of these changes in habitat on the productivity of a particular stream is difficult to predict because of the interaction of so many variables. Most standards for water quality, however, severely restrict the amount of change in temperature permissible because of the many possible consequences.

Increases in the temperature of small streams can be prevented during and after logging by leaving a protective strip of vegetation alongside the stream to provide shade. The efficiency of this strip in controlling water temperature has been demonstrated in several studies (5, 6, 11). Guidelines for the protection of streams in logged watersheds have recommended buffer strips for temperature control (7, 8, 10, 12). In one guide (7), a standard width is specified. This standardization results in utilization of the timber resource that is less than optimum by creating buffer strips larger than necessary for temperature control. In other guides (8, 12), variable widths are suggested. Only generalized specifications are given, however.

STUDY SITES AND METHODS

Study Sites

Study sites were located on nine small mountain streams in Oregon. Three streams, Little Rock, Francis, and Reynolds Creeks, are in the Umpqua National Forest in the southern Cascade Mountains. Five others, Deer, Lake, Grant, Griffith, and Savage Creeks are in the Siuslaw National Forest in the Coast Range. The remaining stream, Needle Branch, is on land owned by Georgia Pacific Corporation in the Coast Range.

The streams all flow through or are adjacent to clearcuttings. All have a strip of vegetation that separates them from the clearcuttings. On Needle Branch, the strip consists of red alder, which has grown up rapidly along the stream after clearcutting. All are valuable for fish production and have a potentially large problem of temperature.

Methods

Discharge, stream travel time past the clearcutting, surface area of the stream in the clearcutting, and water temperature above and below the clearcutting were measured.

The buffer strips were described by the volume of commercial timber in the strip, the average strip width, and the density of forest canopy (Table 1). Volume of commercial timber was determined by conventional timber cruising techniques. Average strip width was measured with a tape. Canopy density was measured along the path of incoming solar radiation rather than vertically, as is done normally. This measure of canopy density, called angular canopy

Table 1. A Comparison of Various Measured and Calculated Parameters for the Study Streams.

Stream	Temperature change: Predicted	Temperature change: Observed	Heat blocked, ΔH	Angular canopy density, ACD	Average strip width	P-O[1]	Timber volume/ foot of strip	Maximum temperature: Observed	Maximum temperature: Predicted
	F	*F*	*BTU/ft² min*	*Percent*	*Ft*	*F*	*Bd ft*	*F*	*F*
Little Rock	10.1	6.0	1.4	73.6	47	4.0	50	72.0	76.0
Upper Reynolds	4.8	7.5	0.0	18.3	10	-2.7	0	74.5	72.0
Lower Reynolds	1.6	3.0	0.0	46.9	40	-1.4	42	71.5	70.0
Upper Francis	41.9[2]	2.0	3.8	75.9	50	39.9	78	62.0	101.9
Upper Deer	7.6	4.0	2.0	80.3	100	3.6	11	57.0	60.5
Lower Deer	9.0	1.0	3.7	78.3	100	8.0	102	56.0	64.0
Lake	12.5	3.0	3.1	77.7	30	9.5	2	61.0	70.5
Upper Grant	4.4	2.0	2.3	59.1	60	2.4	42	55.0	57.5
Lower Grant	4.3	1.0	3.2	65.2	60	3.3	42	55.0	58.5
Griffith	21.7	3.0	3.5	79.1	50	18.7	137	62.0	80.5
Upper Needle Branch	32.0[2]	9.0	2.8	55.6	8	23.0	0	67.0	90.0

[1]The predicted temperature change minus the observed temperature change.
[2]Predicted from the equilibrium temperature calculation.

density and abbreviated *ACD*, was estimated with the device shown in Figure 1. This instrument consists of a 1-foot-square plane mirror marked with a 3-inch grid. The mirror can be tilted so that the observer, looking down vertically on the mirror, will see the canopy along a predetermined angle. The mirror is canted to an angle equal to the complement of the maximum angle of the sun for the time of year when the temperature problem is greatest, generally July or August. This period will vary depending on streamflow regimes and climate. Usually, the highest temperatures occur during the period with the lowest streamflow.

Angular canopy density was measured at 100-foot intervals. The angular canopy densiometer was placed in the stream, pointed south, leveled, and tilted to the proper angle. Angular canopy density then was determined by counting the number of squares and fractions of squares on the mirror covered by the canopy. This number was converted to percentage of canopy coverage.

Figure 1. The angular canopy densiometer.

Linear and nonlinear regression analyses were used to determine the buffer strip characteristic that had the greatest effect in controlling stream temperature. The dependent variable in each analysis was the heat blocked by the buffer strip. The heat blocked by the strip (ΔH) was calculated by two methods. One was based upon a temperature prediction formula developed by Brown (4) and the other upon equilibrium temperature formulae developed by Brady, Graves, and Geyer (1). Both methods utilize the concept that the difference between the observed change in temperature and that predicted must be because of the protective ability of the buffer strip. In other words, the strip intercepts the quantity of heat necessary to raise the temperature of the water from the observed to the predicted levels. The effectiveness of the buffer strip increases as the amount of heat blocked (ΔH) increases. Details for calculating ΔH are presented by Brazier (2).

RESULTS

Commercial Timber Volume and Buffer Strip Efficiency

Hypothetically, there should be little relation between commercial timber volume and ΔH. This is because commercial timber volume alone has no relation to the shading ability of the vegetation in the buffer strip. Species such as salmonberry have no commercial volume, but are often excellent sources of shade for small streams. In contrast, a strip composed only of a few large trees with a large commercial volume may have little protective ability because of spacing. Eventually, on any given stream, as the commercial volume per foot of stream increases, the spacing of the trees will decrease so that the strip will have a positive effect on stream temperatures.

The relation between volume of commercial timber and efficiency of the buffer strip is illustrated in Table 2 and Figure 2. One stream, Savage Creek, received no shade from the conifers in the strip; they were on the north side of the stream. Linear regression analysis was used to describe the relation between commercial timber volume and ΔH in Figure 2. The hypothetical limits are shown on this figure as the upper horizontal line, which indicates maximum shading regardless of volume, and the lower curved line, which indicates some minimum shade level. Two streams, noted by circles, are not included in the analysis because these streams were physiographically different from the other streams. Both streams lie in

Table 2. A Comparison of the Commercial Volume of the Buffer Strips in Conifers and the Percentage of Shade Contributed by the Conifers.

Stream	Commercial volume in conifers[1]	Shade contributed by conifers
	Bd ft	*Percent*
Little Rock	75,000	87.5
Lower Reynolds	25,118	33.0
Upper Francis	187,885	79.2
Lower Francis	55,145	83.3
Lower Deer	138,830	25.0
Upper Grant	36,073	10.0
Lower Grant	36,073	10.0
Griffith	411,625	74.2
Savage	194.980	0.0

[1]The other buffer strips were composed entirely of hardwood and brushy species of vegetation.

broad, flat valleys rather than V-shaped canyons. They are included in Figures 2, 3, and 4 to illustrate the influence of topography on the amount of radiation received by streams. On these two streams, canyon walls do not help shade the stream and additional energy reaches the stream by side lighting. Thus, the energy blocked (ΔH) is less. The analysis showed a poor relation ($R^2 = 0.2661$ between commercial volume per foot of stream and ΔH.

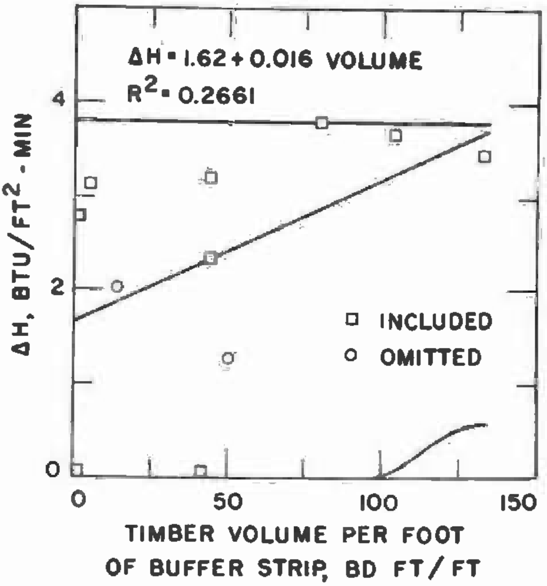


Figure 2. The observed relation between buffer strip volume and heat blocked (ΔH).

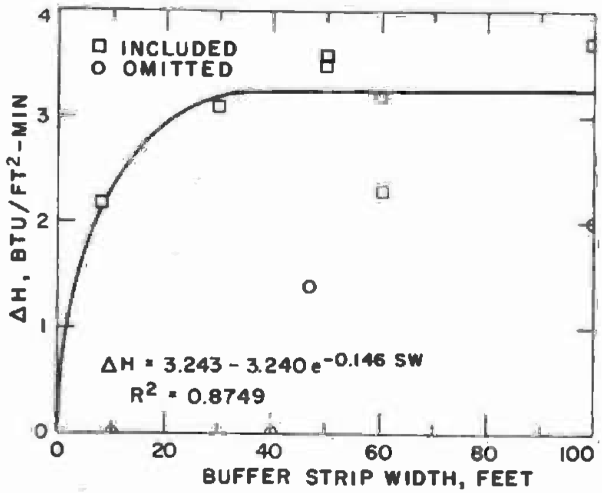


Figure 3. The observed relation between buffer strip width (SW) and heat blocked (ΔH).

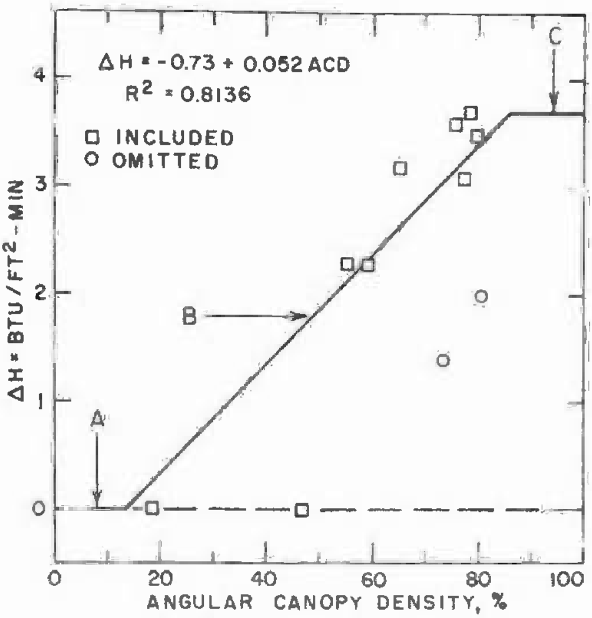


Figure 4. The observed relation between angular canopy density (ACD) and heat blocked (ΔH).

Buffer Strip Width and Efficiency

Strip width, alone, should have little to do with the ability of the vegetation in the strip to shade the stream. Strip width is related to the effectiveness of buffer strips through a complex interrelation of canopy density, canopy height, stream width, and stream discharge. On small streams such as those included in this study, the relation between ΔH and strip width can be viewed as asymptotic. The quickness with which the relation approaches some asymptote is a function of the type of vegetation contained in the strip. Vegetation such as salmonberry provides only a narrow band of shade along the stream because of its height. Strips wider than this narrow section should not improve in effectiveness. Trees generally have canopies of lower density than species such as salmonberry and, thus, require more space to provide the same shade.

The relation between strip width and efficiency is shown in Figure 3. Four sections were omitted from the analysis: two because of channel shape and two because of difficulties in defining precisely the strip width because of irregularity. Nonlinear regression analysis was used to analyze this relation. The curve in Figure 3 was forced through the origin. The high value of R^2. (0.8749) indicates that the curve is a good approximation of the relation.

Angular Canopy Density and Buffer Strip Efficiency

The hypothetical relation between ΔH and angular canopy density, *ACD*, may be considered logistic in nature. Low canopy densities, although reducing the solar radiation incident to the stream in direct proportion to the percentage of sky covered, do not provide sufficient shade for the effect to be measurable. Thus, the value for ΔH is zero until some measurement threshold is reached.

Above this value, there should be a direct, linear relation between ΔH and *ACD* until the canopy approaches full closure. As the canopy density approaches 100 percent, additional increments of density should block less radiation than the previous increment. This is because, at high canopy densities, the possibility for reflection and absorption of the incident radiation increases, which allows mostly diffuse radiation to reach the stream.

The level of this diffuse radiation is controlled by factors other than canopy density. The volume of vegetation in the canopy influences the amount of transmission. The thicker canopies provided by conifers are more efficient traps of radiation than the thin canopies of hardwoods, even though the canopy densities may be the same. Thus, with greater canopy density, the relation between ΔH and ACD should approach some asymptote at a level less than complete blockage of incident radiation. Values of ΔH for undisturbed canopies are in the range from 3.0 to 3.6 British thermal units per square foot per minute (BTU ft^{-2} min^{-1}) (3,6). This corresponds with values calculated in this study.

The relation between angular canopy density and ΔH is shown in Figure 4. Two streams again are omitted from the analysis because of the surrounding terrain. Problems with the computer programs prevented fitting a logistic curve to the data. For this reason, a straight-line approximation to the logistic curve was used. Segment A represents the ACD values below the measurement threshold level, which occurs at about 14 percent with these data. This point was determined by the zero intercept of the linear regression analysis used for segment B. Line segment B is the section of increasing buffer-strip effectiveness with increasing ACD. The line fits the data well with an R^2 value of 0.8939. Segment C is the area of maximum protection. The maximum value was determined from data on net radiation from protected streams as explained above. Once the maximum protection has been reached, increases in ACD offer no greater protection.

The relation between angular canopy density and strip width for all the streams studied is illustrated in Figure 5. This figure provides additional evidence that for small streams, narrow buffer strips may be sufficient to provide stream protection. For the streams included in this study, the maximum angular canopy density is reached within a width of 80 feet. Moreover, 90 percent of that maximum is reached within 55 feet.

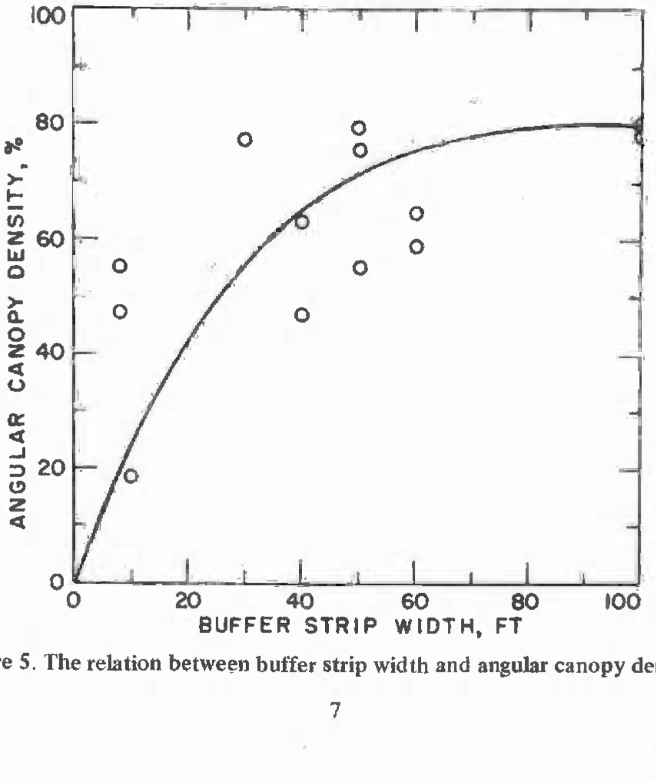


Figure 5. The relation between buffer strip width and angular canopy density.

Establishing Buffer Strips

Buffer strips can be designed easily with the results of this study so that no change in the natural temperature regime will occur after logging, and the volume of commercial timber left in the strip will be minimized. The procedure for laying out such a strip is as follows:

Place the angular canopy densiometer in the stream. Level it, point the mirror south, and tilt it to the complement of the solar angle for July or August.

Look into the mirror and determine which trees and shrubs are providing shade for the stream. Mark these for inclusion in the strip.

Move to the next station and repeat the procedure. The distance between stations is a matter of judgment, but should be no more than 100 feet. Fewer stations are required in uniform conditions of vegetation and topography. In many instances, the shade contribution of each tree must be evaluated if it is particularly valuable.

The buffer-strip boundaries determined by this method later can be modified to provide protection from destruction of the stream bank or accumulation of debris in the channel if the situation demands. A strip designed with the angular canopy densiometer probably should be regarded as minimum for these purposes.

CONCLUSIONS

The results of this study lead to some interesting conclusions about designing buffer strips for temperature control.

Commercial timber volume alone is not an important criterion for temperature control. The effectiveness of buffer strips in controlling temperature changes is independent of timber volume.

Width of the buffer strip, alone, is not an important criterion for control of stream temperature. For the streams in this study, the maximum shading ability of the average strip was reached within a width of 80 feet; 90 percent of that maximum was reached within 55 feet. Specifying standard 100- to 200-foot buffer strips for all streams, which usually assures protection, generally will include more timber in the strip than is necessary.

Angular canopy density is correlated well with stream-temperature control. It is the only single criterion the forester can use that will assure him adequate temperature control for the stream without overdesigning the buffer strip.

LITERATURE CITED

1. BRADY, D. K., W. L. GRAVES, and J. C. GEYER. Surface Heat Exchange at Power Plant Cooling Lakes. Edison Electric Institute, New York City, New York. Publ. 69-901. 153 p. 1969.

2. BRAZIER, J. R. Controlling Water Temperatures with Buffer Strips. M.S. Thesis. Oregon State Univ., Corvallis. 65 p. 1973.

3. BROWN, G. W. "Predicting Temperatures of Small Streams." Water Resources Res. 5:68-75. 1969.

4. BROWN, G. W. "Predicting the Effect of Clearcutting on Stream Temperature." J. Soil and Water Conserv. 25:11-13. 1970.

5. BROWN, G. W. and J. T. KRYGIER. "Effects of Clearcutting on Stream Temperature." Water Resources Res. 6:1133-1139. 1970.

6. BROWN, G. W., G. W. SWANK, and J. ROTHACHER. Water Temperature in the Steamboat Drainage. Pac. N.W. For. and Range Expt. Sta., For. Service, U.S. Dept. of Agric., Portland, Oregon. Res. Paper PNW-119. 17 p. 1971.

7. FEDERAL WATER POLLUTION CONTROL ADMINISTRATION. Industrial Waste Guide on Logging Practices. U. S. Dept. of Interior, Northwest Reg., Portland, Oregon. 40 p. 1970.

8. LANTZ, R. L. Guidelines of Stream Protection in Logging Operations. Oregon State Game Comm., Portland, Oregon. 29 p. 1971.

9. LEVNO, A. and J. ROTHACHER. Increases in Maximum Stream Temperatures After Logging in Old-Growth Douglas-Fir Watersheds. Pac. N. W. For. and Range Expt. Sta., For. Service, U.S. Dept. of Agric., Portland, Oregon. Res. Note PNW-65. 12 p. 1967.

10. SOCIETY OF AMERICAN FORESTERS, COLUMBIA RIVER SECTION, WATER MANAGEMENT COMMITTEE. "Recommended Logging Practices for Watershed Protection in Oregon." J. Forestry 57:460-465. 1959.

11. SWIFT, L. W. and J. B. MESSER. "Forest Cuttings Raise Temperatures of Small Streams in the Southern Appalachians." J. Soil and Water Conserv. 26:111-116. 1971.

12. U.S. DEPARTMENT OF AGRICULTURE, FOREST SERVICE. Guides For Protecting Water Quality. Pac. N. W. For. and Range Expt. Sta., Portland, Oregon. 27 p.

JDSF Newsletter
Jackson Demonstration State Forest
State of California Dept. of Forestry P.O. Box 1185 Fort Bragg, CA. 95437

No. 39 October 1990

TEMPERATURE REGIMES OF SMALL STREAMS ALONG THE MENDOCINO COAST

Peter Cafferata

Stream temperature measurements have been collected in the Caspar Creek drainage on Jackson Demonstration State Forest periodically over the past 25 years. Review of this data and other recently collected data from western Mendocino County illustrates much about the temperature regimes of small coastal drainages, and how they are impacted by timber harvesting. This article gives a synopsis of these studies and summarizes reasons for concern. Additionally, it presents a model currently in use by the U.S. Forest Service to predict changes in maximum summer temperatures resulting from canopy reductions.

INTRODUCTION AND BASIC PRINCIPLES

Concern over elevated stream temperatures resulting from logging have generally centered around impacts on the fisheries resource. Field and laboratory studies done in many areas show that high water temperatures increase the metabolic rate of fish, increase their susceptibility to pathogens, and decrease the dissolved oxygen content of the water. Temperature changes that can result from logging may have indirect or sub-lethal effects on salmonid fish populations. Examples of these impacts include: decreases in the emergence time of fry from gravels; earlier, less favorable smolt migration to the sea; and lowered abundance and diversity of food organisms (Holtby 1988).

Various species of salmonids respond differently to elevated stream temperatures. Water temperatures for good survival and growth of juvenile coho salmon range from 50° to 59° F, with 55° appearing to be the optimum. Growth is slowed considerably at 64° and ceases at 68°. The upper lethal limit has been reported to be 78° from laboratory studies (Bell 1973). Young steelhead trout prefer temperatures between 45° and 68° F, with the optimum about 56°. The upper lethal limit is considered to be 82° (W. Jones, CDF&G, pers. comm.). Both species are stressed at temperatures over 68° F. Chinook salmon juveniles rarely over-summer in freshwater, so they are the least affected.

Researchers have documented that slight temperature increases in small headwater streams following harvesting sometimes increases fish biomass. This results from greater primary production, and subsequently higher production throughout the food chain for these fishes. The cumulative or additive effect resulting from harvesting many areas in a sizable watershed on mid-order (i.e., larger) streams usually has not been addressed. It is likely that moderate stream temperature increases are a significant problem for streams inland from the buffered coastal environment.

Stream temperatures increase after logging largely because of the increased exposure of the stream surface to solar radiation. Higher air temperatures resulting from harvesting are not the reason for higher water temperatures (Brown 1969). The key factors to consider are the surface area of the stream exposed to sunlight, and its discharge (i.e., amount of streamffow at a given time).

CALIFORNIA DEPARTMENT OF FORESTRY AND FIRE PROTECTION
Harold R. Walt, Director

George Deukmejian
Governor
State of California

Gordon K. Van Vleck
Secretary for Resources
The Resources Agency

Buffer strips have been required along all streams bearing fish since 1973 in California. One of the reasons for this requirement was to reduce the potential adverse impacts of increased stream temperatures due to logging. These protection zones vary in width based on the steepness of the ground, and require half of the initial shade-producing canopy to remain following harvest. Effective buffer strips for temperature control are those which leave the trees and shrubs that actually shade the stream during the critical summer months of the year. The size of a stream, its orientation(east-west vs north-south), surrounding topography, and type and density of vegetation need to be considered when designing a buffer strip. In addition, attention must be given to stability during windstorms and damage from logging and slash burning.

TWO CASE STUDIES OF COASTAL STREAMS

A. Caspar Creek

As part of the Caspar Creek Watershed Study, stream temperatures were measured in the North and South Forks from 1965 to 1969,and again from 1988 to the present. When the first data was collected, the second-growth redwood and Douglas-fir forest was 60 to 80 years old. The entire 5,000-acre basin extends inland only six miles and empties directly into the ocean. Periods of summer fog exist, but often burns off before mid-day beyond three miles inland. Both gauged tributaries are slightly more than 1,000 acres.

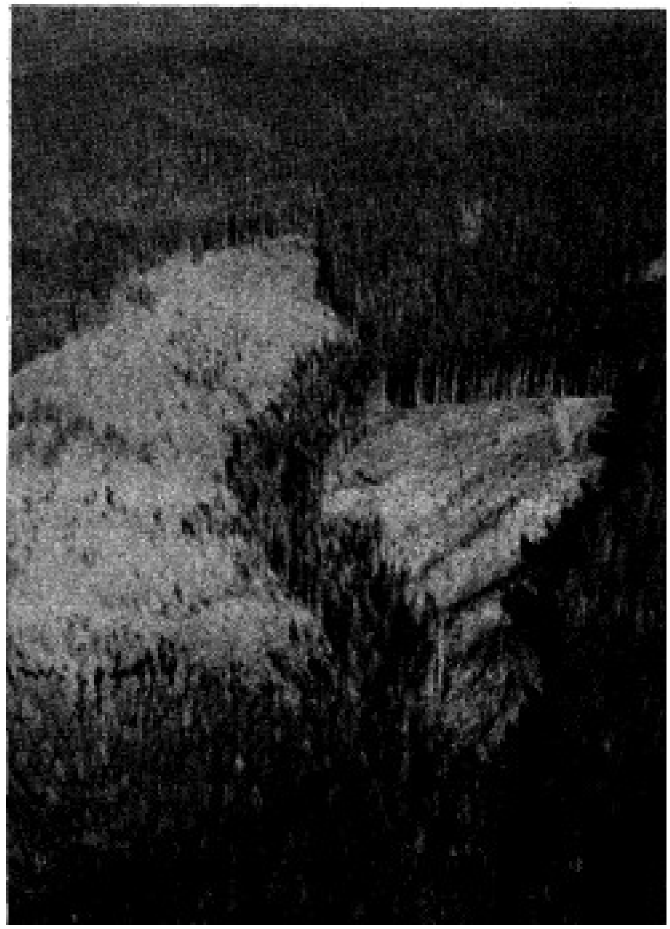


Figure 1. Aerial view of the North Fork of Caspar Creek.

Most observed summer maximum stream temperatures (i.e., the highest temperature during a 24-hour period) in both forks before disturbance were slightly below 60° F. Absolute maximums of 62° F were recorded several times. Road building in the South Fork in 1967 left 3,000 feet of the channel with greatly decreased shading. Maximum water temperatures were frequently near 70° F, and most were above 60°. The highest single temperature observed after roading was 78° F. Two years after the road was built, temperature increases of 3° to 4° F were documented for water flowing from shaded to open areas. No data was collected after selective harvesting was done in the South Fork.

In 1988, electronic data loggers were installed to record water temperatures at two locations in the South Fork and five locations in the North Fork, prior to clearcut harvesting. Small, totally uncut tributary basins in the North Fork show summer maximum temperatures of about 56° F. Average daily highs are about 54° F. Diurnal fluctuations are slight, with daytime highs usually only about 1.3° F higher than nighttime lows. A temperature station on the mainstem below recent clearcut harvests with buffer strips on both sides of the channel shows summer maximums of 61° F (see Figure 1). Average daily highs are approximately 59° F. Diurnal fluctuations here are common ly 4° F (see Figure 2). Large masses of filamentous algae now grow in most of the open stretches, probably due to the increased light. Further down the mainstem, summer maximums are 60° F; this site is slightly diluted with cooler water from three uncut tributaries below the clearcuts. The highest stream temperatures in the North Fork are found just above the large weir pond. Shading is very poor and sum mer peaks reached 65° F.

Winter low temperatures on these streams have dropped down to 36° F, but usually are no lower than 37.5° F. High temperatures for winter days are around 46° F. During cloudy, rainy conditions, temperatures show little fluctuation and may be considerably warmer (e.g., 50° F).

B. Railroad Gulch

Railroad Gulch is a 2000-acre tributary of the Albion River, located about seven miles south of Caspar Creek. This drainage is owned by Louisiana-Pacific Corporation and ex-

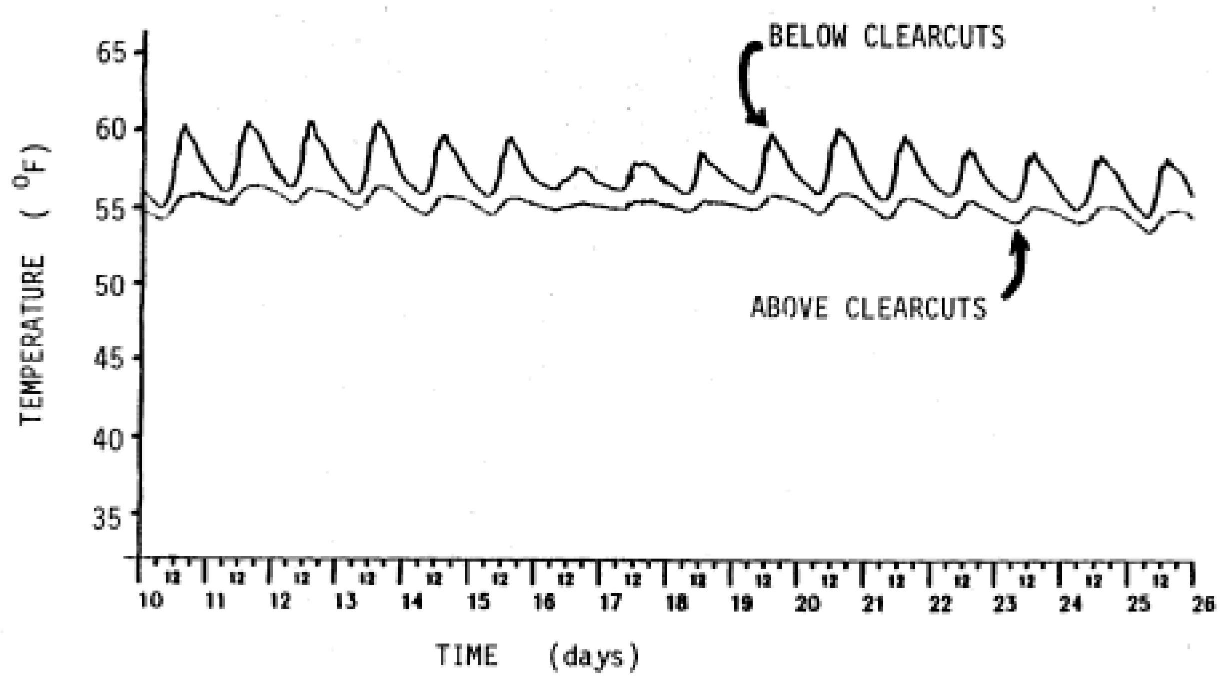


Figure 2. Plot of stream temperature, North Fork of Caspar Creek, July 10 - 25, 1990.

tends inland five miles from the ocean. Electronic data loggers were installed at two locations prior to harvesting. The first site is an uncut fork of the gulch (800 acres) with a measured shade canopy of 93 percent (see Figure 3). A device called a solar pathfinder was used to determine the canopy shading the water; it has proven to be an excellent tool for this job (see Figure 4). Maximum summer temperatures were found to be 58.5° F, with daily highs averaging 54.5° F. The lower site was used to document the impacts of clearcut harvesting a 40-acre block, with a buffer strip on both sides. A high water table through this reach had partially killed shade producing trees prior to harvest, and pre-logging maximums were 61.5° F. Daily highs averaged about 57° F. Following harvest, the effective shade for the stream was measured at 62 percent, and maximum water temperatures were 63° F. Average daily highs were 57.5° F.

PREDICTING STREAM TEMPERATURE INCREASES

In order to predict stream temperature increases, several parameters must be measured or estimated. These include: discharge, stream length impacted by logging, average stream width, travel time for the water to move through the harvested area, the effective shade before harvest, and estimated shade after harvest. Using an equation developed by Brown (1969) and modified by Amaranthus (1983), it is possible to calculate what the maximum increase in stream temperature will be.

The recent clearcuts in the North Fork of Caspar Creek were used to test this equation (see Figure 1). We measured the parameters on July 17, 1990. The North Fork example is shown in Table 1.

The observed increase is about 4° F, based on measurements taken above and below the clearcut reach (see Figure 2). Incomplete information was available to test the equation for Railroad Gulch. No estimate of shade before logging was made, and no measurement of travel time through the logged reach was done.

Table 1. A method to predict maximum stream temperature increase.

discharge = 0.20 cfs
length of flowing stream impacted by harvesting = 1800 feet
average stream width = 3.4 feet
travel time for the water through the unit = 6 hours
heat input, based on latitude and travel time = 4.19 BTU/ft^2-min (from published data)
shade before logging = 93 percent
shade after logging = 80 percent

The equation to predict temperature change (Δ T) is:

$$\Delta T = \frac{\text{Area x Heat x Percent Shade Lost}}{\text{Discharge}} \text{ x conversion factor}$$

$$\Delta T = \frac{\text{1800 feet x 3.4 feet x 4.19 BTU/ft}^2\text{–min x 0.13}}{\text{0.20 cfs}} \text{ x 0.000267}$$

$$\Delta T = 4.5° F$$

SUMMARY

Small coastal streams in Mendocino County provide valuable anadromous fish habitat. Prior to timber harvest operations in second-growth forests, maximum stream temperatures are generally below 60° F. Full exposure to solar radiation, as was permitted before modern Forest Practice Rules went into effect, sometimes allowed unacceptable temperature increases to occur. For the two case studies presented here, large temperature increases did not occur from clearcut harvesting with buffer strips. The predictive equation can be used to estimate what the maximum temperature increase will be from logging. The California Department of Forestry and Fire Protection (CDF) will soon pro vide foresters in California with a guidebook on watercourse tempera ture prediction.

ACKNOWLEDGMENTS

The Caspar Creek data was collected as part of a joint watershed study being conducted by CDF and the USFS's Pacific Southwest Research Station. The Railroad Gulch data was supplied by Lee Susan of Louisiana-Pacific Corporation.

REFERENCES

Amaranthus, M. P. 1983. Quantification of effective streamside shade utilizing the solar pathfinder. USDA For. Serv. Reg. 6. Siskiyou N.F., Grants Pass, OR.

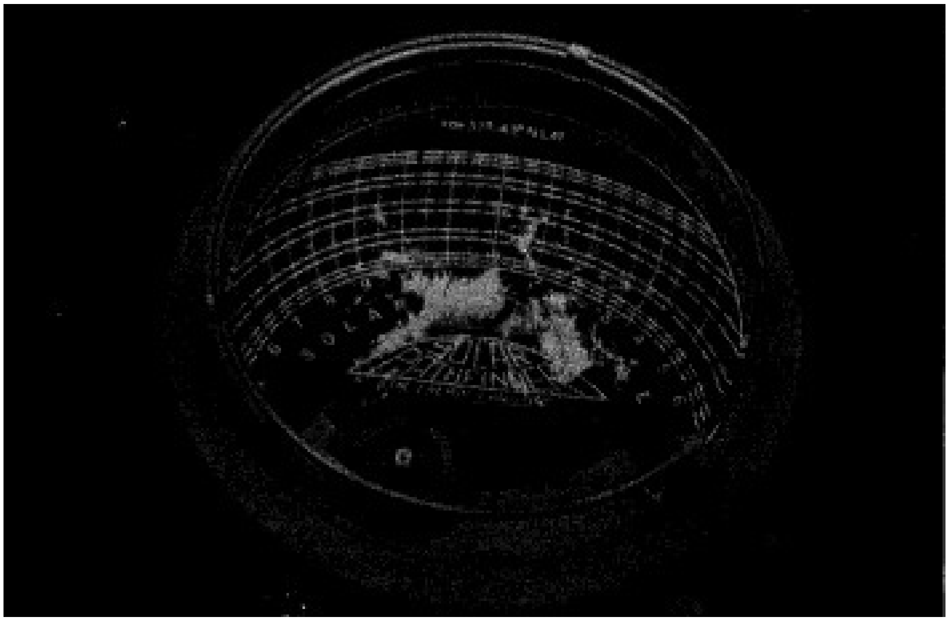
Bell, M. C. 1973. Fisheries handbook of engineering requirements and biological criteria. U.S. Army Corps. of Engineers. Portland, OR. Contract No. 57-68-C-0086. 425 pp.

Brown, G. W. 1969. Predicting temperature of small streams. Water Res. Research. 5(1):68-75.

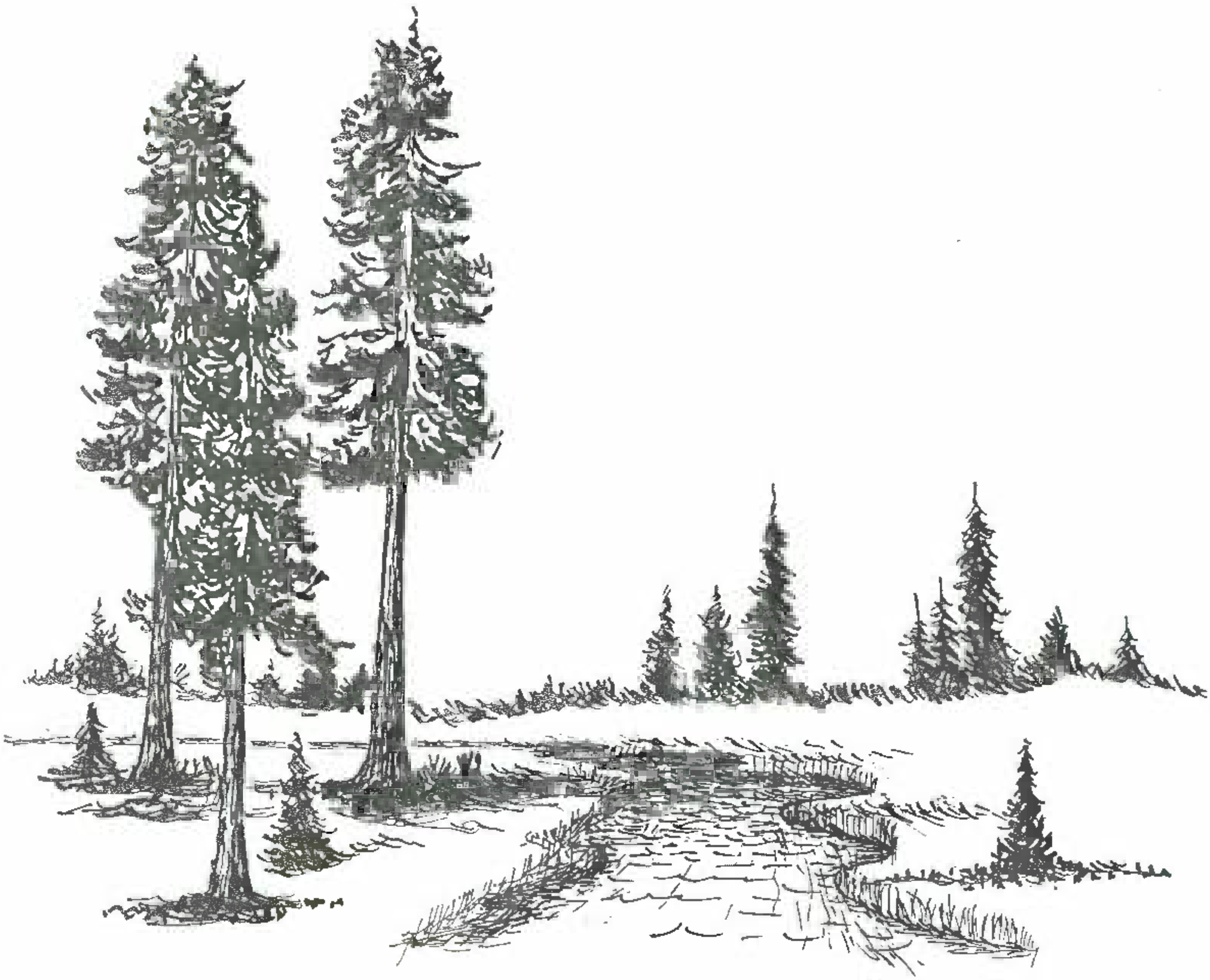
Holtby, L. B. 1988. Effects of logging on stream temperatures in Carnation Creek, British Columbia, and associated impacts on the coho salmon. Can. J. Fish. Aquat. Sci. 45:502-515.

Figure 3. Measuring canopy shade at Railroad Gulch. (Above)

Figure 4. Top view of a solar pathfinder. (Below)
(Dark areas indicate shade, light areas are unshaded)



Watercourse Temperature Evaluation Guide



Peter H. Cafferata
Prepared by California Department of Forestry and Fire Protection

George Deukmejian
Governor
State of California

Gordon Van Vleck
Secretary for Resources
The California Resources Agency

Harold R. Walt
Director
California Department of Forestry and Fire Protection

1990

WATERCOURSE TEMPERATURE EVALUATION GUIDE

I. INTRODUCTION

There are several reasons to be concerned about increased stream temperatures in the forest environment. Fishery impacts are generally considered to be the most important. Elevated stream temperatures can reduce salmonid juvenile survival rates and lower the abundance and diversity of food organisms for fish (Beschta et.al. 1987). High water temperatures increase the metabolic rate of fish, increase the number of pathogens attacking them, and decrease the dissolved oxygen content of the water. These problems are most pronounced in the late summer months, when streamflows are very low and there is a large amount of solar energy available to heat the water. Temperature changes which can occur from logging often result in indirect or sublethal effects on fish populations (Holtby 1988). Examples of these types of impacts include the decrease in the emergence time of fry from gravels, and also earlier, less favorable smolt migration to the sea. Other reasons for concern about high stream temperatures exist as well. They include the increase of algae production, reducing the esthetic qualities of the water, as well as affecting its color, odor, and taste (Amaranthus 1984). Additionally, high temperatures result in reduced waste assimilation capacities of streams (McGurk 1988)

Various species of salmonids respond differently to elevated stream temperatures. In California, coho salmon require the coolest summer water (see Table 1). Steelhead trout are not as sensitive to higher temperatures as the coho, and chinook salmon juveniles do not over-summer in freshwater; they migrate to the ocean after only two to three months. Generally, stream temperatures of 50° to 64° F are optimum for salmonids, with chronic stress experienced from 65° to 75° F (Patton 1973). Coho juveniles are found in abundance where there are undercut banks, large amounts of in-stream woody cover, overhanging vegetation, and an overstory canopy shading the channel. The need for cool water is particularly important to coho in northern California, because of the warmer summer temperatures at this latitude, and the fact that this location is the southern part of the species range. Also, the farther inland one goes, away from the cooling summer fog along the ocean, the greater the need for cool stream water. In addition, salmonids have more acute temperature problems during periods of drought, when low summer flows have less capacity to buffer the heat inputs (Cafferata et.al. 1989). Finally, increased temperatures can favor the introduction and proliferation of warm water species, while more desirable salmonids are displaced (Amaranthus 1984).

In addition to the need to look at stream temperature changes in a regional context, one must consider the location within the watershed being impacted. Many studies have shown increases in fish biomass following harvesting along headwater streams, but the cumulative effect on mid-order streams has not generally been considered (Toews and Moore 1982, Beschta et.al. 1987). Heat, once added to a stream, is not easily

Table 1. Temperature ranges for coho salmon fry (after McMahon 1983).

Optimum rearing habitat in summer	50 to 59° F
Habitat unsuitable if temperature exceeds	68° F
Growth ceases at temperatures of	68.5° F
Upper incipient lethal temperatures	73.2 to 77° F

dissipated (Brown 1980). Small, narrow streams may be adequately shaded by understory vegetation to a large degree (i.e., alders, willows, berries, etc.), while wider streams lower in the drainage may require large overstory trees of significant height and density.

Clearcuts along small forest streams have been shown to increase water temperatures from 5° to 28°F when no buffer strip has been left. Examples of these increases in the Pacific Northwest include: the Alsea drainage in the coastal mountains of central Oregon - 28°F (Brown and Krygier 1970), the H. J. Andrews Experimental Forest in the Oregon Cascades - 12°F (Levno and Rothacher 1967), and the Steamboat Creek drainage in southwestern Oregon - 13°F (Brown et.al. 1971). The South Fork of Caspar Creek on Jackson Demonstration State Forest in coastal Mendocino County exhibited a 10°F rise in stream temperature after building a main haul road near the channel (DeWitt 1968). Increases at Caspar Creek were well correlated with the degree of canopy removal. When buffer strips were left with no removal, a small stream at Alsea showed no temperature change. In the Steamboat Creek drainage, where thin buffer strips were left, increases of 1° to 4°F were documented.

Stream temperatures increase after logging largely because of the increased exposure of the stream surface to solar radiation (Brown 1969). Conductive heat transfer to channel bedrock, as well as evaporative and convective heat transfers are of only minor concern. Therefore, high air temperatures do not cause stream temperatures to increase following timber harvest. The key factors to consider are the surface area of the stream and its discharge. For a given net input of solar radiation, change in temperature is directly proportional to surface area and inversely proportional to discharge. Net radiation comprises both short and long wave components, but shortwave, or incoming solar radiation, is by far the most important factor. Exposed streams may experience large diurnal fluctuations in temperature, because the amount of direct solar radiation available to them can be substantial.

To reduce the potential impacts of increased stream temperatures, buffer strips (i.e., watercourse protection zones) are required in California along streams with fisheries resources, and generally along streams which provide habitat for non-fish aquatic life. While buffer strips supply benefits beyond just stream shading (i.e., sediment filtering, stream-bank stabilization, large woody debris for future stream use, wildlife habitat, etc.), for the purposes of this discussion we will only consider the widths and densities needed for temperature control.

Effective buffer strips for temperature control are those which leave the trees and shrubs which actually shade the stream during the critical months of the year. For small forest streams, the maximum shading ability of the average strip is usually reached within a width of 80 feet up the side slope. About 90 percent of that maximum will be reached within the first 55 feet (Brazier and Brown 1973). The size of a stream, its orientation, surrounding topography, and type and density of vegetation need to be considered when designing a buffer strip. In addition, the forester must consider how stable the buffer strip will be. Wind damage accounts for most of the loss, with the remainder due to logging damage, insects, and disease (Steinblums et.al. 1984).

The recovery of shade producing species in the riparian zone after harvesting varies with location. Alder, willows, and cottonwood may provide some shade within five years of stream disturbance (Brown et.al. 1971). Summers (1983) observed that it took 14 years for effective shade density to equal that of undisturbed stands following harvesting and burning in the Oregon Coast Range. In eight years, 70 percent had returned along the streambanks. In the Oregon Cascades, it took 18 years for 70 percent of the effective shade density to return.

Despite the significance of streamside shade in the protection of water quality, the factors which affect stream temperatures are poorly understood, and the amount and quality of riparian vegetation which will be left after logging are rarely quantified in the field (Amaranthus 1984). This guide book should help foresters in California assess the impact of management activities on stream temperature. It consists of three parts. First, the physical parameters which affect the amount of solar radiation reaching streams are explained. Second, an effective method to measure shade canopy is presented. Next, a simple predictive model for stream temperature is given. Finally, an example of how the model works is shown. Hopefully, this will provide California's foresters with a simple, quantifiable method to estimate the impact of canopy removal on stream temperature.

II. PHYSICAL PARAMETERS AFFECTING STREAM TEMPERATURE (after Amaranthus 1984)

A. Topographic Shading - At certain times of the day and year, topographic influences can partially shade the stream. This is particularly true for east-west oriented streams with large, steep ridge systems to the south. During the maximum temperature low flow period, however, the sun angle is great and topography by itself rarely provides shade in the maximum radiation midday hours. Topographic shading commonly occurs in early morning and late afternoon when the percentage of average daily solar radiation is minimal.

B. Latitude - The sun's angle increases at lower latitudes and decreases at higher latitudes.

C. Orientation - Stream orientation is critical in determining which vegetation will be important in providing shade. On east-west oriented streams, vegetation on the south side of the stream is critical for providing shade, and north side vegetation has minimal importance for shade. On north-south oriented streams, morning shade is provided by east side vegetation and afternoon shade is provided by west side vegetation. At midday, vegetation which occurs nearest the stream or overhanging streambank vegetation is most effective for shading the water. It is important to remember that most streams meander to some degree.

D. Vegetative Density - Vegetation which is sparse or poorly stocked provides less effective shade than thick, dense stands.

E. Vegetative Height - Vegetative height is very important for stream shading. Taller vegetation can provide shade at a greater distance from the stream. Additionally, tall vegetation nearest the stream can provide shading against high sun angles during the critical midday high solar radiation period.

F. Stream Width - The temperature change of a stream is related to the area of stream exposed and the duration of exposure. For equal volumes of water, a wide stream heats up to a greater degree than a narrow stream, because of greater area exposed to incoming solar radiation.

G. Stream Discharge - Streams with greater discharges are more resistant to temperature changes than those with smaller discharges. Discharge is the product of cross sectional area multiplied by stream velocity.

H. Bed Characteristics - Streams scoured to bedrock do not heat up or cool down as rapidly as streams with sand, gravel, or boulder bottoms. Solid rock bottoms act as a heat sink, heating and cooling water at a slower rate.

III. Measuring Shade Canopy

Most foresters in California currently utilize a qualitative and subjective approach in estimating the amount of effective shade producing canopy which will be left along a stream after harvesting. In many cases, this is appropriate. In other situations, however, more quantitative estimates are needed. This is particularly the case in stream systems where water temperatures are already high (e.g., in the mid-60^{o}F's) and additional harvesting may push the temperatures to unacceptable levels.

In the past, several methods to quantify shade have been tried. "Canopy densiometers" are highly polished stainless steel domes with grids etched on their surfaces, and have been used with limited success. Awkward devices called "angular canopy densiometers" have been used in Oregon with good success. They consist of a one foot square mirror, etched with a grid, which is tilted at an angle equal to the compliment of the maximum angle of the sun in July or August. Simpler equipment to evaluate shade includes a forester's compass and clinometer. For this method, one must know the sun's path for the maximum temperature period. Standing in the channel with the clinometer, sight directly south along the zenith angle of the sun during the critical summer month. Trees whose canopy are seen can be identified and marked to leave (Brown 1980). This will allow the trees along the stream with the ability to cast a shadow across the water during the summer to remain.

Perhaps the best method currently available for easy field use utilizes a device called a "Solar Pathfinder[r]." This instrument consists of a transparent spherical dome, which reflects a panorama of the site, including shadow casting objects. A sun path diagram, viewed through the dome, depicts the sun's path every hour of the day for every month of the year. Therefore, information on the maximum stream temperature period can be gathered at any time of the year.

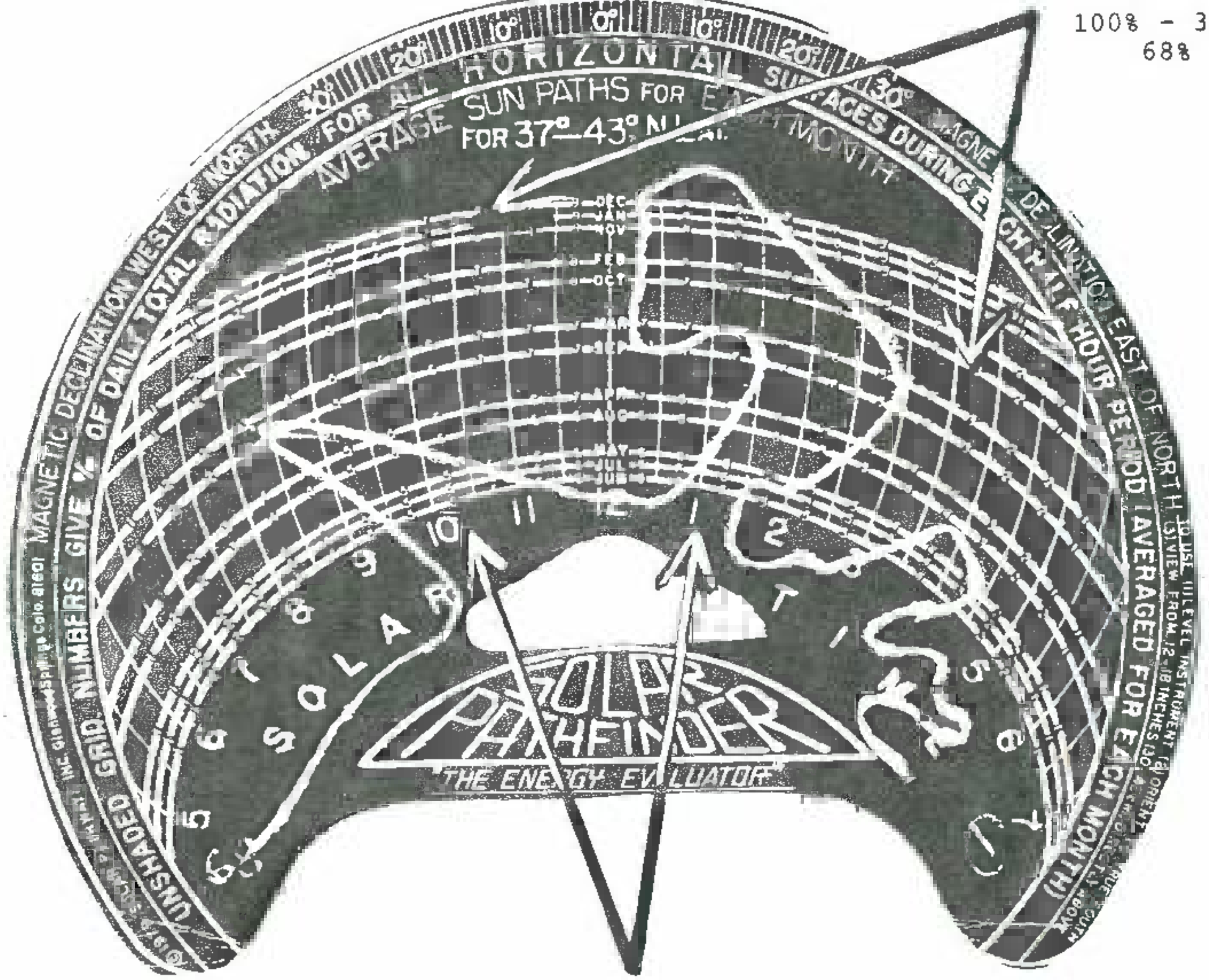
With the Solar Pathfinder set up on a mini-tripod in the middle of a stream and oriented to the south, all the vegetation and topography providing stream shading are displayed instantly and clearly (see Fig. 1). The average daily total solar radiation at a given point for a given month is calculated simply by summing the site radiation percentages for the shaded area on the sun path diagram. Tracing overlays, which are easily photocopied, enable a fast and accurate recording of all vegetative and topographic shading site characteristics for that point. Sightings and recordings can be done very quickly (e.g., 2 to 5 minutes). By placing stations at say two chain intervals, an excellent average shading measurement can be made before and after harvesting (see Table 2). Even without tracing shade producing objects for several points, the Pathfinder can quickly give a forester a feel for which trees are important for producing shade, and which are not. The method allows a variety of field personnel the opportunity to effectively monitor streamside vegetation changes quickly, inexpensively, and accurately (Amaranthus 1983).

Table 2. Percent of total daily potential solar radiation shaded for Hare Creek, sun path for July.

Station	Adjacent area	Post Activity
1	78	71
2	87	66
3	95	83
4	98	50
5	95	49
6	92	80
7	93	69
8	97	70
9	97	81
10	95	58
	--	--
$\bar{X}$	93%	68%

Area shaded by trees and topography:

100% - 32% = 68%



Area exposed to sunlight :

Using July sunpath, sum the numbers in the unshaded area: 2 + 5 + 5 +4 + 2 + 6 + 1 + 1 + 4 + 2 = 32%

Figure 1. Example of Solar Pathfinder sun path diagram.

IV. A MODEL FOR PREDICTING INCREASES IN STREAM TEMPERATURE

In 1969, Dr. George Brown of Oregon State University developed a simple predictive model for the change in stream temperature if an area was clearcut and the watercourse was left with no buffer strip. His model is:

$$\Delta T = \frac{A \times H}{D} \times 0.000267$$

where: ΔT = predicted change in temperature (^{o}F)

A = surface area of stream exposed to solar radiation (length x width) (ft^2)

D = stream discharge in cubic feet per second (cfs)

H = amount of heat absorbed in British Thermal Units per square foot per minute (BTU/ft^2-min)

The constant, 0.000267, converts discharge in cubic feet per second to pounds of water per minute.

While this model has proven to be accurate in several validations, it is not directly applicable to Forest Practices as they are, and have been, implemented in the Pacific Northwest and Northern California for several years (McGurk 1988). Federal, state, and private timberland owners all are mandated by law to leave buffer strips or watercourse protection zones along active stream channels. The timber which may be removed from these zones varies depending on landowner. Usually at least 50% of the existing shade producing overstory canopy is required to be left after harvest (CAC 916.5). The width of the zones often varies with the steepness of the side slopes.

In the early 1980's, Amaranthus (1984) modified Brown's equation to make it applicable to current forest practices. This modified approach is:

$$\Delta T = \frac{A \times H \times P}{D} \times .000267$$

The new <u>P</u> factor is defined as the increase in direct solar radiation reaching a stream channel due to vegetative manipulation, expressed as a percentage, divided by 100. This does not mean that you calculate a percent change, but rather that you subtract post-logging percent shade from pre-logging percent shade, and express it in decimal form. It allows a forester to partially harvest in a buffer strip and predict the affect this will have on stream temperature.

V. FIELD PROCEDURE TO UTILIZE BROWN'S MODIFIED MODEL

A) Determine the boundaries of the streamside area which is going to be impacted by timber harvesting.

B) Determine the surface area of the flowing stream within these boundaries which will be affected during low flow conditions The area (in square feet) equals the length multiplied by the width. Limit the distance along the stream to a maximum of 2000 feet.

C) Estimate or measure the lowest discharge during the period of maximum water temperatures. This can be very difficult. Usually this will have to be estimated by multiplying cross-sectional area by water velocity. When estimating water velocity by floating small organic objects on the surface for a given length of time, the velocity should be multiplied by 0.8 to correct for the vertical velocity profile of the stream. Also, cross-sections should be selected to minimize stagnant pools near the stream's edge, or discharge can be over-estimated by 50 to 100 percent (McGurk 1988). It is preferable to use a small current meter to estimate discharge.

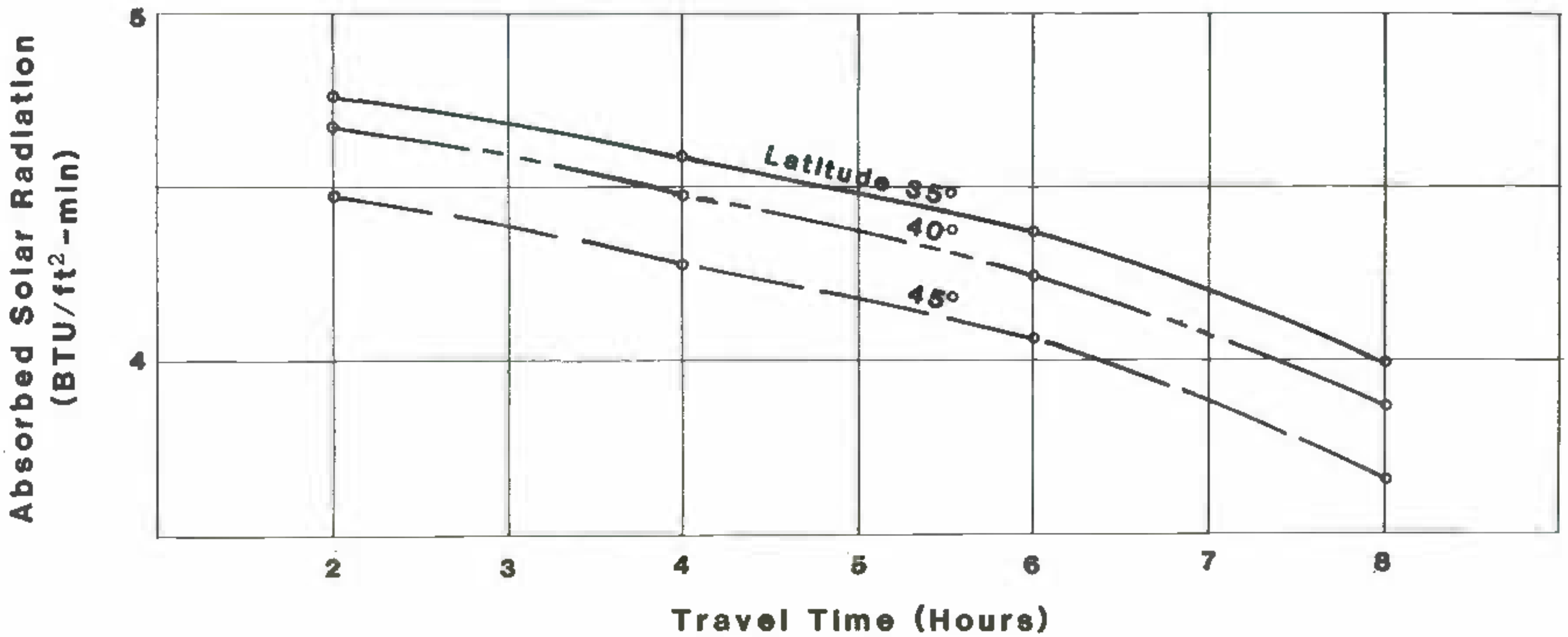
Alternately, one can estimate discharge by using the unit area approach. This requires a nearby stream to be gaged with a reasonable number of years of record (check with the USGS). Divide the lowflow discharge in cfs by the number of square miles in the watershed, to put runoff in cubic feet per second per square mile (CSM). Then multiply this number by the number of square miles in the watershed of interest. This generates an estimate of discharge in cfs.

D) Determine the travel time of the stream at low flow through the area which will be affected. This can be done with non-toxic dye, until one's eye is calibrated to make reasonable estimates. Travel times for openings between 500 and 1500 feet are usually between 1 and 2 hours, so generally use 2 hours for these size openings, or those slightly larger (McGurk 1988).

E) From Table 3 or Fig. 2, determine the net solar radiation absorbed by water surfaces for the appropriate travel time and latitude for the maximum water temperature period. This is the H factor. The numbers given are for July 1st, and could be reduced by one percent for each week following this date to account for the seasonal decrease in insolation, but such minor adjustments are not necessary due to larger inherent errors in area and discharge measurements (McGurk 1988). It may be necessary to extrapolate between the given numbers.

F) Reduce H by 15 to 20 percent on streams with solid rock beds, or do a weighted average for streams with some percentage of a solid rock bottom (Brown 1980).

Figure 2. Average Net Solar Radiation (for July 1st) Absorbed for Streams between 35° & 45° Latitude for various travel times. (After Brown 1980, McGurk 1988).



G) Determine the percent increase in direct solar radiation due to harvesting in the buffer strip from the methods described in Section III, or estimate the change.

H) Compute the maximum change in temperature using Brown's Modified Model.

I) Add this change to previously measured temperatures in this stream to see if you are in an unacceptable range for the salmonids present.

The following factors should be taken into account when utilizing this method:

1) Measurement of stream width, discharge and travel time are critical on very small streams.

2) Cooling ground water influx is not considered, and theoretically could represent error.

3) Streams do not have an infinite capacity to absorb heat. For this reason, the distance along a stream channel should be limited to 2000 feet when calculating surface area (A). As stream temperatures approach air temperatures, an equilibrium is reached.

Table 3. Average values of net solar radiation absorbed by water surfaces for July in middle latitudes for a range of exposure times (BTU's/ft^2-min) (after Brown 1980, List 1951, McGurk 1988).

Water Travel Time (hrs)	Latitude (degrees) 35	40	45
2	4.78	4.71	4.49
4	4.60	4.49	4.30
6	4.38	4.19	4.08
8	4.01	3.90	3.68

VI. EXAMPLE OF BROWN'S MODIFIED MODEL

A timber harvest has been completed along Hare Creek, a 5,000-acre drainage which empties into the ocean just south of the town of Fort Bragg, CA on the Mendocino Coast. The Hare Creek 1988 Timber Sale Unit A is about three miles in from the ocean. Harvesting of second growth redwood and Douglas-fir took place along a Class I stream which supports runs of coho salmon and steelhead trout. Approximately 68 percent of the overstory shade canopy exists after cable logging this unit. About 93 percent shade canopy existed before timber harvesting. Subtracting pre-existing shade from post-harvest shade yields a difference of 25 percent. Unit A impacts 2,640 feet of stream channel on the southwest-facing side; the other side was not harvested. Hare Creek has a discharge of 0.6 cfs on July 15, based on unit area analysis from 20 years of record on adjacent Caspar Creek. Average width at that time of the year is 2 feet. The latitude is 39^{o} 25'at this location. Travel time is two hours. No bed-rock is exposed in the stream channel.

$$\Delta T = \frac{A \times H \times P}{D} \times 0.000267$$

$$= \frac{4000\ ft^2 \times 4.7\ BTU/ft^2\text{-min} \times 0.25}{0.6\ cfs} \times 0.000267$$

$$= 2^{o}F$$

Hare Creek can be expected to reach temperatures in low 60^{o}'s in July, so a 2^{o} increase is all that could be accepted without stressing the coho salmon here.

If all the shade producing canopy were removed, including hard-woods and conifers, the predicted temperature increase would be:

$$\Delta T = \frac{A \times H \times P}{D} \times 0.000267$$

$$= \frac{4000\ ft^2 \times 4.7\ BTU/ft^2\text{-min} \times 1.0}{0.6\ cfs} \times 0.000267$$

$$= 8^{o}F$$

Note: The Solar Pathfinder can be ordered from the following company:

Solar Pathways, Inc.
31 Chaparral Circle
Glenwood Springs, CO 81601
(303) 945-6503

The cost of the instrument without tripod or case is $89.00, including shipping. The cost with those items is $149.00, including shipping.

References:

Amaranthus, M. P. 1983. Quantification of effective streamside shade utilizing the solar pathfinder. USDA For. Service. Region 6. Siskiyou National Forest. Grants Pass, OR.

Amaranthus, M. P. 1984. Stream temperatures in the Pacific Northwest: critical factors and prediction method. Unpubl. report. USDA For. Service. Region 6. Siskiyou National Forest. Grants Pass, OR. 25 p.

Beschta, R. L., R. E. Bilby, G. W. Brown, L. B. Holtby, and T. D. Hofstra. 1987. Stream temperatures and aquatic habitat: fisheries and forestry interactions. Chap 6 IN: streamside management: forestry and fisheries interactions. Ed. by E. O. Salo and T. W. Cundy. Symposium proceedings held Feb 12-14, 1986. Univ. of Wash., Seattle. pp 191-232.

Brazier, J. R. and G. W. Brown. 1973. Buffer strips for stream temperature control. Res. Paper No. 15. For. Research Lab. Oregon State Univ., Corvallis, OR. 9 p.

Brown, G. W. 1969. Predicting temperature of small streams. Water Resources Res. 5(1):68-75.

Brown, G. W. 1980. Forestry and water quality. Oregon State University. OSU Bookstores, Corvallis, OR. 74 p.

Brown, G. W. and J. T. Krygier. 1970. Effects of clear-cutting on stream temperature. Water Resources Res. 6(4):1133-1140.

Brown, G. W. , G. W. Swank and J. Rothacher. 1971. Water temperature in the Steamboat Drainage. Res. Paper PNW-119. USDA For. Service. Portland, OR. 17 p.

Cafferata, P., K. Walton, and W. Jones. 1989. Coho salmon and steelhead trout of Jackson Demonstation State Forest. JDSF Newsletter No. 32. Jan. 1989. 7 p.

DeWitt, J. W. 1968. Caspar Creek ecology project: annual report 1967-1968. Unpubl. report. Humboldt State University, Arcata, CA. 20 p.

Holtby, L. B. 1988. Effects of logging on stream temperatures in Carnation Creek, British Columbia, and associated impacts on the coho salmon (Oncorhynchus kisutch). Can. J. Fish. Aquat. Sci. 45:502-515.

Levno, A. and J. Rothacher. 1967. Increases in maximum stream temperature after logging old growth Douglas-fir watersheds. Res. Paper PNW-65. USDA For. Service. Portland, OR. 12 p.

List, R. J. 1951. Smithsonian Meteorological Tables, 6th ed. Washington: Smithsonian Institution Pub. 4014, Vol 114. 527 p.

McGurk, B. J. 1988. Predicting stream temperature after riparian vegetative removal. Paper presented at the California Riparian Systems Conf., Sept. 22-24, 1988. Davis, CA. 12 p.

McMahon, T. E. 1983. Habitat suitability index models: coho salmon. USDI. Fish and Wildlife Serv. Div. of Biol. Serv. Washington, D.C. 29 p.

Patton, D. R. 1973. A literature review of timber harvesting effects on stream temperature. Res. Note RM-249. USDA For. Service. Ft. Collins, CO. 4 p.

Steinblums, I. J., H. A. Froehlich, and J. K. Lyons. 1984. Designing stable buffer strips for stream protection. J. For. 82(1):49-52.

Summers, R. P. 1983. Trends in riparian vegetation regrowth following timber harvesting in western Oregon watersheds. M.S. thesis. Oregon State University. Corvallis, OR. 151 p.

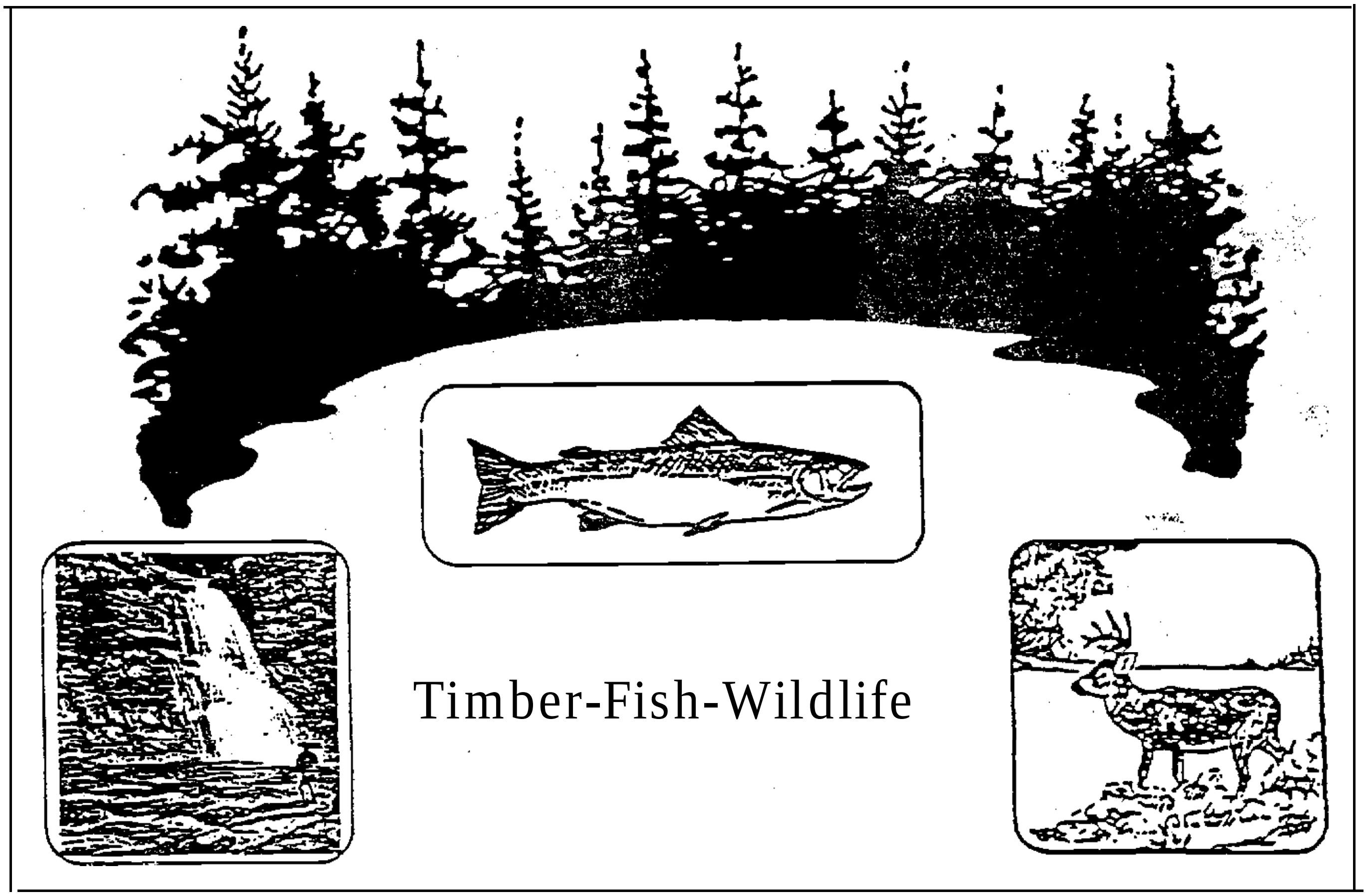
Toews, D. A. and M. K. Moore. 1982. The effects of streamside logging on large organic debris in Carnation Creek. Land Management Report No. 11. Ministry of Forests, Province of British Columbia.

41

TFW-WQ5-91-004

TIMBER-FISH-WILDIFE

EVALUATION OF DOWNSTREAM TEMPERATURE EFFECTS OF TYPE 4/5 WATERS



JUNE 1991

Evaluation of Downstream Temperature Effects of Type 4/5 Waters

T/F/W Report No. WQ5-91-004

Prepared By:

Jean E. Caldwell, Kent Doughty, and Kate Sullivan

Prepared For:
T/F/W CMER Water Quality Steering Committee
and Washington Dept. of Natural Resources
1007 South Washington M.S. EL-03
Olympia WA 98504

September, 1991

Table of Contents

Tables and Figures

Tables

Figures

Disclaimer

The opinions, findings, conclusions or recommendations expressed in this report are those of the authors and do not necessarily reflect the views of any participant in, or committee of, the Timber/Fish/Wildlife Agreement, the Washington Forest Practices Board, or the Department of Natural Resources, nor does mention of trade names or commercial products constitute endorsement or recommendation of use.

Acknowledgements

The authors of this report would like to thank the T/F/W co-operators who took time during their busy 1990 summer field season to help us with suggestions for study sites, and to arrange access to study streams. Recording thermographs used in the study were provided by the Ryan Corporation, with additional instruments from Dept. of Ecology and Weyerhaeuser Co. Weyerhaeuser Co. also provided excellent technical assistance (John Heffner, thanks again), as well as mainframe computer access. Stu Smith and Hui Jin at DNR generated township maps for us using their Geographic Information System. We appreciate the review of the draft report by Bob Bilby, Weyerhaeuser Co., Deigh Bates, U.S. Forest Service, and John Tooley, Dept. of Ecology. While their comments have much improved the final product, the report contents, conclusions, and errors remain the responsibility of the authors.

Project Cooperators:

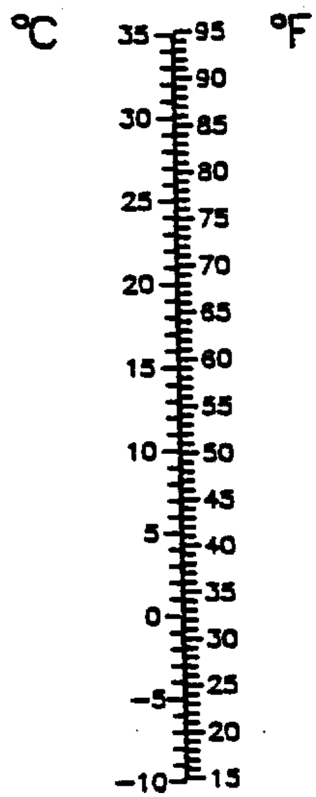
Bill Evans, Ryan Corporation
Jim Lycatowich, Jamestown Clallam Tribe Fisheries
Art Larson, Cavenham Forest Industries
Zoltan Kosa, DNR Southwest Region
Jim Booher, John Keatley, Mike Gobat, Norm Vogt,
Steve Anderson, Jack Ward, Weyerhaeuser Co.
Fred Nichol, International Paper Co.
Craig Beals, Champion Timber Co.
Kip Kelley, DNR Northwest Region
Keith Wyman, Skagit System Co-operative
Kurt Nelson, Tulalip Tribes Fisheries
Norm Schaff, Crown Pacific
Al Zander, USFS Mt. Baker-Snoqualmie National Forest

CONVERSION TABLES

Multiply Metric Units	BY	To Obtain English Units
Meters (m)	3.28	Feet (ft)
Kilometers (km)	0.621	Miles (mi)
Sq. Kilometers (km^2)	0.386	Sq. Miles (mi^2)
CMS (m^3/s) (cubic meters per second)	35.314	CFS (ft^3/sec) (cubic feet per second)

Degrees Celsius to Degrees Fahrenheit: °C = (OF - 32)(0.55)

Degrees Fahrenheit to Degrees Celsius: °F = (1.8) (°C) + 32



I. Executive Summary

Streams in Washington State are classified, with respect to forest practices, into one of five water types (WAC 222-16-030). Stream Types l-3 include, by definition, all larger streams and shorelines of the state. Any stream with a late-summer base flow greater than 0.009 cms (0.3 cfs), and any stream that supports a significant fish population, is classed Type 1, 2 or 3. Stream Types 4 and 5 are generally small headwater streams that do not support significant fish populations. Current forest practices regulations do not require any riparian trees to be left after harvest on Type 4 and 5 streams, as they do on stream Types 1-3.

The possibility of temperature impacts from removal of riparian trees along Type 4 waters on downstream, salmonid-bearing waters has remained a concern within T/F/W. This study investigates the effect on stream temperatures of forest practices along Type 4/5 waters in Washington. Consideration is given to both stream temperature effects within the Type 4/5 water as well as potential downstream temperature effects in fish bearing waters.

This study supplements a previous study (Sullivan and others, 1990) which investigated stream temperatures for larger Type l-3 rivers and streams in Washington. It was anticipated that stream temperatures in Type 4/5 streams would behave similarly with respect to two basic principles reported for larger streams. First, stream temperature tends towards equilibrium with the surrounding environmental conditions. The interaction between temperature and environmental conditions occurs in a complicated yet predictable manner. Second, the maximum equilibrium temperature for a stream reach (the hottest temperature reported for a stream reach) can readily be categorized with minimal information; specifically shade and elevation. However, we would also anticipate temperatures in smaller streams to be much more responsive to localized factors such as groundwater.

Three primary objectives of this study were:

1) Characterize temperature regimes in Type 4 waters of Washington.

2) Assess the magnitude and extent of downstream effects related to water temperatures of upstream Type 4 waters.

3) Provide recommendation for management of riparian areas on Type 4 waters relevant to potential downstream temperature impacts.

All study objectives were met, except that the streams surveyed were limited to western Washington. In summer 1990 air and water temperatures were monitored at multiple points along the 4/3 water type interface for nine locations in western Washington. The conclusions and recommendations within this report are based upon the results of this monitoring.

Maximum water temperatures within Type 4 streams where the riparian overstory had been removed ranged between 13.5 and 23.1°C. Although the sample size was small, environmental conditions appear to effect Type 4 stream temperatures in similar predictable ways as reported for larger streams (Sullivan and others, 1990). Water temperatures in the Type 4 streams studied are influenced by air temperatures as evidenced by similar diurnal patters. However, there is a maximum equilibrium temperature above which water temperatures will not increase, even though air temperatures do. Other important characteristics influencing water temperatures in Type 4 streams include shading levels, groundwater temperatures and groundwater proportion of flow, although effects from groundwater seem to be quite localized and to vary between sites. Maximum stream temperatures are strongly influenced by elevation, with warmer temperatures observed at lower elevations.

Higher than expected shade levels were encountered for many Type 4 streams surveyed as part of this study. Where harvest of the Type 4 riparian zone had occurred, logging debris and understory brush still provided substantial shade. Although not verified except by extensive visual observations, it appears that under TFW management, total riparian harvest along Type 4 streams in western Washington is primarily limited to streams substantially smaller than the 0.009 cms (0.3 cfs) upper size limit stated in the regulations for Type 4 waters. Larger streams have been commonly reclassified as Type 3 due to the presence of significant fish populations and landowners are voluntarily leaving buffers on many of the larger Type 4 streams in western Washington.

Type 4 tributaries varying in water temperature and entering as a triiutary to Type 3 streams were found to have very minimal influence on the downstream water temperature. This is primarily because of the size difference in water types. Using a stream flow mixing equation and the relationship between distance from divide and discharge (Sullivan and others, 1990) it was determined that a Type 4 stream as defined by the forest practices regulations could not affect the temperature in a receiving Type 3 or larger water by more than 0.49°C if the confluence is more than 7 km (4.5 miles) distance from divide for the Type 3 stream.

Small streams are very responsive to localized conditions. For single streams transitioning in water type, the harvested Type 4 stream reach responds quickly to increased shade levels as the stream flow passes downstream into shaded Type 3 reach. Stream temperatures quickly come to equilibrium with downstream conditions with the influence of the upstream Type 4 water temperature extending 150 meters or less beyond the water type interface. This distance equates to travel times of one to two hours for equilibrium to become established.

Concern had also been expressed for the potential temperature impacts of multiple Type 4 harvested streams causing cumulative downstream temperature impacts. Since the longitudinal effect of any one Type 4 stream on downstream temperatures is limited to 150 meters or less, cumulative impacts need only be concerned with a small reach. Farther downstream the water temperature would be responding to ambient conditions rather than any temperature effects of the Type 4 stream. A map-based investigation into whether a potential for multiple Type 4 tributaries to be present within the 150-meter zone of influence showed that the average distance between western Washington Type 4 tributaries is on the order of 200 meters or longer, and thus too far apart to contribute to a cumulative impact. In the headwaters of small streams, no situation was observed where more than two Type 4 tributaries combined to form a Type 3 reach. It can be concluded that the downstream temperature effects of Type 4 streams are extremely limited in extent for western Washington. Though this study did not include any eastern Washington sites, is likely that streams in that region would behave similarly.

Management recommendations should be developed after technical review of this report. Management recommendation should recognize the limited downstream temperature effects of timber harvest along Type 4 waters, and that Type 3 waters farther than 7 km from the watershed divide will show virtually no effect from the temperatures of incoming Type 4 tributaries, because the size of the Type 3 stream is too large relative to the size of the Type 4 stream.

This study is not geographically comprehensive, and the number of streams studied was too small to fully characterize the entire range of temperature regimes in all of Washington's Type 4 waters. If shade recommendations are developed for controlling temperatures within Type 4 reaches themselves, it is recommended that additional sites be investigated, using relatively simple maximum-minimum thermometers, to further characterize maximum equilibrium temperatures in ecoregions not studied as part of this project.

The conclusions and recommendations for the management of riparian areas along Type 4 streams are only based on stream temperature concerns. Numerous other factors also must be considered in the management of forest practices along type 4 streams. Though downstream temperature impacts are negligible, erosion and other factors are still relevant to the management of Type 4 streams.

II. Introduction

T/F/W Synopsis

Streams in Washington State are classified, with respect to forest practices, into one of five water types (WAC 222-16-030). Stream Types 1-3 include, by definition, all larger streams and shorelines of the state. Any stream with a late-summer base flow greater than 0.009 cms (0.3 cfs), and any stream that supports a significant fish population, is classed Type 1, 2 or 3.

Stream Types 4 and 5 are generally small headwater streams that do not support significant fish populations, are not used as water supplies, and are not specifically targeted to protect downstream water quality (Macdonald and Ritland, 1989).

A general comparison of Washington's water types with stream classification systems currently used by the Olympic National Forest, and the states of Oregon and California is presented in Figure 1. (Readers interested in a more specific comparison should consult the source documents.)

While previous T/F/W temperature studies have provided recommendations for riparian management on Type 1-3 streams, temperature concerns relative to Type 4 streams have not yet been addressed. Specifically, the possibility of temperature effects from Type 4 waters, for which riparian buffers are typically not required, on downstream, salmonid-bearing waters is a concern within T/F/W. This research project builds upon the previous findings of Sullivan and others (1990) to investigate the downstream temperature effects of Type 4 waters.

In Washington, no shading is currently required to be left after timber harvest on Type 4/5 streams, although typically some understory shade remains after logging from brush and logging debris. Recovery of shade from overstory canopy can be expected approximately 5 years or more after timber harvest (Summers, 1982). Removal of shade along Type 4 streams could potentially result in large increases in maximum temperature since small shallow streams respond rapidly to changes in heat energy exchange (Brown, 1969).

We expected Type 4 streams to show temperature regimes similar to those reported for larger streams. Observed maximum temperatures in small, open Type 3 streams studied in 1988 (Sullivan and others, 1990) ranged from 18 - 22°C. Higher elevation streams tended to be cooler than lower-elevation streams. A slightly wider range in temperatures was expected in Type 4 waters for two reasons. Type 4 streams with lower maximum temperatures were expected since incoming groundwater which is relatively cool makes up a proportionately greater amount of the total flow in smaller streams. Type 4 streams with very high groundwater inflow rates would be expected to not exceed 15°C. However, we also expected some Type 4 streams to have very high maximum temperatures since they tend to be very shallow and thus respond rapidly to diurnal air temperature fluctuations.

While many unshaded Type 4 streams could be expected to show similar temperature patterns, and to respond similarly at similar elevations as the Type 3 streams studied, the extent that these streams affect downstream, fish-bearing waters remains unclear. Since Type 4 streams within a basin tend to be at higher elevations, they are likely to be somewhat cooler than similar streams at lower altitudes. In addition, Type 4 streams are generally shallow, and make up a small volume of the total flow in downstream reaches, where riparian areas maintain cooler temperatures. However, in the headwaters of a basin, Type 4 streams make up a large proportion of the stream length. Because of these offsetting factors, the overall importance of Type 4 streams in determining downstream temperatures is uncertain.

The characterization of stream temperature regimes of Type 4 waters, and their downstream effects on Type 2/3 waters is the focus of this study.

Figure 1. Stream Classification Systems.

Washington	USFS: Olympic NF	Oregon	California	Stream Orders
Type 1	Class I	Class I	Class I	Fifth
Type 2				Fourth
Type 3	Class II	Class 2 SP	Class 2	Third
Type 4	Class III	class 2	Class 3	Second
Type 5	Class IV			First

Sources:

1: Washington Forest Practice Regulations, WAC 222-16-030
2 : J. Seymour, R. Stephens, USFS Olympic National Forest, pers. comm.
3 : Oregon Forest Practice Rules OAR 629-24-101
4 : California Forest Practice Rules CCR 916.5, Table 1-14
5 : Adapted from Dunne and Leopold, 1978.

Notes:

1. Oregon State stream classifications are currently under review, and will be revised by September 1992.

2. Stream characteristics (such as size and slope), as well as allowable forest practices, are not the same between all classifications listed here as similar. This table is intended to convey a general sense of comparable stream types. Readers interested in more complete comparisons should consult the source documents.

Theoretical Background

The water temperature observed at any location within a stream system reflects a balance between heat input and heat loss. The exchange of heat across the air-water interface is one of the more important factors that governs the temperature of a water body for a given solar input. The rates of both input and loss of heat are influenced by local environmental factors. Heat input is determined by the amount of direct solar radiation reaching the stream environment which varies daily and seasonally with position of the sun, and with shading by riparian vegetation or topography. Heat loss is largely regulated by the difference between air and water temperature. Conduction to the stream bed and groundwater inflow also account for heat loss.

As a stream is heated by solar radiation and convection over a daily solar cycle, heat loss from evaporation and radiation back to the sky also increases rapidly. Some stream temperature will always be reached where heat loss balances heat gain and no further change in water temperature occurs with increased energy input. Edinger and others (1968) referred to the water temperature at which heat input just balances heat loss as "equilibrium temperature". Since most of the energy exchange terms involve air temperature, this factor is very influential in determining the equilibrium stream temperature (Adams and Sullivan, 1990). Air temperature continually changes in response to varying meteorological conditions on a daily and seasonal basis and there is an equilibrium water temperature for each air temperature (Edinger and others, 1968). The water temperature is continually driven towards the air temperature with the rate determined by the difference between the two. A useful illustration of this principle is the tendency for both hot and cold water to change over a short time to match room temperature.

Importantly, rapid heat loss at high temperatures sets an upper limit to stream temperature relative to air temperature that is independent of stream size. During hot summer days when the temperature differential is greater than this amount, the heat loss from evaporation and radiation losses is also great and additional incoming heat to the water is quickly lost back to the air. Thus each stream has a maximum water temperature observed at a threshold level of air temperature. (When air temperature is lower than the threshold value, water temperature responds to it, but when air temperature rises above this level there will be no increase in the observed water temperature.) We refer to this water temperature as the "maximum equilibrium temperature."

Maximum Equilibrium Temperature: The maximum equilibrium temperature of each stream reach is independent of observed air temperature and is related primarily to the site conditions (Figure 2). Each reach's equilibrium temperature is determined by its unique combination of physical characteristics that influence stream heating. These include stream channel features (depth, width, velocity, substrate composition), riparian shading, and geographic location (latitude, elevation).

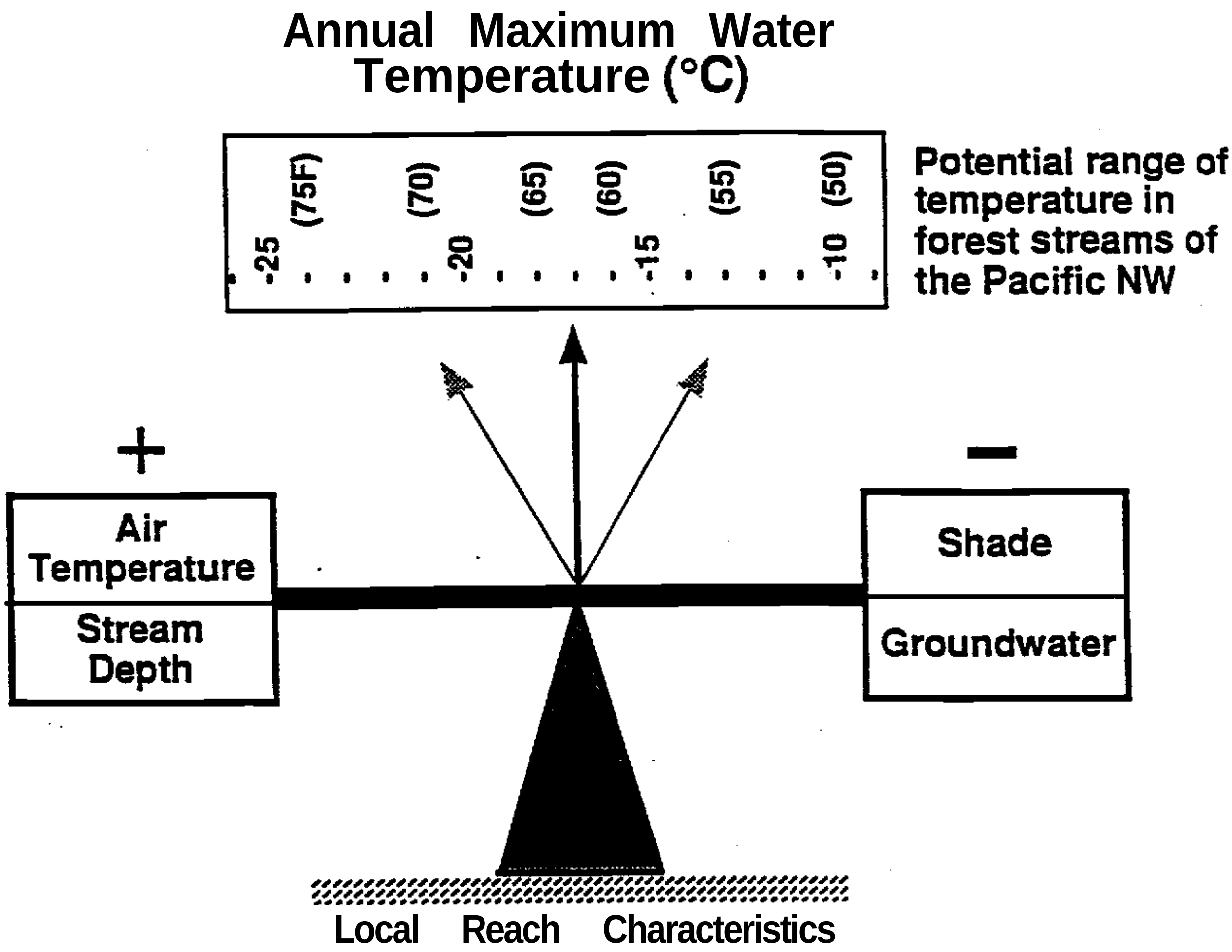


Fig 2. Maximum equilibrium water temperature for a stream reach is a function of the balance between heat energy losses and gains. High values of air temperature and stream depth tend to increase water temperature as high as approximately 25°C for Washington streams. High amounts of shade or high groundwater inflow rates will decrease the maximum equilibrium water temperature.

The numerous site characteristics contributing to the determination of stream temperature may vary inter-dependently, independently, or inversely. The maximum equilibrium temperature relates to site characteristics in identifiable, albeit complicated, ways. Nevertheless, common relationships between maximum equilibrium water temperature and site conditions exist (Sullivan and others, 1990). Changes in the local environmental conditions cause a change in the equilibrium temperature to a new value. Common responses to changes in site conditions with land use can be identified.

The annual maximum temperature is a good measure of the maximum equilibrium temperature. This temperature may not be observed frequently, depending on the climatic conditions, but it is indicative of the balance of site characteristics. Generally, the maximum equilibrium temperature in all streams and rivers will occur somewhere within the range between 9 and 25°C (48-77°F).

The 1988 - 1990 T/F/W temperature study demonstrated several other principles of stream heating at both the stream reach and basin scales. The following information summarizes some of the findings reported in Sullivan and others (1990).

Stream Reach Temperature: Stream temperature and site characteristics were evaluated to identity what features could be used to recognize streams exceeding the Washington water quality temperature criteria. A number of environmental factors were well correlated with stream temperature and several good empirical relationships between stream characteristics and water temperature were developed based on five of the most important environmental variables including stream shading, mean air temperature, elevation, stream discharge, and bankfull width. Other variables more directly influential in the physical processes of stream heating were also identified, but of the well-correlated variables those that are easiest to measure were selected. Typically, a combination of local environmental factors had an important influence on water temperature, but no one factor alone was a good predictor of stream temperature.

Baseline Maximum Temperature: The temperatures within reaches flowing through mature forests were evaluated to estimate the expected baseline maximum equilibrium temperatures within watersheds fully forested with mature conifers. Sullivan and others (1990) used measured values of maximum daily temperature during the warmest summer period of approximately 20 forested stream reaches of all sixes to draw the relationship between maximum water temperature and increasing stream size (indexed as distance downstream from the watershed divide) shown in Figure 3. This graph depicts the best estimate of baseline maximum daily temperature within fully forested Washington watersheds available at present.

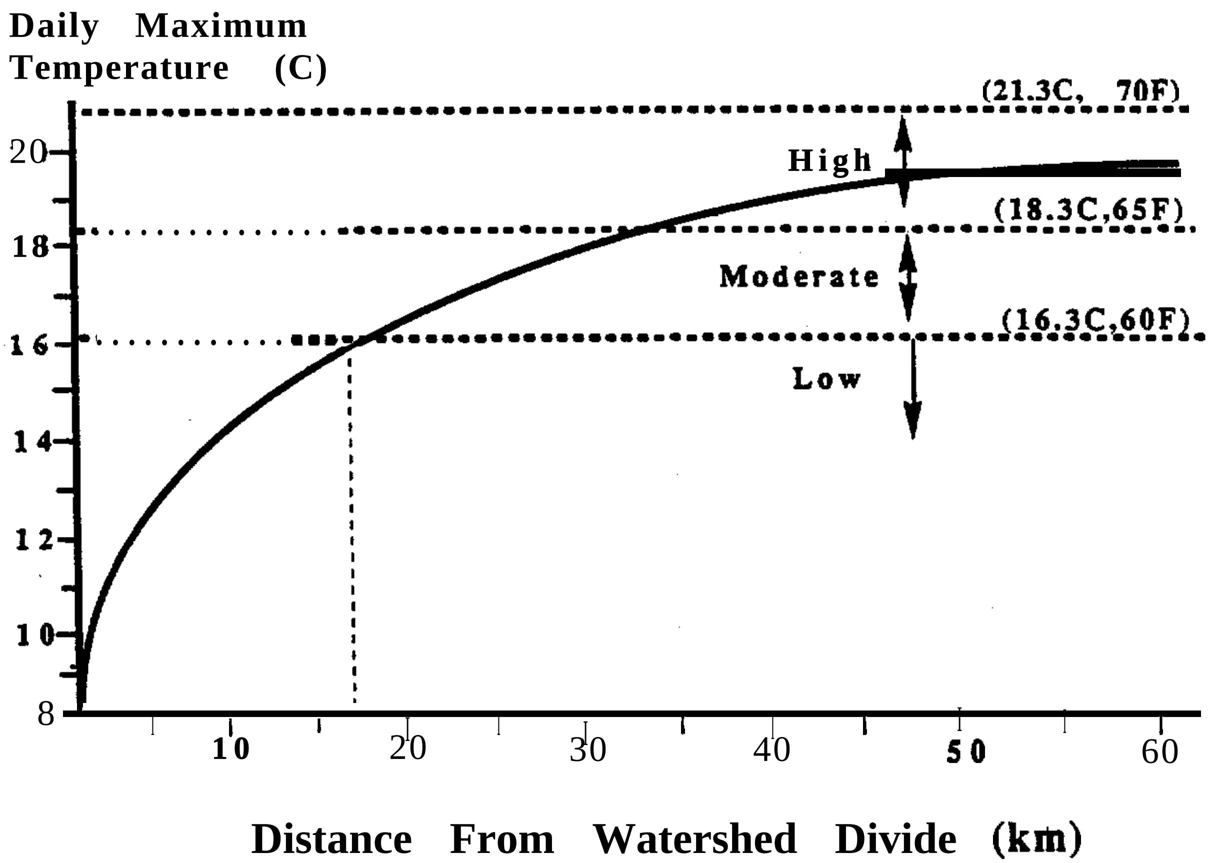


Fig. 3 Baseline Maximum Temperatures. Estimated baseline daily maximum temperature during the warmest summer days under a mature forest canopy as a function of distance from watershed divide.

Small streams relatively close to the watershed divide tend to be very cool (between 10 and 14°C or 50-56°F) with the smallest streams near groundwater temperature. (This represents the minimum possible summer temperature.) Stream reaches within forested riparian zones located approximately 20 or more kilometers (12 miles) downstream from the watershed divide are likely to exceed 16.3°C (62°F). Those sites greater than 50-60 km (30-40 miles) from divide are likely to exceed 18.3°C (65°F) during the warmest periods of the year, regardless of forest management activities upstream. Local deviations in this general trend can occur such as where cooler or warmer tributaries join the system, or at the interface between rivers and oceans where air temperatures may be cooler than similar elevations located inland. Therefore, the baseline maximum temperature in Figure 3 should be considered a rule-of-thumb and can vary with local conditions. Regional validation of this relationship would be useful.

Response Distance: Sullivan and others (1990) calculated that temperature equilrbrium was established in 600 meters or less for Type 3 streams. (Stream sixes reported in that study ranged in depth from 0.07 m to 0.6 m and in width from 0.6 - 22.8 m.) This estimate was based on a theoretical understanding of the heat exchange processes in streams and water stream flow velocities. The distance required for streams to reach equihbrium has not been empirically validated.

The concept of temperature equilrbrium is important to understanding basin temperature effects. Small streams are expected to heat quickly (i.e., within minutes to several hours) with a reduction in shade. Canopy removal should establish a new elevated equilibrium temperature for that reach. As the water enters a downstream reach with shade, it will quickly cool to the equilibrium temperature of the downstream reach. The exact length of stream required to reach equihbrium has not yet been determined but probably varies from several hundred meters in small streams to several kilometers for large rivers. Similarly, a small shaded stream is expected to be cooler relative to a downstream reach with reduced shade. However, as the stream flows through the downstream reach, the water will reach equihbrium with surrounding conditions, and the effect of the initially cooler upstream water will no longer be felt. The response times of small streams determines the extent of downstream impacts of upstream riparian management decisions.

The response time, or response distance, is defined in this study as the time required by a Type 2/3 stream to reach temperature equilibrium following the introduction of water at a different temperature from incoming Type 4 waters. This response time can be equated with the downstream distance needed to reach equilibrium (response time * water velocity = equihbrium distance). From a management perspective the equilrbrium distance defines the downstream area that a temperature response to riparian alteration can be detected.

III. Study Objectives

The objectives of this study are as follows.

1. Characterize temperature regimes and important channel characteristics which influence stream temperatures, and response to management related changes, of Type 4 waters in Washington. We hypothesize that stream temperatures in these smaller streams respond according to the same physical principles and conditions as previously reported for larger streams (Sullivan and others, 1990).

2. Determine the downstream zone of influence within salmonid bearing waters that results from shade canopy removal along upstream Type 4 waters. Both the magnitude and the total stream distance affected till be investigated.

3. Assist the Water Quality Steering Committee regarding management recommendations on downstream temperature effects, if any, of current regulations for Type 4 streams.

IV Methods

Water Types

Type 4 and 5 waters, defined in the Washington Forest Practices Rules and Regulations (WAC 222-16-030), are small headwater streams that do not support significant fish populations, are not developed water supplies, and are of importance in protecting water quality downstream. An upper limit on the size of Type 4 stream channels is 5-10 feet wide at ordinary high water (depending on the species of fish that have access to the stream), and the lower limit is 2 feet wide. Type 4 streams have a minimum summer flow less than 0.009 cubic meters per second (0.3 cfs), while Type 5 waters are defined as areas not designated Types l-4 and include intermittent streams. Type 4 and 5 waters correspond to zero order, first order, second order, and small third order streams (MacDonald and Ritland, 1989).

Land units containing Type 4 and 5 waters are subject to a number of regulations on forest practices and harvesting, such as the requirements to buffer the stream from road sedimentation, and to minimize skidding timber across Type 4 stream channels. However, streamside strips of trees and other vegetation, or Riparian Management Zones, are required on Types 1-3 waters, and are typically not required on Types 4 & 5 stream reaches.

Assumptions

This study's approach to site selection and data analysis methods rested on several assumptions. This study focused on the downstream temperature effects from harvest practices on Type 4 waters. We assumed that temperature concerns for, larger Washington streams were addressed by other studies (Sullivan and others, 1990). Type 5 waters were not eliminated from consideration, but also were not emphasized since they typically have only minimal flows during the warmest part of the year, and thus are typically too small to affect downstream temperatures. The identification of Type 4 streams was based on the definitions in the Forest Practices Manual (1988), as well as available Department of Natural Resources Water Type maps. When information was available from local foresters, recent changes in water typing of stream reaches was incorporated. When other information was not available, we assumed that the boundary between Type 4 and Type 3 reaches coincided with the start of a streamside buffer area or the edge of an unharvested unit.

We also assumed that the same physical principles of heat exchange that determine stream temperatures in Type 1-3 streams (Sullivan and others, 1990) also operate in smaller streams. These principles have been extensively studied and are well understood (Edinger and others, 1968; Theurer and others, 1974). A brief description of the important physical heat exchange processes is presented in section II of this report.

Stream discharge was assumed to be constant over the short late-summer monitoring periods. The stream flow was measured either once during the monitoring period, or calculated as the average of flows measured at the beginning and end of the monitoring period.

Even though all of the instruments used are capable of precision within 0.3°C and instrument accuracy was verified prior to their use, only differences in measured temperature greater than 0.5°C were considered significant.

We also assumed that Type 4 streams with total harvest of the overhead canopy were of primary concern within T/F/W. The most extreme temperature impacts would be associated with total riparian removal. Se sought harvested Type 4's flowing into shaded Type 3 streams since it was assumed that, with time, the new T/F/W regulations would provide adequate shade on all Type l-3 waters whereas buffers on Type 4 streams are not routinely mandatory.

Studv Site Selection

Candidate study sites were evaluated on several criteria, defined by the hypothesis being tested. First, both Type 3 and 4 stream reaches needed to be adequately long (to have reached equilibrium temperature), on the order of 460 meters. Study sites were chosen to represent as wide a range of stream characteristics such as shade levels, stream sizes, geographic distribution and elevation as possible. Priority was placed on Type 4 stream reaches where area on both sides of the stream had been harvested, not one side only. Finally, practicality was considered with regard to site accessibility and budget constraints. Unfortunately, this last factor precluded the opportunity to include study sites in ail ecoregions of the state.

Shade characteristics were a primary consideration in site selection. Three site configuration situations were sought. These included:

1. A Type 4 stream, after harvest, flowing into a Type 3 stream with a riparian zone or a Type 3 with a mature canopy cover.

2. A shaded Type 4 stream, with relatively cool temperatures, flowing into a warmer Type 3 stream.

3. A harvested Type 4 stream that had suffered a dam-break flood event, flowing into a Type 3 stream with a riparian zone or a mature canopy cover.

Both site configurations where the Type 4 stream was a tributary to the Type 3, as well as where the single stream channel crossed the 4/3 boundary were sought. Sites on harvest units within 2-4 years of harvesting were targeted, since significant shading from understory plants and replanted trees could be assumed to be present 5 years after harvest.
In addition to shade, the stream flow geometry was important for site selection. Streams with beaver ponds, intermittent surface flow, or an undefined stream channel were

eliminated as candidate sites due to the complexity of descniing the groundwater interactions.

Site selection required that the channel characteristics, including shade levels, of the downstream Type 3 water be uniform for a sufficient length to allow the stream to reach equilibrium. Furthermore, in the case of a confluence of a Type 4 and a Type 3 stream, the Type 3 stream reach had to be in equilibrium upstream of the confluence for at least 460 meters. In the case of a Type 4 stream crossing into a forested zone, the upstream reach also needed to have a homogenous shading level for at least 460 m.

The size of the Type 4 stream relative to the Type 3 stream was also an important consideration. Where a Type 4 stream joins a Type 3 stream, its discharge must be large enough relative to the receiving Type 3 stream to be capable of influencing the temperature of the downstream reach. This constraint limited candidate sites to those where the downstream waters were smaller Type 3 streams. Type 1 & 2 waters are too large, by definition, to be affected by a stream as small as a Type 4. The size of receiving waters needed at candidate sites was calculated using the flow mixing equation described below.

Stream Flow Mixing

Two types of stream configurations were studied; Type 4 streams converting to a downstream Type 3 reach, and a Type 4 stream joining a Type 3 stream. In the latter case, a simple mixing equation (Brown, 1969) was used to both verify the size of Type 4 streams needed to influence the receiving Type 3 stream enough to cause a measurable difference in stream temperature immediately below the confluence. The mixing equation is as follows. T_1 and Q_1 equal the temperature and stream flow, respectively, for inflowing Type 4 stream and T_2 and Q_2 represent the same values for the Type 3 stream.

$$\frac{(T_1 * Q_1) + (T_2 * Q_2)}{Q_1 + Q_2}$$

Figure 4 provides an example of the influence of incoming water at a different temperature. For example, if the incoming tniutary temperature is 20°C and has 20% the discharge of the receiving stream, which is at 12°C, then the resulting temperature when the two streams mix is 14°C.

Using this equation, and a range of theoretical Type 4 incoming stream temperatures, we estimated that the Type 4 stream would need to be at least 10% of the Type 3 stream's size in order to influence its temperature. This limited site selection to the smaller Type 3 streams, and eliminated many Type 4 candidates as too small.

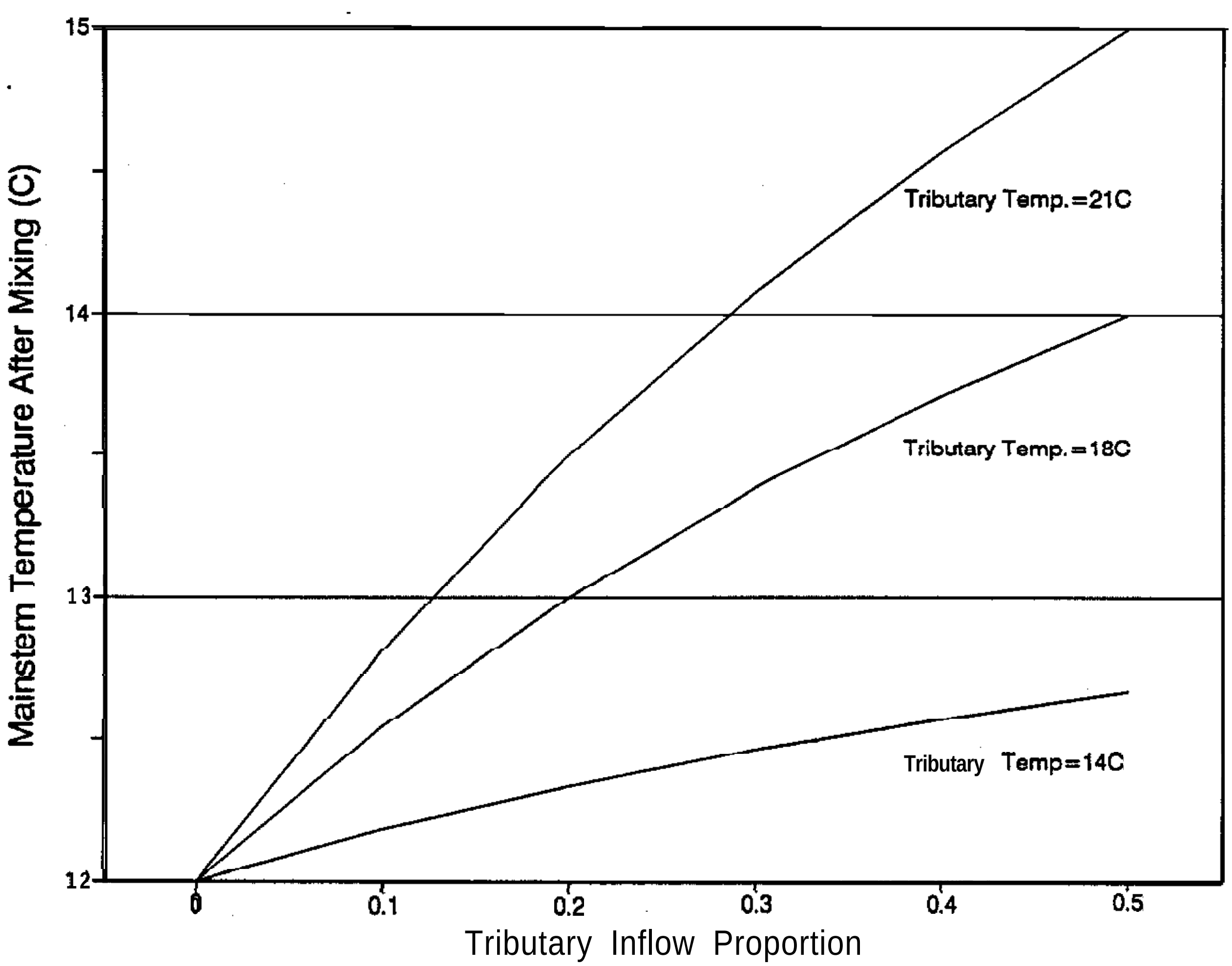


Figure 4. Temperature effects of tributary mixing. The mainstream temperature upstream of the confluence is assumed to be 12 degrees celcius. The influence on the downstream temperature is shown for incoming tributaries of three different temperatures.

Temoerature Measurement

At each site, thermographs were set out according to site configuration. Temperatures were measured in the Type 4 waters, and in the Type 3 waters upstream and downstream of the confluence with the Type 4. Temperature was also measured at regular points downstream, within the projected zone of influence from the Type 4 stream, as well as downstream of the projected return to equilibrium of the Type 3 stream. For both Type 3 and Type 4 streams, riparian conditions upstream of the thermograph were homogeneous for at least 460 m. Moving downstream in the Type 3 stream, conditions were chosen either to be homogeneous throughout the instrumented reach, or at least were homogeneous for the most downstream 460 m of the instrumented reach. Figure 5 shows study site locations, and Figures 6 - 13 illustrate actual instrument deployment.

After a suitable site was identified, calibrated continuous-recording thermographs were installed at several measuring points within each study site. A combination of Omnidata[tm], Unidata[tm], and Ryan[tm] instruments were used. Air and water temperatures were measured every ten minutes, and recorded hourly. (A list of temperature instruments used and their estimated accuracy is in Table 1.) Water temperatures were measured at all measuring points, and air temperatures were measured where necessary (for instance, redundant air temperature measurements of the same Type 3 riparian conditions were not made.) Instrument probes were placed in the central flow of the channel. Air temperature probes were placed as close to the stream as possible, and shaded from direct sunlight. Sites were monitored for a minimum of two consecutive weeks between July and early September, 1990.

Table 1. Instrument Accuracy

Omnidata Datapod DP212	± 0.2% of reading[1]
Unidata 6507A	± 0.2 degrees C[2]
Ryan Tempmentor RTM	± 0.2 degrees C[3]

1. Omnidata Intl., 1982. DP212 Operating Manual.
2. Unidata America, 1987. Starlog Portable Data Logger Product Catalog.
3. Ryan Instruments, 1990. Ryan Tempmentor Calibration Certification Sheets.

For all measurement points, instantaneous thermograph measurementswere checked against hand-held thermometer measurements made at the time of installation, removal, and during the site characterization visit.

Site Characterization

At each site, for each homogenous stream reach, an array of site characteristics were measured. These included stream width, depth, and amount of flow, as well as substrate character, channel characteristics, water velocity (for Type 3 streams), riparian shade levels, stream azimuth and site altitude. Stream width and depth were calculated by averaging 4 - 9 randomly selected measurements between each thermograph measuring point, using a hip chain, a tape or a calibrated wading rod. Distances were measured using a hip chain. Canopy shading was calculated using a forest densiometer, while shading from understory plants and logging debris at ground level was estimated visually. Shading measurements were also made by averaging 4 - 9 measurements. Water velocity was determined by timing the movement of a small amount of tracer dye a measured distance downstream. Stream flow was measured with a Swoffer™ velocity meter and top-set wading rod. Visual descriptions were made of forest type and age, as well as riparian vegetation and overall site characteristics. Sites were mapped and documentary photographs were taken.

Stream azimuths and gradients were determined using USGS maps, and any unmeasured distances between measuring points were determined using maps and aerial photographs.

Data Analysis

Temperature data was downloaded from the thermographs to personal computers, and checked for quality prior to transferring data to a mainframe computer for data processing. Hourly air and water measurements were summarized into files containing daily maximum, mean, and minimum temperatures. For each site, daily air and water temperatures were graphed over time, to estimate equilibrium temperature regimes at each site. Typical temperature regimes of the Type 4 and 3 streams were analyzed. Data analysis focussed on maximum temperatures for two reasons. First, forest practices regulation are primarily concerned with maximum temperatures. Second, the maximum equilibrium temperature is predominantly a function of site conditions, unlike the mean water temperature, which is more closely related to climatic conditions. The temperatures at each site were analyzed with regard to site configuration, to see if downstream effects of the Type 4 waters could be identified.

For site configurations where the Type 4 stream was a tributary to the Type 3 stream, the mixing equation was used to see if the observed temperatures downstream of the confluence differed from that predicted by the mixing equation. If the stream temperature calculated by the mixing equation did not differ from that observed in the Type 3 stream above the confluence with the Type 4 stream, mixing was considered to be instantaneous, and the Type 4 stream was considered to have no downstream effect on water temperatures in the Type 3 reach. If a temperature difference was seen downstream, then a zone of influence of the Type 4 was determined to be present. (Temperatures within 0.5 °C were considered not to be different from one another.)

For site configurations where the water type changed from 4 to 3 in a single stream channel, maximum temperatures were evaluated with regard to their distance downstream of the change in riparian shade, to investigate the response distance of the stream temperature to the new riparian configuration. Analysis was done on a site-by-site basis, with attention to any changes in stream or channel characteristics that might explain an observed temperature change.

V Results

Site Candidate Search

Despite a large number of suggestions from T/F/W co-operators, and a search effort covering many forested areas of Ring, Whatcom, Skagit, Snohomish, Clallam, Pierce, Thurston, Lewis, Grays Harbor, Pacific and Cowlitz counties, good site candidates proved surprisingly difficult to find.

Most of this difficulty lay in the stringent criteria we had developed, which we hypothesized to be necessary in order to document what we felt would be the worst case scenarios of downstream temperature effects of Type 4 waters. Our target criteria, which were not always met, included:

- a Type 4 stream with flow at least 15% of the size of the receiving Type 3 stream flow.
- stream crossing a land unit less than five years after timber harvest.
- both Type 4 and Type 3 reaches to be homogeneous with respect to channel and riparian characteristics for approximately 460 m upstream of their confluence, or the start of the riparian zone (for Type 4's changing to Type 3's).

The most common disqualifying factor was that the candidate Type 4 stream flowed into a Type 3 stream much larger than itself. Our target that the tributary must be close to 15% of the size of the stream it flowed into eliminated most Type 4 candidates, because their receiving Type 3 water was too large. This criteria was based on the theoretical potential of a Type 4 stream to affect temperatures in the larger downstream Type 3 reach. Many of the Type 3 streams were contained flows of 0.056 - 0.11 cms, and some as much as 0.34 cms. Most of the Type 4 streams were much smaller than the 0.009 cms upper limit in the regulations, with flows on the order of 0.003 cms, much lower than the 15% size criteria.

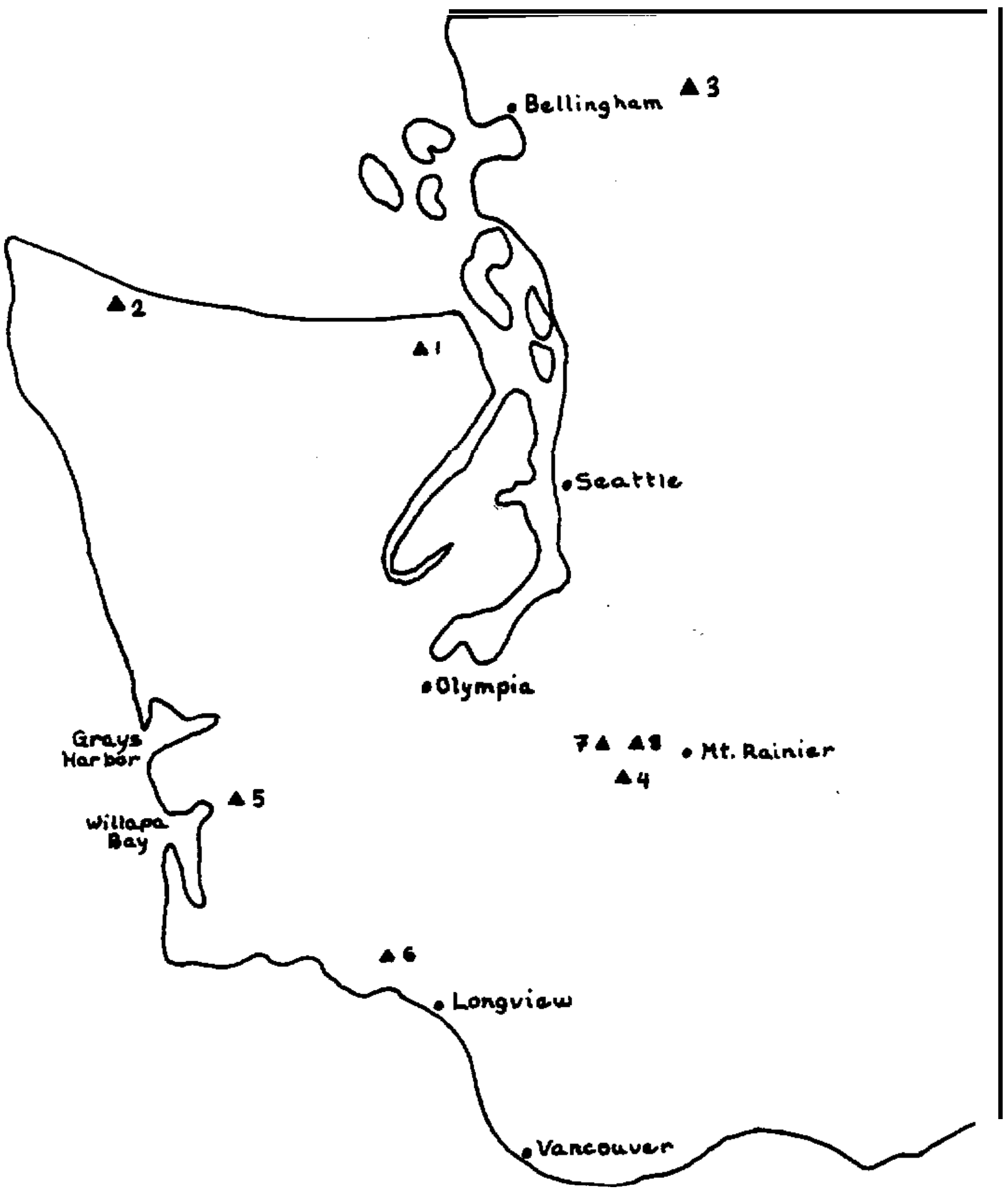
Some of the difficulty in finding sites lay in the transitory nature of the conditions we were investigating. We were looking for land units less than five years from harvest (to minimize compensating shading effects from replanted trees and understory plants). Several sites were also rejected because active falling and yarding were taking place, for safety and because we could not assume that the stream conditions were in equilibrium.

Another common disqualifying factor was the relatively large number of Type 4 streams that moved from surface to subsurface flow in part of the proposed study reach, or flowed into small beaver ponds or forest wetlands at the 4/3 boundary. Further sites were eliminated because the Type 3 stream could not be assumed to be in equilibrium, due to changes in riparian vegetation patterns below the Type 4 confluence. Another class of sites we investigated were those where both the Type 4 stream and the downstream Type 3 had suffered a dam-break flood or debris flow event. Most of these candidates were disqualified either because there was no shade on the Type 3 stream reach, or because there was no homogeneity to the Type 3 stream's riparian character.

Also, in some cases we found that land managers were leaving vegetation buffer strips on larger Type 4 streams. Since we were targeting on the larger streams (because of the relative size requirement), a number of possible candidates were disqualified because the stream reach had canopy-level riparian shade.

In summary, the investigators found that, under the new regulations and practices within T/F/W, while there are a number of Type 4 streams in any given basin, they are also very small, particularly in relation to their receiving streams. It appears that riparian buffers are voluntarily being left on many of those west side Type 4 streams which may be large enough to exert a downstream temperature influence.

Fig. 5 Site Vicinity Map
1990 T/F/W Type 4/5 Stream Temperature Study



Site Key

1' Jimmy Come Lately Creek
2 Green Creek
3 Hoff Creek
4 Hanaford Creek
5 Ward Creek
6 Abernathy Creek
7 Huckleberry Creek
8 Thorn Creek

With respect to minimum water temperatures the only thermograph to differ from the others was the most upstream thermograph (A) located in the shaded portion of the Type 4. Point (A) minimum daily water temperatures averaged 13.2°C while minimum daily temperatures for the other thermographs averaged 12.5°C.

Although the establishment of equilibrium conditions within uniform stream reaches cannot be concluded from Figure 7, a comparison of all daily maximum temperatures between thermographs demonstrates that equilibrium conditions did exist within the Type 4 harvested reach. The mean difference in daily maximum temperatures between the two thermographs placed in the harvested Type 4 stream reach was only 0.05°C whereas these two thermographs differed significantly from the measurements at the upstream thermograph in the shaded section of the Type 4 stream.

The shade level varied between the two reaches within the Type 3 section so that a comparison of temperatures between the two monitoring points is inconclusive with regards to the establishment of equilibrium temperature regimes. It is probable that each of the two Type 3 stream reaches had unique equilibrium temperatures associated with their respective shade levels.

In conclusion, Jimmy Come Lately Creek increased in temperature within the unshaded Type 4. Stream temperatures decreased within 150 meters upon entering the downstream shaded Type 3 reach. The careful selection of trees for harvest along the Type 3 provided adequate shade to protect stream temperatures.

Green Creek

Characterization

The study site on Green Creek, a tributary to the Pysht River on the Olympic Peninsula, included a harvested Type 4 stream flowing into Green Creek, which is a Type 3 stream with a substantial riparian zone (figure 8). The Type 4 stream had only 5% canopy shade. However, understory plants and logging debris in the channel provided an average of 90% shade in the Type 4 reach. The Type 3 averaged 85% canopy shade in the study reach. (Water typing was confirmed from recent forest practices applications.)

The measured streamflow in the Type 4 reach at its mouth was 0.002 cms, and the Type 3 stream above the confluence had a flow of 0.008 cms. (Streamflow was measured both at the beginning and the end of the monitoring period, and the two measurements averaged.) The Type 4 had a moderate gradient and mostly cobble substrate. The Type 3 stream was a low gradient stream, with numerous pools. Substrate is primarily gravel and cobble with occasional bedrock outcrops.

Results

The site on Green Creek was monitored from August 16 through September 10, 1991. Maximum stream temperatures were recorded on August 20. Although the overhead canopy was completely removed from the Type 4 reach for its entire length of 610 meters, it remained cool relative to the heavily canopied Green Creek. The water temperature in the Type 3 stream was reduced by 0.5°C from 17.8°C above the confluence with the introduction of the cooler Type 4 stream entering at 15.7°C. Measured temperatures were consistent with those predicted from the mixing equation. The maximum temperature for all of the monitoring stations downstream of the confluence showed little variation with all maximum temperatures for August 20 being between 17.3°C - 17.0°C; indicating the stream was in equilibrium with the conditions within this reach. Figure 8 displays maximum temperatures for the monitoring points on Green Creek.

Minimum daily temperatures during the monitoring period did not differ significantly between the six monitoring points and averaged 13.0°C.

Discussion

Cool temperatures were maintained in the Type 4 tributary due to understory plants and logging debris, which provided an average of 90% shade. A high proportion of groundwater in the total streamflow also probably contributed to the cool temperatures recorded in the Type 4 stream.

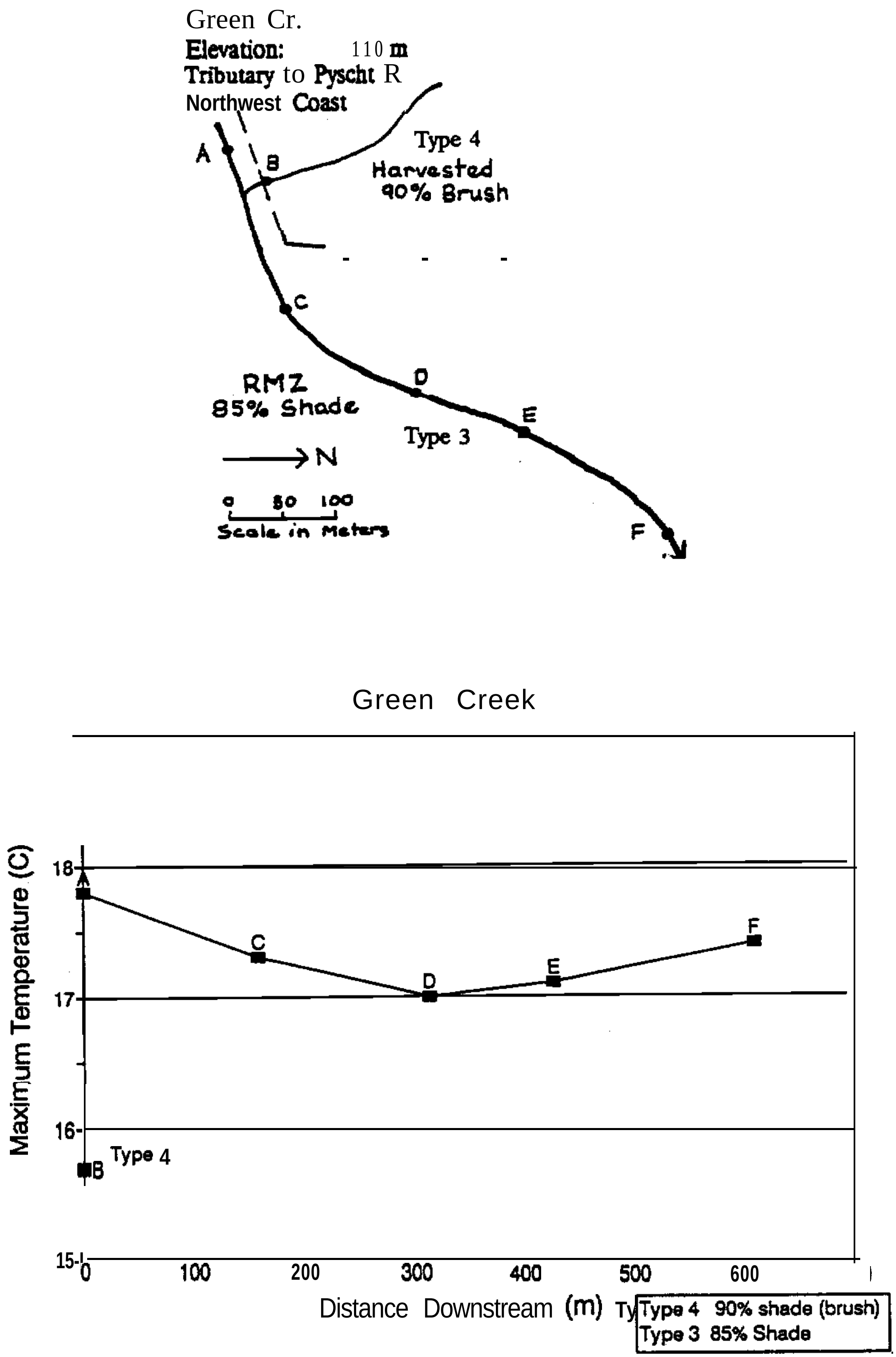


Figure 8. Green Creek site configuration and maximum temperatures. Locations of thermographs are noted by their letter designation. Shade percentages may vary between thermograph monitoring points. Average shade levels for the entire reach are shown.

Although the Type 4 tributary comprised 20% of the flow of Green Creek upstream of their confluence and was substantially cooler, little effect was noted immediately downstream. The moderately high temperatures in the shaded Type 3 stream both above and below the Type 4 confluence are a function of the site's elevation and shade. The maximum temperature of 17°C is consistent with those predicted by equations presented in Sullivan and others (1990).

Ward Creek Tributary

Characterization

This study site was situated on a small tributary to Ward Creek, a low-elevation (12 m) coastal tributary to the Willapa River in southern coastal Washington (Figure 9). (Ward Creek Tributary enters Ward Creek near the confluence of Ward and Fairchild Creeks.) The upper section of the Type 4 reach of Ward Creek contained an older harvested area, perhaps 4-5 years old and not replanted except by volunteer grasses, and another section that had been harvested during the summer of 1990. Approximately 80% of the triiutary watershed was in the newly harvested area, although the lower 150 m of stream in the open zone was in the older section, with logging debris and grasses covering the stream. The low-gradient Type 4 reach (approximately 2%) entered a mature alder forest, with almost no gradient, a meandering stream channel, and extensive streambank cover from devils' club and other brush. Streamflows were too low to measure with available equipment, and were estimated to be 0.0028 - 0.007 cms. The Type 4 reach had 90% shade provided by brush but minimal overhead canopy. The Type 3 reach had 95% canopy shade.

Site configuration included one measurement point at the lower end of the harvested reach, and three measurement points in the forested reach, extending over 223 meters of forested, meandering stream. At that point, the stream entered a swampy meadow, just above its confluence with Ward Creek.

Results

Temperatures were monitored from August 9 through August 28, 1990, with maximum temperatures observed on August 11. Maximum water temperatures at point (A) in the open section was 18°C, and dropped to 17.5°C at point (B), then to 17°C at points (C) and (D) (Figure 9). Minimum water temperatures averaged 13.5 - 14.0°C for all sites.

Air temperatures were higher in the open zone (a maximum of 27°C), than in the middle of the forested zone (a maximum of 23 - 24°C), where canopy shade levels were 95%.

Discussion

In this case, it appears that stream temperatures reached equilibrium with the new riparian conditions in 26 - 150 m downstream of which there were no temperature effects of the harvested Type 4 stream. Although temperatures in the forested zone remained high (17 - 17.5°C) they were as expected based on elevation and shade. Ward Creek is a very low elevation stream. Water temperatures at low elevation streams in Washington will be high even under mature forest canopy conditions.

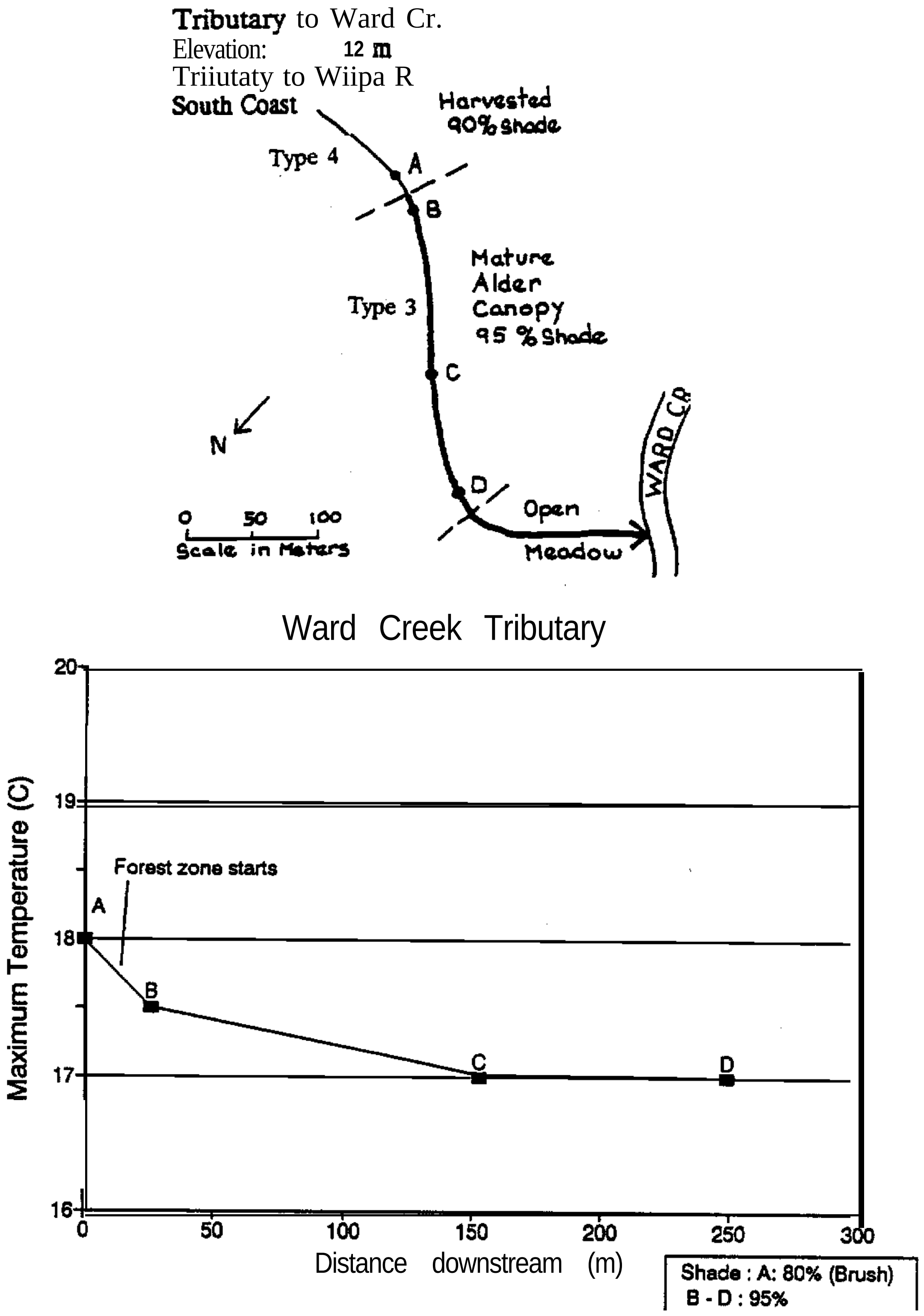


Figure 9. Ward Creek Tributary site configuration and maximum temperatures. Locations of thermographs are noted by their letter designation. Shade percentages may vary between thermograph monitoring points. Average shade levels for the entire reach are shown.

Huckleberry Creek

Characterization

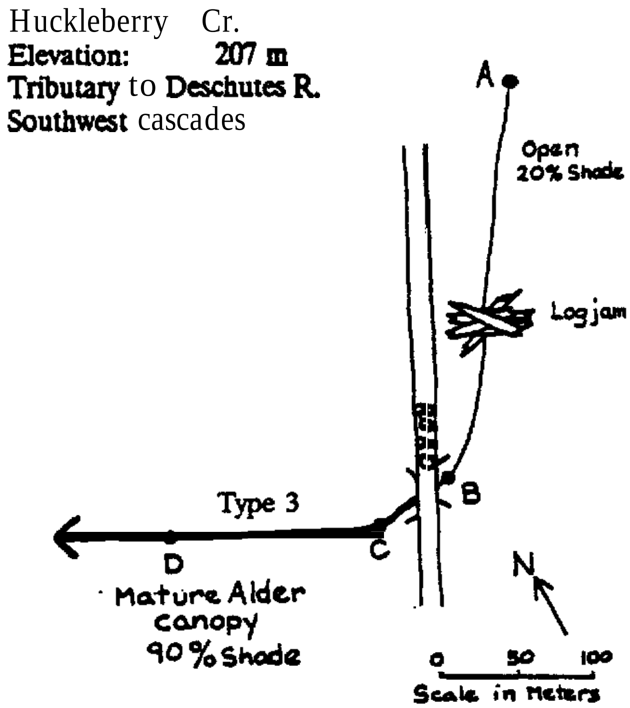
Huckleberry Creek, a small Type 3 stream, was included in this study for two reasons. First, temperature data existed from other ongoing monitoring activities and we had relatively few other sites. Second, this stream had experienced a dam-break flood event during the winter of 1989-1990 which affected the upper end but did not alter the canopy immediately downstream. Despite the fact that Huckleberry Creek is not regulated as a Type 4 stream for this reach it was thought that information from this site would be useful in evaluating smaller streams. (All other debris flow/ dam-break flood site candidates were unacceptable, either because the debris flow continued down the Type 3 channel, eliminating its shade, and often deposition of a large sediment wedge altered the surface expression of stream flow.)

The stream, a tributaxy to the Deschutes River in the Southern Cascades, had a site elevation of 207 m, and a flow of 0.028 cms. The most upstream measuring point was set in a meandering, braided, open channel, with a small amount of instream log debris (Figure 10). The open reach extended upstream of the measuring point at least 350 m. Below this site 150 m, the stream entered a large pile of log debris, which completely covered the channel for 125 meters. A second measuring point was set just below this logjam. Below the logjam, the stream crossed a road through a culvert, and entered an area unaffected by the dam-break flood, with a mature alder canopy, and shade levels of 90%. Two measuring points were placed in this area. Downstream of the lowest point, the stream flowed through a small residential area before its confluence with the Deschutes River. Stream gradients were approximately 3-4%.

Results

Temperatures were measured from July 27 through August 27, 1990, with maximum temperatures observed on August 12.

At point **(A),** the open stream had about 20% shading from log debris. Maximum air temperatures reached 30°C, and water temperatures reached 23°C. (The maximum water temperature was 6.7°C higher than that recorded prior to the dam break flood.) Below the logjam, at point (B), maximum air temperatures had cooled to 25°C, although it is possible that air temperatures inside the logjam were even cooler, because of the total shading. Water temperatures had cooled to 19°C below the logjam. Over the 57 meters between points (B) and (C) [the first in the forested stream zone], maximum water temperatures increased to 20.5°C. By the time the water had reached point (D), 130 m downstream from point (C), water temperatures had cooled to 19°C again, while air temperatures dropped one degree from point (C), to 26°C. Figure 11 shows maximum water temperatures observed along the study reach.



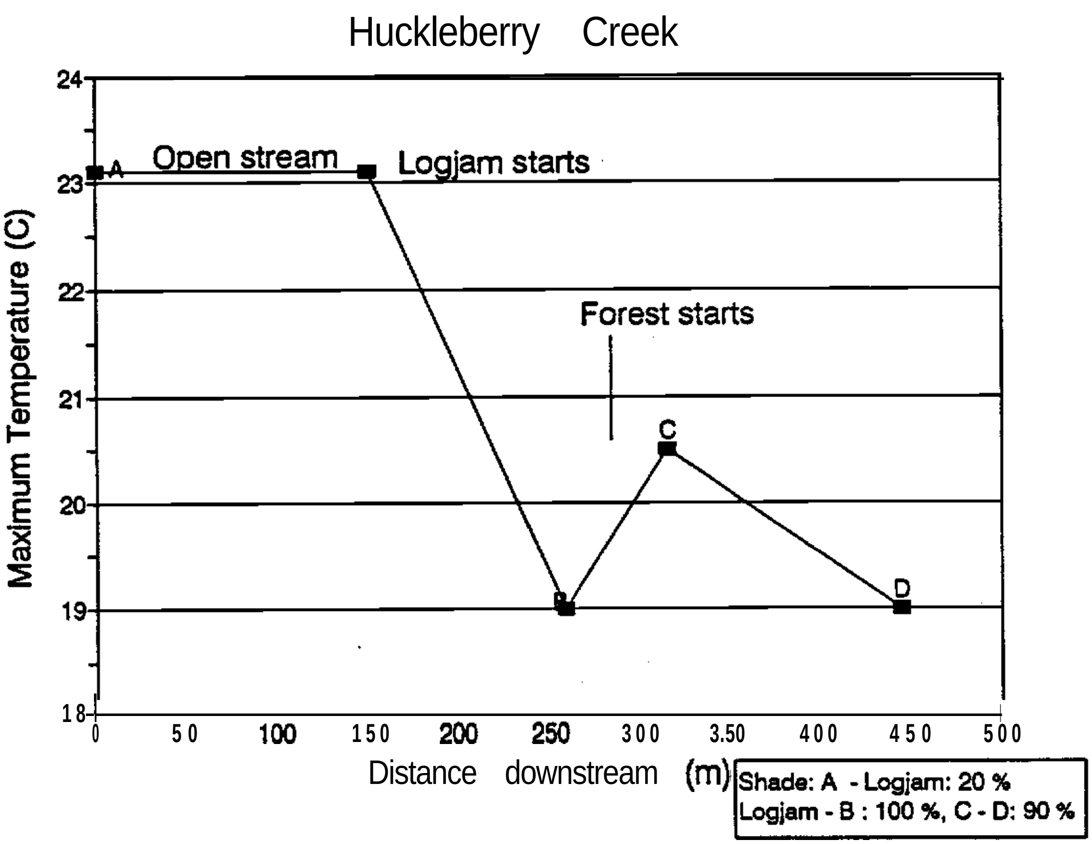


Figure 10. Huckleberry Creek site configuration and maximum temperatures. Locations of thermographs are noted by their letter designation. Shade percentages may vary between thermograph monitoring points. Average shade levels for the entire reach are shown.

Discussion

Stream temperatures within the upper reach affected by the dam break flood were some of the highest recorded during this project. The lack of riparian vegetative shade resulted in high water temperatures. A 4.1°C drop in temperature occurred between point A and point B, the latter being inside the log jam. The rapid cooling within the log jam is due to both increased shade (100% shade in the log jam) and the possibility that the much of the stream may well have been temporarily subsurface beneath the log jam as it traversed the sediment wedge.

The 1.5°C warming in water temperature as the stream emerged from the log jam may have been an anomaly of the monitoring point within the log jam rather than a movement towards equilibrium temperature in the shaded downstream reach. One would expect a maximum equilibrium temperature of approximately 15 - 16°C based on predictive models (Sullivan and others, 1990). Although the stream continued to cool between points (C) and (D), equilibrium conditions had not yet been reached. Huckleberry Creek is larger than the other streams studied and is regulated as a Type 3 stream throughout the study reach. The greater stream depth necessitates a longer travel time for the stream to come to equilibrium. The 1.2 hours estimated travel time between point (B), in the log jam, and the most downstream point, (D), is insufficient for the stream to-reach equilibrium after the extreme temperature elevation occurring in the open reach. This larger stream would probably require another 100 m before coming into equilibrium with the shaded downstream conditions.

Hanaford Creek

Characterization

Hanaford Creek, at 280 m elevation, is a tributary to the Skookumchuck River in the Central Cascades. The main stem of the stream above two Type 4 tributaries (0.00059 cms), has a mature alder riparian zone, which is thin in some places from blow downs (33 % canopy level shade). Understory plants provide additional shade (50% brush level shade) along some sections of the study reach. Approximate stream gradient is 2-3%. Two Type 4 tributaries flow across a single large harvested unit, and join the stream 133 m from one another. Both tributaries ($8.0 * 10^{-5}$ cms and $1.0 * 10^{-4}$ cms) flow down through at least 450 m of open area before joining Hanaford Creek, with stream gradients of 6-7%. The unit had been harvested during the summer of 1990, and while yarding had occurred, some logging debris was still on the ground. The lower section of Hanaford Creek, below the tributaries, contained 70 - 85 % canopy shade (Figure 11).

Site configuration included a measurement point above both tributaries, one just above the second triiutary, in both tributaries themselves, and three sequentially downstream with the farthest-downstream thermograph 450 m from the confluence with the lowest tributary.

Results

The monitoring period at this site was from August 10, 1990 through September 5, 1990, with the warmest temperatures observed on August 12. Maximum air temperatures were warmer in the tributaries (34°C) than at the mainstem sites, where maximum air temperatures were 29 - 31°C.

The upper tributary (B), had a maximum water temperature equal to that at point (A), in the mainstem just above it (14.5°C). Thus, there was no significant change in the maximum temperature of the main stem, seen at downstream point (C) with a maximum water temperature of 15.0°C.

The lower tributary, D, had a warmer maximum temperature (16.5°C) than point (C), just upstream of it (15.0°C). The mixing equation predicts a water temperature of 15.2 for (C) and (D) together, which equals the maximum observed temperatures of 15.0°C at both points (C) and (E). This shows that mixing of the lower tributary and the mainstem was instantaneous. The lower tributary's flow is approximately 15% of the flow in Hanaford Creek at point (C).

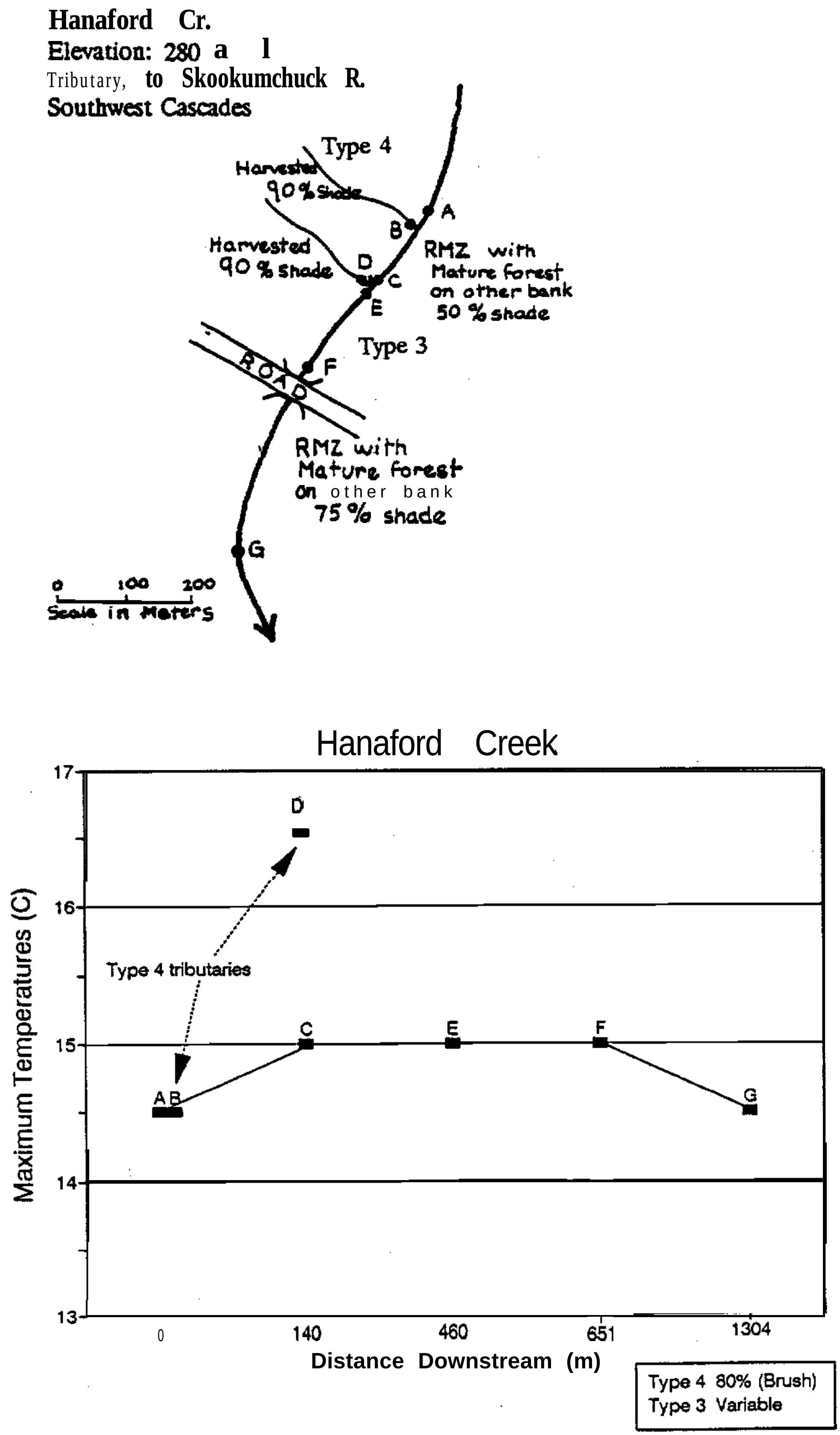


Figure 11. Hanaford Creek site configuration and maximum temperatures. Locations of thermographs are noted by their letter designation. Shade percentages may vary between thermograph monitoring points. Average shade levels for the entire reach are shown.

Downstream of the confluence, maximum water temperatures in Hanaford Creek remain at 14.5 - 15°C, indicating that the stream is in equilibrium in this reach with surrounding conditions, even though canopy shade levels increase (to 70- 85%) and understory shade decreases (to 10-40%) downstream from measuring point (C) to measuring point F.

Minimum water temperatures were similar at all measuring points, averaging 12°C.

Discussion

Water temperatures in the two Type 4 tributaries are relatively cool (14.5 and 16.5°C), even though air temperatures are much warmer (maximum 34°C) in the harvested unit than in the riparian zone (maximum 29°C). This may be due to the moderate site elevation (280 m), or a high groundwater proportion of flow in the tributaries. Both Type 4 streams contained small amounts of flowing water at the top of the harvested unit, and flowed out of forested areas. In both cases, the Type 4 streams mixed immediately with the Type 3 streams at the confluence.

In the mainstem of Hanaford Creek, water temperatures remain relatively cool, even though the riparian canopy shading is thin in places resulting from blow downs. Groundwater inflow may contribute to this, as well as the high levels of shading from understory plants on some stream reaches.

The incoming Type 4 stream (lower tributary), which was warm relative to the Type 3 stream did not affect downstream temperatures. The mixing equation supports the conclusion that the difference in size between the two streams prevents any downstream temperature impact.

Thorn Creek

Characterization

The study site on Thorn Creek, a tributary to West Fork Creek and the Deschutes River in the Southwest Cascades, contains two Type 4/3 stream boundaries. The first, upper Thorn Creek, is where an open Type 4 stream reach flows into a, mature forest canopy at 580 m elevation (Figure 12). This upper unit was harvested approximately four years earlier. The stream gradient was 9%, with 0.002 cms flow. The stream then flows through a 600-meter canyon section, with a steep gradient (18%), bedrock outcrops and mature alder and conifer canopy (shade level 90%). At the end of the canyon reach, now at 457 m elevation, lower Thorn Creek is joined by another Type 4 tributary, flowing 0.0002 cms. This smaller tributary drained a replanted area approximately 4 years old, and was 20% shaded by debris in the stream. Thorn Creek then continued another 925 m, through a mixed riparian area, containing a thin alder riparian zone with some blow downs (canopy shade 25 - 40%, understory shade 60%), alternating with reaches containing uncut second-growth conifer and alder. Stream gradients in this lower reach were 10%, and the flow measured at the lowest point, 363 m elevation, was 0.012 cms.

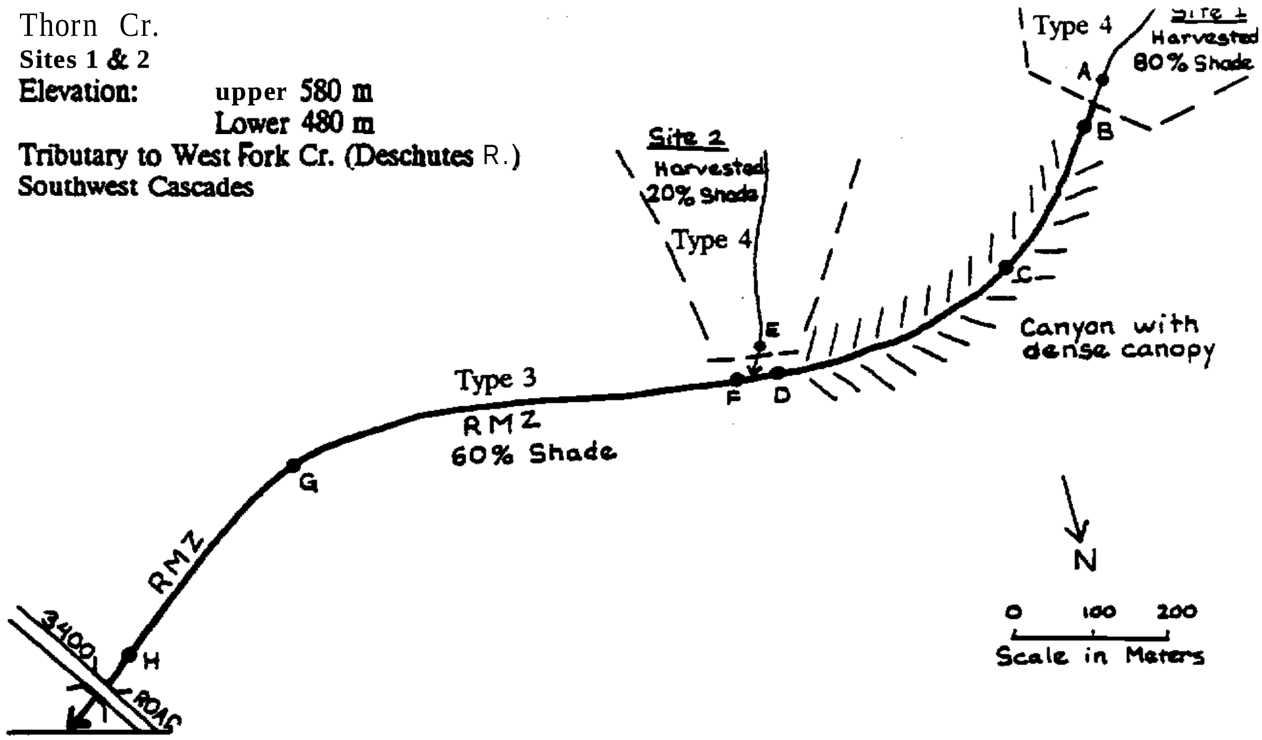
Results

Temperatures were measured from July 18 to August 5, 1990, with the warmest temperatures observed on August 5, 1990. The daily temperatures (Appendix B) show that temperatures at all monitoring points on Thorn Creek are relatively cool, with minimal diurnal fluctuation. Figure 13, observed maximum air and water temperatures, illustrates that in spite of high air temperatures, water temperatures do not exceed approximately 14.5°C.

Minimum water temperatures ranged from 9.7 to 11.7°C for all monitoring points.

Maximum air temperature in the harvest area was 31.5°C as opposed to 26°C in the immediately adjacent forested area.

The Type 4 stream at upper Thorn Creek is moderately cool even in the open section, which has approximately 70% shading from understory plants and logging debris over the stream. Maximum water temperatures drop 0.5 degrees as the stream moves beneath an overhead canopy of shade, from measuring point (A) (open) to (B) (shaded). Further cooling is evidenced within the canyon reach, (B)-(D), where the shade is very dense; both vegetation and topography contributing. An influx of additional groundwater is also suspected in this canyon reach.



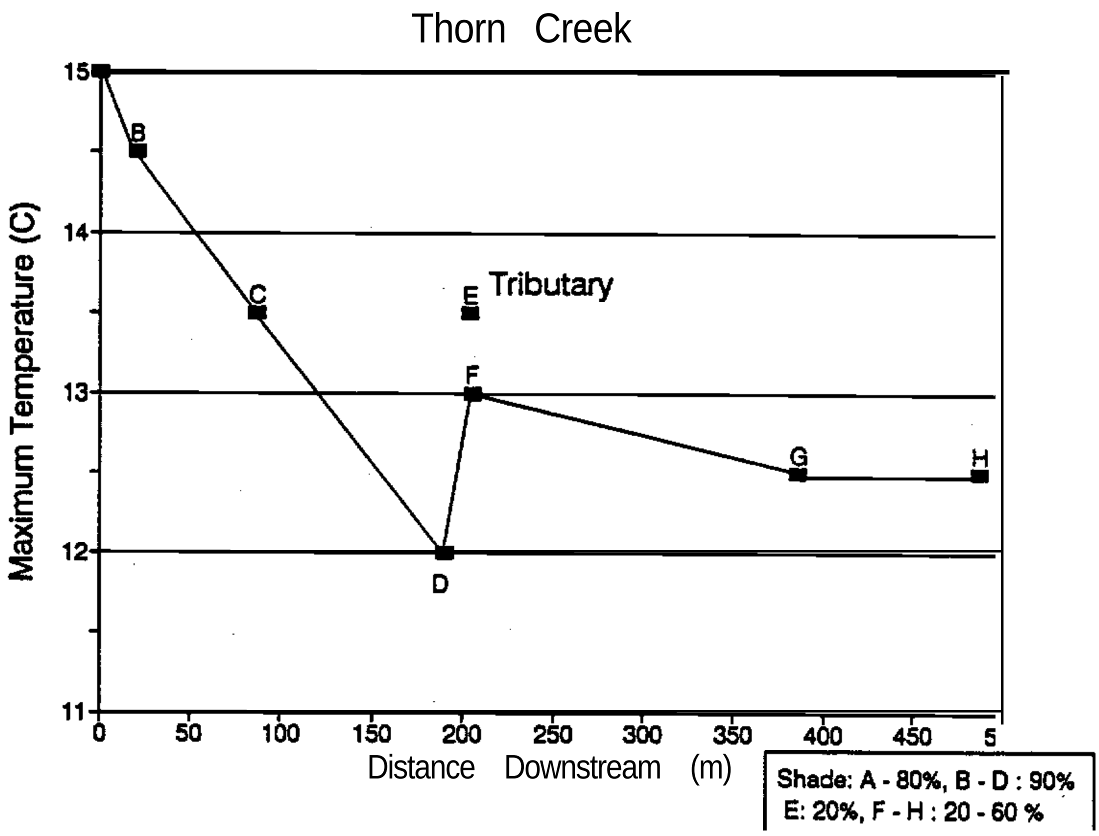


Figure 12. Thorn Creek site configuration and maximum temperatures. Locations of **thermographs** are noted by their letter designation. Shade percentages may vary between thermograph monitoring points. Average shade levels for the entire reach are shown.

At lower Thorn Creek, the stream exits the canyon reach just above measuring point (D), and a second Type 4 tributary (E) joins the stream just above measuring point (F). Maximum water temperatures at (D) are 12°C. The tributary's maximum temperature is 13.5°C, and Thorn Creek temperatures rise to 13°C at point (F), 30 meters below the confluence. The mixing equation predicts that the tributary is too small to change the temperature at point (D). Predicted mixed temperatures are 12.1°C, and observed temperatures at point (D) are 12°C. The increase in maximum temperature at point (F) is due to the stream's exit from the heavily shaded canyon reach, into a more open riparian area. This more open zone, 20-60% canopy shade, remains similar downstream for Points (F), (G) and (H), and the maximum water temperatures remain 12.5 - 13°C for all three measuring points, covering a downstream reach of 922 meters, and a drop of 95 m in elevation from (F) to (H).

Discussion

Measured temperatures are consistent with predicted temperatures for this higher elevation site. Predictive models (Sullivan and others, 1990) show that for this elevation and shade levels reported, temperatures should range between 12 - WC, depending upon shade level. In spite of high air temperatures the stream temperature did not increase beyond 14.5°C (Figure 13). This is due to the greater efficiency of the heat energy loss processes at higher elevation. The equilibrium temperature represents the balance between heat energy gains and losses. At higher elevations energy losses offset gains as rising air temperature tries to increase the stream temperature.

High groundwater rates may also have contributed to the low water temperatures at all of the monitoring points for Thorn Creek. Groundwater inflow rates (0.02 $m^3/s/km$, measured by difference in discharge) are at the high end of the range reported in Sullivan and others, 1990.

Also noteworthy is the high level of shade (70%) in the harvested reach contniuted by brush and debris. This shade also kept temperatures low within the open Type 4 stream.

At lower Thorn Creek, the mixing equation can be used to demonstrate that the inflow of the Type 4 tributary at point (E) did not significantly affect the temperature below the confluence. The increase in temperature at point (F), downstream of the confluence, is due to a new equilibrium temperature being established, within 43 meters, for the changing channel conditions as the stream exits the shaded canyon reach into a more open riparian area. The temperature predicted by the mixing equation for combining the hiiutary (point E) and the mainstem (point D) is 12.1°C, identical to the measured stream temperature at point (D). The tributary is too small to affect the downstream temperature.

The mixing equation can be further used to denionstrate the tributary did not cause the increase in temperature measured at point (F). An estimate could be made of either the size or temperature of the lower Type 4 tributary that would have to be present to change Thorn Creek's water temperature by 1°C, from 12 to 13°C. The tributary would either have to be 0.004 cms (20 times its current flow), or have a temperature of 23°C at its current size, to affect that change. A tributary of that size would exceed the upper size limit for a Type 4 stream (0.009 cms) and temperatures of that magnitude at that elevation are highly unlikely. Therefore, the lower Thorn Creek reach, like the upper Thorn Creek reach, came into equilibrium with new channel conditions in the distance between measuring points (D) and (F), 43 m. Using measured water velocities, the time for water to travel between points (D) and (F) is on the order of 0.5 hours.

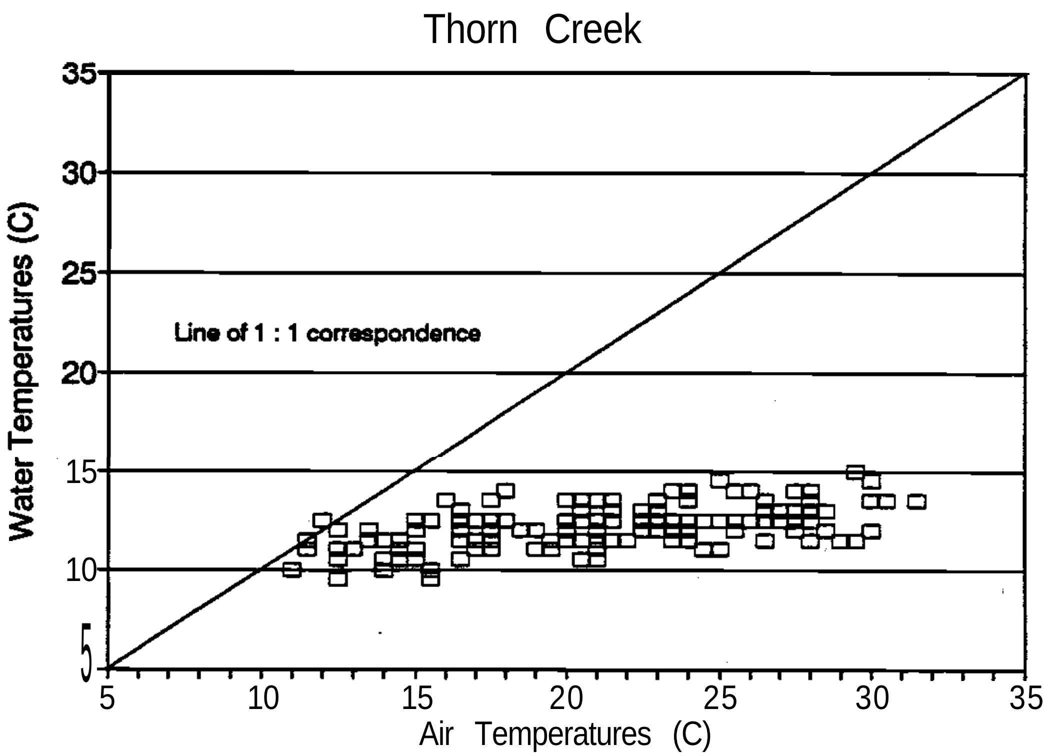


Figure 13. Maximum daily temperatures for all monitoring points on Thorn Creek. Groundwater strongly regulates stream temperatures.

Abemathv Creek

Characterization

Abernathy Creek, a small triiutary to the lower Columbia River, is a relatively large (for this study) Type 3 stream (0.14 cms) with a mature alder riparian zone (shade levels 95%). Site elevation was 195 m. A Type 4 tributary entered Abernathy Creek after crossing a harvested unit, portions of which had been harvested in 1986, and portions in 1988. The tributary stream had a gradient of 3-4%, a flow of 0.0085 cms, and a cobble channel, with approximately 80% shade from understory plants. The tributary flowed through a 66 meter wide riparian area before the confluence with Abernathy Creek (Figure 14).

Site configuration included two measurement points in the Type 4 tributary, one at the lower end of the harvest unit, and one at the lower end of the riparian area, just above the confluence. On Abernathy Creek, a measurement point was set above the confluence, one just below the confluence, and two more downstream.

The Type 4 tributary was small compared to Abernathy Creek (6% of Abernathy Creek's flow), although close to the maximum size for a Type 4 stream. It was chosen for two reasons. One was to test the hypothesis regarding necessary tributary size, and the second was to investigate the effects of a riparian area along a Type 3 reach on a warm Type 4 stream that must flow through it.

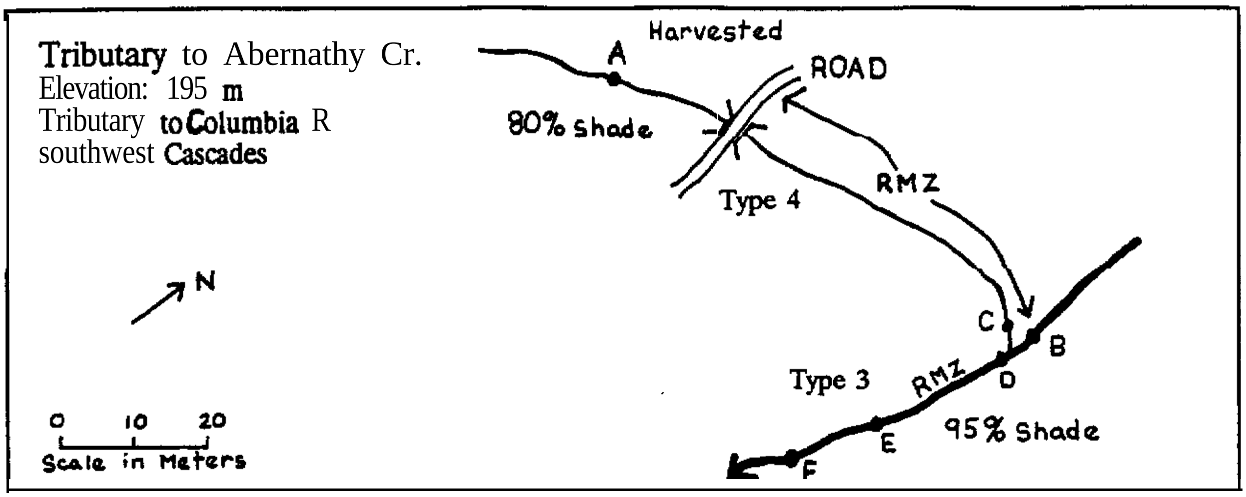
Results

Stream temperatures were measured from August 4 to August 28, with the hottest water temperatures observed on August 9, 1990.

The tributary, which had a maximum air temperature of 34°C in the open unit, and a maximum water temperature of 21.5°C, cooled as it traversed the 66 m of riparian zone. Maximum air temperatures cooled to 24.7°C, and the maximum water temperatures to 20.8°C.

Maximum water temperatures above the tributary were 18.5°C, and remained between 18.5 and 19.0°C below the confluence, and downstream. Observed temperatures were equal to those predicted by the mixing equation.

Minimum water temperatures in the Type 4 tributary were 14.9°C, while minimum temperatures in Abernathy Creek averaged 12.6°C.



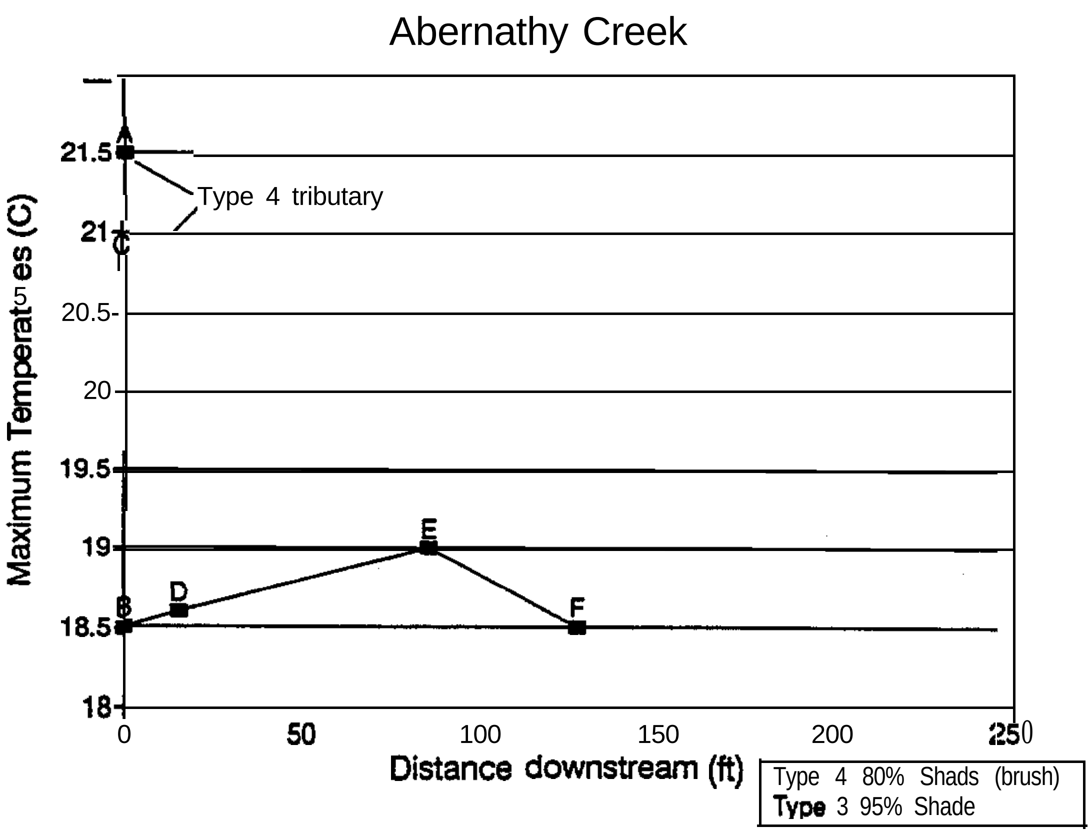


Figure 14. Abernathy Creek site configuration and maximum temperatures. Locations of thermographs are noted by their letter designation. Shade percentages may vary between thermograph monitoring points. Average shade levels for the entire reach are shown.

Discussion

Since water temperatures did not change in Abernathy Creek below the confluence with the tributary, mixing occurred between the tributary confluence and measuring point (D), 5 m downstream. This supports the hypothesis that the tributary was too small in size to influence the temperature of Abernathy Creek, which is in equilibrium with its own channel conditions. The riparian zone did reduce the tributary's maximum water temperature, probably due to the 10°C drop in maximum air temperature.

Using the mixing equation, an estimate can be made of either the size or temperature of the Type 4 tniutary that would have to be present to change Abernathy Creek's water temperature upward by 1°C, from 18.5 to 19.5°C. The tniutary would either have to be 0.113 cms in size (43% of the combined flow), or have a temperature of 36.8°C at its current size, to affect that change. A hypothetical stream of that size would exceed the upper size limit for a Type 4 stream (0.009 cms), while the calculated temperature in the second case is 2.8°C higher than the maximum air temperature recorded in the harvested unit, and 15.3°C higher than maximum water temperatures recorded in the tributary.

One possible explanation for the high temperatures observed in the Type 4 tributary might be a lack of groundwater inflow. Minimum water temperatures in the tributary averaged 14.9°C, while minimum temperatures in Abernathy Creek were 12.6°C, which indicates either that the groundwater was warmer entering the tributary, or there was less groundwater inflow.

Temoerature Regimes in Harvested Type 4 Waters

Temperature regimes for Type 4 waters as characterized in this report are based on a small sample of streams for which the riparian canopy had been recently harvested. Though sample size is limited, the authors believe temperature regimes observed in this study are representative of temperature regimes for Type 4 streams throughout Western Washington that cross recently harvested land units. Furthermore, temperature regimes in Type 4 streams in Eastern Washington are likely to behave in a similar manner. As discussed elsewhere in this section, the Type 4 streams function in the same manner with respect to environmental site conditions as did streams reported in Sullivan and others (1990).

Late-summer stream temperatures were monitored for a period of at least two weeks for eleven Type 4 stream reaches. Though some of these reaches existed within the same Type 4 stream, distinctive channel conditions were identified within each reach and all eleven reaches appeared to be in equilibrium. A range of site elevations, from 12 m to 580 m, and a range of western Washington climate conditions is represented. All of the sites had been harvested within the last few years, with several sites just harvested. Even immediately after harvest, high levels of understory shade were common. The understory provided an average of 60% shade for these reaches.

Figure 15 shows the average daily temperature regimes observed for the Type 4 stream reaches. Average daily maximum stream temperatures for the Type 4 sites ranged from 12.6°C - 23.1°C. The highest recorded temperature was in Huckleberry Creek, where a recent dam-break flood removed nearly all the shade. (Huckleberry Creek is regulated as a small Type 3 stream.) The next-highest temperatures were in Hoff Creek and Abernathy Creek (18.4°C). The relatively low elevations of these sites, 166 m and 200 m, most likely accounts for the high temperatures. Average daily maximums observed at all other sites ranged from 12.6°C to 16.2°C. Of these eleven recently-harvested Type 4 sites, eight met the state Water Quality standard for maximum temperatures in Class AA streams (not to exceed 16.3 °C).

Except Huckleberry Creek (average daily minimum 18.1°C), minimum water temperatures ranged from 11.7 - 15.7°C.

Those Type 4 harvested streams included in this study had an average size of 0.00053 cms (0.02 cfs), considerably smaller than the maximum size of 0.009 cms (0.3 cfs) in the Forest Practices regulations. (We noted a number of larger Type 4 streams with riparian leave areas during our site candidate search.) Since the downstream zone of temperature influence is shorter for smaller streams, because they have less capability to store heat energy for downstream transport, the potential for downstream temperature impacts is reduced. More Type 3 receiving streams will be too large to be affected by temperatures of these typically small Type 4 tributaries.

Average daily maximum air temperatures in the harvested areas were observed to be higher than those within the riparian areas. For instance, air temperatures at Jimmy Come Lately Creek increased 8.7°C between the harvested area and the riparian zone (27.6°C to 18.9°C). Abernathy Creek air temperatures increased 5°C (23.9 to 18.9°C), and a drop of 4.3°C was observed at upper Thorn Creek (24.3 to 20.2°C).

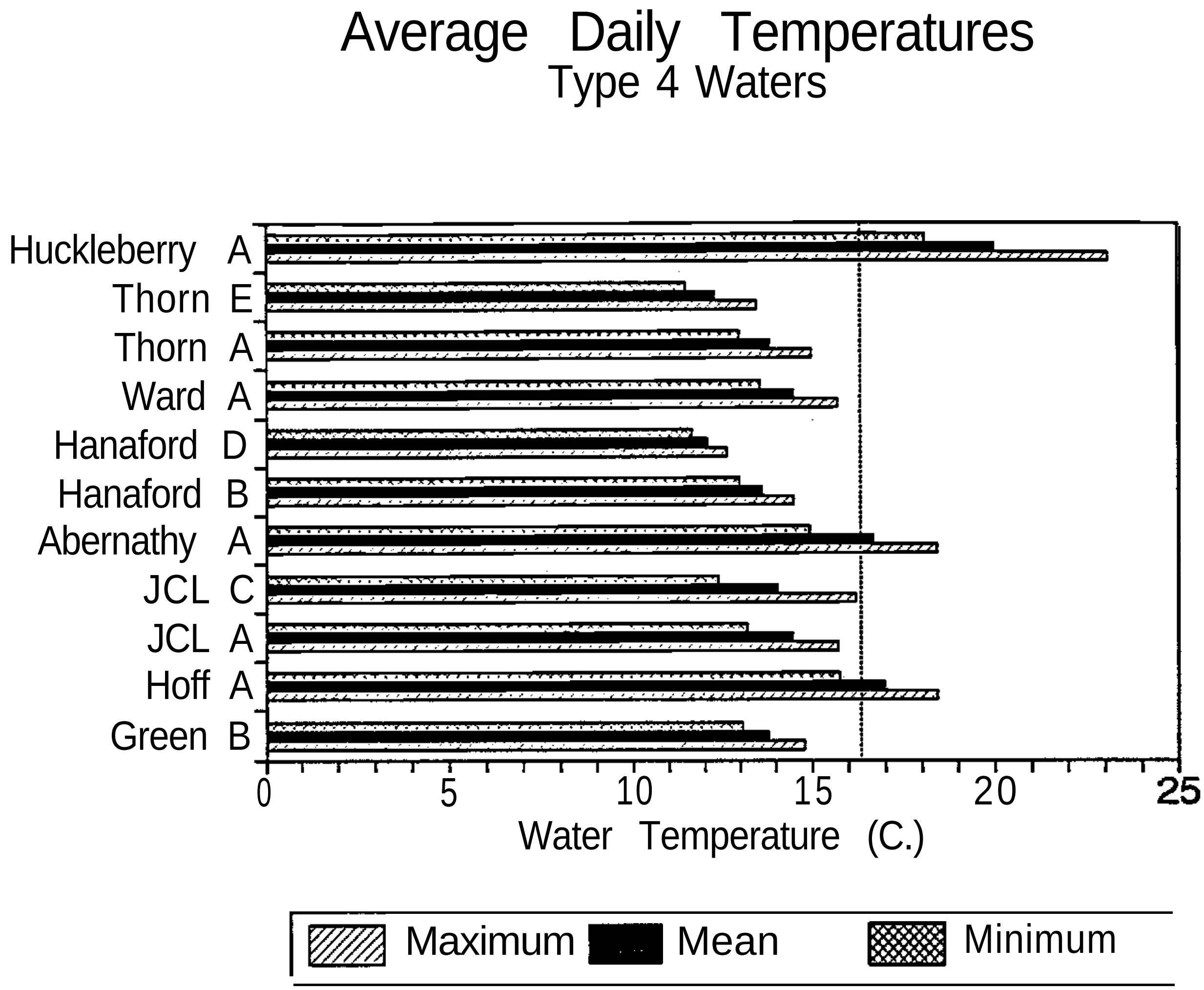


Figure 15. Average daily temperatures for harvested Type 4 study sites, summer 1990.

1990 Air Temperatures Compared to Lone-term NOAA Averaees

NOAA monthly climatological records were consulted for an indication of 1990 summer air temperatures in relation to long-term averages. Using the NOAA "division data" for Western Washington climate zones (temperature records grouped in areas with similar climatological characteristics), it appears that 1990 temperatures were slightly warmer than the long-term averages.

Table 2. 1990 Climate Information

NOAA climate division	Departure from "Normal" temperatures (degrees C, positive numbers indicate temperatures warmer than normal)		
	July	August	September
West Olympic/ Coastal	1.8	1.7	1.8
N.E. Olympic	1.5	1.5	0.9
Puget Lowlands	1.6	1.7	1.4
E. Olympic/ Cascade Foothills	2.0	1.7	1.9
Cascade Mtns. West	2.4	2.1	1.5

Overall Average: 1.7 degrees C warmer than "normal"

(NOAA 1990)

Temperature Screen Evaluation

One of the products on T/F/W research into stream temperature was a simple evaluation tool, for determining expected stream temperatures before and after timber harvest. This temueerature screen, presented in Sullivan and others (1990), is not used to predict actual stream temperatures, but rather to predict temperature categories, according to standards set by the Washington State Water Quality regulations (WAC 173-201). In this discussion, a "Low" temperature category refers to a stream with maximum temperatures less than 16.3°C (meeting the Water Quality criteria for class AA streams). A "Moderate" category refers to streams with maximum temperatures between 16.3 and 18.3°C (meeting the Water Quality criteria for class A streams). A "High" temperature category refers to streams with maximum temperatures exceeding 18.3°C (see Figure 16).

The temperature screen was developed using information from the Type 1-3 streams studied in 1988, and correctly predicted temperature categories of 89% of those streams. We wished to investigate the temperature screen's accuracy with this data set, to see if the smaller, shallower Type 3 and 4 streams we studied behaved in similar ways with respect to the screen as the previous data, which was from larger stream reaches.

We hypothesized that the general relationship of stream temperatures to shading level and site elevation expressed by the screen would hold true for these smaller streams as well, but that the exact stream temperatures might vary. On one hand, smaller streams will have a greater proportion of groundwater than larger streams, and might be expected to be cooler than a larger stream for a given shade level and site elevation. However, smaller streams are shallower, and could also be expected to be warmer for a given shade level and site elevation than a larger stream.

Methods

Homogeneous reaches within each study stream were defined, and the most downstream monitoring point in the homogenous reach was used to test the temperature screen. Reaches known not to be in temperature equilibrium with channel conditions were excluded.

The temperature screen requires an estimate of each site's shading level and elevation. Shading level at each site was specified by using the higher value from either the shade canopy measurements or from estimates of ground level shading from understory plants and logging debris. Site elevation was determined either from field altimeter measurements, or from USGS maps. Each site was plotted on the screen, and the temperature category predicted by the screen was compared to the actual temperature category, determined by the maximum recorded temperatures.

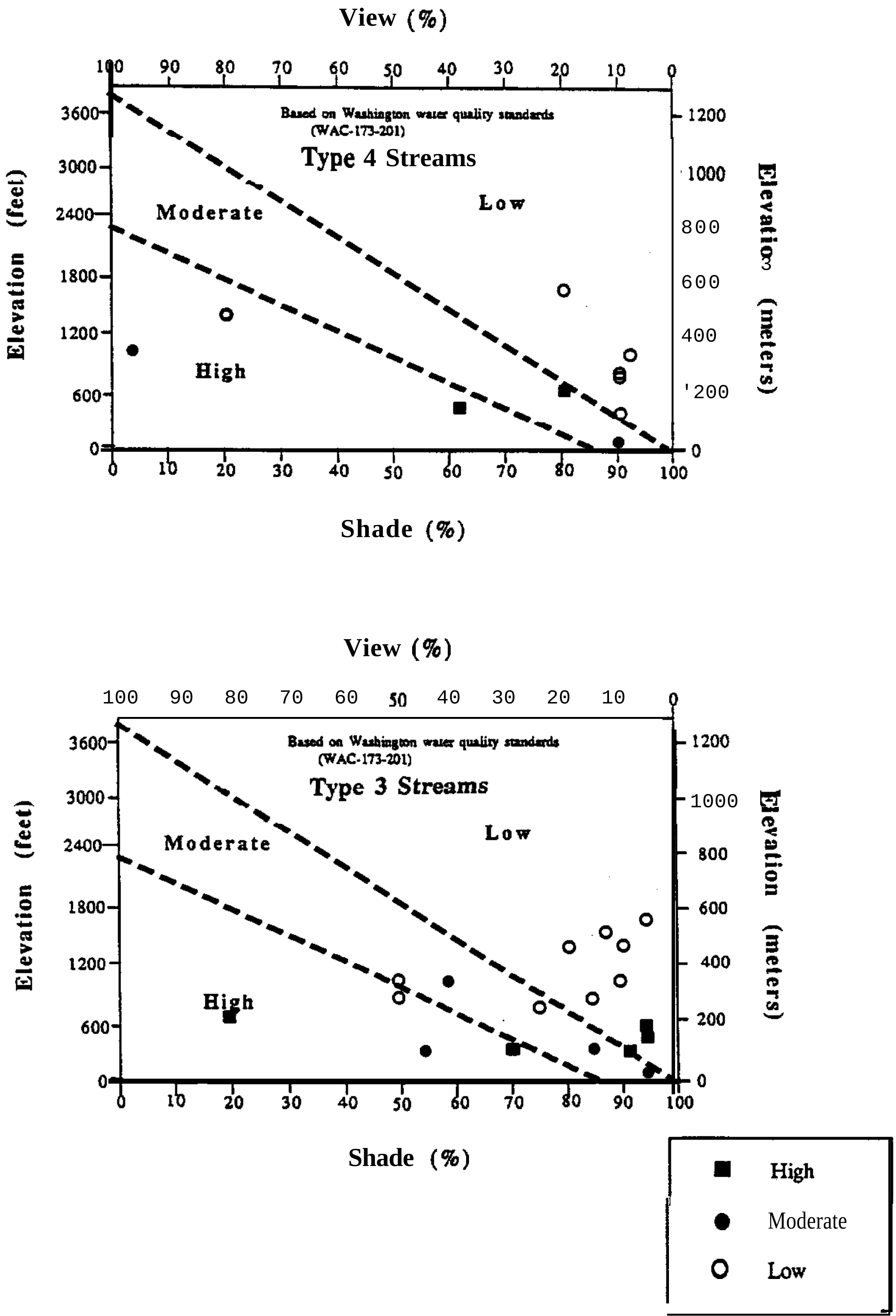


Fig. 16 Temperature Screen. Application of the temperature screen developed for Type I-3 waters (Sullivan and others, 1990) to the 1990 Type 4 study sites. The upper graph pbts the Type 4 streams while the bwer graph plots the small downstream Type 3 study sites.

Results

While the shade/elevation relationships presented in the screen did hold true, in general, local site conditions seemed to have a strong influence on temperatures of these small stream reaches. Some temperatures were much lower than the screen predicted, indicating an influence of groundwater. Some temperatures were higher, indicating an absence of groundwater, or simply atypically warm conditions.

A total of 28 reaches (18 Type 3 reaches and 10 Type 4) were tested against the screen. Seventeen reaches (60%) were correctly classed by the screen for temperature category. Eleven reaches (40%) were incorrectly classified (7 Type 3 reaches, and 4 Type 4 reaches). Six sites were classed too high, and 5 sites too low. Results are presented in Table 3 and Figure 16.

There was a relatively wide range of stream depths present in the 1988 dataset from which the screen was developed. Since the 1990 data included shallower streams, some inaccuracy in screen classifications might be expected. Small, shallow streams will be more strongly influenced by localized conditions so categorizing is less successful. Also, many of the sites were at low to moderate elevations making them susceptible to changes in temperature category with relatively minor changes in shade.

Table 3 . Temperature Screen Evaluation

Site/ Monitoring Point	Elevation (m)	% Shade Canopy	% Shade Brush	Maximum water Temp(C)	Actual Temperature category	Screen Temperature Category/ Screen Fit
Type 3 Streams						
Hanaford C	270	33	50	16.5	Low	High N
Hanaford E	270	85	10	15.0	LAW	Low Y
Hanaford G	244	75	40	14.5	Low	Low Y
Green A	109	70	0	17.8	High	Mod. N
Green E	109	85	25	17.1	Moderate	Mod. Y
Green F	109	55	15	17.4	Moderate	High N
Thorn B	580	95	10	14.5	Low	Low Y
Thorn c	530	87	10	13.5	Low	Low Y
Thorn D	480	90	50	12.0	Low	Law Y
Thorn F	480	80	20	13.0	Law	Law Y
Thorn H	363	46	50	12.5	Low	Mod. N
Huckleberry A	207	0	20	23.1	High	High Y
Abernathy F	195	95	10	18.5	High	Low N
JCL D	326	59	7	17.1	Moderate	Mod. Y
JCLE	326	90	35	16.2	Low	Low Y
Hoff C	146	95	26	18.8	High	Low N
Hoff E	91	98	17	19.6	High	Low N
Ward D	12	95	50	17.0	Moderate	Mod. Y
Type 4 Streams						
Hanaford B	280	0	90	14.5	Low	Low Y
Hanaford D	270	0	90	15.0	Low	Low Y
Green B	109	5	90	15.7	Low	Low Y
Thorn A	580	0	80	15.0	Low	Low Y
Thorn E	480	0	20	13.5	Low	High N
Abernathy A	200	0	80	21.5	High	Mod. N
JCLA	326	93	3	16.7	Low	Mod. N
JCLC	326	-0	3	17.2	Moderate	High N
Hoff B	166	62	47	19.8	High	High Y
Ward A	12	0	90	18.0	Moderate	Mod. Y

Multiole Type 4 Tributaries

Thus far only the downstream temperature effects of a single Type 4 stream have been discussed. T/F/W managers have expressed concern about the potential for a cumulative downstream effect of multiple Type 4 streams on Type 3 receiving waters. Information gained on response distance allows this concern to be framed in a quantitative analysis. Since site data showed the effect on temperature from the Type 4 only extends 150 m or less downstream of the Type 4/3 boundary, only multiple Type 4 tributaries within a 150 m reach are of concern. Type 4 streams entering a Type 3 water at intervals greater than 150 m will have no cumulative effect.

To address the issue of a cumulative temperature impact the distribution of Type 4/3 stream boundaries was analyzed for western Washington forested lands. (A Type 4/3 stream boundary is defined as a place where a Type 4 reach either becomes a Type 3 reach, or is tributary to one.) Ten township maps were generated by the DNR Geographic Information System, with all streams shown. Since not all townships are available on the GIS, selection was not random, but townships were chosen to represent typical timberland areas in various counties in western Washington.

Table 4 describes the townships chosen. On each map, the total number of Type 4/3 stream boundaries were counted. The total number from all townships was 295, ranging from a low of 8 to a high of 58 in one township.

Three types of stream boundaries were seen. The first, single channel, was where a single stream changed class from a Type 4 to a Type 3 without gaining any tributaries. A total of 45%, or 134 boundaries, were of this type.

The second type, headwaters tributaries, was where two Type 4 streams joined, and the Type 3 boundary was at their confluence. A total of 12%, or 36 boundaries, were seen of this type. The maximum summer low flow at the confluence could not exceed 0.017 cms (0.6 cfs), and Type 3 streams of this size are included in this study. Stream temperatures would be expected to come into equilibrium with the Type 3 channel conditions in distances of 150 meters or less.

The third boundary type found was where the Type 3 stream gained Type 4 tributaries. A total of 42%, or 125 boundaries, were found in this sample. The mean distance between Type 4 tributaries in typical western Washington topography was 542 meters, with a range of 200 to 1013 meters. Since this distance, on average, is much longer than the 150 meters our study results indicate is the zone of concern, it would appear that there is little risk of cumulative temperature impacts of multiple Type 4 tributaries on Type 3 streams in western Washington.

A Type 4 stream may cause some localized effect on downstream water temperatures but the downstream waters will be in equilibrium to their own surrounding conditions, not the upstream Type 4 stream, within 150 m. In almost all cases this would be before a second Type 4 tributary enters, thus no cumulative effect exists.

For those rare instances where Type 4 tributaries enter a Type 3 water at intervals less than 150 m, a flow mixing equation, described in the methods section of this report could be used to identify if a potential for cumulative effect existed at that site's elevation, stream size and shade level.

Table 4. Distribution of Type 4/3 Stream Boundaries for Selected Areas in western Washington.

Township	County	No. of Type 4/3 stream boundaries: Single channel	Headwater tributaries	Multiple tributaries	Average downstream distance (m) between Type 4/3 stream boundaries
T27N R8E	Snohomish	15	0	3	363
T6N R4E	Cowlitz	11	1	4	539
T15N R8W	Lewis	13	8	39	241
T16N R4W	Pacific	29	6	14	498
T16N R7W	Thurston	5	3	5	1013
T31N R12W	Grays Harbor	21	11	26	619
T34N R7E	Clallam	17	3	5	968
T39N R7E	Skagit	10	3	25	385
T39N R4E	Whatcom	6	1	3	591
T28N R1E	Jefferson	7	0	1	202

VI Discussion and Conclusions

Characteristics of Tvoe 4 waters

The analysis using the temperature screen, as well as the site by site descriptions in section V, indicate that the Type 4 reaches studied act, with regard to temperature, much like the larger streams studied in the 1988-1990 T/F/W temperature study. Reductions in shade levels result in an increase in stream temperature. Harvested Type 4 streams may be 2 - 8°C higher than would be expected for similar streams under a mature riparian canopy. The temperature of Type 4 streams is strongly influenced by elevation in the same manner as other streams (Sullivan and others, 1990). Low elevation streams are warmer, with temperatures recorded up to 21.5°C at very low elevations for open canopy streams. Stream temperatures for moderate elevation streams observed in this study were well below the regulatory limit of 16.3°C for Class AA streams in Washington.

Since Type 4 streams are small by regulatory definition their temperature response to changes in channel conditions is rapid, and conditions within the immediate stream reach control the temperature within these streams. Localized conditions affecting temperature include: air temperature, elevation, groundwater inflow, and shade.

This study showed that Type 4 streams are influenced by air temperatures. However a maximum equilibrium temperature exists for streams above which water temperatures will not increase, even if air temperatures do. This maximum equilibrium temperature is dictated by channel conditions, particularly elevation and shade, and is partially independent of air temperature. Elevation affects both air temperatures and the efficiency of heat energy exchange processes (Edinger and others, 1968). The close fit of the Type 4 stream data to the temperature screen supports the importance of the effect of elevation on temperature.

Groundwater strongly influences temperatures in small Type 4 streams. Groundwater inflow which enters the stream at cool temperatures (10 - 12.5°C average) is proportionately large with respect to the total flow in headwater streams. Groundwater rates appear to vary widely geographically. Where groundwater inflow rates are substantial, the Type 4 stream temperature is largely a function of groundwater temperature. Type 4 streams are responsive to very localized groundwater conditions as well as to the other localized conditions affecting stream temperature. The daily temperature profiles (Appendix B) for Thorn Creek graphically demonstrate the strong influence of groundwater. As a comparison, the daily temperature profiles for Hoff Creek, where groundwater recharge was documented, closely track air temperature with little effect of groundwater temperatures.

High temperatures in harvested Type 4 streams were not as common as some had expected. Temperatures in harvested Type 4 streams are as much as 2-8°C higher than for streams at similar elevations with mature forest canopies. However, many of the harvested Type 4 streams displayed cool water temperatures well below the water quality standards. One of the reasons for this is that, in most cases, substantial amounts of understory shade remain after harvest of the trees. Brush and slash remaining after harvest accounted for an average of 40% shade for the study sites. During site selection numerous sites were not chosen because a dense understory canopy had developed on stream channels where harvest had occurred four or more years previously.

A last point is that shade reduction in a completely harvested Type 4 reach is a relatively short-lived phenomena, existing for less than 5 years in stream reaches not affected by catastrophic flooding events. Even within that five-year period, many sites contain a fair level of channel shading from understory plants and wood debris. Both this shading, and in some cases the relatively high proportion of groundwater flow, can tend to depress stream temperatures even though air temperatures in the harvested units are typically higher than those in nearby riparian areas.

The sample size of streams studied for this project is too small to specifically characterize Type 4 streams separately from adjoining Type 3 reaches, or to make any generalizations regarding streams across Washington state (our sample did not include sites in Eastern Washington). However, there is no indication that the small Type 4 and 5 streams react in any way differently than the Type l-3 streams studied in the 1988-1990.

Of the 11 Type 4 stream reaches with distinctive channel characteristics (includes Huckleberry Creek which is a regulated as a small Type 3) eight met the Class AA maximum temperature water quality standard, i.e. less than 16.3°C. Those sites which did not meet the water quality standard were at lower elevations; approximately 200 m or less. The warmest creek, Huckleberry, had experienced a dam break flood which scoured the channel and most of the brush shading the channel. The five reaches with maximum temperatures exceeding 16.3°C also had warmer minimum temperatures relative to other sites. The effect of elevation on temperature does not fully account for these warmer minimum temperatures. Summer minimum temperatures in small streams are typically at or near groundwater temperature. The higher minimum temperatures suggests groundwater inflow was minimal within these five reaches.

Downstream effects of Tvoe 4 waters on Tvoe 3 waters

Increases to stream temperature for salmonid bearing (i.e., downstream) waters resulting from timber harvest on upstream Type 4 waters appear to be negligible. In cases where a single stream channel changed from a Type 4 to Type 3 water type, short response distances were seen, in response to changes in the riparian shading levels. Maximum equilibrium temperatures were quickly established dependent on the downstream conditions once the water entered the Type 3 (shaded) reach. The response distance was typically 150 meters or less with no effect on temperature from the harvested Type 4 stream downstream of the response distance. Using measured stream velocities, these response distances equate to a water travel time on the order of one to two hours for equilibrium temperatures to be reached. This conforms with the analysis of equilibrium response time presented in Adams and Sullivan (1990).

With regard to Type 4 streams flowing into an independent Type 3 stream, the flow mixing equation which is a weighted average of the incoming stream temperatures (Brown, 1969), fully describes the temperature response. The response of the Type 3 stream never exceeded 0.5°C change in temperature attriiutable to the incoming Type 4 stream. Reasons include the typically small size of the Type 4 mbutaries in relation to the Type 3 receiving streams, and the relatively cool temperatures seen in some Type 4 reaches despite total removal of overstory canopy. This lack of response was seen both in cases where warm and where cool Type 4 streams flowed into Type 3 reaches.

The flow mixing equation can also be used to demonstrate minimal downstream effect from Type 4 streams. Assuming a warm Type 4 stream (21.5°C, the highest temperature observed) with a low flow of 0.009 cms flowing into a cool Type 3 stream (for example, 15.8°C), the size of the downstream Type 3 stream which would be affected can be calculated using the mixing equation. This calculation shows that, in this worst case situation, the Type 3 must be no larger than 0.09 cms to be affected. If the Type 3 were any larger relative to the Type 4, the effect on temperature would not be great enough to result in the Type 3 exceeding the water quality standard for class AA streams (the temperature would remain below 16.3°C.) Sullivan and others (1990) related minimum stream flow to distance from watershed divide. Using this relationship and the results of the flow mixing equation, it can be concluded that the temperature in Type 3 streams greater than seven km (4.5 miles) distance from watershed divide (measured along the Type 3 stream channel) would not be affected by incoming Type 4 waters. This holds true for incoming Type 4 streams which are both cooler and warmer than the receiving Type 3 stream. This distance from divide was calculated using a worst case scenario for the Type 4 temperatures. Effects of Type 4 mbutaries on downstream Type 3 water temperatures are commonly more limited.

$$\frac{(21.5^{\circ}C * 0.009\ cms) + (15.8^{\circ}C * Q_3)}{0.009\ cms + Q_3}$$

Where Q_3 = stream discharge in the Type 3 receiving water

Riparian management along Type 4 streams for temperature control will only affect water temperatures within the Type 4 and for a limited downstream distance in Type 3 waters. Type 3 streams beyond 7 km from watershed divide will have virtually no effect with respect to temperature impacts from incoming Type 4 streams. Though there may be downstream effects other than temperature, in most cases harvest within Type 4 streams does not seem to affect stream temperatures for salmonid bearing waters.

Multiple Type 4 Triiutaries

T/F/W managers have expressed concern as to the cumulative downstream effect of multiple Type 4 streams. Since site data showed that the effect on temperature from a Type 4 stream only extends 150 m or less downstream of the Type 3/4 interface, only multiple Type 4 tributaries within 150 m are of concern. Type 4 streams entering a Type 3 at greater space intervals will have no cumulative effect. A map analysis for western Washington forested lands indicated that Type 4 tributaries to a Type 3 stream are typically spaced at 200 m to greater than 1000 m intervals; thus no cumulative temperature impact could occur. In the case of one or two headwater Type 4 streams converting to a downstream Type 3 stream any elevated temperatures due to harvest along the Type 4 would only persist 150 m downstream. Type 4 streams flowing into Type 1 and Type 2 waters would have no discernable effects on water temperature.

Stream Depth and Temperature Response

Stream depth is one of the most important channel characteristics which control a stream's rate of temperature response. Heat energy transfer processes are more rapid in shallower streams and thus shallow streams can potentially have greater diurnal temperature fluctuations in response to diurnal climate patterns. Shallow streams respond rapidly to direct solar radiation reaching the stream's surface (Brown, 1969). Shallow streams are apt to respond to changing channel conditions as the water passes downstream within l-2 hours or less whereas large rivers may only respond within several days or more to changing ambient conditions (Adams and Sullivan, 1990).

Average stream depths of streams studied in 1988 (Types 1-3 reaches) can be compared to average depths of the smaller Type 3 and 4 stream reaches studied for this project. Both sets of data, considered together, present a range of typical stream depths for each various water type. Stream depths in the 1988 study ranged from 0.13 - 0.56 m for Type l-3 waters while Type 3 and 4 streams included in this study ranged from 0.07 - 0.56 m in depth. The 1990 data include the lower end of the range present in Washington streams.

The response distance of 150 m or less is comparable to a response time of 1 - 2 hours given the velocities of the streams studied. This fairly rapid response is due to the shallow nature of these streams. Deeper Type 1 - 3 streams can be expected to respond slower to changing ambient conditions and thus have somewhat longer response distances.

VII Recommendations

Increases to stream temperature for salmonid bearing (i.e., downstream) waters resulting from timber harvest on upstream Type 4 waters appear to be negligible. Maximum equilibrium temperatures were quickly established dependent on the downstream conditions once the water entered the Type 3 (shaded) reach. The response distance was typically 150 meters or less with no effect on temperature from the harvested Type 4 stream downstream of the response distance.

We recommend that management recommendations to T/F/W be developed following a technical review of this report. Management recommendations should recognize the limited downstream temperature effect of harvest along Type 4 waters. Furthermore, cumulative effects from multiple Type 4 waters entering Type 3 or larger waters seldom occur for western Washington streams. The potential for cumulative temperature impacts for Type 4 streams in eastern Washington could be similarly examined using maps for that region.

A policy decision is required regarding management actions to regulate stream temperature within Type 4 stream reaches as opposed to downstream effects. Several of the Type 4 streams monitored in this study exceeded the Washington water quality standards (WAC 173-201). However, temperatures exceeding of the water quality standard were seen for both harvested and forested Type 4 streams. This study was not geographically comprehensive and the number of streams is too small to fully characterize the range of temperature regimes within Washington's Type 4 waters. If shade recommendations are developed for controlling stream temperatures within Type 4 streams themselves, it is recommended that additional sites be investigated to characterize Type 4 water temperature regimes. Maximum - minimum thermometers placed in streams at various elevations, ecoregions, and shade levels for a few days during July 15 - August 15 would suffice for characterizing maximum temperatures. The maximum equilibrium stream temperature will be observable using this simple approach. Any management regulations adopted for control of stream temperature within Type 4 waters should recognize the effect of elevation as well as shade on stream temperature. Unlike larger Type l-3 streams, use of the temperature screen to categorize stream temperatures is not recommended for Type 4 streams. The strong influence of localized conditions, particularly groundwater inflow rate and temperature, render the screen less applicable to Type 4 waters.

The conclusions and recommendations for the management of riparian areas along Type 4 streams are only based on stream temperature concerns. Numerous other factors also must be considered in the management of forest practices along type 4 streams. Though downstream temperature impacts are negligible, erosion and other factors are still relevant to the management of Type 4 streams.

References

Adams, T.A. and K. Sullivan, 1990. The physics of forest stream heating: a simple model. Timber/Fish/Wildlife Report TFW-WQ3-90-007, Washington Dept. of Natural Resources, Olympia, WA.

Beschta, R.L. and W.S. Platts, 1986. Morphological features of small streams: significance and function. Wat.Res.Bull. 22(3):369 - 379.

Brown, G.W., 1969. Predicting temperatures of small streams. Wat. Resources Res. S(1): 68 - 75.

Doughty, K., J.E. Caldwell and K. Sullivan, 1990. Work plan: evaluation of downstream temperature effects of riparian management on Type 4 waters, submitted to Cooperative Monitoring and Research Committee, Timber/Fish/Wildlife, June 1990.

Dunne, T. and L.B. Leopold, 1978. Water in environmental planning. W.H. Freeman and Co., San Francisco, CA.

Edinger, J.E. and J.C. Geyer, 1968. Analyzing stream electric power plant discharges. J.Sanit.Eng., Proc. Amer. Soc. Civil Eng., 94(SA4): 611-623.

Hynes, H.B.N, 1970. The ecology of running waters. University of Toronto Press, Toronto, Canada. 55.5 pp.

MacDonald, A., and K.W. Ritland, 1989. Sediment dynamics in Type 4 and 5 waters: a review and synthesis. T/F/W Report TFW-012-89-002, Washington Dept. of Natural Resources, Olympia, WA.

National Oceanographic and Atmospheric Administration, 1990. Local Climatological Data, Monthly Summary (Yakima Airport, Olympia Airport, Seattle/Tacoma Airport), National Climatic Data Center, Asheville, N.C.

National Oceanographic and Atmospheric Administration, 1990. Climatological Data, Washington, July-September, 1990, National Climatic Data Center, Asheville, N.C.

Sullivan, K., S.H. Duncan, P.A. Bisson, J.T. Heffner, J.W. Ward, R.E. Bilby, and J.L. Neilson, 1987. A summary report of the Deschutes basin: sediment, flow, temperature and fish habitat. Weyerhaeuser Co. Technical Report, Paper # 044-.5002/87/1, Tacoma, WA.

Sullivan, K., J. Tooley, K. Doughty, J.E. Caldwell and P. Knudsen, 1990. Evaluation of prediction models and characterization of stream temperature regimes in Washington. Timber/Fish/Wildlife Report TFW-WQ3-90-006, Washington Dept. of Natural Resources, Olympia, WA.

Summers, R., 1982. Trends in riparian vegetation regrowth following timber harvesting in western Oregon watersheds. M.S. thesis. Oregon State University, Corvallis, OR.

Tennessee Valley Authority, 1972. Heat and mass transfer between a water surface and the atmosphere. Water Res. Lab. Report # 14, Norris, TN.

Theurer, F.D., K.A. Voos and W.J. Miller, 1984. Instream water temperature model, Instream Flow Information Paper # 16. U.S. Fish & Wildlife Service FWS/OBS-84/15.

Washington Administrative Code, Chapter 173-201. Water Quality Standards for Surface Waters of the State of Washington.

Washington State Forest Practices Board, 1988. Washington Forest Practices Rules and Regulations. Washington Dept. of Natural Resources, Olympia, WA.

Appendix A Site Characteristics

Site Name	Abernathy Creek						
Tributary to	**Columbia River**	**WRIA: 25**					
Monitoring Point	**ALL**	**A**	**B**	**C**	**D**	**E**	**F**
T/S/R	**S9,T9N,R4W**						
Latitude	46-10						
Longitude	123-00						
Instrument type	**Datapod,** Unidata						
Start date	**8/4/90**						
End date	**8/28/90**						
Site visit	**8/28/90**						
Cumulative downstream distance (m)		**0**	**0**	**0**	**5**	**26**	**39**
Maximum water temperature observed		21.5	18.5	20.8	18.6	19	18.5
Elevation (m)		200	195	195	195	195	195
Average width (m)		1.39	6.26	1.39	6.26	6.26	6.26
Average depth (m)		**0.09**	**0.52**	**0.09**	**0.52**	**0.52**	**0.52**
Discharge **(cms)**		0.0085	0.1470	0.0140	0.1470	0.1470	0.1470
Velocity (m/s)		0.01	0.22	0.06	0.22	0.22	0.22
Stream azimuth		**80E**	140E	**80E**	140E	140E	140E
Canopy Cover (% shade)		**0**	**96**	**96**	**96**	**95**	**95**
Brush Cover (% shade)		80	10	10	10	10	10
Canopy Characteristics Type 4	Brush						
Canopy Characteristics Type 3	Mature alder/conifer RMZ						
Substrate	Sm **boulder/lg** cobble/gravel						
Sideslope Gradient (%)		**RB&LB**	< 10	30-40	< 10	< 10	< 10

Appendix A Site Characteristics

Site Name	Green Cr.						
Tributary to	**Pysht River WRIA : 19**						
Monitoring Point	**ALL**	**A**	**B**	**C**	**D**	**E**	**F**
T/S/R	**S22,T31N,R12W**						
Latitude	48-10						
Longitude	124-25						
Instrument type	Ryan						
Start date	**8/16/90**						
End date	**9/11/90**						
Site visit	**9/11/90**						
Cumulative downstream distance (m)		**0**	**0**	**159**	**313**	**427**	**610**
Maximum water temoerature observed		17.8	15.7	17.3	17	17.1	17.4
Elevation (m)		109	109	109	109	109	109
Average width (m)		2.20	1.04	1.80	2.37	1.27	2.72
Average depth (m)		**0.17**	**0.09**	**0.12**	**0.25**	**0.25**	**0.16**
Discharge (cms)		**0.0079**	**0.0018**	**0.0079**	**0.0079**	**0.0051**	**0.005**1
Velocity (m/s)			0.03	0.08			
'Stream azimuth							
Canopy Cover (% shade)		**70**	**5**	**85**	**85**	**85**	**55**
Brush Cover (% shade)		**0**	**90**	**30**	**0**	25	15
Canopy Characteristics Type 4	Brush						
Canopy Characteristics Type 3	Alder RMZ						
Substrate	Cobble & gravel						
Sideslope Gradient (%)		0	15	15	15	10	0

Appendix A Site Characteristics

Site Name		Hanaford Creek						
Tributary to	4	Skookumchuck R.	WRIA: 23					
Monitoring Point	ALL	A	B	D	C	E	F	G
T/S/R	S3,T14N,R1E							
Latitude	46-40							
Longitude	122-40							
Instrument type	Datapod							
Start date	8\9\90							
End date	9\6\90							
Site visit	8\9\90							
Cumulative downstream distance (m)		0	0	140	0	152	305	609
Maximum water temperature observed		14.5	14.5	16.5	15	15	15	14.5
Elevation (m)		280	280	270	270	270	260	244
Average width (m)		1.86	0.46	1.86	0.46	2.29	2.13	3.05
Average depth (m)		0.21	0.09	0.21	0.09	0.20	0.14	0.15
Discharge (cms)		0.0181	0.0025	0.0181	0.0028	0.0275	0.0275	0.0258
Velocity (m/s)		0.24	0.09	assume A	assume B	assume F	0.09	assume E
Stream azimuth		320W	260W	260W	320W	320W	340W	240W
Canopy Cover (% shade)		33	0	0	33	85	70	75
Brush Cover (% shade)		50	90	90	50	10	25	40
Canopy Characteristics Type 4	harvested/ logging debris							
Canopy Characteristics Type 3	Alder RMZ, devils club, vine maple							
Substrate		sm&l gra	sm gravel	sm gravel	sm&l gra	sm cobble	sm%lg	cobbles,ripra
Sideslope Gradient (%)		RB&LB	RB&LB	RB&LB	RB&LB	RB>60,LB>40		

Appendix A Site Characteristics

Site Name		Hoff Creek				
Tributary to		**Nooksack River WRIA : 01**				
Monitoring Point	**ALL**	**A**	**B**	**C**	**D**	**E**
T/S/R	**S22,T39N,R4E**					
Latitude	**48-50**					
Longitude	**122-20**					
Instrument type	**Ryan**					
Start date	**7/30/90**					
End date	**8/14/90**					
Site visit	**8/14/90**					
Cumulative downstream distance (m)		**0**	**38**	**197**	**366**	**644**
Maximum water temperature observed		**19.8**	**19.8**	**18.8**	**19.4**	**19.6**
Elevation (m)		**166**	**164**	**146**	**140**	**91**
Average width (m)		**1.10**	**1.10**	**1.33**	**1.06**	**0.90**
Average depth (m)		**0.07**	**0.07**	**0.14**	**0.08**	**0.07**
Discharge (cms)		**0.0014**	**0.0020**			**0.0014**
Velocity (m/s)		**0.04**		**0.03**		
Stream azimuth						
Canopy Cover (% shade)		**51**	**62**	**95**	**98**	**98**
Brush Cover (% shade)		**32**	**47**	**26**	**17**	**17**
Canopy Characteristics Type 4		Brush (also steep side slopes)				
Canopy Characteristics Type 3		Mature alder/conifer				
Substrate		cobble	cobble	boulder	gravel	gravel
Sideslope Gradient (%)		50	50	15	**5**	5

Appendix A Site Characteristics

Site Name		Huckleberry Creek			
Tributary to		**Deschutes R.**		**WRIA: 13**	
Monitoring Point	ALL	A	B	C	D
T/S/R	**S17,R4E,T15N**				
Latitude	46-40				
Longitude	122-30				
Instrument type	**Unidata/Datapod**				
Start date	7127190				
End date	8127190				
Site visit	**8/27/90**				
Cumulative downstream distance (m)		0	259	316	446
Maximum water temperature observed		**23.1**	**19**	**20.5**	**19**
Elevation (m)		**207**	**207**	**205**	**200**
Average width (m)		**2.74**	**1.74**	**3.22**	**3.22**
Average depth (m)		0.10	0.20	0.37	0.37
Discharge (cms)		**0.0159**	**0.0159**	**0.0125**	**0.0125**
Velocity (m/s)		0.13		0.042	0.042
Stream azimuth		260w	**250W**	**280w**	320w
Canopy Cover (% shade)		0	0	90	95
Brush Cover (% shade)		20	100	20	20
Canopy Characteristics Type 4	Open, wide, small amt. log debris				
Canopy Characteristics Type 3	Lower end of logjam @ B, C & D mature alder				
Substrate		Small gravels		Gravel, sm & lg cob	
Sideslope Gradient (%)		All sites < 10			

Appendix A Site Characteristics

Site Name		**Jimmy Come Lately Cr.**				
Tributary to		**Sequim Bay WRIA : 17**				
Monitoring Point	**ALL**	**A**	**B**	**C**	**D**	**E**
T/S/R	**S22,T29N,R3W**					
Latitude	**48-0**					
Longitude	**123-0**					
Instrument type	**Ryan**					
Start date	**8/25/90**					
End date	**9/10/90**					
Site visit	**9/10/90**					
Cumulative downstream distance (m)		**0**	**152**	**305**	**457**	**610**
Maximum water temperature observed		**16.7**	**16.8**	**17.2**	**17.1**	**16.2**
Elevation (m)		**326**	**326**	**326**	**326**	**326**
Average width (m)		**1.10**	**1.09**	**1.17**	**1.14**	**1.52**
Average depth (m)		**0.09**	**0.14**	**0.10**	**0.08**	**0.18**
Discharge (cms)		**0.0054**	**0.0054**			**0.0065**
Velocity (m/s)			**0.10**			**0.04**
Stream azimuth						
Canopy Cover (% shade)		**93**	**11**	**0**	**59**	**90**
Brush Cover (% shade)		3	6	3	7	35
Canopy Characteristics Type 4		Mature deciduous above road; none for points B - C				
Canopy Characteristics Type 3		Selectively thinned conifer				
Substrate		gravel	gravel	gravel	gravel	gravel
Sideslope Gradient (%)		0	steep short banks (1		minimal	minimal

Appendix A Site Characteristics

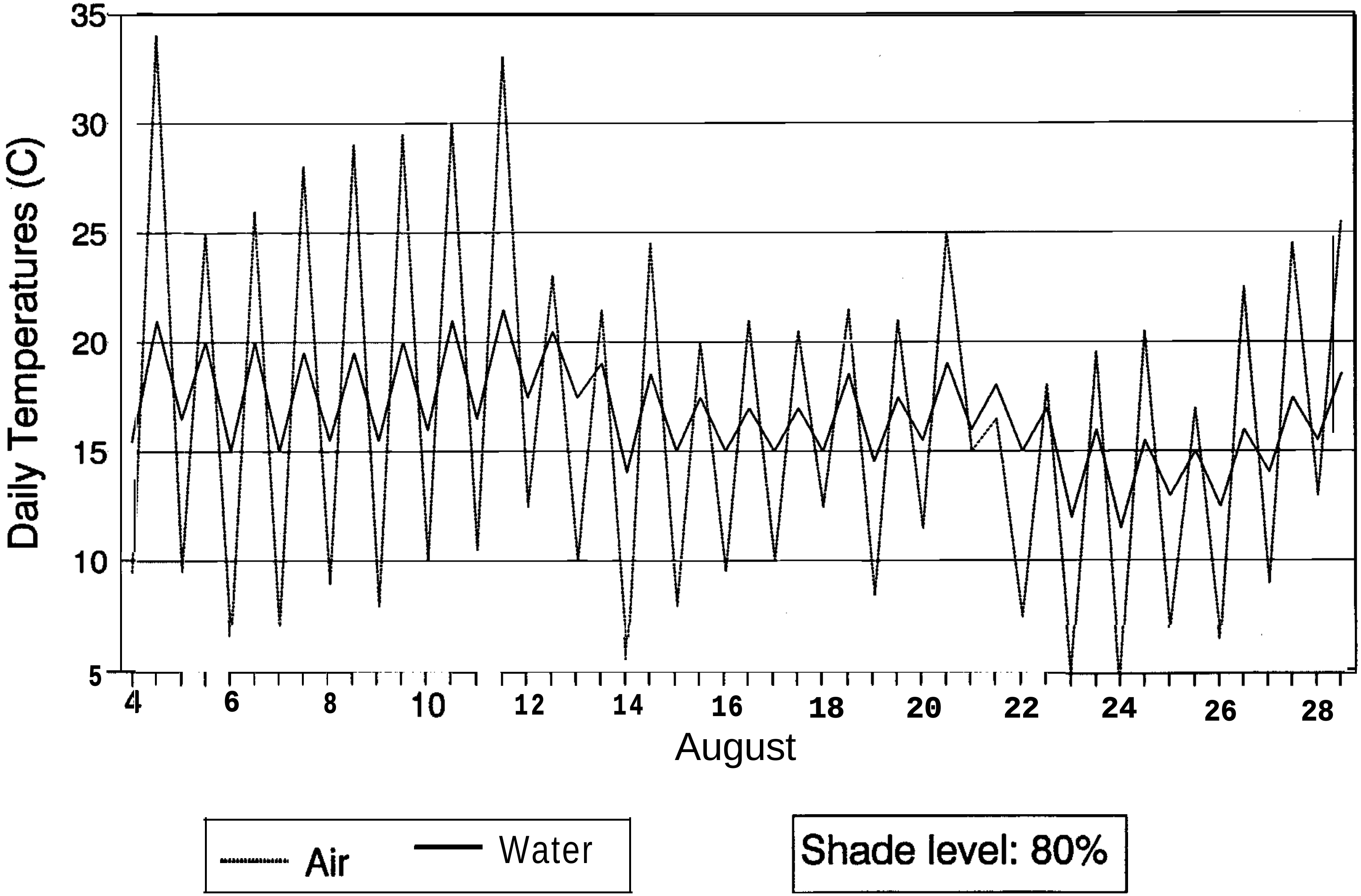
Site Name	Thorn Creek								
Tributary to	West Fork Cr. Deschutes River WRIA : 13								
Monitoring Point	ALL	A	B	C	D	E	F	G	H
T/S/R	**S11,T14N,R4E**								
Latitude	**46-40**								
Longitude	122-20								
Instrument type	**Datapod**								
Start date	**7/18/90**								
End date	**8/15/90**								
Site visit	**8/6/90**								
Cumulative downstream distance (m)	0	0	69	284	626	0	675	1268	1597
Maximum water temperature observed		1s	14.5	13.5	12	13.5	13	12.5	12.5
Elevation (m)		580	580	530	480	480	480	366	363
Average width (m)	**0.00**	**1.87**	**1.17**	**1.11**	**2.12**	**0.73**	**2.81**	**1.52**	**2.35**
Average depth (m)	0.00	0.12	0.09	0.21	0.18	0.11	0.35	0.28	0.28
Discharge **(cms)**		**0.0020**	**0.0020**	**0.0020**	**0.0020**	**0.0002**	**0.0031**	**0.0119**	**0.0202**
Velocity (m/s)		0.036	0.036		0.076	0.031	0.003	0.246	0.246
Stream azimuth		140E	160E	**100E**	**80E**	40E	40E	**45E**	40E
Canopy Cover (% shade)		0	95	87	90	0	80	25	46
Brush Cover **(%** shade)		80			**50**	20	20	60	**50**
Canopy Characteristics Type 4		Brush, grasses				Brush, grasses			
Canopy Characteristics Type 3		Alder RMZ, brush, **instream** logs							
Substrate	ble	Boulder/cobble							
Sideslope Gradient **(%)**		For all sites, **>** 60							

Appendix A Site Characteristics

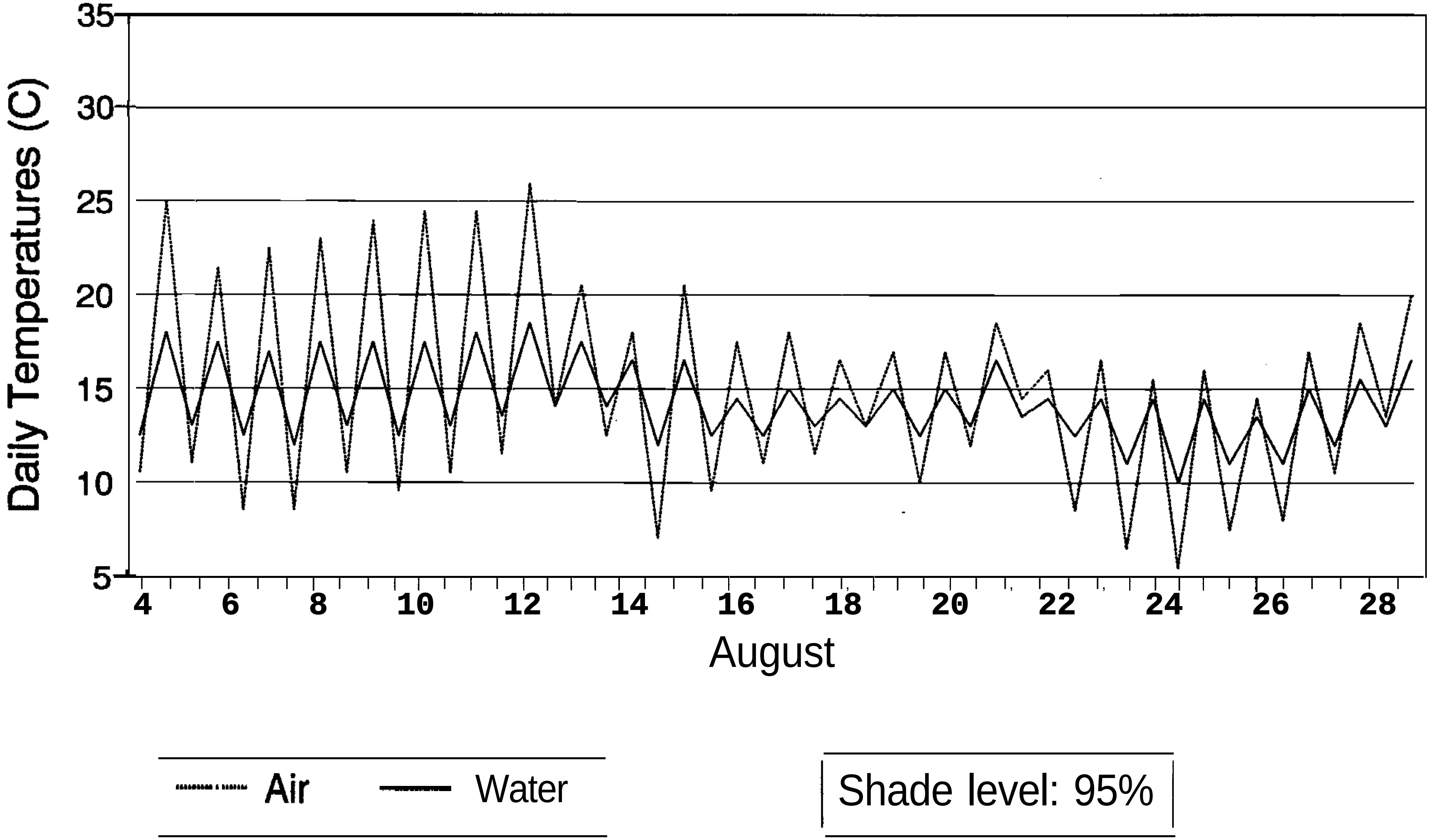
Site Name		Ward Cr Tributary			
Tributary to		**Ward Creek, Willapa River**			**WRIA: 2**
Monitoring Point	**All**	**A**	**B**	**C**	**D**
T/S/R	**S14,T14N,R8W**				
Latitude	**46-40**				
Longitude	123-50				
Instrument type	**Datapod**				
Start date	**8/9/90**				
End date	**8/28/90**				
Site visit	**8/28/90**				
Cumulative downstream distance (m)		**0**	**26**	**153**	**249**
Maximum water temperature observed		**18**	**17.5**	**17**	**17**
Elevation (m)		**12**	**12**	**12**	**12**
Average width (m)		**0.46**	**0.76**	**0.76**	**0.76**
Average depth (m)		**0.09**	**0.09**	**0.09**	**0.09**
Discharge (cms)		**0.0050**	**0.0050**	**0.0050**	**0.0050**
Velocity (m/s)	**very low, estimated at 0.003 - 0.007 cms**				
Stream azimuth		**280W**	**300W**	**260W**	**200W**
Canopy Cover (% shade)		**0**	**95**	**95**	**96**
Brush Cover (% shade)		**90**	**50**	**50**	**50**
Canopy Characteristics Type 4	Brush only				
Canopy Characteristics Type 3	mature alder				
Substrate	**sand/small** gravels				
Sideslope Gradient (%)		30	0	0	0

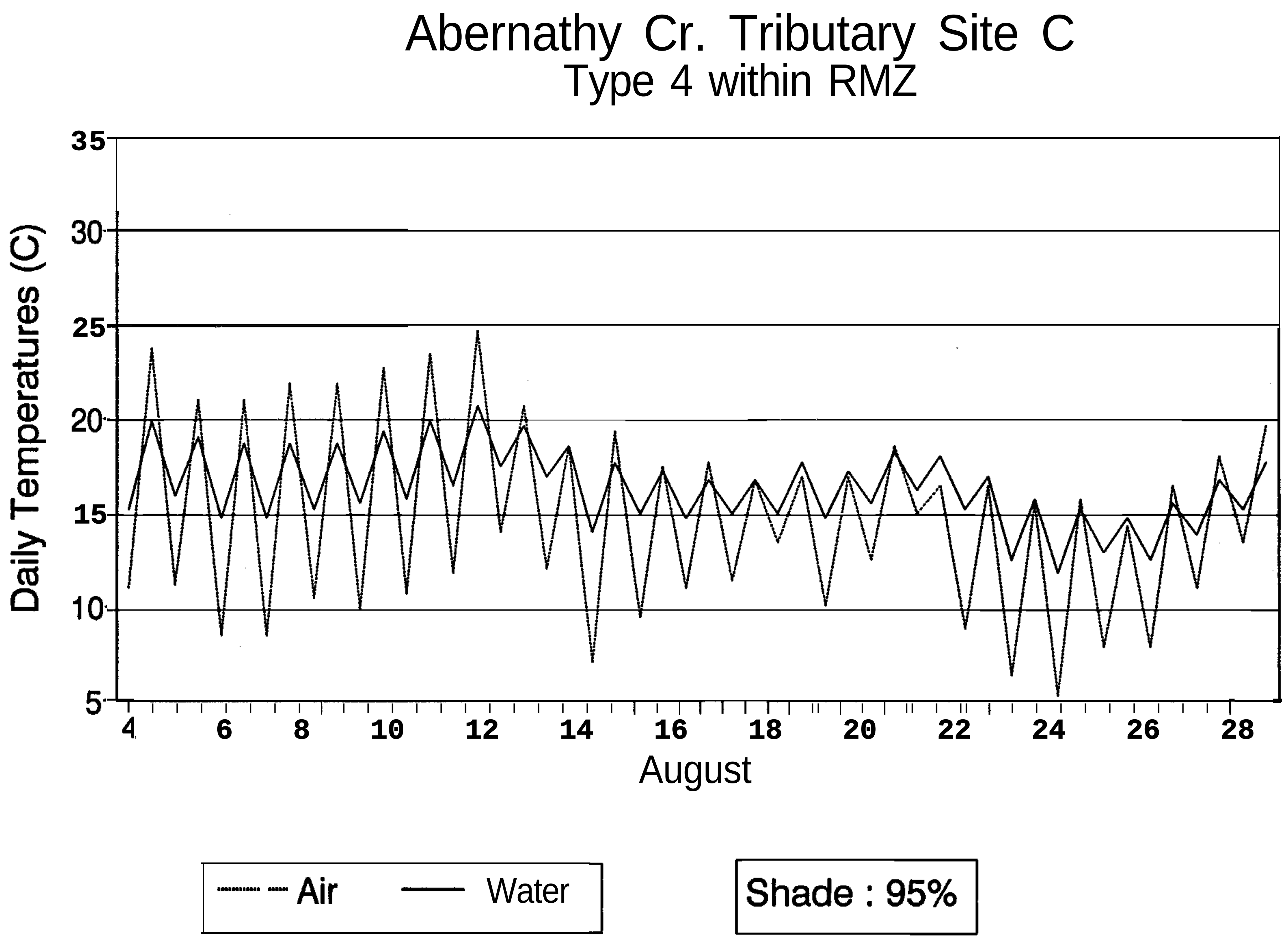
Abernathy Cr. Tributary Site A

Type 4 Harvested



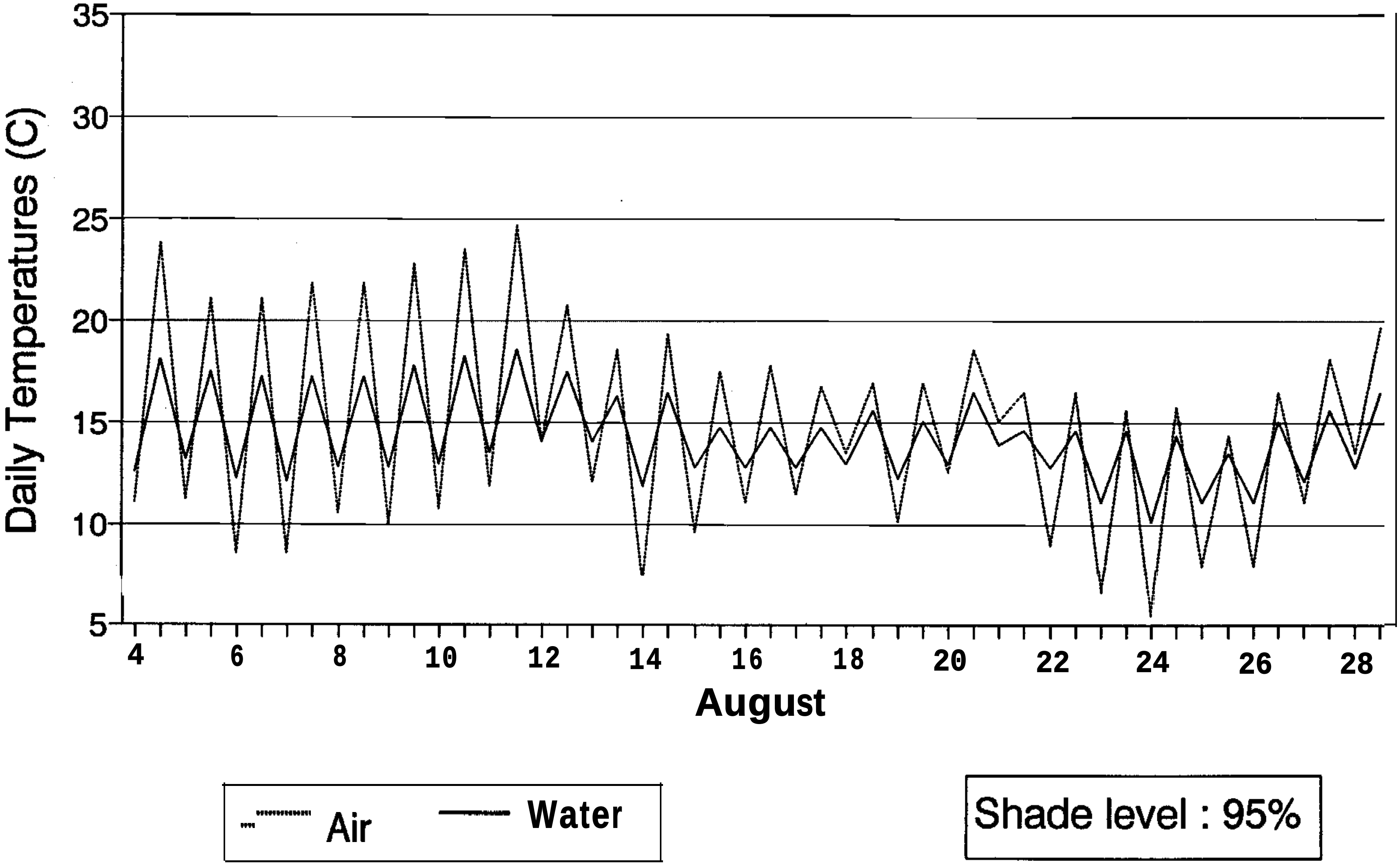
Abernathy Cr. Tributary Site B
Type 3 Above confluence

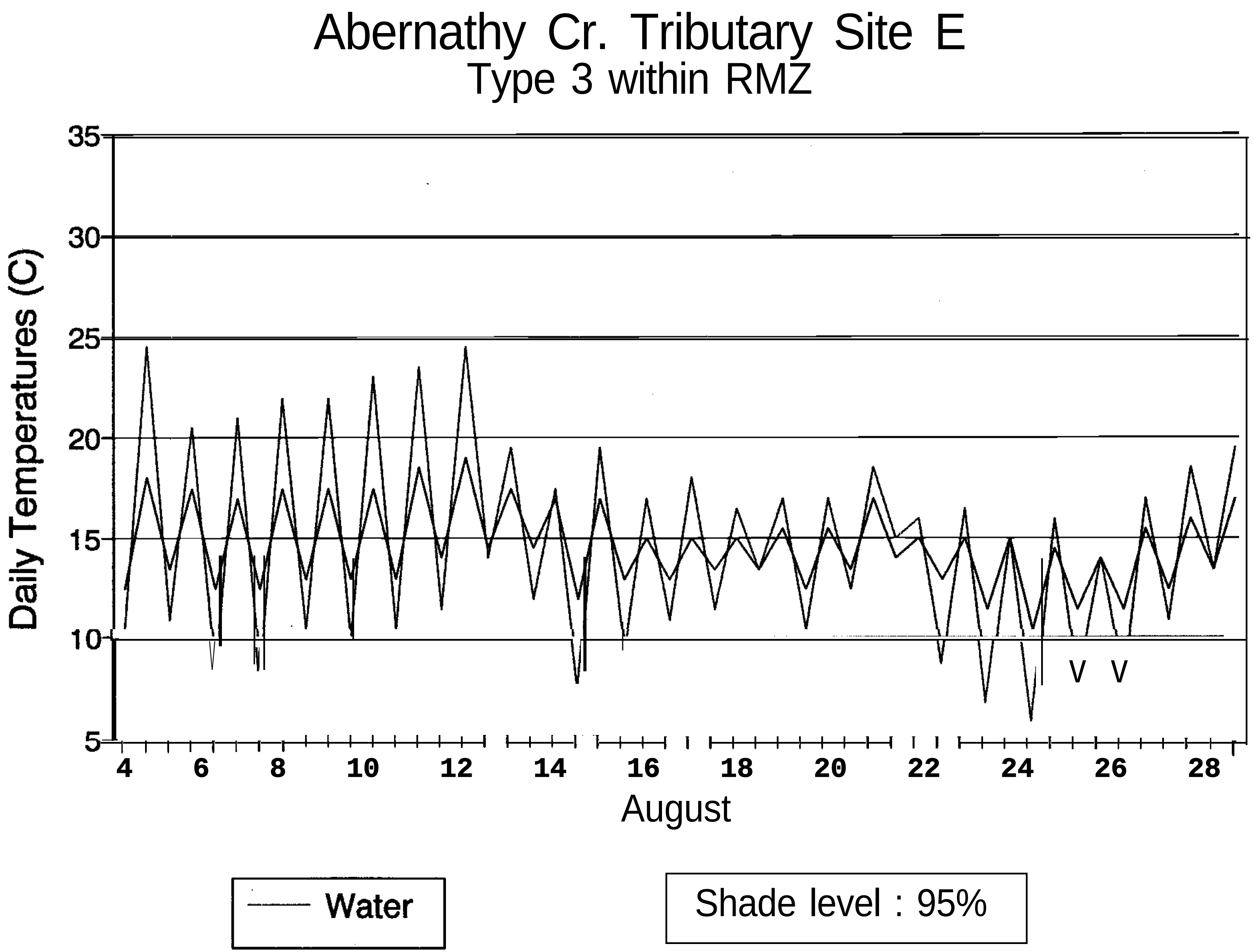




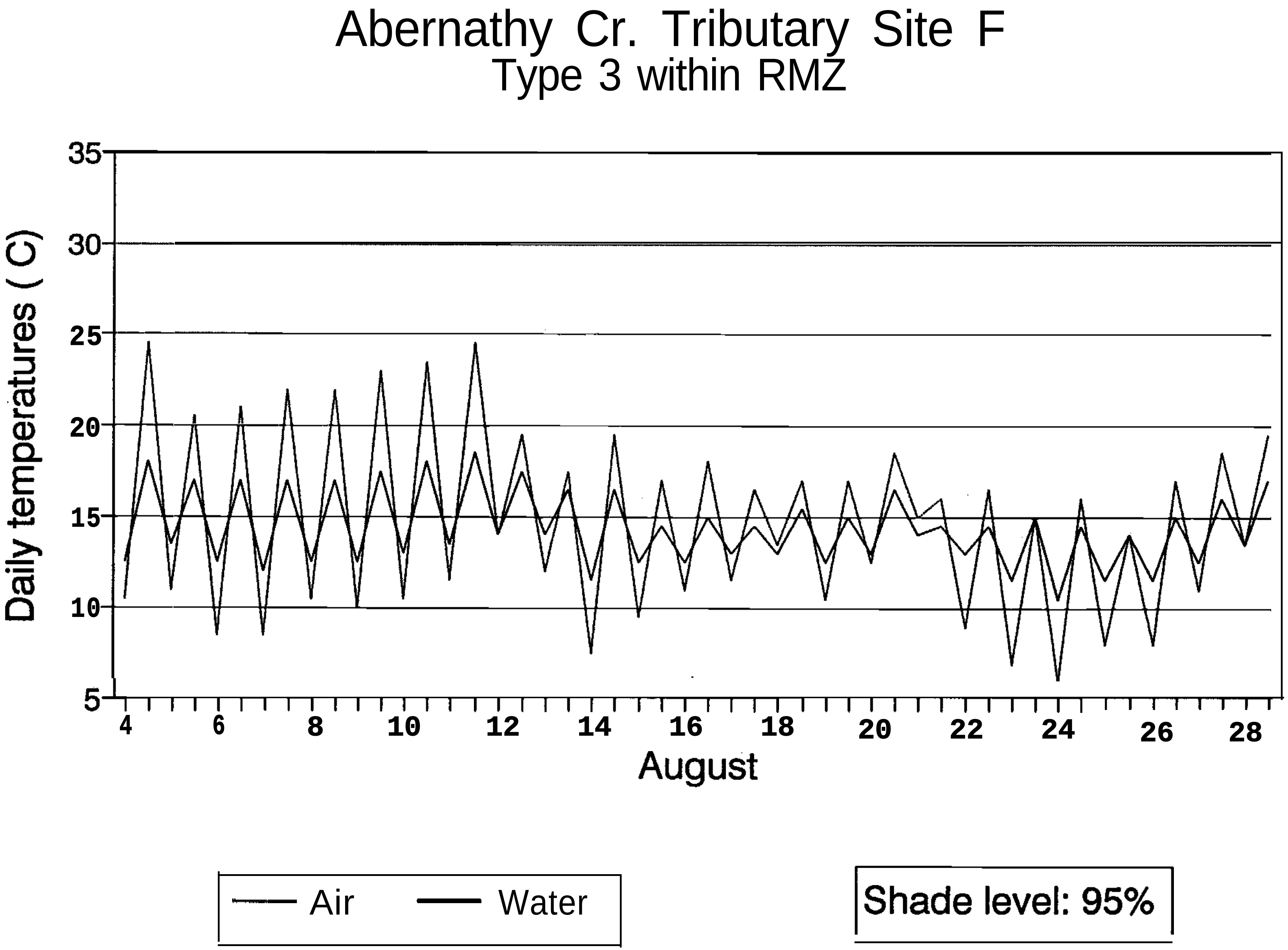
Abernathy Cr. Tributary Site C
Type 4 within RMZ
Daily Temperatures (C)
35
30
25
20
15
10
5
4
6
8
10
12
14
16
18
20
22
24
26
28
August
Air
Water
Shade : 95%

Abernathy Cr. Tributary Site D
Type 3 below confluence



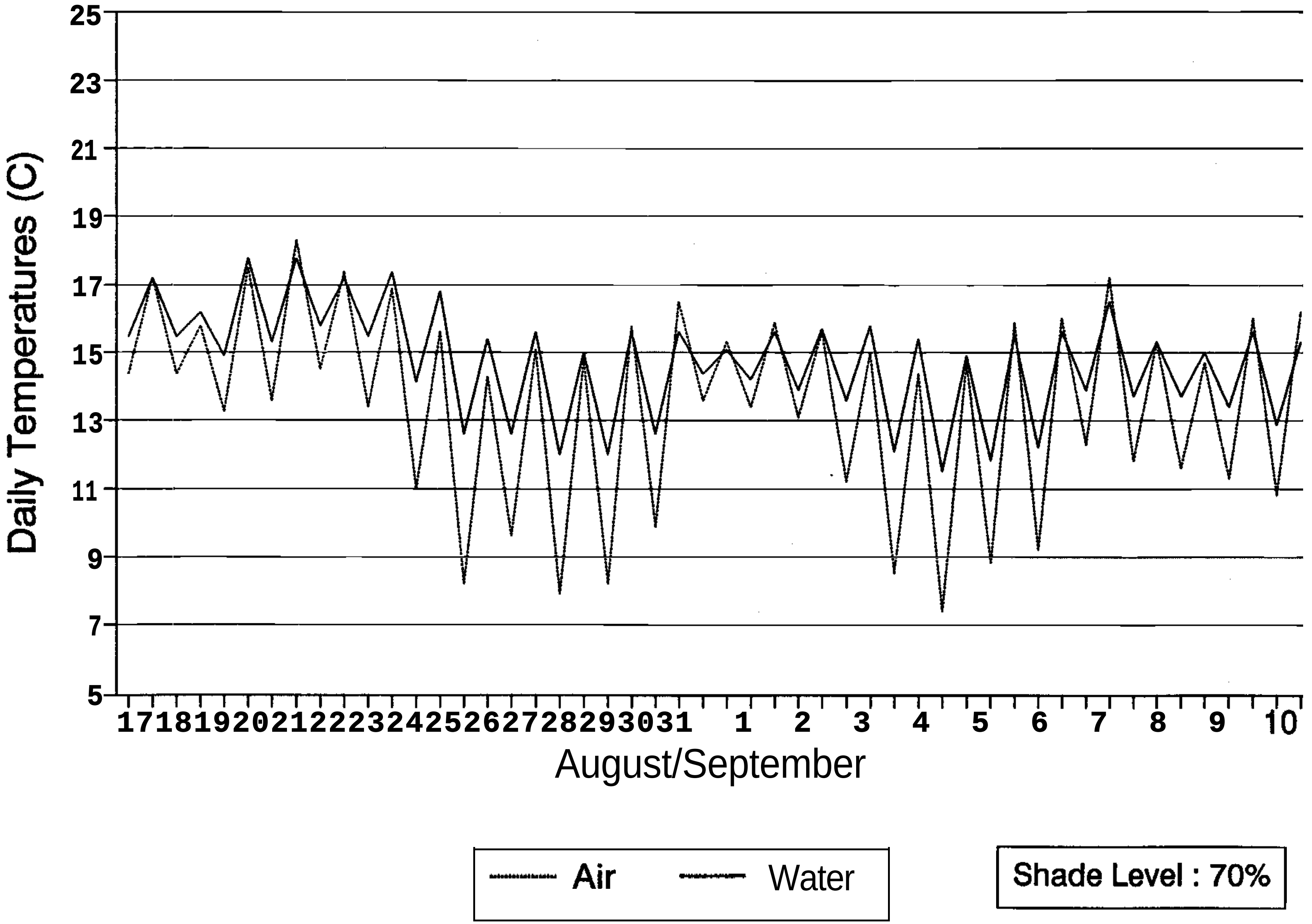


Abernathy Cr. Tributary Site E
Type 3 within RMZ
Daily Temperatures (C)
35
30
25
20
15
10
5
4
6
8
10
12
14
16
18
20
22
24
26
28
August
Water
Shade level : 95%



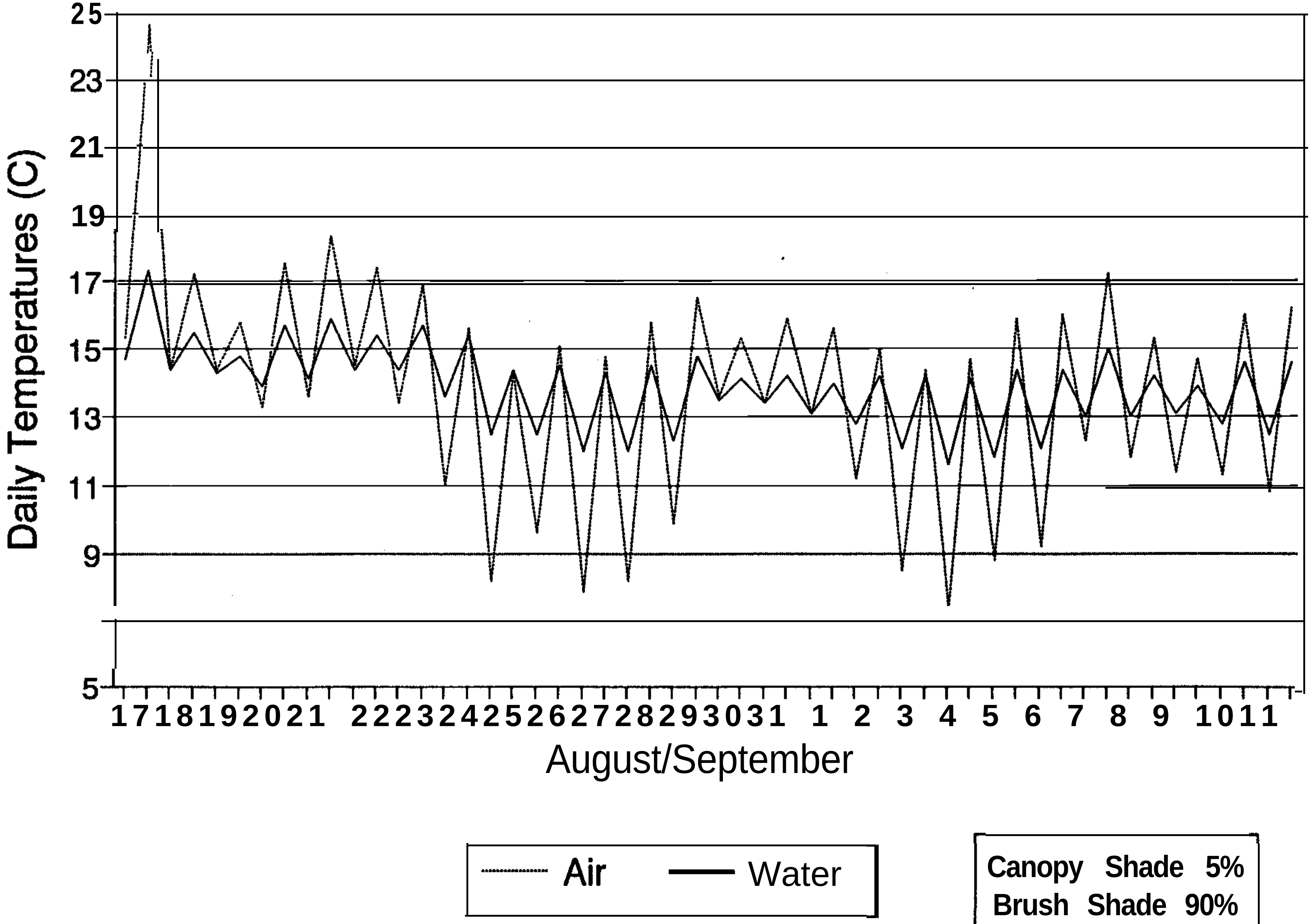
Abernathy Cr. Tributary Site F
Type 3 within RMZ
Daily temperatures (C)
35
30
25
20
15
10
5
4
6
8
10
12
14
16
18
20
22
24
26
28
August
Air
Water
Shade level: 95%

Green Creek Site A
Type 3 Above Confluence



Shade Level : 70%

Green Creek Site B
Type 4



Canopy Shade 5%
Brush Shade 90%