Ref. #136

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

by

T.E. Lewis, D.W. Lamphear, D.R. McCanne, A.S. Webb, J.P. Krieter, and W. D. Conroy

Forest Science Project

1 Harpst Street
Humboldt State University
Arcata, CA 95521
(707) 825-7350
(707) 825-7350 (FAX)
fsp@axe.humboldt.edu
http://www.humboldt.edu/~fsp/

About the Forest Science Project

The Forest Science Project was formed by private landowners in Northern California who are concerned about ecological resources on managed lands. The Project is supported largely by donations made by these private landowners. The Forest Science Project is a non-profit trust that operates within the Humboldt State University Foundation, a 501C-3 corporation.

Mission Statement

The Forest Science Project is dedicated to the acquisition, compilation, dissemination, and application of knowledge about the ecological systems in Northern California. The Forest Science Project contributes to a regional understanding of the ongoing processes of forest and habitat management. The Forest Science Project actively participates in regional decision-making regarding the ecological management of natural resources, and promotes a broader awareness of the importance of ecological relationships to human welfare.

ACKNOWLEDGMENTS

Many students at Humboldt State University, who have since moved on to good positions with private, public, and government organizations, contributed their talents in the analyses of the data that have gone into this report. We wish to thank Jason Butcher, Maia Cheli-Colando, Adam Deem, David Gibney, David Jones, Scott Leonard, Paul Meyer, Kareen Moriarty, and Brent Petrzak for their assistance, and wish them great success in their future endeavors.

David Cassell , Jack Lewis, and Trent McDonald provided invaluable statistical support and advice throughout the analyses and modeling of the data. To them we extend our sincere thanks and appreciation.

We greatly appreciate the critical reviews and helpful comments provided by John Bartholow, Alan Herlihy, George Ice, and Kate Sullivan.

We are indebted to Angie Brown for her assistance in technical editing, word processing, and general administrative support during the final stages of document preparation. We sincerely thank Joe Lance for his perseverance in preparing the CD-ROM version of the report.

We thank the Forest Science Project Board of Directors and Technical Committee for helpful suggestions and comments throughout the development of this regional stream temperature assessment.

We are grateful to the various organizations and individuals that were willing to provide data and collect additional information for this assessment. Without their generous contribution of both time and data, this report would not have been possible.

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 data contributors, participants in, or committees of, the Forest Science Project. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the Forest Science Project.

Cite this report as:

T.E. Lewis, D.W. Lamphear, D.R. McCanne, A.S. Webb, J.P. Krieter, and W. D. Conroy. 2000. *Regional Assessment of Stream Temperatures Across Northern California and Their Relationship to Various Landscape-Level and Site-Specific Attributes*. Forest Science Project. Humboldt State University Foundation, Arcata, CA. 420 pp.

Table of Contents

Chapter 8 - Influence of Site-Specific Attributes on Stream Temperature

Chapter 9 - Influence of Canopy on Stream Temperature

Chapter 10 - Empirical Modeling of Regional Stream Temperatures

Chapter 11 - Historical Perspectives

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, and W.D. Conroy
Forest Science Project
Humboldt State University Foundation, Arcata, CA

Executive Summary

INTRODUCTION

Stream temperature has been and continues to be a concern in watersheds throughout Northern California. There has been heightened interest in the potential effects of altered stream temperatures on salmonids and other aquatic/riparian species. Several regulatory measures have been promulgated to mitigate potential impacts of increased water temperatures on aquatic biota. Restoration activities have been initiated, conservation measures developed, and land use practices altered in an attempt to counteract possible alterations in stream temperatures throughout the state of California and the Pacific Northwest. Land stewards in the private and public sector have been gathering temperature data for several years. With the onset of continuous temperature sensor technology, large volumes of stream temperature data are now being assembled and analyzed. More and more state and federal agencies and private landowners are choosing continuous stream temperature monitoring devices over thermometers because of the need for diurnal and seasonal water temperature data.

Stream temperature is an important factor in aquatic ecosystems for several reasons. Water temperature directly and indirectly influences fish physiology and behavior in several ways:

- Metabolism
- Food requirements, appetite, and digestion rates
- Growth rates
- Developmental rates of embryos and alevins
- Timing of life-history events, including adult migrations, fry emergence, and smoltification
- Competitor and predator-prey interactions
- Disease-host and parasite-host relationships

Stream temperature may also influence other aquatic and riparian species such as reptiles, amphibians, and macroinvertebrates. Collection of stream temperature data is driven largely by the concern for aquatic biological resource protection. Monitoring of stream temperature to assess diurnal and seasonal variation is a prerequsite to assessing potential acute and chronic thermal impacts to aquatic biota. The seasonality of life histories of the species of interest must also be considered when monitoring stream temperatures. Thus, monitoring that captures the temporal trends in stream temperature is needed to assess thermal exposures of different life stages.

BACKGROUND

With the onset of continuous temperature sensor technology, large volumes of stream temperature data are available and are continuing to be gathered. Despite the hundreds of gigabytes of stream temperature data collected by various groups and agencies throughout the state, no regional synthesis and assessment of these data has been published and no clear understanding of temperature regimes and their association with land use practices exists. This regional stream temperature assessment focuses on a well-defined geographic area of interest (AOI), namely the California portion of the Southern Oregon Northern Coastal California (SONCC) and the Central California (CC) evolutionarily significant units (ESUs) for coho salmon (*Oncorhynchus kisutch*). It is unknown whether all streams in the AOI are temperature sensitive in relation to the California Forest Practice Rules or other pertinent land management treatments (i.e., Northwest Forest Plan). To identify sensitive streams in the AOI, characterization of stream temperature regimes in the various watersheds, basins, and ecoregions comprising the AOI is essential. A characterization of contemporary thermal regimes across a broad geographic area was the primary goal of the Forest Science Project's regional stream temperature assessment.

Decision makers and land managers need to know what is achievable

State and federal agencies are lacking information on what range of stream temperatures are physically achievable in a stream reach, watershed, or basin, given the prevailing management prescriptions and climatic conditions. Provided with this information, agencies would be better able to (1) set reach- or watershed-specific temperature standards that are scientifically defensible, (2) identify and prioritize stream reaches that are grossly out of compliance and most in need of remediation, and (3) establish realistically attainable temperature-reduction goals for streams, watersheds, and basins that have naturally high water temperatures. The Forest Science Project's regional stream temperature assessment provides agencies, land stewards, and landowners with the information needed to make important decisions regarding adaptive management, remedial measures, and restoration goals.

SCOPE

The watersheds and basins within the California portion of the SONCC and Central California ESUs were defined as the geographic AOI. This area extends from the Oregon border south to San Francisco and eastward to the Central Valley. Figure 1 shows the AOI and the distribution of stream temperature monitoring sites for which data were submitted for inclusion in this regional assessment.

This assessment report is based on data gathered by numerous private landowners, and various state and federal agencies. Land stewards that submitted data for the assessment collected stream temperature data under a multitude of objectives and assumptions. These diverse objectives can be grouped into three broad categories:

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

Forest Science Project cooperators and other parties that submitted stream temperature data can be characterized as forested landowners and stewards. Therefore, the population of stream temperature monitoring locations all fell in predominately forested catchments or on lands zoned as Timber Protection Zone (TPZ) or Agriculture Exclusive (AE). Data from both private landowners and public resource management agencies

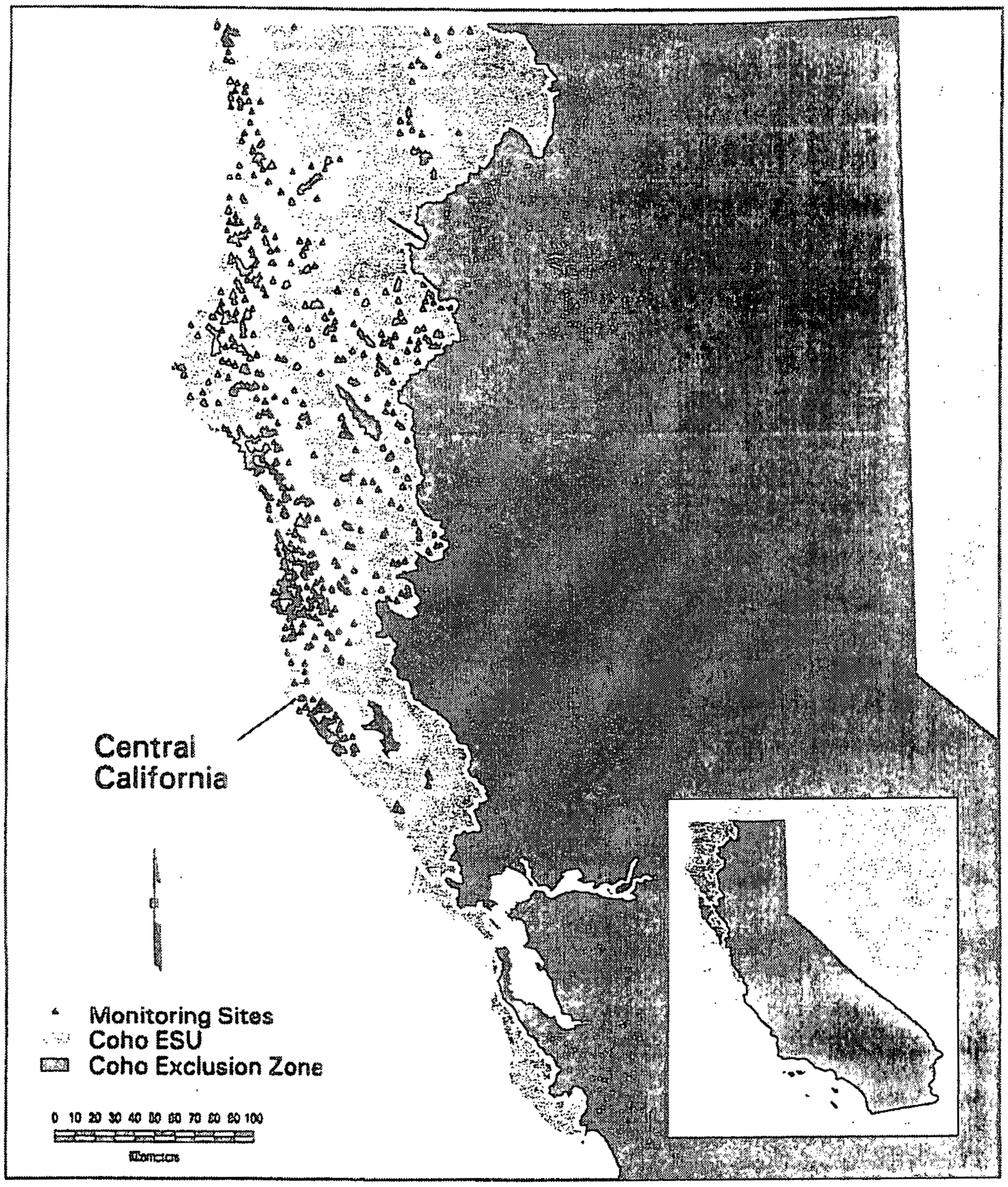


Figure 1. Area of interest for the Forest Science Project's Regional Stream Temperature Assessment as defined by the Southern Oregon Northern Coastal California and Central California evolutionarily significant units. There were 1087 unique sites where water temperature data were available for the regional assessment.

Table 1. Stream Temperature Data Sources for the Forest Science Project's Regional Stream Temperature Assessment.

Source	1990	1991	1992	1993	YEAR 1994	1995	1996	1997	1998
Barnum Timber Company								12	23
Bureau of Land Management							2		
CA Dept. Fish & Game								4	
Elk River Timber Company								6	4
Fruit Growers Supply								14	18
Georgia Pacific West, Inc.				63	54	66	64	64	75
Gualala Redwoods, Inc.					17	27	27	26	28
Humboldt County RCD							154	161	113
Humboldt State University									12
Jackson State Forest							49	34	27
Louisiana Pacific Corporation					16	15	53	36	
Mattole Salmon Group							16		
Natural Resources Cons. Serv.						11	14	13	4
NRM Corporation						3	15	23	26
Pacific Lumber Company					4	10	25	54	27
Pacific Southwest Experiment Station					7	7	13		
Pioneer Resources								41	39
Redwood National Park						1	1	11	10
Russ Ranch & Timber Company							2	4	9
Shasta-Trinity National Forest	15	18	17	10	23	14	6	16	13
Sierra Pacific Industries							14	24	17
Simpson Timber Company					40	30	10	29	44
Six Rivers National Forest				3	5	12	26	42	42
Soper/Soper-Wheeler Company					1				
Stimson Redwood Company					4		7	6	7
Timber Products Company							4	9	10
TOTALS	15	18	17	76	171	196	500	627	548

were acquired. Thus, the land management prescriptions were dependent upon whether monitored streams were on private or public lands. Stream temperature records from 1087 sites spanning nine years were assembled and analyzed. Not all sites were monitored every year. Table 1 shows the number of sites by year and data contributor. Predominantly, results from analyses of 1998 data were included in the various chapters found in this report since 1998 was the most complete data set with which to work.

The assessment was restricted to data collected using continuous sensor technology. Snapshot (synoptic) data using hand-held thermometers or min-max thermometers were not included in statistical analyses in the regional assessment. Some synoptic data were used in qualitative comparisons of contemporary to historical stream temperatures. Hourly (or other time interval) data from continuous sensors were obtained from the various data contributors. Data that were aggregated to a particular temporal or spatial level prior to submission to the Forest Science Project were not used due to potential differences in statistical analytical procedures and aggregation approaches. Consistent data verification, validation, and spatial and temporal aggregation were deemed critical for increasing the likelihood of data comparability for statistical comparisons (i.e., comparing apples with apples).

The amount of site-specific information provided by data contributors was limited. In some instances, analyses on a reduced subset of the data were performed to explore important site-level or landscape-level relationships. In such cases, the number of sites

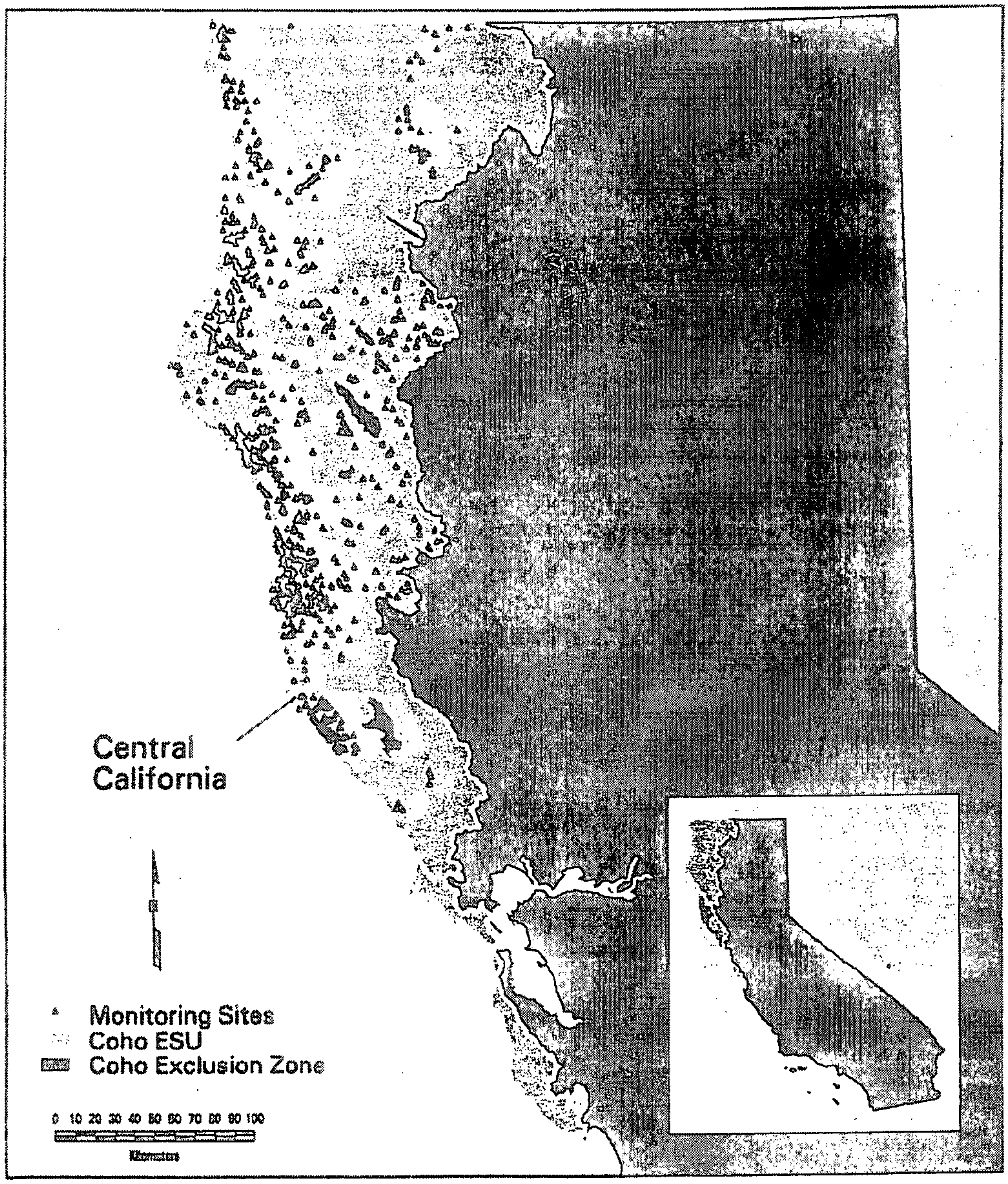


Figure 1. Area of interest for the Forest Science Project's Regional Stream Temperature Assessment as defined by the Southern Oregon Northern Coastal California and Central California evolutionarily significant units. There were 1087 unique sites where water temperature data were available for the regional assessment.

Table 1. Stream Temperature Data Sources for the Forest Science Project's Regional Stream Temperature Assessment.

Source	1990	1991	1992	1993	YEAR 1994	1995	1996	1997	1998
Barnum Timber Company								12	23
Bureau of Land Management							2		
CA Dept. Fish & Game								4	
Elk River Timber Company								6	4
Fruit Growers Supply								14	18
Georgia Pacific West, Inc.				63	54	66	64	64	75
Gualala Redwoods, Inc.					17	27	27	26	28
Humboldt County RCD							154	161	113
Humboldt State University									12
Jackson State Forest							49	34	27
Louisiana Pacific Corporation					16	15	53	36	
Mattole Salmon Group							16		
Natural Resources Cons. Serv.						11	14	13	4
NRM Corporation						3	15	23	26
Pacific Lumber Company					4	10	25	54	27
Pacific Southwest Experiment Station					7	7	13		
Pioneer Resources								41	39
Redwood National Park						1	1	11	10
Russ Ranch & Timber Company							2	4	9
Shasta-Trinity National Forest	15	18	17	10	23	14	6	16	13
Sierra Pacific Industries							14	24	17
Simpson Timber Company					40	30	10	29	44
Six Rivers National Forest				3	5	12	26	42	42
Soper/Soper-Wheeler Company					1				
Stimson Redwood Company					4		7	6	7
Timber Products Company							4	9	10
TOTALS	15	18	17	76	171	196	500	627	548

were acquired. Thus, the land management prescriptions were dependent upon whether monitored streams were on private or public lands. Stream temperature records from 1087 sites spanning nine years were assembled and analyzed. Not all sites were monitored every year. Table 1 shows the number of sites by year and data contributor. Predominantly, results from analyses of 1998 data were included in the various chapters found in this report since 1998 was the most complete data set with which to work.

The assessment was restricted to data collected using continuous sensor technology. Snapshot (synoptic) data using hand-held thermometers or min-max thermometers were not included in statistical analyses in the regional assessment. Some synoptic data were used in qualitative comparisons of contemporary to historical stream temperatures. Hourly (or other time interval) data from continuous sensors were obtained from the various data contributors. Data that were aggregated to a particular temporal or spatial level prior to submission to the Forest Science Project were not used due to potential differences in statistical analytical procedures and aggregation approaches. Consistent data verification, validation, and spatial and temporal aggregation were deemed critical for increasing the likelihood of data comparability for statistical comparisons (i.e., comparing apples with apples).

The amount of site-specific information provided by data contributors was limited. In some instances, analyses on a reduced subset of the data were performed to explore important site-level or landscape-level relationships. In such cases, the number of sites and their geographic distribution are illustrated for evaluation. In some instances, Geographic Information System (GIS)-derived data (e.g., elevation, distance to coast) or regional data (e.g., air temperature, flow, degree day) were used to perform analyses. As mentioned previously, 1998 had the most complete data set in terms of stream temperature and site-specific attribute data. Thus, many of the analyses presented in the report are based on 1998 data.

The majority of data contributors collected stream temperature data during the summer months (June through September). Some investigators allowed temperature recorders to remain in the stream for longer or shorter periods of time. Inasmuch as the preponderance of data was gathered during the summer season, the assessment report focused on summertime stream temperatures. The juvenile life stage of coho salmon and other anadromous species is the stage most commonly encountered during the summer. Thus, the report places stream temperature analyses in the context of potential thermal stress on summer juvenile coho salmon primarily, with some reference to other anadromous juvenile salmonids. This is not to imply that adult stages of various species are not present in the stream systems in the AOI during the summer months, e.g., chinook salmon and steelhead trout. However, juvenile stages are known to be the most sensitive to thermal stress, hence the reason for this focus.

OBJECTIVES

The objectives of this stream temperature assessment report were:

1. Compile available stream temperature data in a verified and validated database for purposes of regional assessment
2. Assess status and trends in stream temperatures across the region
3. Evaluate the influence of regional scale factors (e.g., climate, geographic location, watershed position, etc.) and site-specific factors (e.g., canopy closure, channel orientation, etc.) on status and trends in stream temperatures
4. Through the assessment process identify areas where improvements in existing protocols and analysis and synthesis are needed
5. Identify knowledge gaps in site-specific information that should be collected on a routine basis to improve our assessment capabilities and move us closer to a regional stream temperature sampling design
6. Identify knowledge gaps between stream temperature monitoring and information on the distribution of coho salmon and other aquatic species

SIGNIFICANT FINDINGS

One size does not fit all

A single stream temperature standard is difficult to apply across a broad region, such as the entire range of the coho salmon in Northern California, because streams differ markedly in size, drainage area, elevation, geographical location, prevailing climatic conditions, aspect, riparian vegetation, etc. These factors act directly or indirectly to influence water temperature by affecting the degree of shading or the ambient climatic conditions (air temperature, humidity, and solar radiation). For example, maximum water temperatures would be expected to differ markedly between a wide, low-altitude, near-coastal stream in Southern Humboldt County as compared to a narrow, well-shaded mountain stream in northeastern California. Streams in diverse settings behave very differently, and temperature standards, whether narrative or numeric, should reflect those differences.

Regional Trends in Air Temperature

Air temperature is known to have a significant influence on stream temperatures. Bartholow (1989) and Sinokrot and Stefan (1994) ranked air temperature as the single most important parameter for predicting water temperature, followed by solar radiation. Most stream temperature models use air temperature as a driver to predict temporal change in water temperature. To determine the effects of air temperatures on mean stream temperature, acquisition of ***local*** air temperatures is particularly important. If one uses remote or approximate air temperature data, then one can only hope for remote or approximate stream temperature predictions.

Elevation is not always a good surrogate for air temperature

Air temperatures did not follow expected adiabatic cooling trends across the entire study area. Near the coast, air temperature was more a function of distance from the coast rather than elevation. In the interior portion of the study area air temperatures follow the more expected trend: decreasing air temperature with increasing elevation. The relationship between air temperature and the two independent variables, distance from the coast and elevation varied seasonally. During the winter months air temperatures in the coastal portion of the study area conformed more to the expected negative relationship with elevation.

In addition to yearly data acquired from 72 remote air sites, 30-yr long-term regional air temperature data were acquired from the Oregon State University Climate Analysis Service and the Oregon Climate Service at Oregon State University. These data were developed using PRISM (Parameter-elevation Regressions on Independent Slopes Model). PRISM is a climate analysis system that uses point data, a digital elevation model (DEM), and other spatial datasets to generate gridded estimates of annual, monthly and event-based climatic parameters.

Examination of 30-yr long-term average PRISM air temperature data revealed that air temperatures exhibit appreciable gradients within and across U.S. Geological Survey hydrologic units (HUCs) that comprise the range of the coho salmon in Northern California. Hydrologic units that are predominantly coastal have cooler air temperatures whereas those that have a somewhat southeasterly to northwesterly orientation show strong thermal gradients. Some HUCs are 10°C to 15°C warmer in the upper reaches than near the coast. Interior HUCs have warmer air temperatures throughout the drainage, with cooler air temperatures at higher elevations. Figure 2 presents the HUC-level August monthly average maximum air temperatures over the study area.

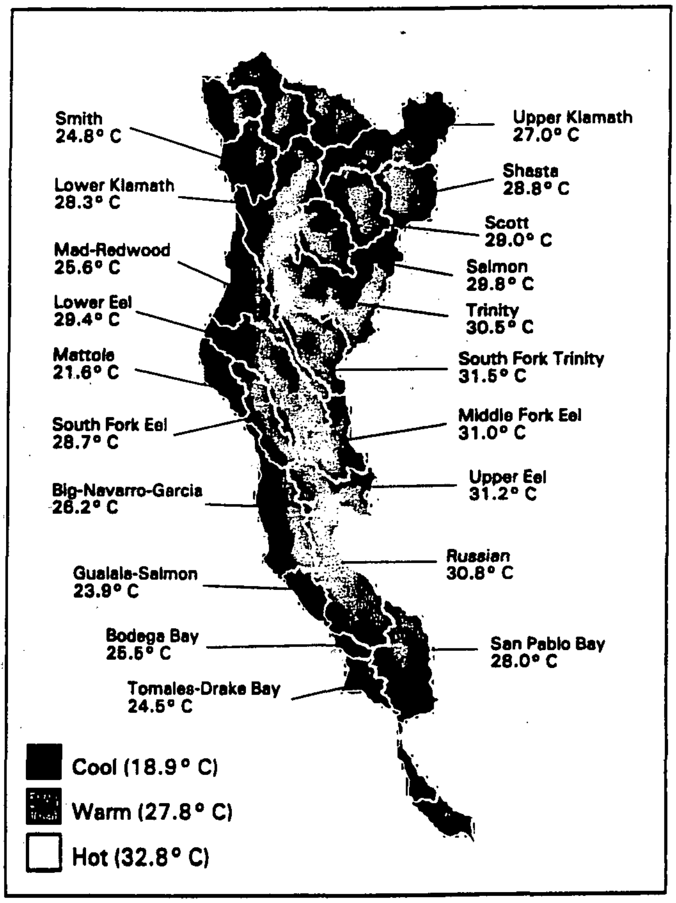


Figure 2. PRISM-derived August monthly average maximum air temperatures across HUCs that comprise the range of the coho salmon in Northern California.

PRISM air temperature data sets were used to develop a relationship between the 30-year average maximum monthly air temperature (AVGMAX) and the inland extent of the coastal effect. The zone of coastal influence (ZCI) was derived from 30-yr long-term PRISM air temperature data by defining the steepest rate of change in air temperature along transects at increasing distances from the coast (Figure 3). The ZCI is an approximation of the fog zone, which intuitively would have a cooling influence on water temperatures due to its associated cooler air temperatures and solar energy interception. Using the ZCI as a spatial coverage, stream temperature monitoring sites were stratified by whether they were inside or outside of the ZCI.

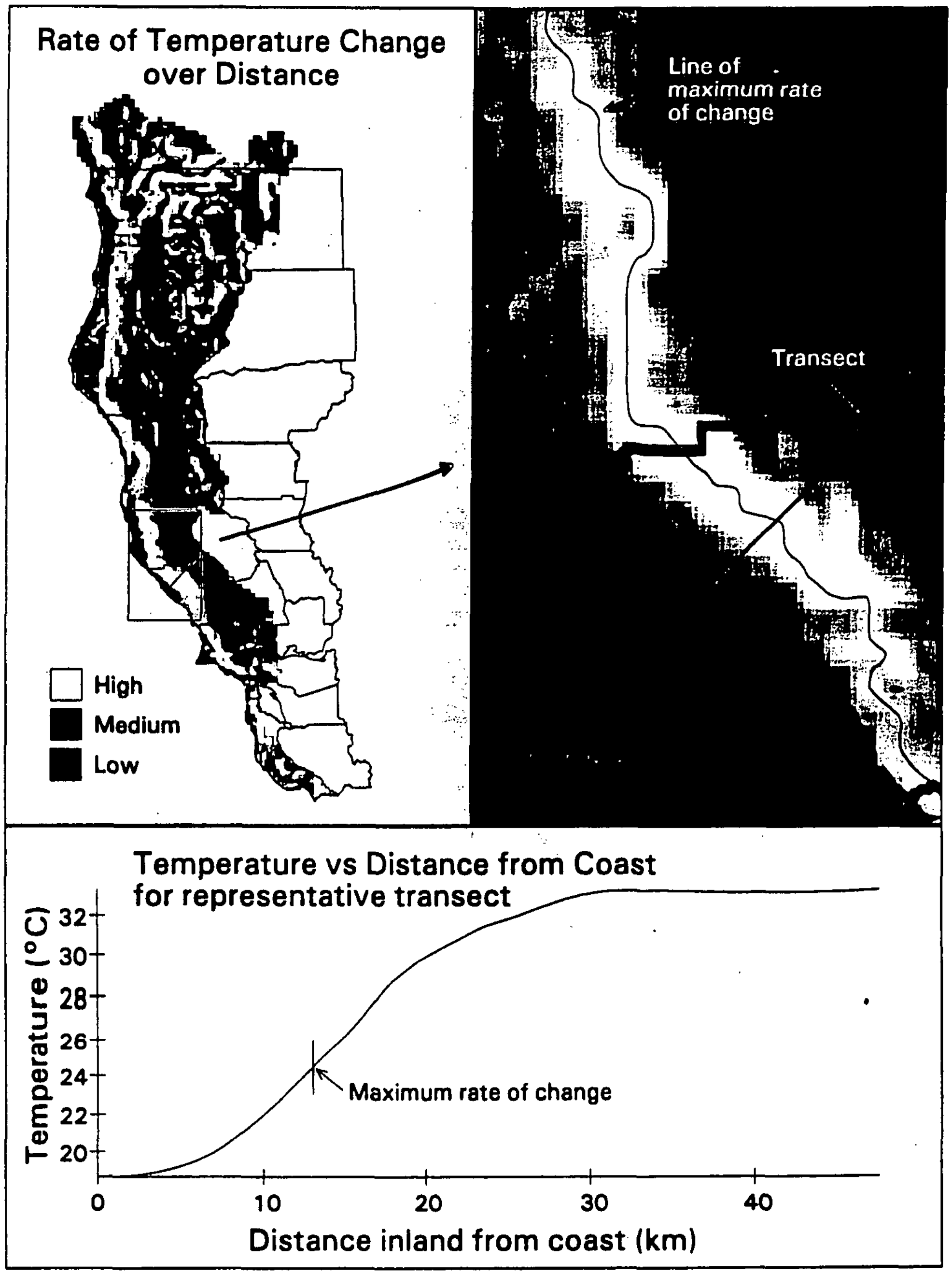


Figure 3. Derivation of the zone of coastal influence. Maximum rate of change determined using 30-yr PRISM August average maximum air temperature grid coverage across the range of coho salmon. Maximum rate of change is shown for a representative transect.

Spatial trends in air temperatures across the region must be understood in order to predict their influence on water temperatures. A useful air temperature database has been developed to characterize air temperature regimes across Northern California. In the future, acquisition of the monthly average PRISM air temperature data for individual water temperature years will greatly improve our understanding of the role air temperature plays in influencing water temperatures at large spatial scales.

Air and Water Temperature Relationships

Nearest-neighbor air stations were identified using a 12-dimensional Euclidian distance model. Air temperatures from these nearest-neighbor air stations, referred to as macroair temperatures, were found to show some correlation with water temperatures at a regional scale. Monthly minimum water temperatures were greater than monthly minimum macroair temperatures at most sites. Conversely, monthly maximum water temperatures were usually lower than monthly maximum macroair temperatures. Monthly mean water temperatures in the interior ecoprovince varied more closely with monthly mean macroair temperatures than water temperatures in the coastal ecoprovince.

The water-to-air temperature ratio increased with increasing distance from the watershed divide. The divide distance at which the ratio began to exceed unity varied by HUC, but generally fell between 6 km and 10 km. HUCs with tributaries that originate in the warm interior portions of the study area and drain into the zone of coastal influence exhibited greater numbers of sites with water-to-air ratios greater than one. HUCs that lie entirely within the interior portion of the study area exhibited fewer sites with water-to-air temperature ratios exceeding one.

The assessment report explores the correlations between water temperature and air temperatures measured at streamside (microair) and at remote air monitoring sites (macroair).

Geographic Position and Stream Temperature

Stream temperatures across Northern California vary with geographic position. The variation in water temperature with respect to distance from the coast, UTM y-coordinate (a surrogate for latitude), ecoprovince, zone of coastal influence, and elevation was large for the highest 1998 values of the daily maximum (XY1DX) and the 7-day moving average of the daily average (XYA7DA) and daily maximum (XYA7DX) stream temperatures. Variation in lowest daily minimum temperature (IY1DI) in relation to various geographic position factors was not as great, with much clearer trends discernable. Geographic position factors are largely surrogates for air temperature. Since the daily minimum temperature, in this case the lowest 1998 daily minimum observed at each site, occurs at the time when solar radiation is absent, the reduced scatter in IY1DI values suggests that air temperature may be asserting more influence on this stream temperature metric than on those metrics that have more of a solar-heating and daily-maximum-air-temperature component. While air temperature is known to influence water temperatures, the large variation observed for XY1DX, XYA7DA, and XYA7DX suggests that other factors are important in explaining the observed variability across the region. These factors include canopy closure, watershed area, distance from the watershed divide, flow, gradient, and channel orientation.

Watershed Position and Stream Temperature

Water temperatures have a tendency to increase with increasing distance from the watershed divide and with increasing drainage area. Water temperature near the source is the coolest, normally close to groundwater temperature. Groundwater temperature is typically within 1 °C to 3 °C of mean annual air temperature. Using PRISM 30-yr long-term air temperature data, the 30-yr mean annual air temperature was computed at 4-km grid resolution. Figure 4 shows these mean annual air temperatures, that can serve as estimates of groundwater temperature throughout HUCs that comprise the range of the coho salmon in Northern California. Since groundwater temperatures vary with air temperature, large variability is also exhibited in estimated groundwater temperatures.

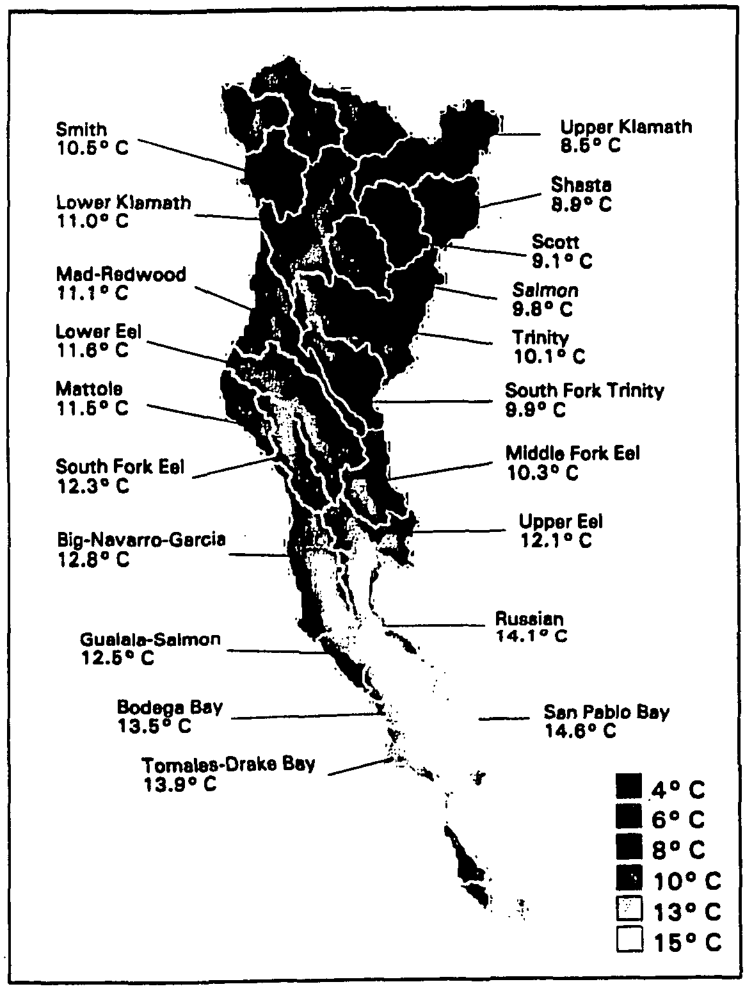


Figure 4. PRISM-derived 30-yr long-term annual average air temperatures across HUCs that comprise the range of the coho salmon in Northern California. Average annual air temperatures are reportedly within 1 °C to 3°C of groundwater temperatures.

Groundwater temperatures may be within a few degrees of the MWAT threshold

In some HUCs, estimated groundwater temperatures are within a few degrees of the maximum weekly average temperature (MWAT) threshold. Some headwater streams may originate in areas with warm groundwater temperatures. Well monitoring data is being acquired by the Forest Science Project to assess the accuracy of groundwater temperatures estimated from PRISM air temperature data.

Fourteen HUCs contained sufficient numbers of stream temperature monitoring sites to characterize the change in water temperature with watershed position. All HUCs exhibited a trend of increasing water temperature with increases in both watershed area and distance from the watershed divide. Streams that drain HUCs that are predominantly situated inland (i.e., away from the zone of coastal influence) showed much greater increases in stream temperature with increasing watershed area and divide distance.

Influence of Site-Specific Attributes on Stream Temperature

Channel Orientation

With an understanding of the hydrology and basin characteristics of Northern California it was not surprising to find that there were fewer streams in the 0° to 90° and 90° to 180° orientation classes. These are streams with northerly-to-northeasterly and southeasterly-to-southerly flows, respectively.

Graphical and statistical evaluations of the relationship between the highest 1998 daily maximum stream temperature (XY1DX) and the daily maximum on 26 June 1998 and channel orientation showed slight, albeit not significant, differences between channel orientation classes. Examination of canopy closure in relation to channel orientation did not show any significant differences between channel orientation class within each canopy class. Average daily maxima were slightly lower in the E-W orientation class for intermediate canopy classes, although they were not significantly different from the N-S orientation class.

Given all the other factors (e.g., canopy, air temperature) that have been shown to influence various stream temperatures metrics, such as the highest daily maximum, 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. However, GIS-derived channel orientation estimates may not be completely representative of the orientation of the entire stream reach.

There is a need for consistent canopy protocols and a sampling design

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. However, out of 548 sites with water temperature data available for regional analyses in 1998, only 207 of these were accompanied by canopy data. There was an even greater paucity of canopy data in years prior to 1998. Null data were 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 water temperature with increasing gradient. This trend may have several underlying mechanisms. Generally, 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.

Habitat Type

While the Forest Science Project Stream Temperature Protocol (found in the Appendix of the full report) 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. In 1998, temperature sensors were about equally divided into pools and riffles/runs. Generally, pools were cooler than riffles/runs. Statistical analysis revealed that shallow, medium, and deep pools could be combined, as well as riffles and runs, for subsequent modeling.

Influence of Canopy on Stream Temperatures

Canopy has been widely acknowledged as influencing stream temperature. It has been shown that forest harvesting or road building that removes riparian vegetation (canopy) increases the water temperature of the adjacent stream. In a comparison of stream temperature models by Washington's Timber, Fish, and Wildlife found that canopy, in some form, was included in all but one of the six stream temperature models that were evaluated.

Some cooperators estimated canopy closure optically. A canopy closure computer-generated card (Figure 5) was provided to cooperators for use in 1998 in an attempt to increase the number of sites with non-null canopy values. The card served to calibrate the eye to different canopy levels. The card presented canopy closure in 10% increments, in three different crown geometries. The field person could visually match the canopy closure observed overhead to the nearest canopy closure image on the card.

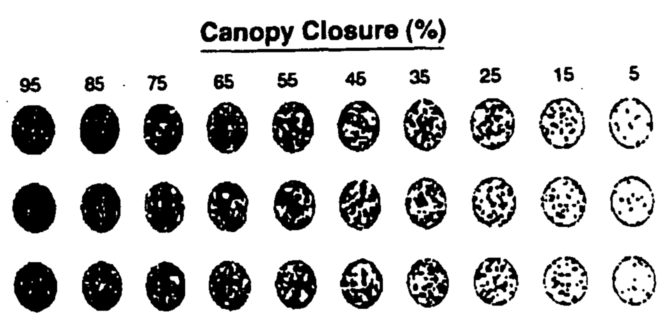


Figure 5. Example of computer-generated canopy closure card used by some FSP cooperators to estimate canopy closure at stream temperature monitoring sites.

Sullivan and coworkers (1991) developed the concept of *threshold distance*, that is the distance from the watershed divide at which streams become too wide for riparian vegetation to provide adequate shading. They found that streams seemed to reach an equilibrium temperature at approximately 40-50 km from the watershed divide. At this point, stream temperature was more a function of air temperature than canopy cover. This theoretical threshold distance is a function of stream width and riparian vegetation. Thus, the threshold distance will be different for different drainages and no single value should be applied to all streams.

The threshold distance concept was explored empirically using data gathered on streams throughout Northern California. Figure 6 is a plot of canopy closure versus distance from watershed divide for all 1994-1998 sites with reported canopy closures (456 sites).

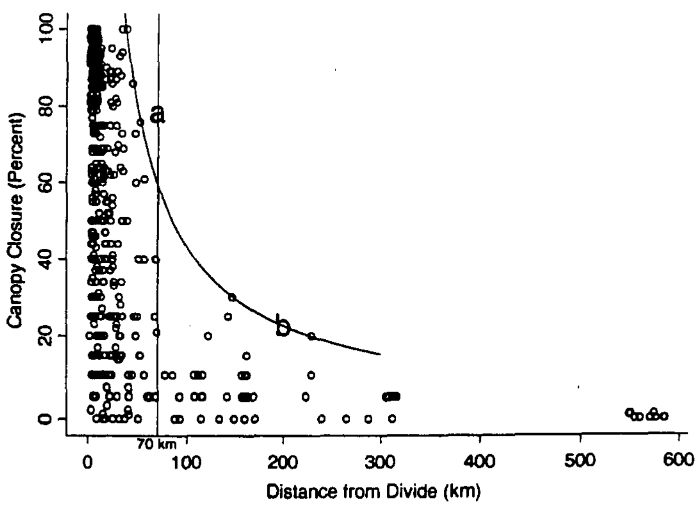


Figure 6. Relationship between canopy and distance from watershed divide. The vertical line (a) delineates the theoretical *threshold distance* (70 km) where the stream may be too wide for canopy to influence stream temperature. The curve (b) represents the maximum canopy closure potential a site has at a given distance from watershed divide.

Canopy was generally less than 10% at approximately 70 km (~43 mi) from the watershed divide.

At a divide distance greater than 70 km, there were no reported canopy closure values greater than 30%, and most were 10% or less. This suggests that 70 km may be the distance from the divide where streams become too wide for streamside vegetation to have an effect on shading. However, the data were from many basins. Thus, this distance is considered the theoretical maximum threshold distance. The threshold distance for some basins may be less than the theoretical 70-km threshold. The lack of higher canopy values at distances greater than 70 km from the watershed divide may be a result of relatively few canopy closure measurements at greater distances from the divide and the lack of a sampling design. If a curve is fit to the outer most points, representing the maximum canopy closure potential for a given distance from watershed divide, a threshold distance becomes much more difficult to define.

A similar analysis was performed for canopy versus watershed area. Sites with watershed areas of approximately 63,000 ha (~243 sq. mi.) or larger had canopy closure values less than 20%.

In Figure 7, the box plots and scatter plots are displayed side by side. Displayed in this manner, it is clear that there was a trend in higher canopy values or classes resulting in lower stream temperatures, even though the correlation was not high. Much of the variability will be taken into account by other variables that are explored in the stream temperature modeling chapter (Chapter 10).

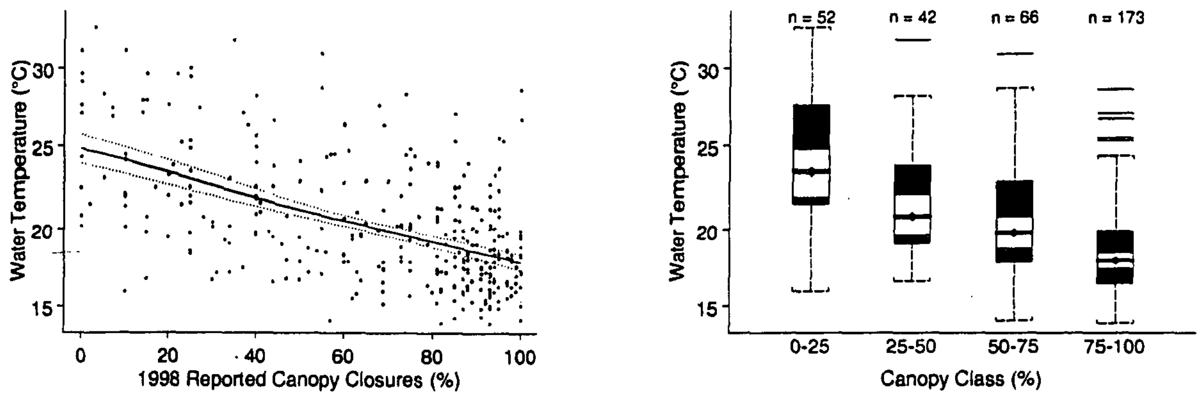


Figure 7. Scatter plot and box plot with fitted regression lines for the highest daily maximum stream temperature metrics versus canopy. For the box plots, canopy values were grouped into four canopy classes. Box plot outliers are defined as 1.5 times the inter-quartile range. The solid regression lines are the average stream temperature metric for a given canopy closure, and the dotted lines are 95% confidence bands for the average temperature values.

Hardly any values within 95% band.

Stream Temperature Empirical Modeling

The assessment report presents results of multivariate linear regression modeling development. Models were developed for all sites combined, each ecoprovince, and for sites inside and outside of the zone of coastal influence. Akaike's Information Criterion was used to select the model (using 1998 data) which contained the most information. Independent variables that proved to be highly influential on stream temperature throughout the preceding chapters were also found to be highly significant in empirical models.

Historical Perspectives

Historical stream temperature data were acquired from various sources: USGS, California Fish and Game Administrative Reports, the Pacific Gas and Electric's Potter Valley Project. More contemporary FSP sites were spatially matched with historical sites for comparisons. Unfortunately, most of the historical sites were located on mainstem systems. However, very interesting trends were found.

USEFUL TOOLS

In the appendixes of the assessment report can be found many useful tools for collecting, processing, and analyzing stream temperature data. Arc macro language (AML) and avenue script code are provided for deriving various site attributes. These can be adapted to meet individual analytical needs. The FSP's regional stream temperature protocol, field forms, and data formatting guidelines are including to assist other organizations in designing a stream temperature monitoring program.

Chapter 2

METHODS

Study Design

There was no study design in place for this stream temperature assessment. Land stewards that submitted data for the assessment collected stream temperature data under a multitude of objectives and assumptions. These diverse objectives can be grouped into three broad categories:

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

Forest Science Project cooperators and other parties that submitted stream temperature data can be characterized as forested landowners and stewards. Therefore, the population of stream temperature monitoring locations fell predominately in forested catchments or on lands zoned as Timber Protection Zone (TPZ) or Agriculture Exclusive (AE). Some mainstem river sites were exceptions. Data from both private landowners and public resource management agencies were acquired. Thus, the land management prescriptions were dependent upon whether monitored streams were on private or public lands.

Site Selection

The stream temperature data available for analysis and assessment were entirely dependent upon the willingness of the cooperator to provide the data. The data collected reflects 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. Site selection was not based on a probabilistic or random sampling design. Rather, the sites reflect a multitude of cooperator interests and monitoring objectives in a particular stream or watershed. Table 2.1 lists the various data contributors whose data were included in this assessment.

Data were accepted from contributors for inclusion in the assessment if they met all required criteria. Additionally, many data contributors submitted one or more of the optional criteria.

Required

- Stream temperature measured with a continuous monitoring device capable of taking an integrated or instantaneous reading every 2.5 hours (as opposed to a hand-held thermometer or max-min thermometer read infrequently)
- Site coordinates provided (lat/long, UTM, state plane, or hard copy maps)
- Monitors placed in Class I streams (data from some Class II streams were received)

Optional

- Air temperature measured simultaneously at the water temperature monitoring site
- Site-specific characteristics (e.g., slope, aspect, canopy closure, habitat type) measured for a (thermal) reach. Thermal reach defined as approximately 600 m for this study.

Table 2.1. Stream Temperature Data Sources for the Forest Science Project's Regional Stream Temperature Assessment.

	YEAR								
Source	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**
Barnum Timber Company								12	23
Bureau of Land Management							2		
CA Dept. Fish & Game								4	
Elk River Timber Company								6	4
Fruit Growers Supply								14	18
Georgia Pacific West, Inc.				63	54	66	64	64	75
Gualala Redwoods, Inc.					17	27	27	26	28
Humboldt County RCD							152	159	113
Humboldt State University									12
Jackson State Forest							49	34	27
Louisiana Pacific Corporation					16	15	53	36	
Mattole Salmon Group							16		
Natural Resources Cons. Serv.						11	14	13	4
NRM Corporation						3	15	23	26
Pacific Lumber Company					4	10	25	54	27
Pacific SW Experiment Station					7	7	13		
Pioneer Resources								41	39
Redwood National Park						1	1	11	10
Russ Ranch & Timber Company							2	4	9
Shasta-Trinity National Forest	15	18	17	10	23	14	6	16	13
Sierra Pacific Industries							14	24	17
Simpson Timber Company					40	30	10	29	44
Six Rivers National Forest				3	5	12	26	42	42
Soper/Soper-Wheeler Company					1				
Stimson Redwood Company					4		7	6	7
Timber Products Company							4	9	10
TOTAL	15	18	17	76	171	196	500	627	548

- Microclimatic data such as relative humidity, evaporation, sky cover, available in association with water temperature

The regional stream temperature assessment data base included 2168 site-years representing 1090 spatially unique continuous stream temperature monitoring sites. Site coordinates were available for all sites used in the assessment report. In most cases, coordinates were provided by the cooperator with the stream temperature data. In some cases, location of monitoring sites were denoted on maps that were provided by the cooperators. Coordinates were assigned to these sites using heads-up (interactive, on-screen) digitizing techniques and 1:24,000 scale digital raster graphic (DRG) topographic quadrangles. A spatial accuracy assessment was performed in January of 1999. The procedures used for the spatial accuracy assessment are described below.

Spatial Accuracy Assessment

Site coordinates provided by the project cooperators were evaluated using 1:24,000 scale DRG images. DRGs are an accurate, georeferenced digital representation of United States Geological Survey (USGS) topographic quadrangles. Note, USGS 1:24,000 scale data are purported to meet National Map Accuracy Standards for 1:20,000 or smaller scale, which state that 90% of well-defined features are within 40 ft of their true position.

An initial examination yielded varying degrees of displacement from the hydrographic component ranging from a few meters to 63 kilometers. The sources of these errors may include: base mapping sources other than USGS 1:24,000 quadrangles, transcription, digitizing and geocoding anomalies, projection and datum differences. While the potential problems arising from an error in position of 63 kilometers are quite obvious, errors of less than 10 meters can cause misleading analytical results. Small positional errors within a stream network, especially near a tributary confluence, can cause the incorrect association of a mainstem temperature site with a tributary site or visa versa. This leads to invalid relationships between sites, errors in drainage area and aspect computation, and other erroneous results. Large displacement errors will lead to the incorrect association of elevation, ownership, basin membership and other attributes necessary for spatial stratification and reporting which are critical to a regional assessment.

From the initial site survey, it was determined that a 100% site location validation strategy be developed. Stream temperature site locations were divided into groups by cooperating organization. ArcView projects consisting of site locations, DRG images, and other relevant geospatial data were developed for each group. Office visits with each cooperator were scheduled with the individual having the most knowledge of the site location to assist in the repositioning process.

There were 817 out of 1090 total sites that included both before and after site coordinate validation. The remaining 273 sites had their initial coordinates derived during office visits and were not used in the spatial accuracy analysis.

Examination of the horizontal displacement exposed 294 sites with errors greater than 50 m. A frequency distribution graph of the horizontal spatial error for 817 sites is shown in Figure 2.1. This level of spatial displacement can have severe adverse effects. Stream network position can be altered by changing a site's relationship to a tributary-mainstem confluence. Since many temperature sensors are located within 50 m of a confluence, many mainstem sites were incorrectly located above, below, or on the tributary. This will have deleterious effects when modeling the influence of a tributary's temperature input.

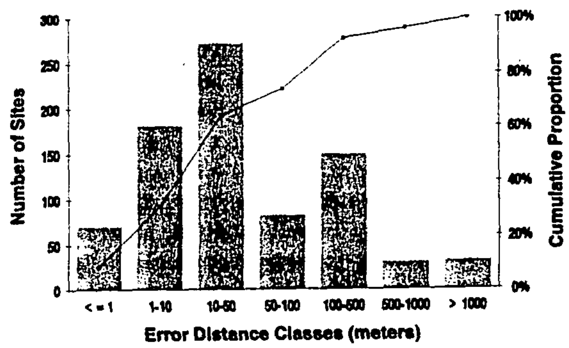


Figure 2.1. Frequency and magnitude of inaccuracies in the spatial location of stream temperature monitoring sites before site coordinate validation.

Of these 294 sensor sites, 62 sites had horizontal errors of greater than 500 m. These positional errors located many sites in the wrong drainage basin.

Upon completion of this process, the database was updated with the upgraded position and additional GIS-derived attributes.

Determining and Documenting Location

As discussed above, establishing and documenting the correct site location was critical. Key to this process was determining the required level of accuracy necessary for analysis. Digital data at a scale of 1:100,000 were found to be both lacking in spatial quality and quantity. Many stream temperature monitoring sites were located on streams represented only on 1:24,000 scale data. Hence, it was determined that the majority of GIS-based analyses would be undertaken at a scale of 1:24,000.

Two important considerations of site location are absolute positional accuracy and network topology. A high degree of absolute positional accuracy can be achieved by obtaining the site location coordinates using the Global Positioning System. This system of 28 satellites and a ground-based receiver can typically locate a site to within several meters of the true location. However, this will not ensure that a site's network topology is correctly established. Due to the spatial error in 1:24,000 scale data, a site with a high degree of absolute positional accuracy may well be incorrectly located within the network topology. Network topology describes a site's relative location within a network, in our case a hydrological network, e.g., the site is on the mainstem of the Mad River, 20 m downstream of confluence with Mill Creek.

Characterizing a site's network location with reference to well-defined features in addition to locating the site on a 1:24,000 scale topographic quadrangle will ensure that the spatial relationships between sites are maintained and that a site can be located and reestablished in the future.

GIS-Derived Variables

Once the spatial accuracy of stream temperature monitoring locations was confirmed, certain attributes were derived in GIS using standard overlay principles, raster modeling, and other methods facilitated by Arc macro language (AML) and Avenue script programs. The AML and Avenue script code can be found in Appendix A. The GIS- and Avenue-script-derived attributes were:

AML-derived
coho ESU
steelhead ESU
chinook ESU
ecoprovince
hydrologic unit (HUC)
CAL planning watershed
total maximum daily load (TMDL) Consent Decree Basin
elevation
shortest distance to coast
watershed area
distance to watershed divide

Avenue-derived
channel orientation
channel gradient
channel sinuosity

Watershed area and distance to divide were acquired by applying a simple hydrologic model to a compiled and edge-matched 1:24,000 scale digital elevation model (DEM). The compiled DEM was created by mosaicing more than 400 U.S. Geological Survey (USGS) 7.5-minute tiles. DEMs are generally available from the USGS in two distinct levels of quality. DEMs classified as Level I are created using a manual profiling procedure or the Gestalt Photo Mapper. Typically, Level I DEMs have inherent errors exhibited by elevation shifts in bands along the east-west axis. Level II DEMs are elevation data sets that have been processed for consistency and edited to remove identifiable systematic errors. Level II DEMs are created using hypsographic (contours) and hydrographic (streams) data which produce a somewhat smoother more continuous surface model. Where Level II DEMs did not exist, one of two procedures were used to create the necessary tiles. Several 30-meter DEMs were created in-house from 1:24,000 scale vector contour data while others were created by resampling USGS Level II 10-meter DEMs to a 30-meter spacing.

The compiled DEM was processed to remove spurious sinks, i.e., areas of undefined flow, by filling these to a surrounding outlet elevation. The assembled DEM was evaluated for internal and along-tile boundary errors by computing a flow-direction and flow-accumulation model for each logical basin within the Area of Interest (AOI). Any break in flow within a logical basin before reaching the natural outlet (Pacific Ocean) was determined to be an error requiring an appropriate correction. Once a flow corrected DEM existed, upstream watershed (drainage) area and divide distance were derived for each temperature monitoring site.

Using 1:24,000 scale digital raster graphics (DRGs) and USGS 30-meter digital elevation models ArcView (Environmental Systems Research Institute, Redlands [ESRI], CA) combined with Avenue scripts were used to acquire the necessary information to compute the desired attributes. Channel orientation was calculated by tracing a 600-meter reach upstream of each temperature sensor location. From this point a straight-line distance and bearing was calculated back to the sensor location. Channel orientation represents this bearing in compass degrees where north equals 0 degrees. Elevation was acquired from the DEM for the sensor site and the location 600 meters upstream. Channel gradient was calculated as the difference in elevation between these two sites divided by the reach length. Channel sinuosity was calculated by dividing the reach length (600 meters) by the straight-line distance between the two locations. Very straight reaches yielded sinuosity values nearly equal to 1.

It is important to be aware of and understand the associated errors of these products and how these errors can affect results. For example, gradient values of less than or equal to zero were occasionally acquired from sites located along channels with little natural elevation change. While a negative upstream gradient may be disconcerting, these sites can confidently be described as very low gradient reaches. Since our application was at a regional scale and we were looking at general classifications (e.g., flat, sloped, very sloped, steep), the realized error was considered acceptable.

Calculated Water Temperature Metrics

Various water temperature metrics were calculated from the data. These metrics were considered important in characterizing the thermal regimes in water temperature across Northern California. These included:

- daily minimum
- daily mean
- daily maximum
- seven-day moving average of the daily minimum
- seven-day moving average of the daily mean
- seven-day moving average of the daily maximum

The above six metrics comprise the core set of statistics that were used throughout the regional assessment. Other metrics, representing both chronic and acute thermal stress, are presented in subsequent chapters and are therein defined.

Daily and weekly temperature metrics were further reduced to single statistics for each site for each year. For example, for a given site, the highest daily maximum temperature for the year was used as a temperature index that was compared to various climatic, landscape, and site-specific attributes. Similarly, the highest seven-day moving average of the daily average was compared to similar independent variables. A list of the yearly summary statistics calculated from the daily and weekly data and most commonly used in our analyses is presented in Table 2.2.

A naming convention was developed for assigning variable names to yearly temperature metrics. While the abbreviations may seem unwieldy upon first encounter, they become second nature once an understanding of the naming convention is acquired. The first letter denotes that the yearly statistic is the maXimum (X), Average (A), or mInimum (I) for the year. The second letter denotes that the statistic is a Yearly statistic (Y). While a complete year (i.e., January 1 through December 31) of temperature is not used to calculate the yearly statistic, the value

Table 2.2. Most Commonly Used Yearly Temperature Statistics Calculated from Daily and Weekly Data Sets.

Yearly Site-Level Statistic	Abbreviation
highest daily maximum	XY1DX
lowest daily minimum	IY1DI
highest seven-day moving average of the daily average	XYA7DA
highest seven-day moving average of the daily maximum	XYA7DX

represents the maximum, average, or minimum for the defined sampling window in a given year. Obviously, the minimum for the year is not captured in the defined sampling window. For seven-day moving averages, the third letter specifies that the statistic is the maXimum (X), Average (A), or mInimum (I). If the metric is based on a daily value, e.g., the daily average, daily minimum, or daily maximum, the third character in the variable name is a one ('1') and the fourth is a 'D' for Daily. If the statistic is based on a seven-day moving average the fourth and fifth characters in the variable denote this by '7D'. The last character specifies that the statistic is the daily value or seven-day moving average of the maXimum, Average, or mInimum.

Some examples will help clarify the naming convention. The maXimum (or highest) daily (1 Day) maXimum for the Year would be represented as **XY1DX**, where

X = maXimum for the year
Y = a Yearly statistic
1D = 1 Day or daily
X = maXimum.

The mInimum (or lowest) daily (1 Day) mInimum temperature for a site in a given Year would be denoted as **IY1DI**, where

I = mInimum for the year
Y = a Yearly statistic
1D = 1 Day or daily
I = mInimum.

The maXimum (or highest) 7-Day moving Average of the daily Average for a site in a given Year would be encoded as **XYA7DA**, where

X = maXimum for the year
Y = a Yearly statistic
A = Average
7D = 7 Day moving average
A = Average.

Potential Errors in Calculating Water Temperature Metrics

In calculating summary statistics for the various temperature metrics it was found that a potential error was inherent in the data. The highest daily minimum and lowest daily maximum were influenced by daily records that did not contain a complete number of observations due to removal of anomalous readings, e.g., ambient air spikes. If only a portion of the daily observations were removed, an incomplete daily record resulted. For example, if the sampling frequency of a device was set to take an instantaneous reading every hour, 24 observations per day should be found for each daily observation. However, if anomalous readings were removed from the daily record, less than 24 observations were observed for certain days. When the daily minimum and daily maximum temperatures were calculated using Statistical Analysis System (SAS) (SAS, 1996), days that had an incomplete number of observations had elevated daily minimum and depressed daily maximum temperatures, depending on the time of day data were missing.

Due to errors introduced in the data due to missing observations, a SAS program was written to search the hourly data set for days where the number of observations was less than the maximum number of daily observations or the maximum number of daily observations minus one. The ***maximum minus one*** provision was used to compensate for sites where the number of daily observations oscillated by one. This occurs when the device start time and sampling frequency results in the last observation of the day being very close to midnight. For example, depending on the start time, a monitoring device set at a 1.6- hr sampling frequency will have 15 daily observations on one day, then have 14 daily observations on the next day. When days with daily fragments were encountered the daily observation was left in the data set, however, the temperature values were set to missing. Without the ***maximum minus one*** provision, every other day (the day with 14 observations) would have had all the temperature values set to missing. The data set with daily fragments removed (set to missing) is henceforth referred to as the ***defragmented weekly data set.***

Additional temporal refinement was applied to the defragmented weekly data set for statistical analyses. Many multivariate analyses and modeling in this regional assessment were based on the highest daily maximum (XY1DX), the highest seven-day moving averages of both the daily average (XYA7DA) and the daily maximum (XYA7DX) for the year. Limiting the temporal window of the temperature data to June 1 through September 30 for all sites and all years helped ensure that stream temperatures across a consistent time frame were used in summary statistics. However, even with this precaution it became apparent that the "highest" value for a particular site may not necessarily have been captured if data were missing during the time the "true" highest stream temperatures occurred. Thus, the defragmented weekly data set converted daily and seven-day moving average temperature values to missing values for days with incomplete observations. It was deemed critical to refine the temporal window to the time period when the highest stream temperature metrics were most likely to occur. This time frame was determined from the defragmented weekly data set by calculating the mean and median day of year in which the highest seven-day moving average occurred.

To briefly summarize, there were 1090 spatially unique study sites monitored between 1990 and 1998 inclusive. The mean day of the year the XYA7DA and XYA7DX occurred was determined by running a series of queries. The mean value for the day of occurrence was 215, which corresponds to August 4. This calendar date may vary by one day, depending on whether or not a given year was a leap year. A 15-day period on either side of day 215 was used as the temporal window (day of year between 201 and 230 or approximately July 21 through August 19). Additionally, sites having five or more days within this period with missing values were removed from further analyses. This criterion represents about 85% of the days within the desired time frame required to have non-missing observations. This missing data criterion is the same as that used by the National Weather Service for inclusion of air temperature monitoring data in their data summaries. Of the 1090 study sites, 1034 sites had data within the 30-day window, with 1014 sites having data that met all criteria. The most data-rich year, that is existence of data for both stream temperature and many of the site-specific attributes, was 1998 – there were 518 sites for this year. This year was used predominantly throughout the report to explore relationships between stream temperature and various landscape and site-specific variables.

Temporal, Spatial, and Physical Stratification

The temporal delimiters placed on the data to remove errors in statistical analyses were discussed above. Certain spatial and physical criteria were also imposed on the data used in stream temperature analyses to render the data comparable within and between years. Table 2.3 lists the criteria used in data standardization. Figure 2.2 shows the spatial distribution of sites for each year and all years combined (1990-1998) that met the criteria shown in Table 2.3. As can be noted from the spatial displays in Figure 2.2, the spatial distribution of sites was not uniform across all years. The lack of uniformity in spatial coverage was taken into consideration when relationships between stream temperature and certain landscape- and site-level attributes were examined

The spatial qualifiers that were applied to the data ensured that data used in the regional assessment were gathered from the appropriate areas of interest. A spatial hierarchy was used to post-stratify the data by these areas of interest. The focus of this temperature assessment was on anadramous fish,

Table 2.3. Criteria Used to Standardize Stream Temperature Data Within and Between Years.

Criterion	Value	Description
Stream class	= 1	Class 1, fish-bearing streams
	= 5	Stream class not specified
	= ' '	Stream class missing
Site type	= water air	Water or air temperature. Relative humidity data were excluded from analyses.
Temporal	≥ 21 July	Date was greater than or equal to 21 July for each year
	≤ 19 Aug	Date was less than or equal to 19 August for each year
Spatial	Only sites that fell within the boundaries of the California portion of the Southern Oregon Northern Coastal California and Central California evolutionarily significant units	

namely coho salmon. Thus, the largest spatial boundary applied to the geographic distribution of sampling points was the combined SONCC and CC evolutionarily significant units for coho salmon (*O. kisutch*) (Figure 1.1). If in the assessment, status and trends in stream temperatures pertinent to coho salmon within one of the ESUs were of interest, the coho ESU boundary for that ESU was used to poststratify sampling points by this area of interest. Likewise, if relationships between stream temperature and certain landscape- and site-specific variables were explored by ecoprovinces (USDA, 1997), the spatial boundaries of these ecoprovinces were used to aggregate data by this area of interest.

Measurement Techniques and Data Processing

The measurement techniques used by the various data contributors and the Forest Science Project's methods of data processing are presented in Appendix A.

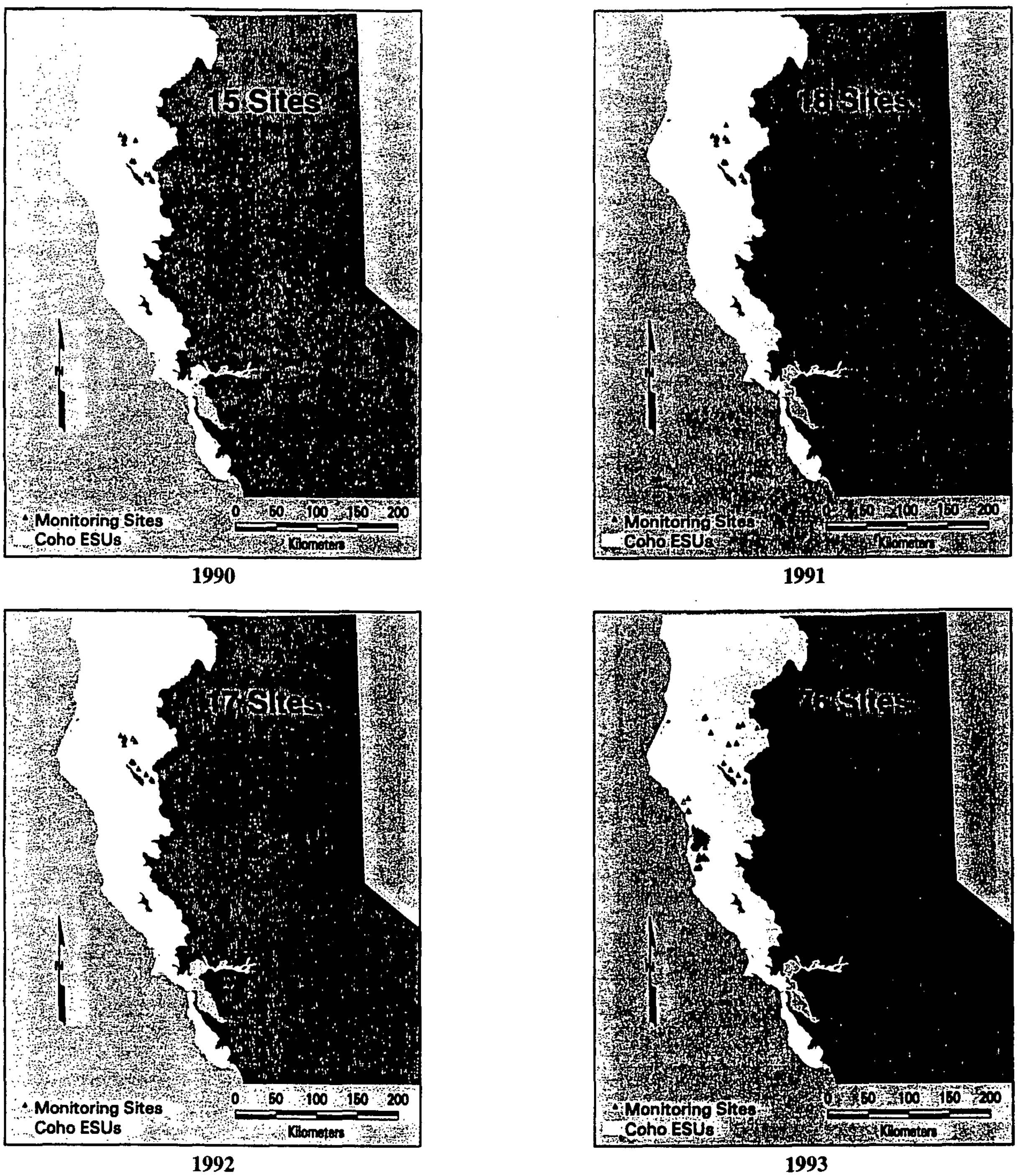
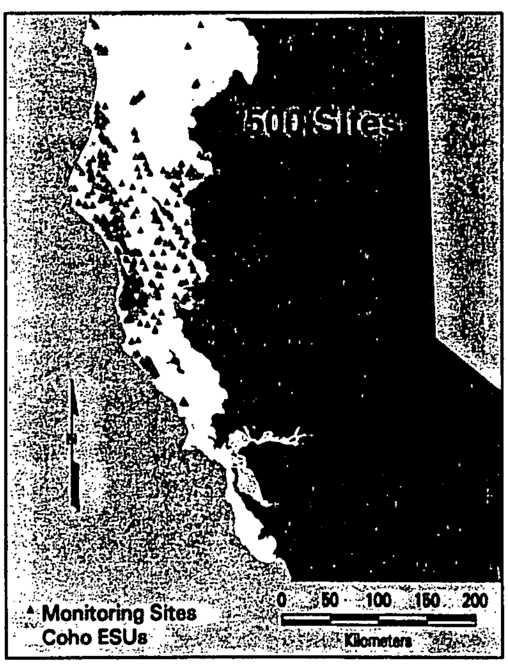


Figure 2.2. Location of stream temperature monitoring sites used in the Regional Stream Temperature Assessment.

1994

1995

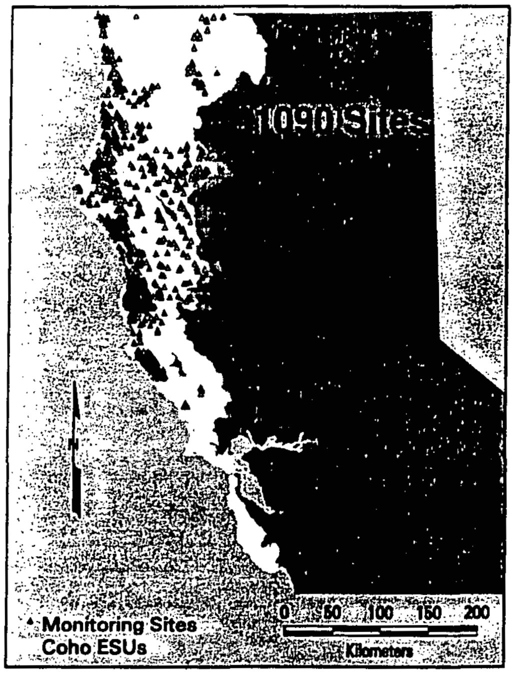


1996

1997

Figure 2.2. (continued)

1998



All Sites, All Years (1990-1998)

Figure 2.2. (continued)

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.

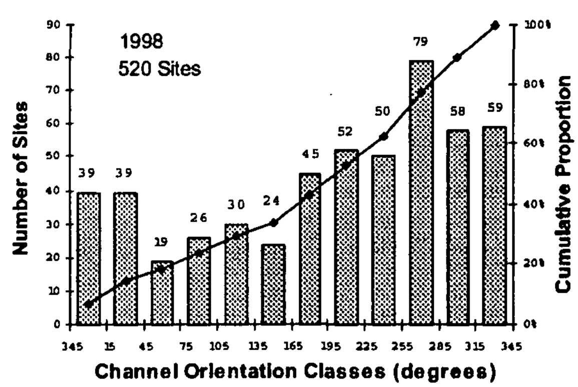


Figure 8.1. Distribution of stream temperature monitoring sites by channel orientation classes. Orientation was derived in GIS at a point ~600 meters upstream from the stream temperature monitoring site. Orientation is in a downstream direction.

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

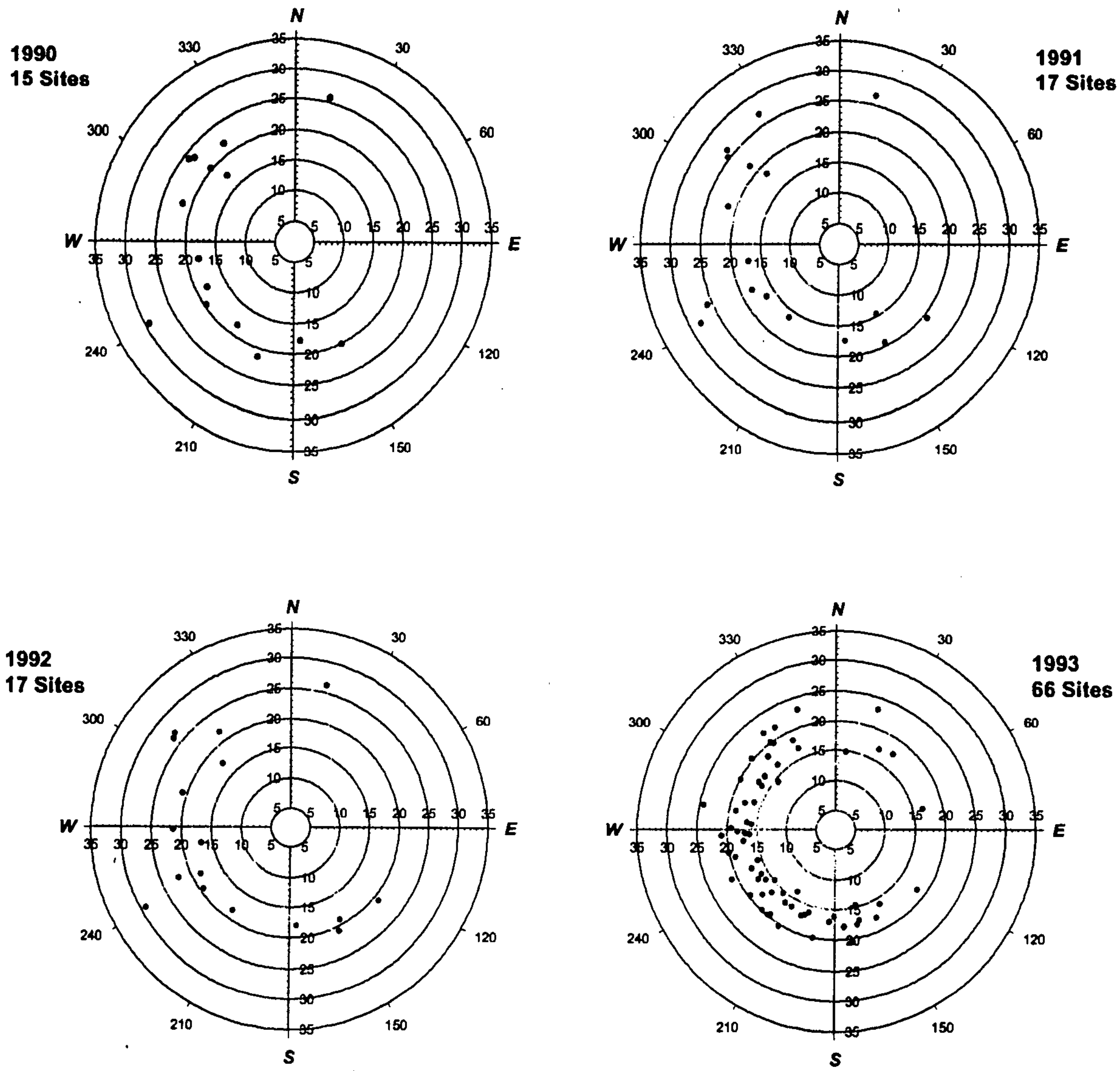


Figure 8.2. Highest daily maximum stream temperature (°C) with respect to channel orientation (degrees) for years 1990 - 1998. Orientation was derived in GIS over the reach ~600 meters upstream from the stream temperature monitoring location. Orientation was determined in a downstream direction along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

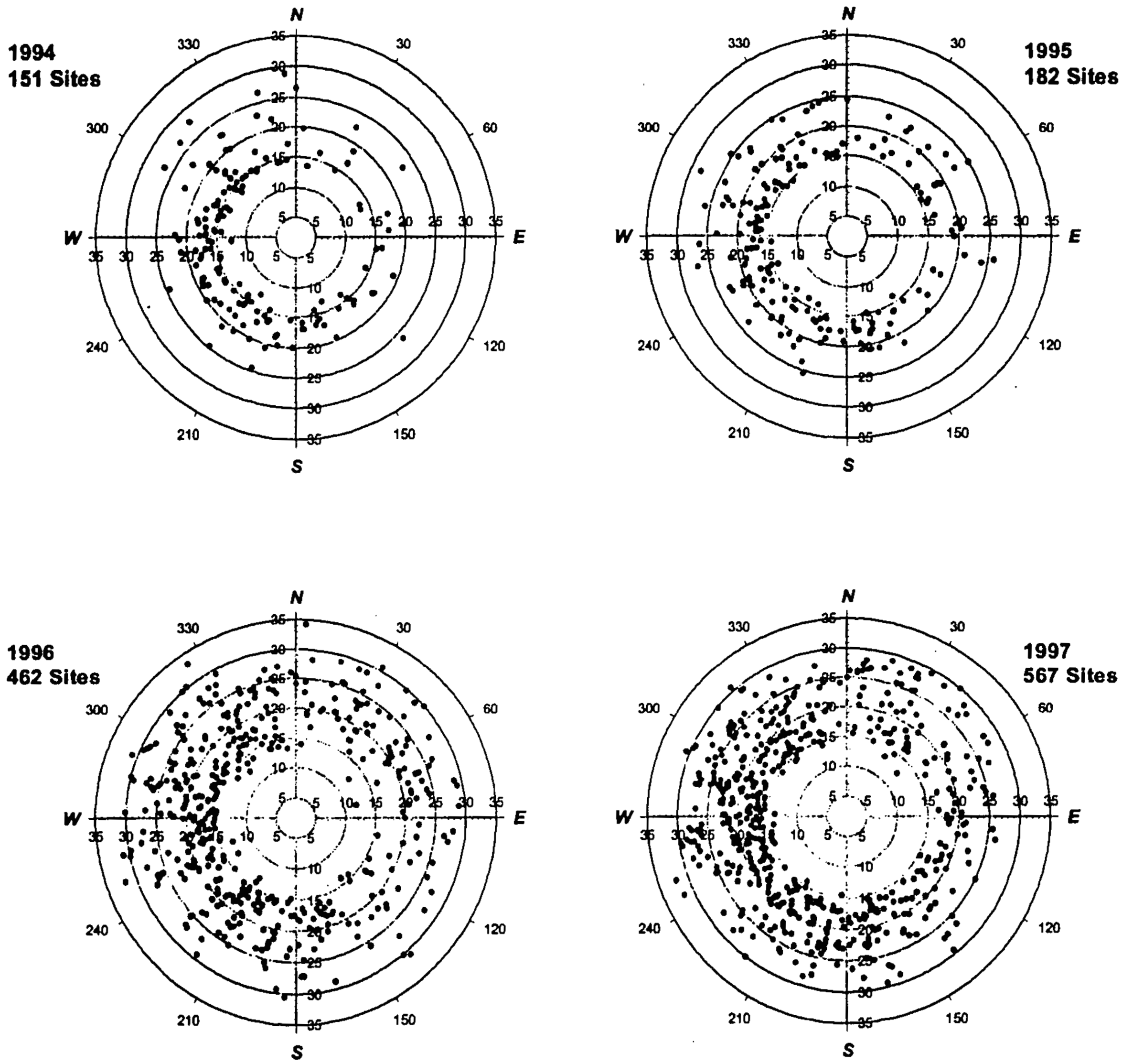


Figure 8.2. (continued)

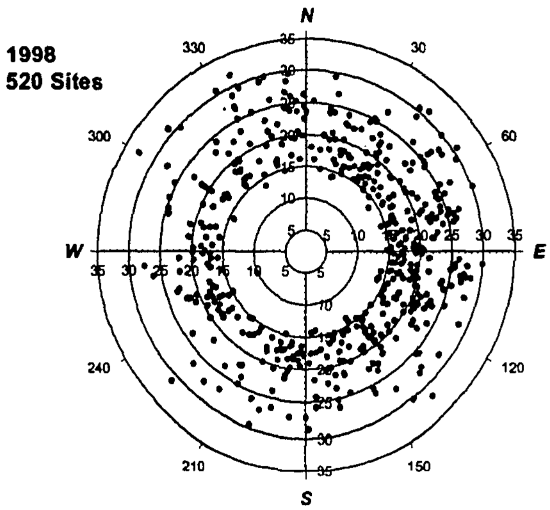


Figure 8.2. (continued)

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

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

OR

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

EW

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

OR

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

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).

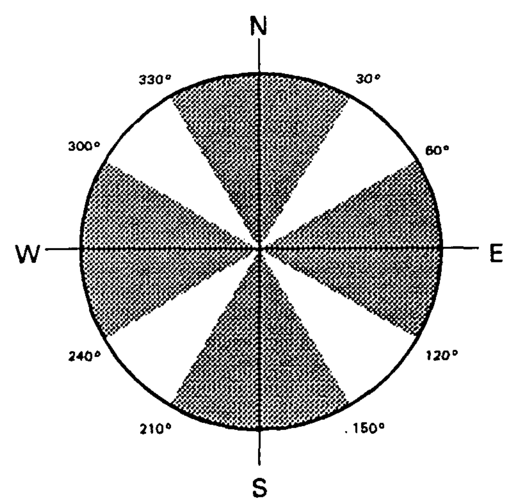


Figure 8.3. North-South and East-West channel orientation classes used to assess the influence of channel orientation on stream temperatures. Shaded area represents 30 degrees on either side of cardinal directions.

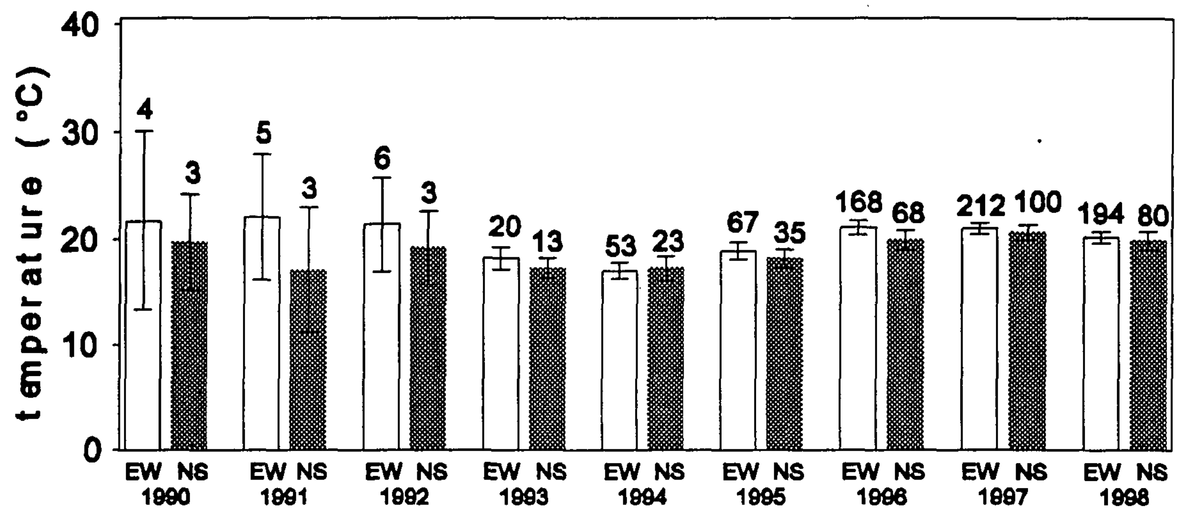


Figure 8.4. Average of the highest daily maximum stream temperature by orientation class and year. EW = streams with orientations flowing east-west or west-east; NS = streams with orientations flowing north-south or south-north. Error bars represent two standard deviations. Number of sites in each orientation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

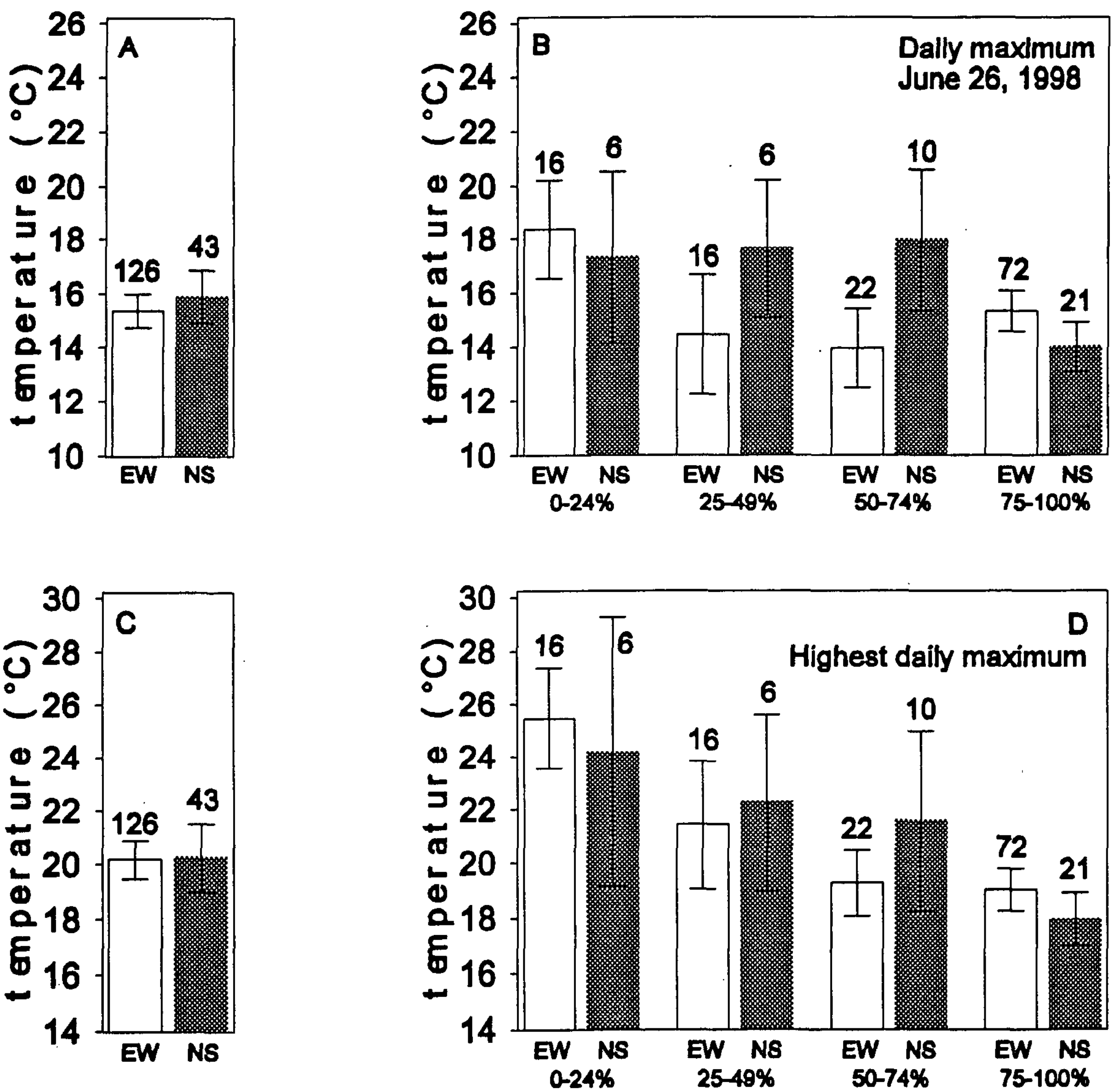


Figure 8.5. Comparison of the daily maximum stream temperature measured on 26 June 1998 and the highest 1998 daily maximum by orientation class and canopy class. (A) 26 June daily maximum by orientation class, (B) 26 June daily maximum by orientation class and canopy class, (C) highest 1998 daily maximum 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.

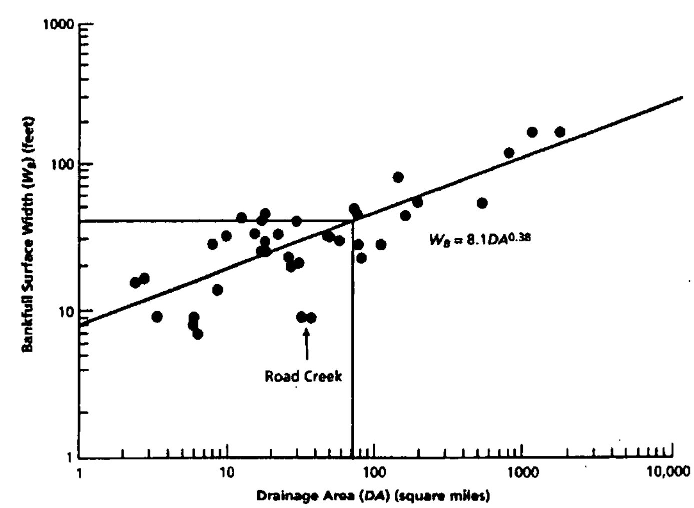


Figure 8.6. Bankfull surface width versus drainage area - Upper Salmon River, Idaho. Local variations in bankfull width may be significant. Road Creek widths are narrower because of lower precipitation. Taken from FISRWG (1998).

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.

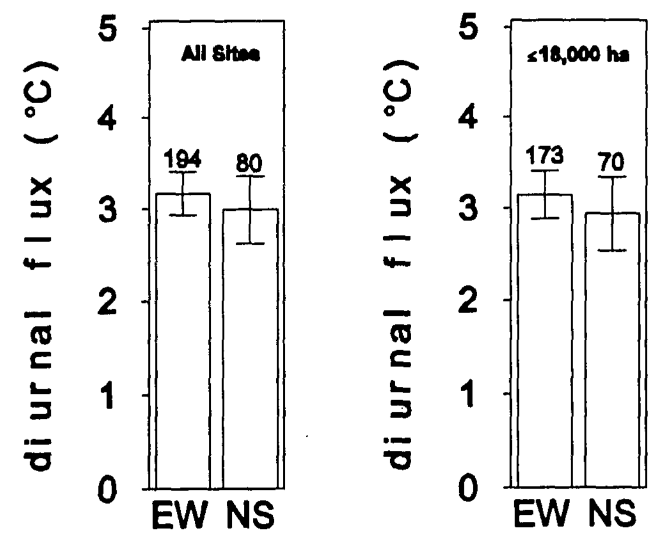


Figure 8.7. Comparison of average diurnal fluctuation by channel orientation class. Diurnal fluctuation averaged for July 21 through August 19, 1998. All sites (A) and sites with watershed area less than or equal to 18,000 ha (B).

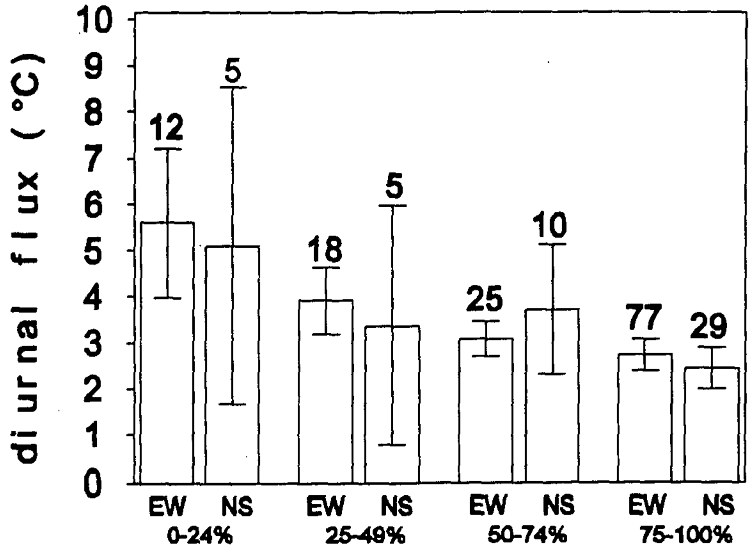


Figure 8.8. Average 1998 diurnal temperature fluctuation by orientation class and canopy class for 181 sites with watershed area less than or equal to 18,000 hectares (~70 sq. mi.). EW = streams with east-west or west-east orientations; NS = streams with north-south or south-north orientations. Error 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.

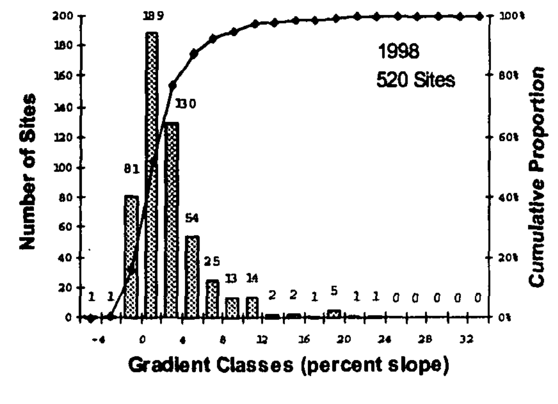


Figure 8.9. Distribution of 1998 stream temperature monitoring sites by channel gradient classes. Gradient was derived in GIS along a ~600-m reach upstream from the stream temperature monitoring site.

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

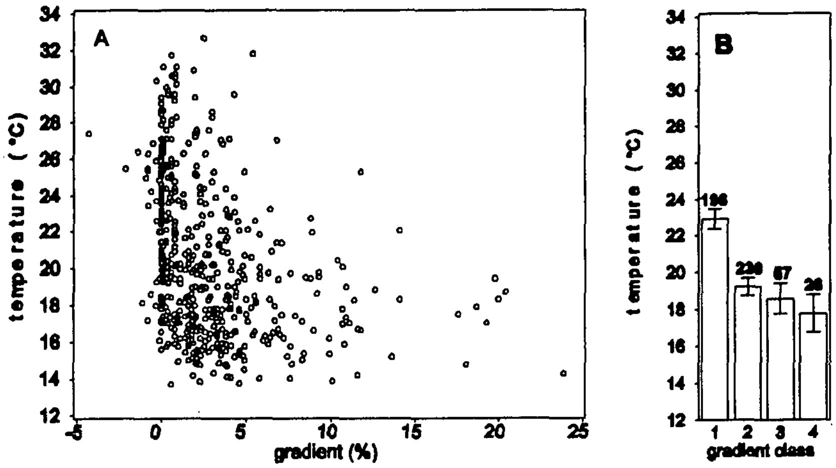


Figure 8.10. Variation in the highest 1998 daily maximum stream temperature (XY1DX) with channel gradient. Scatter plot (A) and bar chart (B). Gradient classes are 1 = <1%, 2 = 1% to <5%, 3 = 5% to <10%, and 4 = >10%. Gradient was derived in GIS along a ~600-m reach upstream from the stream temperature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

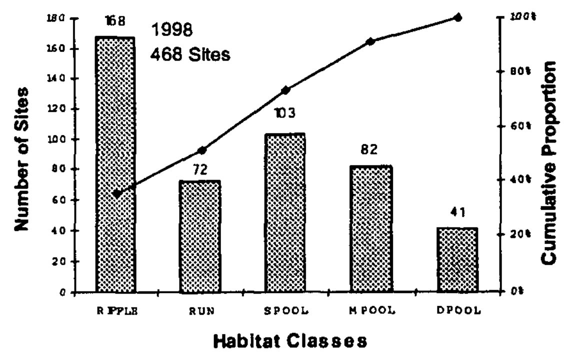


Figure 8.11. Distribution of 1998 stream temperature monitoring sites by habitat type. Plotted line is the cumulative proportion. SPOOL = shallow pool less than 2 ft in depth, MPOOL = medium-depth pool 2 to 4 ft in depth, DPOOL = deep pool greater than 4 ft in depth or pools suspected of maintaining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

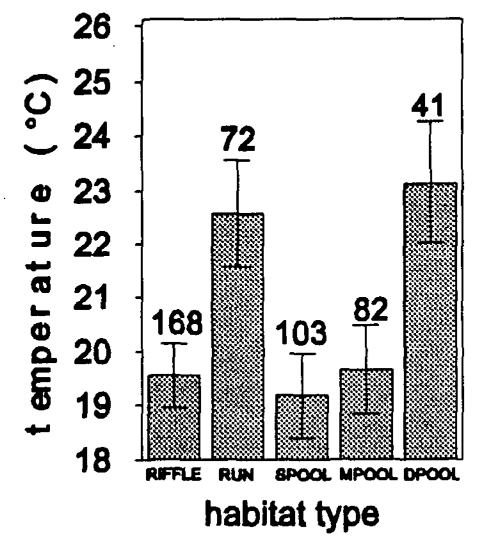


Figure 8.12. Average of the highest 1998 daily maximum stream temperature by habitat type. Habitat types are defined in *Figure 8.11* caption. Error bars represent ±2 standard deviations. Number of sites in each habitat type are shown above error bar.

Influence of Bankfull Width on Stream Temperatures

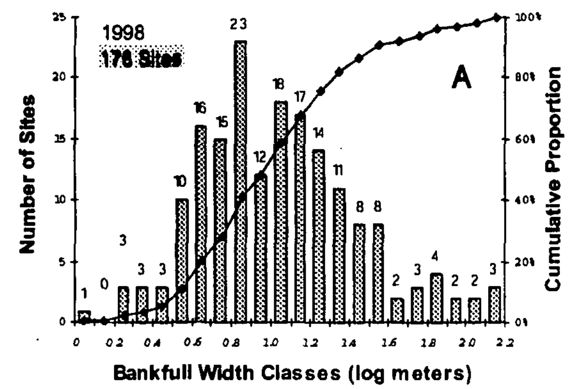
The number of sites for which bankfull width was provided was somewhat limited. In 1998 there were 176 sites for which bankfull width was available. The frequency distribution of 1998 bankfull width values is shown in Figure 8.13-A. Approximately 90% of the sites had bankfull widths less than 32 m. This 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.



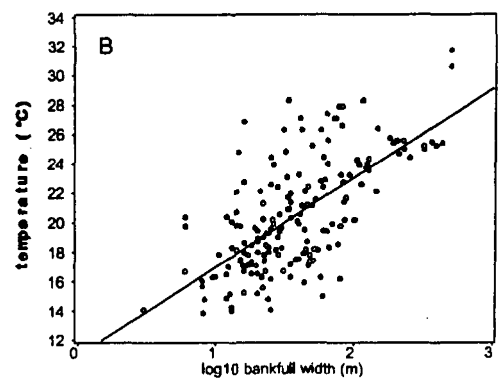


Figure 8.13. Frequency distribution (A) of 176 stream temperature monitoring sites measured in 1998 with non-null bankfull widths. Plotted line is the cumulative proportion. Plot B shows the highest daily maximum temperature versus $\log_{10}$ bankfull width in meters. Regression equation is: XY1DX = 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 9

INFLUENCE OF CANOPY ON STREAM TEMPERATURES

Introduction

Canopy has been widely acknowledged as influencing stream temperature. Canopy, or some derivative thereof, is an input variable in many process-based stream temperature models. In Sullivan et al. (1990) canopy, in some form, was included in all but one of the six stream temperature models that were evaluated.

It has been shown that timber harvesting or road building that removes riparian vegetation (canopy) increases the water temperature of the adjacent stream. In Northern Coastal California, maximum stream temperature has been documented to increase by as much as 9.4°C (17°F) after complete removal of riparian vegetation (Kopperdahl et al., 1971). The report cites numerous other increases in northern coastal stream temperature after complete removal of riparian canopy. Increased solar radiation due to canopy removal was cited as the primary cause of increased stream temperature.

There is little debate today over the fact that complete removal of riparian vegetation can elevate stream temperatures. Scientific literature abounds documenting increased stream temperature with decreased canopy. The debate today is more over how much canopy must be retained to provide adequate stream protection. Changes made in the 1980's to California's Forest Practice Rules prohibit complete removal of streamside vegetation and require *"at least 50% of the overstory and 50% of the understory canopy covering the ground and adjacent waters shall be left in a well distributed multi-storied stand composed of a diversity of species similar to that found before the start of operations* (CDF, 1999).

What exactly is *canopy*? What may appear as a trivial question is actually quite complex. The canopy that influences stream temperature is more than just the riparian cover over the site where temperature is monitored. Water temperature at a site is a function of both the local site conditions and the temperature of the incoming upstream water. The theoretical upstream distance above a water temperature site where factors, such as air temperature and canopy, influence water temperature is known as a *thermal reach* (TFW, 1993). Once above the thermal reach, different canopy values or other changes in riparian conditions are not expected to affect stream temperature at the downstream terminus of a thermal reach. A study of 14 Oregon streams found that water that was slightly warmer in areas recently clearcut, with 8.6- to 30.5-m buffers along the stream, cooled to "trend line" temperatures, in most cases, within 150 m downstream (Zwieniecki and Newton, 1999). The decrease in canopy affected stream temperature for approximately 150 m. For those streams, the thermal reach may have been about 150 m. However, the larger the stream the slower it is to respond to changes in the physical environment. Thus, larger streams have longer thermal reaches. The length of a thermal reach varies from site to site and is difficult to determine. The notion of thermal reach may be useful from a conceptual standpoint, but may have little operational value because it cannot be measurably defined.

> A ***thermal reach*** is a reach with similar (relatively homogenous) riparian and channel conditions for a sufficient distance to allow the stream to reach equilibrium with those conditions. The length of reach required to reach equilibrium will depend on stream size (especially water depth) and morphology (TFW, 1993). A deep, slow moving stream responds more slowly to heat inputs and requires a longer thermal reach, while a shallow, faster moving stream will generally respond faster to changing riparian conditions, indicating a shorter thermal reach. Generally, it takes about 300 meters (or 1000 feet) of similar riparian and channel conditions to establish equilibrium with those conditions in fish-bearing streams.

The canopy of interest is canopy cover over the entire thermal reach. Since the length of a thermal reach varies from site to site and is not clearly understood, it is entirely possible that the canopy that was measured in the field and submitted to the FSP was not the operative canopy that influences stream temperature.

Prior to a discussion on canopy closure and stream temperature relationships it should be pointed out that canopy closure is not the operative variable for assessing trends in stream temperature. In reality, effective shade is the variable that would best correlate with stream temperature. For example, in an east-west flowing stream found at Northern California latitudes the sun on August 1 would be north of the river at midday. If all the shade-producing vegetation was on the north side of the stream, than the effective shade may be near 100%, whereas canopy closure may be only 50%. In the case where shade-producing vegetation was found on both north and south banks, on August 1 the effective shade would still be near 100% and canopy closure may be also be near 100%. The relationship between effective shade and canopy closure should be borne in mind when interpreting the relationships between canopy closure and stream temperature discussed below.

Canopy Measurements

The canopy values submitted to the Forest Science Project for inclusion in the regional stream temperature assessment were collected using a diversity of methodologies. Some cooperators used concave spherical densiometers and measured canopy only at the location where the temperature sensor was deployed. Others, using the same device, measured canopy along a *thermal reach*, the reach length of which varied by cooperator, and submitted average canopy along the reach. The length of the thermal reach along which the canopy was measured was requested from each cooperator. However, often the thermal reach length value was null. Other times, the reported thermal reach length was tens of thousands of meters. Most likely the cooperator submitted the length of the entire tributary.

Some cooperators estimated canopy closure optically. A canopy closure computer-generated card (Figure 9.1) was provided to cooperators for use in 1998 in an attempt to increase the number of sites with non-null canopy values. The card served to calibrate the eye to different canopy levels. The card presented canopy closure in 10% increments, in three different crown geometries. The field person could visually match the canopy closure observed overhead to the nearest canopy closure image on the card. The card is an adaptation of one used by the National Forest Health Monitoring Program (Lewis and Conkling, 1994).

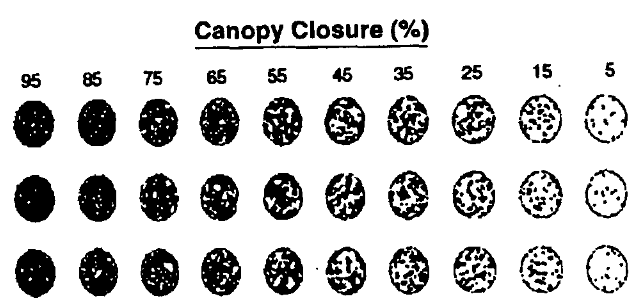


Figure 9.1. Example of computer-generated canopy closure card used by some FSP cooperators to estimate canopy closure at stream temperature monitoring sites.

Considering the different methodologies used to collect canopy data submitted to the FSP, large sources of variability exist. A FSP *Technical Note* can be found in Appendix B that compares different canopy measurement methodologies. The canopy data supplied by the cooperators may represent different attributes of canopy cover and geometry. This leads to two substantial concerns. First, a great amount of "noise" is introduced into fitted models when mixed canopy measurement systems are used. Second, different canopy measurement systems probably have their own characteristic canopy-temperature relationships. Thus, the parameters for any fitted model using canopy data may be a function of the diversity of different methods used to measure canopy. Analyses would be less ambiguous if the same protocol was used for measuring all canopy values at each stream temperature monitoring site.

Distribution of Canopy Data

Figure 9.2 shows the frequency distribution of canopy values in each year. Without a probability-based sampling design, the true distribution of canopy values cannot be determined. There were no canopy data submitted in conjunction with temperature data collected in 1993 and earlier. There were relatively few values submitted for 1994 through 1996. Figure 9.2 shows that the distributions of canopy closure values were not evenly distributed across all canopy bins. There were greater numbers of sites in the lowest (0 - 10%) and highest (90 - 100%) canopy bins than in the midrange of the distribution. It is unknown if the distribution was due to a bias in canopy estimation methods, a bias in site selection, or if the distribution reflects the "true" distribution in canopy values.

Figure 9.3 shows that the geographic distribution of canopy data in each year was not uniformly distributed. In 1995-1997, sites were clustered in the northern and southern portion of the study area. This pattern is particularly true for 1994 through 1996, making them inappropriate for regional analyses. In 1997, data were still somewhat patchy, while 1998 was much more geographically homogeneous. Thus, the focus of this chapter will be on 1998 canopy data.

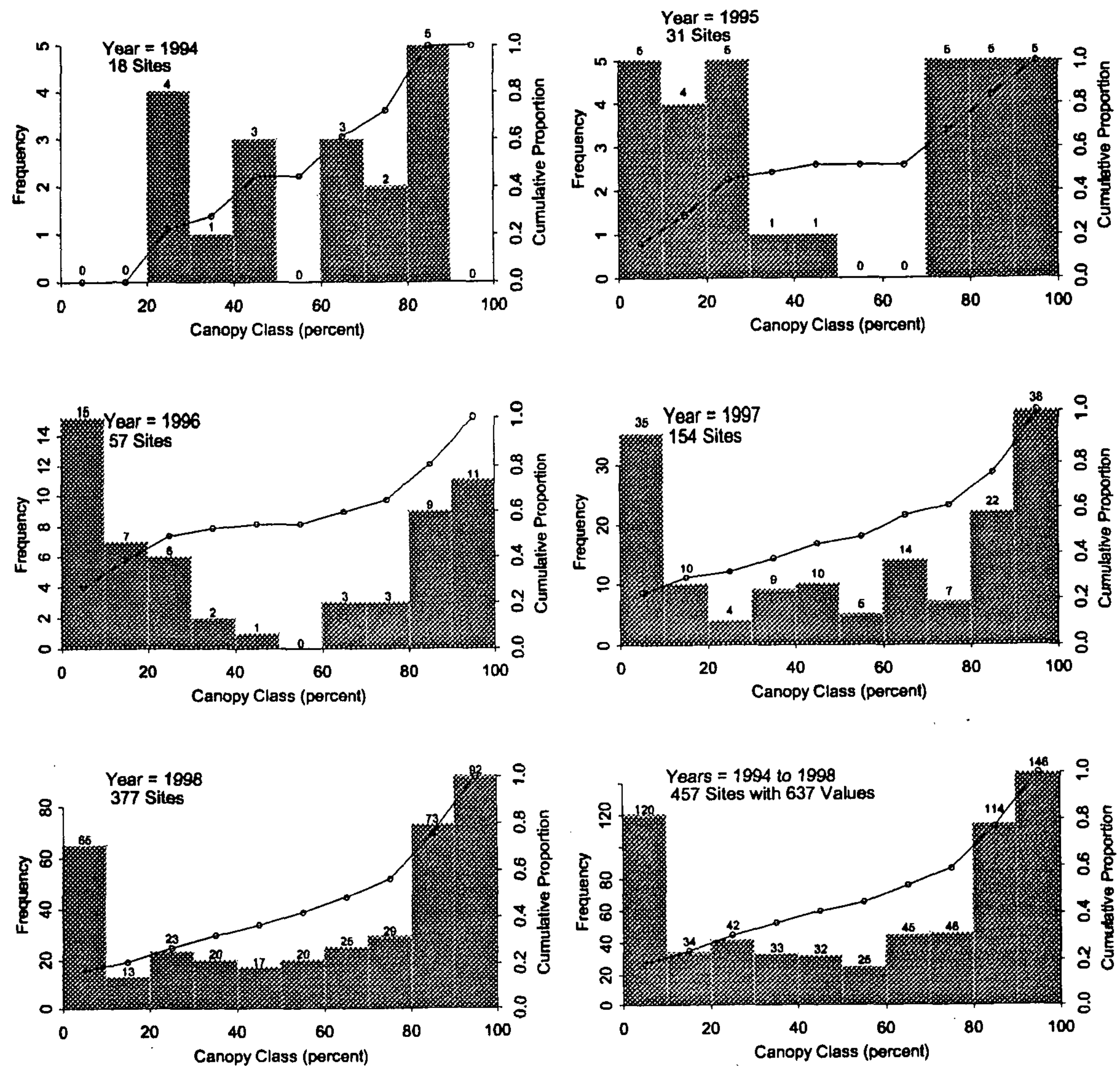


Figure 9.2. Frequency distribution of stream temperature monitoring sites by ten-percent canopy bins for 1994 through 1998 and all years combined. Plotted line is the cumulative proportion.

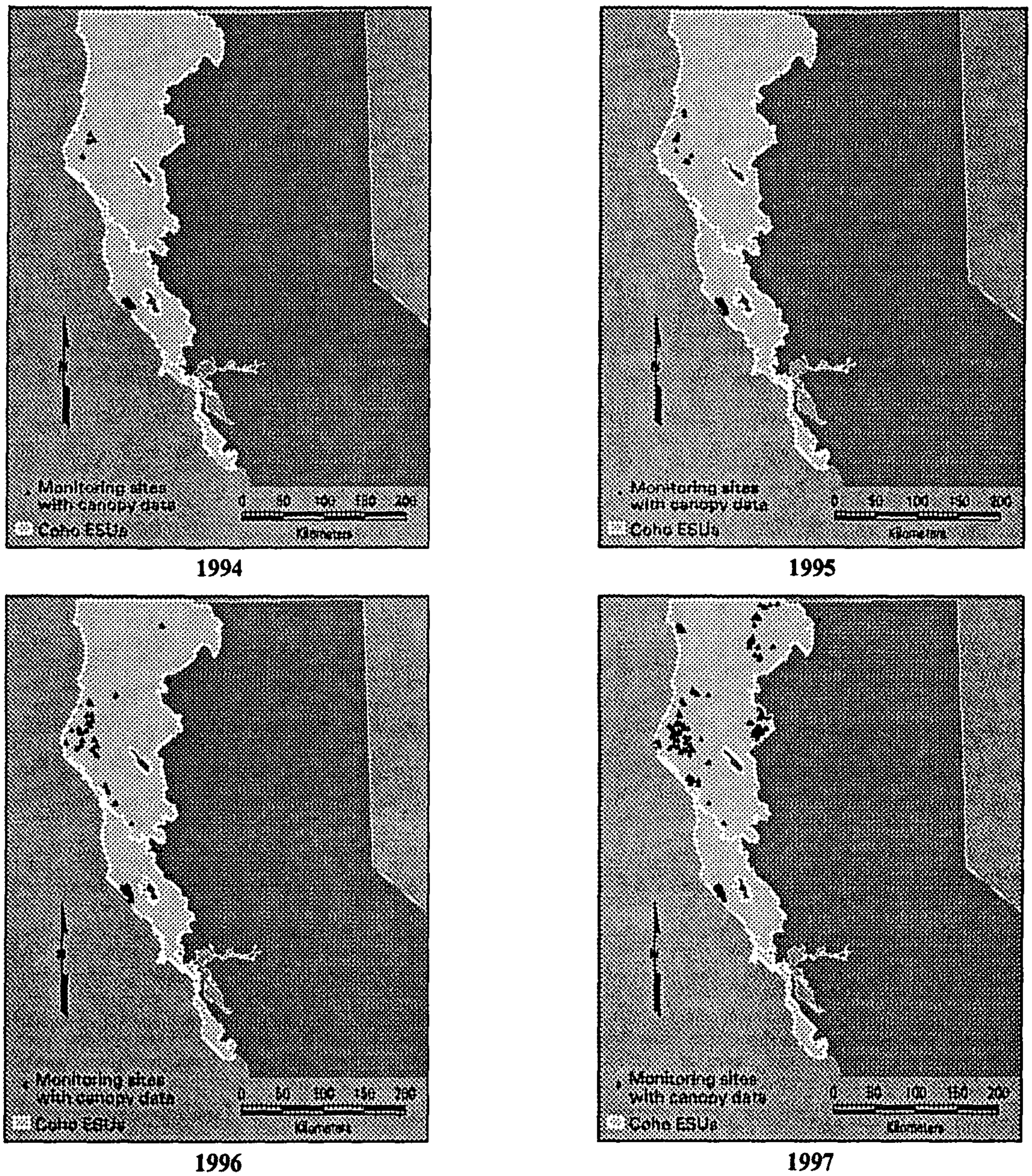
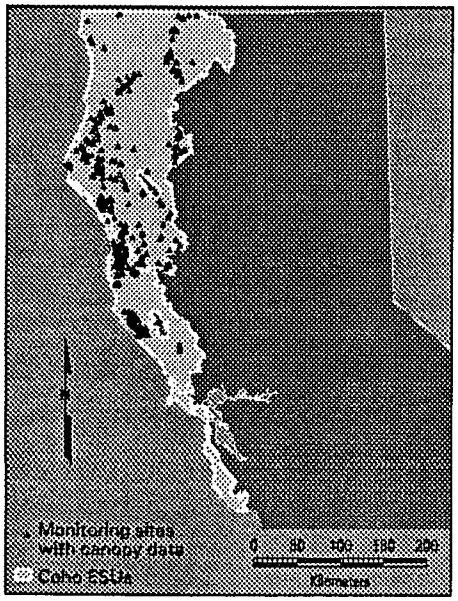
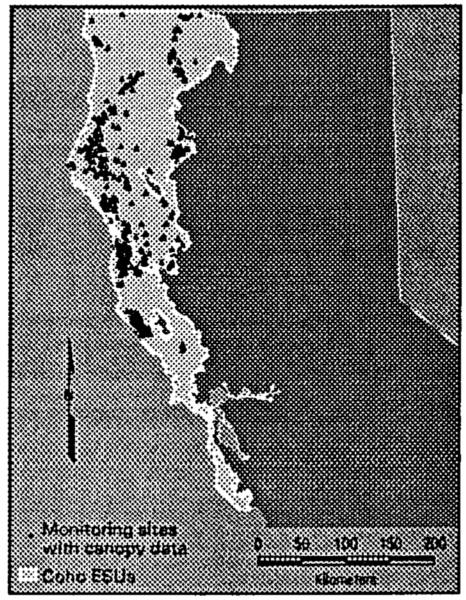


Figure 9.3. Geographic distribution of stream temperature monitoring sites with non-null canopy closure values for 1994 through 1998 and all years combined.



1998



1994-1998 (combined)

Figure 9.3. (continued)

Threshold Distance

Sullivan et al. (1990) developed the concept of *threshold distance*, that is the distance from the watershed divide at which streams become too wide for riparian vegetation to provide adequate shading. They found that streams seemed to reach an equilibrium temperature at approximately 40-50 km from the watershed divide. At this point, stream temperature was more a function of air temperature than canopy cover. This theoretical threshold distance is a function of channel width and riparian vegetation. Thus, the threshold distance will be different for different drainages and no single value should be applied to all streams. Moreover, as streams widen, the influence of topographic shading diminishes.

The threshold distance concept was explored empirically using data gathered on streams throughout Northern California. Figure 9.4 is a plot of canopy closure versus distance from watershed divide for all 1994-1998 sites with reported canopy closures. At a divide distance greater than 70 km, there were no reported canopy closure values greater than 30%, and most were 10% or less. This suggests that 70 km may be the approximate distance from the divide where streams become too wide for streamside vegetation to have an effect on shading. However, the data were from many basins. Moreover, canopy closure was measured and not effective shade. Thus, this distance is considered the theoretical maximum threshold distance. The threshold distance for some basins may be less than the 70 km. The lack of higher canopy values at distances greater than 70 km from the watershed divide may be a result of relatively few canopy closure measurements at greater distances from the divide and the lack of a sampling design. If a curve (curve b in Figure 9.4) is fit to the outer most points, representing the maximum canopy closure potential for a given distance from watershed divide, a threshold distance becomes much more difficult to define. The decision then becomes what is acceptable and what is realistically achievable. More importantly, the threshold distance is based on contemporary canopy levels along streams and rivers in Northern California and may not be representative of historical levels.

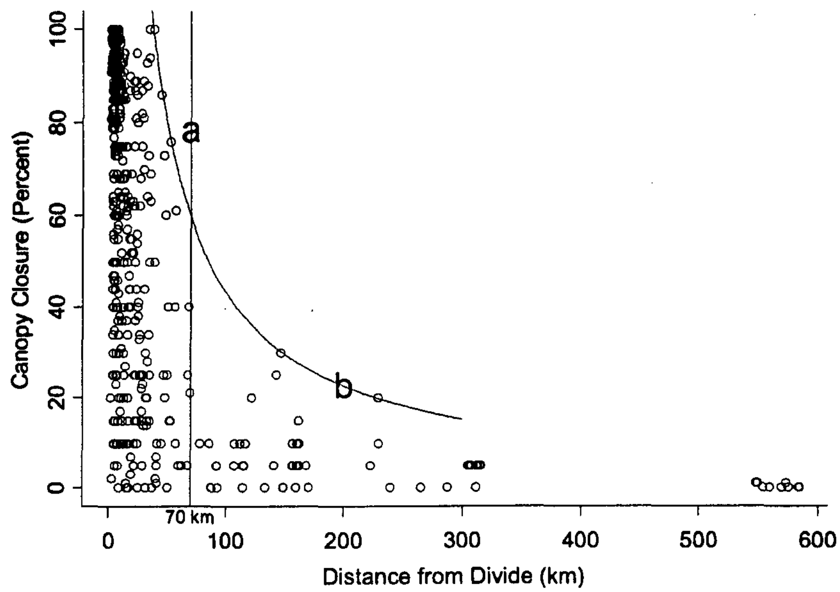


Figure 9.4. Relationship between canopy and distance from watershed divide. The vertical line (a) delineates the theoretical *threshold distance* (70 km) where the stream may be too wide for canopy to influence stream temperature. The curve (b) represents the maximum canopy closure potential a site has at a given distance from watershed divide. Using the points as the only clue to find the threshold distance, 70 km seems like a reasonable choice, but if the curve (b) is appropriate, then defining a threshold might not be recommendable.

Brown and Brazier (1972) found a decline in effectiveness of buffer widths and streamside vegetation with increasing stream size (Figure 9.5). Stream size would correspond to distance from the watershed divide. The shape of the curve in Figure 9.5 is strikingly similar to *curve b* shown in Figure 9.4.

Watershed area is another attribute that will influence channel widths. There may be a watershed area threshold value where channels become too wide to have a significant amount of shade provided by riparian canopy. Figure 9.6 is a plot of canopy closure versus the natural log of watershed area for all 1994-1998 sites with reported canopy closures.

With the exception of two Russian River sites, sites with watershed areas about 63,000 ha or larger had canopy closure values of less than 20%. The Russian River sites had vegetation growing within the bankfull channel and are an exception to this concept. The visually estimated value of 63,000 ha for a watershed area threshold value has similar problems as the distance from watershed divide threshold. This should be viewed as the maximum watershed area threshold. The threshold watershed area value in some basins may actually be less.

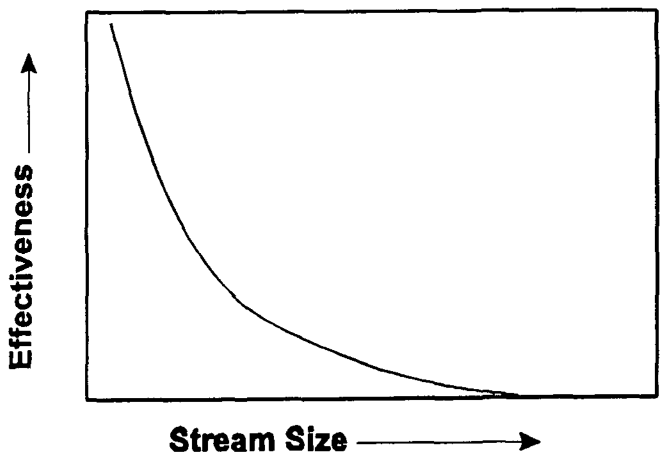


Figure 9.5. Decline in importance of buffer strips (effectiveness) for water temperature control with increasing stream size. Taken from Brown and Brazier (1972).

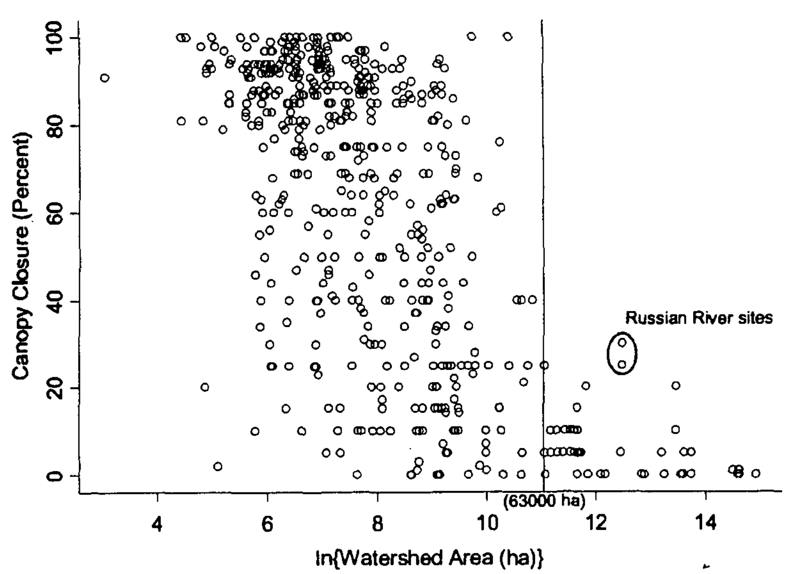


Figure 9.6. Relationship between percent canopy closure and the natural log of watershed area (ha). The vertical line delineates the theoretical *threshold distance* (63,000 ha) where the stream may be too wide for canopy to influence stream temperature. The Russian River sites had vegetation growing in the bankfull channel. Thus, those sites had higher canopy closure values than other large streams.

Watershed area not only provides information on the width of the channel, but also discharge. Flow and canopy interact to influence stream temperature through a simple equation developed by Brown (1969):

$$\Delta T = \frac{A(H_1)}{D}(C)$$

where ΔT is the predicted change in temperature in °F, A is the surface area of the section of stream exposed by riparian vegetation removal, H_1 is the net radiation absorbed by the stream in BTU/ft^2-min, D is the stream discharge in cubic feet per second, and C converts discharge to pounds of water per minute. ΔT is then expressed in BTU/pound of water, which is equivalent to °F.

From the two threshold criteria, stream sites that were small enough to be influenced by canopy closure could be identified. Stream sites that had a distance from watershed divide less the 70 km **and** that had a watershed area less than 63,000 ha were classified as the small-stream group. There were ten sites that had a distance from watershed divide less than 70 km (group minimum was ~52 km) and also had watershed areas greater than 63,000 ha. Additionally, there were two sites that had a distance from watershed divide greater than 70 km and had watershed areas less than 63,000 ha (group minimum was ~52,000 ha). These 12 sites have been classified as too large to have a significant level of canopy from streamside vegetation.

The approach described above is somewhat backwards. A better approach would be to start with the species composition and geometry of riparian vegetation and establish a relationship between maximum potential canopy closure and bankfull width for the existing riparian vegetation. However, the FSP database lacked riparian vegetation data for the stream temperature sites, thus such a relationship could not be established. Instead, the relationship between bankfull width and distance from watershed divide or watershed area was examined to discern if the selected thresholds were reasonable.

A linear regression of the natural log of bankfull width versus the natural log of the distance from watershed divide was fit using the S-PLUS function *lm*. Approximate 95% confidence bands to predict the natural log of bankfull widths for a given natural log of distance from watershed divide was estimated using the S-PLUS function *predict.lm* with the option *se.fit=T*:

$$\hat{b}_d \pm 2\sqrt{r^2 + s.e._d{}^2}$$

where $\hat{b}_d$ is the estimated natural log of bankfull width at a natural log of distance from watershed divide *d*, *r* is the residual scale from the *predict.lm* output; and $s.e._d$ is the estimated standard error for the average $\hat{b}_d$.

Points for the fitted lines were created by fitting $\hat{b}_d$ and the confidence bands to the vector $\bar{d}$, where $\bar{d}$ is an evenly spaced vector on the interval (0,7). These points were transformed to the original scale, by $e^{(x,y)}$, where x is an element of $\bar{d}$ and y is either $\hat{b}_d$ or a corresponding confidence value. Figure 9.7 is a scatter plot of bankfull width versus distance from watershed divide with lines drawn by connecting the points $e^{(x,y)}$, yielding the fitted relationship and the approximate 95% confidence bands for prediction.

The divide-distance-defined threshold of 70 km had a mean bankfull width of 32 m with a 95% confidence band for prediction of a particular bankfull width of 10 m to 100 m. However, there were only 14 points for divide-distance values greater than 70 km, compared to 162 points with distances less than or equal to 70 km. Of the larger divide distance points, 10 were from the mainstem Klamath River, two from the mainstem Eel River, and one each from the Salmon and Trinity Rivers. The two Eel River points have much wider bankfull widths than any of the other sites even though the distance from the watershed divide was less than either the Klamath

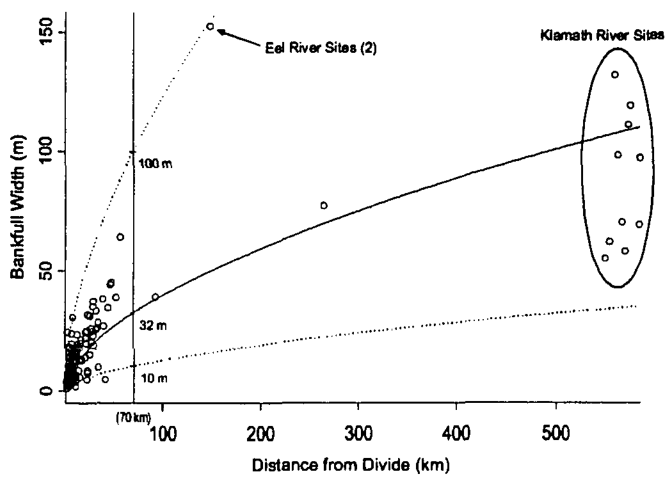


Figure 9.7. Relationship between percent bankfull width (m) and distance from watershed divide (km) with the fitted line (solid line) and the approximate 95% confidence bands for prediction (dotted line). The vertical line delineates the theoretical *threshold distance* (70 km) where the stream may be too wide for canopy to influence stream temperature. The average bankfull width at the threshold distance was 32 m with an approximate 95% confidence interval for predicting bankfull width from a given distance from watershed divide of (10 m, 100 m). The two Eel River sites with high bankfull widths were the only mainstem Eel River sites with reported bankfull widths. All of the points with large distance from watershed divide values were from the mainstem Klamath River.

River or Trinity River sites. The inability of the model to select a well-defined bankfull width given the selected divide-distance threshold is partly due to the large number of different basins used to fit the model. Thus, a single threshold is not a useful assessment tool across all basins. Still, the model indicates that most streams with bankfull widths of 100 m or more would be excluded from the canopy-affected divide-distance group. The intent of this exercise was to remove sites that may be too wide for shade-producing canopy to reach a significant level. It is possible that some sites with bankfull widths slightly greater than 10 m might be excluded, but the low confidence value is due to the high range in Klamath River bankfull widths at large distances from the watershed divide. More bankfull width data is required for each individual basin in order to better define threshold distances.

A model was fit for bankfull width versus watershed area using the same method as the model fit for bankfull width versus distance from the watershed divide. The watershed-area model produced similar results for estimating bankfull width as the divide-distance model. The bankfull width at the threshold watershed area (63,000 ha) had an average of 36 m (compare to 32 m for divide-distance model) and a 95% confidence band for prediction of bankfull width of 13 m to 99 m (Figure 9.8).

Canopy and Stream Temperature Relationships

Three 1998 stream temperature metrics were fit against the reported canopy closure values using the S-PLUS function *lm*. The three stream temperature metrics were (1) the maximum seven-day moving average of the daily average (XYA7DA), (2) the maximum seven-day moving average of the daily

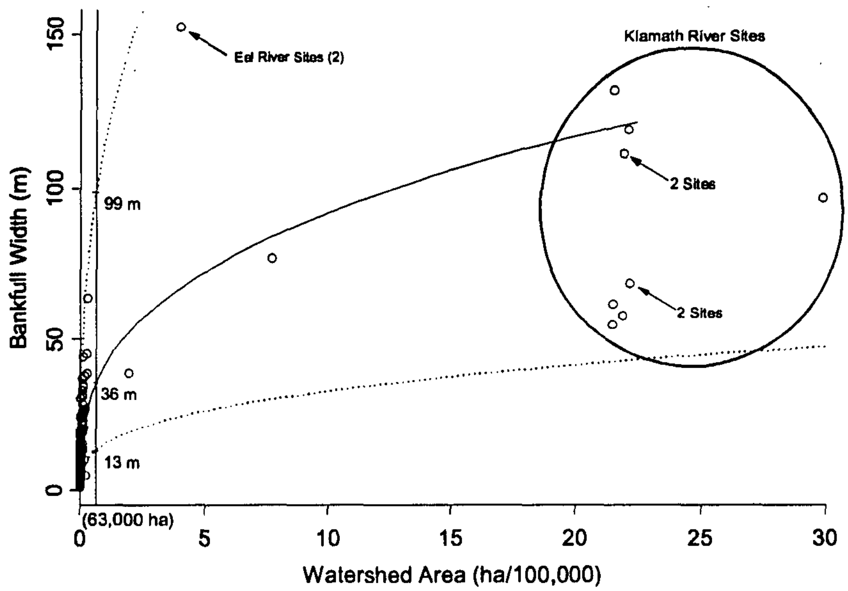


Figure 9.8. Relationship between percent bankfull width (m) and watershed area (ha) with the fitted line (solid line) and the approximate 95% confidence bands for prediction (dotted line). The vertical line delineates the theoretical *threshold distance* (63,000 ha) where the stream may be too wide for canopy to influence stream temperature. The average bankfull width at the threshold distance was 36 m with a approximate 95% confidence interval for predicting bankfull width from a given distance from watershed divide of (13 m, 99 m). The two Eel River sites with the high bankfull widths are the only mainstem Eel River sites with reported bankfull widths. All of the points with large watershed areas (>2,000,000 ha) are from the mainstem Klamath River.

maximum (XYA7DX), and (3) the highest daily maximum stream temperature (XY1DX). R^2 was small for all three regressions (0.232 to 0.286), but the fits were significant ($F = 100$ to 132 on df = 1 and 331, $p \approx 0$) with the average stream temperature for all metrics decreasing with increasing canopy closure. Approximate 95% confidence bands were also fit about the line. From the scatter plot (Figure 9.9) and the low R^2 values, it is apparent that there is a high variability in the temperature metrics for all levels of canopy closure. This is due partly to the myriad of other factors influencing stream temperature and partly to the error in measuring stream-temperature-influencing canopy. The confidence bands fit around the regression lines assumed that there was no error in the canopy values, thus the bands do not necessarily capture the true average. However, the true variability is probably lower than the reported data, thus the confidence bands about the relationship using "true" canopy values is probably much tighter.

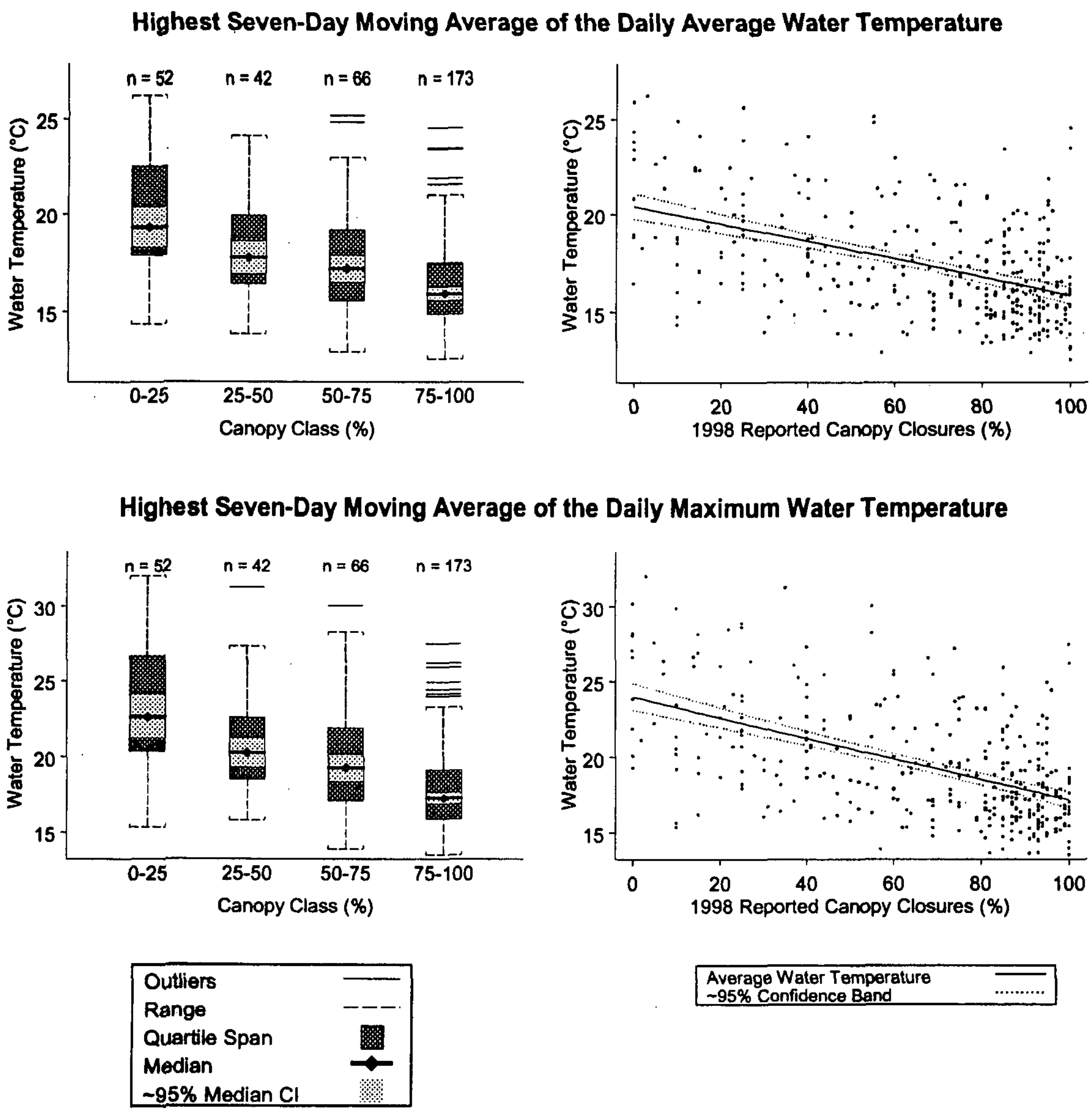


Figure 9.9. Box plot and scatter plot with fitted regression lines for three different stream temperature metrics against canopy. For box plots, canopy values were grouped into four canopy classes. Box plot outliers are defined as 1.5 times the inter-quartile range. The solid regression line is the average stream temperature metric for a given canopy closure, and the dotted lines are 95% confidence bounds for the average temperature values.

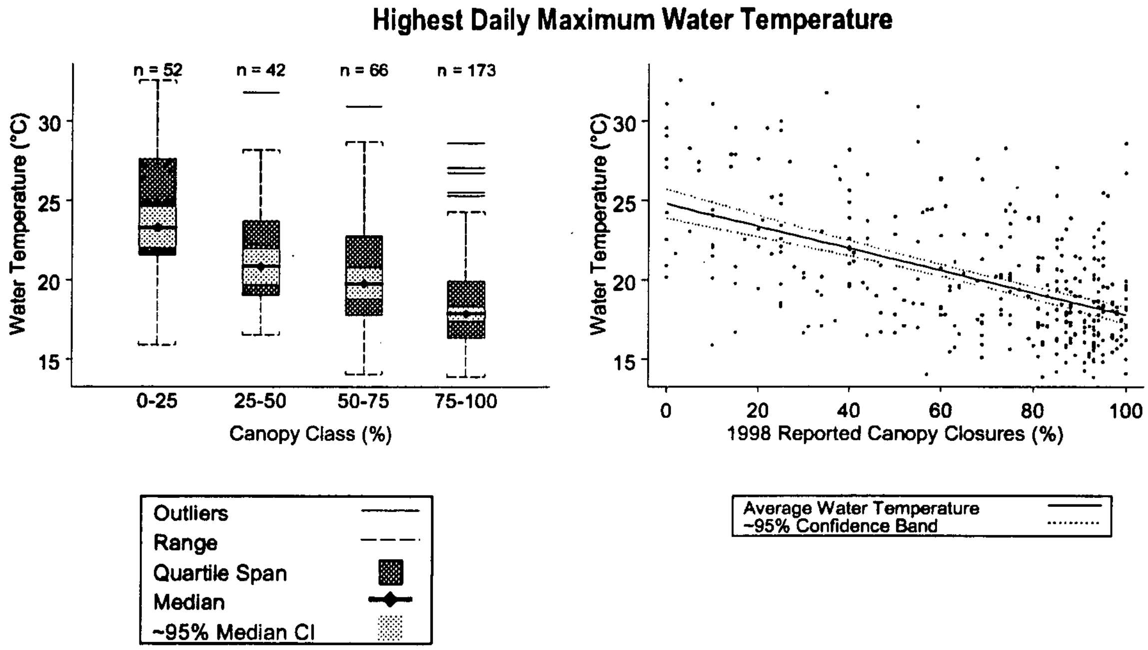


Figure 9.9. (continued)

Because of the uncertainty in the canopy data, the canopy values were combined into 25 percent ranged bins: the bin groups were 0 - 24%, 25 - 49%, 50 - 74%, and 75 - 100. Box plots were created for (1) the highest seven-day moving average of the daily average temperature, (2) the highest seven-day moving average of the daily maximum stream temperature, and (3) the highest daily maximum stream temperature by canopy class using the S-PLUS function *boxplot*. The median and the approximate 95% confidence band for the median of each canopy group was estimated with the *boxplot* function.

The medians for each group for all temperature metrics showed a decreasing trend with increasing canopy (Figure 9.9). The 95% confidence intervals about the medians for the 75 - 100% group did not overlap with and were lower than all other intervals for all temperature metrics (Table 9.1). Although the medians for the 50 - 74% group were lower than the 25 - 49% group, the median confidence intervals overlapped substantially and might not be different for all temperature metrics. The medians for the 50 - 74% group were higher than the 75 - 100% group but the median confidence interval overlapped a minimal amount for XYA7DA. The intervals about the other two metrics between the 50 - 74% and 75 - 100% groups did not overlap. The medians of the three temperature metrics for the 75 - 100% group were lower than the other canopy groups.

A Kruskal-Wallis rank sum test also revealed significant differences in each of the three temperature metrics at various canopy classes. A Welch Modified Two-Sample t-Test for Unequal Variances indicated that the three temperature metrics were significantly different at the $p = 0.01$ level except for the two middle canopy classes, i.e., 25 - 49% and 50 - 74%.

Table 9.1. Median Values and Approximate 95% Confidence Intervals about the Median by Canopy Group for Three Different 1998 Stream Temperature Metrics.

		Canopy Group			
Temperature Metric	**Statistic**	0 - 24%	25 - 49%	50 - 74%	75 - 100%
	Upper CI[4]	20.30°C	18.56°C	17.82°C	16.20°C
XYA7DA[1]	Median	19.29°C	17.70°C	17.12°C	15.89°C
	Lower CI	18.27°C	16.8°C	16.43°C	15.59°C
	Upper CI	24.00°C	21.27°C	20.19°C	17.65°C
XYA7DX[2]	Median	22.64°C	20.27°C	19.26°C	17.27°C
	Lower CI	21.28°C	19.28°C	18.32°C	16.88°C
	Upper CI	24.65°C	21.99°C	20.76°C	18.32°C
XY1DX[3]	Median	23.34°C	20.85°C	19.79°C	17.89°C
	Lower CI	22.03°C	19.71°C	18.82°C	17.46°C

[1]XYA7DA = Highest Seven-Day Moving Average of the Daily Average Temperature
[2]XYA7DX = Highest Seven-Day Moving Average of the Daily Maximum Stream Temperature
[3]XY1DX = Highest Daily Maximum Stream Temperature
[4]CI = approximate 95% confidence interval

NOTE: The highest canopy group of 75 - 100% had statistically lower medians than all other groups for all metrics; there was no overlap in confidence intervals. With the exception of a 0.29 °C overlap between median confidence intervals for the 0 - 25% and 25 - 49% groups, the lowest canopy group had statistically higher median stream temperatures than the other groups.

In Figure 9.9 box plots and scatter plots are displayed side by side. Displayed in this manner, it is clear that there was a trend in higher canopy values or classes resulting in lower stream temperatures, even though the correlation was not high. Much of the variability will be taken into account by other variables that will be explored in the stream temperature modeling chapter (Chapter 10).

Canopy and the Zone of Coastal Influence

The cooling influence of coastal air currents has been shown to influence water temperatures. Does canopy influence stream temperatures in streams inside or outside of the zone of coastal influence (ZCI)? Sites were stratified by whether they fell inside or outside of the ZCI. Sites were then grouped by canopy class. Figure 9.10 shows that there was a significant difference in the highest 1998 daily maximum stream temperature for the 0 - 24% canopy class, with sites outside of the ZCI (encoded as zero) being warmer than sites inside the ZCI. The mean for the 0-24% class outside the ZCI was above the 24°C acute thermal exposure threshold minus a 2°C safety margin (Coutant, 1972). In all canopy classes the mean XY1DX was higher for the ZCI-out group than the ZCI-in group, although not significantly different. Figure 9.10 illustrates that even within the cooler ZCI, stream temperatures decrease with increasing canopy. While air temperatures may be cooler in the ZCI, solar heating still occurs while skies are clear or overcast.

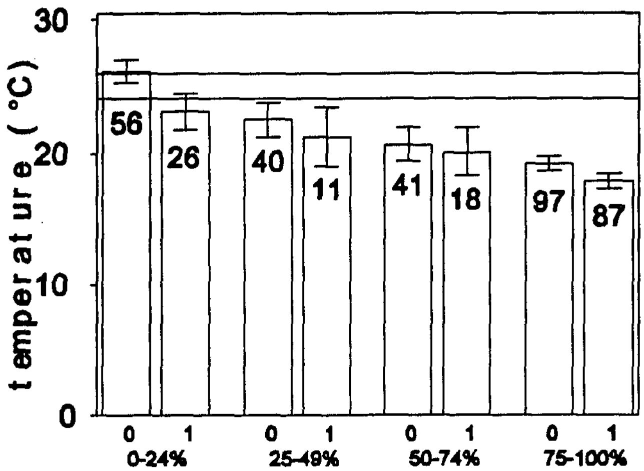


Figure 9.10. Highest 1998 daily maximum stream temperature for sites in four different canopy classes, grouped by whether the site was outside (0) or inside (1) the zone of coastal influence. Horizontal reference lines are drawn at 24°C and 26°C. Number of sites in each group are shown below error bars.

The highest daily maximum stream temperature for sites with canopy greater than or equal to 75% was plotted against $\log_{10}$ divide distance. Sites were stratified by whether they were inside or outside the zone of coastal influence (ZCI). Figure 9.11 shows plots for two HUCs that had adequate representation of sites with canopy ≥75% and sites inside and outside of the ZCI. These HUCs are Mad River - Redwood Creek and Big-Navarro-Garcia. Fully canopied sites inside and outside the ZCI both showed increases in stream temperature with increasing distance from the watershed divide. However, the sites inside the ZCI were 1°C to 2°C lower at similar divide distances than sites outside of the ZCI.

The rate of increase in stream temperature with increasing downstream distance was similar in both the ZCI-out and ZCI-in sites. The two linear regression lines in both HUCs were nearly parallel. Even with high canopy cover, sites inside the ZCI continued to increase in temperature, although the temperatures remained lower than the sites outside the ZCI.

The regression lines shown for the two HUCs (Figure 9.11) could be considered analogous to the "trend lines" developed for single streams in Oregon by Zwieniecki and Newton (1999), although at a much larger HUC scale. It is conceivable and highly desirable that HUC-level or watershed-level regression lines be developed for other drainages that could be used as assessment tools for determining what stream temperatures are achievable under fully canopied conditions. This would require a more integrated stream temperature monitoring program with a well thought out sampling design to provide adequate sample sizes at various divide distances. Additionally, more complete and consistent canopy measurements collected along a thermal reach would need to be part of such a monitoring program.

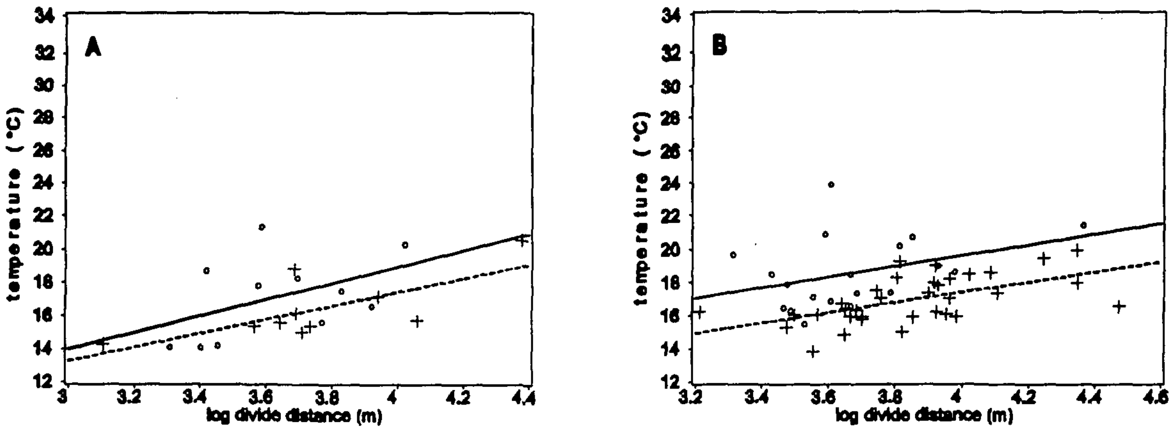


Figure 9.11. Variation in the highest 1999 daily maximum stream temperature with $\log_{10}$ distance from the watershed divide for sites with canopy values greater than or equal to 75%. Sites in the Mad River - Redwood Creek (A) and Big-Navarro-Garcia River (B) hydrologic units are presented. Linear regression lines were fit to sites outside (open circles) and inside (crosses) the zone of coastal influence. Solid lines and dashed lines represent linear regressions for sites outside and inside the ZCI, respectively.

Summary

Canopy values were not well distributed. There were more sites with canopy values in the 0% to 30% bin classes and in the 70% to 100% bin classes. Sites with canopy data were not evenly distributed geographically in 1994-1997. In 1998, sites were more evenly distributed across the study area, thus making 1998 more useful for regional analyses.

Plotting canopy data versus divide distance and watershed area, theoretical maximum thresholds of 70 km and 63,000 ha appear to be plausible for determination of the point where streams may become too wide for streamside vegetation to provide adequate shading. However, these thresholds may vary by basin. The authors do not imply that retention of stream-side vegetation is not important at divide distances greater than the theoretical maximum. We simply attempt to approximate the divide distance at which stream-side vegetation may no longer play a role in mediating stream temperature. There are other important reasons for maintaining stream-side vegetation, such as potential large wood input, sediment retention, and wildlife habitat.

There was a wide range in canopy values in streams at divide distances less than or equal to 70 km and watershed areas less than or equal to 63,000 ha. Despite the diversity of methodologies used to estimate canopy, three stream temperature metrics showed reasonably good response to varying canopy levels. Much of the 'noise" in the temperature-canopy relationship may be due to inconsistent protocols. The variability in stream temperatures due to other independent variables are taken into account in Chapter 10, Modeling.

Sites inside and outside the ZCI with canopy greater than or equal to 75% showed increasing stream temperatures with an increase in distance from the watershed divide. The ZCI-in sites were generally 1 °C to 2 °C cooler than ZCI-out sites, at similar divide distances. The rate of longitudinal temperature increase for ZCI-in and ZCI-out sites with full canopy were very similar (nearly parallel regression lines in Figure 9.11).

While streams that originate in the ZCI and remain within the ZCI along their length exhibit cooler temperatures than those outside the ZCI, it would still be advantageous to maintain adequate canopy. Even within the ZCI, if adequate canopy is not maintained on streams, solar radiation can counteract the cooling influence of coastal air temperatures. Maintaining adequate canopy will provide lower temperatures on both ZCI-in and ZCI-out streams. A goal should be to maximize the total length of low-gradient portions of streams that are potentially suitable for coho salmon by maintaining suitable temperatures in the lower reaches. While all streams tend to come into equilibrium with air temperature along their longitudinal profiles, the downstream distance at which streams approach this equilibrium can be extended by reducing solar heating by maintenance of adequate riparian canopy cover.

While the California Forest Practice Rules require a minimum of 50% canopy retention along Class I and II streams, a random survey of timber harvest plans found that canopy ranged from 74% to 79% (MSG, 1999). In the present study sites located at distances less than the divide-distance-derived and watershed-area-derived threshold distance had canopy values ranging from 0% to 100%. This points out a potential disparity in the way canopy is measured. For compliance purposes canopy is measured in the watercourse and lake protection zone (WLPZ) prior to and following timber harvest. Canopy in the present study was measured in the thalweg of the stream. The objectives and the aquatic resource of concern for why canopy is being assessed should drive the way (method) in which canopy is measured and where (location) it is measured.

To better discern threshold distances and stream temperature differences between canopy classes, a consistent protocol is needed for estimating canopy along thermal reaches above each temperature monitoring site. Additionally, estimates of bankfull width at all temperature monitoring sites would greatly facilitate development of more meaningful threshold distances in a more direct fashion rather than via the more circuitous method applied in this chapter.

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).

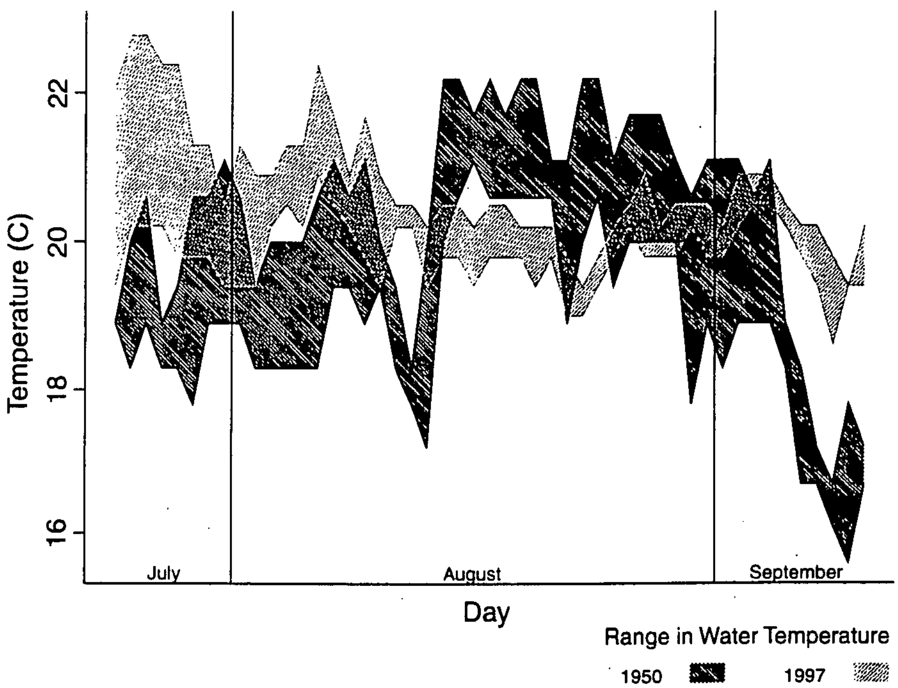


Figure 11.1. Comparison of daily maxima and minima Eel River water temperatures (°C) measured at Fernbridge, CA in 1950 and 1997 from mid-July through mid-September.

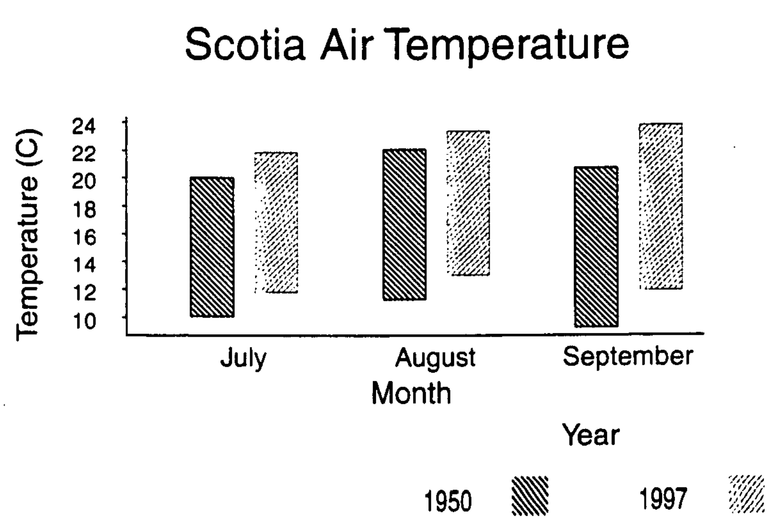


Figure 11.2. Comparison of air temperature for July, August, and September at Scotia, CA in 1950 and 1997. The tops of the bars indicate the average monthly maxima, while the bottoms represent average monthly minima.

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).

Date	Time	Place	Temperature (°C) 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) 1938 H20	1938 Air	1993 H20	1993 Air	1994 H20	1994 Air	1995 H20	1995 Air	1996 H20	1996 Air	1997 H20	1997 Air	1998 H20	1998 Air	Dist (m)	Dir
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

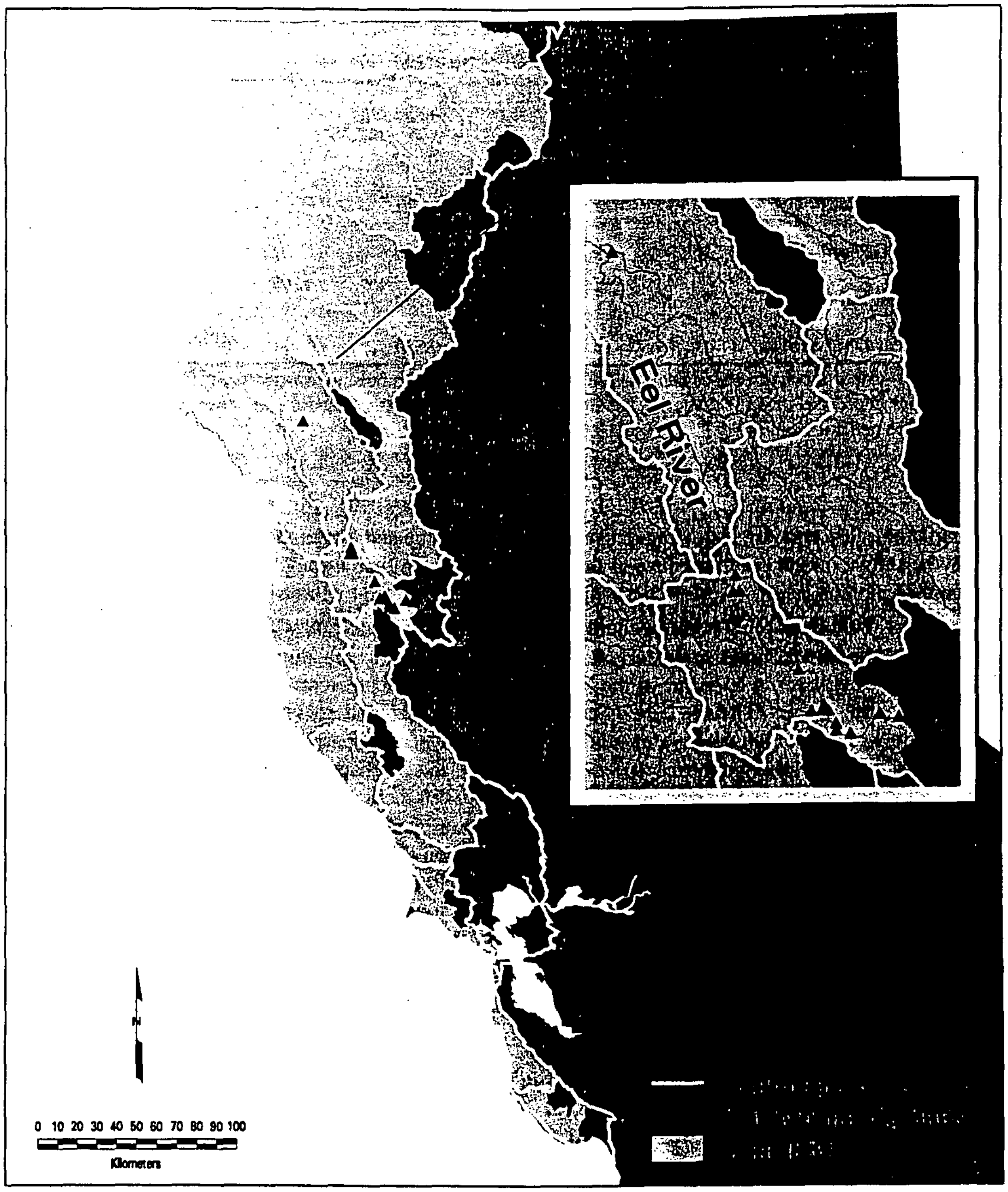


Figure 11.3. Location of PG&E Potter Valley Project stream temperature monitoring sites.

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.

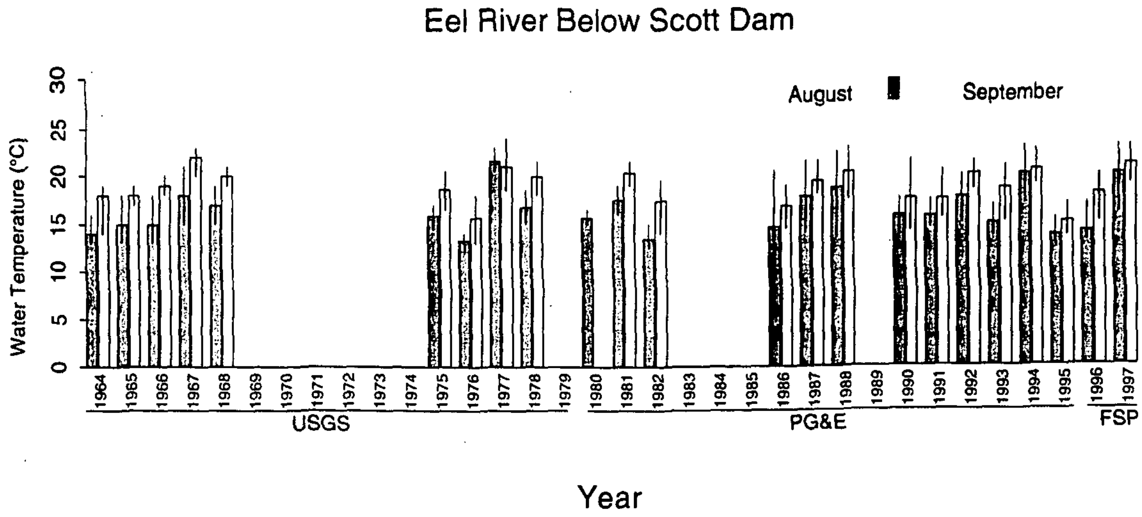


Figure 11.4. Comparison of historical USGS and PG&E monthly average stream temperature data with more recent Forest Science Project data during August and September. The site was located on the Eel River below Scott Dam, near Potter Valley, CA. Vertical lines represent the range in daily minimum and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

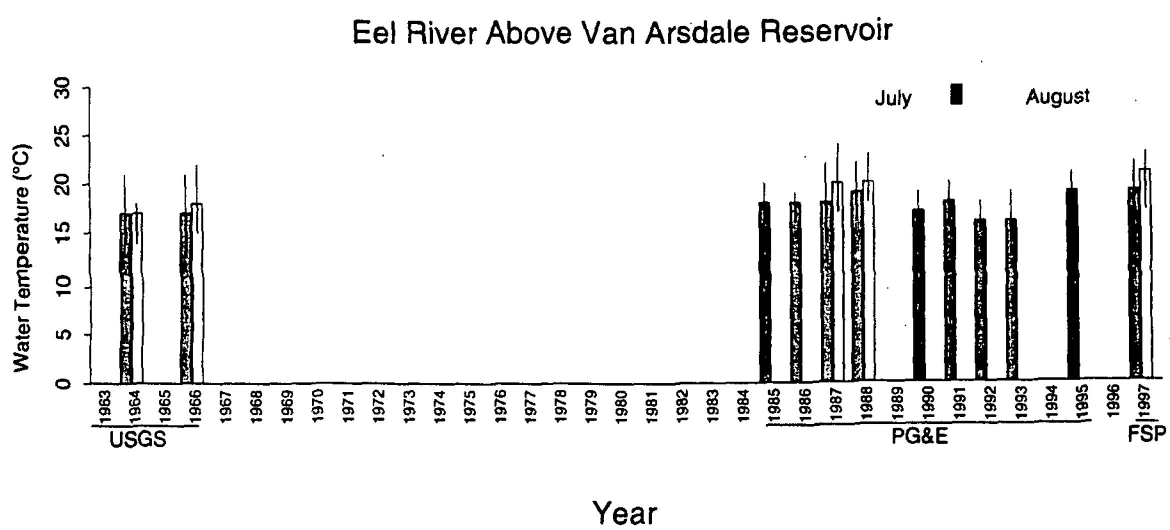


Figure 11.5. Comparison of historical USGS and PG&E monthly average stream temperature data with more recent Forest Science Project data during July and August. The site was located on the Eel River above Van Arsdale Reservoir. Vertical lines represent the range in daily minimum and maximum temperatures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

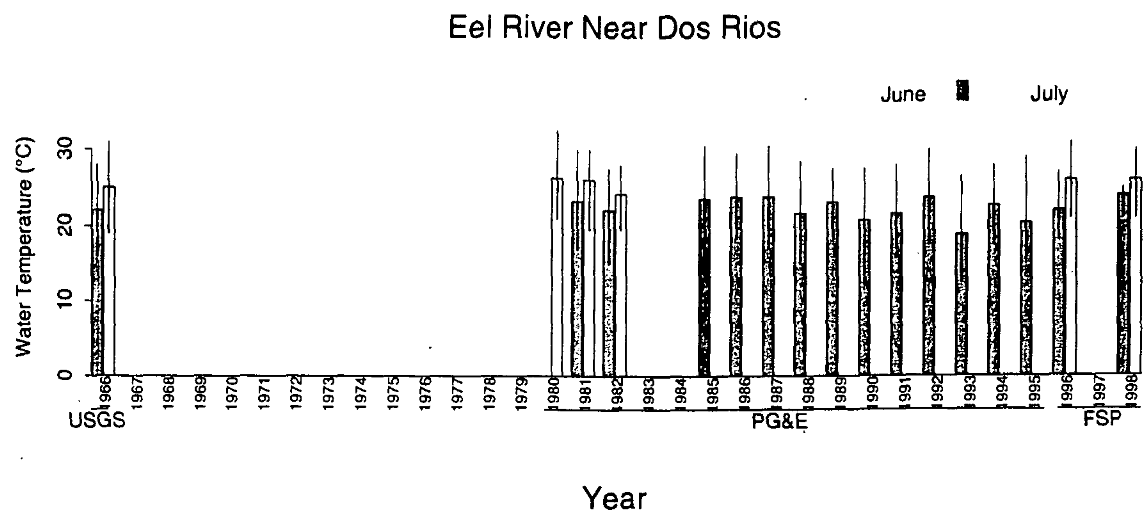


Figure 11.6. Comparison of historical USGS and PG&E monthly average stream temperature data with more recent Forest Science Project data during June and July. Location is on the Eel River near Dos Rios, CA. Vertical lines represent the range in daily minimum and maximum temperatures for each month.

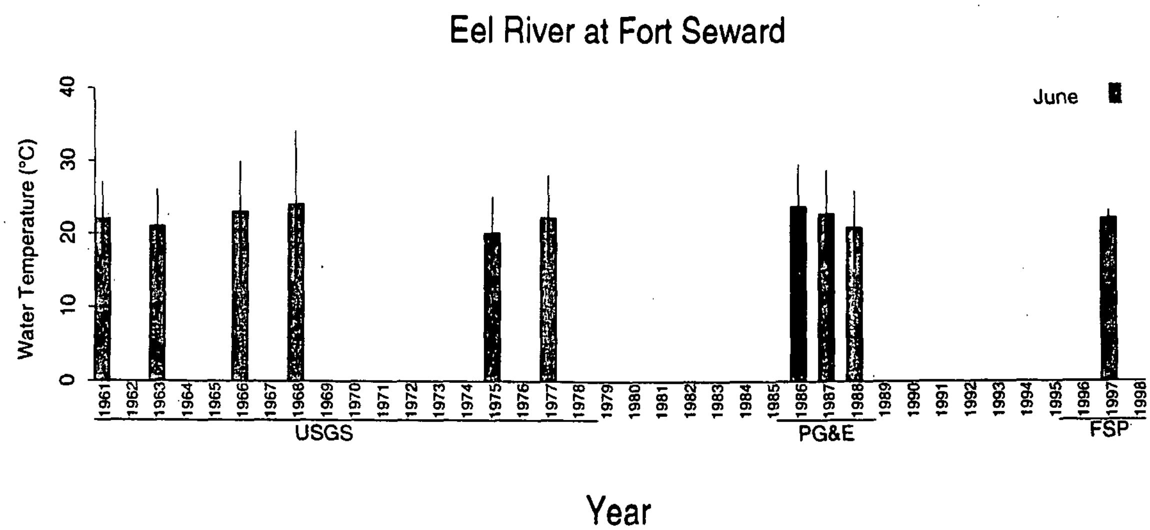


Figure 11.7. Comparison of historical USGS and PG&E monthly average stream temperature data with more recent Forest Science Project data during the month of June on the Eel River at Fort Seward, CA. Vertical lines represent the range in daily minimum and maximum temperatures for each month.

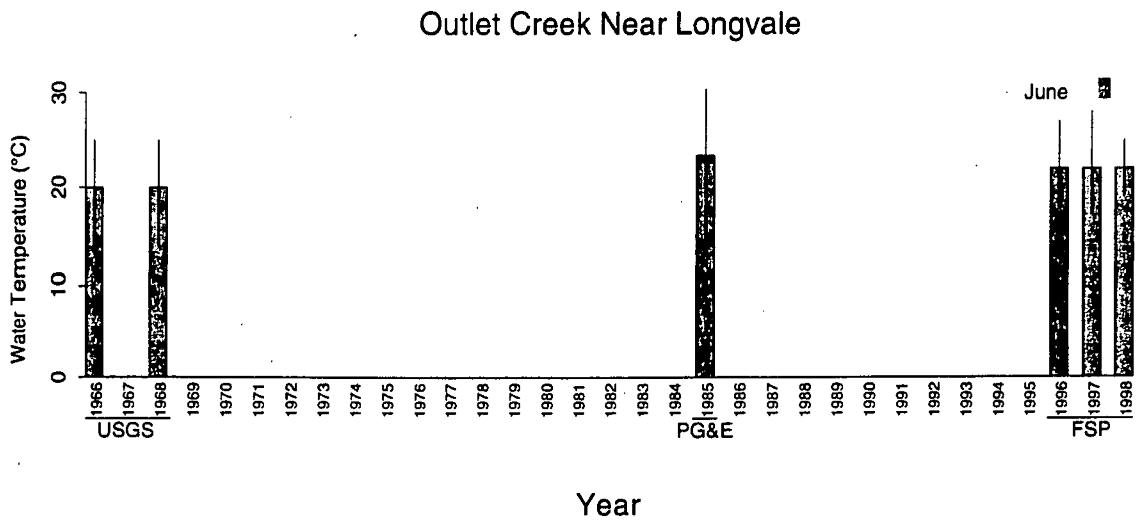


Figure 11.8. Comparison of historical USGS and PG&E monthly average stream temperature data with more recent Forest Science Project data during June for the site at Outlet Creek near the Longvale, CA. Vertical lines represent the range in temperatures for each month.

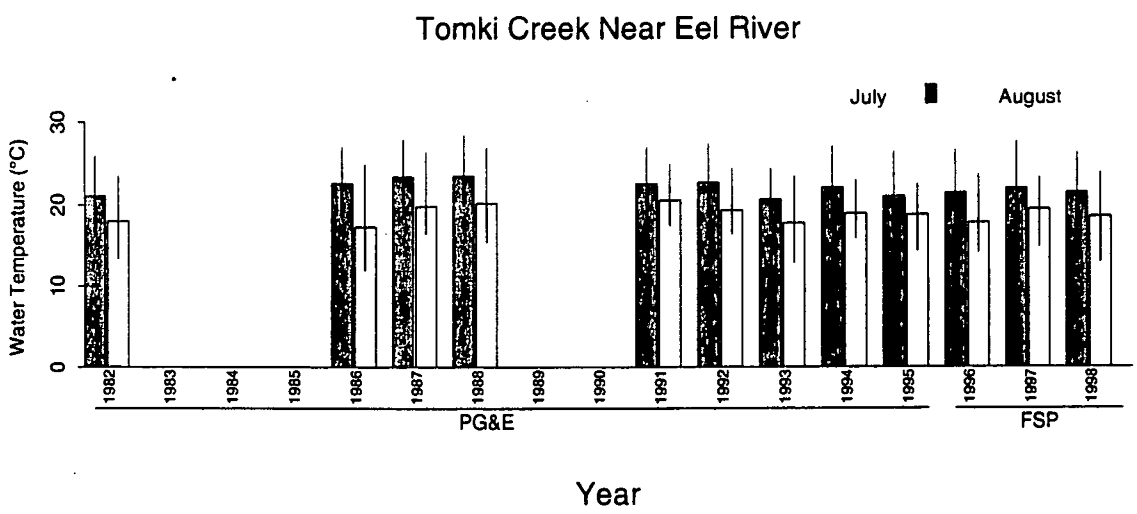


Figure 11.9. Comparison of historical PG&E monthly average stream temperature data with more recent Forest Science Project data during July and August at Tomki Creek near the Eel River. Vertical lines represent the range in temperatures for each month.

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.

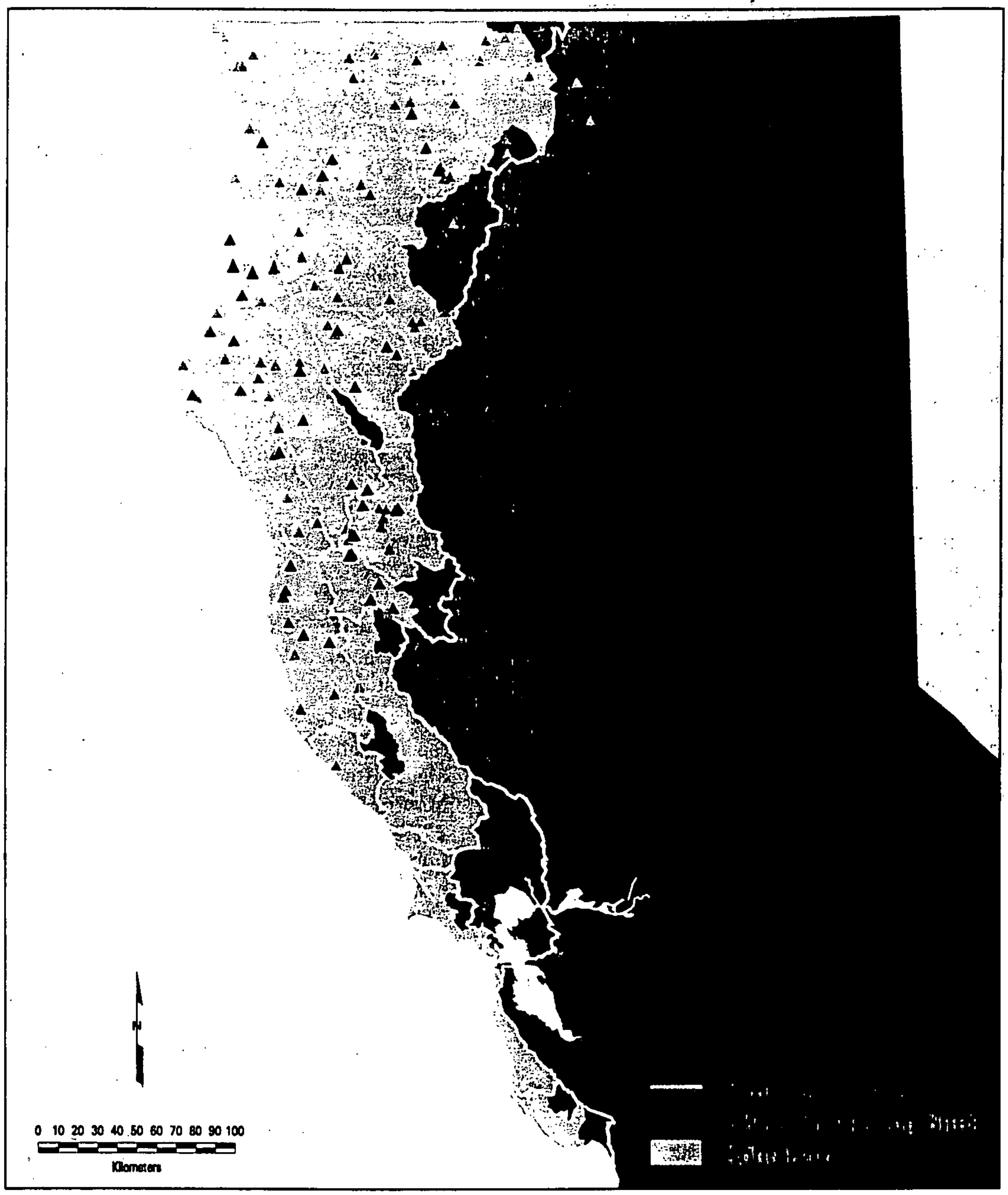


Figure 11.10. Location of USGS sites that were compared to more recent FSP stream temperature monitoring sites. Dark triangles (46 sites) represent USGS-FSP comparisons. Lighter triangles represent USGS sites with historical data available but no matching FSP site.

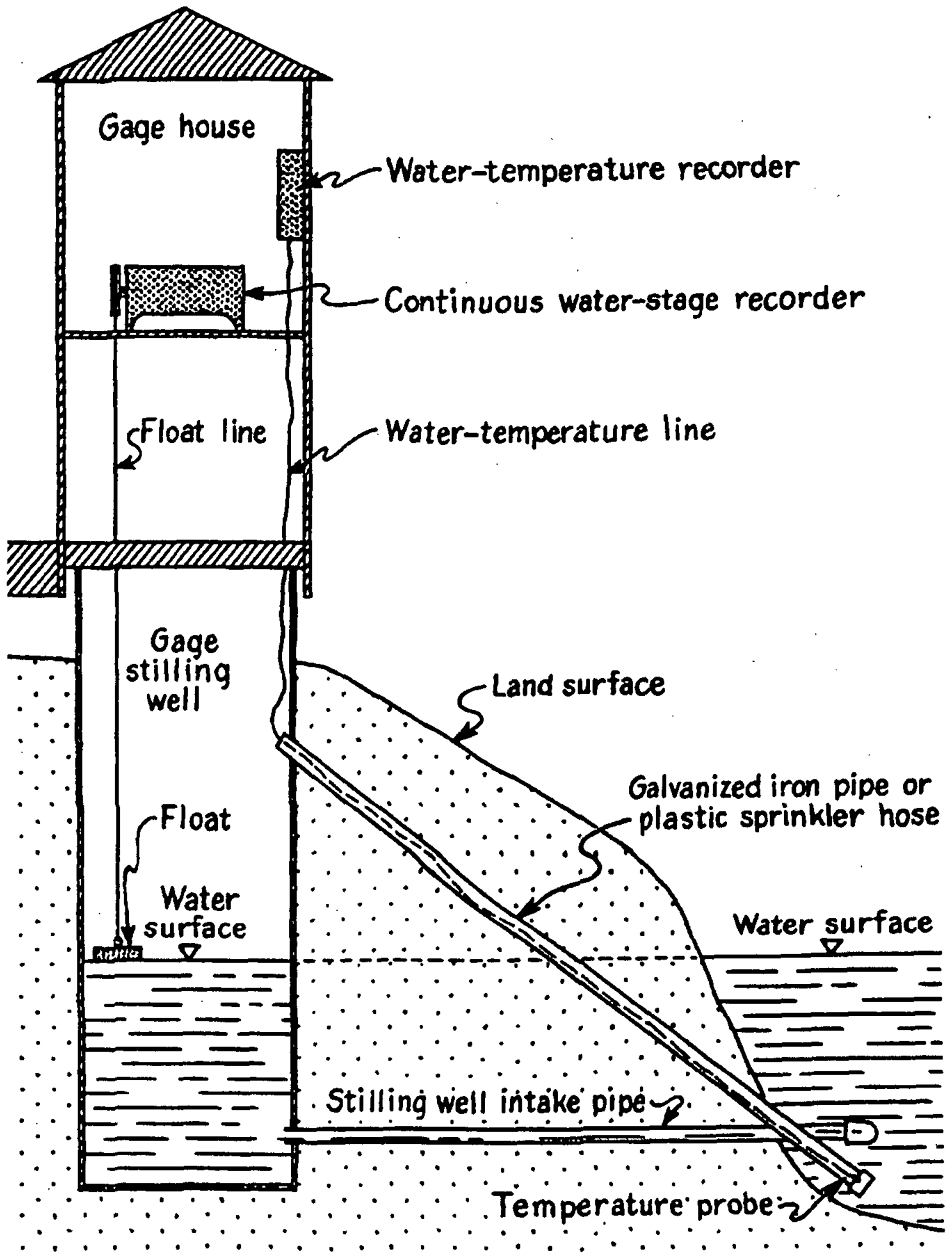


Figure 11.11. Diagram of typical USGS gaging station where both stage and water temperature are recorded. Taken from Blodgett (1970).

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.

EXTREMES. - 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.

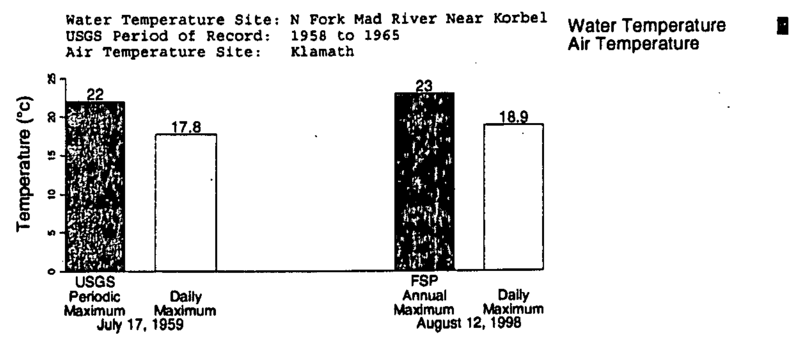


Figure 11.12. Comparison of yearly maximum stream temperatures at a historical USGS site and a more recent FSP site located on the North Fork of the Mad River near Korbel, CA in the Mad River Basin. The FSP site was located 1700 m downstream from the USGS site.

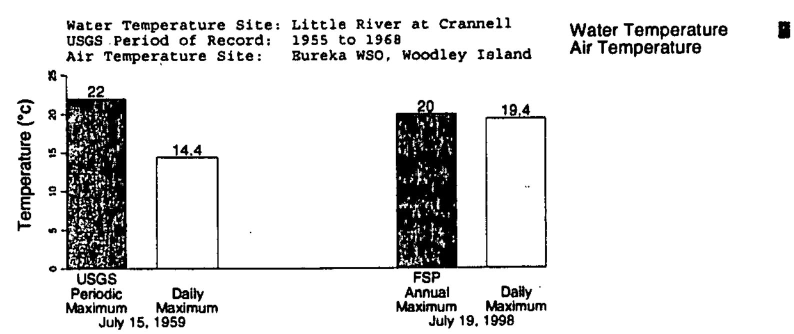


Figure 11.13. Comparison of yearly maximum stream temperatures at a historical USGS site and a more recent Forest Science Project site located in the Little River near Crannell, CA. The FSP site was located 110 m downstream from the USGS site.

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.

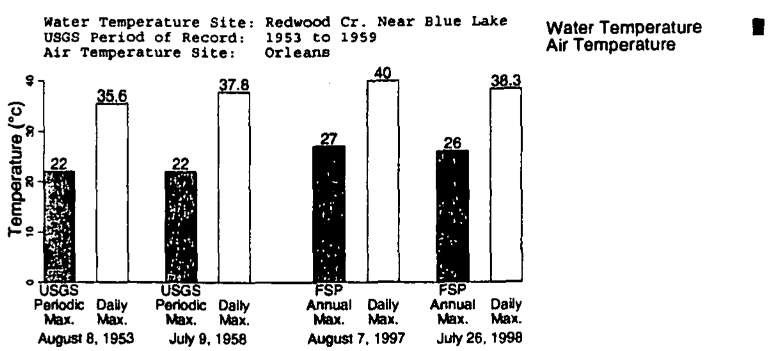


Figure 11.14. Comparison of yearly maximum stream temperatures at a historical USGS site and a more recent Forest Science Project site located in Redwood Creek near Blue Lake. The FSP site was located 30 m upstream from the USGS site.

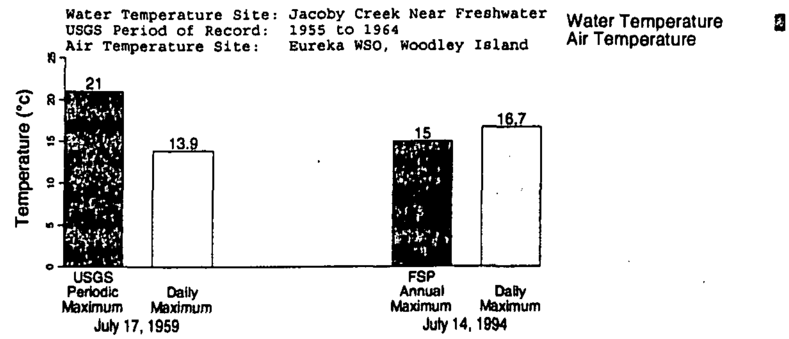


Figure 11.15. Comparison of maximum stream temperatures at a historical USGS site and a more recent FSP site on Jacoby Creek near Freshwater, CA. The FSP site was located 1060 m downstream from USGS site.

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.

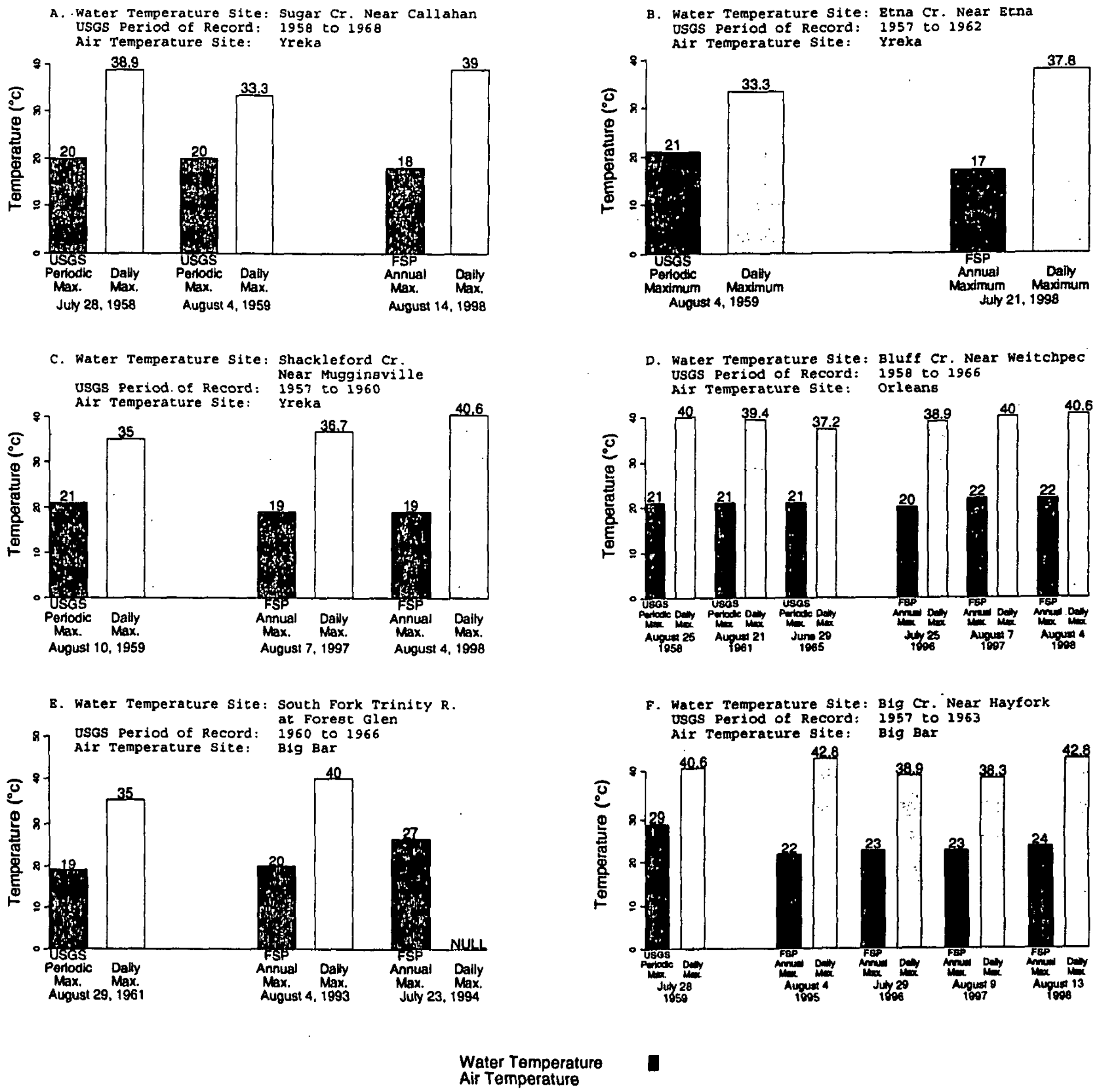


Figure 11.16. Comparison of maximum stream temperatures at historical periodic USGS sites and more recent continuous FSP sites located in the Klamath River Basin. The nearby FSP site was located A) 30 m upstream, B) 2200 m upstream, C) 1320 m upstream, D) 1420 m downstream, E) 740 m downstream, and F)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

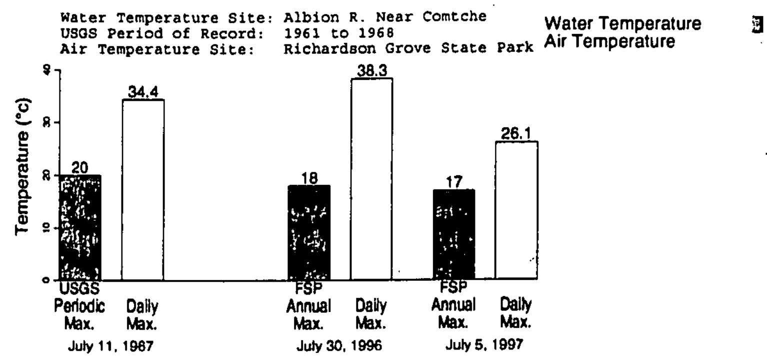


Figure 11.17. Comparison of maximum stream temperatures at historical USGS sites and more recent Forest Science Project sites located in the Albion River Basin. Nearest FSP site was located 1070 m upstream from the USGS site.

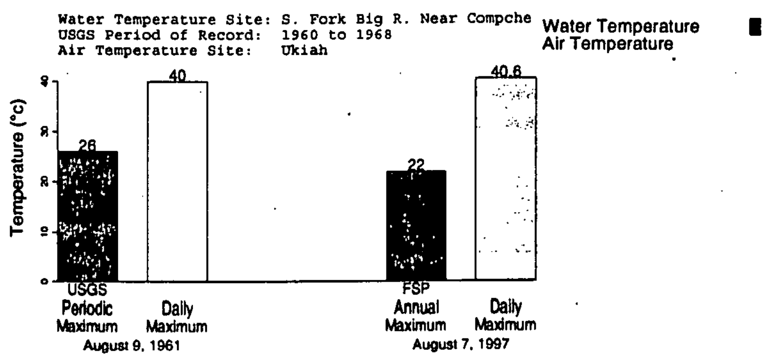


Figure 11.18. Comparison of maximum stream temperatures at a historical USGS periodic site and a more recent Forest Science Project site located on the South Fork of the Big River near Comtche, CA. The FSP site was located 490 m upstream from the USGS site.

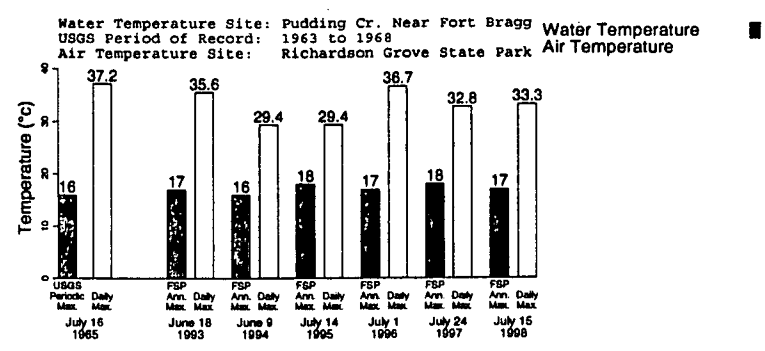


Figure 11.19. Comparison of maximum stream temperatures at a historical USGS site and a more recent Forest Science Project site located on Pudding Creek near Fort Bragg, CA. The nearest FSP site was located 1320 m downstream from the USGS site.

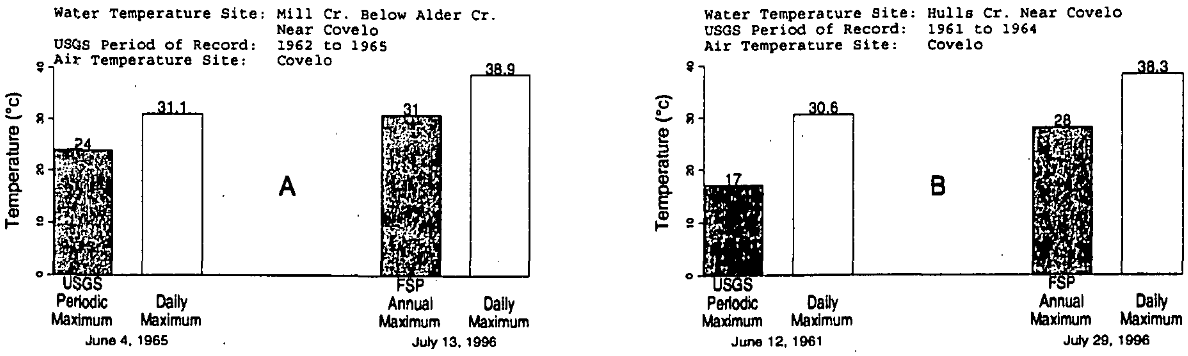
Eel River Basin

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.



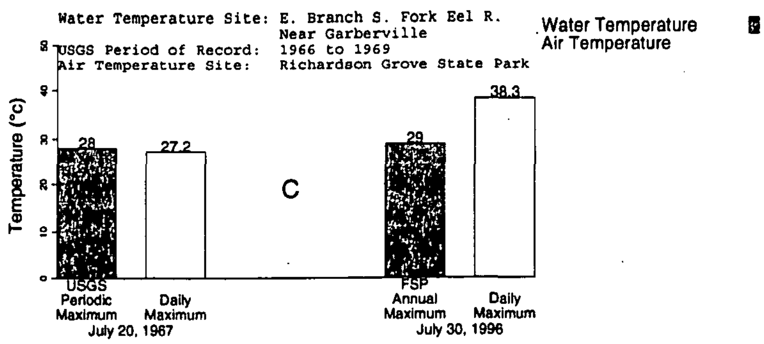


Figure 11.20. Comparison of maximum stream temperatures at historical USGS sites and more recent Forest Science Project sites in the Eel River Basin. Nearest FSP site was located (A) 1330 m downstream, (B) 470 m downstream, and (C) 880 m downstream from the USGS site.

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.

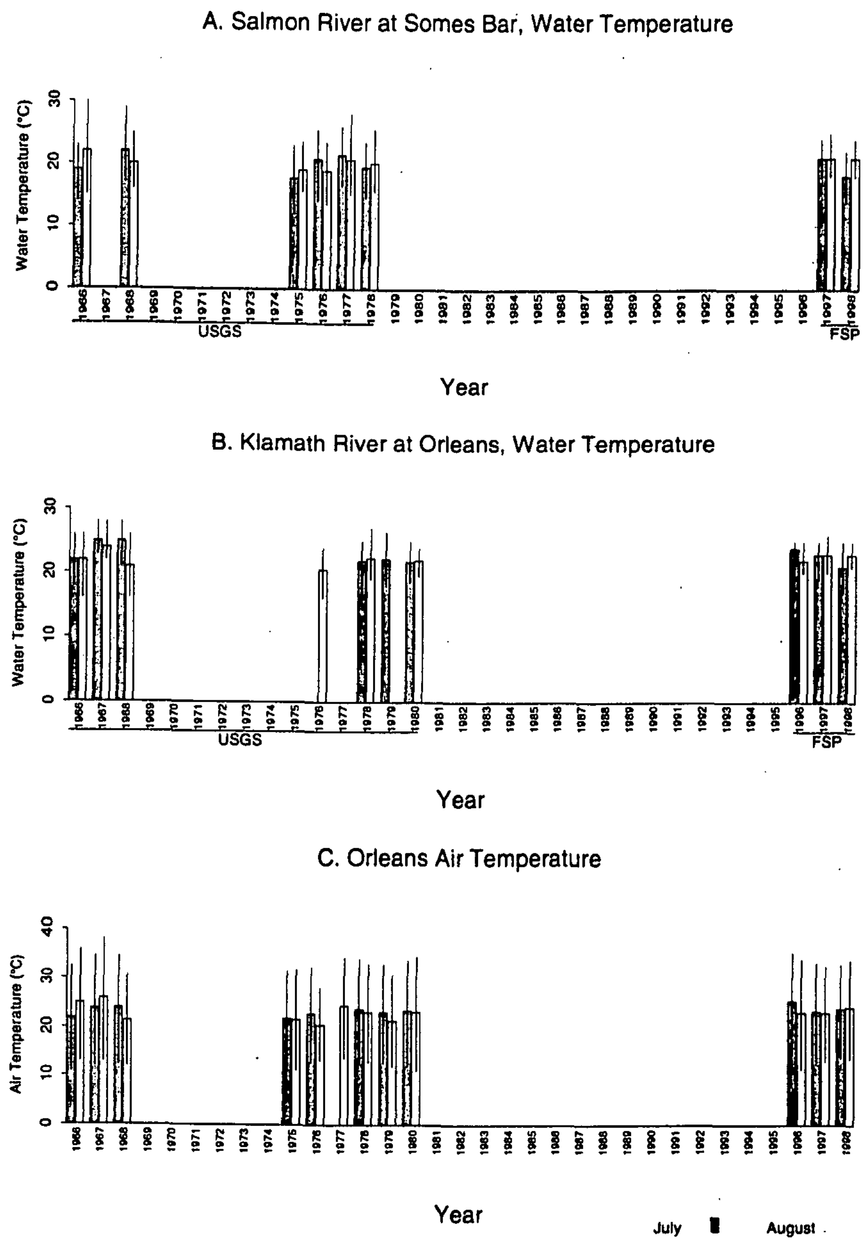


Figure 11.21. Comparison of historical USGS monthly average stream temperature and more recent FSP data for Klamath River Basin sites. Nearby FSP site on the Salmon River (A) was 70 m downstream from the USGS site and on the Klamath River (B) was 470 m downstream. NOAA air temperature site (C) in Orleans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

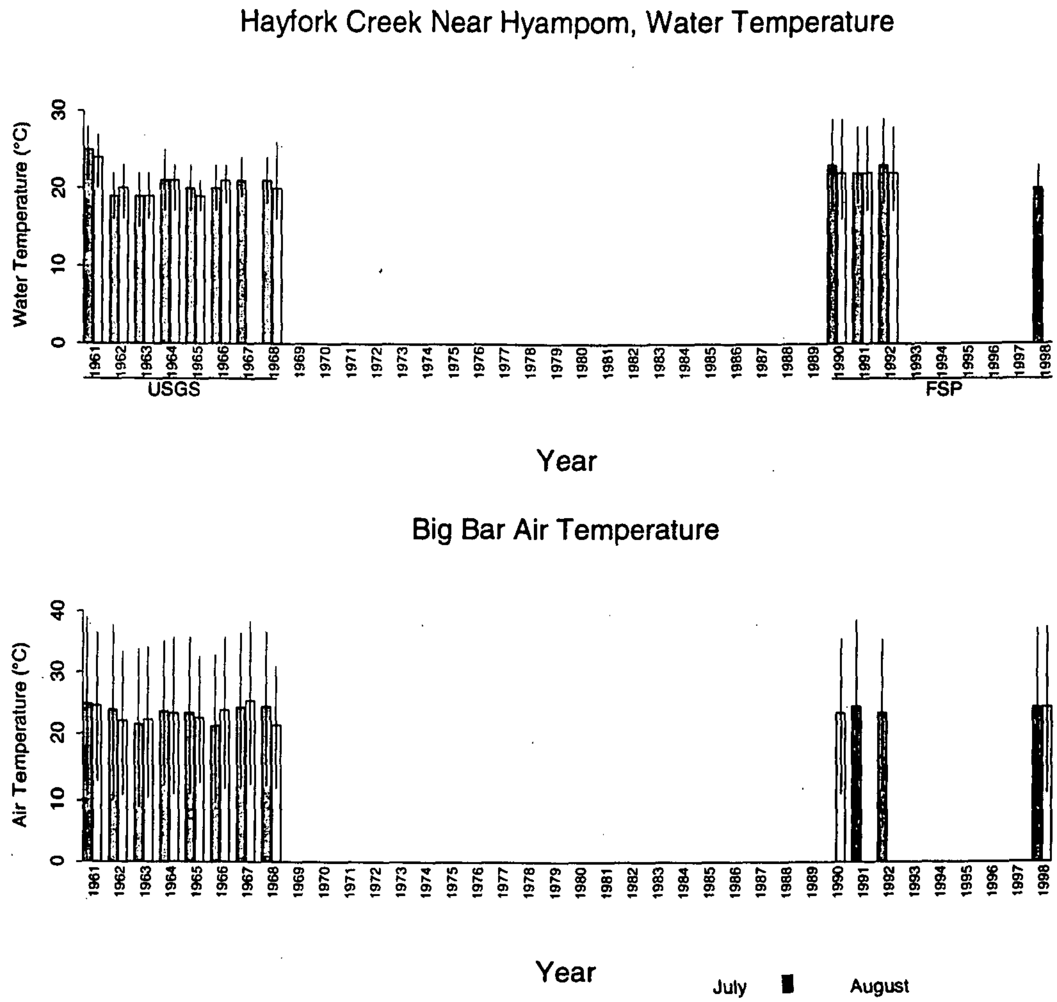


Figure 11.22. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for two sites located in the Klamath River Basin. Nearest FSP site on Hayfork Creek (top) was 1500 m downstream from USGS site. Air temperature was measured at NOAA station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

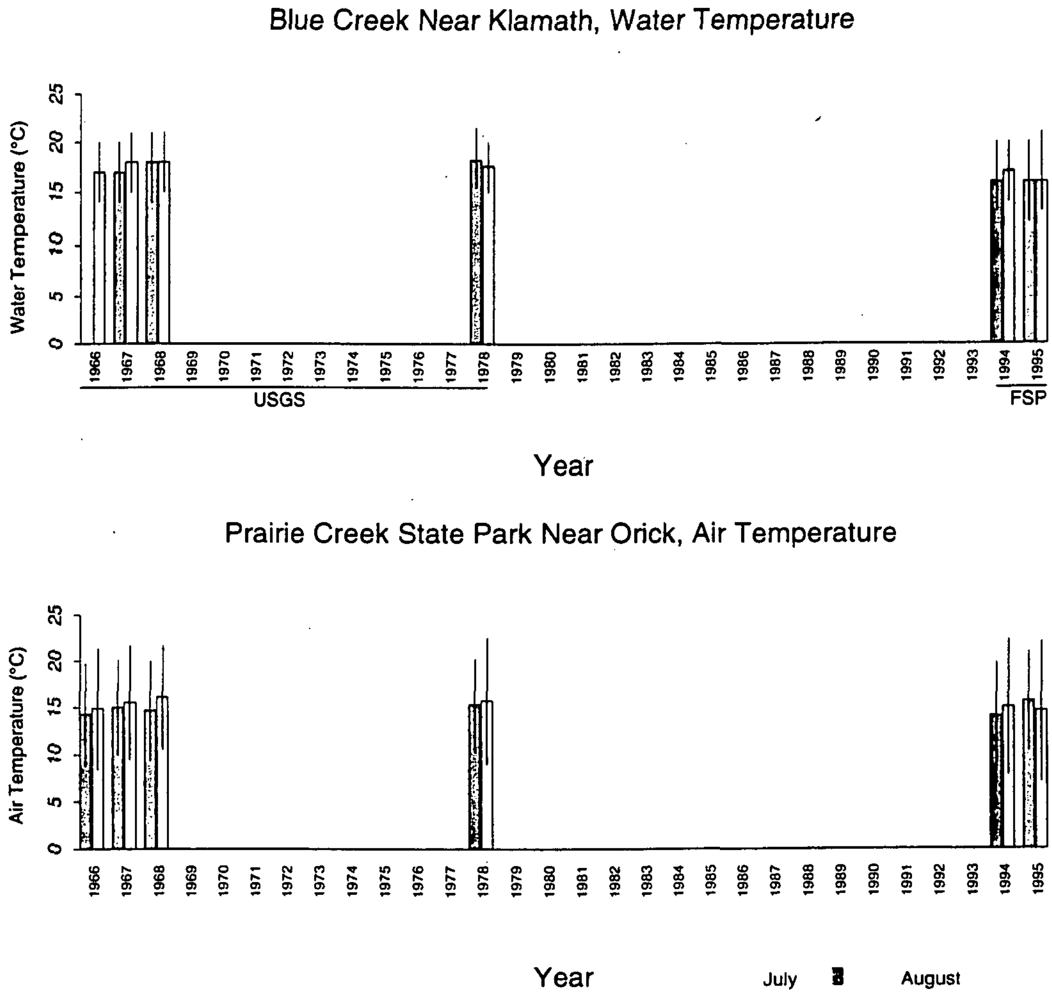


Figure 11.23. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for a site located in the Klamath River Basin. Nearby FSP site on Blue Creek (top) was 1800 m downstream of the USGS site. Air temperature (bottom) was measured at NOAA station 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.

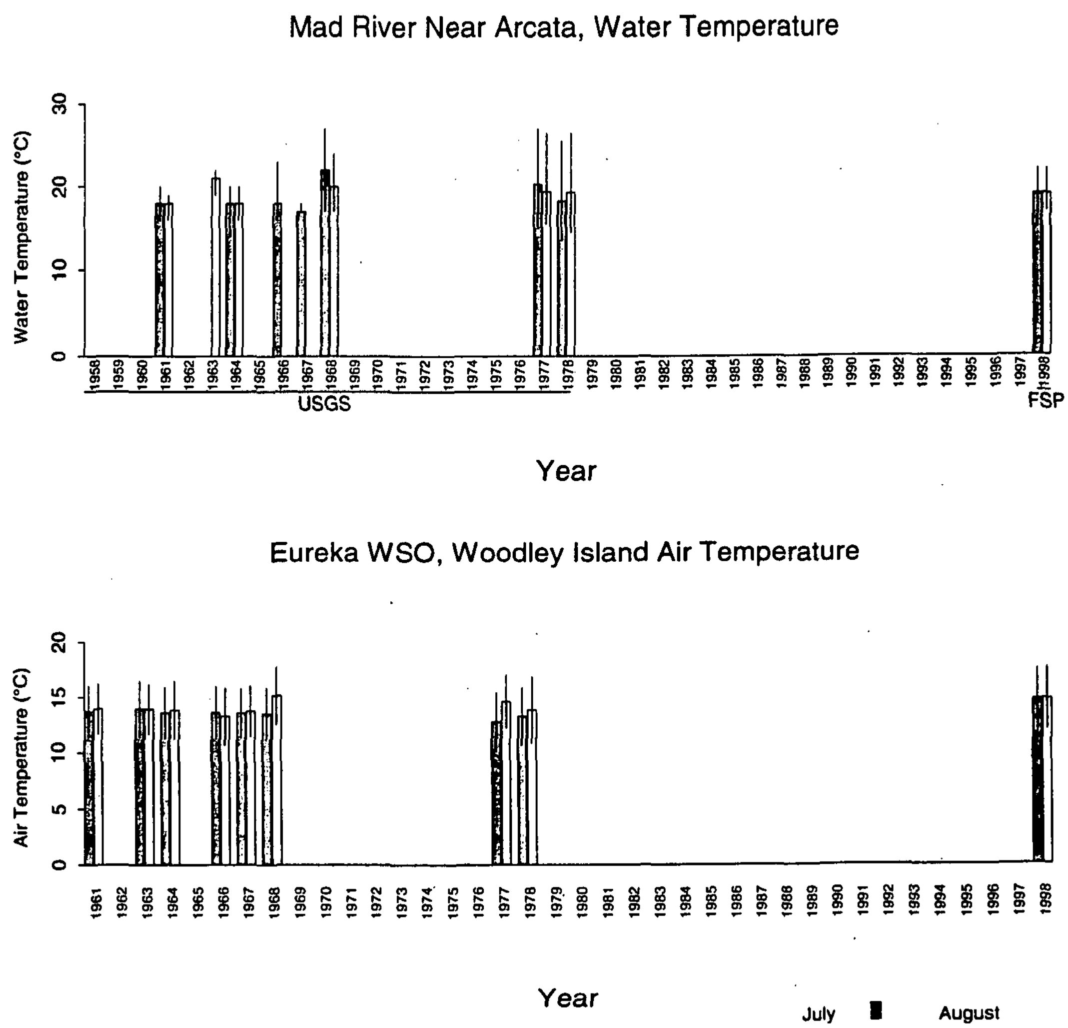


Figure 11.24. Comparison of (top) historical USGS monthly average stream temperature data in the Mad River near Arcata, CA and more recent Forest Science Project data for a site located 1660 m downstream from the USGS site, and (bottom) monthly average air temperature from nearest air site in Eureka,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

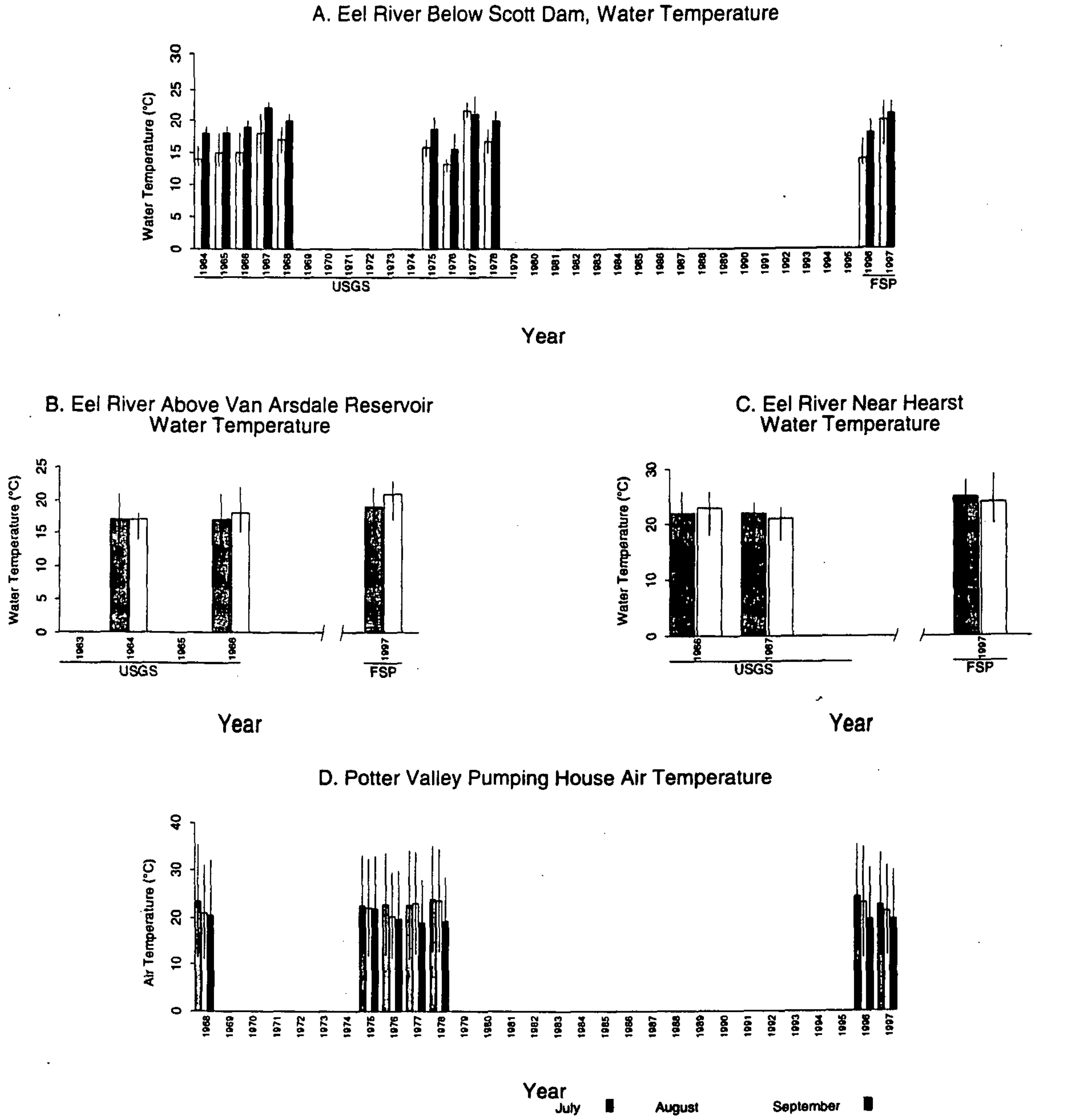


Figure 11.25. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for a site located in the Eel River Basin. Nearby FSP sites were (A) 80 m upstream, (B) 240 m upstream, and (C) 350 m upstream from the USGS site. Air temperature (D) was measured 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

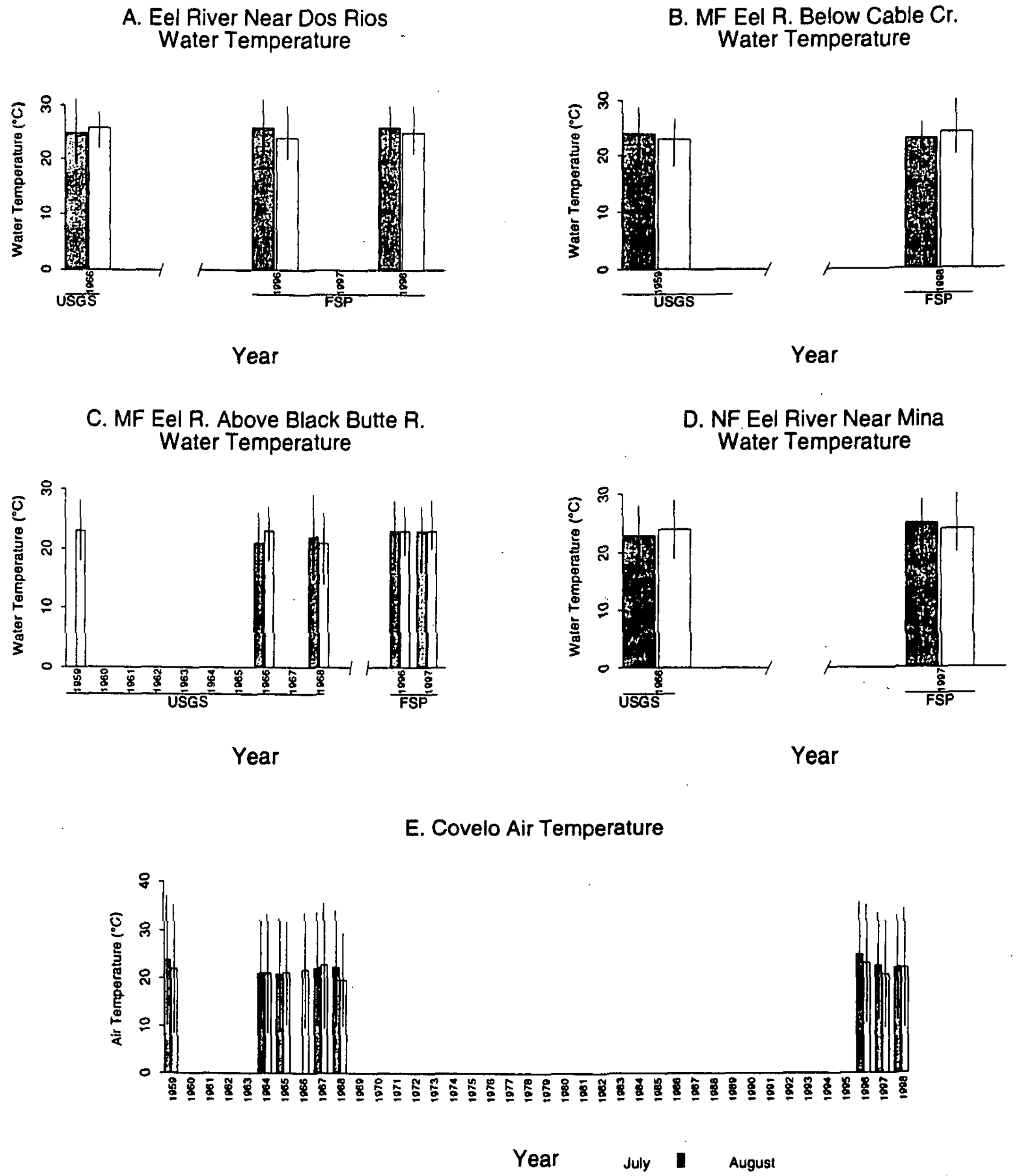


Figure 11.26. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for four sites located in the Eel River Basin. Nearest FSP site was A) 70 m downstream, B) 300 m downstream, C) 1400 m downstream, and D) 360 m upstream from the USGS site. 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

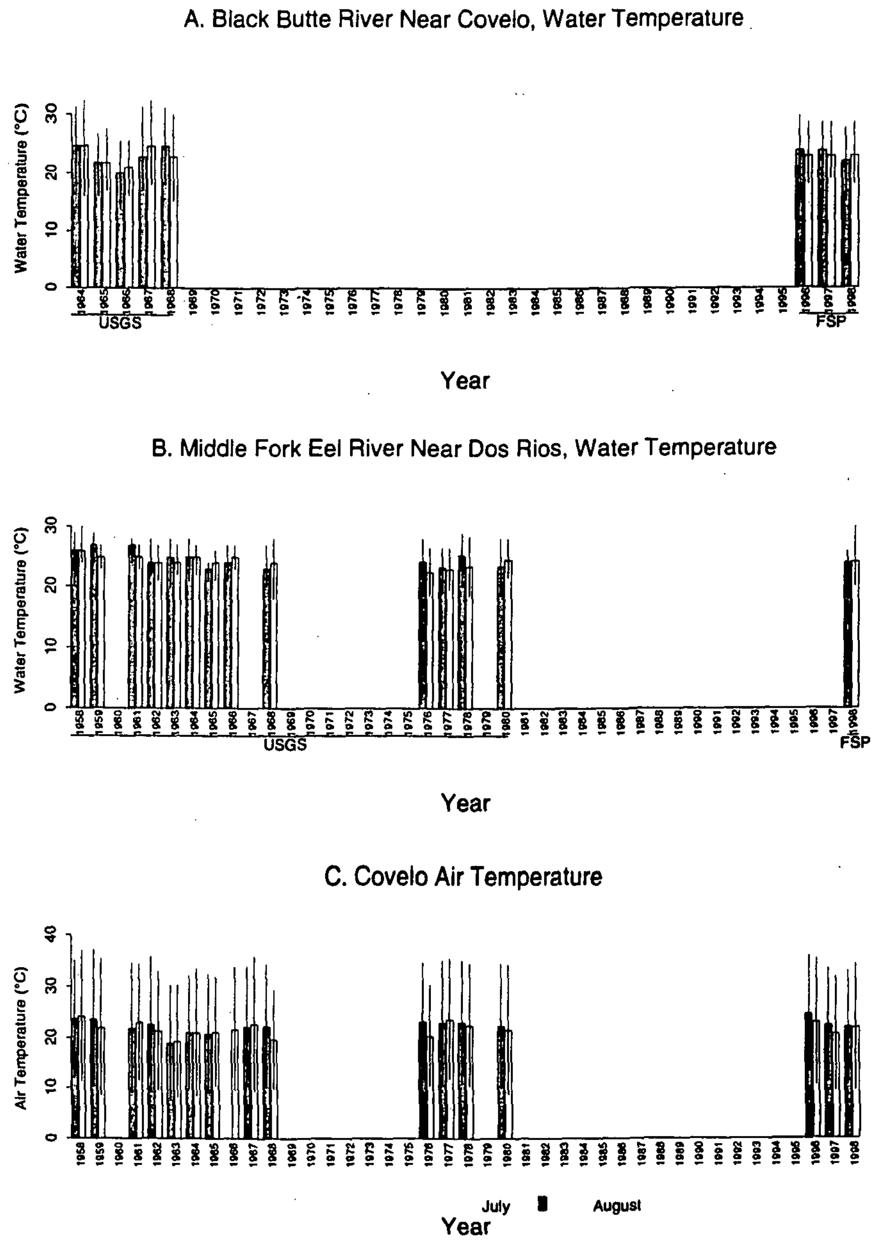


Figure 11.27. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for two sites located in the Eel River Basin. Nearby FSP site was A) 180 m downstream, and B) 610 m downstream from the USGS site. Air temperature (C) was measured at a NOAA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

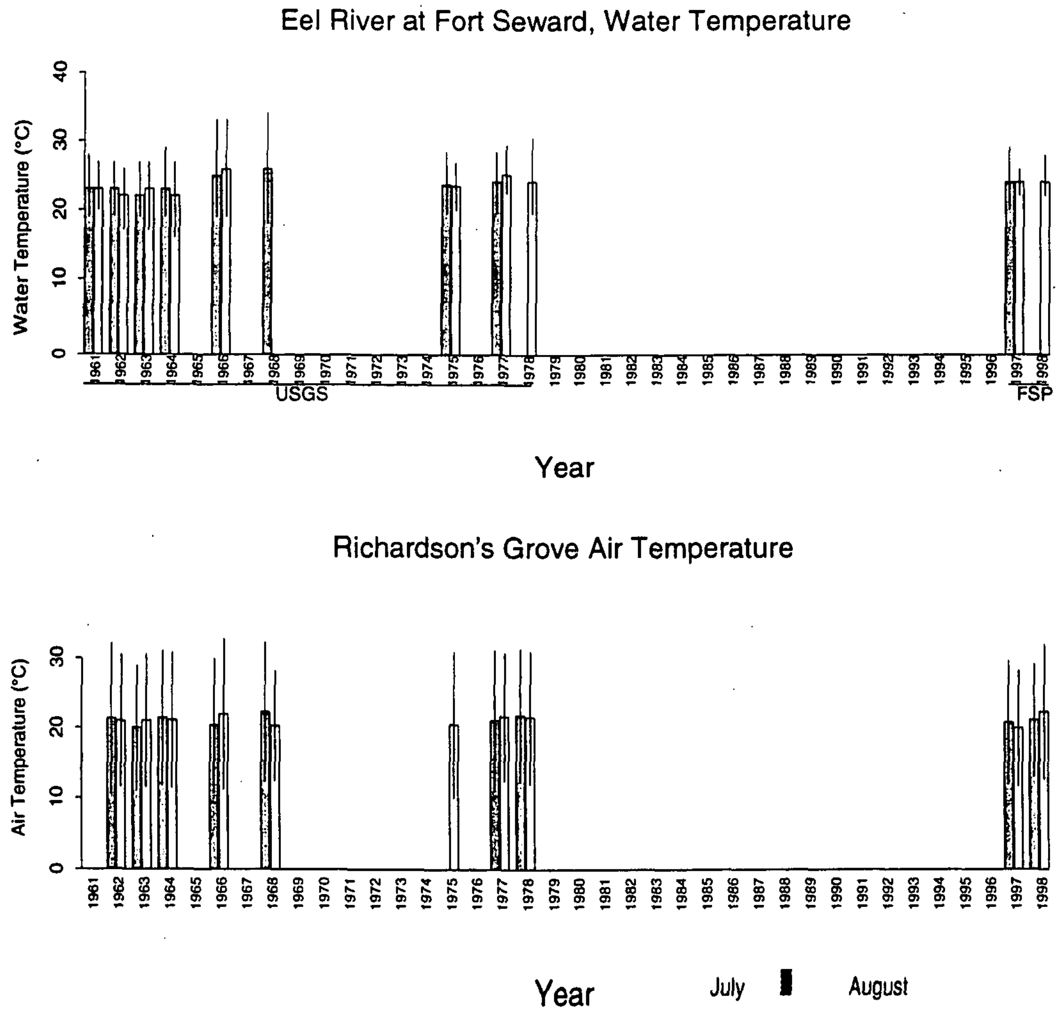


Figure 11.28. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for a site located on the Eel River at Fork Seward (top). From the USGS site, the nearby FSP site was 730 m upstream. Air temperature (bottom) was measured at Richardson's Grove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

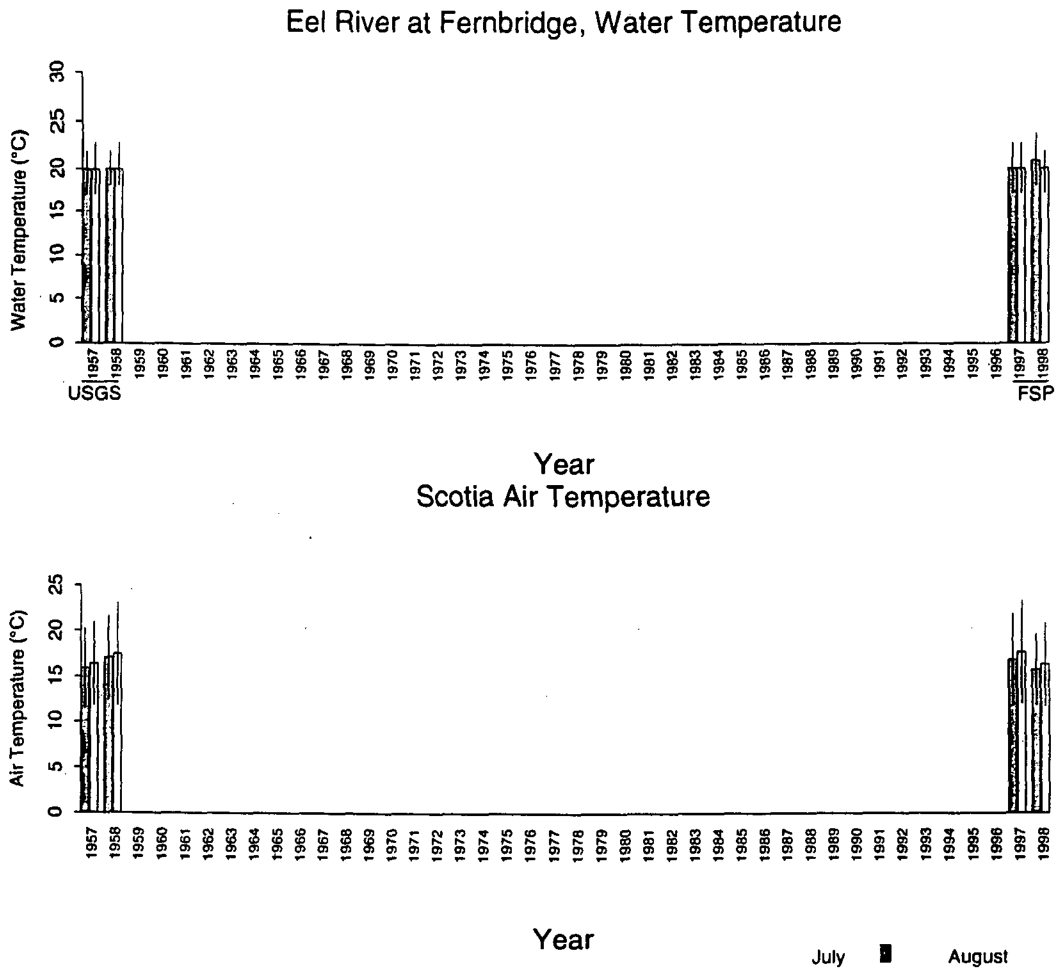


Figure 11.29. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for a site located in the Eel River Basin(top). From the USGS site, the nearby FSP site was 230 m downstream. Air temperature (bottom) measured at a NOAA site located in Scotia,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

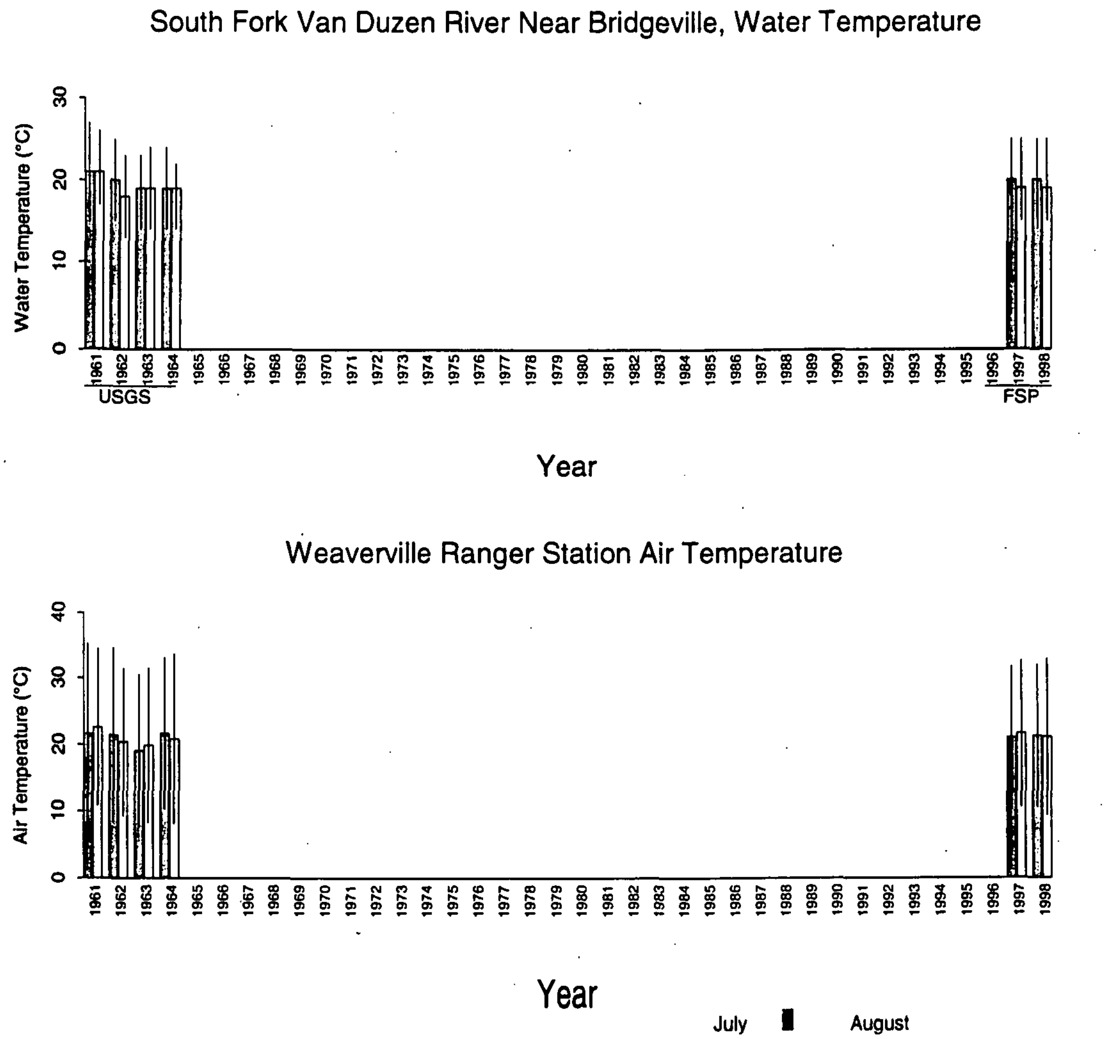


Figure 11.30. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for a site located in the Little Van Duzen River (South Fork, Van Duzen River) of the Eel River Basin (top). From the USGS site, the nearby FSP site was 70 m downstream. Air 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.

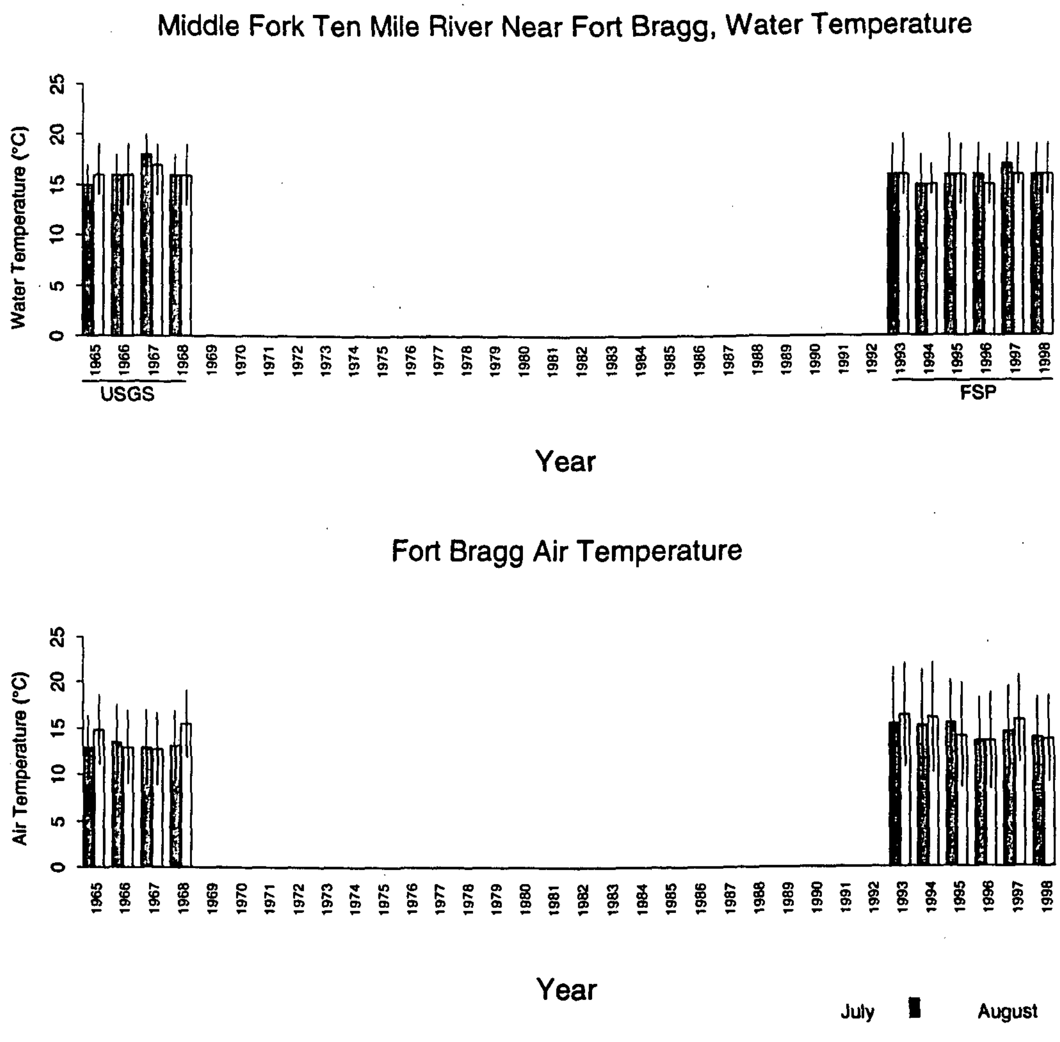


Figure 11.31. Comparison of historical USGS monthly average stream temperature data and more recent Forest Science Project data for a site located on the Middle Fork of Ten Mile River (top). Nearest FSP site is 1070 m downstream. Vertical lines represent the range in monthly minima and maxima. Air temperature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

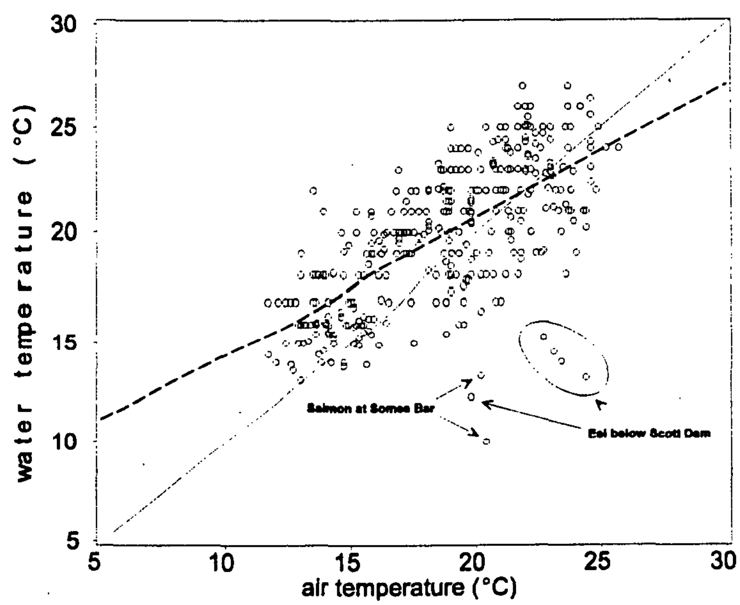


Figure 11.32. Monthly average air versus water temperature for all USGS - FSP matched sites for June, July, August, and September, wherever available. Regression equation (dashed line) is: water temperature = 7.995398 + 0.63657*(air temperature), $R^2 = 0.4436$. Solid line is one-to-one correspondence.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