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

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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

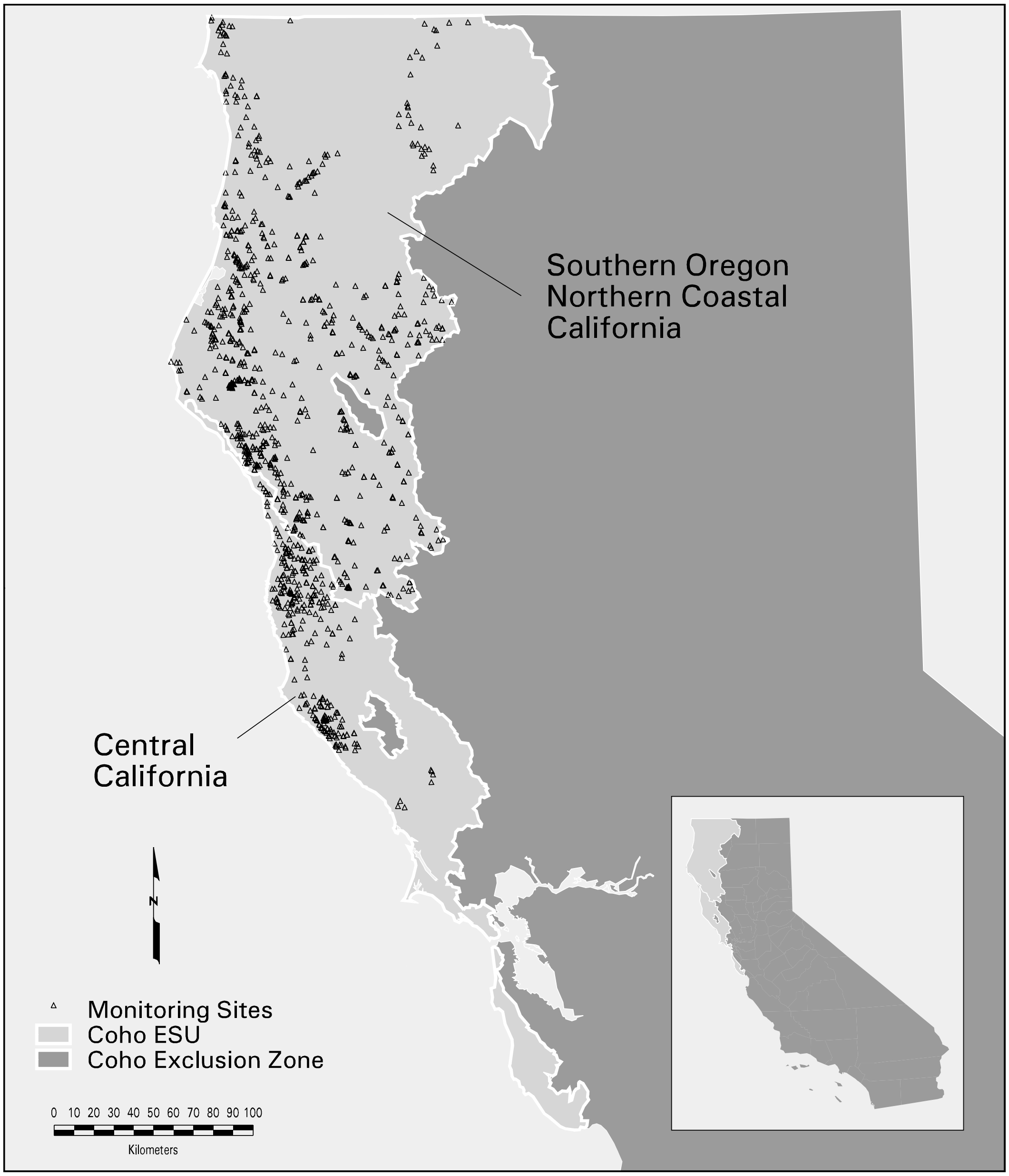

Figure 1. Area of interest for the Forest Science Project's Regional Stream Temperature Assessment as defined by the Southern Oregon Northern Coastal California and Central California evolutionarily significant units. There were 1087 unique sites where water temperature data were available for the regional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

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

					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							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 (**P**arameter-elevation **R**egressions on **I**ndependent **S**lopes **M**odel). 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.

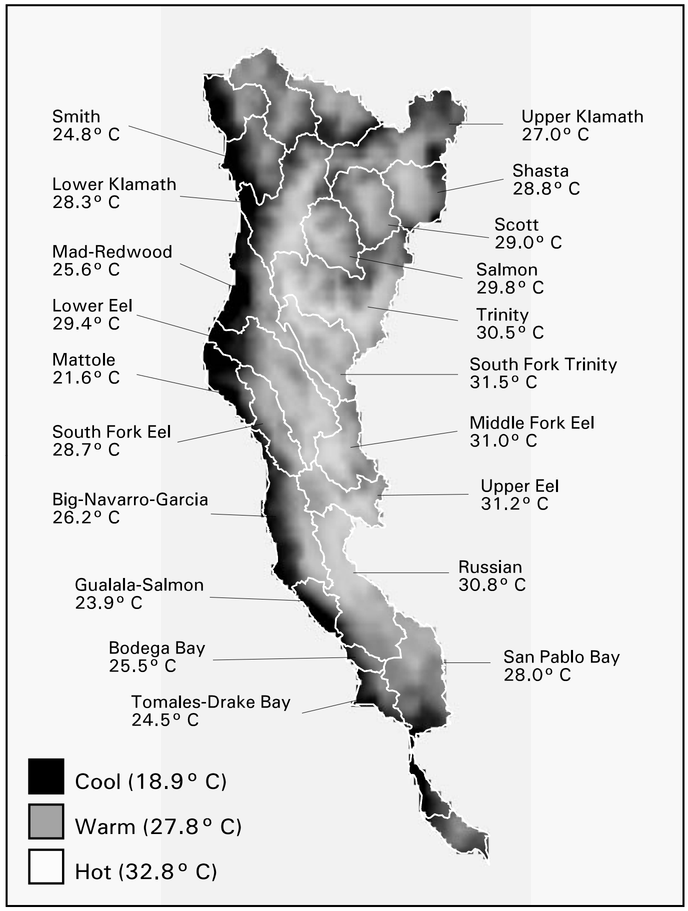

Figure 2. PRISM-derived August monthly average maximum air temperatures across HUCs that comprise the range of the coho salmon in Northern California.

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.

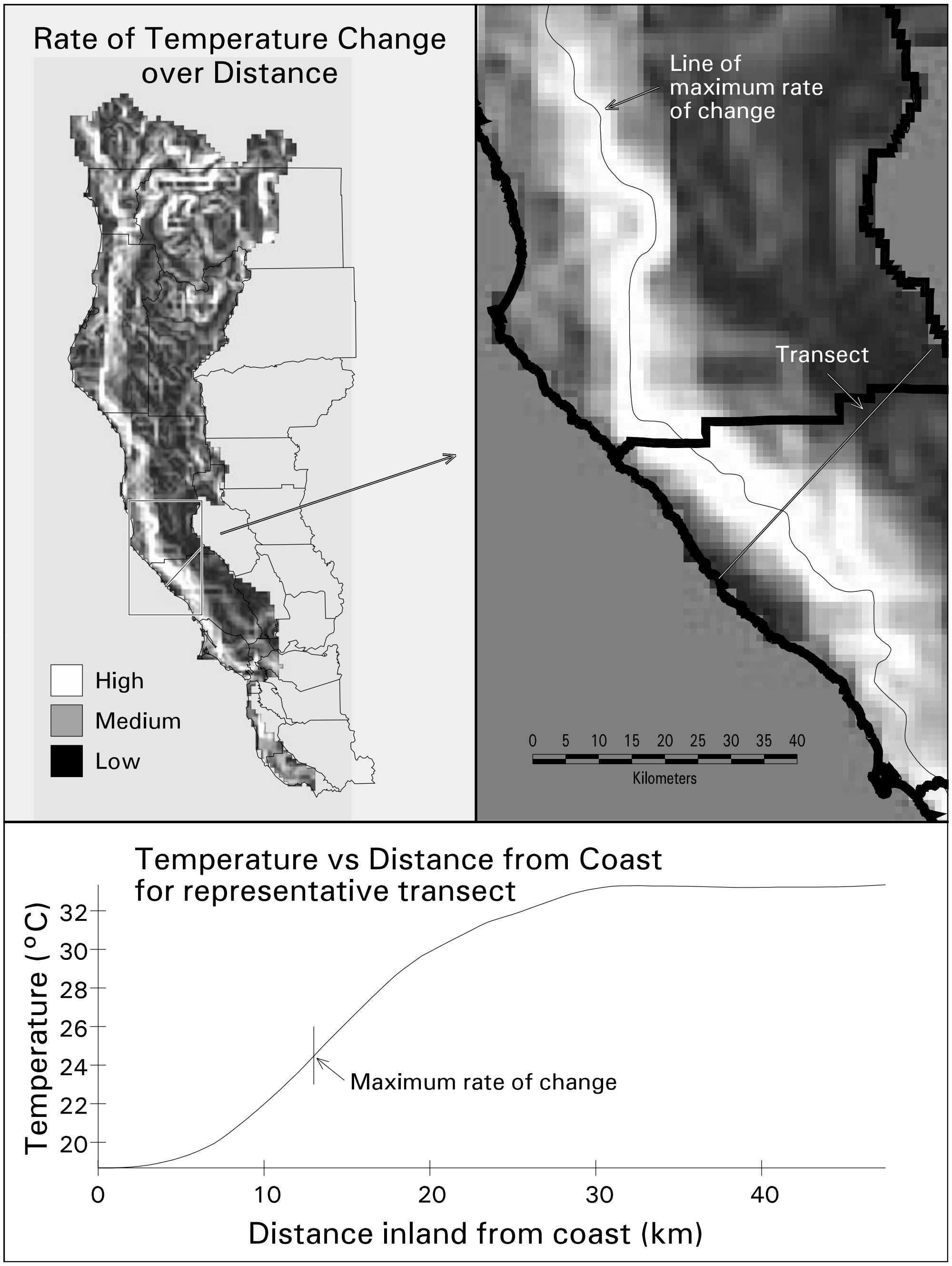

Figure 3. Derivation of the zone of coastal influence. Maximum rate of change determined using 30-yr PRISM August average maximum air temperature grid coverage across the range of coho salmon. Maximum rate of change is shown for a representative transect.

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.

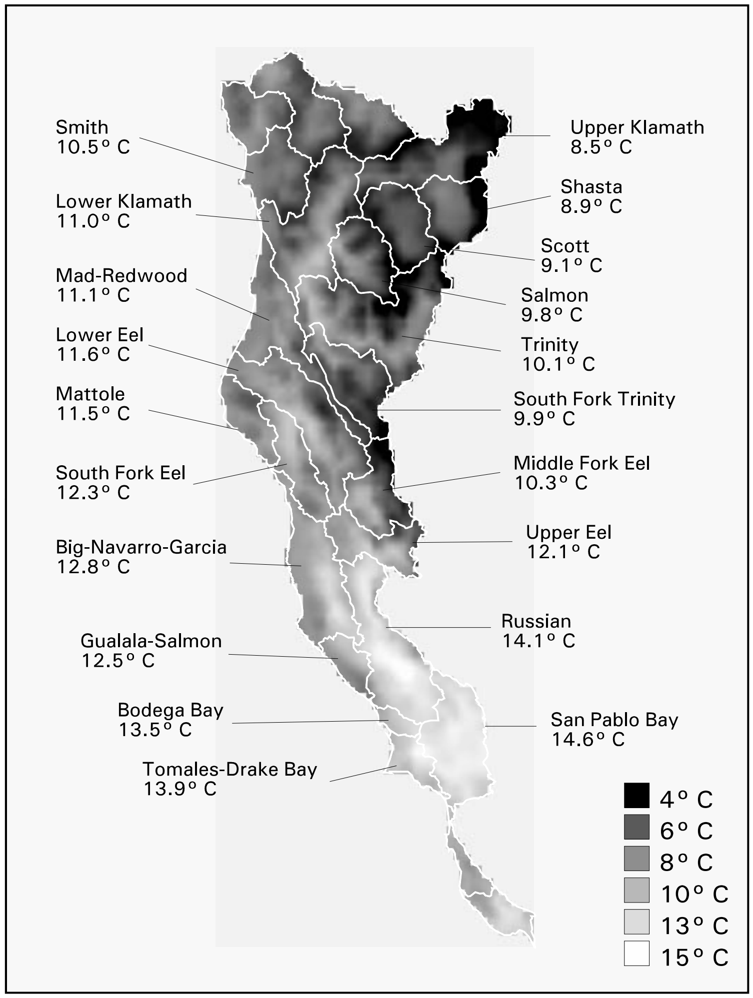

Figure 4. PRISM-derived 30-yr long-term annual average air temperatures across HUCs that comprise the range of the coho salmon in Northern California. Average annual air temperatures are reportedly within 1°C to 3°C of groundwater temperatures.

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.

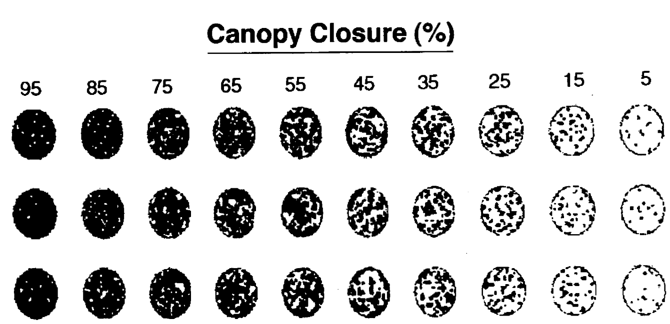

Figure 5. Example of computer-generated canopy closure card used by some FSP cooperators to estimate canopy closure at stream temperature monitoring sites.

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).

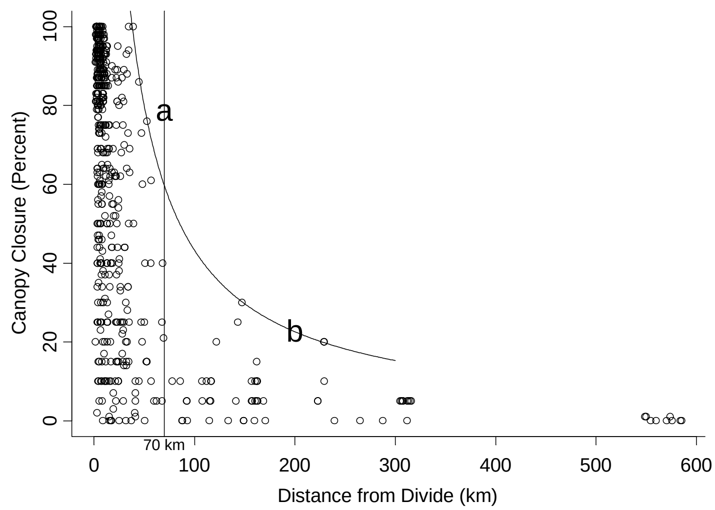

Figure 6. Relationship between canopy and distance from watershed divide. The vertical line (a) delineates the theoretical *threshold distance* (70 km) where the stream may be too wide for canopy to influence stream temperature. The curve (b) represents the maximum canopy closure potential a site has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

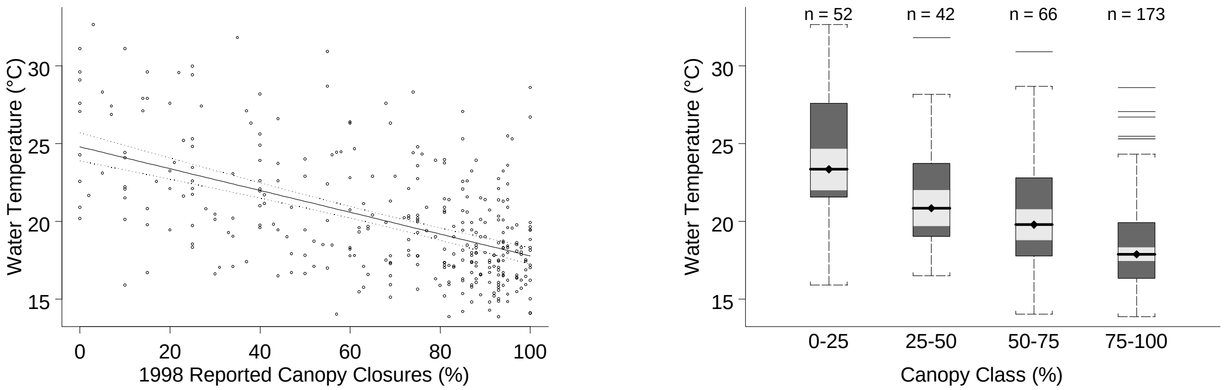

Figure 7. Scatter plot and box plot with fitted regression lines for the highest daily maximum stream temperature metrics versus canopy. For the box plots, canopy values were grouped into four canopy classes. Box plot outliers are defined as 1.5 times the inter-quartile range. The solid regression lines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

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.

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