IN PRESS *California Agriculture* – April/June 2005

Graphical Analysis of Monitoring Data to Evaluate Stream Temperature – A Watershed Scale Case Study

Kenneth W. Tate[1*], David F. Lile[2], Donald L. Lancaster[2], Marni L. Porath3, Julie A. Morrison2, and Yukako Sado[1]

[1] University of California, Agronomy and Range Science, Davis, CA

[2] University of California Cooperative Extension

[3] Oregon State University, Cooperative Extension

[*] Corresponding Author. kwtate@ucdavis.edu

Watershed groups, individuals, and land management and regulatory agencies are collecting stream temperature data to understand specific stream systems in an effort to protect and enhance cold-water fisheries. While great quantities of stream temperature data are generated, data analysis and interpretation is often not adequate to identify stream reaches which are gaining/losing temperature, or to correlate stream temperature changes to factors such as vegetative canopy cover or streamflow levels. We use a case study to demonstrate graphical methods to display and interpret stream temperature data for this purpose.

Stream temperature is an important water quality attribute in many of California's streams, especially those that support cold-water fisheries such as trout, steelhead, and salmon (salmonids). Several species of salmonids have been identified as threatened or endangered, and elevation of stream temperature is often cited as a cause. Numerous California river systems have been targeted by water resource protection agencies for development of watershed scale pollutant reduction plans (Total Maximum Daily Load - TMDL) to reduce stream temperature and improve cold water fisheries habitat. Specific concerns on rangeland and forest watersheds focus on the increase of summer stream temperatures. These concerns include activities such as streamflow diversion for irrigation of pastures, return of warm irrigation runoff to streams, and reduction in riparian canopy cover due to logging and grazing.

While extreme high temperatures can be lethal to salmonids, of equal or greater concern is chronic exposure to sub-lethal temperatures which may effect growth, reproductive success and tolerance to other pollutants or disease (Sullivan et al. 2000). Fish response to temperature is dependent upon fish species and life stage (larval, fry, juvenile, etc.) (Bestcha et al. 1987, Thompson and Larsen 2004). As a result, stream temperature criteria or objectives to safe-guard cold water fisheries habitat are often dependent upon the species occupying a given stream reach, and the life stage at which the species are present in the stream reach. For example, the United States Environmental Protection Agency (1986) recommends 75^{o} F as a short-term maximum and 66^{o} F as a 7-day moving average of daily maximum stream temperature for adult rainbow trout. Oregon's Department of Environmental Quality has established a standard of 66^{o} F as a 7-day moving average of daily maximum stream temperature for general salmonid use, but recommends 55^{o} F for salmonid spawning, egg incubation and fry emergence (DEQ 1995, Boyd and Sturdevant 1997).

Uncertainty and concern about appropriate temperature standards for specific streams, the relative importance of factors such as air temperature, streamflow and riparian canopy for determining stream temperature, and the influence of specific land use practices on stream temperature has generated significant monitoring and data collection on streams across California and the western U.S. Monitoring objectives often include: 1) evaluation of compliance with specific stream temperature criteria; 2) determination of temperature changes above and below a land use activity, through a given property or stream reach, or along an entire stream network; and 3) examination of watershed specific associations between stream temperature and factors such as air temperature, streamflow, and riparian canopy cover. Several publications provide guidance on planning and implementation of water quality and stream temperature monitoring (*e.g.*, ODF 1994, McDonald et al. 1999, U.S. EPA 1997), but few provide guidance on the analysis and interpretation of stream temperature data.

While the collection of temperature data is facilitated by the availability of inexpensive, automatic temperature recorders, it has been our experience that individuals, watershed groups and agencies are often overwhelmed by the sheer volume of temperature data they collect. We have also observed that while groups will collect stream temperature data, they often neglect to collect associated data such as air temperature, streamflow, stream canopy cover, stream reach length, etc. often required to interpret stream temperature data. The combined issues of sheer data volume and lack of important associated data often lead to data not being analyzed, or an inability to reach defendable conclusions from which management, restoration, and regulatory decisions can be made.

The objective of this paper is to demonstrate methods for graphical display and analysis of stream temperature data typically collected in monitoring efforts. In this paper we will illustrate presentation formats and non-statistical approaches which can facilitate the synthesis and interpretation of data to achieve monitoring objectives 1 and 2 listed above. In our subsequent paper in this issue (Tate et al. 2005) we illustrate a statistical approach to analyze stream temperature and associated data to achieve complex monitoring objectives such as number 3 listed above. For both papers, we will utilize the same dataset of stream temperature, air temperature, streamflow, streamside vegetative canopy, and solar input data collected during the summers of 1999-2001 across the Lassen and Willow Creek watersheds in northeastern Modoc County, CA.

Lassen and Willow Creek Watersheds

The Lassen and Willow Creek watersheds are located on the western slope of the Warner Mountains in northeastern Modoc County, CA. The two watersheds lay parallel to each other, have a northwest aspect and flow directly into Goose Lake (Figure 1). The upper reaches of both watersheds are located on the Modoc National Forest and reach elevations of 6,000 to 7,500 feet. Both streams flow out of pre-dominantly publicly owned (United States Forest Service) mountains into pre-dominantly privately owned valleys and plains above Goose Lake which sits at an elevation of 4700 feet. The private lands are used primarily for livestock grazing, as well as irrigated and dry-land hay production. The public lands are managed for multiple uses including extensive livestock grazing and dispersed recreation.

Although both streams reach peak run-off with snow melt in the spring (May-June), they are primarily spring fed during the summer-time base flow. The streams are similar, but do have some clear differences. Perennial streamflow in Lassen Creek begins at ~6000 ft and the stream channel stair-steps its way through a series of small mountain meadows and steep canyons on its way to Goose Lake. Perennial flow in Willow Creek begins at ~ 5200 ft and the stream channel flows through two relatively large open valleys connected by a canyon reach. Lassen Creek is ~ 14 mi in length and Willow Creek is ~ 11 mi in length. Lassen Creek has one perennial tributary, Cold Creek (Figure 1).

As is typical of most mountain streams in northern California, Lassen and Willow Creek provide cold water habitat for trout, as well as other native fish and invertebrate species. These two streams provide habitat to four native fish species that occur only in the Goose Lake Basin; the Goose Lake Redband Trout (*Oncorynchus mykiss*), the Goose Lake Sucker (*Catostomus occidetalis lacusauserinus*), the Goose Lake Tui Chub (*Gila bicolor thalassina*), and the Goose Lake Lamprey (*Lampetra tridentata*). These species spend much of their adult life in Goose Lake, but depend on Lassen and Willow Creek for annual spawning and rearing habitat, as well as an emergency refuge during prolonged drought periods when Goose Lake goes dry. Stream temperature monitoring was initiated in the late 1990's due to the identification of all four species as candidates for listing under the Federal Endangered Species Act, with elevated stream temperature proposed as one of the main factors impairing habitat in both streams.

Stream Temperature Monitoring

Stream temperature data collected from June through September of 1999, 2000, and 2001 across Willow, Lassen, and Cold Creek are presented in this paper. Figure 1 displays the locations monitored across these watersheds during that time period. Locations for Lassen Creek were L1 to L12 and for Willow Creek W1 to W8 from downstream to upstream, respectively. Monitoring locations were selected to: 1) systematically track temperature changes from the upper to lower extent of each stream; 2) dissect each stream into discrete reaches based upon changes in stream morphology and gradient, vegetative community and canopy, aspect, and land management; and 3) account for the confluence of tributaries and springs with each stream channel. During 1997-

98 we conducted preliminary stream temperature data collection with a limited number of temperature recorders, combined with field surveys of each stream to identify these monitoring locations.

At a specific monitoring location, stream temperature was recorded every 0.5 hour using commercially available automatic temperature recorders (Optic StowAway©, Onset Computer Corporation). Data collection at the 0.5 hour time step allows for capture of daily maximum and minimum temperatures, as well as calculation of daily average temperature (48 readings per day), 7-day running average of daily maximum temperature, and other metrics of interest (*e.g.*, hours above a threshold temperature, daily range). For the purposes of this paper we only report the average daily stream temperature and the 7-day running average of daily average temperature. Recorders at all locations were set to record temperature simultaneously on the hour and the half hour (*e.g.*, 0100, 0130, 0200). Temperature recorders were submerged at the bottom of the stream in areas of thorough stream mixing (riffle or run) and held in place with a weight. Temperature recorder depth ranged from 6 to 16 inches due to declining depth as season progressed, and variability in stream size and morphology between monitoring locations.

Side-Bar: Definitions of Commonly used Stream Temperature Metrics

Daily Maximum Temperature: The maximum of 48 temperature observations collected every 0.5 hour during the course of each 24 hour day.

Daily Average Temperature: The average of 48 temperature observations collected every 0.5 hour during the course of each 24 hour day.

7-Day Running Average of Daily Maximum Temperature: Calculated for each day as the average of the daily maximum temperature observed for that day and the 6 consecutive prior days.

7-Day Running Average of Daily Average Temperature: Calculated for each day as the average of the daily average temperature observed for that day and the 6 consecutive prior days.

Maximum Weekly Maximum Temperature: The maximum 7-day running average of daily maximum temperatures observed during a time period of interest (*e.g.*, specific month, critical fisheries life stage).

Maximum Weekly Average Temperature: The maximum 7-day running average of daily average temperatures observed during a time period of interest.

Measurement of Streamflow, Riparian Canopy, Solar Input, and Air Temperature

In order to interpret stream temperature data relative to environmental conditions and land use management it is necessary to collect additional data on associated factors such as streamflow, air temperature, stream canopy cover, and solar input. Air temperature was recorded every 0.5 hour with automatic temperature recorders (Optic StowAway©, Onset Computer Corporation) placed at six feet above the ground surface, out of direct sunlight, and in areas of adequate air mixing at both lower and upper reaches of each stream (locations L1, L10, W1, and W8 on Figure 1). Instantaneous streamflow was measured by hand at each monitoring location as cubic feet per second (cfs) via the area velocity method [stream width (ft) x average stream depth (ft) x average stream velocity (ft per sec)]. Streamflow was measured in late May, late July, and late September at each monitoring location during each year. Stream velocity was measured with a handheld velocity meter. Stream canopy cover (%) and percent available solar input reaching the stream surface were measured in July 2000 at 5 locations equally spaced along the 1000 ft stream reach immediately upstream of each monitoring location. Stream canopy cover, or the amount (%) of sky blocked by vegetation, was measured with a densitometer placed just above the stream surface (California Department of Fish and Game 1999). The percent of available solar input received was measured at the same points as canopy cover (Platts et al. 1987). Solar input readings are correlated to the vegetative canopy readings but are also affected by aspect of the stream, and topographic features such as canyon walls or nearby mountains that may block the sun during portions of the year or day.

Comparing Stream Temperatures along a Stream System

Monitoring groups are often interested in comparing stream temperature at specific locations along a stream. Interest could focus on a specific reach (*e.g.*, Figure 1, L12 v. L10), or along a longitudinal profile from upper to lower stream locations (*e.g.*, Figure 1, L12 v. L11 v. L10). This information can allow identification and prioritization of points of concern for fisheries (*e.g.*, exceeding temperature standards), restoration opportunities (*e.g.*, riparian planting for canopy), and/or management activities which should be mitigated (*e.g.*, excessive warm irrigation water returns). One approach to display and analyze data from a set of monitoring locations along a stream system is to plot temperature at multiple locations over time on the same graph. Figures 2 and 3 plot average daily stream temperature, and the 7-day running average of daily average stream temperature for 1999-2001 at several locations depicting the longitudinal profile of Lassen and Willow Creeks (Figure 1). Figure 2 and 3 are valuable because they present a synthesis of the cumbersome raw dataset (9 locations x 3 years x 122 days/year/location x 48 readings/day = ***158,112 data records***), yet still reveal seasonal trends (*e.g.*, peak temperatures in August, rapid reduction in the first week of September) which would be lost in monthly, seasonal or annual statistics (*e.g.*, average, maximum). Figures 2 and 3 provide a simple means of illustrating which stream is warmer or colder, how stream temperature changed throughout the summer and across years, and an initial examination of how stream temperature changed across a given stream reach or stream system.

For example, examination of Figures 2 and 3 clearly illustrate that Willow Creek is consistently warmer than Lassen Creek, and that Lassen Creek provides more cold water habitat than Willow Creek. Mean stream temperature from the top to bottom of Lassen Creek can increase from 10 to 20^{o} F on a given day (L12 v. L2), with the greatest increase in temperature occurring between locations L12 and L10, a reach flowing through open meadow. Willow Creek, on the other hand, cools as it flows through a long shaded canyon reach between W8 and W4, and then increases in temperature as it continues down stream. The reduction in stream temperature between location W8 and W4 on Willow Creek is year dependent. Cooling through this reach was greatest in 1999 which was a year of relatively high streamflow compared to 2000 and 2001, both years of regional drought and low flow. Figures 2 and 3 illustrate the benefits of simplicity and clarity in plotting the 7-day running average compared to the daily average, resulting in a smoother plot facilitating comparisons between multiple locations. By contrast, if the concern is acute affects of daily temperature variations, then plotting the daily average or maximum for only one or two sites is more clear and informative.

Comparing Changes in Temperature between Stream Reaches

While graphics such as Figures 2 and 3 allow for efficient display and initial interpretation of the large raw datasets typically collected by stream temperature monitoring efforts, additional data reduction and graphical analysis is required to appropriately compare the change in stream temperature occurring between reaches. As in most monitoring efforts, monitoring locations on Lassen and Willow Creeks were selected to isolate reaches based upon changes in geomorphology, vegetation, flow, management, etc. This approach to sample design and monitoring location selection is important to insure that collected data relate to important watershed characteristics. As a result, the distance between monitoring locations, and thus stream reach length, varies (Figure 1). Reach length confounds the direct interpretation of stream temperature changes as illustrated in Figures 2 and 3. One would expect greater overall change in temperature across longer reaches compared to shorter reaches. Direct comparison of stream temperature change through reaches of different lengths requires standardization for reach length.

An efficient and simple approach to account for reach length and allow direct comparison is to divide the change in temperature through each reach by the reach length. The resulting unit is *change in temperature per stream mile (or unit length)*, which can be compared across reaches of different length. To illustrate this approach we examined the change in average daily stream temperature for the summer period (Jun – Sep) across 4 reaches of Lassen and Willow Creek during 1999-2001 (Figure 4a and 5a). We calculated the data illustrated in Figures 4a and 5a by taking the average of the differences in daily average temperature between 2 monitoring locations (e.g. L12 and L10) for each summer (1999, 2000, and 2001) and dividing this average by the distance between the two locations. The average change in temperature for each reach for the 3 years of this study is also displayed. Depending upon the specific interest of the group conducting the monitoring, similar calculations could be generated and graphed on a daily, weekly, monthly time step using average, maximum or minimum temperatures. For the purposes of demonstration we selected a simple summer average.

Figures 4a and 5a provide a significant amount of directly interpretable information to watershed managers, watershed groups and other interested parties working on these watersheds. For example, these figures clearly identify stream reaches within each watershed with the highest gain in temperature per stream mile. In Lassen Creek, the rate of warming is far greater in the reaches between L12 and L10 and L4 to L3 compared to other stream reaches in the system

(Figure 4a). In Willow Creek, the rate of temperature increase was consistently highest in the reach between W4 and W2 (Figure 5a). It is interesting that although Willow Creek is warmer (Figures 2 and 3), the rate of heating across Lassen Creek was consistently greater. It is conceivable that the background, or natural, temperature of Willow Creek is greater than that of Lassen. Perennial flow starts lower in elevation in Willow Creek relative to Lassen Creek, and Willow Creek flows through 2 large open meadows while Lassen Creek has a greater number of forested canyons along its length.

It is also interesting that although both Lassen and Willow Creek gain heat through their lower reaches which are associated with irrigation water diversion and irrigation water return, these lower reaches are not the sections of either creek with the highest temperature gain. This does not imply that irrigation management does not influence stream temperature, simply that in order to significantly reduce stream temperature on these streams temperature gains in the middle and upper reaches must be addressed. It is important to remember that these graphs do not establish cause and effect, rather they facilitate understanding of watershed scale temperature dynamics and serve as an effective watershed assessment tool.

Evaluating the Relationships between Temperature and Factors such as Streamflow, and Riparian Canopy

The results reported in Figures 2, 3, 4a, and 5a inevitably lead to inquiry and speculation about the factors or reasons which caused the differences in temperature change across Lassen and Willow Creeks. Collection of data on factors which probably effect stream temperature is the first step in translating this speculation into defendable conclusions. It is difficult to evaluate the simultaneous and interacting relationships which might exist between factors such as air temperature, streamflow, riparian canopy, etc. and stream temperature using graphical analysis. However, graphical analysis of stream temperature and associated factors can provide useful insight for improvements to local monitoring schemes and for a more thorough statistical analysis to quantify relationships. To illustrate this point and to demonstrate the need for statistical approaches when addressing complex monitoring objectives (Tate et al. 2004) we display data on the change in streamflow as well as the riparian canopy and amount of solar input for the reaches reported in Figures 4a and 5a. Figures 4b and 5b report the change in streamflow measured the last week of July 2001 for the 4 stream reaches on Lassen and Willow Creek. Figures 4c and 5c display the percent of open sky blocked by vegetative canopy cover directly over the stream channel and the percent of available solar input realized for each reach during July for these same reaches.

Comparison of Figures 5a and 5b indicate that all Willow Creek reaches which lost streamflow (less water emerged from the reach than entered it) gained temperature, while the reach which gained streamflow lost temperature (W7 to W4). This reach (W7 to W4) is a bedrock canyon reach situated below a meadow reach. It is highly likely that streamflow lost to the channel's subsurface zone (gravels and sediments in and under the channel bed) in the reach from W8 to W7 was forced up by bedrock to re-emerge as surface flow in the reach from W7 to W4. This is also an area of the watershed known to have multiple diffuse seeps and springs along the stream channel. Regardless the source of increased flow, it is likely that this subsurface return flow would be cooler (~50 to 55 F^o) than surface water in the stream (Stringham et al. 1998). On Lassen Creek, examination of Figures 4a and 4b indicates that the reach from L10 to L5 gained streamflow, and that this reach had relatively low rates of temperature gain.

Following this graphical, single associated variable (univariate) approach one might conclude that flow is the main factor influencing the direction and rate of temperature change, where stream reaches that lose flow gain temperature and reaches that gain flow lose temperature or have a relatively low rates of heating. By the same logic, one could examine Figures 4c and 5c relative to Figures 4a and 5a and conclude that riparian canopy is the primary factor explaining variation in temperature change along these streams. Figure 4c illustrates that in the cooling reach of Willow Creek (W7 to W4), both streamflow and canopy cover increase. The increase in canopy cover results in an associated reduction in solar input to this reach relative to other reaches on the stream, less solar input would logically lead to lower rates of temperature increase. Although less pronounced, there is a similar situation on Lassen Creek for the reach from L10 to L5.

This initial graphical comparison of stream temperature change, streamflow, and canopy indicates there are probably strong relationships between these factors. However, it is inappropriate and likely misleading to use a univariate, graphical analysis approach to: 1) fully explore and quantify these relationships; 2) determine if streamflow and canopy interact to influence stream temperature; or 3) determine if the influence of canopy or streamflow is different between streams. Answering these complex monitoring questions (Objective 3 discussed above) requires a multivariate statistical analysis of the dataset containing stream temperature and factors of interest such as streamflow, air temperature, and canopy. Fortunately, relatively simply collected datasets can be subjected to graphical analysis appropriate for addressing monitoring objectives 1 and 2, as well as statistical analysis to address monitoring objective 3.

Summary

We have demonstrated some display and graphical analysis approaches by which data collected in typical stream temperature monitoring projects can be interpreted by and presented to land managers, watershed groups, and other interested parties. This approach is simple and non-statistical, facilitating timely local analysis to provide sufficient information to achieve several common monitoring objectives. This approach allows for evaluation of stream temperature across a watershed for comparison to temperature criteria, and identification of watershed areas with high or low rates of stream temperature gain. This level of analysis can translate large raw datasets into information for local managers and water resources agencies to identify and prioritize allocation of limited resources for restoration and improvement of management practices relative to stream temperature reduction.

While graphical display and analysis of stream temperature and associated data on factors such as stream canopy cover and streamflow can provide initial insight about the influence these factors have on stream temperature, it does not allow for quantification of these relationships or the examination of interactions between these factors. Often there are several factors acting and interacting simultaneously to determine stream temperature across a stream system. Situations such as this require a multivariate statistical approach which simultaneously evaluates these relationships. In our subsequent paper in this issue (Tate et al. 2005) we demonstrate a statistical approach to analyze the 1999-2001 dataset from Lassen and Willow Creek Watersheds to address more complex monitoring objectives.

Literature Cited

Beschta, R.L., R.E. Bilby, G.W. Brown, L.B. Holtby, and T.D. Hofstra. 1987. Stream temperatures and aquatic habitat: fisheries and forestry interactions. In: Salo, E.O. and T.W. Cundy, eds., Proc. Symposium Streamside Management: Forestry and Fishery Interactions. Held. Feb 12-14 1986. University of Washington, Seattle, WA.: 191-232.

California Department of Fish and Game. 1998. California salmonid stream habitat restoration handbook. Appendix M.

MacDonald, L.H, A.W. Smart, and R.C. Wissmar. 1991. Monitoring guidelines to evaluate effects of forestry activities on streams in the Pacific Northwest and Alaska. EPA 910/9-91-001. United State Environmental Protection Agency.

ODF. 1994. Water temperature monitoring protocol. Forest Stream Cooperative Monitoring. Oregon Department of Forestry. Forest Practices Section, Salem, OR.

Platts, W.S., C. Armour, G.D. Booth, M. Bryant, J.L. Bufford, P. Cuplin, S. Jensen, G.W. Lienkaemper, G.W. Minshall, S.B. Monsen, R.L. Nelson, J.R. Sedell, and J.S. Tuhy. 1987. Methods for evaluating riparian habitats with applications to management. USDA Forest Service General Technical Report INT-221.

Stringham, T.K., J.C. Buckhouse, W.C. Krueger. 1998. Stream temperatures as related to subsurface waterflows originating from irrigation. J. Range Management. 51:88-90.

Sullivan, K., D.J. Martin, R.D. Cardwell, J.E. Toll, and S. Duke. 2000. An analysis of the effects of temperature on salmonids of the pacific northwest with implications for selecting temperature criteria. Sustainable Ecosystems Institute. Portland Oregon.

Tate, K.W., D.F. Lile, D.L. Lancaster, M.L. Porath, J.A. Morrison, and Y. Sado. 2005. Statistical Analysis of Monitoring Data to Examine Factors Influencing Stream Temperature – A Watershed Scale Case Study. California Agriculture. April/June.

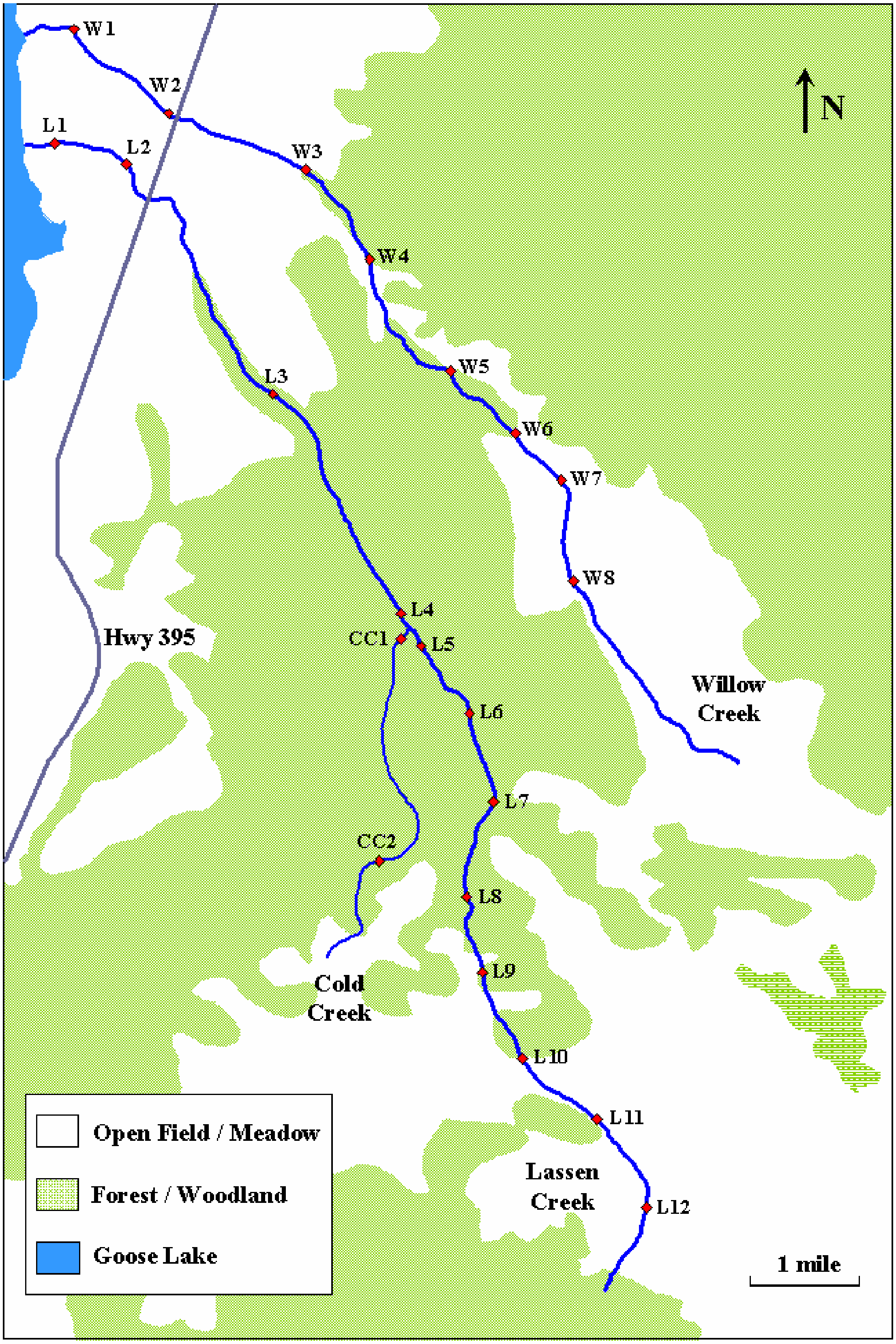
Thompson, L.C., and R.E. Larsen. 2004. Fish habitat in freshwater streams. Publication 8112. UC Division of Agriculture and Natural Resources Publication Series.

U.S. EPA. 1986. Quality criteria for water. EPA 440/5-86-001. Office of Water Regulations and Standards. Washington D.C.

U.S. EPA. 1997. Volunteer stream monitoring: a methods manual. EPA 841-B-97-003. Office of Water. Washington D.C.

List of Figures

Figure 1.



W1
W2
W3
W4
W5
W6
W7
W8
L1
L2
L3
L4
L5
L6
L7
L8
L9
L10
L11
L12
CC1
CC2
N
Hwy 395
Willow Creek
Cold Creek
Lassen Creek
Open Field / Meadow
Forest / Woodland
Goose Lake
1 mile

Figure 2.

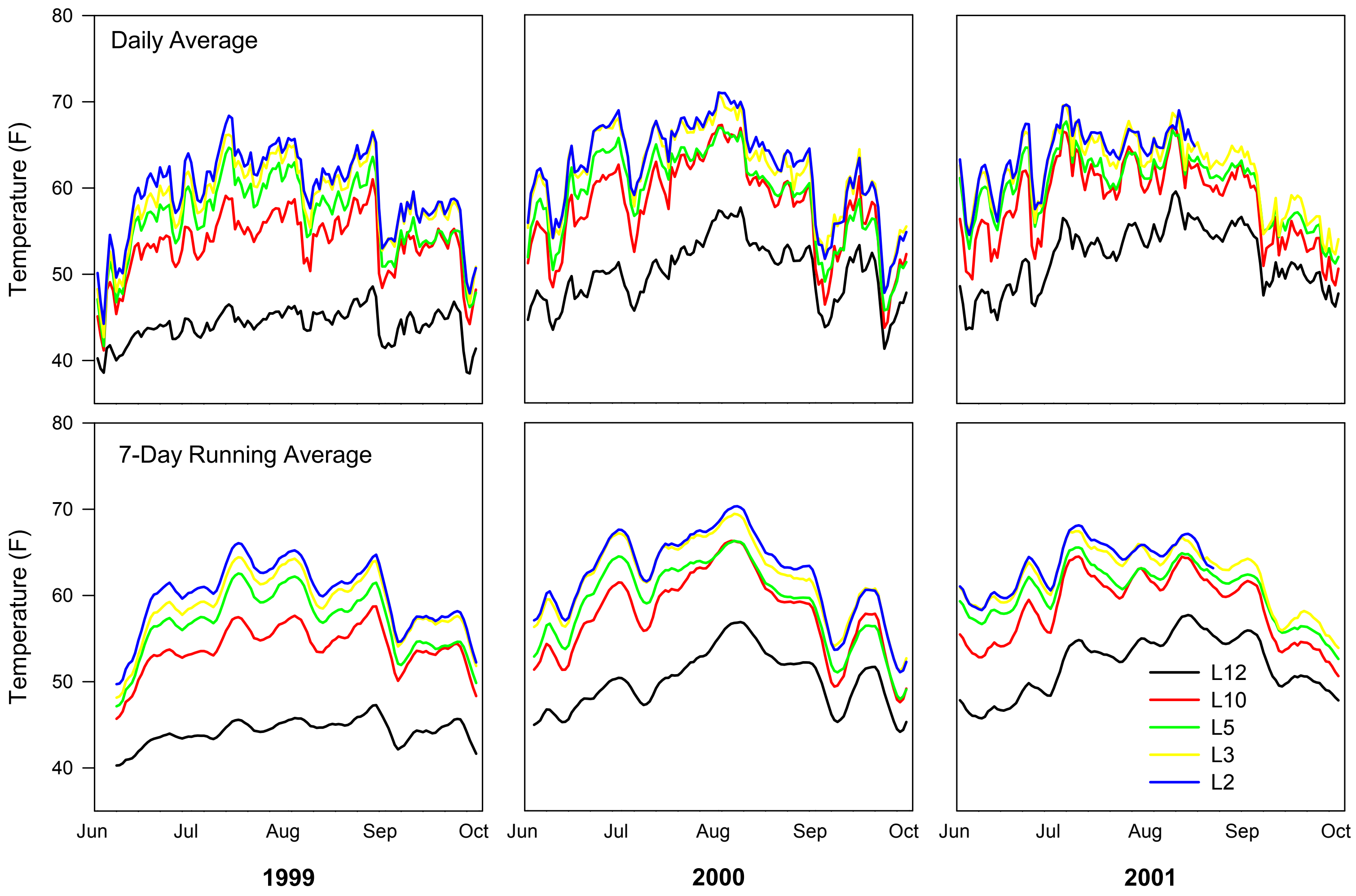
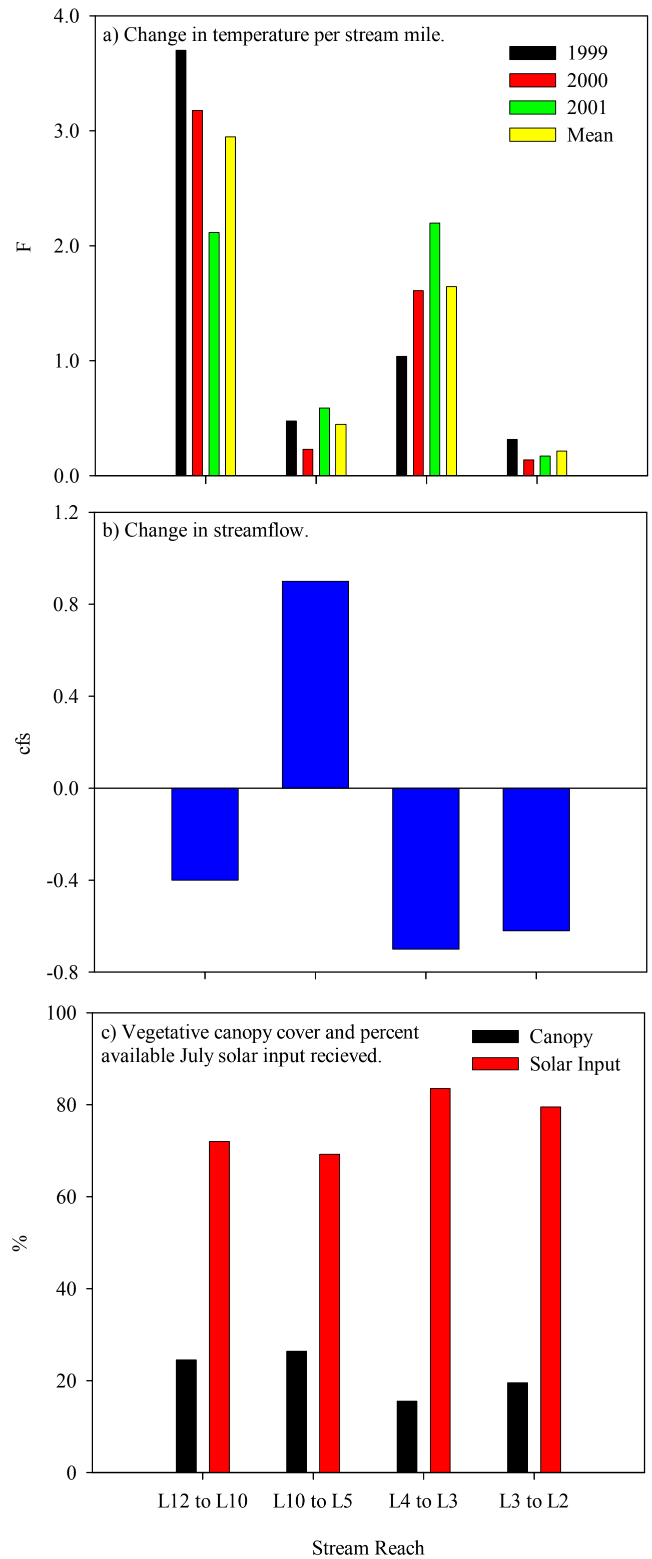

Daily Average
7-Day Running Average
Temperature (F)
Temperature (F)
80
70
60
50
40
Jun
Jul
Aug
Sep
Oct
L12
L10
L5
L3
L2
1999
2000
2001

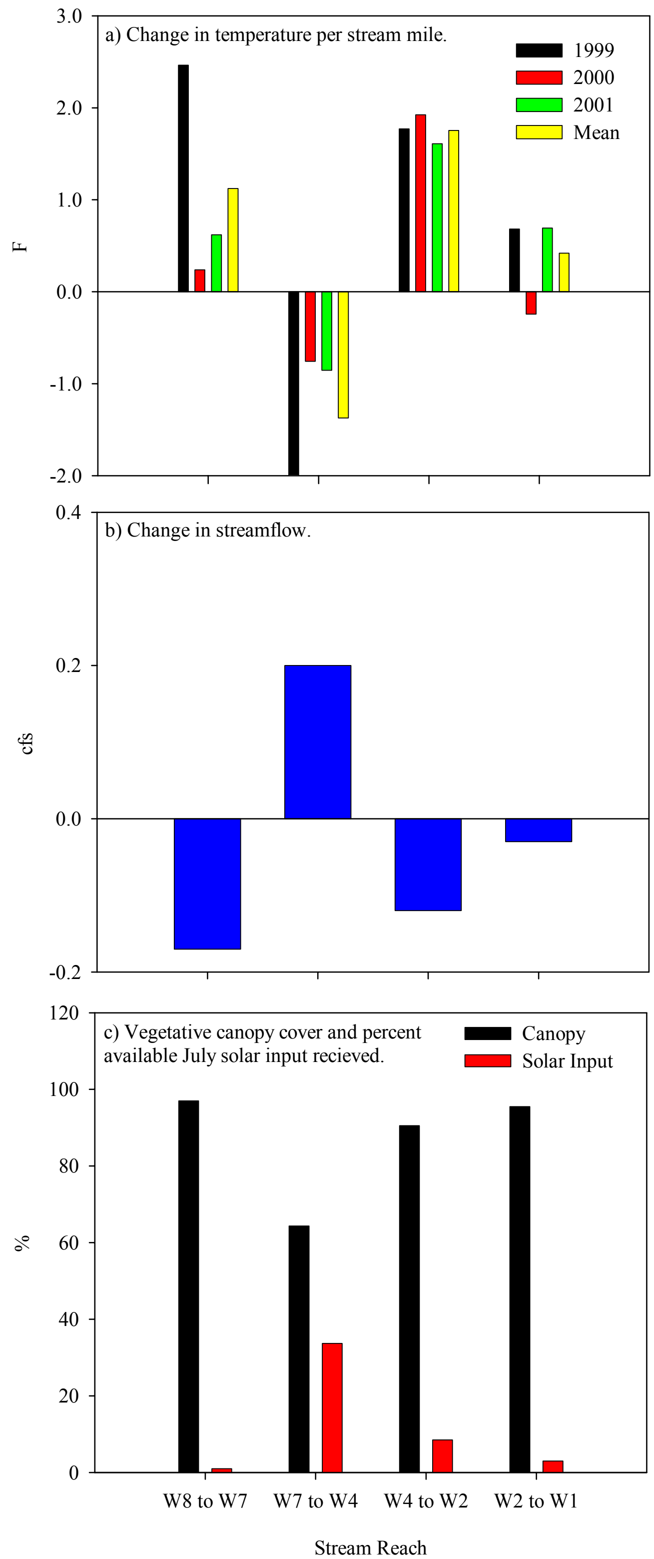
Figure 3.


Daily Average
7-Day Running Average
Temperature (F)
Temperature (F)
80
70
60
50
40
Jun
Jul
Aug
Sep
Oct
W8
W4
W2
W1
1999
2000
2001

Figure 4a, b, c.


a) Change in temperature per stream mile.
1999
2000
2001
Mean
F
4.0
3.0
2.0
1.0
0.0
b) Change in streamflow.
cfs
1.2
0.8
0.4
0.0
-0.4
-0.8
c) Vegetative canopy cover and percent available July solar input recieved.
Canopy
Solar Input
%
100
80
60
40
20
0
L12 to L10
L10 to L5
L4 to L3
L3 to L2
Stream Reach

1 Figure 5a, b, c.



2