EVALUATION OF STREAM TEMPERATURES BASED ON OBSERVATIONS OF JUVENILE COHO SALMON IN NORTHERN CALIFORNIA STREAMS

DAVID HINES
Campbell Timberland Management, Inc.
P. 0. Box 1228
Fort Bragg, CA 95437

JONATHAN AMBROSE
National Marine Fisheries Service
777 Sonoma Avenue, Room 325
Santa Rosa, CA 95404

ABSTRACT

Field observations of juvenile coho salmon, *Oncorhynchus kisutch*, rearing in coastal streams of northern Mendocino County, California, were used to define stream temperature thresholds. Data were collected over a five-year period from 1993 to 1997 at 32 sites in six watersheds. Ten stream temperature metrics, incorporating maximum weekly average temperatures (MWAT), and 19 instream habitat variables other than temperature were fit to presence and absence data using logistic regression. The best model suggests that the number of days a site exceeded an MWAT of 17.6°C was one of the most influential variables predicting coho salmon presence and absence. Stream temperature thresholds should therefore incorporate a time-of-exposure limit within a significant range of temperatures rather than the single MWAT magnitude limit. Certain habitat variables, in combination, also influenced the model, suggesting a synergistic interaction among variables controlling the distribution of juvenile coho salmon. Of the habitat variables, pool depth was the most influential.

INTRODUCTION

The survival of coho salmon, *Oncorhynchus kisutch*, is based on a dynamic interaction between the species and its environment. The relationship of rearing juveniles to stream temperature is one of many important components of this interaction. Elevated stream temperatures can place increased metabolic demands on juvenile coho salmon (Thomas et al. 1986) and directly or indirectly cause shifts in their distribution (Bjornn and Reiser 1991) in addition to the direct mortality associated with more dramatic shifts (Brett 1952). These consequences affect the probability of survival for coho salmon and can therefore reduce the production of individuals contributing to successive generations.

One of the first investigators to quantify the effects of temperature was Brett (1952) who estimated optimal temperature for juvenile coho salmon at 12°C to 14°C'. This was supported by the estimate of 11.8°C to 14.6°C by Reiser and Bjornn (1979). Brett (1952) provided the most thorough demonstration of upper temperature tolerance limits for Pacific salmon under laboratory conditions. His work is the ultimate source for most quantitative criteria used in the evaluation of water temperatures for the beneficial use by juvenile salmonids (Brungs and Jones 1977, Armour 1991). Others have demonstrated that elevated temperatures can induce behavioral (Nielsen and Lisle 1994) and physiological (Thomas et al. 1986) responses that adversely affect the growth and survival of juvenile salmonids (Hall and Lantz 1969, Holtby 1988, Li et al. 1994). The method of measuring these temperatures and the establishment of appropriate thresholds has not been consistently applied among land managers and regulatory agencies in California.

An essential component of assessing stream temperature conditions is the ability to know when the conditions are adversely affecting the species in question. It is the objective of this paper to quantitatively define the point at which chronic exposure to given temperatures have the greatest effect on deterring site selection by juvenile coho salmon. To achieve this, stream temperatures were correlated with juvenile coho salmon presence and absence. These observations of wild fish in their native environments served as a necessary complement to laboratory experiments. Without these, the influence of variation in natural temperature regimes, and other ecological factors, on the distribution of the species could not be determined.

The process of determining appropriate temperature thresholds included and evaluation of various temperature metrics and an analysis of the influence of temperature on coho site selection relative to the influence of other habitat variables. Finally, the results were applied in the development of a method for the evaluation of water temperature data.

METHODS

Study Area

The study area consists of six coastal watersheds ranging in size from 110,640 to 8,599 acres. All watersheds are located in the northwest portion Mendocino County, California between Usal Creek in the north and Salmon Creek in the south (Fig.1) and are therefore near the southern extent of the range of coho salmon. These watersheds are characterized by Franciscan sedimentary rock that has formed convoluted and sometimes steep terrain through erosional processes. They are also subject to the influence of fog and moderated air temperatures due to their proximity to the coast. The principal land use throughout the area is timber production. All six watersheds are in various stages of re-growth following timber harvest.

Sample sites, though concentrated in the Ten Mile River watershed, are distributed throughout the six watersheds. All sites are within 11 miles of the coast and under 600 feet in elevation. The distribution of sample sites is not necessarily representative of the range of conditions that coho salmon are subject to. It is, however, assumed, because of genetic similarities, the species physiological response to temperature is consistent within populations. It is also acknowledged that responses to temperature may vary in different ecological contexts.

In order to investigate how juvenile coho salmon distributed themselves within a system containing various habitat conditions, several criteria had to be met. First, all six watersheds chosen for study had to have coho salmon present in some portion of the watershed; conditions in unoccupied streams were not likely to provide meaningful habitat thresholds. Second, all 32 sample sites had to be located in places physically accessible to salmonids. All watersheds within the study area were habitat typed between 1994 and 1996 using the California Department of Fish and Game stream habitat typing protocol (Flosi and Reynolds, 1994). All sample sites were within stream reaches accessible to salmonids and were in low gradient, fish bearing streams, according to those results (Ambrose et. al.[3] 1996). Steelhead trout were present at all locations and there is evidence of historical coho salmon presence in over half of the sample locations where they were no longer found (California Department of Fish and Game[4] 1961 a, California Department of Fish and Game[5] 1961 b, Grass[6] 1983, Jones[7] 1991, Hines[8] 1998). As an additional requisite, all 32 sites contained five years (160 site-years) of multiple-pass depletion sampling of salmonids and continuous temperature monitoring data throughout the summer months for the same five years. Fourteen site-years were excluded from the analysis due to data gaps, leaving 146 site-years of data.

Selection of Thresholds to be Evaluated

Armour (1991) applied a method, originally developed by Brungs and Jones (1977) to establish theoretical temperature tolerance limits for fish. This method was intended to aid biologists in analyzing temperature regimes of streams and to prepare technically defensible recommendations for fish protection. In that report, Armour presented the following formula as a means of calculating such a threshold:

$$MWAT = OT + (UUILT - OT)/3$$

Where MWAT = maximum weekly average temperature, a theoretical value used to judge actual stream temperature conditions; OT = a reported optimal temperature for the particular life stage or function, and UUILT = the ultimate upper incipient lethal temperature (Fry et al. 1946), the upper lethal temperature where tolerance does not increase with increasing acclimation temperatures. The UUILT is also a time-of-exposure dependent 50% mortality value.

Armour (199 1) intended values entered into the MWAT formula to be based on experimental data. The result would be a recommendation of an upper temperature limit for a specific life stage of a particular species. However, estimates of OT and UUILT vary in the literature (Table 1). The resulting value of an MWAT threshold is therefore dependent upon which estimated OT and UUILT value is entered into the formula and can vary dramatically.

A search of this subject yielded estimates of MWAT thresholds ranging from a high of 19.6°C to a low of 15.9°C (Table 1). Five of these values were chosen to represent the full range of proposed values. Four additional values were included to ensure the significant thresholds were bracketed. The additional four were not based on the MWAT formula and were, in that respect, arbitrary.

The establishment of an MWAT threshold is meaningless unless the in situ stream temperature metric to which it is compared is defined. This study used a seven-day moving average of the daily maximum temperatures (7DMADM) to compare with the MWAT thresholds. Increases in daily maximum stream temperatures are often accompanied by reductions of daily minimums (Beschta et al. 1987). In such cases, daily maxima may increase while daily averages remain relatively constant. Therefore, metrics incorporating daily maximum temperatures are better able to discriminate temperature changes likely to be detrimental to salmonids. Additionally, the use of a moving average, as defined below, more closely reflects the temperatures actually experienced in the aquatic system (Ferraro et al. 1978) than a straight average. For these reasons and because the 7DMADM is being used as a standard in Oregon (DEQ 1995), it is used in this analysis.

Data Collection

Stream temperatures were recorded with Hobo Temp® temperature loggers. Temperature loggers typically recorded instream temperatures at 2.4-hour intervals, although some 1993 data were recorded at 1.2-hour intervals. Data included in this analysis were collected from 1993 through 1997 and were limited to an annual period of continuous sampling from the second week of June through the last week in October.

Observations of behavioral thermoregulation in juvenile salmonids confirm that they preferentially utilize pool habitats when thermally stressed (Nielsen 1992, Nielsen and Lisle 1994). Therefore, pools were determined to be the most appropriate habitat type for temperature measurements. Consequently, temperature loggers were placed in the water near the bottom of the deepest portion of the pool.

Fish sampling occurred during the months of August, September, and October. A backpack electrofisher was used for multiple-pass depletion sampling of a 30 to 50 meter reach of stream

(Reynolds 1996). Each segment included the pool where corresponding temperature data were collected.

Selection of Coho Site and Non-Coho Site Groups

The dataset described above was divided into two groups: 16 Coho Sites, and 16 Non-Coho Sites, with 73 site-years each. Criteria for designation as a Coho Site included, 1) detection of coho salmon for a minimum of two years, and 2) at least 0.02 fish $/m^2$ for at least one year at sites with only two years of coho salmon presence. The criterion of 0.02 fish/m^2 was established to exclude areas with extremely low coho salmon detections. In these cases, detections were assumed to be insignificant uses of habitat. Sites were designated as Non-Coho Sites if they did not meet these criteria.

Additional Habitat Variables

Of the 19 habitat variables analyzed, 17 were collected in the field and two derived from maps (Table 2). Streamflows were measured using a Marsh-McBimey Flo-Mate Model 2000 flow meter. Percent canopy was measured using a convex spherical densiometer. Stream dimensions were measured with a stadia rod. Habitat types, cover values, and substrate compositions were visually estimated. Visual estimation of stream habitat variables is an accepted method used by the California Department of Fish and Game in their stream habitat typing protocol (Flosi and Reynolds 1994). At least one of two permanent crew-members was present at all times to ensure consistency of the estimates. The two watershed variables, acres and aspect, were measured from topographic maps. The analysis of habitat variables was limited to 1996 and 1997 because the data was available only for those years.

Statistical Analysis

Logistic regression was used to relate stream temperature and habitat data to the presence and absence of coho salmon. Two methods of analysis involving logistic regression were used. First. each variable was considered independent of the others in a logistic curve-fitting analysis. The second logistic regression analysis considered the contribution of multiple variables to the probability of coho salmon presence. The basis of this type of regression is the linear relationship between the log of the odds ratio and a linear combination of habitat variables:

$$\log (p/l\text{-}p) = a + bX_1 + cX_2 + dX_3 + \ldots,$$

wherep is the probability that a stream will contain coho salmon, the X_is are the values of the various continuous habitat variables, and the, a, b, c, . . . are estimated constants.

An analysis of correlation and co-linearity among habitat variables was conducted prior to the multivariate logistic regression analysis. The regression assumes relationships among the independent variables are not co-linear. This preliminary analysis was also useful in exploring the relationships between habitat variables.

Ten alternative treatments of stream temperature data were fitted to logistic curves. The first nine sets consisted of the number of 7DMADM data days that exceeded a given threshold temperature (the nine MWAT thresholds) for both the Coho Sites and Non-Coho Sites. The tenth treatment consisted of the highest annual 7DMADM for Coho and Non-Coho Sites. This metric did not measure the amount of time a site exceeded a given threshold, as did the first nine. Habitat variables were also fit to logistic curves.

A multivariate logistic regression analysis was subsequently conducted for five of the ten sets of stream temperature data and 16 of the habitat variables. Inclusion of a variable in this analysis was based on its performance in the curve-fitting analysis and on the subjective judgment of the investigators. Certain variables such as highest annual 7DMADM and pool depth were included in spite of their poor performance in the curve-fitting analysis because they were regarded as potentially key variables. Even with the analysis limited to 2 1 variables, 2,097,15 1 possible models could have been developed. One hundred and fifteen models were actually analyzed. The number of models generated and the choice of variables included in each model was governed by the judgment of the investigators and by the necessity of having a manageable set of results. In particular, when the number of parameters exceeded 25% to 33% of the data points, models were judged over parameterized and were not considered.

The models were compared using the Akaike Information Criterion (AIC), the formula for which is:

AIC = -2*loglikelihood - 2*degrees of freedom.

The model with the lowest AIC best balances goodness of tit (small first term) with simplicity (large second term). The balance of these two terms represents the best combination of explanation and parsimony when considering the factors controlling the distribution of juvenile coho salmon.

AIC scores were then tested for significance using the Wilks' likelihood-ratio test (Wilks, 1938) as recommended by Agresti (1990). This test calculated $-2(L_2-L_1)$ where L_2 is the maximized log-likelihood of a reduced model with n-q parameters and L_1 is the maximized log-likelihood of a model with *n* parameters. This test statistic has a Chi-square (χ^2) distribution with *q* degrees of freedom. With q equal to one, the level of significance of p = 0.05, and χ^2 = 3.84.

RESULTS

Single Variable Analysis

When fitting individual variables to dichotomous variables using logistic regression, values of 0.2 to 0.4 are considered good fits (Hensher and Johnson 198 1). It should also be understood that the use of single variables to predict phenomenon driven by complex interactions will not produce very strong correlations. With these limitations in mind, the MWAT threshold values of 15.9°C, 16.8°C, 17.6°C, and 18.3°C all had enough influence on the observed variation of coho salmon presence and absence to warrant inclusion in the ensuing multivariate analysis (Table 3). The 17.6°C MWAT threshold explained the greatest degree of variability. The highest annual 7DMADM-temperature metric was among the lowest values for the temperature data set. In no case did the fitted logistic curve for a temperature metric exceed a probability of coho salmon presence of 50%. Data associated with the lower thresholds of 12°C, and 13°C did not relate well to coho salmon presence. Apart from temperature, acres and streamflow had the highest r^2 values.

Multivariate Logistic Regression Analysis

Ten variables were included in the multivariate analysis, including five temperature treatments. One hundred and twenty-four models were generated using subsets of these variables and were assigned AIC scores. Fourteen of the most instructive models are presented in Table 4. Model one had the lowest score of any and was, therefore, considered the combination of variables best explaining the probability of coho salmon presence. These variables were Days>17.6°C, Boulder (Cover), Boulders (Substrate), LWD (Cover), and Pool Depth. Model two is similar to model one except no temperature variable is included. The absence of the temperature variable significantly reduced the performance of the model (χ^2 = 36.3) and illustrates the importance of temperature to model one. Model three excludes all of the habitat variables other than temperature. The pronounced drop in performance (AIC = 161.85) demonstrates the important role these variables play in the model. Comparisons of model 3 with models where singular habitat variables were omitted illustrate the synergistic nature of these variables, Model seven is similar to model one except the Highest Annual 7DMADM treatment was substituted for Days>17.6°C. The significant reduction in model performance (χ^2 = 16.2) was useful in establishing the superiority of a metric containing the duration of temperature exceedence over a metric of magnitude of temperature exceedence. Model twelve is similar to model one except for the absence of the Pool Depth variable. It too was significantly less able to predict coho salmon presence (χ^2 = 13.8). Pool Depth had a greater influence than any other habitat variable, other than temperature, on the model. Models one, four, five, and six compare and evaluate the performance of the four most promising threshold candidates: Days>15.9°C, Days>16.8°C, Days>17.6°C, and Days>18.3°C, all of which were substituted as the temperature treatment in their respective models. Model one, with Days>17.6°C, was significantly better than the others (χ^2 = 14.3, 11.6, and 14.8 respectively), which established it as the most predictive temperature metric. However, models four, five, and six demonstrate that their respective threshold values still significantly contribute to model performances.

Fig. 2 represents the average temperature conditions for Coho Sites and is the proposed threshold condition. Fig. 3 demonstrates how site-specific data can be plotted onto the threshold curve for comparison.

The proposed temperature threshold is, therefore, expressed as the time-of-exposure to each of these temperatures within a significant range (Fig. 2). The proposed duration curve also represents the average conditions for juvenile coho salmon. Temperature monitoring data can then be plotted against this duration curve as a means of evaluating the site-specific data. In the example given, the site should be considered temperature limiting because it exceeds the threshold curve at 15.9°C (Fig. 3).

DISCUSSION

The initial goal of this study was to evaluate several proposed MWAT thresholds using field-based observations of the presence and absence of juvenile coho salmon. As the analysis developed, it became apparent that the existing method of setting MWAT thresholds using temperature magnitude limits was not the most biologically relevant approach. Single temperature values, represented by conventional MWAT thresholds (i. e. magnitude limits), correlated poorly with presence and absence. The evaluation of stream temperature conditions using a time-of-exposure curve (i.e. the time a site is above a given temperature) (Fig. 2) provides a more meaningful assessment in that it is associated with observed summer habitat selection of wild juvenile coho salmon. The suggested duration curve is simply a measure of how many times a given MWAT value was exceeded.

The purpose of a threshold is to discriminate favorable from unfavorable conditions. Existing forms of the MWAT metric fail in this regard, because they do not adequately account for how often and how long a given threshold is exceeded. The MWAT, by definition, incorporates a time-of-exposure component, in the form of a weekly average, but this did not establish an association with fish habitat selection. This was evidenced in both the curve-fitting analysis and in the multivariate logistic regression analysis. When Days > 17.6°C was used in the logistic regression model (Table 4, model one), it scored significantly better than did the Highest Annual 7DMADM metric (χ^2 = 16.2). Clearly, the number of days a site exceeds an MWAT of 17.6°C is more useful than the magnitude of its highest 7DMADM in predicting whether or not juvenile coho salmon will be present in a given habitat.

With the suggested threshold format, there is no single temperature that, if exceeded, would be considered detrimental to coho salmon. Rather, there would be a limit to the number of days each temperature could be exceeded within a significant range of temperatures (Fig 2). As the temperature increased, the allowable exceedence would decrease. Any value above this curve would be considered unfavorable to juvenile coho salmon use; particularly if it exceeded the limit of the upper confidence intervals. The curve in Fig. 2 was based on the average conditions for coho salmon presence. This threshold curve was defined, in part, by the total number of days in the temperature sample and by the time of year the sample was taken. For this data set, the sample window consisted of a thirteen-week period defined as the 24th week of the year through the 35th week. This corresponds roughly to a sample period beginning in mid-June and lasting into early September. It is imperative that any comparison of site data to this threshold have the same sample window.

An important consideration in determining thresholds from field observations is that fish presence is only one measure of success. Persistence of fish under certain conditions does not imply health or success. The assumption that average conditions where fish are present will suffice as target conditions may jeopardize the population if they are not actually thriving. For example, fish may be present at temperatures warmer than optimal for growth. This can adversely effect growth of juvenile coho salmon, decreasing their size at smoltification (Holtby 1988). This, in turn, can effect their survival at sea and diminish the number of adults returning to spawn (Pearcy 1992). Although fish may persist, temperature conditions may be contributing to their decline. Therefore, setting a threshold curve based on the average condition of occupied sites does not necessarily reflect ideal temperature conditions for survival of juvenile coho salmon rearing in streams. It does however, provide a reasonable way to rule out unacceptable temperature conditions. Because of the potential for this method to overestimate properly functioning temperature conditions, it should be considered a liberal threshold definition. Its primary purpose should be to rule out proposed thresholds in the higher temperature range. More discriminating thresholds will need to use condition factors of fish in natural environments in order to demonstrate that average conditions are not adequate for the protection of juvenile coho salmon.

Another important function of the multivariate analysis was to establish the relative importance of each variable to the presence and absence of coho salmon. A comparison of models one and two in Table 4 demonstrates that water temperatures were significantly influencing the observed variability in coho salmon presence and absence. However, model three, with all the habitat variables absent, scored very poorly. This clearly indicated that temperature was not alone in influencing the presence of coho salmon. But, when removed one at a time, the habitat variables did not affect the model dramatically. It therefore appears the variables, in combination, create a synergistic effect far exceeding that of any individual variable.

A comparison of models one and 12 in Table 4 suggests pool depth was second only to temperature in its importance as a factor in site selection by coho salmon. Though ancillary to the focus of this study, this observation provides useful support to suggestions that pool habitat is important to juvenile salmonids (Ruggles 1966, Nielsen 1992, Matthews et al. 1994, Nakamoto 1994, Nielsen and Lisle 1994). Deep pools are often associated with cooler water temperatures. both of which were associated with coho salmon presence in this study.

A comparison of models, one, four, five, and six illustrate the relative importance of the four top candidates for stream temperature threshold. In this case 17.6°C is the best performer with the others being slightly less influential. If a simple threshold were to be considered best, it would be 17.6°C. However, for reasons already described, a stand alone number is not recommended.

The map in Fig. 1 shows the distribution of Non-Coho Sites was skewed toward the upper reaches of the study streams, particularly within the Ten Mile River watershed. This suggests the possibility that stream gradient could be controlling the distribution of coho salmon. While this may be possible, all streams within the study area, including the upper reaches of the Ten Mile river, were surveyed according the California Department of Fish and Game stream habitat typing protocol (Flosi and Reynolds 1994). These surveys indicated that access was not restricted by gradient or by any other factor.

Summary

Stream temperature thresholds used as water quality standards for the protection of juvenile coho salmon habitat should take into account the amount of time a site is at or above a given temperature (i.e. time-of-exposure). A meaningful threshold can be defined at or below average conditions for habitats where coho salmon are present. However, it must be understood that this does not necessarily represent ideal conditions. This approach would be no less restrictive than a conventional MWAT threshold, yet it seems to provide a stronger relation to fish habitat selection in northern California. Because fish presence does not necessarily signify optimal environmental conditions, further field investigations into the condition of the fish should be performed as an additional biological foundation for the establishment of any threshold proposed as a standard of protection.

ACKNOWLEDGMENTS

The authors would like to thank the following people who have assisted in data collection over the past five years: E. Bell, T. Burnett, J. Dreier, J. Drew, J. Feola, J. Gragg, A. Hayes, D. Hines, D. Lundby, S. Montgomery, K. Roberts, and D. Wright. Thanks also to R. Taylor for his statistical services and guidance, S. Kramer for her editorial comments, T. Lewis and the Forest Science Project for assistance with data compilation, and D. White for her statistical contributions.

LITERATURE CITED

Agresti, A. 1990. Categorical data analysis. J. Wiley & Sons, New York, New York, USA.

Armour, C. L. 1991. Guidance for evaluating and recommending temperature regimes to protect fish. Instream flow information paper 27 US Fish and Wildlife Service, Biological Report. 90(22), Fort Collins, Colorado.

Becker, C. D., and R. G. Genoway. 1979. Evaluation of the critical thermal maximum for determining thermal tolerance of freshwater fish. Environmental Biology of Fishes 4:245-256.

Beschta, R. L., R. E. Bilby, G. W. Brown, L. B. Hdltby, and T. D. Hofstra. 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions. Pages 19l-232 *in* Salo and Cundy, editors. Streamside Management: Forestry and fishery interactions. University of Washington Institute of Forest Resources, Contribution 57, Seattle, Washington, USA.

Bjornn, T. C., and D. W. Reiser. 1991. Habitat requirements of salmonids in streams. Pages 83-138 *in:* W. R. Meehan, editor. Influences of forest and rangeland management on salmonid fishes and their habitat. American Fisheries Society Special Publication 19.

Brett, J. R. 1952. Temperature tolerance in young Pacific salmon, genus *Oncorhynchus.* Journal of the Fisheries Research Board of Canada 9:265-323.

Brungs, W. A., and B. R. Jones. 1977. Temperature criteria for freshwater fish: protocol and procedures. US Environmental Protection Agency, Environmental Research Laboratory, EPA-600/3-77-061, Duluth, Minnesota, USA.

DEQ (Oregon Department of Environmental Quality). 1994. 1992- 1994 water quality standards review. Final issue papers: Temperature, Portland, Oregon, USA.

Feraro, F. A., A. E. Gaulke, and C. M. Loeffelman. 1978. Maximum weekly average temperature for 3 16(a) demonstrations. Pages 1255-l 36 in Biological Data *in* Water Pollution Assessment: Quantitative and Statistical Analyses. ASTM STP 652. K. L. Dickson, et al., editors. American Society for Testing and Materials, Philadelphia, Pennsylvania, USA.

Fry, F. E., J. S. Hart, and K. F. Walker. 1946. Lethal temperature relations for a sample of young speckled trout, *Salvelinus fontinalis*. University of Toronto Stud., Biological Service, Ontario Fisheries Research Laboratory 66:9-35.

Hall, J. D., and R. L. Lantz. 1969. Effects of logging on the habitat of coho salmon and cutthroat trout in coastal streams. Pages 355-375 *in* T. G. Northcote, editor. Symposium on salmon and trout in streams. H. R. MacMillan Lectures in Fisheries. University of British Columbia, Vancouver, Canada.

Hensher, Johnson. 1981. Applied discrete-choice modeling. Croom Helm, London, England.

Holtby, L. B. 1988. Effects of logging on stream temperatures in Carnation Creek, British Columbia, and associated impacts on the coho salmon *(Oncorhynchus kisutch)*. Canadian Journal of Fisheries and Aquatic Sciences 45:502-515.

Li, H. W., G. A. Lamberti, T. N. Pearsons, C. K. Tait, J. L. Li, and J. C. Buckhouse. 1994. Cumulative effects of riparian disturbances along high desert trout streams of the John Day Basin, Oregon. Transactions of the American Fisheries Society 123:627-640.

Matthews, K. R., N. H. Berg, D. L. Azuma, and T. R. Lambert. 1994. Cool water formation and trout habitat use in a deep pool in the Sierra Nevada, California. Transactions of the American Fisheries Society 123:549-564.

Nakamoto, R. J. 1994. Characteristics of pools used by adult summer steelhead oversummering in the New River, California. Transactions of the American Fisheries Society 123:757-765.

Nielsen, J. L. 1992. The role of cold-pool refugia in the freshwater fish assemblage in northern California rivers. Pages 79-88 *in* H. Kemer, editor. Proceedings of the symposium on biodiversity of northwestern California. University of California, Berkeley, USA.

Nielsen, J. L., and T. E. Lisle. 1994. Thermally stratified pools and their use by steelhead in northern California streams. Transactions of the American Fisheries Society 123: 613-626.

Pearcy, W. G. 1992. Ocean ecology of north Pacific salmonids. University of Washington Press, Seattle, Washington, USA.

Reiser, D. W., and T. C. Bjornn. 1979. Influence of forest and rangeland management on anadromous fish habitat in western north America: Habitat requirements of anadromous salmonids. Idaho Cooperative Fisheries Research Unit, University of Idaho. US Forest Service, Technical Report PNW-96, Moscow, Idaho, USA.

Reynolds, J. B. 1996. Electrofishing. Pages 221-251 *in* B. R. Murphy and D. W. Willis, editors. Fisheries techniques, 2nd edition. American Fisheries Society, Bethesda, Maryland, USA.

Ruggles, C. P. 1966. Depth and velocity as a factor in stream rearing and production of juvenile coho salmon. Canadian Fish Culturist 38:35-53.

Thomas, R. E., J. A. Gharrett, M. G. Carls, S. D. Rice, A. Moles, and S. Kom. 1986. Effects of fluctuating temperature on mortality, stress, and energy reserves of juvenile coho salmon. Transactions of the American Fisheries Society 115:52-59.

Wilks, S. S. 1938. The large-sample distribution of the likelihood-ratio for testing composite hypotheses. Annual Mathematics Statistics 9:60-62.

FOOTNOTES

1 This estimate of optimal temperature was mentioned as part of a general narrative in which Brett lumped the results of pink, sockeye, chum, and coho salmon together. However, when he presented the optimal temperatures graphically by individual species the mean value for coho salmon was slightly above 10°C with a standard deviation of approximately 1 °C ,

2 Flosi, G., and F. L. Reynolds. 1994. California salmonid stream habitat restoration manual, 2nd edition. California Department of Fish and Game, Sacramento, California, USA.

3 Ambrose, J., D. H. Hines, D. I. Hines, D. Lundby, J. Drew. 1996. Ten mile river watershed 1995 instream monitoring results. Unpublished report. Georgia-Pacific West, Inc., Fort Bragg, California, USA.

4 California Department of Fish and Game. 1961a. Stream survey of the south fork ten mile river. Unpublished report. Ukiah, California, USA.

5 California Department of Fish and Game. 1961b. Stream survey of redwood creek. Unpublished report. Ukiah, California, USA.

6 Grass, A. 1983. Field Note. Unpublished electrofishing records for the ten mile river. California Department of Fish and Game, Ukiah, California, USA.

7 Jones, W. 1991. Unpublished electrofishing records for the ten mile river. California Department of Fish and Game, Ukiah, California, USA.

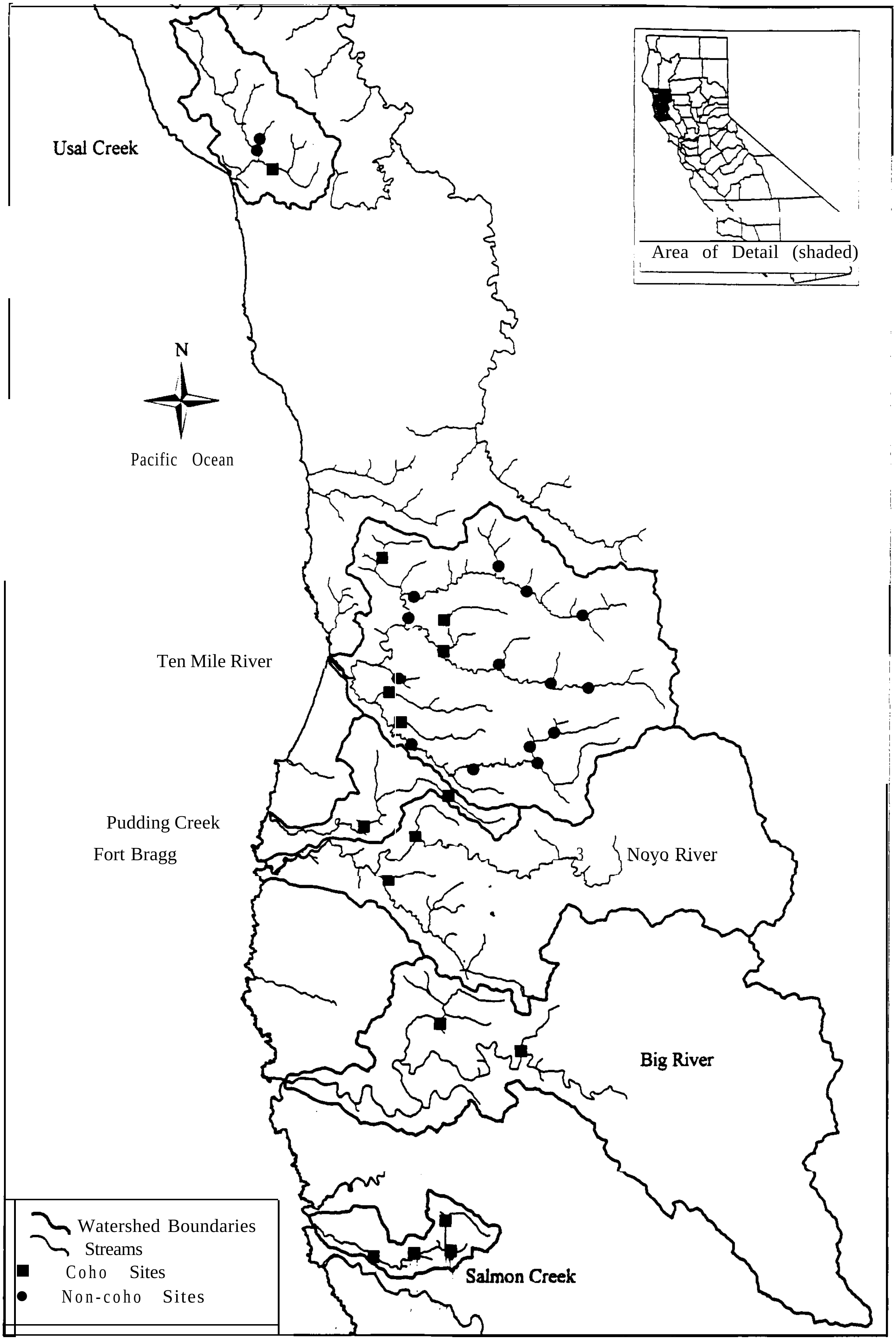
8 Hines, D. 1998. . Unpublished electrofishing records for the ten mile river. Georgia-Pacific West, Inc., Fort Bragg, California, USA.

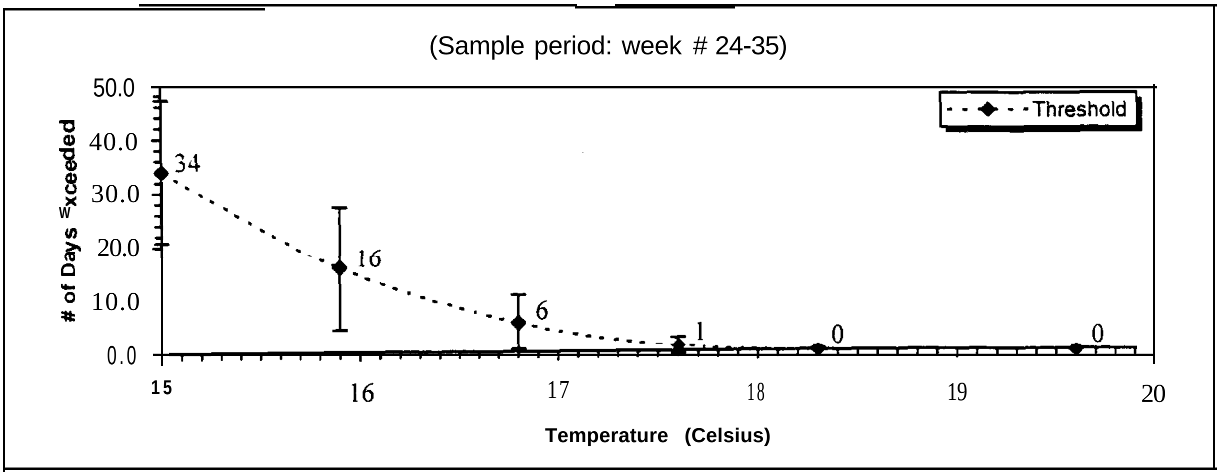
FIGURE CAPTIONS

Figure 1. Study area, sample sites and indications of juvenile coho salmon presence and absence used in the analysis of stream temperature data.

Figure 2. Proposed chronic stream temperature threshold. The duration of exposures for the given temperatures also represent average temperature conditions for juvenile coho salmon in the study. Error bars indicate 95% confidence intervals.

Figure 3. Example of site data plotted against proposed chronic stream temperature threshold. Error bars indicate 95% confidence intervals.


Usal Creek
Area of Detail (shaded)
N
Pacific Ocean
Ten Mile River
Pudding Creek
Fort Bragg
Noyo River
Big River
Salmon Creek
Watershed Boundaries
Streams
Coho Sites
Non-coho Sites


(Sample period: week # 24-35)
Threshold
# of Days Exceeded
50.0
40.0
30.0
20.0
10.0
0.0
34
16
6
1
0
0
15
16
17
18
19
20
Temperature (Celsius)

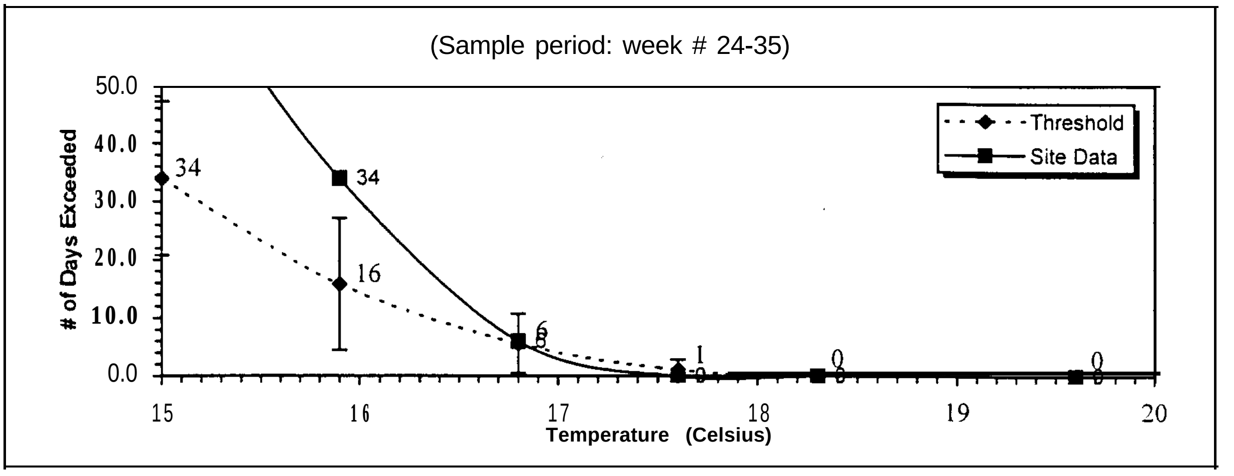

(Sample period: week # 24-35)
# of Days Exceeded
50.0
40.0
30.0
20.0
10.0
0.0
15
16
17
18
19
20
Temperature (Celsius)
Threshold
Site Data
34
34
16
6
1
0
0

Table 1. MWAT thresholds and associated references evaluated for their effectiveness using observations of coho salmon presence and absence on managed forestlands in Northern California.

MWAT	OT	Source	UUILT	Source
19.6	15.0	(USDI 1970 *in* Brungs and Jones 1977)	28.8	(Becker and Genoway 1979)
18.3	15.0	(USDI 1970 *in* Brungs and Jones 1977)	25.0	(Brett 1952)
17.6	14.0	(Brett 1952)	25.0	(Brett 1952)
16.8	13.2	(Reiser and Bjom 1979)	24.0	(Brett 1952 *in* Brungs and Jones 1977)
15.9	11.8	(Reiser and Bjom 1979)	24.0	(Brett 1952 *in* Brungs and Jones 1977)
15.0	none		none	
14.0	none		none	
13.0	none		none	
12.0	none		none	

Table 2. Definitions of habitat variables collected at 32 monitoring sites on managed forestlands in the study area. These variables were tested for correlations with the presence and absence of juvenile coho salmon.

Name	Definition
% canopy	Average percent canopy cover over stream at sample site
% Pool	Percent of surface area occupied by pool
% Riffle	Percent of surface area occupied by riffle
% Run	Percent of surface area occupied by run
Acres	Acres of watershed draining into a given site
Aspect	Cardinal direction of stream flow
Pool depth	Deepest portion of sample unit
Relative cover:	Percent contribution of each cover type to the total instream cover
Boulder	Any inorganic substrate providing cover
LWD	Large woody debris (diameter>3Ocm)
Terrestrial vegetation	Overhanging vegetation
SWD	Small woody debris (diameter<3Ocm)
Undercut	Undercut stream bank

Table 2. Continued

Name	Definition
Stream flow	Surface water flow in cubic meters per second
Substrate composition	Surface area of wetted channel represented by each category given as a percent of the total
Bedrock	Solid rock (consolidated substrate)
Boulder	Substrate >25cm in diameter
Fines	Substrate <2mm in diameter
Gravel	Substrate 2mm-6cm in diameter
Large cobble	Substrate 13-25cm in diameter
Small cobble	Substrate 6-13cm in diameter
Total % cover	Percent of surface area occupied by instream cover

Table 3. Coefficients of determination for variables fit to the logistic curve derived from juvenile coho salmon presence/absence data collected from 1993 through 1997 on managed forestlands in the study area.

Variable	r^2	Variable	r^2
12°C	0.001	Aspect	0.020
13°C	0.003	Bedrock	0.006
14°C	0.012	Boulder	0.049
15°C	0.069	Boulders	0.092
15.9°C	0.135	Fines	0.010
16.8°C	0.163	Gravel	0.010
17.6°C	0.171	Large Cobble	0.057
18.3°C	0.118	LWD	0.032
19.6°C	0.038	Terrestrial Veg.	0.056
Highest annual 7DMADM	0.002	Small Cobble	0.009
% canopy	0.000	Stream Flow	0.118
% Pool	0.000	SWD	0.011
% Riffle	0.005	Total % Cover	0.00 1
% Run	0.037	Undercut	0.023
Acres	0.110	Pool Depth	0.002

Table 4. Multivariate logistic regression models useful in describing the relationship of habitat variables to the presence and absence of coho salmon within the study area. The X symbol indicates the variable in the respective row was included in the model. The AIC score reflects the model's performance. The model with the lowest score is best able to explain the presence and absence of juvenile coho salmon. The log-likelihood is used for significance testing.

	Model #													
Variable	1	2	3	4	5	6	7	8	2	10	11	12	13	14
Days >15.9°C				X										
Days >16.8°C					X									
Days >17.6°C	X		X					X	X	X	X	X	X	X
Days >18.3°C						X								
H. A. 7DMADM							X							
Boulder (cover)	X	X		X	X	X	X	X		X	X	X		
Boulders (substrate)	X	X		X	X	X	X	X	X		X	X	X	
LWD (cover)	X	X		X	X	X	X	X	X	X		X		X
Ter. veg. (cover)								X	X	X	X	X		X
Pool depth	X	X		X	X	X	X	X	X	X	X		X	X
AIC score	35.6	73.6	161.9	48.5	45.9	49.0	54.5	36.2	38.8	37.3	38.0	48.1	38.6	81.7
Log-likelihood	-11.79	-31.79	-78.93	-18.27	-16.93	-18.51	-21.23	-11.12	-12.41	-12.65	-12.99	-18.03	-15.27	-35.85