WESTERN WATERSHED ANALYSTS
313 D Street, Suite 203
Lewiston, Idaho 83501
(208) 743-1826 • FAX (208) 746-7468

BioAnalysts, Inc.™

APPLICATION OF NEW APPROACHES TO WATER QUALITY TEMPERATURE CRITERIA

CHIWAWA RIVER CASE STUDY

For

Idaho Department of Environmental Quality
1410 North Hilton
Boise, Idaho 83706

March 2002

Table of Contents

I. Introduction 2
II. Case Study Area 3
  A. Sub-basin Selection 3
  B. General Characteristics of the Chiwawa Basin 3
  C. Hydrology 5
  D. Geomorphology 5
  E. Land Uses 6
  F. Vegetative Characteristics 6
III. Salmonid Species and Distribution 9
IV. Water Temperature Modeling and Model Sensitivity 11
V. Data Sources, Model Calibration and Validation 12
VI. Natural Thermal Potential 15
  A. Stream Channels 16
  B. Groundwater 17
  C. Streamflow 18
  D. Meteorologic Factors 18
  E. Vegetative Shade 19
  F. NTP Modeling Results 22
  G. Modeling Uncertainty 24
VII. Reconciliation of Biological Criteria and NTP 29
VIII. Practicality of Application 33
  A. Geomorphology and Management History 33
  B. Current Species Distribution 33
  C. Potential Species Distribution 33
  D. Current Thermal Conditions 34
  E. Natural Thermal Potential 35
  F. Time Requirements 37
IX. Discussion 38
X. Summary 39
XI. Literature Cited 40
XII. Appendices 44

I. INTRODUCTION

The EPA Region 10 has developed draft guidance for how states and authorized tribes may adopt water quality standards for temperature that will support native salmonid populations and meet the requirements of the Clean Water Act and Endangered Species Act (EPA, 2001). The guidance requires estimation of the natural thermal potential (NTP) of mainstem river and tributary reaches within sub-basins through modeling or other estimation procedures. EPA defines NTP as the thermal regime that existed prior to Euro-American Settlement. The guidance also recommends "species-life stage numeric criteria" that the EPA believes represent thermal conditions that are protective of native salmonids that would apply where and when the different life stages occur. Maps are to be prepared that describe the potential distribution of each guild and life-stage within sub-basins. The species-life stage numeric criteria would then apply until "thermal potential numeric criteria" are developed from the NTP in a process that may accommodate some level of anthropogenic impact. The thermal potential numeric criteria would then replace the species-life stage numeric criteria as a spatially explicit distribution of temperatures across the sub-basin.

This case study was developed to examine application of the EPA guidance in a real watershed. Key requirements for the case study include:

- Choose a test watershed that is generally representative of watersheds in Idaho, Oregon, and Washington, with anadromous salmon and bull trout fisheries, and that is known to have data readily available to support the required modeling and fish distribution mapping requirements.
- Assemble the required watershed data, track the sources of the data, and track the effort required to acquire and assemble it.
- Model the current thermal regime of the mainstem and tributaries, and model the NTP through estimation of current versus historical conditions of streamflow, channel morphology, groundwater, meteorology, and riparian vegetation. Include parameter sensitivity analysis, error analysis, and model validation procedures.
- Map existing and potential species-life stage occurrence and time of occupancy in the mainstem and tributaries.
- Integrate and reconcile the NTP with the species-life stage numeric criteria.
- Illustrate how the temperature criteria would be applied across the test watershed.
- Discuss application of the Guidance and temperature criteria to real watershed conditions, including assessment of relative difficulty of application.

II. CASE STUDY AREA

A. Sub-basin Selection

A number of sub-basins were suggested as candidates for the case study, and the suitability and feasibility of each was examined. Eventually we narrowed our recommendation to two basins with a diversity of fish species where both physical and biological data were readily accessible within a short time frame: the Umatilla River in northeastern Oregon, and the Chiwawa River in north central Washington.

The Umatilla basin contains substantial agricultural and other land uses that likely have altered its thermal regime. These circumstances would provide a challenging effort to estimate the NTP that existed prior to Euro-American settlement, a good demonstration of the effort required to do so, and an examination of the degree of uncertainty entailed.

In contrast, the Chiwawa River watershed is almost entirely forestland managed by the US Forest Service (USFS), and has experienced management on only approximately 15% of its area, predominantly in the lower portions of the watershed near its confluence with the Wenatchee River. It also contains a wide array of fish species throughout the watershed. These circumstances would allow estimation of NTP with relatively high certainty, but would not provide a rigorous examination of the difficulty of NTP estimation where the watershed and streams had been subject to substantial anthropogenic influence.

The EPA's Technical Workgroup considered the relative merits of these two basins and chose by a narrow margin to pursue the test case in the Chiwawa watershed.

B. General Characteristics of the Chiwawa Basin

The Chiwawa River is a fourth-order stream in Chelan County in north central Washington with a drainage area of about 189 mi^2.[1] The river flows primarily through the Wenatchee National Forest with 96% of the basin managed by the USFS. The upper 32% of the watershed is designated wilderness with nearly an additional one-third of the watershed managed to date as roadless area. The Chiwawa sub-basin is located on the east side of the Cascade crest and flows southeasterly for approximately 61 kilometers to its confluence with the Wenatchee River near Plain. The river has been described as a cold, low conductive stream bounded within a U-shaped valley by steep-sided, heavily forested mountains with flows sustained by snowfields and glaciers in summer and fall (Mullan et al, 1992). Precipitation in the basin averages 80 inches per year, ranging from 30 inches near the Wenatchee River to 140 inches at higher elevations near the Cascade crest. Snowfall is heavy, averaging 225 inches per year. Elevations range from 1,880 to 9,082 feet.

[1] From GIS based on USGS 7.5 minute topographic maps.

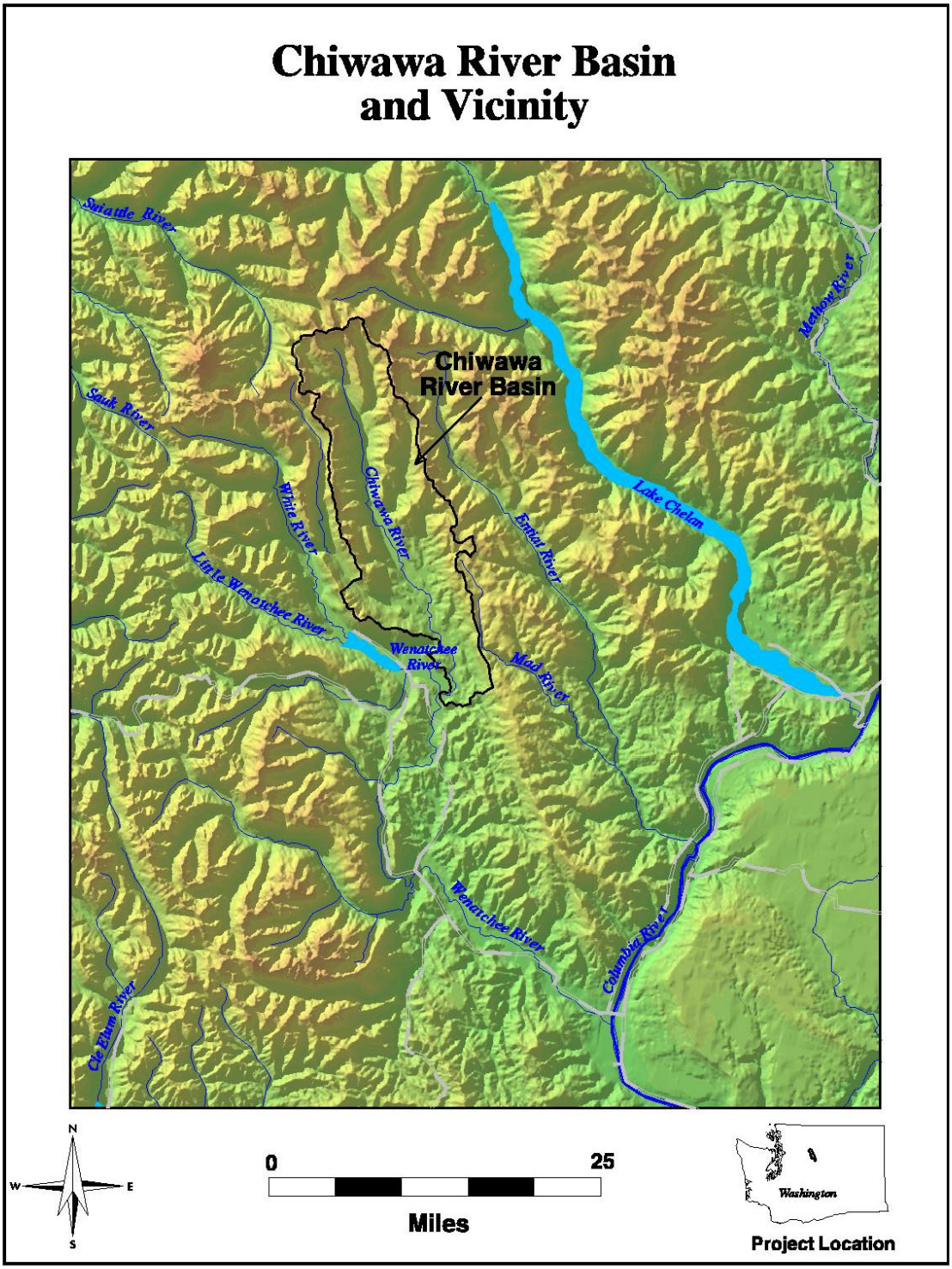


Figure 1. Location of Chiwawa watershed in north central Washington.

C. Hydrology

Mean annual flow of the Chiwawa River at the USGS gauging station number 12456500, located at approximately river kilometer 10.7, with an upstream drainage area of 170 mi^2, is 488 cfs. Maximum peak flow events typically occur as mid-winter rain-on-snow events, with maximum annual peak flows also occurring as spring snowmelt events. Persistent snowfields at upper elevations maintain relatively favorable flow regimes in the river well into late summer. Summer low flows generally occur in late August to early September, but may occur as early as late July or as late as the first half of October. Flood magnitudes for the river as reported by the US Forest Service (1977) are shown in Table 1.

Table 1. Chiwawa River Gauge Flood Magnitudes

Return Interval (Years)	2	5	10	25	50	100
Flood Magnitude (cfs)	3,027	4,180	4,885	5,710	6,244	6,846

D. Geomorphology

The Chiwawa River Basin is underlain by Cretaceous igneous rocks, with sedimentary rocks in the lower reaches and near the mouth. Alpine glaciation has formed a classic U-shaped valley within these formations. Detailed geomorphic descriptions of the watershed, the river, and tributaries, by reach, are provided by the Chiwawa Watershed Assessment (USFS, 1977). Glacial drift and alluvial formations heavily influence the character of the river and stream network. Mainstem river gradients remain well below 1% for over 80% of the river's total length. The central half of the mainstem valley from Brush Creek to Phelps Creeks (river kilometer 20 to 52) is broad and flat due to glacial moraines that were deposited near the mouth of Brush Creek. The river is typically wide, shallow, sinuous and naturally unstable as it meanders through and reworks glacial alluvium within these reaches. This natural character of the river creates young alluvial bars and persistent wetland meadows and brush fields near the channel that reduce stream shade below levels that would be found if the channel were bordered by forest.

Gradients progressively increase in the river's headwaters above Phelps Creek and in its tributaries. An exception to this rule is Big Meadow Creek, which runs at low gradient for approximately five kilometers through a remnant glacial lake that has evolved into a brushy meadow. Mainstem gradient increases (but remains below 1%), the channel narrows somewhat, and the river becomes far less sinuous below Brush and Chikamin Creeks.

E. Land Uses

Logging has occurred on only 15% of the basin, nearly all of which occurred in the lower one-third of the basin. Logging began some time in the early 1900's, and was heaviest from 1960 through 1990. Log drives down the lower sections of the river reputedly occurred annually in the 1920's to early 1930's (USFS, 1997). Acreage logged since 1990 totals approximately 1,000 acres (less than one percent of sub-basin area), and units are primarily located near ridge tops remote from all but the smallest streams. The heaviest logging, 35% of watershed area through 50 or more years, has occurred within Big Meadow and Brush Creeks, two adjacent 6th field watersheds (USFS, 1997).

There are two water diversions in the Chiwawa basin: no more than 16 cfs for irrigation at river kilometer 5.8 in the Chiwawa River; and 1/3 of total flow or 5 cfs, whichever is smaller, for the lower 4 kilometers of Phelps Creek. Mining activity has occurred in the Phelps and Chikamin Creek drainages, but no mines have been active since 1997. Grazing within three adjacent lower Chiwawa River tributaries, Clear Creek, Deep Creek, and Goose Creek, was reported to have caused some loss of shrub vegetation adjacent to streams within meadow areas based on assessment of 1992 aerial photos (USFS, 1997). Residential and agricultural development occurs adjacent to the river within a patchwork of forests for approximately six kilometers upstream of its confluence with the Wenatchee River.

F. Vegetative Characteristics

The Chiwawa watershed has a wide array of vegetative types. 74% of total acreage is conifer forest, 3% deciduous forest, and the remaining 23% is non-forested shrubs, meadows, and rocks (USFS, 1997). Dominant vegetative groups include subalpine communities at the higher elevations and along many headwater streams, moist forest and valley bottom conifer at low and mid elevations, extensive mesic forest, and dry forest at the lowest elevations at the western end of the river's valley near the confluence with the Wenatchee River. Conifer forests are the dominant riparian vegetation downstream of Brush Creek and upstream of Phelps Creek.

Figure 2. Chiwawa River downstream from Chikamin Creek representative of lower valley conditions. Note confined channel with moderately low sinuosity and bordered by continuous conifer forest.

In the center portion of the watershed between Phelps Creek and Brush Creek, cottonwoods and other hardwood trees commonly occur and occasionally are dominant along the river (Figure 3). The riparian forest is also interrupted by brush and meadow communities that occur within extensive wetland area formed in abandoned river channels and along tributaries as they approach the river within the valley floor. Forest stand structure is also commonly patchy and thin in many areas bordering the river, and to a lesser degree, along some tributary reaches due to wetlands.

Figure 3. Chiwawa river conditions representative of the central part of the valley. The main road accessing most of the roaded part of the watershed can be seen on the high terrace to the northwest of the river.

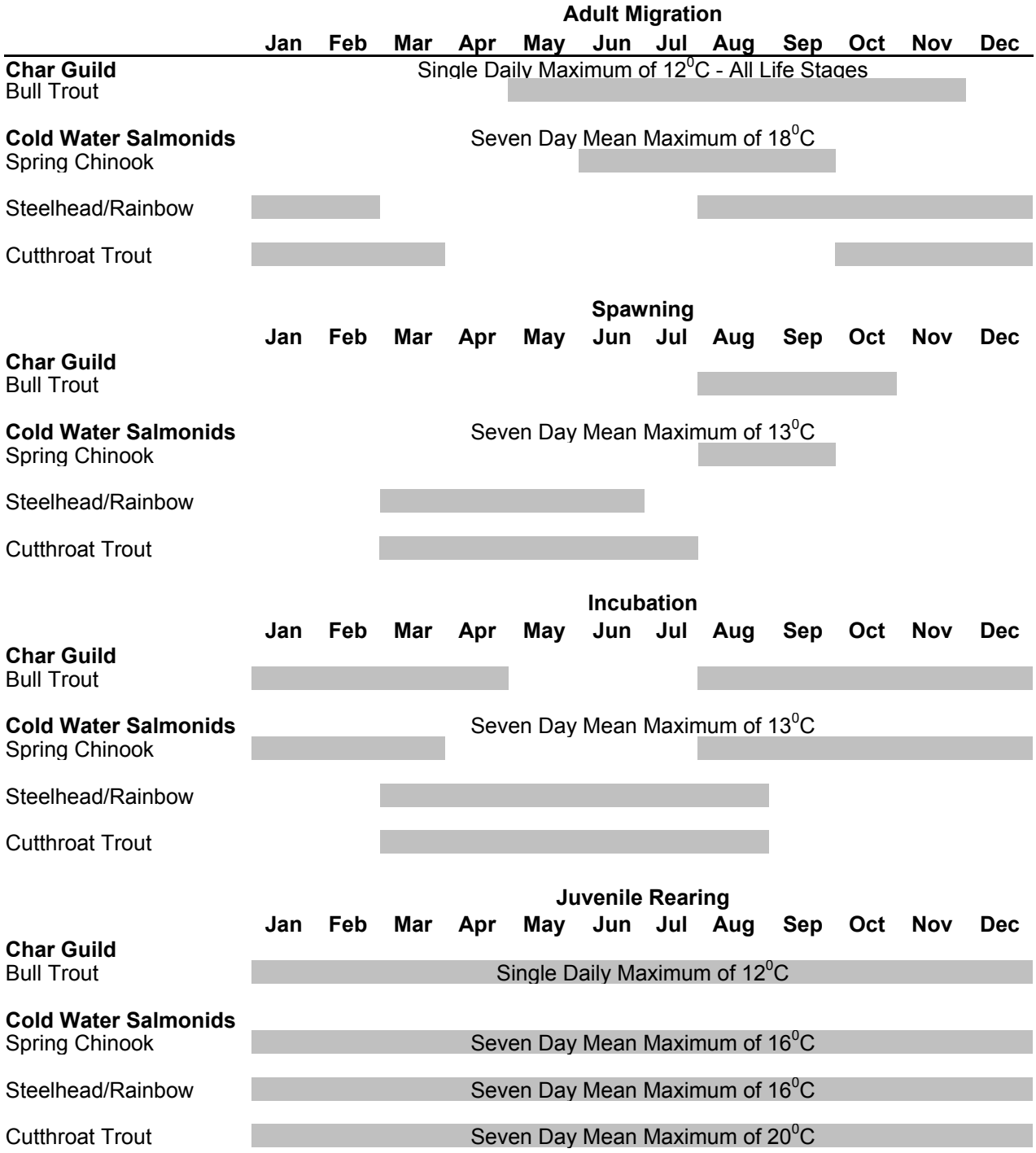
The Chiwawa River watershed has evolved with periodic fire, with stand replacing fire occurring at infrequent intervals in the mid elevation mixed-coniferous forest and wet forest communities (USFS, 1997). No recent large-scale fires bordering stream systems in the watershed were noted during aerial photo review of riparian stand and shade characteristics. However, extensive areas of immature conifer and patchy, poorly regenerated stands 30 or more years old were noted that had resulted from older fires, particularly along Phelps and Rock Creeks. Tributary stream shade is currently less than site potential to a small to moderate degree in some areas because of these naturally occurring fire effects. The Forest Service reports that decades of fire suppression have resulted in increased fuel density, particularly in the dryer forest types found at the lower elevations near the Wenatchee River (USFS, 1997), and fire hazards have increased above natural levels. Large-scale fire hazard in the watershed poses the potential for dramatically reduced levels of shade and attendant water temperature effects some time in the future (Knudsen, 1994; Amaranthus et al, 1989).

III. SALMONID SPECIES AND DISTRIBUTION

Fish species in the Chiwawa watershed include spring chinook salmon (*Oncorhynchus tshawytscha*), steelhead/rainbow trout (*O. mykiss*), cutthroat trout (*O. clarki lewisi*), bull trout (*Salvelinus confluentus*), brook trout (*S. fontinalis*), mountain whitefish (*Prosopium williamsoni*), dace (*Rhinichthys sp.*), and sculpin (*Cottus sp.*). In addition, catchable rainbow trout were stocked prior to the early 1990's in the mainstem Chiwawa River, and Rock, Chikamin, and Phelps Creeks (Hillman and Miller, 2001). An in-depth discussion by Bioanalysts, Inc. of species occurrence, timing of occurrence, life stage histories, data sources, methodology for estimating potential occurrence, and life stage maps for the watershed are included in this report as Appendix A. The salmon and trout species have extensive distributions throughout the sub-basin, beginning at the river's mouth and extending far upstream. Because of the limited extent of land uses in the watershed and the extensive distribution of species, effects of land use on the distribution of fishes within the watershed are likely very minor.

Species-life stage occurrence timing is shown in Table 2, with the draft EPA species-life stage temperature criteria included in the table.

Table 2. Char and Salmonid Species-Life Stage Occurrence in the Chiwawa Watershed



IV. WATER TEMPERATURE MODELING AND MODEL SENSITIVITY

There are numerous computer models available for prediction of stream temperatures. Our primary experience revolves around two in particular: SSTEMP (Theurer et al, 1984), and *Heat Source* (ODEQ, 1999). However, SSTEMP was designed to predict only daily average water temperatures, and in our experience SSTEMP is poor at predicting daily maximum water temperatures. *Heat Source*, on the other hand, predicts hourly water temperatures throughout the course of the day, from which we can derive daily maximum and/or daily average temperatures. We therefore chose to use *Heat Source* as the temperature modeling vehicle.

The *Heat Source* model was developed at Oregon State University as a tool for analyzing stream temperature data (Boyd, 1996). The model is used to predict effects on stream temperatures resulting from changes in various stream parameters, and allows evaluation of variations due to different management scenarios. The *Heat Source* model has been described in detail by ODEQ (1999). The code is written in Visual Basic, with an Excel spreadsheet input/output interface. *Heat Source* uses the same fundamental physical and thermodynamic concepts as many other process-based models. The fundamental premise of the model is that the water temperature at any given time and location in the stream is the result of the physical heat transfer processes between the stream and its surrounding environment. As a reach-based model, *Heat Source* predicts water temperatures at a downstream location based on some known water temperatures at an upstream location; it cannot predict stream temperatures at a given location in the stream system unless it is given water temperature inputs from an upstream location.

The model itself requires four basic types of input:

1. stream characteristics - location, aspect, wetted width, flow, etc.
2. riparian characteristics - buffer height, width, density, overhang, etc.
3. atmospheric conditions - air temperature, humidity, wind speed
4. hourly water temperatures at the upstream end of the reach through the course of a day

Based on these inputs, the model predicts the hourly water temperatures at the downstream end of the reach, and displays the results in tabular and graphic formats.

The most sensitive input parameters (in terms of effect on output temperatures) are primarily (in approximate order of importance) air temperature, relative humidity, buffer height, stream depth, buffer density, and wind speed. The relative sensitivity of maximum water temperatures to these input parameters is illustrated in Table 3. The input parameters shown in Table 3 were varied one at a time and the resulting range of maximum water temperatures noted as shown in the table (the one exception was that air temperature and relative humidity were varied simultaneously, because these two parameters are interrelated). Other input parameters, such as buffer width, stream width, streamflow, and stream aspect, also influence output temperatures, but their effect is relatively small.

Table 3. Heat Source Model Sensitivity

Input parameter	Input range	Output maximum temperature range (°C)
Buffer height	10 - 30 m	4.2°C
Daily average air temp./ Daily average humidity	16 - 26°C 30 - 60%	2.9°C
Average stream depth	0.1 - 0.3 m	2.1°C
Buffer density	10 - 90%	2.0°C
Average wind speed	1 - 4 m/s	1.3°C
Buffer width	10 - 30 m	0.4°C

V. DATA SOURCES, MODEL CALIBRATION AND VALIDATION

The Chiwawa River was chosen for this test case, at least in part because of the relative abundance of available data. Measured water temperatures were available from two different sources. Wenatchee National Forest had data from eight monitoring locations (5 mainstem and 3 tributaries) during the summer of 2000. US Fish and Wildlife Service (USFWS) had data for nineteen monitoring locations (15 mainstem and 4 tributaries), also during the summer of 2000. The approach to using these measured water temperatures was three-fold: 1) calibrate the model using Forest Service data for the date of warmest recorded water temperatures in 2000; 2) validate the predicted temperatures against the USFWS data for the same date; and 3) for further validation, model another date in the summer of 2000 and compare those predicted temperatures against both the Forest Service and USFWS data for that date.

The stream system was divided into 56 reaches for modeling (see Figure 4), with reach breaks taken at major tributary junctions or significant changes in stream characteristics, such as aspect or riparian shade characteristics. A total of approximately 128 kilometers of stream was modeled.

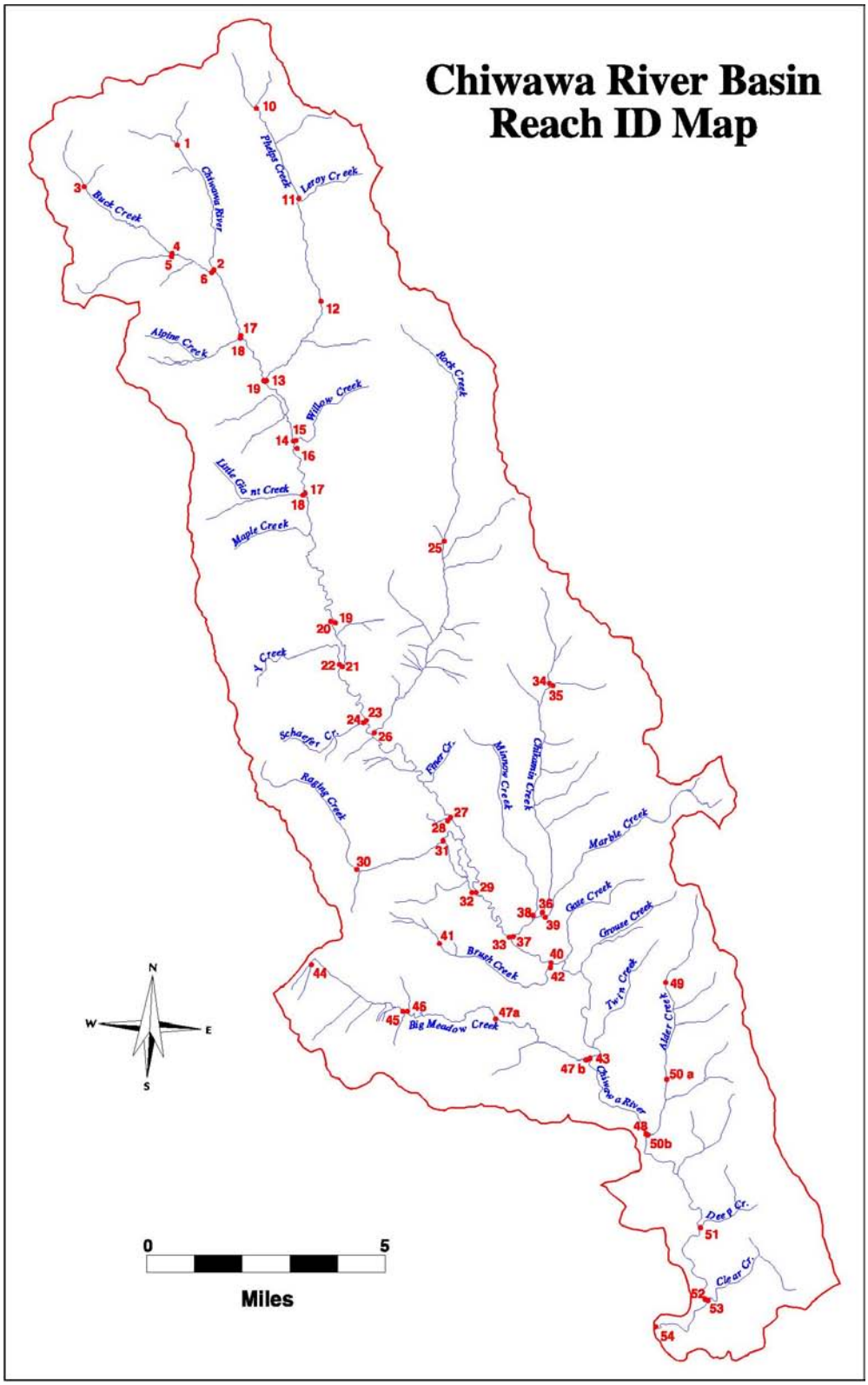


Figure 4. Chiwawa River reach identification map. Reach number labels are located at the downstream end of each reach.

The complete set of input parameters used for the *Heat Source* model is shown in Appendix B. The Appendix shows the input values used to calibrate the model from data derived for August 5, 2000, the date that the warmest water temperatures were recorded in the study drainage in 2000.

Stream gauge data was recorded in the Chiwawa River near the upstream end of Reach # 51 (USGS gauge number 12456500). Flows for all other reach locations were estimated by multiplying the flow at Reach # 51 by the ratio of the drainage areas, as measured from GIS. Reach lengths and elevations were also obtained from GIS.

Latitude, longitude, stream aspect, and topographic shade angles were estimated for each reach from topographic maps. Average wetted width for each reach was estimated from the 1992 stereo aerial photography and from stream survey data obtained by Wenatchee National Forest (WNF). Stream depth of each reach was estimated from the WNF data. Average stream velocity for each reach was then estimated from flow, width, and depth using the continuity relation. Height, width, and density of riparian vegetation along each reach were estimated from 1992 stereo aerial photography. Historic vegetative conditions were also estimated from the aerial photography based on visual evidence of harvested and cleared areas.

Minimum and maximum air temperatures in 2000 were obtained from Forest Service temperature monitoring data recorded within the Chiwawa River drainage. Minimum and maximum air temperatures for prior years, as well as relative humidity, and average wind speed, were obtained from weather station data taken at the Lake Wenatchee Ranger Station (1,800 feet elevation). Air temperatures were adjusted for variations in elevation using a lapse rate of 2.7ºC per 1,000 feet (this lapse rate was calculated using air temperature data recorded by the Forest Service at two temperature monitoring stations located within the Chiwawa River drainage). Groundwater temperature was assumed to be equal to the average annual air temperature as reported for Plain, Washington (located near the mouth of the Chiwawa River, elevation 1,880 feet), and again adjusted for elevation.

Initial runs of the model resulted in predicted water temperatures well below those actually measured on August 5, 2000. Several input parameters were therefore adjusted to calibrate the model (see Appendix B). Air temperatures over the water column of the stream system is not a well known quantity, so air temperature was used as one calibration variable. The daily variation in air temperature was reduced to one-half of the actual measured variation, and the daily average air temperature was raised 1ºC (i.e., measured minimum and maximum temperatures on August 5, 2000, of 12ºC and 29ºC, respectively, near Plain were adjusted to 17.5ºC and 25.5ºC, respectively, in the modeling). Because groundwater temperatures that occur throughout forested sub-basins of this size are also not well known quantities, the value for groundwater/tributary inflow temperature was also raised by 7ºC, yielding the following relationship:

$$T_{gw} = 14.5 + 0.009\ (573 - E)$$

where T_{gw} = groundwater/tributary inflow temperature (ºC)
E = average stream reach elevation (meters)

Two different tests were performed to validate the model calibration. After calibrating the model to the Forest Service data on August 5, 2000, predicted temperatures on August 5, 2000 were also compared to USFWS data for the same date. In addition, another date in the summer of 2000 was chosen (August 24), the model was run for that date, and the predicted temperatures were compared to both the Forest Service and USFWS data for August 24, 2000.

To predict temperatures on August 24, 2000, the only input parameters that required changing were stream flow and air temperature. Flow on that day was considerably less (1.2 cfs/mi^2 vs. 3.0 cfs/mi^2 on August 5). Measured air temperatures near Plain for that date were 8.5ºC minimum and 25ºC maximum. Therefore, consistent with the adjustments made for the calibration on August 5, 2000, air temperatures input to the model for August 24, 2000 were 13.7ºC minimum and 21.7ºC maximum (at 1,960 feet elevation). The Forest Service temperature monitoring data also indicated a substantially lower lapse rate on August 25, 2000; therefore, the lapse rate was adjusted to 1.2ºC per 1,000 feet.

VI. NATURAL THERMAL POTENTIAL

As mentioned earlier in this report, the EPA defines natural thermal potential (NPT) as the thermal regime that existed in rivers and streams prior to Euro-American settlement. The EPA guidance documents also note that the best way of estimating NPT, at least for large rivers, is through application of mechanistic models. *Heat Source* is a physical process-based "mechanistic" model.

Current thermal conditions as measured by the 27 USFWS and Forest Service thermistor networks directly reflect the existing conditions in the Chiwawa sub-basin's stream channels under current conditions of streamflow, groundwater inflow, hyporheic exchange, meteorology, and vegetation. *Heat Source* considers and accounts for all of these processes with exception of hyporheic exchange, a poorly understood process with unknown effects. Accordingly, *Heat Source* was used to model current thermal conditions. Estimation of NTP is based on systematic consideration of how the factors that affect each key process may have been altered from the historic condition to current conditions.

The following sections provide our interpretation of how anthropogenic effects have potentially affected these processes and the thermal regime of the Chiwawa sub-basin's stream system. A recurrent theme in this discussion is the limited management activity that has occurred in the sub-basin and the limited potential for change from historic to current conditions that these activities currently pose.

A. Stream Channels

Management activities that potentially affect stream channels include those that increase peak streamflows, physically disturb beds and banks due to poorly located roads or skid trails, or alter streambank vegetation through logging, grazing, or clearing.

Significant increases in small fall and winter storm peak flows following forest harvest and road construction have been detected in several studies (Beschta et al, 2000; Lewis et al, 2000; Thomas and Megahan, 1998; Ziemer, 1981; Harr et al, 1982; Rothacher, 1973). Changes in small peak flows have been found to be significant where clearcut harvest and roads have affected 20% to 100% of watershed area. However, significant increases in peak flows large enough to modify stream channels are rarely reported (Lewis et al, 2000; Beschta et al, 2000; WFPB, 1997). Nonetheless, detecting harvest-induced changes in large peak flows is inherently difficult; this leads researchers to caution that substantial increases in large peak flows may occur if harvest is highly concentrated in a watershed.

In the Chiwawa sub-basin, from just upstream of Rock Creek, located in the middle of the sub-basin, there has been no harvesting, with exception of very limited acreage harvested near the mouth of Phelps Creek in the 1960's or earlier. Harvest further downstream in the sub-basin was dispersed through a period of five decades or more and was limited in overall extent. Harvest history within the sub-basin is provided by the Chiwawa River Watershed Assessment Map 2: Harvest History of the Chiwawa Watershed (USFS, 1997). Visual assessment of this map reveals that harvest acreage never exceeded 20% of watershed area in a single decade in any of the Chiwawa sub-basin's tributary drainages. Cumulative harvest acreage may have approached 20% of watershed area in the twenty-year period from 1970 to 1989 in the two most heavily harvested watersheds in the sub-basin, Brush and Big Meadow Creeks. Substantial hydrologic recovery and diminution of peak flow response would occur even within twenty years, and given a greatly decreased rate of harvest activity in these watersheds, it does not appear that impacts further accumulated. This level of activity would not be expected to affect channel morphology.

Potential effects of roads on peak flows depend on the specific characteristics of the road and the watershed in question. For example, according to a recent Forest Service document (Gucinski et al, 2000):

> *The effects of roads on peak streamflow depend strongly on the size of the watershed. For example, capture and re-routing of water can dewater one stream while causing major channel adjustments in the stream receiving the additional water. In large watersheds, roads constitute a small proportion of the land surface and have relatively insignificant effects on peak flow.*

Road systems, even within the Brush and Big Meadow watersheds, and certainly within the mainstem of the Chiwawa, fit the model offered by Gucinski et al (2000) and do not reach the densities and percent land area found to produce detectable peak flow effects reported in the literature (Harr et al, 1975; Rothacher, 1973; Ziemer, 1981; Wright et al, 1990; Jones and Grant, 1996; King and Tennyson, 1984).

Stream banks and beds of the river mainstem have not been destabilized due to direct disturbance associated with harvest. Disturbance of tributary stream banks may have occurred at some locations, but the pattern and extent of activities in managed tributary watersheds does not suggest disturbance to a degree that would affect their thermal regimes. With rare exception, harvest within the Chiwawa River floodplain has not occurred. Harvest has occurred on old abandoned outwash terraces that abut the active channel in some areas. However, the harvest units are separated from the channels by buffer strips and undisturbed riparian zones of 50 to hundreds of feet in width. Although stream banks and channels have not been disturbed due to harvest, riparian shade has been affected at several locations, as discussed in Section E below.

In most areas, the main river valley road is located remote from the channel and/or on the terraces to the north side of the river. There is one approximately 150-foot long location where the road *may* have destabilized the streambank resulting in bank failure. However, this location is imbedded within many kilometers of naturally unstable and actively meandering channel; there is no measurable effect from this road on general channel morphology that can affect the thermal regime.

The Chiwawa River Watershed Assessment (USFS, 1997) reports that logs were driven down the Chiwawa in the 1920's and sometime into the 1930's. We assume that this activity was limited to that portion of the mainstem somewhere downstream of Brush Creek. Area harvested above Brush Creek prior to 1960 is very limited, and the channel is obstructed by glacial moraine and depositional channel morphology not conducive to log transport above this point. Although channel morphology below Brush Creek *may* have been affected by log drives to a degree that could persist even to the current era, streambanks and beds are more densely vegetated and far more stable than is the case above Brush Creek, and we could detect no obvious effects from observation of the 1992 aerial photography. Earlier photography was not available for observation. Nonetheless, we examined hypothetical effects of channel widening.

To examine the potential magnitude of the effect of log drives that ended 60 or more years ago, we hypothetically assumed that the channel could have been widened by as much as 20% at river bends and other locations subject to streambank scour that constitute 50% of total channel length below Brush Creek. Overall, this equates to a 10% increase in channel width. Modeling this potential effect produced an increase in maximum daily water temperature of 0.3ºC at the mouth of the Chiwawa River for the warmest day of 2000 (16.0ºC to 16.3ºC on August 5, 2000), and 0.2ºC for the warmest day of the median year (16.0ºC to 16.2ºC on July 28). In other words, NTP could at least hypothetically be 0.2 to 0.3ºC less than the current maximum temperatures at the river's mouth due to lingering log drive effects on channel morphology.

B. Groundwater

It is unlikely that groundwater regimes and interchange with the Chiwawa River have been affected by management activities within the sub-basin. Once again, harvesting activities and road construction are limited in extent and have occurred very little within the river's floodplain. Residential and agricultural activities are limited to outwash terrace locations at the extreme lower end of the sub-basin. Although some groundwater is withdrawn from wells, the amount of potential loss of groundwater contribution to the river is inconsequential in relation to the large volumes of surface flow that occur even during annual minimum flows.

C. Streamflow

Nearly all studies in North America, and worldwide for that matter, demonstrate increased water yield following forest harvest (Bosch and Hewlett, 1982). Increases in streamflow are proportional to the amount of cover removed (Hibbert, 1967; Rothacher, 1971; Keppeler, 1998). In addition, nearly all studies demonstrate that summer minimum flows also increase following forest harvesting (Troendle, 1988; Bosch and Hewlett, 1982; Harr, 1979). The absolute magnitude of the volume increase in low flows is generally small (because the low flows themselves are so small), but percentage increases of 50% to 100% above pre-harvest flows are commonly found. However, levels of harvest activity in the Chiwawa sub-basin do not approach intensities where detectable effects on low flows would be expected within the mainstem or its immediate tributaries. Groundwater regime effects on surface flows have not occurred, as discussed above.

Two surface water diversions occur within the sub-basin. Surface diversions potentially increase water temperatures by decreasing flow velocity and stream depth, and by subjecting a greater percentage of the wetted stream surface to solar radiation as the wetted water column recedes from streambanks where shade is concentrated.

The first diversion occurs on Phelps Creek, where water is diverted for approximately 4 kilometers beginning near the upstream end of Reach 13. The water right allows diversion of 1/3 of total flow, or 5 cfs, whichever is less. Flow modeled at the upstream end of reach 13 on August 5, 2000 was 41 cfs. The diversion creates a maximum modeled temperature increase at the lower end of Phelps Creek of less than 0.1ºC. Combined flow of Phelps Creek and the Chiwawa River at their confluence was 127 cfs, with Phelps Creek contributing 48 cfs (as modeled for August 5, 2000), and therefore there is no measurable effect of the diversion on the river's thermal regime.

The second diversion occurs on the mainstem Chiwawa River where as much as 16 cfs is diverted for the final 5.8 river kilometers through reaches 52 and 54. Flow modeled at the upstream end of reach 52 on August 5, 2000 was 542 cfs. Because the diversion is so small in relation to even the minimum flows that occur in the river, the diversion creates a maximum temperature increase in the affected reaches of less than 0.1ºC.

D. Meteorologic Factors

Water, topography, and vegetation generally combine to make riparian areas more humid and mild than upland areas (Knutson and Naef, 1997). Vegetation removal causes riparian sites to become drier, hotter in summer, and colder in winter (Knutson and Naef, 1997; Geiger, 1965; Beschta et al, 1987). Although riparian microclimate affects are known to affect water temperature (Geiger, 1965; Beschta et al, 1987), considerable uncertainty remains regarding riparian zone width effects on microclimatic relationships over stream water columns, and meteorologic effects remain the subject of considerable research (James, 1999;Brosofske et al, 1997).

Microclimates over some of the more heavily managed Chiwawa sub-basin tributary streams may have been affected locally by historic harvest units in some locations. However, we would expect such effects on stream thermal regimes to be relatively minor; harvest units along tributaries were generally buffered; the lower reaches of tributaries were always buffered or have never been harvested; a considerable number of years has passed since harvest and shade at least partial shade recovery has occurred; and although removal of riparian vegetation potentially increases air temperatures, which increases water temperature, wind speed and humidity are affected in the opposite manner. Increases in wind speed and decreases in humidity that potentially follow harvest near streams increase the rate of water column energy loss (i.e., cooling). Effects could potentially occur along the lower reaches of the mainstem where riparian vegetation has been removed in association with agriculture and residential development. However, as discussed above, thermal response mechanisms are to some degree compensating, and the net effect on stream temperatures would be small, particularly given the volume and depth of flow that must be affected by such energy transfer processes in these lower river segments.

E. Vegetative Shade

Riparian vegetative shade adjacent to both the mainstem and tributaries has been affected by management to a degree that affects water temperatures within the sub-basin. Grazing appears to have reduced vegetative shading of three lower tributaries. Based on observations of 1:15,840 scale 1992 aerial photos, the Forest Service reports loss of shrub vegetation in meadows adjacent to Clear Creek, Deep Creek, and Goose Creek, three north side tributaries draining to the lower Chiwawa between river kilometers 3 and 10, due to 100 years of grazing activity (USFS, 1997). We examined these aerial photos and the potential thermal effects of this shade loss.

Clear Creek, with a watershed area of approximately 1,600 acres, is the lowest tributary of any size. Meadows that appear to have been affected by grazing occur intermittently through a length of approximately 2,000 feet. These meadows lie upstream of the mainstem by approximately 1,500 feet of stream that flows through relatively dense forest. Although we did not model Clear Creek because of its small size, temperatures likely are elevated within these grazed meadow areas. However, Clear Creek is too small to measurably affect the thermal regime of the Chiwawa River due to these grazing effects; it increases the watershed area by only 2.2% (2,600 acres/116,600 x 100%) and likely adds an even smaller percentage of flow due to its lower average annual precipitation compared to the river's watershed. The temperature of Clear Creek would have to increase by 4.6ºC at its mouth to affect the River by even 0.1ºC. Temperature increases of this magnitude even immediately below the meadows are extremely unlikely. Moreover, substantial cooling would occur within the stream as it passes through the 1,500 feet of forest before reaching the river.

Similarly, Deep Creek also has a small watershed area relative to the river (approximately 1,600 and 114,000 acres, respectively), and stream waters that may have been affected by grazing of meadows flow through approximately 3,500 feet of forest before reaching the river. Goose Creek grazing effects appear to be much more limited and again are remote from the river. Moreover, there is no potential for cumulative effect; although these tributaries flow from adjacent drainages, the confluences of these tributaries with the river are separated by 2.6 to 3.5 kilometers, and are therefore subject to substantial equilibration energy exchange as the water

column travels through these intervening distances of mainstem river. In other words, thermal conditions within these river reaches are controlled by the local environment surrounding them and the energy exchange processes that result, plus the influence of input water temperature as it is "input" to the upstream end of each reach. Elevation of input temperature of less than 0.1ºC due to a tributary input becomes even smaller by the time the water column travels downstream to the next tributary input. Potential point or cumulative effect of even 0.1ºC is virtually undetectable within the resolution of both modeling and stream monitoring capabilities.

Forest harvesting conducted 10 or more years ago has reduced the height, density, and width of riparian vegetation along some areas of both the mainstem and its tributaries. Agricultural and residential clearing has also affected riparian vegetation in the two lower reaches of the watershed between river kilometers 0 and 5. Current and historic riparian conditions (conditions that would exist in the absence of recent management activities) as estimated from the 1992 aerial photography are provided in Table 4 (if there is no entry in the "historical" column of Table 4, it means that riparian conditions have not visibly changed in that reach). These reductions in riparian vegetation are the dominant cause of temperature deviation operative in the basin, as discussed in the following section.

Table 4. Riparian Vegetative Characteristics as Estimated From Aerial Photography[2]

Reach	Stream	Mainstem River km at D/S end	Tree Height (ft)		Riparian Forest Width (ft)		Riparian Forest Density (%)	
			existing	historical	existing	historical	existing	historical
02	Chiwawa	56.6	90		150		60	
04	Buck	-	80		150		50	
06	Buck	-	90		150		50	
07	Chiwawa	54.0	100		150		50	
09	Chiwawa	52.0	120		150		50	
11	Phelps	-	90		150		50	
12	Phelps	-	80		150		40	
13	Phelps	-	110		150		50	
14	Chiwawa	49.4	130		150		50	
17	Chiwawa	47.0	120		150		40	
19	Chiwawa	42.3	120		150		40	
21	Chiwawa	39.0	120		150		50	
23	Chiwawa	35.9	120		145	150	50	
26	Rock	-	90		150		60	
27	Chiwawa	29.4	130		150		50	
29	Chiwawa	25.9	110		150		30	
32	Raging	-	120		150		80	
33	Chiwawa	22.6	120		150		40	
36	Chikamin	-	140		150		75	
37	Chikamin	-	100	130	110	150	40	50
40	Chiwawa	20.7	110		135	150	70	75
42	Brush	-	160		125	150	75	
43	Chiwawa	15.0	110		130	150	70	75
45	Big Meadow	-	150		50	150	75	
47A	Big Meadow	-	20		150		80	
47B	Big Meadow	-	140		145	150	70	
48	Chiwawa	11.1	160		140	150	70	75
50A	Alder	-	140		50	150	70	
50B	Alder	-	140		150		70	
51	Chiwawa	6.4	140	150	120	150	60	70
52	Chiwawa	2.7	120	140	80	150	40	70
54	Chiwawa	0.0	120	140	80	150	40	70

[2] Riparian forest widths wider than 150 feet have little or no effect on riparian shade, and virtually no effect upon maximum daily water temperatures. Values for tree height and forest density in the table represent average conditions integrated over the riparian zone within 150 feet of the stream channel, even though actual riparian forest may be wider than 150 feet.

F. NTP Modeling Results

Once the model was calibrated and validated for the Chiwawa, historic vegetative conditions were input to the model to estimate natural thermal potential. Changes in vegetation, as estimated from the 1992 photography, are summarized in Table 4. For comparison purposes, NTP was first evaluated for the date of August 5, 2000; the results of this comparison are illustrated in Figures 5 and 6. The greatest change in daily maximum temperatures from historic conditions to current conditions is 0.5ºC, which occurs at the mouth of the Chiwawa River (Figure 5); daily average water temperatures changed by 0.3ºC (Figure 6). Although we hypothetically examined the effect of channel widening due to log drives, we have no evidence that such effects ever actually occurred, or that they remain into the current time. Accordingly, we elected not to adjust NTP for this mechanism.

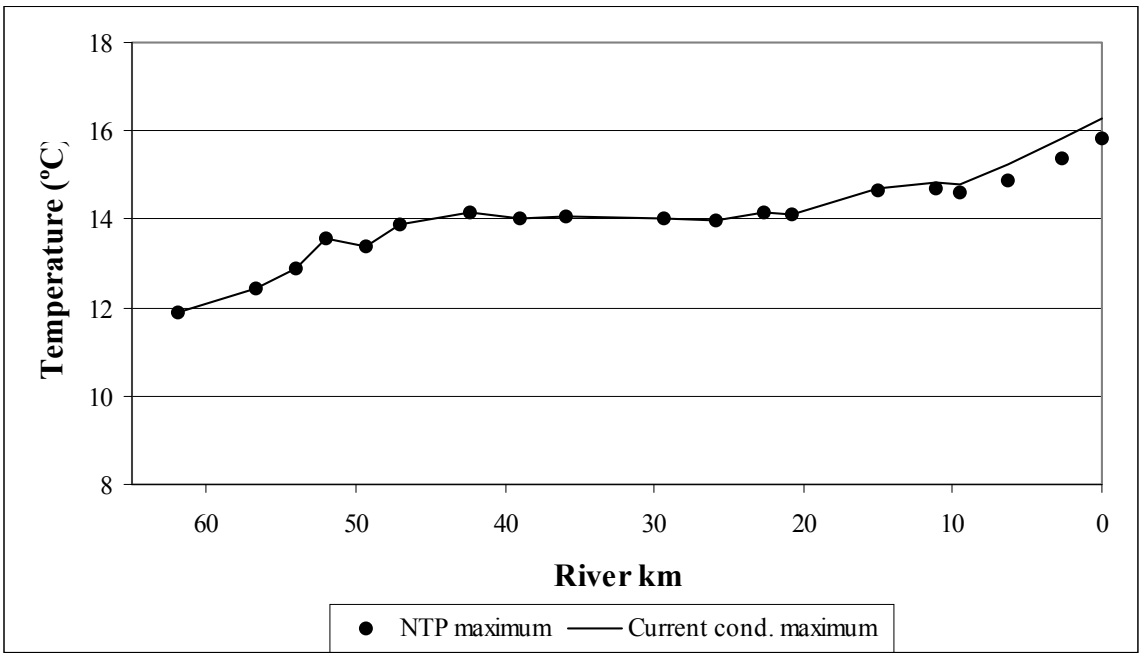


Figure 5. Chiwawa River natural thermal potential - maximum temperatures on August 5, 2000.

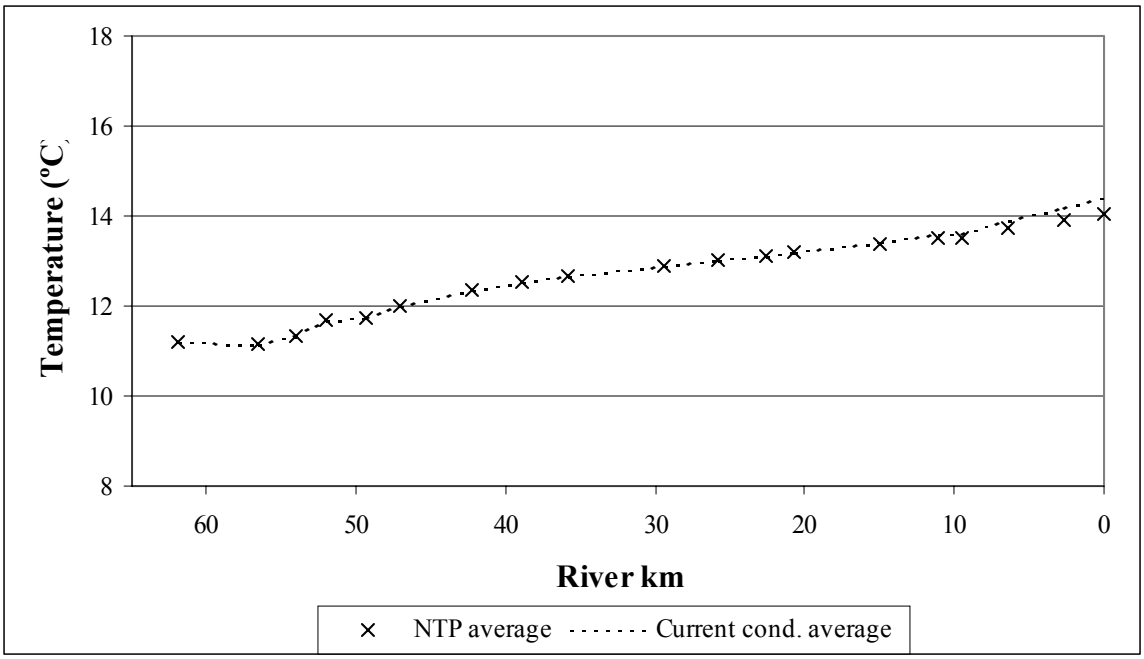


Figure 6. Chiwawa River natural thermal potential - average temperatures on August 5, 2000.

According to the Forest Service records at Lake Wenatchee Ranger Station, on average, the warmest day of the year is July 28, so that date was chosen to model natural thermal potential for a typical year using 30-year average meteorological conditions and median streamflow (2.7 cfs/mi^2). In order to characterize typical inter-annual variation, a warm, dry year and a cool, wet year were also modeled. Inputs used for a warm, dry year included increasing air temperatures by one standard deviation (2.5ºC) above the 30-year average and decreasing streamflow to the 16th percentile (1.5 cfs/mi^2, or the equivalent of subtracting one standard deviation). Similarly, inputs used for a cool, wet year included decreasing air temperatures by one standard deviation (2.5ºC) below the 30-year average and increasing streamflow to the 84th percentile (5.0 cfs/mi^2, or the equivalent of adding one standard deviation). All other input parameters remained the same between the three modeling runs for July 28. Figure 7 illustrates the results of the evaluation of inter-annual variation. Maximum water temperatures are predicted to vary by 1.6ºC to 2.8ºC between a warm, dry year and a cool, wet year, depending on specific location in the stream system.

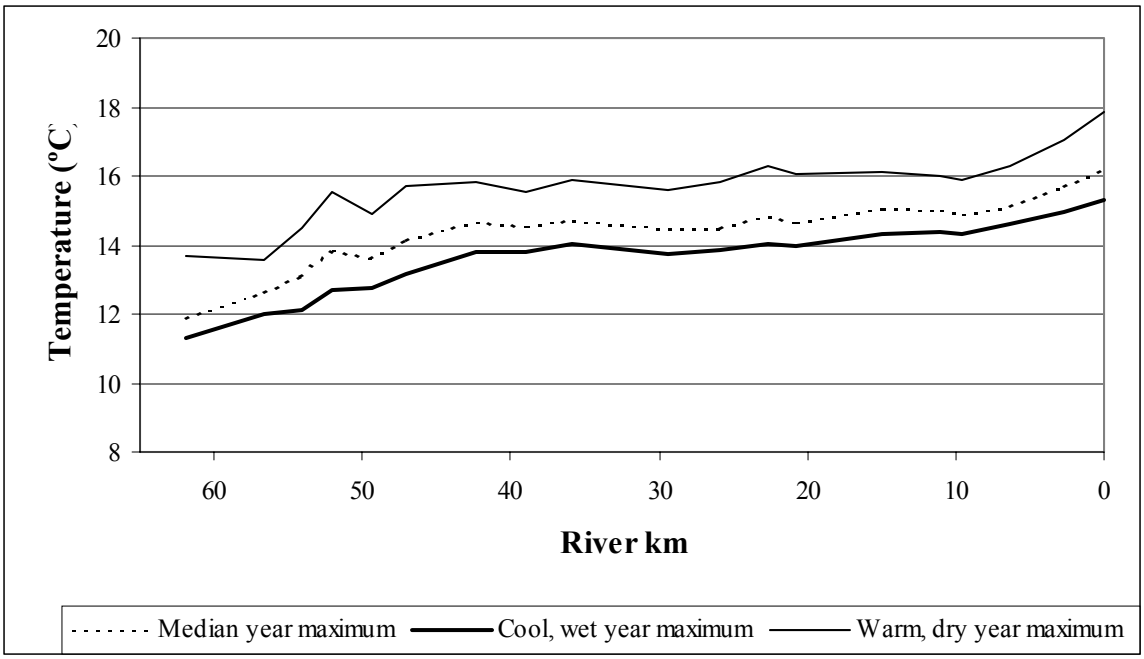


Figure 7. Chiwawa River modeled annual variation - maximum temperatures on July 28.

G. Modeling Uncertainty

There are at least two independent sources of uncertainty in the temperature modeling exercises. The first is related to uncertainties in the model inputs, which occur because all of the input parameters must be estimated for each reach based on a limited amount of measured data. The second source of uncertainty is due to the inherent way in which the model works, that is, the way in which it simulates heat transfer processes and the fact that the model is calibrated to measured water temperatures for a specific set of conditions.

The first uncertainty, or parameterization error, can be evaluated through a Monte Carlo simulation. To do this, one mainstem river reach (Reach # 48) was chosen, and input parameters were varied around a mean value in a random fashion. The degree of variation in each input parameter that we believe could reasonably occur was estimated and is shown in Table 5. For each input parameter, a random value within the specified range was generated, these values were input to the model, the model was run for the reach in question, and the results recorded. Then new random values for each input parameter were generated and input to the model. This process was repeated 500 times, with the results of all 500 runs tabulated in a spreadsheet. The results of the Monte Carlo simulation yielded a standard deviation of ±0.15°C in the predicted daily maximum temperature, with an extreme range of ±0.38°C. Although uncertainties can conceivably propagate downstream, in this case the variation is random, so the deviations in two consecutive reaches are just as likely to be in the opposite direction as they are to be in the same direction. Overall, therefore, an estimate of the standard deviation in predicted maximum temperatures associated with parameterization uncertainty is approximately ±0.15°C.

Table 5. Random Variation in Input Parameters for Monte Carlo Simulation

Input parameter	Random variation
Stream aspect (°)	±10°
Stream width (m)	±20%
U/S flow volume (cms)	±20%
Velocity (m/s)	±20%
G/W inflow (cms)	±20%
Buffer height (m)	±25%
Buffer width (m)	±15%
Canopy density	±10%
Distance to stream (m)	±50%
Tree overhang (m)	±50%
Min. humidity	±10%
Max. humidity	±10%
Wind speed (m/s)	±90%

The other source of uncertainty, calibration error, can be characterized by the "goodness of fit" obtained in the calibration and validation steps. The calibration to the Forest Service measured temperature data on August 5, 2000 is illustrated in Figure 8, validation with USFWS measured temperatures on August 5, 2000 is shown in Figure 9, and validation with both Forest Service and USFWS measured data on August 24, 2000 is shown in Figure 10. Deviations from ideal fit are illustrated in Figures 11 and 12. The standard deviation of the residuals (difference between measured and predicted maximum temperatures) was 0.49°C for calibration on August 5, 2000; 0.61°C for validation on August 5, 2000; and 0.89°C for validation on August 24, 2000. Therefore, an estimate of the standard deviation in predicted maximum temperatures associated with calibration uncertainty is approximately ±0.89°C.

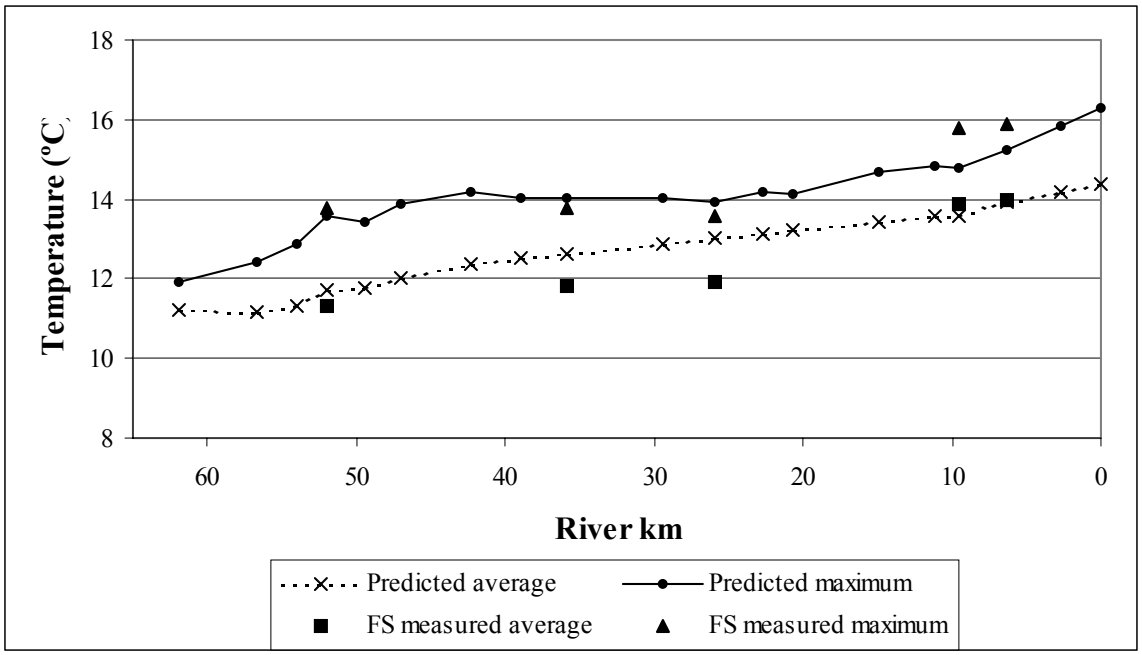


Figure 8. Chiwawa River *Heat Source* model calibration to Forest Service data on August 5, 2000.

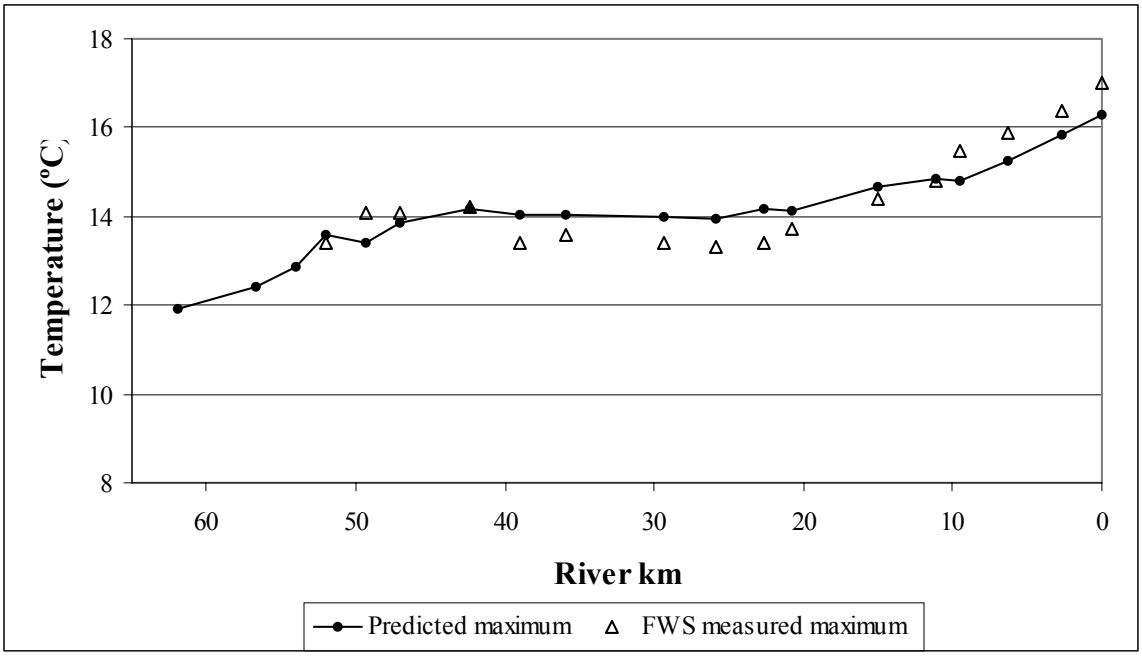


Figure 9. Chiwawa River *Heat Source* model validation with USFWS measured maximum temperatures on August 5, 2000.

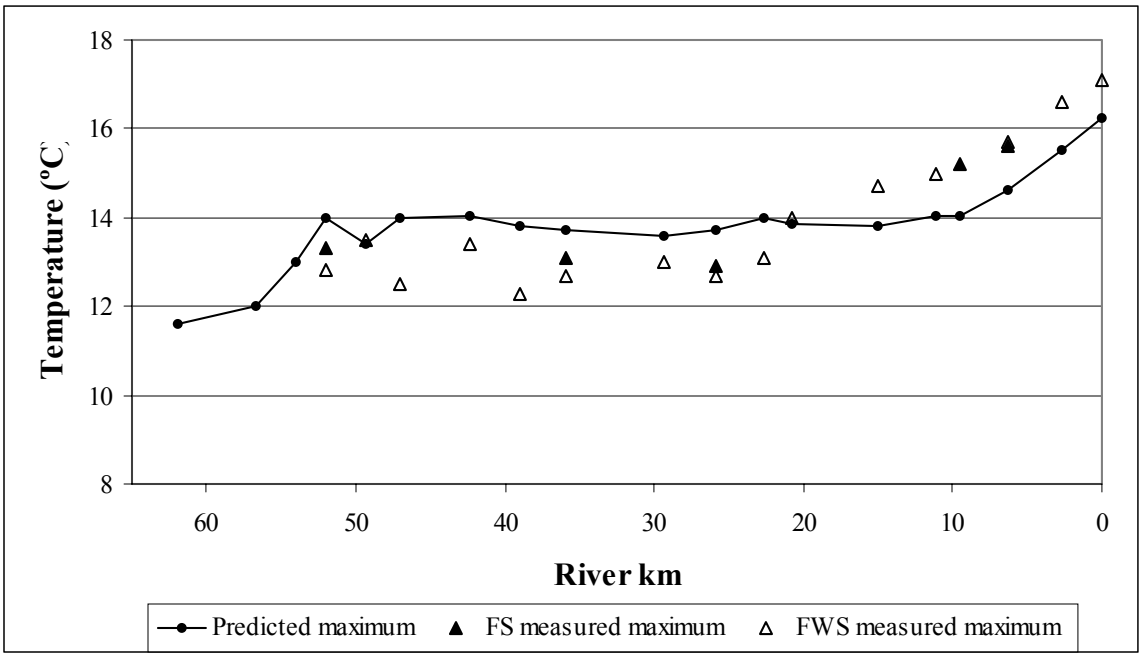


Figure 10. Chiwawa River *Heat Source* model validation with Forest Service and USFWS measured maximum temperatures on August 24, 2000.

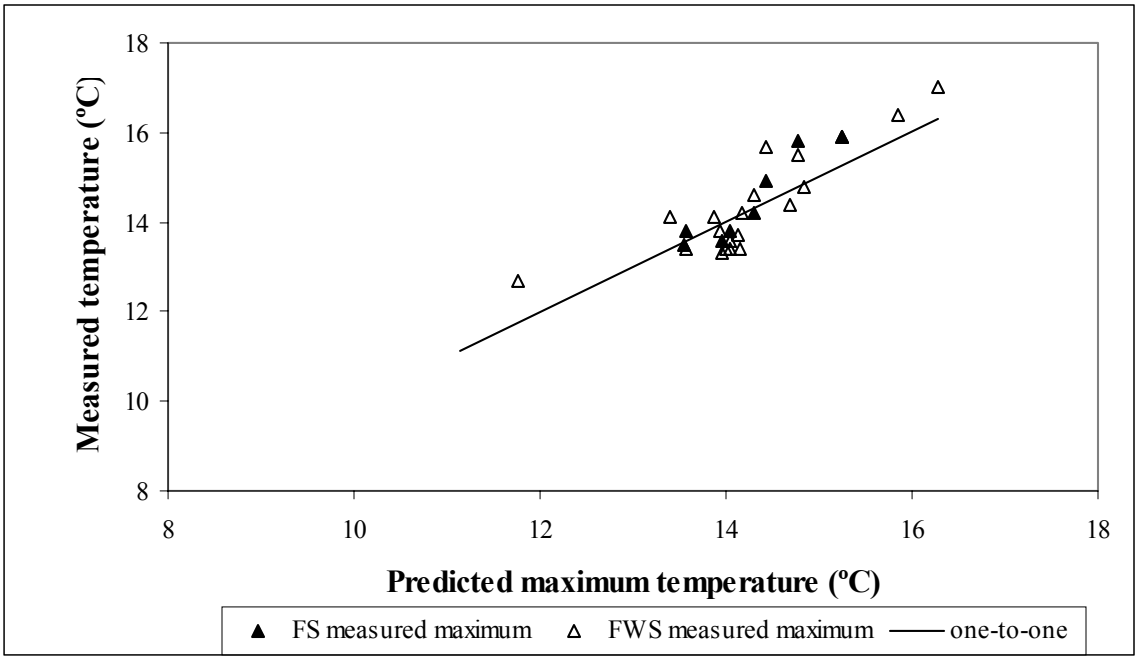


Figure 11. Measured maximum temperatures compared to *Heat Source* model predictions on August 5, 2000.

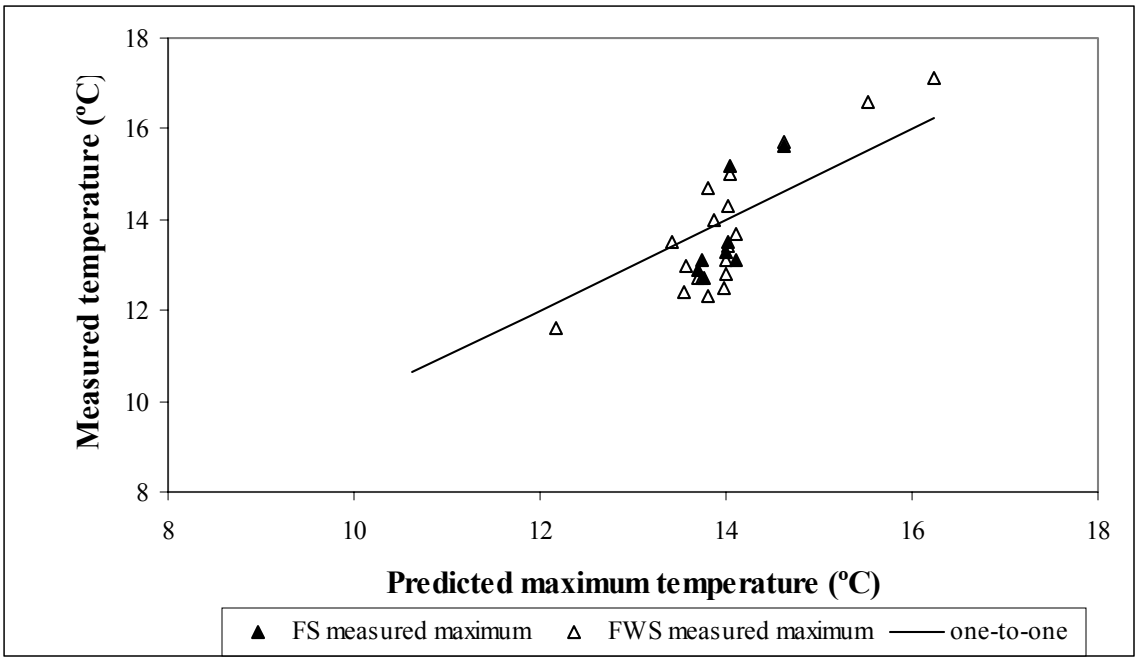


Figure 12. Measured maximum temperatures compared to *Heat Source* model predictions on August 24, 2000.

Both sources of uncertainty, parameterization and calibration, ought to be combined in order to arrive at confidence bounds on the predicted maximum temperatures. However, since both sources of uncertainty are essentially random, they need to be combined in a root-mean-square (RMS) method. In this case, an RMS combination of ±0.15°C and ±0.89°C results in a combined uncertainty of ±0.90°C on the predicted maximum temperatures.[3]

The last step in the modeling exercise is to compare the (modeled) natural thermal potential to the biological criteria for the various species of fish in the drainage. This is complicated by the fact that some temperature standards are expressed in terms of maximum weekly maximum temperature (MWMT), which is the average of the daily maximum water temperatures for the hottest seven-day period of the season, whereas the modeled temperatures are single-day maximum water temperatures. Examination of the Forest Service and USFWS water temperature measurements indicated that the highest daily maximum water temperature in the summer of 2000 was an average of 0.8°C higher than the MWMT (Figure 13); this is consistent with other studies done in eastern Washington, northern Idaho, and western Montana (Sugden et al, 1998). Therefore, for those cases that required comparison to a MWMT standard, 0.8°C was subtracted from the daily maximum water temperatures predicted by the model.

[3] Since standard deviations were used to calculate uncertainties in this analysis, ±0.90°C represents the 68% confidence interval.

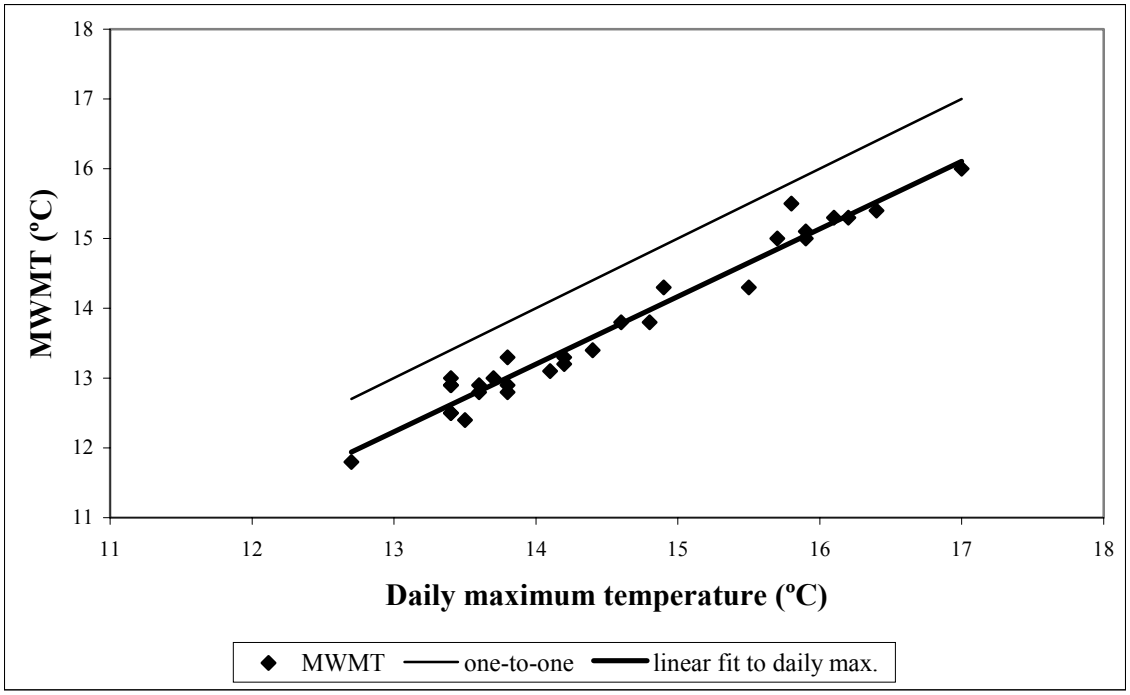


Figure 13. MWMT compared to daily maximum temperatures in the Chiwawa watershed on August 5, 2000.

VII. RECONCILIATION OF BIOLOGICAL CRITERIA AND NTP

Appendix B to the EPA Guidance recommends graphical display and reconciliation of the species-life stage numeric criteria with the modeled estimate of NTP. The approach calls for plotting the species-life stage numeric criteria for each life stage wherever the species-life stage occurs on a continuum from mainstem mouth to headwaters along with the modeled NTP and the estimated confidence boundaries. The Guidance Appendix B, page 27, states that the modeled estimate of NTP is reconciled with the species-life stage numeric criteria in the following manner: "If the lower end of the certainty bounds is higher than the biological threshold, and you have greater confidence in the model data then (sic) the biological data, then you can set the NTP at the lower confidence bound of the modeled estimate."

As explained previously, on average, July 28 is the date of highest summer air temperatures, so conditions on July 28 in a median year were used to compare predicted NTP to biological criteria. Due to the different life stages of various fish species, it was also necessary to model a date in the spring (during the steelhead spawning season), so the NTP was modeled on May 31 in a median year. The May 31 date also provides perspective by illustrating thermal maximums for late spring conditions when water temperatures are substantially lower than those in July. The results of these comparisons are shown for the mainstem Chiwawa River in Figures 14-17 (the figures also show a confidence interval of ±0.9°C on the predicted NTP, as derived above). Because the EPA draft criteria for all life stages of bull trout is a single day maximum of 12°C, whereas the criteria for all other species life stages is an average seven-day maximum, the

relationships for bull trout are depicted separately in Figures 14 and 15. Predicted daily maximum temperatures in tributaries for July 28 and May 31 in a median year are shown in Table 6.

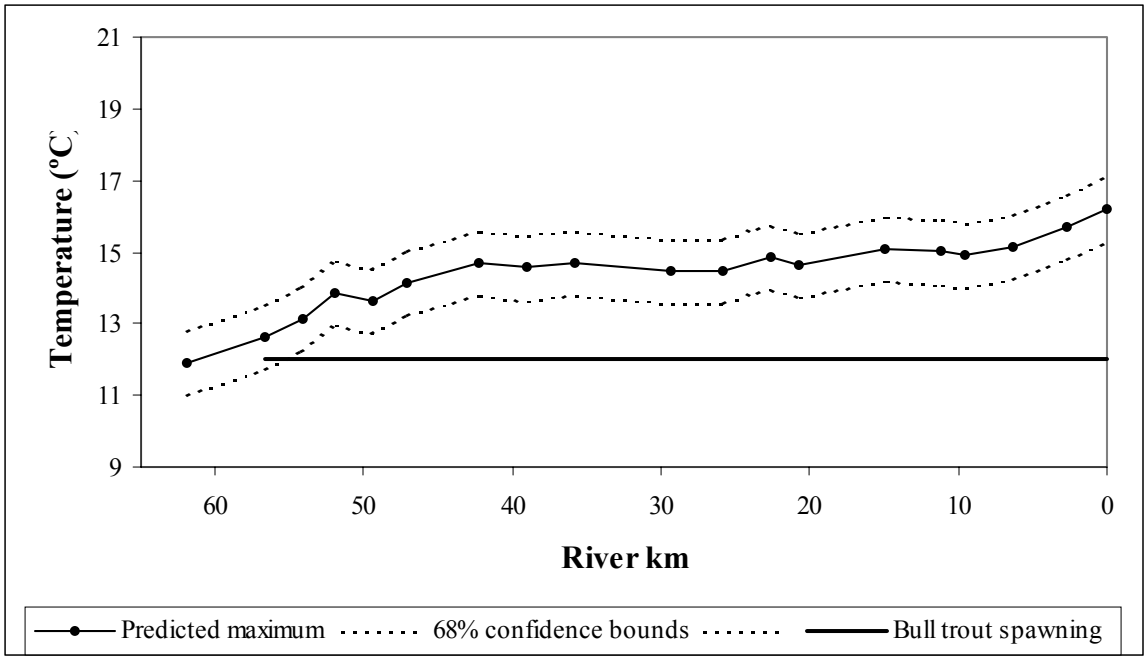


Figure 14. Chiwawa River natural thermal potential on July 28 compared to bull trout criteria.

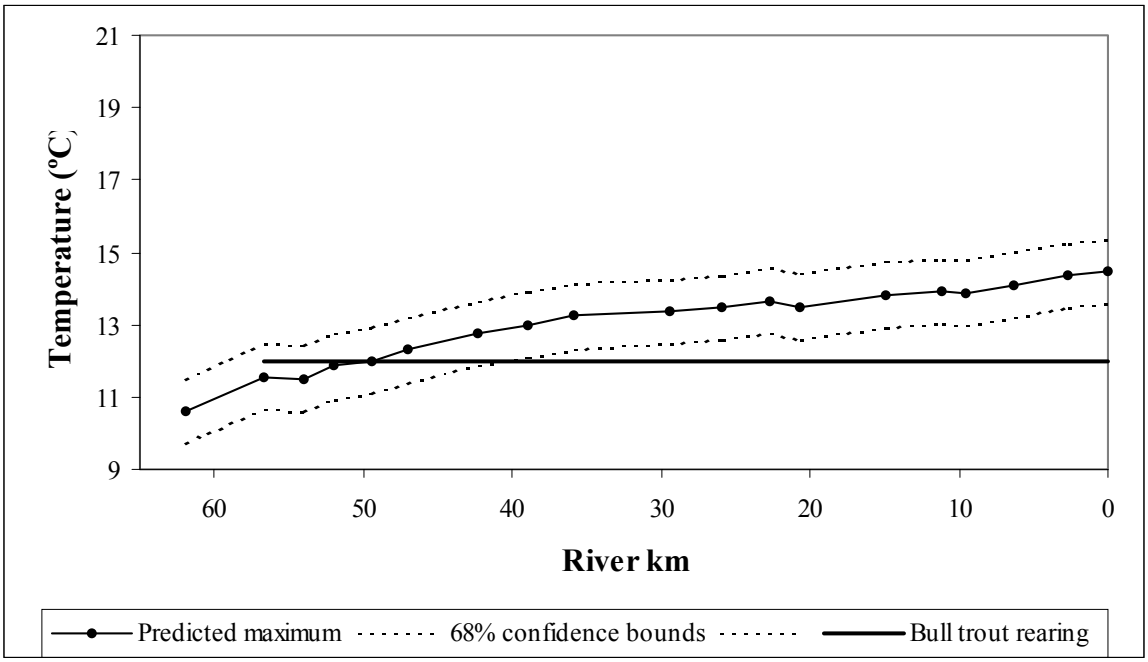


Figure 15. Chiwawa River natural thermal potential on May 31 compared to bull trout criteria.

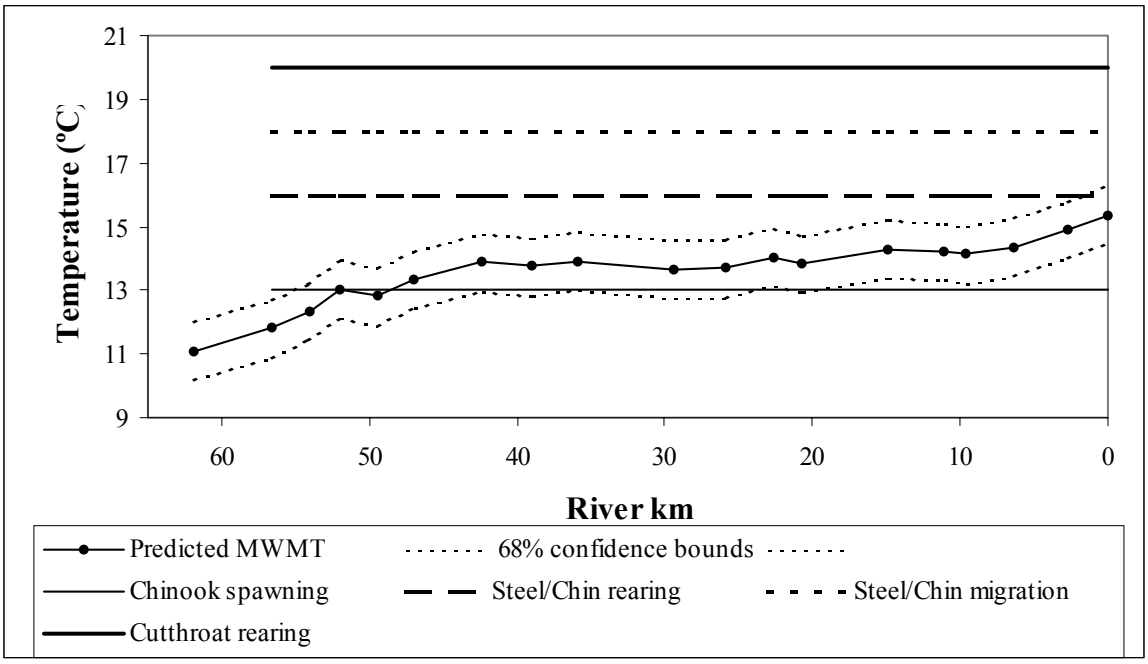


Figure 16. Chiwawa River natural thermal potential on July 28 compared to salmonid criteria.

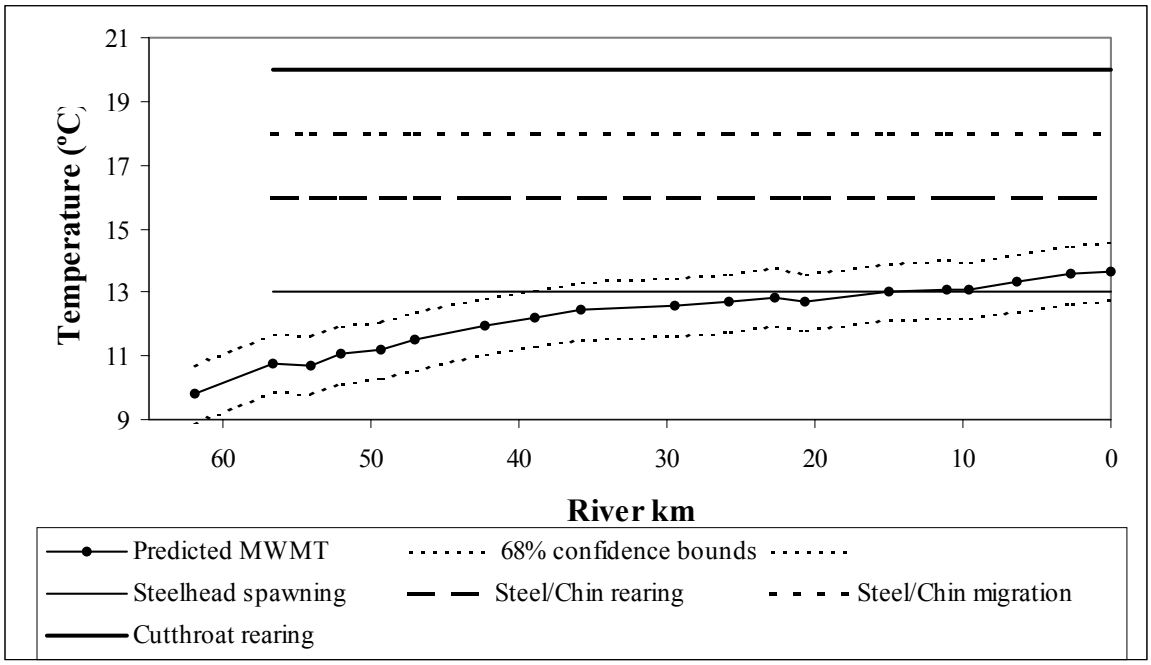


Figure 17. Chiwawa River natural thermal potential on May 31 compared to salmonid criteria.

Table 6. Chiwawa Tributary Daily Maximum Temperatures

Tributary	Reach #	Predicted Daily Maximum Temperature (ºC)	
		July 28	May 31
Buck Creek	4	11.3	10.4
Buck Creek	6	12.4	10.8
Phelps Creek	11	11.5	9.6
Phelps Creek	12	12.0	10.4
Phelps Creek	13	14.0	11.4
Rock Creek	26	14.4	13.2
Raging Creek	31	12.8	12.1
Raging Creek	32	13.0	12.4
Chikamin Creek	36	14.1	13.1
Chikamin Creek	37	14.5	13.0
Brush Creek	42	13.5	12.7
Big Meadow Creek	45	12.9	12.5
Big Meadow Creek	47A	14.4	13.2
Big Meadow Creek	47B	13.9	13.2
Alder Creek	50A	12.6	12.1
Alder Creek	50B	14.1	13.2

We are confident that the lower bound of the NTP estimate provides a conservative estimate of the lower (cooler) bound of the true value of NTP. Because of the relative wealth of locations where stream temperatures have been recorded in the Chiwawa watershed, an alternative approach would be to estimate NTP by adjusting downward for management effects on NTP beginning with *measured* river temperatures, rather than *modeled* temperatures. This approach would provide an estimate of NTP that is somewhat higher in the lower reaches of the river, and somewhat lower for several of the central reaches of the river, as can be seen from Figures 9 and 10.

For bull trout, we see from Figures 14 and 15 that the modeled NTP temperature is higher than the EPA draft species-life stage numeric criteria. Consistent with the EPA guidance, NTP would be set at the lower error bound of the July 28 NTP from Figure 14, which represents the median year maximum daily temperatures predicted for where and when bull trout occur in the mainstem.

For steelhead spawning, Figure 17 indicates that the lower bound of the NTP estimate for May 31 is less than the life stage numeric criteria except at the mouth of the sub-basin. Steelhead also spawn through the month of June, when water temperatures are somewhat higher. Although we did not model a median year June NTP, such modeling would reveal that the June NTP would exceed the steelhead spawning life stage criteria in the lower reaches of the river.

The applicable life stage criteria and modeled NTP for all species-life stages, other than for bull trout and steelhead spawning, are shown in Figure 16. The species-life stage criteria exceed the NTP estimate for cutthroat rearing, steelhead and chinook migration, and steelhead and chinook

rearing. The lower bound of the NTP estimate exceeds the chinook spawning life stage criteria in the lower 20 km of the river.

In summary, the lower confidence bound of the modeled NTP temperatures exceed the life stage criteria for steelhead spawning and chinook spawning in lower reaches of the river. NTP temperatures exceed life stage criteria for bull trout for virtually all life stages for the entire length of the river where bull trout occur. Integrating all of these results, our interpretation of the EPA Guidance is that the applicable criteria for the Chiwawa mainstem would be based upon the modeled estimate of NTP.

VIII. PRACTICALITY OF APPLICATION

A. Geomorphology and Management History

Correct interpretation and explanation of current stream channel condition demands understanding of how the watershed and its streams have formed and are controlled by the natural land forming processes operative in the watershed. The relative impact of management activities that have occurred throughout the history of these activities must be interpreted within this natural context.

For the Chiwawa, the Forest Service watershed assessment (USFS, 1997) provided readily accessible and unusually complete geomorphic description and interpretation of process. The assessment also provided good information on management activity in the watershed. Coupled with study of the 1992 aerial photography, description of the Chiwawa sub-basin's geomorphology and management history was straightforward and easily accomplished.

Other basins may have more complex and/or less well-documented geomorphology, and management histories will often be far more complex. Estimation of NTP in these more complex circumstances will require more effort and may entail a higher degree of uncertainty.

B. Current Species Distribution

An unusually large amount of fisheries population survey data was available for this sub-basin, and a substantial amount of this data had actually been collected by Bioanalysts through the course of earlier projects. This familiarity with the watershed and data availability allowed mapping of life stage areas and timing of occupancy relatively easy and certain for the Chiwawa. Other basins may have less well-documented fisheries population survey data. Mapping of life stage areas and timing of occupancy may require more effort and may entail a higher degree of uncertainty in these circumstances.

C. Potential Species Distribution

Determining potential species distributions invariably demands selection of a series of decision rules that must be systematically applied. Decision rules applicable to the Chiwawa had previously been developed by Washington state, and these could be reasonably applied to the Chiwawa. Decision rules applicable to basins outside Washington may be less well documented and/or accepted in the biological community, and may include variables such as streamflow,

channel width, or other variables that are difficult to know throughout a watershed network. This would make determination of potential species distributions more difficult. In the absence of such problems, the difficulty of determining potential species distributions for basins will be similar to that of the Chiwawa.

D. Current Thermal Conditions

1. Assemble existing data

The modeling exercise requires information on local meteorological conditions, stream hydraulic parameters, and riparian vegetation characteristics. For the Chiwawa, stream surveys done by Wenatchee National Forest provided some riparian and stream channel characteristics, which was supplemented by aerial photography interpretation. A long-term USGS stream gauge near the mouth of the Chiwawa provided sufficient streamflow data. Weather information for the Chiwawa was available from several sources, including a weather station at Lake Wenatchee Ranger Station and summer air temperature measurements at two of the Forest Service stream temperature monitoring locations.

Other basins may have less data available in many cases. In particular, in forested and/or mountainous watersheds, weather stations are often not located near the watershed of interest, so information would have to be extrapolated from some distance away. Stream gauges, if any, are often only located on larger rivers, and may require considerable extrapolation of flows to the sub-basin of interest based on nearby gauges or regional relationships.

2. Develop parameter values

Specific values for all input parameters must be derived for each reach in the system of interest based on the existing data available. With rare exception, values for input parameters developed for Chiwawa River and tributary reaches were based on few measurements made within or even external to the watershed. Although agencies such as the Forest Service do have channel and riparian vegetation data, this data is generally gathered at a specific point or transect, and it is difficult to extrapolate this form of information to relatively long stream reaches. As a result, a great deal of the information developed for the Chiwawa was based on aerial photography, as we believe would currently be necessary for most other basins as well. This is not a difficult exercise, as long as aerial photos are available. In addition, as previously mentioned, other basins often may not have as much meteorological data available, making it more difficult to estimate air temperatures, humidity, and wind speed. While these difficulties do not cause a great deal of error in the estimate of current and natural temperatures for the Chiwawa, error for other basins may increase with relative increases in the degree of data extrapolation required. As further addressed in Section IX, collection of even a minimal amount of riparian vegetation and channel data at discreet locations marked accurately on aerial photography and collection of air temperature and humidity at selected water temperature monitoring locations would be of great benefit.

3. Calibrate model

Model calibration requires measured stream temperatures during the period of interest. The eight temperature measurement locations monitored by the Forest Service provided a relative abundance of measured temperature data, yielding a reasonably high confidence in the model predictions. Other basins may often have far fewer water temperature measurements available, resulting in lower confidence in model predictions, particularly in areas of the basin far removed from the temperature monitoring locations.

4. Validate model

Similar to calibration, model validation requires measured stream temperatures during the period of interest. Between the Forest Service and USFWS, an abundance of measured temperature data was available (total of 28 locations), yielding a reasonably high confidence in the model predictions. Most other basins would have far fewer water temperature measurements available, resulting in lower confidence in model predictions, particularly in areas of the basin far removed from the temperature monitoring locations.

5. Model median, cool/wet, and warm/dry years

Modeling meteorologically extreme years requires sufficient record lengths to adequately define the range of variability in air temperatures and streamflow in the basin. For the Chiwawa, this was possible due to the long-term stream gauge located within the basin (29 years of record) and the weather station located at Lake Wenatchee Ranger Station (30+ years of record), and was not a difficult step to perform. Other basins may not have such long meteorological records, or stations may not be located within or near the basin of interest. This would not cause the modeling to be more difficult, but would increase uncertainty in the results.

6. Estimate modeling error

Estimation of modeling error stems directly from calibration/validation combined with estimates of uncertainties in the input parameters. However, at least in the case of the Chiwawa, it appears that the combined uncertainty estimate is nearly entirely due to calibration/validation uncertainty, which for the Chiwawa was relatively low due to the abundance of water temperature data available. Other basins are likely to have fewer water temperature measurements available, resulting in higher uncertainty in model predictions.

E. Natural Thermal Potential

Estimating NTP requires determination of how current conditions have been altered from their natural state. In theory, NTP could be estimated based on historic thermal data, reference conditions, or modeling. For the Chiwawa, NTP was best estimated through modeling calibrated to the extensive thermal data recently gathered within the basin. In this approach, condition of stream channels, groundwater, surface streamflows, meteorologic conditions, and shade must be addressed.

1. Stream channels

Management activities in the Chiwawa basin that could potentially have altered stream channels are limited in geographic scope and intensity. Approximately two-thirds of the watershed area lies within wilderness or roadless areas that have not been subject to management impacts. Even for more downstream mainstem river reaches, potential management impacts are very limited. This simplicity makes estimation of potential impacts on channel characteristics relevant to thermal regime relatively easy and practical. Management within some tributary watersheds has been more intense, with attendant potential for greater impact, and tributary channels are more difficult to observe reliably from aerial photos because of their smaller size and because riparian vegetation often blocks the view. However, based on our limited field observations and accounts of management history and impacts from the watershed assessment (USFS, 1997), we determined that impacts on tributary channels (other than on local stream sections with highly localized effects) were highly unlikely to affect thermal characteristics of most of the tributary channels examined at the reach scale as we defined it, and effects would certainly not be discernible on the mainstem river.

For the Chiwawa, assessment of natural versus current channel effects was relatively easy and practical, although a small degree of uncertainty is introduced due to the potential for continued impact of historic log rafting through lower sections of the river. In highly altered sub-basins, it may be very difficult to quantify impacts of current and historic management activities on channel characteristics with any degree of certainty.

2. Groundwater

Effects on groundwater in the Chiwawa watershed are limited to minor withdrawals only on the very lowest river reaches. There is essentially no potential effect on thermal regimes; estimation of current versus historic conditions was easy. However, we believe that quantification of thermal effects of groundwater withdrawals in basins more subject to this activity could prove to be very difficult, and may prove to be impractical to do with accuracy sufficient to provide estimates of NTP within useful accuracy bounds. We discuss this more in Section IX.

3. Surface streamflows

Surface streamflows in the Chiwawa watershed are well documented for the mainstem at the USGS gauging station, and have been recorded at some tributary locations by the Forest Service. We estimated streamflow throughout the watershed from the USGS data strictly on a watershed area basis. More accurate estimates of streamflow *may* have been developed by also adjusting with local tributary data and/or by adjusting for annual precipitation from isohyetal maps. However, the calibration and validation exercises for the Chiwawa suggest that this was not necessary. Either approach is practical and relatively easy as long as a sufficiently long record (i.e., ten years or more) of streamflow exists for the mainstem of the basin of concern. Quantification of surface flows for the Chiwawa is not complicated by groundwater withdrawals, multiple surface diversions, or return flows.

In other basins, determining the effects of management activities on flow relationships could be far more complex, and determining impacts of current activities on NTP could prove to be extremely difficult, to the point of impracticality.

4. Meteorologic conditions

Determining meteorologic conditions for the stream system reaches of the Chiwawa sufficient to allow reasonably accurate modeling of current water temperatures was not difficult. Because of the limited extent of management activities, and because streams have been protected with riparian buffers, effects of meteorologic alteration on NTP was not difficult to estimate. In watersheds where riparian vegetation has been highly altered, water temperatures may be affected. However, we are not aware of *currently available* information that would allow estimation of the magnitude of such effects. The results of ongoing research efforts may soon fill this knowledge gap.

5. Shade

Shade on the water column of streams is dependent on distance to and characteristics of adjacent riparian vegetation (i.e., vegetative height, width, and density), and to a lesser degree on adjacent topography. For the Chiwawa, these were easily determined from recent aerial photography with sufficient accuracy to allow reasonably accurate estimation of both current temperatures and NTP. Difficulty and uncertainty of determining the natural state of riparian vegetative characteristics will increase in other sub-basins where management activities have more extensively altered the riparian conditions. Older sets of aerial photography and historical accounts of native vegetation may help in these circumstances, but the effort becomes more difficult and time consuming.

F. Time Requirements

This case study required that we provide a summary of the time we spent completing each required key step. Our summary was developed directly from our daily timesheets. Time required to similarly implement the Guidance in other basins is addressed in Section IX.

Table 7. Time Required to Complete Key Case Study Requirements

Task	Time Required (Hours)
Select case study watershed	26
Characterize watershed	24
Species life histories	26
Current species distribution	120
Potential species distribution	142
Model description and sensitivities	4
Gather and describe available data	91
Model parameterization & calibration	127
Model verification	43
Determination of NTP for median year	49
NTP for cool/wet and warm/dry years	30
Modeling error estimation	32
Reconciliation of NTP with biological criteria	15
Discussion and practicality of application	28
Total	**757**

IX. DISCUSSION

In a previous project for the Idaho Department of Environmental Quality, we found that *Heat Source*, the model we used for this case study, produced simulations as good as or slightly better than SSTEMP (Theurer et al, 1984). Both models are process or "mechanistic" models, but *Heat Source* is capable of predicting maximum daily temperatures directly, whereas SSTEMP predicts maximum temperatures empirically from daily average temperatures. Nevertheless, even process models become somewhat empirical when parameter input values must be estimated from limited data, and during calibration when input values are adjusted to reduce the differential between predicted and measured stream temperatures.

In this case study, we were careful to only adjust input parameters when there was considerable uncertainty as to the true input values, and then the values were adjusted consistently throughout the entire stream system. This approach reduces the likelihood of introducing error into the predictions through introduction of purely empirical fits ("calibration") to the measured temperature data.

Values for input parameters such as wetted channel width, flow velocity, flow depth, and riparian vegetative characteristics are difficult to estimate throughout a stream network. Model application in any system would benefit from even a small number of measurements of these parameters at specific transect locations identifiable on aerial photography. This would allow more accurate determination of reach-averaged parameter values, decreasing the degree of empiricality of model application. Measurement of air temperature and humidity at even a few water temperature monitoring locations would be similarly helpful. Although more difficult, measurement of groundwater temperatures would also be helpful.

The Monte Carlo approach for estimation of temperature prediction error is useful for predicting the likely error around the *predicted* temperatures, but provides no insight regarding potential bias of the estimate. The wealth of thermal monitoring stations placed throughout the length of the Chiwawa mainstem reveals bias in our estimates, even with calibration, for the lower reaches of the river where the estimates were consistently lower than the measured temperatures. The existence of such error would likely remain unknown in systems without such a wealth of measured locations.

Related to the discussion above, our estimate of NTP is based on the lower confidence bound of the modeled values for the median air temperature and streamflow year. This approach is correct and necessary, because the median year is not measured; we only had measured values for the year 2000. *Heat Source* calibrated to the year 2000 then allows modeling of thermal regimes for periods outside the period of record, including other seasons (e.g., months like May), and the median, cold/wet, and warm/dry years. Nonetheless, the difference between the measured and the predicted year 2000 temperatures can be considered a measure of bias and could be used to adjust the NTP estimates, particularly if such adjustments were limited to the seasonal time period of the calibration effort. We made no such adjustments for the Chiwawa, but suggest that the EPA and its advisors consider the merits of this approach for stream systems where the data is available to support the adjustment. The practical implications for the Chiwawa are that the estimate of NTP at the Chiwawa river mouth would increase by the amount that the measured temperature exceeded the modeled estimate - about 0.7°C based on our August 5 and August 24 validations (see Figures 9 and 10) - with lesser adjustments, both positive and negative, at other measured locations.

Based on our best estimates of how conditions currently vary from those that existed prior to Euro-American influences, the maximum increase in NTP at any location is 0.3°C. Clearly, where conditions have been altered by man, the actual deviation of NTP from current conditions could be somewhat larger or smaller, although it is difficult to see how this deviation could be large in relation to the current estimates. For the majority of the Chiwawa stream system, there has been no anthropogenic effect on water temperatures. For the unaltered parts of the system, estimated NTP values for the median or other years can be developed from measured values (given sufficient spatial and temporal extent of water temperature measurement records), in which case the only sources of error are in the accuracy of the thermometers employed and in adjustment for streamflow and air temperature in the year of interest. These errors are small, and not likely to be systematically biased.

X. SUMMARY

Data from 28 temperature-recording instruments was used to calibrate and validate *Heat Source* temperature predictions for the warmest water temperature day of year 2000. 80 miles of perennial stream were divided into 56 stream reaches and modeled. Natural thermal potential was then estimated with the model by providing the model with parameter input values reflective of natural conditions. Estimates of natural conditions on a stream reach specific basis were developed by assessing the degree to which current conditions have been observably affected by management activities. *Heat Source* was then used to predict maximum and seven day mean

maximum stream temperatures throughout the Chiwawa sub-basin for the hypothetical median, cool/wet, and warm/dry air temperature and streamflow years.

Chiwawa River mainstem water temperatures remain close to their natural thermal potential. Predicted maximum increase in current water temperature over NTP is 0.3°C at the river's confluence with the Wenatchee River, decreasing to zero towards the middle of the watershed. Larger increases attributed to anthropogenic effects occur within sections of some river tributaries, but affects of any one tributary on the river are limited to less than 0.1°C and do not accumulate because of long distances and time of travel of river waters between tributaries.

Salmonid species in the Chiwawa watershed include spring chinook salmon (*Oncorhynchus tshawytscha*), steelhead/rainbow trout (*O. mykiss*), cutthroat trout (*O. clarki lewisi*), bull trout (*Salvelinus confluentus*), brook trout (*S. fontinalis*), mountain whitefish (*Prosopium williamsoni*), dace (*Rhinichthys sp.*), and sculpin (*Cottus sp.*). An in-depth discussion of species occurrence, timing of occurrence, life stage histories, data sources, methodology for estimating potential occurrence, and life stage maps for the watershed are included in as Appendix A. These species have extensive life stage distributions throughout the sub-basin, beginning at the river's mouth and extending far upstream. Because of the limited extent of land uses in the watershed and the extensive distribution of species, effects of land use on the distribution of fishes within the watershed are likely very minor.

Because of the extensive network of temperature monitoring stations distributed throughout the sub-basin, NTP can be predicted for the Chiwawa system with relatively little error. Standard deviation of the modeled NTP estimate is 0.9°C. This uncertainty is subtracted from the NTP estimates to provide the lower bound of NTP used in the EPA Draft Guidance for comparison and reconciliation with their suggested life stage temperature criteria.

NTP is lower than the EPA draft life stage temperature criteria for most species life stages. However, NTP exceeds the EPA draft life stage temperature criteria (12°C) for all bull trout life stages throughout the Chiwawa mainstem, and exceeds the chinook spawning criteria (13°C) for several lower mainstem reaches. Consistent with the EPA Guidance, where exceeded by NTP, the species-life stage numeric criteria would be replaced by "thermal potential numeric criteria" developed from the NTP in a process that may accommodate some level of anthropogenic impact.

XI. LITERATURE CITED

Amaranthus, M., H. Jubas, and D. Arthur. 1989. Stream shading, summer streamflow, and maximum water temperature following intense wildfire in headwater streams. In: N. H. Berg, editor, Proceedings of the Symposium on Fire and Watershed Management, October 26-28, 1988, Sacramento, California. General Technical Report PSW-109. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. p. 75-78.

Beschta, R. L., M. R. Pyles, A. E. Skaugset, and C. G. Surfleet. 2000. Peakflow responses to forest practices in the western Cascades of Oregon, USA. Journal of Hydrology 233: 102-120.

Beschta, R. L., R. E. Bilby, G. W. Brown, L. B. Holtby, and T. D. Hofstra. 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions. In: Proceedings: Stream temperature and aquatic habitat: fisheries and forestry interactions. College of Forest Resources, University of Washington, Seattle, Washington. p. 191-232.

Bosch, J. M., and J. D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55: 3-23.

Boyd, M. S. 1996. *Heat Source*: stream temperature prediction. Master's thesis, Departments of Civil and Bioresource Engineering, Oregon State University, Corvallis, Oregon.

Brosofske, K. D., J. Chen, R. J. Naiman, and J. F. Franklin. 1997. Harvesting effects on microclimatic gradients from small streams to uplands in western Washington. Ecological Applications 7 (4): 1188-1200.

EPA. 2001. Draft EPA Region 10 guidance for state and tribal temperature water quality standards - public review draft. Environmental Protection Agency, Seattle, Washington. 12 p. plus appendices.

Geiger, R. 1965. The climate near the ground. Harvard University Press, Cambridge, Massachusetts.

Gucinski, H., M. J. Furniss, R. R. Ziemer, and M. H. Brookes (editors). 2000. Forest roads: a synthesis of scientific information. USDA Forest Service, Internet document, June 2000. 117 p.

Harr, R. D., A. Levno, and R. Mersereau. 1982. Streamflow changes after logging 130-year-old Douglas-fir in two small watersheds. Water Resources Research 18: 637-664.

Harr, R. D. 1979. Effects of timber harvest on streamflow in the rain-dominated portion of the Pacific Northwest. In: Proceedings of Workshop on Scheduling Timber Harvest for Hydrologic Concerns, November 27-29, 1979, Portland, Oregon. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station. 45 p.

Harr, R. D., W. C. Harper, J. T. Krygier, and F. S. Hsieh. 1975. Changes in storm hydrographs after roadbuilding and clearcutting in the Oregon Coast Range. Water Resources Research 11 (3): 436-444.

Hibbert, A. R. 1967. Forest treatment effects on water yield. In: W. E. Sopper and H. W. Lull, editors, International Symposium on Forest Hydrology Proceedings, August 29 to September 10, 1965, Penn State University. Pergamon Press, New York. p. 527-543.

James, C. 1999. How do eight different clearcut buffer widths affect steam temperature and riparian zone microclimate? Western Forestry Conference on Coordinating Regulatory

Requirements on Private Lands, December 5-7, 1999, Sacramento, California. Western Forestry and Conservation Association, Portland, Oregon.

Jones, J. A., and G. E. Grant. 1996. Peak flow responses to clear-cutting in small and large basins, western Cascades, Oregon. Water Resources Research 32 (4): 959-974.

Keppeler, E. T. 1998. The summer flow and water yield response to timber harvest. In: R. R. Ziemer, Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story, May 6, 1998, Ukiah, California. General Technical Report PSW-GTR-168. USDA Forest Service, Pacific Southwest Research Station, Albany, California. p. 35-43.

King, J. G., and L. C. Tennyson. 1984. Alteration of streamflow characteristics following road construction in north central Idaho. Water Resources Research 20 (8): 231-243.

Knutson, K. L., and V. L. Naef. 1997. Management recommendations for Washington's priority habitats: riparian. Washington Department of Fish and Wildlife, Olympia, Washington.

Knudson, T. 1994. Smokey's legacy: moonscapes all-killing infernos. The Sacramento Bee, November 30, 1994.

Lewis, J., S. R. Mori, E. T. Keppeler, and R. R. Ziemer. 2000. Impacts of logging on storm peak flows, flow volumes and suspended sediment loads in Caspar Creek, California. In: M. S. Wigmosta and S. J. Burges (editors), The Influence of Land Use on the Hydrologic-Geomorphic Responses of Watersheds. Water Resources Monograph, American Geophysical Union, Washington, D.C.

ODEQ. 1999. *Heat Source* methodology review: reach analysis of stream and river temperature dynamics. Oregon Department of Environmental Quality, Portland, Oregon. 83 p.

Rothacher, J. S. 1973. Does harvest in west slope Douglas-fir increase peak flow in small forest streams? Research Paper PNW-163. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon. 13 p.

Rothacher, J. 1971. Regimes of streamflow and their modification by logging. In: J. T. Krygier and J. D. Hall, editors, Forest Land Uses and Stream Environment, Proceedings of a Symposium, October 19-21, 1970. Oregon State University, Corvallis, Oregon. p. 40-54.

Sugden, B. D., T. W. Hillman, J. E. Caldwell, and R. J. Ryel. 1998. Stream temperature considerations in the development of Plum Creek's Native Fish Habitat Conservation Plan. Native Fish Habitat Conservation Plan Report #12. Plum Creek Timber Company, Columbia Falls, Montana. 57 p. plus tables and figures.

Theurer, F. D., K. A. Voos, and W. J. Miller. 1984. Instream water temperature model. Instream Flow Information Paper No. 16. U.S. Fish and Wildlife Service, Fort Collins, Colorado. 200 p.

Thomas, R. B., and W. F. Megahan. 1998. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: a second opinion. Water Resources Research 34 (12): 3393-3403.

Troendle, C. A. 1988. Effect of partial cutting and thinning on the water balance of the subalpine forest. In: Future Forest of the Mountain West: A Stand Culture, Proceedings of a Symposium, September 29-October 3, 1988, Missoula, Montana. p. 108-116.

USFS. 1997. Chiwawa River Watershed Assessment. Lake Wenatchee Ranger District, Wenatchee National Forest. 78 p. plus plates and appendices.

Washington Forest Practices Board. 1997. Board manual: standard methodology for conducting watershed analysis, Version 4.0, November, 1997. Department of Natural Resources, Olympia, Washington.

Wright, K. A., K. H. Sendek, R. M. Rice, and R. B. Thomas. 1990. Logging effects on streamflow: storm runoff at Caspar Creek in northwestern California. Water Resources Research 26 (7): 1657-1667.

Ziemer, R. R. 1981. Storm flow response to road building and partial cutting in small streams of northern California. Water Resources Research 17: 907-917.

XII. APPENDICES

Appendix A - Bioanalysts, Inc. report on fish distribution in the Chiwawa watershed
Appendix B - *Heat Source* model inputs for August 5, 2000 calibration

Appendix A

(Distributed as a separate document due to its size)

Miller, M., T. Hillman, S. Jensen, T. Dean, and B. Nishitani. 2002. Potential Salmonid Distributions In the Chiwawa River Basin. Prepared by BioAnalysts, Inc., Boise, ID and Whitehorse Associates, Smithfield, UT for Idaho Department of Environmental Quality, Boise, ID. 64 pp.

Appendix B

Heat Source model inputs for August 5, 2000 calibration

APPENDIX B - *Heat Source* Model Inputs for August 5, 2000 Calibration

Reach #	1	2	3	4	5	6	7	8	9
Stream	Chiwawa	Chiwawa	Buck	Buck	Buck	Buck	Chiwawa	Alpine	Chiwawa
Date	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00
Latitude (°)	48	48	48	48	48	48	48	48	48
Longitude (°)	121	121	121	121	121	121	121	121	121
Stream aspect (°)		170		130		130	160		160
% bedrock		0%		0%		0%	0%		0%
Reach length (m)		5,250		3,820		1,650	2,590		2,050
Stream width (m)		4.8		3.6		4.8	7.3		8.5
U/S flow volume (cms)	0.0000	0.2996	0.0000	0.2956	0.0000	0.7166	1.5054	0.0000	2.0051
Velocity (m/s)		0.50		0.59		0.66	0.61		0.58
G/W inflow (cms)	0.2996	0.3536	0.2956	0.1946	0.2264	0.1355	0.2406	0.2591	0.2247
G/W temperature (°C)	6.7	10.7	7.4	9.4	9.4	10.7	11.7	11.7	12.1
Buffer height (m)		27		24		27	30		36
Buffer width (m)		50		50		50	50		50
Canopy density		60%		50%		50%	50%		50%
Distance to stream (m)		2.0		0.0		3.0	3.0		12.0
Incision (m)		1.00		1.00		1.00	1.00		1.00
Tree overhang (m)		0.0		0.0		0.0	0.0		0.0
Topographic west (°)		20		0		20	30		0
Topographic east (°)		0		0		0	0		0
Min. air temp. (°C)	9.9	13.9	10.6	12.6	12.6	13.9	14.9	14.9	15.3
Max. air temp. (°C)	17.9	21.9	18.6	20.6	20.6	21.9	22.9	22.9	23.3
Min. humidity	35%	35%	35%	35%	35%	35%	35%	35%	35%
Max. humidity	90%	90%	90%	90%	90%	90%	90%	90%	90%
Elevation (m)	1,436	992	1,360	1,141	1,141	992	887	887	842
Wind speed (m/s)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Predicted average (°C)	11.2	11.2	11.5	10.3	11.5	10.8	11.3	11.5	11.7
Predicted maximum (°C)	11.9	12.4	11.9	11.1	11.9	12.1	12.9	11.9	13.6

APPENDIX B - *Heat Source* Model Inputs for August 5, 2000 Calibration

Reach #	10	11	12	13	14	15	16	17	18
Stream	Phelps	Phelps	Phelps	Phelps	Chiwawa	Willow	trib	Chiwawa	Little Giant
Date	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00
Latitude (°)	48	48	48	48	48	48	48	48	48
Longitude (°)	121	121	121	121	121	121	121	121	121
Stream aspect (°)		160	165	215	160			160	
% bedrock		0%	0%	0%	0%			0%	
Reach length (m)		3,650	3,930	3,930	2,640			2,320	
Stream width (m)		3.6	5.5	6.4	10.9			12.1	
U/S flow volume (cms)	0.0000	0.2230	0.5333	1.1622	3.5865	0.0000	0.0000	4.2124	0.0000
Velocity (m/s)		0.57	0.56	0.61	0.62			0.58	
G/W inflow (cms)	0.2230	0.3103	0.6289	0.1945	0.3514	0.2218	0.0527	0.2335	0.1893
G/W temperature (°C)	6.6	8.4	9.7	12.1	12.4	12.4	12.4	12.5	12.5
Buffer height (m)		27	24	34	40			36	
Buffer width (m)		50	50	50	50			50	
Canopy density		50%	40%	50%	50%			40%	
Distance to stream (m)		9.0	6.0	5.0	3.0			6.0	
Incision (m)		1.00	1.00	1.00	1.00			1.00	
Tree overhang (m)		0.0	0.0	0.0	0.0			0.0	
Topographic west (°)		0	0	25	0			0	
Topographic east (°)		0	0	25	0			0	
Min. air temp. (°C)	9.8	11.6	12.9	15.3	15.6	15.6	15.6	15.7	15.7
Max. air temp. (°C)	17.8	19.6	20.9	23.3	23.6	23.6	23.6	23.7	23.7
Min. humidity	35%	35%	35%	35%	35%	35%	35%	35%	35%
Max. humidity	90%	90%	90%	90%	90%	90%	90%	90%	90%
Elevation (m)	1,456	1,255	1,104	842	809	809	808	793	793
Wind speed (m/s)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Predicted average (°C)	11.5	9.2	9.9	10.9	11.7	11.5	11.5	12.0	11.5
Predicted maximum (°C)	11.9	11.1	11.8	13.6	13.4	11.9	11.9	13.9	11.9

APPENDIX B - *Heat Source* Model Inputs for August 5, 2000 Calibration

Reach #	19	20	21	22	23	24	25	26	27
Stream	Chiwawa	trib	Chiwawa	Y	Chiwawa	Schaefer	Rock	Rock	Chiwawa
Date	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00
Latitude (°)	48	48	48	48	48	48	48	48	48
Longitude (°)	121	121	121	121	121	121	121	121	121
Stream aspect (°)	160		160		155			200	150
% bedrock	0%		0%		0%			0%	0%
Reach length (m)	4,720		3,360		3,100			8,020	6,460
Stream width (m)	12.1		13.0		13.6			6.1	15.1
U/S flow volume (cms)	4.6351	0.0000	5.3909	0.0000	5.7938	0.0000	0.0000	0.9041	8.0529
Velocity (m/s)	0.60		0.57		0.57			0.66	0.57
G/W inflow (cms)	0.6448	0.1110	0.1885	0.2144	0.2384	0.2075	0.9041	0.9092	0.4071
G/W temperature (°C)	12.8	12.8	12.9	12.9	13.0	13.0	10.2	13.0	13.1
Buffer height (m)	36		36		36			27	40
Buffer width (m)	50		50		50			50	50
Canopy density	50%		60%		60%			60%	60%
Distance to stream (m)	5.0		0.0		7.5			3.0	2.0
Incision (m)	1.00		1.00		1.00			1.00	1.00
Tree overhang (m)	0.0		0.0		0.0			0.0	0.0
Topographic west (°)	0		0		0			30	0
Topographic east (°)	0		0		0			0	0
Min. air temp. (°C)	16.0	16.0	16.1	16.1	16.2	16.2	13.4	16.2	16.3
Max. air temp. (°C)	24.0	24.0	24.1	24.1	24.2	24.2	21.4	24.2	24.3
Min. humidity	35%	35%	35%	35%	35%	35%	35%	35%	35%
Max. humidity	90%	90%	90%	90%	90%	90%	90%	90%	90%
Elevation (m)	762	762	752	752	745	745	1,055	743	733
Wind speed (m/s)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Predicted average (°C)	12.4	11.5	12.5	11.5	12.6	11.5	11.5	12.9	12.9
Predicted maximum (°C)	14.2	11.9	14.0	11.9	14.0	11.9	11.9	14.3	14.0

APPENDIX B - *Heat Source* Model Inputs for August 5, 2000 Calibration

Reach #	28	29	30	31	32	33	34	35	36
Stream	trib	Chiwawa	Raging	Raging	Raging	Chiwawa	Chikamin	Chikamin	Chikamin
Date	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00
Latitude (°)	48	48	48	48	48	48	48	48	48
Longitude (°)	121	121	121	121	121	121	121	121	121
Stream aspect (°)		155		80	170	160			190
% bedrock		0%		0%	0%	0%			0%
Reach length (m)		3,540		3,250	2,270	3,210			8,480
Stream width (m)		15.1		3.6	4.2	15.1			5.5
U/S flow volume (cms)	0.0000	8.5484	0.0000	0.2898	0.5007	9.3292	0.0000	0.0000	0.4952
Velocity (m/s)		0.59		0.59	0.62	0.65			0.57
G/W inflow (cms)	0.0884	0.1542	0.2898	0.2109	0.1258	0.1627	0.2477	0.2476	0.7334
G/W temperature (°C)	13.1	13.1	10.0	13.0	13.1	13.1	9.6	9.6	13.0
Buffer height (m)		34		36	36	36			43
Buffer width (m)		50		50	50	50			50
Canopy density		40%		80%	80%	50%			75%
Distance to stream (m)		7.0		0.0	0.0	4.0			1.0
Incision (m)		1.00		1.00	1.00	1.00			1.00
Tree overhang (m)		0.0		1.0	1.0	0.0			0.0
Topographic west (°)		0		0	0	0			20
Topographic east (°)		0		0	0	0			0
Min. air temp. (°C)	16.3	16.3	13.3	16.2	16.3	16.4	12.8	12.8	16.2
Max. air temp. (°C)	24.3	24.3	21.3	24.2	24.3	24.4	20.8	20.8	24.2
Min. humidity	35%	35%	35%	35%	35%	35%	35%	35%	35%
Max. humidity	90%	90%	90%	90%	90%	90%	90%	90%	90%
Elevation (m)	733	728	1,068	741	728	724	1,119	1,119	740
Wind speed (m/s)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Predicted average (°C)	11.5	13.0	11.5	12.6	12.9	13.1	11.5	11.5	13.1
Predicted maximum (°C)	11.9	14.0	11.9	12.7	12.9	14.2	11.9	11.9	13.9

APPENDIX B - *Heat Source* Model Inputs for August 5, 2000 Calibration

Reach #	37	38	39	40	41	42	43	44	45
Stream	Chikamin	Minnow	Marble	Chiwawa	Brush	Brush	Chiwawa	Big Meadow	Big Meadow
Date	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00
Latitude (°)	48	48	48	48	48	48	48	48	48
Longitude (°)	121	121	121	121	121	121	121	121	121
Stream aspect (°)	220			130		110	170		130
% bedrock	0%			0%		0%	0%		0%
Reach length (m)	1,460			1,940		5,180	5,760		4,220
Stream width (m)	7.6			18.2		2.4	19.7		2.7
U/S flow volume (cms)	1.8414	0.0000	0.0000	11.3576	0.0000	0.1058	11.7019	0.0000	0.0385
Velocity (m/s)	0.64			0.54		0.64	0.62		0.60
G/W inflow (cms)	0.0243	0.2610	0.3519	0.0685	0.1058	0.1700	0.7620	0.0385	0.3763
G/W temperature (°C)	13.1	13.0	13.0	13.2	11.7	13.2	13.5	11.5	12.5
Buffer height (m)	30			34		45	34		45
Buffer width (m)	37			45		42	43		15
Canopy density	40%			70%		75%	70%		75%
Distance to stream (m)	3.0			0.0		0.0	0.0		0.0
Incision (m)	1.00			1.00		1.00	1.00		1.00
Tree overhang (m)	0.0			0.0		0.0	0.0		0.0
Topographic west (°)	0			0		0	0		20
Topographic east (°)	0			0		0	0		20
Min. air temp. (°C)	16.4	16.2	16.2	16.4	14.9	16.4	16.8	14.7	15.7
Max. air temp. (°C)	24.4	24.2	24.2	24.4	22.9	24.4	24.8	22.7	23.7
Min. humidity	35%	35%	35%	35%	35%	35%	35%	35%	35%
Max. humidity	90%	90%	90%	90%	90%	90%	90%	90%	90%
Elevation (m)	724	736	740	721	882	721	680	907	792
Wind speed (m/s)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Predicted average (°C)	13.4	13.6	13.6	13.2	11.5	13.2	13.4	11.5	12.8
Predicted maximum (°C)	14.4	14.1	14.1	14.1	11.9	13.4	14.7	11.9	13.3

APPENDIX B - *Heat Source* Model Inputs for August 5, 2000 Calibration

Reach #	46	47A	47B	48	49	50A	50B	51U	51
Stream	Big Meadow	Big Meadow	Big Meadow	Chiwawa	Alder	Alder	Alder	Chiwawa	Chiwawa
Date	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00	8/5/00
Latitude (°)	48	48	48	48	48	48	48		48
Longitude (°)	121	121	121	121	121	121	121		121
Stream aspect (°)		100	120	160		190	190		160
% bedrock		0%	0%	0%		0%	0%		0%
Reach length (m)		4,130	4,200	3,830		3,910	1,920	1,560	4,760
Stream width (m)		6.1	6.1	23.3		3.0	4.2		25.4
U/S flow volume (cms)	0.0000	0.5226	0.9291	13.8027	0.0000	0.1242	0.4678		14.6237
Velocity (m/s)		0.39	0.61	0.61		0.64	0.61		0.64
G/W inflow (cms)	0.1078	0.4066	0.4096	0.1817	0.1242	0.3435	0.1715		0.7308
G/W temperature (°C)	12.5	13.0	13.4	13.9	10.1	12.0	13.9		14.2
Buffer height (m)		6	43	45		43	43		43
Buffer width (m)		50	50	30		15	15		30
Canopy density		80%	70%	60%		70%	70%		40%
Distance to stream (m)		0.0	0.0	1.0		0.0	0.0		2.0
Incision (m)		1.00	1.00	1.00		1.00	1.00		1.00
Tree overhang (m)		0.0	1.5	0.0		0.0	0.0		0.0
Topographic west (°)		0	0	0		20	20		20
Topographic east (°)		0	0	0		0	0		20
Min. air temp. (°C)	15.7	16.2	16.6	17.1	13.3	15.2	17.1		17.4
Max. air temp. (°C)	23.7	24.2	24.6	25.1	21.3	23.2	25.1		25.4
Min. humidity	35%	35%	35%	35%	35%	35%	35%		35%
Max. humidity	90%	90%	90%	90%	90%	90%	90%		90%
Elevation (m)	792	745	695	645	1,062	850	640		603
Wind speed (m/s)	2.5	2.5	2.5	2.5	2.5	2.5	2.5		2.5
Predicted average (°C)	11.5	13.3	13.4	13.6	11.5	12.3	13.3	13.6	13.9
Predicted maximum (°C)	11.9	14.2	13.8	14.8	11.9	12.9	14.0	14.8	15.2

APPENDIX B - *Heat Source* Model Inputs for August 5, 2000 Calibration

Reach #	52	53	54
Stream	Chiwawa	Clear	Chiwawa
Date	8/5/00	8/5/00	8/5/00
Latitude (°)	48	48	48
Longitude (°)	121	121	121
Stream aspect (°)	170		230
% bedrock	0%		0%
Reach length (m)	3,670		2,690
Stream width (m)	26.3		27.3
U/S flow volume (cms)	15.3545	0.0000	15.8236
Velocity (m/s)	0.61		0.59
G/W inflow (cms)	0.1196	0.3495	0.2250
G/W temperature (°C)	14.4	14.4	14.6
Buffer height (m)	36		36
Buffer width (m)	15		15
Canopy density	30%		30%
Distance to stream (m)	5.0		7.0
Incision (m)	1.00		1.00
Tree overhang (m)	0.0		0.0
Topographic west (°)	0		0
Topographic east (°)	0		0
Min. air temp. (°C)	17.6	17.6	17.8
Max. air temp. (°C)	25.6	25.6	25.8
Min. humidity	35%	35%	35%
Max. humidity	90%	90%	90%
Elevation (m)	583	583	562
Wind speed (m/s)	2.5	2.5	2.5
Predicted average (°C)	14.2	13.6	14.4
Predicted maximum (°C)	15.8	14.1	16.3