An Assessment of Water Temperatures of the Entiat River, Washington Using the Stream Network Temperature Model (SNTEMP)

By

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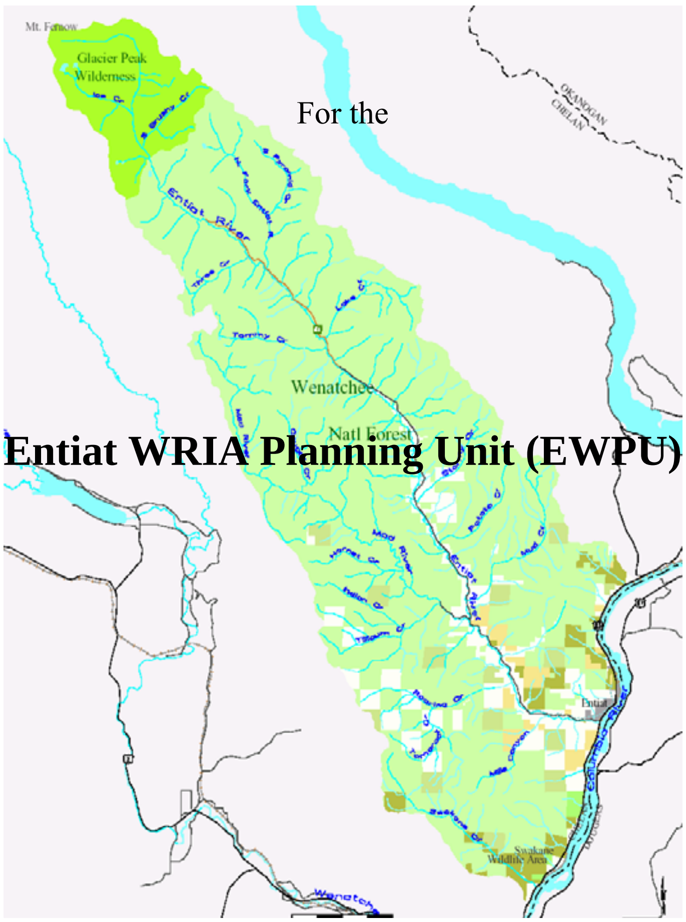
Through the Water Quality Sub-Committee



For the

Entiat WRIA Planning Unit (EWPU)

September, 2003

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Introduction

The Washington State Watershed Planning Act (Revised Code of Washington, Chapter 90.82) enables grass-roots, citizen-based watershed planning groups to assess and recommend means to address natural resource issues within Water Resource Inventory Areas (WRIA, see Washington Administrative Code, Chapter 173-500). Watershed planning units are required to address water quantity, and have the option to address instream flow, habitat, and water quality issues. Watershed planning units that address water quality issues are required to include in their watershed plans:

> "(1) An examination based on existing studies conducted by federal, state, and local agencies of the degree to which legally established water quality standards are being met in the management area;
> (2) An examination based on existing studies conducted by federal, state, and local agencies of the causes of water quality violations in the management area, including an examination of information regarding pollutants, point and nonpoint sources of pollution, and pollution-carrying capacities of water bodies in the management area. The analysis shall take into account seasonal stream flow variations, natural events, and pollution from natural sources that occurs independent of human activities; and
> (3) An examination of the legally established characteristic uses of each of the nonmarine bodies of water in the management area". (**Revised Code of Washington, Chapter 90.82.090, Watershed Planning Act**)

In 1996 the Washington State Department of Ecology (WDOE) identified segments of the Entiat River watershed as exceeding water temperature and instream flow standards (WDOE 1996) under section 303-d of the Clean Water Act (Federal Water Pollution Control Act, 1972). The WDOE (1998) removed water temperatures of the Entiat River from the 303-d listing about the time the Entiat WRIA Planning Unit (EWPU) was organizing under the Watershed Planning Act.

In spite of having been removed from the protection under the Federal Water Pollution Control Act, the EWPU was interested in addressing potential water temperature issues as part of its watershed plan. Thus, consistent with the above referenced portion of the Watershed Planning Act, the EWPU sought information from federal, state, and local agencies supporting an analysis of water temperatures in the Entiat River watershed. The EWPU specifically requested the development of a means to evaluate:

> "What actions can be taken to reduce water temperatures in the Entiat River watershed during critical high temperature periods?"

The EWPU requested that technical members of the planning unit form a Water Quality Sub-Committee to develop a plan of work to address water temperature issues, and other water quality issues under the Watershed Planning Act. The most active members of the sub-committee included staff of the United States Forest Service (USFS), Natural Resource Conservation Service (NRCS), Chelan County Conservation District (CCCD), and the WDOE.

The sub-committee developed a plan of work that recommended to the EWPU that water temperatures in the watershed be assessed and evaluated using a stream network temperature model like the United States Fish and Wildlife Service's (USFWS) Stream Network Temperature (SNTEMP) model (Theurer et al. 1984). The sub-committee recommended using a model, as it would best provide a means to evaluate and quantify the relative benefit of alternatives without having to expend significant resources and time implementing and monitoring all the proposed alternatives. The sub-committee recommended that the EWPU could use results from the modeling work to evaluate what actions could be implemented to reduce water temperatures in the Entiat River watershed during critical high temperature periods. That evaluation could then be used by the EWPU in making recommendations as part of the final watershed plan.

The EWPU adopted the April 11, 2001 Draft Water Quality Plan of Work during the April 18, 2001 Planning Unit meeting, enabling the sub-committee to proceed with an assessment of water temperatures of the Entiat River. This report is the Water Quality Sub-Committee's response to that request by the Entiat WRIA Planning Unit.

Methods

Study Area

The Entiat River watershed (WRIA 46) is centrally located in Chelan County in north-central Washington State (Figure 1). The Entiat River flows southeasterly approximately 43 miles from an elevation of approximately 9,249 feet in the Cascade Mountains to an elevation of approximately 713 feet at its confluence with the Columbia River near the town of Entiat. The watershed drains an area of approximately 267,735 acres, and varies from 5 to 15 miles wide. The North Fork Entiat River and the Mad River are the two main tributaries joining the Entiat River at river miles (RMs) 33 and 10.2 respectively. Numerous small tributaries and springs also join the Entiat River along its length.

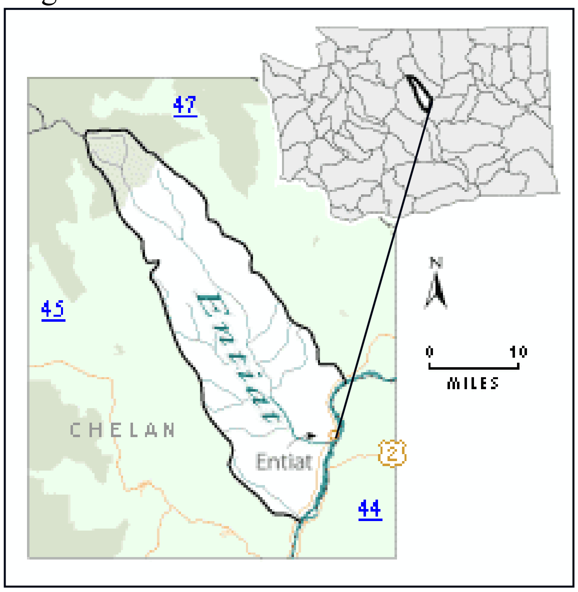
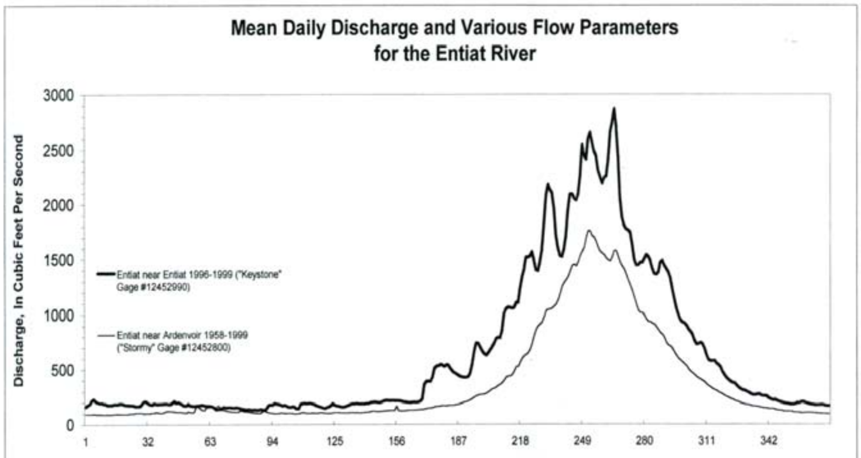


Figure 1: Map illustrating the Entiat River Watershed Resource Inventory Area (WRIA 46) within Washington State.

The upper Entiat River watershed is highly glaciated with a steep sloping U-shaped valley from the headwaters down to the terminal moraine near river mile 16. The middle watershed is heavily influenced by a terminal glacial moraine with a relatively wide valley bottom of low slope. The lower watershed is characterized by steep topography and narrowly cut canyons until the lowermost section of the watershed, which has rolling hills and a gentle slope (CCCD 2002).

Climate within the watershed varies from extremely hot temperatures in the summer (90-100˚ F) to sub-zero temperatures in the winter (CCCD 2002). Most precipitation occurs in the winter in the form of snow, and in the spring in the form of rain. The summer months produce some light to heavy thundershowers and can produce flash flooding (CCCD 2002). Flows in the lower Entiat River range from approximately 100 cubic feet per second (cfs) to 3000 cfs (Figure 2), with a mean annual flow of approximately 500 cfs as measured at the Entiat River near Entiat gage at RM 1.4 (Edwards and Rhodus 2003). Streamflows are typically lowest in the late summer months (August-September) and highest in the late spring/early summer in this snowmelt-based river system (CCCD 2002).



Mean Annual Runoff (acre-feet)		
Entiat at Entiat (Gage #12453000)		
Measured	1951 - 1958	367,379 AF
Estimated	1970 - 1976	528,275 AF
Entiat near Ardenvoir (1957 - 1993)		
	Mean	267,800 AF
	High (1972)	451,140 AF
	Low (1973)	178,970 AF

Stream Flow Parameters	Flows (cfs): Entiat at Entiat*	Flows (cfs): Entiat near Ardenvoir**
Range of mean annual flows	275 - 800	175 - 621
Range of annual peakflows	1,100 - 11,000	900 - 6,800
Range of 7-d mean low flows	45 - 120	36 - 90

* Entiat at Entiat (#12453000); Period of record 1911-1925 & 1951-1958; 419 sq miles
**Entiat near Ardenvoir (#12452800); Period of record 1961-1991; 203 sq miles

Figure 2: Mean daily flow regimes for the mainstem Entiat River as measured at the U.S. Geological Survey's Entiat near Entiat and Entiat near Ardenvoir gages. Illustration provided courtesy of Chelan County Conservation District.

Model Selection

The model selected for this assessment is the U.S. Fish and Wildlife Service's Stream Network Temperature model (SNTEMP; Theurer et al. 1984). This one dimensional heat transport model can, as a function of stream distance and environmental heat flux, predict daily mean and maximum water temperatures based on a dynamic temperature-steady flow equation (Bartholow 1989).

The model was chosen by the EWPU based on the following criteria: ease of use, availability of software, availability of training and support from the U.S. Geological Survey (USGS), record of reliable predictive power, and documented use in other river management decisions. SNTEMP has been peer-reviewed, widely applied, and is recognized as scientifically valid, as evidenced by publication in the primary literature (Blann et al. 2002; Bovee 1998; Bartholow 1991). According to Krause (2002), SNTEMP is one of the most comprehensively documented thermal models available.

Model Development

SNTEMP requires information defining meteorology, hydrology, and stream geometry (see Figure 3). This information is captured in seven input files entitled: meteorology, hydrology node, hydrology data, stream geometry, shade (optional), time period, and study. Input files are not included in this report, but are available with electronic copies of this report distributed on compact discs.

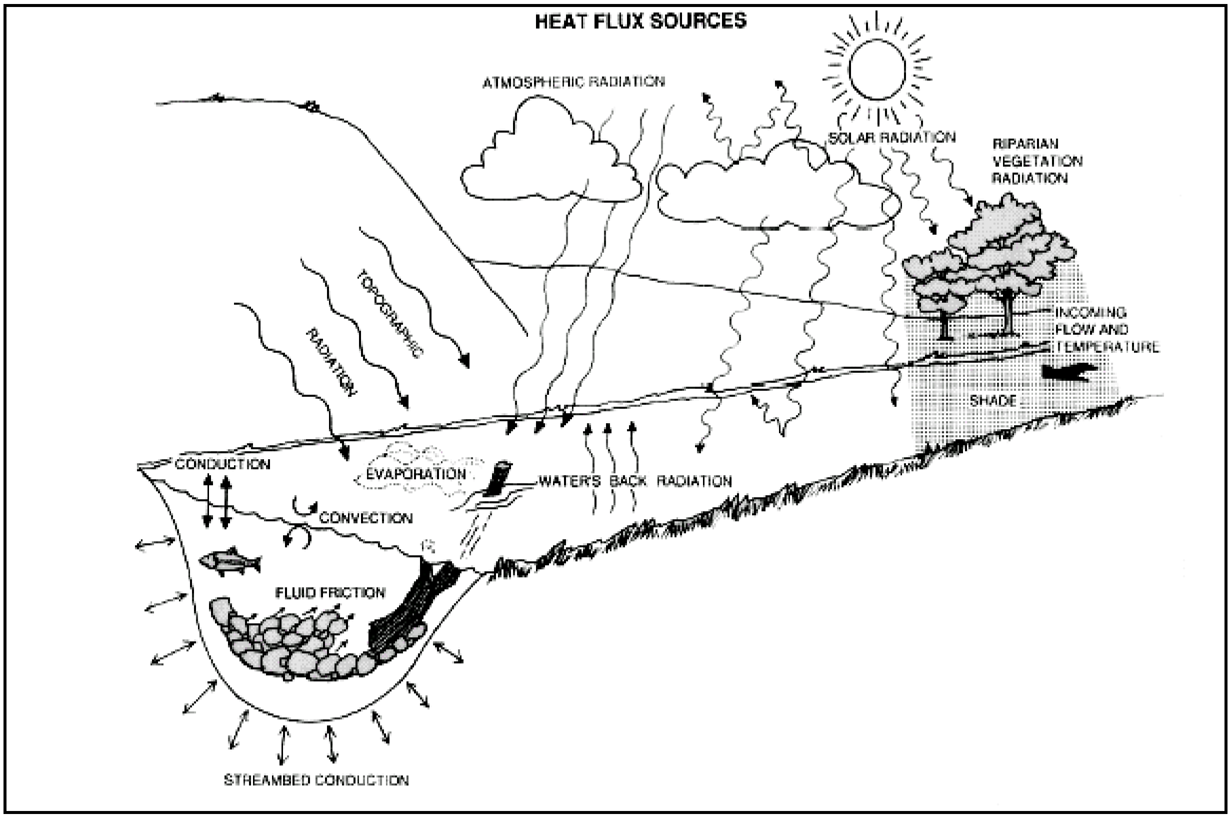


Figure 3: An oblique-view illustration of an idealized river channel and the heat flux input parameters required to operate SNTEMP (From Bartholow 2000)

The Skeleton File

For the purpose of modeling with SNTEMP, a node is defined as a location along the river system to which some type of modeling information is assigned. Prior to collecting all the necessary data, a "skeleton" node network must be developed (Bartholow 2000). A skeleton network defines the minimum number and location of nodes needed to accurately represent the river system being modeled. This node network typically incorporates information about the elevation, latitude, and stream distance of the starting point of the system (headwater node), any tributaries that have significant influence on the main-stem water temperature, and the end of the system (end node). Significant influences are defined as those factors that change the water temperature of the main-stem river ±1˚C (Bovee et al. 1998). The resulting skeleton node network is essential to running SNTEMP, as it is included in every required input file.

Figure 4 is a stick-diagram illustration the skeleton node network used for this application of SNTEMP. The headwater (H) node location was chosen due to the fact that Entiat Falls (RM 34) represents a complete barrier to anadromous fish (CCCD 2002) and because this study is intended to assess high water temperatures which tend to occur lower in the watershed. Also, the EWPU expressed interest in using the water temperature information together with instream flow and fish habitat information to assess the affects of the environment on certain salmonid species that cannot access habitat above this barrier. The availability of measured water temperature values, necessary in establishing a headwater node, was also a determining factor in selecting the barrier location as the headwater node. The end node (E) for the Entiat River model was also an obvious choice because it is, indeed, the end point of the Entiat River at the confluence with the Columbia River. The elevation, latitude, and stream distance information needed to define node locations was obtained from Sarah Walker of the Chelan County Conservation District (CCCD) using digital elevation, river network, and geo-referencing in the Entiat Geographic Information System (EGIS; Walker personal comm.).

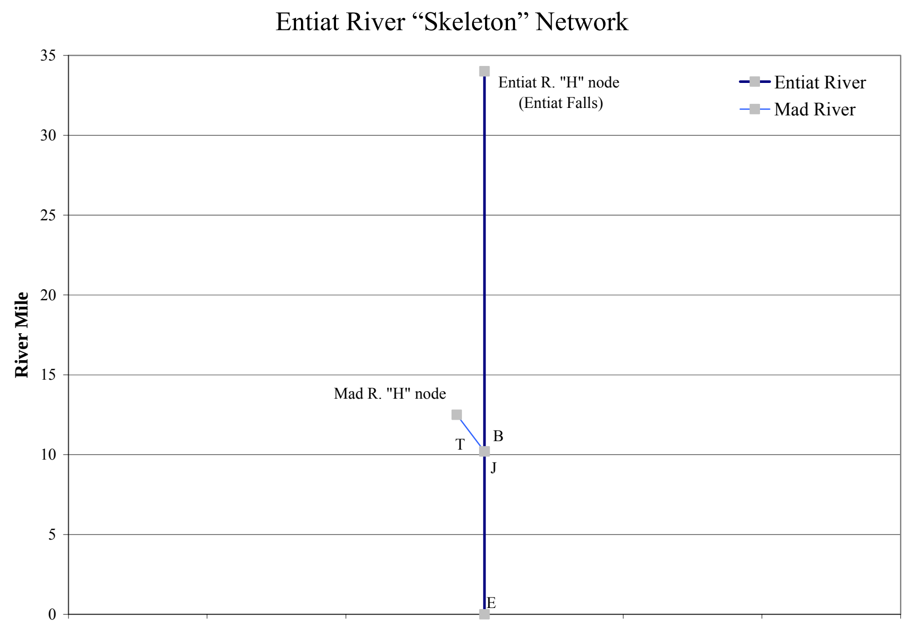


Figure 4: A stick-diagram illustration of the skeleton node network for the Entiat River, Washington. Points along the stick-diagram depict major thermal reaches within the Entiat River system. These major reaches are defined by headwaters (H), branch (B), terminal (T), junction (J), and end (E) nodes.

The Mad River is a major tributary of the Entiat River known to influence water temperature in the lower Entiat River (Archibald 1997-2002). Branch (B), terminal (T), and junction (J) nodes were created at the confluence of the Entiat and Mad Rivers to accommodate this influence. Although the Mad River is almost 26 miles in length, only the lower two miles of the river was used in this study. Data availability enabled inclusion of the lower portion of the Mad River system, but the upper portion of the Mad River watershed was excluded because stream flow data were not available for the upper Mad River, and because unusual water temperature fluctuation occur naturally in the upper drainage (Archibald personal comm.).

Water Temperature

Observed water temperature values are required for the headwater (H) and validation (V) nodes. Observed values are essential to initiate network modeling, to calibrate the model, and to assure defensibility of model results. For proper model calibration, observed water temperatures are compared with predicted water temperatures for common locations and time periods. Absent reliable observed water temperatures, there is no way to assure that the model is accurately and precisely predicting water temperatures.

Observed water temperatures were obtained for the years 1995-2002 for numerous locations along the Entiat and Mad Rivers from Phil Archibald of the U.S. Forest Service (USFS), Entiat Ranger District. Data was collected by the USFS at hourly increments at numerous locations for most years. For this application of SNTEMP, data were reduced to daily mean values for input and calibration/validation purposes at the following locations:

RM 1.4 – Keystone Bridge/USGS gage (Validation node)
RM 5.3 – Knapp Wham Bridge (Validation node)
RM 8.5 – Near Ringstead Canyon (Validation node)
RM 12.5 - Below Medsker Canyon (Validation node)
RM 18 - Stormy Creek/USGS gage (Validation node)
RM 26 – U.S. Forest Service Boundary (Validation node)
RM 34 – Entiat Falls (Headwater node)
RM 2 of Mad River – Mad River near Tillicum Creek (Mad River Headwater node)

Meteorology

The following meteorological parameters are necessary to run SNTEMP: air temperature, relative humidity, wind speed, percent sunshine, solar radiation, dust coefficient, and ground reflectivity. A modeler has the option of providing values for solar radiation, or allowing the model to synthesize values based on other meteorological input values. If the modeler provides solar radiation values, SNTEMP will refer to the solar radiation values of the last year (2002 in this application) for the rest of the modeled period of record (Bartholow 2000).

The meteorology input file also requires estimates of mean annual air temperature, latitude, and elevation of the weather station from which data was collected. SNTEMP applies these parameters to the entire river network, adjusting for changes in elevation with adiabatic correction equations. As such, individual nodes are not required for input of these meteorological parameters (Bartholow 2000).

For this application of SNTEMP, meteorology data were collected from multiple sources. Reliable and accurate climate data specific to the Entiat River Basin were among the hardest input values to find. Several anticipated sources of data proved to have incomplete records, or only some of the input variables estimated on the necessary time-step. The Entiat National Fish Hatchery (WRCC 1971-2000; located near RM 7.5) did not provide the all of the input parameters necessary; however its mean annual air temperature, latitude and elevation information was used as input data because of its central location within the watershed. This provided SNTEMP with a centrally located weather station to perform its adiabatic correction calculations. The Hatchery’s daily maximum and minimum air temperature data also proved useful in calibration of other meteorology data.

The Entiat Fire Station’s Remotely Automated Weather Station (RAWS; NOAA 2002) also proved useful in calibrating meteorology data from other locations, but was not used for input because the necessary input data were only available for one (2002) of the six years modeled (1997-2002), and meteorology data should be from a consistent source over the period of record being simulated (Bartholow 2000). Therefore, most of the meteorology data used for this application of SNTEMP came from a National Oceanographic and Atmospheric Administration (NOAA) weather station located approximately 30 miles southeast of the Entiat

River at the Pangborn Memorial Airport in East Wenatchee, Washington (NOAA 1997-2002). These data were used because of the relatively close proximity of the station to the Entiat River, because data were available for the period of record to be modeled, and because nearly all variables of interest proved reliable due to their collection by experts with acceptable methods. Although experts at the Pangborn weather station likely collected wind speed data with acceptable methods, the data were deemed unacceptable based on comparisons with the 2002 Entiat Fire Station's RAWS data (Figure 5).

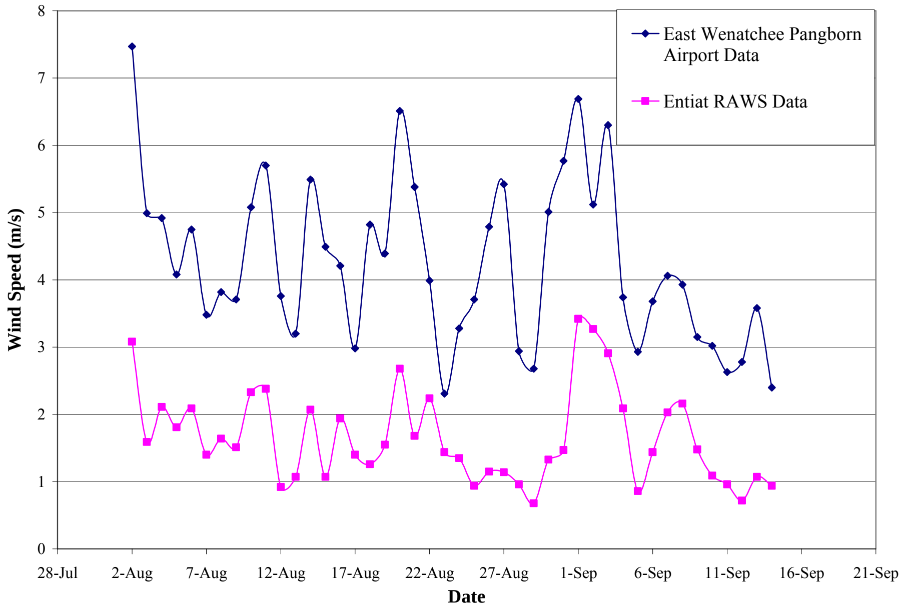


Figure 5: Comparisons of wind speed data from East Wenatchee Pangborn Airport and Entiat Fire Station for the 8/2-9/14 2002 time period.

Wind speed values from an Agriculture and Meteorology Station (AgriMet) in Manson approximately 25 miles north of the Entiat River (USBR 1997-2002) were used as they more closely resembled the 2002 wind speed values from the Entiat Fire Station (Figure 6).

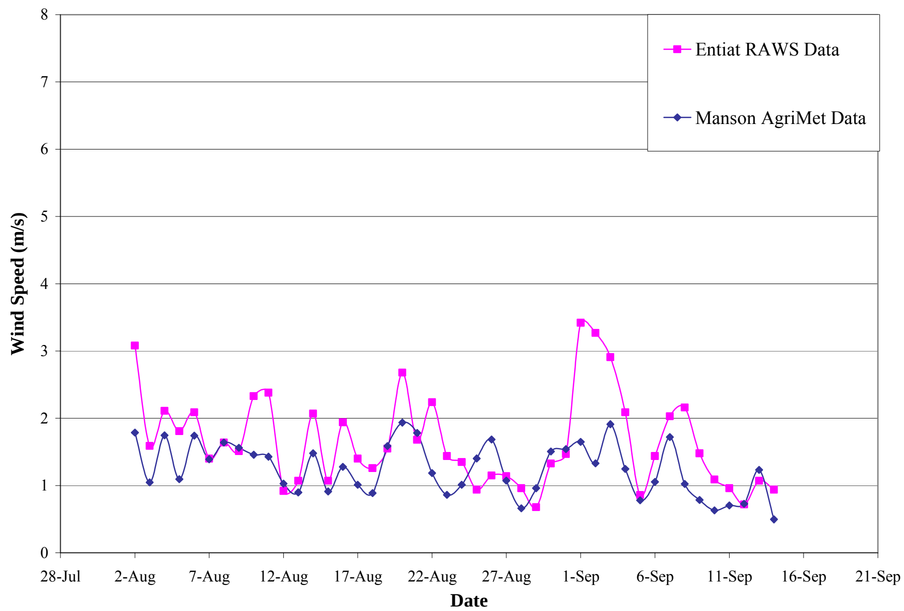


Figure 6: Comparisons of wind speed data from Manson AgriMet Station and Entiat Fire Station for the 8/2-9/14 2002 time period.

Because relative humidity values were not provided by any of the aforementioned weather stations, with the exception of one year of data at the Entiat Fire Station, values for relative humidity had be estimated from the Wenatchee Pangborn airport using the following equation found in Linsely et al. (1982) and suggested by Butkus (personal comm.):

$$f = 100\left((112 - 0.1T + T_d) / (112 + 0.9T)\right)^8$$

Where:

f = relative humidity (%)

T = air temperature (°C)

T_d = dew point temperature (°C)

This calculation is considered accurate within 0.6 percent in the range of -25 to 45°C (Linsley et al. 1982; Butkus personal comm.). However, Figure 7 shows that the Pangborn Airport calculated relative humidity values that were slightly higher compared to the Entiat Fire Station for 2002.

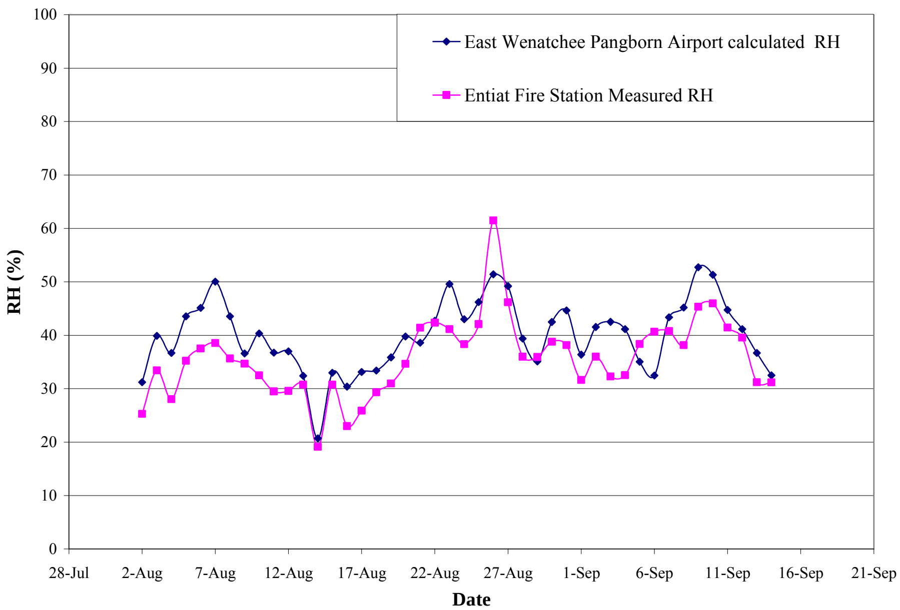


Figure 7: Comparisons of relative humidity data from East Wenatchee Pangborn Airport (calculated form air temperature and dew-point) and Entiat Fire Station (measured) for the 8/2-9/14 2002 time period.

Ambient air temperatures from Pangborn airport also appeared to be higher then those in the Entiat watershed. Figure 8 compares East Wenatchee Pangborn daily mean air temperatures with the average of the daily maximum and minimum air temperatures (estimate of daily mean) recorded at the Entiat National Fish Hatchery. Although the relationship is strong there is some error in using the Pangborn temperatures, but in order to keep data sources from relatively consistent sources combined with the fact that the Fish Hatchery values are averages from maximum and minimum values, the Pangborn data was used knowing that it has potential for adjustment if needed for calibration of the model.

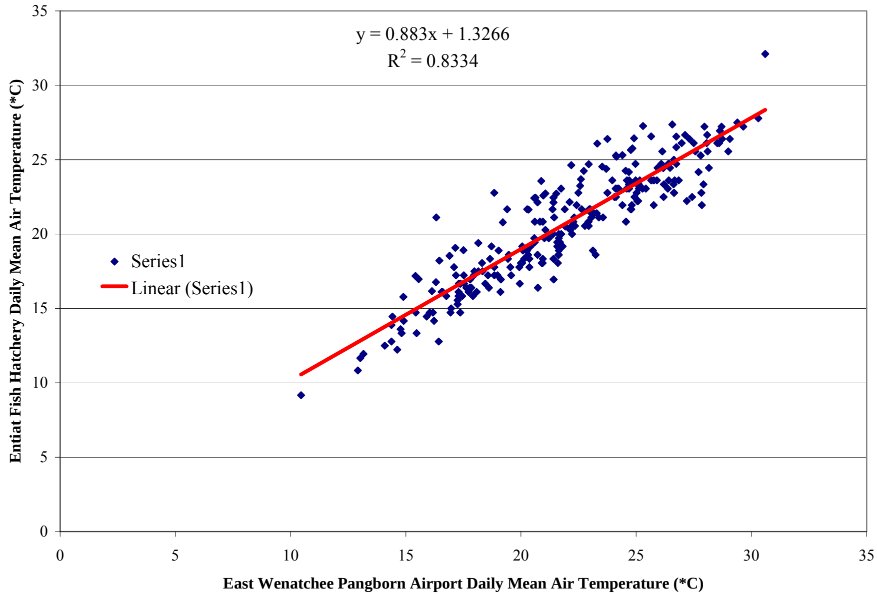


Figure 8: Comparisons air temperature from East Wenatchee Pangborn Airport (daily mean values) and Entiat National Fish Hatchery (daily average values) for the 8/2-9/14, 1997-2002 time period.

Default values were used for dust coefficient and ground reflectivity values according to the time of year and the type of river basin being modeled, as suggested by Bartholow (2000) and found in Tennessee Valley Authority (1972). Calibration runs that allowed SNTEMP to generate solar radiation values based on other meteorology input data produced poor results (East Wenatchee Pangborn station did not provide solar radiation data). Therefore, final calibration and modeling runs were made by this application of SNTEMP using the Entiat Fire Station's 2002 estimates of solar radiation, and allowed SNTEMP to produce solar radiation values for the remaining years based on the 2002 data.

Hydrology

SNTEMP requires stream discharge values for certain locations along the river network. At the absolute minimum, a modeler must include hydrology values for each of the skeleton nodes. Additional discharge data is needed if there are significant ground water-surface water interactions, major tributary inputs, irrigation diversions or return flows, spring contributions or other significant changes in the hydrologic regime. These hydrologic changes are accounted for by the modeler using Validation (V) and Discharge (Q) nodes. SNTEMP uses gradual accretions between each hydrology or validation node, so care must be taken selecting node locations. For example, if a given node has a discharge of 50 cfs, and a node immediately downstream has a discharge of 100 cfs, SNTEMP will gradually increase the discharge over the entire distance that exists between the two nodes (Bartholow personal comm.).

Additional hydrologic inputs necessary to run SNTEMP include starting or "headwater" water temperatures. Groundwater temperatures can be supplied by the modeler if reliable data are available. Otherwise, the model will assume that the mean annual air temperature equals groundwater temperatures.

Hydrologic data necessary for this application of SNTEMP was based primarily on continuous recording gages operated by the USGS at RM 18 (USGS gage number 12452800, Entiat near Ardenvoir) and RM 1.4 (USGS gage number 12452990, Entiat near Entiat). The remaining streamflow input data were synthesized by the U.S. Forest Service, Entiat Ranger District hydrologist Rick Edwards and retired USFS hydrologist Gran Rhodus, as cited in CCCD (2003).

Water temperature data for the headwater (H) and validation (V) nodes came from the USFS-Entiat Ranger District (Archibald 1997-2002). Initial efforts to calibrate this application of SNTEMP using groundwater temperature values synthesized by SNTEMP based on air temperature values proved erroneous. Therefore measured groundwater temperatures were used, based on measurements taken by Scott Wolf (CCCD) and Bob Whitehall (City of Entiat Public Works Department) during the 2002 calendar year (Walker personal comm.). The groundwater temperature values of all wells closest to the river, for the time period being modeled (Aug. 2-Sept. 14), were used to calculate a mean groundwater temperature value, and applied to all nodes and for all years modeled.

Stream Geometry

SNTEMP defines stream geometry at all skeleton nodes based on channel width, substrate roughness (Manning's coefficient, "n"), ground temperature, streambed thermal gradient, elevation, and latitude. To maximize modeling accuracy, stream geometry parameters are necessary for any locations along the longitudinal river profile exhibiting a significant change in the stream geometry (Bartholow 2000). Changes in stream geometry are accommodated with change (C) nodes.

Stream geometry data came from numerous sources, including the CCCD, ENTRIX Inc. consulting firm, USGS, and WDOE for this application of SNTEMP. Stream width coefficients and exponents were created so that stream width could be varied with flow using the power function as explained by Bartholow (2000). The following generalized equation was used to generate this relationship:

$$\textbf{Width} = \textbf{(width coefficient)} * \textbf{flow}^{\textbf{(width exponent)}}$$

Figure 9 illustrates the derivation of width coefficient and exponents for the stream geometry change node at RM 1.4.

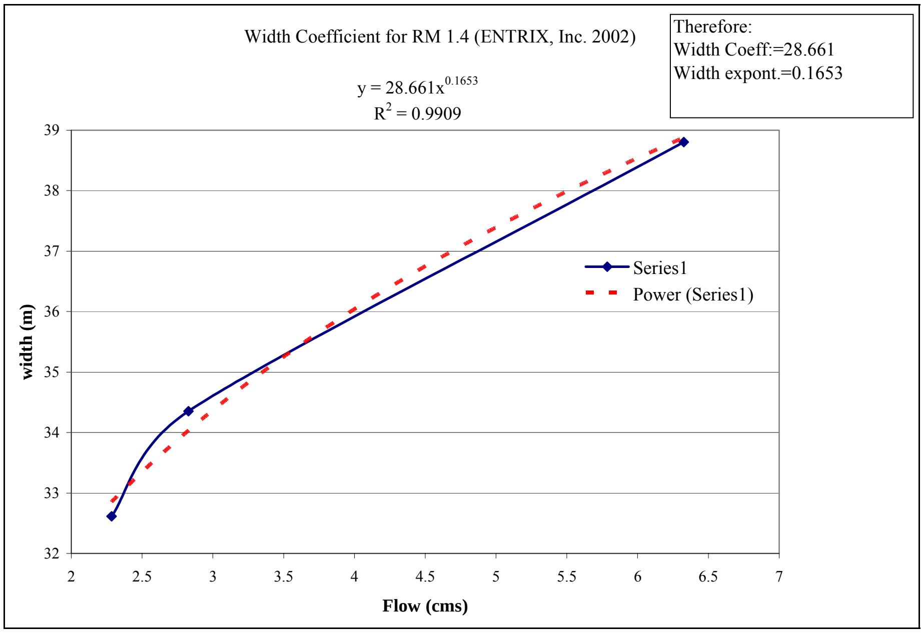


Figure 9: An illustration of the method used to determine width coefficient and width exponent values at RM 1.4.

Manning's roughness coefficients *(n)* were estimated in the field using *Barnes's Roughness Characteristics of Natural Streams* (1967) by Kurt Hosman of the Chelan County Conservation District (CCCD) (personal comm.). Default values were used for ground temperature (mean annual air temperature (˚C)) and streambed thermal gradient (1.65 J/m^2/sec/˚C) as suggested by Bartholow (2000).

Shade

SNTEMP requires shade values for the same locations as stream geometry parameters. A modeler has the option of using simplistic shade inputs based upon estimates of the minimum and maximum percent of vegetation cover for a given node, or can provide more detail based upon estimates of vegetation density, vegetation height, crown diameter, and distance from the water's edge. Whether a modeler selects simplistic or detailed shade parameters depends on the objectives of the study and the availability and reliability of information (Bartholow 2000).

Due to time and resource constraints, we initiated calibration using the less detailed approach to shading input values. However, in using this approach we anticipated that the potential source of error would be reduced, because with fewer measurements made, the chance for human error is reduced. Further, if the model would not calibrate, we planned to use a more detailed set of shade input values that were available.

We used estimates of maximum and minimum percent shade (percentage of sunlight that is blocked from reaching the stream by vegetation) in the lower Entiat River watershed (approximately RM 0 to 21) developed by the Natural Resource Conservation Service's Stream Team, as part of its "Entiat River Inventory and Analysis" (NRCS 1998 in CCCD 2002). For the upper watershed (approximately RM 21 to RM 34), we used estimates of percent shade developed by the US Forest Service - Entiat Ranger District as documented in the "Watershed Assessment – Entiat Analysis Area" (USFS 1996). Because shade inputs were already in a percent form (a requirement for use of SNTEMP), increases in shade during alternative action simulations were calculated simply by adding the percent change amounts to the current conditions. For example, in an area were shade is estimated to have a 10% canopy cover, a 10% increase would be represented as 10% + 10% = 20%, and so on.

Time Period

SNTEMP will predict water temperatures on a yearly, monthly, weekly, or daily time step for any appropriate period to record specified. Selection of time period by the modeler is directed by the purpose of the project, and the availability and reliability of input data.

For this application of SNTEMP, it was determined that the years 1997-2002 for August 2 through September 14 (8/2-9/14) time period would be simulated. These years and time periods were chosen because of availability of data for necessary node-network locations, for a variety of water years necessary to assess inter-annual variation, and for the critical-high water temperature season of interest.

The years selected represent years when reliable water temperature data was measured by the USFS (Archibald 1997-2002), which is essential in providing the model with a "starting" water temperature at the headwater (H) node, and for calibrating the model. The USFS-Entiat Ranger District began monitoring water temperature in earnest, beginning in 1995. However, issues associated with selection of monitoring location, timing of placement of the monitoring device, and reliability of the monitoring equipment were among the reasons why data prior to 1997 we deemed unnecessary for this application of SNTEMP.

A larger number of years were selected for simulation (six, 1997 through 2002) than the one or two years typically done in an application of SNTEMP (Krause 2002; Blann 2002; Bartholow 1991). This was done to determine if SNTEMP was robust enough to handle inter-annual variability. If the modeling effort proved to reliably predict water temperature across a variety of annual conditions then the authors, the Water Quality Sub-Committee and Planning Unit would have greater confidence and evidence that actions recommended by the EWPU to address water temperature issues would be applicable when a variety of conditions were encountered.

The season selected for modeling (August though mid-September) is, indeed, the interval wherein the most extreme water temperatures are encountered. Review of the USFS Stream Temperature Monitoring Reports for the Entiat River (Archibald 1997-2002) confirms that the highest water temperatures do in fact occur within the 8/2-9/14 time period for all years simulated. Although state water quality standards for water temperature are sometimes exceeded in the month of July, most of the higher water temperatures are in August and September. Figure 10 illustrates mean daily water temperatures over the summer of 2001 (an extreme hot and dry year), showing that the hottest temperatures occurred during the 8/2-9/14 time period.

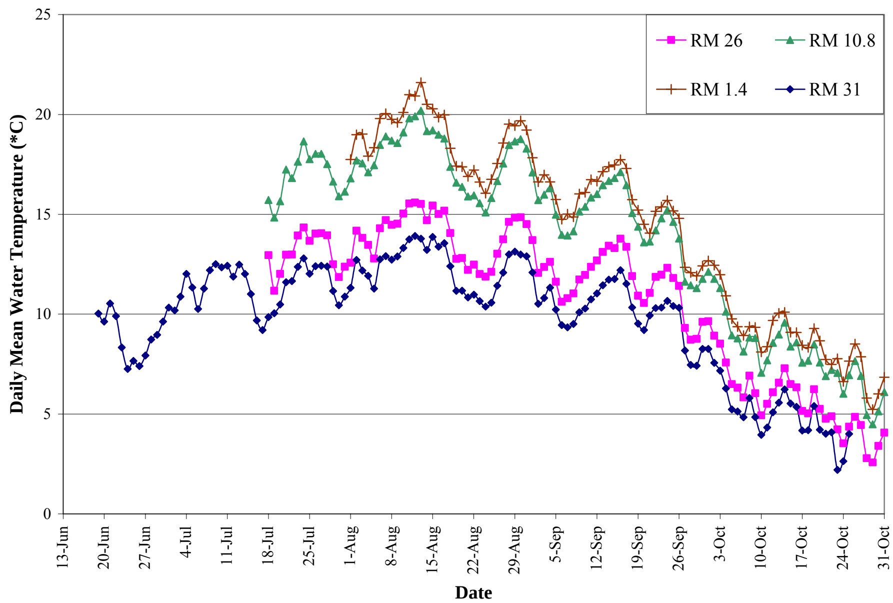


Figure 10: Observed Mean Daily Water Temperatures for 2001 at RMs 1.4, 10.8, 26, and 31.

The 8/2-9/14 time period was selected because it overlaps the known hot-dry period of each water year, and because data were available for all years proposed for analysis. Table 1 lists the dates that water temperature data were available for each year at RM 34, and shows that in 1999, 8/2 is the earliest date available and in 2000, 9/14 is the latest date available.

Table 1: Years modeled and dates that water temperature data was available at the headwater node (RM 34)

Year	Dates Water Temps were available at RM 34
1997	7/10-9/24
1998	5/22-9/15
1999	**8/2**-11/18
2000	6/22-**9/14**
2001	6/19-10/25
2002	5/20-9/19

For this modeling effort, we elected to address water temperatures on a daily time-step, because of the availability of reliable information, and due to the interest in understanding what actions would most benefit aquatic species of interest. We selected this higher resolution time-step with the understanding that day-to-day temperature fluctuations influence anadromous salmonid movement (Workman et al. 2002) habitat selection and competitive interactions (De Staso and Rahel 1994, Taylor 1988) or other ecological factors (Coutant 1976) that may otherwise be lost in a weekly or monthly averaging interval . Furthermore, the authors believe that if we could create and calibrate an application of SNTEMP across a variety of water years, for the most extreme season, on a daily time step, then recommendations to address water temperature issues in the watershed would be most justified, and more likely to secure the funding required to address the issues.

Model Calibration

Model calibration is done to assure that the model will accurately and precisely predict water temperature values. This is done to maximize the reliability of the model as it estimates the effects of the alternative treatments on water temperatures. Model calibration is typically done by comparing observed water temperatures with predicted water temperatures. Comparisons can be done graphically and with summary statistics. Graphical comparisons are done either for a single node over time or for a single time period across the longitudinal node network. Usually both statistical and graphical methods are used in order to assure reasonable accuracy and precision over time, and along the network profile.

To begin the calibration process we made initial modeling runs to determine if trends in predicted temperatures resembled measured trends. Calibration model runs were made using both predicted and measured groundwater temperatures. Calibration model runs were also made with a variety of hydrologic change nodes associated with areas of suspected surface-water and ground-water interactions. Various combinations of these potential input parameters were made until predicted values relatively approximated trends, patterns, and values of observed water temperatures over the entire period of record. We statistically and graphically compared predicted and observed values at selected validation (V) nodes over the entire time period (8/2-9/14) for all years simulated (1997-2002). This helped identify problem areas where the model was over or under predicting temperatures. This also helped determine any data entry errors in the input files or miscalculations in the daily mean observed values that were used in calibration.

To achieve final calibration, input parameters with questionable accuracy were adjusted within a reasonable and defensible range until predicted water temperatures matched observed temperatures with the degree of accuracy and precision set forth by the modeler, consistent with published procedures (Krause 2002; Bovee 1998; Bartholow 1991). Input parameters were deemed to have questionable accuracy if they were measured with imprecise or inaccurate methods, measured at locations other than at the river system being modeled, or otherwise coarsely estimated.

The only input parameters that fit the above criteria were those from the East Wenatchee Pangborn Airport. Initial calibration runs predicted water temperatures that were too high, therefore relative humidity values were decreased 5% for each year. This is justified because relative humidity values where calculated values, based on a weather station 30 miles away from the Entiat River, and as Figure 7 illustrates when comparing the 2002 relative humidity values from the Pangborn airport and the Entiat Fire Station the Pangborn values were higher then those at Entiat. Ambient air temperatures where also decreased using equations based on relationships from air temperatures form the Pangborn site and the Entiat National Fish Hatchery for all years and time periods simulated (see Figure 8).

The model was deemed calibrated when predicted temperatures matched observed temperatures without major errors in trends for all six of the validation nodes within acceptable error ranges. Analyses were conducted on both the temperatures versus time and temperatures versus stream distance axes. We used the following statistical criteria as the standards (adjusted from Bartholow 1989):

1) Mean error – The mean of the absolute values of the simulated temperatures minus the mean of the observed temperatures over all time-steps and all geographic locations should be ≤0.5˚C.
2) Dispersion error – No more than 10% of the simulated temperatures should be more then 1.5˚C from the measured temperatures. This standard was modified from a level of no more than 10% of the simulated temperatures should be more than 1.0˚C from the measured temperatures.
3) Maximum error – No single simulated temperature should be more then 3 ˚C from the measured temperatures. This was modified to from a guideline of 1.5˚C.
4) There should be no trend in spatial, temporal, or prediction error.
5) Predicted vs. observed water temperatures should have a correlation coefficient (R-squared) close to 1.0, generally around 0.9 (TRPA and Monk 2001; Stohr and Leskie 2000; Bartholow 1991).

The modifications in (2) and (3) above were necessary because this application of SNTEMP was attempting to predict water temperatures for 6 years rather than the 2 to 3 usually modeled, for 6 validation nodes rather than the 2-3 usually used (Krause 2002; Stohr and Leskie 2000; Bartholow 1991), for the most refined averaging interval (daily vs. weekly or monthly), for a long reach of river (34 miles) with significant changes in elevation, geomorphology, and flow. We believe that the adjustments to the maximum error and dispersion error standards would not confound modeling results, and were deemed reasonable, given the likelihood of error introduced by this demanding application of the model.

The Final Node Network

Following the procedures above, a final node network was developed for the Entiat River watershed. Several combinations of change, validation, and discharge nodes were combined with the skeleton node, as assessed during the calibration process. The following summarizes the final selection of change and validation nodes for use in this application of SNTEMP.

A change node was ultimately assigned to RM 26 because there is a marked natural change in the longitudinal slope of the river at that point (Figure 12). A change node at this location is important because SNTEMP calculates slope based on the stream distance and elevation values that are input. Similarly, natural changes in channel geomorphology associated with a terminal glacial moraine necessitated change nodes be assigned to points at RMs 18 and 15. A change node was also assigned to RM 1.4 due to changes in channel geomorphology, although this change is intended to represent human-induced widening of the river for flood control reasons in the late 1970's (CCCD 2002).

In this application of SNTEMP, we emphasized validation efforts in the lower 10 RMs of the river. We focused on this because the EWPU has showed particular interest in physical habitat and channel geomorphology restoration in this reach (Mobrand Biometrics, Inc. 2003; NRCS 1998). We assigned validation notes at RMs 1.4, 5.3, 8.5, 12.5, 18, and 26 (6 locations), as measured values were available for these locations in the lower river.

The final combination of headwaters (H), branch (B), tributary (T), junction (J), change (C), validation (V), and end (E) nodes comprise the total node network of the simulated river network. Figures 11 and 12 illustrate the final node network for this application of SNTEMP in the Entiat River watershed in stick-diagram, and longitudinal profile formats respectively.

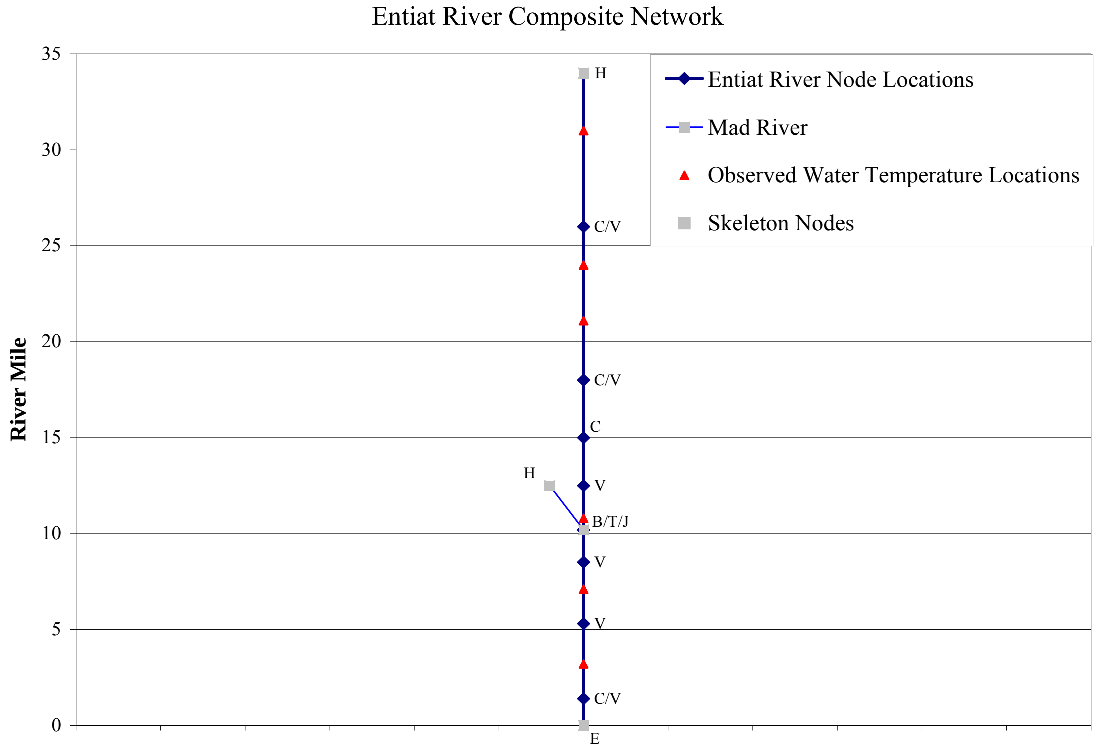


Figure 11: A stick-diagram illustration of the composite network of nodes for the Entiat River, Washington. Points along the diagram depict categories of node type including headwater (H), change (C), validation (V), branch (B), terminal (T) junction (J), and end (E) types.

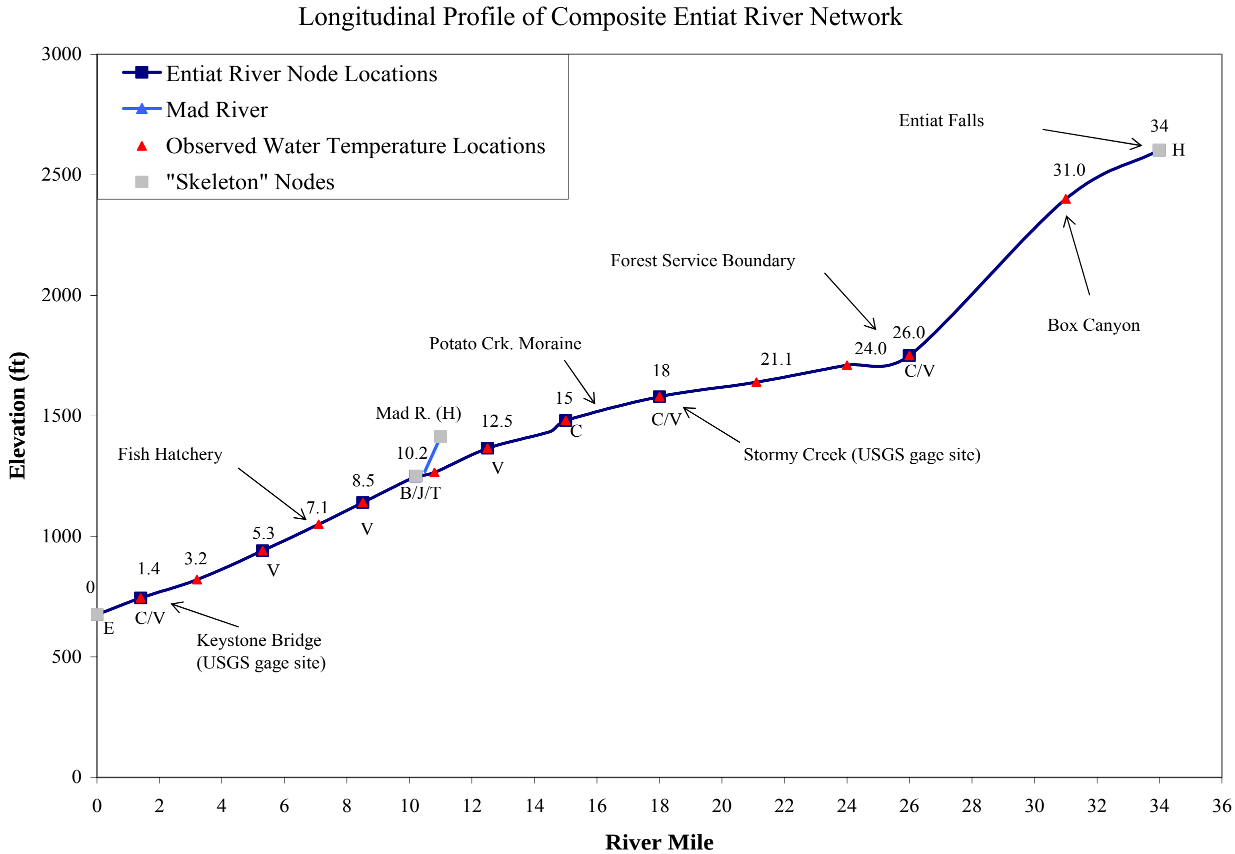


Figure 12: An illustration of the longitudinal profile of the Entiat River, Washington illustrating the composite node network of the river along the relative river gradient. Points along the diagram depict categories of node type including headwater (H), change (C), validation (V), branch (B), terminal (T) junction (J), and end (E) types.

Alternative Actions

This project focuses on determining which alternative actions would best address high water temperatures in the Entiat River Watershed. Three alternative actions were simulated using SNTEMP: system wide (RM 0-34) increase in streamflow, system wide increase in riparian shade, and reduction in stream channel width in the lower river (RMs 0-10). Ranges of change for each of the alternatives included: increases in streamflow and shade by 10%, 25%, 50%, and 100%; increases in streamflow by 150%, 200%, 250%, and 300%; and reduction in channel width by 10%, 25%, and 50%. In addition, simulations of combinations of these alternative actions were preformed. These alternatives were selected based on guidance of the EWPU, the Water Quality Sub-Committee, and the example of others attempting to address water temperature issues.

Increases to streamflow were evaluated because it is thought that a larger mass of water would take longer to warm and absorbs less heat load imposed by warming air temperatures (Stohr and Leskie 2000). Increases in streamflow were simulated by multiplying observed streamflows (from USGS stream gages) by the desired percent increase (e.g., a 10% increase to a

50 cfs observed streamflow was given by multiplying 50 by 1.1 thus equaling 55 cfs, and a 20% increase given by 50 X 1.2 = 60 cfs, and so on…).

Increased shade was evaluated because it is thought to reduce the amount and intensity of solar radiation reaching the water, thus reducing the water temperature. In the Entiat River watershed, numerous forest fires combined with flood control measures in the lower 15 RMs have significantly reduced the overall amount and quality of riparian vegetation along the river (CCCD 2002). The EWPU has recommended actions that would increase the riparian vegetation within the watershed, as well as reduce the threat of future forest fires that would threaten both the existing and proposed improved riparian vegetation (CCCD 2002). Because of the input requirements of riparian shade into the SNTEMP model (see *Methods* section), simulated increases in riparian shade were derived differently as compared to simulated increases in streamflow. Because observed shade inputs were already in a percent form, increases in shade were calculated simply by <u>adding</u> the percent change amounts to the observed percent shade conditions. For example, in an area were shade is estimated to have a 10% canopy cover, a 10% increase would be represented as 10% + 10% = 20%, and so on…

Reductions to stream channel width were evaluated because of anticipated increases in the effectiveness of existing and improved riparian vegetation (CCCD 2002), increases in the velocity at which existing water must travel (same amount of water, less area to move through) and reduced friction between the water and substrate roughness. Furthermore, assessing this alternative would determine the potential effects on water temperature of existing EWPU recommendations to reduce channel width to mitigate channelization in the lower river (CCCD 2002). Decreases to channel width were derived in the same way as streamflow, except as a decrease, using observed stream geometry data. For example, an observed channel width of 50 ft was simulated to decrease 10% by multiplying 50 by 0.9 thus equaling 45 ft.

Results

Calibration

Figure 13 illustrates a linear regression of observed and predicted daily mean water temperatures (˚C) for the Entiat River for the entire modeled period of record. There is a very strong and nearly 1:1 relationship between the observed and predicted values. This relationship held strong across the range of temperatures simulated with close correlations from just below 10°C to through just over 20°C. Figure 13 shows no trend in error and suggests that the model performed well in predicting daily mean water temperatures.

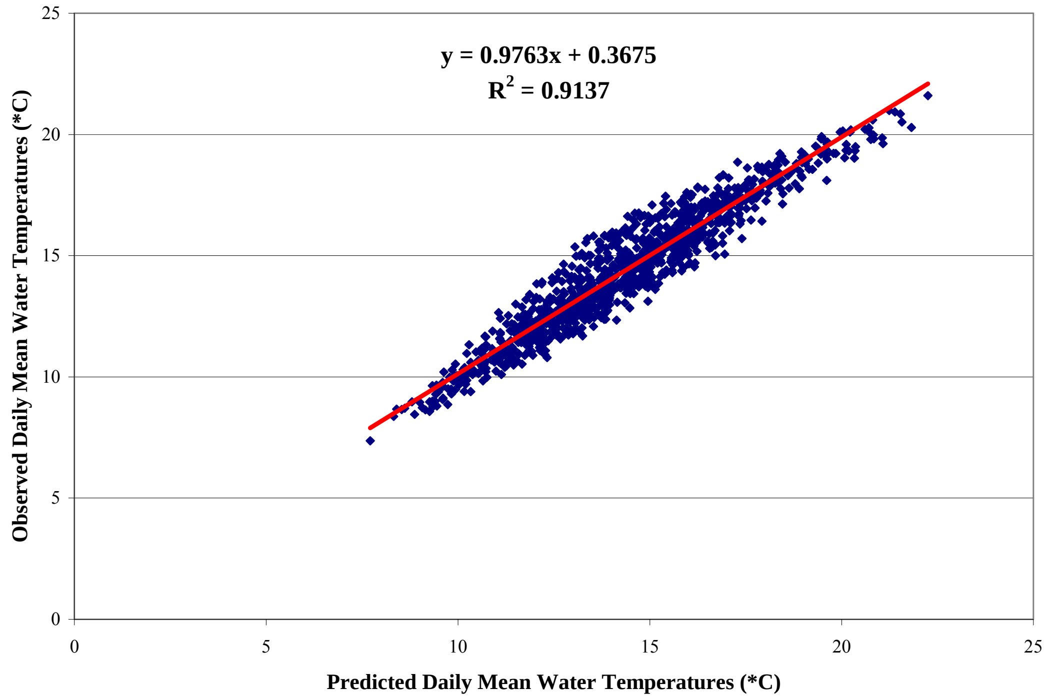


Figure 13: Final calibration results showing observed vs. predicted daily mean water temperatures at all validation (V) nodes for all years and time periods simulated.

Table 2: Summary Statistics for final calibration run
(see *Methods* section for acceptable error values)

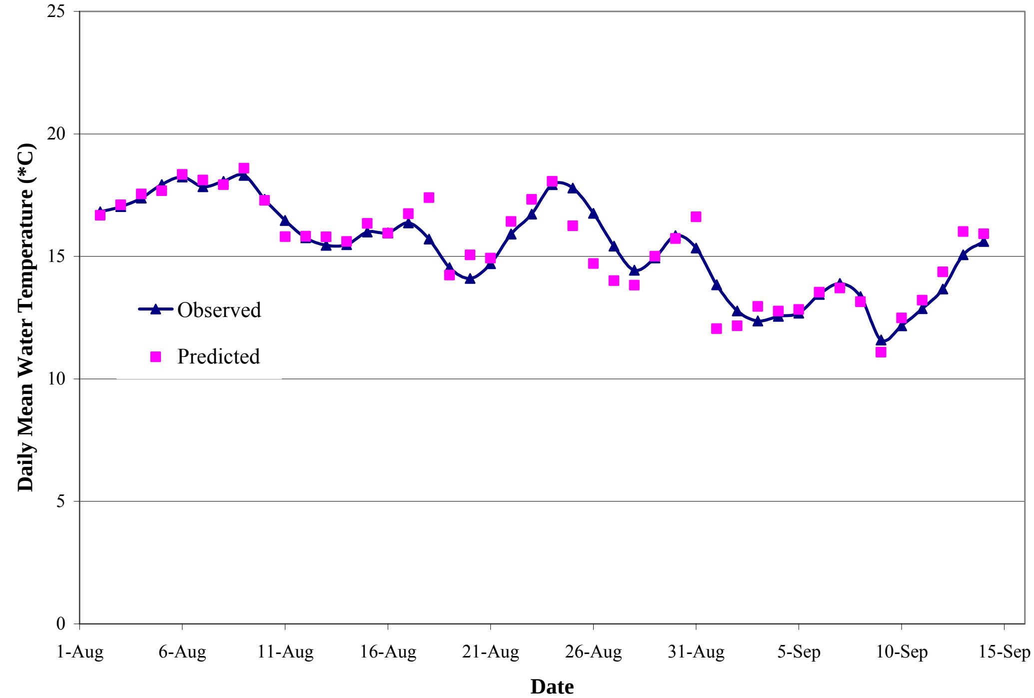
Correlation Coefficient (R^2)	0.9137
Mean Error (°C)	-0.03
Maximum Error (°C)	-2.34
Dispersion Error (%)	5.94

Table 2 illustrates the summary statistics of the final calibration run. The model performed well and produced a correlation coefficient of 0.9137. The absolute mean value of all the measured values at all nodes was 14.42°C, while the absolute mean value of all the simulated values at all nodes was 14.39°C; therefore the mean error was -0.03°C. The a maximum error of -2.34°C, and a dispersion error of 5.94%. These values are well within the acceptable range of error set forth in the *Methods* section.

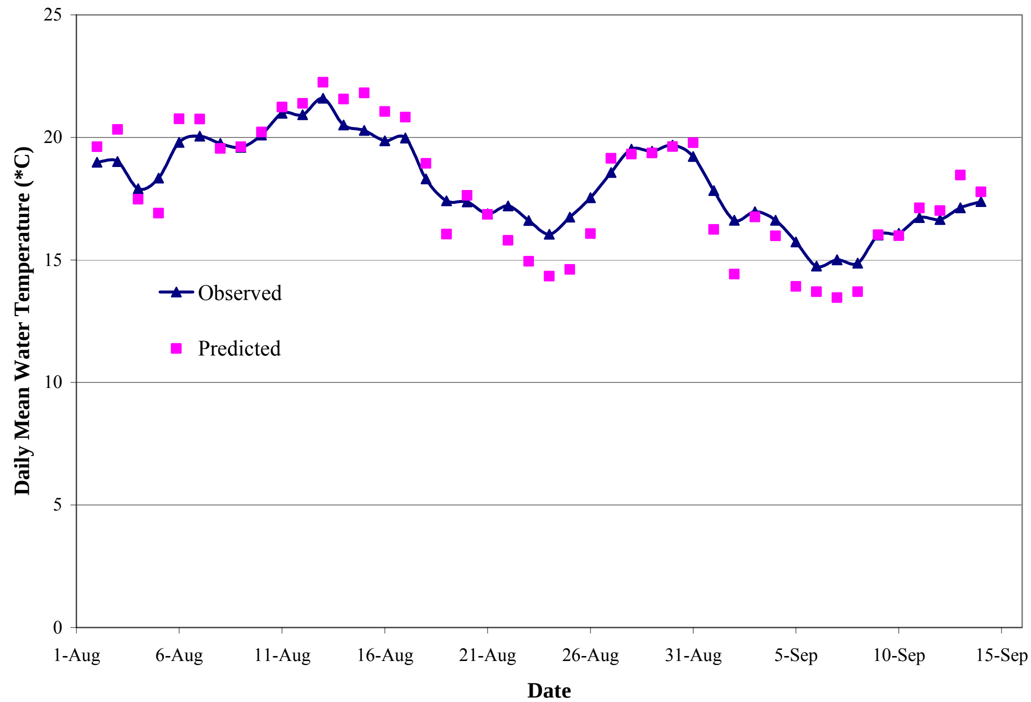
Figure 14 shows time series graphs of observed versus predicted daily mean water temperatures at RM 1.4 for 2000 and 2001. This shows that the model was reasonably predicting daily variation and trends in water temperature over the modeled period. This appears true for both "hot" and "cool" years.

Figure 15 shows observed versus predicted daily mean water temperatures system-wide in a longitudinal profile for August 9, 2000, and August 13, 2001. This again shows reasonable predictions of water temperature variation and trend across the entire profile.

Based on the aforementioned results, the model was considered calibrated and we proceeded with alternative action simulations.

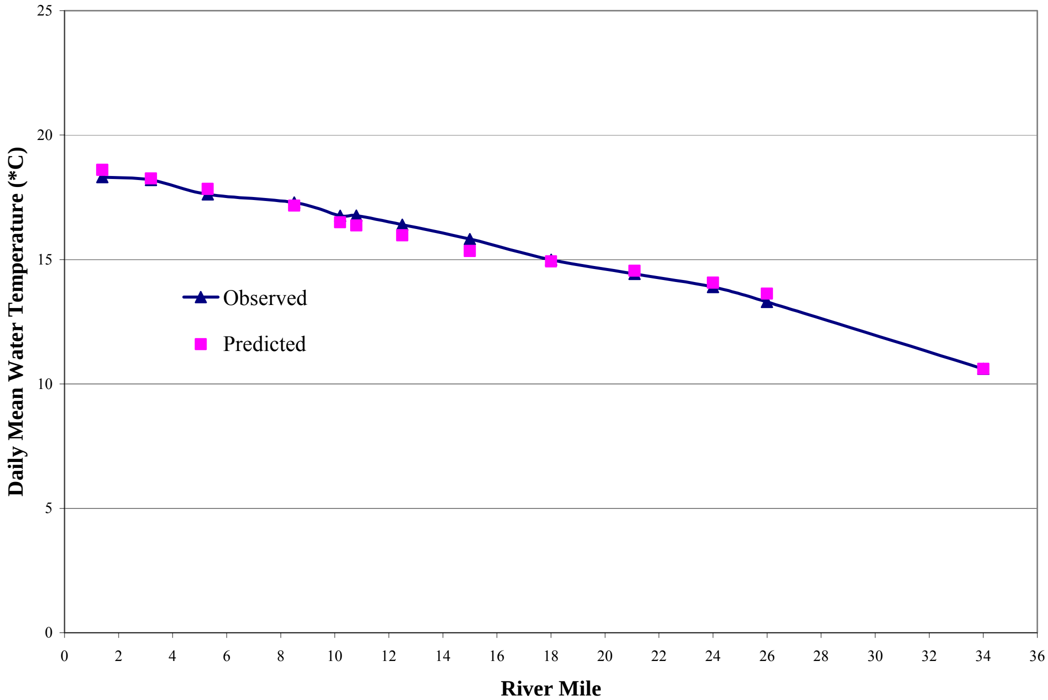


a.

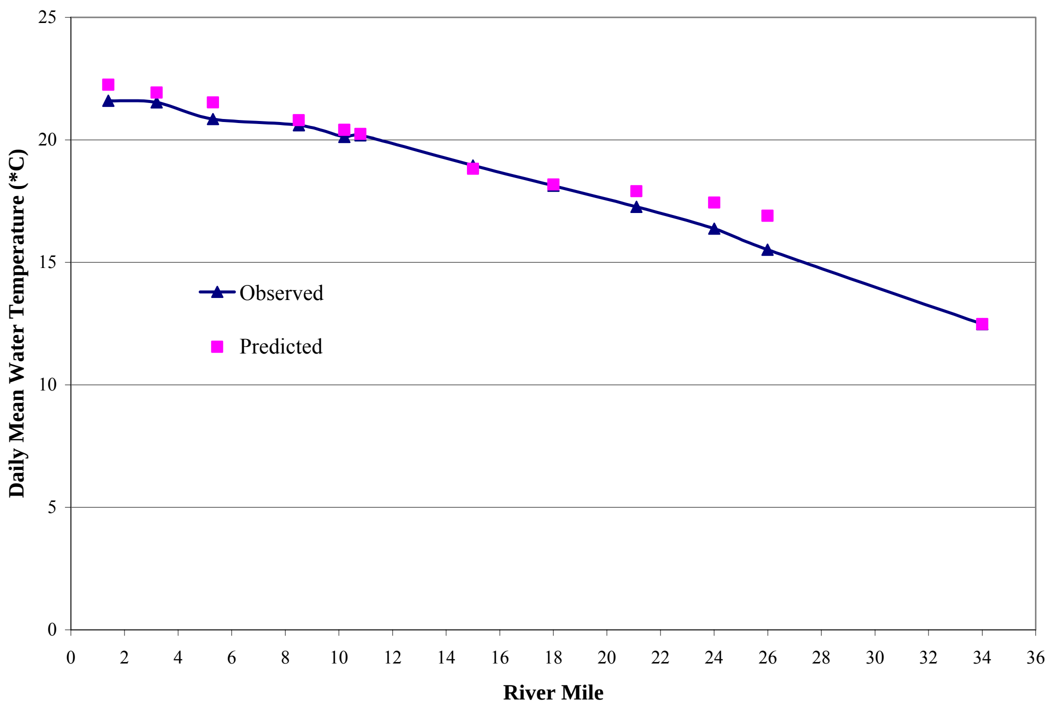


b.

Figure 14: Time series graph showing observed vs. predicted daily mean water temperatures at RM 1.4 for (a) 2000, and (b) 2001.



a.



b.

Figure 15: Longitudinal profile of observed vs. predicted daily mean water temperatures for (a) August 9, 2000 and (b) Aug. 13, 2001.

Alternative Action Results (Longitudinal Profiles)

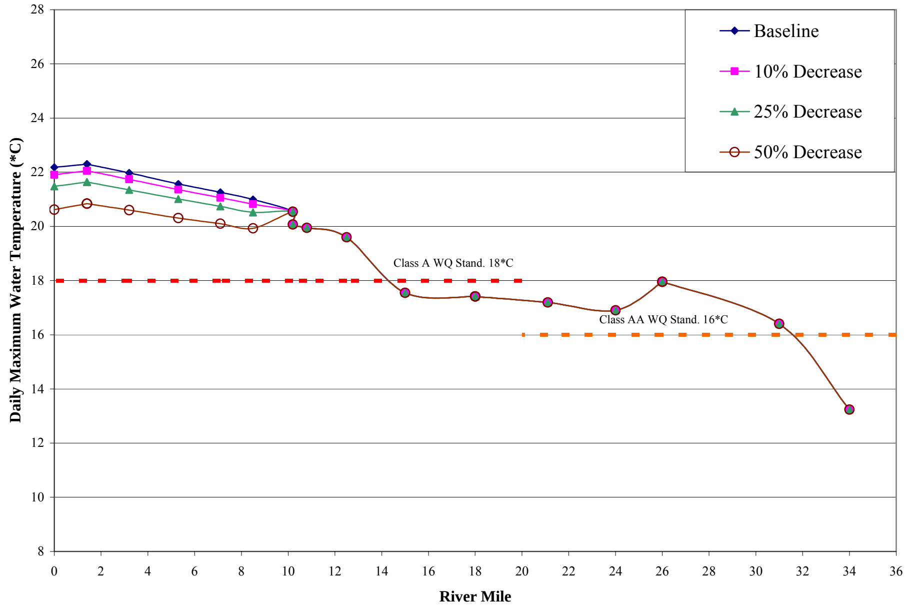
Figures 16-23 show results of each alternative action in a longitudinal profile showing changes in daily maximum water temperatures versus stream distance. These figures show the calibrated, or "baseline" daily maximum water temperatures and how changes in channel width, streamflows, riparian shade, and combinations of the three are predicted to effect daily maximum water temperatures. The graphs also include the Class A (for river miles 0-20; 18˚C) and Class AA (for river miles 20-34; 16˚C) state water quality standards (Chapter 173-201A WAC), so that it could be determined if a given alternative action could reduce water temperatures to or below these standards. This was done for the estimated hottest day of each year simulated (1997-2002; 8/2-9/14 time period), based on meteorological conditions from the East Wenatchee Pangborn Airport weather station and observed water temperatures in the Entiat River as measured by the USFS. The results from the estimated hottest day from the hottest year (August 13, 2001) and hottest day of a cooler year (August 9, 2000) are shown in Figures 16-23 and Tables 3 and 4. The complete set of results that includes all years simulated (1997-2002) can be found in Appendix A. 1999 was the coolest year simulated, however is not included here because this year produced fewer water quality exceedences and therefore the effects of implementing alternative actions could not be seen as well due to the lower baseline temperatures. The extreme day of August 13, 2001 and less extreme day of August 9, 2000 are illustrated in this section in order to assure that recommendations based on these results are justified for extreme and more typical seasons (see *time period* section).

Figures 16-19 show the results of the univariate alternative actions. Each alternative action reduced water temperatures incrementally with each increment of change, for example a 50% increase in shade had larger effects then a 25% increase. Increases to riparian shade (Alternative action 3; Figure 19) had the largest reductions in daily maximum water temperatures (compared to equal adjustment increments of actions 1 and 2). However, not one of these actions predicted a reduction in daily maximum water temperatures below current state water quality standards during the August 13, 2001 extreme day. There is one noteworthy "spike" that occurs at RM 10.2 during this simulation. This sudden increase is thought to reflect the warming effect of the Mad River tributary. Although the proposed action of increasing riparian shade are thought to include the Mad River, because the other alternative actions do not intend to effect the Mad River this application of SNTEMP did not simulate increases to shade in the Mad River, so that comparisons of the three actions remained consistent. Therefore the Mad River's water temperatures are predicted to remain warm while the Entiat River's temperatures are predicted to be cooler due to the influence of increased shade. This spike is not as predominate in alternative action 1 because decreases in width were simulated just below the Mad River in the lower 10 RMs. Also, because of the calculations that take place at Junction (J) nodes (RM 10.2; Mad River junction) increases to streamflow do not exhibit this spike.

Although increases in streamflow also showed large reductions in daily maximum water temperatures (Alternative Actions 2 and 2a; Figures 17-18), only the larger increases (150-300%) showed noteworthy reductions. Furthermore, not even a 300% increase in streamflows was predicted to reduce temperatures below current state water quality standards for the extreme day of August 13, 2001.

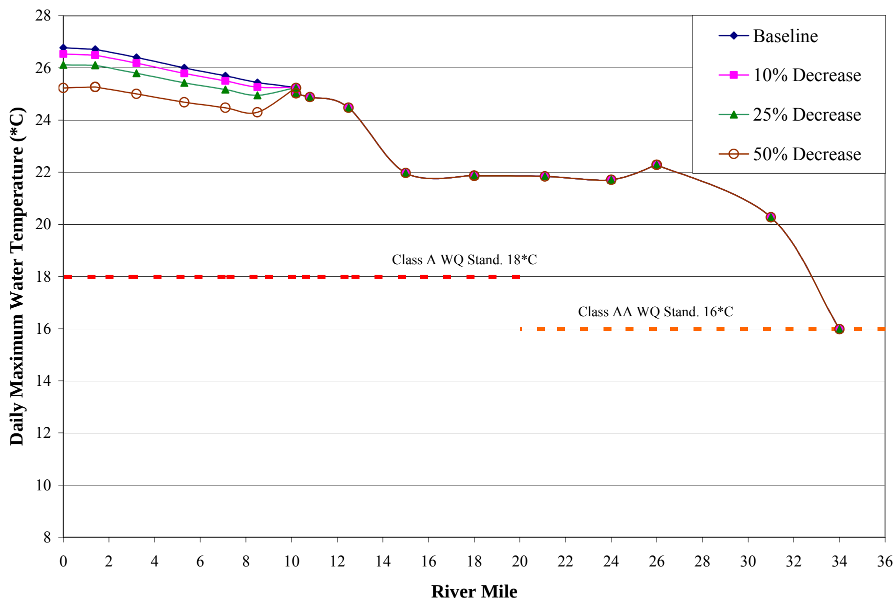
Decreases in channel width (Alternative Action 1; Figure 16) had the smallest effect on daily maximum water temperatures. Reductions to water temperatures are not seen until RM 10.2 for this alternative because decreases to channel width were simulated in the lower 10 RMs only, as altering channel width above RM 10 is thought to be an infeasible action.

Alternative Action #1-Decreasing Channel Width in lower 10 RMs[1].
For August 9, 2000



a.

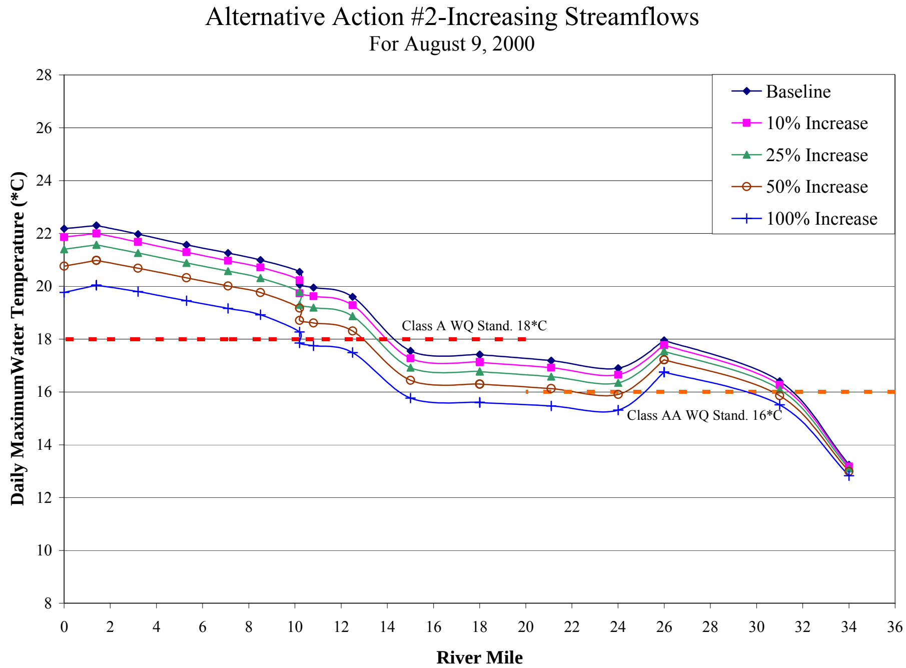
Alternative Action #1-Decreasing Channel Width in lower 10 RMs[1].
For August 13, 2001



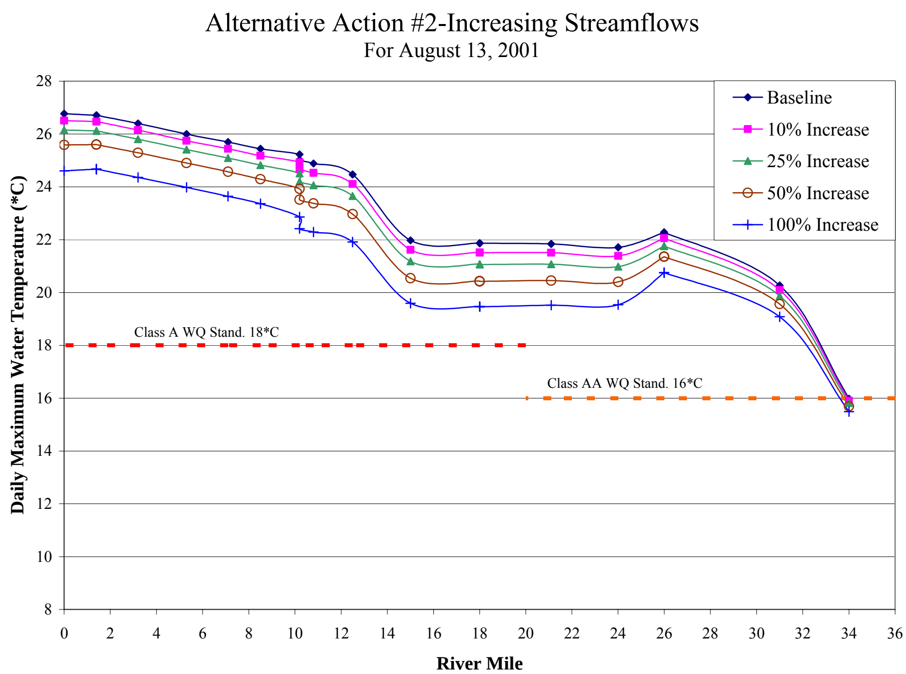
b.

Figure 16: Longitudinal profile of daily maximum water temperatures resulting from the reduction of channel width in the lower 10 RMs for August 9, 2000 (a) and August 13, 2001 (b).

[1]All reductions in channel width were simulated in the lower 10 RMs only, as reducing channel width in RMs 10-34 was thought to be an unfeasible alternative action.

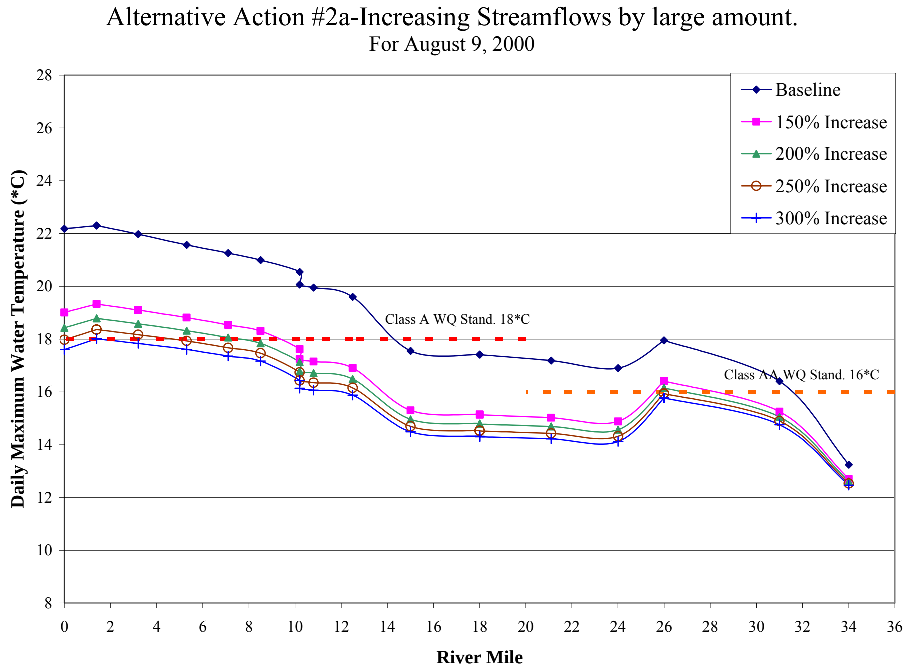


a.

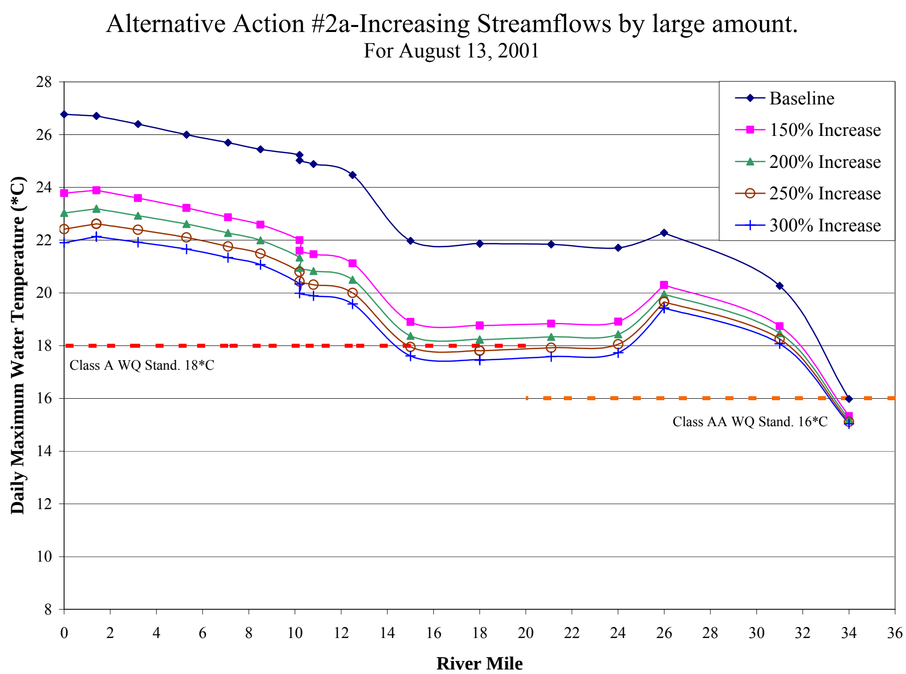


b.

Figure 17: Longitudinal profile of daily maximum water temperatures resulting from increases in streamflow for August 9, 2000 (a) and August 13, 2001 (b).

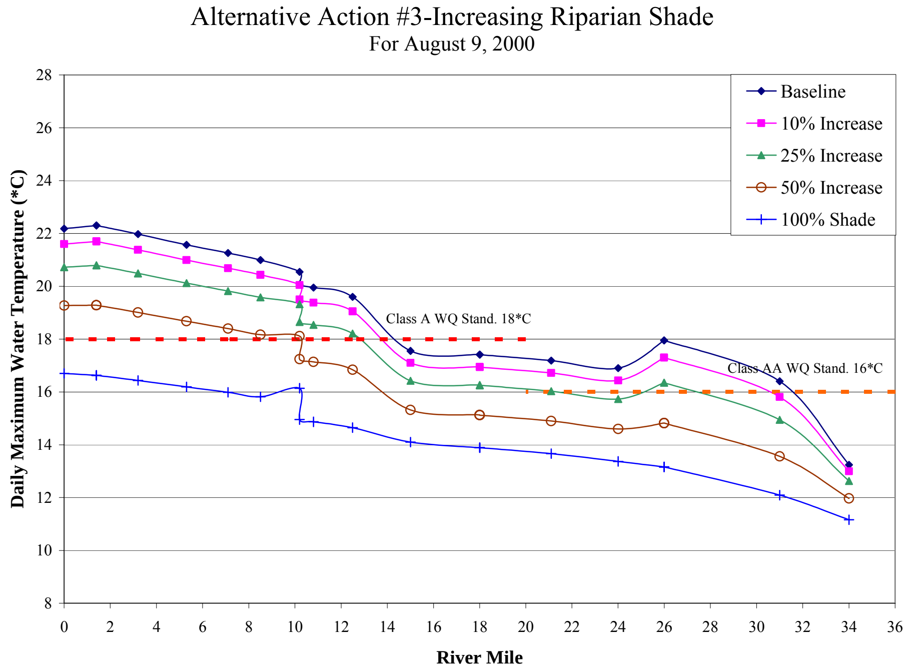


a.

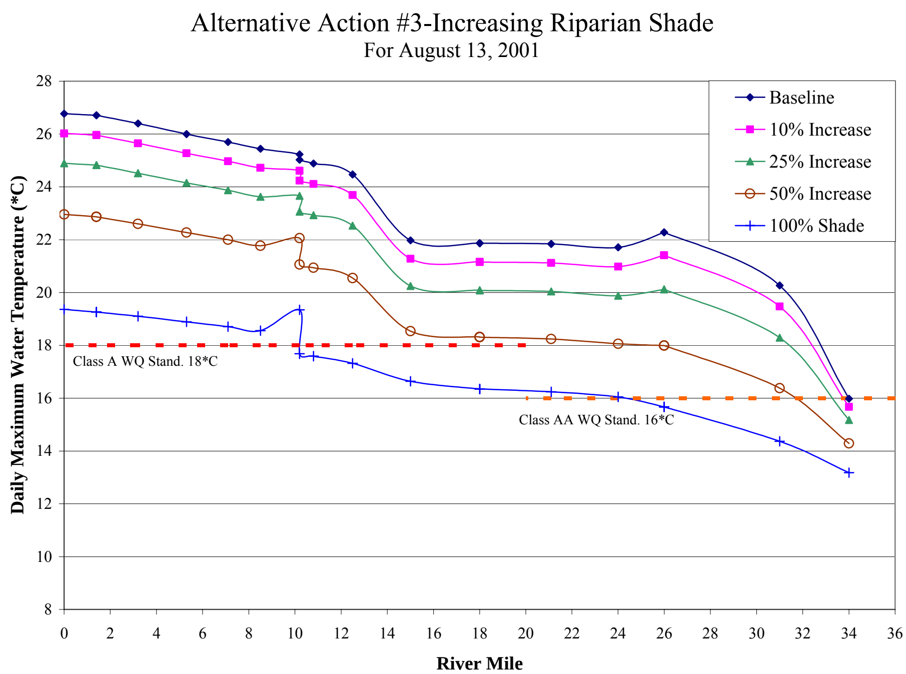


b.

Figure 18: Longitudinal profile of daily maximum water temperatures resulting from increasing streamflows by large amounts for August 9, 2000 (a) and August 13, 2001 (b).



a.

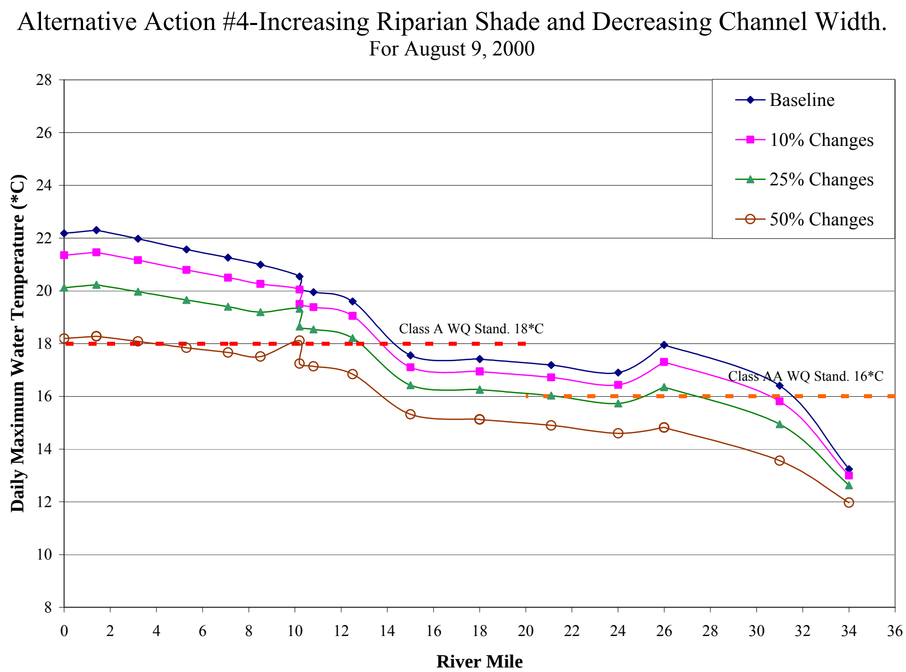


b.

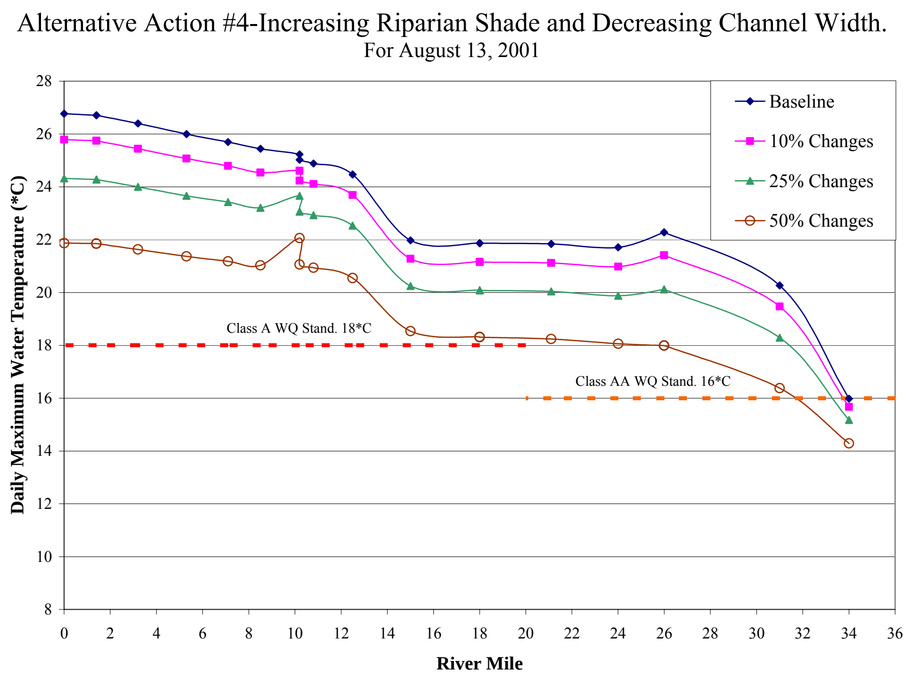
Figure 19: Longitudinal profile of daily maximum water temperatures resulting from increases in riparian shade values for August 9, 2000 (a) and August 13, 2001 (b).

Figures 20-23 show results of multivariate alternative actions illustrating the potential effect that implementing combinations of alternative actions may have on water temperatures. Unless otherwise noted, each variable was adjusted in equal increments. For example, for alternative action 4 (figure 20) when riparian shade was increased by 10%, channel width was *decreased* by 10%. All other methods for the following figures remain the same as with the univariate alternatives.

The multivariate actions also predicted reductions to baseline daily maximum water temperatures. The combination of implementing all three alternative actions (Alternative Action 7; Figure 23), predicted the largest reductions in water temperatures. Increasing streamflows and shade (Alternative Action 5; Figure 21) and the combination of increasing riparian shade and decreasing channel width (Alternative Action 4) also had large reductions in water temperatures. However, not one of the actions was able to simulate reductions in water temperatures below current state standards system-wide for the extreme day of August 13, 2001 for the entire longitudinal profile.

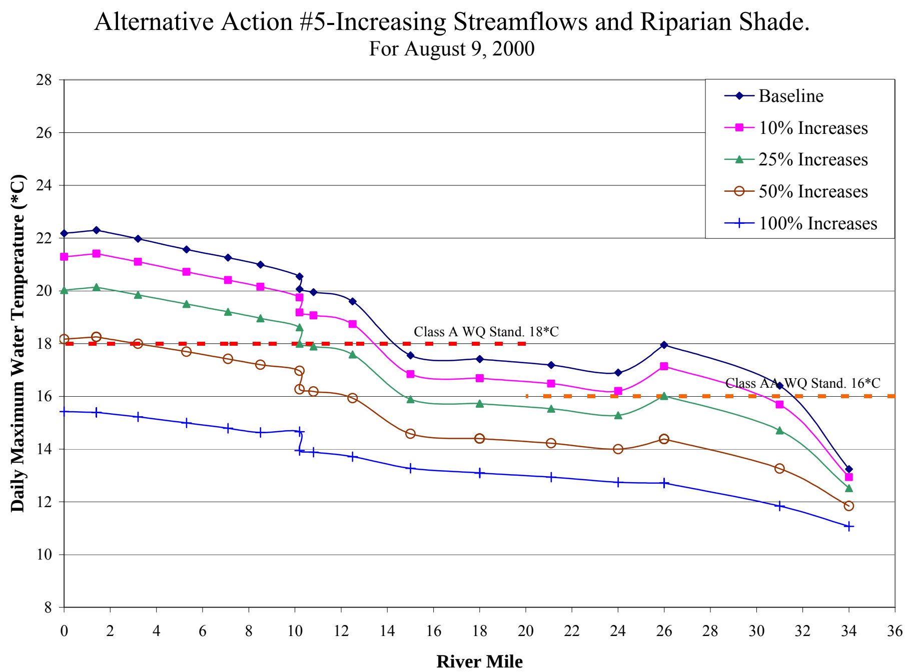


a.

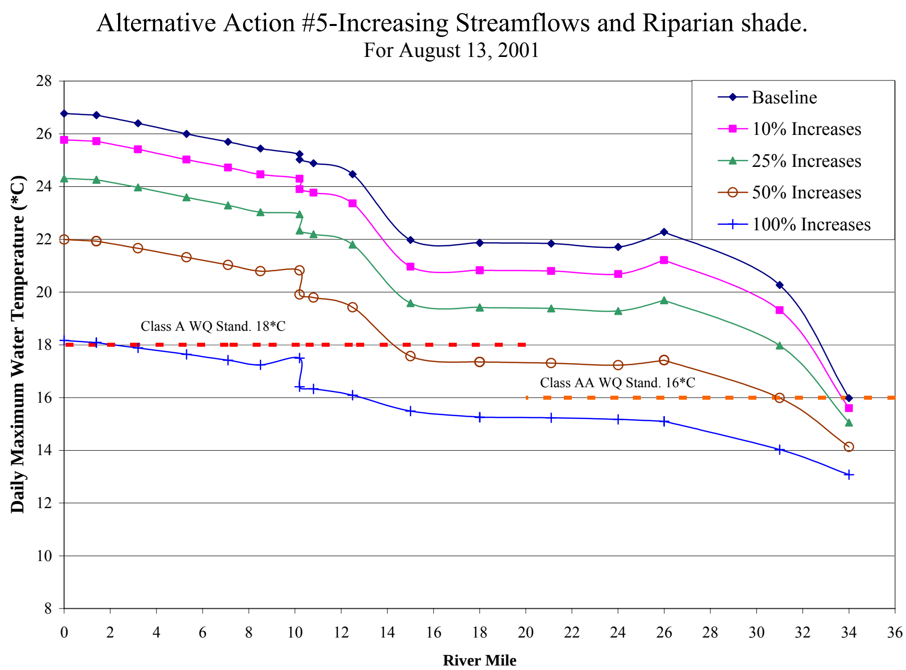


b.

<u>Figure 20:</u> Longitudinal profile of daily maximum water temperatures resulting from increases in riparian shade values and decreases in channel width for August 9, 2000 (a) and August 13, 2001 (b).

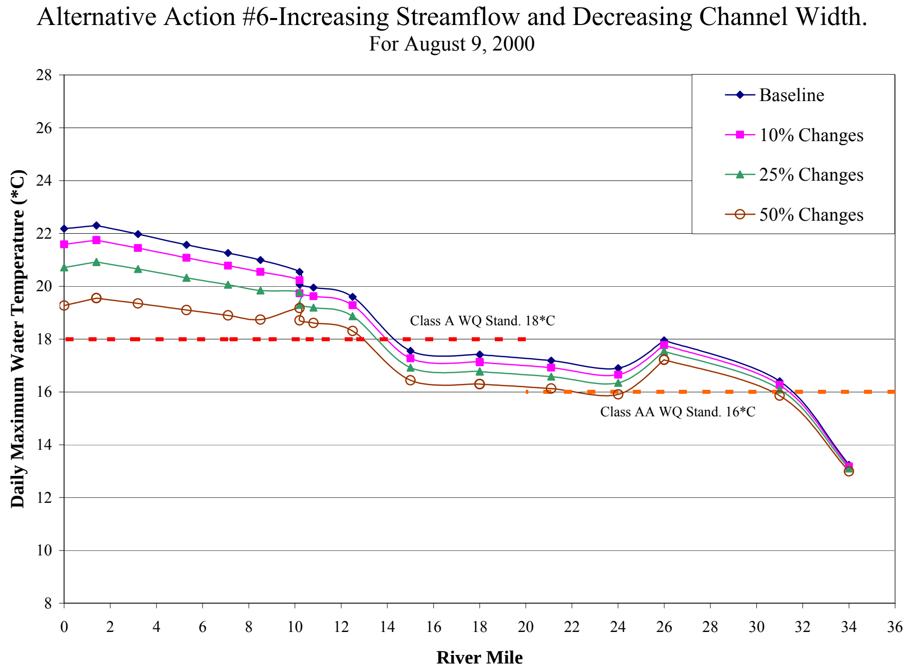


a.

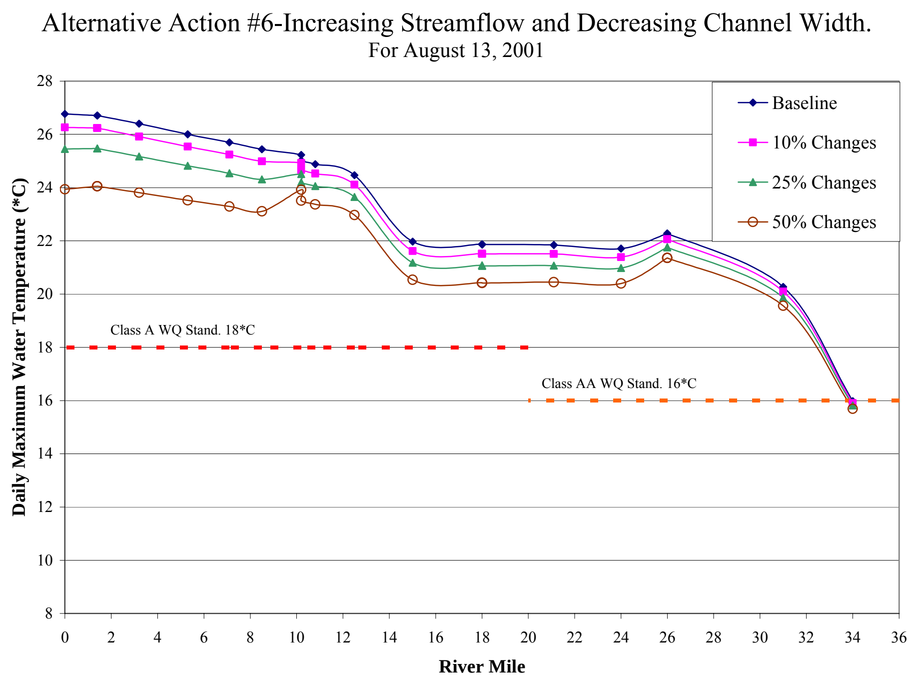


b.

<u>Figure 21:</u> Longitudinal profile of daily maximum water temperatures resulting from increases in streamflows and riparian shade values for August 9, 2000 (a) and August 13, 2001 (b).



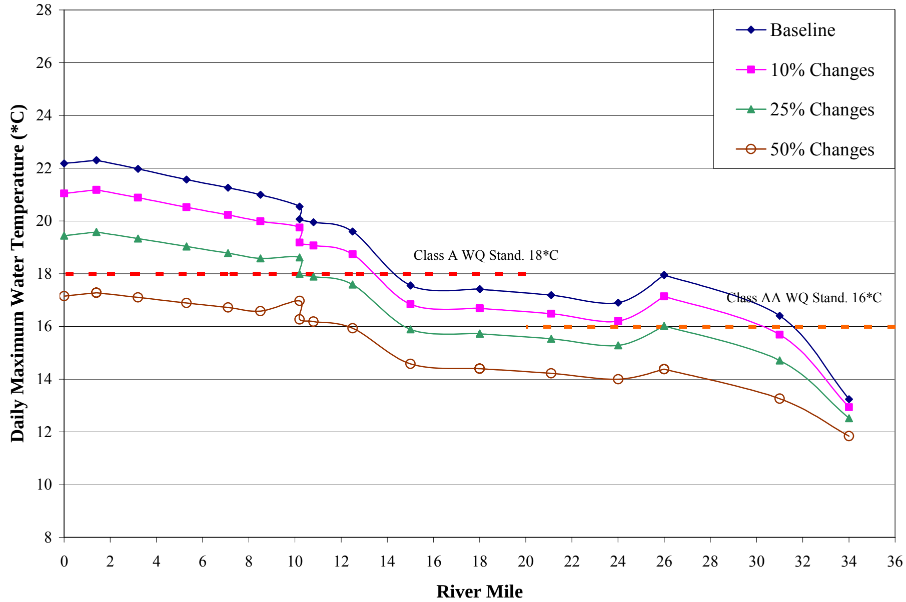
a.



b.

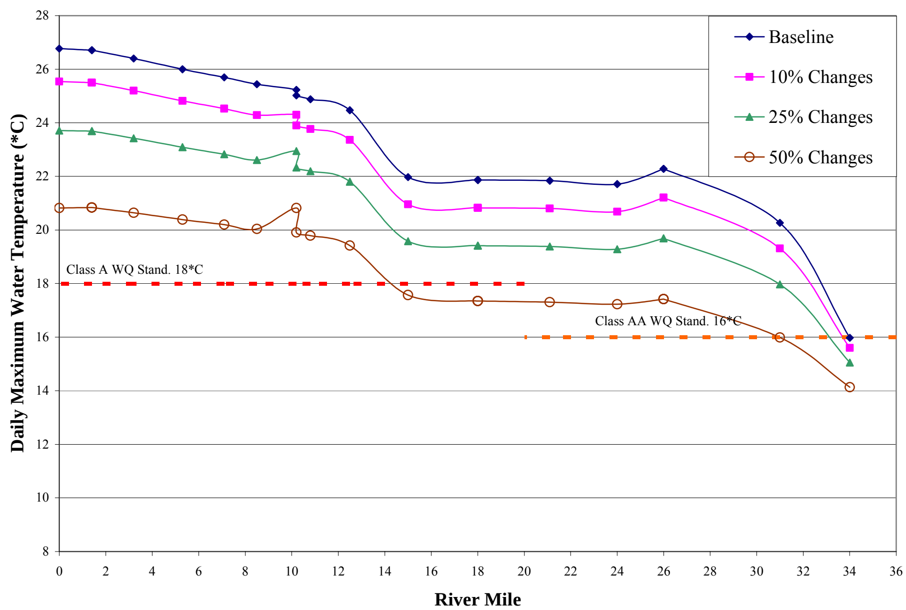
<u>Figure 22:</u> Longitudinal profile of daily maximum water temperatures resulting from increases in streamflow and decreases in channel width for August 9, 2000 (a) and August 13, 2001 (b).

Alternative Action #7-Simulation of all three alternative actions; Increasing Streamflows, Increasing Riparian Shade, and Decreasing Channel Width.
For August 9, 2000



a.

Alternative Action #7-Simulation of all three alternative actions; Increasing Streamflows, Increasing Riparian Shade, and Decreasing Channel Width.
For August 13, 2001



b.

Figure 23: Longitudinal profile of daily maximum water temperatures resulting from increases in streamflow, riparian shade, and decreases in channel width for August 9, 2000 (a) and August 13, 2001 (b).

Alternative Action Results (Summary Statistics)

Summary statistics illustrating the mean and maximum effect that each alternative action simulated had on the simulated baseline daily maximum water temperatures for the dates August 9, 2000 and August 13, 2001, are given in Tables 3 and 4. The remaining summary statistics for the hottest day of each year simulated (1997-2002) can be found in Appendix B. Tables 3 and 4 provide estimates of how much each action is predicted to effect water temperatures, both on average (mean changes) and as a maximum amount of change that could be expected (maximum change) for each alternative action. The tables also show a predicted percent change for each alternative action, which shows the estimated percent decrease in daily maximum water temperatures that each alternative action could have on the baseline. These values are given for each adjustment increment (10%, 25%, 50%, etc…).

Of the univariate alternatives, 50% increases in shade consistently produced greater benefit per unit percent change, then either increases in streamflow or decreases in channel width. For example, comparing a 50% decrease in width, 50% increase in shade, and 50% increase in streamflows the model predicted the largest percent change for shade (15.49% for 8/13/2001; 13.8% for 8/9/2000), the largest maximum change (-4.29°C for 8/13/2001; -3.13°C for 8/9/2000), and the largest mean change (-3.67°C for 8/13/2001; -2.65°C for 8/9/2000).

Of the multivariate alternatives, the combination of simulating all three alternatives (Alternative Action 7) consistently produced greater benefit per unit percent change, then the other multivariate actions. For example, comparing a 50% shade/width combination, 50% streamflow/shade combination, 50% streamflow/width combination, and 50% streamflow/shade/width combination the model predicted the largest percent change for the streamflow/shade/width (Alternative Action 7) combination (20.68% for 8/13/2001; 19.48% for 8/9/2000). This alternative also predicted the largest maximum change (-5.95°C for 8/13/2001; -5.03 °C for 8/9/2000), and the largest mean change (-4.90°C for 8/13/2001; -3.75°C for 8/9/2000).

Table 3: Summary statistics showing the effects of each alternative action on simulated baseline daily maximum water temperatures from RMs 0-34[1], for the hottest day of 2001 (hottest year) and 2000 (cooler year).

		Aug. 9, 2000[2]				Aug. 13, 2001[2]			
Alternative Actions (#)	Amount of adjustment	10%	25%	50%	100%	10%	25%	50%	100%
Univariate									
Decrease channel width (1)[3]	mean ˚C change[4]	-0.20	-0.52	-1.17	-[7]	-0.19	-0.51	-1.19	-
	max. ˚C change[5]	-0.27	-0.70	-1.56	-	-0.24	-0.66	-1.54	-
	percent decrease[6]	0.91%	2.42%	5.39%	-	0.71%	1.95%	4.55%	-
Increase streamflow (2)	mean ˚C change	-0.26	-0.62	-1.10	-1,83	-0.27	-0.64	-1.18	-2.05
	max. ˚C change	-0.34	-0.78	-1.42	-2.41	-0.36	-0.82	-1.51	-2.60
	percent decrease	1.37%	3.22%	5.74%	9.51%	1.16%	2.72%	4.98%	8.66%
Increase shade (3)	mean ˚C change	-0.54	-1.34	-2.65	-4.56	-0.73	-1.82	-3.67	-6.39
	max. ˚C change	-0.65	-1.60	-3.13	-5.67	-0.87	-2.16	-4.29	-7.45
	percent decrease	2.79%	6.95%	13.80%	23.72%	3.07%	7.71%	15.49%	27.00%
Multivariate									
Increase shade and	mean ˚C change	-0.61	-1.51	-2.97	-	-0.80	-2.00	-3.99	-
decrease channel width (4)	max. ˚C change	-0.84	-2.07	-4.02	-	-0.98	-2.45	-4.90	-
	percent decrease	3.18%	7.87%	15.42%	-	3.37%	8.45%	16.87%	-
Increase streamflow and	mean ˚C change	-0.78	-1.87	-3.45	-5.46	-0.99	-2.40	-4.55	-7.44
shade (5)	max. ˚C change	-0.89	-2.16	-4.05	-6.91	-1.12	-2.69	-5.11	-8.63
	percent decrease	4.08%	9.72%	17.92%	28.40%	4.19%	10.13%	19.23%	31.44%
Increase streamflow and	mean ˚C change	-0.34	-0.83	-1.56	-	-0.35	-0.86	-1.68	-
decrease channel width (6)	max. ˚C change	-0.59	-1.47	-2.91	-	-0.51	-1.32	-2.83	-
	percent decrease	1.78%	4.29%	8.09%	-	1.49%	3.62%	7.11%	-
Increase streamflow and	mean ˚C change	-0.86	-2.05	-3.75	-	-1.06	-2.58	-4.90	-
shade, and decrease width (7)	max. ˚C change	-1.14	-2.74	-5.03	-	-1.23	-3.06	-5.95	-
	percent decrease	4.47%	10.63%	19.48%	-	4.49%	10.90%	20.68%	-

[1]Unless noted, alternative actions were simulated system-wide (river miles 0-34), except for reductions in channel width, which were simulated in the lower 10 RMs only.

[2]The "hottest" day for each year (as well as the "hottest" and "cooler" years) were estimated for the 8/2-9/14 time period based on meteorology data from the East Wenatchee Pangborn Airport (NOAA, 1997-2002) and observed daily mean water temperatures from various locations in the Entiat River (Archibald, 1997-2002). See *Methods* section.

[3]For alternative action 1 changes were simulated in the lower 10 RMs only, therefore only the daily maximum water temperatures for the nodes in the lower 10 RMs were used in the calculation of the summary statistics.

[4]*mean ˚C change* = (mean of predicted daily maximum water temperatures minus the mean of baseline daily maximum water temperatures). Shows how much, on average, baseline daily maximum water temperatures were reduced by simulation of a given alternative action.

[5]*max. ˚C change* = largest reduction of baseline daily maximum water temperatures by simulation of a given alternative action at any given node from RMs 0-34. Although the location of the largest reduction varied from year to year, daily maximum water temperatures were typically reduced by the largest amounts near the furthest downstream nodes.

[6]*percent decrease* = (mean of predicted daily maximum water temperatures divided by the mean of baseline daily maximum water temperatures, multiplied by 100). Shows the percentage that baseline daily maximum water temperatures could be reduced by simulation of a given alternative action, based on the mean of daily maximum water temperatures at all nodes for the given day modeled.

[7]For alternative actions that included reductions in channel width, the 100% change increment were not simulated because a 100% decrease in channel width is thought to be an unfeasible alternative action.

Table 4 shows summary statistics for the percent increase in streamflow of 150% through 300%. These alternatives were simulated given interest of the EWPU in streamflow issues, and show incremental decreases in water temperature per increase in streamflow.

Table 4: Summary statistics results showing the effects of alternative action 2a on simulated baseline daily maximum water temperatures from river miles 0-34, for the hottest day of 2001 (hottest year) and 2000 (cooler year).

		Aug. 9, 2000				Aug. 13, 2001			
Alternative Action (#)	Amount of change	150%	200%	250%	300%	150%	200%	250%	300%
Large increase in streamflow (2a)	mean ˚C change	-2.36	-2.75	-3.07	-3.32	-2.73	-3.27	-3.71	-4.08
	max. ˚C change	-3.17	-3.75	-4.21	-4.58	-3.42	-4.07	-4.59	-5.03
	percent decrease	12.25%	14.31%	15.94%	17.26%	11.52%	13.81%	15.68%	17.25%

Alternative Action Results (Number of Exceedences)

Figures 25-30 show the total number of water quality exceedences that were simulated for baseline conditions and for each "feasible" alternative action (see *Discussion* section), and its accompanying increment of change. These figures show how many times that state water quality Class A (18°C) and Class AA (16°C) standards were predicted to be exceeded during each year simulated (1997-2002), and how each alternative action reduced the number of predicted exceedences. This was done by counting the number of times the simulated daily maximum water temperature was above 18°C (Class A standard) in RMs 0-20 and above 16°C (Class AA standard) in RMs 20-34 at each node used in counting exceedences for each stream-day simulated (8/2-9/14 for the years 1997-2002). A stream-day is defined here as being a complete 24-hour period in which water temperatures were measured/simulated as daily mean and maximum values. For each year simulated, a total of 704 "measurement points" were used for counting the number of exceedences from RMs 0-34, this from a total of 16 nodes with each node having 44 stream-days that were simulated (8/2-9/14) in each year (see Figure 24). To better quantify this, Figure 29 shows that the number of stream-day water quality exceedences simulated for 2001 is 510. Knowing the total number of "measurement points" allows one to understand that out of 704 "chances", the water temperature was simulated to be exceeding standards 510 times (or 72% of the time) in 2001. There was a total of 484 "measurement" points in Class A waters (RMs 0-20), and 220 in Class AA waters (RMs 20-34), and 308 in RMs 0-10 (Figure 24).

Figures 25-30 are broken into two graphs because we wanted to compare alternative actions proposed for implementation system wide (RMs 0-34) and in the lower portions of the river (RMs 0-10) separately.

It should be noted that the baseline conditions are simulated conditions and therefore are not actual measured baseline exceedences, but are assumed to represent close approximations to measured baseline exceedences based on the calibration results that are explained in the *Results* section.

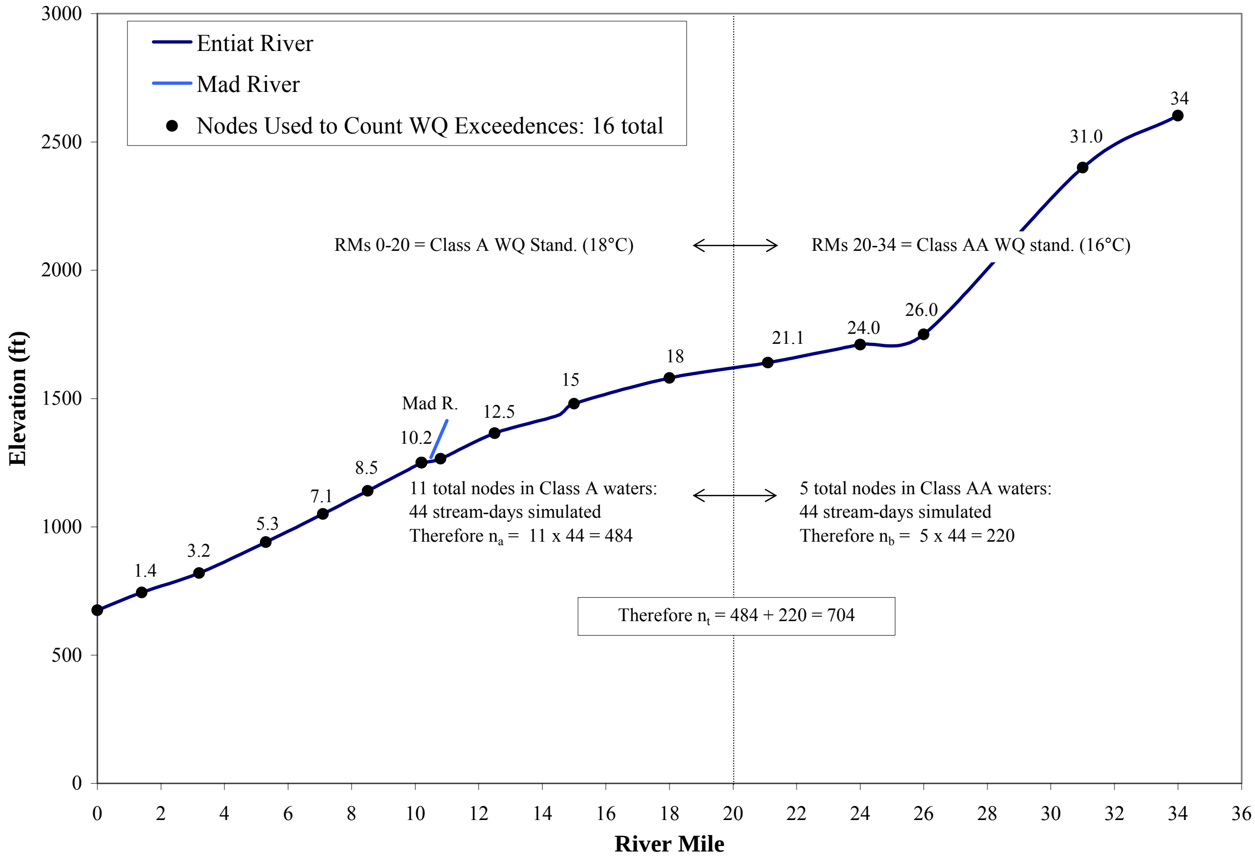
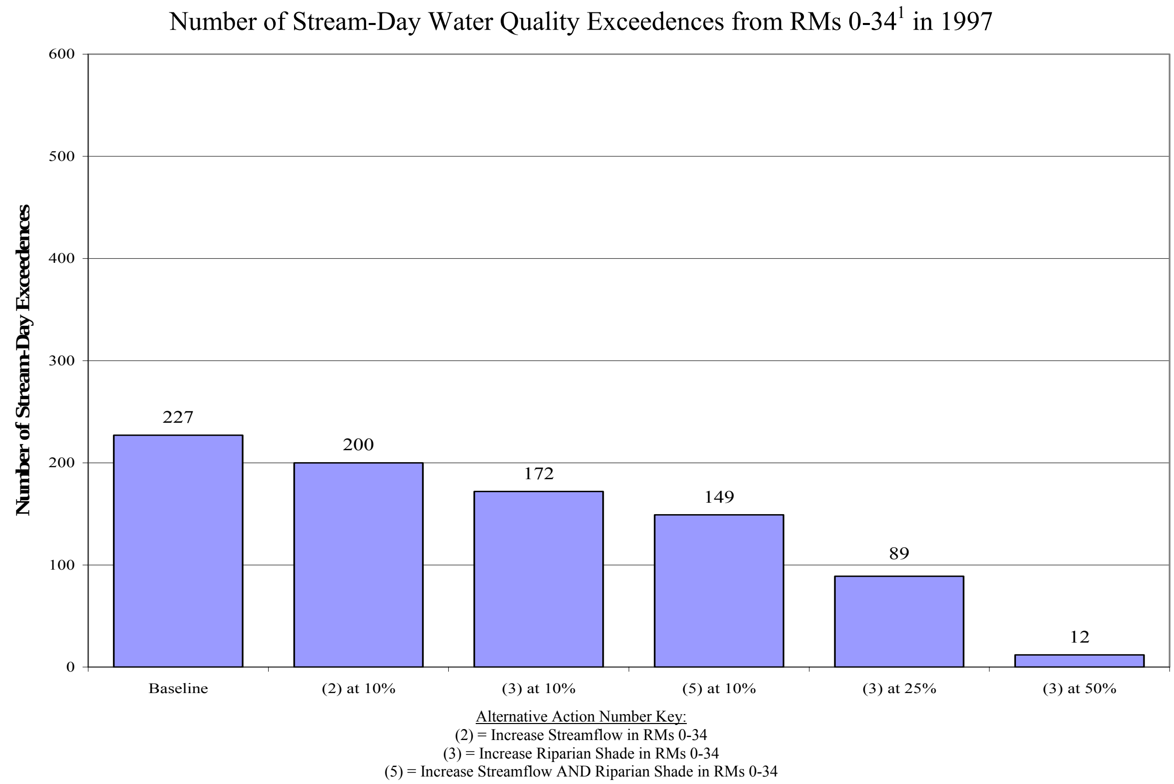


Figure 24: Longitudinal profile of Entiat River showing the location and total number of nodes (labeled by RM) used as simulated "measurement points" for counting exceedences for each time period/year simulated.

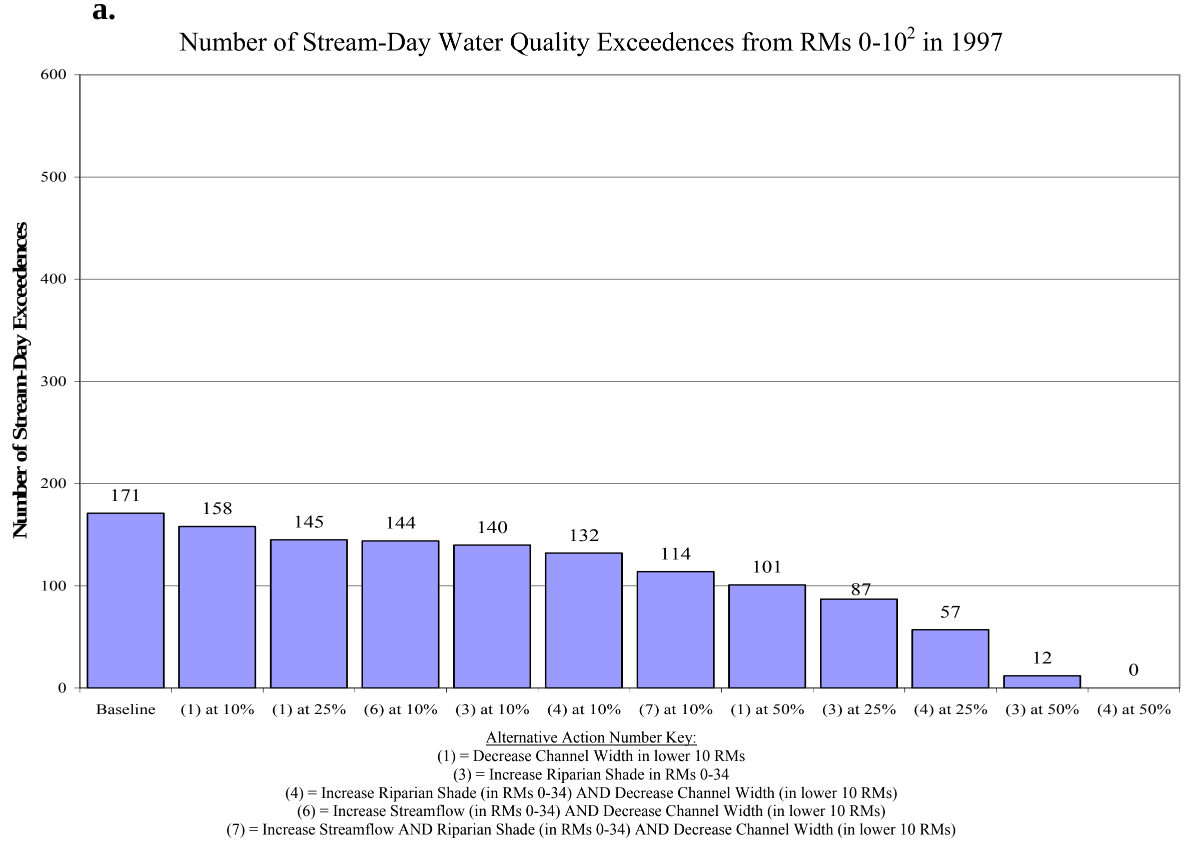
Table 5 shows the values that were used to create the graphs in figures 25-30. The table shows the number of stream-day exceedences for the Class AA water quality standard, Class A water quality standard, as well as the system-wide total number (Class AA + Class A) of exceedences for each year simulated. The table also shows the percent value of exceedences based on the total number of simulated "measurement" points (*n*; see Figure 24).

Table 6 shows similar values but is limited to RMs 0-10 in order to illustrate effects of alternative actions in this reach. This was necessary to understand the predicted effects of alternative actions that included reducing channel width in the lower 10 RMs.

Figures 25-30 and Tables 5-6 show that for all years simulated, increases in riparian shade system-wide (Alternative Action 3) and the combination of increasing riparian shade system-wide and decreasing channel width in the lower 10 RMs (Alternative Action 4) showed the largest and most significant reductions in predicted water quality exceedences.



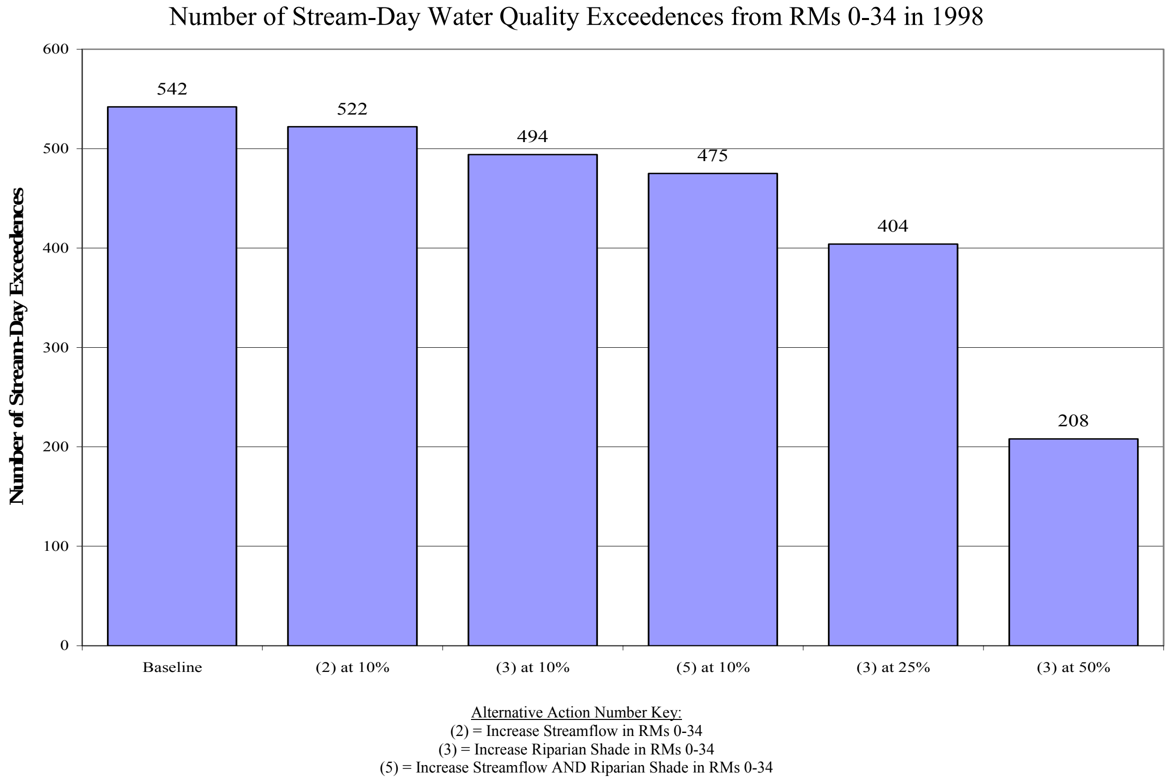
a.



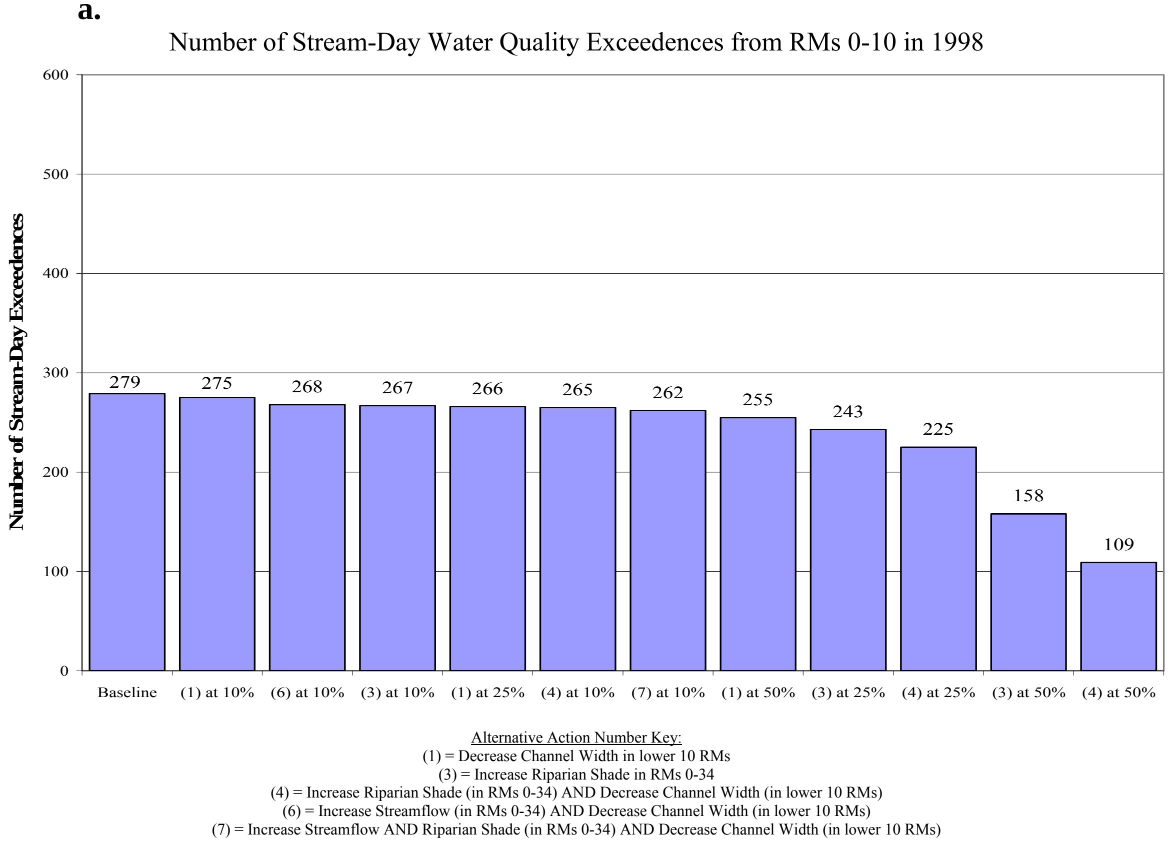
b.

Figure 25: Number of state water quality stream-day exceedences for simulated baseline[3] conditions and alternative actions for RMs 0-34 (a) and RMs 0-10 (b) during the 8/2/97-9/14/97 (44 day) time period.

[1]RMs 0-34 have both the Class AA (16°C) and Class A (18°C) state water quality standards.
[2]RMs 0-10 have only the Class A (18°C) state water quality standards.

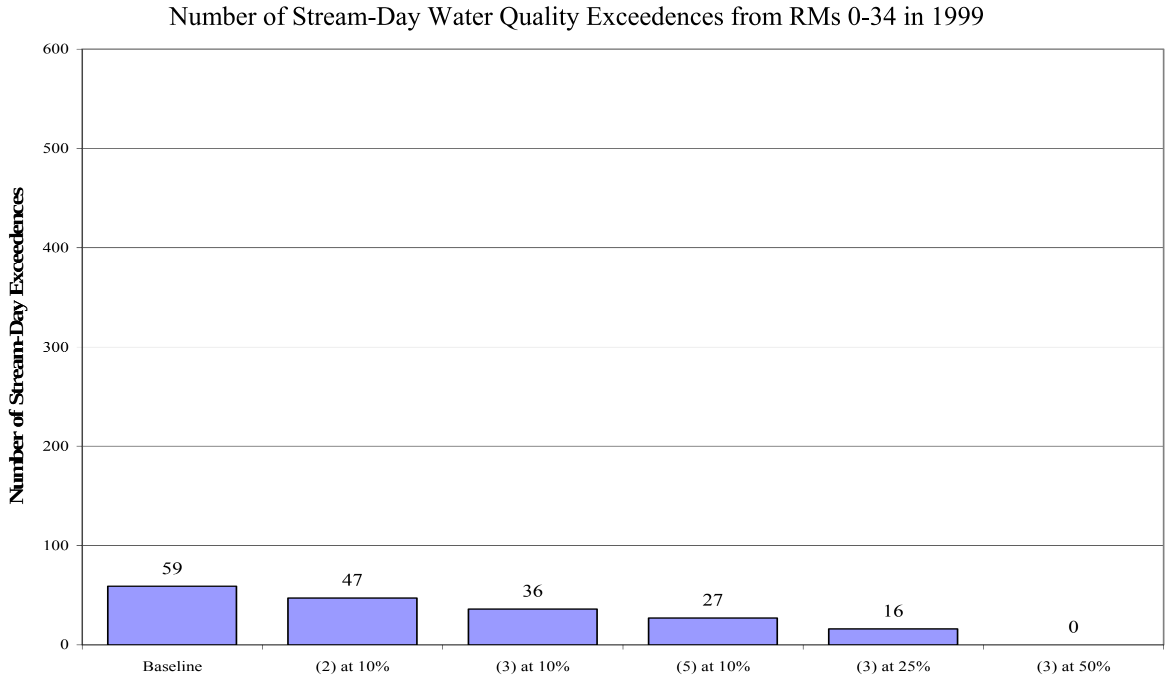


a.



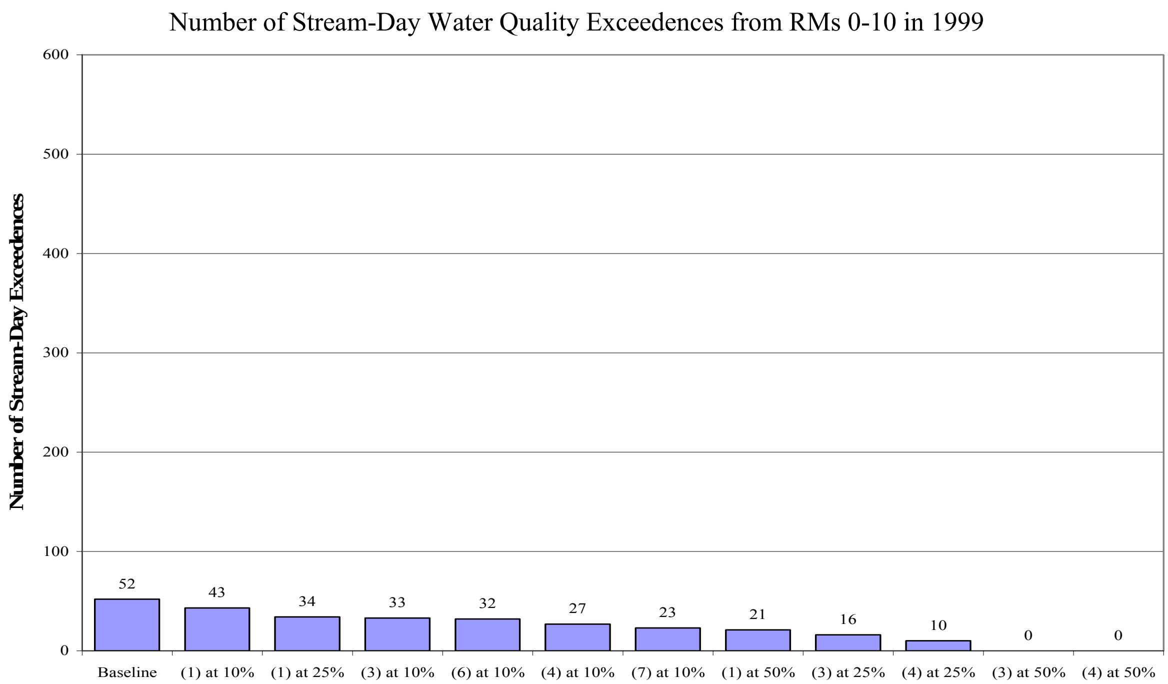
b.

Figure 26: Number of state water quality stream-day exceedences for simulated baseline conditions and alternative actions for RMs 0-34 (a) and RMs 0-10 (b) during the 8/2/98-9/14/98 (44 day) time period.



Alternative Action Number Key:
(2) = Increase Streamflow in RMs 0-34
(3) = Increase Riparian Shade in RMs 0-34
(5) = Increase Streamflow AND Riparian Shade in RMs 0-34

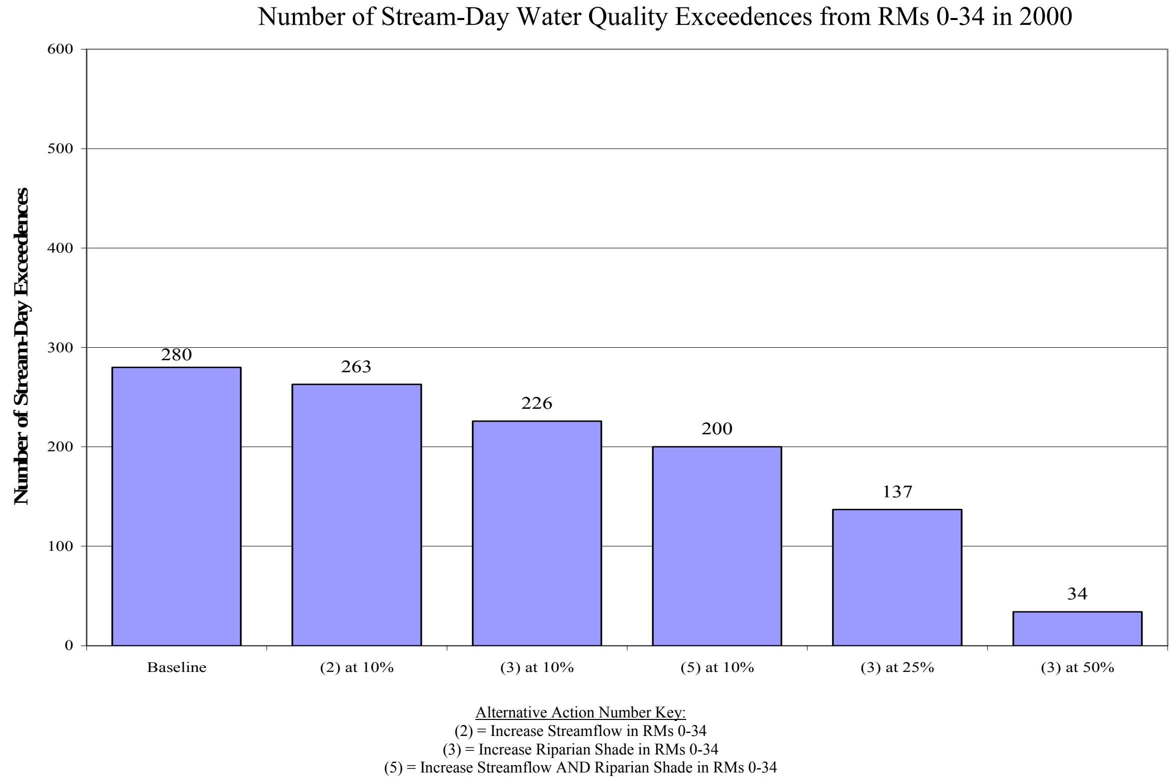
a.



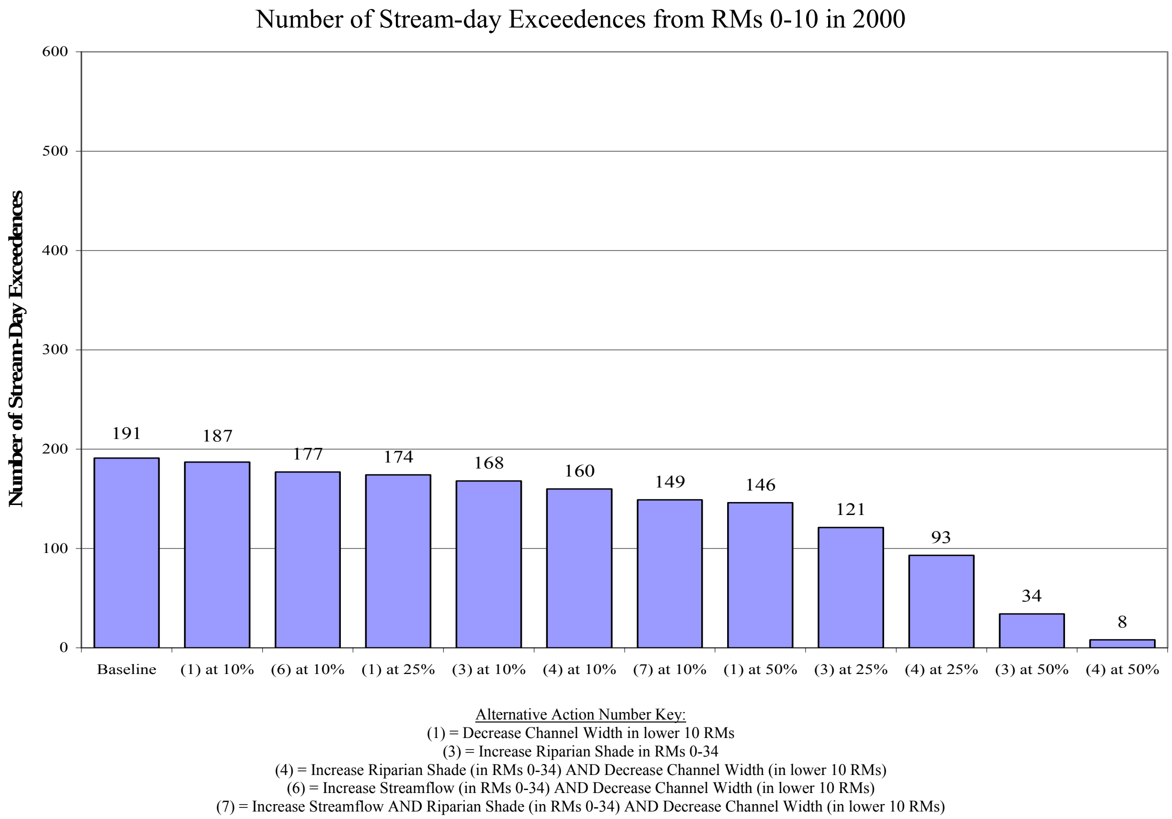
Alternative Action Number Key:
(1) = Decrease Channel Width in lower 10 RMs
(3) = Increase Riparian Shade in RMs 0-34
(4) = Increase Riparian Shade (in RMs 0-34) AND Decrease Channel Width (in lower 10 RMs)
(6) = Increase Streamflow (in RMs 0-34) AND Decrease Channel Width (in lower 10 RMs)
(7) = Increase Streamflow AND Riparian Shade (in RMs 0-34) AND Decrease Channel Width (in lower 10 RMs)

b.

Figure 27: Number of state water quality stream-day exceedences for simulated baseline conditions and alternative actions for RMs 0-34 (a) and RMs 0-10 (b) during the 8/2/99-9/14/99 (44 day) time period.

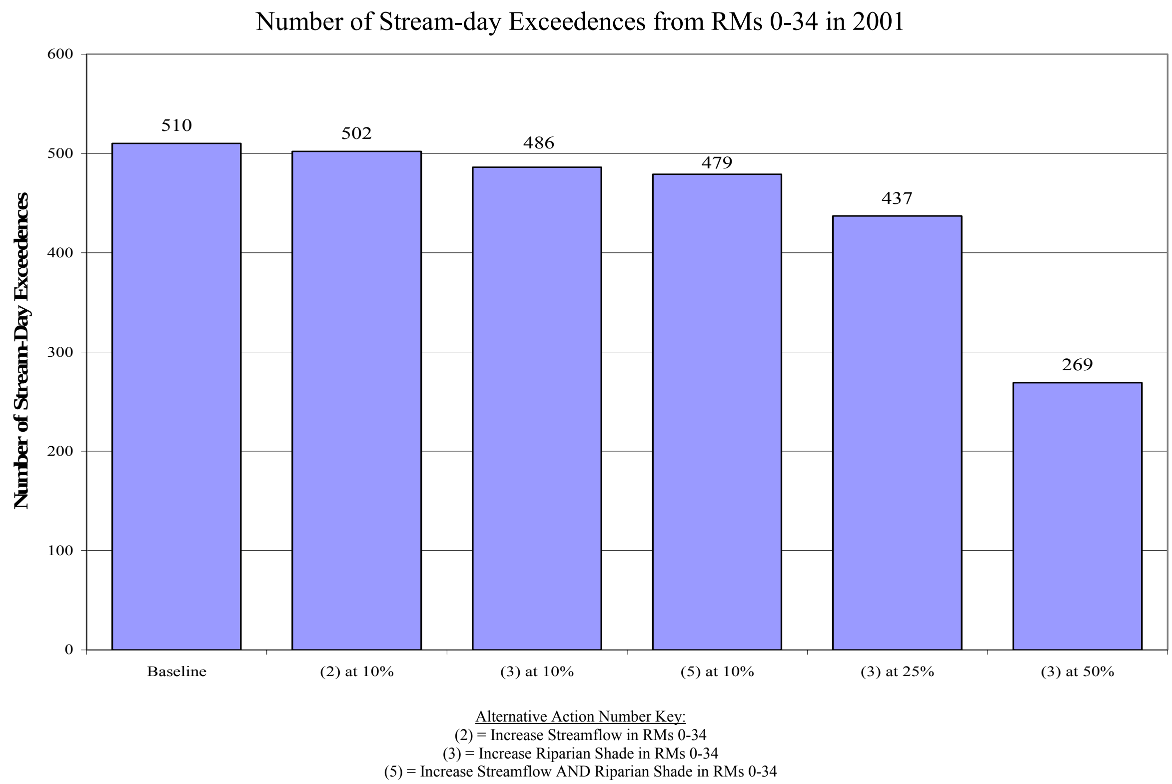


a.

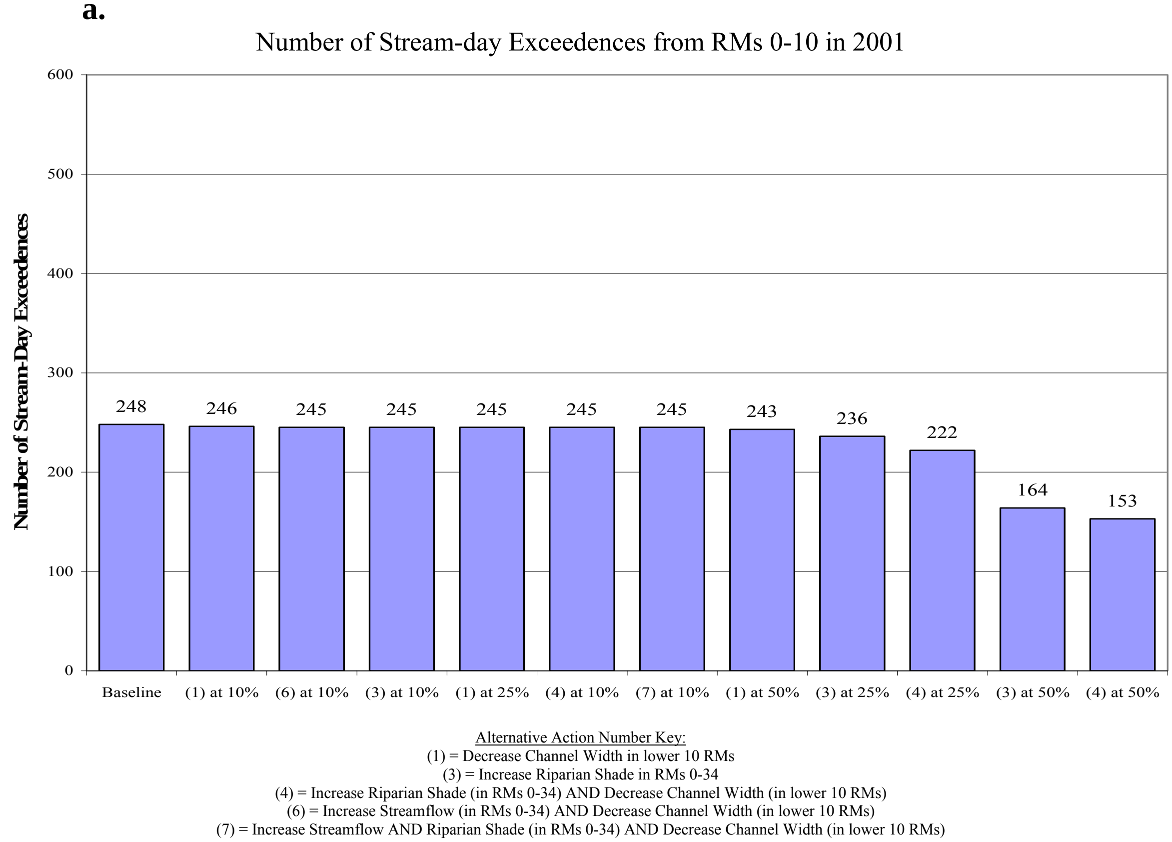


b.

Figure 28: Number of state water quality stream-day exceedences for simulated baseline conditions and alternative actions for RMs 0-34 (a) and RMs 0-10 (b) during the 8/2/00-9/14/00 (44 day) time period.

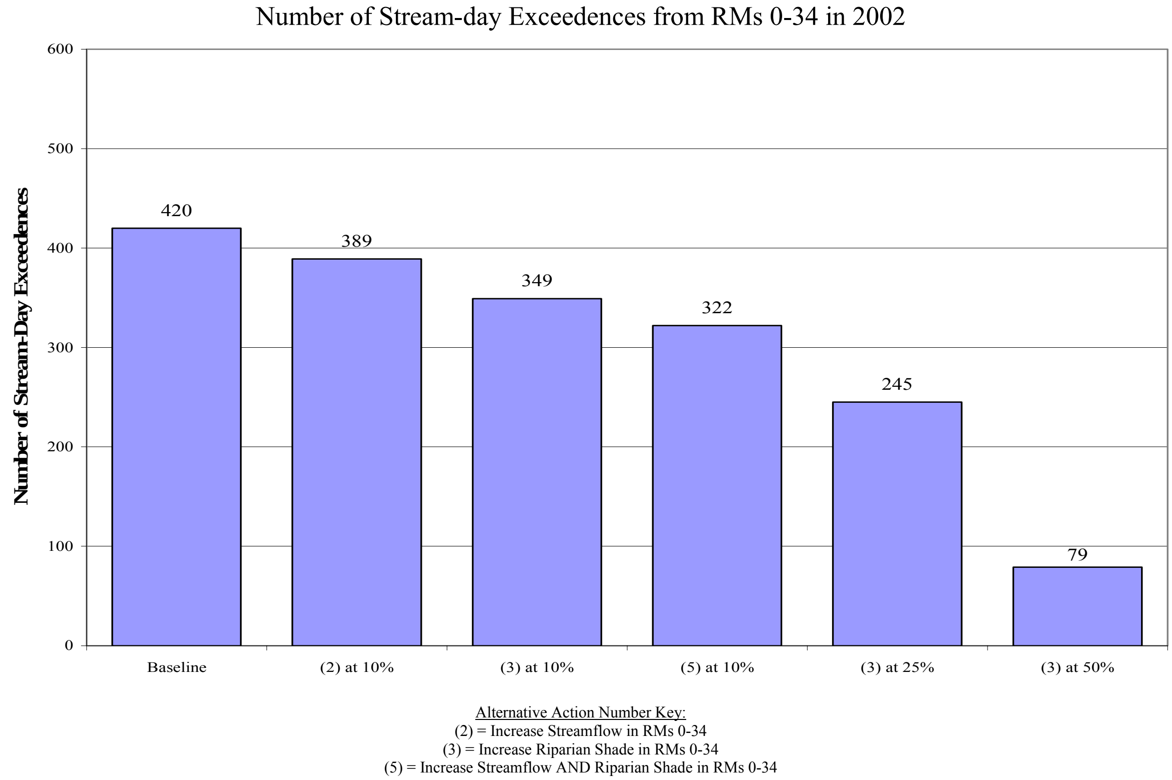


a.

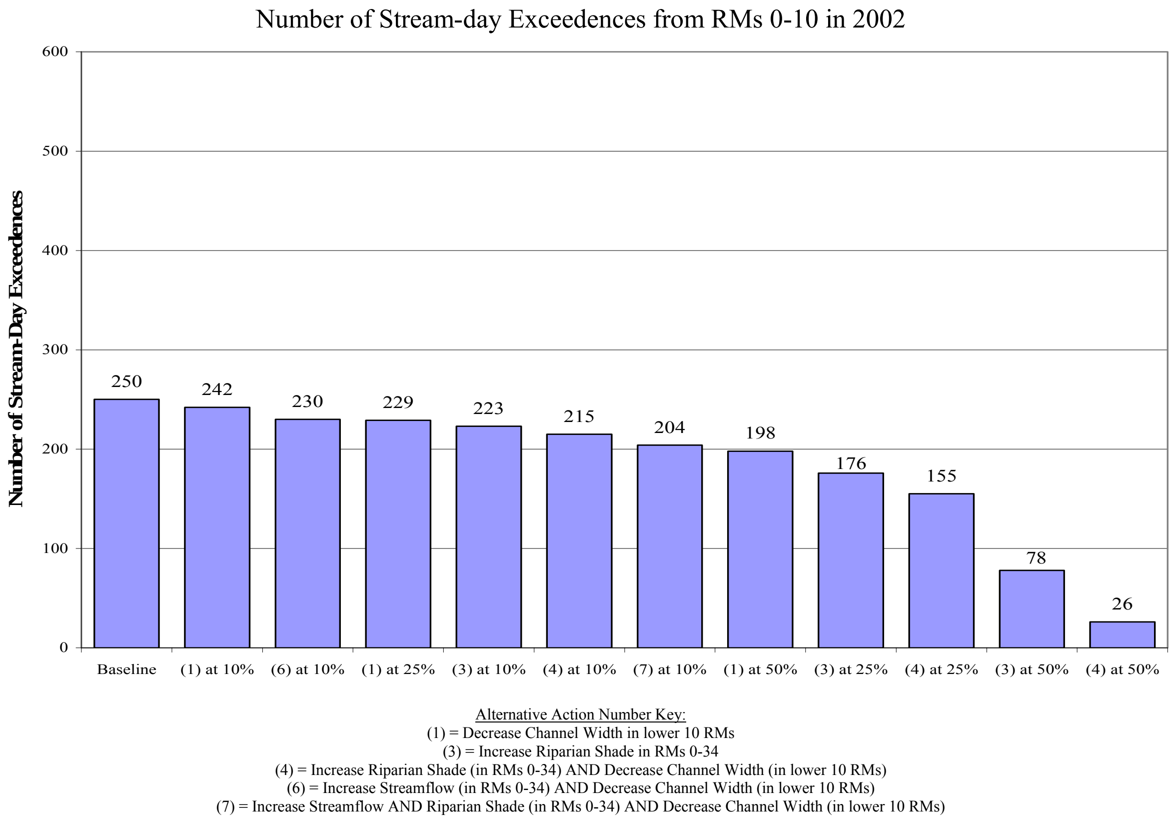


b.

Figure 29: Number of state water quality stream-day exceedences for simulated baseline conditions and alternative actions for RMs 0-34 (a) and RMs 0-10 (b) during the 8/2/01-9/14/01 (44 day) time period.



a.



b.

Figure 30: Number of state water quality stream-day exceedences for simulated baseline conditions and alternative actions for RMs 0-34 (a) and RMs 0-10 (b) during the 8/2/02-9/14/02 (44 day) time period.

Table 5: Exceedence table showing the number **(#)** of state water quality exceedences for simulated baseline conditions and proposed alternative actions system wide (RMs 0-34). Table also shows the percent **(%)** of exceedences based on total number of "measurement" points (***n***).

Alt. Action	Exceedences		Alt. Action	Exceedences		Alt. Action	Exceedences		Alt. Action	Exceedences		Alt. Action	Exceedences		Alt. Action	Exceedences	
	#	%		#	%		#	%		#	%		#	%		#	%
Class AA	*n*=220																
1997			**1998**			**1999**			**2000**			**2001**			**2002**		
Baseline	**33**	15.00	Baseline	**146**	66.36	Baseline	**3**	1.36	Baseline	**54**	24.55	Baseline	**141**	64.09	Baseline	**102**	46.36
(2) at 10%	**26**	11.82	(2) at 10%	**141**	64.09	(2) at 10%	**3**	1.36	(2) at 10%	**46**	20.91	(2) at 10%	**137**	62.27	(2) at 10%	**95**	43.18
(3) at 10%	**17**	7.73	(3) at 10%	**133**	60.45	(3) at 10%	**2**	0.91	(3) at 10%	**32**	14.55	(3) at 10%	**130**	59.09	(3) at 10%	**78**	35.45
(5) at 10%	**12**	5.45	(5) at 10%	**125**	56.82	(5) at 10%	**2**	0.91	(5) at 10%	**25**	11.36	(5) at 10%	**126**	57.27	(5) at 10%	**67**	30.45
(3) at 25%	**1**	0.45	(3) at 25%	**94**	42.73	(3) at 25%	**0**	0.00	(3) at 25%	**8**	3.64	(3) at 25%	**109**	49.55	(3) at 25%	**39**	17.73
(3) at 50%	**0**	0.00	(3) at 50%	**29**	13.18	(3) at 50%	**0**	0.00	(3) at 50%	**0**	0.00	(3) at 50%	**60**	27.27	(3) at 50%	**0**	0.00
Class A	*n*=484																
1997			**1998**			**1999**			**2000**			**2001**			**2002**		
Baseline	**194**	40.08	Baseline	**396**	81.82	Baseline	**56**	11.57	Baseline	**226**	46.69	Baseline	**369**	76.24	Baseline	**318**	65.70
(2) at 10%	**174**	35.95	(2) at 10%	**381**	78.72	(2) at 10%	**44**	9.09	(2) at 10%	**217**	44.83	(2) at 10%	**365**	75.41	(2) at 10%	**294**	60.74
(3) at 10%	**155**	32.02	(3) at 10%	**361**	74.59	(3) at 10%	**34**	7.02	(3) at 10%	**194**	40.08	(3) at 10%	**356**	73.55	(3) at 10%	**271**	55.99
(5) at 10%	**137**	28.31	(5) at 10%	**350**	72.31	(5) at 10%	**25**	5.17	(5) at 10%	**175**	36.16	(5) at 10%	**353**	72.93	(5) at 10%	**255**	52.69
(3) at 25%	**88**	18.18	(3) at 25%	**310**	64.05	(3) at 25%	**16**	3.31	(3) at 25%	**129**	26.65	(3) at 25%	**328**	67.77	(3) at 25%	**206**	42.56
(3) at 50%	**12**	2.48	(3) at 50%	**179**	36.98	(3) at 50%	**0**	0.00	(3) at 50%	**34**	7.02	(3) at 50%	**209**	43.18	(3) at 50%	**79**	16.32
Total	*n*=704																
1997			**1998**			**1999**			**2000**			**2001**			**2002**		
Baseline	**227**	32.24	Baseline	**542**	76.99	Baseline	**59**	8.38	Baseline	**280**	39.77	Baseline	**510**	72.44	Baseline	**420**	59.66
(2) at 10%	**200**	28.41	(2) at 10%	**522**	74.15	(2) at 10%	**47**	6.68	(2) at 10%	**263**	37.36	(2) at 10%	**502**	71.31	(2) at 10%	**389**	55.26
(3) at 10%	**172**	24.43	(3) at 10%	**494**	70.17	(3) at 10%	**36**	5.11	(3) at 10%	**226**	32.10	(3) at 10%	**486**	69.03	(3) at 10%	**349**	49.57
(5) at 10%	**149**	21.16	(5) at 10%	**475**	67.47	(5) at 10%	**27**	3.84	(5) at 10%	**200**	28.41	(5) at 10%	**479**	68.04	(5) at 10%	**322**	45.74
(3) at 25%	**89**	12.64	(3) at 25%	**404**	57.39	(3) at 25%	**16**	2.27	(3) at 25%	**137**	19.46	(3) at 25%	**437**	62.07	(3) at 25%	**245**	34.80
(3) at 50%	**12**	1.70	(3) at 50%	**208**	29.55	(3) at 50%	**0**	0.00	(3) at 50%	**34**	4.83	(3) at 50%	**269**	38.21	(3) at 50%	**79**	11.22

Alternative Action (#) Legend	
(2) =	Increase Streamflow in RMs 0-34
(3) =	Increase Riparian Shade Values in RMs 0-34
(5) =	Increase Streamflow AND Increase Riparian Shade in RMs 0-34

<u>Table 6:</u> Exceedence table showing the number **(#)** of state water quality exceedences for simulated baseline conditions and proposed alternative actions **in the lower 10 RMs**. Table also shows the percent **(%)** of exceedences based on total number of "measurement" points **(*n*).**

	Exceedences			Exceedences			Exceedences			Exceedences			Exceedences			Exceedences	
Alt. Action	#	%	Alt. Action	#	%	Alt. Action	#	%	Alt. Action	#	%	Alt. Action	#	%	Alt. Action	#	%
	n=308																
1997			**1998**			**1999**			**2000**			**2001**			**2002**		
Baseline	**171**	55.52	Baseline	**279**	90.58	Baseline	**52**	16.88	Baseline	**191**	62.01	Baseline	**248**	80.52	Baseline	**250**	81.17
(1) at 10%	**158**	51.30	(1) at 10%	**275**	89.29	(1) at 10%	**43**	13.96	(1) at 10%	**187**	60.71	(1) at 10%	**246**	79.87	(1) at 10%	**242**	78.57
(1) at 25%	**145**	47.08	(6) at 10%	**268**	87.01	(1) at 25%	**34**	11.04	(6) at 10%	**177**	57.47	(6) at 10%	**245**	79.55	(6) at 10%	**230**	74.68
(6) at 10%	**144**	46.75	(3) at 10%	**267**	86.69	(3) at 10%	**33**	10.71	(1) at 25%	**174**	56.49	(3) at 10%	**245**	79.55	(1) at 25%	**229**	74.35
(3) at 10%	**140**	45.45	(1) at 25%	**266**	86.36	(6) at 10%	**32**	10.39	(3) at 10%	**168**	54.55	(1) at 25%	**245**	79.55	(3) at 10%	**223**	72.40
(4) at 10%	**132**	42.86	(4) at 10%	**265**	86.04	(4) at 10%	**27**	8.77	(4) at 10%	**160**	51.95	(4) at 10%	**245**	79.55	(4) at 10%	**215**	69.81
(7) at 10%	**114**	37.01	(7) at 10%	**262**	85.06	(7) at 10%	**23**	7.47	(7) at 10%	**149**	48.38	(7) at 10%	**245**	79.55	(7) at 10%	**204**	66.23
(1) at 50%	**101**	32.79	(1) at 50%	**255**	82.79	(1) at 50%	**21**	6.82	(1) at 50%	**146**	47.40	(1) at 50%	**243**	78.90	(1) at 50%	**198**	64.29
(3) at 25%	**87**	28.25	(3) at 25%	**243**	78.90	(3) at 25%	**16**	5.19	(3) at 25%	**121**	39.29	(3) at 25%	**236**	76.62	(3) at 25%	**176**	57.14
(4) at 25%	**57**	18.51	(4) at 25%	**225**	73.05	(4) at 25%	**10**	3.25	(4) at 25%	**93**	30.19	(4) at 25%	**222**	72.08	(4) at 25%	**155**	50.32
(3) at 50%	**12**	3.90	(3) at 50%	**158**	51.30	(3) at 50%	**0**	0.00	(3) at 50%	**34**	11.04	(3) at 50%	**164**	53.25	(3) at 50%	**78**	25.32
(4) at 50%	**0**	0.00	(4) at 50%	**109**	35.39	(4) at 50%	**0**	0.00	(4) at 50%	**8**	2.60	(4) at 50%	**153**	49.68	(4) at 50%	**26**	8.44

Alternative Action (#) Legend	
(1) =	Decrease Channel Width in lower 10 RMs
(3) =	Increase Riparian Shade Values in RMs 0-34
(4) =	Increase Riparian Shade (in RMs 0-34) AND Decrease Channel Width (in lower 10 RMs)
(6) =	Increase Streamflow (in RMs 0-34) AND Decrease Channel Width (in lower 10 RMs)
(7) =	Increase Streamflow AND Increase Riparian Shade (in RMs 0-34) AND Decrease Channel Width (in lower 10 RMs)

Discussion

Calibration

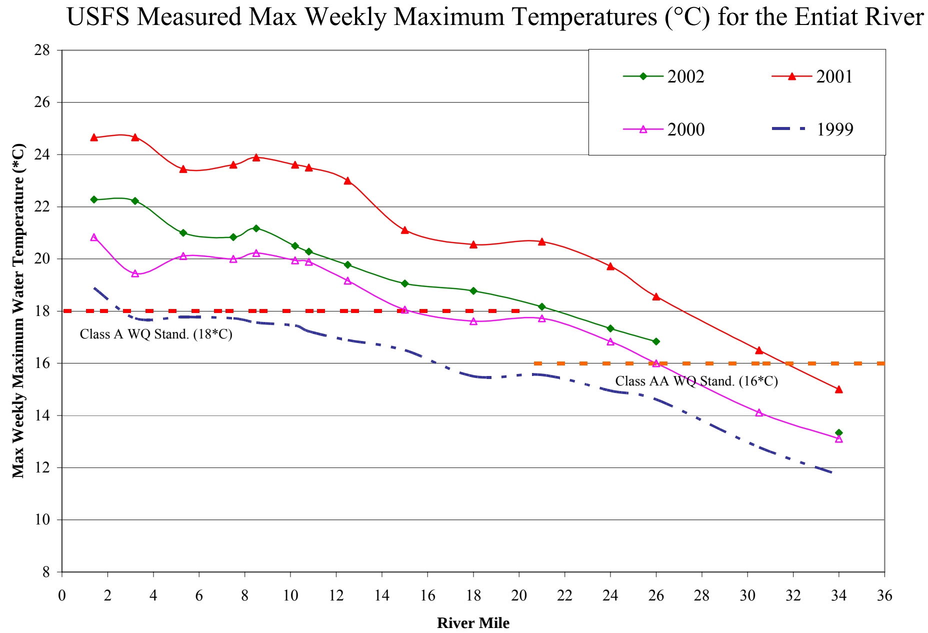
From Figure 13 and Table 2 it can be seen that the model predicted within the acceptable error ranges outlined by Bartholow (1989) and explained in the *Model Calibration* section with a R^2 of 0.9137 and mean error of -0.03°C. The mean error value indicates that the model was underpredicting the mean daily water temperatures over the entire time-series and at all river nodes by only 0.03 °C. The maximum and dispersion errors also were within the acceptable range. The high R^2 value and low mean error suggests that the model produced no trend in error and although the maximum error is fairly high, this is to be expected due to the large population and the dispersion error of 5.94% implies that a only small number of predicted temperatures were more than 1.5°C from observed temperatures.

Figure 14 illustrates how well the model predicted water temperatures at RM 1.4 for an entire time-step during both a hot and cool year, demonstrating that the model can handle the inter-annual and daily variations that take place over the time series and time-step simulated. RM 1.4 was selected for illustration because it represents the furthest downstream validation node, and it has been stated that the model's predictive ability typically decreases with distance from the headwater node (Krause 2002). Therefore, it can be seen that if Figure 14 represents the location where the model's predictive ability is least certain, and if predictive ability improves as you move upstream, then the model should be predicting water temperatures accurately and precisely over the entire time-step for both a hot and cool year system-wide.

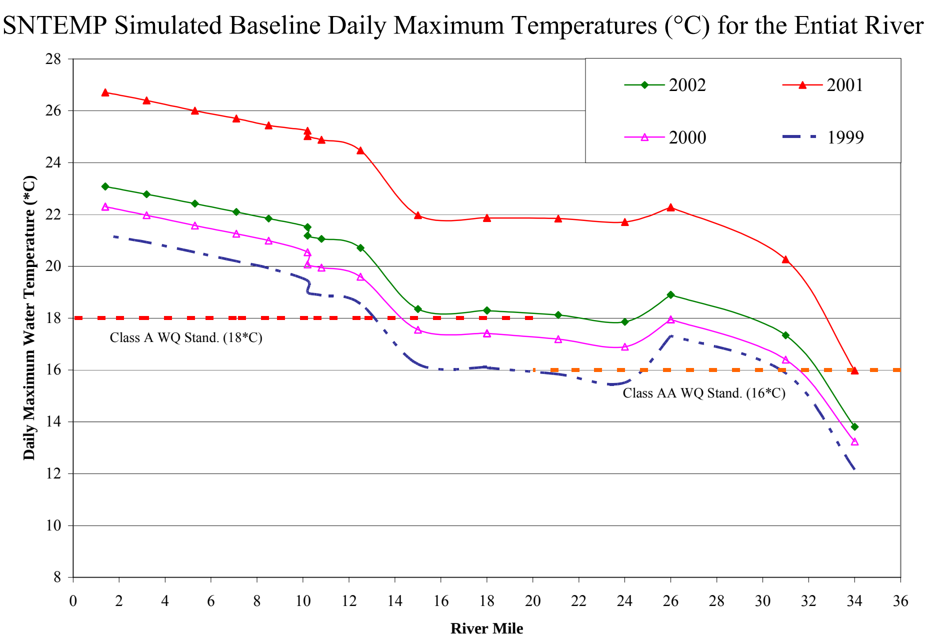
Figure 15 illustrates that the model is also accurately and precisely predicting daily mean water temperatures system-wide with varying geomorphic, hydrologic, and meteorologic conditions during the hottest day of a hot and cool year, again suggesting that the model performed well during inter-annual variations.

Based on the calibration results shown in Figures 13-15 and Table 2, the authors along with the EWPU Water-Quality Sub-Committee feel that the SNTEMP model accurately and precisely predicted daily mean water temperatures over the entire time-series and time-step simulated. We are also confident that the SNTEMP model is robust enough to handle the inter-annual and daily variability that takes place over this large time-series/step. Therefore, the SNTEMP simulations that were performed during this project are considered to be accurately and precisely simulating the conditions within the Entiat River watershed (with annual variations in the meteorology and hydrology parameters). Furthermore, alternative actions that were simulated during this project and the subsequent recommendations set forth by the authors and EWPU water-quality committee are justified as they are likely to have the effects predicted if implemented.

Figure 31 displays the relative accuracy of SNTEMP's ability to predict daily maximum water temperatures. Figure 31 (a) shows the max weekly maximum water temperatures in the Entiat River for the years 1999-2002 as measured by Phil Archibald (USFS). Figure 31 (b) shows SNTEMP's simulated baseline daily maximum water temperatures for the estimated hottest day for the years 1999-2002. Although the time-series and time-steps are different in (a) and (b) the two graphs have similar characteristics: Figure 31 (a) shows the observed maximum weekly maximum water temperature (highest weekly maximum temperature for each given year) while 31 (b) shows the daily maximum temperature from the hottest day of each given year. Therefore, each graph is illustrating extreme water temperature conditions from each year across the longitudinal profile. From the figures it can be seen that SNTEMP predicted maximum temperatures in the same order as was observed. For example 2001 was observed to be the hottest and 1999 was the coolest in both graphs. In addition, in general SNTEMP over predicted maximum water temperatures as compared to the maximum weekly maximum observed temperatures. Although it would be preferable to have assurance that observed and predicted maximum water temperatures are the same, the authors and Water-Quality Sub-Committee have the assurance that alternative actions that are recommended in this report will be effective if implemented. This is typically referred to as a "margin of safety" in Total Maximum Daily Loads (TMDL) reports (Stohr and Leskie 2000, Butkus et al. 1999).



a.



b.

Figure 31: Comparison of observed (a) and simulated (b) maximum water temperatures for "extreme" conditions of 1999-2002. Note different time-steps.

Longitudinal Profiles (Figures 16-23)

From Figures 16-23, it appears that although all the alternative actions had cooling effects on simulated baseline daily maximum water temperatures, during the "hot" day of August 13, 2001 not one of the actions reduced daily maximum water temperatures below current state water quality standards system- wide. Not even a 300% increase in streamflows completely reduced daily maximum water temperatures below standards (Figure 18b) during this hot day, nor did the combination of all three actions (Figure 23b). This suggests that in the Entiat River's meteorological conditions are the driving factors in elevated water temperatures, and that during hot meteorological conditions it may not be possible (by human interaction) to reduce daily maximum water temperatures below current state water quality standards given the proposed alternative actions. Furthermore, for the "cooler" day of August 9, 2000, only the larger increments of change for all alternatives reduced daily maximum water temperatures below current state standards system wide. Again this suggests that the naturally hot meteorological conditions in the Entiat River Watershed are the driving force behind high daily maximum water temperatures in the Entiat River and that implementing the proposed alternative actions may not completely reduce those temperatures below current state standards.

Number of Exceedences (Figures 25-30)

It was determined that in order to make recommendations to the EWPU as to which alternative actions should be implemented, the actions that are considered to be unfeasible be excluded from consideration. Therefore the following alternative actions were deemed unfeasible: (1) Increasing streamflow by more then 10% (Alternative Action 2 and 2a), as flows in the Entiat Watershed is largely unregulated and there are limited diversions and uses of the water, and therefore there is a limited source for increasing streamflows above 10%. (2) Any multivariate action that includes increasing streamflow more then 10% was also excluded (Alternative Actions 5, 6, and 7). (3) Increasing riparian shade values above 50% (Alternative Action 3), as increasing the current riparian zone to produce more then a 50% shading effect is considered to be unfeasible (see *Methods/Alternative Actions* section for explanation of how increases to baseline riparian shade conditions were simulated).

Figures 25-30 show the number of water quality exceedences that occurred during simulated baseline conditions and for each *feasible* alternative action for each year simulated (8/2-9/14 time period). These figures are important because they estimate the true values that each feasible alternative action could produce in terms of how well each alternative could reduce exceedences in state water quality standards. In each year simulated, increases in shade (Alternative Action 3) and increases in shade and decreases in width (Alternative Action 4) produced the largest reductions in state water quality exceedences as compared to simulated baseline conditions. For the August 9, 2000 date, 50% increases in shade values predicted reductions in total (Class AA and Class A) exceedences from 280 to 34, a 88% reduction system wide (Figure 28a) and reduced Class A exceedences in the lower 10 RMs from 191 to 34, a 82% reduction (Figure 28b). Even in the hot year of 2001, 50% increases in shade reduced total exceedences from 510 to 269 system wide, a 47% reduction (figure 29a), and from 248 to 164 in the lower 10 RMs, a 34% reduction (figure 29b). Furthermore, the combination of increasing shade and decreasing channel width was predicted to reduce exceedences by greater amounts (in the lower 10 RMs; as compared to increasing shade alone).

Conclusions

The following recommendations are intended to address water temperature issues within the Entiat River watershed, and how changes to streamflow, channel width and/or riparian shade may affect water temperatures. These recommendations are not intended to address other issues within the watershed related to streamflow, channel width, and/or riparian shade, nor are they intended to controvert other recommendations or studies related to streamflow, habitat or other restoration objectives in the Entiat River watershed. However, these recommendations can be used to compare the cost-benefit of implementing alternative watershed actions intended to better the overall health of the watershed as it relates to human use, aquatic life, etc…

Therefore, based on the results of the model simulations performed with SNTEMP, the authors of this report, through the EWPU Water-Quality Sub-Committee, recommend the following actions in order to reduce water temperatures in the Entiat River Watershed during critical high temperature periods:

- SNTEMP predicted reductions in water temperatures for all three alternative actions, suggesting that implementation of any of the three actions would help reduce water temperatures to some extent.
- Of the feasible alternatives, SNTEMP predicted the largest reductions in water temperatures when riparian shade was increased by 50% (Alternative Action 3). Therefore, an aggressive approach to increasing the current riparian shade conditions throughout the watershed should be undertaken to address high water temperatures.
- In addition, if EWPU resources are available, decreases to channel width in the lower 10 RMs in conjunction with changes in shade should also be considered (Alternative Action 4).
- A 10% change in streamflow is not likely to significantly effect water temperature.

These recommendations are based on the simulated effects that each alternative action had on simulated baseline water temperatures (Figures 16-23; Tables 3-4) according to results produced by SNTEMP, the overall feasibility of implementing each action, and the potential of each action to reduce the number of state water quality exceedences that may occur in the future (Figures 25-30; Tables 5-6). As stated in the *Discussion* section, not one of the alternative actions was predicted to completely reduce water temperatures to or below current state water quality standards. However, given the possibility that the current state water quality standards could be modified in the future, along with the request of the EWPU to address water temperatures issues in the Entiat Watershed for its effects on endangered and/or threatened fish species, the authors of this paper along with the EWPU Water Quality Sub-Committee intended on making a recommendation on which of the proposed alternative actions would best address water temperature issues in the Entiat River Watershed.

Increases in current riparian shade conditions in the Entiat River by 50% produced the best reductions in simulated baseline daily maximum water temperatures of the feasible univariable alternative actions. Recall that for this application, shade inputs were already in a percent form, and therefore increases in shade were calculated simply by <u>adding</u> the percent change amounts to the observed percent shade conditions. For example, most areas along the Entiat River simulated in this study were determined to have between 0-10% (minimum-maximum) canopy cover (CCCD 2002), and therefore a 10% increase to the maximum would be represented as 10% + 10% = 20% canopy cover, and so on…

Although achieving this 50% increase in canopy cover will take considerable time and effort, and a more achievable goal of 25-30% increases in canopy cover is likely, the 50% increases should be the ultimate goal of the EWPU when addressing high water temperatures. Furthermore, in the upper river where current riparian shade is already estimated to be 20-30% (RMs 18-34), it is not likely to increase these conditions by 50% (thus achieving 80% canopy cover), and therefore the goal in these reaches would be to increase these conditions up to the point of a 50% canopy cover.

In addition to increases in riparian shade conditions, the combination of increasing shade 50% and decreasing channel width 50% in the lower 10 RMs had the most significant effect on simulated baseline water temperatures. Again, the 50% adjustments are lofty goals, and 25-30% adjustments may be more likely, but the goal should be to adjust the conditions as much as is reasonably feasible so that the full reduction in water temperature can be realized.

In addition to reductions in water temperatures, increasing riparian shade and decreasing channel width (Alternative Actions 3 and/or 4) could have other positive effects to the overall health of the Entiat River Watershed. For example increasing the current riparian shade conditions system wide has the potential to increase biological diversity within the watershed and increase nutrient sources for fish species (Andonaegui 1999). Increases in shade could also increase the potential source for large woody debris placement, an important component fish habitat, provide refuge from predators and extreme environmental events, and provide buffering effects to erosive forces (Andonaegui 1999). Decreasing channel width in the lower 10 RMs has the potential of improving fish passage, and further increase the effect of current and potential increases to riparian shade conditions (CCCD, 2002). Decreasing channel width using structures such as cross veins (CCCD, 2002) may also support habitat improvement objectives.

Acknowledgments

We would like to thank the Entiat WRIA Planning Unit (EWPU) and the Water Quality Sub-Committee for their input and support, as we would not have been able to complete this project without it. We are particularly grateful to Phil Archibald, Rick Edwards and Karin Whitehall of the USDA Forest Service- Entiat Ranger District; Sarah Walker, Kurt Hosman and Scott Wolf of the Chelan County Conservation District; Gary Mitchell and Joe Lange of the Natural Resource Conservation Service; Tina Gary and Woody Trihey of ENTRIX, Inc; Bob Whitehall of the City of Entiat; Gran Rhodus, retired Forest Service hydrologist; and Bill Taylor of the United States Geological Survey. We would also like to thank the following friendly reviewers of this document who provided comments and suggestions for revisions: Phil Archibald; Sarah Walker; Kurt Hosman; and Bob Vadas of the U.S. Fish and Wildlife Service. We owe a special acknowledgment to the tireless support of John Bartholow of the United States Geological Survey – Biological Resources Division. Mr. Bartholow's knowledge of the SNTEMP model along with his outstanding training material proved invaluable. Mr. Bartholow provided continual support throughout this project, and offered suggestions, comments, and answers to a number of technical and general SNTEMP model development questions, without which this project would not have been complete. We are also grateful to the Washington Department of Ecology for supporting our efforts, and for the Centennial Clean Water Act funding necessary to conduct the research.

Notes

The entire project, including the input and output files produced by SNTEMP, results, raw and reduced data that was obtained to fill input files, and some of the literature cited within this report can be found electronically in the compact disk that accompanies this report (see README.doc file within the compact disk for further explanation of the contents of the disk).

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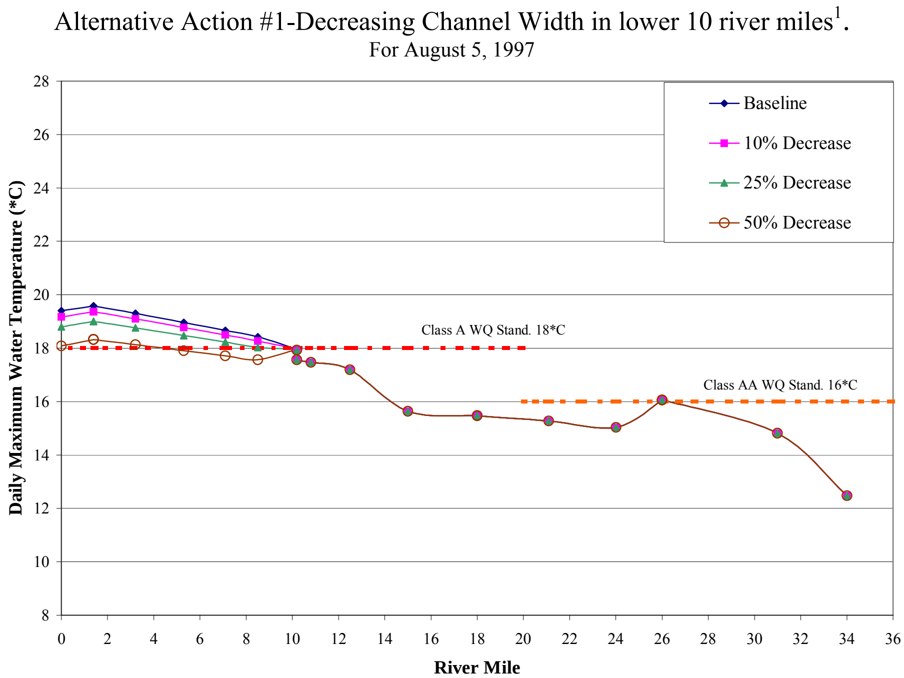
Appendix A

Appendix A (on following page) shows the results of each alternative action in a longitudinal profile showing changes in daily maximum water temperatures (°C) versus stream distance (river mile (RM)). These figures show the calibrated, or "baseline" daily maximum water temperatures and how changes in channel width, streamflows, riparian shade, and combinations of the three are predicted to effect daily maximum water temperatures. The graphs also include the Class A (for river miles 0-20; 18˚C) and Class AA (for river miles 20-34; 16˚C) state water quality standards (Chapter 173-201A WAC), so that it could be determined if a given alternative action could reduce water temperatures to or below these standards. This was done for the estimated hottest day of each year simulated (1997-2002; 8/2-9/14 time period), based on meteorological conditions from the East Wenatchee Pangborn Memorial Airport weather station and observed water temperatures in the Entiat River as measured by the USFS.



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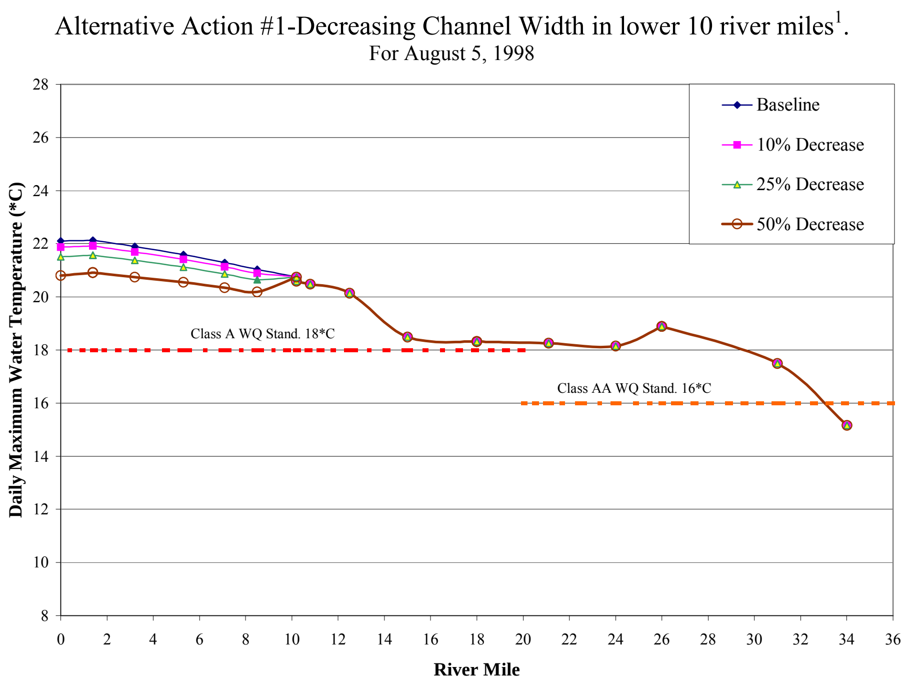

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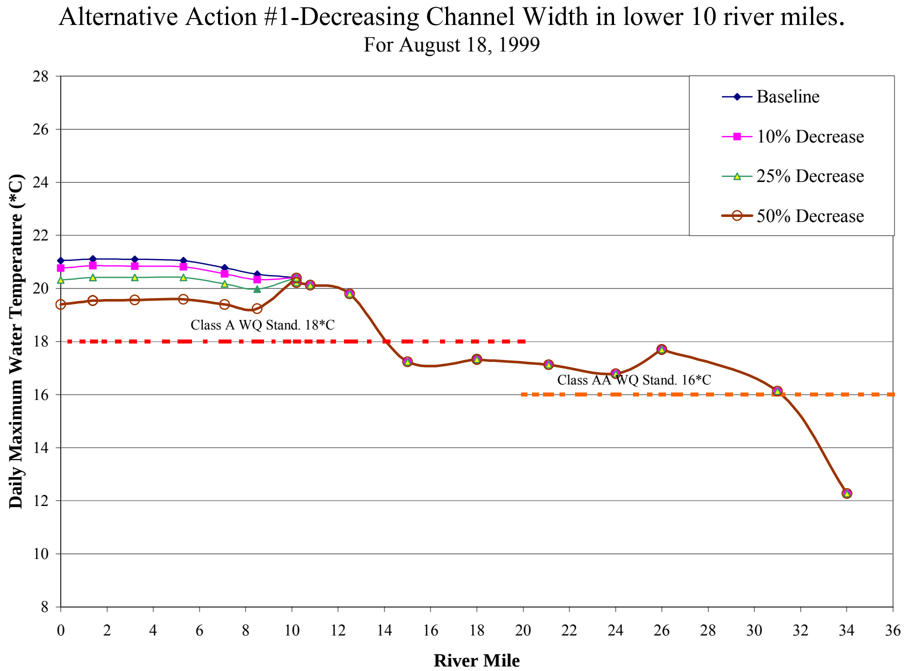
Figure A-1: Longitudinal profile of daily maximum water temperatures resulting from the reduction of channel width in the lower 10 river miles for August 5, 1997 (a) and August 5, 1998 (b).

[1]All reductions in channel width were simulated in the lower 10 RMs only, as reducing channel width from RMs 10-34 was thought to be an unfeasible alternative action.



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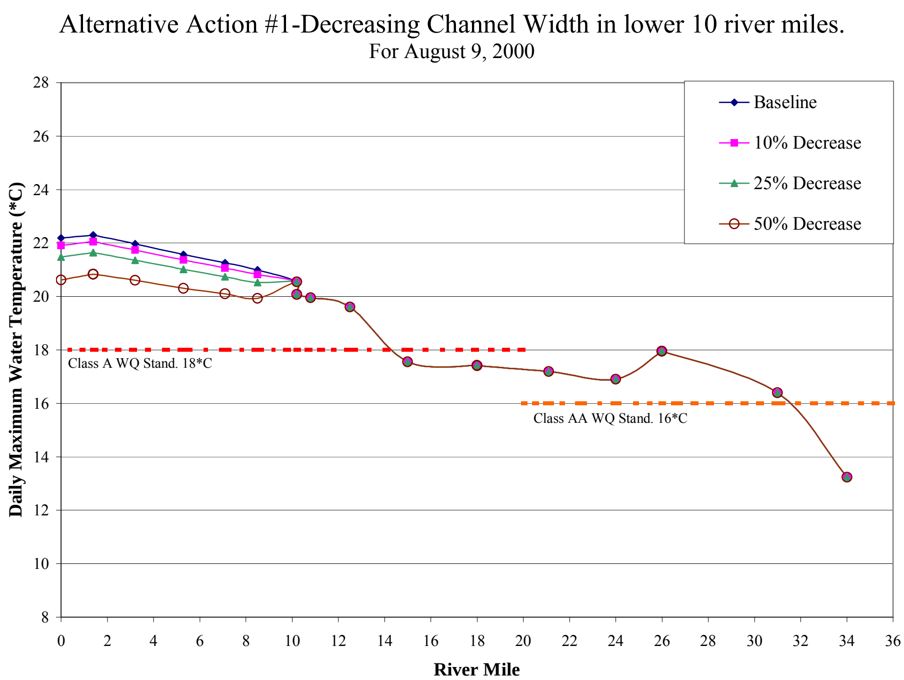

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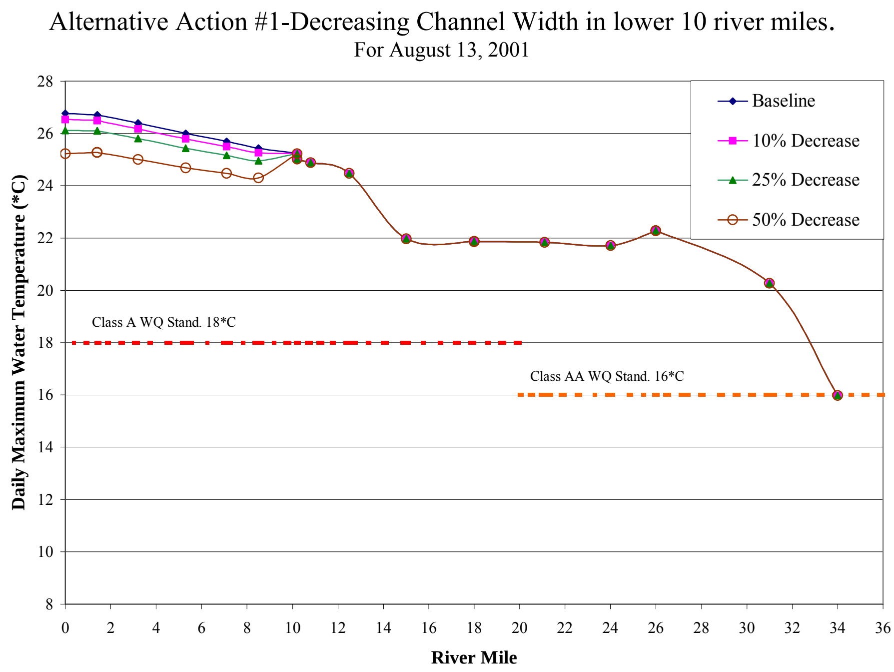
Figure A-2: Longitudinal profile of daily maximum water temperatures resulting from the reduction of channel width in the lower 10 river miles for August 18, 1999 (a) and August 9, 2000 (b).



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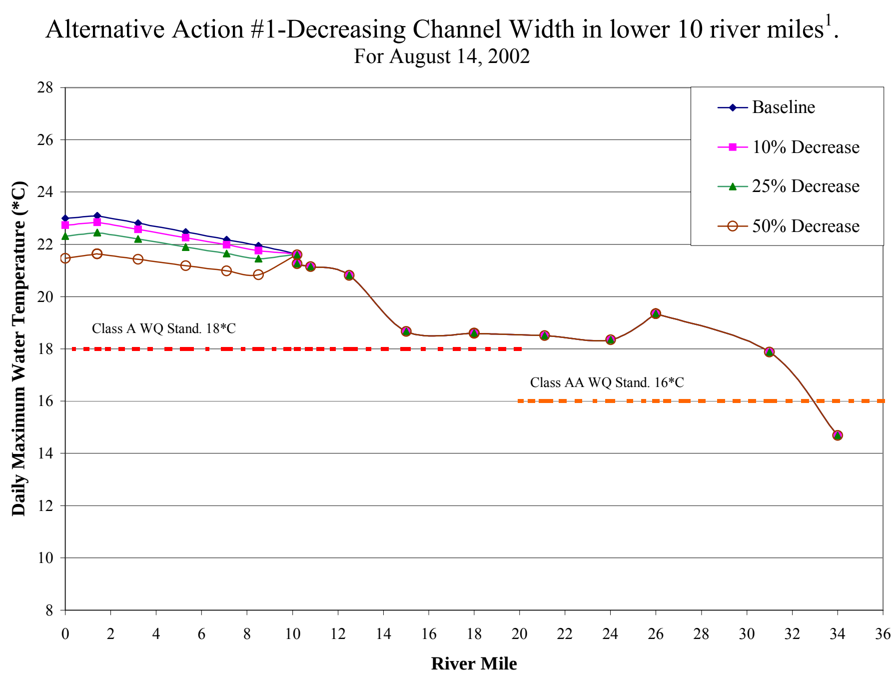

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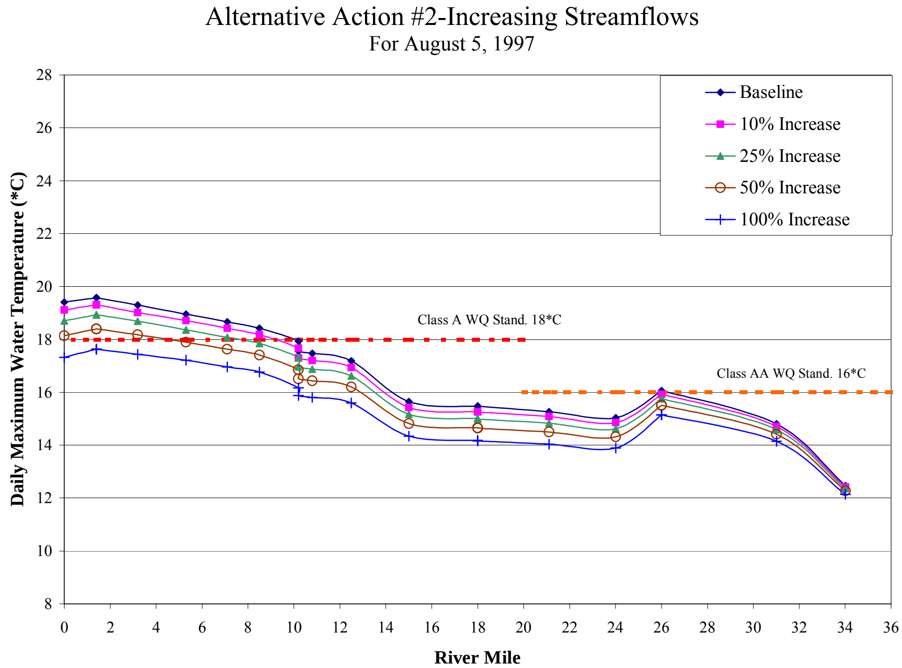
<u>Figure A-3:</u> Longitudinal profile of daily maximum water temperatures resulting from the reduction of channel width in the lower 10 river miles for August 13, 2001 (a) and August 14, 2002 (b).



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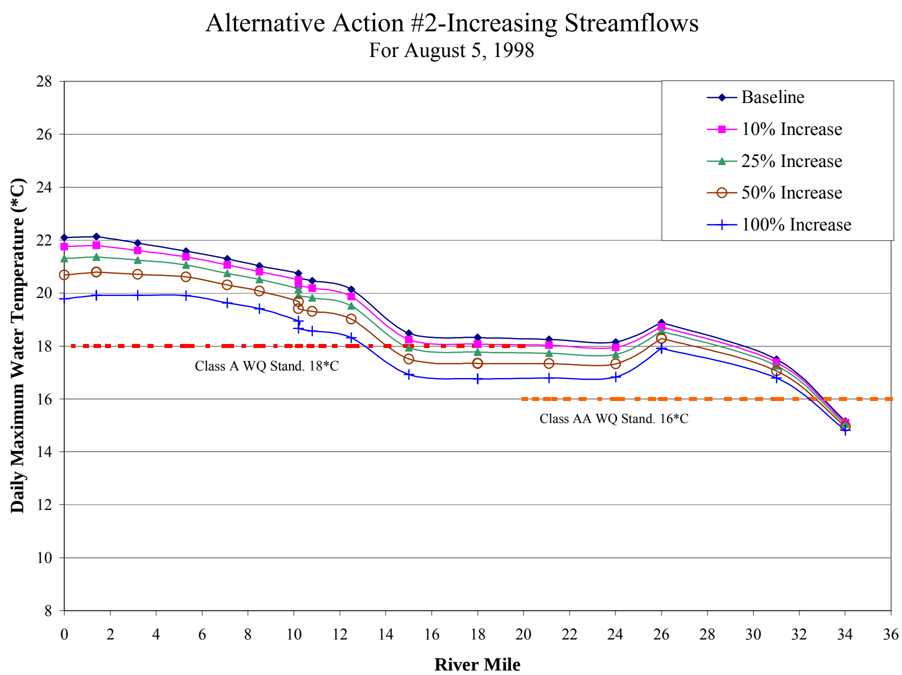

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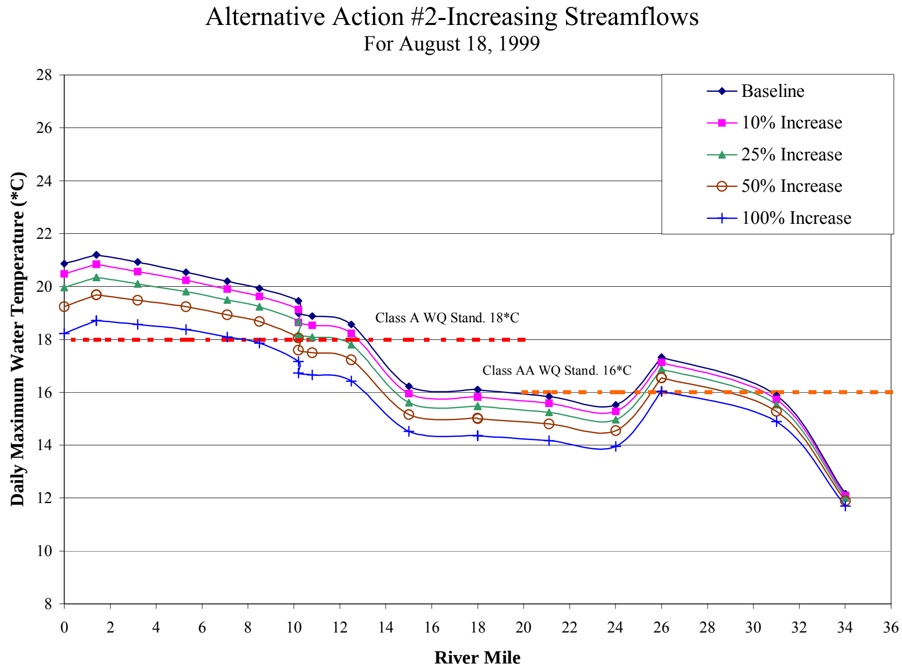
Figure A-3: Longitudinal profile of daily maximum water temperatures resulting from increases in streamflow for August 5, 1997 (a) and August 5, 1998 (b).



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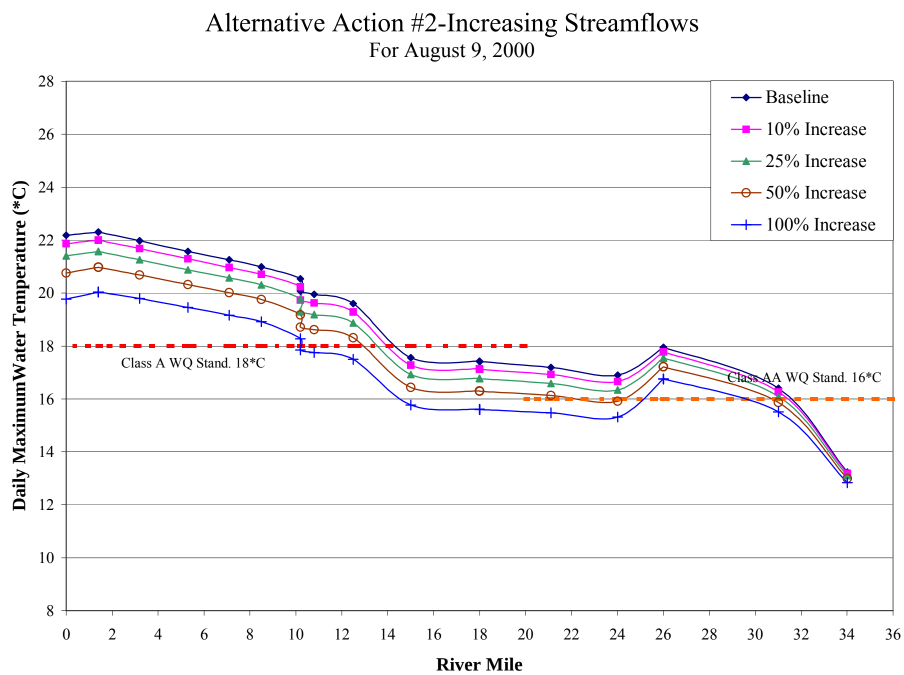

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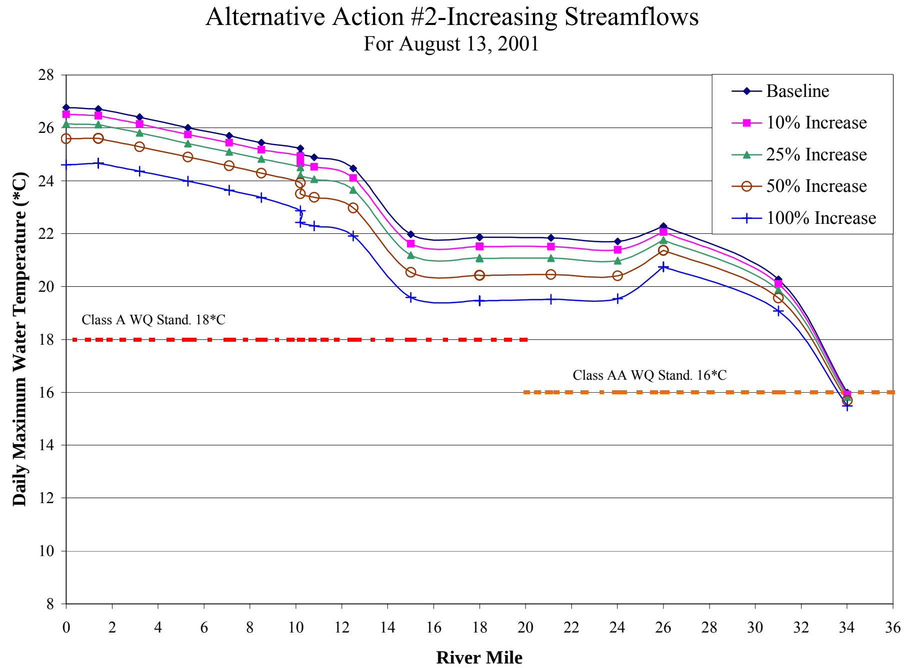
Figure A-4: Longitudinal profile of daily maximum water temperatures resulting from increases in streamflow for August 18, 1999 (a) and August 9, 2000 (b).



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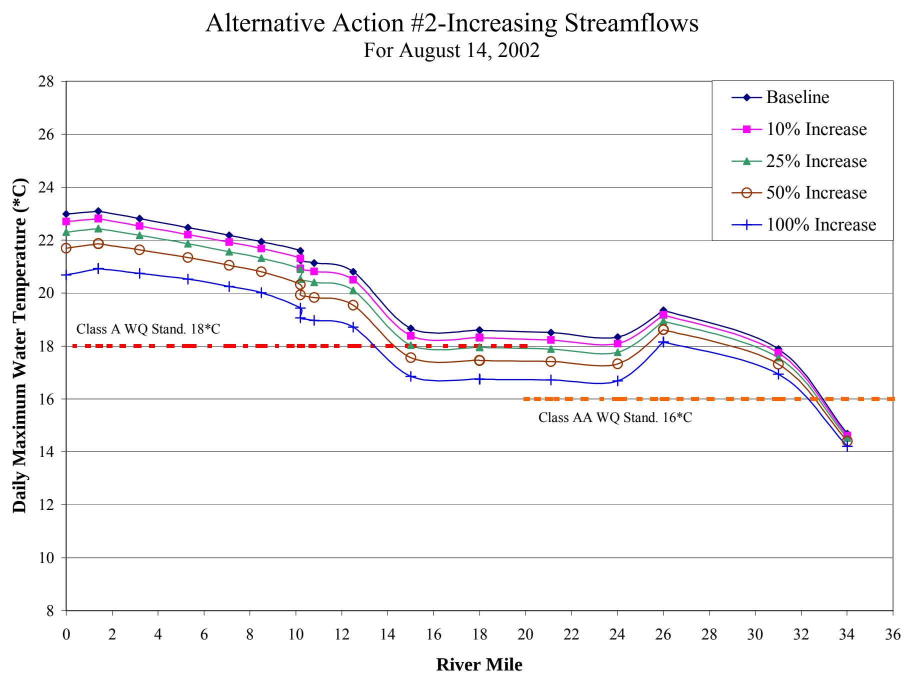

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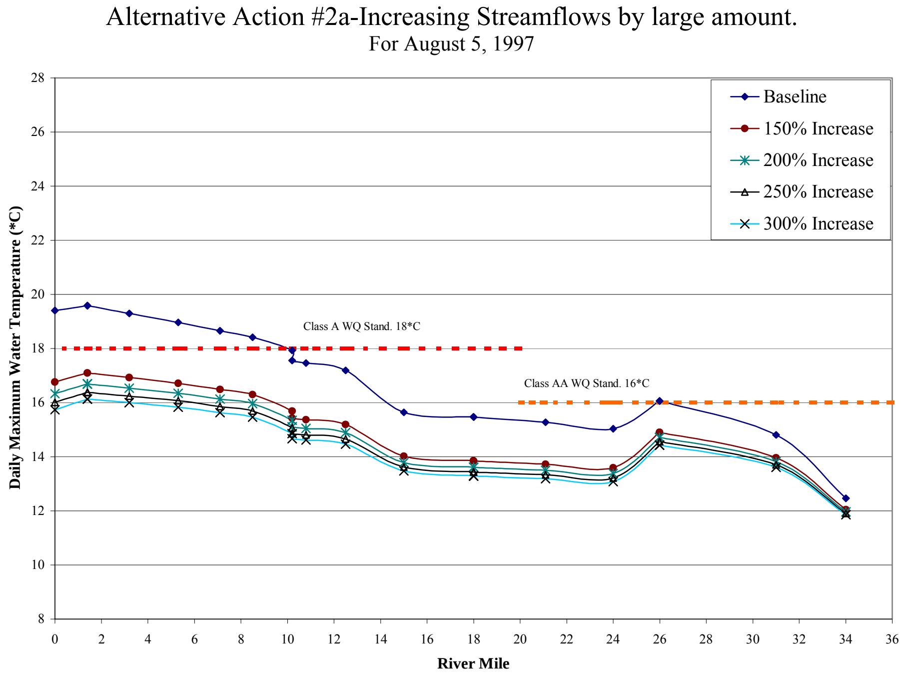
Figure A-5: Longitudinal profile of daily maximum water temperatures resulting from increases in streamflow for August 13, 2001 (a) and August 14, 2002 (b).



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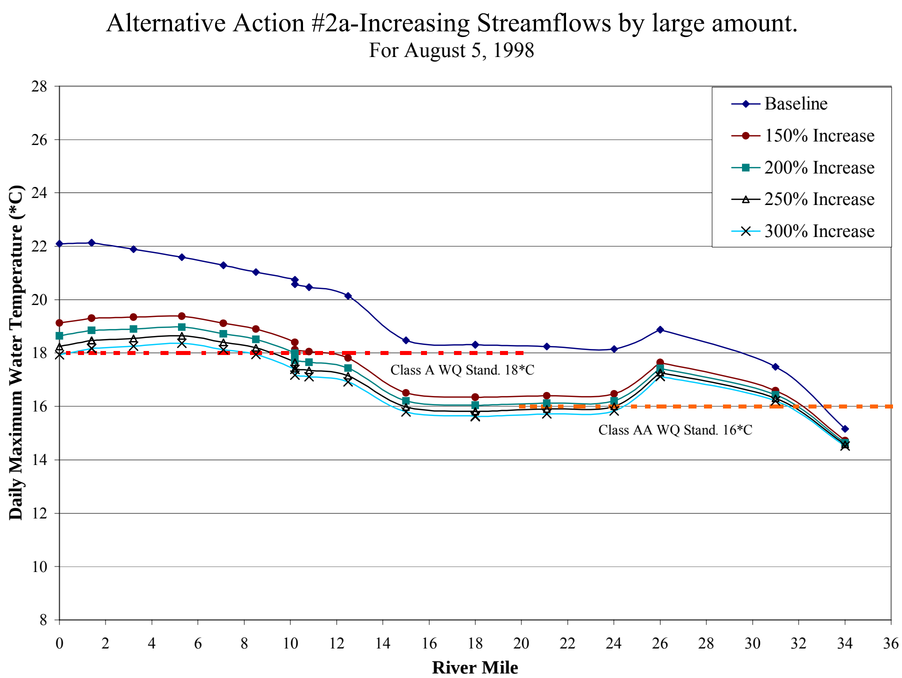

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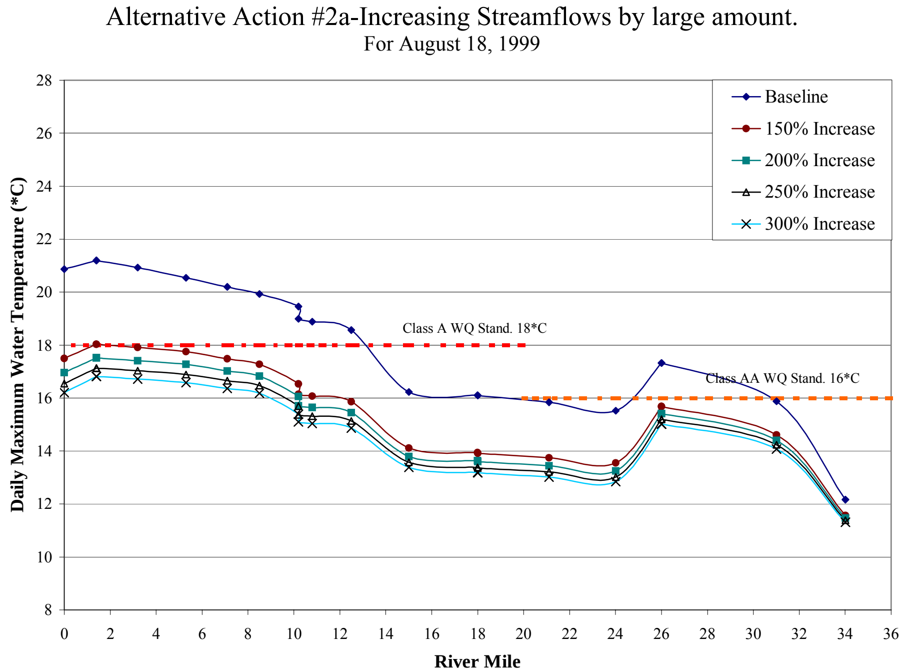
Figure A-6: Longitudinal profile of daily maximum water temperatures resulting from increasing streamflows by large amounts for August 5, 1997 (a) and August 5, 1998 (b).



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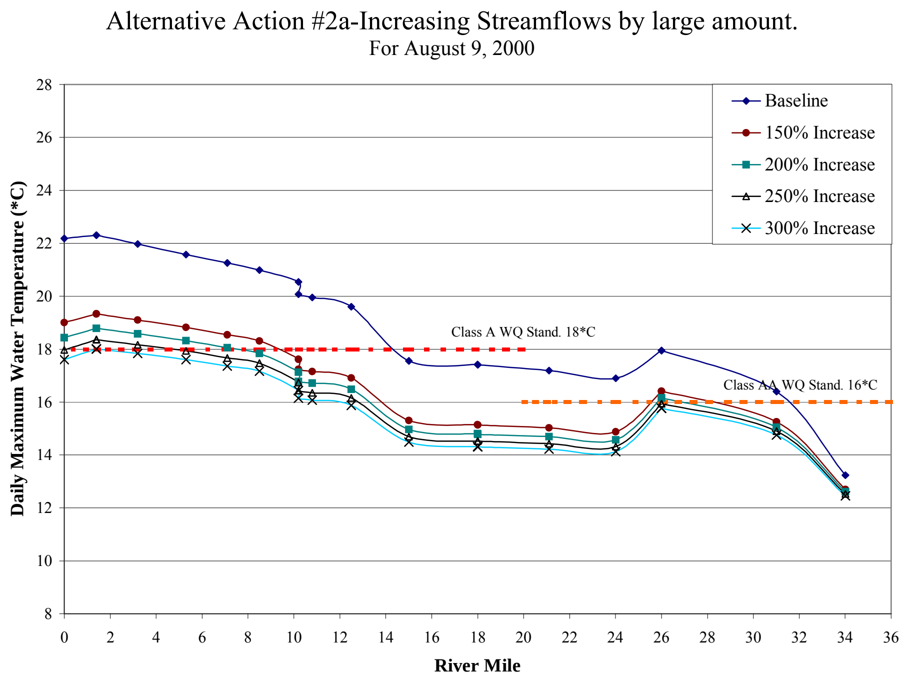

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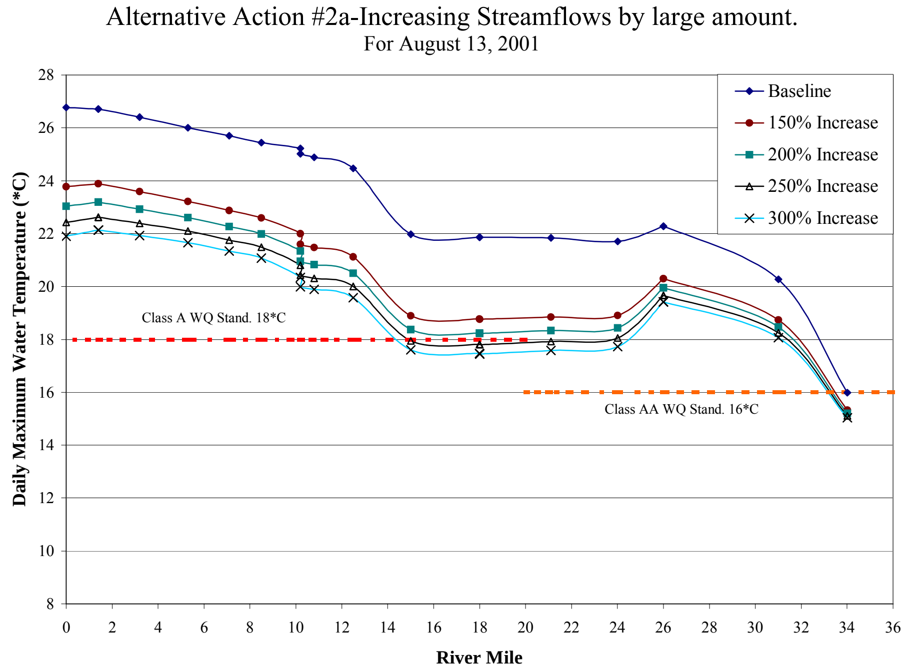
Figure A-7: Longitudinal profile of daily maximum water temperatures resulting from increasing streamflows by large amounts for August 18, 1999 (a) and August 9, 2000 (b).



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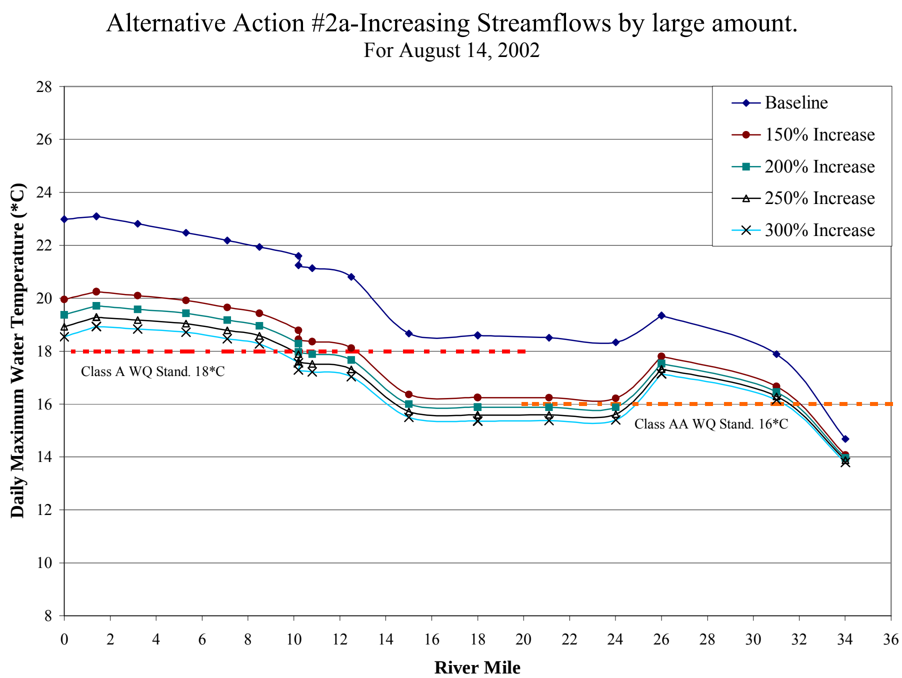

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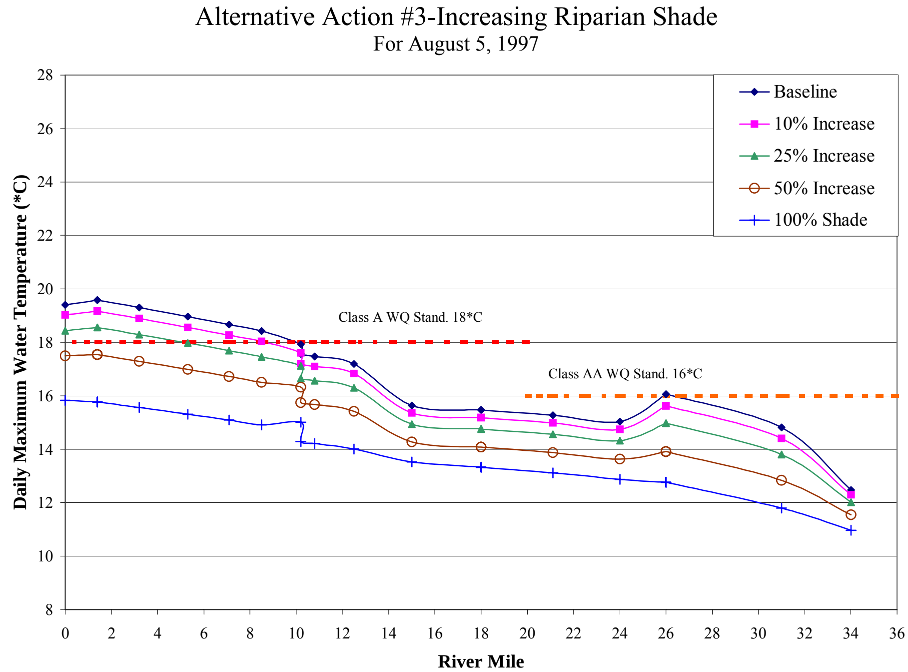
Figure A-8: Longitudinal profile of daily maximum water temperatures resulting from increasing streamflows by large amounts for August 13, 2001 (a) and August 14, 2002 (b).



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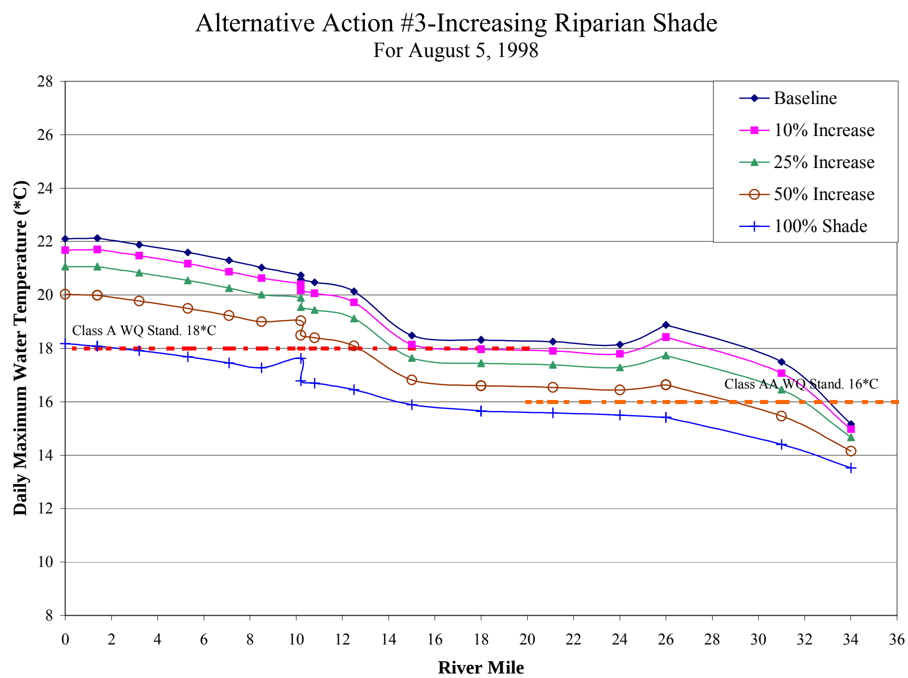
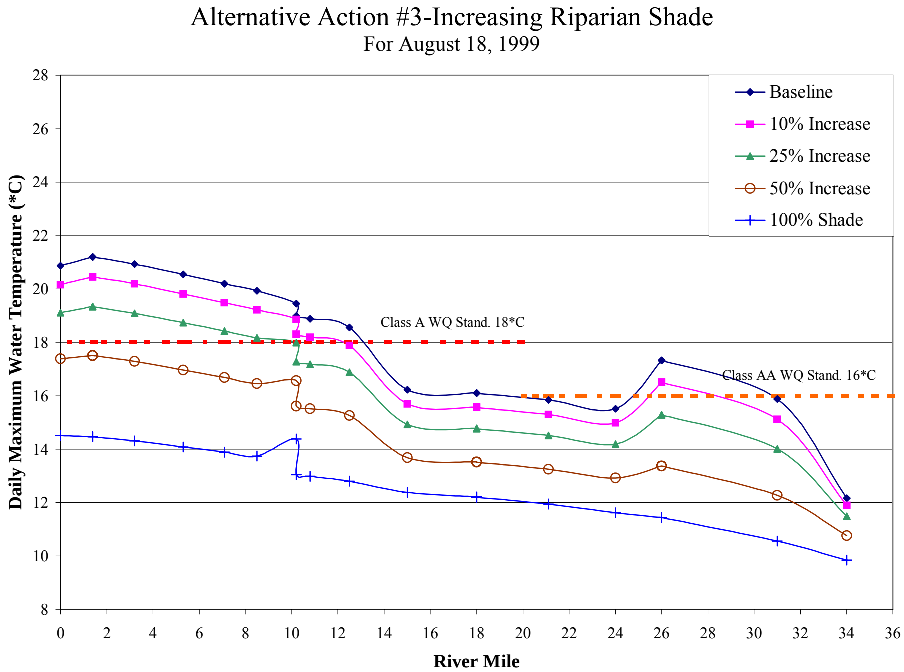


b.

Figure A-9: Longitudinal profile of daily maximum water temperatures resulting from increases in riparian shade values for August 5, 1997 (a) and August 5, 1998 (b).



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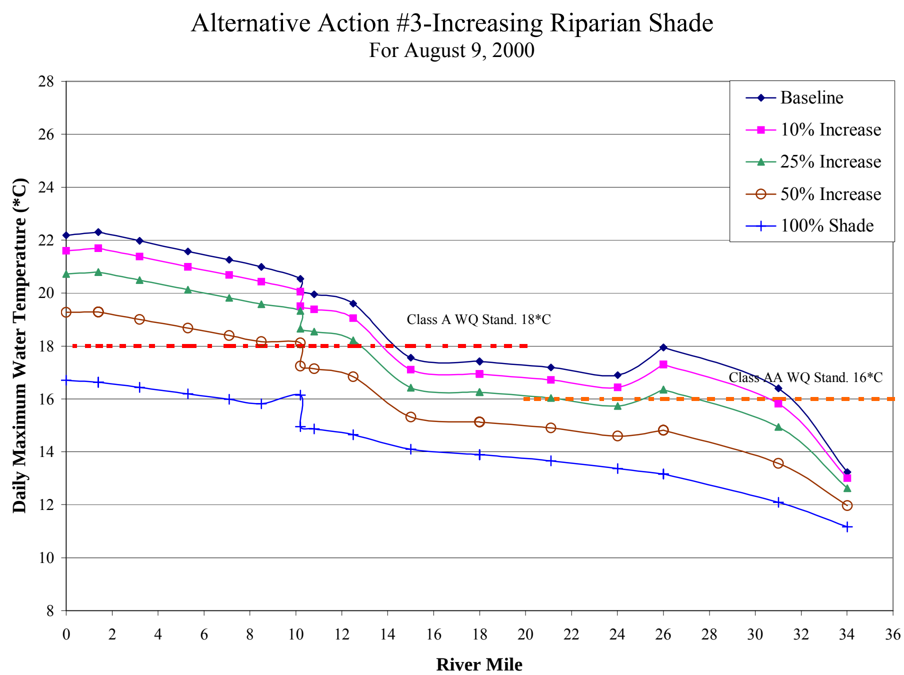

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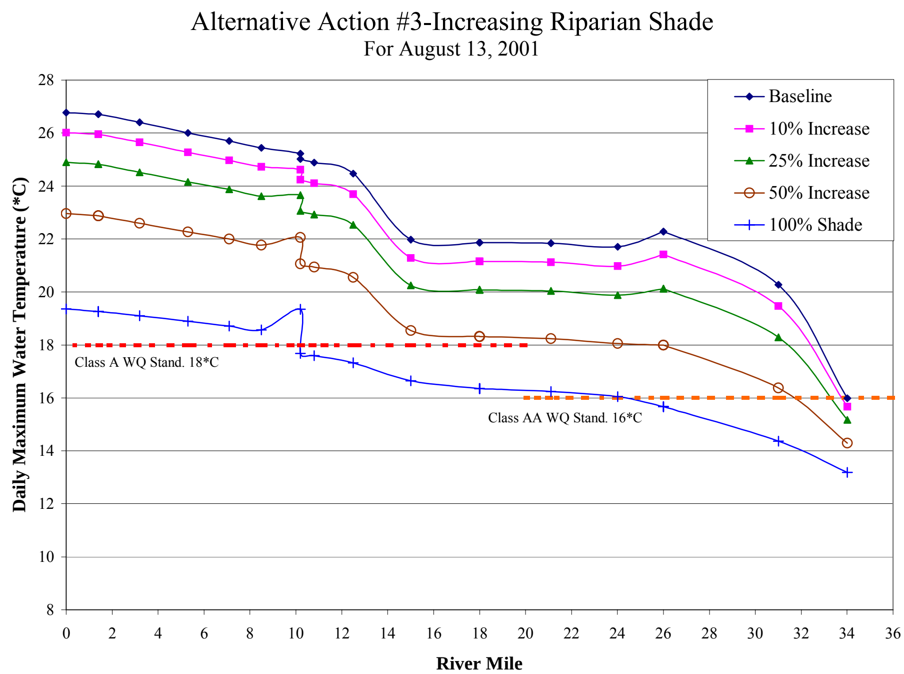
Figure A-10: Longitudinal profile of daily maximum water temperatures resulting from increases in riparian shade values for August 18, 1999 (a) and August 9, 2000 (b).



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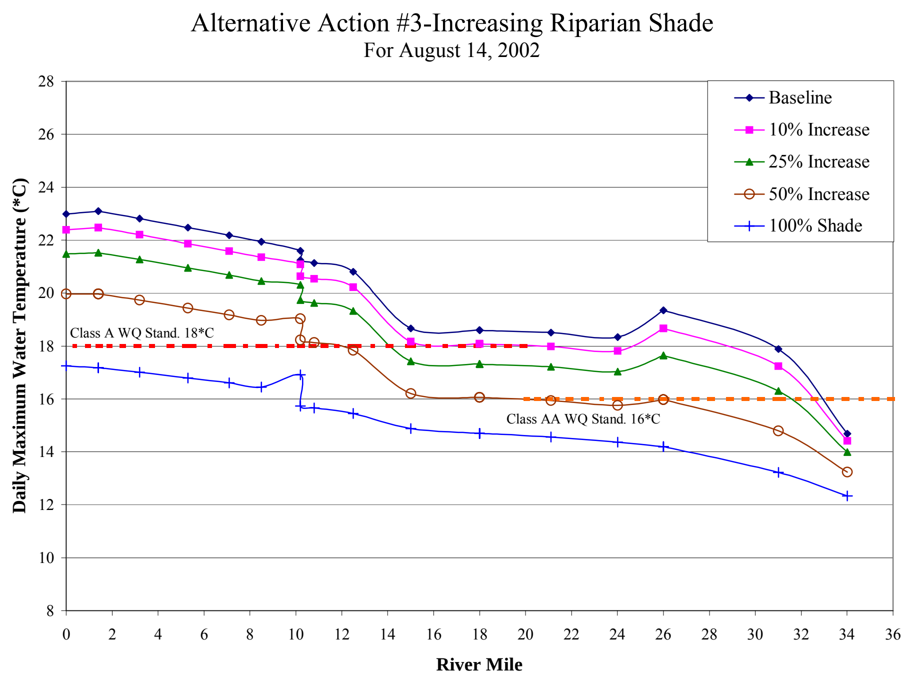

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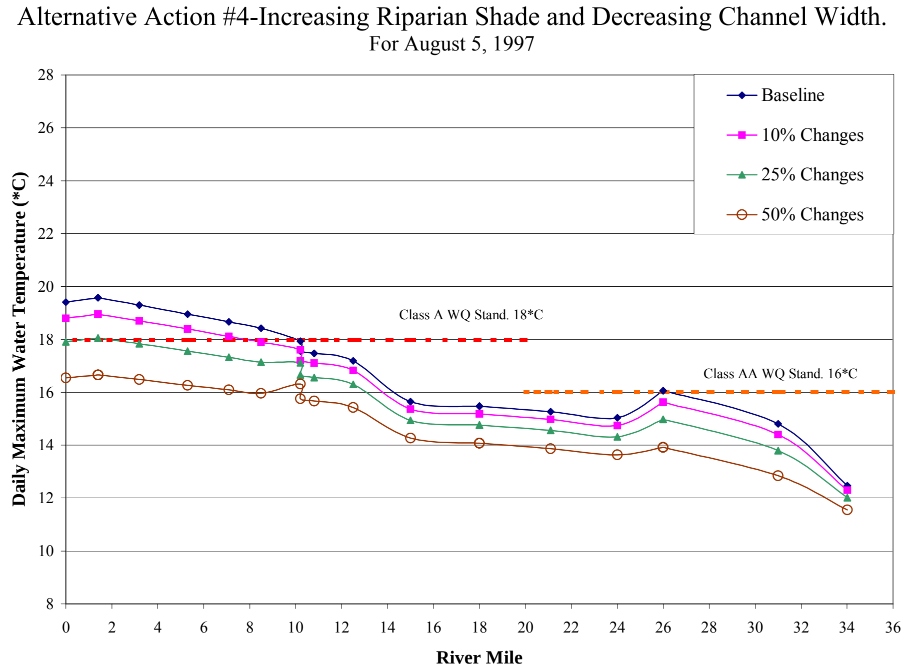
<u>Figure A-11: </u>Longitudinal profile of daily maximum water temperatures resulting from increases in riparian shade values for August 13, 2001 (a) and August 14, 2002 (b).



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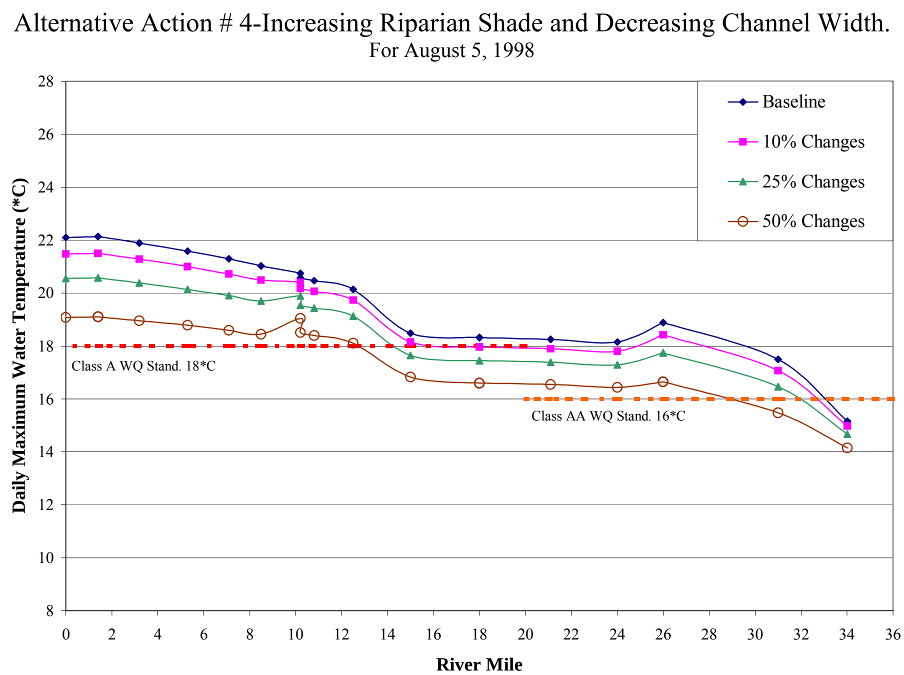
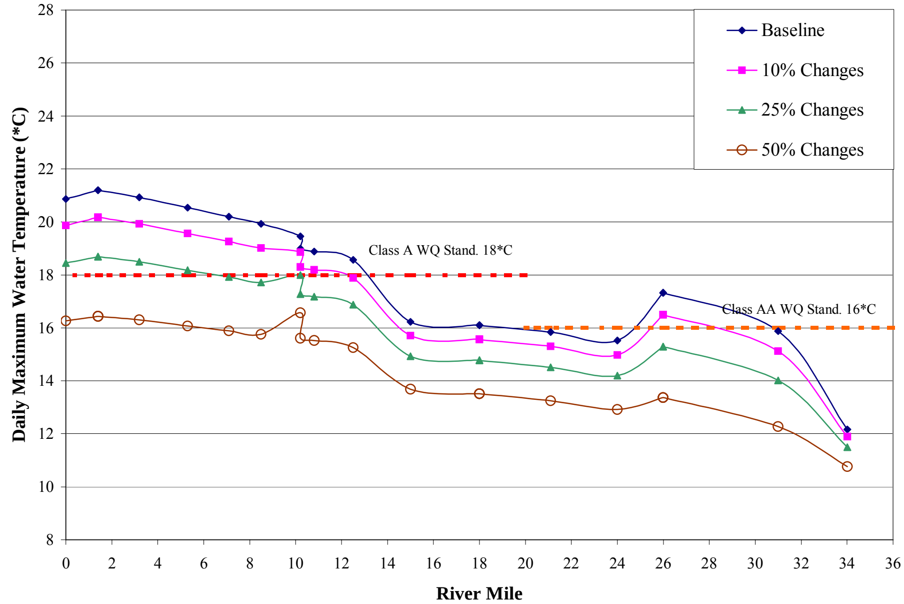


b.

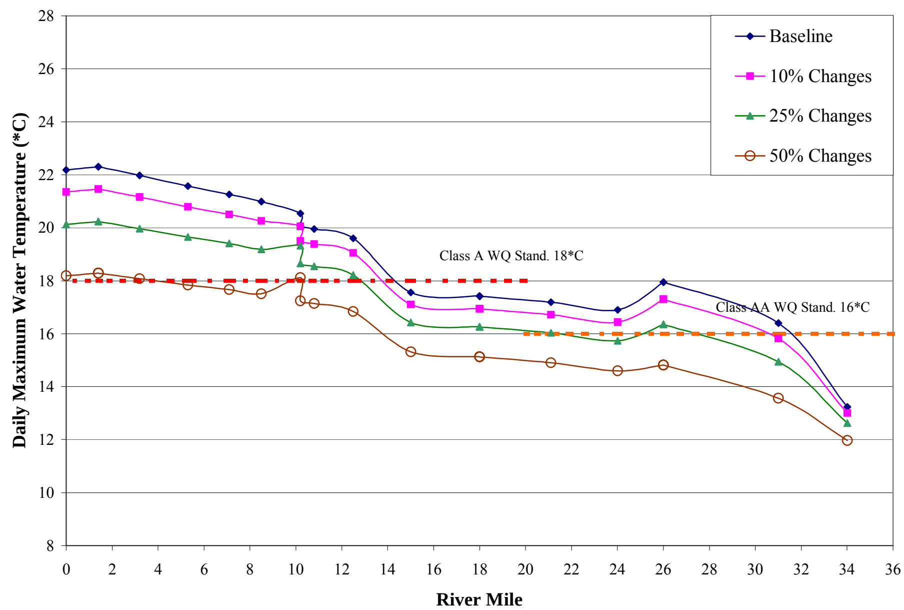
<u>Figure A-12:</u> Longitudinal profile of daily maximum water temperatures resulting from increases in riparian shade values and decreases in channel width for August 5, 1997 (a) and August 5, 1998 (b).

Alternative Action #4-Increasing Riparian Shade and Decreasing Channel Width.
For August 18, 1999



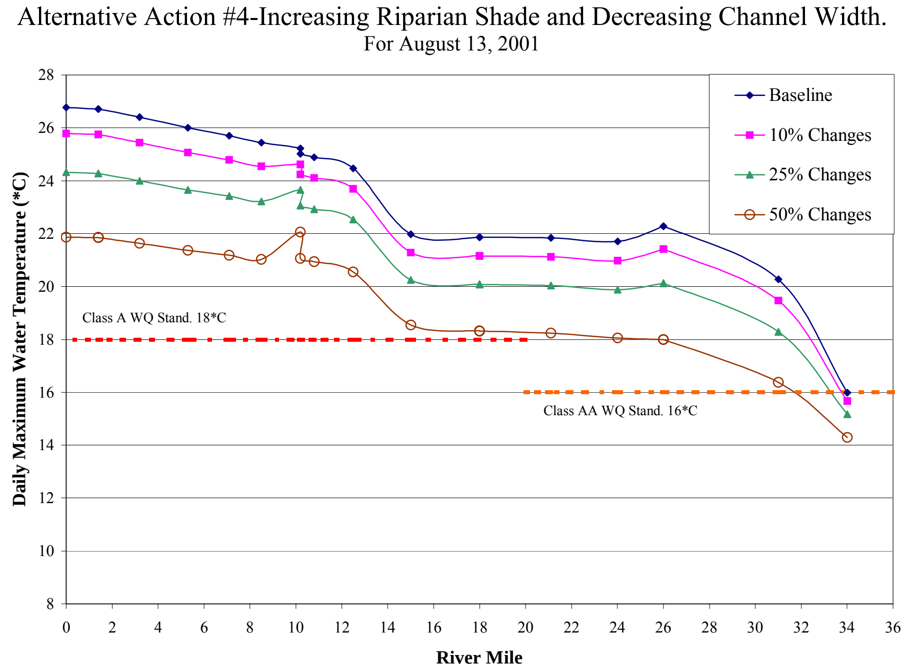
a.

Alternative Action # 4-Increasing Riparian Shade and Decreasing Channel Width.
For August 9, 2000

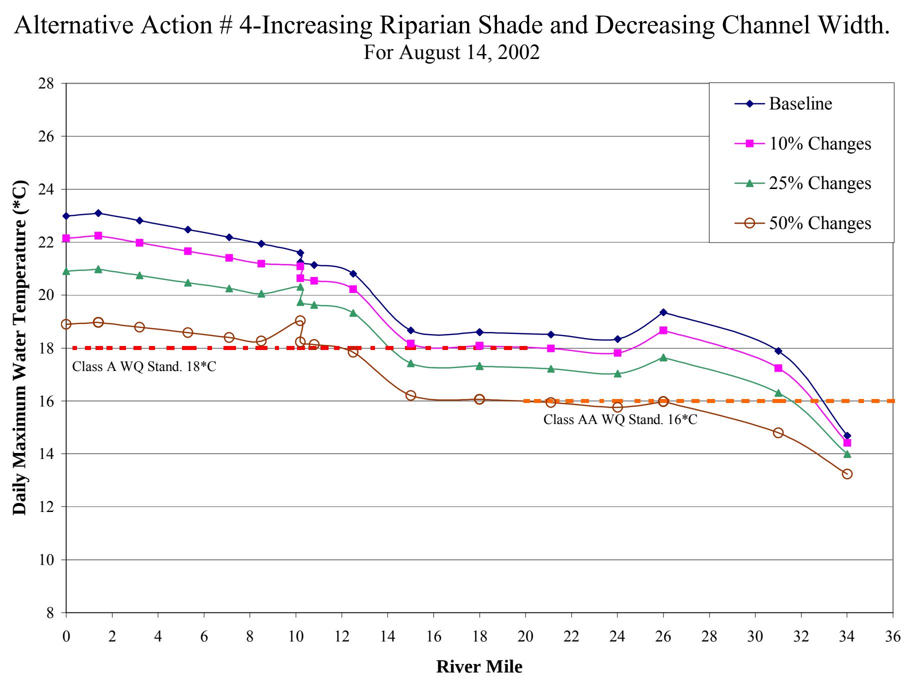


b.

Figure A-13: Longitudinal profile of daily maximum water temperatures resulting from increases in riparian shade values and decreases in channel width for August 18, 1999 (a) and August 9, 2000 (b).

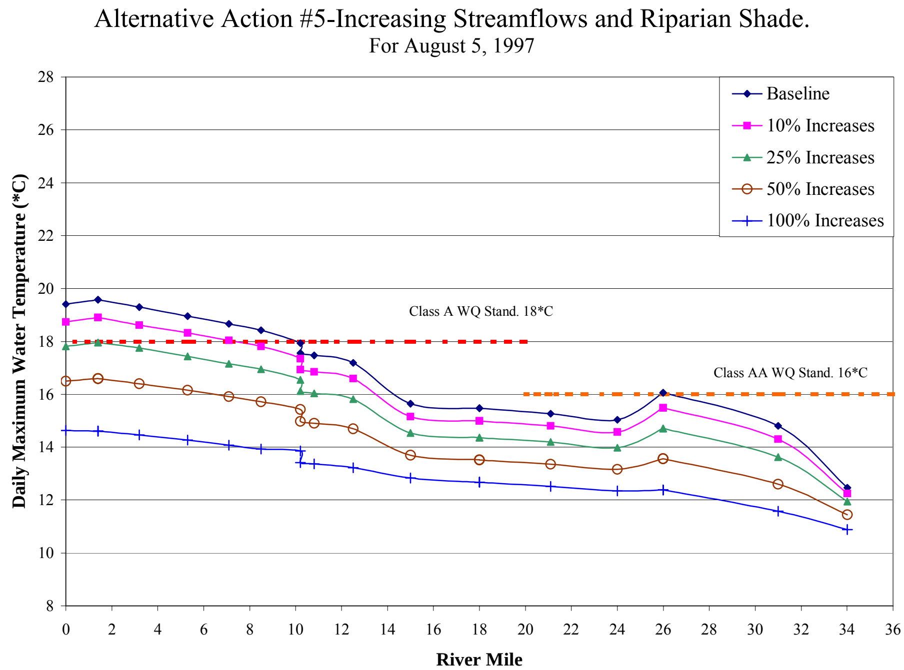


a.

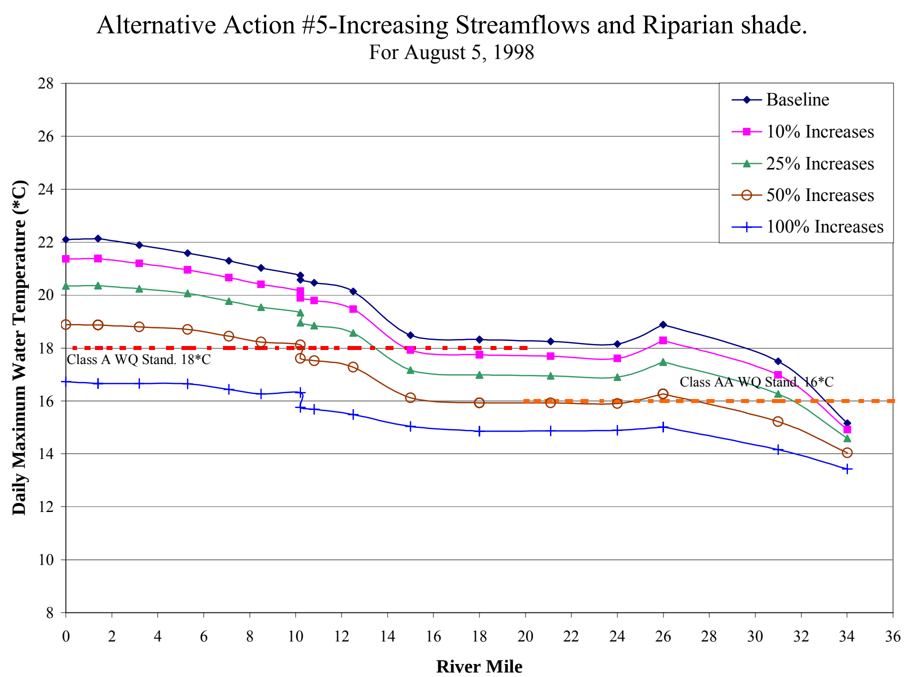


b.

Figure A-14: Longitudinal profile of daily maximum water temperatures resulting from increases in riparian shade values and decreases in channel width for August 13, 2001 (a) and August 14, 2002 (b).

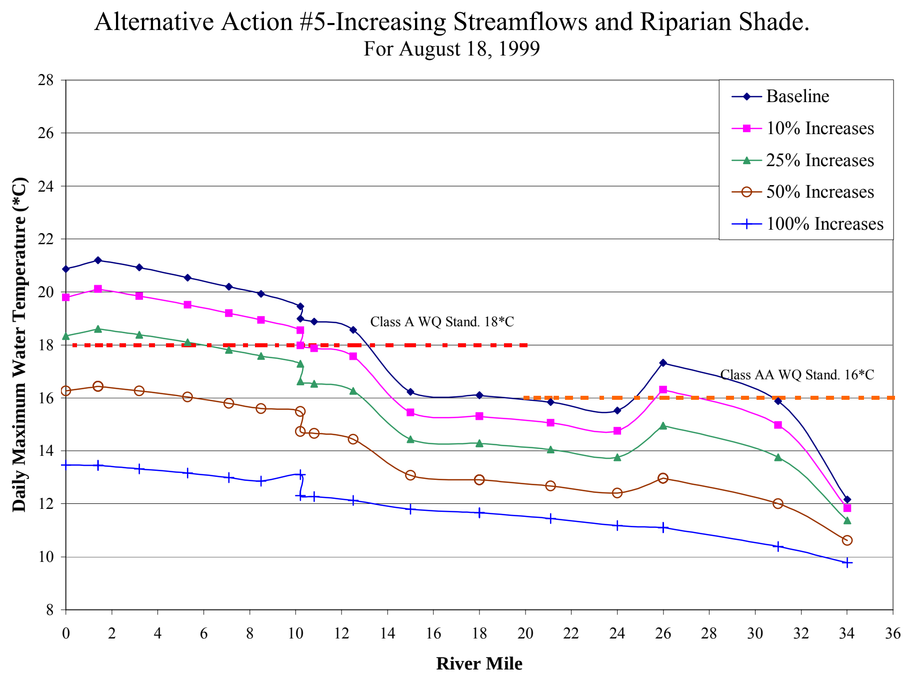


a.

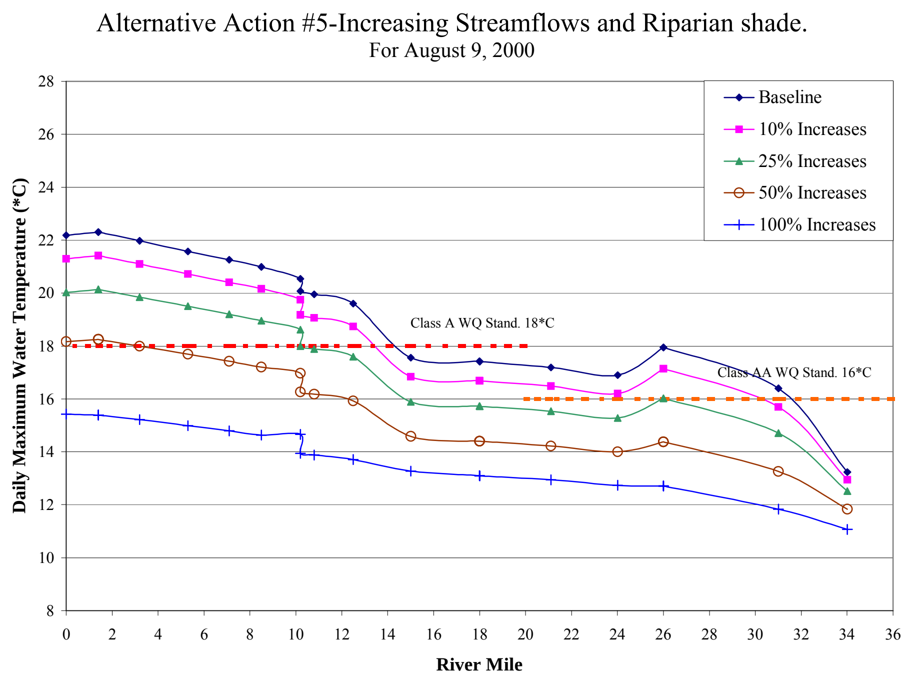


b.

Figure A-15: Longitudinal profile of daily maximum water temperatures resulting from increases in streamflows and riparian shade values for August 5, 1997 (a) and August 5, 1998 (b).

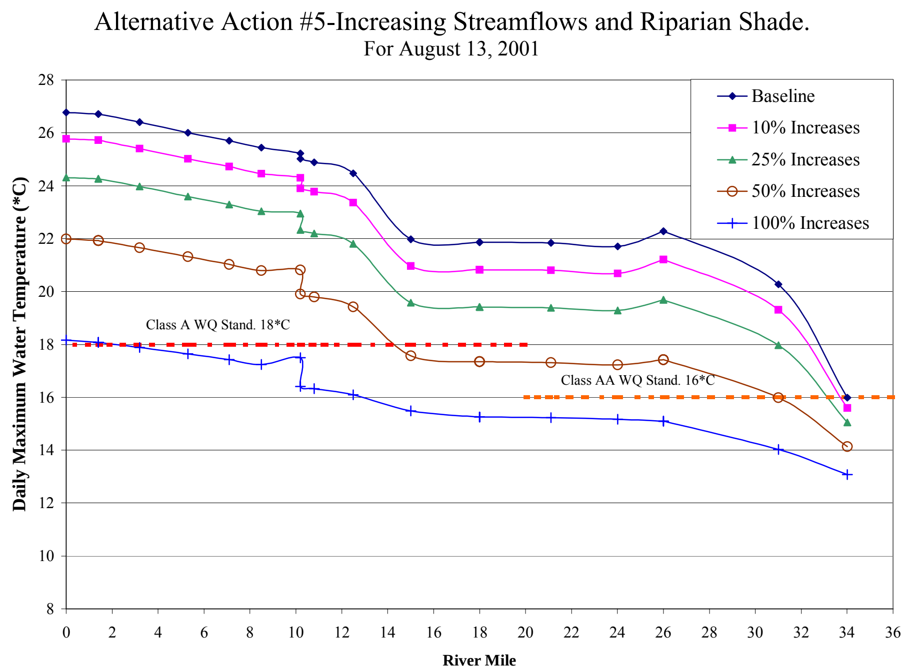


a.

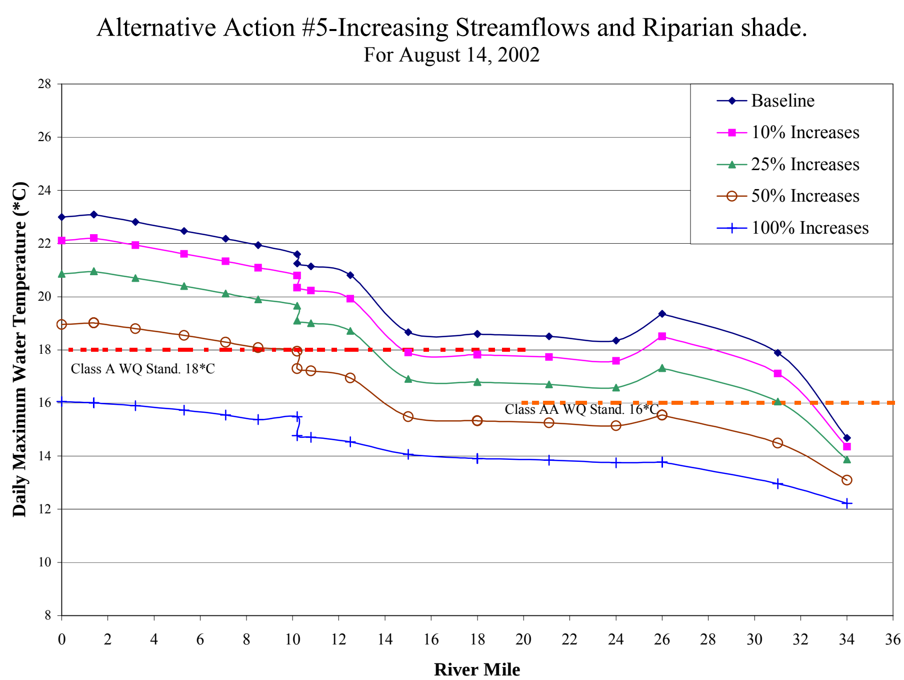


b.

<u>Figure A-16:</u> Longitudinal profile of daily maximum water temperatures resulting from increases in streamflows and riparian shade values for August 18, 1999 (a) and August 9, 2000 (b).

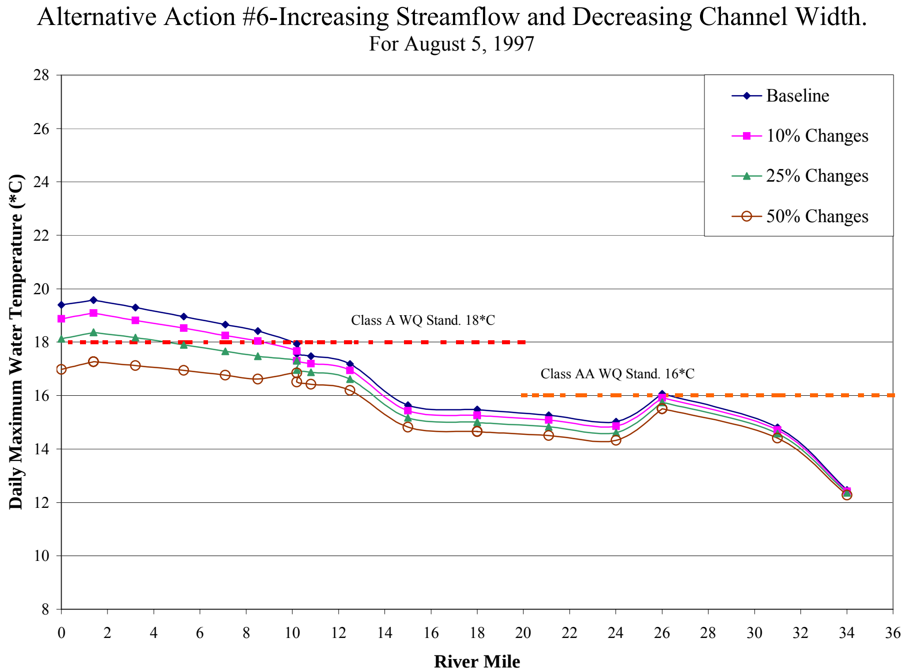


a.

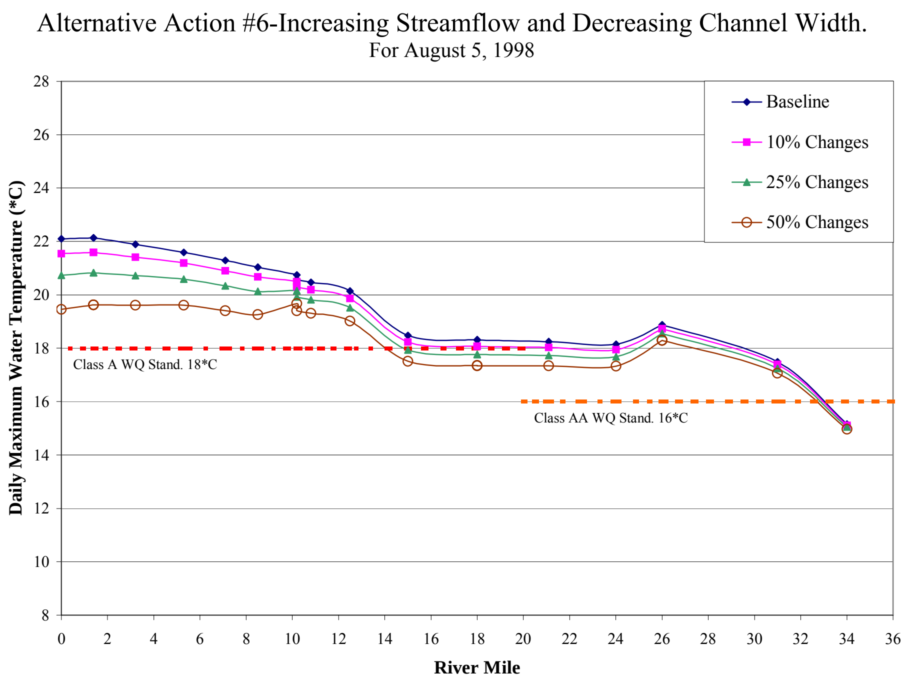


b.

Figure A-17: Longitudinal profile of daily maximum water temperatures resulting from increases in streamflows and riparian shade values for August 13, 2001 (a) and August 14, 2002 (b).

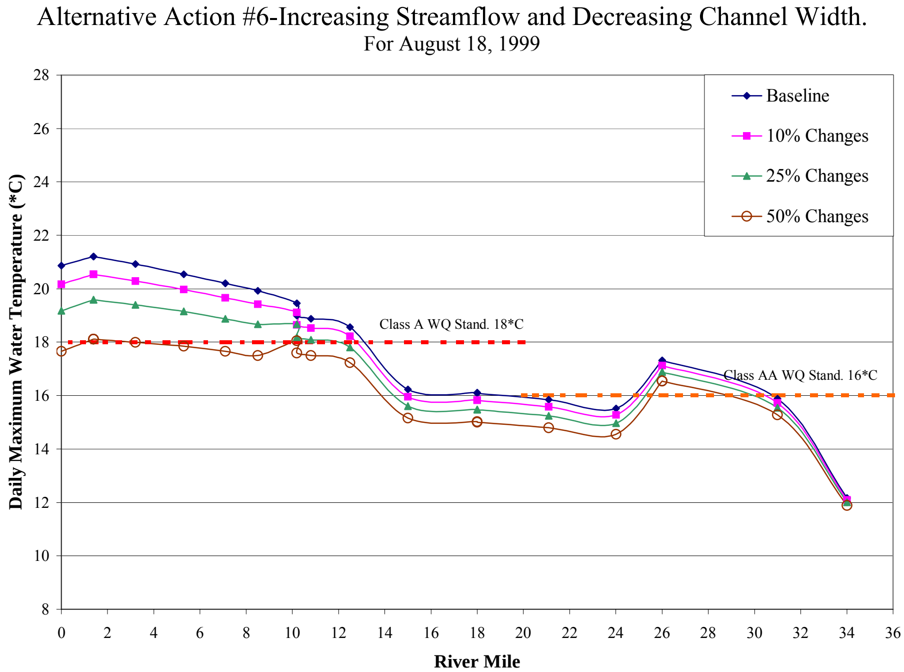


a.

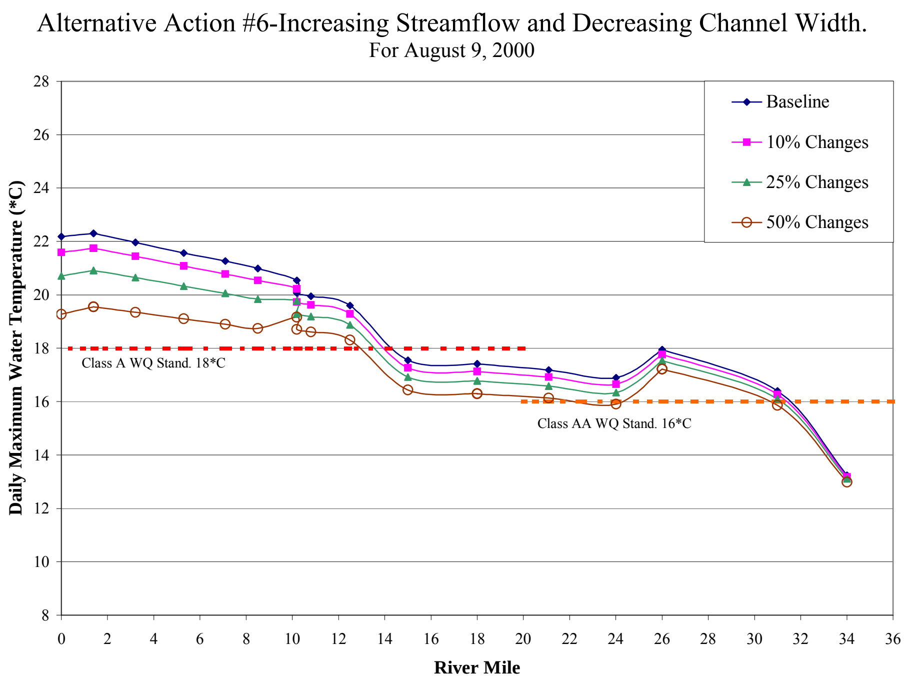


b.

Figure A-18: Longitudinal profile of daily maximum water temperatures resulting from increases in streamflow and decreases in channel width for August 5, 1997 (a) and August 5, 1998 (b).

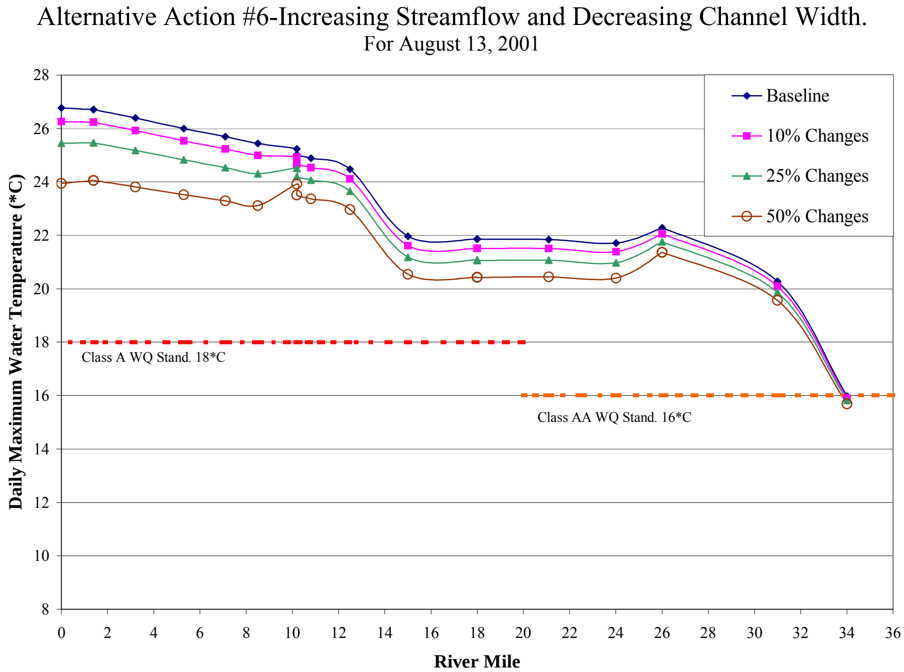


a.

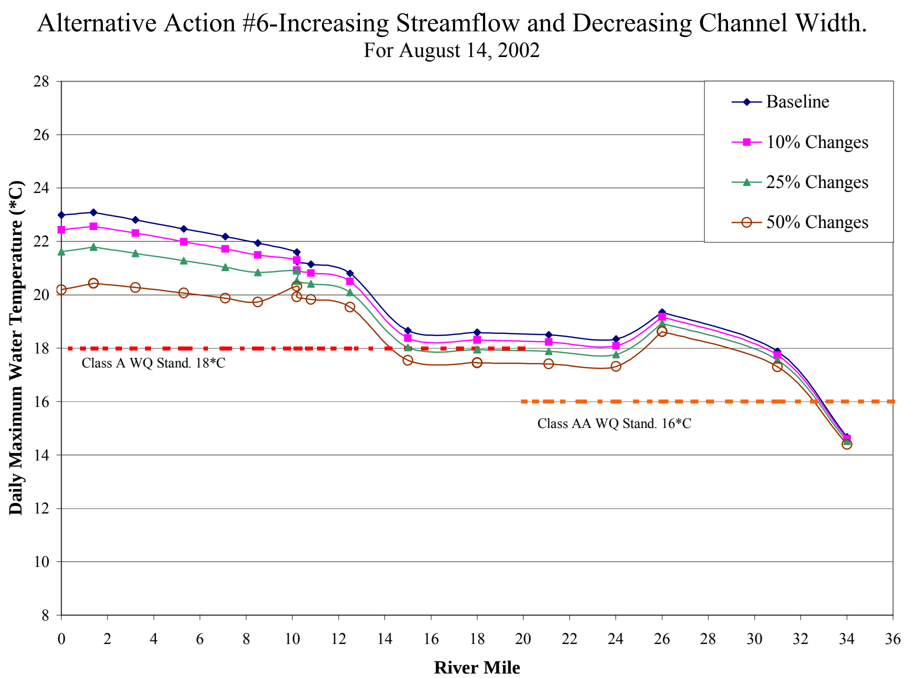


b.

Figure A-19: Longitudinal profile of daily maximum water temperatures resulting from increases in streamflow and decreases in channel width for August 18, 1999 (a) and August 9, 2000 (b).



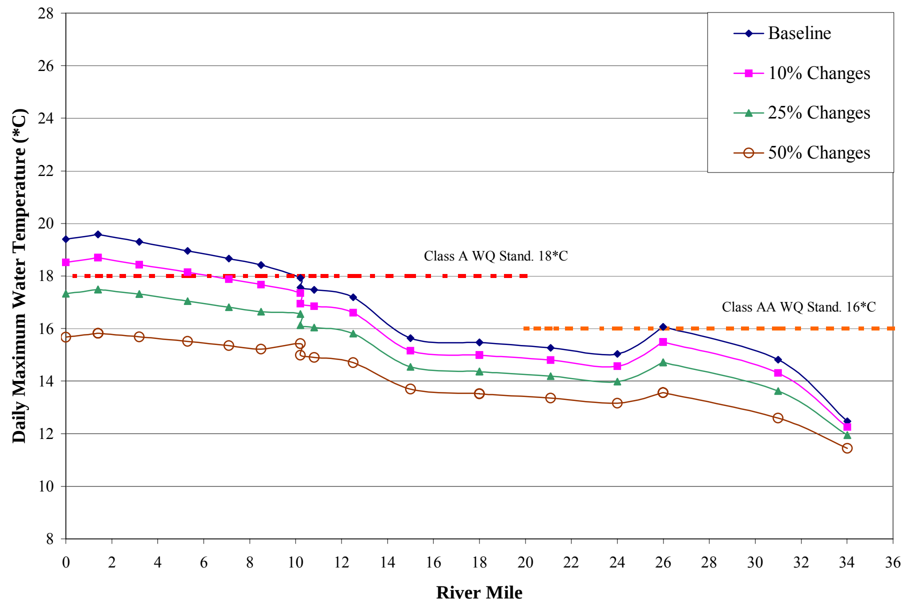
a.



b.

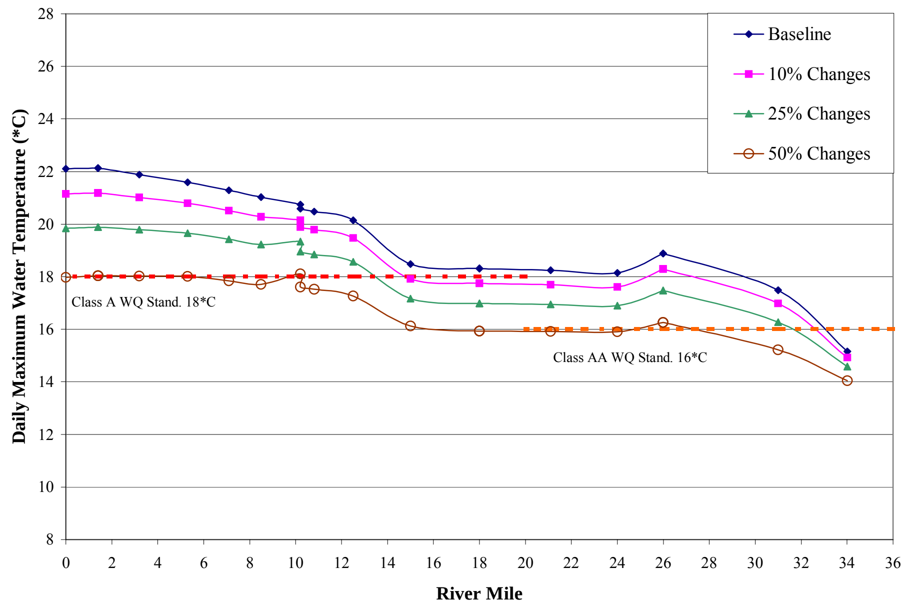
Figure A-20: Longitudinal profile of daily maximum water temperatures resulting from increases in streamflow and decreases in channel width for August 13, 2001 (a) and August 14, 2002 (b).

Alternative Action #7-Simulation of all three alternative actions; Increasing Streamflows, Increasing Riparian Shade, and Decreasing Channel Width.
For August 5, 1997



a.

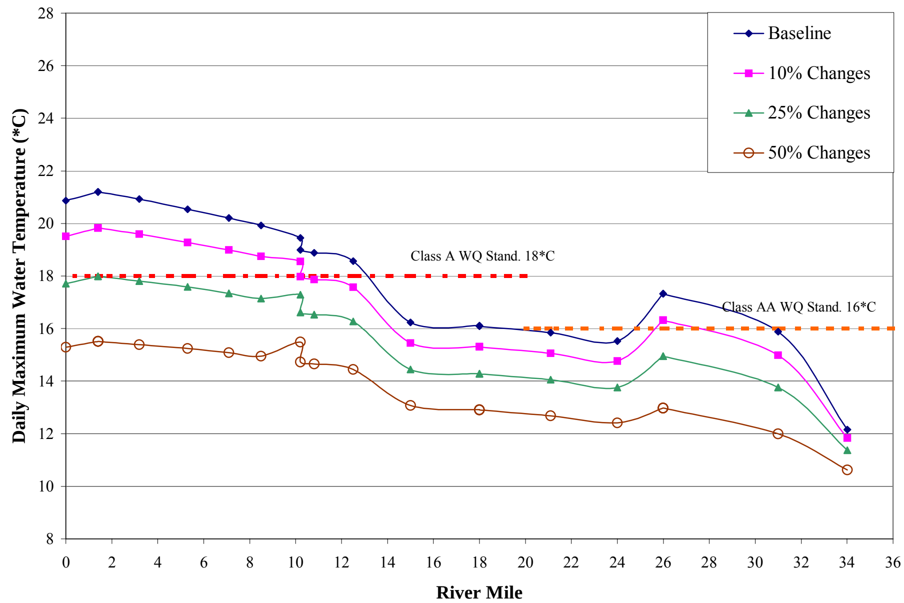
Alternative Action #7-Simulation of all three alternative actions; Increasing Streamflows, Increasing Riparian Shade, and Decreasing Channel Width.
For August 5, 1998



b.

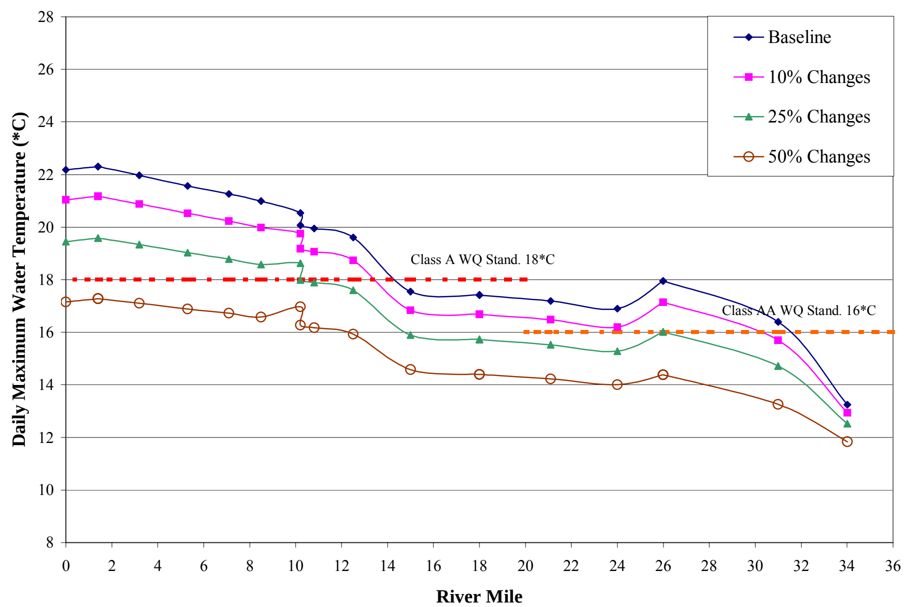
Figure A-21: Longitudinal profile of daily maximum water temperatures resulting from increases in streamflow, riparian shade, and decreases in channel width for August 5, 1997 (a) and August 5, 1998 (b).

Alternative Action #7-Simulation of all three alternative actions; Increasing Streamflows, Increasing Riparian Shade, and Decreasing Channel Width.
For August 18, 1999



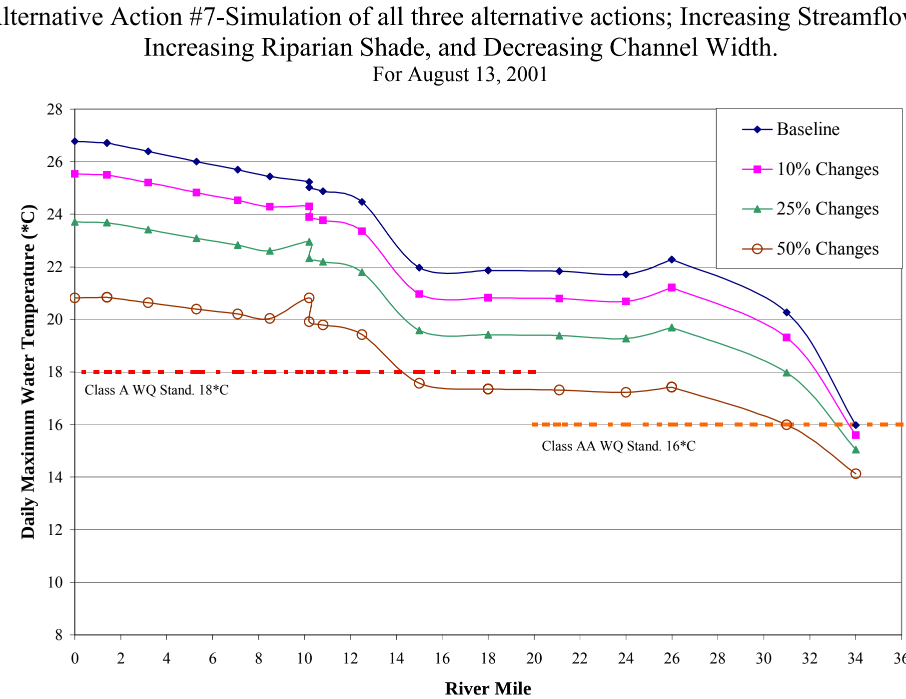
a.

Alternative Action #7-Simulation of all three alternative actions; Increasing Streamflows, Increasing Riparian Shade, and Decreasing Channel Width.
For August 9, 2000

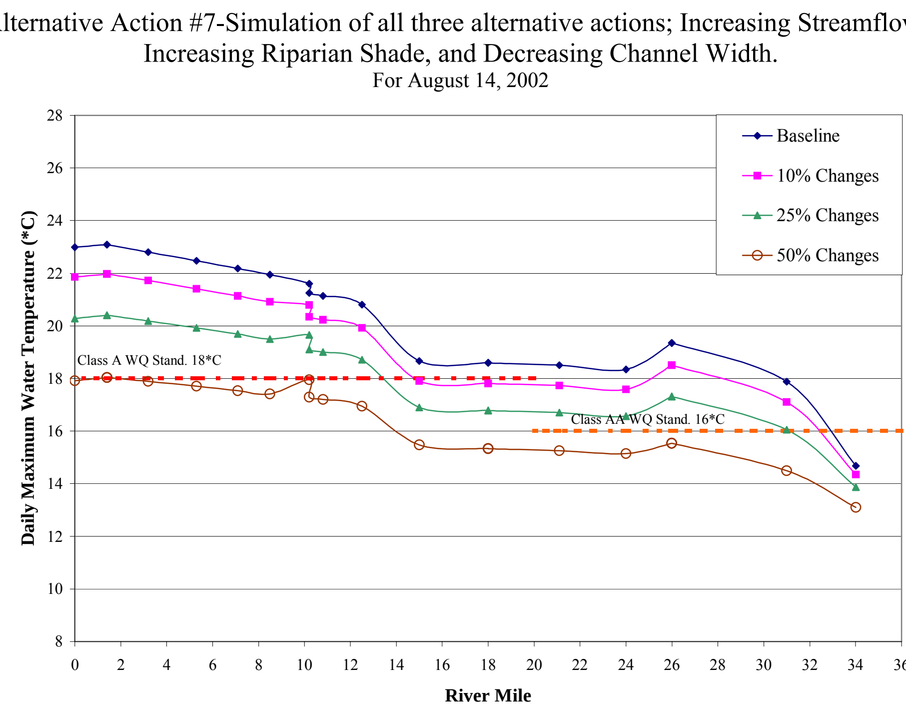


b.

Figure A-22: Longitudinal profile of daily maximum water temperatures resulting from increases in streamflow, riparian shade, and decreases in channel width for August 18, 1999 (a) and August 9, 2000 (b).



a.



b.

Figure A-23: Longitudinal profile of daily maximum water temperatures resulting from increases in streamflow, riparian shade, and decreases in channel width for August 13, 2001 (a) and August 14, 2002 (b).

Appendix B

Appendix B illustrates the effects of each alternative action on baseline daily maximum water temperatures from RMs 0-34[1], for the hottest day of each year modeled (1997-2002). These statistics show how much each action is predicted to effect water temperatures, both on average (mean changes) and as a maximum amount of change that could be expected (maximum change) for each alternative action. The tables also show a predicted percent change for each alternative action, which shows the estimated percent decrease in daily maximum water temperatures that each alternative action could have on the baseline. These values are given for each adjustment increment (10%, 25%, 50%, etc…).

Table B-1: Summary statistics showing the effects of alternative action 1, decreasing channel width in the lower 10 RMs[1], on baseline daily maximum water temperatures from river miles (RMs) 0-10, for the hottest day of each year modeled (1997-2002).

		Decrease width (1)			
Date	Amount of change	10%	25%	50%	100%
Aug. 5, 1997[2]	mean °C change[3]	-0.17	-0.45	-0.98	-[6]
	max. °C change[4]	-0.23	-0.6	-1.31	-
	percent decrease[5]	0.90%	2.38%	5.17%	-
Aug. 5, 1998[2]	mean °C change	-0.17	-0.44	-0.97	-
	max. °C change	-0.23	-0.59	-1.3	-
	percent decrease	0.77%	2.03%	4.47%	-
Aug. 18, 1999[2]	mean °C change	-0.24	-0.63	-1.38	-
	max. °C change	-0.31	-0.82	-1.78	-
	percent decrease	1.17%	3.07%	6.69%	-
Aug. 9, 2000[2]	mean °C change	-0.20	-0.52	-1.17	-
	max. °C change	-0.27	-0.70	-1.56	-
	percent decrease	0.91%	2.42%	5.39%	-
Aug. 13, 2001[2]	mean °C change	-0.19	-0.51	-1.19	-
	max. °C change	-0.24	-0.66	-1.54	-
	percent decrease	0.71%	1.95%	4.55%	-
Aug. 14, 2002[2]	mean °C change	-0.19	-0.52	-1.18	-
	max. °C change	-0.25	-0.67	-1.53	-
	percent decrease	0.86%	2.30%	5.22%	-

[1]For alternative action 1 changes were simulated in the lower 10 RMs only, therefore only the daily maximum water temperatures for the nodes in the lower 10 RMs were used in the calculation of the summary statistics.

[2]The "hottest" day for each year (as well as the "hottest" and "cooler" years) were estimated for the 8/2-9/14 time period based on meteorology data from the East Wenatchee Pangborn Airport (NOAA, 1997-2002) and observed daily mean water temperatures from various locations in the Entiat River (Archibald, 1997-2002). See *Methods* section.

[3]*mean °C change* = (mean of predicted daily maximum water temperatures minus the mean of baseline daily maximum water temperatures). Shows how much, on average, baseline daily maximum water temperatures were reduced by simulation of a given alternative action.

[4]*max. °C change* = largest reduction of baseline daily maximum water temperatures by simulation of a given a alternative action at any given node from RMs 0-34. Although the location of the largest reduction varied from year to year, daily maximum water temperatures were typically reduced by the largest amounts near the furthest downstream nodes.

[5]*percent decrease* = (mean of predicted daily maximum water temperatures divided by the mean of baseline daily maximum water temperatures, multiplied by 100). Shows the percentage that baseline daily maximum water temperatures could be reduced by simulation of a given alternative action, based on the mean of daily maximum water temperatures at all nodes for the given day modeled.

[6]For alternative actions that included reductions in channel width, the 100% change increment were not simulated because a 100% decrease in channel width is thought to be an unfeasible alternative action.

Table B-2: Summary statistics showing the effects of alternative actions 2 and 2a, increases in streamflow, on baseline daily maximum water temperatures from RMs 0-34, for the hottest day of each year modeled (1997-2002).

		Increase streamflow (2)			Large increase in streamflow (2a)				
Date	Amount of change	10%	25%	50%	100%	150%	200%	250%	300%
Aug. 5, 1997	mean ˚C change	-0.22	-0.50	-0.88	-1.44	-1.82	-2.11	-2.33	-2.51
	max. ˚C change	-0.29	-0.70	-1.26	-2.07	-2.64	-3.07	-3.39	-3.66
	percent decrease	1.27%	2.93%	5.18%	8.44%	10.70%	12.38%	13.68%	14.73%
Aug. 5, 1998	mean ˚C change	-0.23	-0.54	-0.96	-1.58	-2.02	-2.36	-2.62	-2.84
	max. ˚C change	-0.34	-0.79	-1.41	-2.32	-2.97	-3.46	-3.85	-4.17
	percent decrease	1.17%	2.71%	4.84%	7.97%	10.22%	11.91%	13.25%	14.35%
Aug. 18, 1999	mean ˚C change	-0.28	-0.66	-1.16	-1.88	-2.39	-2.77	-3.07	-3.31
	max. ˚C change	-0.39	-0.91	-1.63	-2.65	-3.37	-3.91	-4.32	-4.66
	percent decrease	1.57%	3.61%	6.37%	10.38%	13.17%	15.26%	16.89%	18.21%
Aug. 9, 2000	mean ˚C change	-0.26	-0.62	-1.10	-1.83	-2.36	-2.75	-3.07	-3.32
	max. ˚C change	-0.34	-0.78	-1.42	-2.41	-3.17	-3.75	-4.21	-4.58
	percent decrease	1.37%	3.22%	5.74%	9.51%	12.25%	14.31%	15.94%	17.26%
Aug. 13, 2001	mean ˚C change	-0.27	-0.64	-1.18	-2.05	-2.73	-3.27	-3.71	-4.08
	max. ˚C change	-0.36	-0.82	-1.51	-2.60	-3.42	-4.07	-4.59	-5.03
	percent decrease	1.16%	2.72%	4.98%	8.66%	11.52%	13.81%	15.68%	17.25%
Aug. 14, 2002	mean ˚C change	-0.25	-0.59	-1.07	-1.79	-2.32	-2.73	-3.05	-3.32
	max. ˚C change	-0.32	-0.73	-1.32	-2.31	-3.04	-3.62	-4.07	-4.45
	percent decrease	1.24%	2.88%	5.23%	8.81%	11.40%	13.40%	14.98%	16.28%

Table B-3: Summary statistics showing the effects of alternative action 3, increases in riparian shade, on baseline daily maximum water temperatures from RMs 0-34, for the hottest day of each year modeled (1997-2002).

		Increase shade (3)			
Date	Amount of change	10%	25%	50%	100%
Aug. 5, 1997	mean ˚C change	-0.36	-0.88	-1.75	-3.01
	max. ˚C change	-0.44	-1.09	-2.15	-3.81
	percent decrease	2.09%	5.18%	10.27%	17.66%
Aug. 5, 1998	mean ˚C change	-0.39	-0.97	-1.93	-3.34
	max. ˚C change	-0.46	-1.14	-2.24	-4.05
	percent decrease	1.96%	4.89%	9.74%	16.85%
Aug. 18, 1999	mean ˚C change	-0.66	-1.62	-3.19	-5.35
	max. ˚C change	-0.82	-2.03	-3.95	-6.74
	percent decrease	3.61%	8.93%	17.57%	29.44%
Aug. 9, 2000	mean ˚C change	-0.54	-1.34	-2.65	-4.56
	max. ˚C change	-0.65	-1.60	-3.13	-5.67
	percent decrease	2.79%	6.95%	13.80%	23.72%
Aug. 13, 2001	mean ˚C change	-0.73	-1.82	-3.67	-6.39
	max. ˚C change	-0.87	-2.16	-4.29	-7.45
	percent decrease	3.07%	7.71%	15.49%	27.00%
Aug. 14, 2002	mean ˚C change	-0.57	-1.43	-2.85	-4.90
	max. ˚C change	-0.69	-1.71	-3.38	-5.91
	percent decrease	2.80%	7.01%	13.97%	24.05%

Table B-4: Summary statistics showing the effects of alternative action 4, increases in riparian shade and decreases in channel width (in the lower 10 RMs), on baseline daily maximum water temperatures for the hottest day of each year modeled (1997-2002).

		Increase shade and decrease width (4)			
Date	Amount of change	10%	25%	50%	100%
Aug. 5, 1997	mean ˚C change	-0.42	-1.04	-2.02	-
	max. ˚C change	-0.62	-1.52	-2.93	-
	percent decrease	2.47%	6.09%	11.81%	-
Aug. 5, 1998	mean ˚C change	-0.45	-1.12	-2.20	-
	max. ˚C change	-0.63	-1.55	-3.03	-
	percent decrease	2.28%	5.65%	11.11%	-
Aug. 18, 1999	mean ˚C change	-0.74	-1.83	-3.52	-
	max. ˚C change	-1.03	-2.51	-4.76	-
	percent decrease	4.09%	10.05%	19.40%	-
Aug. 9, 2000	mean ˚C change	-0.61	-1.51	-2.97	-
	max. ˚C change	-0.84	-2.07	-4.02	-
	percent decrease	3.18%	7.87%	15.42%	-
Aug. 13, 2001	mean ˚C change	-0.80	-2.00	-3.99	-
	max. ˚C change	-0.98	-2.45	-4.90	-
	percent decrease	3.37%	8.45%	16.87%	-
Aug. 14, 2002	mean ˚C change	-0.64	-1.60	-3.16	-
	max. ˚C change	-0.85	-2.11	-4.12	-
	percent decrease	3.16%	7.88%	15.52%	-

Table B-5: Summary statistics showing the effects of alternative action 5, increases in streamflow and riparian shade, on baseline daily maximum water temperatures from RMs 0-34, for the hottest day of each year modeled (1997-2002).

		Increase streamflow and shade (5)			
Date	Amount of change	10%	25%	50%	100%
Aug. 5, 1997	mean ˚C change	-0.56	-1.32	-2.40	-3.78
	max. ˚C change	-0.68	-1.62	-2.98	-4.97
	percent decrease	3.29%	7.75%	14.11%	22.21%
Aug. 5, 1998	mean ˚C change	-0.61	-1.44	-2.66	-4.23
	max. ˚C change	-0.75	-1.77	-3.26	-5.47
	percent decrease	3.08%	7.30%	13.42%	21.37%
Aug. 18, 1999	mean ˚C change	-0.92	-2.16	-3.93	-6.03
	max. ˚C change	-1.09	-2.60	-4.76	-7.75
	percent decrease	5.06%	11.91%	21.62%	33.20%
Aug. 9, 2000	mean ˚C change	-0.78	-1.87	-3.45	-5.46
	max. ˚C change	-0.89	-2.16	-4.05	-6.91
	percent decrease	4.08%	9.72%	17.92%	28.40%
Aug. 13, 2001	mean ˚C change	-0.99	-2.40	-4.55	-7.44
	max. ˚C change	-1.12	-2.69	-5.11	-8.63
	percent decrease	4.19%	10.13%	19.23%	31.44%
Aug. 14, 2002	mean ˚C change	-0.81	-1.94	-3.60	-5.75
	max. ˚C change	-0.91	-2.15	-4.08	-7.08
	percent decrease	3.99%	9.50%	17.69%	28.24%

Table B-6: Summary statistics showing the effects of alternative action 6, increases in streamflow and decreases in channel width (in lower 10 RMs), on baseline daily maximum water temperatures from RMs 0-34, for the hottest day of each year modeled (1997-2002).

		Increase streamflow and decrease width (6)			
Date	Amount of change	10%	25%	50%	100%
Aug. 5, 1997	mean ˚C change	-0.28	-0.67	-1.24	-
	max. ˚C change	-0.52	-1.27	-2.42	-
	percent decrease	1.67%	3.95%	7.27%	-
Aug. 5, 1998	mean ˚C change	-0.30	-0.71	-1.33	-
	max. ˚C change	-0.56	-1.37	-2.64	-
	percent decrease	1.50%	3.58%	6.70%	-
Aug. 18, 1999	mean ˚C change	-0.38	-0.90	-1.66	-
	max. ˚C change	-0.70	-1.69	-3.21	-
	percent decrease	2.09%	4.94%	9.13%	-
Aug. 9, 2000	mean ˚C change	-0.34	-0.83	-1.56	-
	max. ˚C change	-0.59	-1.47	-2.91	-
	percent decrease	1.78%	4.29%	8.09%	-
Aug. 13, 2001	mean ˚C change	-0.35	-0.86	-1.68	-
	max. ˚C change	-0.51	-1.32	-2.83	-
	percent decrease	1.49%	3.62%	7.11%	-
Aug. 14, 2002	mean ˚C change	-0.33	-0.80	-1.53	-
	max. ˚C change	-0.55	-1.37	-2.80	-
	percent decrease	1.63%	3.91%	7.50%	-

Table B-7: Summary statistics showing the effects of alternative action 7, increases in streamflow and riparian shade, and decreases in channel width (in lower 10 RMs), on baseline daily maximum water temperatures from RMs 0-34, for the hottest day of each year modeled (1997-2002).

		Increase streamflow and shade, and decrease width (7)			
Date	Amount of change	10%	25%	50%	100%
Aug. 5, 1997	mean ˚C change	-0.62	-1.47	-2.64	-
	max. ˚C change	-0.88	-2.09	-3.76	-
	percent decrease	3.67%	8.61%	15.52%	-
Aug. 5, 1998	mean ˚C change	-0.67	-1.59	-2.91	-
	max. ˚C change	-0.95	-2.26	-4.12	-
	percent decrease	3.38%	8.04%	14.72%	-
Aug. 18, 1999	mean ˚C change	-1.01	-2.36	-4.22	-
	max. ˚C change	-1.37	-3.21	-5.69	-
	percent decrease	5.54%	12.97%	23.24%	-
Aug. 9, 2000	mean ˚C change	-0.86	-2.05	-3.75	-
	max. ˚C change	-1.14	-2.74	-5.03	-
	percent decrease	4.47%	10.63%	19.48%	-
Aug. 13, 2001	mean ˚C change	-1.06	-2.58	-4.90	-
	max. ˚C change	-1.23	-3.06	-5.95	-
	percent decrease	4.49%	10.90%	20.68%	-
Aug. 14, 2002	mean ˚C change	-0.89	-2.11	-3.91	-
	max. ˚C change	-1.13	-2.71	-5.07	-
	percent decrease	4.36%	10.36%	19.19%	-