Tucannon River Temperature Study

Prepared for:
Watershed Resource Inventory Area (WRIA) 35

HDR

Tucannon River Temperature Study

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1.0 Introduction

1.1 Project Purpose and Scope

This report presents the results of a temperature analysis of the Tucannon River completed for the WRIA 35 Planning Unit. The Tucannon River is located in southeastern Washington and flows approximately 100 kilometers (km) (62 miles) from the Blue Mountains to the Snake River. High water temperature in the Tucannon River has been identified as a limiting factor for salmonid fish habitat (Columbia Conservation District, 2004). Several segments of the Tucannon River are included on Washington State Department of Ecology (Ecology) 303(d) list of impaired waterbodies due to temperature. Ecology is currently conducting scoping for a temperature Total Maximum Daily Load (TMDL) study of the Tucannon River.

The WRIA 35 Planning Unit retained HDR Engineering to evaluate water temperature in the Tucannon River. The project objectives are listed below.

- Review recent and historic data and studies to characterize temperature conditions in the river.
- Perform field studies and analyses to identify and quantify heating and cooling processes in the river.
- Develop and calibrate a computer temperature model to determine the sources of heat to the Tucannon River and to predict the temperature of the river that would occur with increased natural riparian shading assuming the current river morphology.
- Evaluate differences in river temperatures between current and improved riparian shading during the “critical” period - low river flows and high temperatures.
- Determine the potential benefits of riparian shading as a mechanism to decrease river temperature.

2.0 Washington State Temperature Standards

2.1 Numeric Temperature Criteria

Section 303(d) of the Clean Water Act requires states to define the designated uses of water bodies within their state. Ecology establishes water quality standards to protect beneficial uses of the state’s waters. The beneficial uses identified by Ecology for the Tucannon River include water supply, fish habitat (for example, salmonid migration, rearing, spawning, and harvesting), recreation, wildlife habitat, and commerce and navigation.

The current Washington State water quality standards were approved in 1997 and are described in Washington Administrative Code (WAC) 173-201A. These standards designate the Tucannon River as Class A (Excellent) water from the mouth to the Umatilla National Forest at River Kilometer (RK) 61.5 (River Mile (RM) 38.1)[1]. Above RK 61.5 (RM 38.1), the Tucannon River is classified as Class AA (Extraordinary) water.

Ecology establishes numeric criteria to protect the beneficial uses of the state's waters. The temperature criteria for the Tucannon River are listed in Table 1.

Table 1. Current (1997) temperature criteria for the Tucannon River

Location	Classification	Criteria
Mouth to RK 61.5 (RM 38.1)	Class A	18.0°C (64.4°F)
Above RK 61.5 (RM 38.1)	Class AA	16.0°C (60.8°F)

Notes:

1. Criteria are based on the daily maximum temperatures and apply throughout the year.

2. When natural conditions exceed temperature criteria, no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3 Celsius.

3. Source: WAC 173-201A

Using monitoring data, Ecology develops a Section 303(d) list that names waterbodies that do not meet standards, known as the "impaired waters list" or simply as the "303(d) list". Twelve segments of the Tucannon Rivera are included on the most recently approved 303(d) list (Table 2). The 303(d) list is used to identify and prioritize water quality problems and as a guide for developing and implementing watershed pollution reduction plans or TMDLs to achieve water quality standards.

Table 2. Tucannon River segments included on Ecology's 2002/2004 303(d) list

Stream segment ID #	Basis for listing
13855	7-day mean of daily maximum values of 23.4°C for the week ending 16 August 2001at the station called ' Tucannon River – King Grade RD
13859	7-day mean of daily maximum values of 22.4°C for the week ending 13 August 2001 at the station called ' Tucannon River - Bridge 12
13984	7-day mean of daily maximum values of 18.4°C for the week ending 9 July 2001 at the station called ' Tucannon River - Camp Wooten Bridge

[1] River locations in this report, either as River Kilometer or River Mile, are based on the analysis of river channel length conducted for this project and may not correspond directly to river locations reported in other references or the water quality standards.

Stream segment ID #	Basis for listing
13850	7-day mean of daily maximum values of 25.3°C for the week ending 16 August 2001 at the station called ' Tucannon River - HWY 12 Bridge
13853	7-day mean of daily maximum values of 24°C for the week ending 3 August 2000 at the station called ' Tucannon River - Enrich RD
13864	7-day mean of daily maximum values of 20.6°C for the week ending 17 July 2002 at the station called ' Tucannon River - Cummings Creek Br
13849	7-day mean of daily maximum values of 25.5°C for the week ending 17 July 2002 at the station called ' Tucannon River - Smith Hollow RD
13983	7-day mean of daily maximum values of 19.1°C for the week ending 18 July 2002 at the station called ' Tucannon River - Big 4 Lake
13856	7-day mean of daily maximum values of 22.9°C for the week ending 4 August 2000 at the station called ' Tucannon River - Marengo Bridge '2 excursions beyond the criterion out of 12 samples collected between 1993 - 2001 measured on these dates: 97/07/06, 97/08/03
13857	7-day mean of daily maximum values of 22.6°C for the week ending 12 August 2001 at the station called ' Tucannon River - Bridge 10
13848	7-day mean of daily maximum values of 25.9°C for the week ending 14 July 2001 at the station called ' Tucannon River - Smolt Trap (HW261)
13861	7-day mean of daily maximum values of 21.7°C for the week ending 16 August 2001 at the station called ' Tucannon River - Bridge 14

*Category 5 segments.

Source: Ecology's 303(d) list web page: (http://www.ecy.wa.gov/programs/wq/links/wq_assessments.html)

2.2 Natural Conditions Temperature Criteria

In addition to specific numeric criteria, water quality standards reference "natural conditions" temperatures based on what temperatures would be without changes caused by humans. According to the policy Ecology uses to place waterbodies on the 303(d) list, Water Quality Program Policy 1-11 (Ecology 2002):

> *"Under the water quality standards, a measurement of temperature (or other pollutant) in excess of a standard is not a violation of the standard if the exceedance results from natural conditions. In the case of temperature and dissolved oxygen, when natural conditions exceed the standard, an allowance for human contribution is provided; a human contribution less than this allowance is not considered a violation, but a human contribution in excess of it is."*

During critical conditions for temperature in the summer, natural conditions temperatures may exceed the numeric temperature criteria specified in the water quality standards. In this case, the natural conditions temperatures represent the water quality criteria:

"Whenever the natural conditions of said waters are of a lower quality than the criteria assigned, the natural conditions shall constitute the water quality criteria." (Chapter 173-201A-070(2) WAC).

Computer modeling can be used to estimate temperatures under natural conditions and assess compliance with the water quality standards. Natural conditions temperatures and TMDL temperature load allocations are often based on the results of "system potential vegetation"[2] model scenarios when the natural conditions temperatures exceed the numeric water quality criteria.

3.0 Description of Tucannon River Basin

3.1 Drainage Basin

The Tucannon River basin is located in southeastern Washington State and has a watershed area of about 500 square miles with a channel length of approximately 100 kilometers (60 miles), as shown on Figure 1. Tributaries to the river include Pataha Creek, Little Tucannon River, Tumalum Creek, Hixon Creek, Kellogg Creek and Sheep Creek. The maximum elevation in the basin is 6,400 feet at Oregon Butte. The river flows north and northwest to the confluence with the Snake River at elevation 540 feet, as shown on Figure 2.

3.2 Land Ownership and Land Use

The upper basin above RM 40 (RK 64.4) is located within the Umatilla National Forest and the Wenaha-Tucannon Wilderness Area, which contains approximately 25 percent of the watershed area (Figure 3). Below RM 49 (RK 78.9) the Tucannon River flows through the W.T. Wooten Wildlife Recreation Area that is owned and managed by the Washington Department of Wildlife (WDFW). The riparian area on WDFW and Federal lands is vegetated with conifer forest. The lower basin is primarily used for irrigated pasture or stock range and the riparian zone vegetation is less dense, varying from conifer trees to scrub-shrub or grassland. Land use in the Tucannon River basin is 37 percent cropland, 35 percent rangeland, and 27 percent forest (McCullough, 1999). Land use in the basin is shown on Figure 4.

3.3 Geology, Soils, and Groundwater

The headwaters of the Tucannon River basin are located within the Blue Mountains. The Blue Mountains are comprised of a core of Paleozoic and Mesozoic metamorphic rocks overlain by the Grande Rhone and Wanapum Formations of the Columbia River Basalt Group (CRBG) (Covert et al., 1995). Overlying the bedrock units are diverse unconsolidated sediments. The most common in the uplands is wind-deposited loess, which blankets highland areas between drainages (Figure 5). Cobble, sand, gravel and silt alluvium is present within the Tucannon River valley.

[2] "System potential vegetation" refers to the maximum level (mature) of riparian vegetation that would grow on a site given plant biology, site elevation, soil characteristics, and local climate.

The Hite Fault is located along the western margin of the Blue Mountains between Pomeroy, Washington and Pendleton, Oregon, and has been the locus of many historic earthquakes (U.S. Department of Energy, 1988 as reported in Covert et al., 1995). This fault is 84 miles (135 kilometers) in length and crosses the Tucannon River near the Cummings Creek confluence (Covert et al., 1995).

Very few of the shallow local wells for which well logs exist have recorded water temperatures. However, a few of the shallower wells that do show temperatures are in the low 50 degrees Fahrenheit (°F) (10 degrees Celsius [°C]) range (Covert et al., 1995). The fish-hatchery well located two miles upstream from the Hite Fault as it crosses the Tucannon River (10N/41E- 27) was drilled to 100 feet in depth into basalt and encountered water temperatures of 51 °F (10.6 °C) (Covert et al., 1995).

3.4 River Flow

Flow in the Tucannon River has been historically recorded at nine gaging stations. These flow records are presented and analyzed in the report, *WRIA 35 Middle Snake River Watershed Level 1 Assessment Report,* January 2005 by HDR/EES.

Most of the historic gage records span short periods and/or are not currently operational. Flow data was available for the 2005 water year at two flow gaging stations (Starbuck and Marengo). Flow data was used from the Starbuck and Marengo gaging stations (along with flow data collected specifically for this project) to assess the river flow for the temperature analysis. Figure 6 shows the locations of the gaging stations and Table 3 presents a summary of the gage record.

Table 3. Summary of flow gaging records used for the temperature analysis

Gage Name	Agency	Gage Number	River Kilometer	Period of Daily Flow Record	Length of Record
Tucannon River nr. Starbuck	USGS	13344500	13	1914 - 1917; 1928 - 1931; 1958 - 1990; 1994 - 2005	~50 yrs
Tucannon River nr. Marengo	Ecology	35B150	43	2003 - 2005	~3 yrs

The flow recorded at the Marengo and Starbuck gage stations during 2005 are presented on Figures 7 and 8. The flow recorded at Marengo peaked at about 250 cubic feet per second (cfs) during May and ranged from 50 to 100 cfs during June to September in 2005. The flow recorded at Starbuck peaked at about 230 cfs during May and ranged from 40 to 100 cfs between June and September.

A long-term gage record is necessary to identify the relative recurrence frequency during any specific period. The Starbuck gage station has about 50 years of flow record and is sufficient to analyze the Tucannon River flow frequency. The 10, 50 and 90-percent exceedance flow record from the Starbuck gage station is presented on Figure 9. The exceedance analysis shows that the flow conditions during the 2005 water year from June to September were very low and close to the 90 percent exceedance level. The 7-day, 10 year (7Q10) low flow, for the Tucannon River at the Starbuck station is estimated at 37.9 cfs.

3.5 River Temperature

Existing and past temperature conditions of the Tucannon River are documented in previous studies and reports (Theurer et al., 1984; Theurer et al., 1985; HDR/ESS 2005; HDR 2005; Columbia Conservation District 1997; Columbia Conservation District 2001; Columbia Conservation District 2004; USDA SCS 1982a, USDA SCS 1982b, Washington Department of Fisheries 1990; Washington State University, 2001; WDFW 2001; WDFW 2002). The WDFW, with support from the Columbia Conservation District, and the United States Forest Service (USFS) have monitored temperatures on a continuous (approximately hourly) basis for the last 20 years at various locations in the Tucannon River and its tributaries. Ecology currently has three continuous temperature loggers in the basin.

Temperatures were monitored at 20 main stem stations in the Tucannon River during 2005 as shown on Figure 6. Water temperatures are the highest in the lower river reaches. As shown on Figures 10 and 11, river temperatures increase in the spring and summer reaching a maximum during late July and August and cooling in September and October. The high river water temperature occurs when the river flow is the lowest, as shown on Figure 12. Daily maximum river temperatures at the Smolt Trap/Power Bridge station (RK 2.8, RM 1.7) and at Hwy 12 Bridge station (RK 50.9, RM 31.6) are above 68 °F (20 °C) during June, July and August and reach a maximum of about 77 °F (25 °C) during late July and early August. River temperatures higher in the watershed are cooler, reaching a maximum of 59 °F (15 °C) at Panjab Creek Bridge (RK 80, RM 50).

The daily maximum water temperatures recorded in 2005 are compared to the Washington State temperature criteria on Figures 10 through 12. The data show that the temperature criteria for the Tucannon River are exceeded generally June through early September for the entire reach below approximately RK 80 (RM 50) near Panjab Bridge.

The historical data indicate relatively consistent differences in river temperature with changes in elevation and river location. The daily maximum water temperature during the spring and summer of 2004 is compared to the elevation at individual recording stations on Figure 13, and to the RK location at each station on Figure 14. These figures show that the river temperature in the upper watershed is lower (colder) than the river temperature in the lower watershed. The change in daily maximum temperature ranges from about 3 °C/1000 feet in elevation change in the May and June to 4 to 5 °C/1000 feet in elevation change in July and August. Similarly, the daily maximum temperatures in the river changes at a rate of about 0.10 °C/ RK in May and June and 0.15 °C/RK in July and August (Figure 14).

4.0 Field Investigations and Analysis

Field data were collected during July 2005 to support the temperature assessment and to obtain data necessary to develop the temperature model. Data collected and analyzed include:

- River and tributary flow
- Ground water inflow/outflow
- River temperature
- River channel morphology
- Riparian vegetative cover and shade conditions
- Climate data

The field investigations methods, data collected and analyses are presented in Appendix A.

5.0 Analysis of River Temperature

5.1 Overview Stream Heating Influences[3]

The temperature of a river depends on the changes in the amount of heat entering and leaving the water through the course of a day. Heat is expressed in terms of energy units over a specific time period, such as watts per foot per day. Processes that influence the heat content of a river are (Chapra, 1997):

- Heat input from point and non-point sources.
- Solar radiation: (i) shortwave solar radiation. (ii) longwave radiation exchange between air and water.
- Convection: exchange between air and water due to temperature differences.
- Conduction: exchange between water and sediment due to temperature differences.
- Evaporation: when vapor pressure is less than the dew point temperature.
- Stream bed conduction
- Ground water exchange

Figure 15 shows the major sources and losses of heat of a stream or river. The dominant contributor to heat in the river is shortwave solar radiation. The river temperature depends not only on the heat energy exchanges listed above, but also from the sources and losses of water (mass transfer processes) within a river reach. These include water from the upstream river section, water leaving the river section, tributaries, diversions, ground water flux and storage.

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[3] This overview is based on several temperature TMDL study reports prepared by Ecology. Refer to Ecology's web page for additional examples of temperature TMDLs studies. http://www.ecy.wa.gov/apps/watersheds/temperature/index.html

The warming of water temperatures as a stream flows downstream is a natural process. However, the rate of heating and the increase in water temperature can be dramatically reduced when high levels of shade exist and heat flux from solar radiation is minimized. Shading from riparian vegetation does not directly cool the river, but reduces the amount of solar radiation reaching the water. The daily maximum temperatures in a stream are strongly influenced by removal of riparian vegetation because of diurnal patterns of solar shortwave heat flux (Adams and Sullivan, 1989). Several studies of forest streams report that most of the potential shade comes from the riparian area within about 75 feet (23 meters) of the channel (CH2MHill, 2000; Castelle and Johnson, 2000).

5.2 Tucannon River Temperature Model

An analytical temperature model was developed for the Tucannon River using the program QUAL2Kw (Pelletier and Chapra, 2003). The QUAL2Kw model was used to simulate water temperatures in the Tucannon River by calculating the components of the heat budget and mass transfer processes. The temperature model includes approximately 55 miles (88 kilometers) of the Tucannon River, from the mouth of the river to the river's confluence with Sheep Creek.

Figure 16 shows that the Tucannon River temperature increases during the summer are coincident with the on-set of summer low-flow conditions. Low-flow and high temperature conditions are typically used for water quality investigations to evaluate periods when water quality is most-impaired and aquatic biota in the river are most-stressed.

The Tucannon River temperature model was developed based on date from July 13, 2005. The river flow during July is representative of low-flow conditions at less than a 90 percent recurrence frequency, as shown on Figure 17. Table 4 shows that air temperature in the region during July was average for this time of year. This information indicates that July 2005 is typical of a low-flow and high-temperature river flow conditions.

Table 4. Summary of July Air Temperatures (^oF)

	Max	Min	Average
Long term July air temperature record	87	54	70
July 2005 monthly air temperature	85	51	no data
July 13, 2005 daily air temperature	79	46	no data

Data based on long-term data collected Pomeroy Station 456610 between 1948 -2005.

The Tucannon River is represented as 88 kilometer (0.6 mile) reaches in the QUAL2Kw model, in which stream characteristics, such as channel width, bottom depth, and shade, are averaged for each reach. Tributaries and withdrawals are located at specific reaches where they enter or withdraw water from the river. The model simulates the daily changes in water temperature on July 13, 2005. The QUAL2Kw model was applied by assuming that flow remains constant but other factors that affect temperature change throughout the day, such as solar radiation, air temperature, relative humidity, headwater temperatures, and tributary water temperatures. This approach is consistent with the model guidance and the process typically used to evaluate water temperature for TMDL studies in Washington State. Additional information on the Tucannon River QUAL2Kw temperature model is presented in Appendix B.

5.2.1 Model Calibration

Flow and temperature data from July 13, 2005 were used to calibrate the QUAL2Kw model. The model was constructed through an iterative process that involved adjustments and comparisons to observed temperature data. The comparison of measured and predicted daily maximum, daily average, and daily minimum temperatures for the calibrated model is shown on Figure 18. The model was calibrated to a relative accuracy of 1.0 °C root mean square error (RMSE)[4].

5.2.2 Model Scenarios

The calibrated QUAL2Kw model was used to assess the effects of changes in riparian shade on Tucannon River temperatures. The following model scenarios were run:

- **Current Conditions** – The Current Conditions scenario represents current riparian vegetation (height, density, and overhang) and channel morphology. The calibrated model without changes represents this scenario.
- **Full Shade** – The Full Shade scenario represents the maximum (i.e., at full mature vegetation stage) effective shade that would naturally occur in riparian areas along the Tucannon River. Full Shade scenario results are often used by Ecology to establish “natural condition” temperatures for rivers when assessing compliance with water quality standards.
- **Full Shade in Forested Areas** – The Full Shade in Forested Areas scenario was used to assess the benefits from improved shade in the forested area only, upstream of RK 66 (RM 41) and to assess how conservative the Full Shade scenario compares to the existing forested conditions.
- **Topographic Shade** – The Topographic Shade scenario represents shading from topography only. This scenario was used to assess the contribution that the current vegetation has on river temperatures.
- **No Withdrawals** – The No Withdrawals scenario is a model run without irrigation diversion to evaluate the relative effects of irrigation diversions on river temperature in the Tucannon River.

The Full Shade, Full Shade in Forested Areas and Topographic Shade model scenarios address changes to riparian vegetation because riparian vegetation can be relatively controlled through management practices and the Full Shade scenario is often used in temperature TMDLs to represent “natural conditions” temperatures. These model scenarios did not assess other factors that can influence river temperatures, such as channel

[4] As estimated by the root mean square error (RMSE) of the predicted versus measured daily minimum, average, and maximum temperatures.

morphology or microclimate. However, the Full Shade scenario represents a conservative estimate of shade conditions as described below. Previous modeling of the Tucannon River (Theurer et al., 1985) indicated that riparian shade was relatively more important in controlling river temperatures as compared with channel morphology.

5.2.3 Model Results

Full Shade Scenario

The Full Shade scenario predicts the decrease in river water temperature that would occur from increased effective shade by increasing riparian vegetation up to the "full system potential"[5]. The increase in effective shade along the riparian zone for this scenario is presented on Figure 19. Figures 20 and 21 compare the predicted temperature conditions in the Tucannon River for the Current Conditions and Full Shade scenarios. Daily minimum and average temperatures for the current vegetation condition are generally about 2 and 3°C (about 4 to 5°F) warmer than the full shade conditions below RK 50 (RM 31).

Maximum daily temperatures for the Current Conditions Model scenario results are approximately 2 to 3°C (about 4 to 5°F) warmer in the headwaters to about 3 to 4 °C (about 7 °F) warmer below RK 60 (RM 37). Other results of the Full Shade scenario are summarized below:

The greatest differences in temperature between Current and Full Shade conditions occurred in the middle section, between RK 20 and 50 (RM 13 and 31). The greatest difference in the daily maximum temperature (3.7°C or 7°F) occurred at RK 24 (RM 15).

Significant improvements in temperatures in the lower reaches, downstream of RK 14 (RM 9), are not expected to occur with improved shading as shown in Figure 21. For example, the peak temperatures in the lower section of the river for current conditions are simulated as about 25 °C (77 °F). Under the Full Shade scenario, the temperature at the mouth of the river is predicted to be 24 °C (75 °F), a reduction of only 1 °C compared with the Current Conditions scenario. Temperatures are predicted to remain above 20 °C (68 °F) for the lower 36 kilometers (22 miles) of the river under Full Shade conditions.

Although water temperatures are expected to be significantly lower in sections of the river under the Full Shade scenario, the daily maximum temperatures would still be above Ecology's current 18 °C and 16 °C temperature criteria for most of river in the Full Shade scenario[6]. Based on this information, the Full Shade scenario may be used to represent the potentially achievable temperatures for the river that would occur by shading with the current river morphology. This scenario may also be considered for evaluating the background

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[5] The Full Shade scenario used in this report is equivalent to the "system potential vegetation" scenario represented in temperature TMDLs conducted by Ecology.

[6] Previous temperature modeling of the Tucannon Riparian conducted in 1985 reported that natural conditions temperatures (as represented by climax vegetation) generally exceeded the numerical criterion of 18 ^{o}C from the mouth to approximately RK 60 during July (Theurer, et al. 1985).

temperature against which human-caused impacts and management strategies can be compared.

As shown by the green line in Figure 21, the difference between current temperature and full shading is above the 0.3 °C increase referenced in the Washington State water quality criteria.

Full Shade in Forested Areas Scenario

As shown in Figure 19, the Full Shade scenario represents a fairly conservative estimate of riparian shade. The Full Shade in Forested Areas scenario represents the potential improvement that could be achieved by increasing the density of forest vegetation in existing forested areas above approximately RK 66 (RM 41). The existing riparian areas in the upper watershed are forested; therefore, these areas would be expected to have more shade than other areas in the watershed. The Full Shade in Forested Areas scenario demonstrates the conservative assumptions of the Full Shade scenario, as mature vegetation is assumed to occur at a constant height and density (at maturity) throughout the entire 150-foot riparian area on each side of the stream. A tree height of 24 meter (79 feet) and canopy density of 80% was used to define the Full Shade scenario in this section of the river. As Figure 22 shows, the current forested areas are not completely vegetated with mature trees.

The Full Shade in Forested Areas scenario also demonstrates that the increases to riparian shade in these upper watershed areas above RK 66 (RM 41) would result in a 1 to 2 °C decrease in river temperature for areas above RM 60 and a negligible improvement in river temperature in the middle and lower watershed (Figure 23).

Topographic Shade Only Scenario

The Topographic Shade scenario is provided to evaluate the current shading benefits from reduced solar heating to the Tucannon River. A comparison of the results of the Topographic Shade scenario with the Current Conditions scenario provides an indication of the current benefits from riparian shading. As shown in Figure 24, current shading provided by vegetation reduces the daily maximum water temperatures in the Tucannon River by about 1 °C.

No Withdrawals Scenario

The No Withdrawals scenario represents the potential decrease in predicted maximum daily temperature that would occur if no irrigation diversions occurred in the basin. The results shown on Figure 25 indicate that irrigation diversions have a negligible effect on river temperatures.

6.0 Summary

The results of this study indicate the following:

- The temperature field data collected for the Tucannon River in 2004 and 2005 indicate that water temperatures in the river are elevated and exceed current water quality standards.
- Existing vegetation reduces the daily maximum temperature by about 1 °C compared with un-shaded conditions.
- Improved riparian shading could lower water temperature by a maximum of 1 to 4 °C (2 to 7 °F) assuming that the riparian vegetation in the watershed could be restored to the full system potential. The least benefit would occur in the upper and lower watershed and the greatest benefit would occur in the middle watershed.
- The Full Shade scenario temperatures also indicate that even with increased riparian vegetation to the full system potential, water temperatures in the river would exceed Washington State water quality criteria up to RK 50.
- Irrigation diversions currently do not have an effect on river temperature because of the relatively small amount of water diverted as compared to the flow in the river.
- Current temperatures exceed the allowable increase above natural conditions (0.3 °C) for the current vegetation conditions are more than 0.3 °C above full shade temperatures.
- Results of this study can be used to define the attainable temperature for the Tucannon River and to assess the progress of restoration measures.
- The Full Shade results indicate the potential improvements to river temperature that are possible and could be considered to represent the temperature criteria for the Tucannon River.

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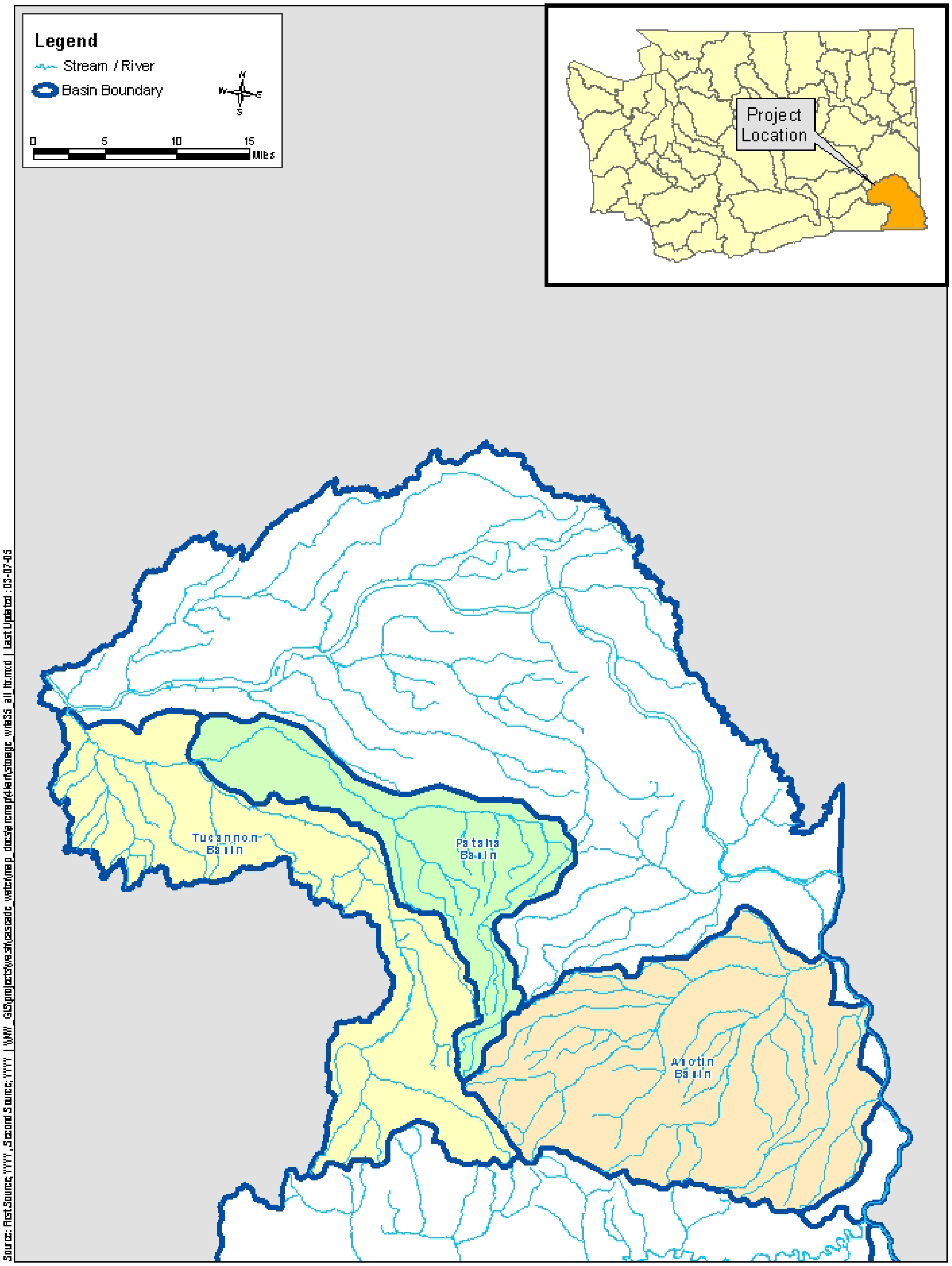
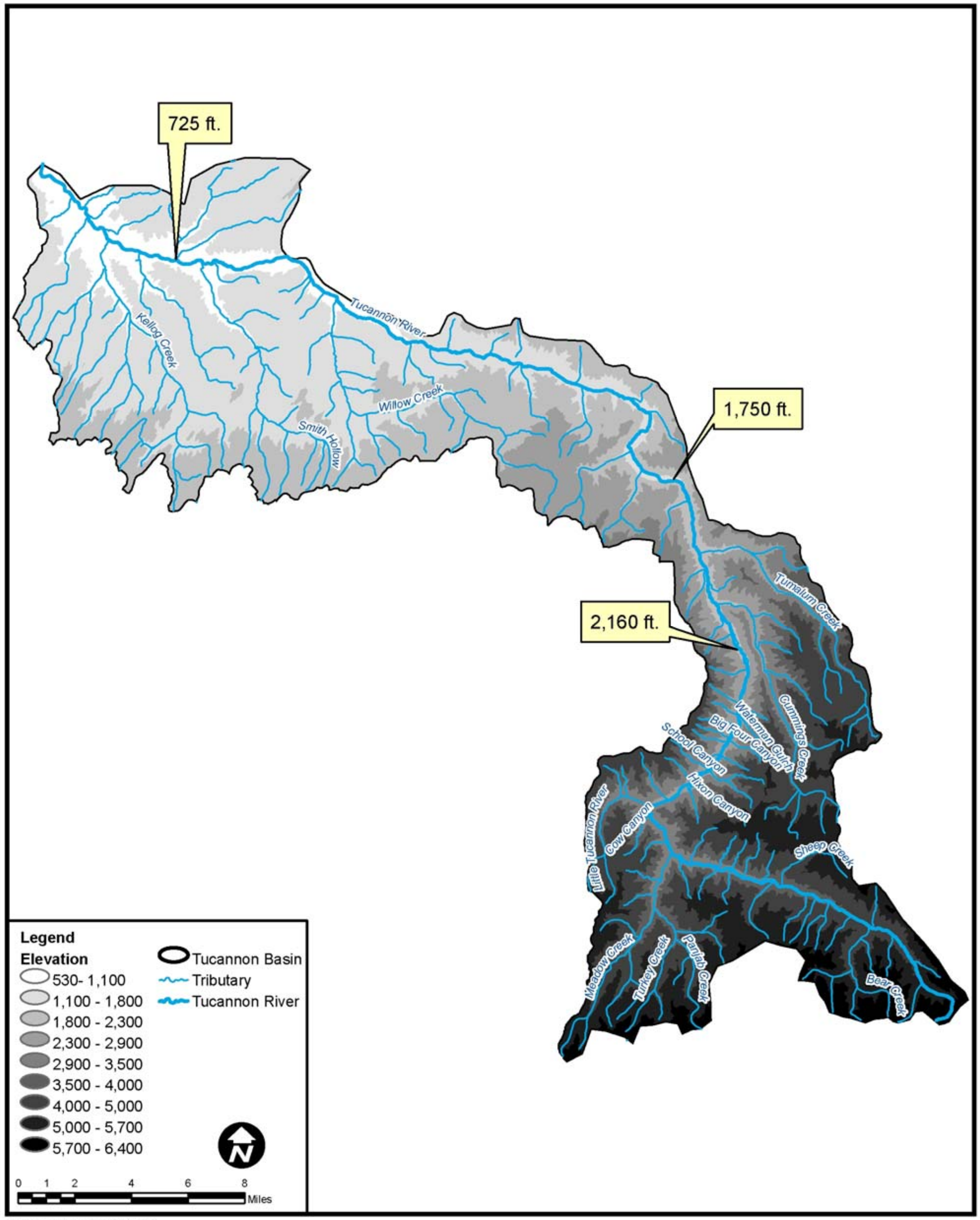


Figure 1 Tucannon river basin project vicinity



Printing Date: June 16, 2006
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Figure 2 Topographic elevation (feet) in the Tucannon River basin

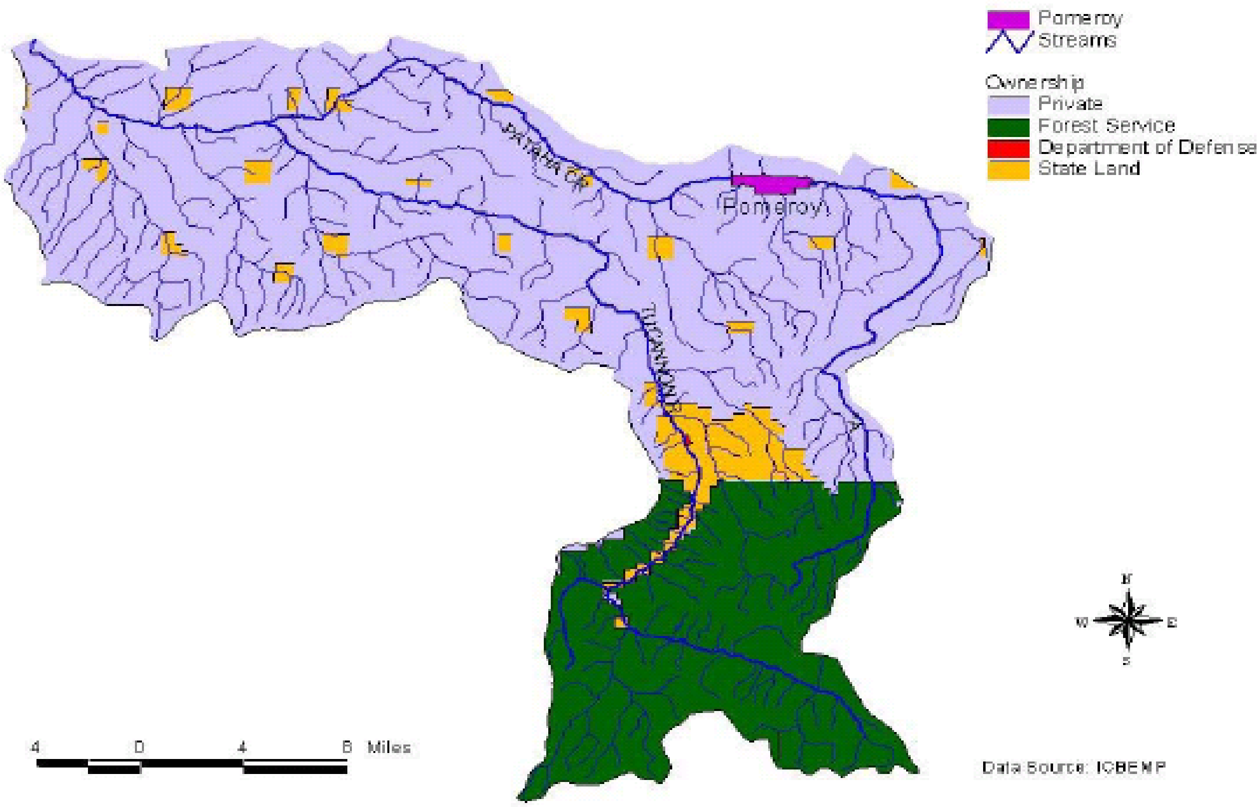
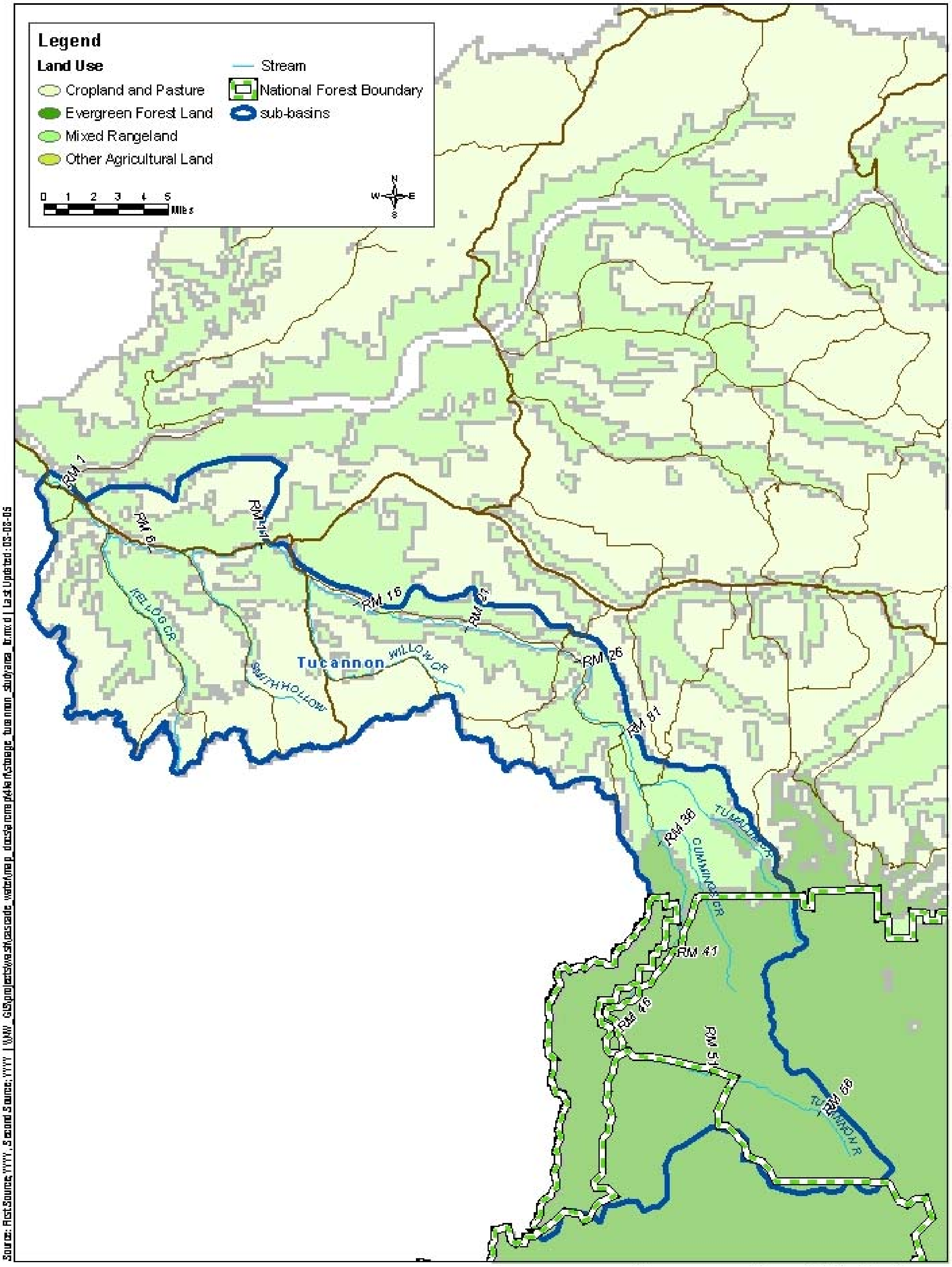
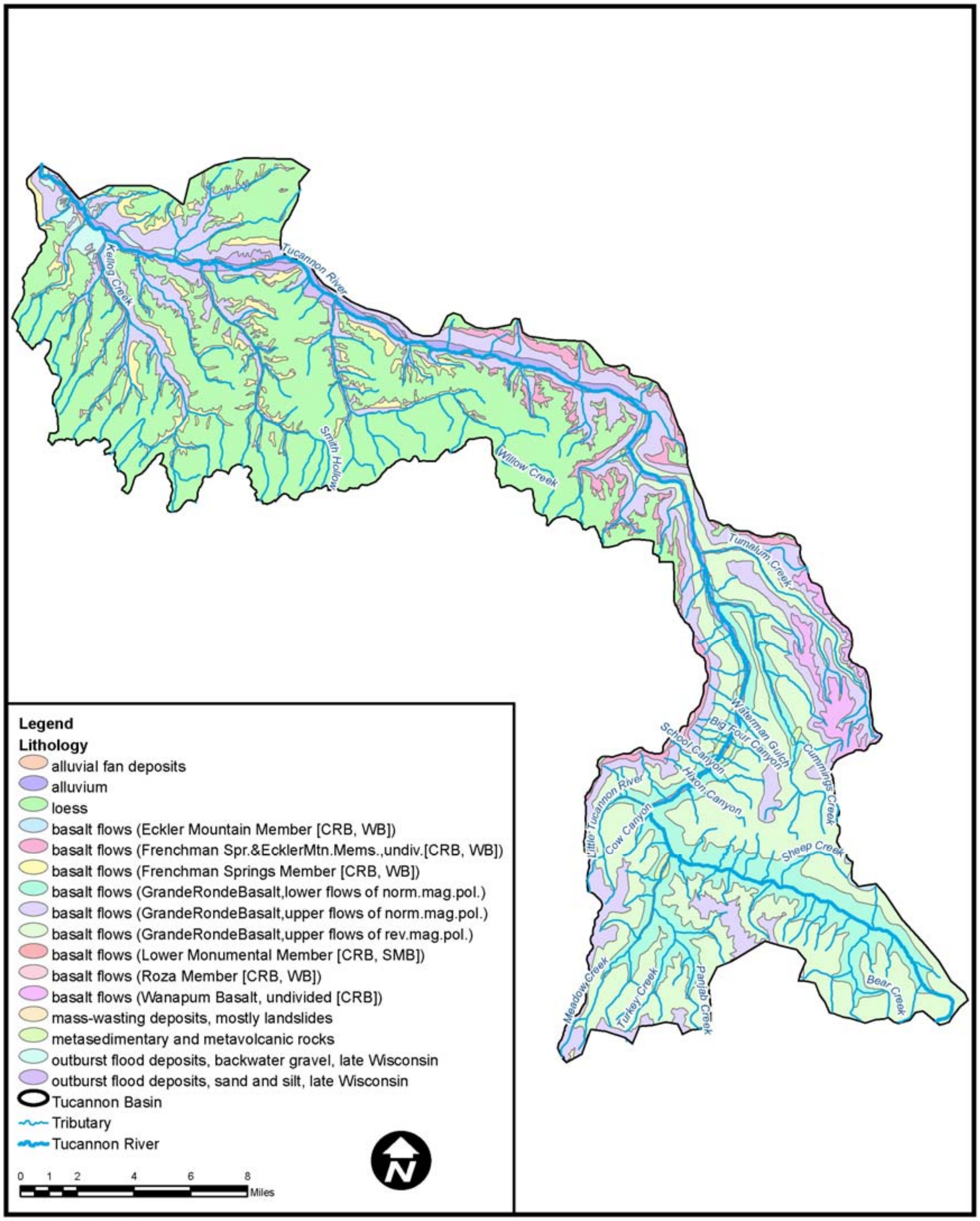


Figure 3. Land ownership in the Tucannon River basin.
Source: Columbia Conservation District 2004



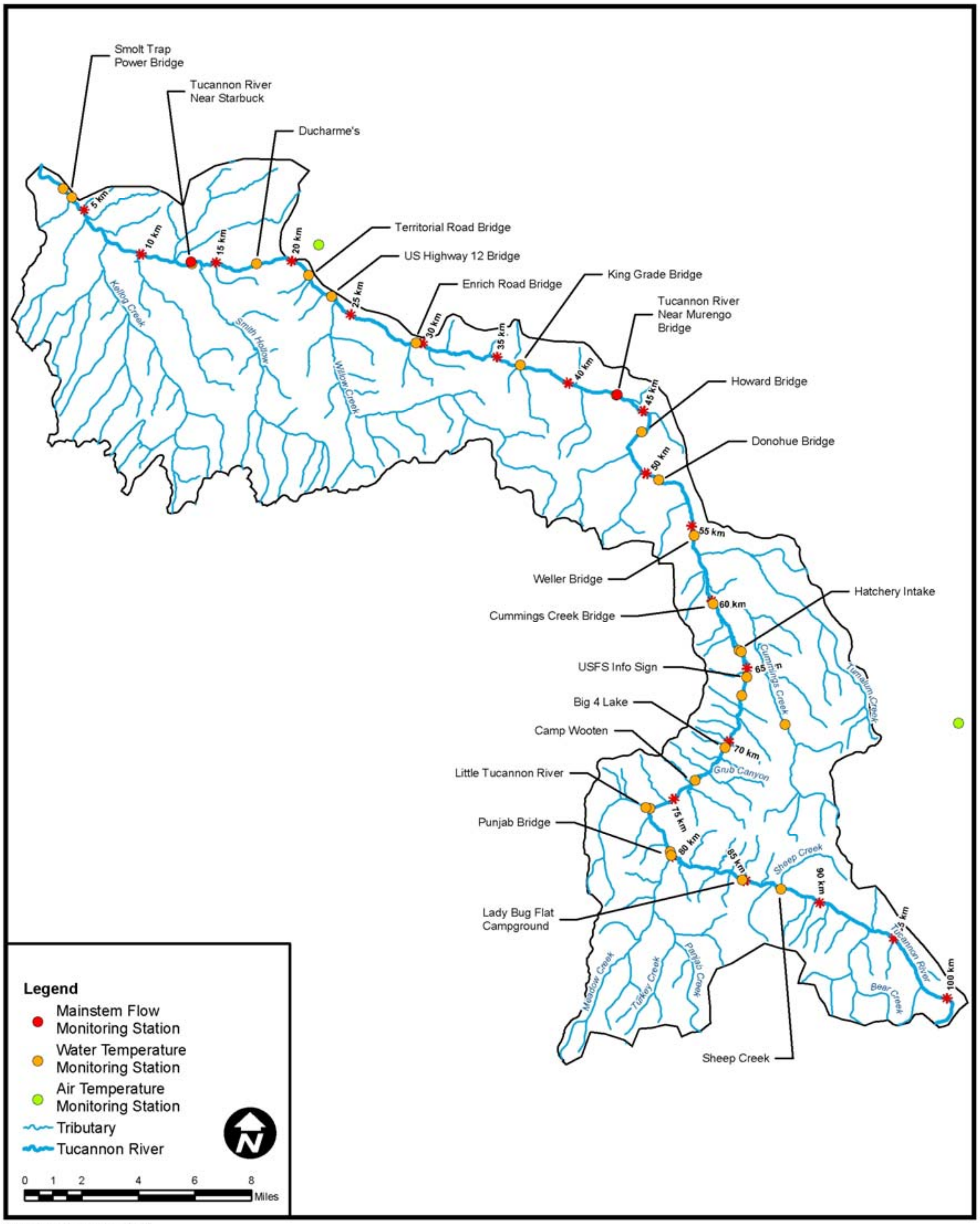
Source: First Source: YYYY, Second Source: YYYY | Last Updated: 03-08-05

Figure 4 Land use in the Tucannon River basin.



Printing Date: April 7, 2006
File: tuc_geology.mxd

Figure 5 Geology in the Tucannon River basin.
Source: Washington State Department of Natural Resources
http://www.dnr.wa.gov/geology/dig100k.htm



Printing Date: June 16, 2006
File: tuc_monitoring.mxd

Figure 6 Tucannon River flow, temperature and air monitoring locations

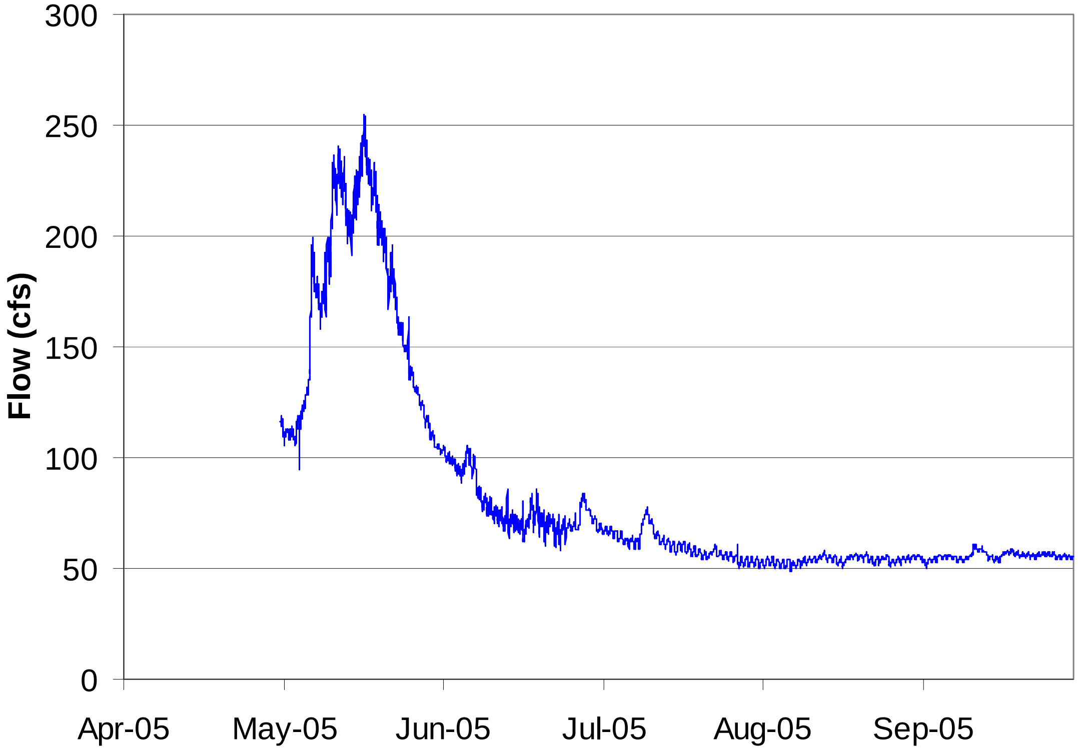


Figure 7 Tucannon River flow recorded during 2005 at Marengo, WA

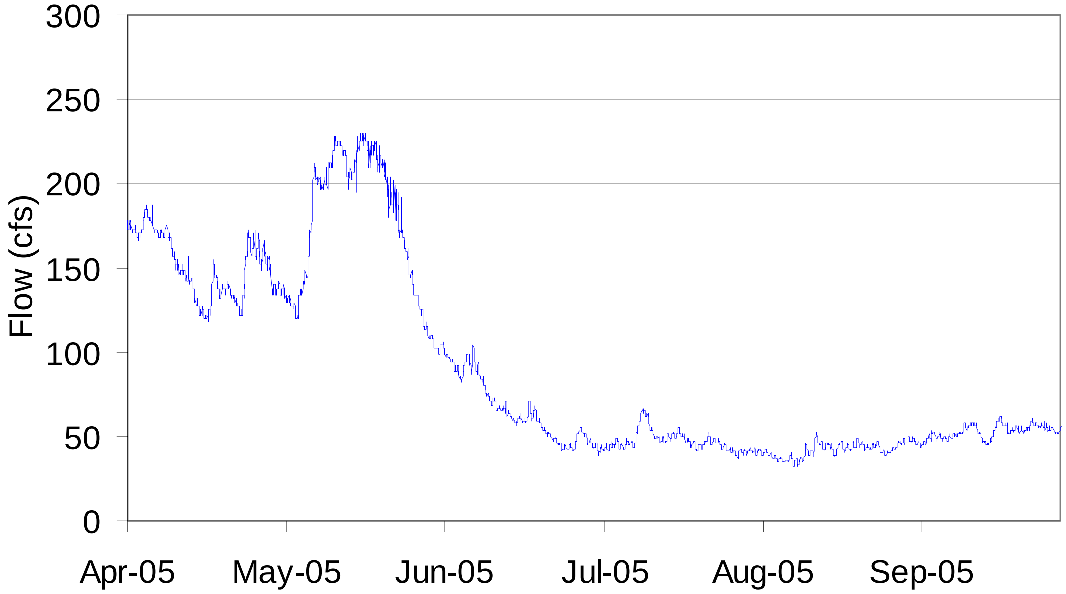


Figure 8 Tucannon River flow recorded during 2005 at Starbuck, WA

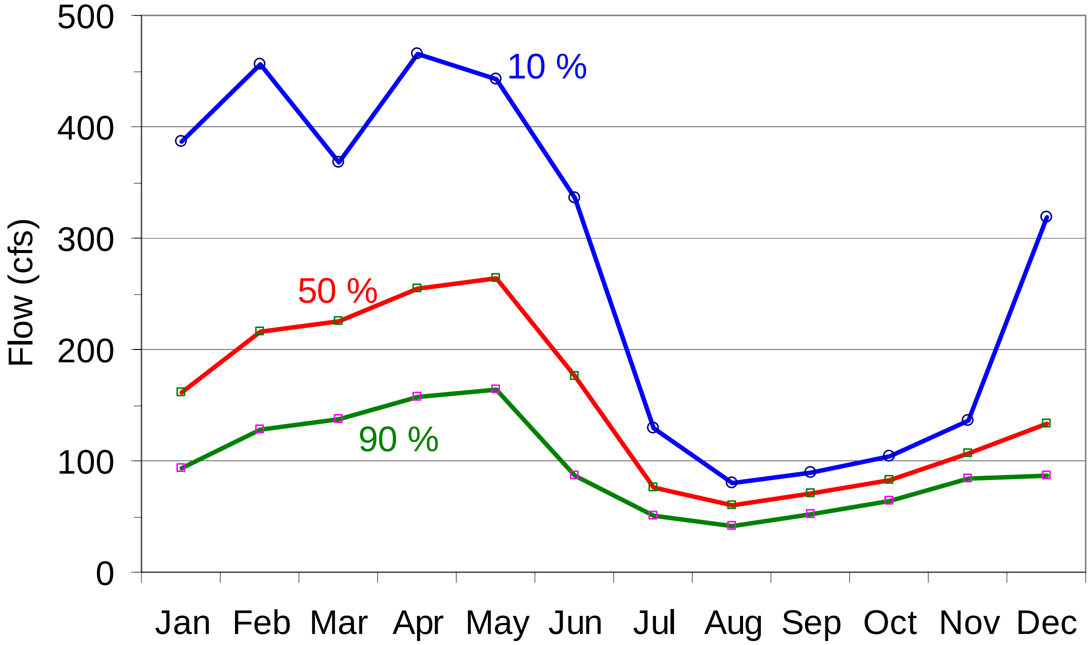


Figure 9 The 10%, 50%, 90% exceedance flows for the USGS' Tucannon River near Starbuck, WA station.

Period of record is 10/1914 to 9/1917; 10/1928 to 9/1931; 10/1958 to 12/1990; 10/1994 to 2004

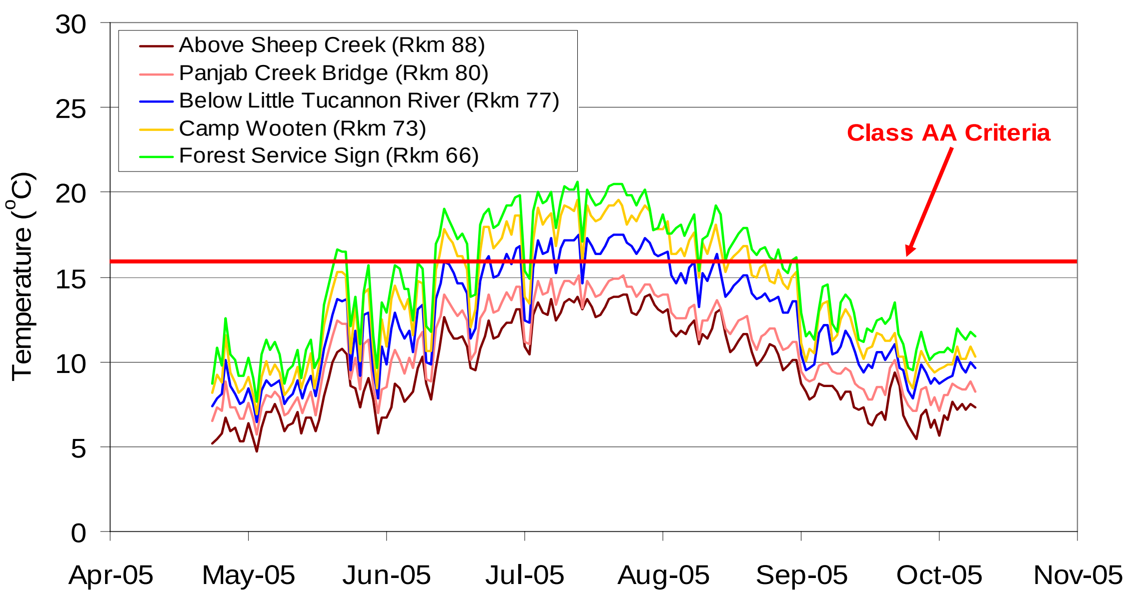


Figure 10 Daily maximum 2005 temperatures measured in the Class AA section of the Tucannon River.

Source: WDFW

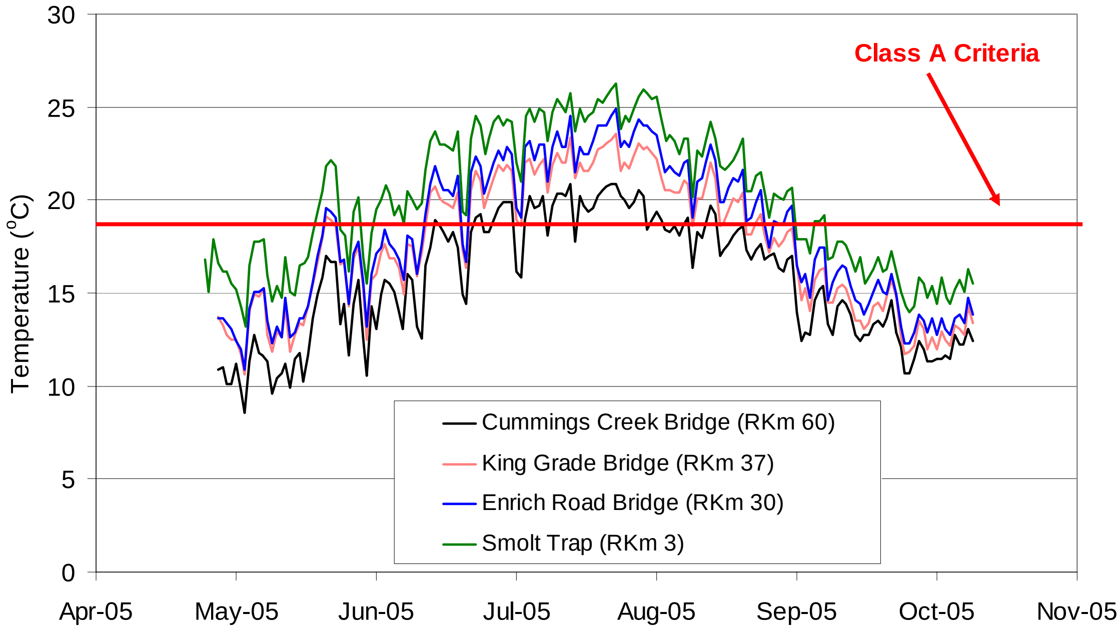


Figure 11 Daily maximum 2005 temperatures measured in the Class A section of the Tucannon River.

Source: WDFW

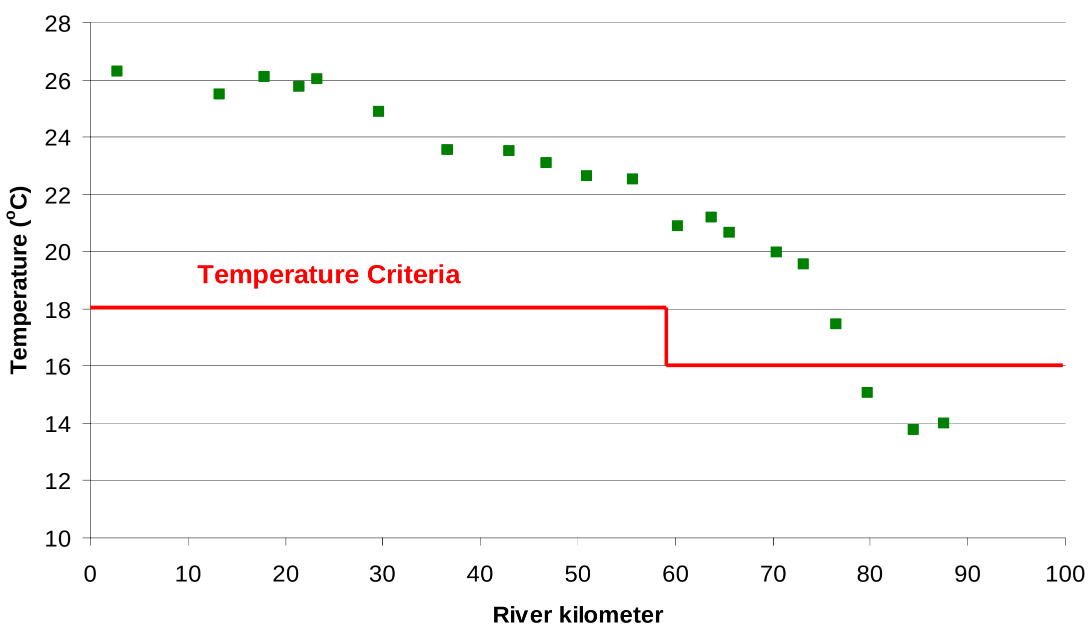


Figure 12 Highest daily maximum temperatures measured in the Tucannon River in 2005
(Note: highest daily maximum temperatures occurred in July).

Source: WDFW.

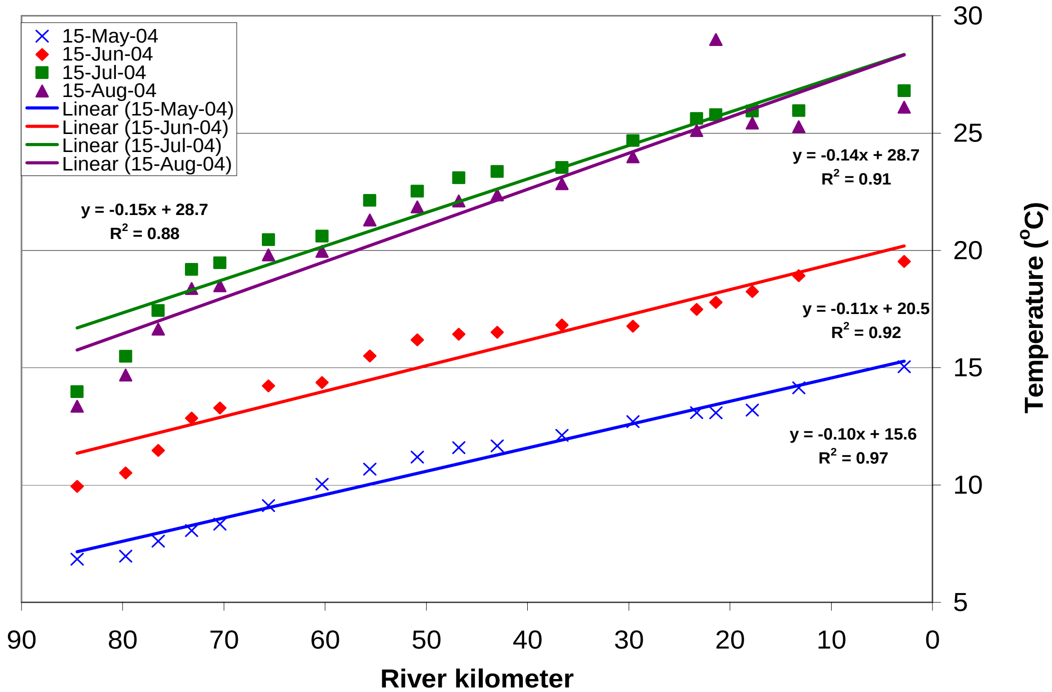


Figure 13 **Tucannon River temperatures with change in elevation based on data collected in 2004.**

Source: WDFW

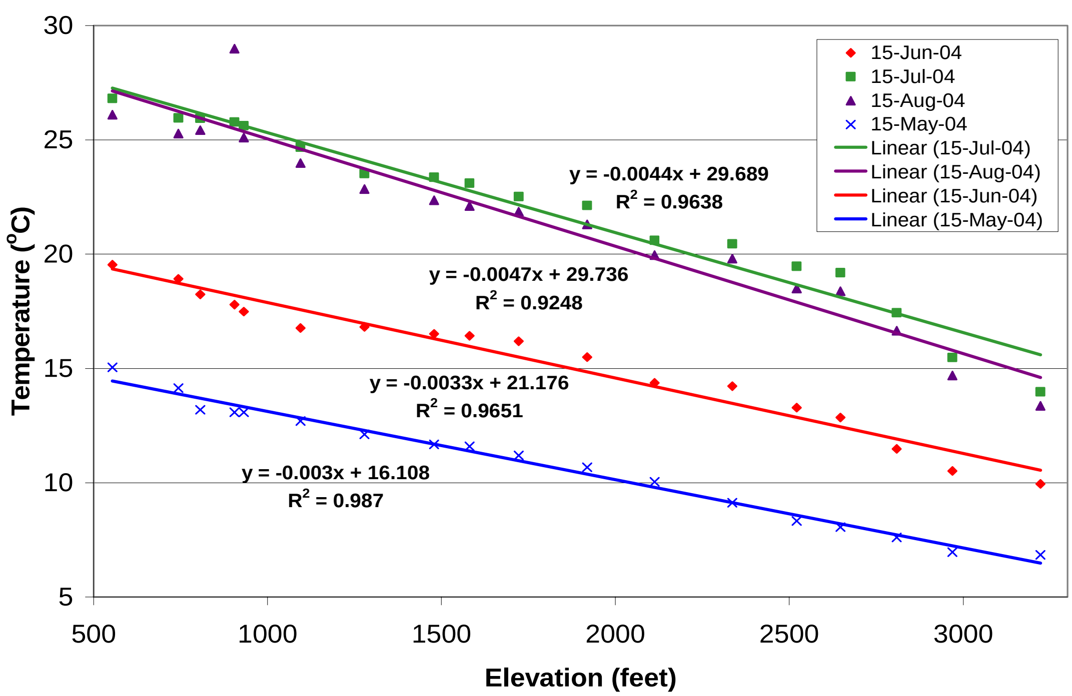
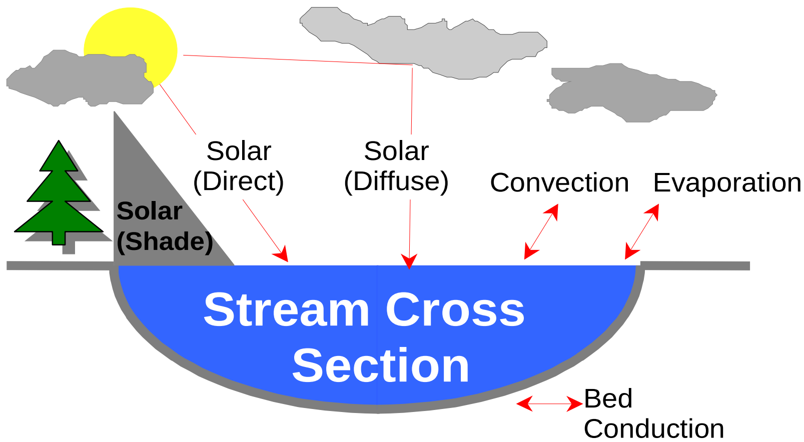


Figure 14 **Tucannon River temperatures with change in river location based on data collected in 2004.**

Source: WDFW



Heat Budget Eq.
Total heat = solar + longwave + convection + evaporation + streambed + groundwater

Figure 15 Major elements of a stream heat budget.
Source: Modified from Pelletier, 2002

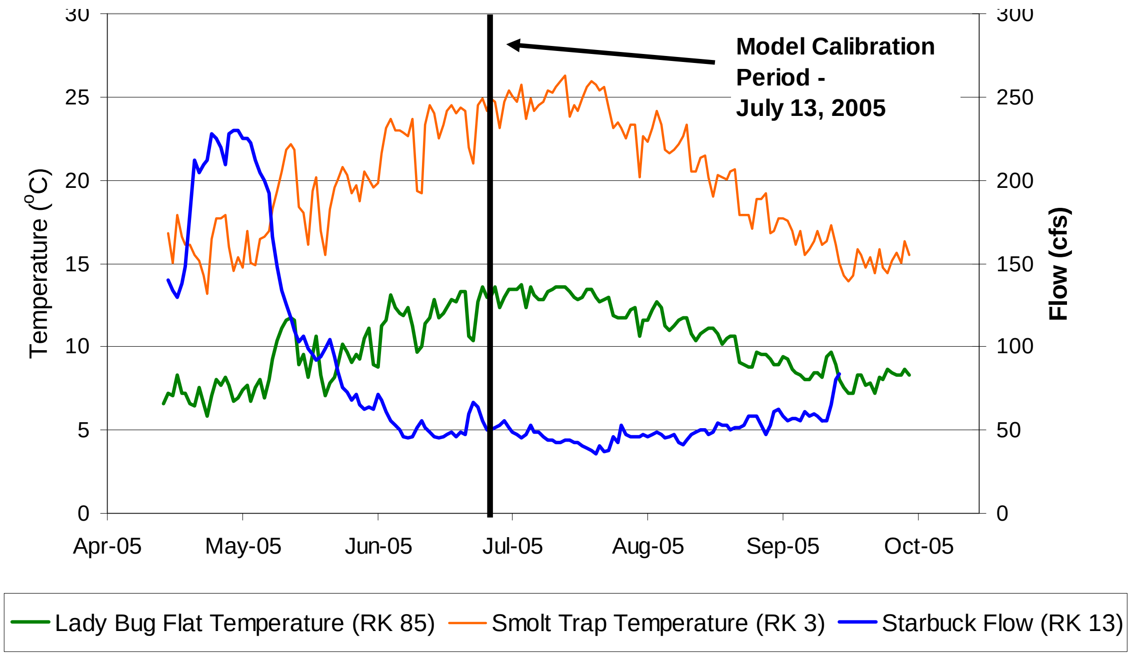


Figure 16 **Comparison of river flow at Starbuck gage and daily maximum water temperature in the upper basin at Lady Bug Flat (RK 85) and in the lower basin at Smolt Trap (RK 3) in 2005.**
Source: WDFW

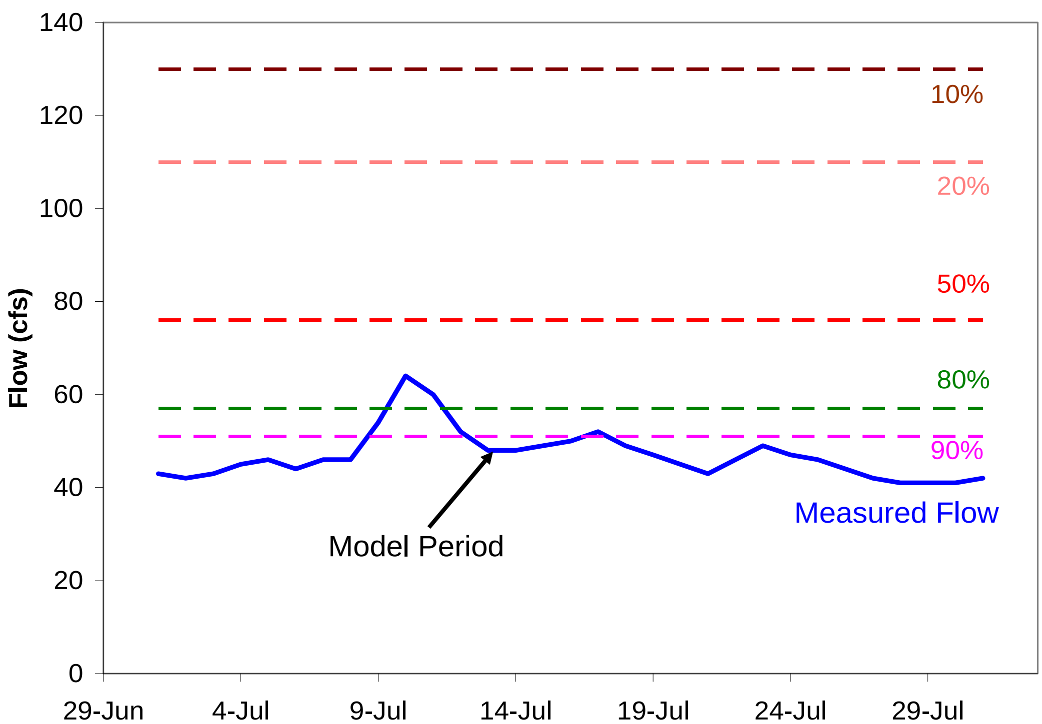


Figure 17 **Recorded river flow at Starbuck gage compared to historic flows**

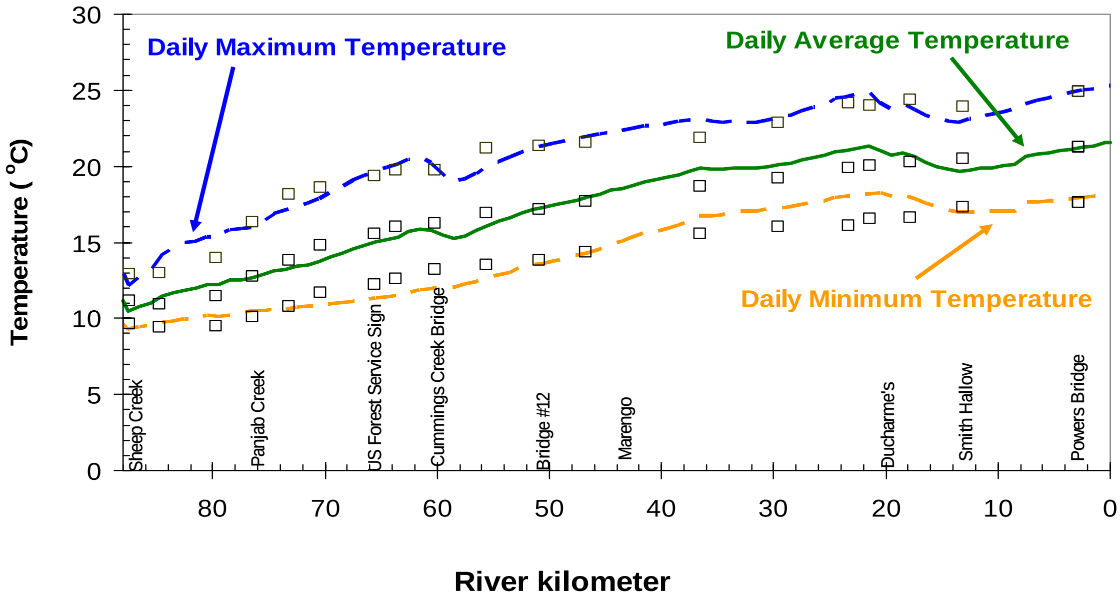


Figure 18 **Predicted and measured water temperatures in the Tucannon River for the calibration period (July 13, 2005) under current riparian conditions**

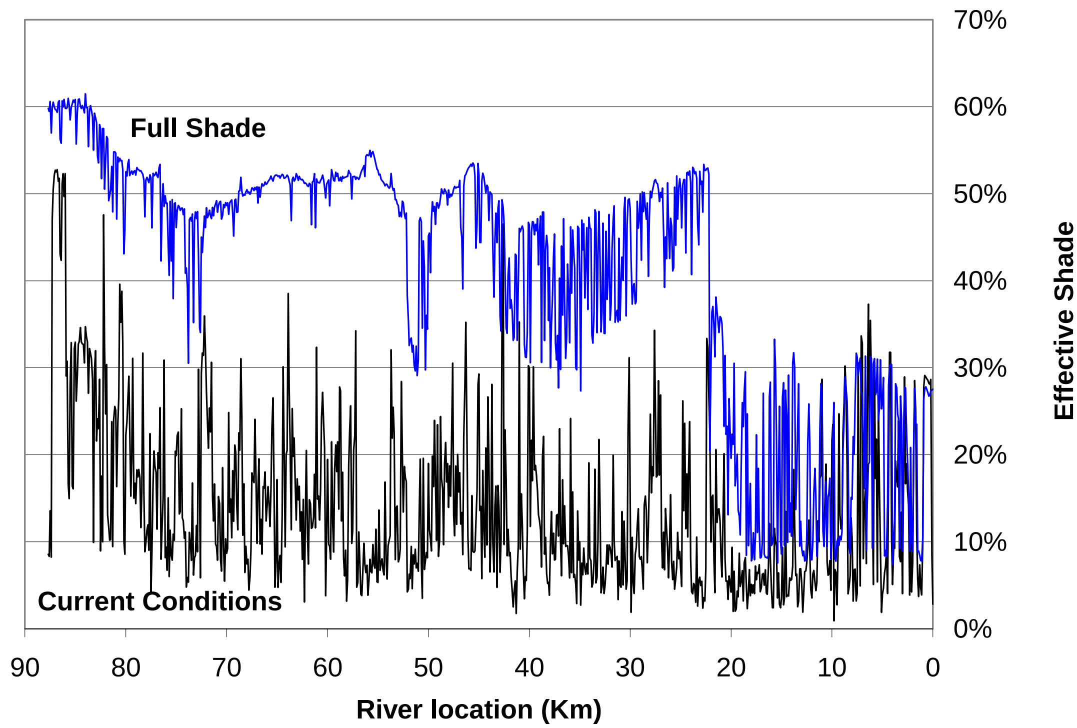


Figure 19 **Estimated effective shade from riparian vegetation and topography for the Current Conditions and Full Shade scenarios**

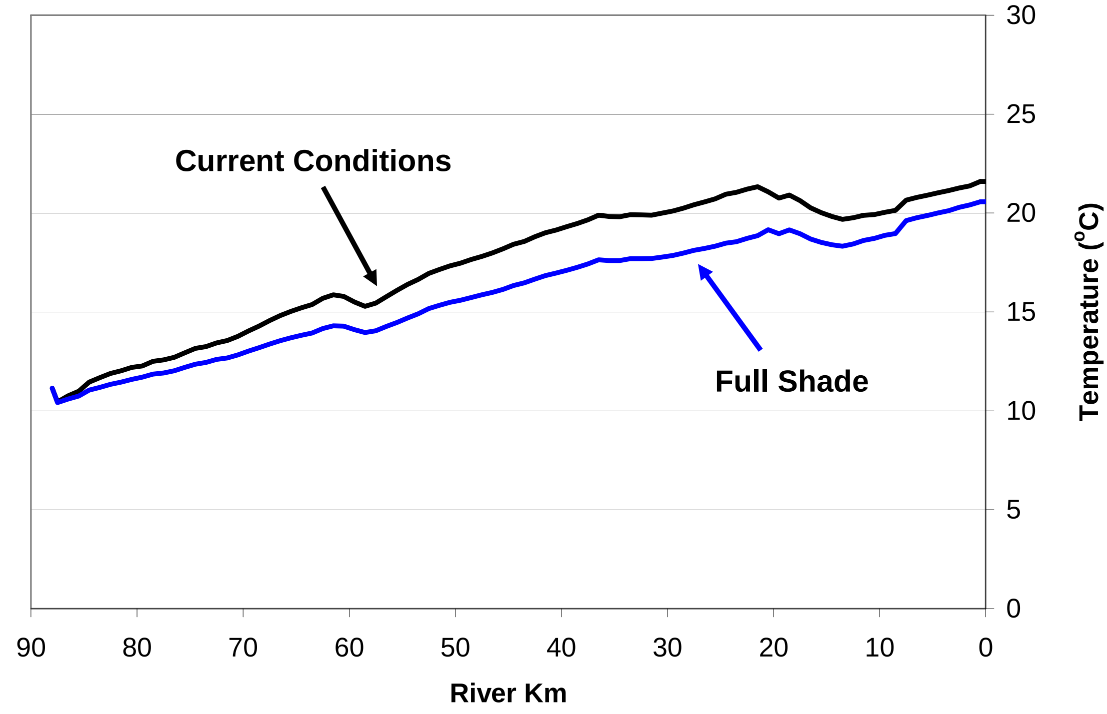


Figure 20 Predicted daily average temperatures in the Tucannon River for the Current Conditions and Full Shade model scenarios

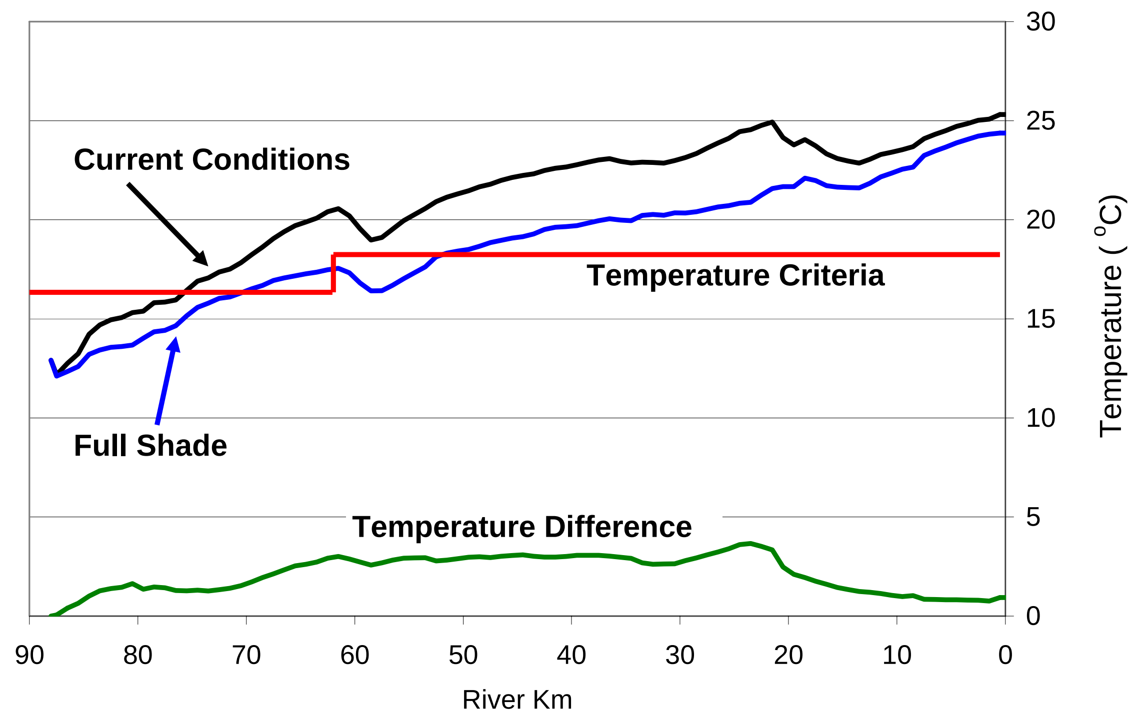


Figure 21 Predicted daily maximum temperatures for the Current Conditions and Full Shade model scenarios

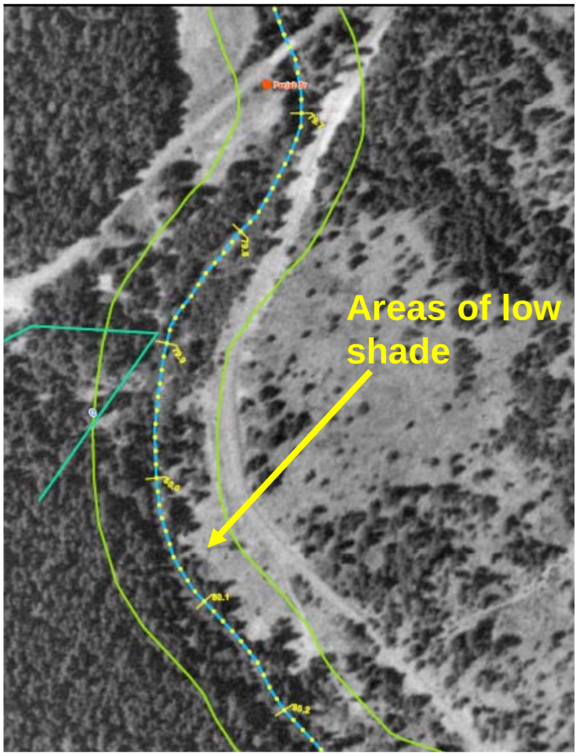


Figure 22 Example of upper watershed (Panjab Creek area, RK 80) riparian shade conditions along the Tucannon River

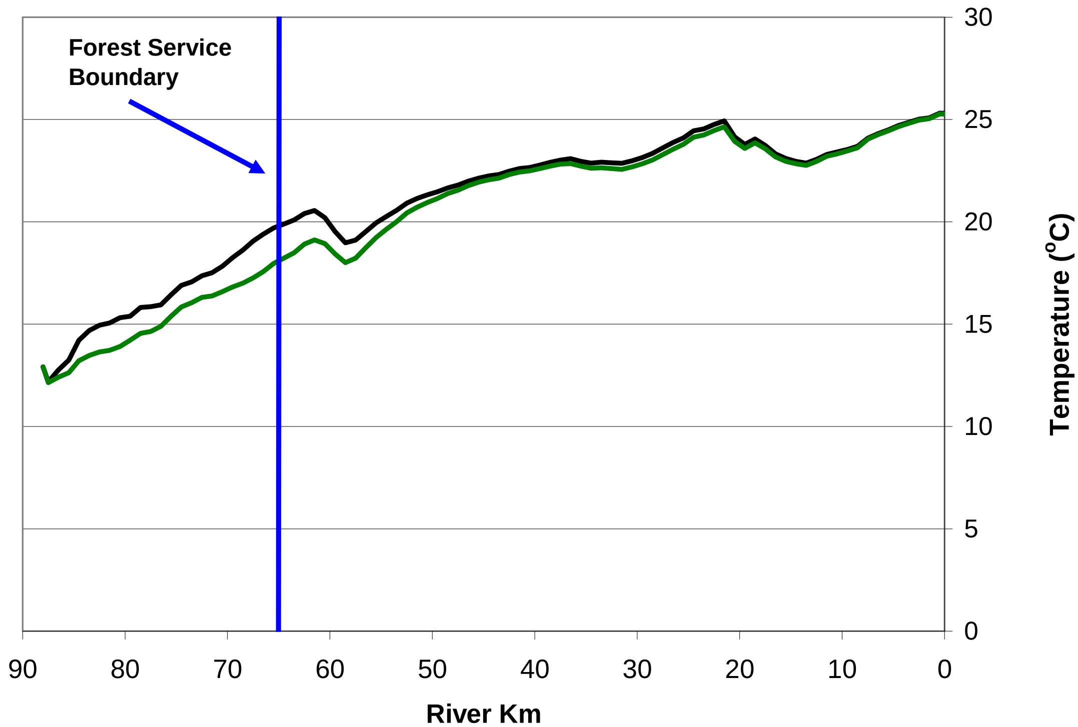


Figure 23 Predicted daily maximum temperatures for the Current Conditions and Full Shade in Forested Areas model scenarios

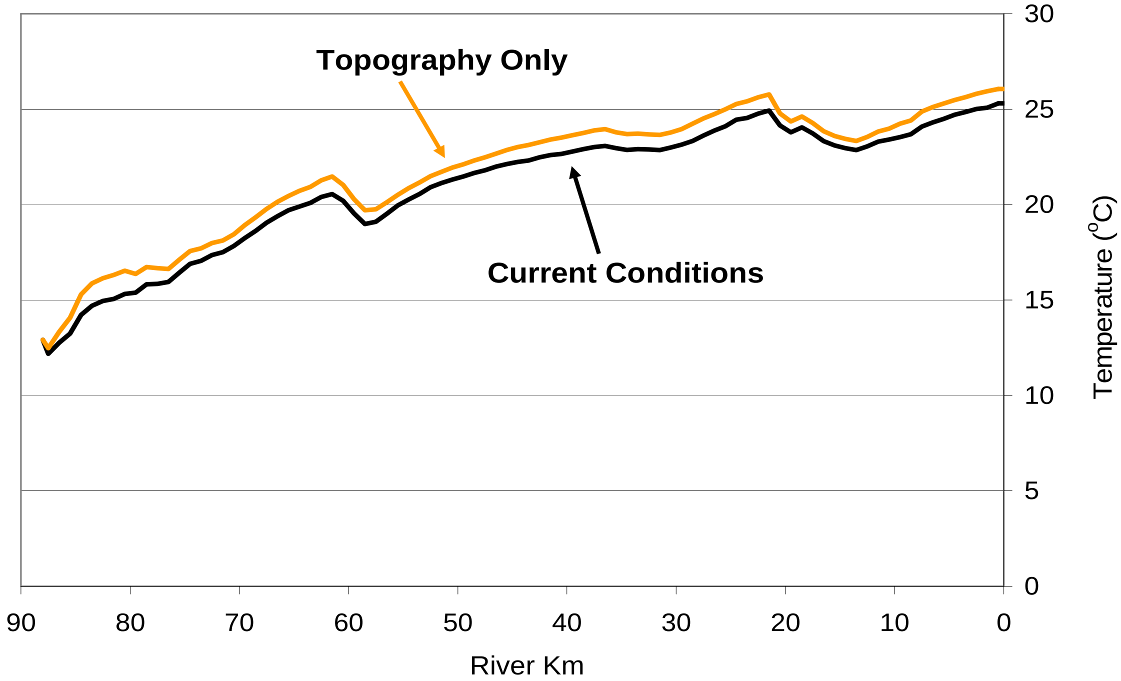


Figure 24 **Predicted daily maximum temperatures for the Current Conditions and Topography Shade model scenarios**

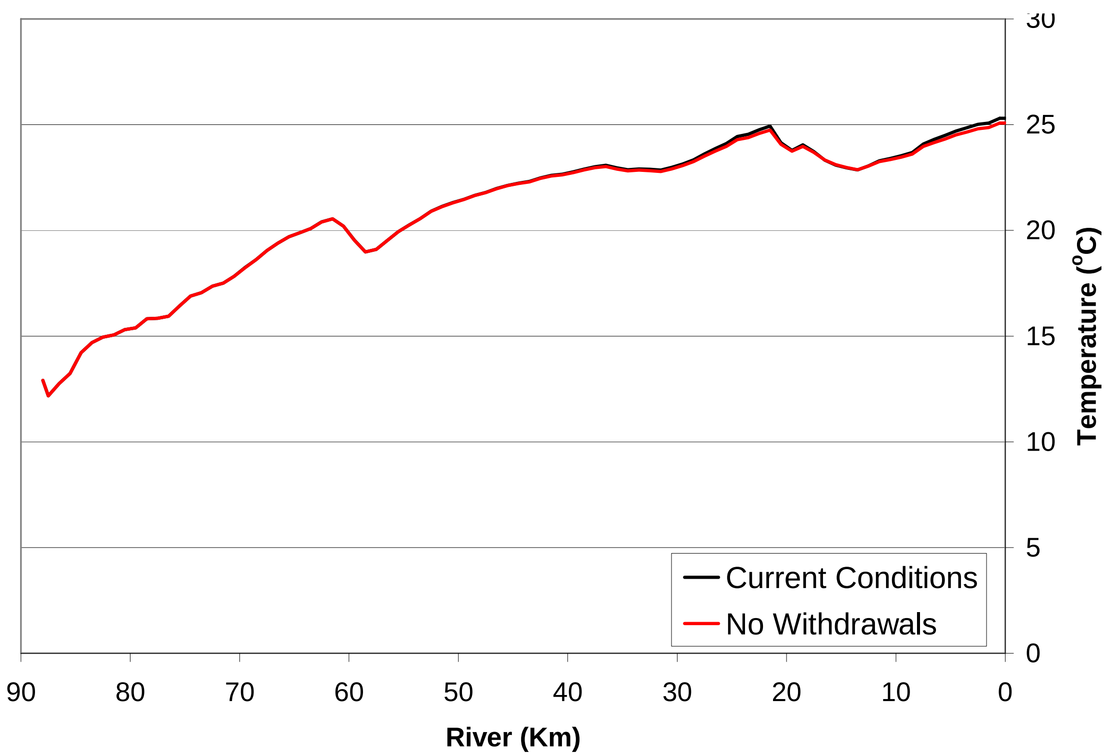


Figure 25 **Predicted daily maximum temperatures for the Current Conditions and No Withdrawal model scenarios**

Appendix A –
Tucannon River Field Data Collection and Analyses

Appendix A
Tucannon River Field Data Collection and Analyses

This appendix provides information regarding the field data collection efforts and data analysis conducted to support the development of the Tucannon River temperature model. The results of the data collection efforts are summarized below for the following:

- River and tributary flow
- Irrigation diversions
- Ground water inflow/outflow from the river channel
- River channel shape, hydraulic gradient and morphology
- River temperature
- Climate data
- Riparian vegetative type and shading conditions

A-1 River and Tributary Flow

A flow balance for the Tucannon River watershed was constructed to estimate groundwater inflows or outflows by differences between the gaging stations. The flow balance includes estimated surface water and groundwater inflows by interpolating between the gaging stations. River and tributary flows in the Tucannon River model were based on a seepage run conducted on the Tucannon River on July 13th and 14th, 2005.

Flow and temperature were monitored during the seepage run at the 38 stations (28 mainstem and 10 tributary stations) listed in Table A-1 and shown in Figure A-1**.** The calculated flow balance for the Tucannon River is shown on Figure A-2. Flows developed from the seepage run were used as the flow values in the QUAL2Kw model. The flow measured at Starbuck during the seepage run was relatively low, ranging between 47.5 and 50 cfs, near the 90 % exceedance flow of 51 cfs. Note: the 7Q10 flow for the Tucannon River is 37.9 cfs.

The tributary flows measured during the seepage run are listed in Table A-2 and shown in Figure A-3. During July, tributary flow represents a relatively small proportion of the overall flow to the river downstream of Panjab Creek, RK 80. Therefore, tributaries would have a small influence on mainstem Tucannon River temperatures. Additionally, there are no point sources to the river.

Table A-1. Seepage run stations

Station	RK	Station name	Mainstem or Tributary
1	2.78	261 Bridge (smolt trap, 150' upstream of bridge)	Mainstem
2	7.62	Kellogg Creek Bridge	Mainstem
3	7.71	Kellogg Creek Just Upstream of Confluence	Tributary
4	13.17	Smith Hollow Road Bridge	Mainstem
5	17.78	Kessels Bridge*	Mainstem
6	19.55	Below Pataha Creek @ Private Bridge	Mainstem
7	20.90	Pataha Creek	Tributary
7a	21.39	Territory Road Bridge	Mainstem
8	23.30	Hwy 12 Bridge (downstream Willow Cr)	Mainstem
9	23.60	Willow Creek	Tributary - Dry
10	29.50	Brine Road Bridge (60' downstream)	Mainstem
11	36.57	Below King Grade Bridge	Mainstem
12	42.99	Below Marengo Bridge	Mainstem
13	46.81	Bridge 10	Mainstem
14	50.86	Bridge 12 (50' upstream)	Mainstem
15	52.87	Bridge 13 (100' downstream, near WDFW land)	Mainstem
16	52.98	Hartsock Creek @ Road	Tributary
17	55.60	Below Tumalum Creek (at bridge)	Mainstem
18	56.85	Tumalum Creek Upstream of Confluence	Tributary
18a	57.55	Between Cummings and Tumalum Creeks	Mainstem
19	60.40	Cummings Creek 50' Upstream of Confluence	Tributary
19a	60.41	Just Upstream of Cummings Creek	Mainstem
19b	60.24	Just Downstream of Cummings Creek (at bridge)	Mainstem
20	65.60	USFS Sign	Mainstem
21	70.4	Near Big Four Lake	Mainstem
22	73.23	Camp Wooten Bridge	Mainstem
23	73.76	Hixon Creek near Camp Wooten	Tributary
24	76.60	Below Little Tucannon Confluence	Mainstem
25	76.63	Little Tucannon River Near Mouth	Tributary
26	77.17	Cow Camp Bridge (underneath)	Mainstem
27	79.64	Panjab Bridge	Mainstem
28	79.88	Panjab Creek Near Mouth (First Campground)	Tributary
29	84.08	Ladybug Campground	Mainstem
30	87.46	Sheep Creek @ Bridge Above Confluence	Tributary
31	87.47	Main Stem Below Sheep Creek	Mainstem
Site 31a	87.48	Main Stem above Sheep Creek	Mainstem

Table A-2. Tucannon River model inflows (tributaries)

Name	Location (km)	Inflow (m3/s)	Inflows (cfs)
Sheep Creek	87.5	0.225	8.0
Panjab Creek	79.9	0.191	6.7
Little Tucannon River	76.6	0.028	1.0
Hixon Creek	72.7	0.017	0.6
Cummings Creek	60.4	0.070	2.5
Tumalum Creek	56.9	0.009	0.3
Hartsock Creek	53.0	Dry	Dry
Willow Creek	23.6	Dry	Dry
Pataha Creek	20.9	0.232	8.2
Kellogg Creek	7.71	0.165	5.8
Total		**0.9370**	**33.1**

Notes: Based on measured flow data from July 2005 seepage run.

A-2 Irrigation Diversions

Water diverisons during the seepage run were estimated based on the observed number and types of sprinklers in use. A general survey of water use during the seepage run was measured by observing water diverted directly from the Tucannon River. The number of sprinklers was multiplied by an estimated flow for each type of sprinkler to estimate total water use. For example, between sites Seepage Run Sites 5 and 6, two irrigation center pivots, estimated to use 0.45 cfs water each, and 30 lawn sprinklers, each using approximately 0.011 cfs (5 gallons per minute), were in use at the time of the seepage run. This resulted in an estimated subtotal diversion for this reach of 1.23 cfs.

The estimated irrigation diversion during the seepage run are listed in Table A-3 and shown cumulatively on Figure A-4. The estimated diversion flows represent a small portion of the Tucannon River flow and therefore would have a negligible influence on mainstem river temperatures.

A-3 Groundwater inflows/outflows from the Tucannon River

Estimates of groundwater inflows and outflows from the Tucannon River (gaining and losing reaches) were based on the flow balance calculated from the seepage run. The estimated groundwater inflows and outflows are listed in Tables A-4 and A-5. The data estimated from the water balance indicate that the Tucannon River has significant amount of both groundwater gaining and losing reaches. This is not unexpected given the geology within the subbasin.

Table A-3. Tucannon River model irrigation diversions

River Reach Designation	River Reach Location (km)	Estimated Diversion (m3/s)	Estimated Diversion (cfs)
Wooten Wildlife Area	73.5	0.003	0.1
Site 18a	57.6	0.004	0.1
Upstream Site 13	47.1	0.021	0.7
At Bridge 9	45.3	0.014	0.5
Marengo	43.0	0.014	0.5
Upstream Site 11	37.0	0.014	0.5
Downstream Site 10	29.0	0.016	0.6
Between Sites 9 and 10	27.5	0.064	2.3
Downstream Site 6	19.3	0.035	1.2
Downstream Site 4	13.0	0.022	0.8
SE Starbuck	8.8	0.074	2.6
Central Starbuck	8.0	0.022	0.8
Upstream Site 1	3.4	0.055	2.0
Total		**0.357**	**12.6**

Notes: Based on estimated flow data from July 2005 seepage run.

Table A-4. Tucannon River model (groundwater) inflows (gaining reaches)

Approximate Reach (RK)	Estimated Ground Water Inflow (m^3/s)	Estimated Ground Water Inflow (cfs)
83.0 – 77.2	0.3220	11.37
77.2 – 76.6	0.2519	8.90
74.0 – 70.3	0.2469	8.72
60.4 – 57.6	0.4823	17.04
36.6 – 29.5	0.2316	8.18
21.0 – 19.0	0.1662	5.87
17.8 – 13.2	0.3707	13.09
13.2 – 7.6	0.1185	4.19
Total	**2.19**	**77.36**

Notes: Based on estimated flow data from July 2005 seepage run.

Table A-5. Tucannon River model (groundwater) outflows (losing reaches)

Approximate Reach (RK)	Estimated Ground Water Outflows (m3/s)	Estimated Ground Water Outflows (cfs)
88 - 87.5	0.0208	0.735
76.6 – 74.0	0.0404	1.426
70.3 – 66.0	0.1388	4.903
66.0 – 60.4	0.1397	4.933
57.6 – 55.6	0.0140	0.494
55.6 – 52.9	0.0364	1.287
52.9 – 50.9	0.2072	7.320
50.9 – 46.8	0.0013	0.044
46.8 – 43.0	0.0828	2.926
43.0 – 36.6	0.1359	4.799
29.5 – 23.3	0.1879	6.637
23.3 – 21.0	0.2742	9.686
19.0 – 17.87	0.1638	5.787
7.62 – 2.8	0.1627	5.746
Total	1.6	56.7

Notes: Based on estimated flow data from July 2005 seepage run.

A-4 River Channel Shape, Hydraulic Gradient and Morphology

The Tucannon River centerline was mapped from the most recent black and white Digital Orthophoto Quads (DOQ) for Columbia County. Measurements of reach channel morphology were collected at the 28 mainstem stations during the seepage run and at 170 stations during the riparian survey summarized below. Channel geometry in the field included bankfull width and depth, wetted width and depth, and estimates of Manning's n. This field data, along with GIS analysis, were used to develop the channel morphology used in the Tucannon River model.

A-5 River Temperature

Continuous temperature loggers were installed in the mainstem Tucannon River by WDFW, Ecology, and the USFS at the stations listed in Table A-6. Temperatures were generally recorded hourly. Temperature loggers were also placed in seven of the river's tributaries (Table A-7). The temperature data collected in 2005 are compared to the Washington State numeric criteria on Table A-8.

Table A-6. Mainstem Tucannon River 2005 temperature stations

	Station Name	River Km	River mile	Elevation (meter)	Elevation (feet)	Agency
1	Smolt Trap	2.8	1.7	169	554	WDFW
2	Smith Hollow	13.2	8.2	227	744	WDFW
3	Ducharme's	17.8	11.1	246	807	WDFW
4	Territorial Rd Br	21.4	13.3	276	905	WDFW
5	US HWY 12 Br	23.3	14.5	284	932	WDFW
6	Enrich Rd Br	29.6	18.4	334	1095	WDFW
7	King Grade Br	36.6	22.7	390	1279	WDFW
8	Marengo Br	43.0	26.7	451	1479	WDFW, Ecology
9	Howard Br	46.8	29.1	482	1581	WDFW
10	Donohue Br	50.9	31.6	525	1722	WDFW
11	Weller Br	55.6	34.5	585	1919	WDFW
12	Cummings Creek Br	60.3	37.5	644	2113	WDFW
13	Hatchery Intake	63.7	39.6	678	2224	WDFW
14	USFS Info Sign	65.6	40.8	712	2336	WDFW, USFS
15	Big 4 Lake	70.4	43.7	768	2521	WDFW
16	Camp Wooten	73.2	45.5	715	2647	WDFW
17	Little Tucannon R	76.5	47.5	856	2809	WDFW
18	Panjab Br	79.7	49.5	905	2969	WDFW, USFS
19	Lady Bug Flat CG	84.8	52.5	982	3222	WDFW
20	Above Sheep Creek	87.5	54.4	1065	3494	WDFW

Table A-7. Tucannon River 2005 tributary temperature stations

	Station Name	River km	Agency
1	Pataha Creek	19	WDFW, Ecology
2	Cummings Creek	61	WDFW, USFS
3	Hixon Creek	74	WDFW
4	Little Tucannon R	77	WDFW, USFS
5	Panjab Creek	79	WDFW, USFS
6	Cold Creek	85	WDFW
7	Sheep Creek	87	WDFW

Table A-8. Mainstem temperatures measured in the Tucannon River in 2005

ID	Station Name	River km	2005 Highest Daily Max		2005 7dadMax		1997 Ecology criteria		EPA 2006 Recommended 7dadMax	
			(°C)	(°F)	(°C)	(°F)	(°C)	(°F)	(°C)	(°F)
1	Smolt Trap	2.8	**26.3**	**79.3**	25.4	77.7	18	64.4	17.5	63.5
2	Smith Hollow	13.2	**25.5**	**77.9**	24.6	76.3	18	64.4	17.5	63.5
3	Ducharme's	17.8	**26.1**	**79.0**	25.2	77.4	18	64.4	17.5	63.5
4	Territorial Rd Br	21.4	**25.8**	**78.4**	24.9	76.8	18	64.4	17.5	63.5
5	US HWY 12 Br	23.3	**26.0**	**78.9**	25.1	77.2	18	64.4	17.5	63.5
6	Enrich Rd Br	29.6	**24.9**	**76.8**	23.9	75.0	18	64.4	17.5	63.5
7	King Grade Br	36.6	**23.6**	**74.4**	22.7	72.9	18	64.4	16	60.8
8	Marengo Br	43.0	**23.5**	**74.3**	22.8	73.0	18	64.4	16	60.8
9	Howard Br	46.8	**23.1**	**73.6**	22.3	72.1	18	64.4	16	60.8
10	Donohue Br	50.9	**22.6**	**72.8**	22.0	71.6	18	64.4	16	60.8
11	Weller Br	55.6	**22.5**	**72.6**	21.9	71.4	18	64.4	16	60.8
12	Cummings Creek Br	60.3	**20.9**	**69.6**	20.5	68.9	18	64.4	16	60.8
13	Hatchery Intake	63.7	**21.2**	**70.2**	20.7	69.3	16	60.8	12	53.6
14	USFS Info Sign	65.6	**20.7**	**69.2**	20.2	68.4	16	60.8	12	53.6
15	Big 4 Lake	70.4	**20.0**	**67.9**	19.4	66.9	16	60.8	12	53.6
16	Camp Wooten	73.2	**19.6**	**67.2**	19.0	66.2	16	60.8	12	53.6
17	Little Tucannon R	76.5	**17.5**	**63.5**	17.2	63.0	16	60.8	12	53.6
18	Panjab Br	79.7	15.1	59.1	14.7	58.5	16	60.8	12	53.6
19	Lady Bug Flat CG	84.8	13.8	56.8	13.4	56.1	16	60.8	12	53.6
20	Above Sheep Creek	87.5	14.0	57.2	13.6	56.5	16	60.8	12	53.6

Notes:

1. Bold temperatures indicate temperatures above current (1997) criteria. EPA's 2006 recommended criteria provided for information only.
2. Tucannon River is classified as Class A to river mile 38.1.
3. 7dadMax: 7-day average of the daily maximum temperature.

A-6 Climate Data

Climate data collected for calibration of the Tucannon River Model included air temperature, solar radiation, wind, and dew point temperature.

- **Air temperature** – Hourly air temperatures were collected by Ecology at the Pataha, and Marengo stations and by the USFS at the Alders Ridge Station. A lapse rate based was calculated based on elevation between the stations.

- **Solar radiation** – Hourly solar radiation data were obtained from three surrounding Agrimet stations.
- **Wind data** – Hourly wind data used in the model were based on the USFS Alder Ridge Station.
- **Dew point temperatures** – Hourly dew point data were obtained from USFS Alder gage and Powers gages.

A-7 Riparian Vegetation and Shading Conditions

Current vegetation characteristics, including height and density, are used to estimate effective shade from the riparian zone. Vegetation characteristics were developed from field riparian surveys and estimated from the most recent orthophotos within 150 feet of the centerline of the Tucannon River. Vegetation height, type, and canopy cover categories were assigned to nine zones on each side of the river, based on visual interpretation and field observations collected in the habitat surveys described below.

Field Data Collection

Riparian vegetation data were collected during stream surveys of 17 WDFW temperature monitor stations in July 2005. An adapted form of the Timber-Fish-Wildlife Stream Temperature Survey methodology was followed to collect this data (Schuett-Hames et al., 1999). Stream surveys began at the location of each temperature monitor and continued upstream for 1000 feet. Measurements were taken at 100 feet intervals above each temperature monitor. Data collected consisted of bankfull width and depth, wetted width and depth, effective shade (using a Solar Pathfinder), vegetation height, vegetation density, general vegetation type, distance that vegetation covers the stream channel, and bank incision. A Solar pathfinder was used to measure effective shade at each transect to verify the range of vegetation classes digitized from review of digital orthophotos and assess the accuracy of estimates developed in Ecology's Shade Model.

GIS Analyses

GIS riparian vegetation type and density mapping was conducted at 100-meter intervals using the most recent black and white orthophotograhs for Columbia County (1994-1996). At each stream transect, the vegetation was sampled at 5.1-meter intervals and progressing to 45.7 meters (150 feet) from each side of the stream (Refer to Figure A-5). Riparian coverages were created by qualifying three attributes: tree height, vegetation group (conifer, deciduous, shrub), and average canopy density. The near-stream disturbance zones (NSDZ) were based on field measurements collected from the field.

The sources of other elements required by Ecology’s Shade Model are listed below:

- West, east, and south topographic shade angle calculations were made from the 10-meter DEM grid using ODEQ’s Ttools extension for ArcView.

- Stream elevation and gradient were sampled from the 10-meter DEM grid with the ArcView Ttools extension. Gradient was calculated from the longitudinal profiles of elevation from the 10-meter DEM.
- Aspect (streamflow direction in decimal degrees from north) was calculated by the Ttools extension for ArcView.

Field observations of vegetation type, height, and density were also compared against the digitized GIS data. Effective shade produced by current riparian vegetation was estimated using Ecology's Shade model (Ecology, 2003). Effective shade is defined as the fraction of incoming solar short wave radiation above the vegetation and topography that is blocked from reaching the surface of the stream.

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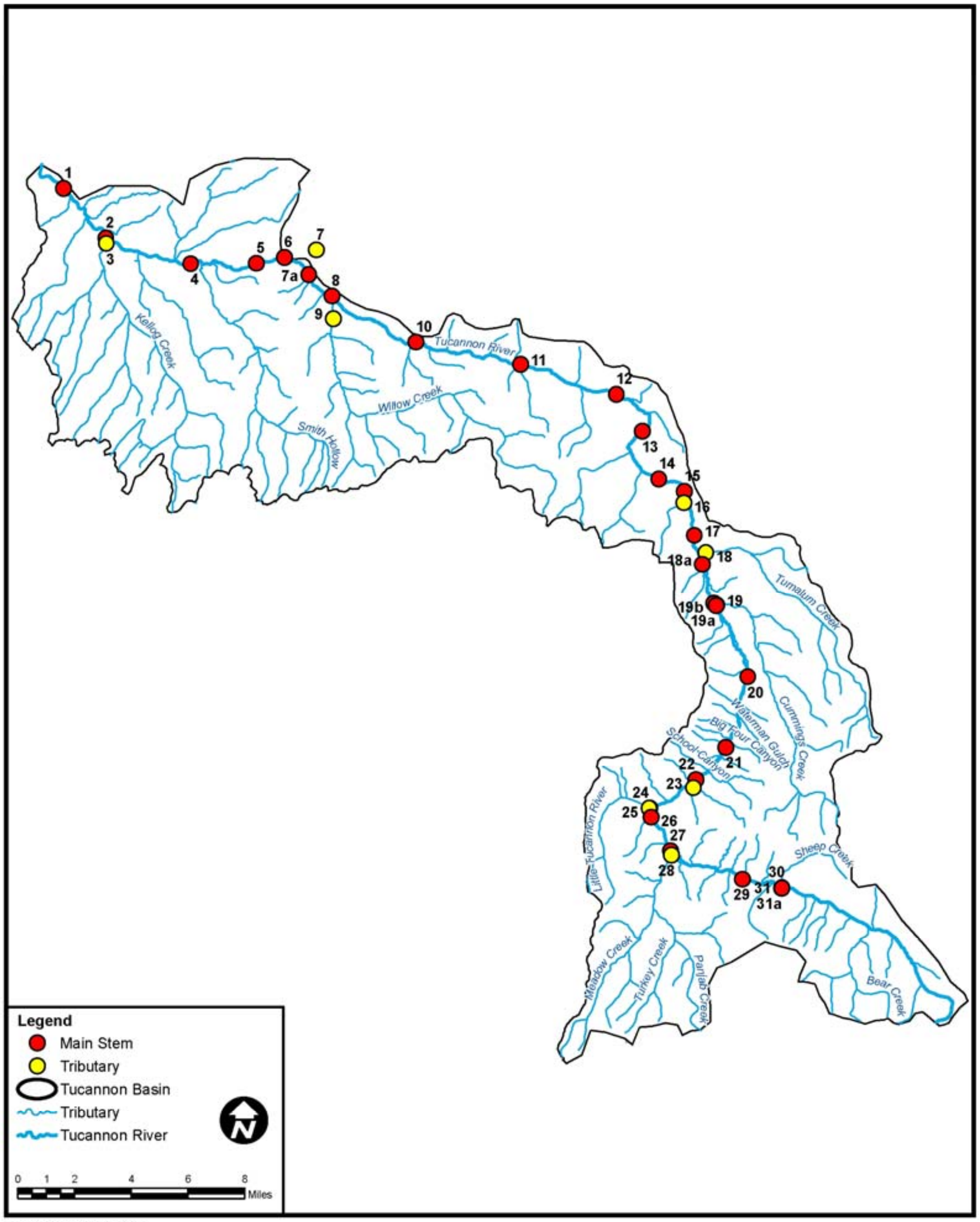

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Figure A-1 Tucannon River seepage study monitoring stations

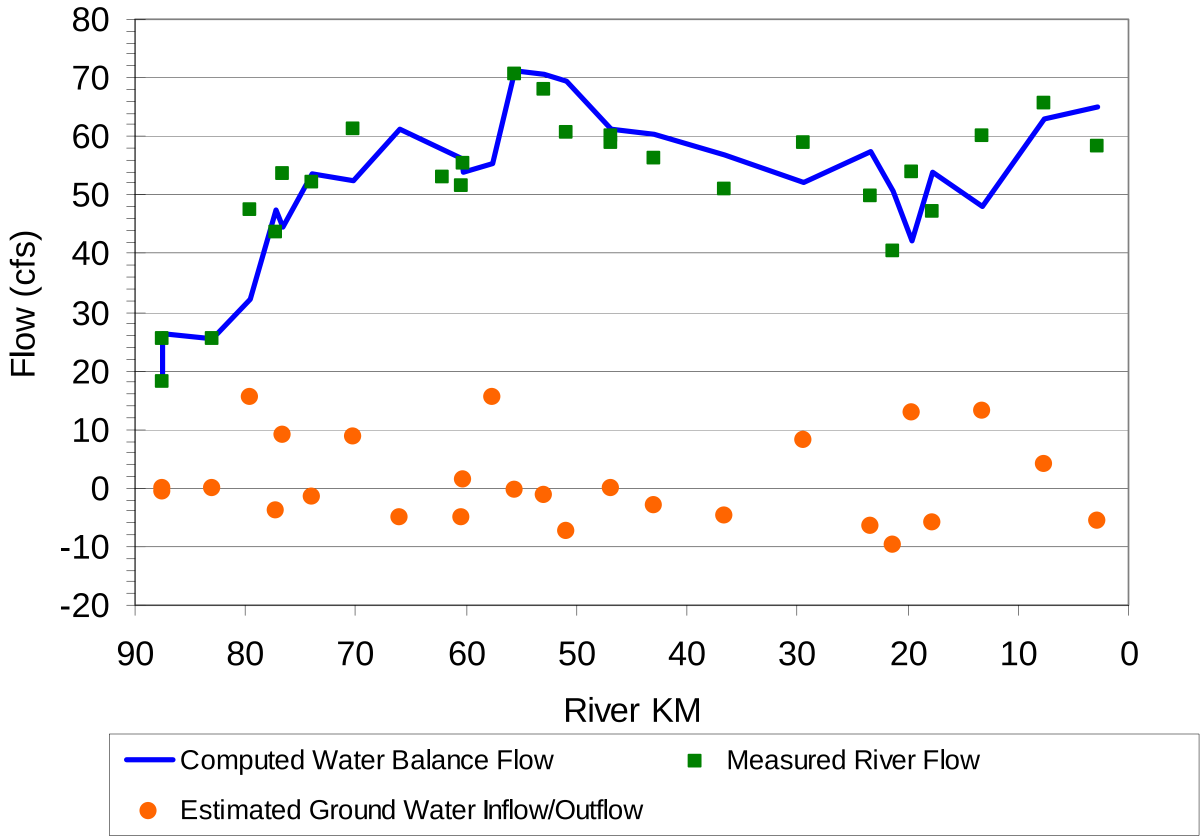

Figure A-2 Seepage run flow balance

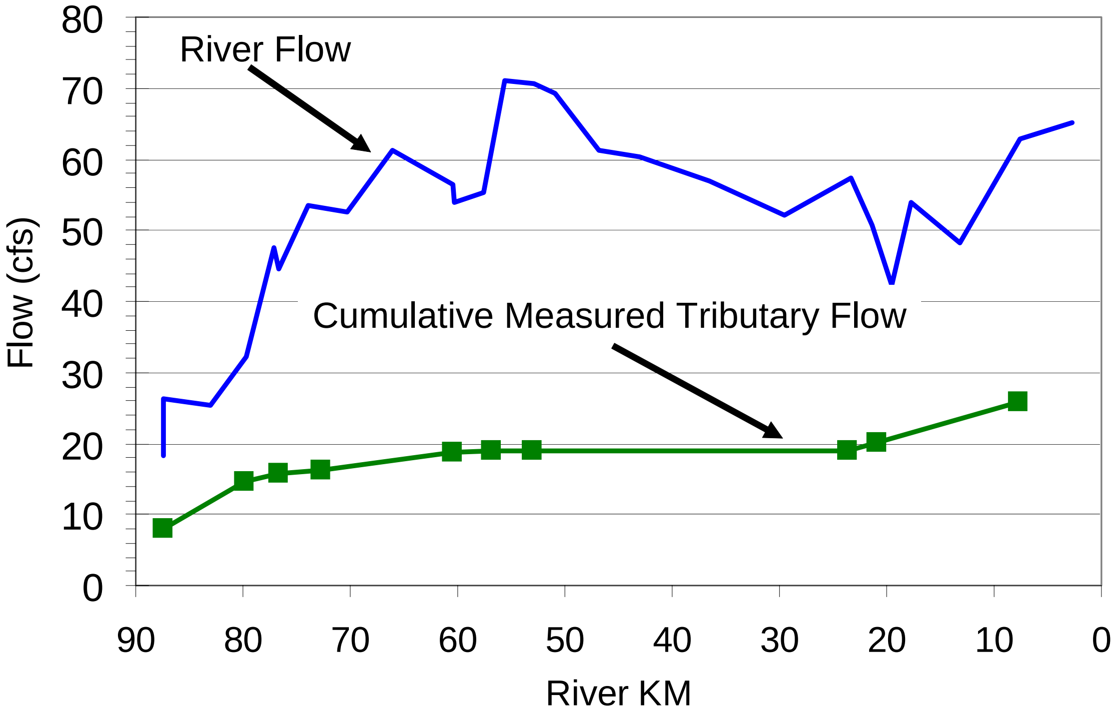

Figure A-3 Measured tributary flow to the Tucannon River during the July 13th Seepage run

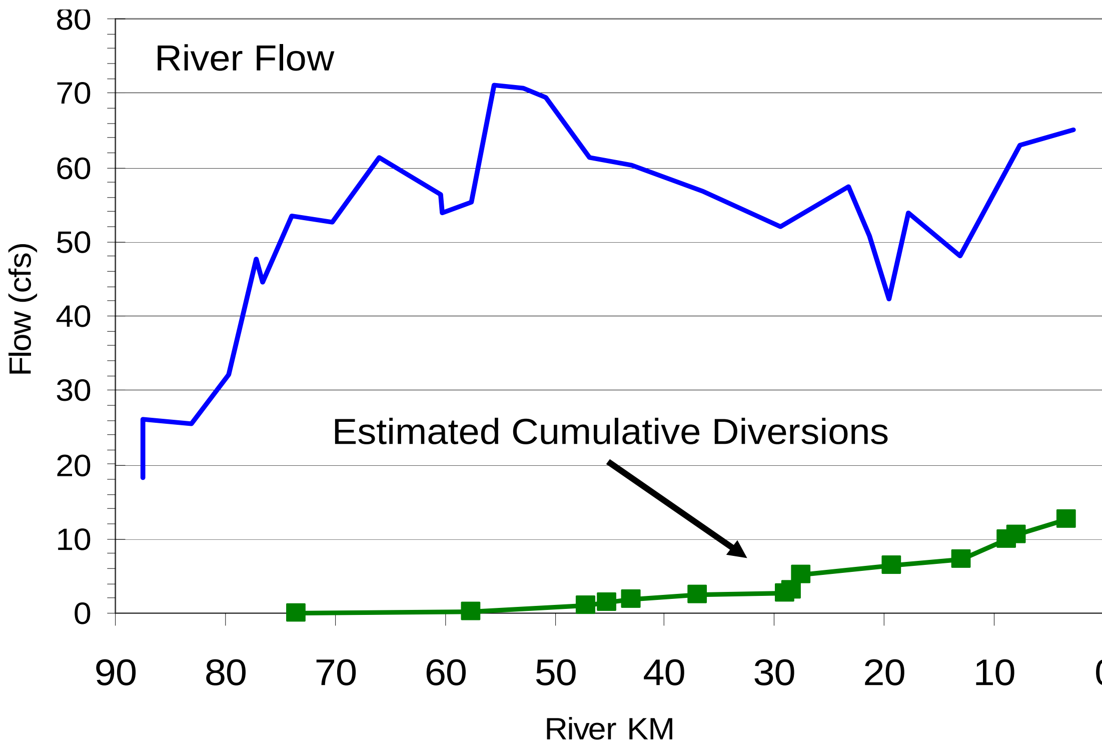

Figure A-4 Estimated withdrawals from Tucannon River during the July 13th Seepage run

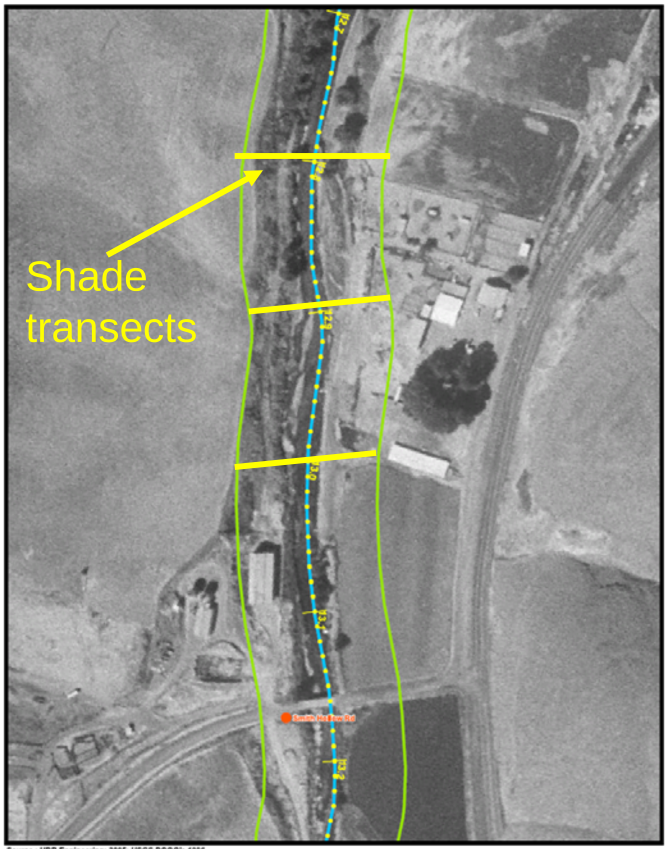

Figure A-5 Example of the black and white digital orthophoto quad (DOQ) for the mainstem of the Tucannon River.

Appendix B –
Tucannon River QUAK2Kw Model Description

Appendix B
Tucannon River QUAL2Kw Model Description

This appendix provides an overview of the methods used to develop the Tucannon River temperature QUAL2Kw model (Tucannon River model). The QUAL2Kw model was used to calculate the components of the heat budget and simulate water temperatures. Ecology's Shade model was used to represent effective shade from vegetation and topography. Ttools, a GIS analytical tool developed by the Oregon Department of Environmental Quality (ODEQ), was used generate aspect and other physical characteristics of the river in the model. A schematic representation of the Tucannon River model is shown in Figure B-1.

B-1 Model Approach

The approach for modeling used in this project is similar to the methods used by Ecology for temperature TMDL modeling studies. The following three software tools used in Ecology's temperature TMDL modeling studies were used for this project:

- ODEQ's Ttools extension for ArcView (ODEQ, 2001) was used to sample and process GIS data for input to the Shade and QUAL2Kw models.
- Ecology's Shade model (Ecology, 2003) was used to estimate effective shade along the Tucannon River. Effective shade was calculated at 100-meter intervals along the river and then averaged over 1-kilometer intervals for input to the QUAL2Kw model.
- The QUAL2Kw model, version 5.1 (Pelletier and Chapra, 2003; Chapra and Pelletier, 2003) was used to calculate the components of the heat budget and to simulate water temperatures. QUAL2Kw simulates diurnal variations in stream temperature for a steady flow condition. QUAL2Kw was applied by assuming that flow remained constant for a 1-day period, but key variables were allowed to vary with time over the course of a day.

B-2 Summary of Model Input Parameters

- **Boundary conditions -** The hourly measured temperatures for the boundary conditions at the headwaters and tributaries were used as input to the QUAL2Kw model for the July 13th calibration period.
- **Reach hydraulic geometry -** Reach hydraulic geometry (wetted width and depth) was based on field measurements. The bottom widths for the model stations were calculated using Ecology's Manning's n spreadsheet. The input variables included side slopes, channel slope, Manning's n, flow, and water depth. A constant side slope estimated from the average cross section side slopes was used. Channel slope of each segment based on GIS data was used. Manning's n values were estimated based on field surveys, measured data, and photographs for the measured stations.

The Manning's n values were linearly interpolated between the measured stations for the additional model reaches. Measured flows from the seepage run were used for the measured stations and remained constant for the intermediate model stations. Flow changed at the next measured station since measurements were taken at each location of flow changes, i.e., tributaries. The water depth was used for each measured station and linearly interpolated between the measured stations for the additional model stations. This assumes a steady change in water depth. Bottom widths were then calculated for all stations based on this input data and then entered into the Tucannon River model.

- **Groundwater temperature -** The temperature of groundwater (diffuse inflow in the QUAL2Kw model) is often assumed to be the mean annual air temperature (Theurer et al, 1984). A temperature of 11 °C was used in the Tucannon River model to represent groundwater temperatures, based the mean annual temperature measured at Dayton (Western Regional Climate Center Data 2006). This corresponds well with groundwater temperatures measured in the Tucannon River basin (Covert et al., 1995). Groundwater inflows typically cool summertime stream temperatures. Subsurface water is insulated from surface heating processes and groundwater temperatures typically do not fluctuate little and are relatively cool.
- **Cloud cover -** No cloud cover was entered into the model, based on observations of clear skies during field data collection on July 13, 2005.
- **Air temperatures -** Hourly air temperatures were interpolated between reaches based on elevation using the air temperature data recorded at the lower end of the drainage basin (Ecology's Pataha station, elevation 886 feet) and the upper end of the drainage basin (USFS Alder Ridge RAWS [Remote Automated Weather Station] station, elevation 4,500). The result was an average air temperature lapse rate of 6.6 °C/km. For the study, air temperature ranged from 9.5 °C at Alder Ridge to 31.5 °C at Pataha on July 13, 2005.
- **Dew point temperatures** - Hourly dew point temperatures were interpolated between reaches based on elevation using the air temperature data recorded at the lower end of the drainage basin (Ecology's Pataha station and Powers stations) and the upper end of the drainage basin (USFS Alder Ridge RAWS [Remote Automated Weather Station] station). The difference in air temperature between the Powers and Pataha gages and the Power dew point temperature were used to estimate the dew point temperature for Pataha. The data from primarily the Pataha and Alder gages were used to develop an elevation dew point temperature lapse rate based on their elevations of 886 and 4,500-feet, respectively. The result was an average dew point temperature lapse rate of 10.4 °C /Km. The Pataha station dew point

temperatures were then used to estimate dew point temperatures for each of the reaches based on their elevation and the dew point temperature lapse rate.

- **Wind speed** - Hourly wind speed was based on the USFS Alder Ridge RAWS [Remote Automated Weather Station] station.
- **Solar radiation** - Solar radiation from three surrounding Agrimet stations (Silcott Island, Lake Bryan, Legrow) was compared to the results from the Solar Position and Radiation Calculator available from the Ecology website. The Ryan-Stolzenbach method (using a default coefficient of 0.8) was used in the Tucannon River model because it produced average and peak solar radiation values similar to the data from the three observation stations.
- **Point Sources and tributaries -** For point sources and tributaries input, no point sources were included and ten tributaries were included. The tributaries were: Sheep, Panjab, Hixon, Cummings, Tumalum, Hartsock, Willow, Pataha, and Kellogg Creeks and the Little Tucannon River. Most of the streams had hourly water temperature data from the WDFW temperature probes. Tumalum and Kellogg Creeks did not and the temperatures measured during the seepage run survey were used in the Tucannon River model.
- **Groundwater inflows and outflows -** Diffuse sources were entered for reaches in the Tucannon River based on the water budget calculated from the Seepage Run water budget. The average groundwater temperature was based on annual average air temperatures as described above.
- **Withdrawals** - There are thirteen point source abstractions (irrigation diversions) which were included based on the estimated flows from the seepage run survey.
- **Hyporheic exchange** - Hyporheic exchange was input to the model and adjusted as part of the calibration process.

B-3 Existing Riparian Shade

Existing vegetation attributes were verified or refined in the field using observations of vegetation type. Habitat surveys also provided Solar Pathfinder readings at each riparian survey transect. Effective shade produced by current riparian vegetation was estimated using Ecology’s Shade model (Ecology, 2003b). The riparian vegetation codes used to represent the Current Conditions scenario are listed in Table B-1. Effective shade is defined as the fraction of incoming solar short wave radiation above the vegetation and topography that is blocked from reaching the surface of the stream.

Figure B-2 presents effective shade predicted along the Tucannon River within the study area. Effective shade generally ranges from 0 to 60% due to a combination of vegetation removal, a wide bankfull width, and relatively little topographic shade during this time of year.

Table B-1. Riparian codes used in the Current Conditions Shade Model for calibrated Tucannon River model

Code	Description	Height (m)	Density (%)	Overhang (m)
111	Conifer, small, sparse	12.8	25%	1.5
112	Conifer, small, moderate	12.8	50%	1.5
113	Conifer, small, dense	12.8	75%	1.5
121	Conifer, medium, sparse	18.3	25%	2.1
122	Conifer, medium, moderate	18.3	50%	2.1
123	Conifer, medium, dense	18.3	75%	2.1
124	Conifer, medium, very dense	18.3	100%	2.1
132	Conifer, large, moderate	21.3	50%	3.0
133	Conifer, large, dense	21.3	75%	3.0
134	Conifer, large, very dense	21.3	100%	3.0
211	Deciduous, small, sparse	5.2	25%	0.8
212	Deciduous, small, moderate	5.2	50%	0.8
213	Deciduous, small, dense	5.2	75%	0.8
214	Deciduous, small, very dense	5.2	100%	0.8
221	Deciduous, medium, sparse	10.7	25%	1.5
222	Deciduous, medium, moderate	10.7	50%	1.5
223	Deciduous, medium, dense	10.7	75%	1.5
224	Deciduous, medium, very dense	10.7	100%	1.5
232	Deciduous, large, moderate	18.3	50%	2.7
233	Deciduous, large, dense	18.3	75%	2.7
311	Mixed, small, sparse	4.9	25%	1.1
312	Mixed, small, moderate	4.9	50%	1.1
313	Mixed, small, dense	4.9	75%	1.1
321	Mixed, medium, sparse	10.4	25%	1.8
322	Mixed, medium, moderate	10.4	50%	1.8
323	Mixed, medium, dense	10.4	75%	1.8
332	Mixed, large, moderate	17.7	50%	2.9
333	Mixed, large, dense	17.7	75%	2.9
411	Herbaceous, sparse	0.9	25%	0.2
433	Herbaceous, dense	0.9	75%	0.2
555	Barren	0.0	100%	0.0

B-4 Full Shade Riparian Vegetation

The height and density of riparian vegetation for the Full Shade model scenario were based on estimates of system potential vegetation developed for the Touchet River, an adjacent drainage basin (Anita Stohr, Ecology, personal communication). In developing the Full Shade scenario, Ecology relied on work conducted for the Walla Walla temperature TMDL (ODEQ 2005).

The distances along the Tucannon River covered by the vegetation categories in the Full Shade Scenario coincide with elevations of the vegetation categories used for the Touchet River. For example, shrub vegetation occurs up to an elevation of 902 feet (275 meter) in the Touchet River, which corresponds to RK 0 to 22.1 (river mile 0 to 13.7) along the Tucannon River.

The riparian vegetation codes used to represent the Full Shade scenario are listed in Table B-2.

Table B-2. Vegetation characteristics used in the Tucannon River model to represent the Full Shade scenario

River Kilometer	River Mile	Elevation (m)	Elevation (feet)	Riparian Zone Name	Height (m)	Height (feet)	Density	Overhang (m)
0 - 22.1	0 -13.7	0 - 275	0 – 902	Shrub	9.4	31	80%	0.8
22.1 – 53.4	13.7 – 33.2	275 - 556	902 - 1824	Deciduous	22.0	72	80%	2.0
53.4 – 65.8	33.2 – 40.9	556 - 706	1824 - 2316	Mixed	25.0	82	80%	2.0
> 65.8	> 40.9	> 706	> 2316	Conifers	24.0	79	80%	2.0

Figures B-3 through B-5 compare the effective shade for Current and Full Shade scenarios for the lower, mid and upper Tucannon River riparian areas. The figures indicate the largest differences in shade occur in the middle section of the river.

B-5 Model Calibration

The goodness of fit for the calibration period was summarized using the root mean square error (RMSE) as a measure of the deviation of model-predicted stream temperature from the measured values. The RMSE represents an estimation of the overall model performance. The headwater measurement location (at Sheep Creek) was not used in the computation because it influenced the model prediction as a headwater boundary condition. The RMSE were calculated for daily average, daily maximum, and daily minimum temperatures for the calibration period (Table B-3). The RMSEs for the final model calibration were less than 1.0 °C.

Table B-3. Comparison of measured and modeled Tucannon River temperatures (°C)

			Measured			Modeled			Delta		
	Location	River km	Daily Mean	Daily Minimum	Daily Maximum	Daily Mean	Daily Minimum	Daily Maximum	Daily Mean	Daily Minimum	Daily Maximum
1	**at Sheep Creek**	87.5	11.2	9.7	12.9	10.5	9.3	12.2	-0.7	-0.4	-0.7
2	**Lady Bug Flat CG**	84.8	10.9	9.4	13.0	11.5	9.7	14.2	0.5	0.3	1.2
3	**Panjab Br**	79.7	11.5	9.5	14.0	12.3	10.1	15.4	0.8	0.7	1.4
4	**at Little Tucannon R**	76.5	12.7	10.1	16.4	12.7	10.5	15.9	0.0	0.3	-0.4
5	**Camp Wooten**	73.2	13.8	10.8	18.1	13.2	10.6	17.1	-0.6	-0.2	-1.1
6	**Big 4 Lake**	70.4	14.8	11.7	18.6	13.8	10.8	17.8	-1.1	-0.9	-0.8
7	**USFS Sign**	65.6	15.6	12.3	19.4	15.0	11.3	19.7	-0.5	-1.0	0.4
8	**Hatchery Intake**	63.7	16.0	12.6	19.7	15.4	11.5	20.1	-0.6	-1.1	0.4
9	**Cummings Cr Br**	60.3	16.3	13.2	19.7	15.8	11.9	20.2	-0.5	-1.3	0.5
10	**Weller Bridge**	55.6	17.0	13.5	21.2	16.1	12.6	19.9	-0.9	-0.9	-1.3
11	**Donahue**	50.9	17.2	13.8	21.3	17.3	13.6	21.3	0.1	-0.2	0.0
12	**Howard**	46.8	17.7	14.3	21.6	18.0	14.3	22.0	0.3	0.0	0.4
13	**Marengo**	43.0	18.3	15.5	21.4	18.6	15.0	22.3	0.3	-0.5	0.9
14	**King Grade**	36.6	18.7	15.6	21.9	19.9	16.7	23.1	1.2	1.1	1.2
15	**Enrich Rd Bridge**	29.6	19.2	16.0	22.8	20.1	17.2	23.1	0.8	1.2	0.3
16	**US Hwy 12 Bridge**	23.3	19.9	16.1	24.1	21.0	18.0	24.5	1.2	1.9	0.4
17	**Territorial Rd Br**	21.4	20.1	16.6	24.0	21.3	18.2	24.9	1.3	1.6	0.9
18	**Ducharme**	17.8	20.3	16.6	24.4	20.6	17.8	23.7	0.3	1.2	-0.6
19	**Smith Hollow Rd**	13.2	20.5	17.3	23.9	19.7	16.9	22.9	-0.8	-0.4	-1.0
20	**Smolt Trap**	2.8	21.2	17.6	24.9	21.3	17.9	25.0	0.0	0.4	0.1
	RMSE								**0.73**	**0.95**	**0.81**

Notes: 1. Headwater station (at Sheep Creek) not included in estimate of root mean square error (RMSE).

2. Measured data from July 13th 2005.

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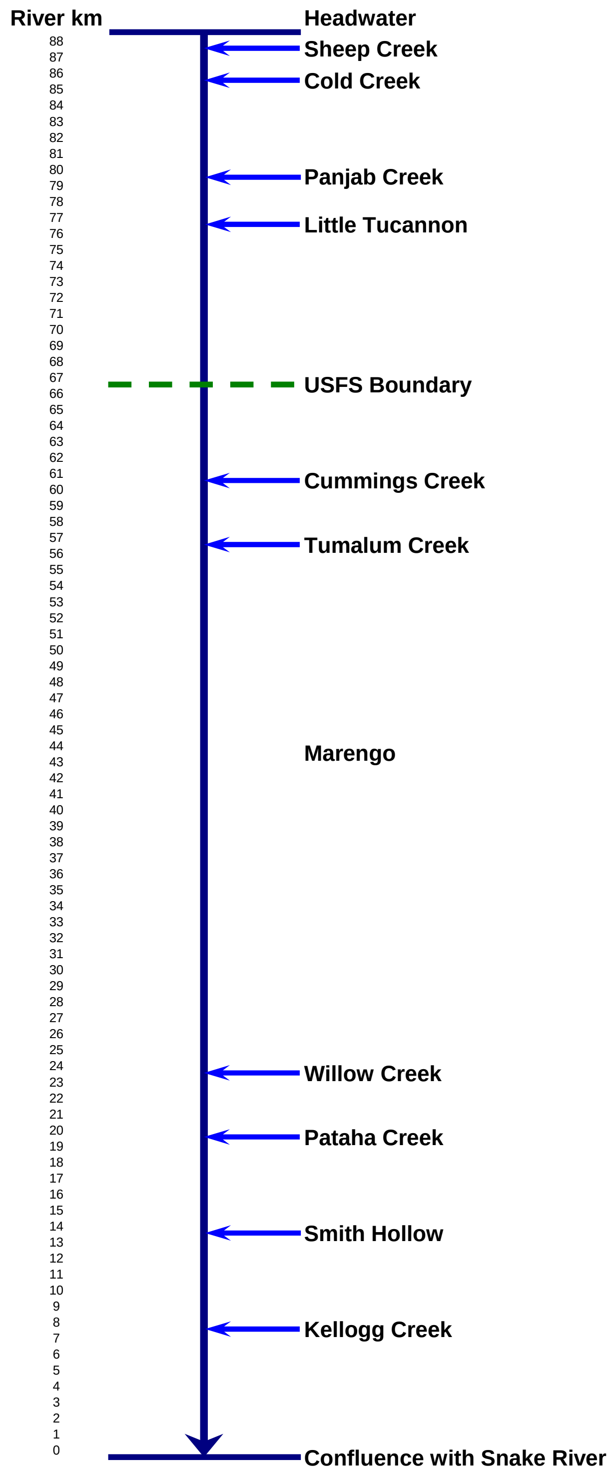

Figure B-1 Schematic of Tucannon River QUAL2Kw temperature model

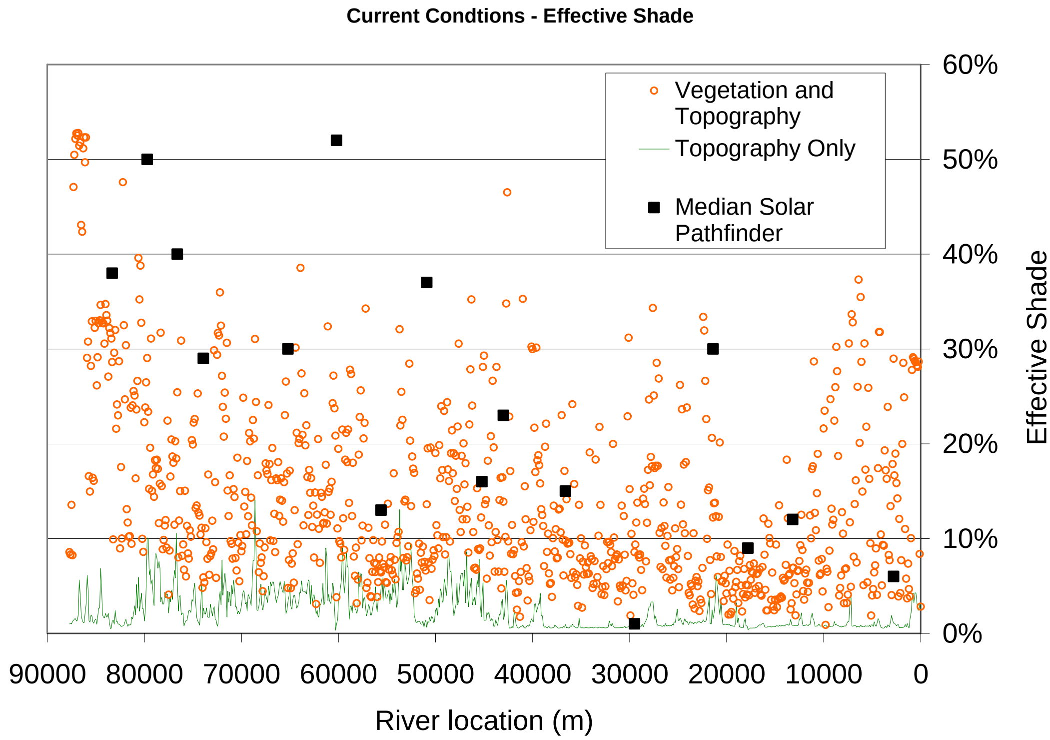

Figure B-2 **Effective shade predicted for the Current Conditions and Topographic Shade scenarios**

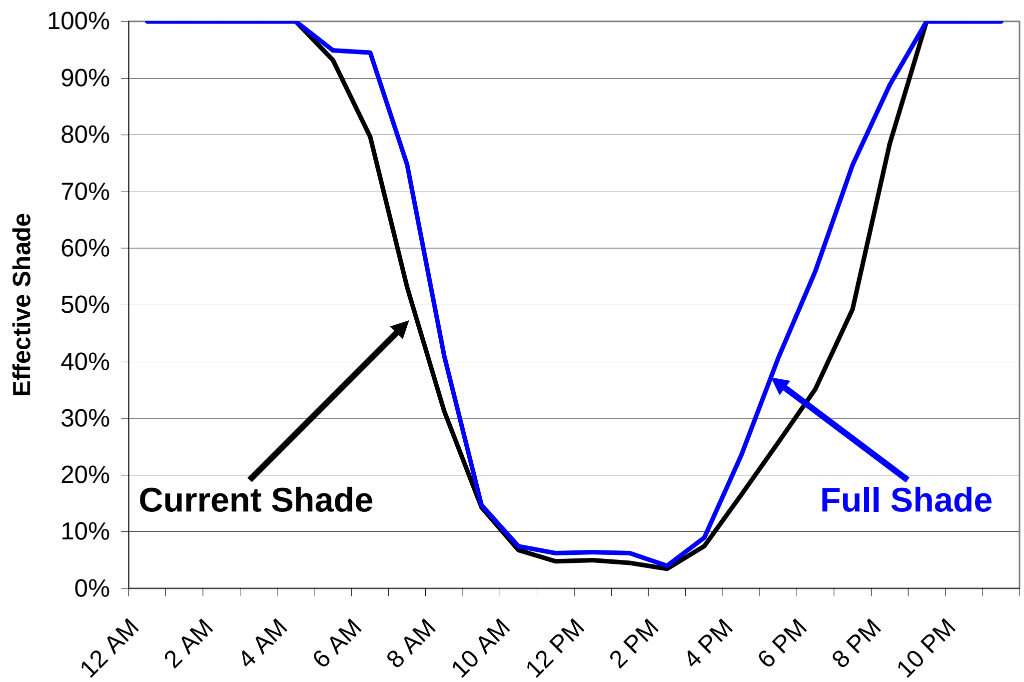

Figure B-3 **Tucannon River modeled effective shade at Powers Bridge (RK 3) for Current Conditions and Full Shade scenarios**

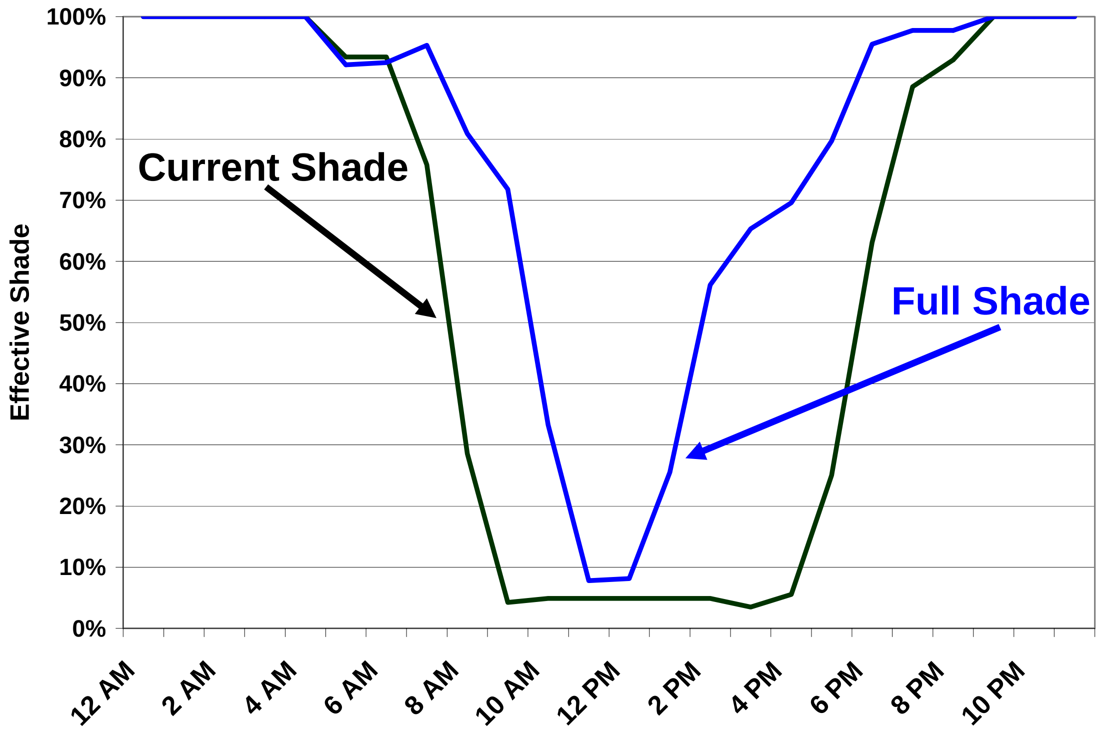

Figure B-4 Tucannon River modeled effective shade at Marengo (RK 43) for Current Conditions and Full Shade scenarios

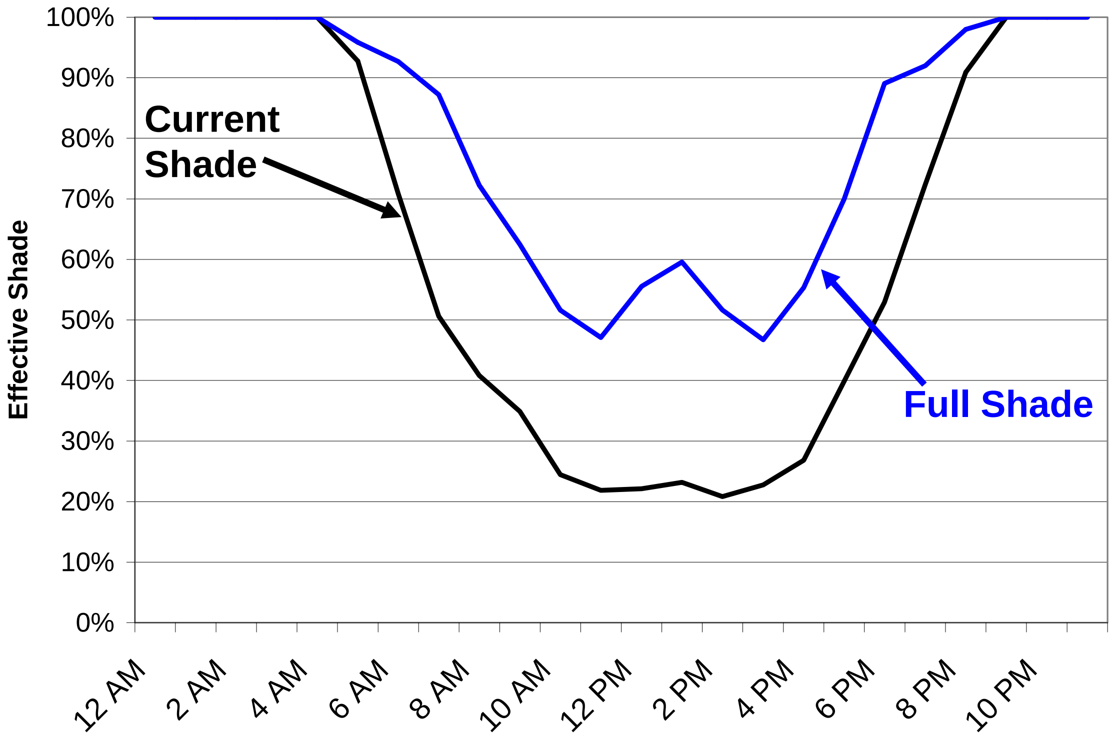

Figure B-5 Tucannon River modeled effective shade at Lady Bug Flat Campground (RK 84) for Current Conditions and Full Shade scenarios