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DEPARTMENT OF
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Lower Skagit River Tributaries Temperature Total Maximum Daily Load Study

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Lower Skagit River Tributaries Temperature Total Maximum Daily Load Study

by

Brian Zalewsky and Dustin Bilhimer

Washington State Department of Ecology
Environmental Assessment Program

January 2004

Waterbody Numbers: See Table 1

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Table of Contents

List of Appendices

List of Figures

List of Figures (cont.)

List of Tables

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Abstract

The study area for this Total Maximum Daily Load (TMDL) includes the major tributaries to the lower Skagit River below Skiyou Island. The federal Clean Water Act Section 303(d) listings for impaired stream temperature in the lower Skagit River basin include these creeks: Carpenter, Fisher, Hansen, Lake, Nookachamps, East Fork Nookachamps, Red, Turner, and Otter Pond.

Significant reductions in water temperature are predicted for hypothetical conditions with 100-year-old riparian vegetation, improvements in riparian microclimate, and reductions in channel width. Maximum reductions in water temperature would likely result from a combination of mature riparian vegetation, historic channel complexities, and pre-settlement flow regimes.

Potential reduced temperatures are predicted to be less than the Washington State water quality standard of 18°C for Class A waters in most of the segments evaluated. Those segments not expected to be less than the 18°C are the outlets of Lake McMurray and Big Lake. Surface water temperatures in these two lakes frequently exceed 22°C during the summer.

Natural conditions may exceed the numeric temperature criteria mandated by the water quality standards. In these cases, the antidegradation provisions of those standards apply (Chapter 173-209A-030 WAC). These provisions state that "*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.*"

This technical study uses effective shade as a surrogate measure of heat flux to fulfill the requirements of Section 303(d) for a temperature TMDL. Effective shade is defined as the fraction of incoming solar shortwave radiation, above the vegetation and topography, that is blocked from reaching the stream surface.

In addition to load allocations for effective shade, other management activities are recommended for compliance with water quality standards for water temperature, including measures to promote efficient water use and increase groundwater inflows into the streams.

Acknowledgements

We would like to thank the following Washington State Department of Ecology staff for their contributions to this study:

- Sally Lawrence for reviewing the draft report, coordinating the public review process for the study, and drafting the section of the report on instream flow rules.
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- Joan LeTourneau for formatting and editing the final report.

Introduction

The lower Skagit River basin includes portions of Skagit and Snohomish counties in northwest Washington State (Figure 1). Ecology's assessment of the lower Skagit River watershed identified the system as a high priority for the development of a Total Maximum Daily Load (TMDL) for temperature.

The purpose of the lower Skagit River temperature TMDL is to characterize water temperatures in the basin and to establish load and wasteload allocations for heat sources in order to meet water quality standards for surface water temperature. This study focuses on the 303(d) listings in Carpenter, Fisher, Hansen, Nookachamps, East Fork Nookachamps, Red, Turner, and Otter Pond creeks for exceeding the state's water quality standards for temperature (Table 1).

Table 1. 1998 303(d) listings for temperature in the lower Skagit River basin.

Waterbody Name	Township	Range	Section	Watercourse IIP 303(d) number	Waterbody ID number	1996 303(d) List	1998 303(d) List
CARPENTER CREEK	**33N**	**04E**	**17**	**YA61IC**	**WA-03-1011**		**X**
CARPENTER CREEK	**33N**	**04E**	**20**	**YA61IC**	**WA-03-1011**		**X**
CARPENTER CREEK	**33N**	**04E**	**9**	**YA61IC**	**WA-03-1011**		**X**
COAL CREEK	35N	05E	10	RE17FI	None11		X
CUMBERLAND CREEK	35N	06E	23	QX54OS	None7		X
DAY CREEK	35N	06E	28	QT99QB	None8		X
FISHER CREEK	**33N**	**04E**	**30**	**JK73SN**	**WA-03-1012**		**X**
HANSEN CREEK	**35N**	**05E**	**29**	**PU87PF**	**WA-03-1019**		**X**
HANSEN CREEK	**35N**	**05E**	**20**	**PU87PF**	**WA-03-1019**		**X**
HANSEN CREEK	**35N**	**05E**	**17**	**PU87PF**	**WA-03-1019**		**X**
INDIAN (BIG) SLOUGH				390KRD	WA-03-3100	X	X
INDIAN (BIG) SLOUGH				390KRD	WA-03-3100	X	X
INDIAN (BIG) SLOUGH				390KRD	WA-03-3100		X
JOE LEARY SLOUGH				390KRD	WA-03-3000		X
JOE LEARY SLOUGH				390KRD	WA-03-3000	X	X
JOE LEARY SLOUGH				390KRD	WA-03-3000	X	X
JONES CREEK	35N	06E	17	UT72SQ	None9		X
MUD LAKE CREEK	34N	04E	11	IL21OS	None10		X
NOOKACHAMPS CREEK	**34N**	**04E**	**25**	**LZ60MT**	**WA-03-1017**		**X**
NOOKACHAMPS CREEK	**34N**	**04E**	**25**	**LZ60MT**	**WA-03-1017**		**X**
NOOKACHAMPS CREEK	**33N**	**05E**	**8**	**ZZ50GP**	**WA-03-1017**		**X**
NOOKACHAMPS CREEK	**34N**	**04E**	**4**	**LZ60MT**	**WA-03-1017**		**X**
NOOKACHAMPS CREEK	**34N**	**04E**	**14**	**LZ60MT**	**WA-03-1017**		**X**
NOOKACHAMPS CREEK, E.F.	**34N**	**04E**	**11**	**DV97DN**	**WA-03-4200**		**X**
NOOKACHAMPS CREEK, E.F.	**34N**	**05E**	**19**	**FE06WU**	**WA-03-4200**		**X**
OTTER POND CREEK	**34N**	**04E**	**25**	**GK78TY**	**None5**		**X**
RED CREEK	**35N**	**05E**	**17**	**TL30EW**	**None6**		**X**
TURNER CREEK	**34N**	**05E**	**18**	**EI77IQ**	**None12**		**X**
WISEMAN CREEK	35N	05E	27	XZ26WG	None13		X

Waterbodies in bold denote 303(d) listings included in the study area.

Separate TMDLs are planned in the future that will address temperature impairments in the sloughs and Mid-Skagit tributaries. These waterbodies are not addressed in this TMDL.

Section 303(d) of the federal Clean Water Act mandates that the state establish TMDLs for surface waters that do not meet standards after application of technology-based pollution controls. The U.S. Environmental Protection Agency (EPA) has promulgated regulations (40 CFR 130) and developed guidance (EPA 1991) for establishing TMDLs.

Under the Clean Water Act, each state has its own water quality standards designed to protect, restore, and preserve water quality. Water quality standards consist of designated uses, such as cold water biota and drinking water supply, and criteria, usually numeric criteria, to achieve those uses. When a lake, river, or stream fails to meet water quality standards, the Clean Water Act requires the state to place the waterbody on a list of "impaired" waterbodies and to prepare an analysis called a TMDL.

The goal of a TMDL is to ensure the impaired water will attain water quality standards. A TMDL includes a written, quantitative assessment of water quality problems and of pollutant sources that cause the problem. The TMDL determines the amount of a given pollutant that can be discharged to the waterbody and still meet standards, meet the loading capacity, and allocate that load among the various sources.

If the pollutant comes from a discrete (point) source such as an industrial facility's discharge pipe, that facility's share of the loading capacity is called a *wasteload allocation*. If the pollutant comes from a diffuse (nonpoint) source, that portion of the loading capacity is called a *load allocation*. No point sources of heat were found in the lower Skagit study area; therefore, no wasteload allocation was developed.

The TMDL must also consider seasonal variations and include a margin of safety that takes into account any lack of knowledge about the causes of the water quality problem or its loading capacity. The sum of the individual allocations and the margin of safety must be equal to or less than the loading capacity. This TMDL addresses both the numeric and narrative condition provisions of the state's temperature criteria.

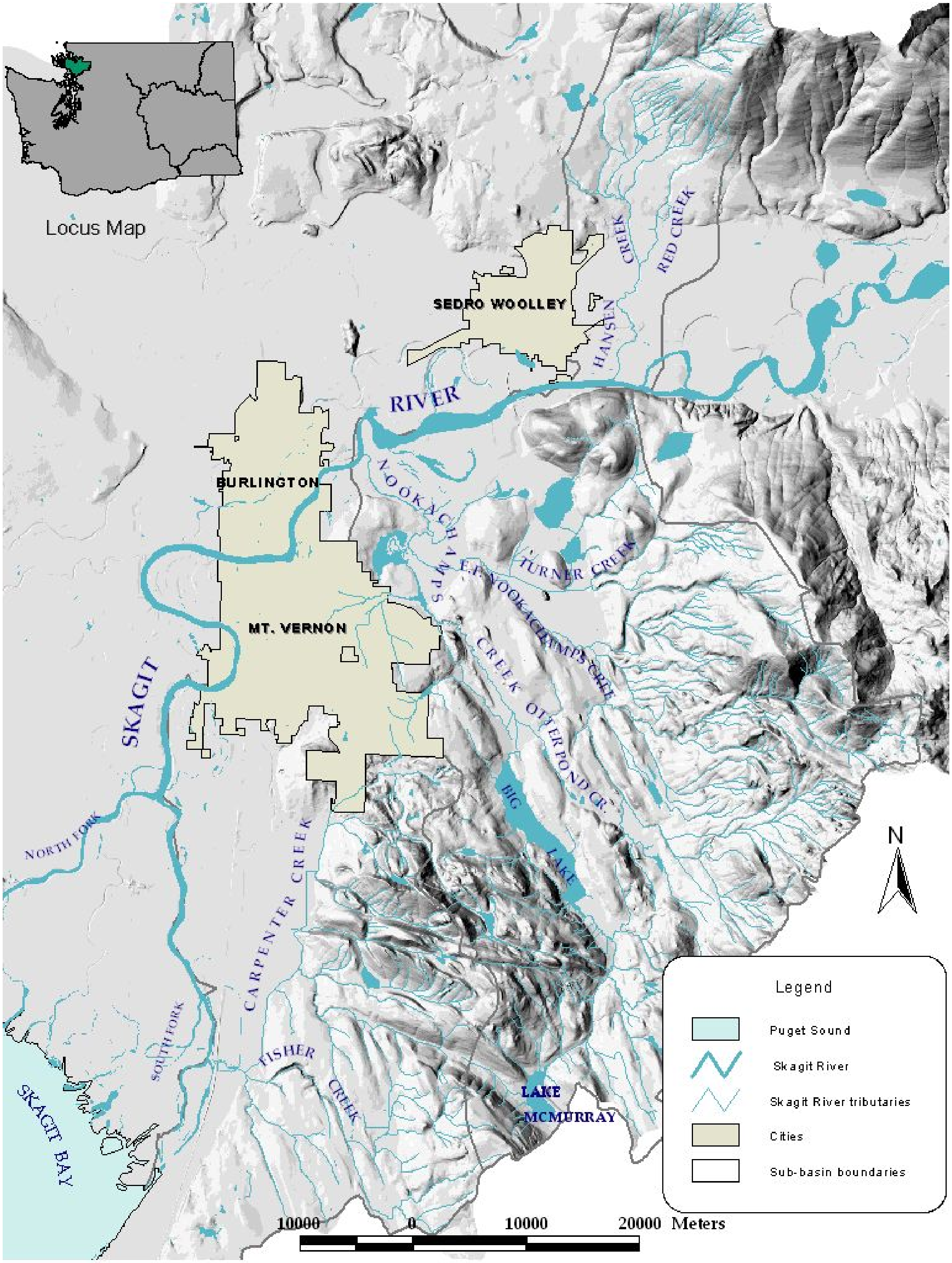

Figure 1. Lower Skagit River study area.

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Overview of Stream Heating Processes

At any particular instant of time, a defined stream reach is capable of sustaining a particular water column temperature. A parcel of water traversing a stream/river reach enters that reach with a given temperature. If that temperature is greater than the energy balance is capable of supporting, the temperature will decrease. If that temperature is less than the energy balance is capable of supporting, the temperature will increase. Stream temperature change within a stream segment is induced by the energy balance in the parcel of water that is affected by the surrounding environment during transport of the parcel through the reach. The general relationships between stream parameters, thermodynamic processes (heat and mass transfer), and stream temperature change are outlined in Figure 2.

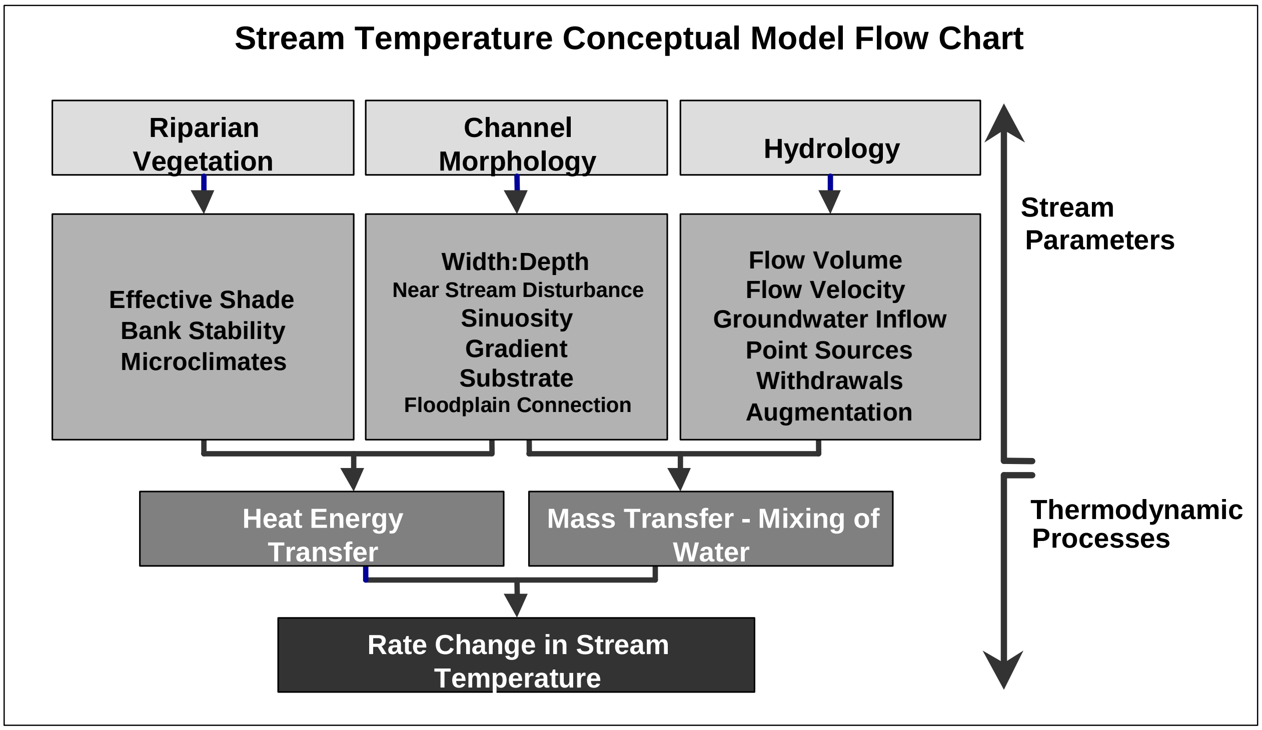

Figure 2. Conceptual model of factors that affect stream temperature.

Adams and Sullivan (1989) reported that the following environmental variables were the most important drivers of water temperature in forested streams:

- *Stream depth.* Stream depth is the most important variable of stream size for evaluating energy transfer. Stream depth affects both the magnitude of the stream temperature fluctuations and the response time of the stream to changes in environmental conditions.

- *Air temperature.* Daily average stream temperatures are strongly influenced by daily average air temperatures. When the sun is not shining, the water temperature in a volume of water tends to approach the dew-point temperature (Edinger et al. 1974).

- *Solar radiation and riparian vegetation.* Riparian vegetation moderates the amount of solar radiation that reaches the stream channel, thereby dampening seasonal and diel fluctuations in stream temperature (Beschta et al. 1987). The effectiveness of riparian vegetation in providing shade to the stream channel depends on local topography, channel orientation and width, forest composition, and stand age and density (Beschta et al. 1987).

- *Groundwater.* Since groundwater is generally much cooler than the stream temperatures during summer, inflows can have an important depressing effect on stream temperature. This effect will depend on the rate of groundwater inflow relative to the flow in the stream, as well as the difference in temperatures between the groundwater and the stream.

Heat Budgets and Temperature Prediction

The transport and fate of heat in natural waters has been the subject of extensive study. Edinger et al. (1974) provide an excellent and comprehensive report of this research. Thomann and Mueller (1987) and Chapra (1997) have summarized the fundamental approach to mathematical modeling of temperature in natural waters that was used in this temperature TMDL analysis. Figure 3 shows the major heat energy processes or fluxes in a heat budget that control temperature changes in a given volume of water. Heat flux between the water and streambed occurs through conduction and hyporheic exchange.

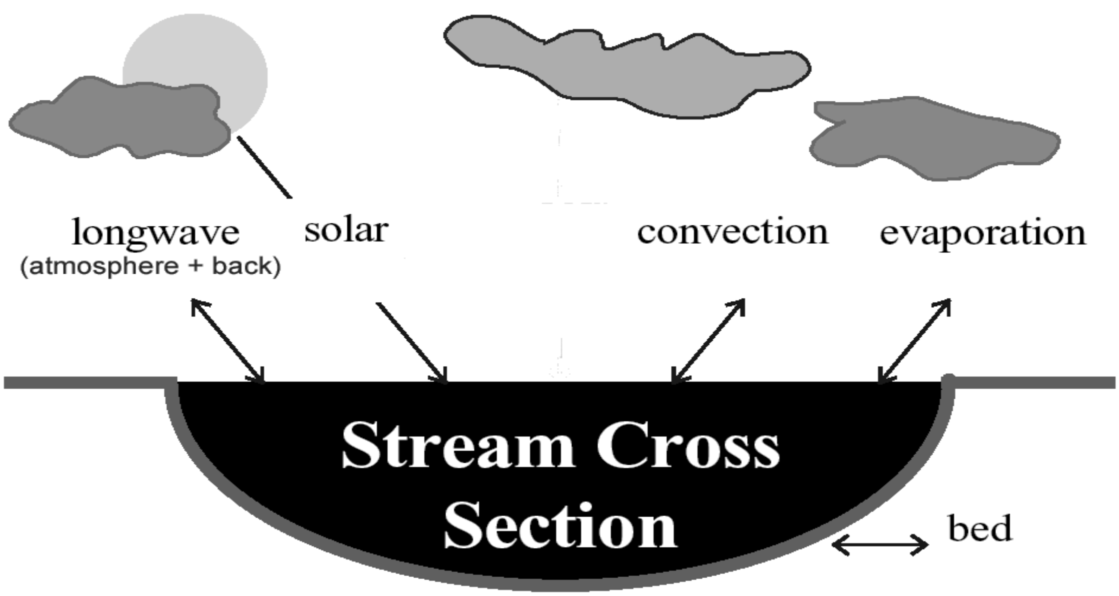

Figure 3. Heat transfer processes in the QUAL2Kw model that affect water temperature.
(net heat flux = solar + longwave atmosphere + longwave back + convection + evaporation + bed)

The heat flux components with the greatest magnitude, and therefore the greatest influence on water temperature, are as follows (Edinger et al. 1974):

- *Shortwave solar radiation.* Shortwave solar radiation is the radiant energy which passes directly from the sun to the earth. Shortwave solar radiation is contained in a wavelength range between 0.14 µm and about 4 µm. At NOAA's ISIS station in Seattle, the daily average global shortwave solar radiation for July-August 2001 was 240 W/m^2 (NOAA 2003). The peak values during daylight hours are typically about 3 times higher than the daily average. Shortwave solar radiation constitutes the major thermal input to an un-shaded body of water during the day when the sky is clear.

- *Longwave atmospheric radiation.* The longwave radiation from the atmosphere ranges in wavelength range from about 4 µm to 120 µm. Longwave atmospheric radiation depends primarily on air temperature and humidity, and increases as both of those increase. It constitutes the major thermal input to a body of water at night and on warm cloudy days. The daily average heat flux from longwave atmospheric radiation typically ranges from about 300 to 450 W/m^2 at mid latitudes (Edinger et al. 1974).

- *Longwave back radiation from the water to the atmosphere.* Water sends heat energy back to the atmosphere in the form of longwave radiation in the wavelength range from about 4 µm to 120 µm. Back radiation accounts for a major portion of the heat loss from a body of water. Back radiation increases as water temperature increases. The daily average heat flux out of the water from longwave back radiation typically ranges from about 300 to 500 W/m^2 (Edinger et al. 1974).

Figure 4 shows the relative importance of the fluxes in the heat budget at a station near the mouth of Hansen Creek with current riparian vegetation. This figure was derived using Ecology's QUAL2Kw (Ecology 2003b). 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). The net heat flux into a stream can be managed by increasing the shade from vegetation, which reduces the shortwave solar flux. Other processes, such as longwave radiation, convection, evaporation, bed conduction, or hyporheic exchange, also influence the net heat flux into or out of a stream.

Heat exchange between the stream and the streambed has an important influence on water temperature. The temperature of the streambed is typically warmer than the overlying water at night and cooler than the water during the daylight hours. Heat is typically transferred from the water into the streambed during the day then back into the stream during the night (Adams and Sullivan 1989). This has the effect of dampening the diurnal range of stream temperature variations without affecting the daily average stream temperature.

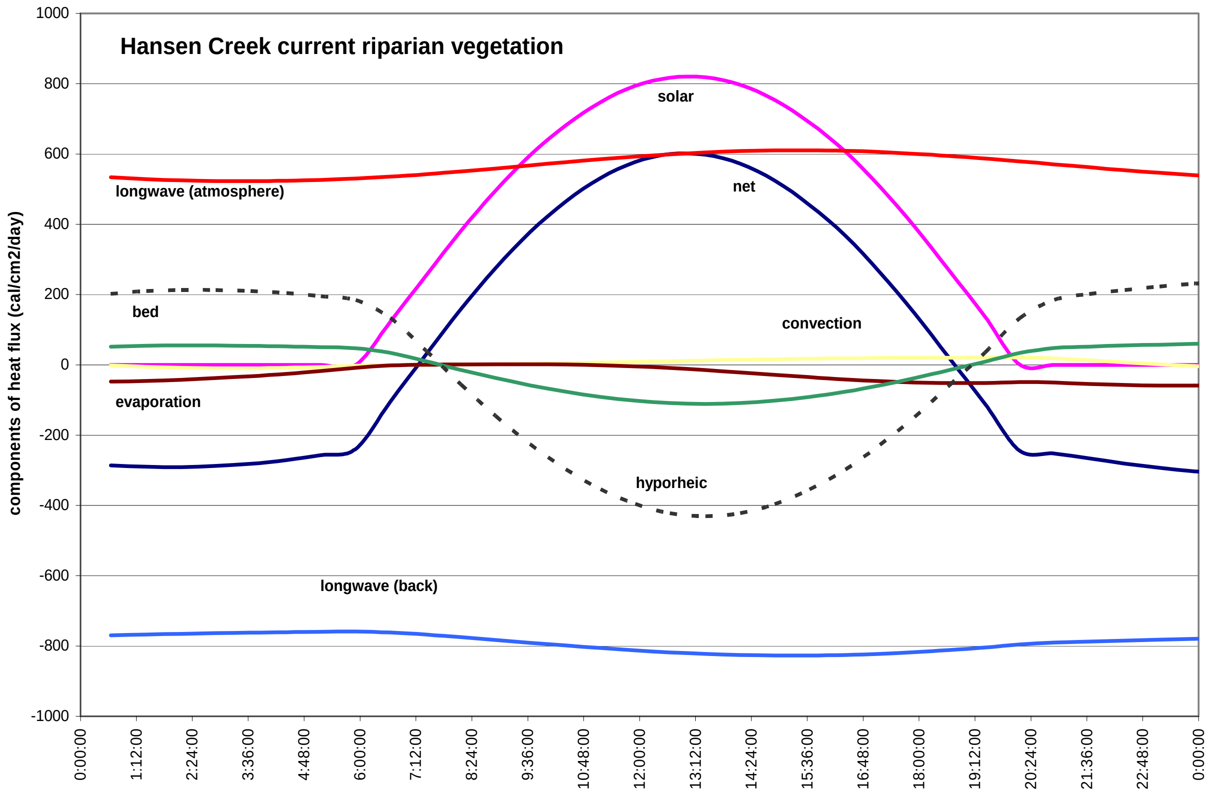

Figure 4. Heat fluxes in Hansen Creek near the mouth under current riparian vegetation conditions and during hottest 7-day air temperatures in 2001. (Net heat flux = solar + longwave atmosphere + longwave back + air convection + evaporation + sediment conduction + hyporheic.)

The bulk temperature of a vertically mixed volume of water in a stream segment under natural conditions tends to increase or decrease with time during the day according to whether the net heat flux is either positive or negative. When the sun is not shining, the water temperature tends toward the dew-point temperature (Edinger et al. 1974; Brady et al. 1969). The equilibrium temperature of a natural body of water is defined as the temperature at which the water is in equilibrium with its surrounding environment, and the net rate of surface heat exchange would be zero. The dominant contribution to the seasonal variations in the equilibrium temperature of water is from seasonal variations in the air temperature and dew-point temperature. The main source of hourly fluctuations in water temperature during the day is solar radiation. Solar radiation at the stream surface generally reaches a maximum during the day when the sun is highest in the sky unless cloud cover or shade from vegetation interferes.

The complete heat budget for a stream also accounts for the mass transfer processes which depend on the amount of flow and the temperature of water flowing into and out of a particular volume of water in a stream segment. Mass transfer processes in open channel systems can occur through advection, dispersion, and mixing with tributaries and groundwater inflows and outflows. Mass transfer relates to transport of flow volume downstream, instream mixing, and the introduction or removal of water from a stream. For instance, flow from a tributary will cause a temperature change if the temperature is different from the receiving water.

Thermal Role of Riparian Vegetation

The role of riparian vegetation in maintaining a healthy stream condition and water quality is well documented and accepted in the scientific literature. Summer stream temperature increases due to the removal of riparian vegetation is well documented (e.g., Holtby 1988, Lynch et al. 1984, Rishel et al. 1982, Patric 1980, Swift and Messer 1971, Brown et al. 1971, and Levno and Rothacher 1967). These studies generally support the findings of Brown and Krygier (1970) that loss of riparian vegetation results in larger daily temperature variations and elevated monthly and annual temperatures. Adams and Sullivan (1989) also concluded that daily maximum temperatures are strongly influenced by the removal of riparian vegetation because of the effect of diurnal fluctuations in solar heat flux.

Summaries of the scientific literature on the thermal role of riparian vegetation in forested and agricultural areas are provided by Belt et al. 1992, Beschta et al. 1987, Bolton and Monahan 2001, Castelle and Johnson 2000, CH2MHill 2000, Ice 2001, and Wenger 1999. All of these summaries recognize that the scientific literature indicates that riparian vegetation plays an important role in controlling stream temperature. The list of important benefits that riparian vegetation has upon the stream temperature includes:

- Near-stream vegetation height, width, and density combine to produce shadows that can reduce solar heat flux to the surface of the water.

- Riparian vegetation creates a thermal microclimate that generally maintains cooler air temperatures, higher relative humidity, lower wind speeds, and cooler ground temperatures along stream corridors.

- Bank stability is largely a function of near-stream vegetation. Specifically, channel morphology is often highly influenced by land cover type and condition by affecting floodplain and instream roughness, contributing coarse woody debris, as well as influencing sedimentation, stream substrate compositions, and stream bank stability.

The warming of water temperatures as a stream flows downstream is a natural process. However, the rates of heating can be dramatically reduced when high levels of shade exist and heat flux from solar radiation is minimized. The overriding justification for increases in shade from riparian vegetation is to minimize the contribution of solar heat flux in stream heating. There is a natural maximum level of shade that a given stream is capable of attaining. The importance of shade decreases as the width of a stream increases.

The distinction between reduced heating of streams and actual cooling is important. Shade can significantly reduce the amount of heat flux that enters a stream. Whether there is a reduction in the amount of warming of the stream, maintenance of inflowing temperatures, or cooling of a stream as it flows downstream depends on the balance of all of the heat exchange and mass transfer processes in the stream.

Effective Shade

Shade is an important parameter that controls the stream heating derived from solar radiation. Solar radiation has the potential to be one of the largest heat transfer mechanisms in a stream system. Human activities can degrade near-stream vegetation and/or channel morphology, and in turn, decrease shade. Reductions in stream surface shade have the potential to cause significant increases in heat delivery to a stream system. Stream shade is an important factor in describing the heat budget for this TMDL analysis. Stream shade may be measured or calculated using a variety of methods including hemispherical photography, solar pathfinder, and angular canopy densiometer (Chen 1996, Chen et al. 1998a, Ice 2001, OWEB 1999, Teti 2001).

Shade is the amount of solar energy that is obscured or reflected by vegetation or topography above a stream. Effective shade is defined as the fraction or percentage of the total possible solar radiation heat energy that is prevented from reaching the surface of the water:

$$\text{effective shade} = (J_1 - J_2)/J_1$$

where J_1 is the potential solar heat flux above the influence of riparian vegetation and topography and J_2 is the solar heat flux at the stream surface.

In the Northern Hemisphere, the earth tilts on its axis toward the sun during summer months, allowing longer day length and higher solar altitude, both of which are functions of solar declination (i.e., a measure of the earth's tilt toward the sun) (Figure 5). Geographic position (i.e., latitude and longitude) fixes the stream to a position on the globe, while aspect provides the stream/riparian orientation (direction of streamflow). Near-stream vegetation height, width, and density describe the physical barriers between the stream and sun that can attenuate and scatter incoming solar radiation (i.e., produce shade) (Table 5). The solar position has a vertical component (i.e., solar altitude) and a horizontal component (i.e., solar azimuth) that are both functions of time/date (i.e., solar declination) and the earth's rotation.

Table 2. Factors that influence stream shade.

Description	Parameter
Season/time	Date/time
Stream characteristics	**Aspect channel width**
Geographic position	Latitude, longitude
Vegetative characteristics	**Riparian vegetation height, width, and density**
Solar position	Solar altitude, solar zenith

Bold indicates factors influenced by human activities.

While the interaction of these shade variables may seem complex, the mathematics that describes them is relatively straightforward geometry (Ice 2001, OWEB 1999, Teti 2001). Using solar

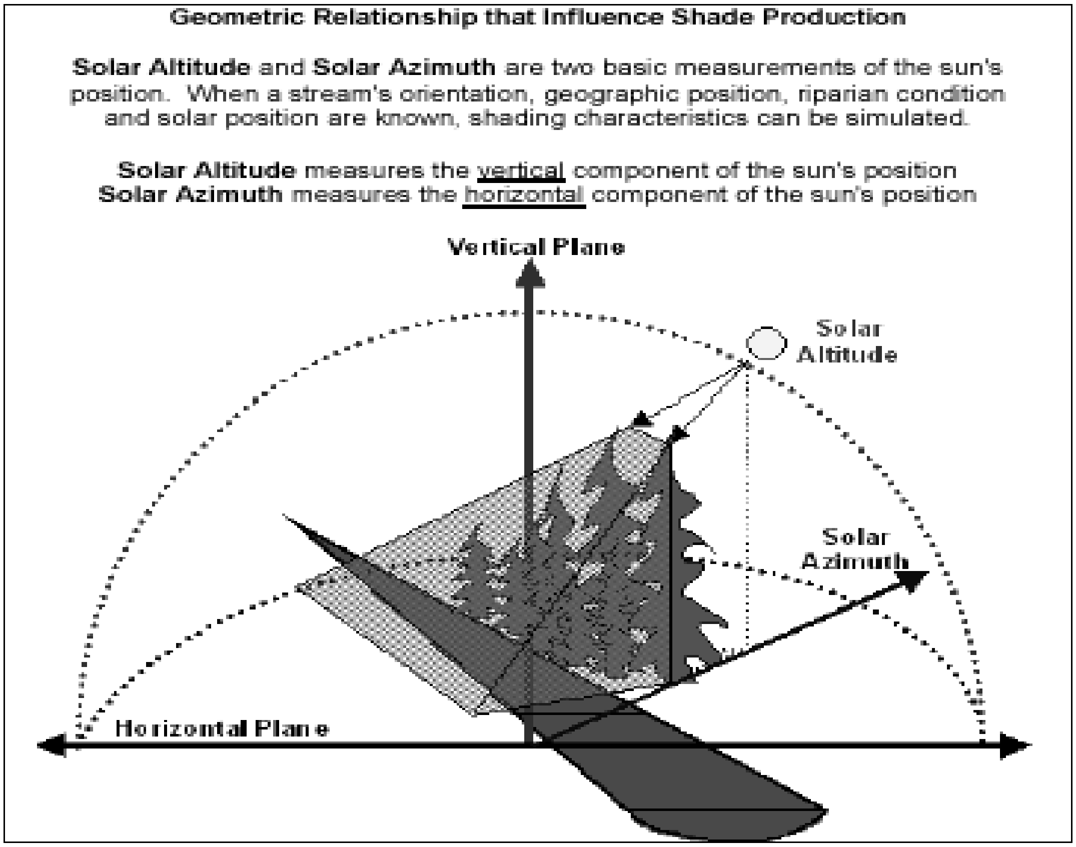

Figure 5. Parameters that affect shade and geometric relationships. Solar altitude is a measure of the vertical angle of the sun's position relative to the horizon. Solar azimuth is a measure of the horizontal angle of the sun's position relative to north.

tables or mathematical simulations, the potential daily solar load can be quantified. The shade from riparian vegetation can be measured with a variety of methods, including:

- Hemispherical photography
- Angular canopy densiometer
- Solar pathfinder

Hemispherical photography is generally regarded as the most accurate method for measuring shade, although the equipment that is required is significantly more expensive compared with other methods. Angular canopy densiometers provide a good balance of cost and accuracy for measuring the importance of riparian vegetation in preventing increases in stream temperature (Teti 2001, Beschta et al. 1987.) Whereas canopy density is usually expressed as a vertical projection of the canopy onto a horizontal surface, the angular canopy density (ACD) is a projection of the canopy measured at an angle above the horizon at which direct beam solar radiation passes through the canopy. This angle is typically determined by the position of the sun above the horizon during that portion of the day (usually between 10 A.M. and 2 P.M. in mid to late summer) when the potential solar heat flux is most significant. Typical values of the ACD for old-growth stands in western Oregon have been reported to range from 80 to 90%.

Computer programs for the mathematical simulation of shade may also be used to estimate shade (Ecology 2002, Chen 1996, Chen et al. 1998b, Boyd 1996, and Boyd and Park 1998).

Riparian Buffers and Effective Shade

Tree retention in riparian areas provides shade to streams and minimizes undesirable water temperature changes (Brazier and Brown 1973; Steinblums et al. 1984). The shading effectiveness, as measured by the ACD of riparian vegetation, can be correlated to riparian area width (Figure 6). ACDs for a given riparian buffer width vary over space and time because of differences among site potential vegetation, forest development stages (e.g., height and density), and stream width. For example, a 50-foot-wide riparian area with fully developed trees could provide from 45 to 72% of the potential shade in the two studies shown in Figure 6.

The Brazier and Brown (1973) shade data show a stronger relationship between ACD and buffer strip width than the Steinblums et al. (1984) data; the r^2 correlation for ACD and buffer width was 0.87 and 0.61 in Brazier and Brown (1973) and Steinblums et al. (1984), respectively. This difference supports the use of the Brazier and Brown curve as a base for measuring shade effectiveness under various riparian buffer proposals. These results reflect the natural variation among old growth sites studied, and show a possible range of potential shade.

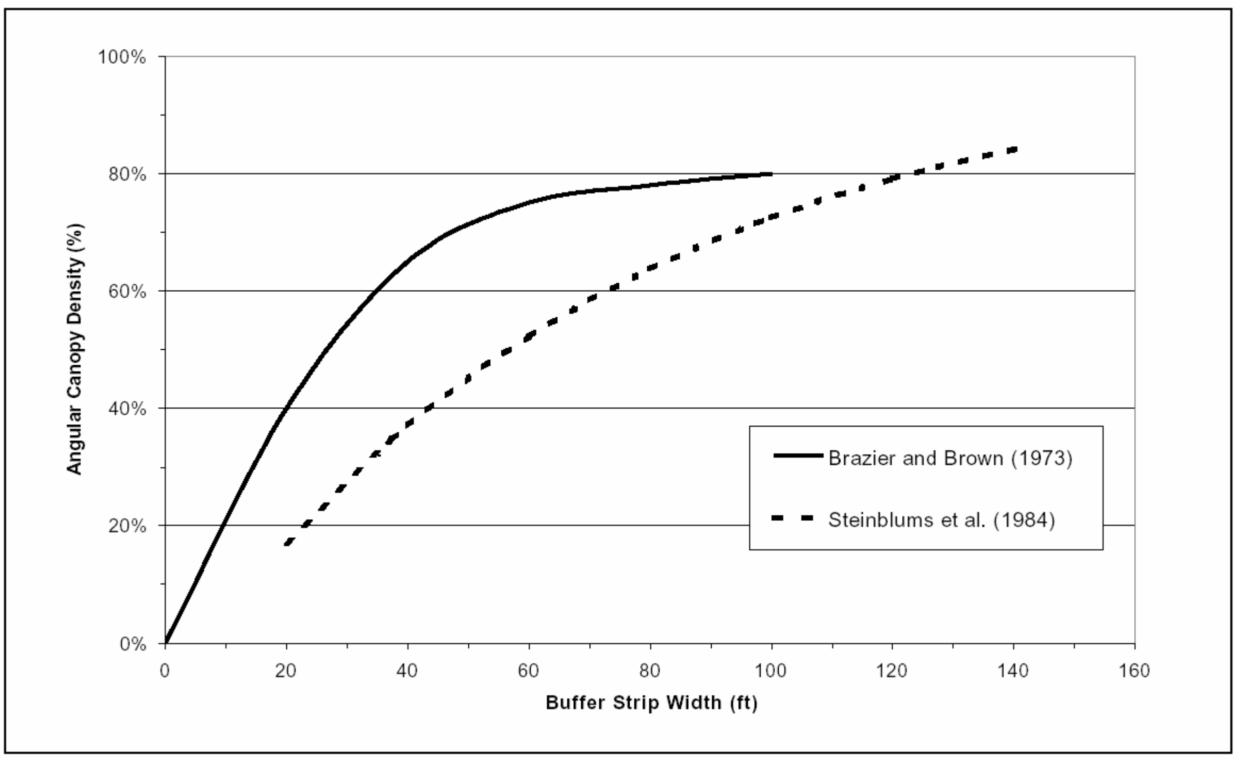

Figure 6. Relationship between angular canopy density and riparian buffer width for small streams in old-growth riparian stands (Beschta et al. 1987, CH2MHill 2000).

Several studies report that most of the potential shade comes from the riparian area within about 75 feet (23 m) of the channel (CH2MHill 2000, Castelle and Johnson 2000):

- Beschta et al. (1987) report that a 98-foot-wide (30-m) buffer provides the same level of shading as that of an old-growth stand.
- Brazier and Brown (1973) found that a 79-foot (24-m) buffer would provide maximum shade to streams.
- Steinblums et al. (1984) concluded that a 56-foot (17-m) buffer provides 90% of the maximum ACD.
- Corbett and Lynch (1985) concluded that a 39-foot (12-m) buffer should adequately protect small streams from large temperature changes following logging.
- Broderson (1973) reported that a 49-foot-wide (15-m) buffer provides 85% of the maximum shade for small streams.
- Lynch et al. (1985) found that a 98-foot-wide (30-m) buffer maintains water temperatures within 2°F (1°C) of their former average temperature.

Steinblums et al. (1984) found that shade could be delivered to streams from beyond 75 feet and potentially out to 140 feet. In some site-specific cases, forest practices between 75 and 140 feet from the channel have the potential to reduce shade delivery by up to 25% of maximum. However, any reduction in shade beyond 75 feet would probably be relatively low on the horizon, and the impact on stream heating would be relatively low because the potential solar radiation decreases significantly as solar elevation decreases.

Microclimate - Surrounding Thermal Environment

A secondary consequence of near-stream vegetation is its effect on the riparian microclimate. Riparian corridors often produce a microclimate that surrounds the stream where cooler air temperatures, higher relative humidity, and lower wind speeds are characteristic. Riparian microclimates tend to moderate daily air temperatures by decreasing daily maximum and increasing daily minimum air temperatures. Increases in relative humidity result from evapotranspiration that is occurring by riparian plant communities. Wind speed is reduced by the physical blockage produced by riparian vegetation.

Riparian buffers commonly occur on both side of the stream, compounding the edge influence on the microclimate. Brosofske et al. (1997) reported that a buffer width of at least 150 feet (45 m) on each side of the stream was required to maintain a natural riparian microclimate environment in western Washington forests with predominantly Douglas-fir and western hemlock. Ledwith (1996) recommended that a minimum buffer width of 30 m was required to avoid significantly altering the microclimate of a riparian zone.

Bartholow (2000) provided a thorough literature summary of documented changes to the environment of streams and watersheds associated with extensive forest clearing. Changes summarized by Bartholow (2000) are representative of hot summer days and indicate the mean daily effect unless otherwise indicated:

- *Air temperature.* Edgerton and McConnell (1976) showed that removing all or a portion of the tree canopy resulted in cooler terrestrial air temperatures at night and warmer temperatures during the day, enough to influence thermal cover sought by elk (Cervus canadensis) on their eastern Oregon summer range. Increases in maximum air temperature varied from 5 to 7ºC for the hottest days (estimate). However, the mean daily air temperature did not appear to have changed substantially since the maximum temperatures were offset by almost equal changes to the minima. Similar temperatures have been commonly reported (Childs and Flint 1987; Fowler et al. 1987), even with extensive clearcuts (Holtby 1988). In an evaluation of buffer strip width, Brosofske et al. (1997) found that air temperatures immediately adjacent to the ground increased 4.5ºC during the day and about 0.5ºC at night (estimate). Fowler and Anderson (1987) measured a 0.9ºC air temperature increase in clearcut areas, but temperatures were also 3ºC higher in the adjacent forest. Chen et al. (1993) found similar (2.1ºC) increases. All measurements reported here were made over land instead of water, but in aggregate support about a 2ºC increase in ambient mean daily air temperature resulting from extensive clearcutting.

- *Relative humidity.* Brosofske et al. (1997) examined changes in relative humidity within 17 to 72 m buffer strips. The focus of their study was to document changes along the gradient from forested to clearcut areas, so they did not explicitly report pre- to post-harvest changes at the stream. However, there appeared to be a reduction in relative humidity at the stream of 7% during the day and 6% at night (estimate). Relative humidity at stream sites increased exponentially with buffer width. Similarly, a study by Chen et al. (1993) showed a decrease of about 11% in mean daily relative humidity on clear days at the edges of clearcuts.

- *Wind speed.* Brosofske et al. (1997) reported almost no change in wind speed at stream locations within buffer strips adjacent to clearcuts. Speeds quickly approached upland conditions toward the edges of the buffers, with an indication that wind actually increased substantially at distances of about 15 m from the edge of the strip, and then declined farther upslope to pre-harvest conditions. Chen et al. (1993) documented increases in both peak and steady winds in clearcut areas; increments ranged from 0.7 to 1.2 m/s (estimated).

Chen (1991) reported that soil and air temperatures, relative wind speed, humidity, soil moisture, and solar radiation all changed with increasing distance from clear-cut edges in upslope forests of the western Cascades. Based on Chen's results, the Forest Ecosystem Management Assessment Team (FEMAT 1993) concluded that loss of upland forests likely influences conditions within the riparian zone. FEMAT also suggested that riparian buffers necessary for maintaining riparian microclimates need to be wider than those for protecting other riparian functions (Figure 7).

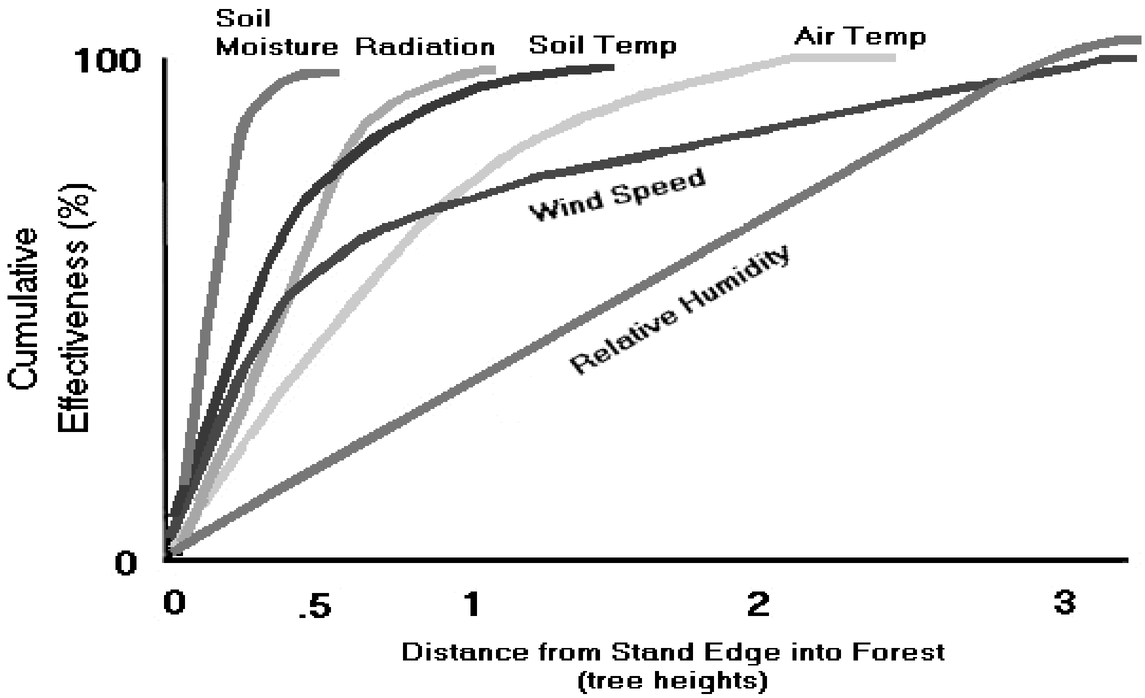

Figure 7. Riparian buffer effects on microclimate (FEMAT 1993).

Thermal Role of Channel Morphology

Channel widening (increased width-to-depth ratios) increases the stream surface area exposed to heat energy processes. In addition, wide channels are likely to have decreased levels of shade due to the increased distance created between vegetation and the wetted channel. Conversely, narrow channels are more likely to experience higher levels of shade. Riparian vegetation contributes to channel stability by increasing roughness and dissipating the erosive energies of higher flows.

Channel widening is often related to degraded riparian conditions that allow increased streambank erosion and sedimentation of the streambed, both of which correlate strongly with riparian vegetation type and condition (Rosgen 1996). Channel morphology is not solely dependent on riparian conditions. Sedimentation can deposit material in the channel, fill pools, and aggrade the streambed, reducing channel depth and increasing channel width.

Channel modification usually occurs during high-flow events. Land uses that affect the magnitude and timing of high-flow events may negatively impact channel width and depth. Riparian vegetation conditions will affect the resilience of the streambanks/floodplain during periods of sediment introduction and high flow. Disturbance processes may have differing results depending on the ability of riparian vegetation to shape and protect channels. Channel morphology is related to riparian vegetation composition and condition by:

- *Building streambanks:* Trapping suspended sediments, encouraging deposition of sediment in the floodplain, and reducing incoming sources of sediment.

- *Maintaining stable streambanks:* Preventing streambank erosion by high rooting strength and high streambank and floodplain roughness.

- *Reducing flow velocity (erosive kinetic energy):* Supplying large woody debris to the active channel, high pool:riffle ratios, and adding channel complexity that reduces shear stress exposure to stream bank soil particles.

Channel straightening, diking, and dredging are all undertaken to prevent the lateral movement of stream channels and increase channel efficiency. These activities focus the erosive energy of streams toward the middle of the channel, encouraging downcutting (National Research Council 1996), and ultimately decreasing the interaction of stream channels with their floodplain in all but extreme flood events. This loss of connectivity between the channel and floodplain can occur through one or all of the following mechanisms:

- Since engineered channels carry water more efficiently, both the amount of time floodwaters spend on the floodplain and the surface area inundated are reduced during average annual high-flow events. This action reduces the opportunity for floodwaters to penetrate the alluvial aquifer and, in turn, decreases baseflow by reducing groundwater discharge during the low-flow season (Steiger et al. 1998).
- Engineered channels reduce the heterogeneity in channel pattern and topography, thereby reducing hyporheic flow (Jurajda 1995).

In summary, channel modifications sever the linkages between the channel and the floodplain, thereby reducing groundwater buffering of streamflow and temperature (Ward 1998) as well as eliminating interactions between the channel and riparian zone that would insulate the stream from exchange of heat with the atmosphere.

Water Withdrawals and Stream Temperature

Water withdrawals reduce instream flow and therefore reduce the assimilative capacity of streams (Dauble 1994). Although some of this water is eventually returned to the stream, the fraction is typically low. Solley et al. (1993) estimated that only one-third of the water withdrawn in the Pacific Northwest was returned to lakes and streams. Additionally, water withdrawn from the river or stream is often at a markedly different temperature than it was when withdrawn, thereby affecting the heat load to the stream. Water withdrawals in the Skagit River study area are typically used for agriculture, with maximum withdrawals occurring during the hottest summer months.

Reductions in instream flows also can reduce the magnitude of hyporheic flow. For hyporheic flow to act as a temperature buffer, differential storage of heat and water over time must occur. Differential heat and water storage is driven by variations in stream temperature and flow. Since flow regulation dampens variation in both flow and temperature, the potential for hyporheic exchange to act as a temperature buffer is reduced by flow regulation (Poole et al. 2000).

Summary of the Pathways of Human Influence on Stream Temperature

Riparian vegetation, stream morphology, hydrology, climate, and geographic location all influence stream temperatures. While climate and geographic location are outside of human control, riparian condition, channel morphology, and hydrology are affected by human activities.

Human activities can affect water temperature in stream channels by changing the timing or magnitude of the amount of (1) heat delivered to the channel or (2) water delivered to the channel (flow regime). Figure 8 summarizes the web of pathways by which temperature may be increased in stream channels.

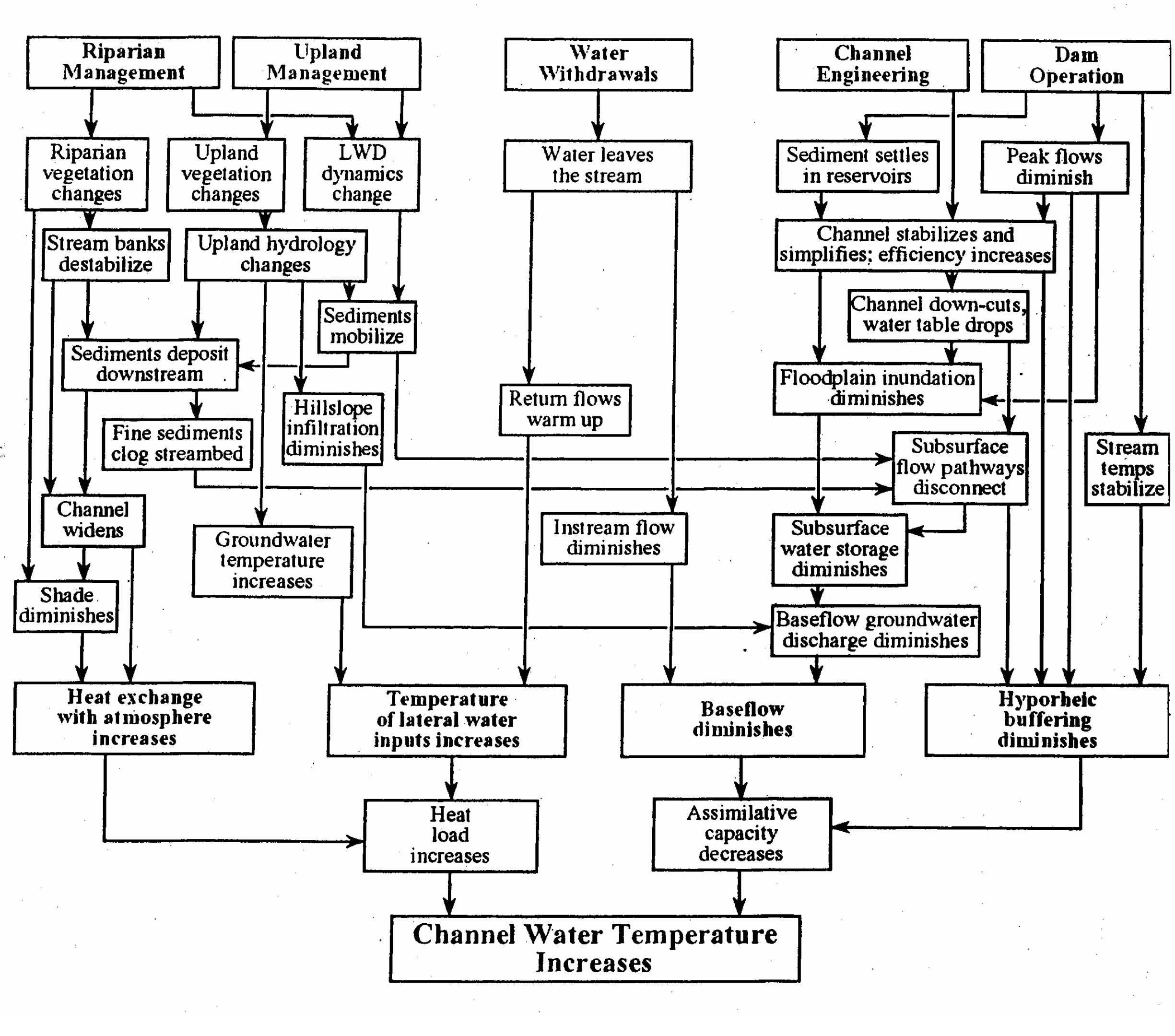

Figure 8. Pathways of human influence on water temperatures in stream channels (Poole et al. 2000).

Pollutants and Surrogate Measures

Heat loads to the stream are calculated in this TMDL study in units of calories per square centimeter per day or watts per square meter. However, heat loads are of limited value in guiding management activities needed to solve identified water quality problems.

This TMDL incorporates measures other than "daily loads" to fulfill the requirements of Section 303(d). This TMDL allocates other appropriate measures or "surrogate measures" as provided under EPA regulations [40 CFR 130.2(i)]. The "Report of the Federal Advisory Committee on the Total Maximum Daily Load (TMDL) Program" (EPA 1998) includes the following guidance on the use of surrogate measures for TMDL development:

"When the impairment is tied to a pollutant for which a numeric criterion is not possible, or where the impairment is identified but cannot be attributed to a single traditional "pollutant," the state should try to identify another (surrogate) environmental indicator that can be used to develop a quantified TMDL, using numeric analytical techniques where they are available, and best professional judgment (BPJ) where they are not."

This technical assessment for the lower Skagit River tributaries temperature TMDL uses riparian shade as a surrogate measure of heat flux to fulfill the requirements of Section 303(d). Effective shade is defined as the fraction of the potential solar shortwave radiation that is blocked by vegetation and topography before it reaches the stream surface. Effective shade accounts for the interception of solar radiation by vegetation and topography.

A decrease in shade due to inadequate riparian vegetation causes an increase in solar radiation and thermal load upon the affected stream section. Other factors influencing the distribution of the solar heat load were also considered, including changes in the width-to-depth ratios.

Channel width is evaluated in this TMDL as a function of stream effective shade production. It is expected that the establishment and maintenance of site potential riparian vegetation will promote channel recovery by decreasing channel widths, increasing channel depths, and increasing channel complexity.

Background

The Skagit River basin covers most of Skagit County and the northeastern and eastern parts of Snohomish and Whatcom counties, respectively, and extends northward into Canada. The basin encompasses approximately 6,138 km^2 (2,370 mi^2). The Skagit River originates in British Columbia, flows through Ross Lake which extends a short distance across the international boundary, and continues in a southwestward path to empty into Skagit Bay below Mount Vernon. The river contributes approximately one-third of the total freshwater discharge to Puget Sound.

The major sub-basins in the Skagit River are the Upper Skagit, Baker, Cascade, Sauk, and Lower Skagit.

Carpenter, Turner, Otter Pond, Red, Fisher, Hansen, Lake, Nookachamps, and East Fork Nookachamps creeks are all temperature-impaired tributaries to the Skagit River in the 520 km^2 of the lower Skagit basin. These creeks are addressed in this TMDL study (Figure 1).

The lower Skagit River, its tributaries, sloughs, and estuaries serve as important migration corridors, spawning areas, and rearing areas for five major species of salmon (chinook, coho, pink, chum, and sockeye), as well as steelhead and cutthroat trout (Entranco 1993). The Skagit River watershed contains the second largest wild run of coho salmon and the largest run of chinook salmon in the Puget Sound watershed.

The climate in the lower Skagit basin is mild with cool, dry summers and mild, wet winters. Mean annual precipitation ranges from 71 to 107 cm per year, increasing from west to east (USDA 1981). The majority of annual precipitation occurs between October and March.

Small farms and rural residential development dominate the lowland portion of the basin. Agricultural land use dominates in the western portion of the basin, largely supporting cropland and pasture. The eastern uplands are predominantly forestland, with some scattered residential development. An extensive drainage network exists in the agricultural portions of the study area, and many of the waterbodies addressed in this study have been diked, dredged, or otherwise channelized. This has resulted in extensive segments with little or no channel complexity and reduced riparian vegetation.

Lower elevation forests (< 700m) are within the western hemlock zone (Franklin and Dyrness 1973). Dominant conifer species in these forests are western hemlock, Douglas-fir, western red cedar, and Sitka spruce. Deciduous trees include red alder, black cottonwood, and big leaf maple. Middle elevation forests (700-1300m) are in the silver fir zone.

Skagit County's population is currently estimated at 103,478 and is projected to grow to about 137,478 by the year 2015 (Skagit County OFM 2003), an increase of 33%. Such rapid growth would be expected to put considerable pressure on the county's natural resources, including potential impacts to surface water quality and quantity.

The Study Area

Carpenter-Fisher Creek Sub-basin

The Carpenter Creek and Fisher Creek drainages are located in southern Skagit County, southeast of the city of Mount Vernon, with a small portion covering northern Snohomish County. The basin topography ranges from a flat-lying alluvial plain (Skagit plain) in the westernmost portion of the basin, low rolling hills to the south (lowland), and rugged upland foothills to the east and northeast (uplands). Basin surface elevations range from approximately 2 to 520 meters above mean sea level.

The Carpenter Creek mainstem occupies the northern half of the basin, draining towards the south. The portion of the Carpenter Creek mainstem that flows across the Skagit plain has been diked and channelized adjacent to the base of the uplands, and is known as Hill Ditch. Hill Ditch is maintained by Skagit County Dike District #3. Tributaries feeding both mainstem Carpenter Creek and Hill Ditch drain largely from the east. Elevated stream temperatures in Carpenter Creek are located primarily in Hill Ditch. Flow in Hill Ditch is fairly sluggish, and there is little riparian vegetation to shade the wide and shallow channel.

The Fisher Creek mainstem drains towards the northwest and is fed by several smaller tributaries that drain the lower elevation hills of the southern and southeastern lowlands. Fisher Creek flows through alternating sections of forest and agricultural lands.

The confluence of Fisher and Carpenter creeks is located approximately 0.8 km east of the South Fork of the Skagit River. The combined drainage area for the two creek systems is approximately 65 km^2. Those portions of the drainage area with an elevation less than the local mean high-water mark may be routinely influenced by the tide (Pitz et al. 2000).

Land use in the Carpenter-Fisher basin consists mostly of a mixture of rural and agricultural uses. Agricultural uses include dairy farming operations, small farm and other livestock operations, and some pastureland. Riparian vegetation is sparse in several areas of the watershed.

Hansen Creek Sub-basin

The Hansen Creek watershed lies in northwestern Skagit County, draining an area of approximately 35 km^2 and flowing from its headwaters in the Lyman Hill area south to its confluence with the Skagit River near Sedro Woolley. Red Creek is the major tributary to Hansen Creek, with several smaller tributaries entering just above the Northern State Recreation Area.

Land use in the Hansen Creek watershed consists mostly of a mixture of forestry, rural, and agricultural uses. Agricultural uses include dairy farming operations, small farm and other livestock operations, and some pastureland. Timber harvesting occurs in the upper reaches of the watershed and is most concentrated in the Lyman Hill area.

The headwater sections of Hansen Creek have been extensively logged, and large amounts of sediment from landslides have filled in the lower portions of the creek (Skagit County 2002). The watershed is forested from just below Lyman Hill to the Northern State Recreational Area; the remainder of Hansen Creek flows through extensive areas with little or no riparian vegetation. Long-term dredging has resulted in the creek's thalweg becoming raised above the level of the surrounding ground and contained within dredge spoils that act as small dikes, allowing little opportunity for surface water to drain back into the creek during flood events. The dredging has also contributed to the wide and shallow channel, which increases the surface area available to solar radiation (Skagit County 2002).

Historically, the Hansen Creek watershed was used by large numbers of several salmon species, including Puget Sound chinook, and bull trout, both currently listed as "threatened" under the Endangered Species Act (Skagit County 2002). The watershed still supports salmon runs; however, the runs are greatly reduced from historic numbers, in part from lack of woody debris and associated pools for refuge, lack of sufficient riparian cover to provide shade, increased sediment load from upstream sources, and decreased floodplain and wetland areas (Skagit County 2002).

Skagit County has several Sub Flood Control Zones (SFCZs), established pursuant to RCW 86.15. The purpose of these self-taxing districts is to provide for flood control in small to medium watersheds. Hansen Creek is included in one of these SFCZs. The county is responsible for conducting flood control activities prescribed by these zones on behalf of the residents of the zones. The county will apply reasonable best management practices for flood control activities in an effort to comply with TMDL recommendations. However, anytime this flood control responsibility conflicts with TMDL recommendations for SFCZs, reasonable accommodation for flood control activities must be allowed and take precedence.

Nookachamps Creek Sub-basin

The Nookachamps Creek watershed is located in south-central Skagit County and drains approximately 210 km², making it the largest sub-basin in the study area. High elevations and rugged terrain border the Nookachamps basin on both the east and west sides, while the northern boundary of the watershed is defined by almost 14 miles of the Skagit River. Devils Mountain to the west divides the Nookachamps watershed from the Carpenter-Fisher Creek drainage. Through the Nookachamps Valley, elevations range from 48 m at Lake McMurray to approximately 15 m at the Skagit River. Surface waters in the watershed include approximately 320 kilometers of creeks and streams, including Lake, East Fork Nookachamps, Turner, and Otter Pond creeks. The Nookachamps Creek watershed is the first important salmon-producing tributary in the Skagit River and provides key habitat for a successful wild Coho stock (Skagit County Dept. of Planning 1995).

Lake Creek flows from the outlet of Lake McMurray south to Big Lake. Water from Big Lake discharges into Nookachamps Creek, which flows approximately 11 km through mostly agricultural lands, before its confluence with the Skagit River midway between the cities of Mount Vernon and Sedro Woolley. Nookachamps Creek forks near Barney Lake just south of the mainstem Skagit River. This branch, referred to as the East Fork of Nookachamps Creek, is formed by tributary streams descending from Cultus Mountain. The main tributaries to East Fork Nookachamps Creek are Day Creek, Turner Creek, Mundt Creek, and Walker Creek.

Most of the Nookachamps Creek watershed supports forestry (14,500 hectares) and agriculture (3,640 hectares) (Skagit County Dept. of Planning 1995). Forest lands account for almost 70% of the total watershed area with approximately 4,860 hectares owned and managed by the Washington State Department of Natural Resources. The remaining forest land, approximately 9,800 hectares, is privately owned.

Agricultural uses are found mostly throughout the floor of the Nookachamps Valley from Lake McMurray to the Skagit River. The majority of the lower sections of both Nookachamps Creek and East Fork Nookachamps Creek have been extensively channelized and diked, which has resulted in wide shallow channels with little riparian vegetation. Lake McMurray, a shallow lake (< 2 m at outlet) comprises the headwaters of Lake Creek. Summer outflow temperatures frequently exceed the Class A standard for temperature. Big Lake, a shallow lake (< 2 m at outlet) comprises the headwaters of Nookachamps Creek. Summer outflow temperatures frequently exceed the Class A standard for temperature.

Land Use in the Study Area

Land use in the study area is a mixture of agriculture, urban, suburban, and forestland (Figure 9). Digital orthophotos (Figures 10-12) show the matrix of land uses in each sub-basin. These images provide a good perspective of stream temperature issues within the study area, as they relate to land use, specifically riparian shade. Stream segments lacking substantial riparian areas or those reaches that have been diked or channelized are clearly visible.

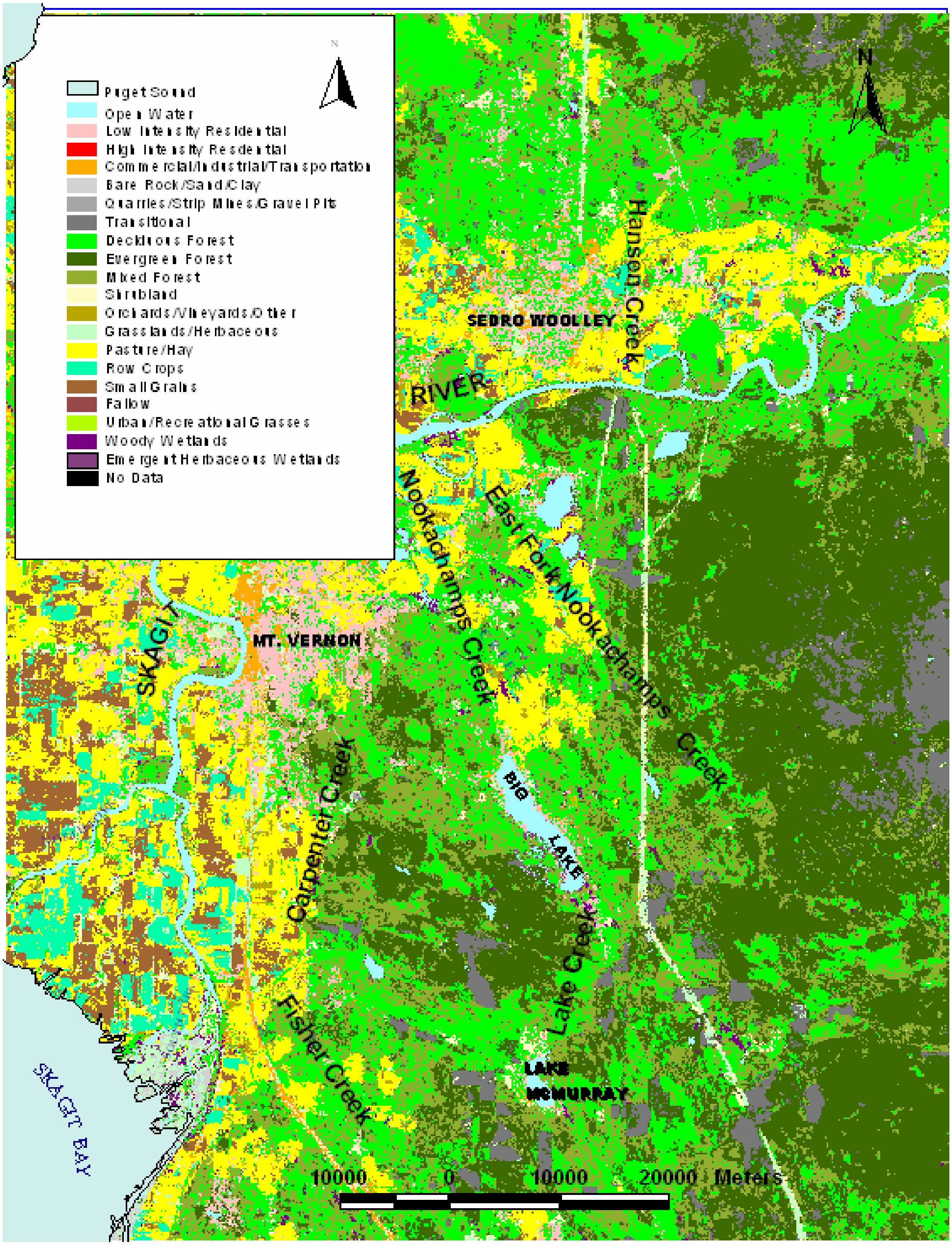

Figure 9. Generalized land use within the study area (1997).

Figure 10. Landsat image of Carpenter and Fisher Creek study area showing a matrix of land uses (1991).

Figure 11. Landsat image of Hansen Creek sub-basin showing a matrix of land uses (1991).

Figure 12. Landsat image of Nookachamps sub-basin showing a matrix of land uses (1991).

Fisheries Resources

Fisheries resources in the study area include both anadromous and resident fish. Table 3 shows the stream type classifications for streams in the study area. Stream type classifications are designated by the Washington State Department of Natural Resources established under WAC 222-16-031.

Table 3. Stream type classifications in lower Skagit River study area.

Creek Name	Stream Type *
Carpenter	**2**
Fisher	**2**
Hansen	**2**
Red	3
Lake	**1,2**
Otter Pond	3
Nookachamps	**1**
East Fork Nookachamps	**1**,2,3,4
Turner	3,4

* Stream type in bold indicates stream type of modeled segment.

Type 1- All waters inventoried as "Shorelines of the State"

Type 2- Segments of natural waters which are not classified as Type 1 water and have a high fish, wildlife, or human use and which are used for fish spawning, rearing, or migration, and used by fish for off-channel habitat.

Type 3- Segments of natural waters which are not classified as Type 1 or 2 and have a moderate to slight fish, wildlife, and human use and which are used by fish for spawning, rearing, or migration.

Type 4- Segments of natural waters within the bankfull width of defined channels that are perennial non-fish habitat streams.

The Nookachamps system, which includes the East Fork, Lake, Otter Pond, and Turner creeks produces several species of anadromous fish, including coho salmon, chum salmon, chinook salmon, pink salmon, steelhead trout, a small run of sockeye salmon, and sea-run cutthroat trout (Skagit County Dept. of Planning 1995). The most successful anadromous species in the watershed is coho salmon, which is able to use most of the stream systems within the study area. The Nookachamps Creek watershed is a good producer of steelhead and cutthroat trout (Skagit County Dept. of Planning 1995).

The remainder of the creeks within the study area also produce, to varying degrees, several species of anadromous fish, including coho, chum, chinook, and pink salmon, as well as steelhead and sea-run cutthroat trout.

In addition to anadromous resources, streams within the study area also support a variety of resident fish, including rainbow trout, cutthroat trout, bass, perch, crappie, brown trout, bullhead, sculpin, lamprey, and whitefish. Stream temperatures in the lower Skagit River tributaries are of particular concern because of their use by Puget Sound chinook, a species listed as threatened under the Endangered Species Act, as a migration corridor and as spawning and rearing habitat.

Salmonid Stream Temperature Requirements

Many Pacific salmon (*Oncorhynchus spp.*) stocks in the Pacific Northwest are currently listed under the Endangered Species Act because of dramatic population declines in the past few decades. The causes of decline are many and vary within different watersheds; however, virtually all declines are at least partly attributed to changes in freshwater habitat conditions (Spence et al. 1996). In many watersheds, habitat and fishery managers view increases in summer maximum stream temperature as a significant source of mortality for juveniles during their freshwater life history stages (Hicks et al. 1991).

Water temperature plays an important role in regulating biological and ecological processes in aquatic systems. Virtually all biological and ecological processes are affected by ambient water temperature. Below is a list of some of the more important physiological and ecological processes affected by temperature (Spence et al. 1996).

- Decomposition of organic materials
- Metabolism of aquatic organisms, including fishes
- Food requirements, appetite, and digestion rates of fishes
- Growth rates of fish
- Developmental rates of embryos and alevins
- Timing of life-history events including adult migrations, fry emergence, and smoltification
- Competitor and predator-prey interactions
- Disease-host and parasite-host relationships
- Development rate and life history of aquatic invertebrates

Salmonids use a variety of habitats during their life histories. Anadromous species in particular have complex life histories that involve periodic shifts in habitat (Spence et al. 1996). Depending on the species or stock, freshwater streams, lakes, or intertidal sloughs may be used for reproduction; streams, lakes, estuaries, or oceans may be used for juvenile rearing. For all anadromous species, habitats between spawning streams and the ocean are required for upstream and downstream migrations.

Differences in spatial and temporal use of specific habitats exist for each species, yet the diversity among species and by life stage indicates that most freshwater habitats are used year round (Spence et al. 1996). To persist, each species or stock must be able to survive within the entire range of habitats encountered during its life; degradation or alteration of habitat required at any life stage can limit production. Much of the available information on salmonid habitat requirements has been summarized in reviews by Bell (1986), Everest et al. (1985), and Bjornn and Reiser (1991).

A brief summary of the importance of water temperatures to salmonids during adult migration, spawning, and incubation, and juvenile and adult rearing is provided below. Table 4 provides a summary of tolerable and preferred temperature ranges for adult migration, spawning, and incubation of native salmonids. An extensive review of studies examining the temperature requirements of salmonid species during specific life histories is provided by Hicks (2001).

Adult Migration

Most adult salmonids typically migrate at temperatures less than 14°C; however, summer and fall chinook salmon migrate during periods when temperatures are substantially warmer (Spence et al. 1996). Excessively high or low temperatures may result in delays in migration (Hallock et al. 1970; Monan et al. 1975). Adult steelhead that move from the ocean into river systems in the summer and fall may overwinter in larger rivers, delaying entry into smaller spawning tributaries until they are free of ice in the spring. Similarly, spring-spawning resident salmonids, including cutthroat and rainbow trout, may hold at the mouths of spawning streams until temperatures warm up to the preferred temperature range (Bjornn and Reiser 1991). In addition to delaying migration, excessively high temperatures during migration may cause outbreaks of disease.

Table 4. Tolerable and preferred temperature ranges (°C) for adult migration, spawning, and incubation of embryos for native salmonids in the Pacific Northwest (Bjornn and Reiser 1991).

	Life Stage		
Species	Spawning Migration (min - max)	Spawning (preferred range)	Incubation (preferred range)
ANADROMOUS			
Pink salmon	7.2 - 15.6*	7.2 - 12.8*	4.4 - 13.3*
Chum salmon	8.3 - 15.6*	7.2 - 12.8*	4.4 - 13.3*
Coho salmon	7.2 - 15.6*	4.4 - 9.4*	4.4 - 13.3*
Sockeye salmon	7.2 - 15.6*	10.6 - 12.2*	4.4 - 13.3*
Spring chinook	3.3 - 13.3*	5.6 - 13.9*	5.0 - 14.4*
Summer chinook	13.9 - 20.0*	5.6 - 13.9*	5.0 - 14.4*
Fall chinook	10.6 - 19.4*	5.6 - 13.9*	5.0 - 14.4*
Steelhead trout		3.9 - 9.4*	
Cutthroat trout		6.1 - 17.2*	
RESIDENT			
Kokanee		5.0 - 12.8*	
Mountain		0.0 - 5.6†	
Cutthroat trout	5.0 - 10.0†	4.4 - 12.8† 5.5 - 15.5‡	
Rainbow trout		2.2 - 20.0* 4.4 - 12.8†	
Dolly Varden		7.8†	
Bull trout		< 9.0§ 4.5	2.0 - 6.0§

* Bell 1986.
† Everest et al. 1985.
‡ Varley and Gresswell 1988.
§ Pratt 1992.
¶ Ratliff 1992.

Spawning

Salmonids have been observed to spawn at temperatures ranging from 1-20°C (Bjornn and Reiser 1991), but most spawning occurs at temperatures between 4 and 14°C (Table 5). Resident trout, including rainbow and cutthroat trout, may spawn at temperatures up to 20.0°C and 17.2°C, respectively, while coho salmon, steelhead trout, Dolly Varden, bull trout, and mountain whitefish tend to prefer lower temperatures. The wide range of spawning temperatures used by most salmonid species strongly suggests that adaptation has allowed salmonids to persist in a variety of thermal environments and that attempting to identify species-specific preferenda may fail to account for ecological requirements of individual stocks (Spence et al. 1996).

Juvenile and Adult Rearing

Juvenile and resident salmonids are variable in their temperature requirements, though most species are at risk when temperatures exceed 23-25°C (Bjornn and Reiser 1991). Upper and lower lethal temperatures, as well as the "preferred" temperature ranges of several western salmonids, are shown in Table 5. These values provide a general range of tolerable temperatures; however, the ability of fish to tolerate temperature extremes depends on their recent thermal history (Spence et al. 1996).

Table 5. Lower lethal, upper lethal, and preferred temperatures for selected salmonids. Based on techniques to determine incipient lethal temperatures (ILT) and critical thermal maxima (CTM). From Bjornn and Reiser (1991).

Species	Lethal temperature (C)		Preferred temperature (°C)	Technique	Source
	Lower lethal*	Upper lethal†			
Chinook salmon	0.8	26.2	12- 14	ILT	Brett (1952)
Coho salmon	1.7	26.0 28.8‡	12- 14	ILT CTM	Brett (1952) Becker and Genoway (1979)
Sockeye salmon	3.1	25.8	12- 14	ILT	Brett (1952)
Chum salmon	0.5	25.4	12- 14	ILT	Brett (1952)
Steelhead trout	0.0	23.9	10- 13		Bell (1986)
Rainbow trout		29.4 25.0		CTM ILT	Lee (1980) Charlon et al. (1970)
Cutthroat trout	0.6	22.8			Bell (1986)

* Acclimation temperature was 10°C; no mortality occurred in 5,500 min.
† Acclimation temperature was 20°C unless noted otherwise; 50% mortality occurred in 1,000 min.
‡ Acclimation temperature was 15°C.

If stream temperatures become too hot, fish die almost instantaneously due to denaturing of critical enzymes in their bodies (Hokanson et al. 1977). The ultimate *instantaneous lethal limit* occurs in high temperature ranges (above 32°C). Such warm temperature extremes may never occur in the lower Skagit River tributaries. More common and widespread, however, is the occurrence of temperatures in the mid to high 20°C range. These temperatures can cause death of cold water fish species during exposure times lasting a few hours to one day. The exact temperature at which a cold water fish succumbs to such a thermal stress depends on the temperature that the fish is acclimated to, and on life-stage of development. Table 6 summarizes the modes of cold water fish mortality.

Table 6. Modes of thermally-induced cold water fish mortality (Brett 1952, Bell 1986, and Hokanson et al. 1977).

Modes of Thermally-Induced Fish Mortality	Temperature Range (°C)	Time to Death
Instantaneous Lethal Limit - Denaturing of bodily enzyme systems	> 32°C	Instantaneous
Incipient Lethal Limit - Breakdown of physiological regulation of vital bodily processes, namely: respiration and circulation	21°C - 25°C	Hours to days
Sub-Lethal Limit - Conditions that (1) cause decreased or lack of metabolic energy for feeding, growth, or reproductive behavior, and (2) encourage increased exposure to pathogens, decreased food supply, and increased competition from warm water tolerant species	20°C - 23°C	Weeks to months

Protection and restoration of salmonid habitats requires that water temperatures in streams and lakes remain within the natural range for the particular site and season. Although “natural” temperature ranges may vary, the current water quality standards for temperature are intended to maintain the long-term health of fish and other aquatic life. Temperature standards exist to ensure the protection of entire communities of aquatic life and, to the extent consistent with this goal, avoid unnecessary impact on human economic activities.

Ecology (Hicks 2001) conducted a comprehensive review of the available technical literature on the temperature requirements of native fish and aquatic life. Based on this review, Hicks (2001) recommended expanding the existing state water quality standards for temperature to ensure the protection of the key life-stages of adult holding, spawning and incubation, juvenile rearing, smoltification, and adult migration. The proposed standards have also been set to avoid significant increases in the risks of warm water fish diseases and parasites, and include recommendations to avoid acute lethality from wastewater plumes.

Associated with the proposed criteria are directives on how to properly implement the criteria. The recommended criteria have been set at values representing the full protection for the species and their key life-stages. The proposed metrics express the criteria (typically both a 21-day average or the daily average temperatures, and a 7-day average of the daily maximum temperatures) were chosen to better match with laboratory and field research results that were used as the basis for the recommendations.

Instream Flows in the Lower Skagit River

Streamflow is a significant factor in the heat budget of lotic systems. Human-related reductions in flow volume can have a significant influence on stream temperature dynamics, most likely by increasing the diurnal variability in stream temperature. Lower streamflows also decrease hyporheic exchange between the alluvial aquifer and the channel. It follows then that water resource policy should ensure that instream flows be maintained such that biological communities are protected, while still allowing for consumptive uses.

Instream flows and water withdrawals are managed through regulatory avenues separate from TMDLs. However, stream temperature is related to the amount of instream flow, and increases in flow generally result in decreases in maximum temperatures. The complete heat budget for a stream segment accounts for the amount of flow and the temperature of water flowing into and out of the stream. The primary statutes relating to flow setting in the Washington State are as follows:

- Water Code, Chapter 90.03 RCW (1917), Section 247, describes Ecology's exclusive authority for setting flows and describes specific conditions on permits stating where flows must be met. It requires consultation with the state departments of Fish and Wildlife (WDFW); Community, Trade, and Economic Development; and Agriculture; as well as affected Indian Tribes, on the establishment of "minimum flows".

- Construction Projects in State Waters, Chapter 77.55 RCW (formerly 75.20)(1949), Section 050, requires Ecology to consult with the Department of Fish and Wildlife prior to making a decision on any water right application that may affect flows for food and game fish. Fish and Wildlife may recommend denial or conditioning of a water right permit.

- Minimum Water Flows and Levels Act, Chapter 90.22 RCW (1967), set forth a process for protecting instream flows through adoption of rules. Among other provisions, it says Ecology must consult with the Department of Fish and Wildlife and conduct public hearings.

- Water Resources Act of 1971, Chapter 90.54 RCW, particularly Section 020, includes language that says "baseflows" are to be retained in streams except where there are "overriding considerations of the public interest". Further, waters of the state are to be protected and used for the greatest benefit to the people, and water allocation is to be generally based on the securing of "maximum net benefits" to the people of the state. This Act also authorizes Ecology to reserve waters for future beneficial uses.

- In 1998, the legislature passed Engrossed Substitute House Bill 2514, which was codified as "Watershed Planning," Chapter 90.82 RCW. This chapter provides an avenue for local citizens and various levels of governments to be involved in collaborative water management, including the option of establishing or amending instream flow rules. The Watershed Planning process specifies that local watershed planning groups can recommend instream flows to Ecology for rule-making, and directs Ecology to undertake rule-making to adopt flows upon receiving such a recommendation.

Under state laws, the Washington State Department of Ecology (Ecology) oversees both the appropriation of water for out-of-stream uses (e.g., irrigation, municipalities, commercial and industrial uses) and the protection of instream uses (e.g., water for fish habitat and recreational use). Ecology does this by adopting and enforcing regulations, as well as by providing assistance to citizens with both public and private water management issues.

Ecology is required by law to protect instream flows by adopting regulations and to manage water uses that affect streamflow. To develop an "instream flow rule" which sets for a particular stream the minimum flows needed during critical times of year, Ecology considers existing flow data, the hydrology of a stream and its natural seasonal flow variation, fish habitat needs, and other factors. Once adopted, an instream flow rule acquires a priority date similar to that associated with a water right. Water rights existing at the time an instream flow rule is adopted are unaffected by the rule, and those issued after rule adoption are subject to the requirements of the rule.

The Watershed Planning process is expected to address flows in the lower Skagit River tributaries including those tributaries addressed by this TMDL study. Upon recommendation by the Washington State Department of Fish and Wildlife, Carpenter Creek and Nookachamps Creek are closed to further appropriations. Skagit County has adopted these closures under Section 14.24.350 of the Critical Areas Ordinance, which the county developed under the directives of the Growth Management Act.

The rule-making process is expected to take several years. It will involve data collection, modeling and analysis, as well as consultation with other natural resource agencies and affected Tribes, to obtain their recommendations. A draft instream flow regulation will be distributed for public and agency review and revision prior to any Ecology decision to adopt the rule.

Water Withdrawals

Withdrawal of water from a stream is an important consideration for the instream flow and heat budget. Actual water withdrawals at any given time from streams in the lower Skagit River study area are not known, but information from Ecology's Water Rights Application Tracking database system (WRAT) was used as an indicator of the amounts of water that may be withdrawn. The water quantity potentially withdrawn from surface waters for consumptive use is about 0.90 and 1.3 cubic meters per second (cm) from non-consumptive uses (Table 7). Irrigation represents the majority of the consumptive withdrawal from surface waters.

Table 7. Summary of consumptive water rights in selected lower Skagit River tributaries.

Creeks	Consumptive Surface Withdrawals (cms)	Non-consumptive Surface Withdrawals (cms)
Carpenter- Fisher	0.06	0.12
Hansen	0.01	unknown
Nookachamps	0.36	0.001
East Fork Nookachamps	0.47	1.15
Total	0.9	1.271

Stakeholders and Key Projects in the Study Area

Washington State Conservation Commission

The Washington State Conservation Commission was created in 1939 with the passage of Chapter 89.08 Revised Code of Washington, more commonly known as the Conservation Districts Law. The Conservation Commission exists to assist and guide conservation districts in protecting, conserving, and enhancing the natural resources of the state of Washington. The Commission provides leadership, partnerships, and resources to support locally governed conservation districts in promoting conservation stewardship by all. The Commission takes an active role in the development and implementation of state policies. The Commission manages multiple conservation programs, which are discussed below.

Agriculture, Fish and Water

The Governor's Statewide Salmon Recovery Strategy calls for the development of conservation practice standards for use by farmers to provide appropriate levels of resource protection. This is part of the state's effort to restore the habitat functions needed by salmon to meet recovery goals under the federal Endangered Species Act. The basis of these practice standards is the Field Office Technical Guides (FOTGs) developed by the U.S. Department of Agriculture, Natural Resource Conservation Service.

In 1998 Washington State entered into a Memorandum of Understanding with the Natural Resource Conservation Service, the National Marine Fisheries Service, EPA, and the U.S. Fish & Wildlife Service to update the FOTGs to comply with the Endangered Species Act. It is also hoped that the revised FOTGs will meet the federal Clean Water Act standards, giving farmers certainty on both issues.

This Memorandum of Understanding was the vehicle used to negotiate the Riparian Forest Buffer Standards currently used for the Conservation Reserve Enhancement Program. The process, however, did not include agriculture producers or representation from the environmental community. The Agriculture, Fish and Water process expands the negotiations to include these groups.

The state departments of Agriculture, Fish and Wildlife, and Ecology, as well as the Washington Conservation Commission and staff from the Governor's Office, have begun meeting with representatives from the agricultural community, federal agencies, local government, interested legislators, environmental groups, and Tribes to discuss their possible involvement in a collaborative process, called Agriculture, Fish and Water. This is a negotiated process aimed at voluntary compliance.

The Agriculture, Fish and Water process involves (1) negotiating changes to the existing FOTG and (2) developing guidelines for irrigation districts. These guidelines will be used to enhance, restore, and protect habitat for endangered fish and wildlife species, as well as to address state water quality needs. This two-pronged approach has developed into two processes, one involving agricultural interests and the other involving irrigation districts across the state.

Habitat Limiting Factors Analysis

Section 10 of Engrossed Substitute House Bill 2496 (Salmon Recovery Act of 1998) directed the Washington State Conservation Commission, in consultation with local governments and treaty tribes, to invite private, federal, state, tribal, and local government personnel with appropriate expertise to convene as a Technical Advisory Group (TAG). The purpose of the TAG is to identify habitat limiting factors that affect the natural production of salmonids. One important task in identifying these habitat limiting factors is to map salmonid distribution. Maps of salmonid distribution within WRIA 3, and including the lower Skagit River tributaries, are available at the following url: http://salmon.scc.wa.gov/

The results of assessing habitat limiting factors are intended to be used by locally-based selection committees to prioritize projects for funding under the state salmon recovery program. The results are also intended to be used by local organizations and individuals interested in habitat restoration to identify projects by focusing resources on habitat work that will have the greatest benefit to fish. The TAGs also identify gaps in existing information so future data collection can be efficiently targeted.

Conservation Reserve Enhancement Program

The Conservation Reserve Enhancement Program (CREP) was established to provide a flexible and cost-effective means to address agriculture-related environmental issues by targeting federal and state funding for restoration projects in geographic regions of particular environmental sensitivity. In April 1999 the state of Washington submitted a CREP contract proposal to the Farm Service Agency (FSA) to enhance riparian habitat conditions on agricultural lands along streams which provide important habitat for listed salmonid species.

The program, cooperatively administered by the FSA and the Washington State Conservation Commission, relies on voluntary participation by landowners. The farmers and ranchers who participate in the program sign 10- to 15-year contracts with the federal government, agreeing to remove their land from agricultural production and planting it to woody or shrub vegetation. The landowners will be eligible to receive rental payments and other financial incentives in return for the loss of production from their lands.

The Washington State CREP program is designed to address water quality degradation that is a direct or indirect result of agricultural activities on private lands along freshwater streams. On a statewide basis, approximately 37% of the freshwater salmon streams on private lands in Washington pass through agricultural land use areas. Farming and ranching activities on these lands have led to removal or elimination of native riparian vegetation with resultant increases in water temperature, rates of sedimentation, and reductions in channel complexity.

The project area includes private agricultural lands along streams identified in the 1993 Salmon and Steelhead Status Inventory that provide habitat for salmonid stocks in depressed or critical condition and that are listed under the federal Endangered Species Act. Up to 100,000 acres of private cropland and grazing land, including 3-4,000 miles of riparian area, will be eligible for inclusion in this program. The riparian forest buffer is the primary conservation practice authorized in the Washington CREP. It is anticipated that restoring forested riparian buffers will have a significant positive impact on the targeted freshwater streams.

The six objectives of the Washington CREP are directly related to improving riparian and aquatic ecosystems that provide key habitats for salmonids. These six objectives are:

1. Restore 100% of the area enrolled for the riparian forest practice to a properly functioning condition for distribution and growth of woody plant species.
2. Reduce sediment and nutrient pollution from agricultural lands next to the riparian buffers by more than 50%.
3. Establish adequate vegetation on enrolled riparian areas to stabilize 90% of stream banks under normal (non-flood) water conditions.
4. Reduce the rate of stream water heating to ambient levels by planting adequate vegetation on all riparian buffer lands.
5. Help farmers and ranchers to meet the water quality requirements established under Federal law and Washington's agricultural water quality laws.
6. Provide adequate riparian buffers on 2,700 stream miles to permit natural restoration of stream hydraulic and geomorphic characteristics that meet the habitat requirements of salmon and trout.

Washington CREP includes a set of best management practices (BMPs) designed to reduce adverse environmental impacts. These BMPs will be followed on all CREP activities and will be provided to all farmers and ranchers who enroll in the program. The FSA regards these BMPs as integral components of the CREP and consider them to be part of the action.

The FSA believes that this programmatic consultation on the Washington CREP removes the requirement for most project-level consultation. Consequently, unless otherwise identified within the biological opinion, activities performed within the CREP that are consistent with the BMPs described in the biological assessment, reasonable and prudent measures, and terms and conditions described in the biological opinion will not require further consultation. However, the FSA has identified certain activities which have a greater likelihood of adverse impacts to salmonids and their habitat which will require site-specific consultation. These activities are identified within the biological opinion and include, but are not limited to, bank shaping that exceeds 30 linear feet and any activities that are not consistent with the CREP biological assessment (BMPs inclusive) and this biological opinion (reasonable and prudent measures and terms and conditions inclusive).

The National Marine Fisheries Service and the U.S. Fish & Wildlife Service believe that full achievement of the Washington CREP is likely to make a substantial contribution to the survival and recovery of those aquatic species covered by this opinion. Nonetheless, the FSA also believes that some of the site-specific actions associated with CREP may result in short-term adverse effects to listed fish and associated incidental take. Accordingly, the FSA provided a set of nondiscretionary "reasonable and prudent measures" in the accompanying incidental take statement which they believe are necessary to minimize the take of listed species associated with the CREP.

The primary long-term benefits the buffers will provide for salmonids is shade and the corresponding reduction in water temperature, which is a limiting factor for salmonid reproduction in most of the waterways targeted by the CREP.

Skagit County

Water Quality Monitoring

The Skagit County Public Works Department Surface Water Management Section conducts baseline water quality monitoring in streams flowing through agricultural lands. The goal of the monitoring is to establish a baseline that characterizes streams in Skagit County's agricultural areas and to provide a foundation to identify any trends in watershed health in the Samish and Skagit river basins. The Surface Water Management Section plans to expand its water quality monitoring program by adding additional stations in Hansen, Carpenter, Red, and Fisher creeks for continuous temperature monitoring. Current water quality parameters measured at each station include dissolved oxygen, nutrients, fecal coliform, temperature, pH, turbidity, and conductivity.

Growth Management Act and Critical Areas Ordinance

The Washington State Legislature enacted the Growth Management Act in 1990 in response to growth and development pressures in the state. The Act requires local governments to adopt development regulations, such as subdivision and zoning ordinances, to carry out comprehensive plans.

The Growth Management Act has been amended several times between 1991 and 1998 to further define requirements and to establish a framework for coordination among local governments. The plans include the following chapters: land use, housing, capital facilities, transportation, utilities, shorelines, economic development, and rural (for counties). Chapters on economic development and parks and recreation also are required, if state funding is provided.

Under the Growth Management Act, Skagit County has put into place effective regulatory programs for critical areas, including wetlands, geologically hazardous areas, fish and wildlife habitat conservation areas, critical aquifer recharge areas, and frequently flooded areas. Pioneering plans for flood hazard reduction, nonpoint pollution control, and stormwater management have been developed.

Skagit County adopted a new Critical Areas Ordinance in June 2003 that is intended to address the requirements of the Growth Management Act. Under the new Ordinance, which is scheduled to take effect January 1, 2004, agricultural activities are required to do no harm to water quality and fish and wildlife habitat. Farm plans and BMPs would be implemented as necessary to prevent harm. This approach relies to a significant degree on existing federal and state programs that already regulate certain farm practices. Agricultural practices would need to be conducted in a manner that protects and does not degrade the habitat functions and values of adjacent watercourses.

Skagit Watershed Council

The Skagit Watershed Council (SWC) is a non-profit agency of 36 member organizations including tribes, county, state, and federal government entities, conservation organizations, and business and industry groups. SWC is recognized as a state lead entity under the Salmon Recovery Act.

The mission of the SWC is to provide technical assistance, public outreach and education, and a collaborative approach within the Skagit watershed to understand, protect, and restore the production and productivity of healthy ecosystems in order to support sustainable fisheries. The SWC has been instrumental in the coordination, prioritization, funding, and implementation of habitat protection and restoration projects for salmon and other fish species including native char in the Skagit River basin.

Watershed planning for protecting and restoring fish resources in the Skagit basin follows the SWC's "Habitat and Restoration Strategy". This landscape-based strategy is based upon the best available science regarding natural processes, human disturbance, habitat conditions, fish population distribution and trends, and ecosystem health.

The SWC has completed a basin-wide evaluation of habitat conditions for salmon. This planning tool has been used to screen and prioritize fish habitat protection and restoration projects in the basin and to identify "priority" sub-basins in the Skagit River watershed for protection and restoration projects.

Skagit Fisheries Enhancement Group

The Skagit Fisheries Enhancement Group (SFEG) is a nonprofit organization dedicated to the enhancement of salmon resources through education, restoration, and public involvement. Established in 1990 as one of 14 Regional Fisheries Enhancement Groups in Washington State, SFEG is part of a coordinated effort to educate and involve the public in salmon enhancement activities across the state at the community level. SFEG works cooperatively with local landowners to identify restoration opportunities on their property and find the funding to implement them.

SFEG conducts restoration projects that include riparian restoration, improvement of fish passage, nutrient enhancement, and instream enhancement projects such as channel enhancement and streambank stabilization. The SFEG monitoring program is designed to evaluate the effect of restoration work to improve natural watershed conditions and salmon resources. Results of monitoring programs help guide designs for future restoration projects and document successes to funding entities.

Skagit Conservation District

The Skagit Conservation District (SCD) is a legal subdivision of Washington State government organized under "Conservation District Law" RCW Title 89, Chapter 89.08, and is composed of farmers, landowners, and concerned citizens. The district priorities and goals include:

- Protection and Improvement of the Quality of Surface and Ground Water
- Watershed Planning and Implementation
- Riparian Reforestation and Enhancement
- Forest Stewardship
- Wildlife Habitat Enhancement
- Conservation Education
- Protection and Preservation of Prime Farmlands
- County Government Assistance
- Increase District Capacity

The SCD encourages and promotes the preservation and optimum beneficial use of agricultural, range and forested lands by helping landowners plan and implement BMPs that reduce soil erosion, improve water quality and water conservation, as well as protect the natural resource base of the SCD. The SCD also provides:

- Education and technical assistance to non-industrial forest landowners.
- Soils information, conservation maps, and knowledge of BMPs to landowners and land managers.
- Implementation programs aimed at protecting the water resources of Skagit County.
- Surveys, research studies, comprehensive plans, and demonstration and implementation projects on public and private lands within the SCD.
- Responsible and accountable management and financial assistance.
- Conservation leadership to federal, state, and local governmental agencies.
- Monitoring of enhancement projects and BMP implementations that document success and/or the need for adaptive management measures.

Skagit System Cooperative

The Skagit System Cooperative (SSC) is a natural resource consortium of the Swinomish and Sauk-Suiattle tribes with fishing rights in Skagit County waters. The Swinomish Tribe has a reservation on Skagit Island just west of La Conner. The Sauk-Suiattle Tribe has tribal offices near the Sauk River in Darrington in Snohomish County. The SSC's policy is to protect, preserve, and enhance Skagit-area fish habitat and other natural resources and environment that affect the quality of that habitat. In addition, the SSC's and Tribes' policy is to achieve a net gain in the productive capacity of Skagit-area fish habitat.

The Upper Skagit Tribe, which has tribal offices in Sedro-Woolley, was until recently a member of the SSC. As of January 1, 2004, the Tribe will manage its natural resources programs independently of the SSC.

Applicable Water Quality Criteria

Section 303(d) of the federal Clean Water Act mandates that Washington State establish Total Maximum Daily Loads (TMDLs) for surface waters that do not meet water quality standards after application of technology-based pollution controls.

The goal of a TMDL is to ensure the impaired waterbody will attain water quality standards. The TMDL determines the maximum amount of a given pollutant that can be discharged to the waterbody and still meet the state water quality standards (referred to as the loading capacity) and allocates that load among the various sources. If the pollutant comes from a discrete (point) source such as an industrial facility discharge pipe, that facility's share of the loading capacity is called a wasteload allocation. If it comes from a diffuse (nonpoint) source such as a farm, that facility's share is called a load allocation.

The TMDL must also consider seasonal variations and include a margin of safety that takes into account any lack of knowledge about the causes of the water quality problem or its loading capacity. The sum of the individual allocations and the margin of safety must be equal to or less than the calculated loading capacity for the specific pollutant.

All tributaries within the lower Skagit River study area are classified as Class A, excellent, as defined by the Water Quality Standards for Surface Waters of the State of Washington (Hicks 2000; Chapter 173-201A-030 WAC). The standards establish beneficial uses of waters and incorporate specific numeric and narrative criteria for parameters such as water temperature. The criteria are intended to define the level of protection necessary to support the beneficial uses (Rashin and Graber 1992). The beneficial uses of the waters in the lower Skagit River watershed are:

- *Recreation:* Fishing and swimming.
- *Fish and Shellfish:* Spring chinook, cutthroat, and coho use the waters in the study area for migration, rearing, and spawning.
- *Water Supply and Stock Watering:* Agriculture extracts water for irrigation and stock watering.
- *Wildlife Habitat:* Riparian areas are used by a variety of wildlife species which are dependent on the habitat.

Numeric water quality criteria for Class A freshwater streams state that temperature shall not exceed 18.0°C due to human activities. When natural conditions exceed 18.0°C, no temperature increases will be allowed which will raise the receiving water temperature greater than 0.3°C. If natural conditions are below 18.0°, incremental temperature increases resulting from nonpoint source activities shall not exceed 2.8°C or bring the stream temperature above 18.0°C at any time (Chapter 173-201A-030 WAC).

During critical periods, natural conditions may exceed the numeric temperature criteria mandated by the water quality standards. In these cases, the antidegradation provisions of those standards apply.

"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-030 WAC).

Load allocations for Nookachamps Creek and Lake Creek use both the numeric criteria of 18°C and the narrative natural condition provision. The numeric criteria of 18°C are used within the load allocations for the remaining waterbodies within the study area.

Water Quality and Resource Impairments

The 1998 303(d) listings for temperature in the lower Skagit River basin are presented in Table 8.

Table 8. 1998 303(d) listing rationale for temperature in the lower Skagit River basin.

Waterbody ID	Creek	Date placed on 303(d) List	Rationale: Excursions beyond the criterion in 1997*
WA-03-1011	Carpenter	1998	10
WA-03-1012	Fisher	1998	3
WA-03-1019	Hansen	1998	6
WA-03-1017	Nookachamps	1998	20
WA-03-4200	E.F. Nookachamps	1998	5
None5	Otter Pond	1998	9
None6	Red	1998	10
None12	Turner	1998	9

* Data from Skagit System Cooperative

The 303(d) listings for temperature are also confirmed by recent data collected in 2001 and 2002 by Ecology and the Skagit County Surface Water Management Division. Temperatures in excess of the water quality standards (18°C) have been observed throughout the lower Skagit River tributaries at numerous locations (Table 9). Detailed station location maps are given in Figures 15 and 19.

Both Ecology and Skagit County temperature data show that the warmest temperatures in the lower Skagit River tributaries occur in Carpenter, Red, and Nookachamps creeks. Temperatures in these three tributaries have frequently been measured near or above the lethal limit for steelhead of about 24ºC.

Table 9. Highest daily maximum temperatures in the lower Skagit River tributaries during 2001 Data in *italics* indicate values greater than the water quality standard.

Station ID	Station Name	Latitude decimal degrees NAD27	Longitude decimal degrees NAD27	Highest daily maximum temperatures during 2001 (degrees C)	Highest 7-day-averages of daily maximum temperatures during 2001 (degrees C)	Water Quality Classification	Water Quality Standard (degrees C)
Ecology Stations, 2001							
03C01	Carpenter Cr. near mouth	48.323	-122.342	*24.18*	*22.89*	A	18
03C02	Carpenter Cr. at SR534	48.341	-122.323	*23.27*	*22.01*	A	18
03C03	Carpenter Cr. at Stackpole Rd	48.341	-122.307	*18.42*	17.93	A	18
03C04	Carpenter Cr. at Little Mountain	48.395	-122.284	16.16	15.54	A	18
03EF01	EF Nookachamps Cr. at SR9	48.446	-122.251	*19.68*	*19.06*	A	18
03EF02	EF Nookachamps at Beaver Lake Rd	48.424	-122.209	*19.7*	*19.25*	A	18
03F01	Fisher Cr. at Franklin Rd	48.319	-122.328	14.72	14.38	A	18
03F02	Fisher Cr. at Starbird Rd	48.309	-122.296	*19.06*	*18.15*	A	18
03H01	Hansen Cr. at Hoehn Rd	48.503	-122.197	*19.21*	*18.75*	A	18
03H02	Hansen Cr. at Highway 20	48.521	-122.198	17.99	17.19	A	18
03U04	Red Cr. near Highway 20	48.523	-122.191	*28.26*	*26.71*	A	18
03H03	Hansen Cr. at Hansen Cr. Rd	48.559	-122.208	*18.29*	17.93	A	18
03N01	Nookachamps Cr. nr mouth	48.467	-122.292	*25.25*	*24.3*	A	18
03N02	Nookachamps Cr. abv Barney Lake	48.431	-122.263	*22.17*	*21.58*	A	18
03T01	Turner Cr. at Beaver Lake Rd	48.439	-122.219	*18.77*	*18.35*	A	18
03N03	Nookachamps Cr. blw Big Lake	48.4	-122.237	*24.41*	*23.7*	A	18
03N04	Lake Cr. above Big Lake	48.345	-122.205	*20.11*	17.53	A	18
03U03	Otter Pond Cr. near mouth	48.403	-122.227	16.17	15.67	A	18
Skagit County Surface Water Stations, 2001 (Aug - Sept)							
12	Nookachamps Cr. at Swan Rd	48.453	-122.27	*23.44*	*22.56*	A	18
13	EF Nookachamps Cr. at Hwy 9	48.446	-122.251	*19.59*	*18.99*	A	18
15	Nookachamps Cr. at Knapp Rd	48.428	-122.257	*20*	*19.68*	A	18
16	EF Nookachamps Cr. at Beaver Lake Rd	48.424	-122.208	*19.86*	*19.47*	A	18
17	Nookachamps Cr. at Hwy 9-Big Lake outlet	48.4	-122.237	*23.52*	*23.08*	A	18
18	Lake Cr. at Hwy 9	48.356	-122.202	17.6	17.15	A	18
19	Hansen Cr. at Hoehn Rd	48.503	-122.197	*19.66*	*19.02*	A	18
20	Hansen Cr. at Northern State	48.53	-122.199	*19.22*	*18.69*	A	18
Skagit County Surface Water Stations, 2002 (June 1 - Sept 10)							
12	Nookachamps Cr. at Swan Rd	48.453	-122.27	na	na	A	18
13	EF Nookachamps Cr. at Hwy 9	48.446	-122.251	*20.67*	*19.41*	A	18
15	Nookachamps Cr. at Knapp Rd	48.428	-122.257	*22.82*	*21.77*	A	18
16	EF Nookachamps Cr. at Beaver Lake Rd	48.424	-122.208	*20.46*	*19.04*	A	18
17	Nookachamps Cr. at Hwy 9-Big Lake outlet	48.4	-122.237	*26.13*	*24.84*	A	18
18	Lake Cr. at Hwy 9	48.356	-122.202	*18.09*	17.22	A	18
19	Hansen Cr. at Hoehn Rd	48.503	-122.197	*20.03*	*18.75*	A	18
20	Hansen Cr. at Northern State	48.53	-122.199	*18.69*	17.55	A	18

Seasonal Variation and Critical Conditions

The federal Clean Water Act Section 303(d)(1) requires that TMDLs "be established at levels necessary to implement the applicable water quality standards with seasonal variations". The current regulation also states that determination of "TMDLs shall take into account critical conditions for streamflow, loading, and water quality parameters" [40 CFR 130.7(c)(1)]. Finally, Section 303(d)(1)(D) suggests consideration of normal conditions, flows, and dissipative capacity.

Existing conditions for stream temperatures in the lower Skagit River tributaries reflect both seasonal and diurnal variation. Average temperatures are hottest in the summer months, while cooler temperatures predominate in the winter months. Minimum temperatures occur in the evening, while maximum temperatures are observed in the daytime. Figures 13 and 14 summarize the highest daily maximum and the highest seven-day average maximum water temperatures of 2001 for waterbodies in Carpenter-Fisher, Hansen, and Nookachamps creek watersheds. The highest temperatures typically occur from July through August. This time frame is used as the critical period for development of the TMDL.

Seasonal estimates for streamflow, solar flux, and climatic variables for the TMDL are taken into account to develop critical conditions for the TMDL model. The critical period for evaluation of solar flux and effective shade was assumed to be August 12, because it is the mid-point of the period when water temperatures are typically at their seasonal peak.

Critical streamflows for the TMDL were evaluated as the lowest 7-day average flows with a 2-year recurrence interval (7Q2) and 10-year recurrence interval (7Q10) for the months of July and August. The 7Q2 streamflow was combined with air temperatures during a typical climatic year, and the 7Q10 streamflow was combined with atmospheric conditions during a worst-case climatic year.

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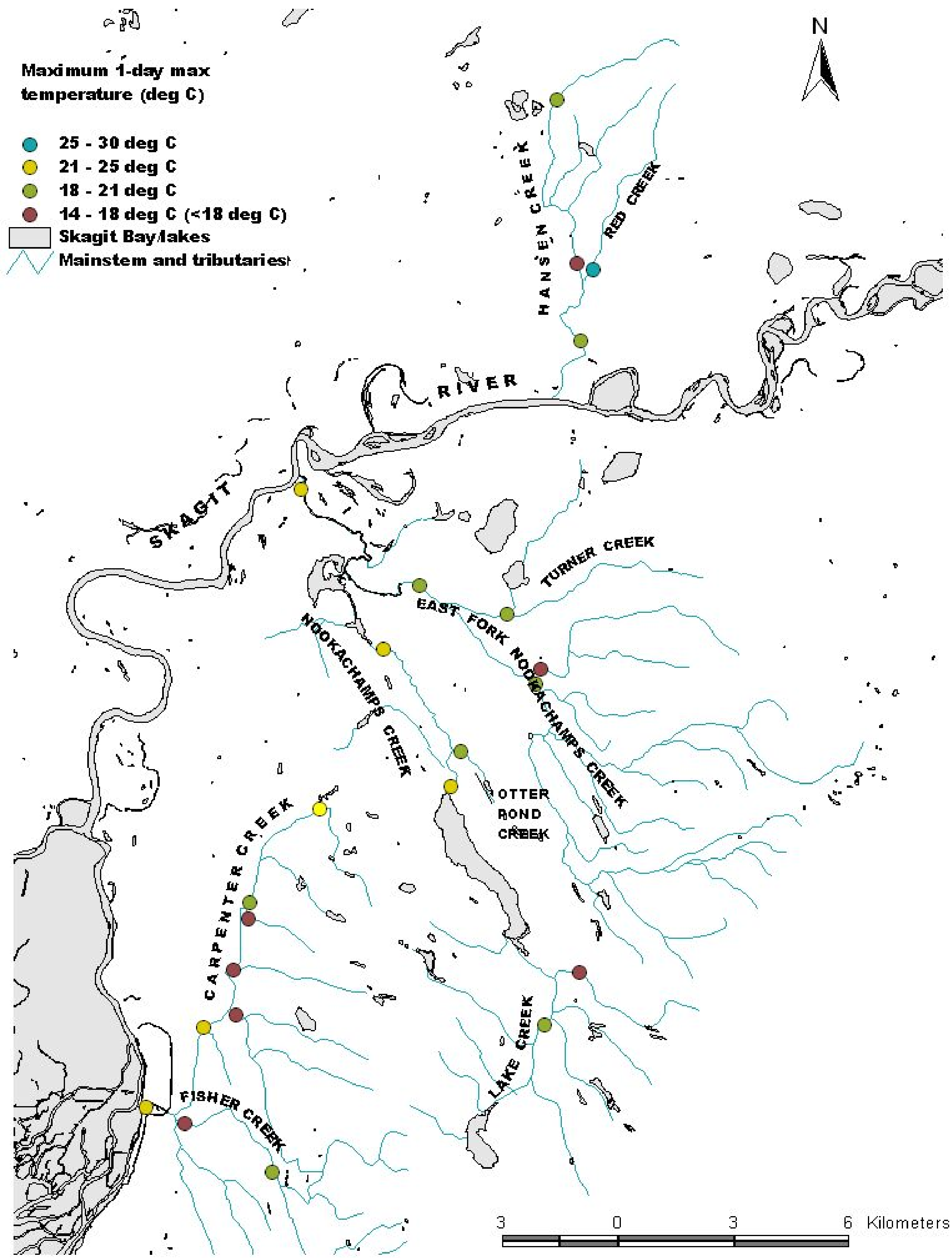


Figure 13. Highest daily maximum temperatures in the lower Skagit River tributaries in 2000 on the hottest day of the year for each station.

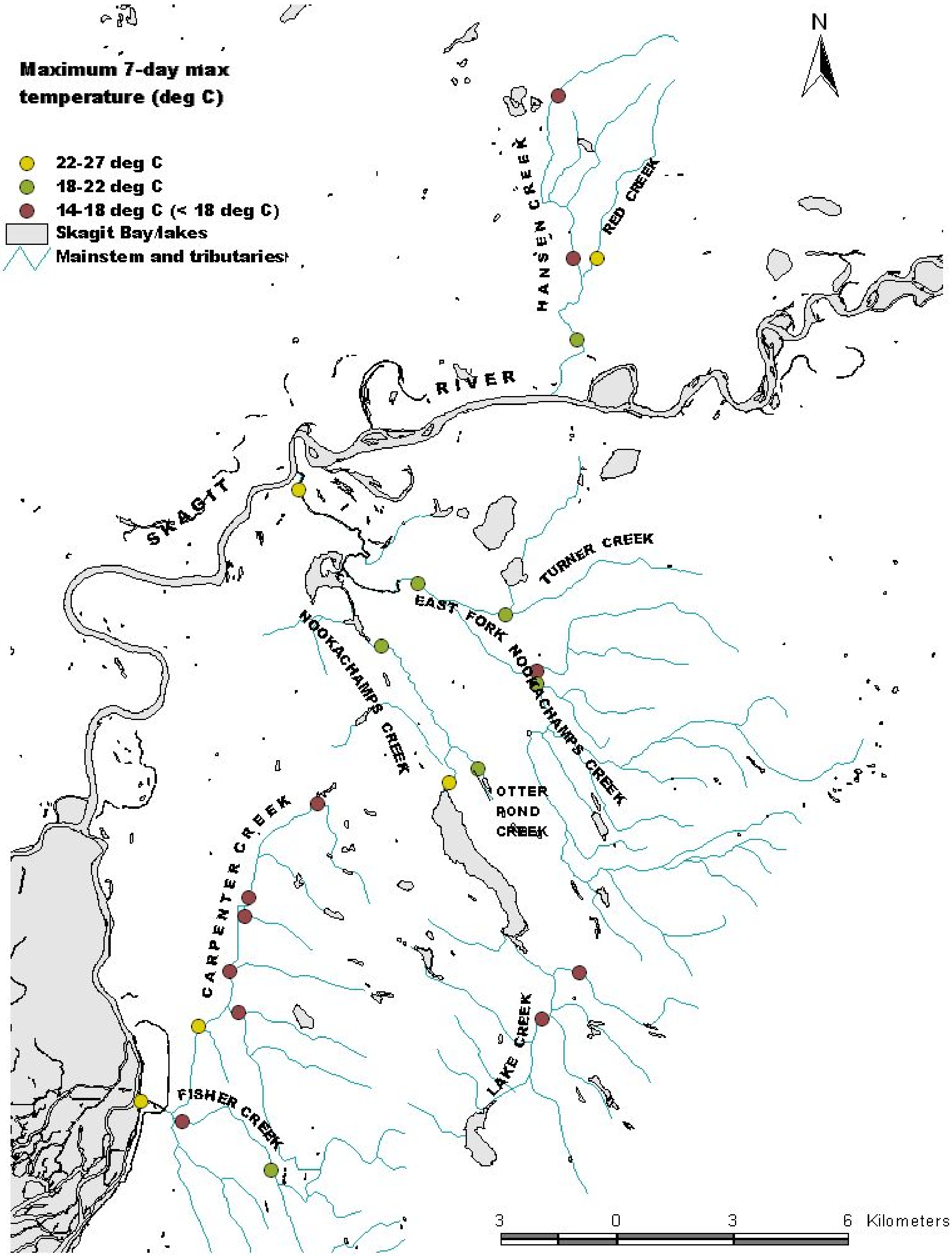


Figure 14. Maximum 7-day averages of daily maximum temperature in the lower Skagit River tributaries in 2000.

Technical Analysis

Stream Heating Processes

Riparian vegetation, stream morphology, hydrology, climate, and geographic location influence stream temperature. While climate and geographic location are outside of human control, riparian condition, channel morphology, hydrology, and ultimately temperature are affected by land use activities. Specifically, the elevated summertime stream temperatures attributed to anthropogenic sources in the lower Skagit River tributaries result from the following:

- Riparian vegetation disturbance reduces stream surface shading via decreased riparian vegetation height, width, and/or density, thus increasing the amount of solar radiation reaching the stream surface. Current riparian forests are extensively degraded compared with historic (circa 1873) conditions (Pess et al. 1999). Pess et al. reported that the most severely degraded riparian forests in the adjacent Stillaguamish River watershed are those with extensive agricultural activity, followed by rural residential development. Forest lands generally have the least degraded riparian forests, and riparian forests in federal lands are generally in much better condition than those on state and private land.
- Past land management activities in the lower Skagit River watershed were likely very similar to those which occurred in the adjacent Stillaguamish River watershed. Landslides triggered by forest practices and riparian logging, as well as agricultural and urban activities, have caused numerous tributaries to widen and aggrade at some point in the last half century. Widening of the channels throughout the lower Skagit River study area has likely decreased the effectiveness of potential shading from near-stream vegetation.
- Reduced summertime baseflows may result from instream withdrawals and hydraulically connected groundwater withdrawals. Reducing the amount of water in a stream can increase stream temperature (Brown 1972).

Current Conditions

Available Water Temperature Data

Ecology installed a network of continuous temperature dataloggers in the lower Skagit River watershed, as described by Pelletier and Bilhimer (2001) (Figure 15). Data from 2001 show that water temperatures in excess of the Class A standards of 18°C are common throughout the study area (Figures 13-14 and 16-18).

A network of continuous temperature dataloggers has also been developed and maintained in Skagit County by the Skagit County Surface Water Management Division. Water and air temperatures were continuously monitored in the spring, summer, and fall of 2001 and 2002 in Nookachamps, East Fork Nookachamps, Lake, and Hansen creeks (Table 9, Figure 19). Water temperatures in excess of 20°C have been observed in the lower Nookachamps Creek, as well as near the outlet of Big Lake and Lake McMurray (Table 9).

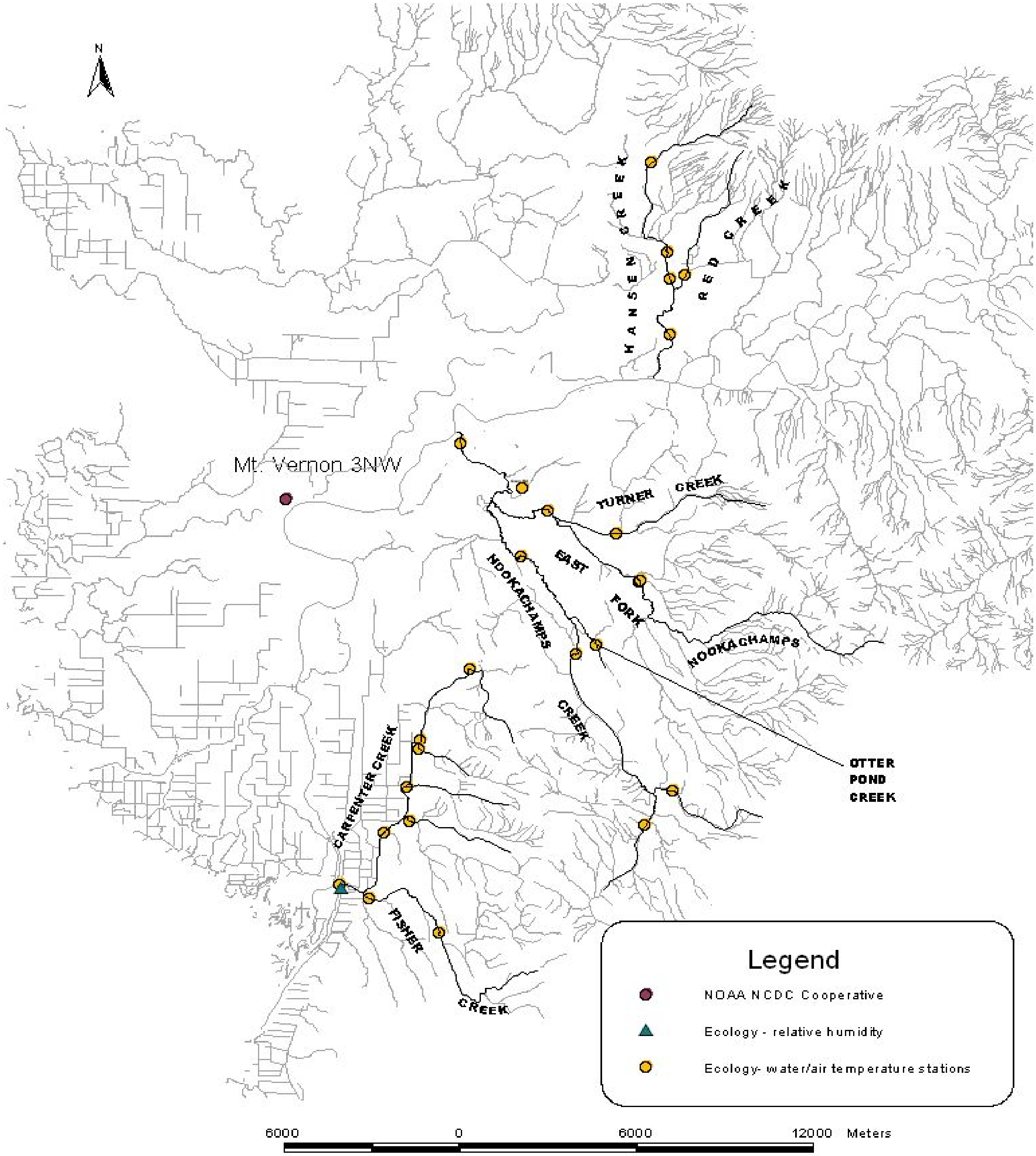
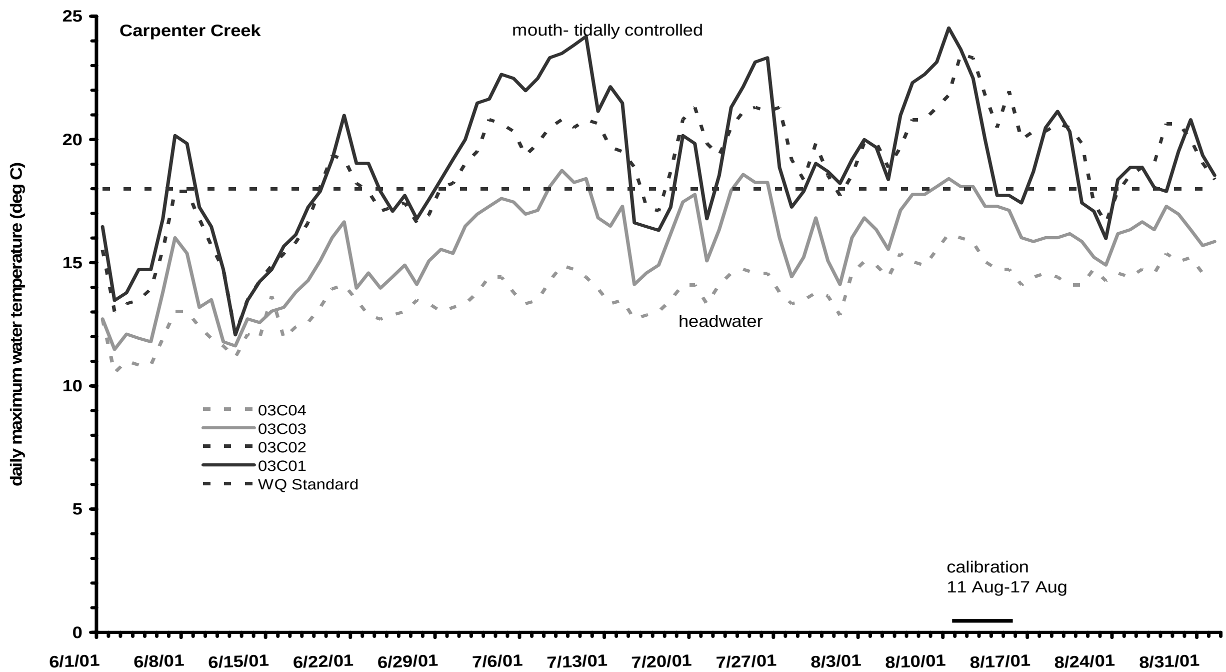


Figure 15. Location of Ecology air and water temperature recording devices, relative humidity station, and NOAA NCDC Cooperative weather station.



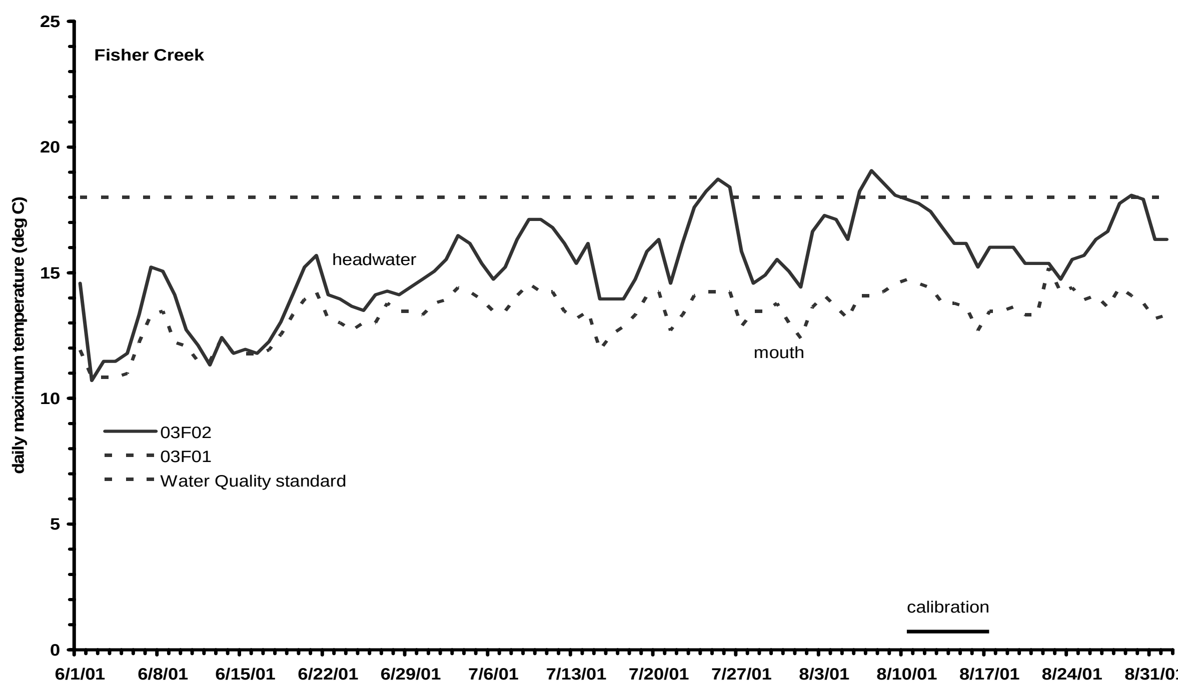
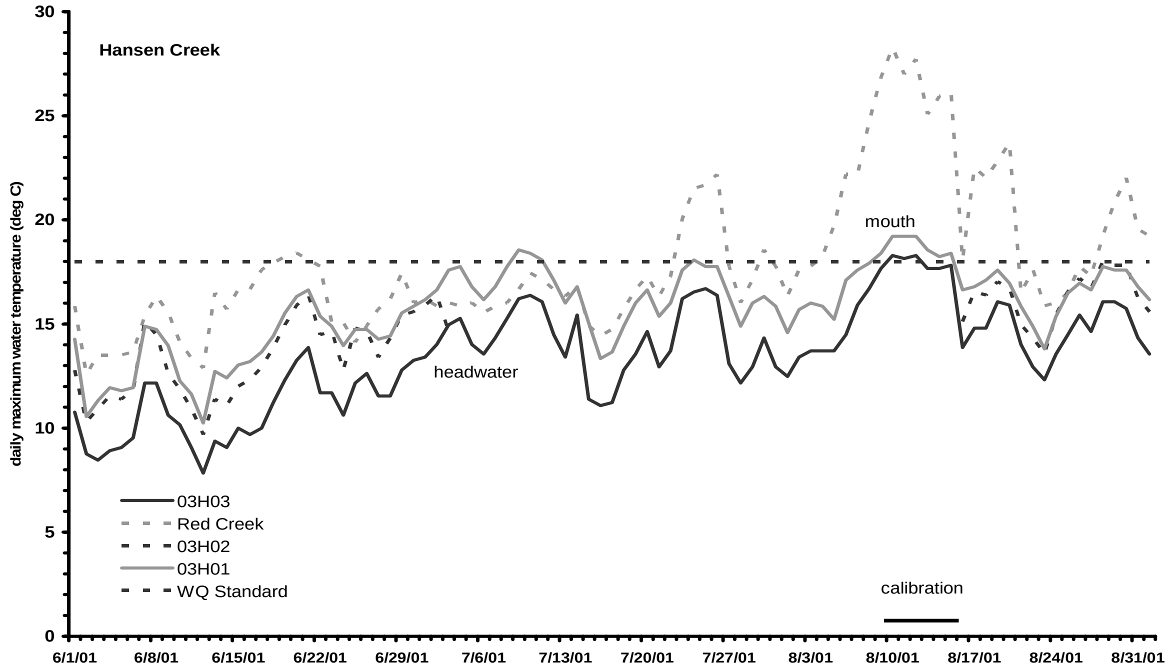


Figure 16. Daily maximum water temperatures in Carpenter and Fisher creeks from June to September 2001.



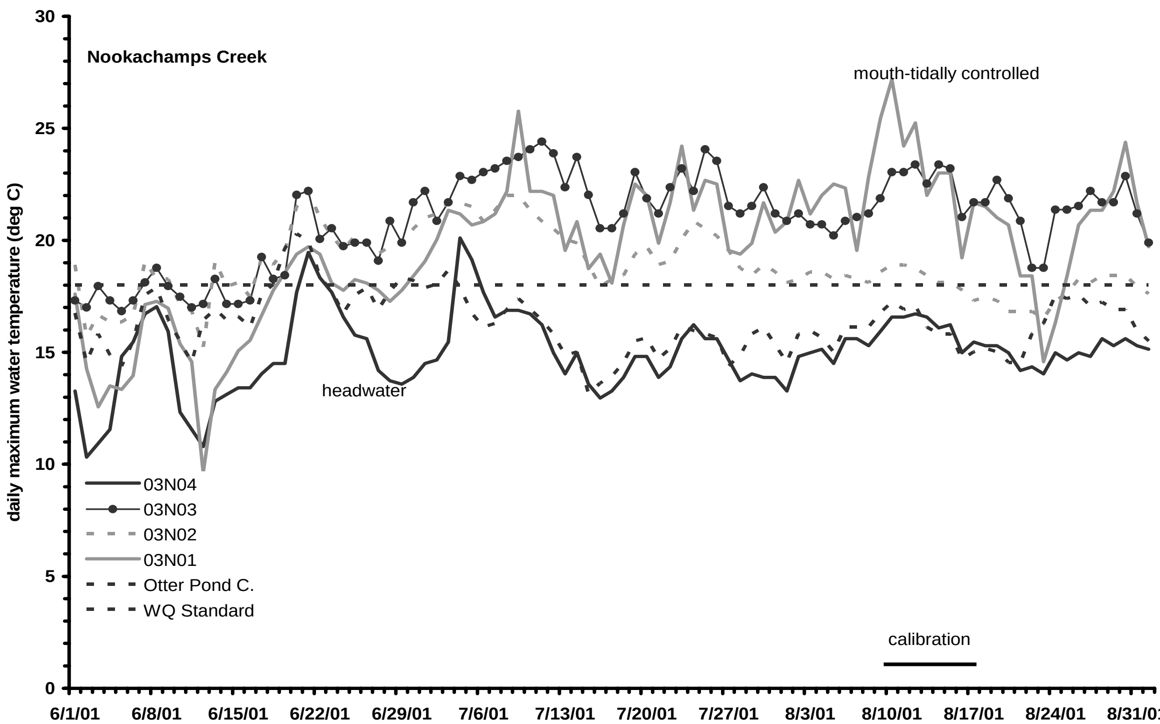


Figure 17. Daily maximum water temperatures in Hansen, Red, Lake (03N04), Nookachamps, and Otter Pond creeks from June to September 2001.

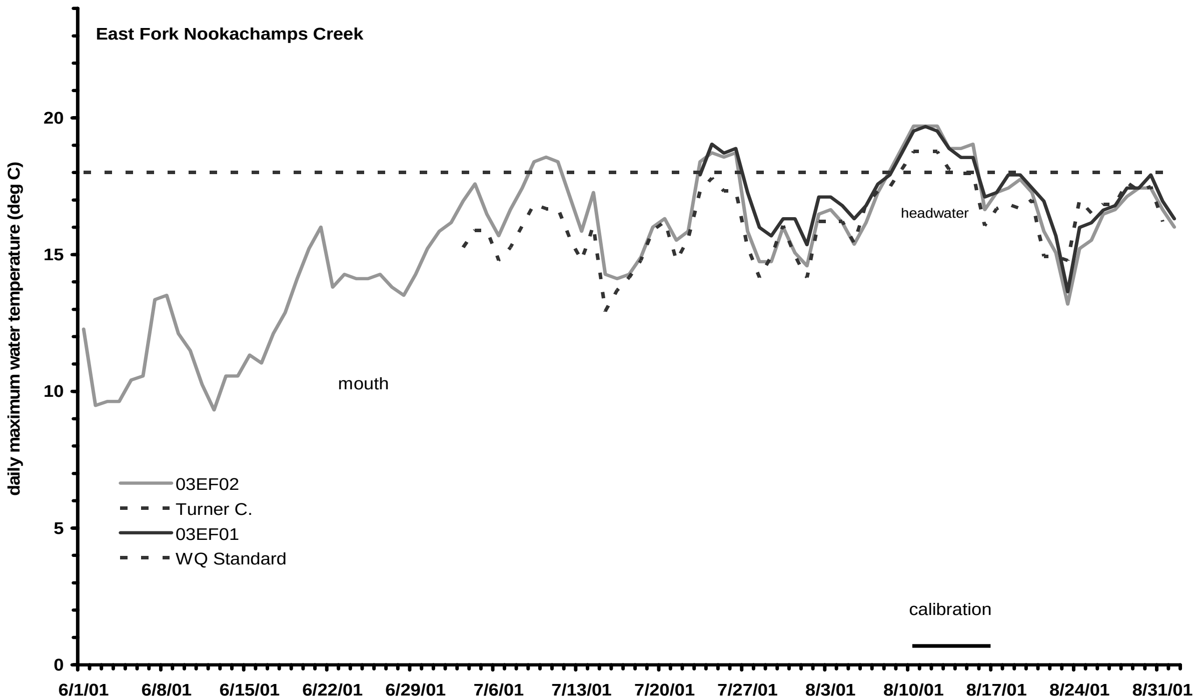


Figure 18. Daily maximum water temperatures in East Fork Nookachamps and Turner creeks from June to September 2001.

Stream Flow Data

Ecology installed a flow measurement station in East Fork Nookachamps Creek during 2001 and made numerous flow measurements at all other stations, including a synoptic flow survey in August 2000. The Skagit County Surface Water Management Division also measured instantaneous flows at a number of stations in Hansen, Nookachamps, and East Fork Nookachamps creeks in 2001. Measured streamflow summaries are given in Appendix B-4. The lowest 7-day-average flows during the July-August period with recurrence intervals of 2 years (7Q2) and 10 years (7Q10) were estimated based on low-flow statistics from the USGS gaging station in Pilchuck Creek (#12168500 Pilchuck Creek near Bryant, WA, elevation 119.8 ft, drainage area 52 mi^2). The 7Q2 and 7Q10 flows in the study area were then estimated by scaling the estimates at the USGS Pilchuck Creek gage (period of record 1929-1998) according to the sub-watershed areas weighted by annual average precipitation[1] (Table 10). Because of the close proximity of the Pilchuck watershed to the study area, similar annual precipitation values were used as part of the 7Q2 and 7Q10 flow estimations. Widths, depths, and velocities under 7Q2 and 7Q10 conditions for each station are given in Appendix B-3.

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[1] Annual average precipitation values were obtained from NOAA NCDC weather stations at Mount Vernon, Arlington, and Sedro Woolley, WA.

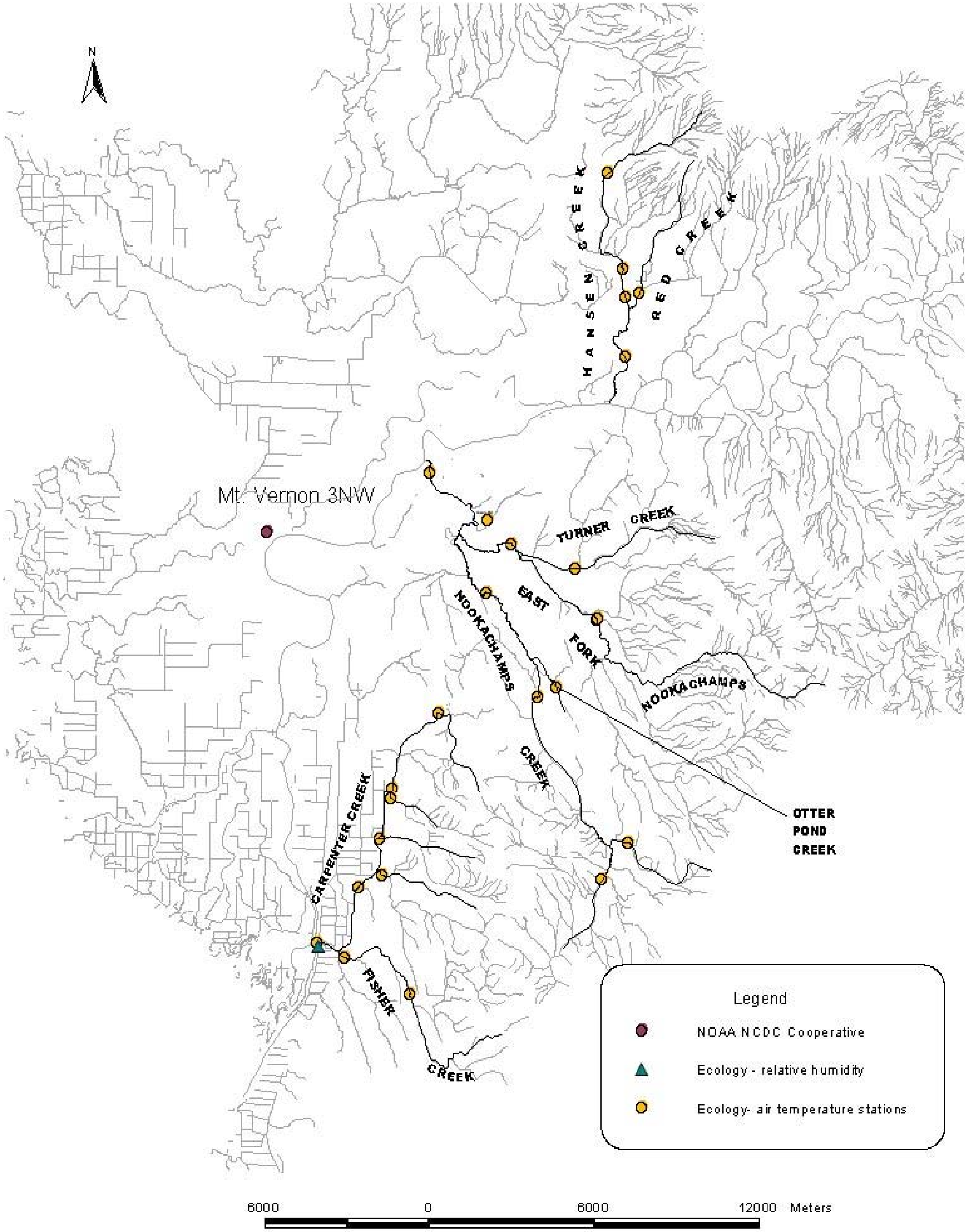


Figure 19. Location of Skagit County air and water temperature recording devices, Ecology relative humidity station, and NOAA NCDC Cooperative weather station.

Table 10. Estimated 7Q2 and 7Q10 flows for selected streams in the lower Skagit River study area.

Creek	Drainage area (km2)	Drainage area (mi2)	Estimated 7Q2 flow (cm)	Estimated 7Q2 flow (cfs)	Estimated 7Q10 flow (cm)	Estimated 7Q10 flow (cfs)
Pilchuck	134	52	0.15	5.40	0.05	1.80
Carpenter	95	37	0.11	3.82	0.04	1.27
Fisher	17	7	0.02	0.65	0.01	0.22
Hansen	33	13	0.04	1.34	0.01	0.46
Lake	40	15	0.02	0.85	0.01	0.28
Nookachamps	180	69	0.20	7.20	0.07	2.40
E.F. Nookachamps	91	35	0.10	3.64	0.03	1.20

Hydraulic Geometry

The channel width, depth, and velocity have an important influence on the sensitivity of water temperature to the flux of heat. The near-stream disturbance zones (NSDZ or bankfull width) were digitized from digital rectified orthophotos. In areas where NSDZ edges were not easily identified from the orthophotos (heavy vegetation, cutbanks, floodplain relief), the NSDZ was estimated from a log-log regression of measured bankfull width versus drainage area (Figure 20).

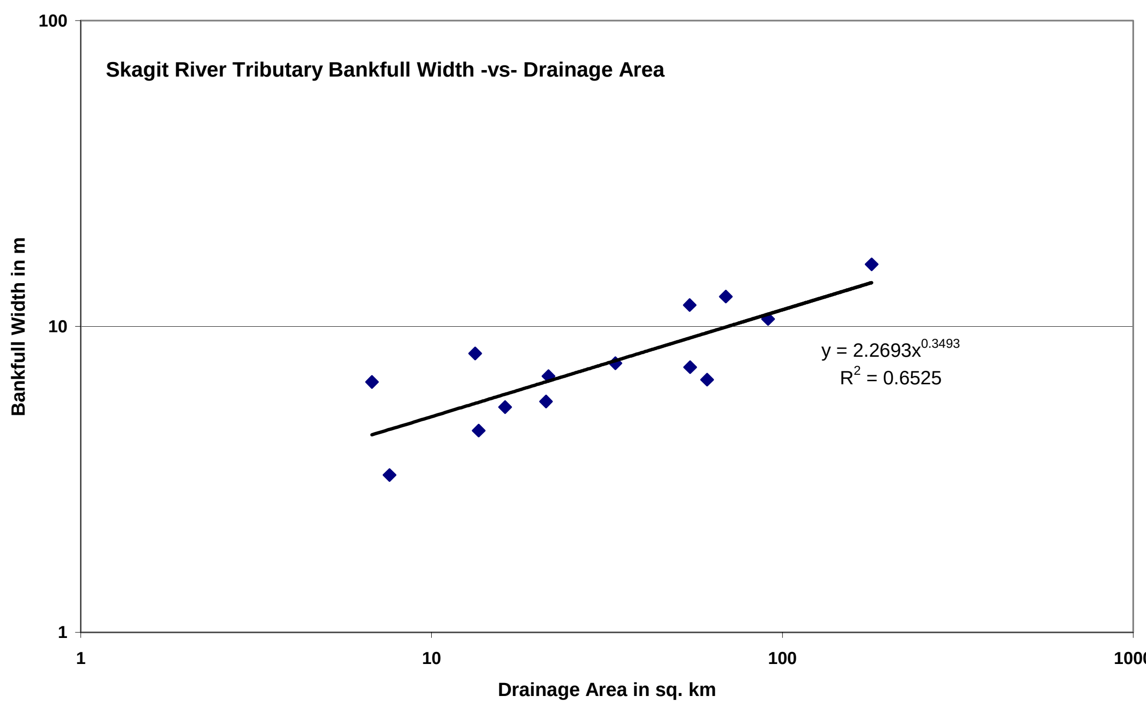


Figure 20. Relationship between bankfull width and drainage area in lower Skagit River tributaries.

Stream widths at low flow were estimated from field measurements as described in Pelletier and Bilhimer (2001). Wetted widths in many parts of the study area were not easily identified from the digital orthophotos. In these reaches the wetted widths were estimated by using the exponents for each basin as shown in Table 11, which shows the general relationships between wetted width, depth, velocity[2], and flow at all stations in the study area during the June to September low-flow period.

Table 11. Summary of hydraulic geometry relationships with flow in the lower Skagit River study area, May-October 2001.

Parameter / Power Function	Coefficient or Exponent	All Stations	Carpenter Creek head-waters	Carpenter Creek "Hill Ditch"	Fisher Creek main-stem	Hansen Creek head-waters	Hansen Creek lower	Lake Creek main-stem	Nooka-champs Creek head-waters	Nooka-champs Creek lower	EF Nooka-champs Creek lower
width	coefficient a	8.0258	3.4597	5.833	2.639	5.8239	7.3012	9.1013	7.4918	5.6837	8.1036
aQ^b	exponent b	0.2405	0.0177	0.14	0.0276	0.1488	0.2895	0.2937	0.3109	0.2206	0.2767
depth	coefficient c	0.3244	0.1509	0.2867	0.2018	0.4358	0.4131	0.2166	0.3417	0.3553	0.328
cQ^f	exponent f	0.4135	0.3011	0.4472	0.0106	0.3327	0.514	0.2395	0.4345	0.3405	0.4253
velocity	coefficient k	0.403	1.8615	0.6141	1.7181	0.3903	0.3027	0.4967	0.5218	0.4834	0.4385
kQ^m	exponent m	0.3596	0.6704	0.4248	0.9154	0.6403	0.1872	0.5142	0.1434	0.4034	0.2494

At different discharges, the observed mean velocity, mean depth, and width of flowing water reflect the hydraulic characteristics of the channel cross section. Graphs of these three parameters as functions of discharge at the cross section constitute a part of what Leopold and Maddock (1953) called the hydraulic geometry of stream channels. The principal hydraulic parameters are related to discharge as power functions. The relations to discharge at a given river cross section can be written as

$$w = aQ^b, \qquad d = cQ^f, \qquad u = kQ^m$$

where w is width, Q is discharge, d is mean depth, and u is mean velocity. The letters b, f, and m are exponents, and a, c, and k are coefficients.

The product of width and mean depth is the cross-sectional area of flowing water. Discharge is the product of mean velocity and cross-sectional area of flow. Thus

$$w \times d = A, \text{ and } w \times d \times v = Q.$$

It follows that $aQ^b \times cQ^f \times kQ^m = Q$, or $b + f + m = 1$, and $a \times c \times k = 1.0$ (Leopold et al. 1992).

[2] Flow is in cubic meters per second. Width and depth are in meters. Velocity is in meters per second.

Using these power functions, it is possible to determine the channel widths, depths, and velocities for each of the modeled segments. Once a specific discharge (7Q2 or 7Q10) is calculated, the exponents and coefficients are used to derive the width, depth, and velocities for a cross section, which can then be applied to an adjacent reach.

Manning's equation is commonly used to solve for depth (y) given flow (Q), Manning's roughness coefficient (n), wetted width (B_0), and channel slope (S). Manning's equation for a rectangular channel (side slope s=0) is as follows (Chapra 1997):

$$Q = \frac{1}{n} \frac{[(B_0 + sy)y]^{5/3}}{\left(B_0 + 2y\sqrt{s^2+1}\right)^{2/3}} S_e^{1/2}$$

equation 1

Manning's n typically varies with flow and depth (Gordon et al. 1992). As the depth decreases at low flow, the relative roughness increases. Typical published values of Manning's n, which range from about 0.02 for smooth channels to about 0.15 for rough natural channels, are representative of conditions when the flow is at the bankfull capacity (Rosgen 1996). Critical conditions of depth for evaluating the period of highest stream temperatures are generally much less than bankfull depth, and the relative roughness may be much higher.

Reach-averaged values of Manning's n may be higher than those estimated at any point where flow was measured because the locations of the cross sections for flow measurements were typically selected for laminar flow conditions that occur in channels that are deeper and narrower than average. Likewise, reach-averaged depth may be considerably less than the depth at the flow measurement stations. Therefore, reach-averaged relative roughness is likely to be greater than the measured roughness at the flow stations. Estimated Manning's roughness coefficients (n) are shown in Table 12.

Table 12. Estimated Manning's roughness coefficients (n)

Stream, Stream segment	Average Manning's n value
Carpenter Creek	0.1
Hill Ditch	0.04
Fisher Creek	0.11
Hansen Creek upper	0.0916
Hansen Creek lower	0.0377
Lake Creek	0.081
Nookachamps Creek nr Hwy 9 and 538	0.03
Nookachamps Creek	0.05
East Fork Nookachamps Creek	used hydraulic geometry coefficients

The relationships in Tables 11 and 12 were used to define the longitudinal channel characteristics used as input to the QUAL2Kw model.

Ecology used the Rosgen stream morphology classification system (Rosgen 1996) to describe the channel characteristics for streams in the lower Skagit River study area (Table 13). This information is helpful in determining what morphological parameters are contributing to elevated water temperatures in the watershed.

Table 13. Rosgen classification for the lower Skagit River study area.

Stream Name	Identifying Station(s)	Average Slope (%)	Bankfull Width/Depth Ratio	Sinuosity	Dominant Bed Material	Rosgen Channel Classification
Hill Ditch	03C01, 03C02, 03C03	1	28	very low	sand, silt, clay	diked-channelized
Carpenter Creek	03C04	5	12	low	gravel-cobble	C3
Fisher Creek	03F01	5	13	moderate	gravel-cobble	C3
	03F02	2	17	moderate	gravel-cobble	C3
Hansen Creek	03H03	2.3	20	moderate	cobble-gravel	B3
	03H02, 03H01	1	19	low	gravel	dredged channel
Nookachamps Creek	03N03	1	28	very low	gravel-cobble	channelized
	03N02	1	28	low	cobble-boulder	C2
	03N01	1	28	very low	sand	diked-channelized
Lake Creek	03N04	1	18	low	gravel-cobble	C4
East Fork Nookachamps Creek	03EF02	1	50	low	sand silt clay	channelized
	03EF01	1	24	low	gravel sand	diked channelized

Climate Data

A network of dataloggers was installed to continuously monitor air temperature throughout the study area according to Pelletier and Bilhimer (2001) (Figure 15). Relative humidity was continuously monitored at one station located near the mouth of Carpenter Creek. The NOAA National Climate Data Center (NCDC) station at Mt. Vernon 3WNW (1956-present) also provides a record of long-term trends in climate data. The Mt. Vernon 3WNW station was used to estimate the median year hottest week and 90th percentile year hottest week conditions for climate.

The highest daily maximum and highest 7-day-average of daily maximum air temperatures for each year of record at the Mt. Vernon 3WNW station were ranked to determine the median and 90th percentile conditions (Table 14).

Intact riparian corridors often produce a microclimate that surrounds the stream where cooler air and ground temperatures, higher relative humidity, and lower wind speeds are characteristic. Riparian microclimates tend to moderate daily air temperatures, reducing maximum air temperatures and increasing minimum air temperatures.

Table 14. Estimated daily maximum and minimum air temperatures at the NCDC station (Mt. Vernon 3WNW) on days and weeks with the highest daily maximum temperatures (ºC) for a median year and 90th percentile year, based on records for 1956 to 2001.

Average daily air temperature	Median year		90th percentile year	
	Hottest week 8/21-8/27 1986	Hottest day 8/17/1997	Hottest week 8/10-8/16 1967	Hottest day 8/17/1977
Maximum	27.2	30.6	29.7	33.9
Minimum	10.1	11.7	10.6	10

An accurate estimation of air temperatures in the riparian areas during the 7Q2 and 7Q10 model simulations should incorporate this 'microclimate' effect. In order to do this, it was necessary to first make comparisons between the air temperatures reported at the Mt. Vernon 3WNW station and those air temperatures measured by the thermistors at each Ecology station during the 2001 model calibration and verification period. Table 15 summarizes these comparisons.

The average difference between the air temperatures at the Mt. Vernon 3WNW station and Ecology stations during the calibration and verification period was either subtracted or added to the median and hottest week air temperature maximum and minimum values calculated from the Mt. Vernon 3WNW dataset. These modified maximum and minimum air temperatures were then used for the 7Q2 and 7Q10 model inputs.

The average wind speed in riparian areas of the streams in the study area during July and August was estimated to be approximately 1 m/sec based on regional grids of long-term monthly average surface winds (Quigley et al. 2001).

Table 15. Comparison between air temperatures at the NCDC station (Mt. Vernon 3WNW) and Ecology stations during 2001 calibration and verification periods (°C).

Ecology Stations	Maximum Temperature, 8-12-01			Minimum Temperature, 8-12-01		
	Ecology Data	Mt. Vernon 3WNW Station Data	Difference	Ecology Data	Mt. Vernon 3WNW Station Data	Difference
03C04	21.6	27.8	**6.2**	11.6	10.6	**-1.0**
03C03	22.2	27.8	**5.6**	12	10.6	**-1.4**
03C02	21.6	27.8	**6.2**	13.8	10.6	**-3.2**
03C01	21.9	27.8	**5.9**	12.1	10.6	**-1.5**
03F02	23.02	27.8	**4.8**	11.69	10.6	**-1.1**
03F01	17.38	27.8	**10.4**	12.7	10.6	**-2.1**
03EF02	21.6	27.8	**6.2**	11.6	10.6	**-1.0**
03EF01	28	27.8	**-0.2**	11	10.6	**-0.4**
03H03	21	27.8	**6.8**	13	10.6	**-2.4**
03H02	25.2	27.8	**2.6**	11.5	10.6	**-0.9**
03H01	21	27.8	**6.8**	11.8	10.6	**-1.2**
03N04	26.2	27.8	**1.6**	11.1	10.6	**-0.5**
03N03	22.7	27.8	**5.1**	10.4	10.6	**0.2**
Knapp Rd	28.2	27.8	**-0.4**	10.39	10.6	**0.2**
Swan Rd	28.11	27.8	**-0.3**	9.79	10.6	**0.8**
03N01	18.12	27.8	**9.7**	10.61	10.6	**0.0**
			avg difference +4.81			**avg difference -0.97**

Ecology Stations	Maximum Temperature, 8-18-01			Minimum Temperature, 8-18-01		
	Ecology Data	Mt. Vernon 3WNW Station Data	Difference	Ecology Data	Mt. Vernon 3WNW Station Data	Difference
03C04	17.2	21.6	**4.4**	13.3	12.8	**-0.5**
03C03	18.3	21.6	**3.3**	13.3	12.8	**-0.5**
03C02	18.8	21.6	**2.8**	13.8	12.8	**-1**
03C01	19.4	21.6	**2.2**	13	12.8	**-0.2**
03F02	18.12	21.6	**3.5**	12.31	12.8	**0.49**
03F01	16.2	21.6	**5.4**	12.99	12.8	**-0.19**
03EF02	17.4	21.6	**4.2**	12.7	12.8	**0.1**
03EF01	20.7	21.6	**0.9**	12.7	12.8	**0.1**
03H03	17.7	21.6	**3.9**	12.4	12.8	**0.4**
03H02	19.6	21.6	**2.0**	12	12.8	**0.8**
03H01	17.6	21.6	**4.0**	13	12.8	**-0.2**
03N04	18.8	21.6	**2.8**	13	12.8	**-0.2**
03N03	18.7	21.6	**2.9**	13	12.8	**-0.2**
Knapp Rd	21.49	21.6	**0.1**	12.88	12.8	**-0.08**
Swan Rd	21.19	21.6	**0.4**	12.43	12.8	**0.37**
03N01	17	21.6	**4.6**	13.08	12.8	**-0.28**
			avg difference +2.96			**avg difference -0.07**

Riparian Vegetation and Effective Shade

In a study focusing on the adjacent Stillaguamish River watershed, Pess et al. (1999) reported that historic floodplain forests along the larger channels were a mix of deciduous and coniferous species. Nearly one-third of the stems were red alder, one-third were other deciduous species (mainly big leaf maple and vine maple), and the remainder were coniferous species (mainly western hemlock, western red cedar, and Sitka spruce). The largest trees in the riparian areas were mainly Sitka spruce and the smallest were mostly red alder. Upland forests were predominantly coniferous species (mainly western hemlock, Douglas-fir, and western red cedar).

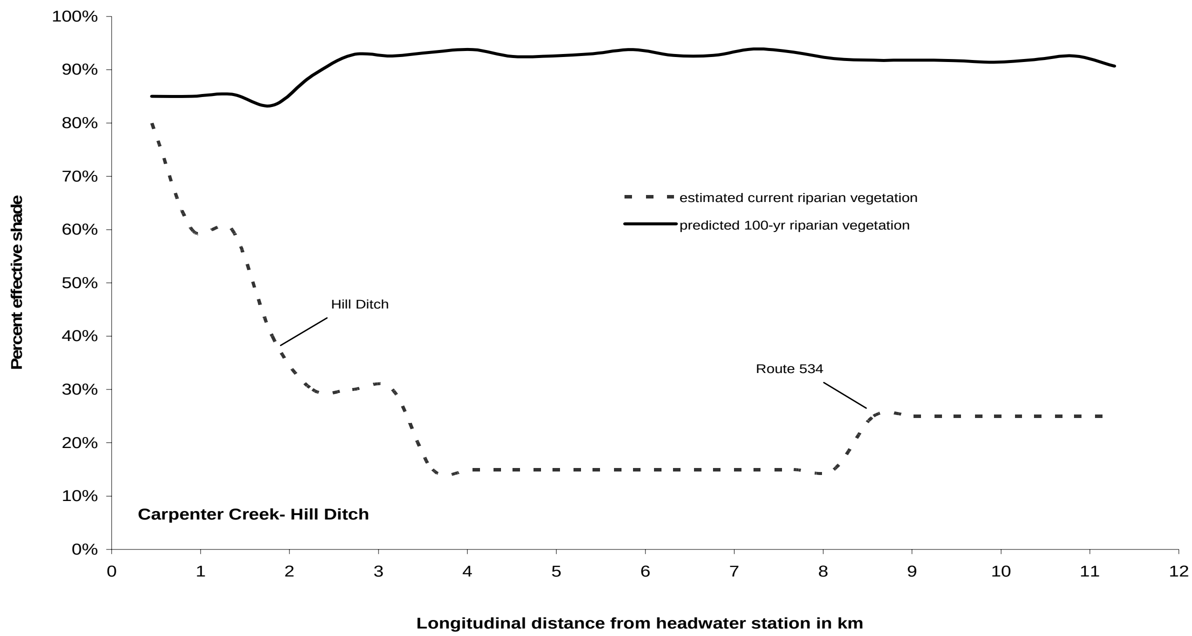
Because of similar climate, geology, and elevation, the lower Skagit River study area was assumed to have similar historic riparian vegetation characteristics as those reported by Pess et al. (1999) in the Stillaguamish River watershed. According to the soil survey for Skagit County (USDA 1981), the most common trees on the riparian soils within the lower Skagit River tributaries study area include Douglas-fir, western red cedar, red alder, big leaf maple, and some western hemlock.

Effective shade produced by current riparian vegetation was estimated using Ecology's Shade model (Ecology 2003a) (Figures 21-23). GIS coverages of riparian vegetation in the study area were created from information collected during the 2001 temperature study as described in Pelletier and Bilhimer (2001) and analysis of the most current digital orthophotos (1990-1993). Riparian forest coverages were created by qualifying four attributes: tree height, species and/or combinations of species, percent vegetation overhang, and the average canopy density of the riparian forest.

All four attributes of vegetation in the riparian zone on the right and left bank were sampled from GIS coverages of the riparian vegetation along the stream at 30-meter to 100-meter intervals using the Ttools extension for Arcview that was developed by ODEQ (ODEQ 2001). Other spatial data that were estimated at each transect location include stream aspect, elevation within the riparian area, and topographic shade angles to the west, south, and east.

For the TMDL load allocations, future riparian characteristics such as dominant species type and height were taken from soils information given in the Soil Survey of Skagit County (USDA 1981). The survey provides predominant species and height for the most common trees found on the riparian soils within the study area. Predominant species are similar to those reported by Pess et al. (1999) in his characterization of historic riparian vegetation characteristics in the adjacent Stillaguamish River watershed.

Table B-5 in Appendix B details the methodology for determining riparian tree species, heights, and widths, based on information given in the Soil Survey of Skagit County (USDA 1981), FEMAT (1993), and Oliver (1988).



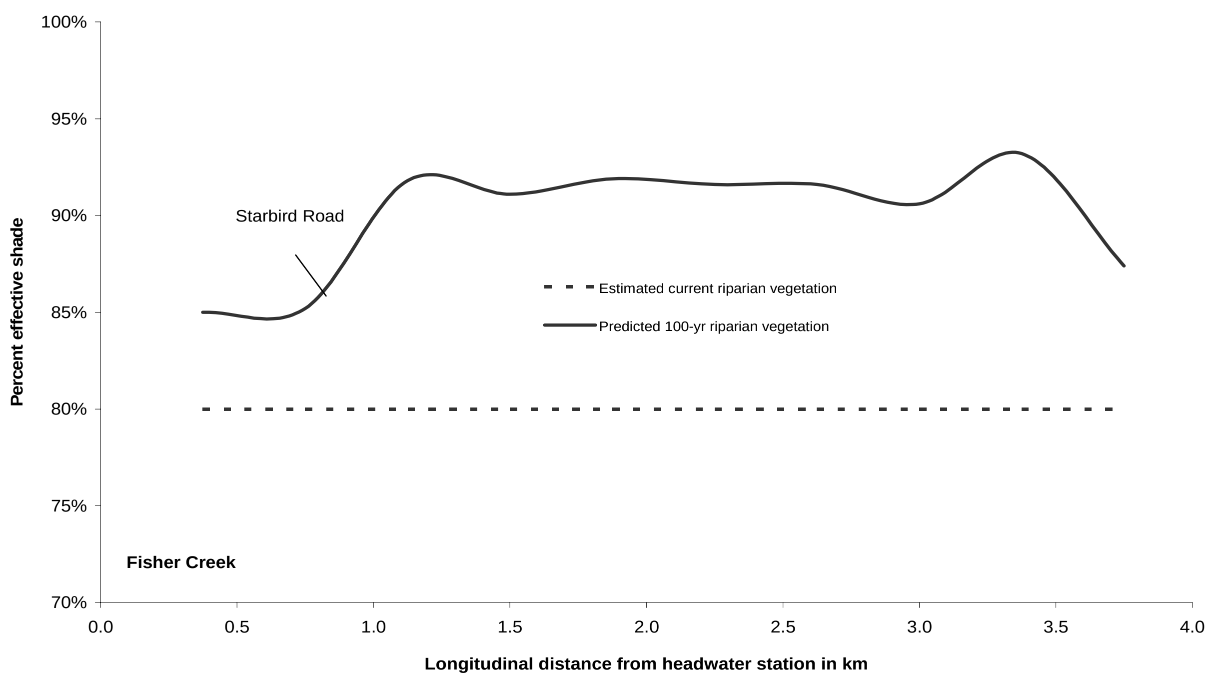
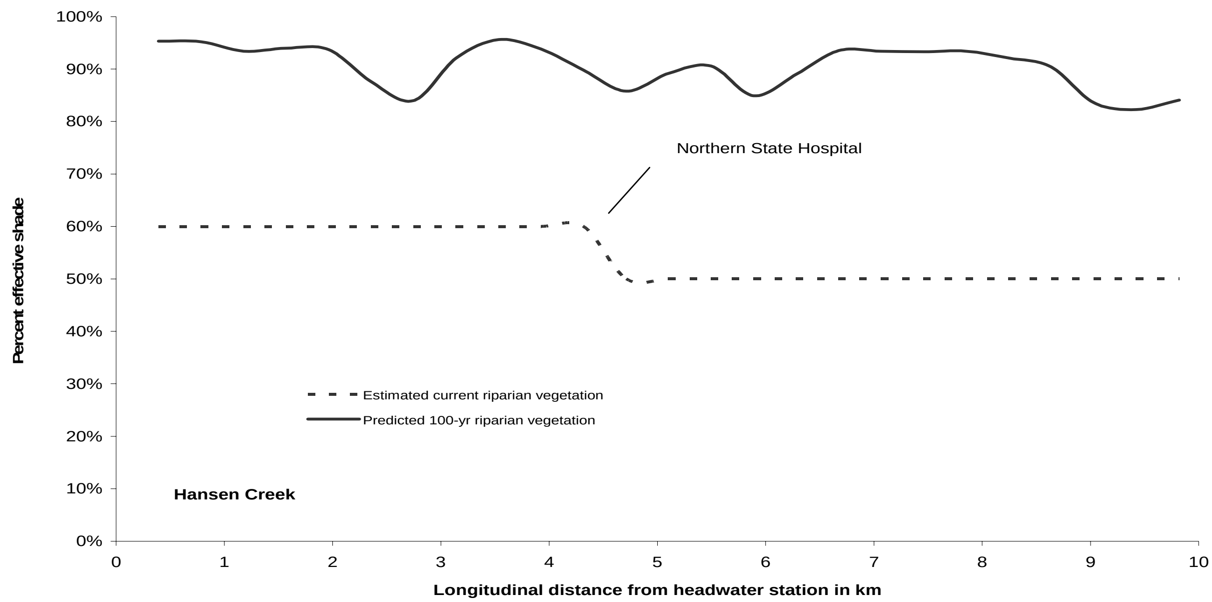


Figure 21. Effective shade from current and potential riparian vegetation in Carpenter Creek and Fisher Creek.



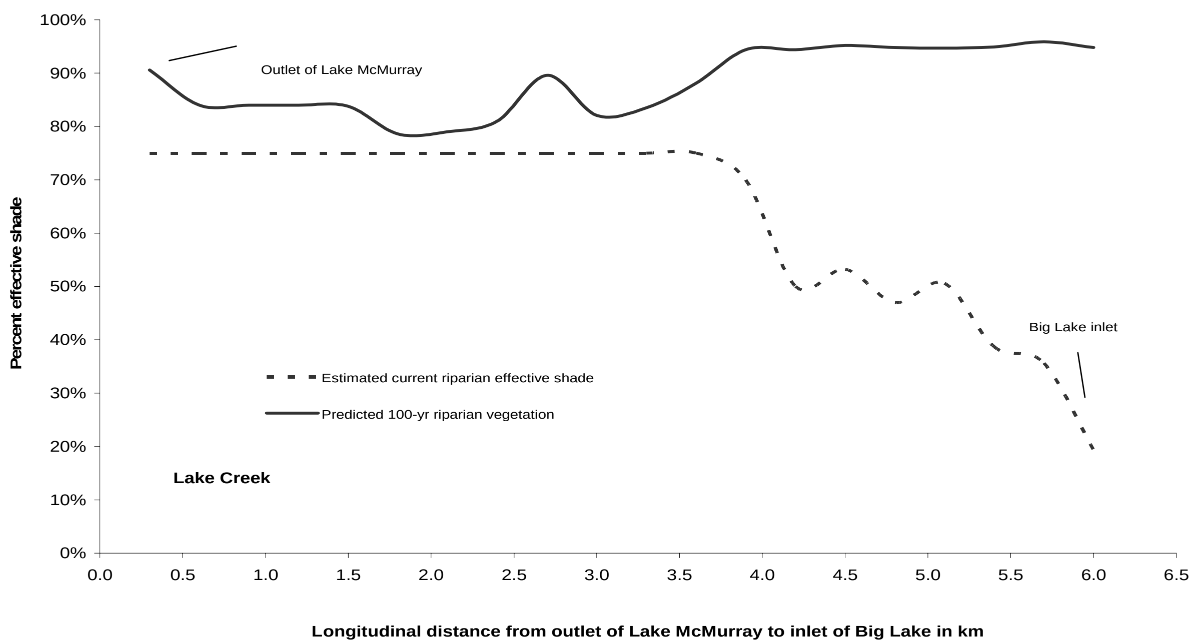
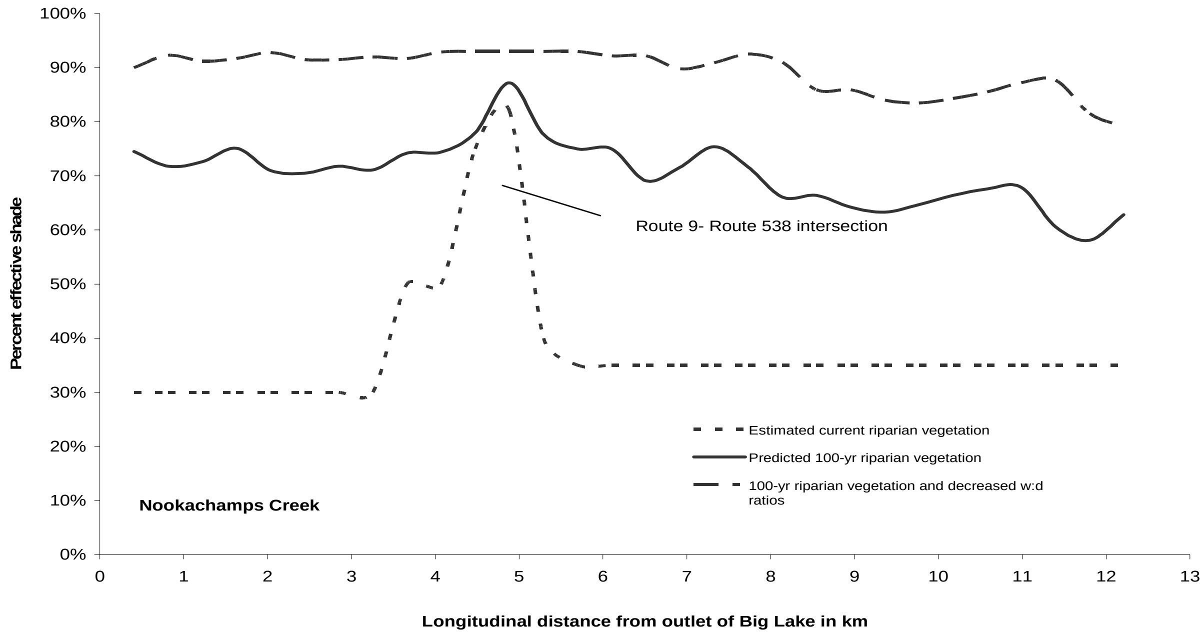


Figure 22. Effective shade from current and potential riparian vegetation in Hansen Creek and Lake Creek.



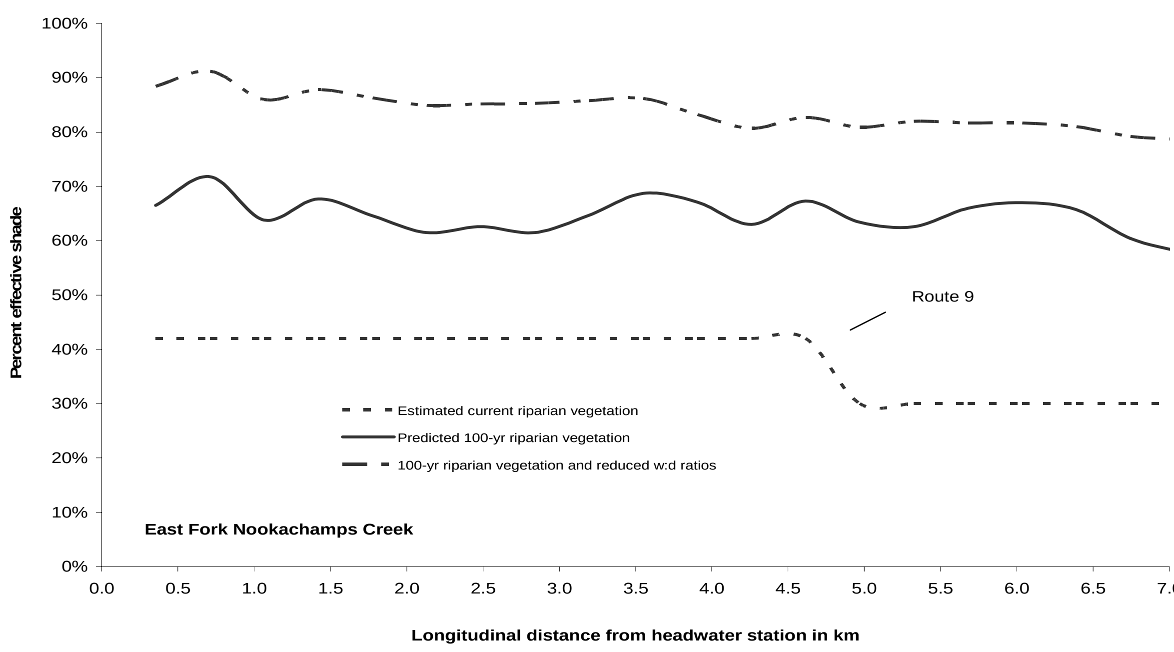


Figure 23. Effective shade from current and potential riparian vegetation in Nookachamps Creek and East Fork Nookachamps Creek.

Effective shade calculations were made for three scenarios of vegetation and channel geometry:

- *Current vegetation.* Estimates for current vegetation were based on spatial data for height and canopy density.
- *Effective shade from 100-year-old riparian vegetation.* The average height of trees for 100-year-old riparian vegetation was taken from site-specific information provided in the U.S. Department of Agriculture Soil Survey for Skagit County (USDA 1981). Riparian vegetation consisted of mixed deciduous and coniferous species in the floodplain, with average tree heights ranging from 28-40 meters and average canopy densities of 75%.
- *Effective shade from 100-year-old riparian vegetation and reduced channel width.* Effective shade from a combination of 100-year-old riparian vegetation and associated natural reductions in the current width-to-depth ratios that may occur in portions of Nookachamps and East Fork Nookachamps creeks, as elsewhere in the study area.

Analytical Framework

Data collected during this TMDL effort have allowed the development of a temperature simulation methodology that is both spatially continuous and which spans full-day lengths (quasi-dynamic steady-state diel simulations). The GIS and modeling analysis was conducted using three specialized software tools:

1. ODEQ's Ttools extension for Arcview (ODEQ 2001) was used to sample and process GIS data for input to the Shade and QUAL2Kw models. Appendices B-1 and B-2 list the codes and descriptions of current and site potential vegetation used in Ecology's Shade model (Ecology 2003a).

2. Ecology's Shade model (Ecology 2003a) was used to estimate effective shade along six of the lower Skagit River tributaries. Effective shade was calculated along the mainstems of Carpenter, Fisher, Hansen, Lake, Nookachamps, and East Fork Nookachamps creeks using the Shade model. Effective shade was calculated at intervals ranging from 30 to 100 meters along the streams and then averaged over 300- to 400-meter intervals for input to the QUAL2Kw model.

3. The QUAL2Kw model (Chapra 2001; Ecology 2003b) 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 remains constant for a given condition such as a 7-day or 1-day period, but key variables are allowed to vary with time over the course of a day. For temperature simulation, the solar radiation, air temperature, relative humidity, headwater temperature, and tributary water temperatures were specified or simulated as diurnally varying functions. QUAL2Kw uses the kinetic formulations for the components of the surface water heat budget that are shown in Figure 2 and described in Chapra (1997). Diurnally varying water temperatures at 300- to 500-meter intervals along the streams in the lower Skagit River study area were simulated using a finite difference numerical method. The water temperature model was calibrated to instream data along the mainstems of the streams.

All input data for the Shade and QUAL2Kw models are longitudinally referenced, allowing spatial and/or continuous inputs to apply to certain zones or specific river segments. Model input data were determined from available GIS coverages using the Ttools extension for Arcview, or from data collected by Ecology or other data sources. Detailed spatial data sets were developed for the following parameters for model calibration and verification:

- Rivers and tributaries were mapped at 1:3,000 scale (or less) from 1-meter-resolution Digital Orthophoto Quads from 1990-1993.
- Riparian vegetation species, size, and density were mapped and sampled from the GIS coverage at 100-meter intervals along the streams in the study area.
- Near-stream disturbance zone (NSDZ) widths were digitized at 1:3000 scale (or less).
- 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 (stream flow direction in decimal degrees from north) was calculated by the Ttools extension for Arcview.
- The daily minimum and maximum observed temperatures for the boundary conditions at the headwaters and tributaries were used as input to the QUAL2Kw model for the calibration and verification periods. The QUAL2Kw model was calibrated and verified using data collected during August 9-15, 2001 and August 17-20, 2001, respectively (Figures 23-28).
- Flow balances for the calibration and verification periods were estimated from field measurements and gage data of flows made by Ecology. The lowest 7-day-average flows during the July-August period with recurrence intervals of 2 years (7Q2) and 10 years (7Q10) were estimated based on low-flow statistics from the USGS gaging station in the adjacent Pilchuck Creek basin. The 7Q2 and 7Q10 flows in the study area were then estimated by scaling the estimates at the USGS gage according to the sub-watershed areas weighted by annual average precipitation. Flow balance spreadsheets of the stream networks for Carpenter, Fisher, Hansen, Lake, Nookachamps, and East Fork Nookachamps creeks were constructed to estimate surface water and groundwater inflows by interpolating between the stream gaging stations.
- Hydraulic geometry (wetted width, depth, and velocity as a function of flow) was estimated using the equations developed in Table 11. Manning's equation was used to estimate channel depth and velocity (Table 12).
- The temperature of groundwater is often assumed to be similar to the mean annual air temperature (Theurer et al. 1984). The mean annual air temperature along the streams in the lower Skagit River study area ranges from approximately 11.2°C at low elevation to about

6°C at the highest elevations. Because there are very limited data, and most of the modeled reaches lie in the lowest elevations, a mean groundwater temperature of 11.2°C was used in the QUAL2Kw model.

- Air temperature and relative humidity were estimated from meteorological data collected by Ecology. The observed minimum and maximum air temperatures and relative humidity at the stations occupied by Ecology during 2001 were used to represent the conditions for the calibration and verification periods. Cloud cover for the calibration and verification periods was estimated from data reported at the Arlington, WA airport weather station. A cloud cover of 40% was used for the calibration period, and 60% was used for the verification period. The average July-August wind speed of 1 m/sec was used for temperature modeling.

- Heat exchange between the water and the streambed is simulated in QUAL2Kw by two processes: (1) conduction according to Fick's law is estimated as a function of the temperature gradient between the water and surface sediment, thickness of the surface sediment layer, and the thermal conductivity which is a function of thermal diffusivity, sediment density, and sediment heat capacity, and (2) hyporheic exchange is estimated as a function of the temperature gradient between the water and surface sediment and the bulk diffusive flow exchange between the water and the streambed, the thickness of the surface sediment layer, the density and heat capacity of water.

  Calibration of the QUAL2Kw model involved specification of the thickness of the surface sediment layer in the range of 10 to 100 cm, and specification of the bulk diffuse flow exchange between the water and the streambed between 0 and 100% of the surface flow in a stream reach. Typical values for the thermal diffusivity at the sediment surface ranged from 0.0045 to 0.0150 cm^2/sec, which is similar to the literature values summarized by Sinokrot and Stefan (1993) for typical streambed materials.

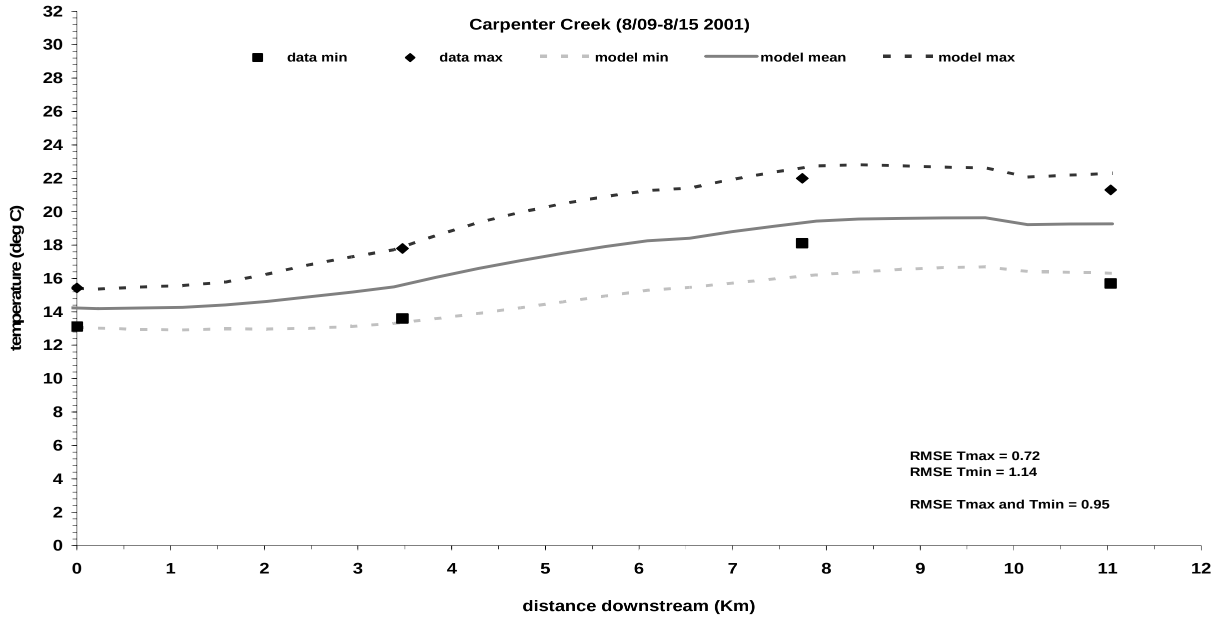
Calibration and Verification of the QUAL2Kw Model

The hottest 7-day period of 2001 occurred from August 9-15, 2001 and was used for calibration of the QUAL2Kw model (Figures 24-29). The August 17-20, 2001 period was used for verification of the QUAL2Kw model to test the calibration (Figures 24-29).

The uncertainty or goodness-of-fit of the predicted temperatures from the QUAL2Kw model was evaluated by calculating the root mean squared error (RMSE) of the predicted versus observed maximum and minimum temperatures (Table 16). The average maximum RMSE for the calibration period was 0.56°C. The average maximum RMSE for the verification period was 0.44°C. In general, the error of the models predictions is less than 1ºC, and slightly greater for Carpenter Creek.

Table 16. Summary of RMSE of differences between the predicted and observed daily maximum temperatures (ºC) in the lower Skagit River study area, 2001.

Modeled Creek	Calibration Period August 9 -15		Verification Period August 17 - 20	
	max	min	max	min
Carpenter	0.72	1.14	0.26	1.41
Fisher	0.66	0.25	0.55	0.42
Hansen	0.51	0.61	0.77	0.67
Lake	0.58	0.35	0.17	0.74
Nookachamps	0.73	0.59	0.71	0.85
E.F. Nookachamps	0.17	0.7	0.25	0.92



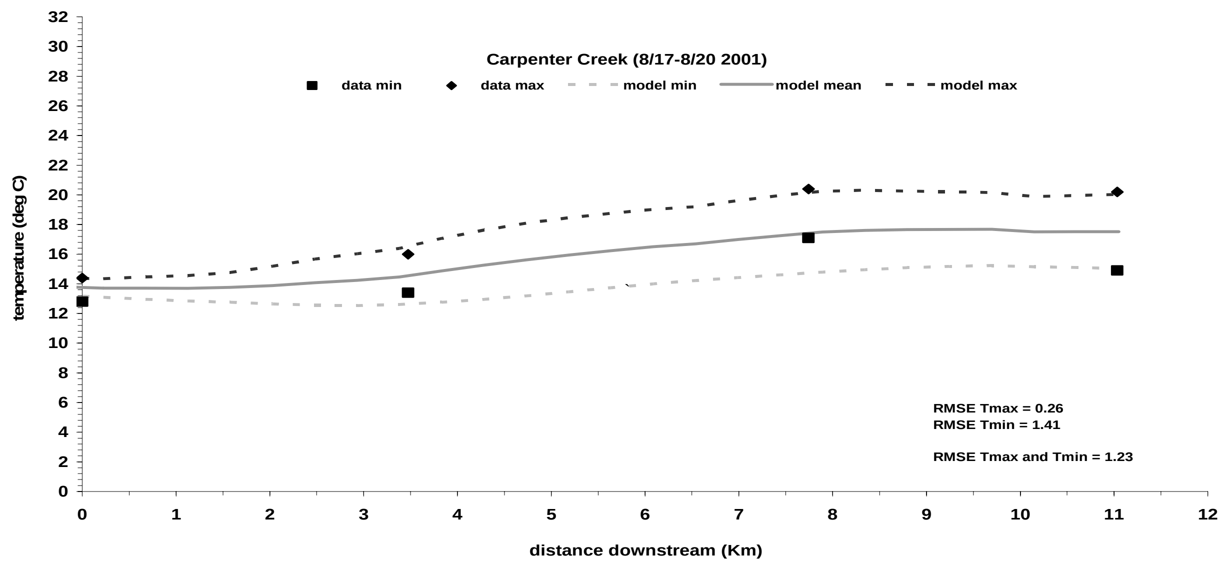
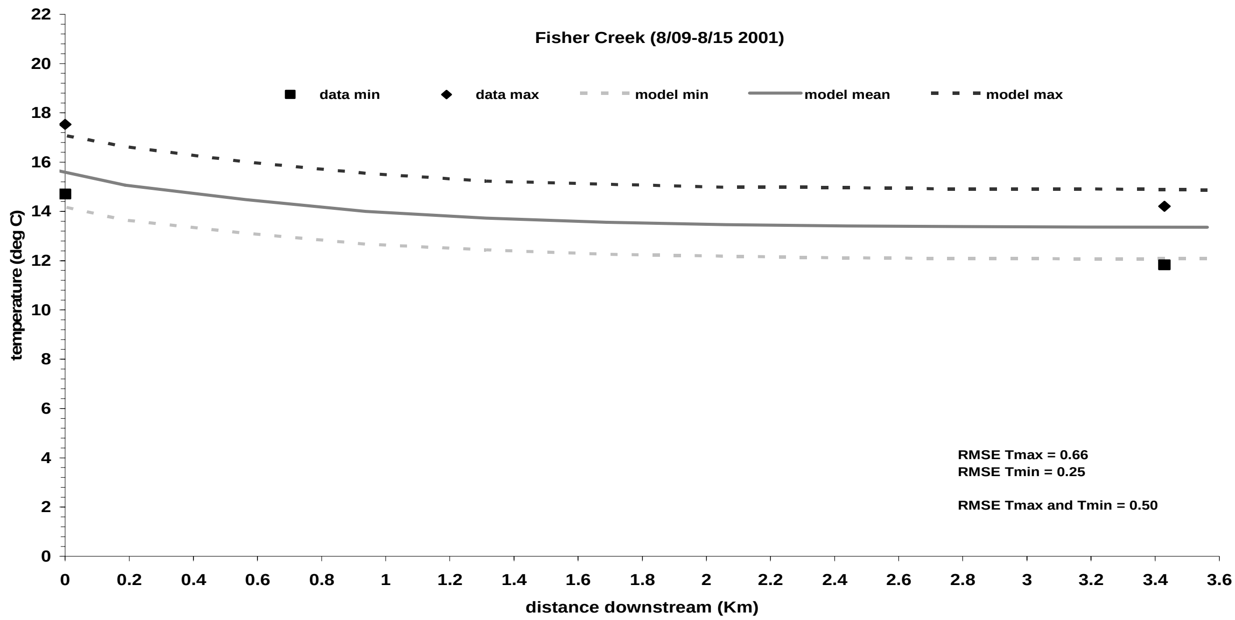


Figure 24. Predicted (top figure) and observed (bottom figure) water temperatures in Carpenter Creek during calibration and verification periods.



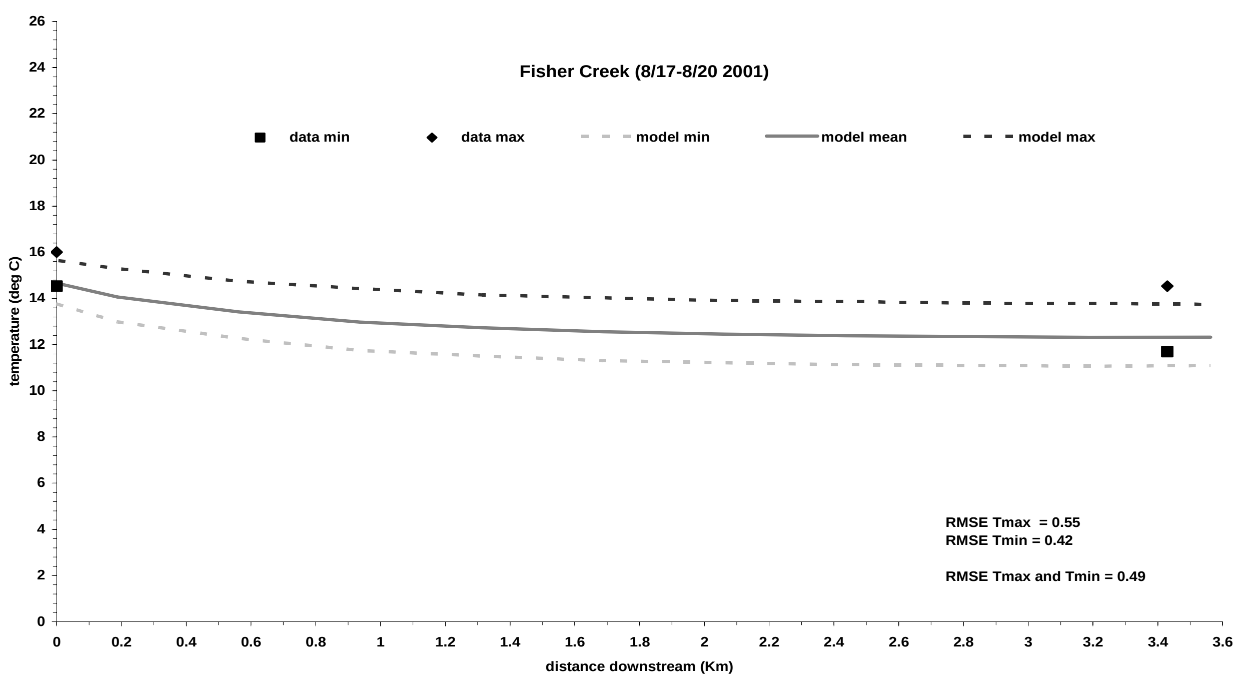
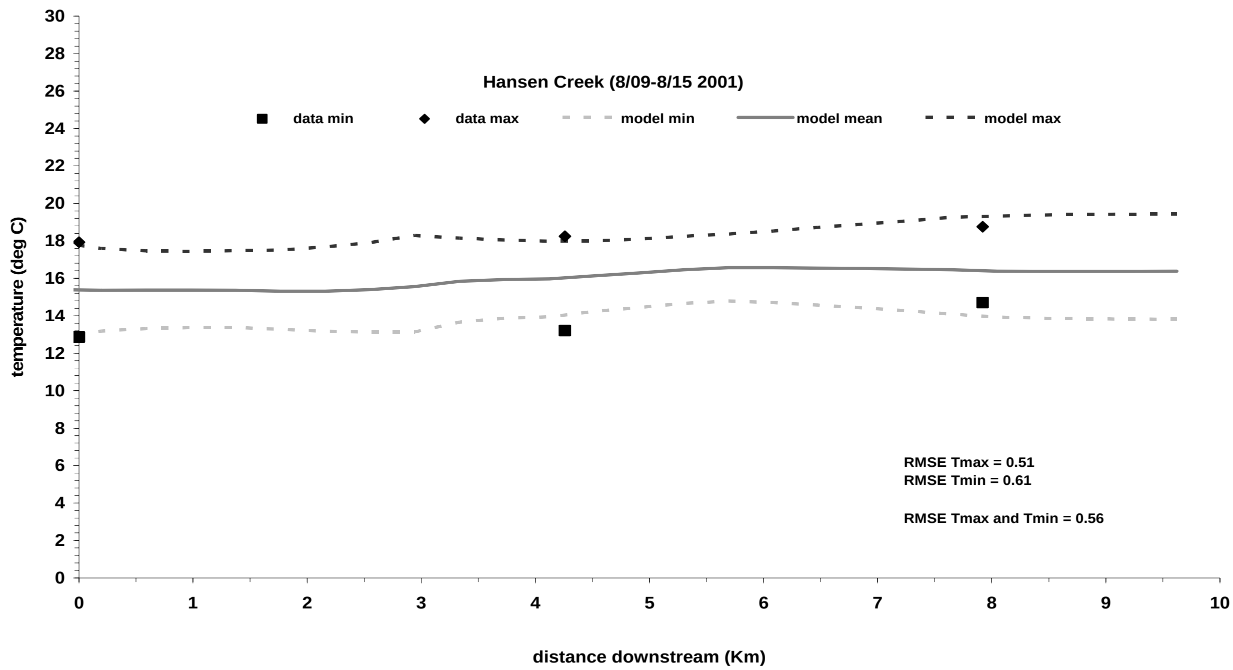


Figure 25. Predicted (top figure) and observed (bottom figure) water temperatures in Fisher Creek during calibration and verification periods.



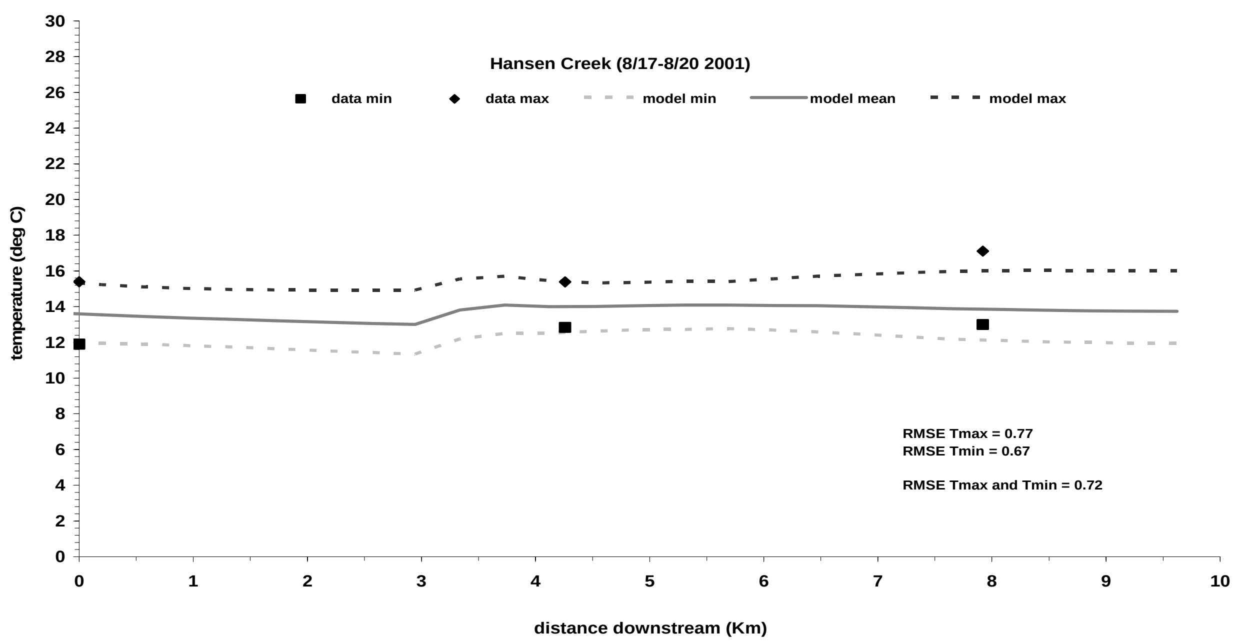
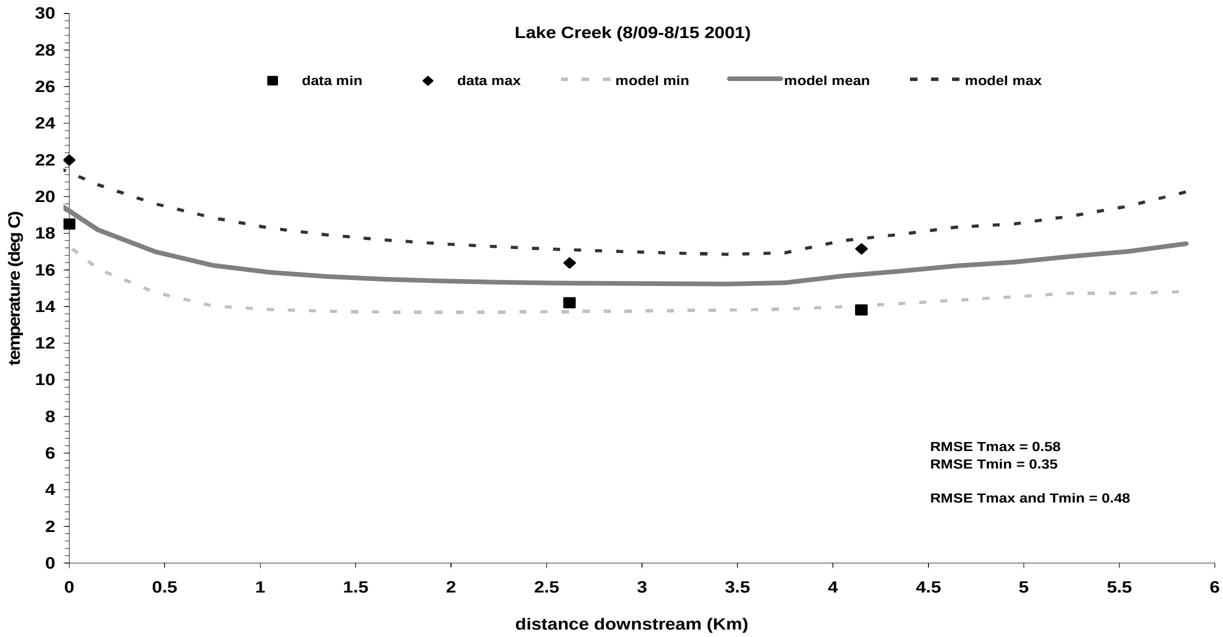


Figure 26. Predicted (top figure) and observed (bottom figure) water temperatures in Hansen Creek during calibration and verification periods.



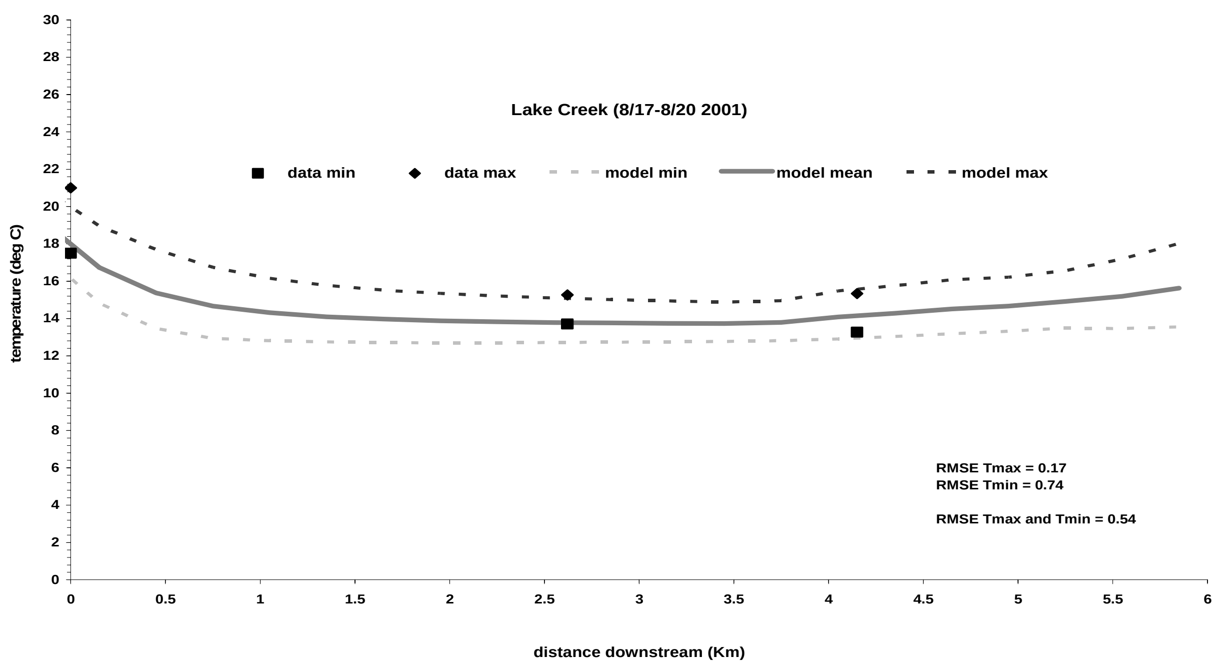
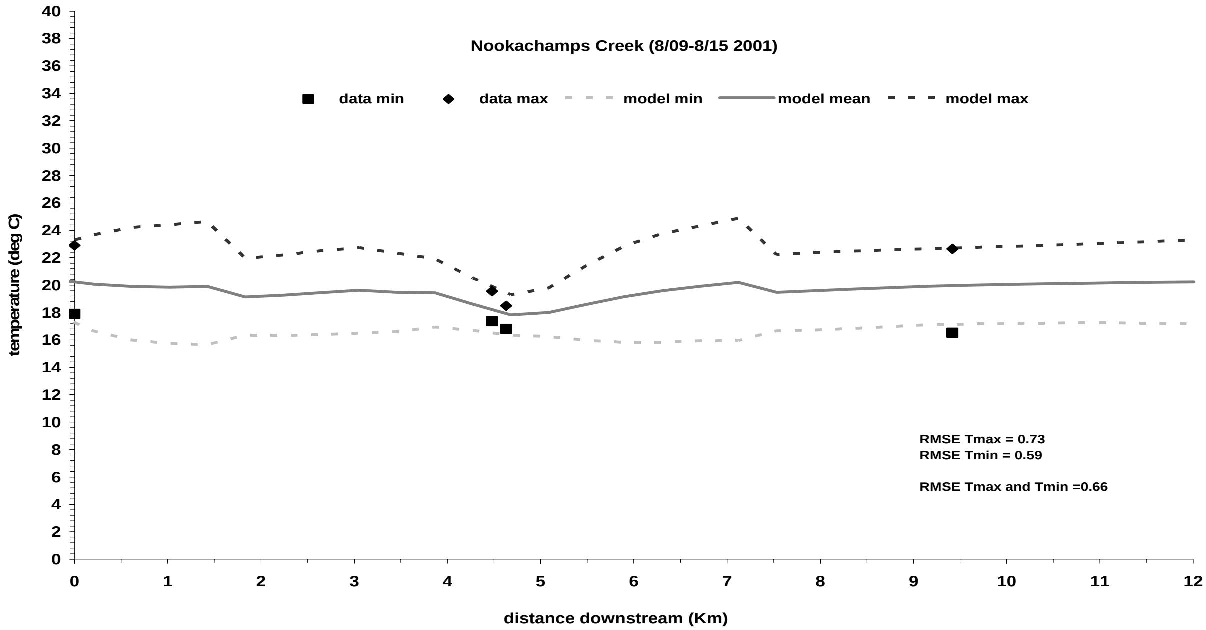


Figure 27. Predicted (top figure) and observed (bottom figure) temperatures in Lake Creek during calibration and verification periods.



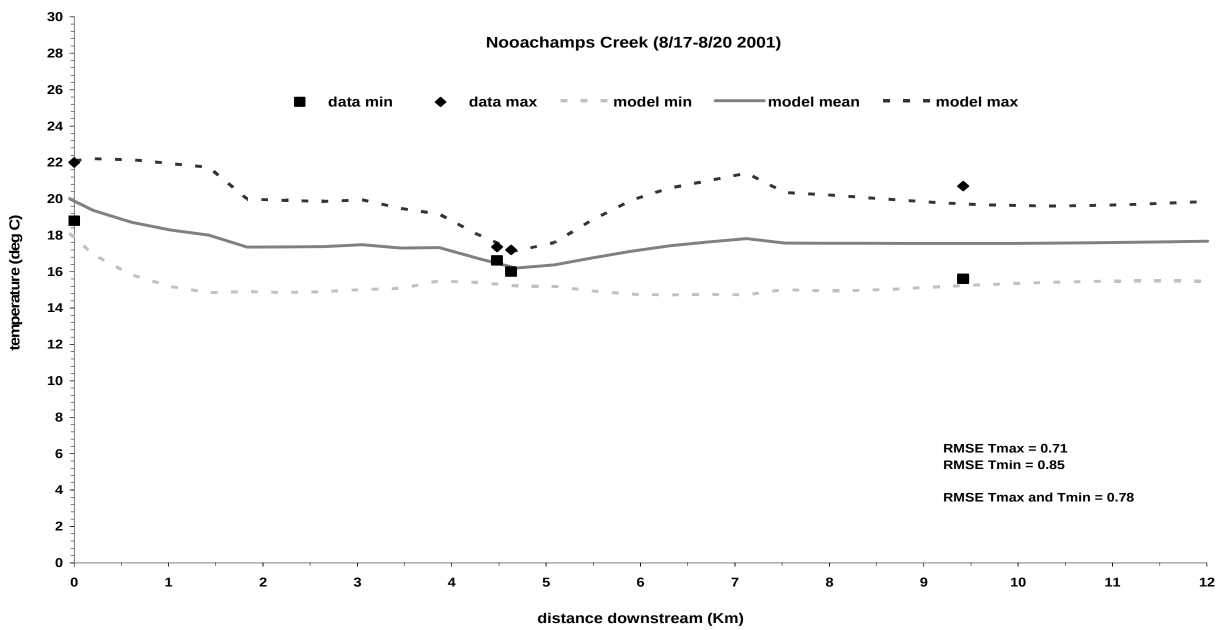
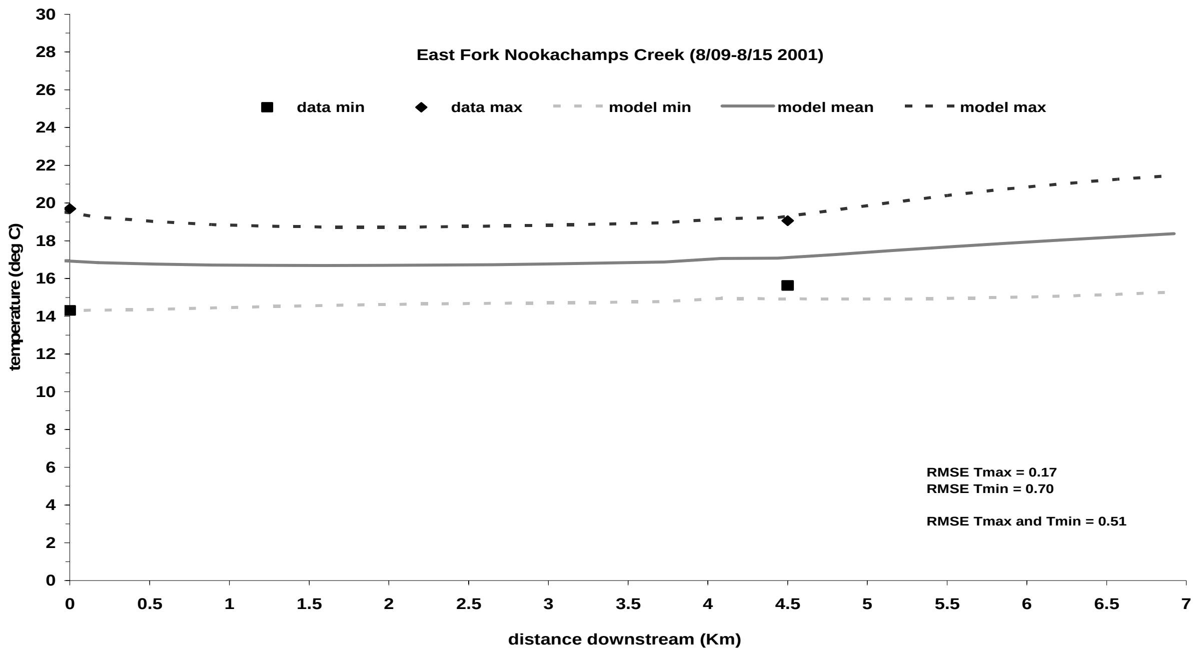


Figure 28. Predicted (top figure) and observed (bottom figure) water temperatures in Nookachamps Creek during calibration and verification periods.



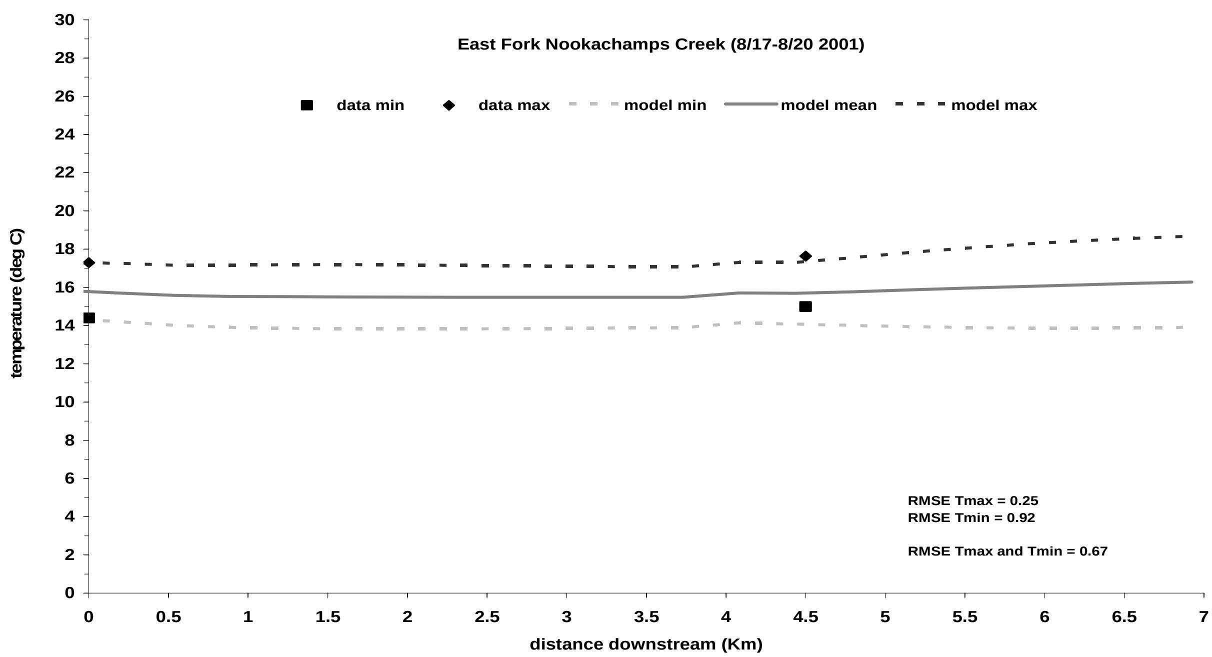


Figure 29. Predicted (top figure) and observed (bottom figure) water temperatures in East Fork Nookachamps Creek during calibration and verification periods.

Loading Capacity

The loading capacity provides a reference for calculating the amount of pollutant reduction needed to bring a waterbody into compliance with standards. EPA's current regulation defines loading capacity as *the greatest amount of loading that a waterbody can receive without violating water quality standards.*

The loading capacity for this TMDL is based on both portions of the temperature standards.

1. The numeric portion states that *temperature shall not exceed 18.0°C….due to human activities*. This standard applies to areas of the lower Skagit study area where pollution is attributed to increases in solar radiation as a result of human-caused decreases in effective shade. The lack of shading has resulted from the removal of trees throughout the study area, and a subsequent widening of stream channels.
2. The natural condition portion states that *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.* In these areas, the natural condition provision of the water quality standard is the basis of the loading capacity.

The calibrated QUAL2Kw model was used to determine the loading capacity for effective shade for streams in the lower Skagit River basin. Loading capacity was determined based on prediction of water temperatures under typical and extreme flow and climate conditions combined with effective shade conditions resulting from 100-year-old riparian vegetation and resulting natural decreases in channel width-to-depth ratios.

The lowest 7-day average flow with a 2-year recurrence interval (7Q2) was selected to represent a typical climatic year, and the lowest 7-day average flow with a 10-year recurrence interval (7Q10) was selected to represent a reasonable worst-case condition for the July-August period. Air temperatures for the 7Q2 condition were assumed to be represented by the hottest week of 1986, which was the median condition from the historical record at Mt. Vernon station 3NW (Table 7). The air temperatures for the 7Q10 condition were taken from the hottest week of 1967, which was the 90^{th} percentile condition from Mt. Vernon station 3NW.

The following scenarios for effective shade were evaluated for the 7Q2 and 7Q10 flow and climate conditions:

- *Effective shade resulting from the existing riparian vegetation and channel conditions.*

- *Effective shade from 100-year-old riparian vegetation that would naturally occur in riparian areas within the study area.* Riparian species were chosen based on soil site potential, as given in the Soil Survey for Skagit County, WA. (USDA 1981). The predominant tree species on all soils within the study area included red alder, western red cedar, and Douglas-fir.

A canopy density of 75% was used for all site potential vegetation (Brazier et al. 1973 and Steinblums et al. 1984). Tree heights (at 100-year site index) ranged from 37 to 53 meters. Riparian zone widths were estimated as 75% of average tree height (FEMAT 1993) and ranged from 28 to 40 meters (Appendix B, Table B-5).

- *Effective shade from 100-year-old riparian vegetation and a natural decrease in channel width for modeled segments of Nookachamps Creek and East Fork Nookachamps Creek.* It is likely that 100-year-old vegetation and associated riparian functions of moderate-aged riparian stands would result in concomitant decreases in width-to-depth ratios. Channel widths are expected to decrease as the maturing riparian vegetation along the stream stabilizes the streambanks and prevents lateral erosion.

  Changes in riparian microclimate, decreases in channel width, and reduction of headwater and tributary temperatures were incorporated into the predictions of water temperatures within the study area:

- *Microclimate.* Increases in vegetation height and density in the riparian zone are expected to result in decreases in air temperature, increases in relative humidity, and decreases in wind speed. In order to evaluate the effect of these potential changes in microclimate on water temperature, the air temperature, relative humidity, and wind speed in the riparian areas for scenarios with maximum potential shade from mature riparian were adjusted relative to the estimated current condition as follows:
  - Based on a study by Dong et al. (1998): average air temperatures within the modeled reaches were decreased by 1°C.
  - Maximum relative humidity remained constant at 100%. Minimum relative humidity ranged from 70-80%.
  - Wind speed was reduced to 0 or 1m/sec.

- *Channel width.* Channel widths are expected to decrease as the riparian vegetation along the stream matures due to reduced loading of sediment from unstable banks. The sensitivity of predicted stream temperatures to reduction of channel width was tested by predicting stream temperatures that would be associated with decreasing bankfull channel widths by one-third in Nookachamps Creek and East Fork Nookachamps Creek.

- *Reduced headwater and tributary temperatures.* Scenarios were evaluated with the assumption that the inflowing headwaters and tributaries did not exceed the 18°C (for Class A waters).

The results of the model runs for the critical 7Q2 and 7Q10 conditions are presented in Figures 30 through 35. The current conditions in the lower Skagit study area are expected to result in daily maximum water temperatures that are greater than 18°C in all or most of the evaluated reaches. Temperatures in portions of Carpenter, Lake, Nookachamps, and East Fork Nookachamps creeks could be greater than the approximate threshold for lethality of 23°C under current conditions.

Substantial reductions in water temperature are predicted for hypothetical conditions with 100-year-old riparian vegetation and concomitant changes in riparian microclimate and reduction of channel widths. Potential reduced temperatures are predicted to be less than 18°C in Class A reaches in most of the streams that were evaluated. Those segments not expected to be less than the 18°C standard comprise the outlets of Lake McMurray and Big Lake. Surface water temperatures in both Big Lake and Lake McMurray frequently exceed 22°C during the summer months.

Carpenter Creek

Figure 30 shows the predicted water temperatures in Carpenter Creek and Hill Ditch for the lowest 7-day average flow during July-August with a 2-year recurrence interval (7Q2) and a 10-year recurrence interval (7Q10). Figure 30 shows that increases in effective shade resulting from 100-year-old riparian vegetation and associated changes in microclimate have the potential to produce water temperatures that would meet the water quality standard in the mainstem of Carpenter Creek and Hill Ditch. Riparian vegetation in Carpenter Creek upstream of the modeled segments should be maintained and protected to ensure that the temperature standard of 18°C is met.

Fisher Creek

Figure 31 shows the predicted water temperatures in Fisher Creek for the 7Q2 and 7Q10 conditions. Increases in effective shade from 100-year-old riparian vegetation and associated changes in microclimate have the potential to produce water temperatures that would meet the water quality standard in the lower portions of Fisher Creek. Those portions of Fisher Creek upstream of the modeled segments have a loading capacity set to equal the effective shade produced by 100-year-old riparian vegetation within the riparian corridor. Stream temperatures are warmest in the upper reaches of Fisher Creek, above the modeled segments. Efforts to increase riparian vegetation should be focused in these upper reaches.

Hansen Creek

Figure 32 shows the predicted water temperatures in Hansen Creek for the 7Q2 and 7Q10 conditions. Effective shade from 100-year-old riparian potential riparian vegetation and associated changes in microclimate has the potential to produce water temperatures that would meet the water quality standard in the mainstem of Hansen Creek. Those portions of Hansen Creek upstream of the modeled segments have a loading capacity set to equal the effective shade produced by 100-year-old riparian vegetation within the riparian corridor.

Skagit County has drafted a Watershed Management Plan (Skagit County 2002) for Hansen Creek, which includes measures to restore historic channel morphology, reduce current width-to-depth ratios, and reestablish connectivity between the floodplain and stream channel. The Hansen Creek plan, currently a ‘concept plan’, presents alternative solutions that address sediment loading from upstream sources. In past years, downstream flooding has been addressed through the periodic dredging of the stream channel, which is no longer desirable due to effects on fish habitat. The plan identifies reaches of the creek system that could be re-engineered and restored to provide sediment storage and return downstream areas to a riparian condition more supportive of fish habitat. These proposed alternatives should be examined in detail to determine which would provide the overall greatest benefit with respect to stream temperature and fish habitat.

Red Creek, a tributary to Hansen Creek, has a loading capacity set equal to the effective shade produced by 100-year-old riparian vegetation.

Lake Creek

Figure 33 shows the predicted water temperatures in Lake Creek for the 7Q2 and 7Q10 conditions. Effective shade resulting from 100-year-old riparian vegetation and associated changes in microclimate have the potential to produce water temperatures that would meet the water quality standard in the majority of the mainstem of Lake Creek. Lake McMurray, a shallow lake (< 2 m at outlet) comprises the headwaters of Lake Creek. Summer outflow temperatures frequently exceed the Class A standard for temperature. Figure 33 shows resulting water temperatures in Lake Creek with the addition of 100-year-old riparian vegetation along the mainstem. Figure 33 shows that the highest water temperatures (exceeding 18°C) in Lake Creek are expected to remain at the outflow of Lake McMurray, even with increases in riparian vegetation.

For this section of Lake Creek (approximately 1 km below the discharge from Lake McMurray), the 'natural condition' provision applies. This provision states that "*During critical periods, natural conditions may exceed the numeric temperature criteria mandated by the water quality standards. 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-030 WAC).* The loading capacity in this reach is set to the natural condition temperature.

Nookachamps Creek

Figure 34 shows the predicted water temperatures in Nookachamps Creek for the 7Q2 and 7Q10 conditions. Effective shade resulting from 100-year-old riparian vegetation and associated changes in microclimate have the potential to produce water temperatures that would meet the water quality standard in the majority of the mainstem of Nookachamps Creek.

Big Lake, a shallow lake (< 2 m at outlet), comprises the headwaters of Nookachamps Creek. Summer outflow temperatures frequently exceed the Class A standard for temperature. Figure 34 shows resulting water temperatures in Nookachamps Creek with the addition of 100-year-old riparian vegetation along the mainstem. Figure 34 shows that the highest water temperatures (exceeding 18°C) in Nookachamps Creek are expected to remain at the outflow of Big Lake, even with increases in riparian vegetation.

For this section of Nookachamps Creek (approximately 1 km below the discharge from Big Lake), the natural condition provision of the temperature water quality standards apply. This provision states that "*During critical periods, natural conditions may exceed the numeric temperature criteria mandated by the water quality standards. 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-030 WAC).* The loading capacity in this reach is set to the natural condition temperature.

Much of the Nookachamps mainstem downstream of the Route 9 and Route 538 intersection has been channelized and diked and currently supports little or no riparian vegetation. Natural reductions of at least 30% of stream width-to-depth ratios are recommended for these sections of Nookachamps Creek to further reduce the water temperatures and produce water temperatures that meet the Class A temperature standard during 7Q10 critical conditions of flow and climate.

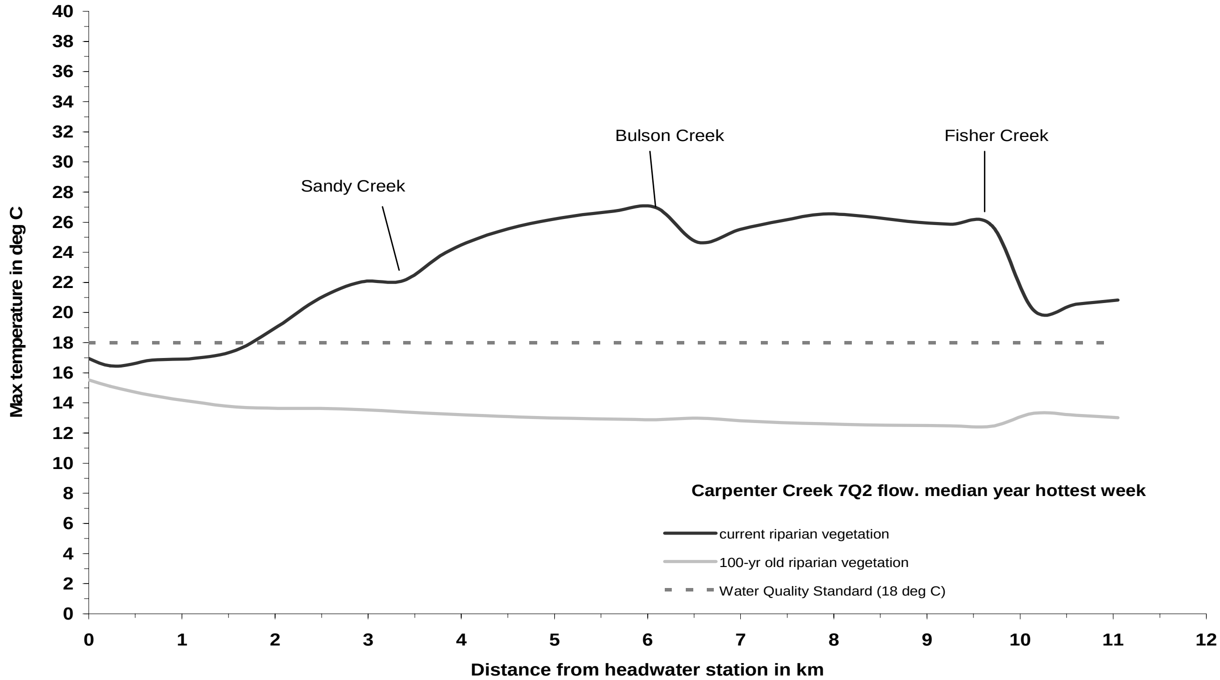
Otter Pond Creek, a tributary to Nookachamps Creek, has a loading capacity set equal to the effective shade produced by 100-year-old riparian vegetation.

East Fork Nookachamps Creek

Figure 35 shows the predicted water temperatures in East Fork Nookachamps Creek for the 7Q2 and 7Q10 conditions. Effective shade resulting from 100-year-old riparian vegetation and associated changes in microclimate have the potential to produce water temperatures that would meet the water quality standard in the majority of the mainstem of East Fork Nookachamps Creek. Those portions of the East Fork upstream of the modeled segments have a loading capacity set to equal the effective shade produced by 100-year-old riparian vegetation within the riparian corridor.

Nearly the entire modeled segment of the East Fork has been channelized and diked and currently supports little or no riparian vegetation. Natural reductions of at least 30% of stream width-to-depth ratios are recommended for these sections of East Fork Nookachamps Creek to further reduce the water temperatures and produce water temperatures that meet the Class A temperature standard during 7Q10 critical conditions of flow and climate.

Turner Creek, a tributary to East Fork Nookachamps Creek, has a loading capacity set equal to the effective shade produced by 100-year-old riparian vegetation along the riparian corridor.



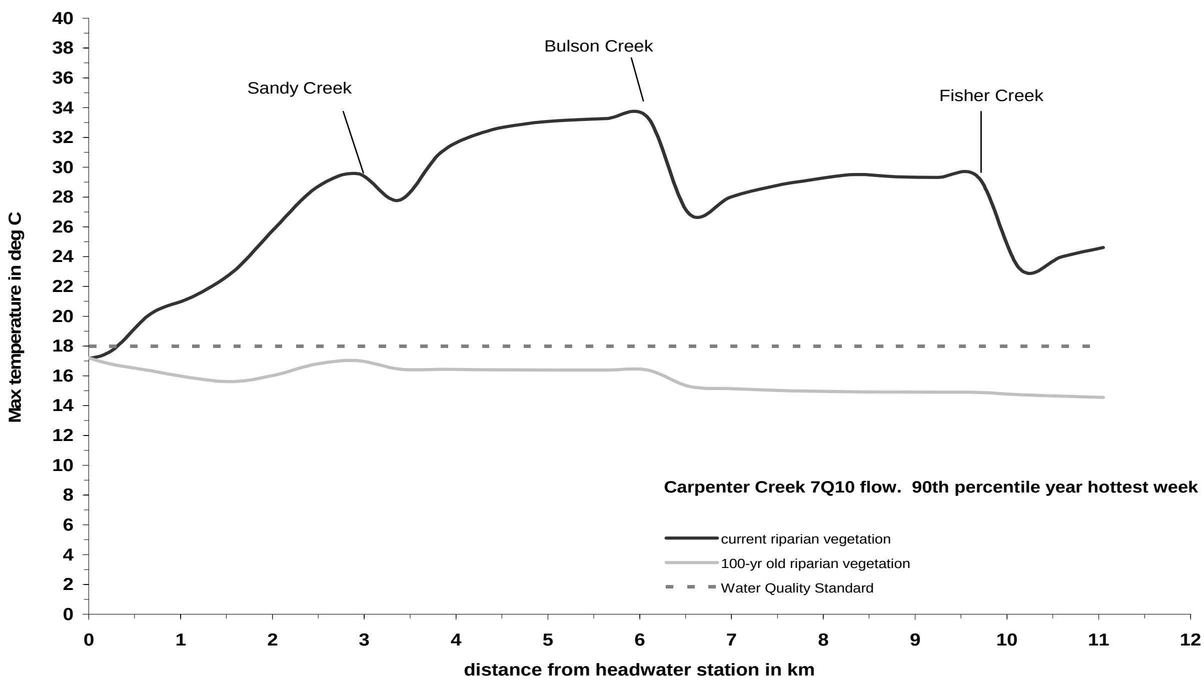
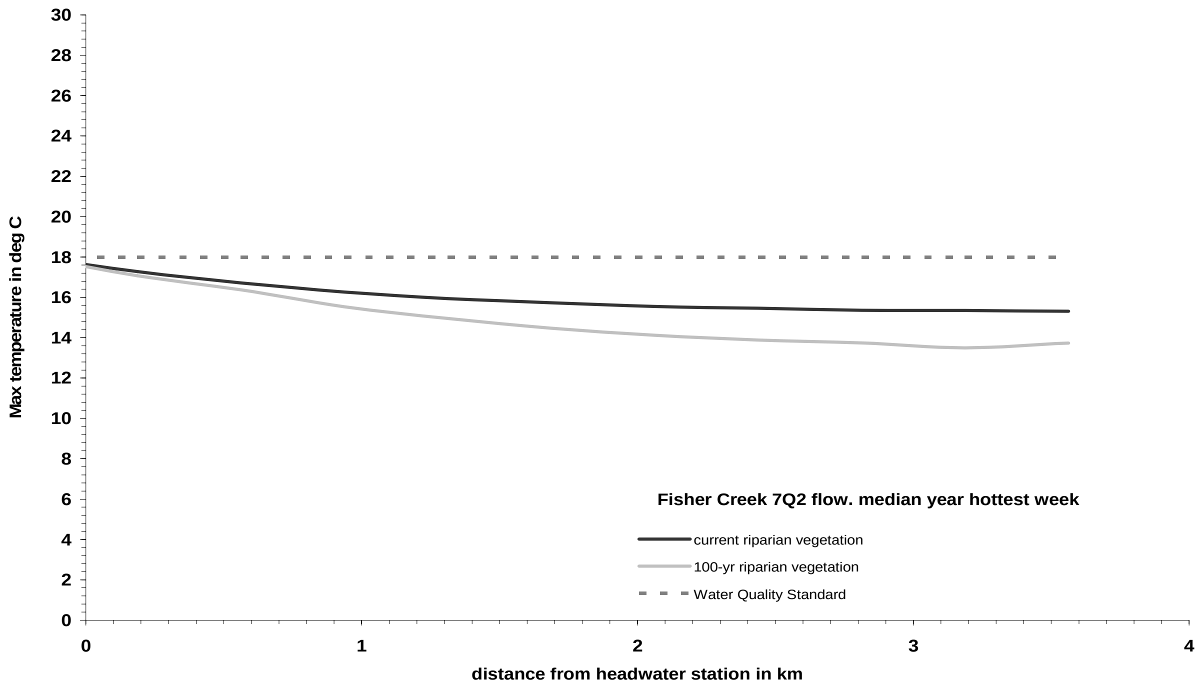


Figure 30. Predicted daily maximum temperature in Carpenter Creek under critical conditions for the TMDL.



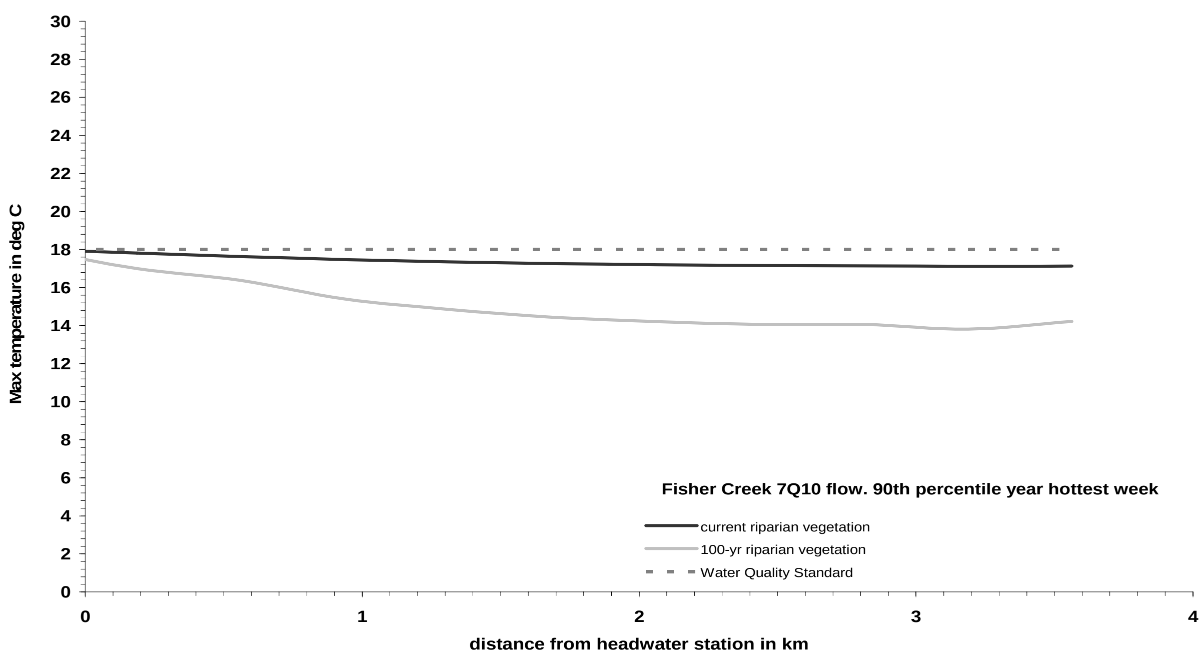
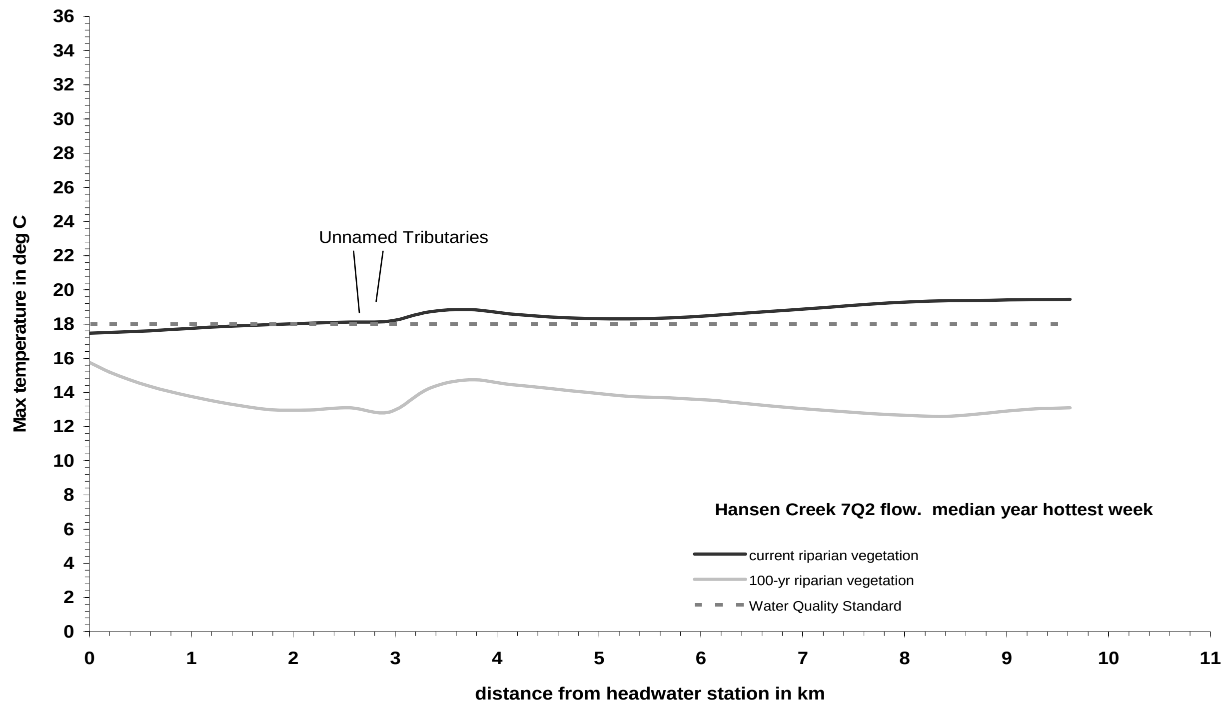


Figure 31. Predicted daily maximum temperature in Fisher Creek under critical conditions for the TMDL.



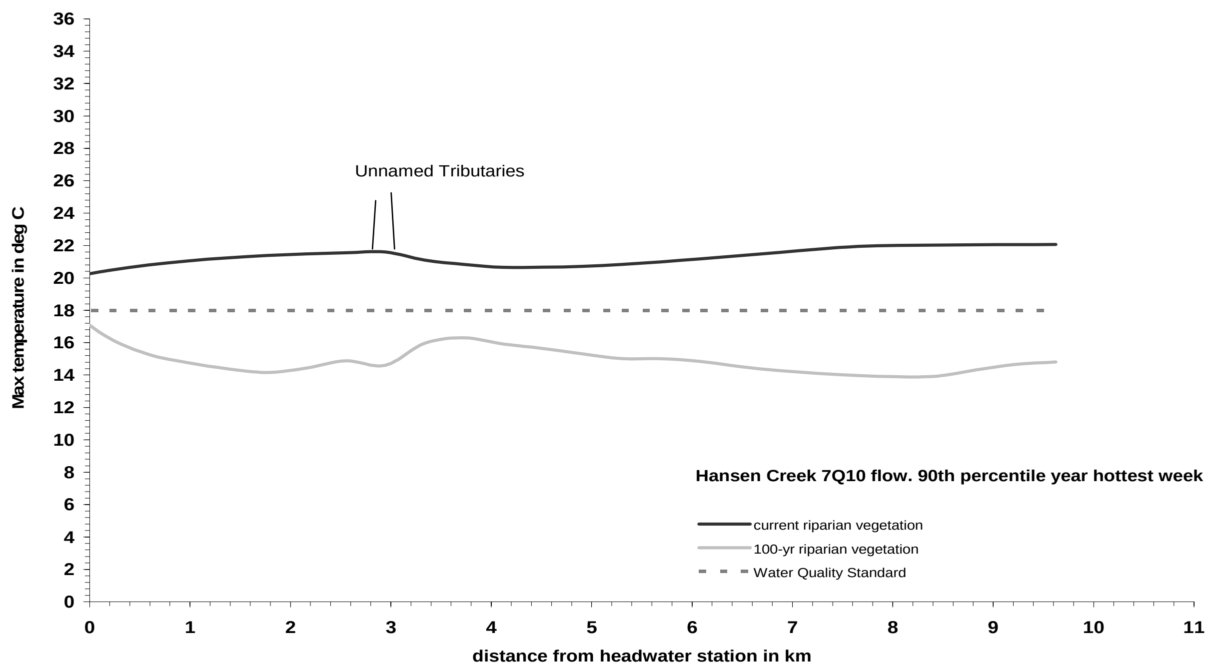
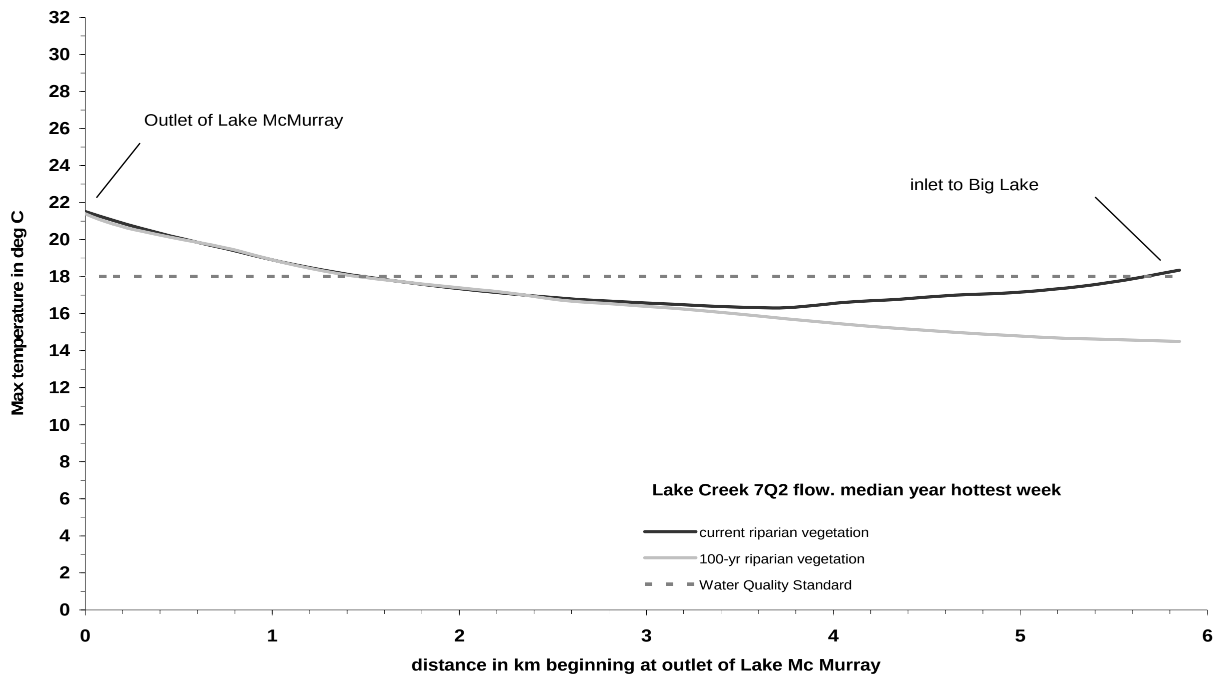


Figure 32. Predicted daily maximum temperature in Hansen Creek under critical conditions for the TMDL.



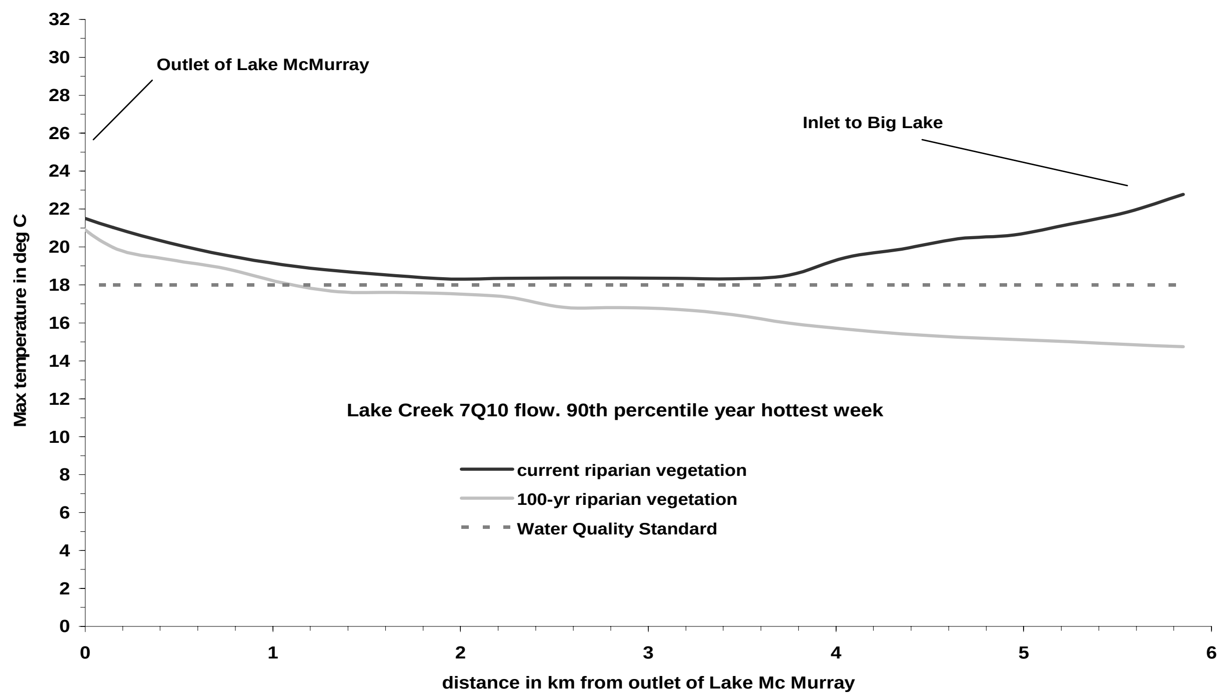
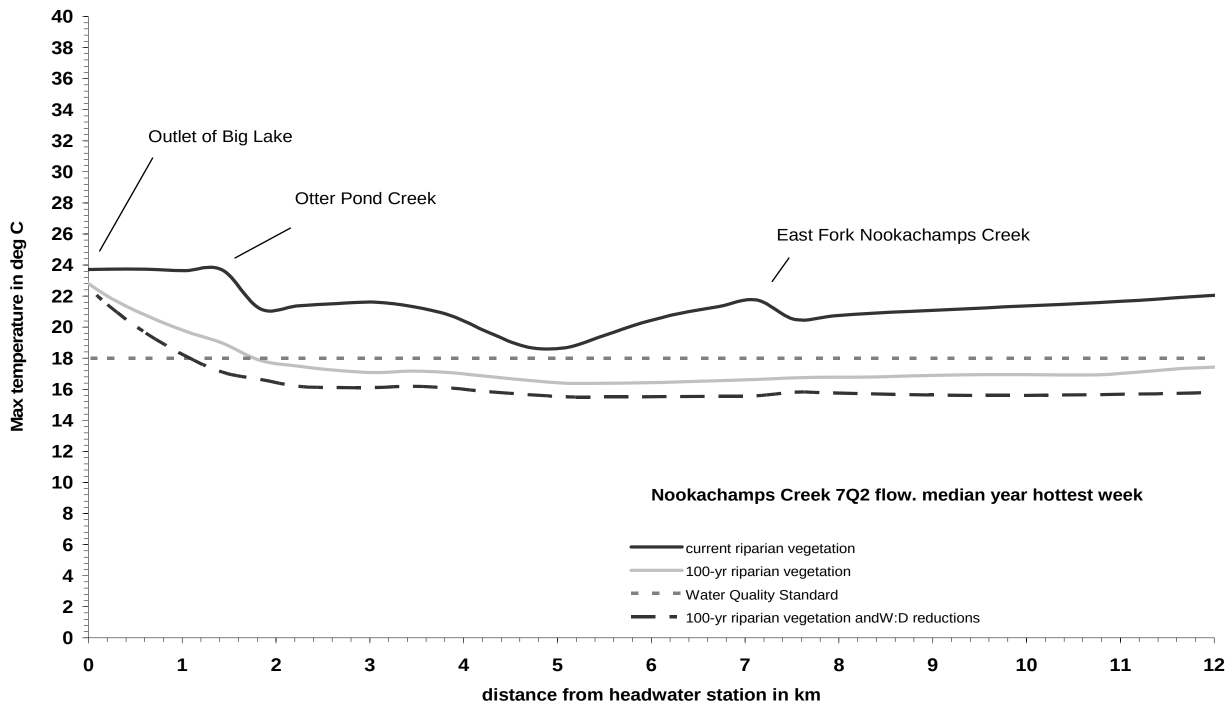


Figure 33. Predicted daily maximum temperature in Lake Creek under critical conditions for the TMDL.



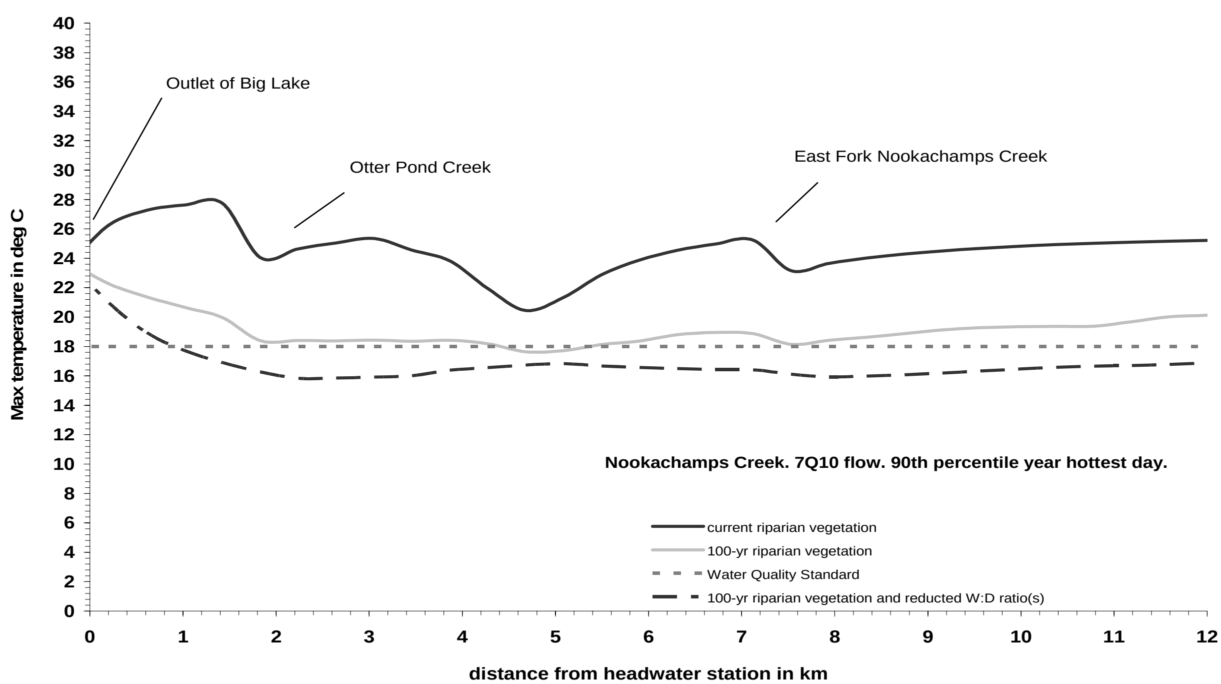
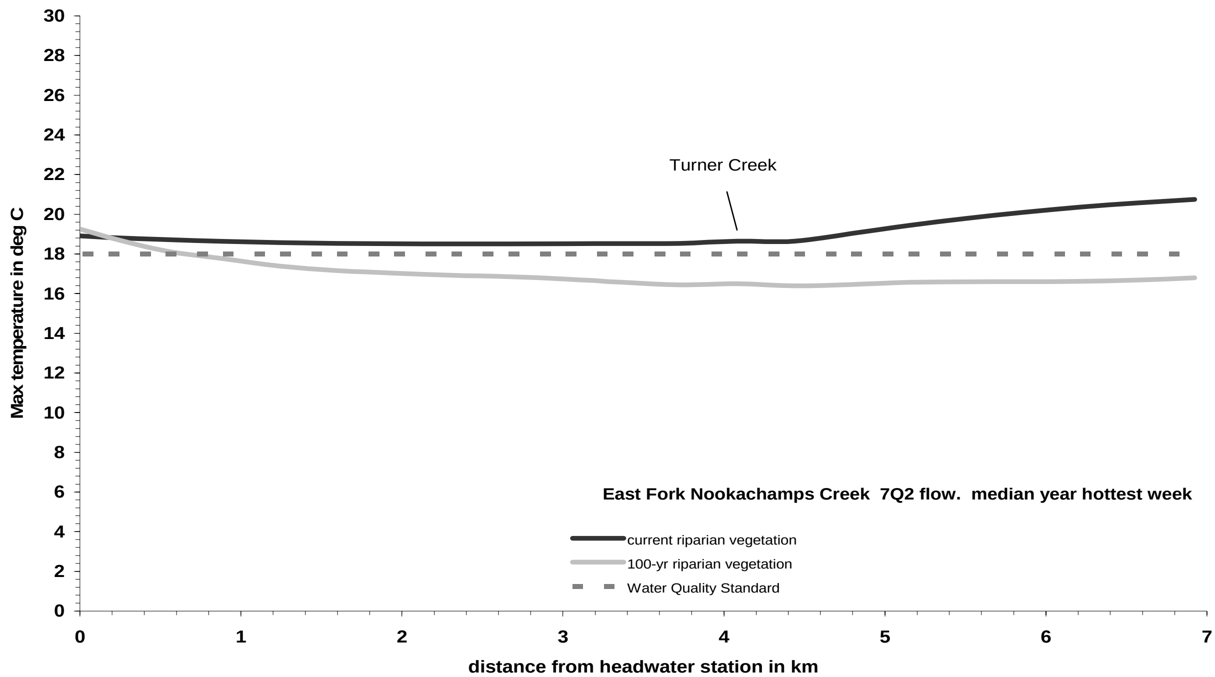


Figure 34. Predicted daily maximum temperature in Nookachamps Creek under critical conditions for the TMDL.



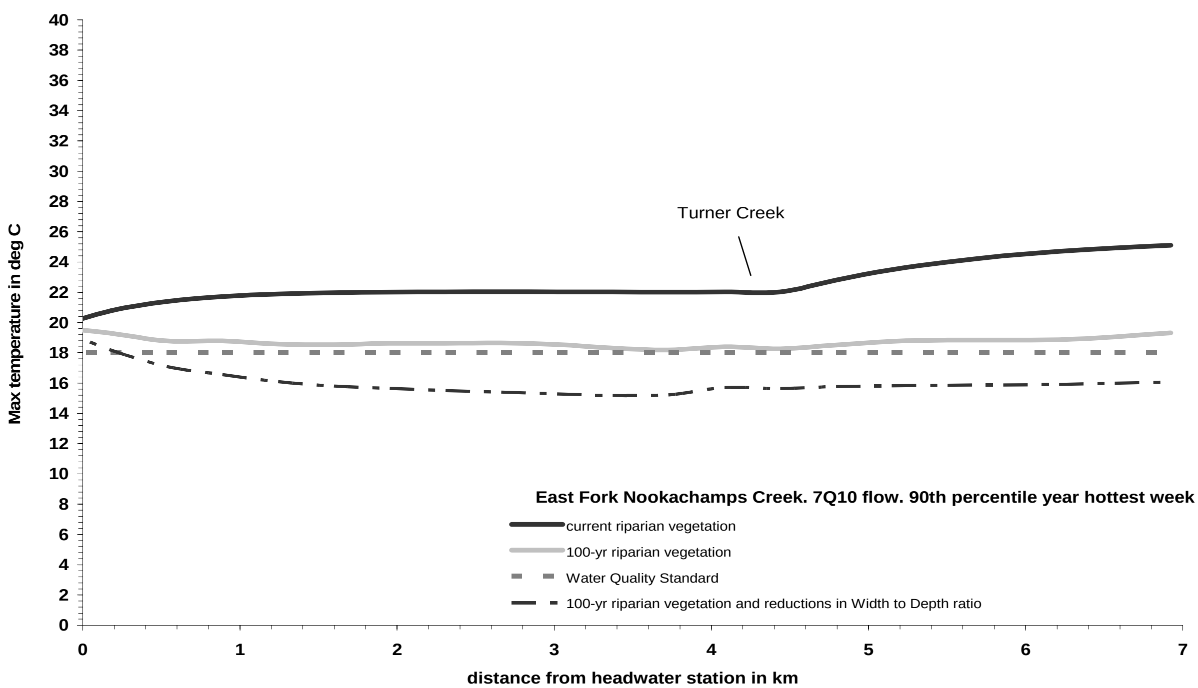


Figure 35. Predicted daily maximum temperature in East Fork Nookachamps Creek under critical conditions for the TMDL.

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Load Allocations

Load allocations for effective shade in the lower Skagit River study area are as follows:

- For Carpenter, Fisher, Hansen, Lake, Turner, Red, and Otter Pond creeks, the load allocation is the effective shade that would result from 100-year-old riparian vegetation.
- For Nookachamps and East Fork Nookachamps creeks, the load allocation is the effective shade that would result from 100-year-old riparian vegetation and natural reductions in channel width-to-depth ratios.

Load Allocations for effective shade are quantified in Tables 17-22 for the following modeled creeks of the lower Skagit River study area: Carpenter, Fisher, Hansen, Lake, Nookachamps, and East Fork Nookachamps. The recommended load allocations for effective shade and reduced channel widths are predicted to result in significant reductions of the flux of solar radiation to streams within the lower Skagit River basin.

The potential future vegetation at 100 years was assumed to be represented by average tree heights ranging from 37 to 53 meters. Riparian zone widths were estimated as 75% of average tree heights (FEMAT 1993) and ranged from 28 to 40 meters. Canopy densities at these widths were estimated as 75%.

The load allocations established by this TMDL study are identical to the loading capacity with both existing channel morphology and reduced channel widths. For those reaches downstream of Big Lake and Lake McMurray, the loading capacity is equal to the natural condition caused by warm outflow temperatures. For Nookachamps and East Fork Nookachamps creeks, the load allocation is based on achieving a stable channel with decreased width-to-depth ratios. The load allocations were compared to the estimated current condition effective shade derived for the model calibration and verification (Tables 17-22).

The load allocations are based on two assumptions: (1) riparian vegetation will be protected and reestablished as the result of management actions, and (2) water quality will be degraded no further by other influences. Although the bulk of this analysis focused on riparian shade, the calibration of the model resulted in estimates of groundwater inflow, stream and tributary flow, and channel morphology of the stream. Since the model was calibrated to predict current conditions, the implication of these assumptions is that existing influences on temperature other than shade must remain constant in order for the shade allocations to effectively control in-channel water temperatures. Since alterations of these influences would affect the assimilative capacity of the stream, existing groundwater inflow, streamflow, tributary inflow, and channel morphology are considered part of the load allocations. The following factors would need to remain constant or unchanged for the above load allocations to be effective:

- *Instream flow levels at critical flows.* Any additional water withdrawals must not be allowed during critical low-flow periods. This includes any groundwater withdrawals with continuity to streams. Control measures need to be implemented to prevent further flow depletion.

- *Processes affecting channel morphology.* For the Nookachamps and East Fork Nookachamps creeks, the process affecting channel morphology must be improved to achieve stable channels with decreasing width-to-depth ratios. The more significant factors affecting stream morphology that must be at least held constant are sediment delivery and watershed hydrology. Restoration activities that would reconnect or reestablish side channels, backwaters, and riverine wetlands would probably further improve channel water temperatures.

- *Sediment delivery to streams.* Sediment delivery to streams must be held constant or reduced. Excessive sediment loading to streams can raise temperatures. Surface erosion and delivery from mass wasting must not increase.

- *Watershed hydrology.* Activities that shift hydrographs from baseflow to more surface storm flow will affect temperatures. Excessive storm flows can result in further stream bank erosion and will likely raise stream temperatures. Lower baseflow in the summer caused by the hydrograph shift will also likely raise stream temperatures. Expansion of dikes and levies that could further alter stream hydrology should be curtailed.

The load allocations described also apply to all tributary streams in the modeled reaches. The load allocations are based on the assumption that lateral temperatures and flows are held at current level. Lateral inflow represents all the smaller surface tributaries and groundwater inflow to the segments that are not specifically modeled. These temperature and flows must not get worse. Activities that increase temperature, reduce the flow, or impact the stream channel-forming processes must be prevented in all tributaries of the watershed.

Load allocations, primarily for the tributary streams in the modeled reaches, are established in this TMDL in accordance with Schedule M-2 of the *Forests and Fish Report*. Also consistent with the Forests and Fish agreement, implementation of the load allocations for private and state forestlands will be accomplished via implementation of the revised forest practice regulations. The effectiveness of the Forests and Fish rules will be measured through the adaptive management processes and monitoring of streams in the watershed. If shade is not moving on a path toward the TMDL load allocation by 2009, Ecology will suggest changes to the Forest Practices Board.

Table 17. Load allocations for effective shade in Carpenter Creek.

Distance in km from headwater station	Current condition average effective shade (%)	Load allocation for effective shade on August 12 (%)
0 (headwater)		
0.45	80.0	85.0
0.90	60.0	85.0
1.35	60.0	85.4
1.80	40.0	83.3
2.26	30.0	88.9
2.71	30.0	92.8
3.16	30.0	92.6
3.61	15.0	93.3
4.06	15.0	93.8
4.51	15.0	92.5
4.96	15.0	92.6
5.41	15.0	93.0
5.86	15.0	93.8
6.31	15.0	92.7
6.77	15.0	92.7
7.22	15.0	93.9
7.67	15.0	93.3
8.12	15.0	92.1
8.57	25.0	91.8
9.02	25.0	91.8
9.47	25.0	91.7
9.92	25.0	91.4
10.37	25.0	91.9
10.82	25.0	92.6
11.28	25.0	90.7

Table 18. Load allocations for effective shade in Fisher Creek.

Distance in km from headwater station	Current condition average effective shade (%)	Load Allocation for effective shade on August 12 (%)
0 (headwater)		
0.38	80.0	85.0
0.75	80.0	85.2
1.13	80.0	91.8
1.50	80.0	91.1
1.88	80.0	91.9
2.25	80.0	91.6
2.63	80.0	91.6
3.00	80.0	90.6
3.38	80.0	93.2
3.75	80.0	87.4

Table 19. Load allocations for effective shade in Hansen Creek.

Distance in km from headwater station	Current condition average effective shade (%)	Load Allocation for effective shade on August 12 (%)
0(headwater)		
0.39	60.0	95.3
0.79	60.0	95.2
1.18	60.0	93.4
1.57	60.0	94.0
1.96	60.0	93.7
2.36	60.0	87.6
2.75	60.0	84.0
3.14	60.0	92.1
3.53	60.0	95.6
3.93	60.0	93.8
4.32	60.0	89.8
4.71	50.0	85.8
5.10	50.0	89.2
5.50	50.0	90.6
5.89	50.0	84.9
6.28	50.0	89.0
6.67	50.0	93.5
7.07	50.0	93.4
7.46	50.0	93.3
7.85	50.0	93.4
8.24	50.0	92.1
8.64	50.0	90.4
9.03	50.0	83.6
9.42	50.0	82.3
9.82	50.0	84.1

Table 20. Load allocations for effective shade in Lake Creek.

Distance in km from headwater station	Current condition average effective shade (%)	Load Allocation for effective shade on August 12 (%)
0 (headwater)		
0.30	75.0	90.6
0.60	75.0	84.0
0.90	75.0	84.0
1.20	75.0	84.0
1.50	75.0	83.8
1.80	75.0	78.6
2.10	75.0	79.0
2.40	75.0	81.0
2.70	75.0	89.6
3.00	75.0	82.1
3.30	75.0	83.5
3.60	75.0	88.1
3.90	70.0	94.4
4.20	50.0	94.4
4.50	53.2	95.2
4.80	47.0	94.8
5.10	50.6	94.7
5.40	38.7	94.9
5.70	35.6	95.9
6.00	19.3	94.8

Table 21. Load allocations for effective shade in Nookachamps Creek.

Distance in km from headwater station	Current condition average effective shade (%)	Load Allocation for effective shade on August 12 (%)
0 (headwater)		
0.41	30.0	90.0
0.81	30.0	92.3
1.22	30.0	91.2
1.63	30.0	91.7
2.04	30.0	92.8
2.44	30.0	91.5
2.85	30.0	91.5
3.26	30.0	92.0
3.66	50.0	91.7
4.07	50.0	92.9
4.48	75.0	93.0
4.88	82.0	93.0
5.29	40.0	93.0
5.70	35.0	93.0
6.11	35.0	92.2
6.51	35.0	92.2
6.92	35.0	89.8
7.33	35.0	90.9
7.73	35.0	92.5
8.14	35.0	91.0
8.55	35.0	85.9
8.95	35.0	85.9
9.36	35.0	84.0
9.77	35.0	83.5
10.18	35.0	84.3
10.58	35.0	85.5
10.99	35.0	87.2
11.40	35.0	87.7
11.80	35.0	81.5
12.21	35.0	79.1

Table 22. Load allocations for effective shade in East Fork Nookachamps Creek.

Distance in km from headwater station	Current condition average effective shade (%)	Load Allocation for effective shade on August 12 (%)
0 (headwater)		
0.36	42.00	88.40
0.71	42.00	91.20
1.07	42.00	86.00
1.42	42.00	87.80
1.78	42.00	86.30
2.13	42.00	84.90
2.49	42.00	85.20
2.84	42.00	85.30
3.20	42.00	85.80
3.55	42.00	86.20
3.91	42.00	83.20
4.26	42.00	80.70
4.62	42.00	82.70
4.97	30.00	80.90
5.33	30.00	82.00
5.68	30.00	81.70
6.04	30.00	81.70
6.39	30.00	81.00
6.75	30.00	79.20
7.10	30.00	78.60

Wasteload Allocations

No point sources of heat were found in the study area; therefore, the wasteload allocation is set to zero.

Margin of Safety

The margin of safety accounts for uncertainties regarding pollutant loading and waterbody response. In this TMDL, the margin of safety is addressed by using critical climatic conditions in the modeling analysis. The margin of safety in this TMDL is implicit because of the following:

- The 90th percentile of the highest 7-day averages of daily maximum air temperatures for each year of record was used to develop a reasonable worst-case condition for prediction of water temperatures in the lower Skagit River study area. Typical conditions were represented by the median of the highest 7-day averages of daily maximum air temperatures for each year of record.

- The lowest 7-day average flows during July-August with recurrence intervals of 10 years (7Q10) were used to evaluate reasonable worst-case conditions. Typical conditions were evaluated using the lowest 7-day average flows during July-August with recurrence intervals of 2 years (7Q2).

- Model uncertainty for prediction of water temperature was assessed by estimating the root mean squared error (RMSE) of model predictions compared with observed temperatures during model validation. The average RMSE for model calibration and verification was 0.56 and 0.44°C, respectively.

- 7Q10 low-flow conditions were used when calculating the effective shade and solar fluxes from site potential vegetation at a 100-year site index.

The modeling results and the loading capacity show that existing shade levels and some channel forms are not sufficient to meet stream temperature standards in the lower Skagit River tributaries. Comparing model predicted stream temperatures to the water quality standard (Figures 30-35) demonstrates that temperature will be improved by increasing riparian shading. However, it also indicates that the standard may not be met during these critical conditions for some stream reaches. Since restoring stream shade and improving stream morphology are the only practical solutions to temperature problems in the watershed, the approach of this TMDL is one of *adaptive management.*

If monitoring documents that restoring riparian shade to near natural-occurring levels, maintaining or enhancing streamflow during critical low-flow conditions, and improving other associated functions of a healthy stream environment do not result in compliance with water quality standards, then either the allocations or the standard itself will need to be re-evaluated and the TMDL amended. The time necessary to reestablish riparian vegetation will provide ample opportunity to gather information on the effectiveness of this TMDL.

Recommendations

For Management

Implementing the three management recommendations described below should result in long-term temperature reductions in streams within the lower Skagit River basin.

1. Riparian zones should be managed to allow full maturation of vegetation, preferably including native woody species that offer shade protection. Such managed zones would not only provide temperature benefits associated with direct shading of streams, but also would provide indirect benefits related to microclimate development, source of woody debris, and eventual narrowing and deepening of the stream.

   Streams identified as having large width-to-depth ratios as a result of erosion and sedimentation should be investigated to determine the causes of erosion and sources of sediment. Sources such as eroding streambanks and poorly managed upland areas should be addressed through riparian restoration projects and/or improved land management practices.

2. Instream flows and water withdrawals are managed through regulatory avenues separate from TMDLs. However, to protect the remaining instream flow, property owners next to streams should be encouraged to reduce water consumption during late-summer, low-flow conditions.

3. Stream restoration activities that increase groundwater inflows to streams should be encouraged.

   Groundwater inflows to streams could increase if recharge is increased as a result of renewed channel-floodplain connectivity. Engineered channels reduce the likelihood of flooding and the amount of time floodwaters spend on the floodplain. This action reduces the opportunity for floodwaters to penetrate the alluvial aquifer and, in turn, decreases baseflow by reducing groundwater discharge during the low-flow season (Steiger et al 1998).

For Monitoring

To determine the effects of management strategies within the lower Skagit River watershed, regular monitoring is recommended. Continuously-recording water temperature monitors should be deployed from July through August to capture the critical conditions. The following streams are suggested for inclusion as part of the Skagit County Surface Water Management sampling program or as a separate sampling program:

- Carpenter Creek
- Hansen Creek
- Lake Creek
- Nookachamps Creek

- East Fork Nookachamps Creek
- Red Creek
- Turner Creek
- Otter Pond Creek
- Coal Creek
- Wiseman Creek
- Mannser Creek
- Cumberland Creek
- Day Creek

Shade management practices involve the development of mature riparian vegetation, which requires many years to become established. Interim monitoring of water temperatures during summer is recommended, perhaps at five-year intervals. Interim monitoring of the composition and extent of riparian vegetation is also recommended (e.g., using photogrammetry or remote sensing methods).

Methods to measure effective shade at the stream center in various segments for comparison with load allocations could employ hemispherical photography, angular canopy densiometers, or solar pathfinder instruments.

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Appendices

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Appendix A. Instream water temperature standard exceedances and station disposition

This appendix totals the daily temperature standard exceedances of the maximum daily temperature for each instream tidbit[3] station in this study during 2001. Station descriptors and any data qualifiers are included in the paragraphs following the total exceedances for each station.

Station 03B01 Bulson Creek at Bulson Road

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	9
Maximum Daily Temperature Threshold of 18°C	0

The tidbit station on Bulson Creek was located on the east side of Bulson Creek Road. The June storm event washed out the instream tidbit, and the data were lost from May 25 through June 21 until the author installed the new tidbit. No other problems with this station were encountered for the remainder of the study period (2001). The temperature instruments were removed on October 16.

Station 03C01 Carpenter Creek near mouth

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	102 (104 not tidally corrected)
Maximum Daily Temperature Threshold of 18°C	50 (67 not tidally corrected)

This station was located beneath the Pioneer Highway bridge on Fisher Slough. The instream tidbit was definitely affected by tidal exchanges that were regulated by a tide gate about 20 feet directly downstream of the tidbit. There were several times the tidbit was checked and found dry because of a low tide (at which point it was repositioned closer to the bottom of the stream); however, it is highly likely that air temperature could have affected the instream tidbit during the periods of low tides. Unfortunately, the daytime low tides occurred during the hottest parts of the day (between 11am and 5pm) during the majority of the study period, and these data should be qualified. It is not clear that the total exceedances above were all instream temperatures. However, the exceedances from the upstream station 03C02, most of the exceedances at station 03C01 were real, although the instream temperatures may be positively skewed.

The relative humidity sensor was found vandalized on August 6, and no data were recovered for the period from June 21 to August 6. The replacement air tidbit recorded air temperature data from August 6 to October 17. The temperature instruments were removed on October 17.

[3] A tidbit is a small (0.8 oz), completely sealed, underwater temperature recording device made by the Onset Computer Corporation. The device is deployed within the waterbody and records continuous stream temperature, given a user-selected sampling interval. Optic communication is used for launch and readout of the data.
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Station 03C02 Carpenter Creek at SR 534

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	97
Maximum Daily Temperature Threshold of 18°C	69

This station was located beneath the Highway 534 bridge over Carpenter Creek. This location was tidally influenced; however, the low water height was still above the instream tidbit so that it never went dry. There was also a soil temperature tidbit buried on the left bank at this location. The temperature instruments were removed on October 19.

Station 03C03 Carpenter Creek at Stackpole Road

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	52
Maximum Daily Temperature Threshold of 18°C	11

This station was located on Carpenter Creek adjacent to Stackpole Road about 200 feet north of Kanoko Lane. Streamflow throughout this reach was sluggish, and there were many aquatic plants in the stream that added to the reduced streamflow. The air tidbit was only about one foot from the water surface and may have been submerged during some of the major storm events during the study period, as evidenced by debris on and around the tidbit. The temperature instruments were removed on October 16.

Station 03C04 Carpenter Creek at Little Mountain Road

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	1
Maximum Daily Temperature Threshold of 18°C	0

This station was located (with permission) on private property near Little Mountain Road and was well shaded by riparian vegetation. The temperature data do not need qualifying. The temperature instruments were removed on October 19.

Station 03CL01 Unnamed tributary from Clear Lake

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	40
Maximum Daily Temperature Threshold of 18°C	25

This station was located on the south side of Swan Lake Road near the intersection of Babcock and Mud Lake roads on an unnamed stream. This seemed to be only an ephemeral stream, and it dried up during the summer. The dry period was discerned from the air and water temperature comparisons as occurring from July 12 until it was recovered in October (at which point the stream was still dry), and data for that time period were excluded.

Station 03EF01 East Fork Nookachamps Creek at SR 9

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	51
Maximum Daily Temperature Threshold of 18°C	25

This station was located immediately downstream of the Highway 9 bridge on the East Fork Nookachamps Creek. The original instream tidbit was anchored to a large piece of woody debris that, unexpectedly, was washed away during the large June storm event. After the instream tidbit was replaced on July 23, no further problems were encountered. The temperature instruments were removed on October 18.

Station 03EF02 East Fork Nookachamps Creek at Beaver Lake Road

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	48
Maximum Daily Temperature Threshold of 18°C	15

This station was initially located on the left bank about 20 feet from the Beaver Lake Road bridge on the East Fork Nookachamps Creek. There was a continuous flow gage operated by Ecology's Stream Hydrology Unit also located at the bridge. This station was placed above any influence from the mouth of the unnamed stream for station 03U01. The instream tidbit was then moved to the right bank on July 3 after the download check found the drop in water height had changed the thalweg from the left to right bank. The second location had more vegetative shade cover than the previous location. There does not appear to be any bad data before the probe was moved, and all data were retained. The temperature instruments were removed on October 18.

Station 03F01 Fisher Creek at Franklin Road

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	0
Maximum Daily Temperature Threshold of 18°C	0

This station was located about 30 feet downstream of the Franklin Road bridge on Fisher Creek. The instream tidbit was well shaded and had no problems with going dry. The air tidbit recorded temperatures much lower than the reference temperatures collected during the download checks. The location of the air tidbit was close to the ground, and the placement seems to have resulted in cooler air temperature measurements than what would more likely represent an "average" air temperature for that site. The temperature instruments were removed on October 19.

Station 03F02 Fisher Creek at Starbird Road

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	43
Maximum Daily Temperature Threshold of 18°C	8

This station was located, with permission, on private property about 500 feet downstream from the Starbird Road crossing of Fisher Creek. The instream tidbit was well shaded and always submerged; however, the creek was found to have stopped almost all surface flow on September 17 (there was only a small trickle between that was probably less than 1% of the normal flow) and the instream tidbit was just basically in a large pond. The author talked with one of the landowners who said the creek had been "pretty much" dried up for the last month. Most of the water data during late July through August are qualified. The temperature instruments were removed on October 17.

Station 03H01 Hansen Creek at Hoehn Road

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	54
Maximum Daily Temperature Threshold of 18°C	11

This station was located about 50 feet downstream of the Hoehn Road bridge on Hansen Creek. There was significant bed movement at this location; on July 3 the instream tidbit was found partially buried with sediment. This was the only time it was found in this condition, and it does not seem to have significantly affected instream temperature measurements during June. Ground temperature was also recorded at this location. The temperature instruments were removed on October 18.

Station 03H02 Hansen Creek at SR 20

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	19
Maximum Daily Temperature Threshold of 18°C	0

This station was located about 50 feet upstream of the Highway 20 bridge crossing Hansen Creek. The instream tidbit was missing the August 16 field check, and all data from July 3 through August 16 were lost. All other data for the study period were recovered. The temperature instruments were removed on October 18.

Station 03H03 Hansen Creek at Hansen Creek Road

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	18
Maximum Daily Temperature Threshold of 18°C	3

This station was located on Hansen Creek about 300 feet downstream from the crossing with Hansen Creek Road. Everything worked well with this station, and none of the data needs to be qualified. The temperature instruments were removed on October 18.

Station 03J01 Johnson Creek at Johnson Road

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	0
Maximum Daily Temperature Threshold of 18°C	0

This station was next to Johnson Creek Road only 10 feet upstream from the culvert crossing the road. This reach of streambed is a deep ditch, although the water was shallow. The tidbit was found partially buried with sediment on August 7; however, this does not appear to have negatively influenced the temperature readings. The instream tidbit appears to have been submerged for the entire study period, although the stream surface water flow was very low when the author checked it (est. <0.5cfs during download checks). The temperature instruments were removed on October 16.

Station 03N01 Nookachamps Creek near mouth

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	116 (118 not tidally corrected)
Maximum Daily Temperature Threshold of 18°C	88 (90 not tidally corrected)

This station was located at the Francis Road crossing of the Nookachamps Creek about 400 feet from its confluence with the Skagit River. This station was tidally influenced similar to station 03C01. The only time the instream tidbit was found dry was during the station's removal on October 18. The instream temperatures exceedances were probably real as exhibited by the next station upstream, 03N02, which was not tidally influenced and never went dry but still had exceedances; however, the maximum temperatures may not be accurate and should be qualified as such. The air tidbit was close to the ground and appears to have been influenced by cooler ground temperatures. The temperature instruments were removed on October 18.

Station 03N02 Nookachamps Creek above Barney Lake

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	111
Maximum Daily Temperature Threshold of 18°C	78

This station was located on the Nookachamps Creek approximately 150 feet downstream of the Highway 9 bridge near the Big Rock gas station. This reach was not tidally influenced and was at the bottom of a steep box-shaped canyon with lots of vegetative shading along with good topographic shading. There did not appear to be any problems with the instream tidbit, although the location was moved about 20 feet downstream to allow for lowering water stage. The author could not find the air tidbit that was originally installed on May 22, so a replacement tidbit was installed on August 30, but the previous air temperature data were lost. However, that air tidbit was mistakenly set to record at one-minute intervals, so only data from August 30 through September 22 were collected. The temperature instruments were removed on October 18.

Station 03N03 Nookachamps Creek below Big Lake

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	133
Maximum Daily Temperature Threshold of 18°C	111

This station was located at the crossing of Highway 9 and the Nookachamps Creek below Big Lake. The instream temperature of this reach is heavily influenced by Big Lake, as indicated in the thermograph comparison with the air temperature. The instream tidbit was found barely covered with water on August 15 and was moved to a location directly underneath the Highway 9 bridge. It is difficult to tell from the temperature data if the instream tidbit was dry at any time, because instream temperatures were higher than recorded air temperatures. From that comparison and the reference temperatures measured in situ, it seems the tidbit was wet for the period leading up to it being checked on August 15. The temperature instruments were removed on October 17.

Station 03N04 Nookachamps Creek above Big Lake

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	25
Maximum Daily Temperature Threshold of 18°C	6

This station was located on the Nookachamps Creek above Big Lake as it crosses Highway 9 near Devil's Creek Lane. The instream tidbit was attached to the side of an old piling under the existing bridge. The instream tidbit was submerged during the entire study period, and no data need to be qualified. The temperature instruments were removed on October 19.

Station 03S01 Sandy Creek at Kanoko Lane

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	0
Maximum Daily Temperature Threshold of 18°C	0

This station was located on Sandy Creek about 15 feet upstream from the culvert on Kanoko Lane. The instream tidbit was submerged during the entire study period. No data need to be qualified. The temperature instruments were removed on October 16.

Station 03T01 Turner Creek at Beaver Lake Road

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	40
Maximum Daily Temperature Threshold of 18°C	5

This station was located on Turner Creek about 20 feet downstream of the crossing with Beaver Lake Road. There is no riparian shading along this reach of the creek, and it is adjacent to the Beaver Lake Rock and Gravel quarry. The location of the instream tidbit was changed on July 3 when it was found dry, and the new location was about 10 feet upstream from the initial location. It was not possible to discern exactly when it went dry since it started recording data four days after it was installed, so the author did not include any water temperature data until after it was moved on July 3. The air tidbit data were corrupt when downloaded on August 20 and October 18, so no air temperature data were used after July 3. The temperature instruments were removed on October 18.

Station 03U01 Unnamed tributary near station 03EF02

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	24
Maximum Daily Temperature Threshold of 18°C	0

This station was located on an unnamed stream that enters the East Fork Nookachamps just above the bridge where station 03EF02 is located. The air temperature information from 03EF02 was compared with the instream temperatures, and the instream tidbit did not appear to go dry at any point during the study period. Streamflow measurements were not possible at this site because shrubs and blackberries grew over the stream, and the author had to crawl along the stream bottom to access the site. The author estimates the amount of water this small stream contributes to the East Fork at about 5% of the East Fork during low-flow conditions. The temperature instruments were removed on October 18.

Station 03U02 Unnamed tributary at Otter Pond Road

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	57
Maximum Daily Temperature Threshold of 18°C	12

This station was located on an unnamed stream on Otter Pond Road approximately 0.5 mile from Highway 9. The instream tidbit appears to have stayed submerged for the entire study period. Small freshwater lampreys, maybe western brook lamprey, were seen creating little mounds (spawning possibly) at this site during the tidbit installations. The temperature instruments were removed on October 17.

Station 03U03 Unnamed tributary at Lake Cavanaugh Road

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	3
Maximum Daily Temperature Threshold of 18°C	0

This station was located on an unnamed creek immediately downstream of the culvert crossing Lake Cavanaugh Road approximately one mile from Highway 9. The instream tidbit was downloaded once on August 15 but was not found when the station was being removed on October 17. Consequently all instream temperature data during this period of mid-August to mid-October were lost.

Station 03U04 Red Creek near Highway 20

	Total Daily Exceedances
Maximum Daily Temperature Threshold of 16°C	97
Maximum Daily Temperature Threshold of 18°C	50

This station was located on Red Creek (previously thought to be unnamed) as it crosses the pedestrian trail adjacent to Highway 20. The only point of access to this creek was in an area where the stream channel was undefined in a muddy grassy area. The instream tidbit was placed in the creek's area of greatest streamflow as close to the fence as possible. The grassy area just upstream has a slight impounding effect on the creek, but water was moving in the area of the instream tidbit. The temperature instruments were removed on October 18.

Appendix B. Tables

Table B-1. Riparian codes used in Shade model vegetation classification.

Code	Description	Height (m)	Density (%)	Overhang (m)
301	water	0.0	0%	0.0
302	pastures/cultivated field/lawn	0.5	75%	0.0
304	barren - rock	0.0	0%	0.0
305	barren - embankment	0.0	0%	0.0
308	barren - clearcut	0.0	0%	0.0
309	barren - soil	0.0	0%	0.0
400	barren - road	0.0	0%	0.0
401	barren - forest road	0.0	0%	0.0
500	l. mixed con/hard (50-100% cc)	24.4	75%	2.4
501	s. mixed con/hard (50-100% cc)	8.2	60%	1.0
502	mixed forest	45.7	90%	4.6
550	l. mixed con/hard (<50% cc)	24.4	25%	2.4
551	s. mixed con/hard (<50% cc)	12.2	25%	1.2
555	l. mixed con/hard (10% cc)	16.4	10%	2.1
600	large hardwood	30.0	75%	4.0
601	small hardwood	12.2	35%	1.2
650	large hardwood	15.0	30%	***2.0***
651	small hardwood	6.2	40%	0.9
652	small hardwood	15.0	35%	0.9
655	large hardwood	15.0	10%	***2.0***
700	large conifer	30.5	90%	3.1
701	small conifer	10.2	60%	1.0
750	large conifer	20.3	30%	2.0
751	small conifer	10.2	30%	1.0
800	upland shrubs	4.6	75%	0.5
800	shrubs on wet floodplain	0.8	25%	0.7
820	riparian shrubs (blackberries)	1.8	75%	0.3
850	upland shrubs	1.8	25%	0.3
851	shrubs on wet floodplain	1.8	25%	0.3
3011	active channel bottom	0.0	0%	0.0
3255	canal	0.0	0%	0.0
3256	dike	0.0	0%	0.0
5555	disturbance	0.0	0%	0.0
4000	upland shrubs	1.8	80%	0.3
4001	riparian shrubs	3.2	90%	0.5
5000	upland grasses	0.5	90%	0.3
4304	barren - rock	0.0	0%	0.0
4500	l. mixed con/hard (50-100% cc)	16.4	60%	2.1
4550	l. mixed con/hard (<50% cc)	16.4	30%	2.1
4600	large hardwood	12.5	60%	2.0
4650	large hardwood	12.5	30%	2.0
4700	large conifer	20.3	60%	2.0
4750	large conifer	20.3	30%	2.0

cc = canopy cover

Table B-2. Riparian codes used for 100-year-old riparian vegetation.

Code	Description	Height (m)	Density (%)	Overhang (m)
67	Douglas-fir, red alder	33.3	85%	3.0
98	red alder, western red cedar	27.4	75%	3.0
136	red alder, western red cedar	24.4	75%	3.0
123	western red cedar, Douglas-fir, red alder	25.9	75%	3.0
125	Douglas-fir, red alder	31.4	75%	3.0
124	Douglas-fir, red alder	31.4	75%	3.0
17	Douglas-fir, red alder	28.0	75%	3.0
114	red alder, western red cedar	25.9	72%	3.0
157	Douglas-fir, red alder	36.5	75%	3.0
92	Douglas-fir, red alder	35.6	75%	3.0
56	Douglas-fir, red alder	34.1	75%	3.0
34	Douglas-fir, red alder	35.2	75%	3.0
11	red alder	25.9	75%	3.0
101	red alder, western red cedar	24.4	75%	3.0
145	red alder, western red cedar	36.6	75%	3.0
101	Douglas-fir, red alder	36.6	75%	3.0
56	Douglas-fir, red alder	34.1	75%	3.0
101	red alder, western red cedar	36.6	75%	3.0
123	red alder, Douglas-fir, western red cedar	36.6	72%	3.0
118	Douglas-fir, red alder	37.1	75%	3.0
89	Douglas-fir, red alder	35.2	75%	3.0
34	Douglas-fir, red alder	35.2	75%	3.0
101	red alder	36.6	75%	3.0
136	red alder, western red cedar	36.6	75%	3.0
56	Douglas-fir, red alder	34.1	75%	3.0

The source for this table is the Site Index (SI), a designation of the quality of a forest site, typically based on soil type and the height of the dominant stand at an arbitrary age. In this case, the SI represents the average height of dominant trees at 100 years of age on that particular soil site.

Table B-3. 7Q2 and 7Q10 low-flow model inputs for discharge, width, depth, and velocity.

Carpenter Creek- 7Q2

Station	Discharge (cms)	Width (m)	Depth (m)	Velocity (m/s)
03C04	0.0195	3.12	0.037	0.091
03C03	0.0195	3.17	0.043	0.122
03C02	0.0195	3.29	0.07	0.305
03C01	0.1082	3.35	0.079	0.427

Hansen Creek- 7Q2

Station	Discharge (cms)	Width (m)	Depth (m)	Velocity (m/s)
03H03	0.029	2.22	0.027	0.152
03H02	0.064	2.91	0.052	0.182
03H01	0.038	3.23	0.067	0.182

Carpenter Creek- 7Q10

Station	Discharge (cms)	Width (m)	Depth (m)	Velocity (m/s)
03C04	0.0065	3.05	0.028	0.031
03C03	0.0065	3.09	0.03	0.061
03C02	0.0065	3.2	0.049	0.152
03C01	0.0361	3.23	0.058	0.213

Hansen Creek- 7Q10

Station	Discharge (cms)	Width (m)	Depth (m)	Velocity (m/s)
03H03	0.011	1.72	0.012	0.12
03H02	0.025	2.26	0.028	0.152
03H01	0.013	2.5	0.037	0.152

Fisher Creek- 7Q2

Station	Discharge (cms)	Width (m)	Depth (m)	Velocity (m/s)
03F02	0.0184	1.71	0.091	0.091
03F01	0.0184	1.78	0.122	0.091

Lake Creek- 7Q2

Station	Discharge (cms)	Width (m)	Depth (m)	Velocity (m/s)
03N04	0.034	3.53	0.085	0.085

Fisher Creek- 7Q10

Station	Discharge (cms)	Width (m)	Depth (m)	Velocity (m/s)
03F02	0.0061	1.39	0.07	0.061
03F01	0.0061	1.43	0.073	0.061

Lake Creek- 7Q10

Station	Discharge (cms)	Width (m)	Depth (m)	Velocity (m/s)
03N04	0.011	2.61	0.064	0.052

Nookachamps Creek- 7Q2

Station	Discharge (cms)	Width (m)	Depth (m)	Velocity (m/s)
03N03	0.048	4.57	0.113	0.128
03N02	0.101	4.88	0.119	0.143
03N01	0.204	6.35	0.155	0.216

EF Nookachamps Creek- 7Q2

Station	Discharge (cms)	Width (m)	Depth (m)	Velocity (m/s)
03EF02	0.0433	4.37	0.116	0.128
03EF01	0.1033	5.00	0.137	0.158

Nookachamps Creek- 7Q10

Station	Discharge (cms)	Width (m)	Depth (m)	Velocity (m/s)
03N03	0.016	3.39	0.082	0.08
03N02	0.034	3.61	0.088	0.088
03N01	0.068	4.7	0.116	0.134

EF Nookachamps Creek- 7Q10

Station	Discharge (cms)	Width (m)	Depth (m)	Velocity (m/s)
03EF02	0.016	3.31	0.082	0.08
03EF01	0.034	3.77	0.098	0.1

Table B-4. Summary of flow measurements in the lower Skagit River study area, 2001.

Station	Date	Creek Name	Wetted Width (ft)	Average Depth (ft)	Average Velocity (fps)	Discharge (cfs)
03B01	8/7	Bulson @ Bulson Rd	6.60	0.24	0.29	0.46
03B01	8/15	Bulson @ Bulson Rd	7.10	0.24	0.24	0.40
03C01	5/23	Carpenter near mouth	14.60	0.36	1.24	6.57
03C02	7/3	Carpenter @ SR 534	13.80	0.34	1.00	4.69
03C02	8/6	Carpenter @ SR 534	11.30	0.23	0.50	1.30
03C02	8/15	Carpenter @ SR 534	9.60	0.08	0.21	0.17
03C02	9/19	Carpenter @ Hwy 534	10.70	0.18	0.35	0.68
03C02	10/19	Carpenter blw Bulson	17.50	0.60	0.78	8.22
03C04	5/23	Carpenter @ headwater	10.73	0.21	1.38	3.12
03C04	7/23	Carpenter @ headwater	10.50	0.07	0.33	0.24
03C04	8/15	Carpenter @ headwater	10.10	0.07	0.22	0.16
03C04	9/19	Carpenter @ headwater	10.10	0.11	0.07	0.07
03C04	10/19	Carpenter @ headwater	11.00	0.32	0.98	3.45
03EF01	5/22	E.F. Nookachamps @ Hwy 9	37.60	1.20	1.87	84.34
03EF01	7/23	E.F. Nookachamps @ Hwy 9	22.90	0.73	0.50	8.29
03EF01	8/15	E.F. Nookachamps @ Hwy 9	13.10	0.26	1.41	4.81
03EF01	8/21	E.F. Nookachamps @ Hwy 9	19.60	0.63	0.32	3.99
03EF01	9/5	E.F. Nookachamps @ Hwy 9	22.33	0.60	0.67	8.99
03EF01	10/18	E.F. Nookachamps @ Hwy 9	25.10	0.84	1.36	28.63
03EF02	8/20	E.F. Nookachamps @ mouth	38.40	0.34	0.17	2.18
03F01	5/23	Fisher near mouth	8.20	0.57	0.96	4.46
03F01	6/21	Fisher near mouth	7.90	0.76	0.59	3.57
03F01	8/6	Fisher @ Franklin Rd	7.80	0.56	0.15	0.65
03F01	8/15	Fisher @ Franklin Rd	13.00	0.12	0.28	0.42
03F01	9/17	Fisher @ Franklin Rd	10.07	0.20	0.27	0.53
03F01	10/19	Fisher near mouth	8.40	0.58	1.18	5.80
03F02	8/15	Fisher @ Starbird Rd	13.50	0.39	0.00	0.00
03H01	5/21	Hansen near mouth	22.60	1.04	1.14	26.71
03H01	8/15	Hansen @ Hoehn Rd	17.40	0.11	0.61	1.18
03H01	8/16	Hansen @ Hoehn Rd	7.40	0.30	0.60	1.31
03H01	9/20	Hansen near mouth	9.08	0.33	0.42	1.27
03H01	10/18	Hansen near mouth	12.55	0.93	0.57	6.67
03H02	8/15	Hansen @ SR 20	17.50	0.16	0.53	1.50
03H02	8/16	Hansen @ SR 20	12.80	0.30	0.59	3.55
03H03	8/16	Hansen @ headwater	6.48	0.22	0.69	0.98
03J01	8/7	Johnson @ Johnson Rd	4.00	0.02	0.06	0.01
03J01	8/15	Johnson @ Johnson Rd	4.50	0.02	0.01	0.00
03N01f	7/3	Nookachamps @ Swan Rd	56.35	1.53	0.38	32.51
03N01f	8/15	Nookachamps @ Swan Rd	28.65	0.52	1.26	18.81
03N01f	8/31	Nookachamps @ Swan Rd	32.80	0.81	0.41	10.96
03N01f	9/17	Nookachamps @ Swan Rd	28.35	0.54	0.39	6.03
03N01f	10/18	Nookachamps @ Swan Rd	49.09	0.98	1.09	52.67
03N02	8/30	Nookachamps @ Hwy 9	18.63	0.39	0.16	1.13
03N03	8/15	Nookachamps blw Big Lake	9.10	0.19	0.33	0.58
03N03	8/21	Nookachamps blw Big lake	9.15	0.18	0.51	0.86
03N04	5/22	Nookachamps abv Big Lake	20.60	0.29	1.34	8.11
03N04	7/23	Nookachamps abv Big Lake	17.50	0.40	0.16	1.14
03N04	8/15	Nookachamps abv Big Lake	4.32	0.12	0.75	0.39
03N04	8/21	Nookachamps abv Big Lake	17.80	0.41	0.10	0.70
03N04	9/5	Nookachamps abv Big Lake	17.40	0.39	0.11	0.76
03N04	10/19	Nookachamps abv Big Lake	18.50	0.71	0.89	12.01
03S01	8/7	Sandy @ Kanoko Ln	5.10	0.17	0.09	0.08
03S01	8/15	Sandy @ Kanoko Ln	4.70	0.14	0.11	0.07
03T01	8/15	Turner @ Beaver Lake Rd	2.50	0.14	0.60	0.20
03T01	8/20	Turner @ Beaver Lake Rd	2.40	0.15	0.54	0.19

Table B-5. Methodology and calculations for estimating future riparian vegetation species, heights, and widths.

Stream Name	TTools Segment ID upstrm to dwnstrm	Soil Type	Potential Productivity Common Trees	50-yr SI* Red Alder (ft)	100-yr SI Douglas Fir (ft)	Estimated SI for W. Red Cedar (ft)	Estimated 100-yr SI for Red Alder (ft)	Buffer Height Tallest Trees (ft)	Estimated Buffer Width (ft)	Estimated Buffer Density (%)	Buffer Height (m)	Buffer Width (m)	Other Trees of Limited Extent
Carpenter Creek	93-118	67	douglas-fir, red alder		156	109.2		156	117.00	75%	47.5	35.7	w. hemlock
	119-126	98	red alder, w. red cedar	90			120	120	90.00	75%	36.6	27.4	w. red cedar
	127-153	136	red alder, w. red cedar	80			120	120	90.00	75%	36.6	27.4	w. red cedar
	154- end of segment	123	w. red cedar, douglas-fir, red alder	85			120	120	90.00	75%	36.6	27.4	w. red cedar, big leaf maple
								avg	**96.75**			**29.5**	
Fisher Creek	199-203	125	douglas-fir, red alder	97	147	102.9		147	110.25	75%	44.8	33.6	w. red cedar, w. hemlock
	204-208	124	douglas-fir, red alder	97	147	102.9		147	110.25	75%	44.8	33.6	w. red cedar, w. hemlock
	209-211	17	douglas-fir, red alder		131	91.7		131	98.25	75%	39.9	29.9	red alder, w. red cedar
								avg	**106.25**			**32.4**	
Hansen Creek	120-142	114	red alder, w. red cedar	85			120	120	90.00	75%	36.6	27.4	w. red cedar, Sitka spruce
	143-152	157	douglas-fir, red alder		171	119.7		171	128.25	75%	52.1	39.1	red alder, w. red cedar
	153-162	136	red alder, w. red cedar	80			120	120	90.00	75%	36.6	27.4	w. red cedar
	163-166	92	douglas-fir, red alder		167	116.9		167	125.25	75%	50.9	38.2	red alder, w. red cedar
	167-205	56	douglas-fir, red alder		160	112		160	120.00	75%	48.8	36.6	w. red cedar
	206- end of segment	34	douglas-fir, red alder	95	165	115.5		165	123.75	75%	50.3	37.7	w. red cedar, w. hemlock
								avg	**112.88**			**34.4**	
Lake Creek	118-180	101	red alder, w. red cedar	80			120	120	90.00	75%	36.6	**27.4**	w. red cedar, w. hemlock
Nookachamps Creek	12-147	145	red alder, w. red cedar	70			120	120	90.00	75%	36.6	27.4	w. red cedar
	148-188	na	na	na	na	na		na	na	na			
	189-263	101	red alder, w. red cedar	80			120	120	90.00	75%	36.6	27.4	w. red cedar, w. hemlock
	264-280	56	douglas-fir, red alder		160	112		160	120.00	75%	48.8	36.6	w. red cedar
	281-307	101	red alder, w. red cedar	80			120	120	90.00	75%	36.6	27.4	w. red cedar, w. hemlock
	308-336	123	red alder, w. red cedar, douglas-fir	85			120	120	90.00	75%	36.6	27.4	w. red cedar, big leaf maple
	337- end of segment	118	douglas-fir, red alder		174	121.8		174	130.50	75%	53.0	39.8	w. red cedar, red alder
								avg	**104.10**			**31.7**	
East Fork Nookachamps Creek	118-127	89	douglas-fir, red alder		165	115.5		165	123.75	75%	50.3	37.7	w. red cedar, hemlock, red alder
	128-147	34	douglas-fir, red alder	95	165	115.5		165	123.75	75%	50.3	37.7	w. red cedar, w. hemlock
	148-161	101	red alder	80			120	120	90.00	75%	36.6	27.4	w. red cedar, w. hemlock
	162-174	136	douglas-fir, red alder	80			120	120	90.00	75%	36.6	27.4	w. red cedar
	175- end of segment	56	douglas-fir, red alder		160	112		160	120.00	75%	48.8	36.6	w. red cedar
								avg	**109.50**			**33.4**	

* SI (site index) is a designation of the quality of a forest site, typically based on soil type and the height of the dominant stand at an arbitrary age. In this table, the SI represents the total height of leading trees at 50 and 100 years of age.