WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

Stillaguamish River Watershed Temperature Total Maximum Daily Load Study

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Stillaguamish River Watershed Temperature Total Maximum Daily Load Study

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Washington State Department of Ecology
Environmental Assessment Program

March 2004

Waterbody Numbers: (see Table 1)

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Abstract

The 1,770 km^2 Stillaguamish River basin contains about 1,400 kilometers of anadromous salmon habitat. The 303(d) listings for stream temperature in the basin include Deer Creek, Higgins Creek, Little Deer Creek, Pilchuck Creek, the mainstem Stillaguamish River, North Fork Stillaguamish River, and South Fork Stillaguamish River.

Substantial reductions in water temperature are predicted for hypothetical conditions with mature riparian vegetation, improvements in riparian microclimate, reduction of channel width, and increases in groundwater inflows. Potential reduced temperatures are predicted to be less than the threshold for lethality of 23°C but greater than 18°C in Class A and greater than 16°C in Class AA waters in some or most of the segments in all streams that were evaluated.

This technical assessment uses effective shade as a surrogate measure of heat flux to fulfill the requirements of Section 303(d) for a Total Maximum Daily Load (TMDL) for temperature. Effective shade is defined as the fraction of incoming solar shortwave radiation that is blocked from reaching the surface of the stream.

In addition to load allocations for effective shade, other management activities are recommended for compliance with the water quality standards for water temperature including measures to reduce channel widths.

Acknowledgements

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Introduction

The Stillaguamish River basin includes portions of Snohomish and Skagit counties in Washington State (Figure 1). The Washington State Department of Ecology's assessment of the Stillaguamish watershed identified the system as a high priority for development of a Total Maximum Daily Load (TMDL) for temperature. The purpose of the Stillaguamish River Temperature TMDL is to characterize water temperature in the basin and to establish load and wasteload allocations for heat sources to meet water quality standards for water temperature.

Section 303(d) of the federal Clean Water Act requires Washington State periodically to prepare a list of all surface waters in the state for which beneficial uses of the water – such as for drinking, recreation, aquatic habitat, and industrial use – are impaired by pollutants. This study was initiated because of 303(d) listings in Deer Creek, Higgins Creek, Little Deer Creek, Pilchuck Creek, the mainstem Stillaguamish River, North Fork Stillaguamish River, and South Fork Stillaguamish River for exceeding the water quality standards for temperature (Table 1). In addition to the 5 segments listed in 1996 and 12 segments listed in 1998, the present TMDL also includes load allocations to address 36 segments that were not listed but were documented as not meeting the water quality standard for temperature in 2001.

Table 1. Summary of watercourse segments included in this TMDL that are either on the 1996 or 1998 303(d) list or known to currently not meet the water quality standard for temperature.

Waterbody Name	**Town-ship**	**Range**	**Section**	**Watercourse IIP303d number**	**Old WBID number**	**1996 303(d) list**	**1998 303(d) list**	**Unlisted impaired IIP303d number**	**Unlisted impaired old WBID number**
Deer Creek	32N	07E	08	PA13UD0.049	WA-05-1021		X		
Deer Creek	34N	07E	36	PA13UD25.160	WA-05-1021		X		
Higgins Creek	32N	07E	20	BH79GG1.583	WA-05-1025	X	X		
Little Deer Creek	34N	07E	35	EX67XM0.000	WA-05-1023	X	X		
Pilchuck Creek	31N	05E	06	VJ74AO0.000	WA-05-1018		X		
Pilchuck Creek	32N	05E	31	VJ74AO0.155	WA-05-1018		X		
Stillaguamish River	31N	05E	06	QE93BW23.077	WA-05-1010	X	X		
Stillaguamish River	31N	05E	02	QE93BW35.996	WA-05-1010		X		
Stillaguamish River	32N	04E	31	ZO73WL2.236	WA-05-1010		X		
Stillaguamish River, N.F.	33N	09E	22	XN66YN5.302	WA-05-1020	X	X		
Stillaguamish River, S.F.	31N	05E	02	SN06ZT0.000	WA-05-1040	X	X		
Stillaguamish River, S.F.	30N	07E	07	SN06ZT26.213	WA-05-1040		X		
Canyon Creek	30N	06E	12	RR46TS0.000				X	X
Canyon Creek	30N	07E	06	RR46TS1.488				X	X
Canyon Creek	30N	07E	04	RR46TS6.254				X	X
Deer Creek	34N	07E	35	PA13UD21.599	WA-05-1021			X	
Deer Creek	33N	08E	09	PA13UD30.302	WA-05-1021			X	
Glade Bekken	31N	04E	04	FJ67XF0.000				X	X
Jim Creek	31N	06E	07	JU33JU0.000				X	X
Jim Creek	31N	06E	16	JU33JU4.411				X	X
Jim Creek	31N	06E	07	SN06ZT5.920				X	X
Little Deer Creek	34N	07E	35	EX67XM0.000				X	X
Pilchuck Creek	33N	05E	27	VJ74AO17.203	WA-05-1018			X	
Pilchuck Creek	33N	06E	17	VJ74AO25.759	WA-05-1018			X	
Pilchuck Creek	32N	05E	16	VJ74AO7.780	WA-05-1018			X	
Stillaguamish River	31N	04E	02	KP14NJ0.000	WA-05-1010			X	
Stillaguamish River	32N	04E	32	QE93BW7.111	WA-05-1010			X	
Stillaguamish River, N.F.	32N	06E	11	WD98VG0.333	WA-05-1020			X	
Stillaguamish River, N.F.	31N	05E	02	WO38NV0.000	WA-05-1020			X	
Stillaguamish River, N.F.	32N	07E	10	WO38NV26.448	WA-05-1020			X	
Stillaguamish River, N.F.	32N	08E	07	WO38NV33.246	WA-05-1020			X	
Stillaguamish River, N.F.	32N	09E	07	WO38NV47.792	WA-05-1020			X	
Stillaguamish River, N.F.	32N	09E	09	WO38NV52.367	WA-05-1030			X	X
Stillaguamish River, S.F.	31N	06E	20	SN06ZT9.949	WA-05-1040			X	
Stillaguamish River, S.F.	31N	06E	34	SN06ZT15.233	WA-05-1040			X	
Stillaguamish River, S.F.	30N	08E	16	SN06ZT45.236	WA-05-1050			X	X
Stillaguamish River, S.F.	30N	08E	15	SN06ZT46.441	WA-05-1050			X	X

The basis and supporting citations for the 1998 303(d) listings of temperature in the Stillaguamish basin are as follows:

Deer Creek:	Sullivan et al., 1990, multiple excursions beyond the criterion at the mouth during 8/88.
	Sullivan et al., 1990, multiple excursions beyond the criterion at RM 14 during 8/88.
Higgins Creek:	Sullivan et al., 1990, 22 excursions beyond the criterion during 8/88.
Little Deer Creek:	Sullivan et al., 1990, 15 excursions beyond the criterion during 8/88.
Pilchuck Creek:	Thornburgh, 1996, 4 excursions beyond the criterion out of 38 samples (11%) at station PILC between 1992 and 1997.
	Thornburgh, 1995, excursions beyond the criterion at least once each year between 1993-1995
Stillaguamish River:	3 excursions beyond the criterion out of 36 samples (3%) at Ecology ambient monitoring station 05A070 (RM 11.1) between 9/91 and 9/96.
	Thornburgh, 1996, 3 excursions beyond the criterion out of 38 samples (8%) at station MSAR between 1992 and 1997.
	Thornburgh, 1995, excursions beyond the criterion at least once each year between 1992-1995 at Marine Drive.
Stillaguamish River, North Fork:	Sullivan et al., 1990, 19 excursions beyond the criterion during 8/88 at RM 38.8.
Stillaguamish River, South Fork:	Two excursions beyond the criterion at Ecology ambient monitoring station 05A090 (RM 18.2) on 8/20/90 and 8/21/91.
	Thornburgh, 1996, 2 excursions beyond the criterion out of 10 samples (20%) at station SFGF between 1992 and 1997.

Under the federal Clean Water Act, every 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.

Section 303(d) of the Clean Water Act mandates that the state establish TMDLs for surface waters that do not meet the water quality standards. The U.S. Environmental Protection Agency (EPA) has promulgated regulations (40 CFR 130) and developed guidance (EPA, 1991) for establishing TMDLs (e.g., www.epa.gov/r10earth/tmdl.htm).

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 the 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 and allocates that load among the various sources. If the pollutant comes from a discrete source (referred to as a point source) such as an industrial facility's discharge pipe, that facility's share of the loading capacity is called a wasteload allocation. If a pollutant enters a stream from a diffuse source (referred to as a nonpoint source), then that share is called a load allocation.

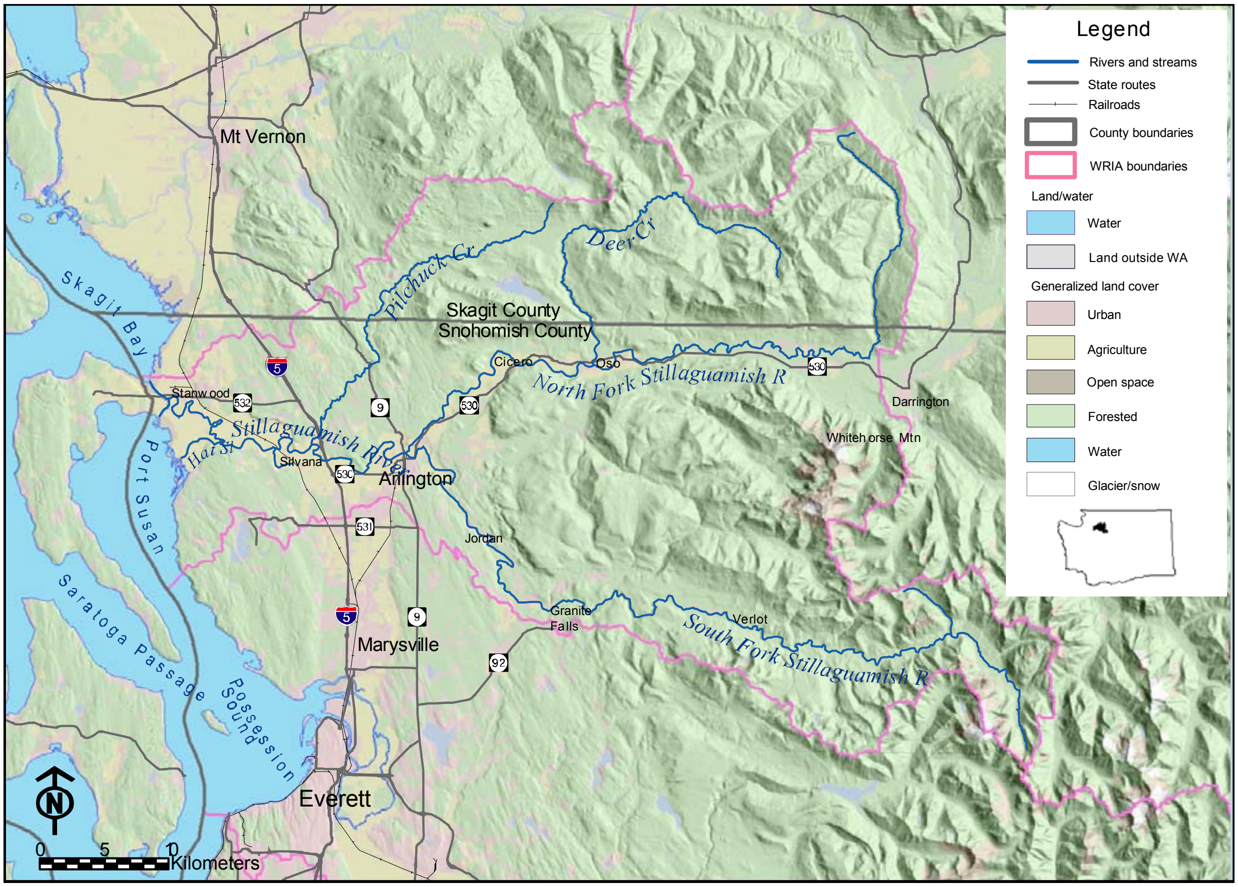

Figure 1. Generalized land cover in the study area of the Stillaguamish River temperature TMDL.

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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.

Overview of stream heating processes

The temperature of a stream reflects the amount of heat energy in the water. Changes in water temperature within a particular segment of a stream are induced by the balance of the heat exchange between the water and the surrounding environment during transport through the segment. If there is more heat energy entering the water in a stream segment than there is leaving, then the temperature will increase. If there is less heat energy entering the water in a stream segment than there is leaving, then the temperature will decrease. The general relationships between stream parameters, thermodynamic processes (heat and mass transfer), and stream temperature change is outlined in Figure 2.

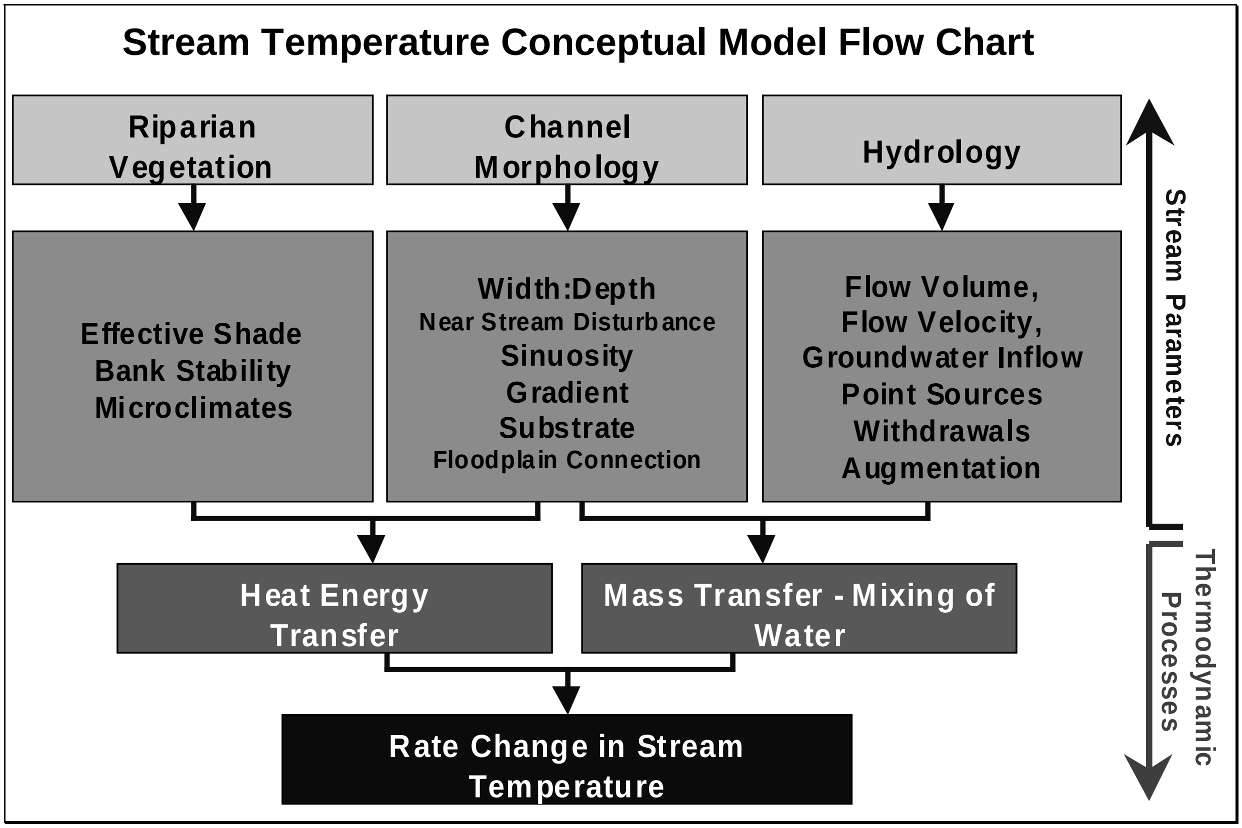

Figure 2. Conceptual model of factors that affect stream temperature.

Adams and Sullivan (1987) 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 toward the dew-point temperature (Edinger et al., 1974).
- **Solar radiation and riparian vegetation.** The daily maximum temperatures in a stream are strongly influenced by removal of riparian vegetation because of diurnal patterns of solar heat flux. Daily average temperatures are less affected by removal of riparian vegetation.
- **Groundwater.** Inflows of groundwater can have an important cooling effect on stream temperature. This effect will depend on the rate of groundwater inflow relative the flow in the stream and the difference in temperatures between the groundwater and the stream.

Regional air temperature, dewpoint temperature, and solar radiation during July-August 2001 are shown in Figure 3. Highest daily average stream temperatures would be expected during the period of maximum air temperatures in mid August.

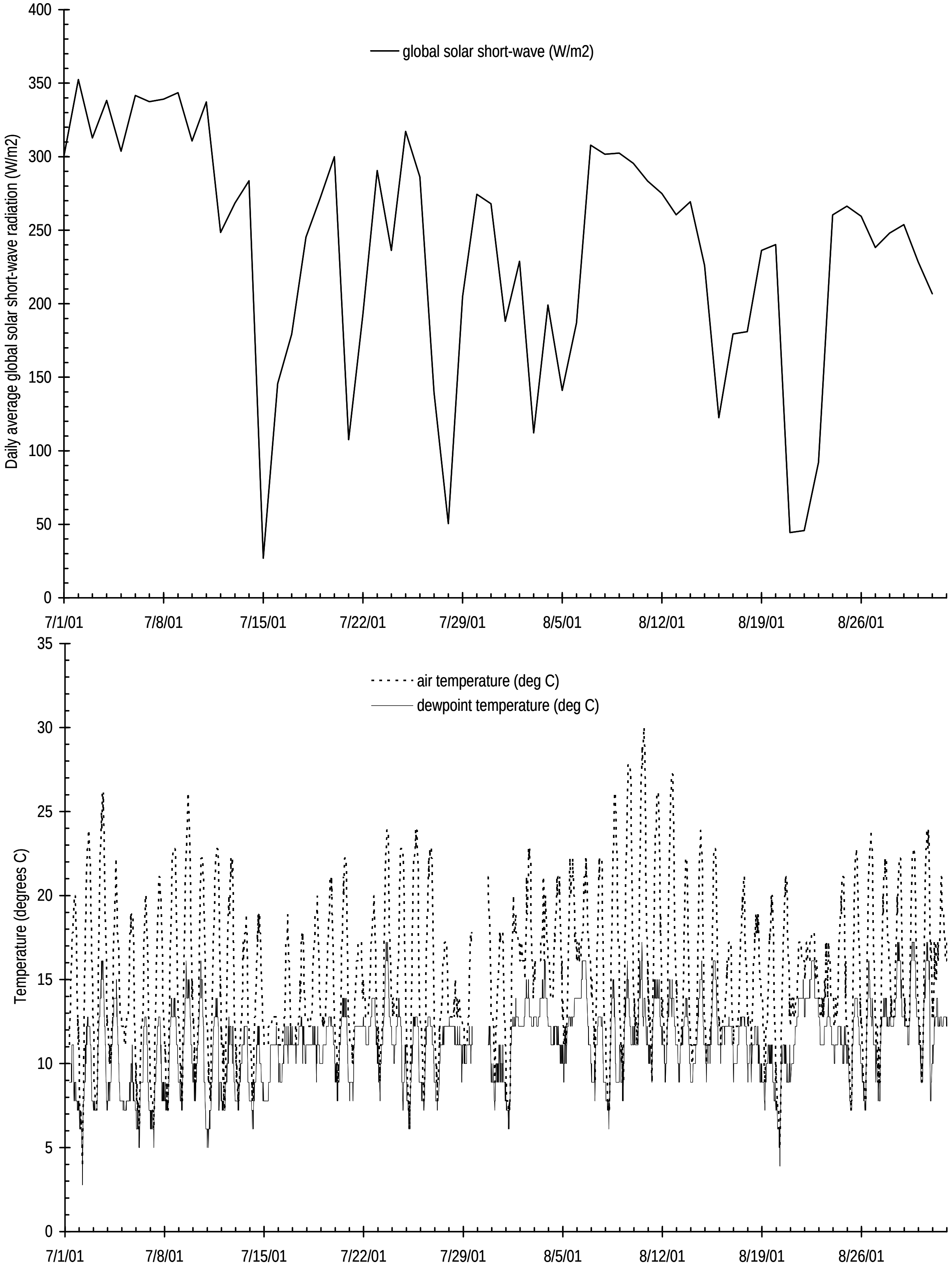

Figure 3. Regional solar radiation (Seattle), air temperatures (Arlington), and dewpoint temperatures (Arlington) during July-August 2001.

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 the analysis of heat budgets and temperature in natural waters that was used in this TMDL. Figure 4 shows the major heat energy processes or fluxes across the water surface or streambed.

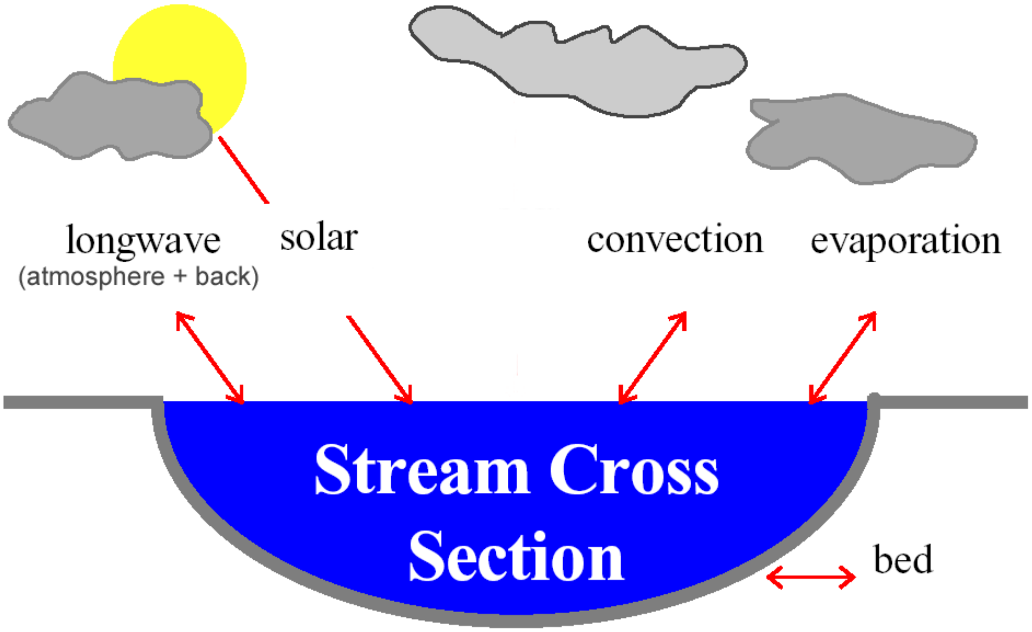

Figure 4. Surface heat exchange processes that affect water temperature.

(net heat flux = solar + longwave atmosphere + longwave back + convection + evaporation + bed). Heat flux between the water and streambed occurs through conduction and hyporheic exchange.

The heat exchange processes with the greatest magnitude 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 watts per square meter (W/m^2). The peak values during daylight hours are typically about three times higher than the daily average. Shortwave solar radiation constitutes the major thermal input to an unshaded 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).

An example of the estimated diurnal pattern of the surface heat fluxes in the segment of Deer Creek near Oso for the week of August 9-15, 2001 is shown in Figure 5. 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.

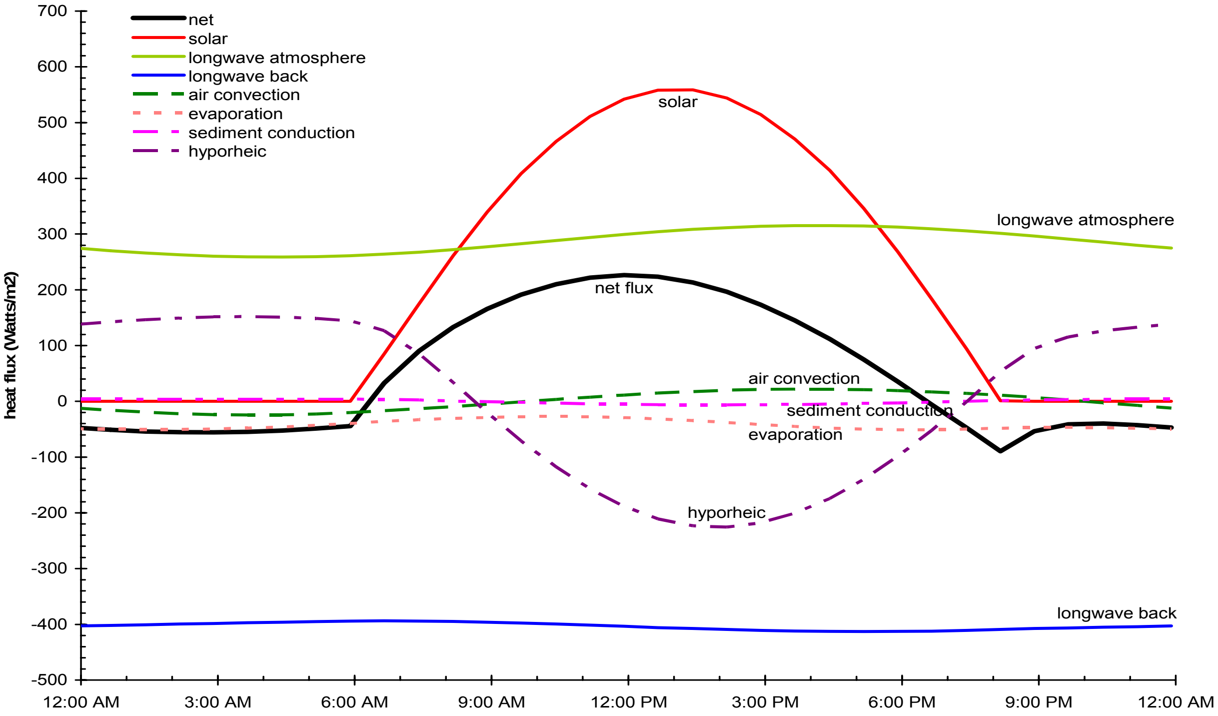

Figure 5. Estimated heat fluxes in Deer Creek near Oso (05D01) during August 9-15, 2001. (net heat flux = solar + longwave atmosphere + longwave back + air convection + evaporation + sediment conduction + hyporheic).

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 (Figure 6). 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.

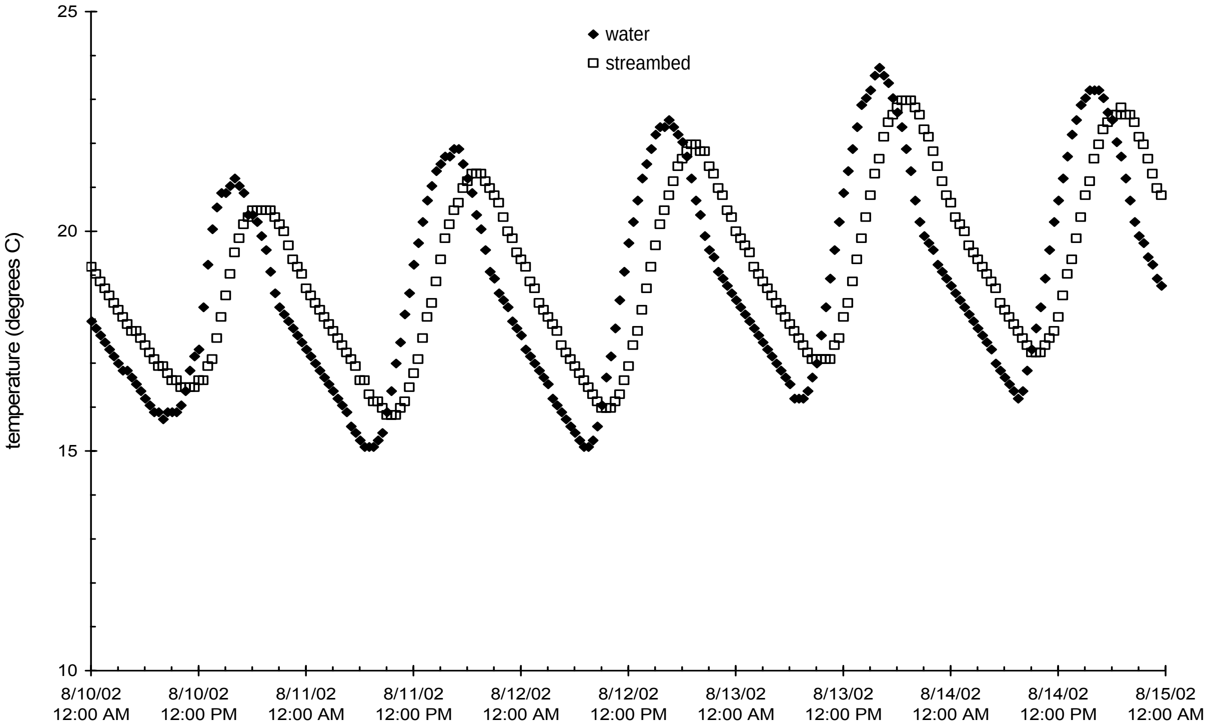

Figure 6. Water and streambed temperatures in mid-August in the North Fork Stillaguamish River at Cicero (station 05NF02).

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 (Edinger et al., 1968; Edinger et al., 1974).

The dominant contribution to the seasonal variations in the equilibrium temperature of water is from seasonal variations in the dew-point temperature (Edinger et al., 1974). The main source of hourly fluctuations in water temperature during the day is solar radiation. Solar radiation 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 segment of a stream. 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 in the mainstem river if the temperature is different in the two waterbodies.

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; GEI, 2002; 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 on 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.
- Near-stream vegetation increases bank stability. Channel morphology is often highly influenced by land cover type and condition. Near-stream vegetation affects flood plain and instream roughness, contributing coarse woody debris and 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 shade have the potential to cause significant increases in heat delivery to a stream system. Stream shade may be measured or calculated using a variety of methods (Chen, 1996; Chen et al., 1998; 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 7). 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 2). 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.

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

- 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 (ACD) provide a good balance of cost and accuracy for measuring the importance of riparian vegetation for 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 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 from measurements or estimates of the key parameters listed in Table 2 (Ecology 2003a; Chen, 1996; Chen et al., 1998; Boyd, 1996; Boyd and Park, 1998).

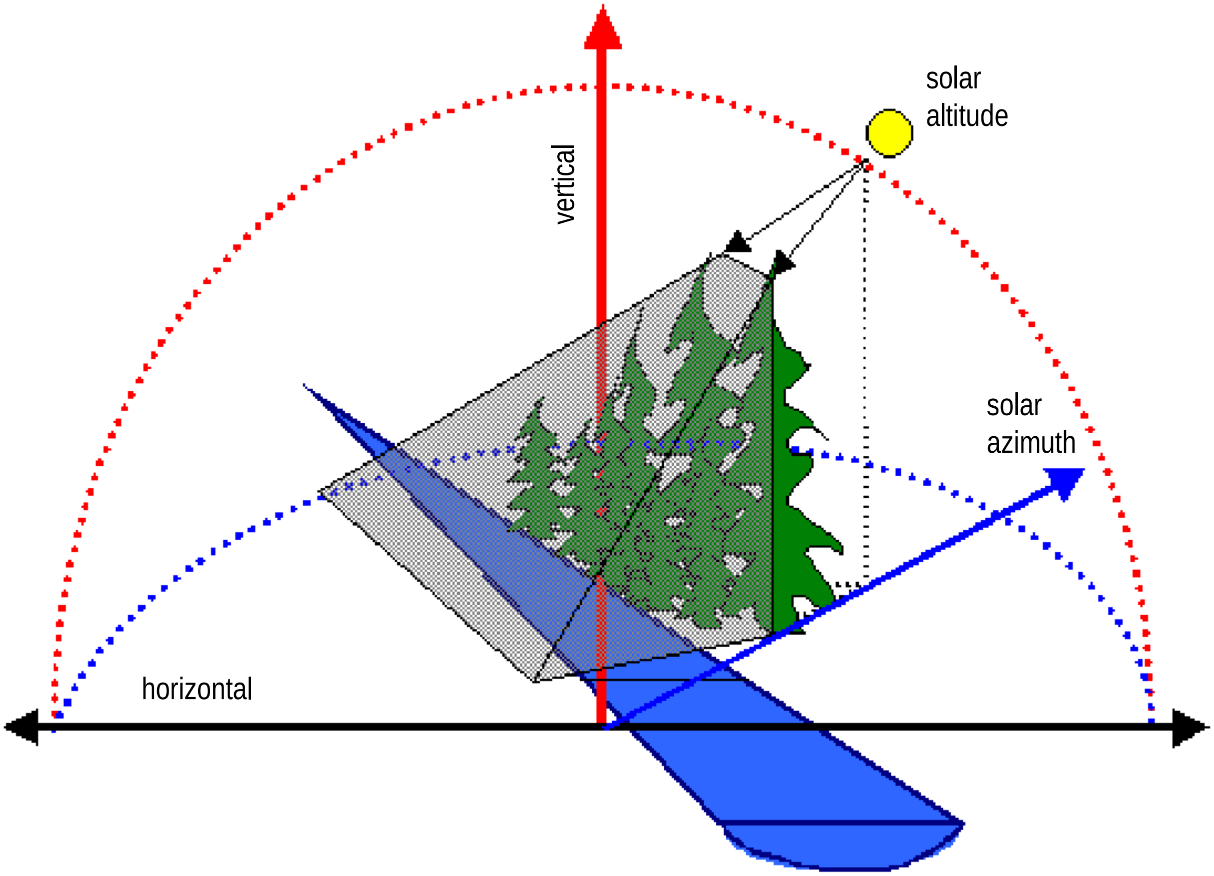

Figure 7. Parameters that affect shade and geometric relationships.

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.

Table 2. Factors that influence stream shade (bold indicates those influenced by human activities).

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 azimuth

Riparian buffers and effective shade

Trees in riparian areas provide shade to streams and minimize undesirable water temperature changes (Brazier and Brown, 1973; Steinblums et al., 1984). The shading effectiveness of riparian vegetation is correlated to riparian area width (Figure 8). The shade, as represented by angular canopy density (ACD) for a given riparian buffer width, varies 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 8. 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 basis 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.

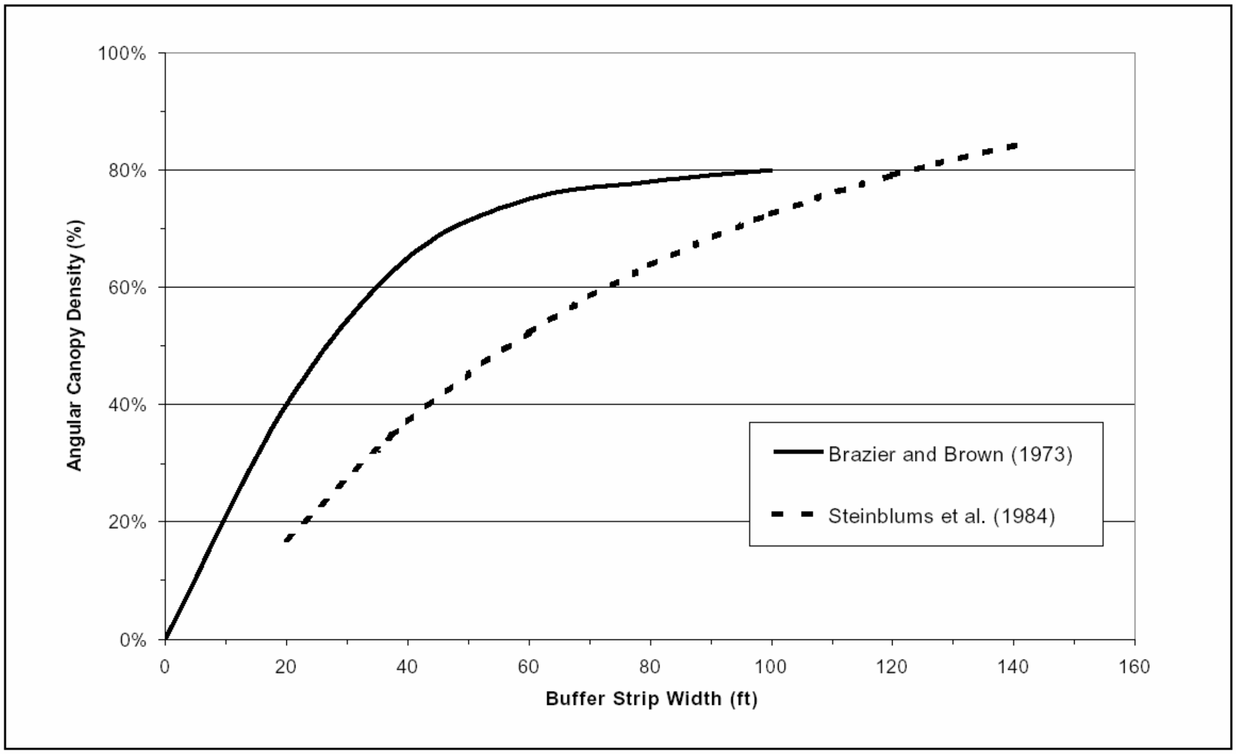

Figure 8. Relationship between angular canopy density and riparian buffer width for small streams in old-growth riparian stands (after Beschta et al., 1987 and CH2MHill, 2000).

Several studies of forest streams 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.
- 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. (1984) found that a 98-foot-wide (30-m) buffer maintains water temperatures within 2°F (1°C) of their former average temperature in small streams (channel width less than 3 m).

GEI (2002) reviewed the scientific literature related to the effectiveness of buffers for shade protection in agricultural areas in Washington and concluded that buffer widths of 10 m (33 feet) provide nearly 80% of the maximum potential shade in agricultural areas. Wenger (1999) concluded that a minimum continuous buffer width of 10-30 m should be preserved or restored along each side of all streams on a municipal or county-wide scale to provide stream temperature control and maintain aquatic habitat. GEI (2002) considered the recommendations of Wenger (1999) to be relevant for agricultural areas in Washington.

Steinblums et al. (1984) concluded that shade could be delivered to forest streams from beyond 75 feet (22 m) and potentially out to 140 feet (43 m). 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. Relative humidity increases result from the evapotranspiration that is occurring by riparian plant communities. Wind speed is reduced by the physical blockage produced by riparian vegetation. The effect of microclimate is probably more pronounced in narrower channels compared with wider channels that are more open and subject to wind and solar radiation.

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 small forest streams (channel width less than 4 m) in the foothills of the western slope of the Cascade Mountains in western Washington with predominantly Douglas-fir and western hemlock.

Bartholow (2000) provided a thorough summary of literature 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).

Spence et al. (1996) also provided a summary of literature related to the influence of riparian vegetation on microclimate as follows:

- Chen (1991) reported that soil and air temperatures, relative wind speed, humidity, soil moisture, and solar radiation all changed with increasing distance from the edges of clearcuts in the western Cascades.
- FEMAT (1993) concluded from Chen’s work that the loss of upland forests probably influences conditions within the riparian zone. FEMAT also suggested that riparian buffers for maintaining microclimates need to be wider than those for protecting other riparian functions.

Thermal role of channel morphology

Changes in channel morphology, namely channel widening, affects stream temperatures. As a stream widens, the surface area exposed to heat flux increases, resulting in increased energy exchange between a stream and its environment (Chapra, 1997). Further, wide channels are likely to have decreased levels of shade due to the increased distance created between vegetation and the wetted channel and the decreased fraction of the stream width that could potentially be covered by shadows from riparian vegetation. Conversely, narrow channels are more likely to experience higher levels of shade.

Channel widening is often related to degraded riparian conditions that allow increased stream bank 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 stream banks/flood plain 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 stream banks**. Trap suspended sediments, encourage deposition of sediment in the flood plain, and reduce incoming sources of sediment.
- **Maintaining stable stream banks**. High rooting strength and high stream bank and flood plain roughness prevent stream bank erosion.
- **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.

Pollutant sources

Anthropogenic heat sources are derived from solar radiation as increased levels of solar radiation reach the stream surface, effluent discharges to surface waters, and flow augmentation. The pollutants targeted in this TMDL are heat from human-caused increases in solar radiation loading to the stream network, and heat from warm water discharges of human origin.

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, and hydrology are affected by land use activities.

Low summertime flows decrease the thermal assimilative capacity of streams. Pollutant loading causes larger temperature increases in stream segments where flows are reduced.

Heat loading from point sources occurs when waters with differing temperatures are mixed. Wasteload allocations are developed for point sources that discharge to temperature-impaired waterbodies or discharge into waterbodies that drain to temperature-impaired waterbodies.

The magnitude and location of nonpoint pollutant and point source pollutant loading or surrogate measures is presented in the sections of this report on Loading Capacity, Load Allocations, and Wasteload Allocations.

Pollutants and surrogate measures

Heat loads to the stream are calculated in this TMDL in units of calories per square centimeter per day or watts per square meter (W/m^2). However, heat loads are of limited value in guiding management activities needed to solve identified water quality problems.

The Stillaguamish River temperature 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.”

Water temperature increases as a result of increased heat flux loads. A loading capacity for radiant heat energy (e.g., incoming solar radiation) can be used to define a reduction target that forms the basis for identifying a surrogate for heat loading from solar radiation. This technical assessment for the Stillaguamish River temperature TMDL uses effective shade as a surrogate measure of heat flux from solar radiation 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. The definition of effective shade allows direct translation of the solar radiation loading capacity.

Because factors that affect water temperature are interrelated, the surrogate measure (effective shade) relies on restoring/protecting riparian vegetation to increase stream surface shade levels, reducing stream bank erosion, stabilizing channels, reducing the near-stream disturbance zone width, and reducing the surface area of the stream exposed to radiant processes. Effective shade screens the water’s surface from direct rays of the sun. Other factors influencing heat flux and water temperature were also considered, including microclimate, channel geometry, groundwater recharge, and instream flow.

Background

The Stillaguamish River watershed covers 1770 km^2 and extends from sea level to 2,086 meters in elevation on Whitehorse Mountain in the Squire Creek drainage (Figure 1). Average annual precipitation in the watershed ranges from about 80 cm/year (about 30 inches/year) at lower elevations to about 380 cm/year (150 inches/year) at higher elevations (Figure 9, Pess et al., 1999). Headwater streams are typically steep (>0.2 m/m) and relatively small (bankfull width < 5 m; Pess et al., 1999). Channel slopes decrease dramatically (channel slopes between 0.01 and 0.06 m/m) as streams traverse terraces carved into valley-filling glacial and alluvial deposits (Figure 10), and channels become larger as tributaries coalesce.

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, and higher elevations (> 1300m) are in the alpine fir zone.

The U.S. Geological Survey (USGS) used Landsat imagery from the 1990s to map land cover (USGS, 1999). The USGS land cover information was summarized to present a broad overview of the land cover categories in the watershed. Generalized land cover in Water Resource Inventory Area (WRIA) 5 is comprised of the following (USGS, 1999):

- Developed: 26.6 Km^2 (1.5%)
- Barren: 142 Km^2 (7.9%)
- Forested: 1487 Km^2 (82.1%)
- Shrubland: 29.1 Km^2 (1.6%)
- Non-natural woody: 1.7 Km^2 (0.1%)
- Herbaceous upland: 29.1 Km^2 (1.6%)
- Herbaceous planted/cultivated: 92.4 Km^2 (5.1%)
- Wetlands: 3.9 Km^2 (0.2%)

Snohomish County used Landsat imagery from 2001 to determine riparian forest cover and showed that approximately 52% of the riparian area in the Stillaguamish basin is forested with mature vegetation (Purser et al., 2003). The riparian forest cover reported to be in each of the sub-basins of the Stillaguamish watershed were as follows (in decreasing order):

Gold Basin	79 % forest cover in the riparian zone
South Fork (upper)	79
North Fork (upper)	77
Canyon Creek (upper)	77
Stillaguamish Canyon	72
Boulder River	70
Deer Creek	67
Robe Valley	64
Jim Creek	57
Canyon Creek (lower)	56
Squire Creek	55
Pilchuck Creek (upper)	55
French-Segelsen	50
North Fork (middle)	48
Harvey Armstrong Creek	39
North Fork (lower)	38
Pilchuck Creek (lower)	36
South Fork (lower)	34
Port Susan drainages	34
Church Creek	20
Portage Creek	19
Stillaguamish River (lower)	16

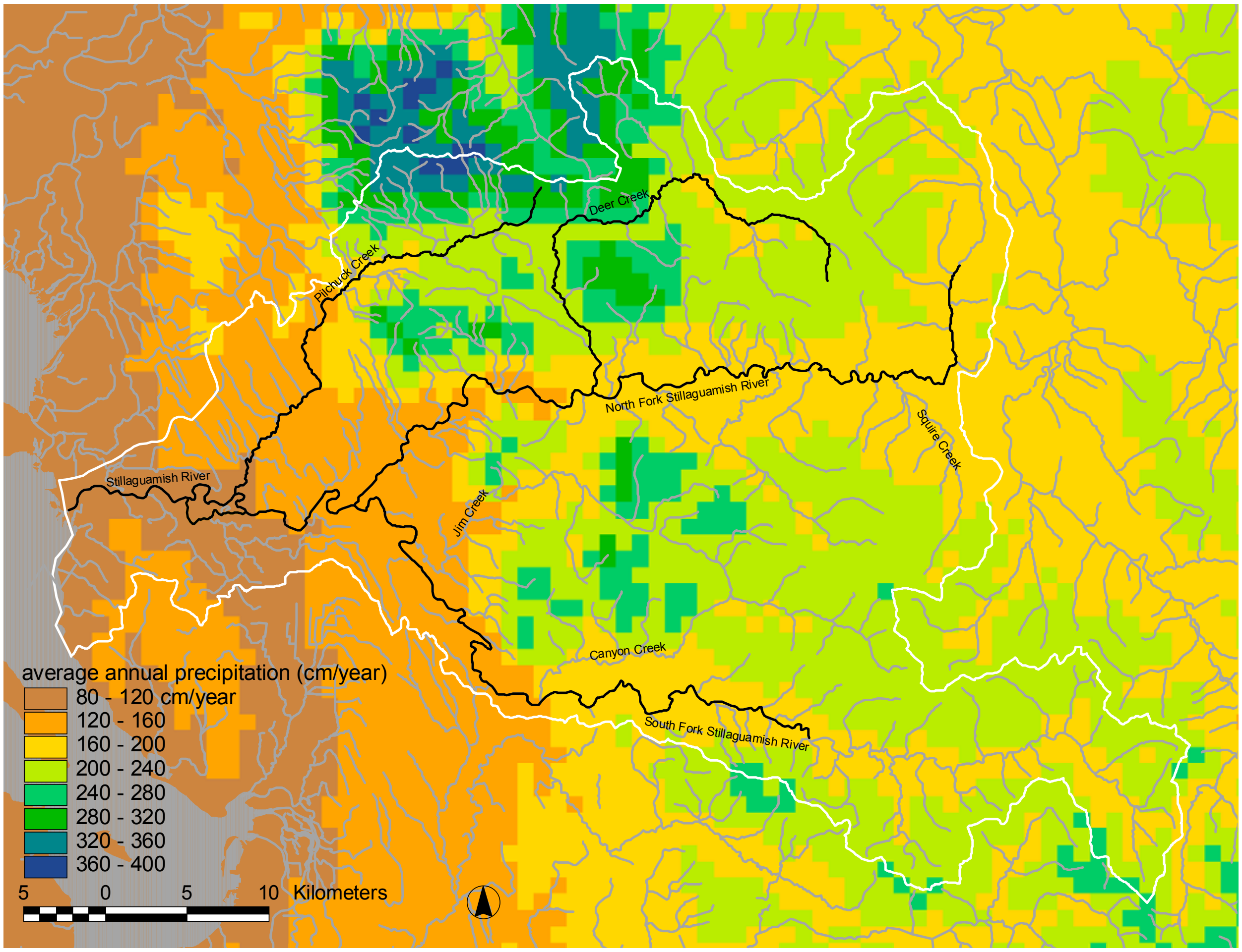

Figure 9. Annual average precipitation in the Stillaguamish River watershed (data from www.daymet.org).

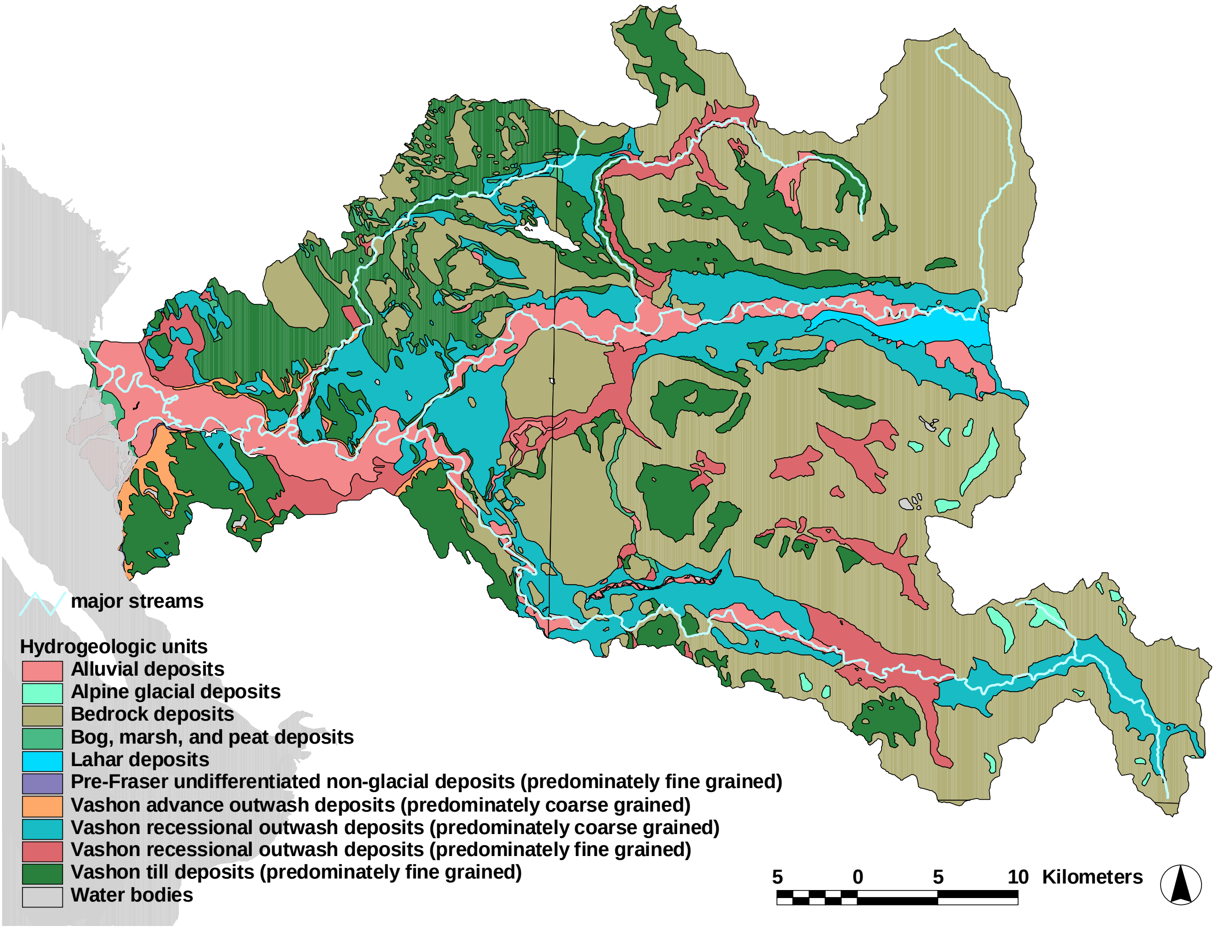

Figure 10. Surface hydrogeology of the Stillaguamish River watershed.

Land ownership

Land ownership in the watershed of the Stillaguamish River is a mixture of public and privately owned land (Figure 11). A large part of the headwater areas of the North and South Fork Stillaguamish River are federally owned and managed by the U.S. Forest Service as part of the Mount Baker Snoqualmie National Forest. The lower portions of the watershed are primarily privately owned. The Washington State Department of Natural Resources owns a significant portion of the middle region watershed.

Forest land cover

Most of the land area in the Stillaguamish River watershed is covered with forest. Federally owned forest land is managed according to the USFS Forest Plan. Other forest land in the watershed is subject to the Washington State DNR Forest and Fish Report.

USFS Forest Plan

Forest plans are required by the National Forest Management Act (NFMA) for each national forest. These plans establish land allocations, goals and objectives, and standards and guidelines used by land managers, other government agencies, private organizations, and individuals.

In April 1993, President Clinton convened a Forest Conference in Portland, Oregon to address the human and environmental needs served by the federal forests of the Pacific Northwest and northern California. President Clinton directed his cabinet to craft a balanced, comprehensive and long-term policy for the management of Forest Service and BLM lands within the range of the northern spotted owl. The Northwest Forest Plan, completed in April 1994, amended 19 Forest Service and 7 BLM plans within the range of the northern spotted owl to include a comprehensive ecosystem management strategy.

The Forest Plan requires establishment of Riparian Reserves, which are portions of watersheds where riparian-dependent resources receive primary emphasis and where special standards and guidelines apply. Riparian Reserves include those portions of a watershed directly coupled to streams and rivers. Riparian Reserves are required for maintaining hydrologic, geomorphic, and ecological processes that directly affect standing and flowing water such as lakes and ponds, wetlands, streams, stream processes, and fish habitats. Riparian Reserves include primary source areas for wood and sediment such as unstable and potentially unstable areas in headwater areas and along streams. Riparian Reserves occur at the margins of standing and flowing water, intermittent stream channels, ephemeral ponds, and wetlands. Riparian Reserves generally parallel the stream network but also include other areas necessary for maintaining hydrologic, geomorphic, and ecological processes.

Riparian Reserves are specified for categories of streams or waterbodies as follows:

- **Fish-bearing streams**. Riparian Reserves consist of the stream and the area on each side of the stream extending from the edges of the active stream channel to the top of the inner gorge, or to the outer edges of the 100-year flood plain, or to the outer edges of riparian vegetation, or to a slope distance equal to the height of two site-potential trees, or 300 feet slope distance (600 feet total, including both sides of the stream channel), whichever is greatest.
- **Permanently flowing non-fish-bearing streams**. Riparian Reserves consist of the stream and the area on each side of the stream extending from the edges of the active stream channel to the top of the inner gorge, or to the outer edges of the 100-year flood plain, or to the outer edges of riparian vegetation, or to a slope distance equal to the height of one site-potential tree, or 150 feet slope distance (300 feet total, including both sides of the stream channel), whichever is greatest.
- **Other categories**. Specific riparian buffer zones ranging from 100 to 300 feet of slope distance are also specified for the following categories of riparian areas: constructed ponds and reservoirs, and wetlands; lakes and natural ponds; seasonally flowing or intermittent streams, wetlands less than one acre, and unstable and potentially unstable areas; wetlands and meadows less than one acre in size.

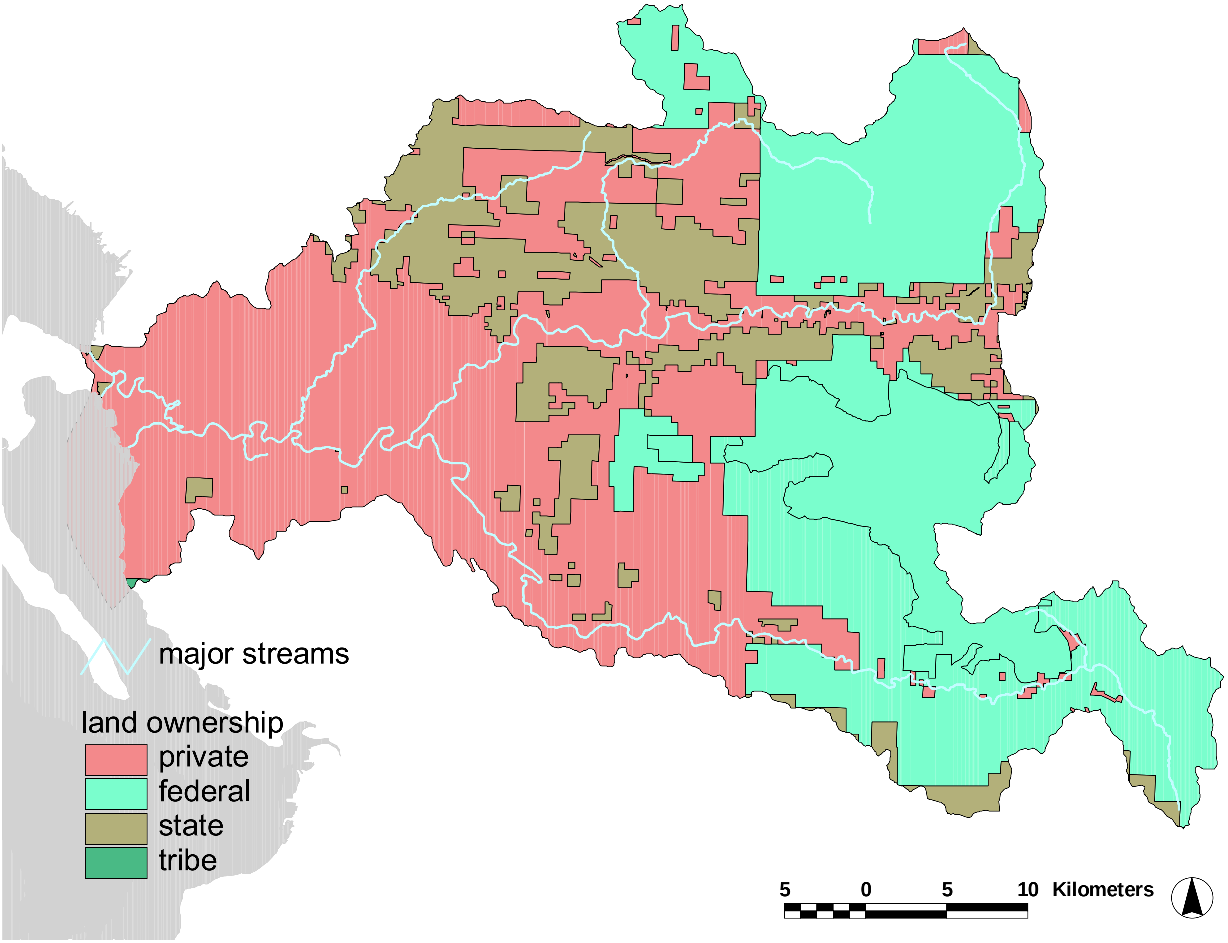

Figure 11. Land ownership in the Stillaguamish River watershed.

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TFW and the Forests and Fish Report

In 1986, as an alternative to competitive lobbying and court cases, four caucuses (the Tribes, the timber industry, the state, and the environmental community) decided to try to resolve contentious forest practices problems on non-federal land through negotiations. This resulted in the first Timber Fish Wildlife (TFW) agreement in February 1987. Subsequent events caused the TFW caucuses to again come together at the policy level to address a new round of issues. Under the federal Endangered Species Act, several salmonid populations have been listed or considered for listing. In addition, over 660 Washington streams have been included on a 303(d) list identifying stream segments with water quality problems under the federal Clean Water Act.

In November 1996, the caucuses – now expanded from the original four to six with the addition of federal and local governments – decided to work together to develop joint solutions to these problems. The Forests and Fish Report was presented to the Forest Practices Board of the state Department of Natural Resources and the Governor's Salmon Recovery Office in February 1999 (www.dnr.wa.gov/forestpractices/rules/forestsandfish.pdf). The goals of the forestry module of the Forests and Fish Report are fourfold:

- Provide compliance with the Endangered Species Act for aquatic and riparian-dependent species on non-federal forest lands
- Restore and maintain riparian habitat on non-federal forest lands to support a harvestable supply of fish
- Meet the requirements of the Clean Water Act for water quality on non-federal forest lands
- Keep the timber industry economically viable in the state of Washington

To achieve the overall objectives of the Forests and Fish initiative, significant changes in current riparian forest management policy are prescribed. The goal of riparian management and conservation as recommended in the Forests and Fish Report is to achieve restoration of high levels of riparian function and maintenance of these levels once achieved. For west-side forests such as the forests in the Stillaguamish River watershed, the Forests and Fish Report specifies riparian silvicultural treatments and conservation measures that are designed to result in "desired future conditions." Desired future conditions are the stand conditions of a mature riparian forest, agreed to be 140 years of age, and the attainment of resource objectives. These desired future conditions are a reference point on the pathway to restoration of riparian functions, not an endpoint of riparian stand development.

The riparian functions addressed by the recommendations in the Forests and Fish Report include bank stability, the recruitment of woody debris, leaf litter fall, nutrients, sediment filtering, shade, and other riparian features that are important to both riparian forest and aquatic system conditions. The diversity of riparian forests across the landscapes is addressed by tailoring riparian prescriptions to the site productivity and tree community at specific sites.

The Washington State Department of Natural Resources (DNR) is encouraged to condition forest practices to prohibit any further reduction of stream shade and not waive or modify any shade requirements for timber harvesting activities on state and private lands. Ecology is committed to assisting DNR in identifying those site-specific situations where reduction of shade has the potential for or could cause material damage to public resources.

New emergency rules for roads also apply. These include new road construction standards, as well as new standards and a schedule for upgrading existing roads. Under the new rules, roads must provide for better control of road-related sediments, provide better stream bank stability protection, and meet current Best Management Practices. DNR is also responsible for oversight of these activities.

Load allocations are included in this TMDL for forest lands in the Stillaguamish River basin in accordance with the section of Forests and Fish entitled "TMDLs produced prior to 2009 in mixed use watersheds". Also consistent with the Forests and Fish agreement, implementation of the load allocations established in this TMDL 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 process 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.

Other regulations affecting riparian land use

For private land that is neither federal forest nor covered by the Forests and Fish Report (i.e., private and state-owned forest), some regulations affect land use and management along rivers and streams:

- Shorelines of rivers with annual flows greater than 1,000 cfs and streams with average flows greater than 20 cfs are managed under the state Shoreline Management Act.
- Within municipal boundaries, land management practices next to streams may be limited if there is a local critical areas ordinance.
- Outside municipalities, county sensitive areas ordinances may affect such practices as grading or clearing next to a stream, if the activity comes under county review as part of a permit application.

Instream flow rule for the Stillaguamish River

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 state of Washington are as follows:

- Water Code, Chapter 90.03 RCW (1917), in 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 Department of Fish and Wildlife, the Department of Community, Trade, and Economic Development, the Department of 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), sets 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 "base flows" 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 utilized 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 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 regarding 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.

Ecology has initiated a rule-making process and will propose to establish minimum flows for the mainstem of the Stillaguamish River and the North and South forks of the Stillaguamish.
In addition, administrative closures will be established on Armstrong, Deer, Fortson, Segelsen, Jim, Moore, Squire, Grant, and French creeks from June to November. In addition, the rule will propose to reaffirm existing closures on Canyon, Pilchuck, Portage, and Church creeks.

Ecology installed additional flow gages on the Stillaguamish in 2003 because insufficient flow data are available for a number of mainstem and tributary locations. 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 Stillaguamish River watershed are not known, but information from the Water Rights Application Tracking database system (WRAT) was used as an indicator of the amounts of water that may be legally withdrawn. Possible undocumented or illegal withdrawals are not considered in this analysis.

The water quantity potentially withdrawn from surface waters for consumptive use is about 2.3 cms (81 cfs) from surface waters and 1.6 cms (56 cfs) from groundwater (Table 3). Irrigation represents the majority of the consumptive withdrawal from surface waters. Actual consumptive withdrawals are probably significantly less than the listed water rights.

Table 3. Summary of consumptive water rights in the Stillaguamish River watershed

Tributaries	Total of all water right flows (cfs)	Total of all water right flows (cms)
Consumptive surface withdrawals		
Alder Brook	4.06	0.115
Armstrong Creek	0.84	0.024
Bulson Creek	0.02	0.001
Canyon Creek	0.12	0.003
Edwards Creek	3.93	0.111
Fish Creek	3.68	0.104
French Creek	0.02	0.001
Hat Slough	15.52	0.439
Jim Creek	0.64	0.018
Lake Cavanaugh	0.05	0.001
Lake Creek	0.39	0.011
Lake Martha	0.01	0.0003
March Creek	1.23	0.035
Miller Creek	0.01	0.0003
North Fork Stillaguamish River	26.43	0.748
Pilchuck Creek	0.54	0.015
Port Susan	1.10	0.031
Portage Creek	1.33	0.038
South Fork Stillaguamish River	7.64	0.216
South Pass	1.00	0.028
South Slough	5.80	0.164
Stillaguamish River	0.30	0.009
Other	6.62	0.187
TOTAL	81.27	2.3
Consumptive groundwater withdrawals	56.40	1.6

Stillaguamish Implementation Review Committee

The Stillaguamish Implementation Review Committee (SIRC) is a watershed-based local stakeholder group established in the early 1990s. Its mission is to restore and maintain a healthy, functioning Stillaguamish River watershed by providing a local forum in which agencies, organizations, communities, and the public can engage in a collaborative watershed-based process of decision making and coordination. Its initial focus was to oversee implementation of the 1990 Stillaguamish Watershed Action Plan, which included 71 recommendations for controlling nonpoint pollution in the watershed. In the mid-1990s, the SIRC added salmon habitat restoration issues to its scope.

Since 1999, with leadership from the Stillaguamish Tribe and Snohomish County, the SIRC has served as the local citizens' committee for recommending prioritized lists of salmon habitat restoration projects to the Washington State Salmon Recovery Funding Board. The SIRC has final oversight authority for lead entity projects, including salmon habitat project lists and the habitat restoration work schedule.

Currently, the following are member organizations of SIRC:

- City of Arlington
- City of Stanwood
- Clean Water District Board
- Federation of Fly Fishers
- Mainstem Stillaguamish community
- North Fork Stillaguamish community
- South Fork Stillaguamish community
- Pilchuck Audubon Society
- Snohomish Conservation District
- Snohomish County Council
- Snohomish County Surface Water Management
- Stillaguamish Flood Control District
- Stillaguamish Grange
- Stillaguamish Tribe
- Stillaguamish-Snohomish Fisheries Enhancement Task Force
- Twin City Foods
- Tulalip Tribes
- U.S. Forest Service
- Washington Dairy Federation
- Washington Dept of Ecology
- Washington Dept of Fish & Wildlife
- Washington Dept of Natural Resources
- Washington Farm Forestry Association
- WSU Cooperative Extension

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Applicable water quality criteria

Under the federal Clean Water Act, every state has its own water quality standards 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.

This report and the subsequent TMDL address impairments of characteristic uses caused by high temperatures. The characteristic uses designated for protection in Stillaguamish River basin streams are as follows (Chapter 173-201A WAC):

> "Characteristic uses. Characteristic uses shall include, but not be limited to, the following:
> (i) Water supply (domestic, industrial, agricultural).
> (ii) Stock watering.
> (iii) Fish and shellfish:
> Salmonid migration, rearing, spawning, and harvesting.
> Other fish migration, rearing, spawning, and harvesting.
> Clam and mussel rearing, spawning, and harvesting.
> Crayfish rearing, spawning, and harvesting.
> (iv) Wildlife habitat.
> (v) Recreation (primary contact recreation, sport fishing, boating, and aesthetic enjoyment).
> (vi) Commerce and navigation."

The characteristic uses that are of the most concern in this TMDL are salmonid and other fish migration, rearing, spawning, and harvesting.

The state water quality standards describe criteria for temperature for the protection of characteristic uses. Streams in the Stillaguamish River basin are designated as either Class AA or Class A. The definitions of Class AA and A are as follows:

- Class AA waters typically exhibit extraordinary water quality that markedly and uniformly exceeds the requirements for all or substantially all uses.
- Class A waters typically exhibit excellent water quality that meets or exceeds the requirements for all or substantially all uses.

The following classifications are designated in the Stillaguamish watershed:

- Class A in the Stillaguamish River from the mouth to the north and south forks (river mile 17.8, river kilometer 28.6)
- Class A in the North Fork Stillaguamish River from the mouth to Squire Creek (river mile 31.2, river kilometer 50.2)
- Class AA in the North Fork Stillaguamish River from Squire Creek (river mile 31.2, river kilometer 50.2) to headwaters.
- Class A in the South Fork Stillaguamish River from the mouth to Canyon Creek (river mile 33.7, river kilometer 54.2)

- Class AA in the South Fork Stillaguamish River from Canyon Creek (river mile 33.7, river kilometer 54.2) to headwaters.
- Class AA in all streams that are located in Mount Baker Snoqualmie National Forest or that discharge to other Class AA waters or lakes.
- Class A in all other unclassified streams.

The temperature criteria for Class AA waters are as follows:

> "Temperature shall not exceed 16.0°C…due to human activities. When natural conditions exceed 16.0°C…, no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3°C."

The temperature criteria for Class A waters are as follows:

> "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 by greater than 0.3°C."

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."

Water quality and resource impairments

The 1998 303(d) listings for temperature in the Stillaguamish River watershed are shown in Table 1. The 303(d) listings for temperature are also confirmed by the data collected by Ecology, the Stillaguamish Tribe, and Snohomish County during 2001 (Table 4). Temperatures in excess of the water quality standards were observed in 2001 throughout the watershed at numerous locations (Table 4).

Table 4. Highest daily maximum temperatures in the Stillaguamish River and its tributaries during 2001, sorted in decreasing order of temperature (data in italics indicate values greater than the water quality standard).

Station ID	Station name	latitude (dec deg NAD27)	longitude (dec deg NAD27)	highest daily maximum temperatures during 2001 (deg C)	highest 7-day-averages of daily maximum temperatures during 2001 (deg C)	Water quality classification	Water quality standard (deg C)
Department of Ecology stations:							
05P03	*Pilchuck Creek blw Crane Creek*	*48.3214*	*-122.1411*	*23.8*	*22.4*	*A*	*18*
05D03	*Deer Creek abv Little Deer*	*48.3861*	*-121.8658*	*23.5*	*22.6*	*A*	*18*
05NF02	*N.F. Stillaguamish abv Cicero bridge*	*48.2678*	*-122.0083*	*22.9*	*22.2*	*A*	*18*
05SF02	*S.F. Stillaguamish at River Meadows*	*48.1621*	*-122.0612*	*22.9*	*22.1*	*A*	*18*
05M03	*Mainstem Stillaguamish at Norman Rd*	*48.2056*	*-122.2608*	*22.8*	*21.8*	*A*	*18*
05P01	*Pilchuck Creek nr mouth*	*48.2139*	*-122.2172*	*22.5*	*21.7*	*A*	*18*
05M02	*Mainstem Stillaguamish at Larson Rd*	*48.2000*	*-122.2628*	*22.4*	*21.4*	*A*	*18*
05P04f	*Pilchuck Creek blw Bear Creek*	*48.3431*	*-122.0553*	*22.3*	*21.5*	*A*	*18*
05P02	*Pilchuck Creek at SR9*	*48.2681*	*-122.1642*	*22.3*	*21.5*	*A*	*18*
05D01	*Deer Creek at Bunker house*	*48.2772*	*-121.9297*	*22.1*	*21.5*	*A*	*18*
05LD01	*Little Deer at mouth*	*48.3875*	*-121.8686*	*21.7*	*20.9*	*A*	*18*
05SF05	*S.F. Stillaguamish at Verlot*	*48.0892*	*-121.7764*	*21.7*	*21.3*	*AA*	*16*
05P04	*Pilchuck Creek blw Bear Creek*	*48.3444*	*-122.0717*	*21.7*	*20.8*	*A*	*18*
05C01	*Canyon Creek nr mouth*	*48.1147*	*-121.9589*	*21.1*	*20.6*	*A*	*18*
05NF07	*N.F. Stillaguamish abv Crevice Creek*	*48.3359*	*-121.6360*	*20.2*	*19.6*	*AA*	*16*
05J01	*Jim Creek at mouth*	*48.1844*	*-122.0758*	*20.1*	*19.5*	*A*	*18*
05SF05f	*S.F. Stillaguamish at Verlot bridge*	*48.0862*	*-121.7603*	*20.0*	*19.5*	*A*	*18*
05B110	*EMTS station nr Darrington*	*48.2798*	*-121.7024*	*18.5*	*18.2*	*A*	*18*
05SF03	*S.F. Stillaguamish at Littlefield*	*48.1269*	*-122.0247*	*18.4*	*17.5*	*A*	*18*
05NF06	*N.F. Stillaguamish nr FR28*	*48.2758*	*-121.6430*	*18.4*	*18.0*	*AA*	*16*
05NF03	N.F. Stillaguamish at 221st	48.2672	-121.9272	17.9	17.3	A	18
05M01	Mainstem Stillaguamish at Marine Drv	48.2106	-122.3353	17.5	14.9	A	18
05NF05	N.F. Stillaguamish at 311th St	48.2793	-121.7337	17.4	16.9	A	18
05SQ01	Squire Creek nr mouth	48.2770	-121.6840	16.8	16.6	A	18
05D04	*Deer Creek at FR 1820*	*48.3681*	*-121.7786*	*16.4*	*16.1*	*AA*	*16*
05F01	French Creek at SR530	48.2777	-121.7535	15.9	15.7	A	18
05B01	Boulder River at SR530	48.2784	-121.7799	15.3	14.1	A	18
05A01	Armstrong Creek	48.2186	-122.1342	14.0	13.8	A	18
Stillaguamish Tribe stations:							
145	*Old Stillaguamish Channel @ Florence*	*48.2212*	*-122.3324*	*26.6*	*24.8*	*A*	*18*
90	*Old Stillaguamish Channel @ Peterson Bridge*	*48.2132*	*-122.3270*	*23.6*	*23.2*	*A*	*18*
115	*S.F. Stillaguamish (Twin Rivers Park) (Thermograph site)*	*48.2011*	*-122.1182*	*23.3*	*22.5*	*A*	*18*
120	*Hat Slough @ Marine Drive*	*48.2111*	*-122.3368*	*23.3*	*22.5*	*A*	*18*
135	*Old Stillaguamish Channel above Hatt Slough*	*48.2132*	*-122.3267*	*23.2*	*22.4*	*A*	*18*
119	*N.F. Stillaguamish (Twin Rivers Park) (Thermograph site)*	*48.2089*	*-122.1235*	*22.5*	*21.7*	*A*	*18*
166	*S.F. Stillaguamish at Bridge above Benson Creek*	*48.0892*	*-121.7764*	*21.4*	*20.9*	*AA*	*16*
14	*NF Stillaguamish @ Whitman Bridge*	*48.2724*	*-121.8867*	*20.5*	*20.0*	*A*	*18*
77	*Canyon Creek near mouth*	*48.0985*	*-121.9711*	*20.4*	*20.0*	*A*	*18*
59	*Jim Creek @ Jordan Rd*	*48.1842*	*-122.0767*	*20.1*	*19.5*	*A*	*18*
43	*Canyon Creek @ Masonic Park*	*48.1216*	*-121.9043*	*20.1*	*19.7*	*A*	*18*
160	*Jim Creek @ Whites Rd*	*48.1788*	*-122.0514*	*19.6*	*19.0*	*A*	*18*
--	*NF Stillaguamish at C-Post bridge*	*48.2830*	*-121.8291*	*18.9*	*18.6*	*A*	*18*
18	Portage Creek @ Hwy 9	48.1830	-122.1290	16.6	16.0	A	18
64	Portage Creek @ 212th. St.	48.1882	-122.2332	15.3	15.1	A	18
20	Portage Creek @ 15th.	48.1824	-122.2128	14.9	14.6	A	18
Snohomish County stations:							
--	*Glade Bekken pond +TS*	*48.2053*	*-122.2908*	*21.8*	*20.8*	*A*	*18*
--	*Glade Bekken @ Silvana Terrace Rd (downstream)*	*48.2067*	*-122.2934*	*18.4*	*17.8*	*A*	*18*
--	Glade Bekken @ Silvana Terrace Rd (long-term)	48.2046	-122.2888	16.8	16.3	A	18

While a simple TMDL that addresses only the listed segments could be done, due to the large amount of data available it is more efficient to develop the present TMDL to address water temperature in perennial streams in the entire watershed.

Seasonal variation and critical conditions

Clean Water Act (CWA) Section 303(d)(1) requires that TMDLs “be established at the level 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 Stillaguamish River watershed reflect seasonal variation. Cooler temperatures occur in the winter, while warmer temperatures are observed in the summer. Figure 12 summarizes the highest daily maximum and the highest seven-day average maximum water temperatures of each year for 2001. The highest temperatures typically occur from mid-July through mid-August. This timeframe 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 1 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 assumed to represent conditions that would occur during a typical climatic year, and the 7Q10 streamflow was assumed to represent a reasonable worst-case climatic year. The 7Q10 streamflow is defined in WAC 173-201A as the critical condition for steady-state discharges in riverine systems.

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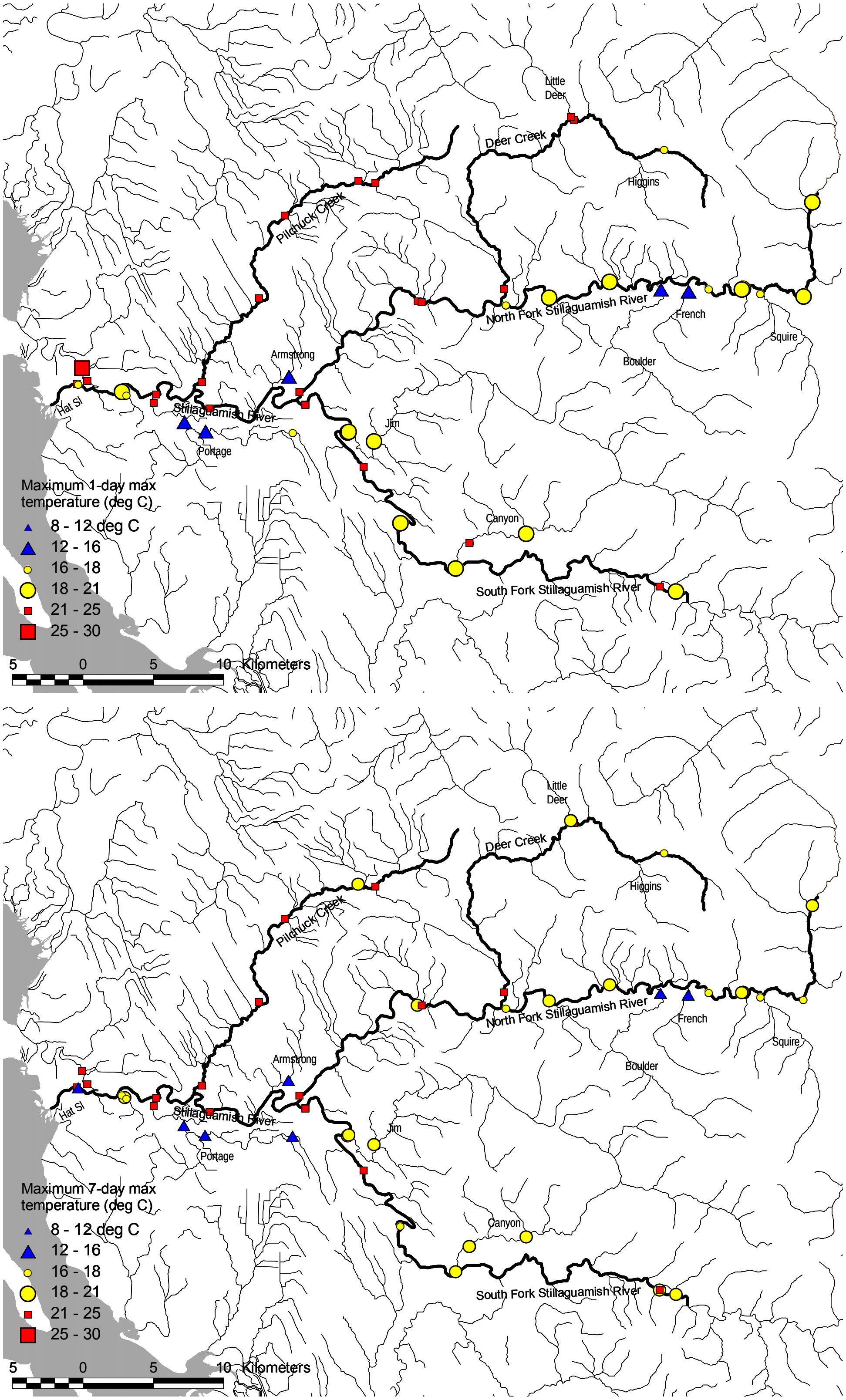

Figure 12. The highest daily maximum (upper map) and highest 7-day averages of daily maximum (lower map) water temperatures in the Stillaguamish River and its tributaries during 2001.

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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, and hydrology are affected by land use activities. Specifically, the elevated summertime stream temperatures attributed to anthropogenic sources in the Stillaguamish River basin 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) reported that the most severely degraded riparian forests are those with extensive agricultural activity, followed by rural residential development. Forest lands generally have the least degraded riparian forests, and riparian forests on federal lands are generally in much better condition than those on state and private land.
- Channel widening increases the stream surface area exposed to energy processes such as solar radiation. Most of the mainstem, North Fork, and lower South Fork channels have lacked large conifer recruitment for a century (Pess et al., 1999). Significant channel widening occurred in the early 1900s. Since the 1930s, the mainstem channels have been narrowed due to revetment, agricultural development, and possibly a recovery from widespread riparian logging early in the century. Landslides triggered by forest practices, in combination with riparian logging, have caused numerous tributaries to widen and aggrade at some point in the last half century. Widening of the channels throughout the Stillaguamish River watershed decreases the effectiveness of potential shading from near-stream vegetation.
- Reduced summertime base flows may result from instream withdrawals and hydraulically connected groundwater withdrawals. Reducing the amount of water in a stream can increase stream temperature (Brown, 1972). Base flows could also have been reduced due to an increase in impervious surface area from changes in land cover in the watershed.

Current conditions

Available water temperature data

A network of continuous temperature dataloggers was installed in the Stillaguamish River watershed by the Department of Ecology as described by Pelletier and Bilhimer, 2001 (Figure 13). Water temperatures were continuously monitored at 30-minute intervals. Data from 2001 show that water temperatures in excess of the Class A or AA standards are common throughout the watershed (Table 4). The hottest 7-day period of 2001 occurred from August 9-15, 2001 (Figure 14)

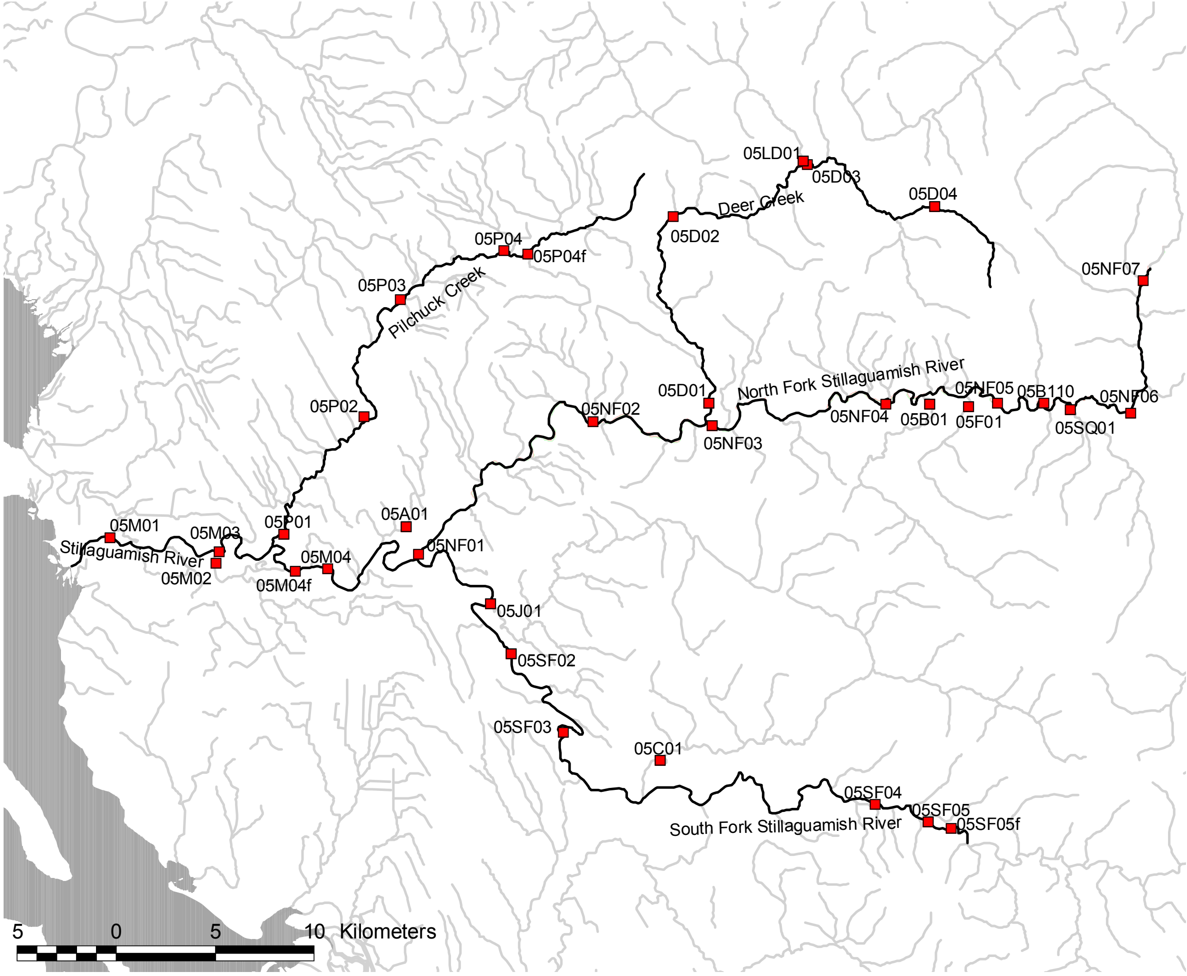

Figure 13. Locations and station ID of Ecology's temperature monitoring stations in the Stillaguamish River watershed.

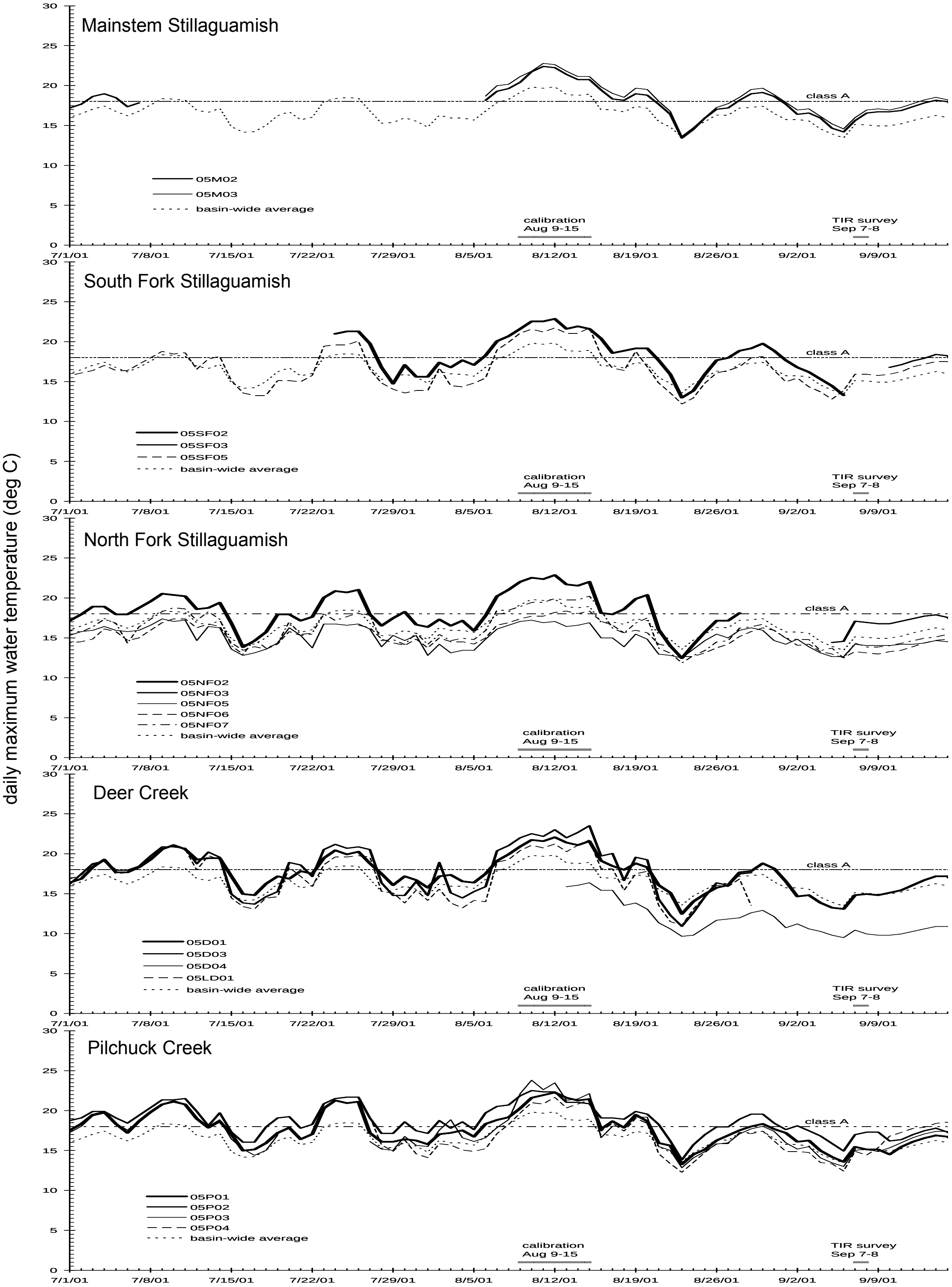

Figure 14. Daily maximum water temperatures in the Stillaguamish River basin from July to mid-September 2001.

Water temperatures in excess of 22ºC have been observed in the mainstem Stillaguamish River, the South Fork Stillaguamish River, the North Fork Stillaguamish River, Deer Creek, and Pilchuck Creek. Cooler maximum temperatures of less than 16ºC have also been observed at several sites including French Creek, Boulder River, Armstrong Creek, and Portage Creek.

Stream flow data

The Department of Ecology installed a network of flow gaging stations during 2001 as described in Pelletier and Bilhimer, 2001 (Figure 15 and Appendix B). The USGS currently gages flows in the North Fork Stillaguamish River near Arlington (station 12167000), and has historically gaged flows at several other stations in the watershed (Figure 15). USGS stations with greater than 10 years of flow data were used to estimate the lowest 7-day average flows during July-August with recurrence intervals of 2 years (7Q2) and 10 years (7Q10, Table 5). The period of record for four of the stations in Table 5 is from 1917 to 1969; current conditions may be different than the historical conditions for those stations.

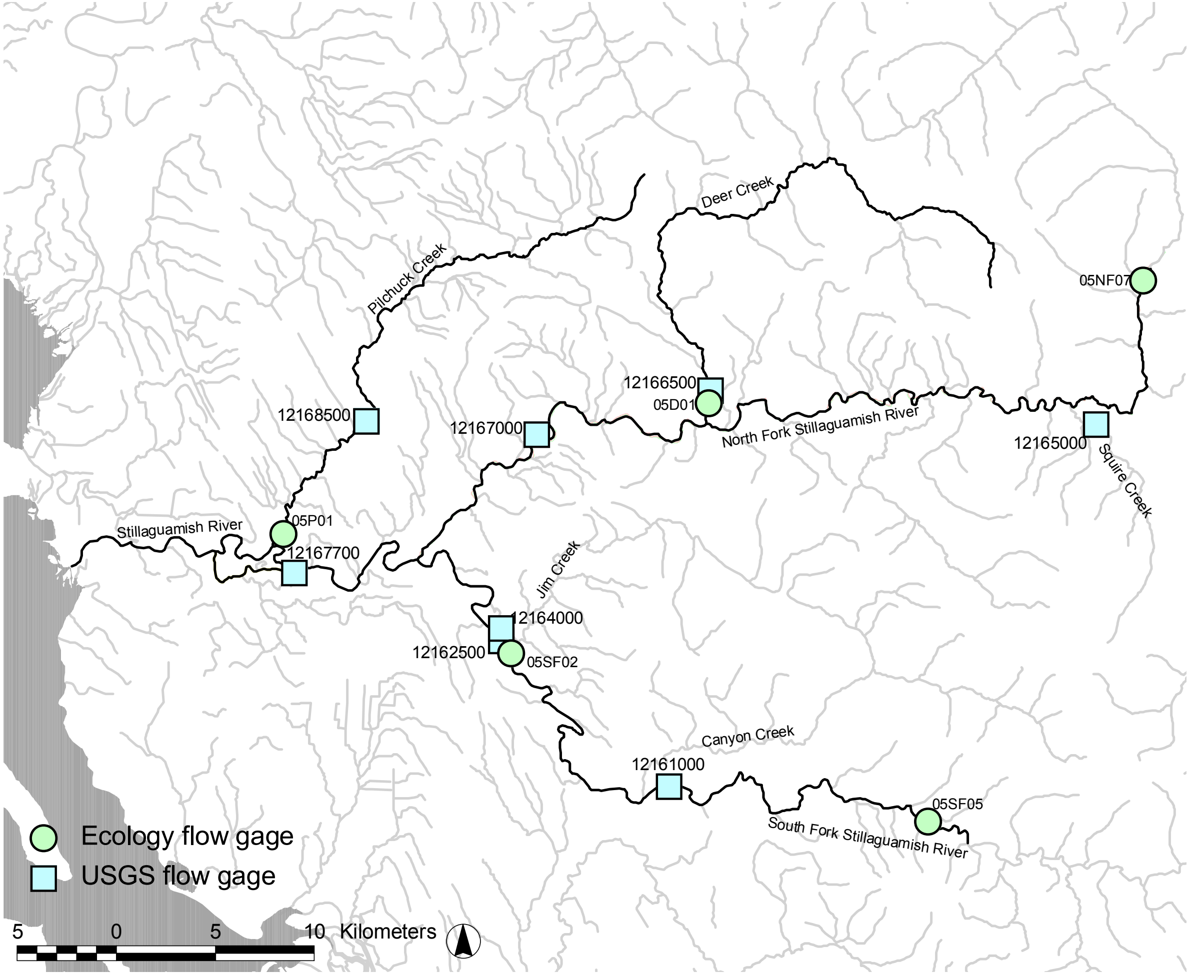

Figure 15. Flow gaging stations in the Stillaguamish River watershed.

Table 5. Summary of low-flow statistics for July-August at USGS gaging stations in the Stillaguamish River watershed.

				Jul-Aug low flows (cms) (1)	
Station	Station name	Period	Drainage area (Km^2)	7Q2	7Q10
12161000	South Fork Stillaguamish River near Granite Falls	1928-1980	308	4.570	2.339
12162500	South Fork Stillaguamish River above Jim Creek	1936-1957	515	6.669	3.126
12164000	Jim Creek near Arlington	1937-1957	120	0.419	0.210
12165000	Squire Creek near Darrington	1950-1969	52	1.195	0.597
12166500	Deer Creek at Oso	1917-1930, 1950	171	0.912	0.660
12167000	North Fork Stillaguamish River near Arlington	1928-2001	679	8.739	5.627
05P01 (2)	Pilchuck Creek near mouth	--	189	0.550	0.288

(1) low-flow statistics were calculated using the Weibull frequency factor or distribution-free methods (Aroner, 2002).
(2) Pilchuck near mouth was estimated from regression of Ecology's instantaneouls measurements at station 05P01 with USGS 12167000.

Hydraulic geometry

The channel width, depth, and velocity have an important influence on the sensitivity of water temperature to the flux of heat. Stream widths at low flow were estimated from digital orthophotos and field measurements as described in Pelletier and Bilhimer (2001). The general relationships between wetted width, depth, and flow at all stations in the watershed are shown in Figure 16 and Table 6.

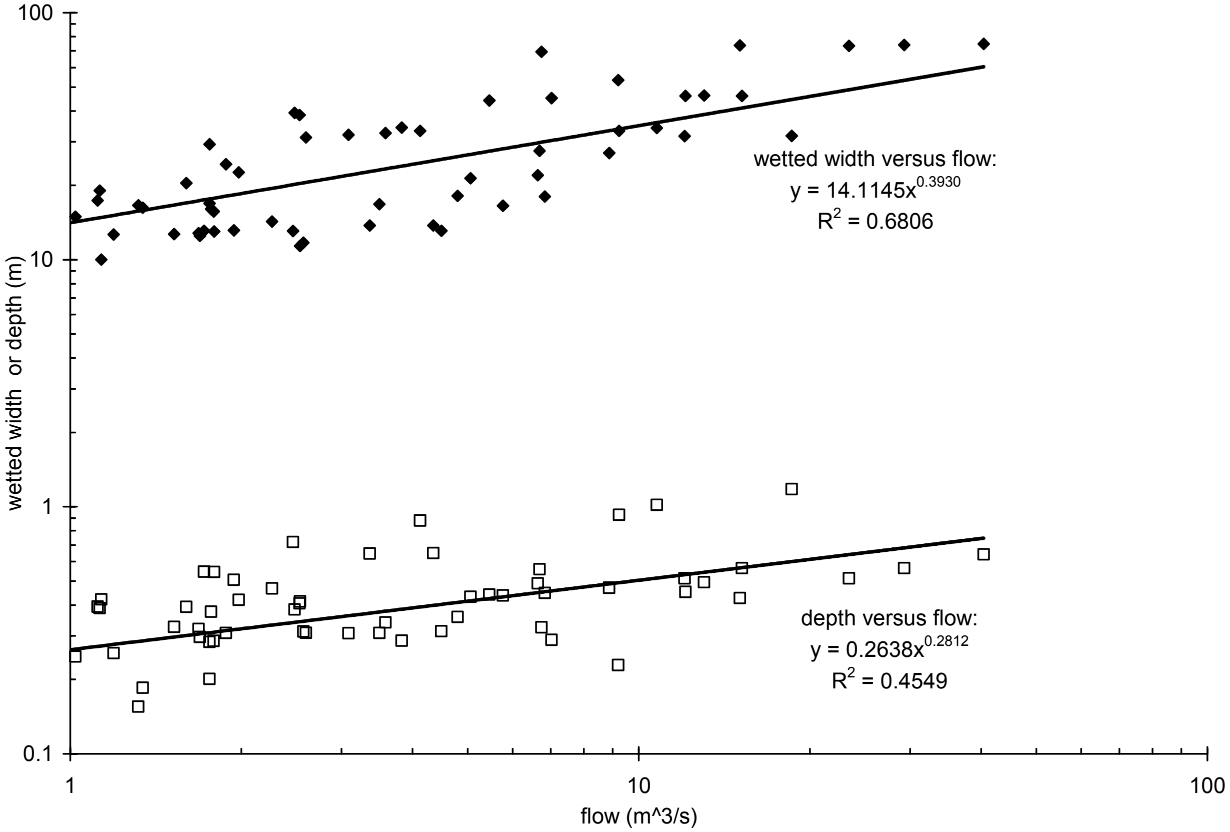

Figure 16. Wetted width and depth versus flow during the low-flow season at all stations in the Stillaguamish River basin, June - October 2001.

The wetted width and near-stream disturbance zones (NSDZ or bankfull width) were digitized from digital orthophotos quads (DOQ) that were flown during low-flow conditions in 1989 or 1990 (Figure 17). The wetted widths at various river flows in the mainstem Stillaguamish River, South Fork Stillaguamish River, and North Fork Stillaguamish River from Squire Creek to the mouth were estimated by scaling the wetted widths that were digitized from the DOQ by assuming that the wetted width (B_0) is proportional to flow raised to an exponent b (Leopold, 1994):

$$B_0 = aQ^b \qquad \text{equation 1}$$

where a is the constant of proportionality and b was estimated as the exponent that was measured from the instantaneous flow measurements that were measured during this study (Figure 15 and Table 6).

Table 6. Summary of hydraulic geometry relationships with flow (Q) in the Stillaguamish River watershed, June-October 2001(1).

		All stations	South Fork Stillaguamish River	North Fork Stillaguamish River	Deer Creek	Pilchuck Creek
width	coefficient "a"	14.11	20.37	17.14	12.69	15.52
= a Q ^b	exponent "b"	0.3930	0.3691	0.3375	0.5247	0.1164
depth	coefficient "c"	0.2638	0.2039	0.3072	0.3064	0.2356
= c Q ^d	exponent "d"	0.2812	0.3101	0.2933	0.3059	0.1489
Manning's n	coefficient "e"	--	0.09839	0.1569	0.1571	0.08545
= e Q ^f	exponent "f"	--	-0.2696	-0.4751	-0.1929	-0.6798

(1) flow (Q) is in cubic meters per second, width in meters, depth in meters.

Figure 17. Example of the digital orthophoto quad (DOQ) for the mainstem of the Stillaguamish River at the I-5 bridge and digitized wetted edges and bankfull edges.

Wetted widths in Deer Creek, Pilchuck Creek, and the North Fork Stillaguamish from the headwater to Squire Creek were not easily identified from DOQ. In these reaches the wetted widths were estimated by the measured flow coefficients and exponents for each basin as shown in Table 6. In areas where NSDZ edges were not easily identified from DOQ, the NSDZ was estimated from the regression of measured bankfull width versus drainage area (Figure 18).

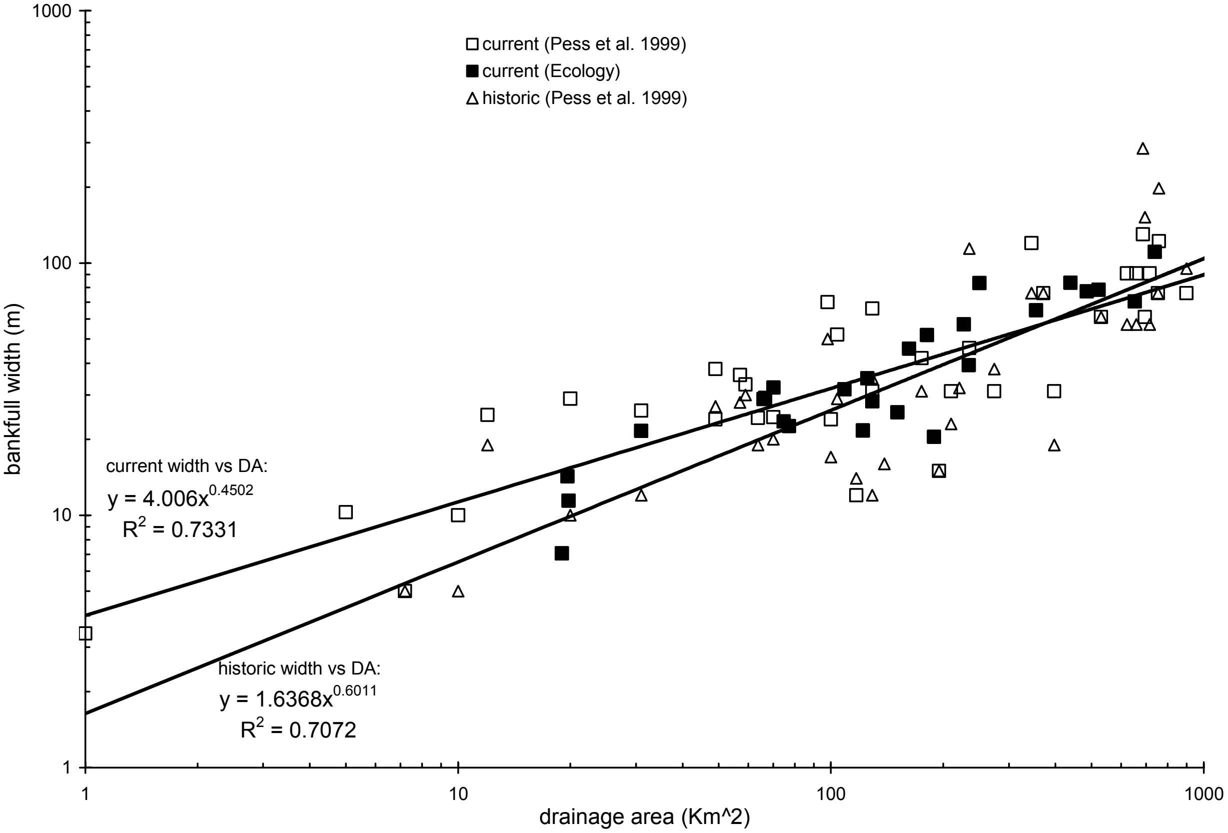

Figure 18. The relationship between current and historic bankfull width and drainage area in the Stillaguamish River watershed.

The active channels of many streams in the watershed have widened as a result of logging of the riparian forest after the late 1800s, which reduced the root strength and allowed bank erosion to widen the channels, and increased sediment supplies, which can cause or exacerbate channel widening (Pess et al., 1999). An historical assessment of the active channel widths in the basin showed that amount of channel widening decreases as drainage area of the watershed increases. The mainstem Stillaguamish River channel from Arlington to Hat Slough and including Hat Slough has shortened, narrowed, and undergone local down-cutting during the period from about 1930 due, in part, to bank revetments (Pess et al., 1999).

The ratio of historic/current bankfull width can be approximated by the following equation based on the regression analysis in Figure 18, which suggests increases in channel widths relative to historic conditions for drainage areas less than about 380 Km^2 (drainage areas greater than 380 Km^2 are present in the North Fork from above the confluence with Deer Creek, South Fork from the confluence with Canyon Creek, and the mainstem Stillaguamish River):

[Ratio of historic/current bankfull width] = 0.4086 [drainage area in Km^2] $^{0.1509}$ equation 2

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_e). Manning’s equation for a rectangular channel (side slope s=0) is as follows (Chapra, 1997):

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

equation 3

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. Values of Manning’s n of nearly 1 were measured at flow gaging stations in the basin (Figure 19). The relationship between Manning’s n and flow was estimated by regression of measured values versus flow (Table 6).

Reach-averaged values of Manning’s n may be higher than those measured at the gaging stations 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. 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.

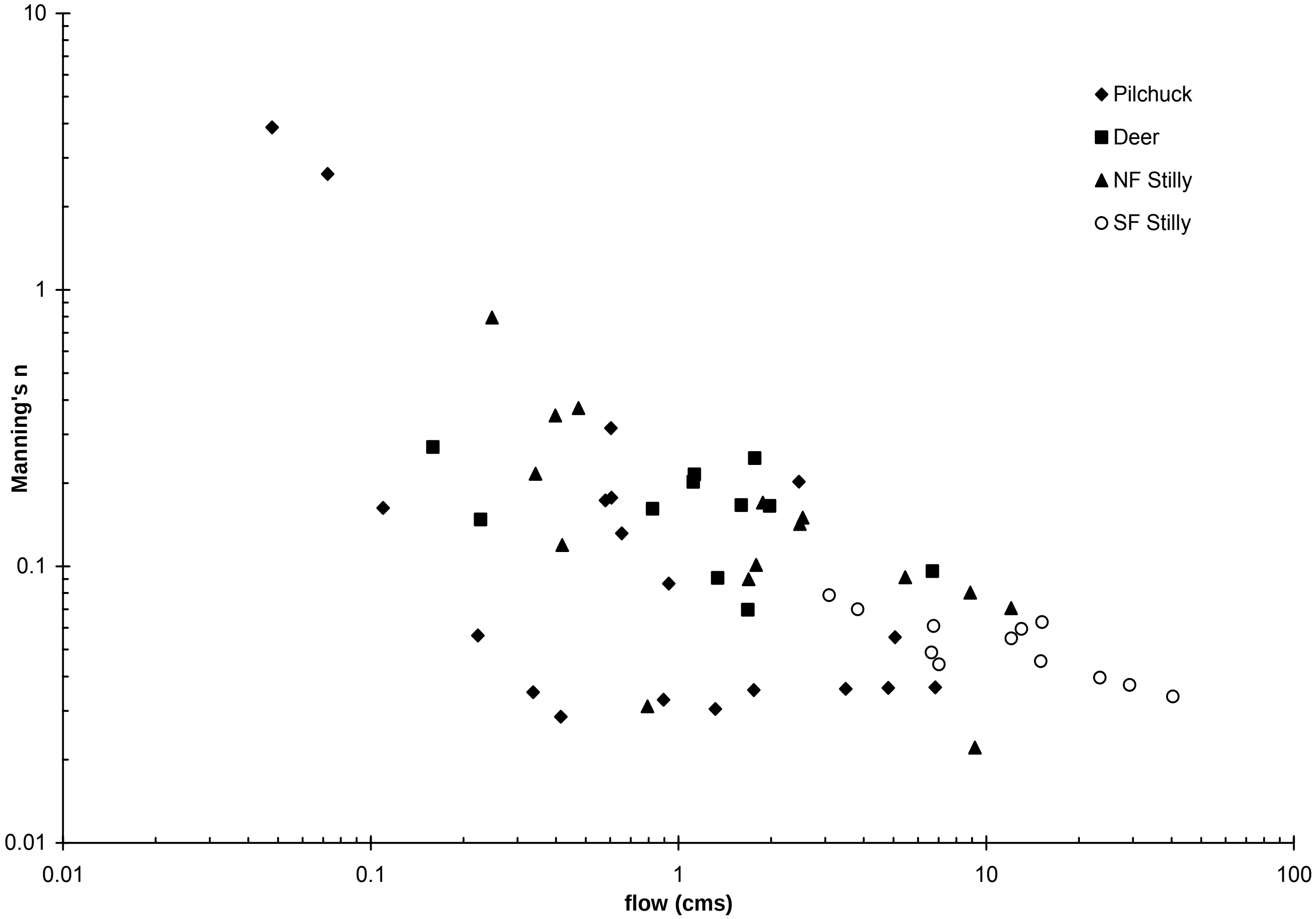

Figure 19. Manning's n versus flow during the low-flow season in the Stillaguamish watershed, June - October 2001.

Climate data

A network of dataloggers was installed to continuously monitor air temperature and relative humidity throughout the study area in accordance with Pelletier and Bilhimer, 2001 (Figure 20). NOAA National Climate Data Center (NCDC) stations at Mount Vernon 3NW (1956-present) and Arlington Airport (1996-present) also provide a record of long-term trends in climate data. The station at Mount Vernon 3NW has a significantly longer record than Arlington Airport. Therefore the Mount Vernon 3NW station was used to estimate the typical year and 90th percentile conditions for climate. Air temperatures at Arlington Airport were found to be highly correlated with conditions at Mount Vernon 3NW (Figure 21).

The highest daily maximum and highest 7-day average of daily maximum air temperatures for each year of record at Mount Vernon 3NW were ranked to determine the median and 90th percentile conditions (Table 7). The median and 90th percentile air temperatures at Arlington Airport were estimated by applying the regression equations in Figure 21 to the observed temperatures at Mount Vernon 3NW.

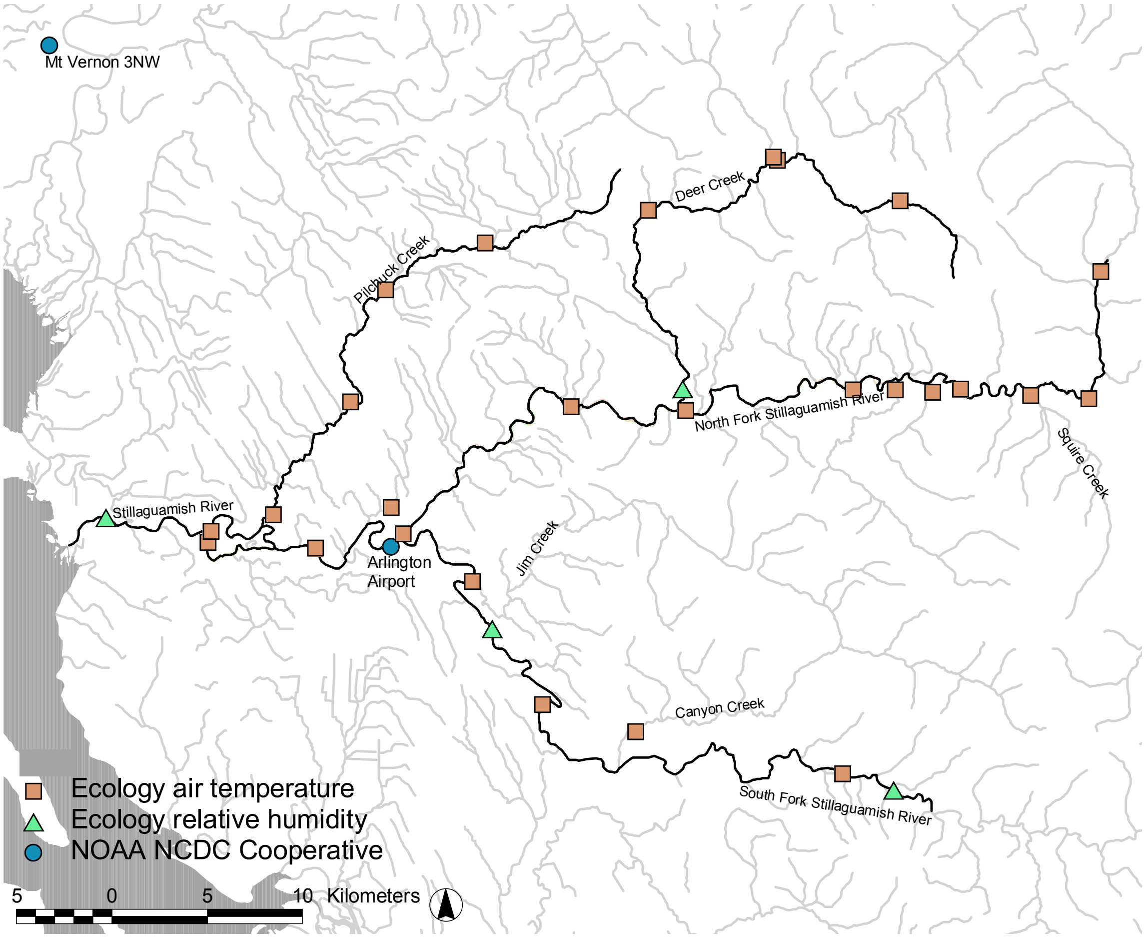

Figure 20. Ecology and NOAA NCDC stations for climate data.

Table 7. Estimated daily maximum and minimum air temperatures at Mount Vernon 3NW and Arlington Airport on days and weeks with the highest daily maximum temperatures for a median year and 90th percentile year.

	median year hottest week	median year hottest day	90th percentile year hottest week	90th percentile year hottest day
date with the hottest daily or weekly maximum air temperature:	8/21-27/86	8/17/97	8/10-16/67	8/17/77
Mount Vernon 3NW				
average daily maximum air temperature on the hottest day or week of the year (degC):	27.2	30.6	29.7	33.9
average daily minimum air temperature on the hottest day or week of the year (degC):	10.1	11.7	10.6	10.0
Arlington Airport				
average daily maximum air temperature on the hottest day or week of the year (degC):	28.2	31.9	30.9	35.6
average daily minimum air temperature on the hottest day or week of the year (degC):	10.2	11.8	10.7	10.1

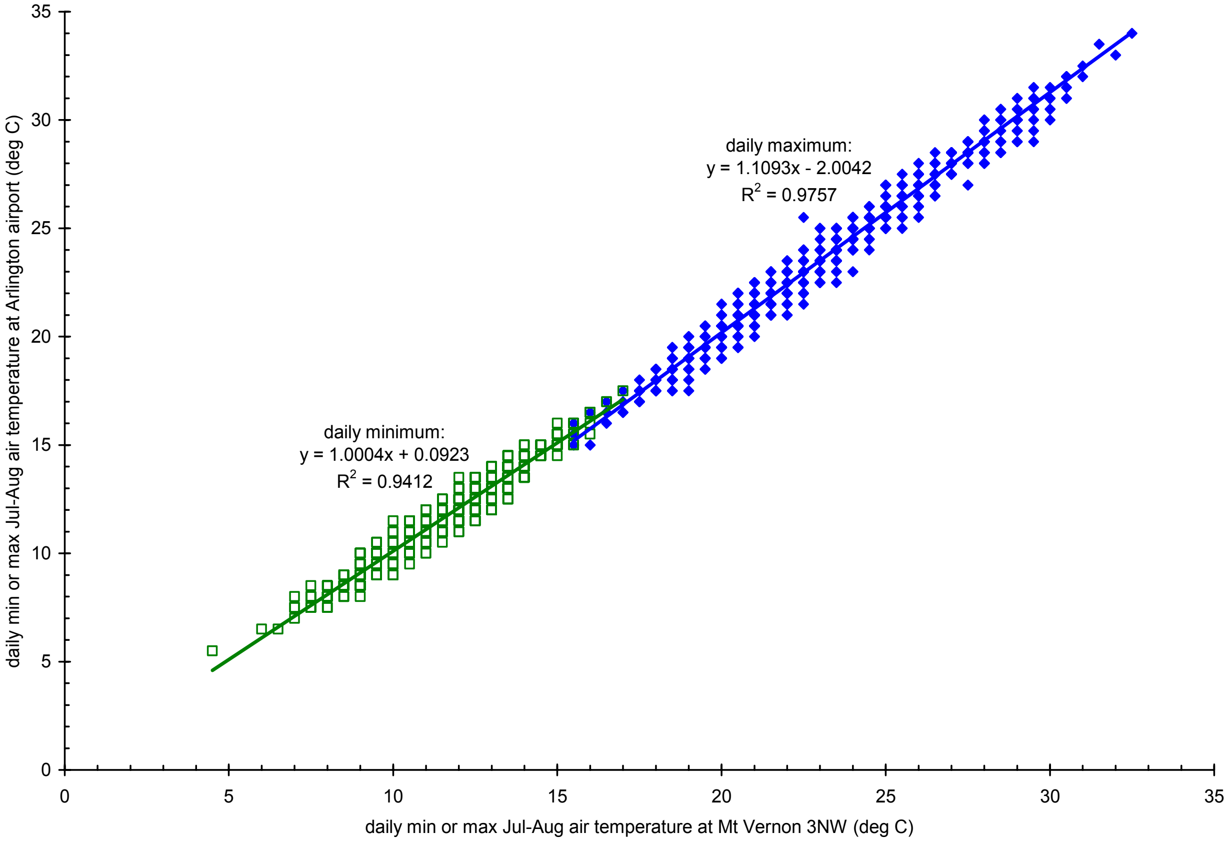

Figure 21. Regression of average daily maximum and minimum air temperatures during July-August at NOAA NCDC stations at Arlington Airport and Mount Vernon 3NW (data from www.daymet.org).

The lapse rate of daily maximum and minimum air temperatures during July and August with elevation along the stream corridors in the study area was determined by regression analysis (Figure 22). Daily maximum air temperatures were found to decrease by 3.0°C per 1000 meter of elevation. The lapse rate for daily minimum air temperatures was found to be 4.9°C per 1000 meter of elevation. Relative humidity was found to increase with elevation during the hottest week of July-August 2001 (Figure 23).

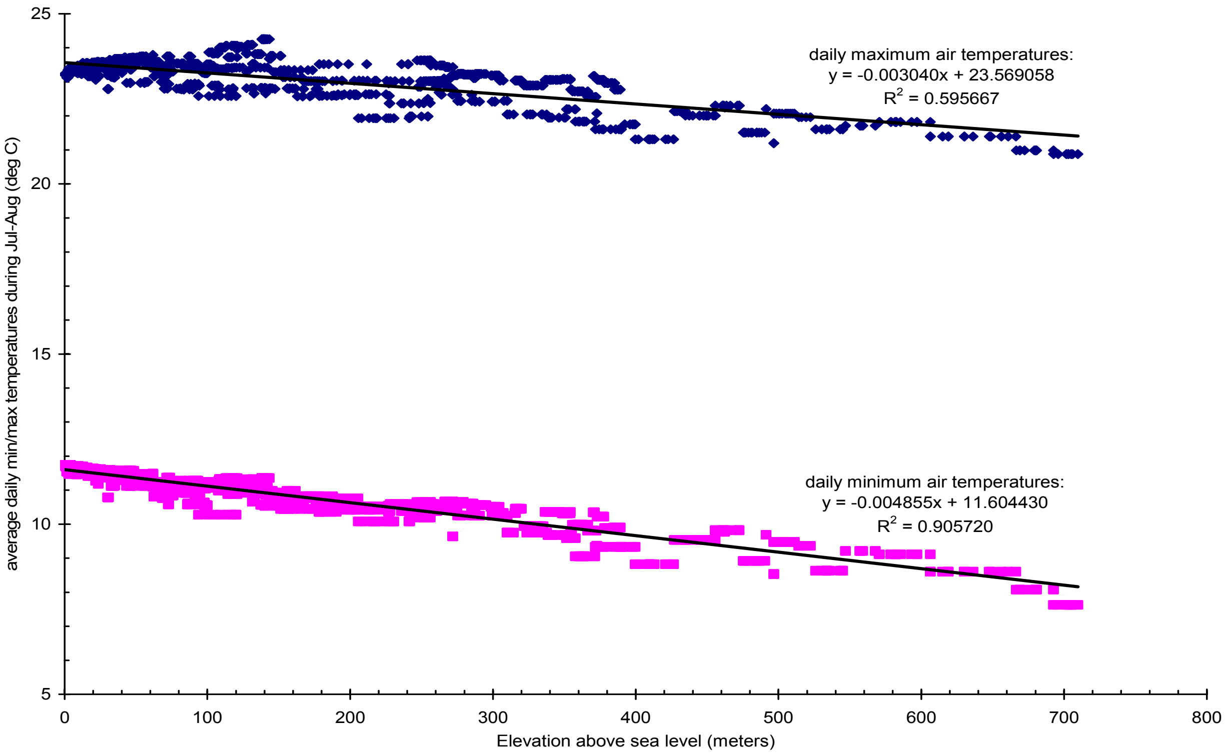

Figure 22. Regression of average daily maximum and minimum air temperatures along the streams in the study area during July-August versus elevation (data from www.daymet.org). The locations plotted in this figure are the values reported for the 1 Km grid cells (along the streams) from the Daymet database.

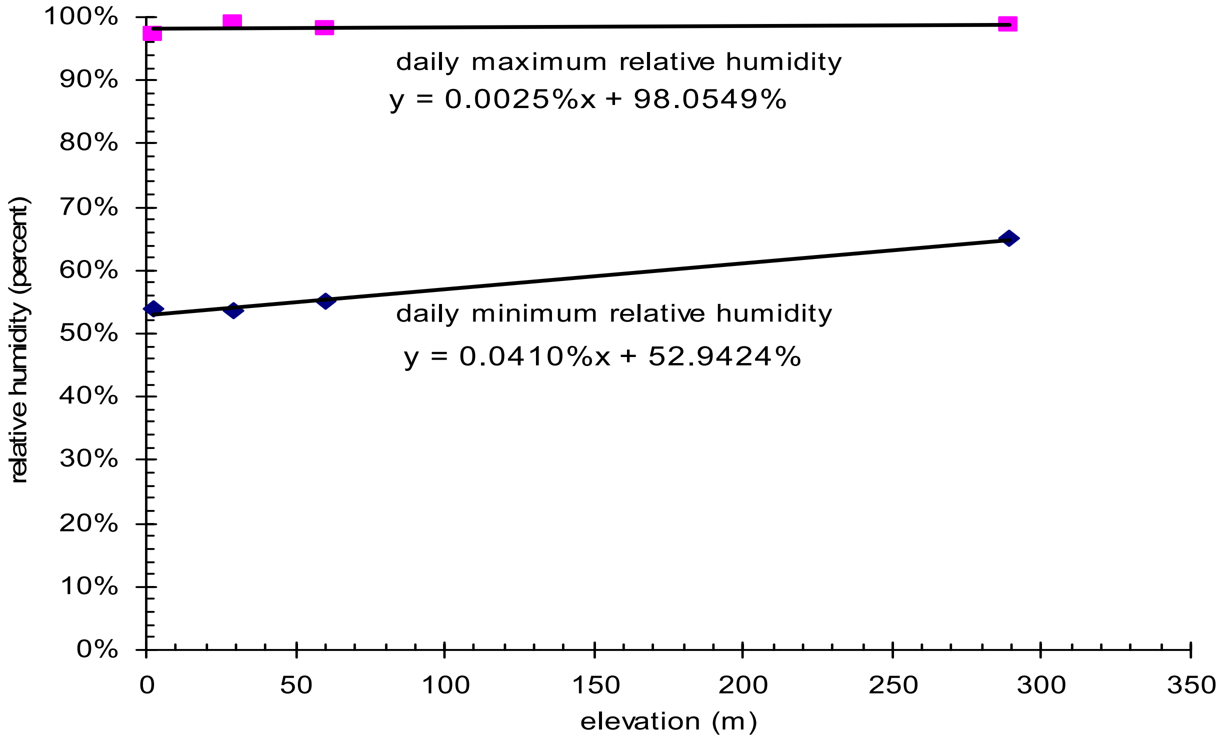

Figure 23. Average daily minimum and maximum relative humidity during August 9-15, 2001 along streams in the Stillaguamish River basin.

The average wind speed in riparian areas of the streams in the watershed 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).

Riparian vegetation and effective shade

The current and historic riparian vegetation in the Stillaguamish River was characterized by Pess et al. (1999). Riparian forests were classified according to three attributes: tree size (Figure 24), the abundance of conifer and deciduous species, and the average density of the riparian forest. The GIS coverage of the riparian forest classes that was created by Pess et al. (1999) was used for this study. This GIS coverage was continuous along the entire length of the streams in the watershed and included forest and other land cover.

Pess et al. (1999) reported that historically the 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).

Effective shade was estimated using Ecology’s Shade and QUAL2Kw models (Ecology, 2003b; Figure 25). Riparian vegetation size and density was estimated from the categories that were delineated by Pess et al. (1999). The vegetation size and density in the riparian zone on the right and left bank was sampled from GIS coverages of the riparian vegetation along the stream at 100-meter intervals using the Ttools extension for Arcview that was developed by the Oregon Department of Environmental Quality (ODEQ, 2001). Other spatial data that were estimated at each transect location includes stream aspect, and topographic shade angles to the west, south, and east.

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.
- **Maximum effective shade from mature riparian vegetation**. The height and density of trees for potential maximum riparian vegetation was estimated based on the description of the historically mixed deciduous and coniferous species in the floodplain (Pess et al., 1999) and was assumed to be represented by an average tree height of 45 meters (about 150 feet) and canopy density of 85%. The estimated characteristics were selected to represent a mid-range for mature vegetation from the values presented by Pess et al. (1999).
- **Maximum effective shade from mature riparian vegetation and reduced channel width**. The height and density of trees for potential maximum riparian vegetation was estimated to be an average tree height of 45 meters (about 150 feet) and canopy density of 85%. The width of the near-stream disturbance zone (NSDZ) was assumed to equal the average value predicted from the regression of bankfull width versus drainage area for historic conditions (for drainage areas less than 380 Km^2) or current conditions (for drainage areas greater than 380 Km^2) shown in Figure 18.

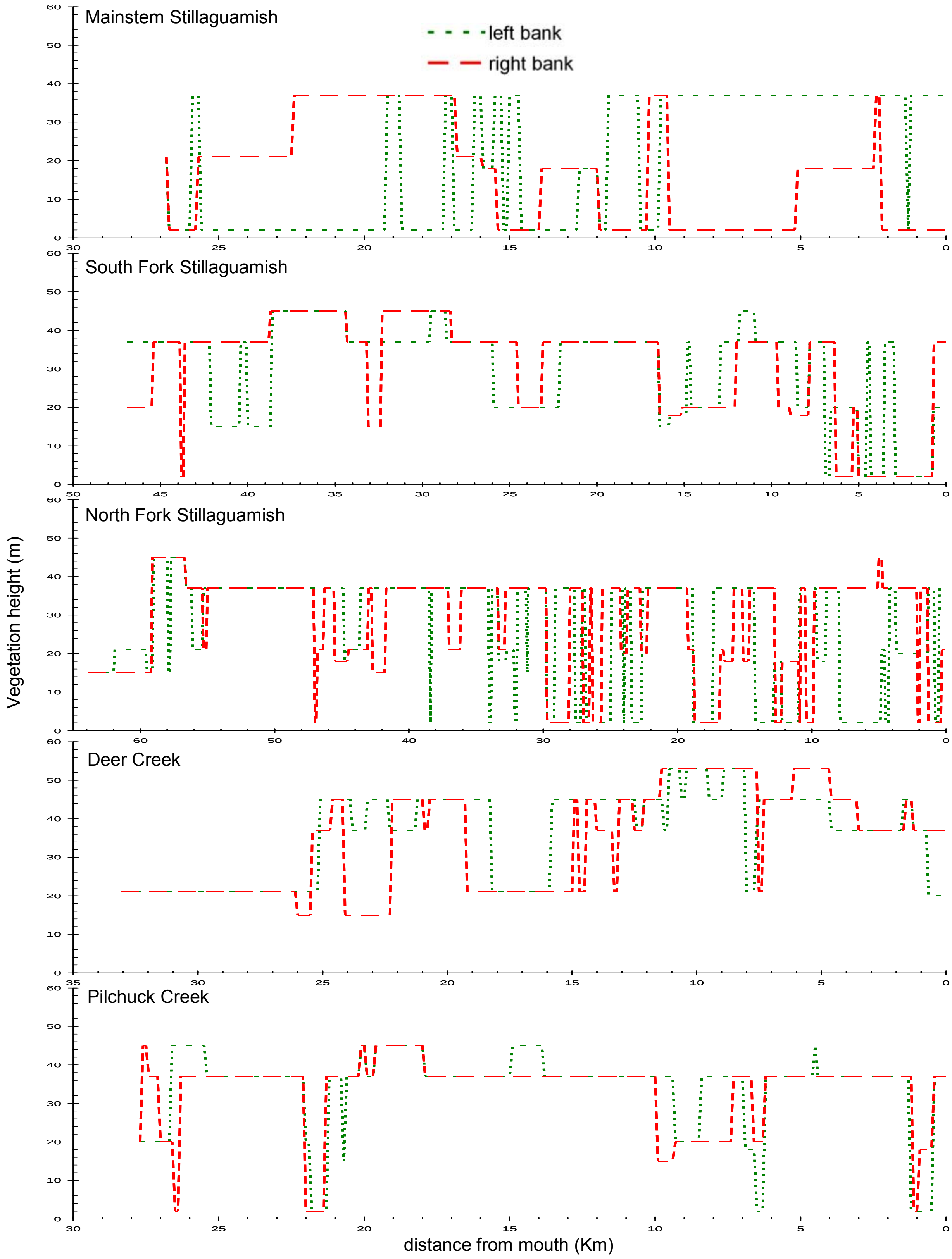

Figure 24. Current riparian vegetation height in the Stillaguamish River basin (data from Appendix D of Pess et al., 1999).

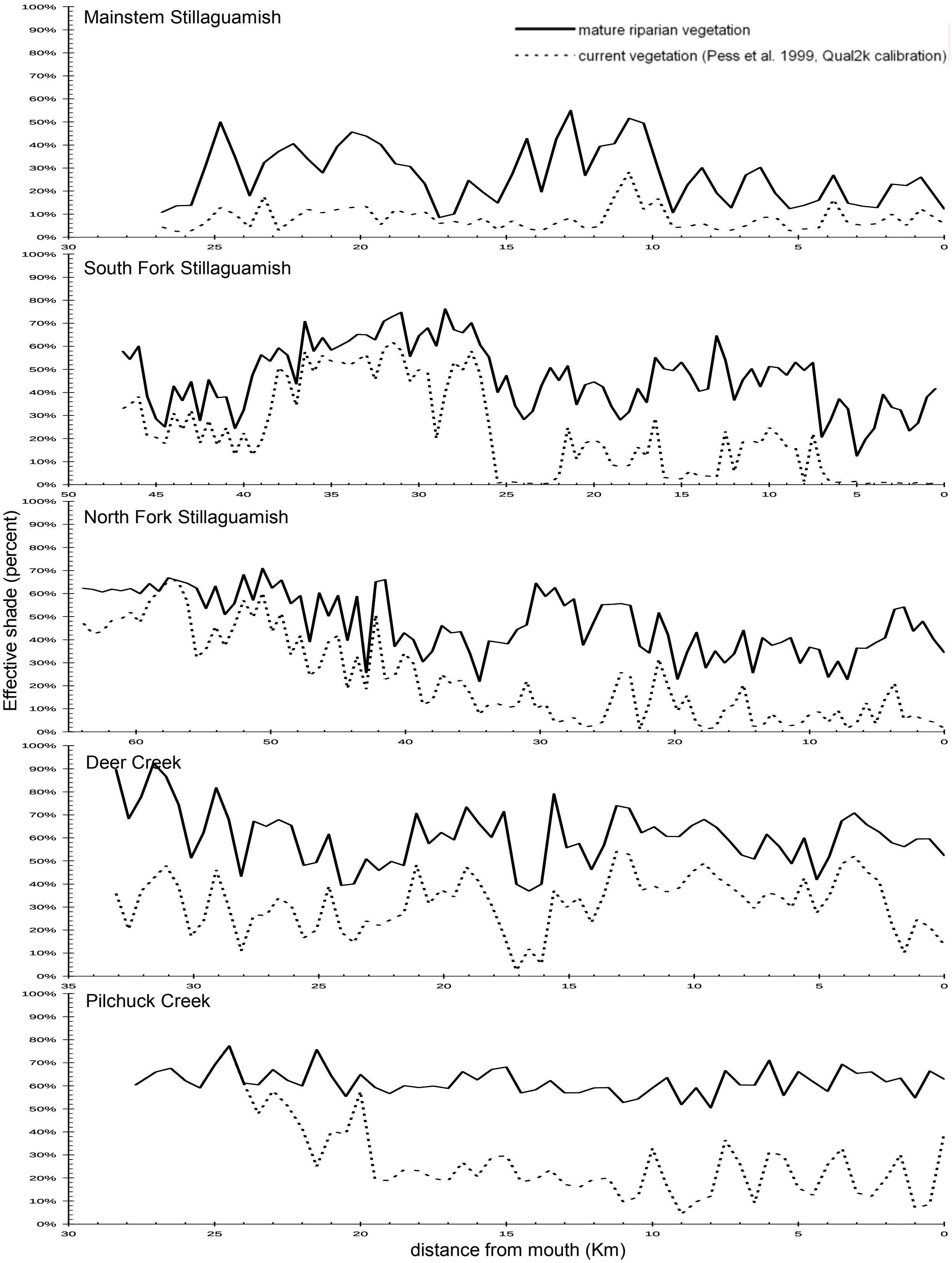

Figure 25. Effective shade from current riparian vegetation and potential mature vegetation in the Stillaguamish River basin (from QUAL2Kw calibration and data from Appendix D of Pess et al., 1999).

Analytical framework

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

- ODEQ's Ttools extension for Arcview (ODEQ, 2001) was used to sample and process GIS data for input to the HeatSource and QUAL2Kw models.
- Ecology's Shade model (Ecology, 2003) was used to estimate effective shade along the mainstems of the major tributaries in the Stillaguamish River basin (Figure 25). Effective shade was calculated along the mainstems of the Stillaguamish River, South Fork Stillaguamish River, North Fork Stillaguamish River, Deer Creek, and Pilchuck Creek using the Shade model. Effective shade was calculated at 100-meter intervals along the streams and then averaged over 500- to 700-meter intervals for input to the QUAL2Kw model.
- The QUAL2Kw model (Chapra, 2001; Chapra and Pelletier, 2003; Pelletier and Chapra, 2003) was used to calculate the components of the heat budget and 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 4 and described in Chapra (1997). Diurnally varying water temperatures at 500 to 700-meter intervals along the streams in the Stillaguamish River basin were simulated using a finite difference numerical method. The water temperature model was calibrated to instream data along the mainstems of the streams and rivers.

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 from 1-meter-resolution Digital Orthophoto Quads (DOQ).
- Riparian vegetation size and density were mapped by Pess et al. (1999) and sampled from the GIS coverage at 100-meter intervals along the streams in the study area. Effective shade was calculated from vegetation height and density with Ecology's Shade model. Calibration of the QUAL2Kw model to current vegetation conditions involved adjustment of the effective shade values within a range that is within the uncertainty of the reported canopy density categories.
- Near-stream disturbance zone (NSDZ) widths were digitized at 1:3000 scale.

- 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 September 7-8, 2001, respectively (Figure 14).
- Flow balances for the calibration and verification periods were estimated from field measurements and gage data of flows made by Ecology and the USGS. 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 USGS gaging stations in the Stillaguamish River basin (Table 5). The 7Q2 and 7Q10 at various other locations were estimated by scaling the estimates at the USGS gage according to the sub-watershed areas weighted by annual average precipitation. A flow balance spreadsheet of the stream networks for the Stillaguamish River, South Fork Stillaguamish River, North Fork Stillaguamish River, Deer Creek, and Pilchuck Creek was constructed to estimate surface water and groundwater inflows by interpolating between the gaging stations.
- Hydraulic geometry (wetted width, depth, and velocity as a function of flow) was estimated using wetted widths from DOQs and measured relationships between wetted width, Manning's n, and flow. Regression equations between Manning's n and flow were developed for each model stream from the data presented in Figure 19. Manning's equation was used to estimate channel depth and velocity.
- 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 Stillaguamish River study area ranges from approximately 11ºC at low elevation to about 6ºC at the highest elevations. Although there are very limited data, the temperature of groundwater in the lower elevations of the Stillaguamish River watershed is known to be spatially variable with reported values ranging from 7.5 to 19.5ºC with a median of 11.5ºC (USGS, 1997). Diffuse inflows in the modeled streams are a mixture of groundwater sources and ungaged surface tributaries. Calibration of the QUAL2Kw model involved selection of the temperature of diffuse inflows ranging from a lower bound of the temperature of groundwater, to an upper bound of the average temperatures of surface waters.
- Air temperature, relative humidity, and cloud cover were estimated from meteorological data. The observed minimum and maximum air temperatures and relative humidity at the stations occupied by Ecology during the study year were used to represent the conditions for the calibration and verification periods. Cloud cover was estimated from data reported at the Arlington Airport. 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, 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, and 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 cm to 50 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. A typical constant value for the thermal conductivity of the surface sediment of 1.5 W/(m°C) (0.0035 cal/sec/cm/°C) was assumed (Chapra, 2001), which is in the typical range of 1 to 2 W/(m°C) in 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 (Figure 14) and was used for calibration of the QUAL2Kw model (Figure 26). An aerial survey of Thermal Infrared Radiation (TIR or FLIR) was conducted during a relatively cool period on September 7-8, 2001 (http://www.ecy.wa.gov/apps/watersheds/temperature/tir/stillaguamish/). The September 7-8, 2001 period was used for verification of the QUAL2Kw model to test the calibration (Figure 27).

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. The RMSE represents the uncertainty that is averaged across all stations in each stream that was modeled. The headwater station for each stream was not used for the computation of the RMSE because it represents a boundary condition that is forced to fit the model prediction. For the calibration and verification periods, the RMSE of the predicted versus observed daily maximum temperatures in the Stillaguamish River basin averaged around 0.7°C (Table 8). The RMSE of predicted daily minimum temperatures was similar to the RMSE of predicted daily maximum temperatures.

Table 8. Summary of RMSE of differences between the predicted and observed daily maximum temperatures in the Stillaguamish River basin.

Watercourse	RMSE for the calibration period of August 9-15, 2001 (deg C)	RMSE for the verification period of September 7-8, 2001 (deg C)
Mainstem Stillaguamish River	0.6	0.3
South Fork Stillaguamish River	0.6	1.3
North Fork Stillaguamish River	1.1	1.3
Deer Creek	0.4	0.0
Pilchuck Creek	0.9	0.8

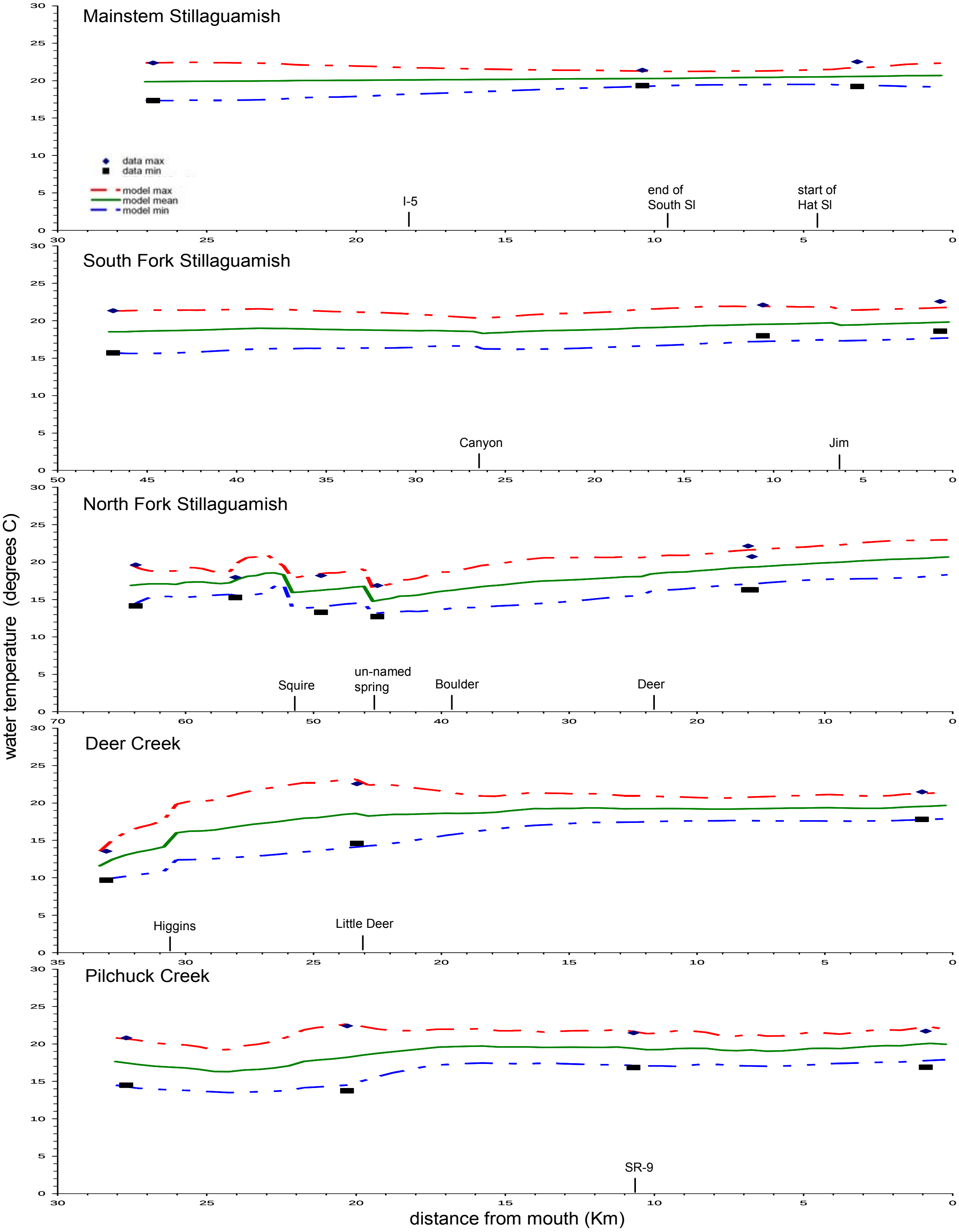

Figure 26. Predicted and observed water temperatures in the Stillaguamish River basin for August 9-15, 2001.

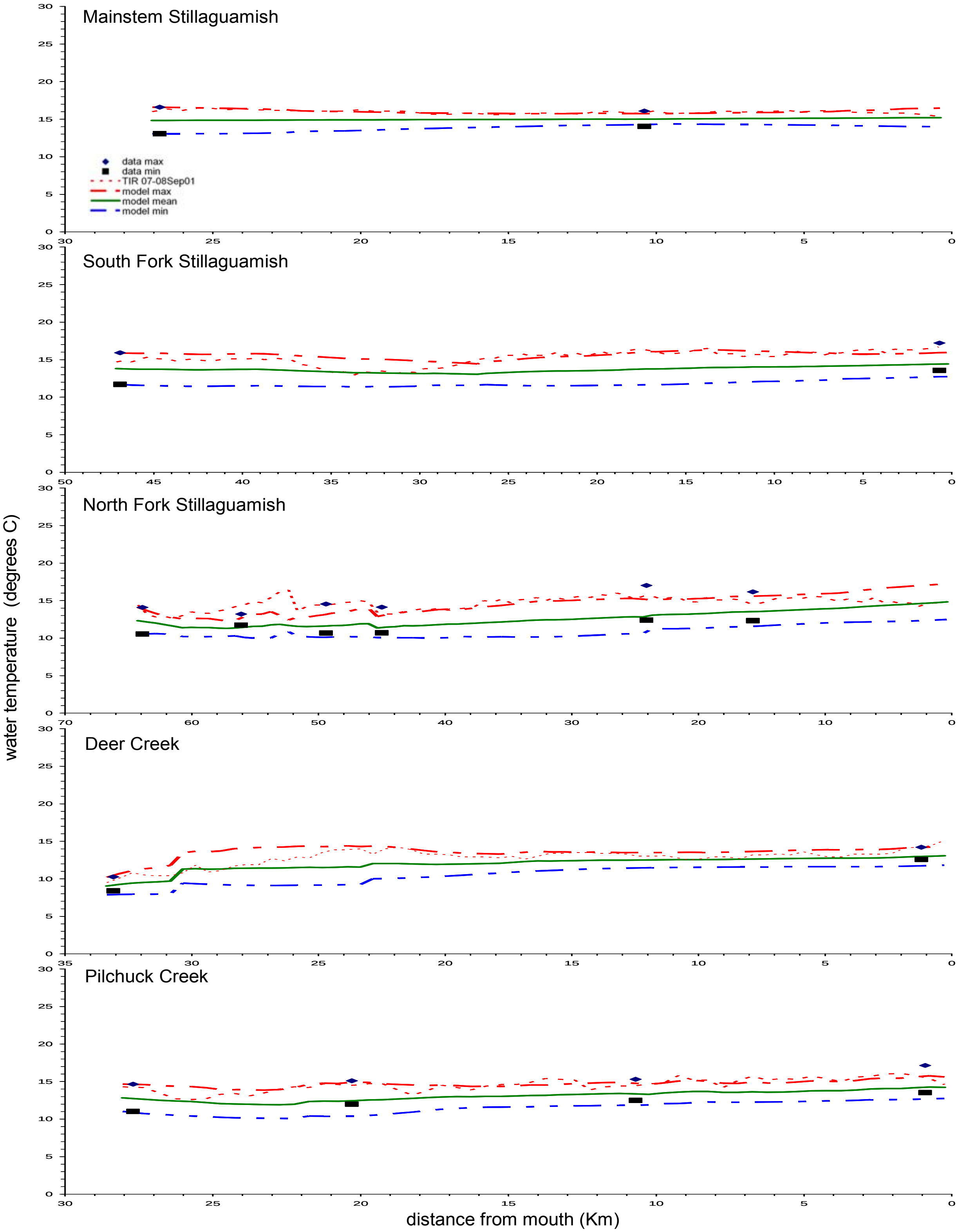

Figure 27. Predicted and observed water temperatures in the Stillaguamish River basin for September 7-8, 2001.

Loading capacity

The loading capacity provides a reference for calculating the amount of pollutant reduction needed to bring water into compliance with standards. EPA's current regulation defines loading capacity as "the greatest amount of loading that a water can receive without violating water quality standards" (40 CFR §130.2(f)).

The system potential temperature is defined in this TMDL as the water temperature that would occur with the combined effect of hypothetical conditions with mature riparian vegetation, improvements in riparian microclimate, reduction of channel width, and increases in groundwater inflows. The combination of those factors that affect the system potential temperature represents the pollutant loading capacity in this TMDL.

The system potential temperature is considered to be an approximation of the temperatures that would occur under natural conditions. In areas where the system potential temperature is greater than the numeric criteria of 18°C in Class A or 16°C in Class AA waters, then the natural conditions provision of the water quality standard is the basis of the loading capacity, load allocations, and wasteload allocations in this TMDL.

The calibrated QUAL2Kw model was used to determine the loading capacity for streams in the Stillaguamish River basin. Loading capacity was determined based on prediction of water temperatures under typical and extreme flow and climate conditions combined with a range of effective shade conditions.

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. The recommended load allocations and wasteload allocations in later sections of this report are based on the 7Q10 condition.

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 Mount Vernon 3NW (Table 7). The air temperatures for the 7Q10 condition were taken from the hottest week of 1967, which was the 90th percentile condition from Mount Vernon 3NW. Critical daily minimum and maximum air temperatures in Arlington and along the streams in the Stillaguamish River watershed were estimated by applying the regression equations and lapse rates from Figure 21 and 22 to the temperature statistics from Mount Vernon 3NW.

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

- The effective shade that is produced by the current condition of riparian vegetation.
- Maximum potential effective shade from mature riparian vegetation that would naturally occur in the Stillaguamish River watershed. The maximum potential shade from vegetation was assumed to be represented by a tree height of 45 meters (about 150 feet), canopy density of 85%, and riparian vegetation width of 150 feet on each side of the stream.

Additional critical scenarios were evaluated to determine the temperature response to changes in riparian microclimate, decreases in channel width, increases in streamflows, and reduction of headwater and tributary temperatures:

- **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 the summary of literature presented by Bartholow (2000): air temperature was decreased by 2°C; relative humidity was increased by 10 percent; and wind speed was reduced to 0.2 m/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 historical channel widths that were calculated by applying equation 2. Channel width was selected to represent the effect of channel geometry on stream temperature because it has an important influence on effective shade, and it also is a surrogate to account for the effect of stream depth.
- **Groundwater recharge.** Groundwater inflows into the streams could increase if recharge is increased with stormwater management. At the request of members of the Stillaguamish Implementation Review Committee (SIRC), the sensitivity of predicted stream temperatures to increases in groundwater inflows was tested by predicting stream temperatures that would be associated with additional inflows of groundwater equal to 10% of the surface flows in reaches that are surrounded by glacial outwash materials. The actual additional inflow which could occur is unknown. The present evaluation is a sensitivity analysis to examine hypothetical conditions. The temperature of these hypothetical groundwater inflows was estimated to be 11°C based on the mean annual air temperature and median value reported by USGS (1997). Hypothetical increases in groundwater inflows were evaluated in Pilchuck Creek below the state Highway 9 bridge, North Fork Stillaguamish River below Cicero, South Fork Stillaguamish River below Granite Falls, and mainstem Stillaguamish River. The reaches that were selected for hypothetical increases in groundwater inflow were proposed by members of the SIRC based on the occurrence of glacial outwash soils and locations of potential projects for groundwater recharge of stormwater.
- **Reduced headwater and tributary temperatures.** A scenario was evaluated with the assumption that the inflowing headwaters and tributaries did not exceed the 18°C (for Class A waters) or 16°C (for Class AA waters). Several headwater locations currently exceed daily maximum water temperatures of 18°C or 16°C, but water temperatures may be reduced in the future if riparian vegetation is increased and other implementation activities occur.
- **Conversion of consumptive withdrawals to instream flow.** A scenario was evaluated for a hypothetical condition with the estimated consumptive surface withdrawals converted to increased instream flows. This assumption could be an overestimate of the hypothetical potential increase in streamflows because actual consumptive withdrawals are probably significantly less than the listed water rights, assuming that undocumented or illegal withdrawals are not significant.

The results of the model runs for the critical 7Q2 and 7Q10 conditions are presented in Table 9 and Figures 28 through 32. The current condition in the Stillaguamish watershed is expected to result in daily maximum water temperatures that are greater than 18°C in all or most of the evaluated reaches. Portions of all of the evaluated streams could be greater than the approximate threshold for lethality of 23°C under current conditions. The model results are intended to represent conditions that are reach-averaged across width and over a length of approximately 500-700 meters. Localized effects such as areas near inflows of cold springs may create thermal refuges for salmonids at a smaller scale.

Substantial reductions in water temperature are predicted for system potential conditions with mature riparian vegetation, improvements in riparian microclimate, reduction of channel width, and increases in groundwater inflows. System potential temperatures are predicted to be less than the threshold for lethality of 23°C but greater than 18°C in Class A and greater than 16°C in Class AA waters in some or most of the reaches in all of the streams that were evaluated.

The averages of potential reductions in daily maximum water temperature in the evaluated reaches are as follows, relative to current conditions based on a summary of the results in Table 9 and Figures 28 through 32:

- 3.0°C reduction with increased shade from mature riparian vegetation
- 0.6°C reduction with improvement in the riparian microclimate
- 0.7°C reduction with reduced channel width
- 0.2°C reduction with increases in groundwater recharge
- 0.6°C reduction with reduction of headwater and tributary temperatures
- 0.2°C reduction with conversion of surface withdrawals to instream flow

The current average daily maximum water temperatures at critical conditions are predicted to be approximately 5.3°C warmer than the system potential temperatures with improved riparian vegetation, microclimate, channel width, groundwater inflow, and reduced consumptive withdrawals. Potential increases in effective shade that could occur with potential mature riparian vegetation are expected to result in an average reduction in daily maximum water temperatures of about 3.0°C relative to current conditions. An additional average reduction of about 1.5°C is predicted if there are improvements in riparian microclimate, reduction of channel width, and increases in groundwater inflows. If the headwater and tributary temperatures can be reduced to less than 18°C in Class A waters and less than 16°C in Class AA waters, then an additional reduction of about 0.6°C is predicted in the reaches downstream from those boundaries. If consumptive surface withdrawals were converted to instream flows then an additional average reduction in daily maximum temperatures of about 0.2°C is predicted.

Table 9. Summary of predicted daily maximum water temperatures at critical conditions in the Stillaguamish River watershed based on the results presented in Figures 28 through 32.

scenario	Stillaguamish	South Fork Stillaguamish	North Fork Stillaguamish	Deer Cr	Pilchuck Cr
	Average predicted daily maximum water temperature across all reaches:				
7Q2					
current condition	23.7	22.7	20.9	21.7	23.2
mature riparian vegetation	20.7	20.9	18.6	18.6	19.3
plus microclimate improvement	20.0	20.5	18.1	18.0	18.6
plus reduced channel width	19.5	20.2	17.3	17.2	17.9
plus groundwater recharge	18.7	20.0	17.3	--	17.8
plus boundaries at WQS	18.4	18.5	17.0	16.8	17.2
plus convert surface withdrawals to instream flow	18.3	18.4	16.8	--	17.2
7Q10					
current condition	26.2	24.8	22.9	23.0	25.3
mature riparian vegetation	23.0	22.4	20.4	19.8	20.9
plus microclimate improvement	22.2	21.9	19.8	19.2	20.1
plus reduced channel width	21.6	21.5	18.7	18.2	19.2
plus groundwater recharge	20.7	21.3	18.6	--	19.1
plus boundaries at WQS	20.5	20.1	18.4	17.8	18.6
plus convert surface withdrawals to instream flow	20.3	19.9	17.8	--	18.5
	Maximum predicted daily maximum water temperature across all reaches:				
7Q2					
current condition	24.5	23.8	23.7	23.2	24.9
mature riparian vegetation	21.9	21.7	20.3	20.2	20.9
plus microclimate improvement	21.1	21.5	19.6	19.8	20.8
plus reduced channel width	20.6	21.3	19.6	18.5	20.8
plus groundwater recharge	19.5	21.3	19.6	--	20.8
plus boundaries at WQS	19.3	19.2	18.2	18.0	18.6
plus convert surface withdrawals to instream flow	19.1	19.1	18.0	--	18.5
7Q10					
current condition	27.3	27.0	26.1	24.8	27.1
mature riparian vegetation	24.6	23.5	22.4	21.3	22.7
plus microclimate improvement	23.9	22.8	21.6	20.8	21.8
plus reduced channel width	23.2	22.5	20.4	19.4	20.9
plus groundwater recharge	22.2	22.0	19.9	--	20.9
plus boundaries at WQS	22.0	21.4	19.9	19.4	20.1
plus convert surface withdrawals to instream flow	21.7	21.2	19.6	--	19.8

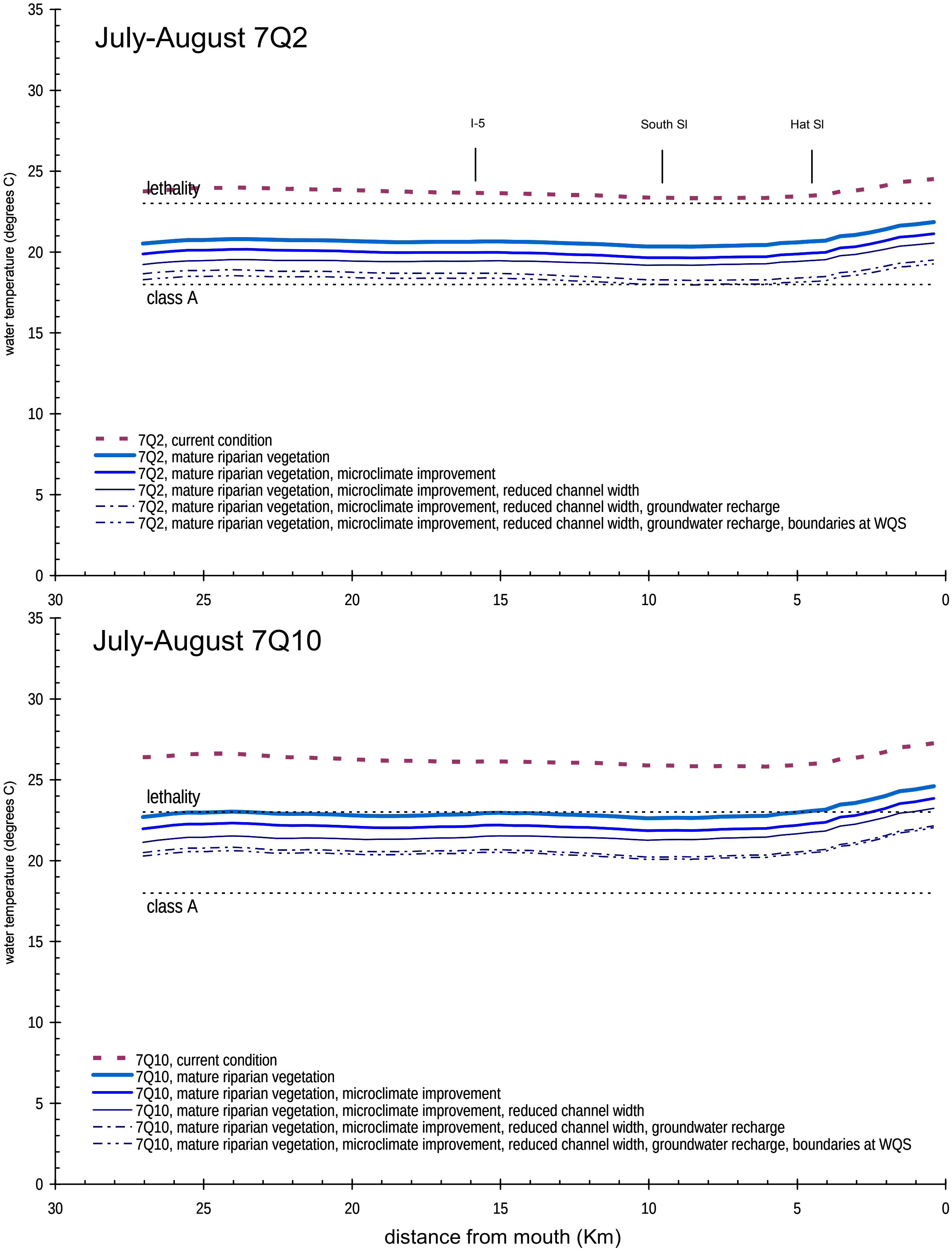

Figure 28. Predicted daily maximum water temperatures in the Stillaguamish River for critical conditions during July-August 7Q2 and 7Q10.

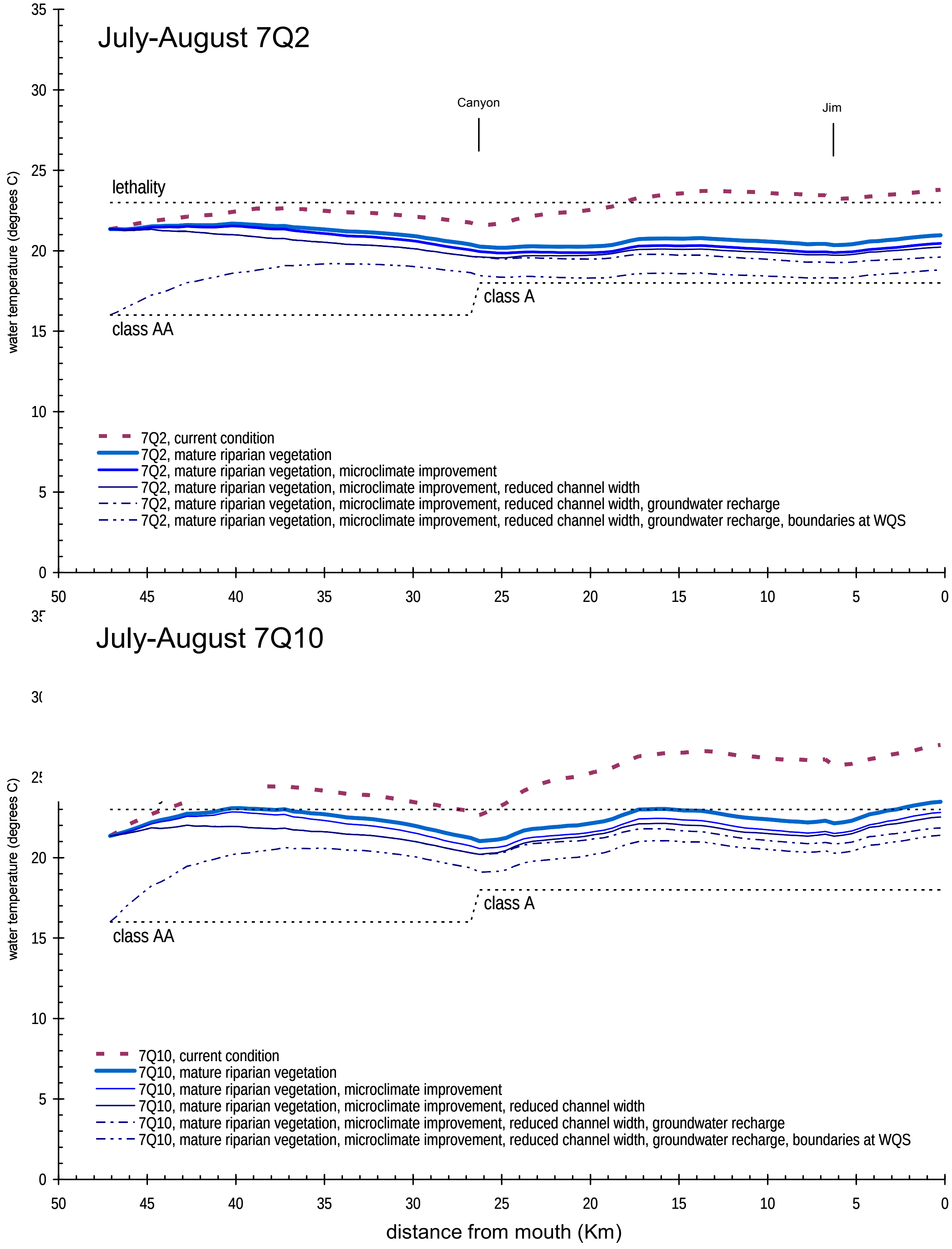

Figure 29. Predicted daily maximum water temperatures in the South Fork Stillaguamish River for critical conditions during July-August 7Q2 and 7Q10.

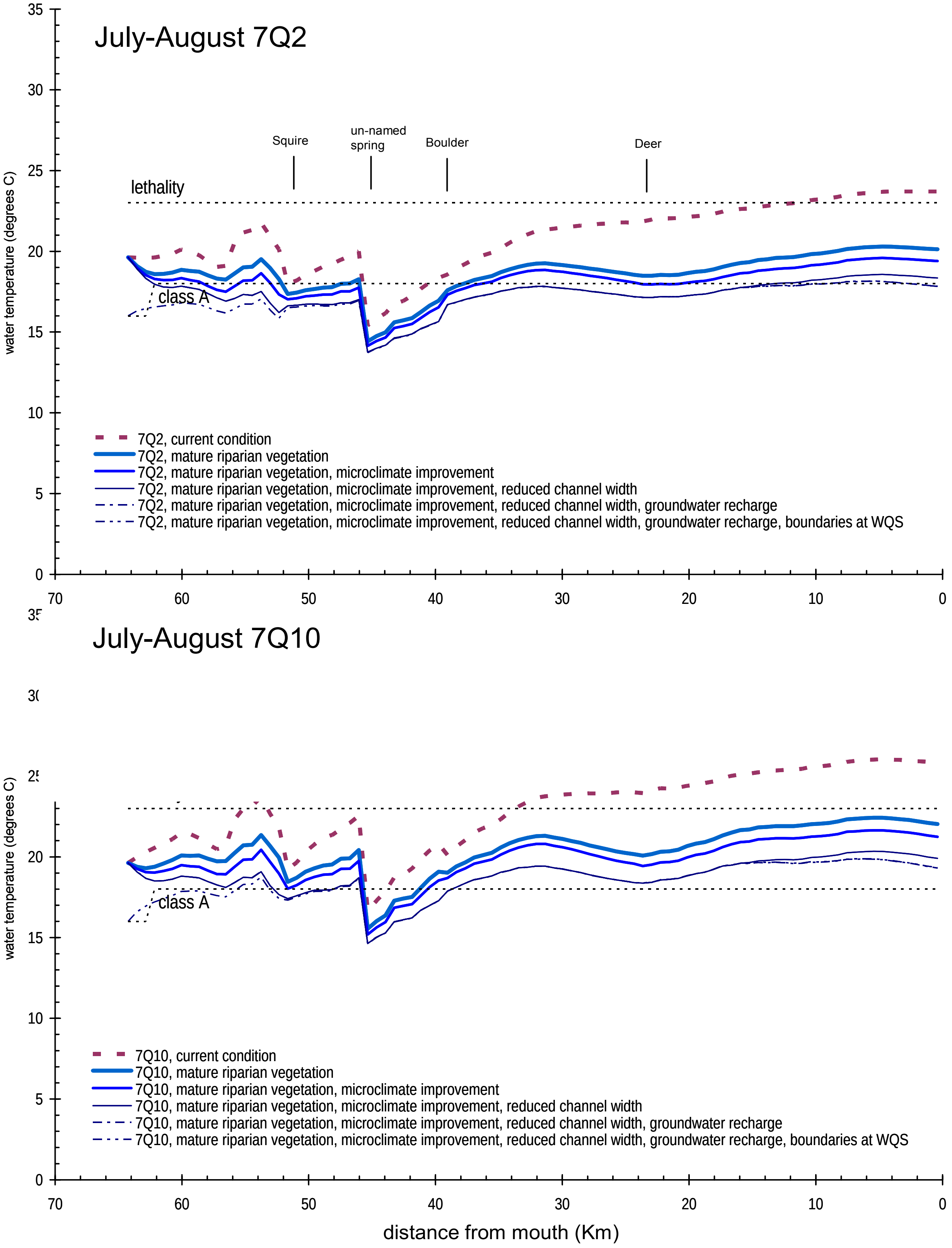

Figure 30. Predicted daily maximum water temperatures in the North Fork Stillaguamish River for critical conditions during July-August 7Q2 and 7Q10.

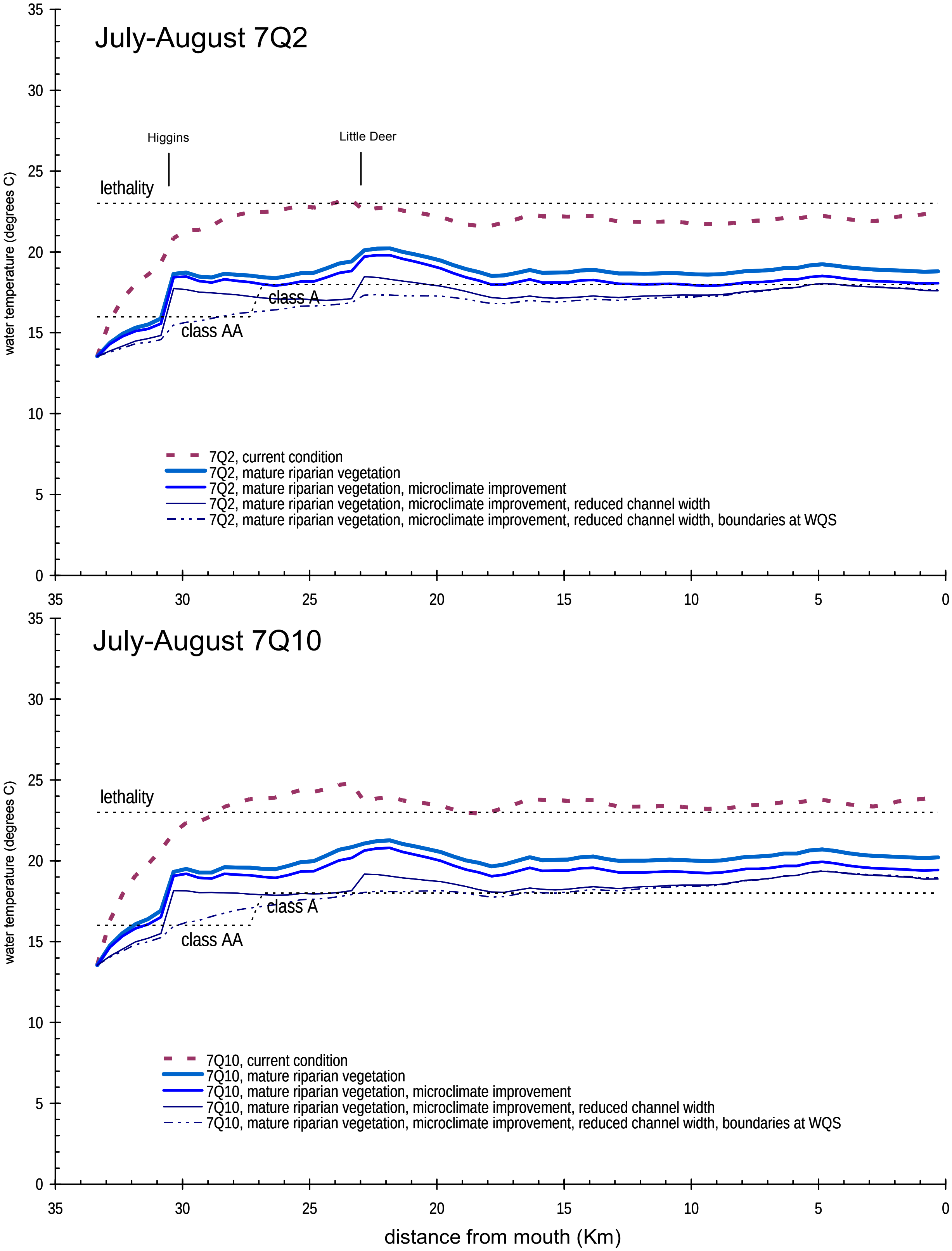

Figure 31. Predicted daily maximum water temperatures in Deer Creek for critical conditions during July-August 7Q2 and 7Q10.

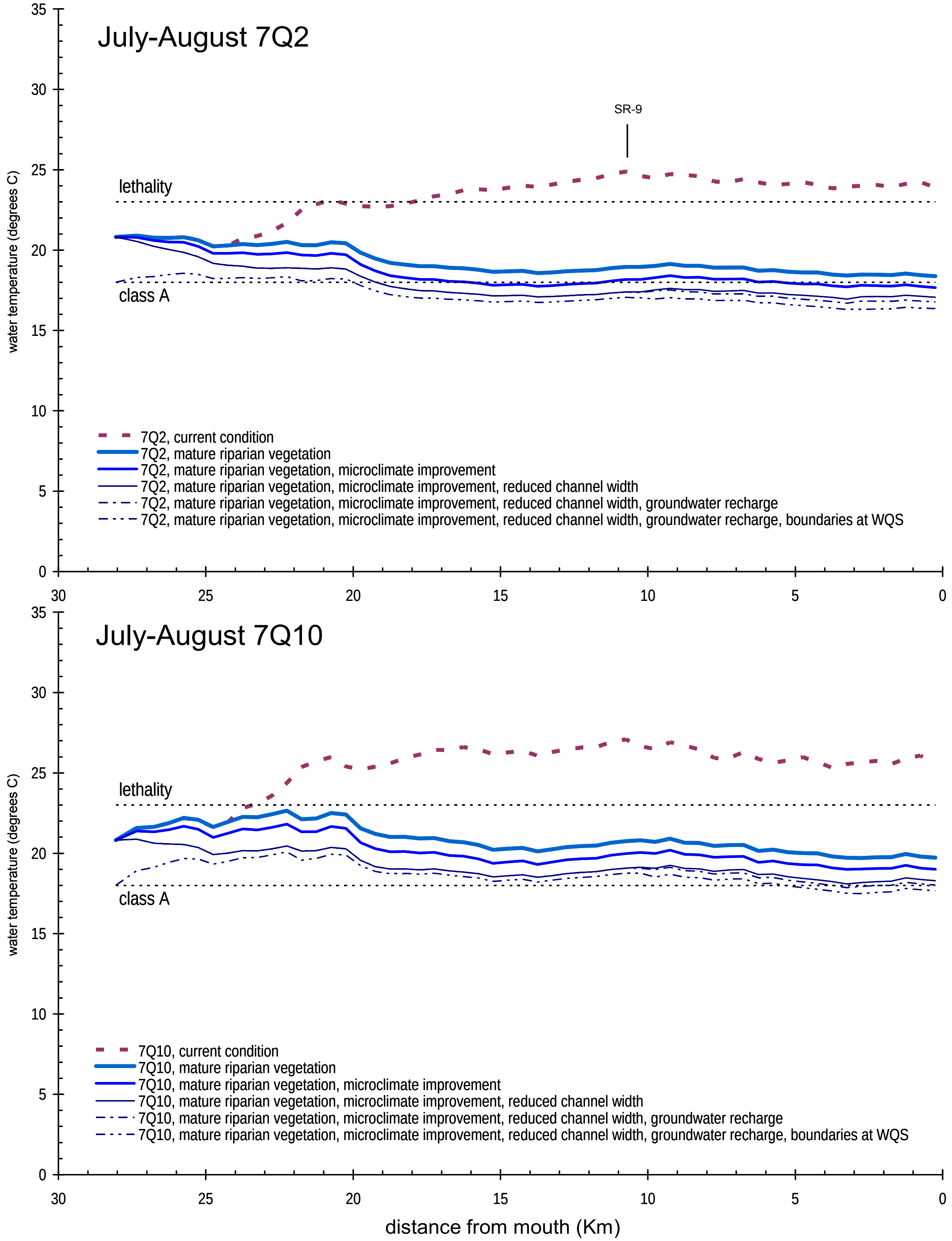

Figure 32. Predicted daily maximum water temperatures in Pilchuck Creek for critical conditions during July-August 7Q2 and 7Q10.

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Load allocations

The natural conditions provision of the water quality standard is the basis of the load allocations in this TMDL (WAC 173-201A-070(2)):

> "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."

The natural condition of temperature was approximated by the system potential temperature, which was an evaluation of the combined effect of hypothetical conditions with mature riparian vegetation, improvements in riparian microclimate, reduction of channel width, and increases in groundwater inflows.

The load allocations are expected to result in water temperatures that are equivalent to the temperatures that would occur under natural conditions. Therefore, the load allocations are expected to result in water temperatures that meet the water quality standard.

The load allocation for effective shade for all perennial streams in the Stillaguamish River watershed is the maximum potential effective shade that would occur from mature riparian vegetation.

Establishment of mature riparian vegetation is expected to also have a secondary benefit of reducing channel widths and improving microclimate conditions to address those influences on the loading capacity. An adaptive management strategy is recommended to address other influences on stream temperature such as sediment loading, groundwater inflows, and hyporheic exchange.

Load allocations for effective shade are quantified in Appendix C for the following modeled reaches of the Stillaguamish River watershed: the Stillaguamish River, South Fork Stillaguamish River, North Fork Stillaguamish River, Deer Creek, and Pilchuck Creek.

For other perennial streams in the watershed, the load allocations for effective shade are represented in Figure 33 and Appendix D based on the estimated relationship between shade, channel width, and stream aspect at the assumed maximum riparian vegetation condition. Figure 33 shows that the importance of shade decreases as the width of the stream channel increases.

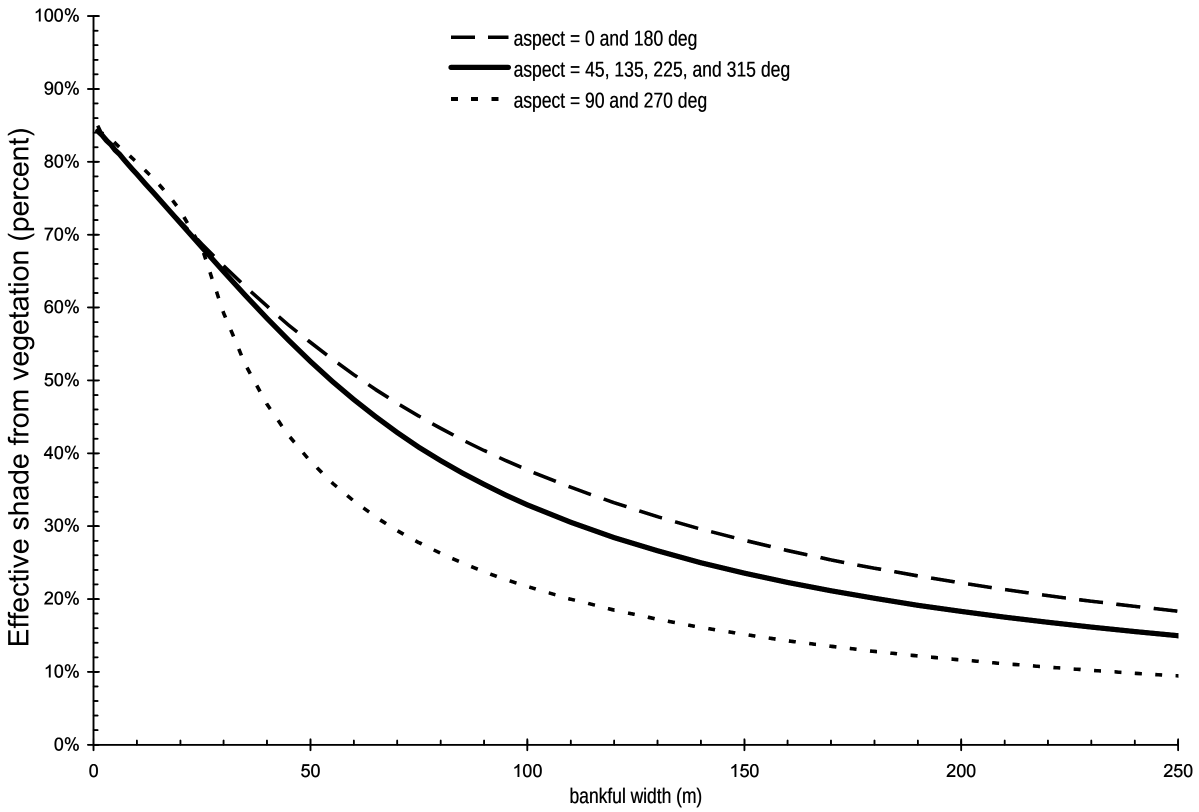

Figure 33. Load allocations for effective shade for various bankfull width and aspect of streams in the Stillaguamish River watershed assuming riparian vegetation height of 45 meters with angular canopy density of 85 percent. Effective shade is defined as the fraction of incoming solar shortwave radiation that is blocked from reaching the surface of the stream.

In addition to the load allocations for effective shade in the study area, the following management activities are recommended for implementation to attain temperatures that comply with the water quality standards provision for natural conditions:

- For U.S. Forest Service land, the riparian reserves in the Northwest Forest Plan are recommended for establishment of mature riparian vegetation.
- For privately owned forest land, the riparian vegetation prescriptions in the Forests and Fish Report (DNR, 1999) are recommended for all perennial streams. Load allocations are included in this TMDL for forest lands in the Stillaguamish River watershed in accordance with the section of the Forests and Fish Report entitled “TMDLs produced prior to 2009 in mixed use watersheds.”
- For areas that are not managed in accordance with either the Forest Plan or the Forest and Fish Report, such as private non-forest areas, voluntary programs to increase riparian vegetation should be developed (for example, riparian buffers or conservation easements sponsored under the U.S. Department of Agriculture Natural Resources Conservation Service’s Conservation Reserve Enhancement Program).

- 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. Future projects that have the potential to increase groundwater inflows to streams in the watershed should be encouraged and have the potential to decrease stream temperatures. Voluntary retirement or purchase of existing water rights for conversion to instream flow should also be encouraged.

- Management activities should control potential channel widening processes. Reductions in channel width are expected as mature riparian vegetation is established. Management activities that would reduce the loading of sediment to the surface waters from upland and channel erosion are also recommended.

- Hyporheic exchange flows and groundwater discharges are important to maintain the current temperature regime and reduce maximum daily instream temperatures. Factors that influence hyporheic exchange flow include the vertical hydraulic gradient between surface and subsurface waters as well as the hydraulic conductivity of the streambed sediments. Activities that reduce the hydraulic conductivity of streambed sediments could increase stream temperatures. Management activities should reduce upland and channel erosion and avoid sedimentation of fine materials in the stream substrate.

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Wasteload allocations

The provisions in the water quality standard for natural conditions (WAC 173-201A-070(2)) and the allowable increase in temperature over natural conditions (WAC 173-201A-030(1)(c)(iv) for Class AA and WAC 173-201A-030(2)(c)(iv) for Class A) are the basis of the wasteload allocations in this TMDL:

> "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."
>
> "… When natural conditions exceed 16.0°C *(in class AA waters)* …, no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3°C."
>
> "… When natural conditions exceed 18.0°C *(in class A waters)*…, no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3°C."

The load allocations for the nonpoint sources are considered to be sufficient to attain the water quality standards by resulting in water temperatures that are equivalent to natural conditions. Therefore, the water quality standards allow an increase over natural conditions for the point sources for establishment of the wasteload allocations.

Wasteload allocations for the National Pollution Discharge Elimination System (NPDES) discharges from the City of Arlington and the Indian Ridge Youth Camp were evaluated. The City of Arlington discharges effluent from a wastewater treatment plant to the Stillaguamish River below the confluence of the North and South forks (Class A). The Indian Ridge Youth Camp discharges effluent to Jim Creek (Class A). Chronic dilution factors were determined in the Engineering Report for the City of Arlington (Earth Tech, 1996) and in the fact sheet for the Indian Ridge Youth Camp NPDES permit (Ecology NWRO NPDES files). Arlington Phase I is projected for effluent discharge rates in year 2004, and Phase II in 2014.

Maximum temperatures for NPDES effluent discharges (T_{NPDES}) were calculated from the following mass balance equation for system potential upstream temperatures greater than or equal to 18°C (all of the point sources in this TMDL discharge to waters that are designated as Class A):

$$T_{NPDES} = [\text{system potential upstream temperature °C}] + [\text{chronic dilution factor}]*0.3°\text{C}$$

Maximum effluent temperatures should also be no greater than 33°C to avoid creating areas in the mixing zone that would cause near instantaneous lethality.

Table 10 presents the maximum effluent temperatures that would cause an increase of 0.3°C for various upstream receiving water temperatures for the reported chronic dilution factors. The most restrictive effluent temperature is predicted for the case when the upstream temperature is assumed to equal 18°C, which would result in maximum effluent temperatures of 27.0°C, 24.1°C, and 23.1°C for Arlington (Phase I in year 2004 described by EarthTech, 1996), Arlington (Phase II in year 2014 described by EarthTech, 1996), and Indian Ridge Youth Camp, respectively. The system potential temperatures upstream from NPDES dischargers are probably greater than 18°C and could range between approximately 18°C and 23°C depending on year-to-year variations in river flow and climate conditions.

Table 10. Wasteload allocations for effluent temperature for NPDES dischargers.

	Arlington Phase I	Arlington Phase II	Indian Ridge Youth Camp
Chronic dilution factor:	30	20.4	17
System potential upstream temperature (deg C)	Maximum allowable effluent temperature (deg C)		
18	27.0	24.1	23.1
19	28.0	25.1	24.1
20	29.0	26.1	25.1
21	30.0	27.1	26.1
22	31.0	28.1	27.1
23	32.0	29.1	28.1
24	33.0	30.1	29.1
25	33.0	31.1	30.1

Margin of safety

The margin of safety accounts for uncertainty about 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 at Mount Vernon 3NW was used to develop a reasonable worst case condition for prediction of water temperatures in the Stillaguamish watershed. 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 square error (RMSE) of model predictions compared with observed temperatures during model validation. The average RMSE for model calibration and verification was 0.7°C.

- The load allocations are set to the effective shade provided by full mature riparian shade, which are the maximum values achievable in the Stillaguamish River system.

Other factors that could increase the margin of safety may be considered during the public process for developing the final implementation strategy for the TMDL.

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Recommendations for monitoring

To determine the effects of management strategies within the Stillaguamish 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 locations are suggested for a minimal sampling program:

- Stillaguamish River at Norman Road
- South Fork Stillaguamish River near mouth
- North Fork Stillaguamish River near mouth
- Deer Creek near mouth
- Pilchuck Creek near mouth

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 (for example, by using photogrammetry or remote sensing methods).

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

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References cited

Adams, T.N. and K Sullivan. 1989. The physics of forest stream heating: a simple model. Timber, Fish, and Wildlife, Report No TFW-WQ3-90-007. Washington State Department of Natural Resources, Olympia, WA.

Bartholow, J.M. 2000. Estimating cumulative effects of clearcutting on stream temperatures. Rivers 7(4), 284-297.

Belt, G.H., J. O'Laughlin, and W.T. Merrill. 1992. Design of Forest Riparian Buffer Strips for the Protection of Water Quality: Analysis of Scientific Literature. Report No. 8. Idaho Forest, Wildlife, and Range Policy Analysis Group, University of Idaho, Moscow, ID.

Beschta, R.L. and J. Weatherred, 1984. A computer model for predicting stream temperatures resulting from the management of streamside vegetation. USDA Forest Service. WSDGAD-00009.

Beschta, R.L., R.E. Bilby, G.W. Brown, L.B. Holtby, and T.D. Hofstra. 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions. In: Streamside management: forestry and fisher interactions, E.O. Salo and T.W. Cundy, editors, pp 192-232. Proceedings of a conference sponsored by the College of Forest Resources, University of Washington, Seattle WA, Contribution No. 57 – 1987.

Bolton, S. and C. Monohan. 2001. A review of the literature and assessment of research needs in agricultural streams in the Pacific Northwest as it pertains to freshwater habitat for salmonids. Prepared for: Snohomish County, King County, Skagit County, and Whatcom County. Prepared by: Center for Streamside Studies, University of Washington, Seattle, WA.

Boyd, M.S. 1996. Heat source: stream, river, and open channel temperature prediction. Oregon State University. M.S. Thesis. October 1996.

Boyd, M. and C. Park. 1998. Sucker-Grayback Total Daily Maximum Load. Oregon Department of Environmental Quality and U.S. Forest Service.

Brady, D.K., W.L. Graves, and J.C. Geyer. 1969. Surface heat exchange at power plant cooling lakes. Cooling water discharge project report No. 5, Edison Electric Institute Publ. No. 69-901, New York.

Brazier, J.R. and G.W. Brown. 1973. Buffer strips for stream temperature control. Res. Pap. 15. Forest Research Laboratory, Oregon State University. 9 pp.

Broderson, J.M. 1973. Sizing buffer strips to maintain water quality. M.S. Thesis, University of Washington, Seattle, WA.

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

Brown, G.W. 1972. An improved temperature prediction model for small streams.
Water Resources Research 6(4):1133-1139.

Brown, G.W. and J.T. Krygier. 1970. Effects of clear-cutting on stream temperature.
Water Resources Research 6(4):1133-1139.

Brown, G.W., G.W. Swank, and J. Rothacher. 1971. Water temperature in the Steamboat drainage. USDA Forest Service Research Paper PNW-119, Portland, OR. 17 pp.

Castelle, A.J. and A.W. Johnson. 2000. Riparian vegetation effectiveness. Technical Bulletin No. 799. National Council for Air and Stream Improvement, Research Triangle Park, NC. February 2000.

CH2MHill. 2000. Review of the scientific foundations of the forests and fish plan. Prepared for the Washington Forest Protection Association. http://www.wfpa.org/

Chapra, S.C. 1997. Surface water quality modeling. McGraw-Hill Companies, Inc.

Chapra, S.C. 2001. Water-Quality Modeling Workshop for TMDLs, Washington State Department of Ecology, Olympia, WA, June 25-28, 2001.

Chapra, S.C. and G.J. Pelletier. 2003. QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality: Documentation and Users Manual. Civil and Environmental Engineering Dept., Tufts University, Medford, MA. Steven.Chapra@tufts.edu
www.epa.gov/athens/wwqtsc/html/qual2k.html

Chen, J. 1991. Edge effects: microclimate pattern and biological responses in old-growth Douglas-fir forests. Ph.D. dissertation. College of Forest Resources, University of Washington, Seattle, WA.

Chen, J., J.F. Franklin, and T.A. Spies. 1993. Contrasting microclimates among clearcut, edge, and interior of old-growth Douglas-fir forest. Agricultural and Forest Meteorology 63, 219-237.

Chen, Y.D. 1996. Hydrologic and water quality modeling for aquatic ecosystem protection and restoration in forest watersheds: a case study of stream temperature in the Upper Grande Ronde River, Oregon. PhD dissertation. University of Georgia, Athens, GA.

Chen, Y.D., R.F. Carsel, S.C. McCutcheon, and W.L. Nutter, 1998. Stream temperature simulation of forested riparian areas: I. watershed-scale model development. Journal of Environmental Engineering. April 1998. pp 304-315.

Chen, Y.D., R.F. Carsel, S.C. McCutcheon, and W.L. Nutter. 1998. Stream temperature simulation of forested riparian areas: II. model application. Journal of Environmental Engineering. April 1998. pp 316-328.

Childs, S.W., and L.E. Flint. 1987. Effect of shadecards, shelterwoods, and clearcuts on temperature and moisture environments. Forest Ecology and Management 18, 205-217.

Corbett, E.S. and J.A. Lynch. 1985. Management of streamside zones on municipal watersheds. P. 187-190 In: R.R. Johnson, C.D. Ziebell, D.R. Patton, P.F. Folliott, and R.H. Hamre (eds.). Riparian ecosystems and their management: reconciling conflicting uses. First North American Riparian Conference, April 16-18, 1985. Tucson, AZ.

DNR. 1999. Forests and Fish Report. Forest Practices Board. Washington State Department of Natural Resources. April 29, 1999.
http://www.dnr.wa.gov/forestpractices/rules/forestsandfish.pdf

Earth Tech. 1996. Engineering report: wastewater treatment plant expansion, City of Arlington, Washington. Prepared by Earth Tech, Bellevue, WA.

Ecology. 2003. Shade.xls - a tool for estimating shade from riparian vegetation. Washington State Department of Ecology. http://www.ecy.wa.gov/programs/eap/models/

Edgerton, P.J. and B.R. McConnell. 1976. Diurnal temperature regimes of logged and unlogged mixed conifer stands on elk summer range. Station Research Note PNW-277. Portland, OR. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 6 pp.

Edinger, J.E., D.W. Duttweiler, and J.C. Geyer. 1968. The response of water temperatures to meteorological conditions. Water Resources Research, Vol. 4, No. 5.

Edinger, J.E., D.K. Brady, and J.C. Geyer. 1974. Heat exchange and transport in the environment. EPRI publication no. 74-049-00-3, Electric Power Research Institute, Palo Alto, CA.

EPA. 1991. Guidance for Water Quality-based Decisions: The TMDL Process. U.S. Environmental Protection Agency. EPA 440/4-91-001.

EPA. 1998. Report of the Federal Advisory Committee on the Total Maximum Daily Load (TMDL) Program. The National Advisory Council For Environmental Policy and Technology (NACEPT). U.S. Environmental Protection Agency, Office of The Administrator. EPA 100-R-98-006.

Faux, R. 2002. Aerial surveys in the Stillaguamish and Skagit River basins, thermal infrared and color videography. March 16, 2002. Report to: Washington State Department of Ecology. Watershed Sciences LLC, Corvallis, OR.

FEMAT. 1993. Northwest Forest Plan Documents, Forest Ecosystem Management: An Ecological, Economic, and Social Assessment. Report of the Forest Ecosystem Management Assessment Team. U.S. Department of Agriculture, U.S. Department of Commerce, U.S. Department of Interior, U.S. Environmental Protection Agency. U.S. Government Printing Agency, report number 1993-793-071. pnwin.nbii.gov/nwfp/FEMAT/

Fowler, W.B. and T.D. Anderson. 1987. Illustrating harvest effects on site microclimate in a high-elevation forest stand. Research Note PNW-RN-466. Portland, OR. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 10 pp.

Fowler, W.B., J.D. Helvey, and E.N. Felix. 1987. Hydrologic and climatic changes in three small watersheds after timber harvest. Res. Pap. PNW-RP-379. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 13 pp.

Franklin, J.F. and C.T. Dyrness. 1973. Natural vegetation of Oregon and Washington. U.S. Forest Service. General technical report PNW-8.

GEI. 2002. Efficacy and economics of riparian buffers on agricultural lands, State of Washington. Prepared for the Washington Hop Growers Association. Prepared by GEI Consultants, Englewood, CO.

Gordon, N.D, T.A. McMahon, and B.L. Finlayson. 1992. Stream Hydrology, An Introduction for Ecologists. Published by John Wiley and Sons.

Hewlett, J.D. and J.C. Fortson. 1983. Stream temperature under an inadequate buffer strip in the southern piedmont. Water Resources Bulletin 18(6):983.

Holtby, L.B. 1988. Effects of logging on stream temperatures in Carnation Creek, B.C., and associated impacts on the coho salmon. Canadian Journal of Fisheries and Aquatic Sciences 45:502-515.

Ice, G. 2001. How direct solar radiation and shade influences temperatures in forest streams and relaxation of changes in stream temperature. In: Cooperative Monitoring, Evaluation, and Research (CMER) workshop: heat transfer processes in forested watershed and their effects on surface water temperature, Lacey, WA, February 2001.

Leopold, L. 1994. A view of the river. Harvard University Press.

Levno, A. and J. Rothacher. 1967. Increases in maximum stream temperatures after logging in old growth Douglas-fir watersheds. USDA Forest Service PNW-65, Portland, OR. 12 p.

Lynch, J.A., E.S. Corbett, and K. Mussallem. 1985. Best management practices for controlling nonpoint-source pollution on forested watersheds. Journal of Soil and Water Conservation 40:164-167.

Lynch, J.A., G.B. Rishel, and E.S. Corbett. 1984. Thermal alterations of streams draining clearcut watersheds: quantification and biological implications. Hydrobiologia 111:161-169.

NOAA. 2003. The NOAA Integrated Surface Irradiance Study (ISIS) - A New Surface Radiation Monitoring Program, B.B. Hicks, J.J. DeLuisi, and D.R. Matt. Bull. Amer. Meteor. Soc. 77, 2857-2864. http://www.atdd.noaa.gov/isis/isis.htm

ODEQ. 2001. Ttools 3.0 User Manual. Oregon Department of Environmental Quality. Portland OR. http://www.deq.state.or.us/wq/TMDLs/WQAnalTools.htm

OWEB. 1999. Water quality monitoring technical guidebook: chapter 14, stream shade and canopy cover monitoring methods. Oregon Watershed Enhancement Board. http://www.oweb.state.or.us/pdfs/monitoring_guide/monguide2001_ch14.pdf

Patric, J.H. 1980. Effects of wood products harvest on forest soil and water relations. Journal of Environmental Quality 9(1):73-79.

Pelletier, G. and D. Bilhimer. 2001. Stillaguamish River temperature total maximum daily load: quality assurance project plan. Washington State Department of Ecology, Olympia WA. Publication No. 01-03-066. http://www.ecy.wa.gov/biblio/0103066.html

Pelletier, G., and S. Chapra. 2003. QUAL2Kw: Documentation and User Manual for a Modeling Framework to Simulate River and Stream Water Quality. Draft Publication. Washington State Department of Ecology, Olympia, WA. www.ecy.wa.gov/programs/eap/models/

Pess, G.R., B.D. Collins, M. Pollock, T.J. Beechie, A. Haas, and S. Grigsby. 1999. Historic and current factors that limit Coho salmon (Oncorhynchus kisutch) production in the Stillaguamish River basin, Washington State: implications for salmonid habitat protection and restoration. Prepared for Snohomish County Department of Public Works, Everett, WA, and The Stillaguamish Tribe of Indians, Arlington, WA.

Purser, M.D., R. Simmonds, S. Brunzell, and D.D. Wilcox. 2003. Classification and analysis of 2001 land cover: Snohomish County, WA. Snohomish County, Department of Public Works, Surface Water Management, Everett, WA. www.co.snohomish.wa.us/publicwk/swm/publications/2003-02LandCoverAsOfAug2001/+Index.htm

Quiqley, T.M, R.A. Gravenmier, and R.T. Graham. 2001. The Interior Columbia Basin Ecosystem Management Project (ICBEMP): project data. Station Misc. Portland OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Rishel, G.B., J.A. Lynch, and E.S. Corbett. 1982. Seasonal stream temperature changes following forest harvesting. Journal of Environmental Quality 11(1):112-116.

Rosgen, D. 1996. Applied river morphology. Wildland Hydrology publishers, Pagosa Springs, CO.

Sinokrot, B.A. and H.G. Stefan. 1993. Stream temperature dynamics: measurements and modeling. Water Resources Research. Vol 29, No. 7, pp. 2299-2312.

Spence, B.C., G.A., Lomnicky, R.M. Hughes, and R.P. Novitzki. 1996. An ecosystem approach to salmonid conservation. Report number TR-4501-96-6057. Management Technology Environmental Services Corp., Corvallis, OR.

Steinblums, I., H. Froehlich, and J. Lyons. 1984. Designing stable buffer strips for stream protection. Journal of Forestry 821(1): 49-52.

Sullivan, K., J. Tooley, K. Doughty, J. Caldwell, and P. Knudsen. 1990. Timber/Fish/Wildlife, Evaluation of prediction models and characterization of stream temperature regimes in Washington, Data appendix. Report number TFW-WQ3-90-006. Washington State Department of Natural Resources, Olympia, WA.

Swift, L.W. and J.B. Messer. 1971. Forest cuttings raise water temperatures of a small stream in the southern Appalachians. Journal of Soil and Water Conservation 26:11-15.

Teti, P., 2001. A new instrument for measuring shade provided by overhead vegetation. Caribou Forest Region Research Section, British Columbia Ministry of Forests, Extension note No. 34, http://www.for.gov.bc.ca/cariboo/research/extnotes/extnot34.htm

Theurer, F.D. K.A. Voos, and W.J. Miller. 1984. Instream water temperature model, instream flow information paper 16. Western Energy and Land Use Team, Division of Biological Services, Research and Development, U.S. Fish and Wildlife Services. FWS/OBS-84/15.

Thomann, R.V. and J.A. Mueller. 1987. Principles of surface water quality modeling and control. Harper and Row, Publishers, Inc., New York, NY.

Thornburgh, K. 1995. Water quality monitoring in the Stillaguamish clean water district: Results of surface water management monitoring: 1994-1995. Snohomish County, Department of Public Works, Surface Water Management, Everett, WA.

Thornburgh, K. 1996. Snohomish County: Ambient water quality monitoring: Summary report for 1992-1995. Snohomish County, Department of Public Works, Surface Water Management, Everett, WA.

USGS. 1997. The ground-water system and ground water quality in western Snohomish County, Washington. U.S. Geological Survey, Water Resources Investigations Report 96-4312, Tacoma, WA.

USGS 1999. Washington Land Cover Data Set. U.S. Geological Survey. http://edcwww.cr.usgs.gov/programs/lccp/nationallandcover.html

Wenger, S. 1999. A review of the scientific literature on riparian buffer width, extent, and vegetation. Office of Public Service and Outreach, Institute of Ecology, University of Georgia, Athens, GA.

Appendices

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Appendix A. Instream water temperature standard exceedances and station disposition report for the 2001 Stillaguamish Temperature TMDL

This appendix presents the daily temperature standard exceedances of the maximum daily temperature for each instream tidbit station maintained by the Department of Ecology in this 2001 study. The stations presented include data from the continuous flow gages (continuous temperatures were reported by the stream hydrology unit) and data from the ambient monitoring stations (continuous instream temperatures using same protocols and type of equipment used in the TMDL study). Station descriptors and any data qualifiers are included in the paragraphs following the total exceedances for each station.

Station 05A01

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**0**
Max Daily Temperature Threshold of 18°C	**0**

This station was located at the Stillaguamish Tribe's fish hatchery on Armstrong Creek, adjacent to the spot where the continuous data logger was placed (August 2000 - April 2001). This location is about 30 feet from the outlet of the hatchery tanks. The tribe draws groundwater from a well to fill and refresh the hatchery tanks on-site; so the temperature of Armstrong is influenced by the hatchery. No data need to be qualified.

Station 05B01

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**0**
Max Daily Temperature Threshold of 18°C	**0**

This station was located under the Hwy 530 bridge over Boulder River. The station was missing when checked on 9/6 so there is a period of instream temperature data from 7/26-9/6 that was lost. This was the critical period for instream temperature, so it is important to note that although there were not temperature exceedances recorded during the other parts of the study period, there are no data for August which is usually when the instream temperatures are highest.

Station 05C01

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**48**
Max Daily Temperature Threshold of 18°C	**25**

This station was located on the right bank of Canyon Creek at the public fishing entrance on Canyon Creek Road, approximately .25 miles upstream from Canyon Creek falls. No problems were encountered with the temperature stations, and no data need to be qualified.

Station 05D01

	Total Daily Exceedances	
Max Daily Temperature Threshold of 16°C	**63**	**66 (continuous flow gage temp.)**
Max Daily Temperature Threshold of 18°C	**30**	**38 (continuous flow gage temp.)**

This station was located on Deer Creek, as entered from Lake Cavanaugh Road and approximately 0.25 mile upstream of the continuous flow gage in Oso. The relative humidity sensor was not launched properly, and the air temperature and relative humidity data were not recorded between field checks on 6/20 - 7/26; however, the instream temperature data during this period are valid. No temperature data need qualification.

Station 05D03

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**44**
Max Daily Temperature Threshold of 18°C	**31**

This station was located on Deer Creek approximately 0.15 mile upstream from the mouth of Little Deer Creek. Access was achieved through an old forest road on the south side of Deer Creek. There were no problems encountered with either temperature datalogger, and no data need to be qualified.

Station 05D04

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**2**
Max Daily Temperature Threshold of 18°C	**0**

This station was located on Deer Creek approximately 100 feet upstream of the FR 1820 bridge. This station was vandalized sometime between 7/5 and 8/13, and no instream temperature data were recovered during this period. The tidbit was found to be dry during the download check on 7/5, and the new station (later vandalized) was placed within 10 feet of the original location. The replacement instream tidbit installed on 8/13 was in the same location as the vandalized tidbit, but no further problems were encountered with either tidbits.

Station 05F01

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**0**
Max Daily Temperature Threshold of 18°C	**0**

The location of this station was under the Hwy 530 bridge in French Creek. The instream temperature data are all good; however, the air tidbit was disturbed from vegetation clearing by DOT under the bridge and was found unshaded on 9/20. Slightly higher air temperatures may have been recorded between 7/26-9/20 as a result of being unshaded.

Station 05J01

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**58**
Max Daily Temperature Threshold of 18°C	**20**

This station was located about 20 feet upstream of the mouth of Jim Creek in a location where there was no mixing with the South Fork Stillaguamish. The location of the instream tidbit was moved another 20 feet upstream from the originally installed location because of lowering water depths. No other problems were encountered at this station.

Station 05LD01

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**38**
Max Daily Temperature Threshold of 18°C	**26**

This station was located approximately 450 feet upstream from the mouth of Little Deer Creek, near the remains of an old bridge. There was no clear indication of the instream tidbit going dry during the study period.

Station 05M01

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**3 (4 not tidally corrected)**
Max Daily Temperature Threshold of 18°C	**0 (0 not tidally corrected)**

This station was located on Hat Slough at the river crossing on Marine View Drive. The only instream temperature data retrieved was for the period of 6/5 - 6/21. The instream tidbit was pulled out by fishermen (direct communication with a fisherman at the site), but the tidbit was not recovered. Another instream tidbit was installed within 30 feet of the original site, but the river stage was too high to recover that by 10/17, and the instream tidbit will not be removed until the stage returns to lower flow conditions. This station was affected by tidal exchanges that had a significant effect on instream temperature in this reach as well as river height that may have exposed the instream tidbit during lower low tides.

Station 05M02

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**47 (47 not tidally corrected))**
Max Daily Temperature Threshold of 18°C	**23 (23 not tidally corrected)**

This station was located approximately 100 feet downstream of the bridge crossing of the mainstem Stillaguamish River and Larson Road. This station was affected by tidal exchanges, and the instream tidbit was found dry on 8/6. The tidbit was installed in deeper water on 8/6 and was not found dry during subsequent download checks. It is possible that many of the higher temperatures recorded during low tides in July (when the river was also low) were not recording instream temperatures. The instream tidbit was not able to be removed on 10/16, so data from 9/19 to present will not be recovered until spring/summer in 2002.

Station 05M03

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**41 (42 not tidally corrected)**
Max Daily Temperature Threshold of 18°C	**24 (24 not tidally corrected)**

This station was located near the railroad crossing with the mainstem Stillaguamish near Norman Road. This station was affected by tidal exchanges, and the instream tidbit was found dry on 8/6. The tidbit was installed in deeper water on 8/6 and was not found dry during subsequent download checks. It is possible that many of the higher temperatures recorded during low tides from mid-June to 8/6 (when the river was also low) were not recording instream temperatures.

Station 05M04

This station was located on the mainstem Stillaguamish River at the public fishing access on 27th Avenue. The instream tidbit could not be found during the download check on 9/19. This location was frequently visited by fishermen, so the tidbit could have been easily snagged and vandalized by fishing. A replacement tidbit was not installed since the critical instream temperature period had already passed.

Station 05NF01

This station was located on the North Fork Stillaguamish at Twin Rivers Park approximately 1000 feet from the confluence with the South Fork, and accessed by Twin Rivers Park. No instream tidbits were recovered from this station. Replacements were attempted twice, but the instream tidbits were never recovered from this site.

Station 05NF02

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**56**
Max Daily Temperature Threshold of 18°C	**29**

This station was located on the North Fork Stillaguamish River approximately 1,000 feet upstream of the Cicero bridge on Hwy 530. Another tidbit was buried just below the streambed to assess the temperature of the water in the hyporheic zone within 1 foot of the instream tidbit. No problems were encountered with any tidbit at this site. Both the instream and hyporheic tidbits were not removed in October due to high water.

Station 05NF03

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**13**
Max Daily Temperature Threshold of 18°C	**0**

This station was located approximately 20 feet upstream of the 221st Street bridge over the North Fork Stillaguamish in the town of Oso. Vandalism and storm events were problems that continually plagued this site. The instream tidbit was lost twice, and the air tidbit was pulled on 8/28. No instream tidbit was replaced because the critical temperature period had passed.

However, it was decided to be replaced on 9/5 and instream temperature data were retrieved from 9/5-10/15. The total temperature exceedances above occurred after 9/5.

Station 05NF04

This station was located on the North Fork Stillaguamish River in Hazel. The instream tidbit could not be found on 8/28, so another tidbit was installed along with a hyporheic tidbit. Removal of the instream station occurred on 10/15, but the download file for the instream tidbit was corrupted and unusable. There are no instream temperature data for this station.

Station 05NF05

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**23**
Max Daily Temperature Threshold of 18°C	**0**

This station was located on the North Fork Stillaguamish River adjacent to a home on 311th Street off of Swede Heaven Road. No problems with either tidbit occurred during the study, and no data need to be qualified.

Station 05NF06

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**21**
Max Daily Temperature Threshold of 18°C	**4**

This station was located on the North Fork Stillaguamish River approximately 150 feet upstream of a bridge crossing from an abandoned forest road next to the power substation near Darrington and Hwy 530. On 7/26 the instream tidbit was found nearly, but not completely, exposed to air. The data for the previous three days were excluded from the data set (7/23 00:00 - 7/26 12:00).

Station 05NF07

	Total Daily Exceedances	
Max Daily Temperature Threshold of 16°C	**33**	**25 (continuous flow gage temp.)**
Max Daily Temperature Threshold of 18°C	**15**	**6 (continuous flow gage temp.)**

This station was located on the North Fork Stillaguamish River approximately 1,500 feet upstream of the mouth of Crevice Creek; access was FR 2820. A continuous flow gage was located within 20 feet of the instream tidbit. There were no problems with either tidbit, and no data need to be qualified.

Station 05P01

	Total Daily Exceedances	
Max Daily Temperature Threshold of 16°C	**88**	**62 (continuous flow gage temp.)**
Max Daily Temperature Threshold of 18°C	**48**	**29 (continuous flow gage temp.)**

This station was located on Pilchuck Creek approximately 200 feet downstream of the Old 99 bridge next to the I-5 southbound lanes. A continuous flow gage was also located about 20 feet upstream of the instream tidbit. The instream tidbit was moved to a deeper location on 7/26 to keep it from going dry. None of the data need to be qualified.

Station 05P02

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**67**
Max Daily Temperature Threshold of 18°C	**32**

This station was located approximately 30 feet downstream of the Hwy 9 bridge crossing with Pilchuck Creek in the main channel on the left bank. No problems were encountered with this station, and none of the data need to be qualified. The instream tidbit was not removed until 11/9.

Station 05P03

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**56**
Max Daily Temperature Threshold of 18°C	**27**

This station was located on Pilchuck Creek approximately 0.8 mile upstream from Pilchuck Falls (unnamed forest road that passes under BPA lines). During post-season calibration, the air tidbit was operating outside of the accuracy specifications for the instrument as given by the manufacturer (ice bath mean temp. was 0.37°Celsius and the acceptable limit is ± 0.2°Celsius). The temperatures from the instream tidbit during the period 7/20 to 7/26 appear to be due to the tidbit drying up; data for this time period were excluded.

Station 05P04

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**35**
Max Daily Temperature Threshold of 18°C	**15**

This station was located on Pilchuck Creek approximately 1,000 feet downstream of the mouth of Bear Creek, and accessed directly by Lake Cavanaugh Road. The instream tidbit was found dry on 7/27, and the data from 6/21-7/27 at 9:30am were excluded from the data set. The rest of the study period looked fine.

Station 05SF02

	Total Daily Exceedances	
Max Daily Temperature Threshold of 16°C	**35**	**72 (continuous flow gage temp.)**
Max Daily Temperature Threshold of 18°C	**23**	**40 (continuous flow gage temp.)**

This station was located on the South Fork Stillaguamish River at River Meadows Park. A continuous flow gage was also located at this site within 20 feet of the instream tidbit and recorded temperatures for the entire study period. Relative humidity was measured alongside air temperature. The data file from 6/22 - 7/24 for the instream tidbit was lost. The instream tidbit was not found during the removal on 10/16. This is likely due to the large amount of pink salmon spawning in this reach and turning the streambed over, loosening the tidbit and anchor enough for the river to pull it out and move it downstream.

Station 05SF03

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**10**
Max Daily Temperature Threshold of 18°C	**2**

This station was located on the South Fork Stillaguamish River approximately 4.25 miles downstream from the Jordan Road bridge crossing. The instream tidbit was lost for the majority of the summer from 6/8 - 9/10, but was replaced on 9/10 and has instream temperature data until 10/17.

Station 05SF04

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**25**
Max Daily Temperature Threshold of 18°C	**15**

This station was located on the South Fork Stillaguamish River at Robe, and was accessed where the river flows near Mountain Loop Hwy. Instream temperature data from 8/1 - 8/21 appear to be when the tidbit was dry; these data were excluded from analysis. No other data need to be qualified.

Station 05SF05

	Total Daily Exceedances	
Max Daily Temperature Threshold of 16°C	**46**	**13 (continuous flow gage temp.)**
Max Daily Temperature Threshold of 18°C	**20**	**7 (continuous flow gage temp.)**

This station was located at the Verlot campground on the South Fork Stillaguamish River (accessed from campsite #11). A continuous flow gage was also located at this site on the left bank. A hyporheic tidbit was installed on 8/28 but was not retrieved in October because the water was too high. Relative humidity was recorded along with air temperature from 7/24 - 10/17. None of the temperature data need to be qualified.

Station 05SQ01

	Total Daily Exceedances
Max Daily Temperature Threshold of 16°C	**7**
Max Daily Temperature Threshold of 18°C	**0**

This station was located in Squire Creek at the location where the BPA lines cross the creek. No problems were encountered with the instream tidbit. However, the data file downloaded from the air tidbit on 9/11 was corrupted, and air temperature data from 7/25 - 9/11 was not recovered. No other data need to be qualified.

Ambient Monitoring Stations

The following temperature stations were maintained by the Environmental Monitoring & Trends Section of Ecology's Environmental Assessment Program.

Station 05A070

	Total
Max Daily Temperature Threshold of 16°C	**74**
Max Daily Temperature Threshold of 18°C	**47**

This station was located on the mainstem Stillaguamish River crossing with the I-5 bridge just north of the Arlington-Silvana exit 208.

Station 05A090

	Total
Max Daily Temperature Threshold of 16°C	**71**
Max Daily Temperature Threshold of 18°C	**50**

This station was located on the South Fork Stillaguamish River crossing with the SR 530 bridge at the Twin Rivers Park, Arlington.

Station 05B070

	Total
Max Daily Temperature Threshold of 16°C	**64**
Max Daily Temperature Threshold of 18°C	**27**

This station was located on the left bank of the North Fork Stillaguamish River under the SR 530 bridge at Cicero.

Station 05A110

	Total
Max Daily Temperature Threshold of 16°C	**27**
Max Daily Temperature Threshold of 18°C	**5**

This station was located on the South Fork of the Stillaguamish River just upstream from the fishway at the crossing with Mountain Loop Highway.

Appendix B. Flow data from Ecology’s gaging stations.

Table B-1. Daily flows (cms) in the Stillaguamish River watershed from May through November 2001.

date	South Fork Stillaguamish River at Verlot	South Fork Stillaguamish River at River Meadows	North Fork Stillaguamish River at Crevice Creek	Deer Creek at Oso	Pilchuck Creek near mouth	North Fork Stillaguamish River (USGS 12167000)
5/23/01					3.953	60.60
5/24/01					3.743	59.47
5/25/01					3.346	49.55
5/26/01					3.001	45.87
5/27/01					2.681	42.19
5/28/01					2.481	39.36
5/29/01					5.129	39.36
5/30/01					4.270	32.56
5/31/01					3.205	28.60
6/1/01					2.684	34.83
6/2/01					12.082	58.90
6/3/01					15.583	55.50
6/4/01					7.448	37.10
6/5/01					5.339	31.15
6/6/01		27.84			5.613	30.02
6/7/01		28.02	2.063		5.330	29.45
6/8/01		27.74	2.122		4.004	28.88
6/9/01		38.23	2.605		5.850	36.53
6/10/01		35.45	2.187		6.734	34.55
6/11/01		47.57	4.390		26.248	71.92
6/12/01		76.66	5.354			97.98
6/13/01	18.27	51.30	4.127			60.03
6/14/01	16.70	36.82	3.281			43.89
6/15/01	15.07	31.66	2.780			37.10
6/16/01	13.84	27.83	2.444			32.85
6/17/01	13.00	25.38	2.182			30.02
6/18/01	12.20	23.31	1.961			27.24
6/19/01	12.85	23.38	1.815			26.33
6/20/01	14.56	25.96	1.727			26.93
6/21/01	15.51	27.85	1.621	4.92		27.58
6/22/01	15.32	27.46	1.497	4.69		27.27
6/23/01	13.69	24.90	1.356	4.16		25.46
6/24/01	11.64	20.90	1.242	3.63		22.88
6/25/01	13.32	26.92	1.196	4.32		23.90
6/26/01	11.27	22.26	1.089	3.77		21.69
6/27/01	12.68	21.75	1.158	3.91		21.72
6/28/01	24.36	44.94	1.346	7.52		34.26
6/29/01	15.26	29.96	1.045	4.87		26.62
6/30/01	12.87	23.60	0.937	3.79		22.77
7/1/01	12.19	21.77	0.871	3.36		21.46
7/2/01	11.06	19.88	0.809	3.08		20.05
7/3/01	10.86	19.03	0.757	2.96		19.40

Table B-1. Daily flows (cms) in the Stillaguamish River watershed from May through November 2001.

date	South Fork Stillaguamish River at Verlot	South Fork Stillaguamish River at River Meadows	North Fork Stillaguamish River at Crevice Creek	Deer Creek at Oso	Pilchuck Creek near mouth	North Fork Stillaguamish River (USGS 12167000)
7/4/01	11.45	19.72	0.721	3.00		19.65
7/5/01	10.98	19.46	0.676	2.79		19.51
7/6/01	9.28	16.67	0.635	2.46		17.61
7/7/01	8.38	15.11	0.606	2.28		16.54
7/8/01	8.30	14.72	0.578	2.18		16.03
7/9/01	8.47	14.85	0.557	2.26		16.00
7/10/01	8.67	15.04	0.536	2.35		16.20
7/11/01	8.38	14.54	0.513	2.21		15.72
7/12/01	7.75	13.66	0.493	2.02		15.01
7/13/01	7.04	12.44	0.476	1.93		14.13
7/14/01	6.59	11.85	0.458	1.83		13.48
7/15/01	5.95	10.96	0.460	1.72		12.77
7/16/01	6.32	11.17	0.503	1.85		13.08
7/17/01	7.57	13.58	0.500	2.18	2.045	14.27
7/18/01	7.20	14.89	0.520	2.61	2.091	14.36
7/19/01	5.88	12.54	0.470	2.23	1.498	13.25
7/20/01	5.22	10.63	0.443	1.82	1.165	12.01
7/21/01	5.10	9.94	0.424	1.62	0.834	11.44
7/22/01	5.10	9.68	0.421	1.56	0.702	11.19
7/23/01	5.10	9.48	0.410	1.55	0.695	11.02
7/24/01	5.10	9.17	0.396	1.52	0.652	10.79
7/25/01	5.10	9.02	0.381	1.42	0.580	10.48
7/26/01	5.10	8.56	0.368	1.34	0.509	10.02
7/27/01	12.50	8.23	0.361	1.25	0.424	9.66
7/28/01	16.43	27.55	0.836	6.10	1.841	21.69
7/29/01	10.05	36.60	0.557	4.05	2.522	20.39
7/30/01	8.15	18.70	0.440	2.45	1.412	14.72
7/31/01	7.29	13.70	0.402	1.91	0.950	12.40
8/1/01	6.30	11.66	0.383	1.67	0.772	11.21
8/2/01	5.87	10.71	0.376	1.61	0.731	10.70
8/3/01	5.69	11.03	0.377	1.63	0.655	11.16
8/4/01	5.61	11.19	0.388	1.83	0.805	11.69
8/5/01	5.08	10.12	0.367	1.54	0.866	10.70
8/6/01	4.81	9.40	0.377	2.14	0.913	11.04
8/7/01	4.73	9.32	0.368	1.98	1.337	11.16
8/8/01	4.60	8.77	0.351	1.55	0.928	10.08
8/9/01	4.51	8.30	0.337	1.42	0.722	9.34
8/10/01	4.31	7.98	0.327	1.33	0.601	8.95
8/11/01	4.15	7.68	0.320	1.23	0.511	8.69
8/12/01	3.90	7.44	0.316	1.18	0.455	8.44
8/13/01	3.63	7.17	0.313	1.13	0.367	8.27
8/14/01	3.51	7.08	0.309	1.08	0.367	8.13
8/15/01	3.41	6.84	0.306	1.05	0.326	7.99
8/16/01	3.32	6.80	0.304	1.02	0.272	7.90
8/17/01	3.22	6.77	0.303	1.02	0.275	7.96
8/18/01	3.00	6.51	0.303	0.99	0.266	7.65
8/19/01	2.74	6.23	0.301	0.96	0.292	7.28

Table B-1. Daily flows (cms) in the Stillaguamish River watershed from May through November 2001.

date	South Fork Stillaguamish River at Verlot	South Fork Stillaguamish River at River Meadows	North Fork Stillaguamish River at Crevice Creek	Deer Creek at Oso	Pilchuck Creek near mouth	North Fork Stillaguamish River (USGS 12167000)
8/20/01	2.50	6.00	0.298	0.91	0.286	6.91
8/21/01	3.64	6.25	0.320	1.22	0.313	7.62
8/22/01	34.51	71.31	7.893	34.87	19.396	90.61
8/23/01	35.90	124.20	6.699	26.84	21.904	106.47
8/24/01	18.54	40.71	3.002	13.56	7.902	49.84
8/25/01	12.20	23.78	1.701	7.89	4.463	29.45
8/26/01	9.30	17.44	1.207	5.60	2.739	22.57
8/27/01	7.66	14.28	0.957	4.33	1.963	19.06
8/28/01	6.65	12.44	0.818	3.58	1.571	16.79
8/29/01	5.98	11.21	0.727	3.08	1.297	15.21
8/30/01	5.47	10.32	0.659	2.71	1.041	13.99
8/31/01	5.25	9.89	0.625	2.64	0.859	13.31
9/1/01	6.54	11.36	0.894	7.72	0.882	19.68
9/2/01	7.65	15.49	0.824	7.25	2.053	22.99
9/3/01	6.13	11.55	0.647	4.55	1.220	16.34
9/4/01	5.95	11.43	0.589	4.04	1.325	15.26
9/5/01	5.08	9.95	0.540	3.31	1.071	13.54
9/6/01	4.63	9.14	0.508	2.92	0.966	12.43
9/7/01	4.39	8.75	0.489	2.71	0.881	11.69
9/8/01	4.06	8.28	0.463	2.41	0.826	10.90
9/9/01	3.75	7.74	0.440	2.16	0.754	10.39
9/10/01	3.49	7.37	0.422	1.96	1.225	9.66
9/11/01	3.27	7.05	0.408	1.80	1.450	9.15
9/12/01	3.10	6.80	0.395	1.68	1.391	8.86
9/13/01	2.98	6.55	0.385	1.57	1.310	8.58
9/14/01	2.89	6.48	0.375	1.49	1.236	8.33
9/15/01	2.82	6.23	0.369	1.42	1.173	8.18
9/16/01	2.76	6.23	0.363	1.36	1.086	7.99
9/17/01	2.66	6.14	0.357	1.31	1.048	7.79
9/18/01	2.55	5.95	0.355	1.28	1.013	7.56
9/19/01	2.46	5.95	0.349	1.26	0.984	7.42
9/20/01	2.34	5.74	0.343	1.21	0.957	7.16
9/21/01	2.34	5.78	0.383	1.30	0.951	7.28
9/22/01	2.30	5.96	0.396	1.50	1.048	7.62
9/23/01	2.27	5.69	0.353	1.25	1.027	7.28
9/24/01	2.27	5.45	0.337	1.14	0.897	6.97
9/25/01	2.28	5.38	0.330	1.09	0.846	6.82
9/26/01	11.84	12.82	0.413	4.78	1.048	11.44
9/27/01	14.88	35.68	0.816	8.19	6.949	25.20
9/28/01	7.23	14.08	0.423	3.44	3.397	13.56
9/29/01	5.25	10.08	0.371	2.40	2.452	10.45
9/30/01	4.27	8.52	0.350	1.94	2.005	9.20
10/1/01	3.69	7.67	0.339	1.67	1.742	
10/2/01	3.26	7.04	0.330	1.51	1.577	
10/3/01	2.94	6.58	0.323	1.39	1.512	
10/4/01	2.67	6.28	0.315	1.28	1.403	
10/5/01	2.43	6.00	0.307	1.19	1.446	

Table B-1. Daily flows (cms) in the Stillaguamish River watershed from May through November 2001.

date	South Fork Stillaguamish River at Verlot	South Fork Stillaguamish River at River Meadows	North Fork Stillaguamish River at Crevice Creek	Deer Creek at Oso	Pilchuck Creek near mouth	North Fork Stillaguamish River (USGS 12167000)
10/6/01	2.40	5.94	0.307	1.19	1.458	
10/7/01	2.53	6.16	0.312	1.26	1.449	
10/8/01	4.02	7.00	0.335	1.60	1.468	
10/9/01	6.35	10.78	0.355	1.89	1.613	
10/10/01	7.70	10.77	0.538	3.09	1.793	
10/11/01	28.01	45.39	1.667	11.56	6.582	
10/12/01	30.21	50.22	2.116	18.69	9.487	
10/13/01	33.45	75.43	1.943	15.18	11.908	
10/14/01	38.06	87.09	2.997	21.63	19.751	
10/15/01	21.74	42.99	1.610	10.98	9.805	
10/16/01	15.74	28.60	1.208	8.61	6.483	
10/17/01	16.50	32.86	2.060	9.62	7.451	
10/18/01			1.771	7.40	5.631	
10/19/01					29.960	
10/20/01					14.707	
10/21/01					9.672	
10/22/01					34.078	
10/23/01					39.051	
10/24/01					22.648	
10/25/01					40.779	
10/26/01					20.828	
10/27/01					33.287	
10/28/01					18.533	
10/29/01					12.327	
10/30/01					10.256	
10/31/01					23.093	
11/1/01					17.642	
11/2/01					13.397	
11/3/01					10.728	
11/4/01					8.793	
11/5/01					9.982	
11/6/01					7.949	
11/7/01					6.740	
11/8/01					6.545	
11/9/01					6.171	
11/10/01					5.852	
11/11/01					5.702	
11/12/01					5.295	
11/13/01					5.634	
11/14/01					51.510	
11/15/01					95.112	

Appendix C. Load allocations for effective shade for the Stillaguamish River, South Fork Stillaguamish River, North Fork Stillaguamish River, Deer Creek, and Pilchuck Creek.

Table C-1. Load allocations for effective shade in the Stillaguamish River for the condition of mature riparian vegetation.

Distance from mouth to upstream segment boundary (Km)	Distance from mouth to downstream segment boundary (Km)	Load allocation for effective shade on August 1 (percent)	Load allocation for daily average shortwave solar radiation on August 1 (W/m2)
26.8	26.3	14%	301
26.3	25.8	14%	300
25.8	25.3	31%	240
25.3	24.8	50%	174
24.8	24.3	35%	227
24.3	23.8	18%	286
23.8	23.3	32%	236
23.3	22.8	37%	219
22.8	22.3	41%	207
22.3	21.8	34%	230
21.8	21.3	28%	251
21.3	20.8	39%	211
20.8	20.3	46%	189
20.3	19.8	44%	196
19.8	19.3	40%	208
19.3	18.8	32%	237
18.8	18.3	31%	241
18.3	17.8	23%	267
17.8	17.3	9%	318
17.3	16.8	10%	313
16.8	16.3	25%	262
16.3	15.8	20%	280
15.8	15.3	15%	296
15.3	14.8	27%	253
14.8	14.3	43%	199
14.3	13.8	20%	280
13.8	13.3	42%	200
13.3	12.8	55%	157
12.8	12.3	27%	255
12.3	11.8	39%	211
11.8	11.3	41%	207
11.3	10.8	52%	169
10.8	10.3	50%	176
10.3	9.8	29%	246
9.8	9.3	11%	311
9.3	8.8	23%	269
8.8	8.3	30%	243
8.3	7.8	19%	281
7.8	7.3	13%	304
7.3	6.8	27%	254
6.8	6.3	30%	243
6.3	5.8	19%	281
5.8	5.3	12%	305
5.3	4.8	14%	300
4.8	4.3	16%	292
4.3	3.8	27%	255
3.8	3.3	15%	297
3.3	2.8	14%	301
2.8	2.3	13%	304
2.3	1.8	23%	268
1.8	1.3	22%	270
1.3	0.8	26%	258
0.8	0.0	12%	306

Table C-2. Load allocations for effective shade in the South Fork Stillaguamish River for the condition of mature riparian vegetation.

Distance from mouth to upstream segment boundary (Km)	Distance from mouth to downstream segment boundary (Km)	Load allocation for effective shade on August 1 (percent)	Load allocation for daily average shortwave solar radiation on August 1 (W/m2)
46.9	46.5	54%	159
46.5	46.0	60%	139
46.0	45.5	38%	215
45.5	45.0	29%	249
45.0	44.5	25%	261
44.5	44.0	43%	199
44.0	43.5	36%	221
43.5	43.0	45%	193
43.0	42.5	28%	251
42.5	42.0	45%	190
42.0	41.5	38%	217
41.5	41.0	38%	216
41.0	40.5	24%	263
40.5	40.0	32%	235
40.0	39.5	48%	183
39.5	39.0	56%	152
39.0	38.5	54%	162
38.5	38.0	59%	142
38.0	37.5	56%	153
37.5	37.0	44%	196
37.0	36.5	71%	102
36.5	36.0	58%	147
36.0	35.5	64%	126
35.5	35.0	58%	145
35.0	34.5	60%	138
34.5	34.0	62%	131
34.0	33.5	65%	121
33.5	33.0	65%	122
33.0	32.5	63%	129
32.5	32.0	71%	101
32.0	31.5	73%	94
31.5	31.0	75%	88
31.0	30.5	56%	154
30.5	30.0	65%	124
30.0	29.5	68%	111
29.5	29.0	60%	139
29.0	28.5	76%	83
28.5	28.0	67%	114
28.0	27.5	66%	119
27.5	27.0	70%	104
27.0	26.5	61%	137
26.5	26.0	55%	156
26.0	25.5	40%	209
25.5	25.0	47%	183
25.0	24.5	34%	229
24.5	24.0	28%	250
24.0	23.5	32%	237
23.5	23.0	43%	199
23.0	22.5	51%	171
22.5	22.0	45%	191
22.0	21.5	52%	169
21.5	21.0	35%	227
21.0	20.5	43%	197
20.5	20.0	45%	193
20.0	19.5	42%	200
19.5	19.0	34%	230
19.0	18.5	28%	250
18.5	18.0	32%	238
18.0	17.5	42%	203
17.5	17.0	36%	224
17.0	16.5	55%	156
16.5	16.0	50%	173
16.0	15.5	49%	176
15.5	15.0	53%	163
15.0	14.5	48%	182
14.5	14.0	41%	207
14.0	13.5	42%	204
13.5	13.0	65%	123
13.0	12.5	54%	160
12.5	12.0	37%	220
12.0	11.5	45%	190
11.5	11.0	50%	173
11.0	10.5	43%	200
10.5	10.0	51%	170
10.0	9.5	51%	172
9.5	9.0	47%	183
9.0	8.5	53%	163
8.5	8.0	50%	176
8.0	7.5	53%	164
7.5	7.0	21%	276
7.0	6.5	28%	251
6.5	6.0	37%	218
6.0	5.5	33%	234
5.5	5.0	12%	305
5.0	4.5	20%	280
4.5	4.0	24%	263
4.0	3.5	39%	212
3.5	3.0	34%	231
3.0	2.5	32%	235
2.5	2.0	23%	267
2.0	1.5	27%	255
1.5	1.0	38%	216
1.0	0.5	42%	203
0.5	0.0	33%	235

Table C-3. Load allocations for effective shade in the North Fork Stillaguamish River for the condition of mature riparian vegetation.

Distance from mouth to upstream segment boundary (Km)	Distance from mouth to downstream segment boundary (Km)	Load allocation for effective shade on August 1 (percent)	Load allocation for daily average shortwave solar radiation on August 1 (W/m2)
63.9	63.2	62%	133
63.2	62.5	61%	137
62.5	61.8	62%	133
61.8	61.1	61%	135
61.1	60.4	62%	132
60.4	59.7	60%	140
59.7	59.0	64%	124
59.0	58.3	61%	136
58.3	57.6	67%	116
57.6	56.9	66%	120
56.9	56.2	65%	124
56.2	55.5	62%	131
55.5	54.8	54%	162
54.8	54.1	63%	128
54.1	53.4	51%	171
53.4	52.7	56%	154
52.7	52.0	68%	111
52.0	51.3	57%	149
51.3	50.6	71%	101
50.6	49.9	62%	131
49.9	49.2	66%	119
49.2	48.5	56%	154
48.5	47.8	59%	142
47.8	47.1	39%	212
47.1	46.4	60%	138
46.4	45.7	50%	173
45.7	45.0	59%	142
45.0	44.3	40%	210
44.3	43.6	59%	144
43.6	42.9	26%	259
42.9	42.2	65%	122
42.2	41.5	66%	118
41.5	40.8	37%	219
40.8	40.1	43%	199
40.1	39.4	40%	209
39.4	38.7	30%	242
38.7	38.0	35%	226
38.0	37.3	46%	188
37.3	36.6	43%	199
36.6	35.9	43%	197
35.9	35.2	34%	230
35.2	34.5	22%	272
34.5	33.8	39%	211
33.8	33.1	39%	213
33.1	32.4	38%	215
32.4	31.7	44%	193
31.7	31.0	46%	187
31.0	30.3	65%	124
30.3	29.6	59%	144
29.6	28.9	63%	130
28.9	28.2	55%	158
28.2	27.5	58%	147
27.5	26.8	38%	217
26.8	26.1	47%	186
26.1	25.4	55%	156
25.4	24.7	55%	156
24.7	24.0	56%	154
24.0	23.3	55%	157
23.3	22.6	37%	219
22.6	21.9	34%	229
21.9	21.2	52%	168
21.2	20.5	42%	202
20.5	19.8	23%	269
19.8	19.1	34%	228
19.1	18.4	43%	198
18.4	17.7	28%	252
17.7	17.0	35%	226
17.0	16.3	30%	244
16.3	15.6	34%	230
15.6	14.9	44%	195
14.9	14.2	26%	259
14.2	13.5	41%	206
13.5	12.8	38%	218
12.8	12.1	39%	213
12.1	11.4	41%	206
11.4	10.7	30%	245
10.7	10.0	37%	220
10.0	9.3	36%	224
9.3	8.6	24%	266
8.6	7.9	31%	241
7.9	7.2	23%	269
7.2	6.5	36%	222
6.5	5.8	36%	222
5.8	5.1	39%	214
5.1	4.4	41%	206
4.4	3.7	53%	163
3.7	3.0	54%	159
3.0	2.3	44%	196
2.3	1.6	48%	181
1.6	0.8	40%	208
0.8	0.0	34%	228

Table C-4. Load allocations for effective shade in Deer Creek for the condition of mature riparian vegetation.

Distance from mouth to upstream segment boundary (Km)	Distance from mouth to downstream segment boundary (Km)	Load allocation for effective shade on August 1 (percent)	Load allocation for daily average shortwave solar radiation on August 1 (W/m2)
33.1	32.6	68%	110
32.6	32.1	73%	94
32.1	31.6	75%	86
31.6	31.1	79%	72
31.1	30.6	69%	107
30.6	30.1	51%	172
30.1	29.6	62%	134
29.6	29.1	81%	68
29.1	28.6	67%	116
28.6	28.1	43%	197
28.1	27.6	66%	119
27.6	27.1	64%	124
27.1	26.6	68%	112
26.6	26.1	64%	124
26.1	25.6	48%	182
25.6	25.1	48%	182
25.1	24.6	61%	135
24.6	24.1	39%	211
24.1	23.6	40%	209
23.6	23.1	50%	173
23.1	22.6	45%	190
22.6	22.1	49%	177
22.1	21.6	48%	181
21.6	21.1	69%	107
21.1	20.6	56%	152
20.6	20.1	61%	136
20.1	19.6	58%	145
19.6	19.1	72%	97
19.1	18.6	66%	118
18.6	18.1	60%	139
18.1	17.6	69%	106
17.6	17.1	39%	211
17.1	16.6	37%	219
16.6	16.1	40%	210
16.1	15.6	77%	81
15.6	15.1	55%	155
15.1	14.6	57%	150
14.6	14.1	45%	191
14.1	13.6	56%	152
13.6	13.1	74%	90
13.1	12.6	73%	95
12.6	12.1	61%	135
12.1	11.6	63%	128
11.6	11.1	59%	143
11.1	10.6	59%	143
10.6	10.1	64%	124
10.1	9.6	67%	114
9.6	9.1	64%	126
9.1	8.6	58%	146
8.6	8.1	51%	169
8.1	7.6	50%	174
7.6	7.1	61%	137
7.1	6.6	55%	155
6.6	6.1	48%	181
6.1	5.6	60%	141
5.6	5.1	41%	205
5.1	4.6	52%	168
4.6	4.1	67%	114
4.1	3.6	71%	101
3.6	3.1	66%	120
3.1	2.6	62%	132
2.6	2.1	58%	147
2.1	1.6	56%	153
1.6	1.1	59%	141
1.1	0.6	58%	145
0.6	0.0	52%	166

Table C-5. Load allocations for effective shade in Pilchuck Creek for the condition of mature riparian vegetation.

Distance from mouth to upstream segment boundary (Km)	Distance from mouth to downstream segment boundary (Km)	Load allocation for effective shade on August 1 (percent)	Load allocation for daily average shortwave solar radiation on August 1 (W/m2)
27.7	27.0	66%	118
27.0	26.5	68%	113
26.5	26.0	62%	132
26.0	25.5	59%	143
25.5	25.0	69%	108
25.0	24.5	77%	79
24.5	24.0	61%	135
24.0	23.5	60%	138
23.5	23.0	67%	115
23.0	22.5	62%	131
22.5	22.0	60%	140
22.0	21.5	76%	85
21.5	21.0	64%	124
21.0	20.5	55%	155
20.5	20.0	65%	122
20.0	19.5	59%	142
19.5	19.0	57%	151
19.0	18.5	60%	139
18.5	18.0	59%	142
18.0	17.5	60%	140
17.5	17.0	59%	143
17.0	16.5	66%	118
16.5	16.0	63%	130
16.0	15.5	67%	115
15.5	15.0	68%	111
15.0	14.5	57%	150
14.5	14.0	58%	145
14.0	13.5	62%	131
13.5	13.0	57%	150
13.0	12.5	57%	150
12.5	12.0	59%	143
12.0	11.5	59%	142
11.5	11.0	53%	165
11.0	10.5	54%	159
10.5	10.0	59%	142
10.0	9.5	64%	127
9.5	9.0	52%	168
9.0	8.5	59%	142
8.5	8.0	50%	173
8.0	7.5	67%	116
7.5	7.0	60%	138
7.0	6.5	60%	138
6.5	6.0	71%	101
6.0	5.5	56%	154
5.5	5.0	66%	118
5.0	4.5	62%	133
4.5	4.0	58%	148
4.0	3.5	69%	107
3.5	3.0	65%	121
3.0	2.5	66%	118
2.5	2.0	62%	133
2.0	1.5	63%	128
1.5	1.0	55%	157
1.0	0.5	66%	117
0.5	0.0	63%	129

Appendix D. Load allocations for effective shade for miscellaneous perennial streams in the Stillaguamish River watershed based on bankfull width and stream aspect.

Stream aspect (degrees from north)	Bankfull width (m)	Effective shade from vegetation (percent) at the stream center at various stream aspects (degrees from N)			Daily average global solar short-wave radiation (W/m2) at the stream center at various stream aspects (degrees from N)		
		0 and 180 deg aspect	45, 135, 225, and 315 deg aspect	90 and 270 deg aspect	0 and 180 deg aspect	45, 135, 225, and 315 deg aspect	90 and 270 deg aspect
0 and 180 deg	1	84.9%	84.2%	84.4%	52	55	54
0 and 180 deg	2	83.6%	83.7%	83.9%	57	57	56
0 and 180 deg	3	83.1%	82.9%	83.5%	59	59	58
0 and 180 deg	4	82.3%	82.4%	83.0%	62	61	59
0 and 180 deg	5	81.7%	81.6%	82.5%	64	64	61
0 and 180 deg	6	81.0%	81.0%	81.9%	66	66	63
0 and 180 deg	7	80.3%	80.3%	81.5%	69	69	65
0 and 180 deg	8	79.6%	79.7%	81.0%	71	71	66
0 and 180 deg	9	78.9%	79.0%	80.4%	73	73	68
0 and 180 deg	10	78.3%	78.3%	79.9%	75	76	70
0 and 180 deg	12	77.0%	76.9%	78.8%	80	80	74
0 and 180 deg	14	75.7%	75.6%	77.6%	85	85	78
0 and 180 deg	16	74.3%	74.3%	76.3%	89	90	83
0 and 180 deg	18	73.1%	72.9%	74.9%	94	94	88
0 and 180 deg	20	71.8%	71.6%	73.3%	98	99	93
0 and 180 deg	25	68.7%	68.3%	68.1%	109	111	111
0 and 180 deg	30	65.7%	64.9%	59.2%	119	122	142
0 and 180 deg	35	62.9%	61.7%	52.1%	129	133	167
0 and 180 deg	40	60.2%	58.5%	46.7%	139	144	186
0 and 180 deg	45	57.6%	55.5%	42.4%	148	155	201
0 and 180 deg	50	55.2%	52.6%	38.9%	156	165	213
0 and 180 deg	55	52.9%	49.9%	35.9%	164	174	223
0 and 180 deg	60	50.8%	47.4%	33.4%	171	183	232
0 and 180 deg	65	48.8%	45.0%	31.3%	178	191	239
0 and 180 deg	70	46.9%	42.8%	29.4%	185	199	246
0 and 180 deg	75	45.1%	40.8%	27.7%	191	206	252
0 and 180 deg	80	43.4%	39.0%	26.3%	197	212	257
0 and 180 deg	85	41.8%	37.3%	24.9%	202	218	261
0 and 180 deg	90	40.4%	35.7%	23.7%	208	224	266
0 and 180 deg	95	39.0%	34.3%	22.7%	212	229	269
0 and 180 deg	100	37.7%	32.9%	21.7%	217	234	273
0 and 180 deg	110	35.3%	30.5%	20.0%	225	242	279
0 and 180 deg	120	33.2%	28.4%	18.5%	233	249	284
0 and 180 deg	130	31.3%	26.6%	17.2%	239	256	288
0 and 180 deg	140	29.6%	25.0%	16.1%	245	261	292
0 and 180 deg	150	28.0%	23.6%	15.1%	251	266	295
0 and 180 deg	160	26.6%	22.3%	14.3%	255	271	298
0 and 180 deg	170	25.4%	21.1%	13.5%	260	275	301
0 and 180 deg	180	24.2%	20.1%	12.8%	264	278	304
0 and 180 deg	190	23.2%	19.2%	12.2%	268	281	306
0 and 180 deg	200	22.2%	18.3%	11.6%	271	284	308
0 and 180 deg	210	21.3%	17.5%	11.1%	274	287	309
0 and 180 deg	220	20.5%	16.8%	10.7%	277	290	311
0 and 180 deg	230	19.7%	16.1%	10.2%	280	292	313
0 and 180 deg	240	19.0%	15.5%	9.8%	282	294	314
0 and 180 deg	250	18.3%	15.0%	9.5%	284	296	315
0 and 180 deg	260	17.7%	14.4%	9.1%	287	298	316
0 and 180 deg	270	17.1%	13.9%	8.8%	289	300	318
0 and 180 deg	280	16.6%	13.5%	8.5%	290	301	319
0 and 180 deg	300	15.6%	12.7%	8.0%	294	304	320