WASHINGTON STATE
DEPARTMENT OF
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Willapa River Watershed Temperature Total Maximum Daily Load Study

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Willapa River Watershed Temperature Total Maximum Daily Load Study

by
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September 2004

Waterbody Numbers: See Table 1

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Abstract

The Willapa River basin contains high quality anadromous fish habitat that supports Fall Chinook, Coho, Fall Chum, and Winter Steelhead. The 303(d) listings for temperature in streams in the basin include the mainstem Willapa River and Fork Creek.

Substantial reductions in water temperature are predicted for hypothetical conditions with mature riparian vegetation, improvements in riparian microclimate, and reduction of channel width. Potential reduced temperatures are predicted to be less than the Class A standard of 18°C in almost all segments of the streams evaluated.

This technical assessment uses effective shade as a surrogate measure of heat flux to fulfill the requirements of the federal Clean Water Act Section 303(d) for a Total Maximum Daily Load (TMDL) for temperature. Effective shade is defined as the fraction of incoming solar shortwave radiation above the vegetation and topography 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 increase channel stability and complexity.

Acknowledgements

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Introduction

The 570 km^2 Willapa River basin lies in Pacific County in Washington State (Figure 1). The Washington State Department of Ecology (Ecology) assessment of the Willapa watershed identified the system as a high priority for development of a Total Maximum Daily Load (TMDL) for temperature. The purpose of this Willapa 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 to periodically 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 the mainstem Willapa River and in Fork Creek[1] for exceeding the water quality standards for temperature (Table 1). In addition to the two segments listed in 1998, this TMDL includes load allocations to address segments that were not listed but were documented as not meeting the water quality standard for temperature in 2001 or 1998 (Pickett, 2000).

Table 1. Summary of watercourse segments included in this TMDL that are either on the 1996 or 1998 303(d) list or on the proposed 2002/2004 list as impaired (Class 5) or a water of concern (Class 2).

Waterbody	T	R	S	New Waterbody ID	Old Waterbody ID	1996 303d list	1998 303d list	Proposed 2002 list
Fork Creek	12N	07W	06	MO06ZS	WA-24-2037	Y	Y	Y (Class 5)
Willapa River	14N	08W	43	YN05JR	WA-24-2020	Y	Y	Y (Class 5)
Willapa River	12N	07W	04	YN05JR	WA-24-2030	Y	N	Y (Class 5)
Half Moon Creek	12N	07W	04	HR47WD	--	N	N	Y (Class 5)
Mill Creek	13N	08W	02	EQ10DO	--	N	N	Y (Class 2)
Fern Creek	12N	07W	02	CO94AN	--	N	N	Y (Class 5)
Wilson Creek	13N	08W	02	RX96AH	--	Y	N	Y (Class 2)

T = township, R = range, S = section

Under the 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, as well as criteria, usually numeric criteria, to achieve those uses.

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[1] The names Fork Creek and Forks Creek in this report refer to the same location. The USGS names database refers to the creek as Fork Creek and the name of the hatchery on that creek as Forks Creek Hatchery; however, other source documents are not consistent in the naming of this creek.

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

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 pollutant sources that cause the problem. The TMDL determines the amount of a given pollutant that can be discharged to the water body and still meet standards, and allocates that load among the various sources. If the pollutant comes from a discrete (point) source such as an industrial facility's discharge pipe, that facility's share of the loading capacity is called a *wasteload allocation*. If a pollutant enters a stream from a diffuse (nonpoint) source, then that share is called a *load allocation.*

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

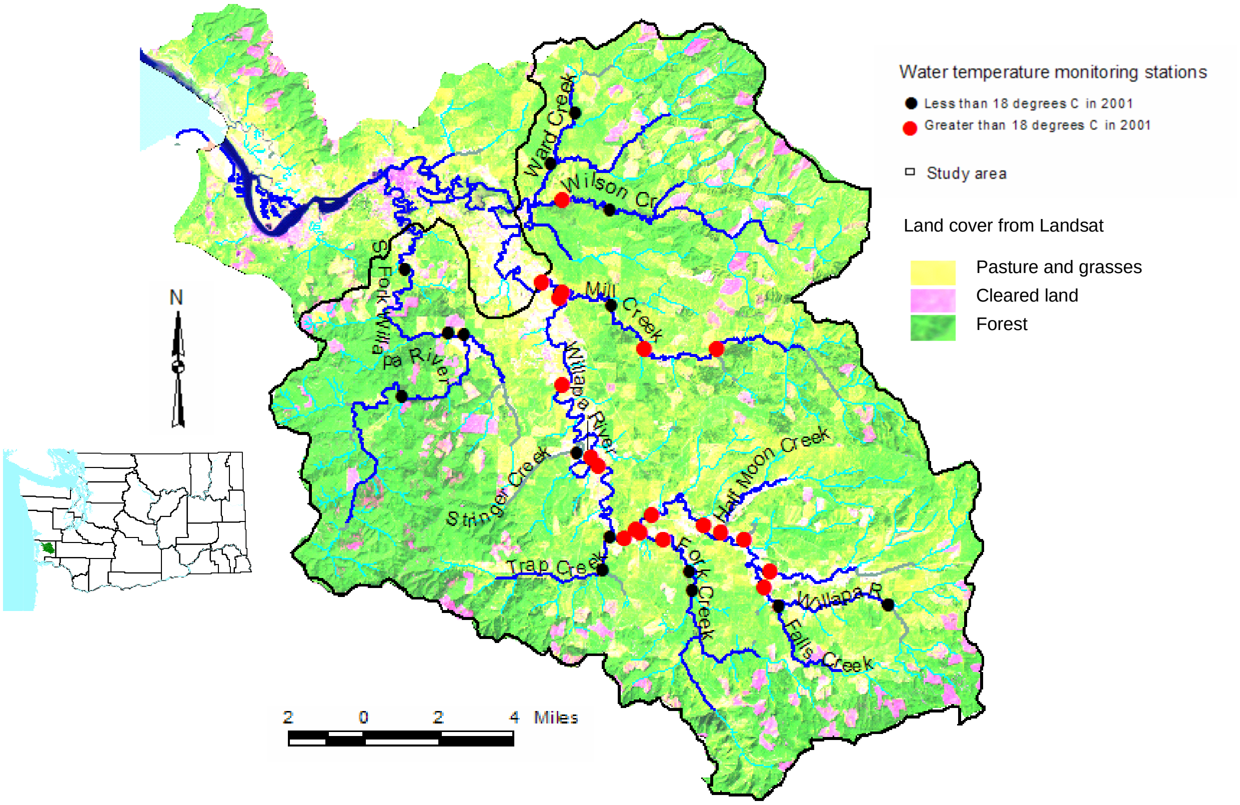

Figure 1. Land cover from satellite image (2000) in the study area of the Willapa River temperature TMDL.

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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, 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.

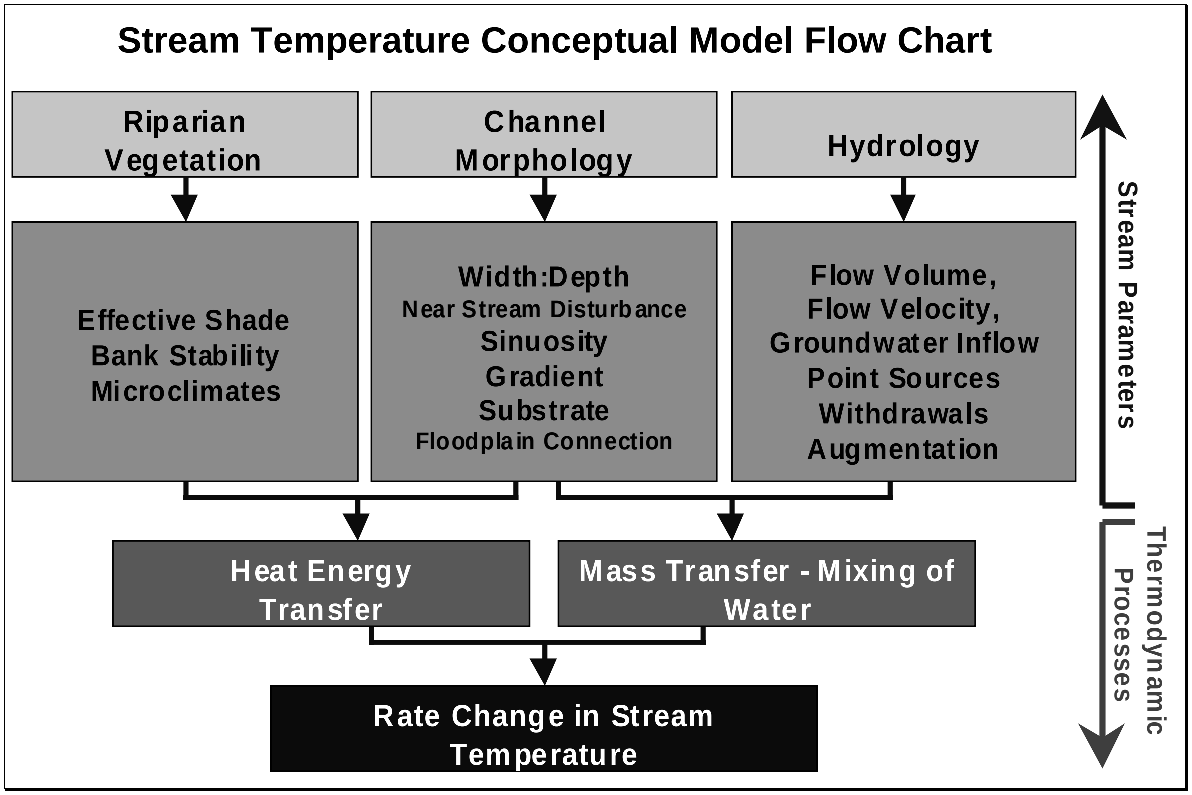

Figure 2. Conceptual model of factors that affect stream temperature.

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

- **Stream depth.** 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 to the flow in the stream and the difference in temperatures between the groundwater and the stream.

Heat budgets and temperature prediction

The transport and fate of heat in natural waters has been the subject of extensive study. Edinger et al. (1974) provide an excellent and comprehensive report of this research. Thomann and Mueller (1987) and Chapra (1997) have summarized the fundamental approach to the analysis of heat budgets and temperature in natural waters that was used in this TMDL. Figure 3 shows the major heat energy processes or fluxes across the water surface or streambed.

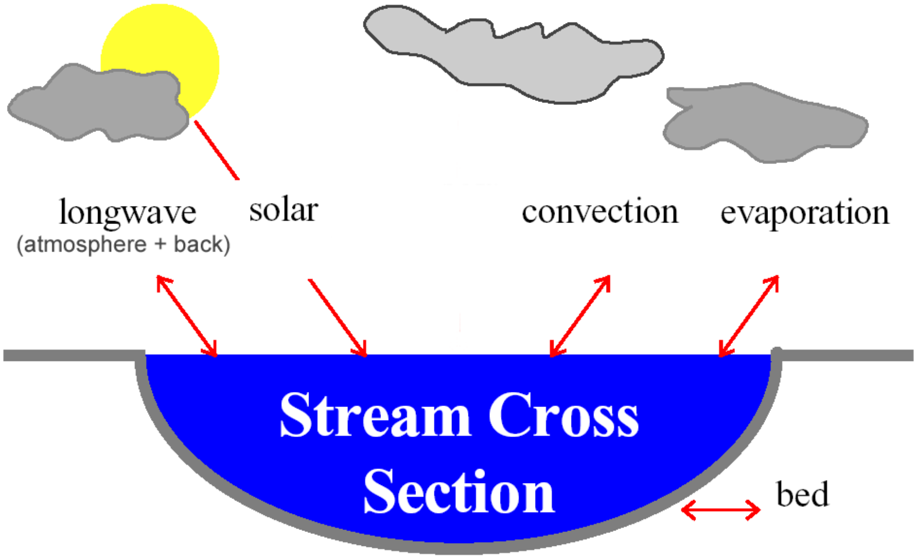

Figure 3. Surface heat exchange processes that affect water temperature (net heat flux = solar + longwave atmosphere + longwave back + convection + evaporation + bed). Heat flux between the water and streambed occurs through conduction and hyporheic exchange.

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 Integrated Surface Irradiance Study (ISIS) station in Seattle, the daily average global shortwave solar radiation for July-August 2001 was 240 W/m^2 (NOAA, 2003). The peak values during daylight hours are typically about 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).

Figure 4 shows an example of the estimated diurnal pattern of the surface heat fluxes in the mainstem Willapa River (near Menlo) for the week of August 8-14, 2001. 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 solar shortwave flux can be controlled by managing vegetation in the riparian areas adjacent to the stream.

Figure 5 shows an example of the estimated diurnal pattern of the surface heat fluxes in a more heavily shaded location in the Willapa River. Shade that is produced by riparian vegetation can reduce the solar shortwave 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.

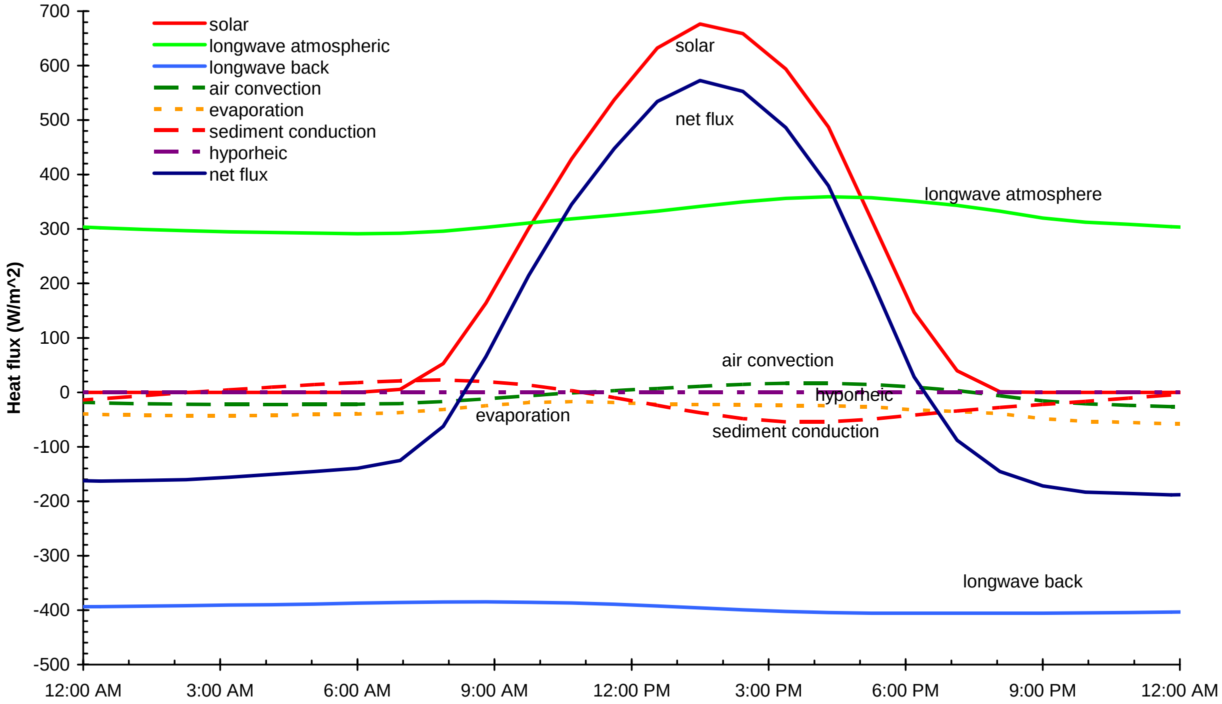

Figure 4. Estimated heat fluxes in the Willapa River near Menlo (Site 3) during August 8-14, 2001 (net heat flux = solar + longwave atmosphere + longwave back + air convection + evaporation + sediment conduction + hyporheic).

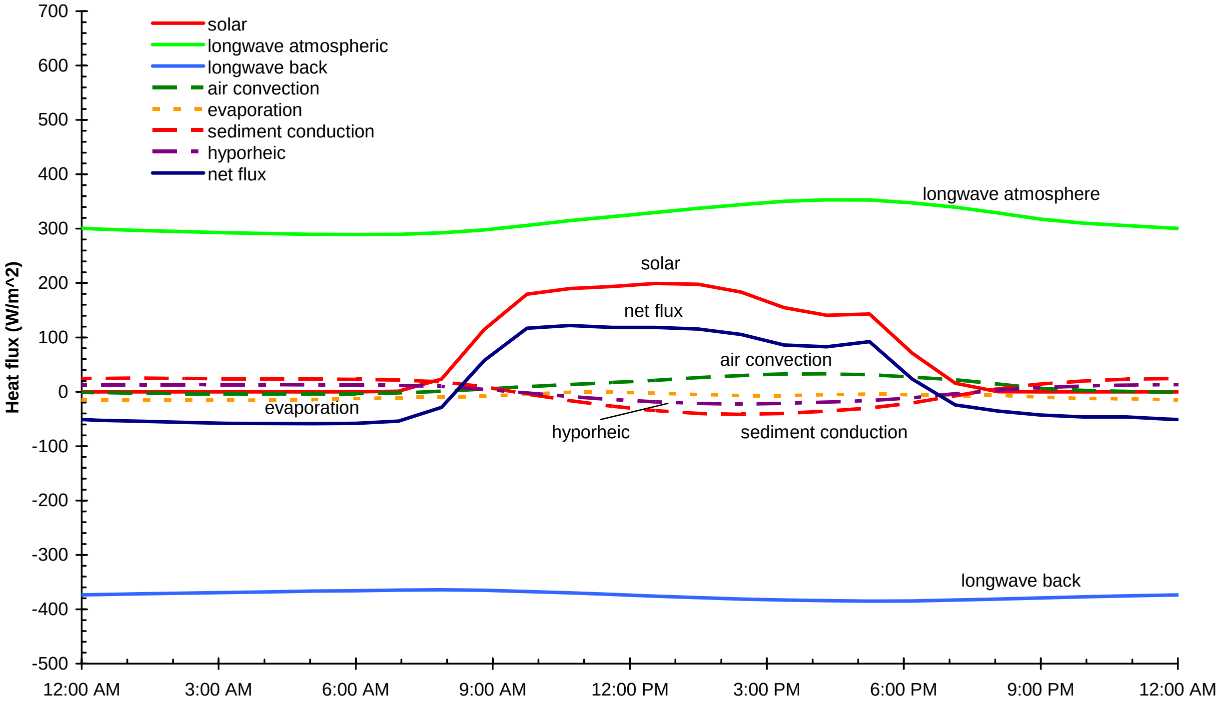

Figure 5. Estimated heat fluxes in the Willapa River approximately one mile downstream from Patton Creek during August 8-14, 2001 (net heat flux = solar + longwave atmosphere + longwave back + air convection + evaporation + sediment conduction + hyporheic).

Heat exchange between the stream and 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.

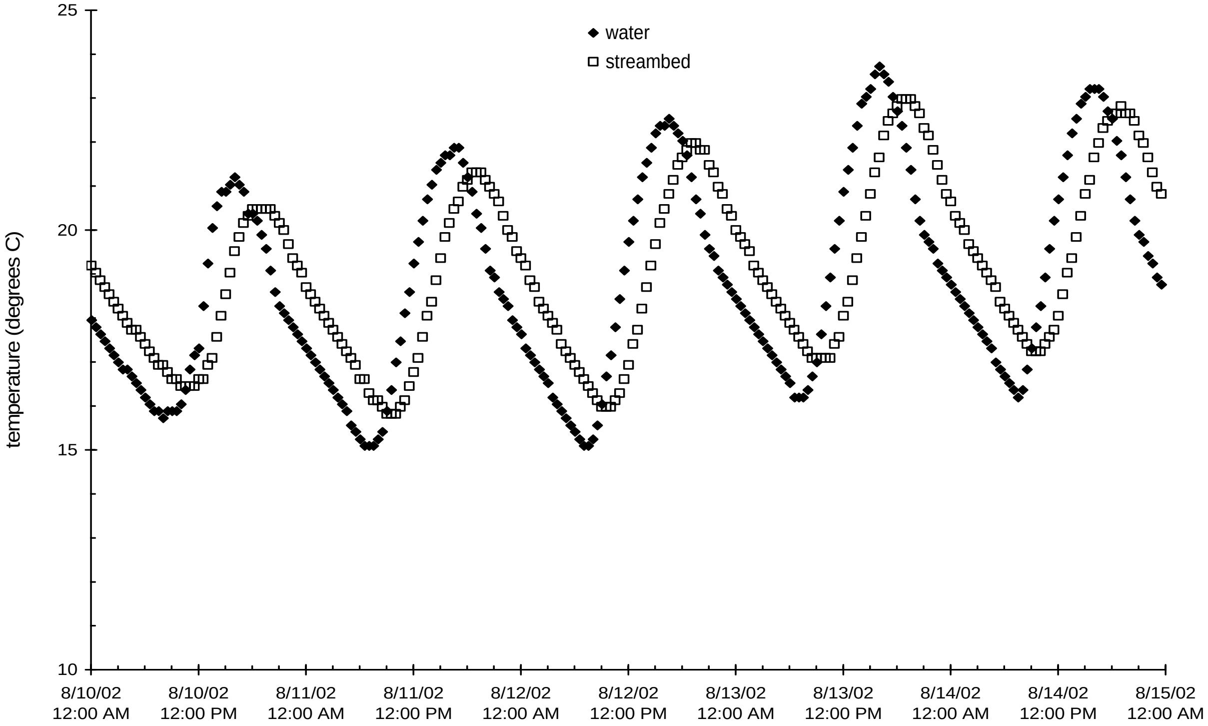

Figure 6. Water and streambed temperatures in mid-August in the North Fork Stillaguamish River at Cicero (station 05NF02).

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 stream segment. Mass transfer processes in open channel systems can occur through advection, dispersion, and mixing with tributaries and groundwater inflows and outflows. Mass transfer relates to transport of flow volume downstream, instream mixing, and the introduction or removal of water from a stream. For instance, flow from a tributary will cause a temperature change if the temperature is different from the receiving water.

Thermal role of riparian vegetation

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

Summaries of the scientific literature on the thermal role of riparian vegetation in forested and agricultural areas are provided by Belt et al., 1992; Beschta et al., 1987; Bolton and Monahan, 2001; Castelle and Johnson, 2000; CH2MHill, 2000; 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 upon the stream temperature includes:

- Near-stream vegetation height, width, and density combine to produce shadows that can reduce solar heat flux to the surface of the water.
- Riparian vegetation creates a thermal microclimate that generally maintains cooler air temperatures, higher relative humidity, lower wind speeds, and cooler ground temperatures along stream corridors.
- Bank stability is largely a function of near-stream vegetation. Specifically, channel morphology is often highly influenced by land-cover type and condition by affecting 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 stream surface shade have the potential to cause significant increases in heat delivery to a stream system. Stream shade is an important factor in describing the heat budget for the present analysis. 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 (solar altitude) and a horizontal component (solar azimuth) that are both functions of time/date (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 hemispherical photography, angular canopy densiometer, and solar pathfinder (Ice, 2001; OWEB, 1999; Teti, 2001).

Hemispherical photography is generally regarded as the most accurate method for measuring shade, although the equipment 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%.

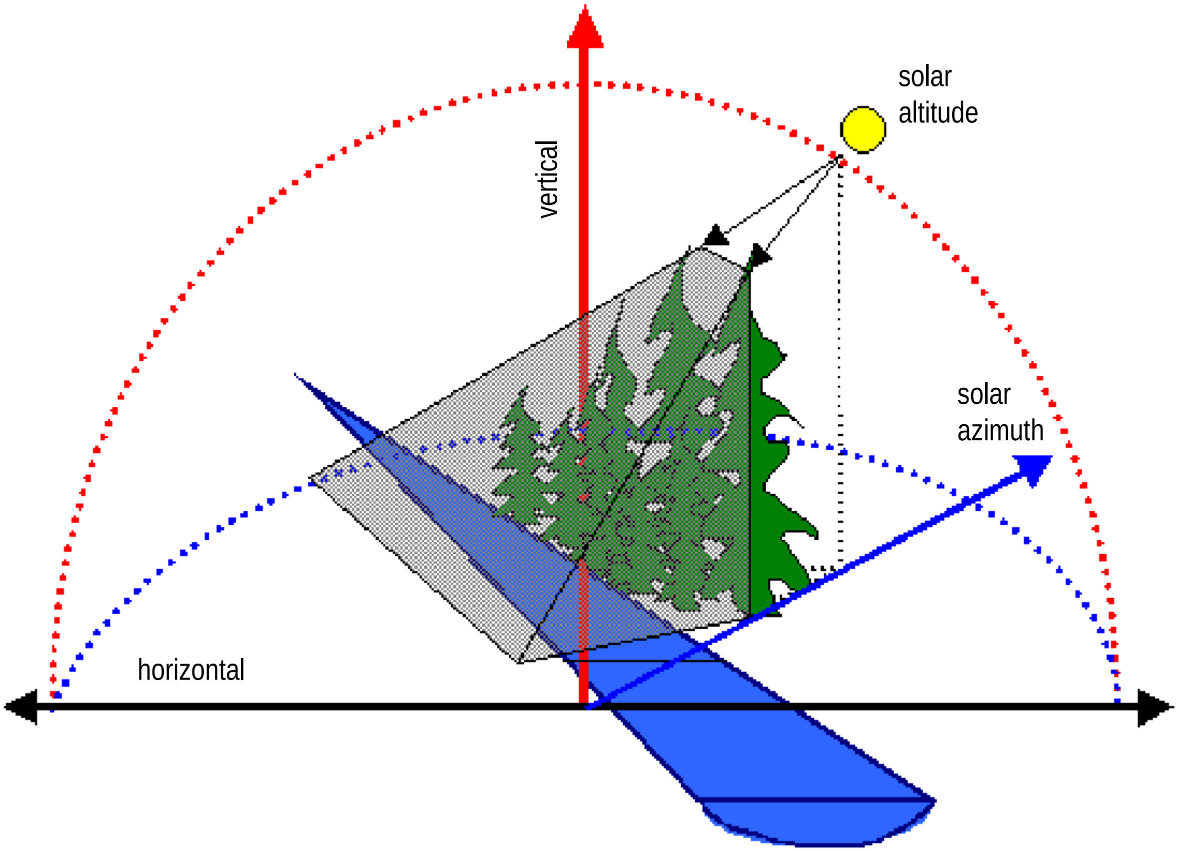

Figure 7. Parameters that affect shade and geometric relationships. Solar altitude is a measure of the vertical angle of the sun's position relative to the horizon. Solar azimuth is a measure of the horizontal angle of the sun's position relative to north.

Table 2. Factors that influence stream shade (bold indicates 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

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).

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 base for measuring shade effectiveness under various riparian buffer proposals. These results reflect the natural variation among old-growth sites studied, and show a possible range of potential shade.

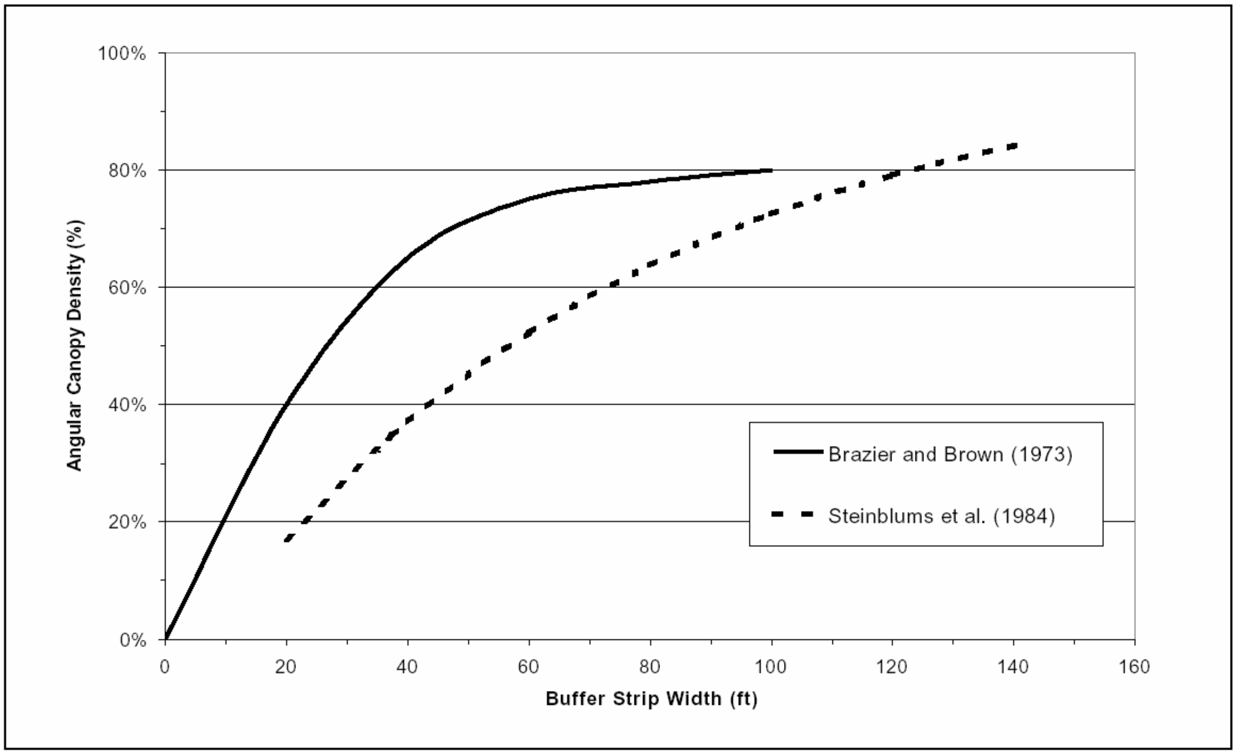

Figure 8. Relationship between angular canopy density and riparian buffer width for small streams in old-growth riparian stands (after Beschta et al., 1987 and CH2MHill, 2000).

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.
- Steinblums et al. (1984) concluded that a 56-foot (17-m) buffer provides 90% of the maximum ACD.
- Corbett and Lynch (1985) concluded that a 39-foot (12-m) buffer should adequately protect small streams from large temperature changes following logging.
- Broderson (1973) reported that a 49-foot-wide (15-m) buffer provides 85% of the maximum shade for small streams.
- Lynch et al. (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 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.

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 7 °C 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 4.5 °C during the day and about 0.5 °C at night (estimate). Fowler and Anderson (1987) measured a 0.9 °C air temperature increase in clearcut areas, but temperatures were also 3 °C 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 2 °C 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).

Thermal role of channel morphology

Changes in channel morphology impact 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**. Traps suspended sediments, encourages deposition of sediment in the flood plain, and reduces incoming sources of sediment.
- **Maintaining stable stream banks**. High rooting strength and high stream bank and flood plain roughness prevents stream bank erosion.
- **Reducing flow velocity** (erosive kinetic energy). Supplies large woody debris to the active channel, provides a high pool to riffle ratio, and adds channel complexity that reduces shear stress exposure to stream bank soil particles.

Pollutants and Surrogate Measures

Heat loads to the stream are calculated in this TMDL in units of calories per square centimeter per day ($cal/cm^2/day$) 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 Willapa 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."

This technical assessment for the Willapa River temperature TMDL uses riparian shade as a surrogate measure of heat flux to fulfill the requirements of Section 303(d). Effective shade is defined as the fraction of the potential solar shortwave radiation that is blocked by vegetation and topography before it reaches the stream surface. Other factors influencing heat flux and water temperature were also considered, including microclimate, channel geometry, groundwater recharge, and instream flow.

Background

Study Area

The study area includes all major tributaries to the Willapa River upstream of the area of tidal influence. This 220 square mile area consists of the South Fork of the Willapa River, the Wilson and Ward Creek drainages, and the mainstem and tributaries of the Willapa River above the USGS gage near Camp One Road (RM 14.5) (Figure 9).

The watershed includes a mix of public and private land. The lower elevation land along the mainstem and smaller tributaries is owned primarily by small landowners and is in agriculture or rural use. Upper elevation land and land along the larger tributaries is dominated by private timber or Washington State Department of Natural Resources (DNR) forest lands and is subject to the DNR Forests and Fish Report.

The climate of the basin is heavily influenced by its proximity to the ocean with cool, wet winters and mild summers. Annual precipitation ranges from 80 inches in the lowlands to 120 inches in the higher elevations, and occurs primarily between October and June.

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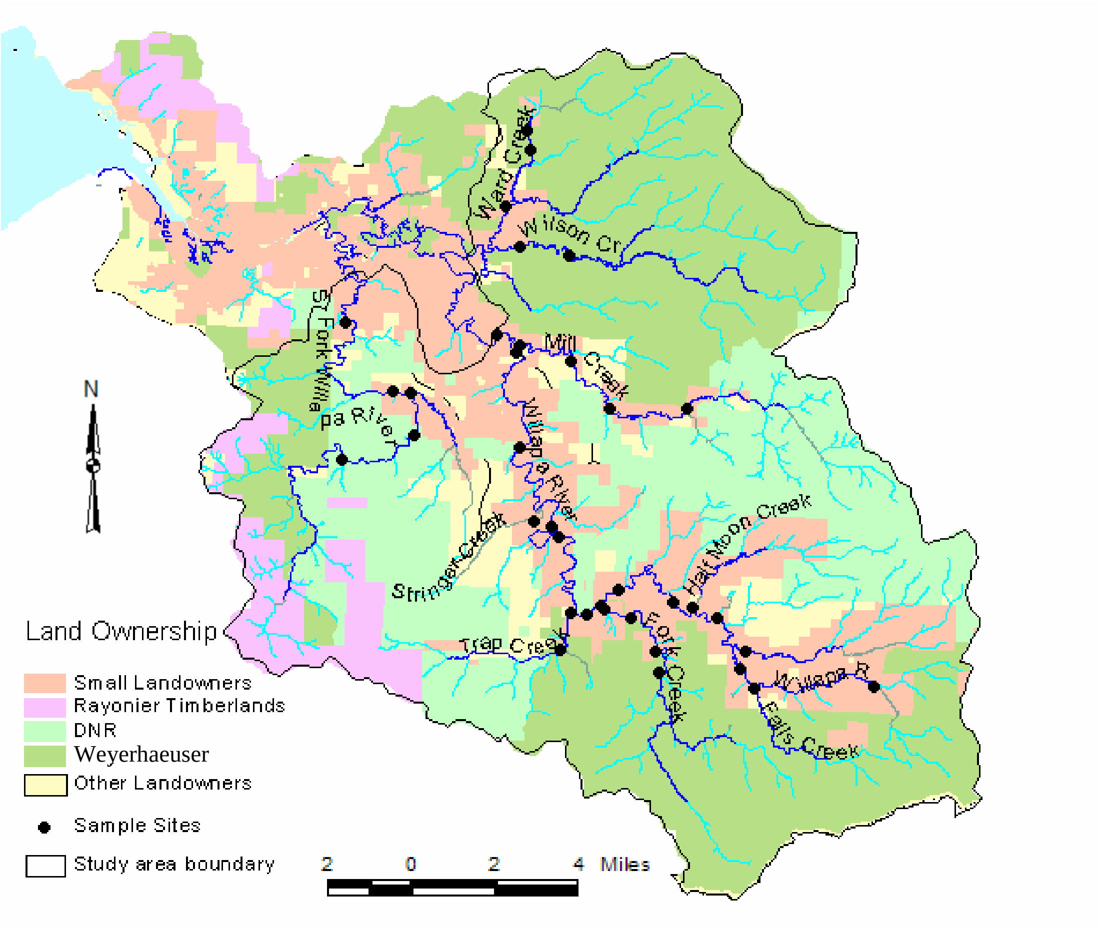

Figure 9. Land ownership in the Willapa River watershed.

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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, timber industry, state, and 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 Washington State

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 westside forests such as the forests in the Willapa 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, 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.

Load allocations are included in this TMDL for forest lands in the Willapa 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 forest lands 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.

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.

Other Regulations Affecting Riparian Land Use

For private land that is not covered by the Forests and Fish Report, 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 protected under the 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 Flows and Water Withdrawals

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. Actual water withdrawals at any given time from streams in the Willapa River watershed are not known, but information from the Water Rights Application Tracking database system (WRATS) was used as an indicator of the amounts of water that may be legally withdrawn. In many cases, actual consumptive withdrawals are significantly less than the listed water rights. This project used actual field-measured streamflows in analysis and used data from WRATS to verify likely stream segments where water is diverted.

Willapa Basin Studies by Others

As part of the Willapa Headwaters Watershed Evaluation (Weyerhaeuser, 1994), Weyerhaeuser installed 12 water temperature gages in the Willapa River and select tributaries during June 1994. Data collected at the gages indicate that Willapa River and tributary peak water temperatures ranged from 17^{o}C (62.6^{o}F) within Ellis Creek waters to 22.4^{o}C (72.3^{o}F) within a reach of the lower Willapa River. Additionally, the Willapa Headwaters Watershed Evaluation found that approximately 30% of the fish-bearing waters in the watershed were found to have canopy closure levels below what is necessary to maintain state water quality standards for temperature. Relatively high shade levels are required to achieve Class A water quality standards due to low stream elevations in the basin.

The evaluation found that 80% shade is the required target for the lower mainstem Willapa River. However, due to present agricultural land-use practices and the history of timber harvest in the watershed, it is unlikely that riparian zones on these lands could be returned to sufficient vegetative standards to provide the target 80% shade.

The Willapa Headwaters Watershed Evaluation found that most riparian stands along fish-bearing streams are characterized as mature hardwood stands. Approximately 7% of the watershed is characterized as having good near-term, large woody debris (LWD) recruitment potential; 65% has fair near-term recruitment, and 28% has poor near-term LWD recruitment potential. The evaluation found that the poor and fair recruitment sites can be attributed to prior riparian harvest and agricultural land uses.

Existing levels of in-channel LWD were low throughout the watershed, with the exception of three localized areas: one in the old-growth section of Ellis Creek, one channel segment in Trap Creek, and one segment in Silver Creek. The lack of in-channel LWD is likely the most significant factor affecting channel morphology and fish habitat. The evaluation indicates that long-term LWD recruitment projections based on stand succession estimates suggests that most of the poor and fair LWD recruitment sites could be dominated by conifer species in the future.

The Salmon and Steelhead Habitat Limiting Factors Report for the Willapa Watershed (Washington State Conservation Commission, 1999) summarizes limiting factors to anadromous fish. The Willapa River and tributaries support populations of Fall Chinook, Coho, Fall Chum, and Winter Steelhead. The mainstem and many tributaries, including Wilson Creek, Trap Creek, Fork Creek, South Fork Willapa River, Rue Creek, Mill Creek, and Ellis Creek are important salmon habitat. The Willapa has lost 162 acres of off-channel habitat. The presence of LWD is very poor in much of the basin, with quantities ranging from .07-.52 pieces per channel width with less than 1 being poor. Riparian vegetation conditions in the Willapa mainstem have been considerably impacted. Because all salmonid production in the Willapa depends on good mainstem habitat, the impact is considerable.

The Pacific County Conservation District and Pacific County currently collect water quality data in the Willapa River basin. The North Pacific County Infrastructure Action Team (NPCIAT) is an active participant in water quality management and improvement in the county.

Applicable Water Quality Criteria

This report and the subsequent TMDL are designed to address impairments of characteristic uses caused by high temperatures. The characteristic uses designated for protection in Willapa 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 state water quality standards describe criteria for temperature for the protection of characteristic uses. Streams in the Willapa River basin are designated as Class A. 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."*

Water Quality and Resource Impairments

The 1998 303(d) listings for temperature in the Willapa River watershed (Table 1) are confirmed by data collected by Ecology during 2001 (Table 3). Temperatures in excess of the water quality standard of 18°C were observed in 2001 throughout the watershed at numerous locations.

Because the locations where temperature exceeds the water quality standard are spread throughout the watershed, this TMDL was developed to address water temperature in perennial streams in the entire watershed.

Table 3. Highest daily maximum temperatures in the Willapa River and its tributaries during 2001, sorted in decreasing order of temperature. (Data above the bold line show values greater than the water quality standard of 18°C.)

Station ID (2001)	Station name	Latitude (decimal degrees NAD27)	Longitude (decimal degrees NAD27)	Highest daily maximum temperatures during 2001 (°C)	Highest 7-day averages of daily maximum temperatures during 2001 (°C)
2	Willapa R abv Mill Creek	46.6447	-123.6424	23.99	23.08
1	Willapa R at Camp One Road	46.6504	-123.6523	23.45	22.54
4	Willapa R at Oxbow Road	46.5855	-123.6216	22.18	21.19
3	Willapa R at SR 6 nr Menlo	46.6120	-123.6393	22.12	21.32
6	Willapa R at SR 6 nr Holcomb	46.5820	-123.6177	21.77	20.75
8	Willapa R abv Trap Creek	46.5555	-123.6024	20.73	19.87
13	Willapa R abv Half Moon Creek	46.5563	-123.5369	20.69	19.76
10	Willapa abv Fork Ck at Doyle Road	46.5645	-123.5871	19.93	19.29
12	Half Moon Creek near mouth	46.5591	-123.5492	19.84	18.64
11	Willapa R at Lebam	46.5612	-123.5590	19.60	18.67
14	Fern Creek at Elk Prairie Road	46.5449	-123.5219	19.26	18.40
15	Willapa R at Swiss Picnic Campg.	46.5387	-123.5243	19.14	18.23
9	Fork Creek near mouth	46.5585	-123.5957	19.02	18.10
20	Mill Creek at 5th bridge RM 4.7	46.6266	-123.5950	18.81	18.00
18	Mill Creek at 1st bridge RM 0.2	46.6471	-123.6412	18.64	17.95
21	Mill Creek at 7th bridge RM 7.6	46.6278	-123.5559	18.60	17.84
9a	Fork Creek abv State Hatchery	46.5578	-123.5935	18.43	17.65
29	Wilson Creek at 1st Weyco bridge	46.6814	-123.6430	18.33	17.66
9b	Fork Creek at 1st bridge RM 1.0	46.5551	-123.5805	18.25	17.45
30	Wilson Creek at 3rd Weyco bridge	46.6786	-123.6181	17.91	17.61
9c	Fork Creek RM 3	46.5438	-123.5669	17.58	16.78
27b	Ward Creek blw Fairchild Creek	46.6947	-123.6510	17.46	16.73
19	Mill Creek at 4th bridge RM 2.4	46.6428	-123.6151	17.38	16.81
16	Falls Creek abv Retreat Center	46.5321	-123.5170	17.27	16.54
7	Trap Creek above Hwy 6	46.5558	-123.6104	17.05	16.39
7a	Trap Creek at B-line bridge	46.5433	-123.6143	16.81	16.17
22	South Fork at Golf Course	46.6529	-123.7283	16.80	16.16
27	Ward Creek at Flow Site RM 3.2	46.7145	-123.6392	16.63	16.02
23	South Fork blw Rue at 1999 bridge	46.6296	-123.7035	16.42	15.68
25	Upper South Fork RM 11	46.6052	-123.7270	16.37	15.82
5	Stringer Creek at Highland Road	46.5869	-123.6303	15.94	15.31
9d	Fork Creek at A-400 bridge RM 4	46.5365	-123.5649	15.93	15.39
17	Willapa R below Patton Creek	46.5343	-123.4571	15.75	15.07
24	Rue Creek near mouth	46.6297	-123.6948	15.56	15.04

Seasonal Variation

The federal Clean Water Act 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 Willapa River watershed reflect seasonal variation. Cooler temperatures occur in the winter, while warmer temperatures are observed in the summer. Figures 10 and 11 summarize the highest daily maximum and the highest seven-day average maximum water temperatures 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.

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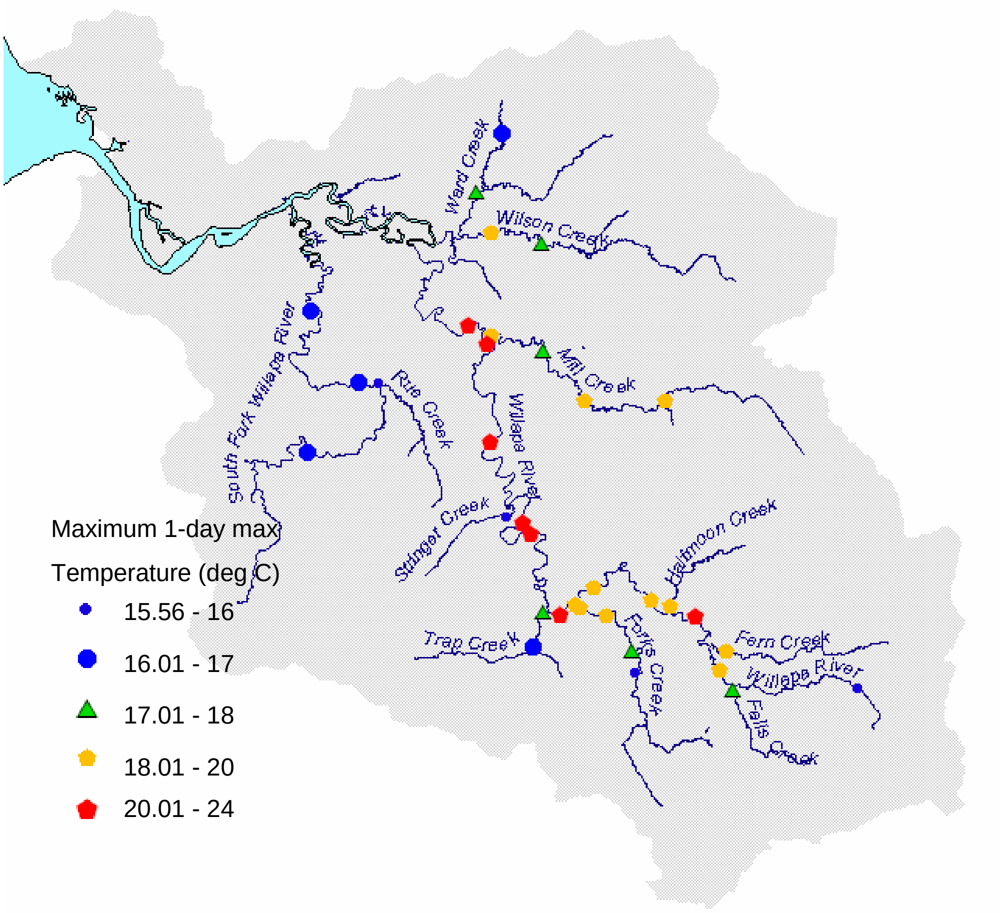

Figure 10. The highest daily maximum water temperatures in the Willapa River and its tributaries during 2001.

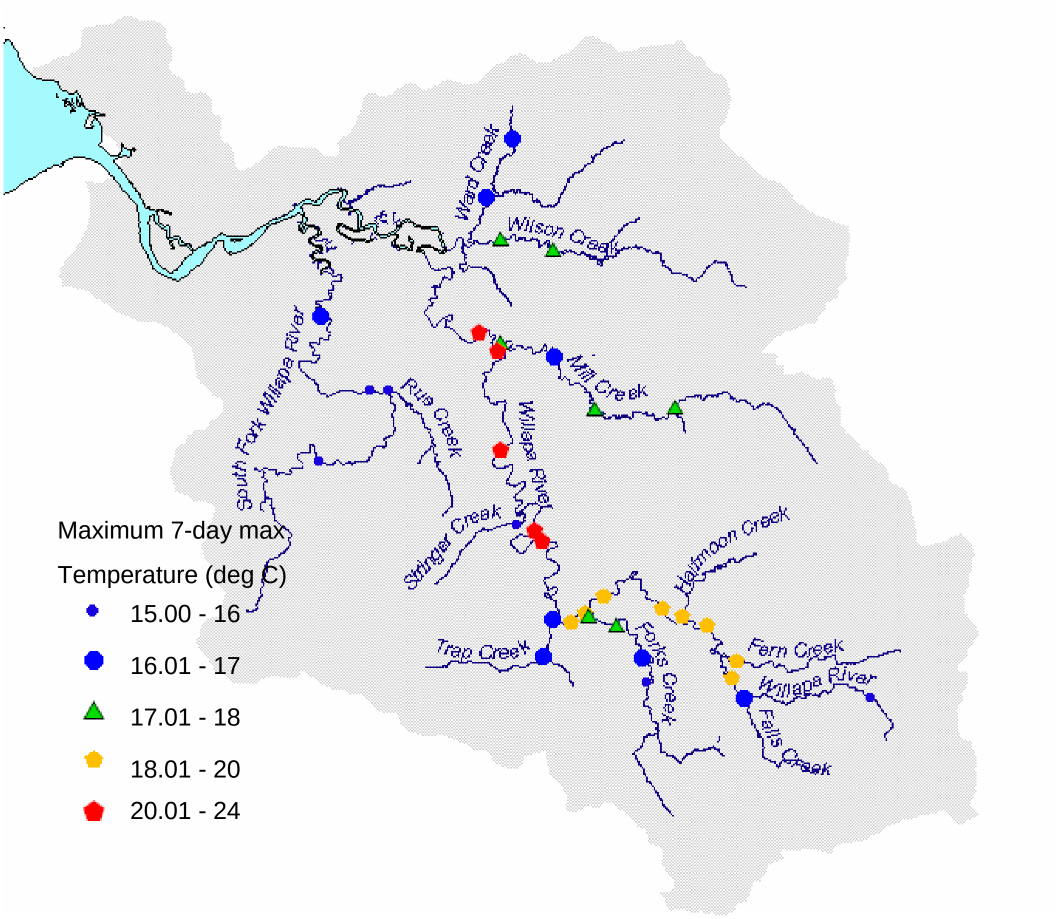

Figure 11. The highest 7-day averages of daily maximum water temperatures in the Willapa River and its tributaries during 2001.

Technical Analysis

Current Conditions

Water temperature data – continuous dataloggers

A network of continuous temperature dataloggers was installed in the Willapa River watershed by Ecology as described by Stohr (2001) (Figure 12). Data from 2001 show that water temperatures in excess of the Class A standard of 18°C are common throughout the watershed (Table 3 and Appendix A). Water temperatures in excess of 20°C were observed in the mainstem Willapa River. Cooler maximum temperatures of less than 16°C were observed at several sites including Stringer Creek, Rue Creek, and the uppermost sites in Fork Creek and the mainstem Willapa River. The hottest 7-day period of 2001 occurred from August 8-14.

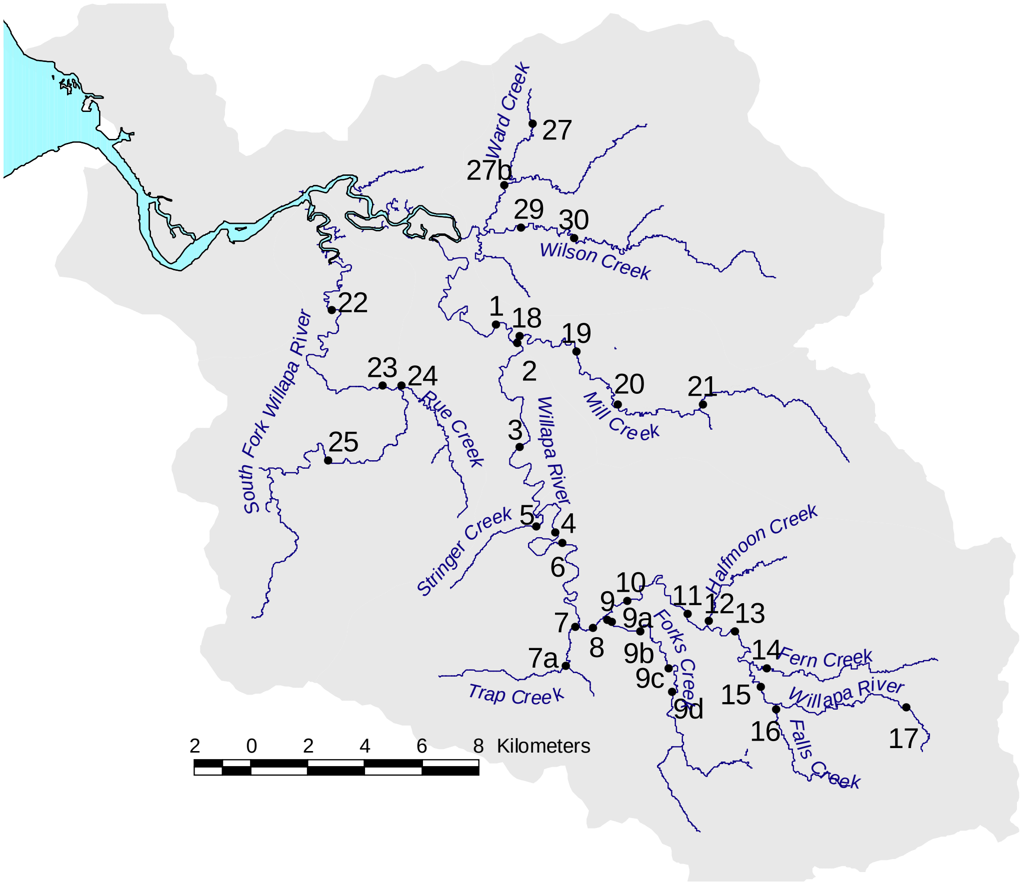

Figure 12. Locations and station IDs of Ecology's temperature monitoring stations in the Willapa River watershed.

Water temperature data – aerial surveys

In addition to the network of continuously recording temperature dataloggers, a helicopter-mounted thermal infrared radiation (TIR) sensor and color video camera were used to take TIR and visible color images of selected segments of the streams and rivers in the watershed to provide a spatially-continuous image of surface temperature. Surveys of the mainstem Willapa River, the South Fork Willapa River, Fork Creek, a one-mile segment of Trap Creek, and a two-mile segment of Mill Creek were conducted on August 30, 2001.

This August 30th flight showed cooler temperatures than were measured earlier in the summer. Although flown on a warm day, streamflows were still higher than normal because of a large storm on August 22, 2001. Figure 13 shows which areas of the watershed are cooler, which are hotter, and how some of these waters mix. The mainstem of the Willapa River is very warm compared to the cooler tributaries of Falls Creek, Forks Creek, and Trap Creek. These tributaries contribute water cold enough to reduce the hotter mainstem for a short distance below their confluences. The South Fork Willapa stays cool throughout the summer, even though its summer time streamflow and elevation near the mouth are similar to those in the mainstem. The upper portion of the Willapa River near Patton creek (station 17) is very cold but heats rapidly after reaching areas of little shade, even though still at fairly high elevation.

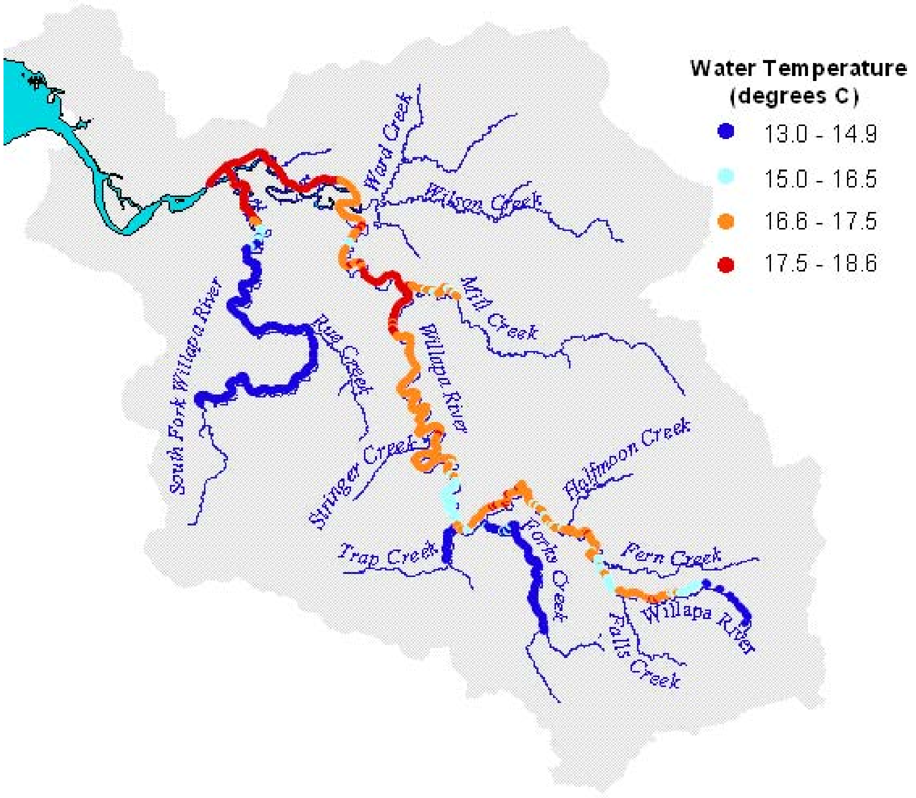

Figure 13. Water temperature measured by Thermal Infrared Survey on August 30, 2001.

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Stream flow data

Ecology installed four continuous flow measurement stations during 2001 as described in Stohr (2001) and Springer (2004) (Figure 14). The Ecology stations recorded stage height continuously from May to October, 2001. Instantaneous flow measurements at temperature monitoring stations were taken approximately monthly during this period (Appendix B). The U.S. Geological Survey (USGS) currently gages flows in the Willapa River near Willapa (station 12013500) and has historically gaged flows at several other stations in the watershed.

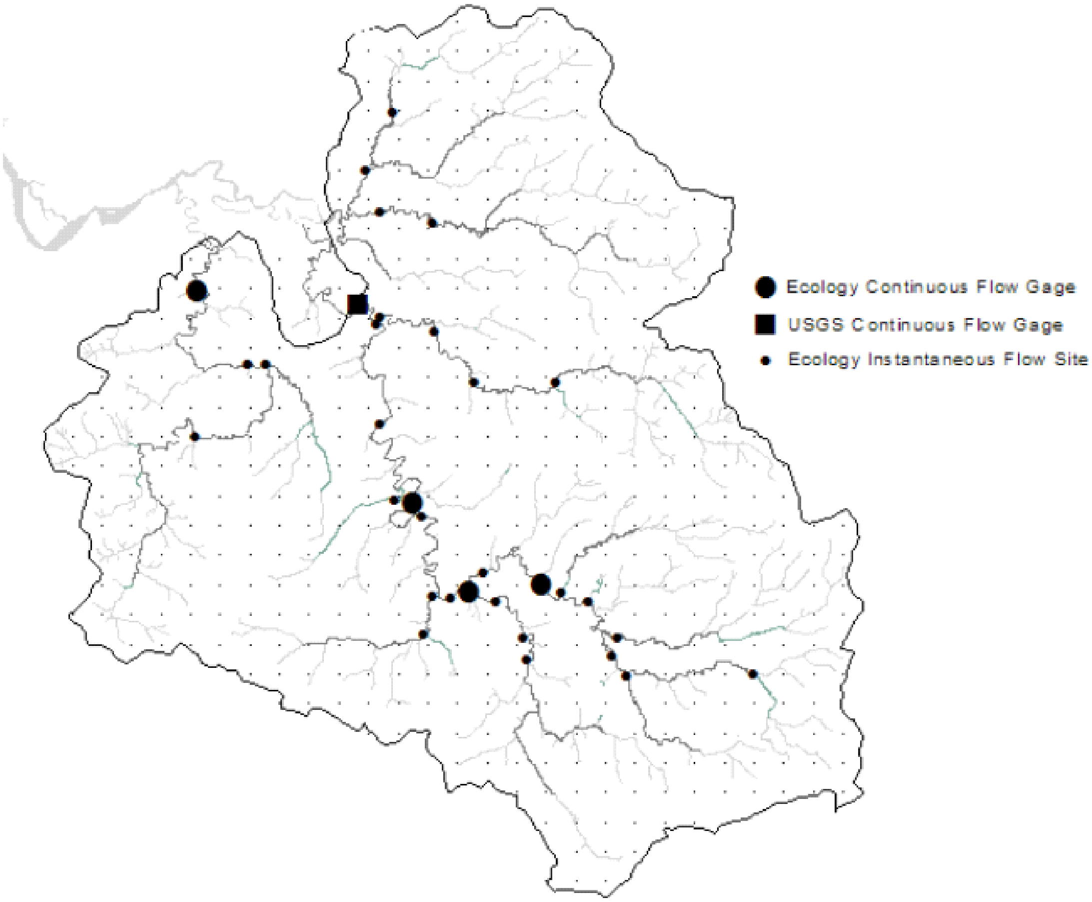

Figure 14. Flow gaging stations in the Willapa River watershed

Flow statistics calculated by WQHYDRO (Aroner, 1994) for the 53 years of data at the Willapa River near Willapa USGS gage are reported in Table 4. 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. Flows selected to represent the critical conditions are 30 cfs for 7Q2 and 20 cfs for 7Q10.

Table 4. Low-flow statistics for July-August at USGS Willapa gage (12013500)

Statistic	Distribution	Discharge (cfs)
7Q2	Distribution free	29.4
	Log Pearson III	29.9
	Weibull	30.2
7Q10	Distribution free	19.9
	Log Pearson III	20.0
	Weibull	19.4

Groundwater data

A synoptic flow survey was performed on July 31, 2001 to determine the influence of groundwater in the basin and to assist in developing a water balance for the low-flow season. The survey consisted of measuring instantaneous flow at each tributary and at regular intervals along the mainstem Willapa on one day during low-flow conditions in the basin. The flow data, coupled with the water rights in the basin, obtained from the WRATs database, determined reaches that gain and lose groundwater. This analysis determined there was little groundwater inflow along much of the mainstem Willapa River. These findings were consistent with the findings of Pitz (1998) and Erickson (2001) from hydrogeologic data available in the basin. Extensive streamflow data was also collected in 1998 (Pickett, 2001) including a synoptic survey on August 4, 1998.

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 and depths were measured during stream surveys that took place during the low-flow period as described in Stohr (2001). Ten cross-sections were established, beginning at the monitoring station and then moving upstream at 100-ft intervals. At each cross-section, the wetted width, bankfull width, width of the near-stream disturbance zone, channel incision, and bankfull depth were recorded. Bankfull and wetted widths for stream segments that occurred between survey reaches were estimated from log-log regressions of measured bankfull width versus drainage area (Figure 15) and measured wetted width versus drainage area (Figure 16). Regression coefficients compared well with those reported by Montgomery (2001) for Willapa basin streams (Table 5). Channel data collected during these surveys are reported in Appendix C.

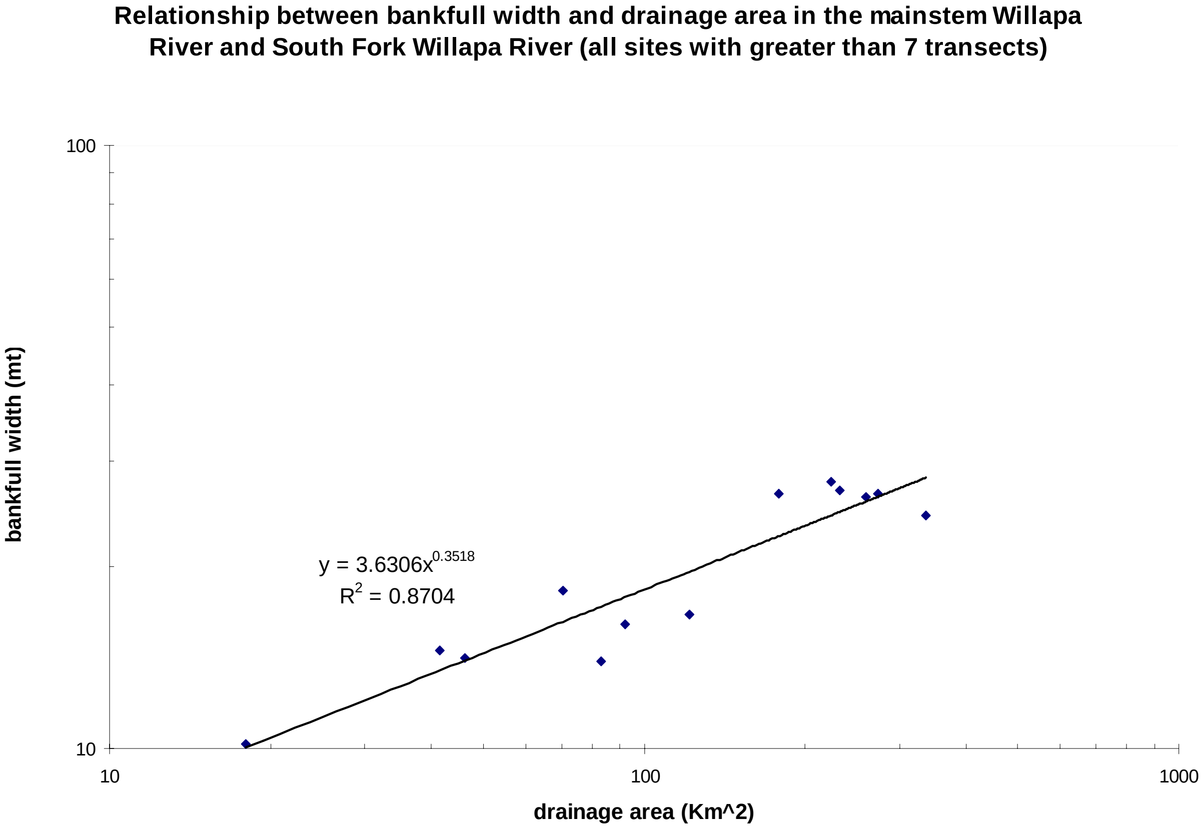

Figure 15. Bankfull width versus drainage area at all stations in the mainstem Willapa River and South Fork Willapa River, June-October 2001.

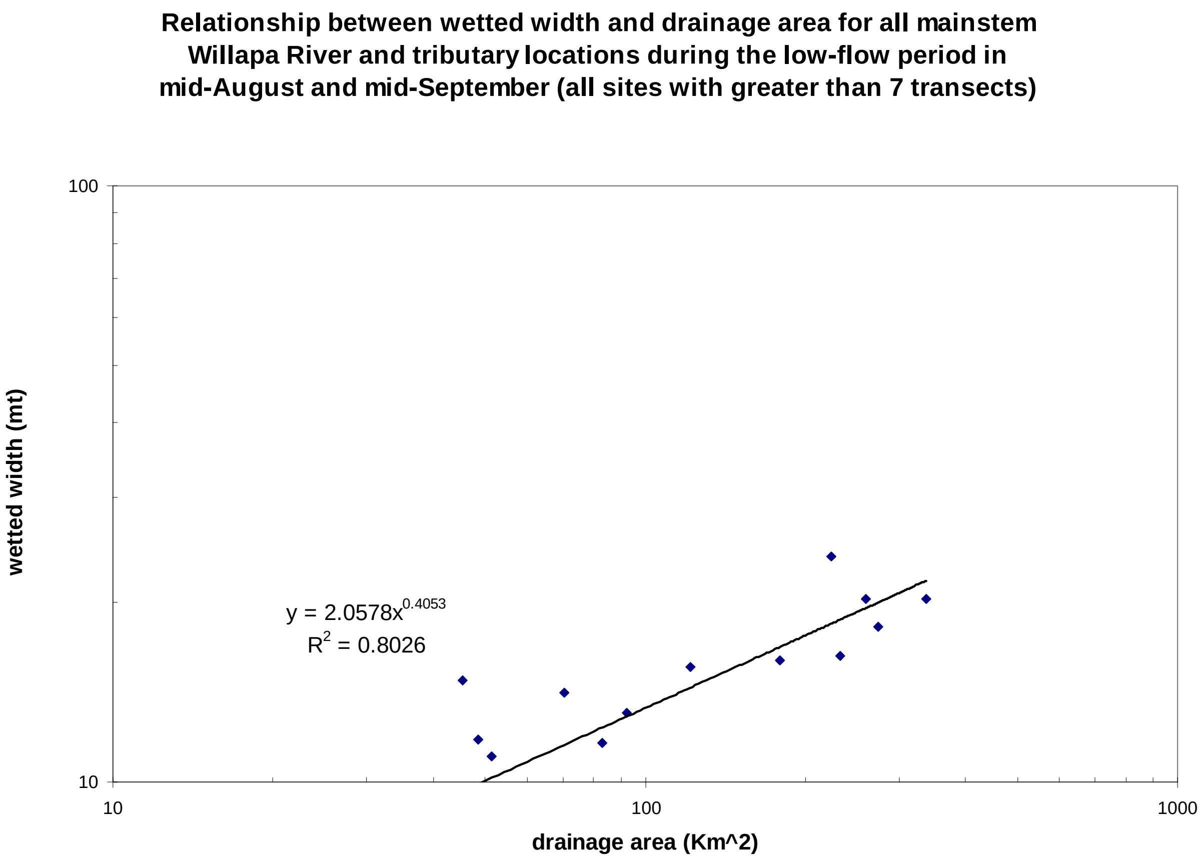

Figure 16. Wetted width versus drainage area during the low-flow season (mid-August to mid-September) at all stations in the Willapa River basin, 2001.

Table 5. Exponents (b) and coefficients (c) for bankfull width versus drainage area in the Willapa River basin.

Study area	Source	c	b	R2
Willapa River bedrock reaches	Montgomery	0.054	.32 ± 0.02	0.83
Willapa River alluvial reaches	Montgomery	0.020	.39 ± 0.03	0.86
Willapa TMDL study combined reaches	Stohr	0.028	0.35	0.87

The coefficient (c) values in this table are reported in different units than shown in Figure 15 for comparison with those in Montgomery (2001). Units are bankfull channel width in meters and drainage area in square meters.

At different discharges, the observed mean velocity, mean depth, and width of flowing water reflect the hydraulic characteristics of the channel cross-section. Graphs of these three parameters as functions of discharge at the cross-section constitute a part of what Leopold (1994) called the hydraulic geometry of stream channels. Width, depth, and velocity can be related to discharge (Q) by power functions:

W=aQb d=cQf u=kQm

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

Coefficients were determined for individual stream segments by fitting power curves to data collected for instantaneous discharge measurements. The curves are used to estimate width and depth for flow regimes not specifically measured (e.g., 7Q2 or 7Q10). Table 6 summarizes these equations. The exponents and coefficients calculated for the Willapa were very similar to those found in South Prairie Creek (Roberts, 2003) which has similar stream slope.

Relationships for a particular station were assumed to hold for reaches half the distance to the upstream station and half the distance to the downstream discharge station.

Table 6. Summary of hydraulic geometry relationships with flow (Q) in the Willapa River watershed, June-October 2001 and June-October 1998.

		All stations with greater than 7 transects	Upper Willapa mainstem	Mid-Willapa mainstem	Deep portions near Doyle Road	Lower Willapa watershed
width	coefficient "a"	16.2	12	16	14.3	19.2
=aQ^b	exponent "b"	0.12	0.19	0.05	0.14	0.13
depth	coefficient "c"	0.38	0.26	0.4	0.79	0.44
=cQ^d	exponent "d"	0.27	0.2	0.1	0.14	0.38
velocity	coefficient "g"	0.24	0.47	0.2	0.15	0.12
=gQ^h	exponent "h"	0.6	0.56	0.7	0.7	0.56

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):

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

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 17).

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.

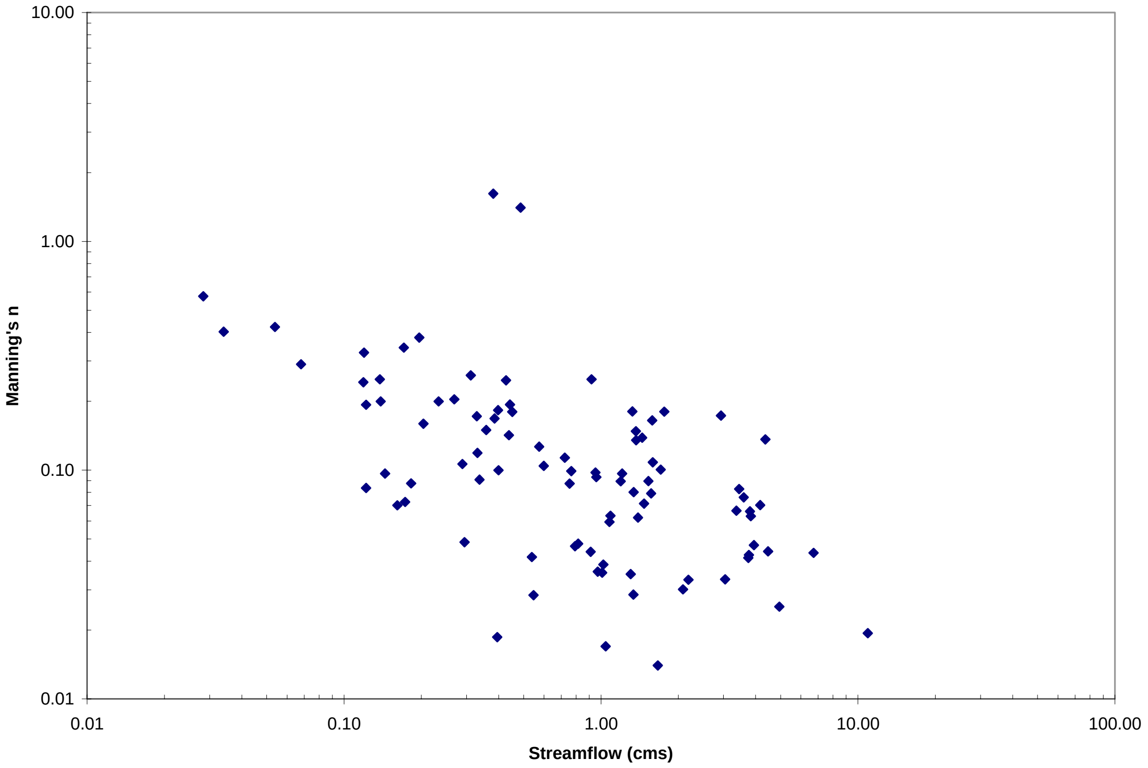

Figure 17. Manning's n versus flow during the low-flow season in the Willapa watershed, June-October 1998 and 2001.

Climate data

A network of dataloggers was installed to continuously monitor air temperature and relative humidity throughout the study area in accordance with Stohr, 2001. NOAA National Climate Data Center (NCDC) stations at Raymond 2S (1979-present), Hoquiam (1926-present), and RAWS station Huckleberry Ridge (1996-present) also provide a record of long-term trends in climate data. The station at Raymond gathers less data than the station at Hoquiam, but air temperature data gathered there is closely correlated to air temperature data gathered by Ecology along the mainstem Willapa River. The Hoquiam station is nearer to the ocean and thus experiences cooler air temperatures, higher relative humidity, and higher wind and cloud cover. The Huckleberry Ridge station is a good indicator of long-term temperature patterns; however, it is located on the ridge just inland of the Willapa River and generally had lower relative humidity values than those gathered in the basin by Ecology.

Air temperatures at Raymond S2 were found to be highly correlated with conditions measured at the nine mainstem air temperature stations monitored by Ecology; therefore, Raymond 2S was used to estimate the typical year (50th percentile) and extreme (90th percentile) conditions for climate (Figure 18).

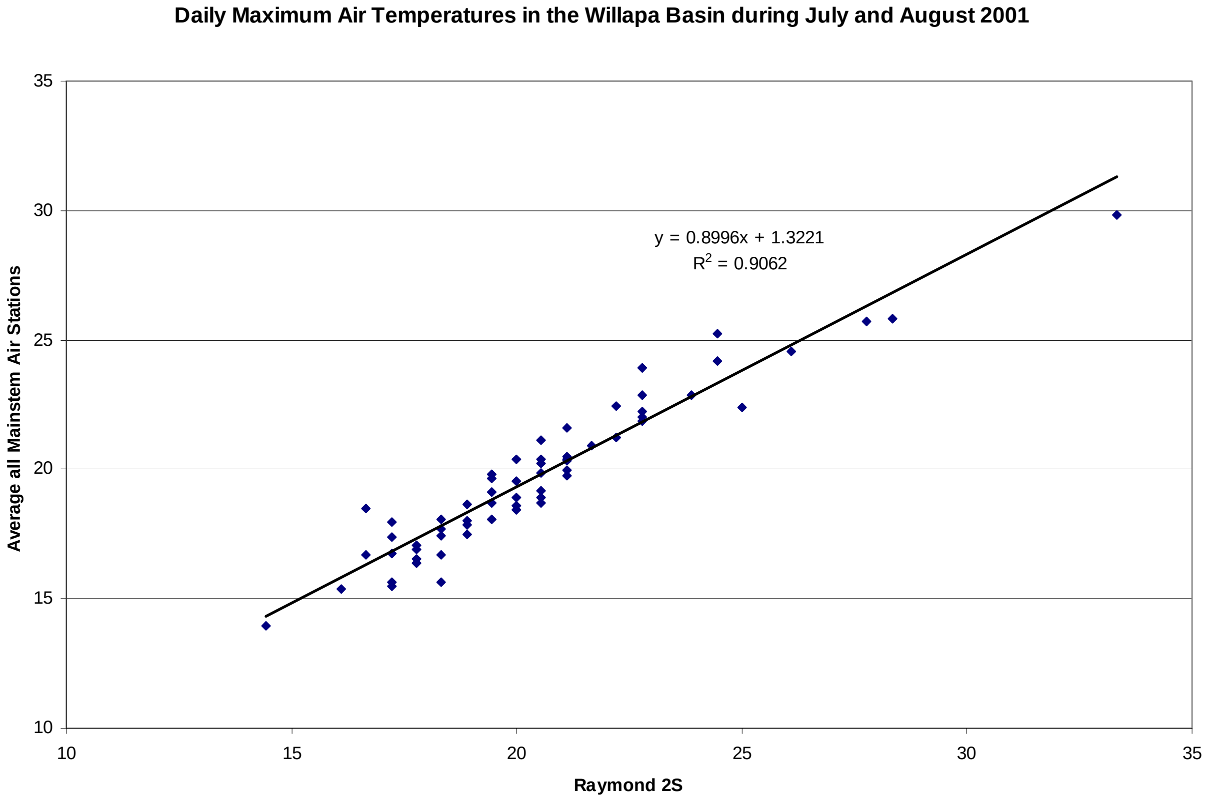

Figure 18. Regression of average daily maximum air temperatures during July and August, 2001 at NOAA NCDC station at Raymond 2S and average daily maximum air temperature at Ecology measured Willapa mainstem stations.

The highest 7-day average of daily maximum air temperatures for each year of record at Raymond 2S were ranked to determine the median and 90th percentile conditions (Table 7). The corresponding median and 90th percentile air temperature conditions for the near-stream conditions along the mainstem Willapa were calculated by applying the regression equation from Figure 18.

Table 7. Air temperature statistics for Raymond, Washington.

	Raymond 2 S		Average mainstem temperature	
Condition	(°F)	(°C)	(°F)	(°C)
August 8-14, 2001 7-day average of daily maximum	75.6	24.21	74.19	23.44
Typical weather condition (exceeded 50% of time)	79.71	26.51	**77.31**	**25.17**
Extreme weather condition (exceeded 10% of time)	83.86	28.81	**81.03**	**27.24**

Air temperatures determined from Figure 18 regression are shown in bold.

In many watersheds, such as the Fork Creek watershed, as elevation increases air temperature decreases. In the Willapa River mainstem, as elevation increases so does distance from the cooler ocean air. Regression of daily maximum air temperatures along the mainstem Willapa River during the critical period shows little correlation with elevation (Figure 19). Proximity to the ocean has a large influence on the air temperature and humidity patterns in this watershed. Since there is not a large difference in air temperature between the mainstem sites measured, an average air temperature for these sites was used as input to the mainstem model. The Fork Creek model uses lower air temperatures for the upstream sites based on the field data collected in 2001. Relative humidity was found to decrease with elevation and distance from the ocean during the hottest week of July-August 2001 (Figure 20). Relative humidity values were applied by site.

The average wind speed in riparian areas of the streams in the watershed during the hot periods modeled was estimated to be approximately 0.5 m/sec. Wind speed measurements made with a handheld meter did not meet the minimum measurable speed of 2 mph during these time periods. The South Prairie Creek temperature TMDL also used a wind speed of 0.5 m/sec for this same time period (Roberts, 2003).

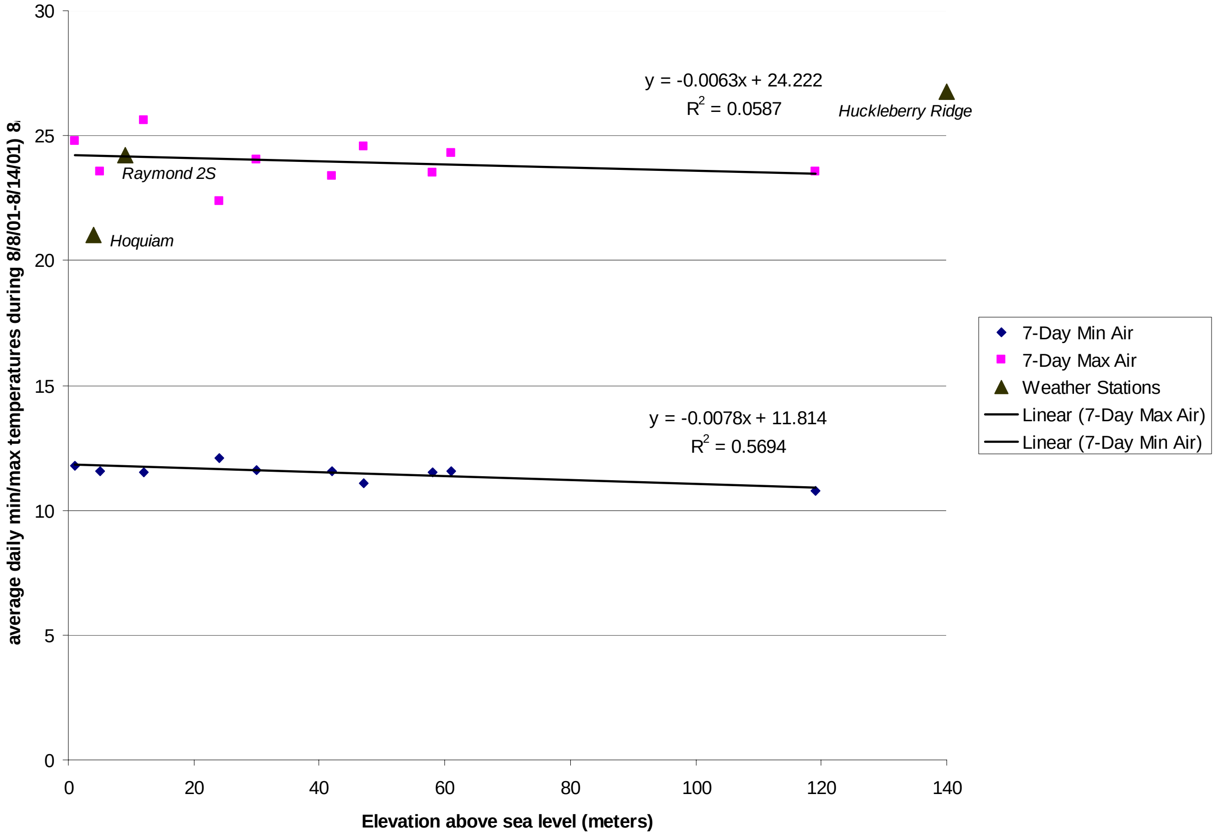

Figure 19. Regression of 7-day average daily maximum and minimum air temperatures along the mainstem Willapa River during August 8 - 14, 2001.

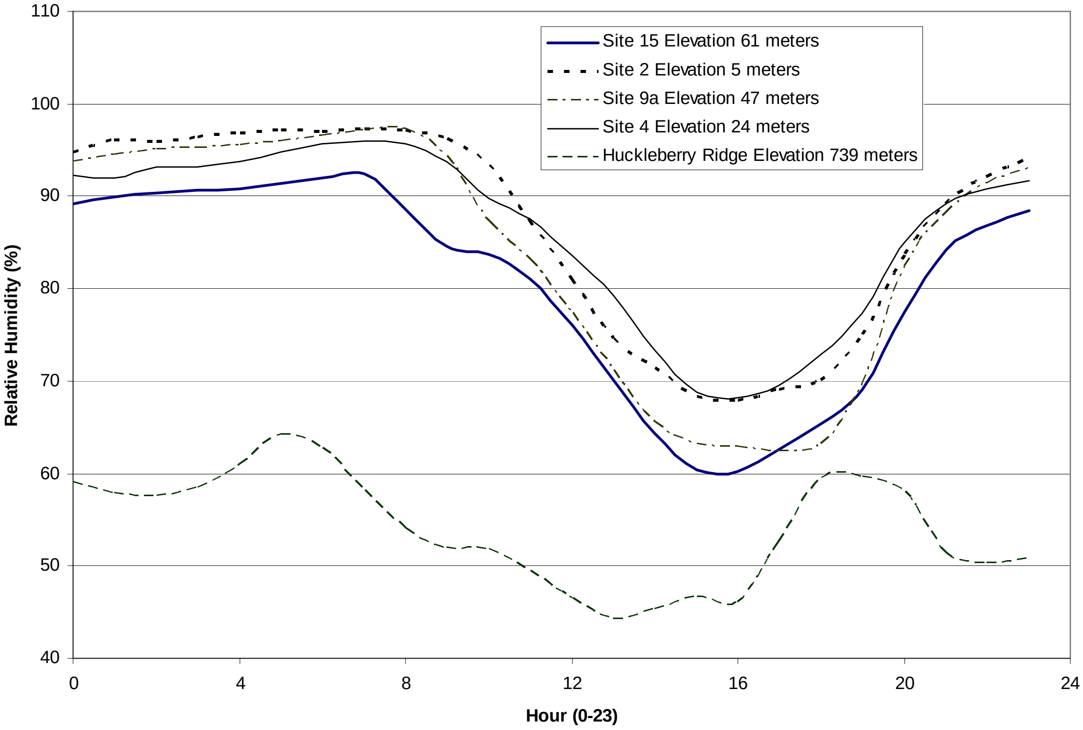

Figure 20. Average hourly relative humidity measured during August 8-14, 2001 along streams in the Willapa River basin.

Riparian vegetation and effective shade

Effective shade produced by current riparian vegetation was estimated using Ecology's Shade model (Ecology, 2003b). GIS coverages of riparian vegetation in the study area (Figure 21) were created from information collected during the 2001 temperature study as described in Stohr (2001), analysis of the most current digital orthophotos (1990-1993), and analysis of the aerial photos taken by Watershed Sciences (Faux, 2002) during the summer of 2001. Riparian forest coverages were created by qualifying three attributes: tree height, species (conifer, deciduous, or mixed), and average canopy density. Average percent vegetation overhang was calculated by species from field data.

The near-stream disturbance zones (NSDZ) were digitized from digital rectified orthophotos. The NSDZ is the active channel area without riparian vegetation that includes features such as gravel bars. In areas where NSDZ edges were not easily identified from the orthophotos because of overhanging vegetation, the NSDZ was estimated from a log-log regression of measured bankfull width versus drainage area (Figure 15).

The wetted widths for the low-flow condition were estimated from a relationship between wetted width and watershed area (Figure 16).

- A 420-foot buffer was created around the stream, and different vegetation polygons were delineated using GIS.
- The vegetation map was coded in the office, then verified with field observations and measurements.

After the GIS vegetation coverages were completed as described above, the vegetation size and density in the riparian zone on the right and left bank was sampled from the coverages along the stream at 100-foot intervals using the Ttools extension for Arcview that was developed by ODEQ (2001). Stream aspect, elevation, and topographic shade angles to the west, south and east were also calculated at each transect location.

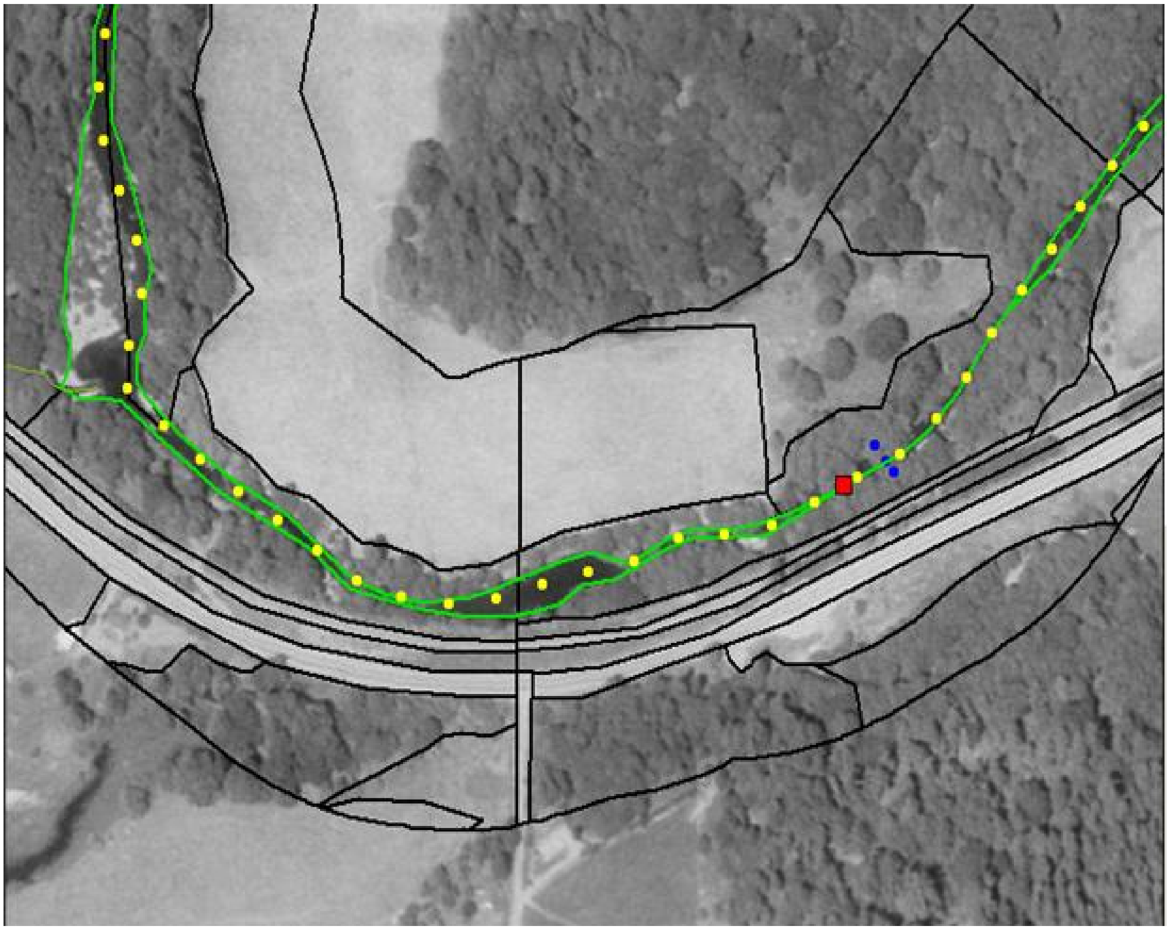

Figure 21. Example of the digital orthophoto quad (DOQ) for the mainstem Willapa River below the confluence with Fork Creek, and digitized wetted edges and bankfull edges.

Effective shade calculations were made for three scenarios of riparian vegetation:

- **Current vegetation.** Effective shade estimates for current vegetation were based on spatial data for height and canopy density (Figure 22).
- **Maximum effective shade from 100-year-old riparian vegetation that would naturally occur in riparian areas within the study area**. Riparian species were chosen based on soil site potential, as given in the Soil Survey of Pacific County (USDA, 1986) and in the DNR Site Index GIS coverage. The survey provides predominant species and height for the most common trees found on the riparian soils within the study area. Four soil types cover 90% of the land within the riparian zone. Douglas-fir and red alder are the principal forest species found on these soils, with western hemlock and others being less prevalent. The average 100-year-index height for conifers on these soils is 179 feet (55 m), and the average 50-year-index height for red alder on these soils is 98 feet (30 m). These tree heights, along with the most commonly measured canopy density of 85% and a buffer width of one site-potential tree height (180 feet), were used to construct the maximum effective shade scenario (Figure 23).
- **Effective shade from 50-year-old riparian vegetation that would naturally occur in riparian areas within the study area.** The Soil Survey of Pacific County (USDA, 1986) estimates the 50-year-index height for red alder is 98 feet. The average 50-year-index for conifers on these soils is 110 feet (Figure 24). For ease of understanding, this was done as a mixed stand of alder and conifer trees all at heights of 100 feet, a density of 85%, and a buffer width of one site potential tree height (100 feet).

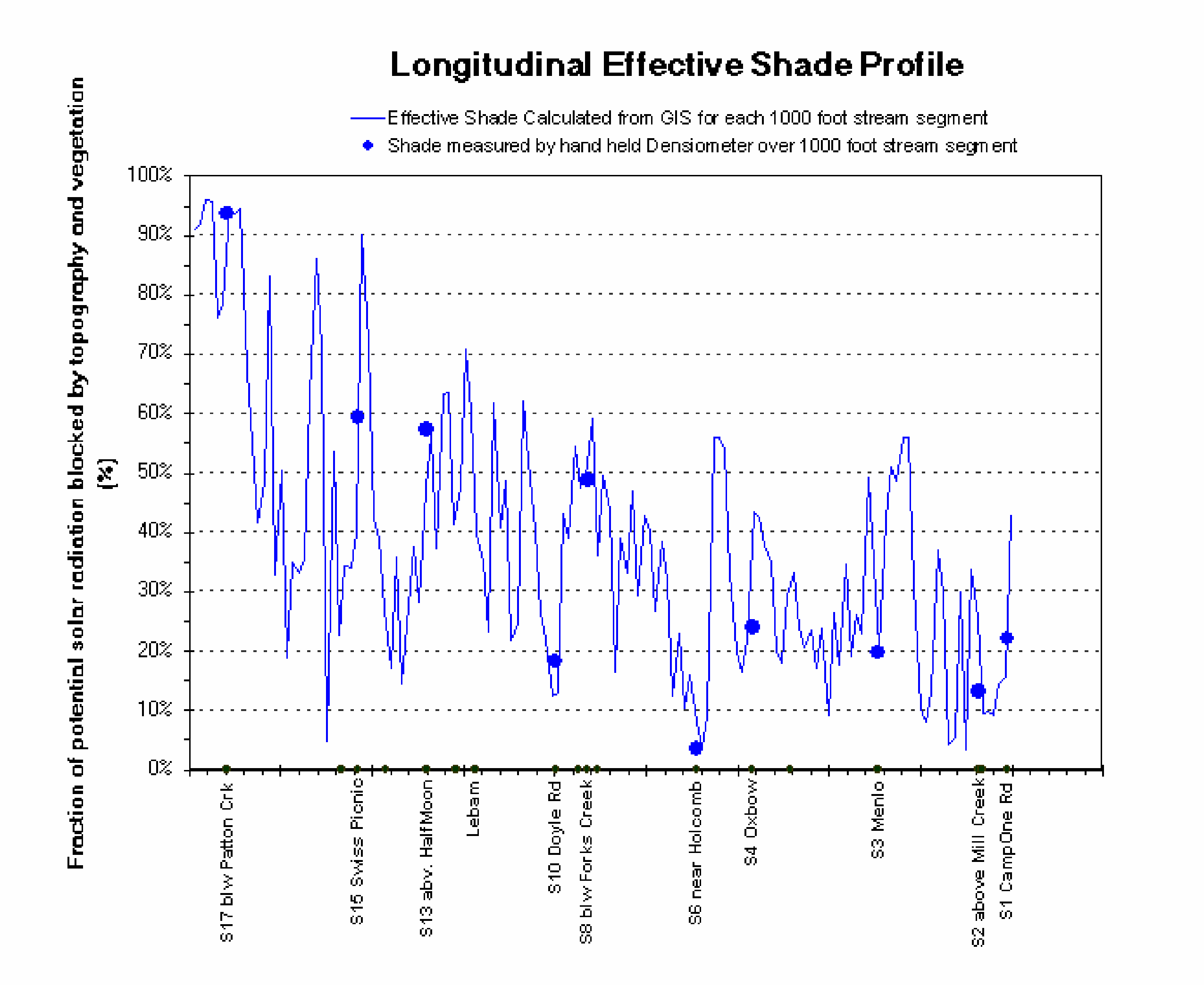

Figure 22. Effective shade from current riparian vegetation in the Willapa River basin.

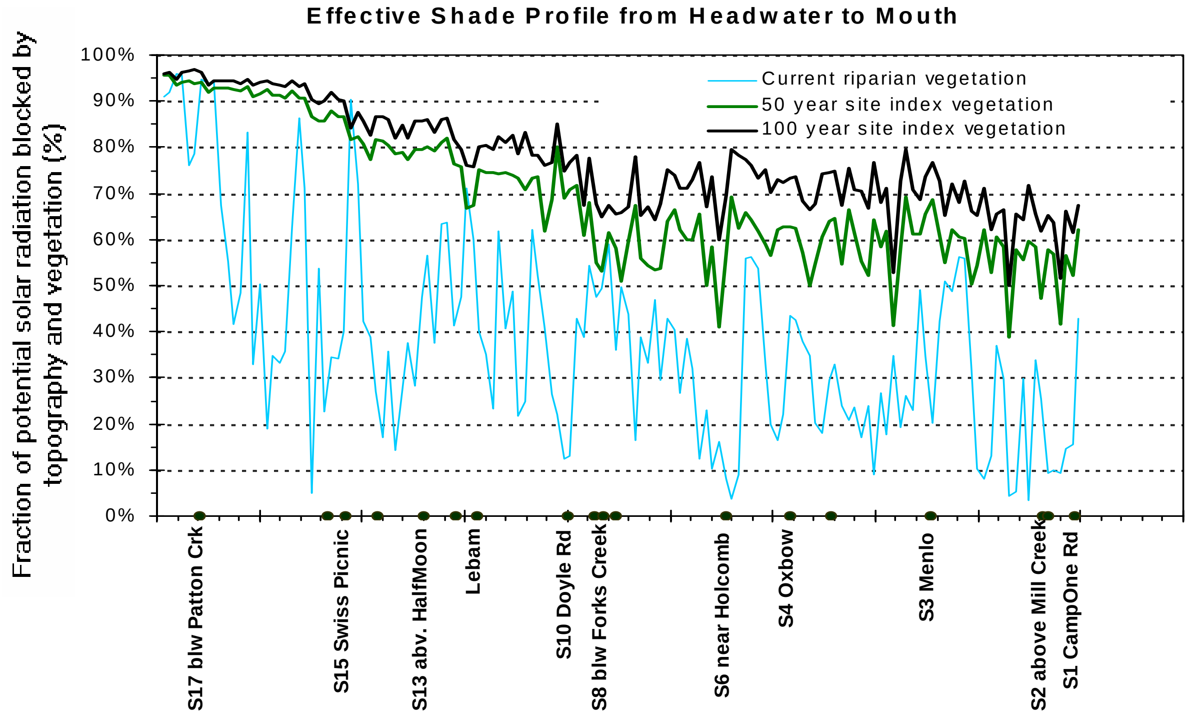

Figure 23. Effective shade from potential mature vegetation in the mainstem Willapa River.

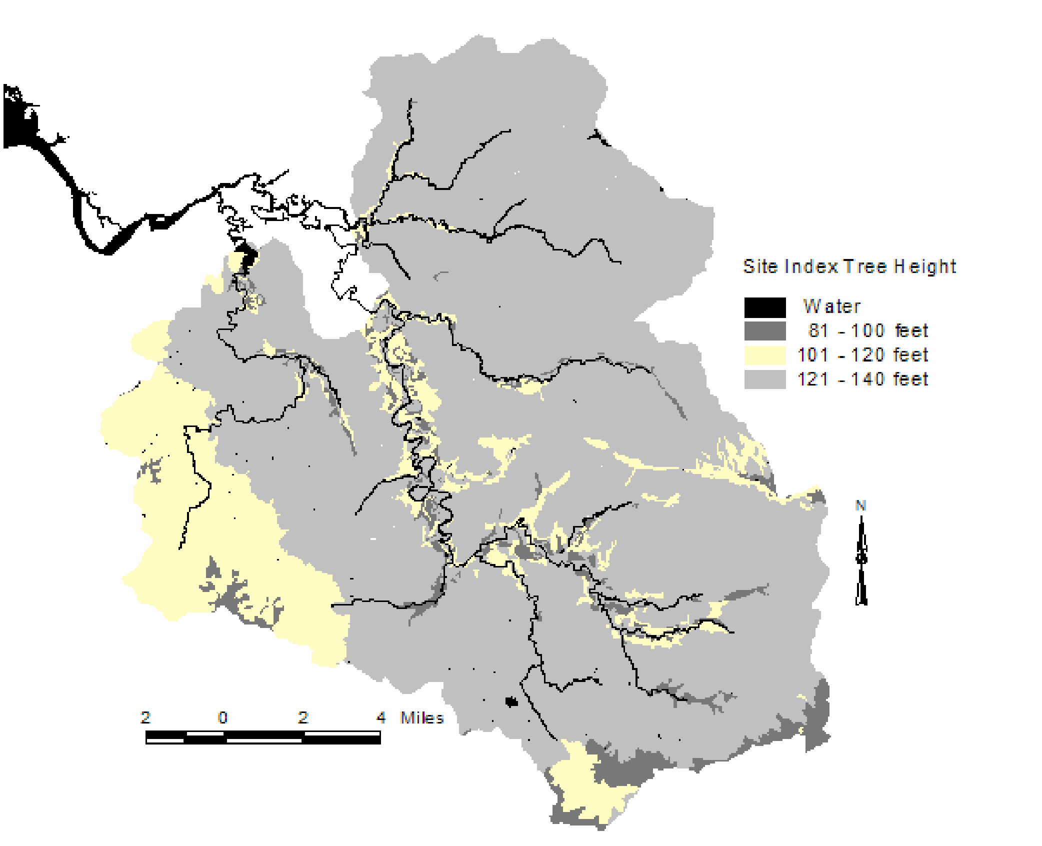

Figure 24. Site index of tree height (50-year) from soil surveys in the Willapa River watershed study area.

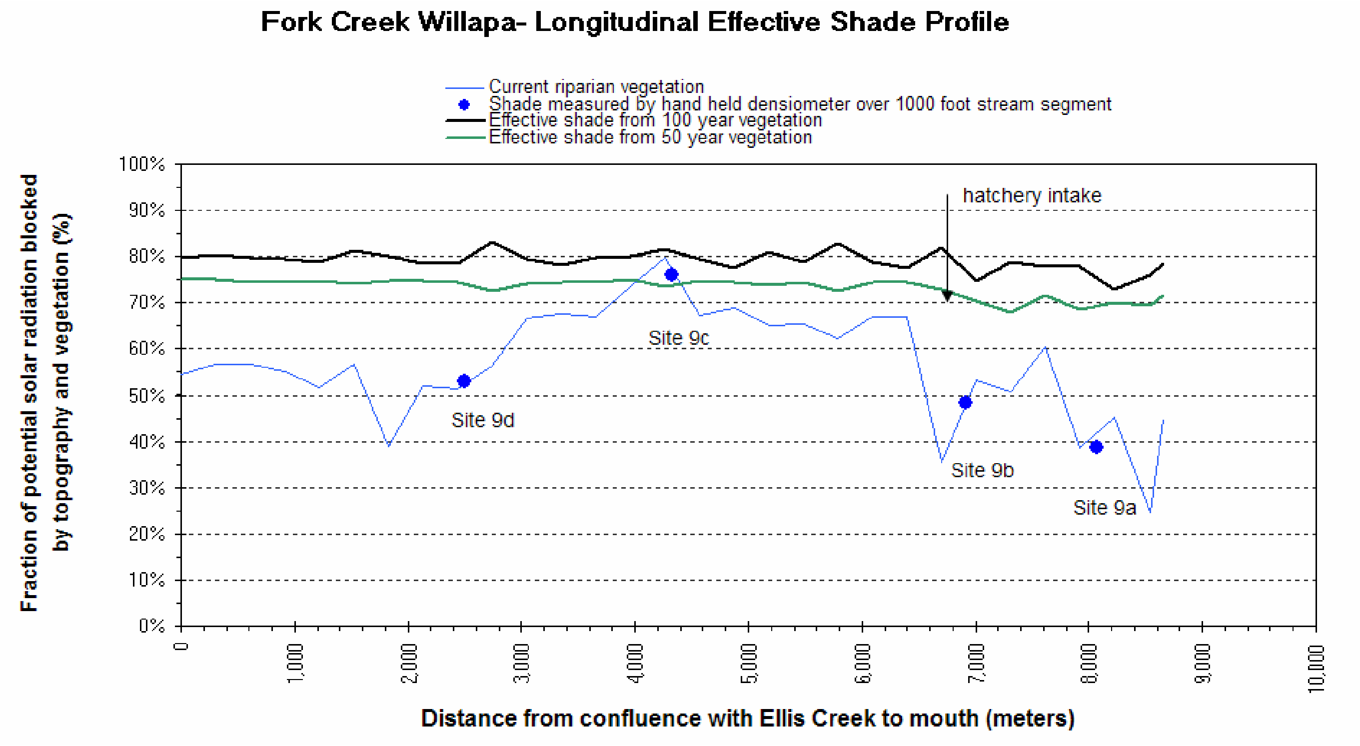

Figure 25. Effective shade from current and potential mature vegetation in the Fork Creek tributary of the Willapa River.

Analytical Framework

Data collected during this TMDL effort have been used to simulate temperatures continuously along streams using a methodology that is both spatially continuous and which spans full-day timeframes. The GIS and modeling analysis was conducted using three specialized software tools:

1. ODEQ's Ttools extension for Arcview (ODEQ, 2001) was used to sample and process GIS data for input to the QUAL2Kw model.

2. Ecology's Shade model (Ecology, 2003a) was used to estimate effective shade along the mainstems of the Willapa River (Figure 23) and Fork Creek (Figure 25). Effective shade was calculated at 100-foot intervals along the streams and then averaged over 1000-foot intervals for input to the QUAL2Kw model.

3. The QUAL2Kw model (Chapra, 2001; Chapra and Pelletier, 2003; and 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 3 and described in Chapra (1997). Diurnally varying water temperatures at 1000-foot intervals along the streams in the Willapa River basin were simulated using a finite difference numerical method. The water temperature model was calibrated to instream data.

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 at 1:3,000 scale from 1-meter-resolution DOQ and sampled from the GIS coverage along the streams at 100-foot intervals in the study area. Effective shade was calculated from vegetation height and density with Ecology's Shade model. The effective shade values calculated from the Shade model were found to be highly correlated with field measurements taken during the summer 2001 stream surveys (Figure 23, Figure 25).

- 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 was sampled from the 10-meter DEM grid with the Milagrid Arcview extension. Gradient was calculated from USGS 1:24,000 quad maps.

- Aspect (stream flow direction in decimal degrees from north) was calculated by the Ttools extension for Arcview.

- The hourly observed temperatures for the boundary conditions at the headwaters and the daily minimum and maximum observed temperatures for the tributaries were used as input to the QUAL2Kw model for the calibration and verification periods. The QUAL2Kw model of the mainstem was calibrated using data collected during August 8-14, 2001 and August 28-30, 2001, and verified using data from August 1-4, 1998.

- Flow balances for the calibration and verification periods were estimated from field measurements and gage data of flows made by Ecology. The lowest 7-day-average flows during the July-August period with recurrence intervals of 2 years (7Q2) and 10 years (7Q10) were estimated based on low-flow statistics from USGS gaging stations in the Willapa River basin (Table 4). The 7Q2 condition for the mainstem was well represented by the synoptic flow taken August 4, 1998 so actual field data were used. The 7Q2 and 7Q10 flow statistics for Fork Creek were estimated using the average ratio of flow between the USGS Willapa River near Willapa gage (12013500) and the USGS historical flow gage at Forks Creek (12012000) for the 18 years that flows were recorded at both locations. Flow balance spreadsheets of the stream networks for the Willapa River and Fork Creek were 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 relationships between wetted width, wetted depth, average velocity, and flow.

- The groundwater temperature in the lower elevations of the Willapa River watershed is known to be spatially variable, with reported values ranging from 10.4 to 13.1°C with a median of 11.3°C (Erickson, 2001; Appendix D). Soil temperature monitors showed values in this same range. Calibration of the QUAL2Kw model involved selection of the temperature of diffuse inflows ranging from the groundwater temperature to representative 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 periods. For the August 4, 1998 period, the observed minimum and maximum air temperatures at the Raymond 2S station were used. For all periods, cloud cover observed from the Swiss Picnic Campground located near the middle of the watershed was used. The relative humidity (RH) for August 4, 1998 was assumed to be equal to that of the August 8-14, 2001 because the Raymond 2S station does not collect RH and because air temperatures were similar during the two periods. A wind speed of 0.5 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, the density and heat capacity of water.

  Calibration of the QUAL2Kw model involved specification of the thickness of the surface sediment layer in the range of 10 to 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, August 8-14, was used for calibration of the QUAL2Kw model (Figure 26 and Figure 27). An aerial survey of Thermal Infrared Radiation (TIR, often referred to as FLIR) was conducted during a period of cooler air temperature and higher flows on August 30, 2001 (Stohr, 2001; Faux, 2002). The August 30, 2001 period was used to assist in calibration of the QUAL2Kw model for the mainstem and was used for verification of the QUAL2Kw model for Fork Creek. August 1-4, 1998, a warm low-flow period when numerous streamflow and field measurements were taken, was used for verification of the mainstem model (Figure 26).

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. For the calibration and verification periods, the RMSE of the predicted versus observed daily maximum temperatures in the Willapa River basin averaged around 0.5°C (Table 8). The RMSE of the combined maximum and minimum predicted daily temperatures was slightly higher at around 0.6°C.

Table 8. Summary root mean square error (RMSE) of differences between the predicted and observed daily maximum temperatures and combined maximum and minimum temperatures in the Willapa River basin.

Watercourse	Statistic	RMSE		
		August 8-14, 2001 (ºC)	August 28-30, 2001 (ºC)	August 1-4, 1998 (ºC)
Willapa mainstem	Maximum	0.51	0.42	0.69
	Total (max + min)	0.70	0.62	0.74
Fork Creek	Maximum	0.56	0.14	NA
	Total (max + min)	0.61	0.22	NA

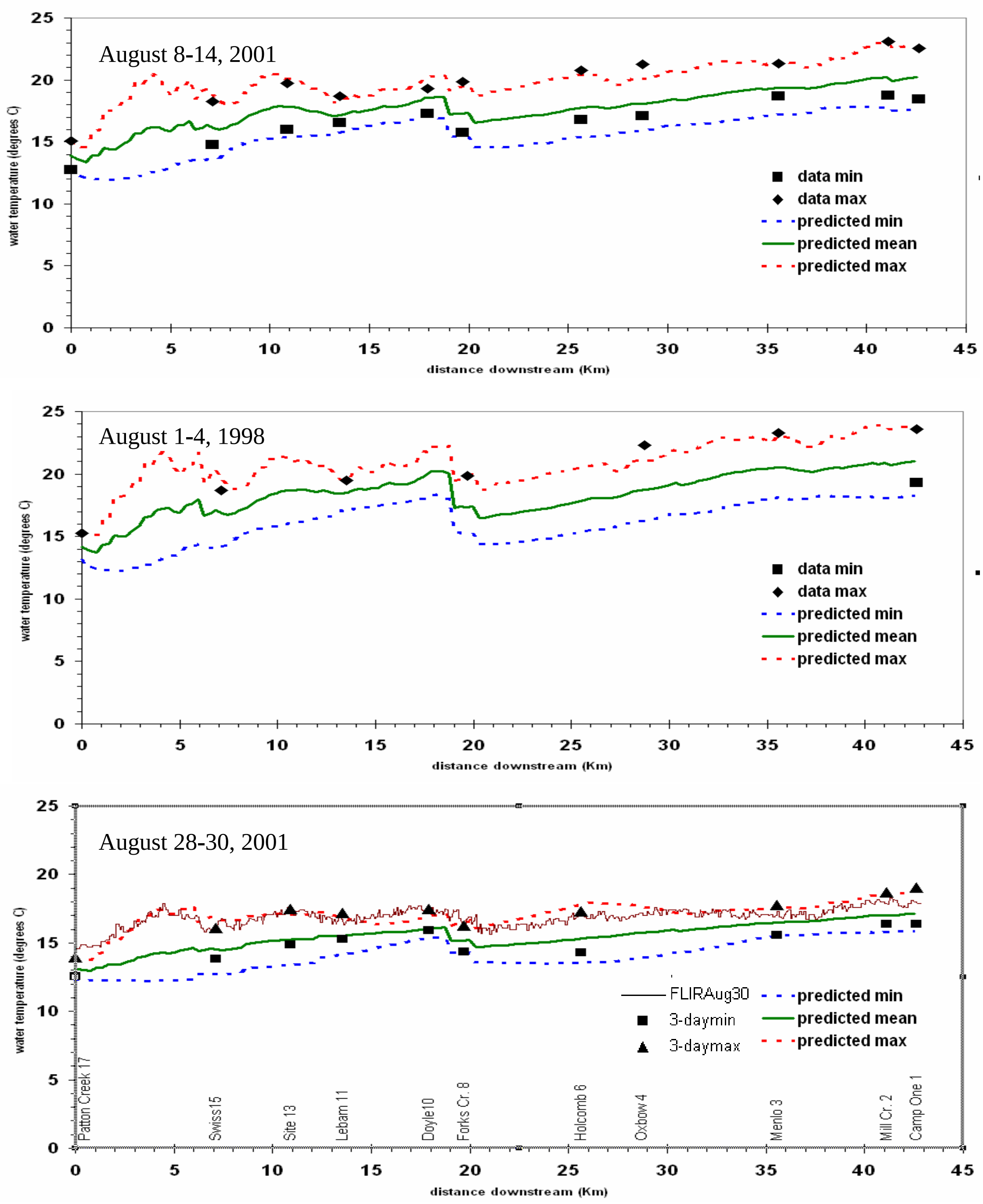

Figure 26. Predicted and observed water temperatures in the Willapa River for calibration (August 8-14 and 28-30, 2001) and verification (August 1-4, 1998) periods.

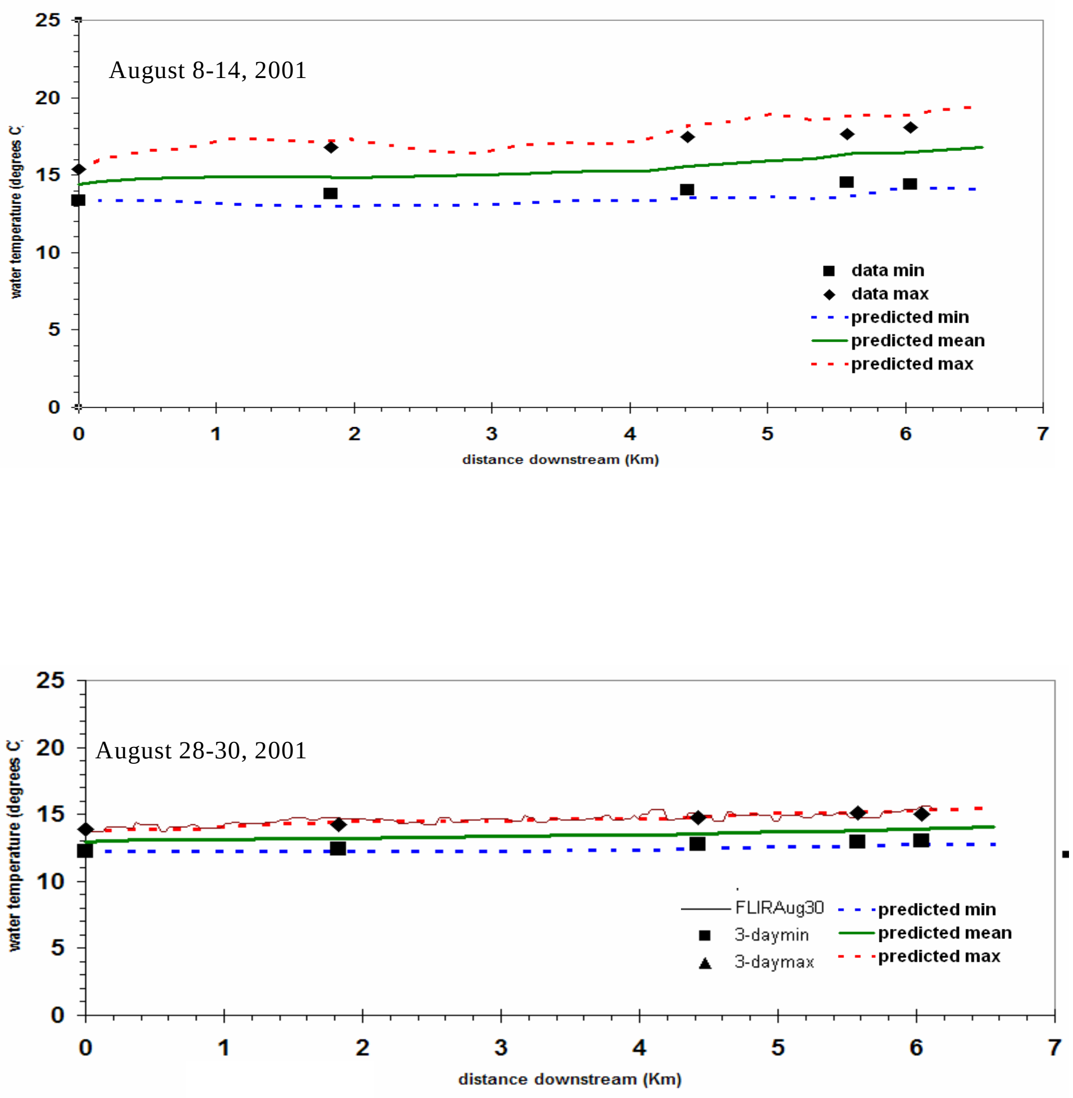

Figure 27. Predicted and observed water temperatures in Fork Creek for calibration (August 8-14, 2001) and verification (August 28-30, 2001) periods.

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Loading Capacity

The calibrated QUAL2Kw model was used to determine the loading capacity for effective shade for streams in the Willapa 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.

Air temperature values for the 7Q2 condition were assumed to be represented by the average of the hottest weeks of 1997 and 1985, which was the median condition from the historical record at Raymond 2S (Table 7). The air temperatures for the 7Q10 condition was the average of the hottest weeks of 1996 and 1982, which was the 90th percentile condition from Raymond 2S. Critical daily maximum air temperatures along the mainstem Willapa River were estimated by applying the regression equation from Figure 18 to the temperature statistics from Raymond 2S. A similar regression equation showing the relationship between daily minimum air temperatures measured along the river and at Raymond 2S was used to estimate the minimum air temperature for the critical condition. The Fork Creek model used the same air temperatures for the reaches near the confluence to the mainstem, but lower air temperatures were calculated for upper elevation sites based on the continuous air temperature data collected.

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 Willapa River watershed. The maximum potential shade is assumed to be that of a 100-year-old forest condition described in the USDA Soil Survey for Pacific County (USDA, 1986). Mature vegetation was represented by a tree height of 55 meters (about 180 feet), canopy density of 85%, and riparian vegetation width of 180 feet on each side of the stream.
- Maximum potential effective shade from mature red alder and 50-year site index conifer that would naturally occur in the Willapa River watershed. The maximum potential shade from vegetation was assumed to be represented by a tree height of 30.5 meters (about 100 feet), canopy density of 85%, and riparian vegetation width of 100 feet on each side of the stream.

Additional critical scenarios were evaluated to test the sensitivity of predicted water temperatures to changes in riparian microclimate, decreases in channel width, and reduction of tributary temperatures:

- **Microclimate.** Increases in vegetation height, density, and riparian zone width are expected to result in decreases in air temperature. In order to evaluate the effect of this potential change in microclimate on water temperature, the daily maximum air temperature was reduced by 2°C for reaches modeled with a 100-year-old forest condition based on the summary of literature presented by Bartholow (2000) and as reported in the Stillaguamish Temperature TMDL (Pelletier, 2004).
- **Channel width.** Channel banks are expected to stabilize and become more resistant to erosion as the riparian vegetation along the stream matures. Current bankfull width-to-depth ratios in the watershed are comparable to those found in the literature (Rosgen, 1996) for similar channel types. It is not expected that a large reduction in channel width will take place in this watershed. Although much of the Willapa River has channel widths that would be considered typical, there are some areas where large amounts of erosion have occurred and stream banks are very wide as seen from the aerial orthophotos. The sensitivity of predicted stream temperatures to reduction of channel width was tested by predicting stream temperatures that would be associated with channel widths that were calculated from the equation shown in Figure 15. This simulation keeps most of the channel widths the same as the current channel, but reduces the wide areas where erosion of the banks has taken place.
- **Reduced tributary temperatures.** A scenario was evaluated with the assumption that the inflowing Mill Creek and Fork Creek tributaries did not exceed 18°C. Several tributary locations currently exceed daily maximum water temperatures of 18°C, but water temperatures may be reduced in the future if riparian vegetation is increased and other implementation activities occur.

The results of the model runs for the critical 7Q2 and 7Q10 conditions are presented in Figures 28 and 29. The current condition in the Willapa watershed is expected to result in daily maximum water temperatures that are greater than 18°C in most of the evaluated reaches. Portions of the evaluated streams could be greater than the approximate threshold for lethality of 23°C under current riparian conditions.

Substantial reductions in water temperature are predicted for hypothetical conditions with mature riparian vegetation, improvements in riparian microclimate, and reduction of channel width. Potential reduced temperatures are predicted to be less than 18°C in most of the evaluated reaches and less than the threshold for lethality of 23°C in all of the streams that were evaluated (Table 9). Further reductions are likely if all tributaries and channel complexity are restored.

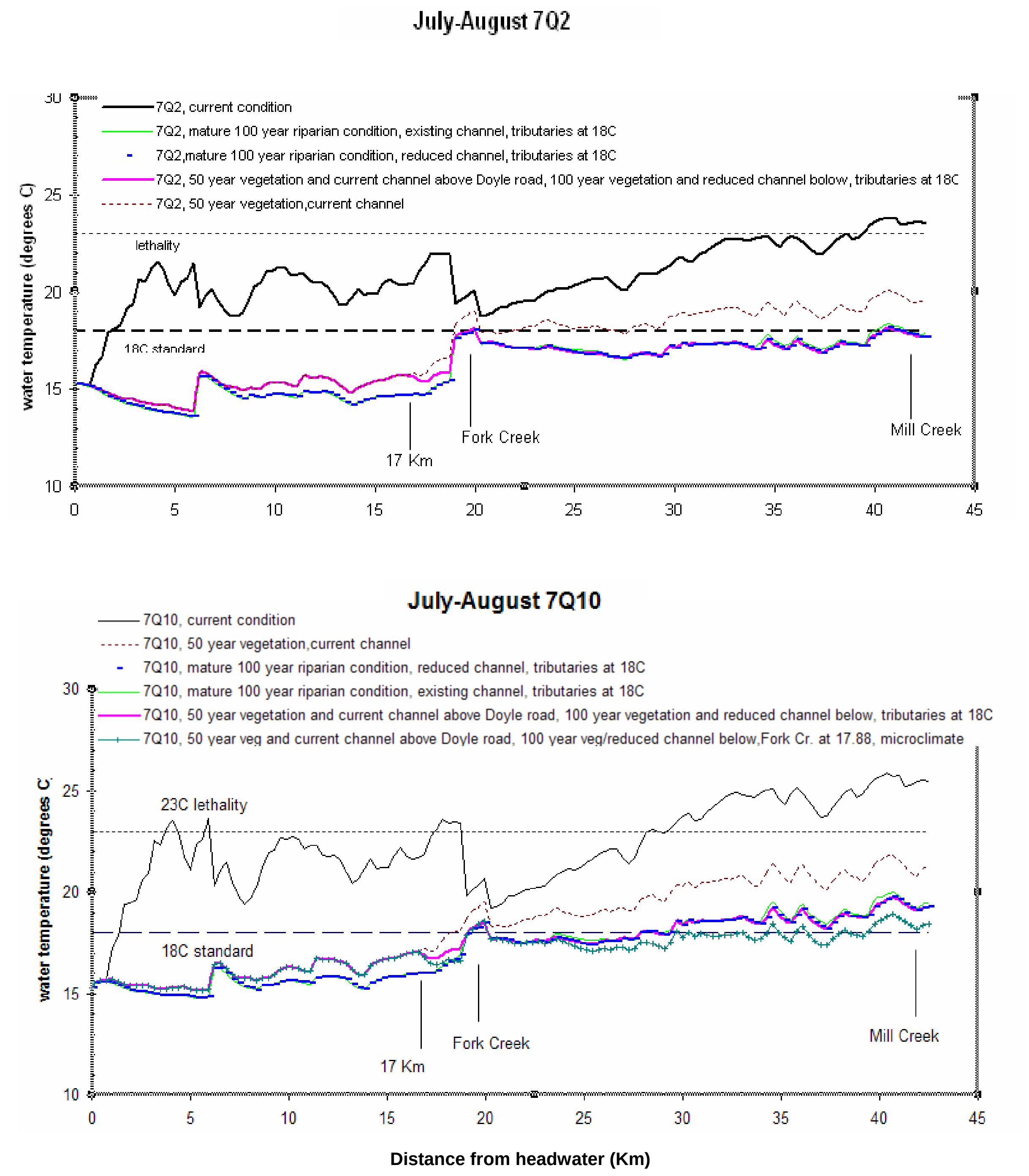

Figure 28. Predicted daily maximum water temperatures in the Willapa River for critical conditions during July-August, 7Q2 and 7Q10.

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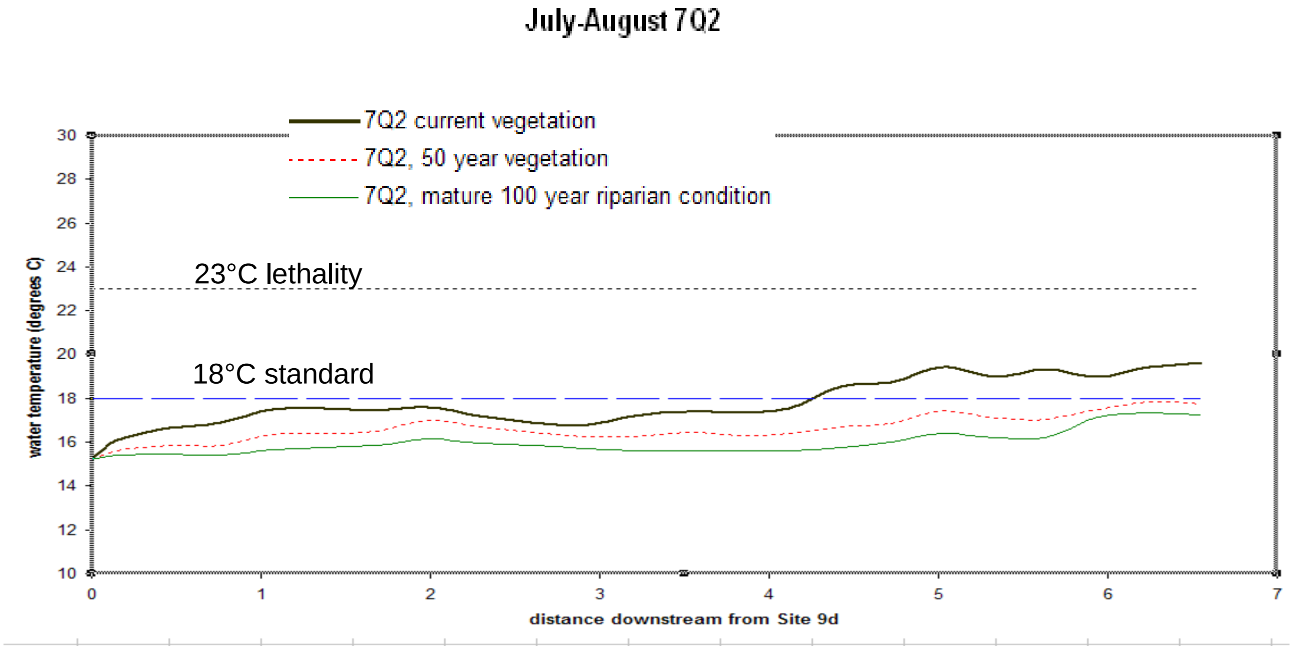

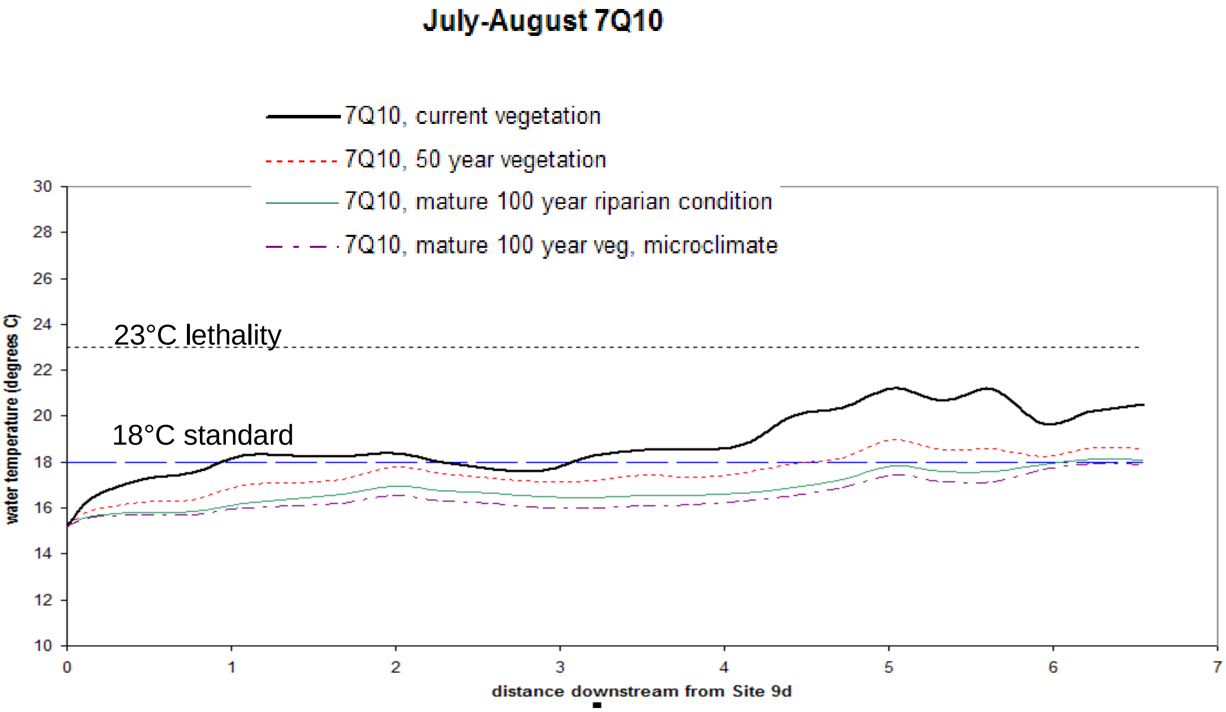

Figure 29. Predicted daily maximum water temperatures in Fork Creek for critical conditions during July-August 7Q2 and 7Q10.

Table 9. Management scenarios and decreases in peak temperature in the Willapa River for extreme hydrologic conditions (7Q10)

Scenario	Description	Maximum temperature (ºC)	Potential temperature reduction from current conditions (ºC)
1	Current vegetation	25.9	0.0
2	50-year mixed species vegetation and current channel	21.8	-4.0
3	100-year riparian condition, existing channel, Fork and Mill creek tributaries at 18ºC	20.0	-5.9
4	100-year riparian condition, reduced channel, Fork and Mill creek tributaries at 18ºC	19.8	-6.1
5	50-year riparian vegetation and current channel from one mile above Doyle Road (km 17.07) to headwater, 100-year vegetation and reduced channel below, Mill and Fork creeks at 18ºC	19.8	-6.1
6	Same split vegetation and channel as scenario 5, Mill Creek 18ºC, Fork Creek (km 17.88) with 100-yr vegetation and microclimate, plus microclimate for mainstem below km 17.07	18.9	-7.0

Load Allocations

Load allocations for effective shade in the Willapa River watershed are as follows:

- For the mainstem Willapa River from a location approximately one mile above the Doyle Road bridge crossing to the headwaters, the load allocation for effective shade is the maximum potential effective shade that would be produced by naturally occurring 50-year-old riparian vegetation. Fifty-year-old vegetation is estimated to have a height of 100 feet and a density of 85%, and result in effective shade values ranging from 67% to 96%.

- For the mainstem Willapa River from a location approximately one mile above the Doyle Road bridge downstream to the USGS gage near Camp One Road, the load allocation for effective shade is the maximum potential effective shade that would occur from mature riparian vegetation. Mature riparian vegetation is estimated to have a height of 180 feet and a density of 85%, and result in effective shade values ranging from 57% to 86%.

- For all unmodeled perennial streams in the Willapa River watershed with bankfull widths less than 60 feet (18.3 m), the load allocation for effective shade is the maximum potential effective shade that would be produced by naturally occurring 50-year-old riparian vegetation. Fifty-year-old vegetation is estimated to have a height of 100 feet and a density of 85%.

- For all unmodeled perennial streams in the Willapa River watershed with bankfull widths greater than 60 feet (18.3), the load allocation for effective shade is the maximum potential effective shade that would occur from mature riparian vegetation. Mature riparian vegetation is estimated to have a height of 180 feet and a density of 85%.

Load allocations for effective shade are quantified in Appendix E for the modeled reaches of the mainstem Willapa River and Fork Creek.

For other perennial streams in the watershed, the load allocations for effective shade are represented in Figure 30 and Appendix E, based on the estimated relationship between shade, channel width, and stream aspect at the assumed maximum riparian vegetation condition.

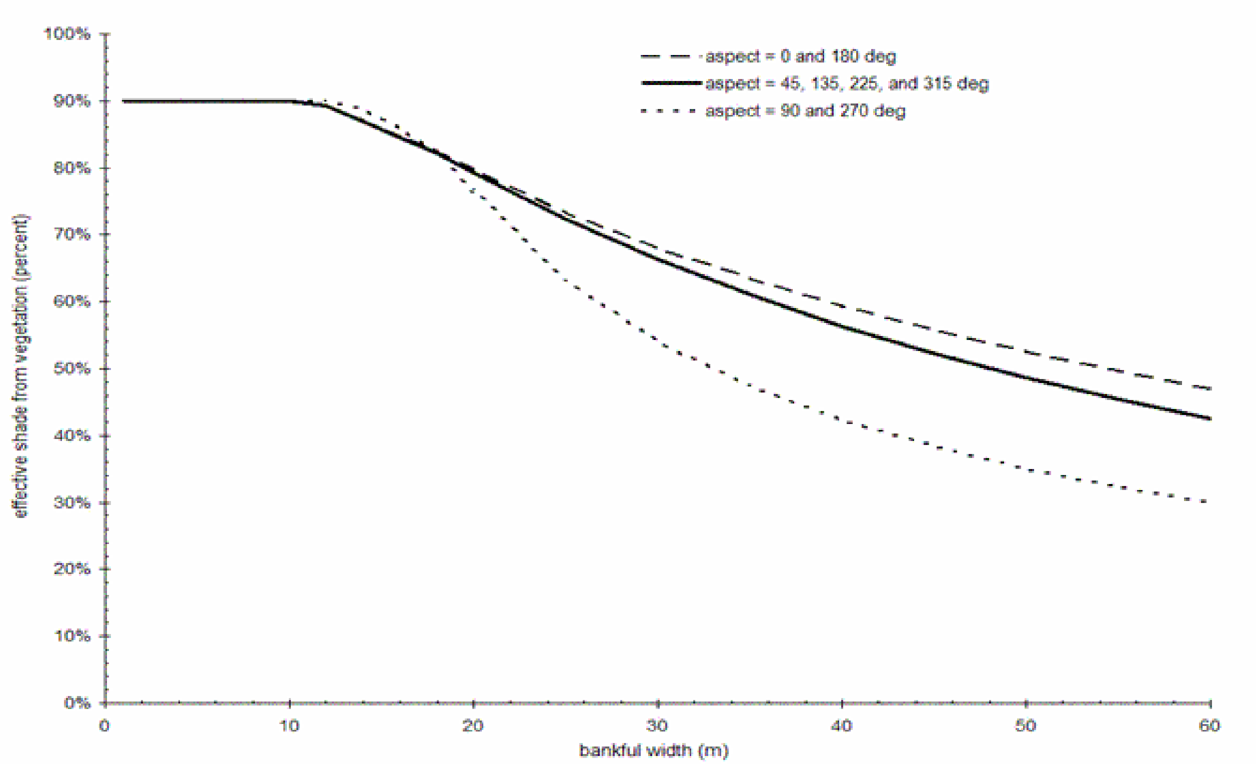

Figure 30. Load allocations for effective shade for various bankfull width and aspect of unmodeled perennial streams in the Willapa River watershed.

In addition to load allocations for effective shade in the study area, the following management activities are recommended for compliance with the water quality standards throughout the watershed:

- For privately-owned forest land, the riparian vegetation prescriptions in the Forests and Fish Report are recommended for all perennial streams. Load allocations are included in this TMDL for forest lands in the Willapa 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 or surface water inflows to streams in the watershed should be encouraged and have the potential to decrease stream temperatures.

- 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.

- Management activities that increase the amount of large woody debris in the Willapa River system will assist in pool forming processes and will assist in reducing flow velocities that wash out spawning gravels and contribute to channel downcutting.

- The South Fork Willapa River currently maintains cool water and does not exceed state standards. Management activities in this basin should take care to ensure that future activities maintain the existing riparian vegetation and shade levels. Current riparian vegetation and buffers are sufficient to maintain temperatures in this subbasin. Further harvest of existing riparian stands will negatively affect stream temperature.

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Wasteload Allocations

Wasteload allocations for the NPDES discharge from the Forks Creek Fish Hatchery were evaluated. The Forks Creek Fish Hatchery diverts water from Fork Creek approximately one mile upstream of the hatchery. The hatchery augments the creek water with well water and from a nearby smaller creek. The hatchery discharges effluent to Fork Creek a short distance upstream from the confluence with the mainstem Willapa River.

The water quality standards contain the following provision for allowable increases in water temperature when natural conditions are less than 18°C in Class A waters:

"Incremental temperature increases resulting from point source activities shall not, at any time, exceed t=23/(T+5). For purposes hereof "t" represents the maximum permissible temperature increase measured at a mixing zone boundary; and T represents the background temperature as measured at a point or points unaffected by the discharge and representative of the highest ambient water temperature in the vicinity of the discharge"

When natural or system potential conditions are greater than 18°C then the following language applies:

"…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."

Figure 31 shows the water temperature upstream of the hatchery, the temperature below the hatchery, and the water quality temperature standard if the upstream temperature is used as a surrogate for background conditions. For most of the summer, the difference caused by hatchery effluent is within the water quality standard. There is a four-day period, August 8-12, 2001, when the temperature measured below the hatchery ranged from 0.12 - 0.45°C warmer than the standard would allow. In general, a hatchery relies on having cold water for its fish. As hatchery improvements are made, shading the concrete ponds and other methods to keep water from heating during hatchery operations should be considered.

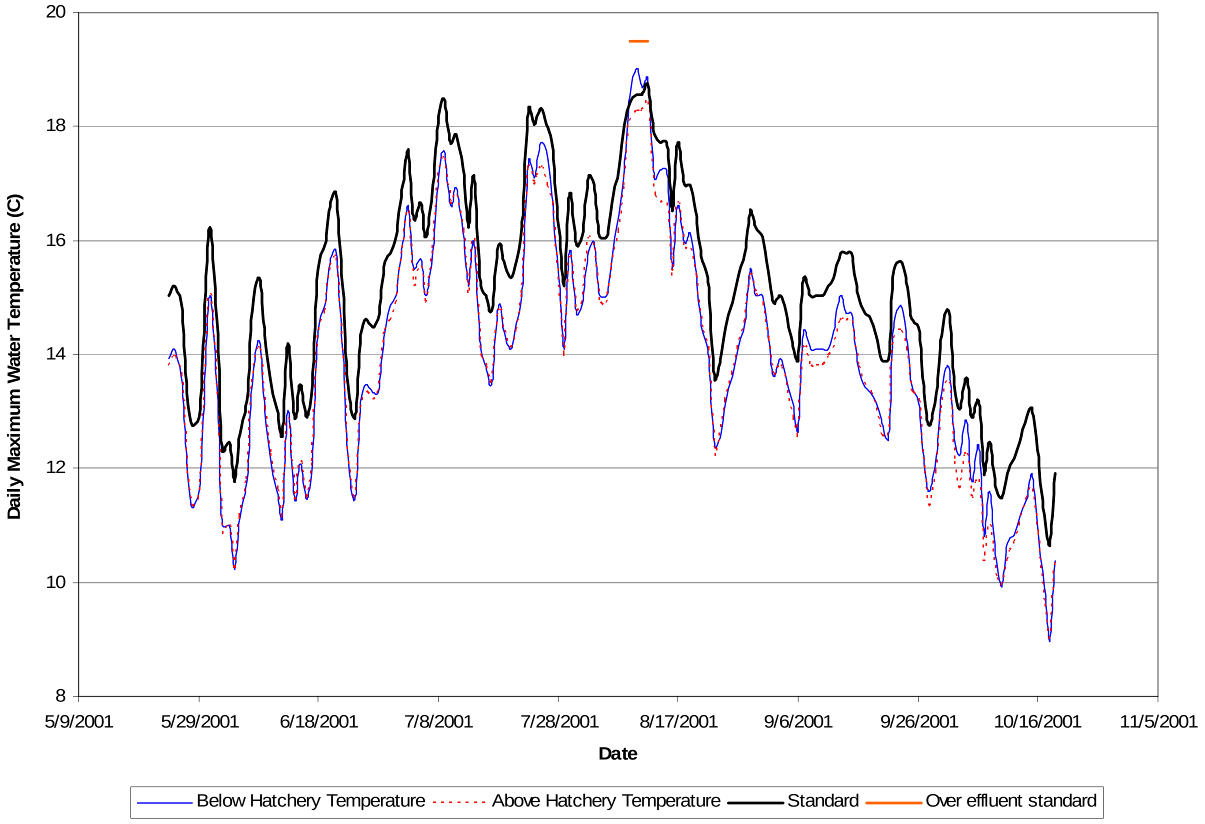

Figure 31. Fork Creek water temperatures immediately upstream and downstream of the hatchery.

The federal Clean Water Act requires development of a wasteload allocation for the Forks Creek Fish Hatchery because it falls within the TMDL study area. The Forks Creek Hatchery does not have a mixing zone or dilution factor, so water quality standards need to be met at the end of the pipe (Greg Cloud, Ecology Southwest Regional Office permit manager, June 9, 2004).

The best estimate of background temperature immediately upstream of the hatchery after nonpoint controls are in place is 17.14°C (Figure 29). To account for any variability in system potential estimates, effluent limits were calculated for a small range of system potential values.

Maximum temperatures for NPDES effluent discharges (T_{NPDES}) were calculated from the following mass balance equation for system potential upstream temperatures less than 18°C (Table 10):

T_{NPDES} = 23/([system potential upstream temperature°C] +5°C) + [system potential upstream temperature°C

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:

T_{NPDES} = [system potential upstream temperature°C] +0.3°C

Table 10. Wasteload allocations for effluent temperature from the Forks Creek Fish Hatchery NPDES discharge.

System potential water temperature upstream of hatchery for 7Q10 critical condition (°C)	7Q10 flow upstream of hatchery	Allowable temperature change at edge of mixing zone (°C)	Allowable effluent temperature (°C)
17.14	.1045 cms (3.69cfs)	**1.04**	**18.18**
18	.1045 cms (3.69cfs)	0.3	18.3
19	.1045 cms (3.69cfs)	0.3	19.3

bold = best estimate of system potential water temperature and allowable effluent temperature for the Forks Creek Fish Hatchery

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 Raymond 2S represents a reasonable worst-case condition for prediction of water temperatures in the Willapa 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 maximum daily 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 0.5°C.

Recommendations for Monitoring

To determine the effects of management strategies within the Willapa River watershed, regular monitoring is recommended. Continuously-recording water temperature monitors should be deployed from July through September to capture the critical conditions.

The following locations are suggested for a minimal sampling program:

- Willapa River at Camp One Road (site of USGS flow station)
- Fork Creek above the hatchery
- Willapa River near Oxbow
- Willapa River at Lebam or at Swiss Picnic Campground
- South Fork Willapa near drinking water withdrawal

Mature riparian vegetation requires many years to become established. Interim monitoring of summer water temperatures is recommended, such as at five-year intervals.

Interim monitoring of the composition and extent of riparian vegetation is also recommended (e.g., by using photogrammetry or remote sensing methods).

Measurement of effective shade at the stream center in various segments, for comparison with the load allocations, could be done using hemispherical photography, angular canopy densiometers, solar pathfinder instruments, or the more-common spherical densitometers.

Monitoring implementation activities by keeping a record of miles/acres of stream in restoration will provide valuable information on riparian restoration progress.

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Appendices

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Appendix A

Water and air continuous temperature monitoring data for May - October 2001

This appendix presents the water and air temperature data gathered by the Department of Ecology during this study. Temperatures were recorded every 30 minutes by Onset Stowaway Tidbit monitors (Stohr, 2001).

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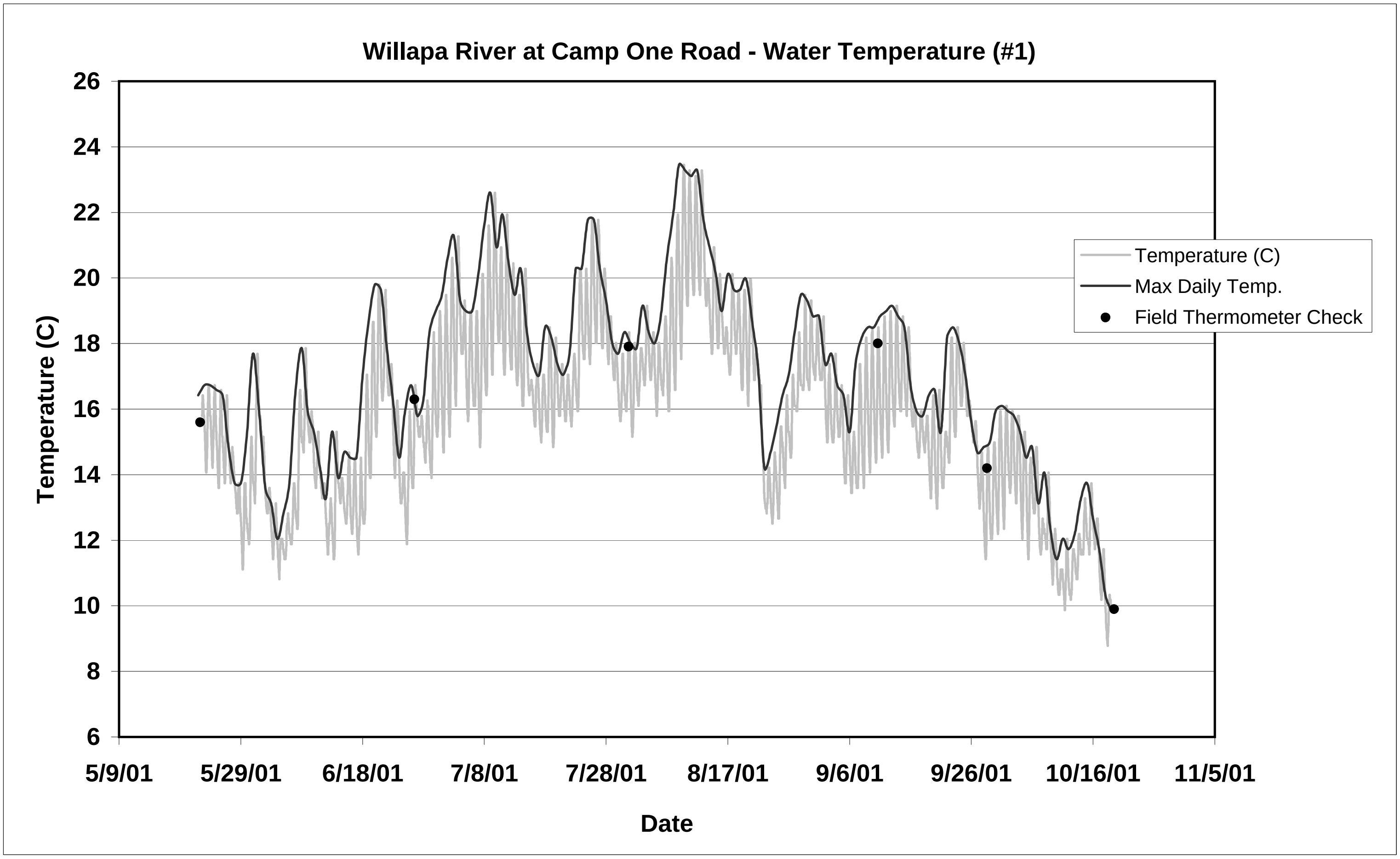
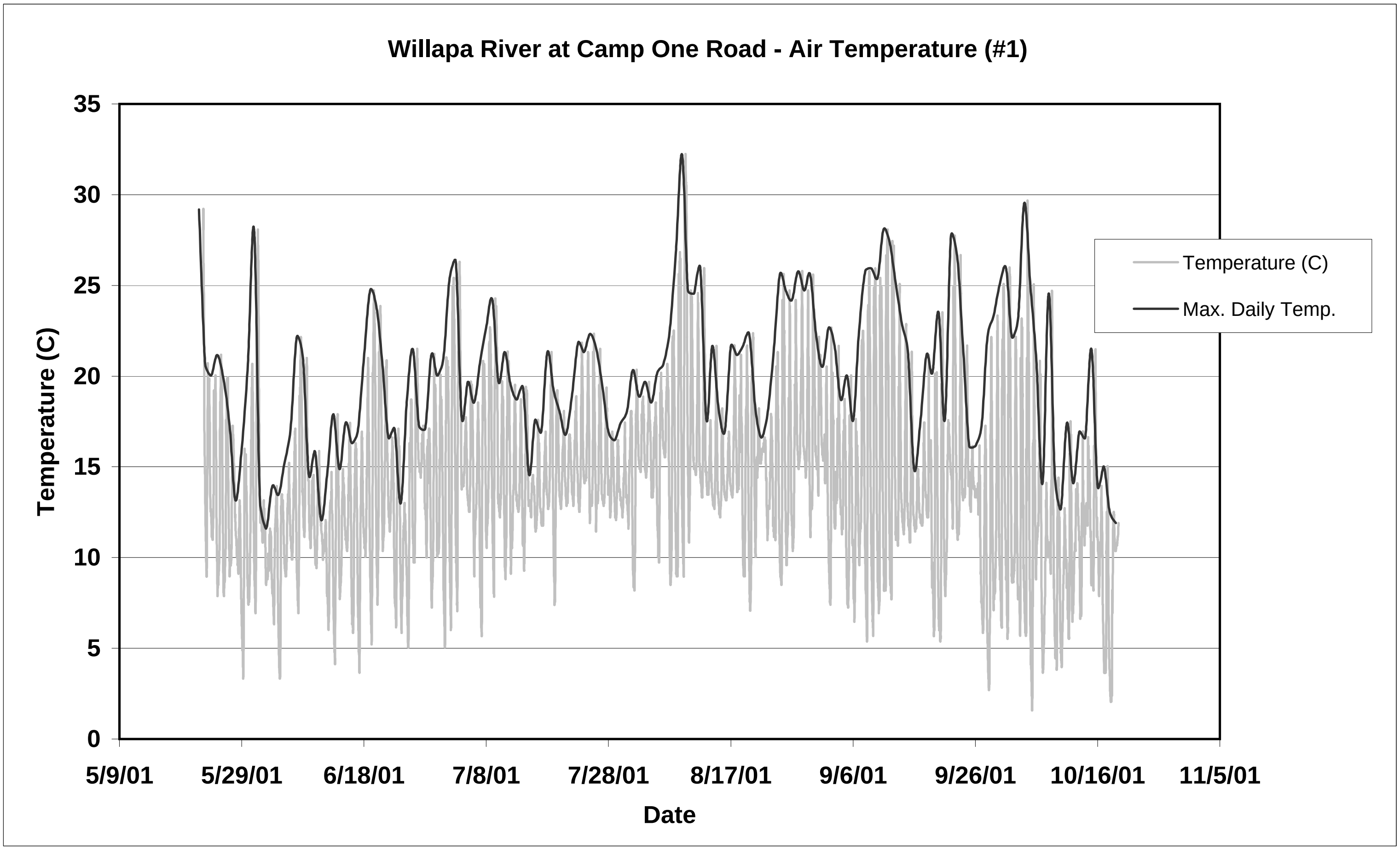
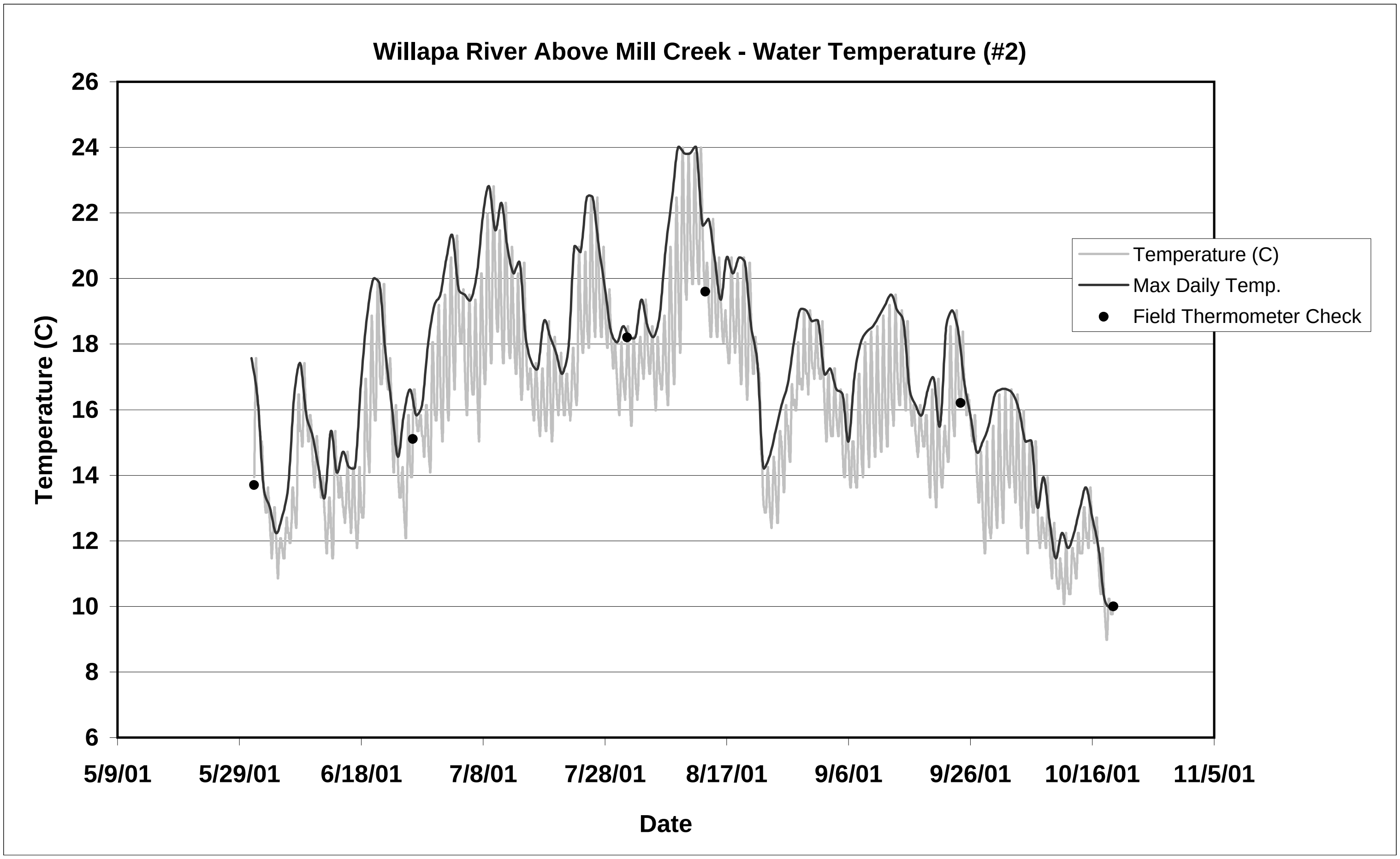
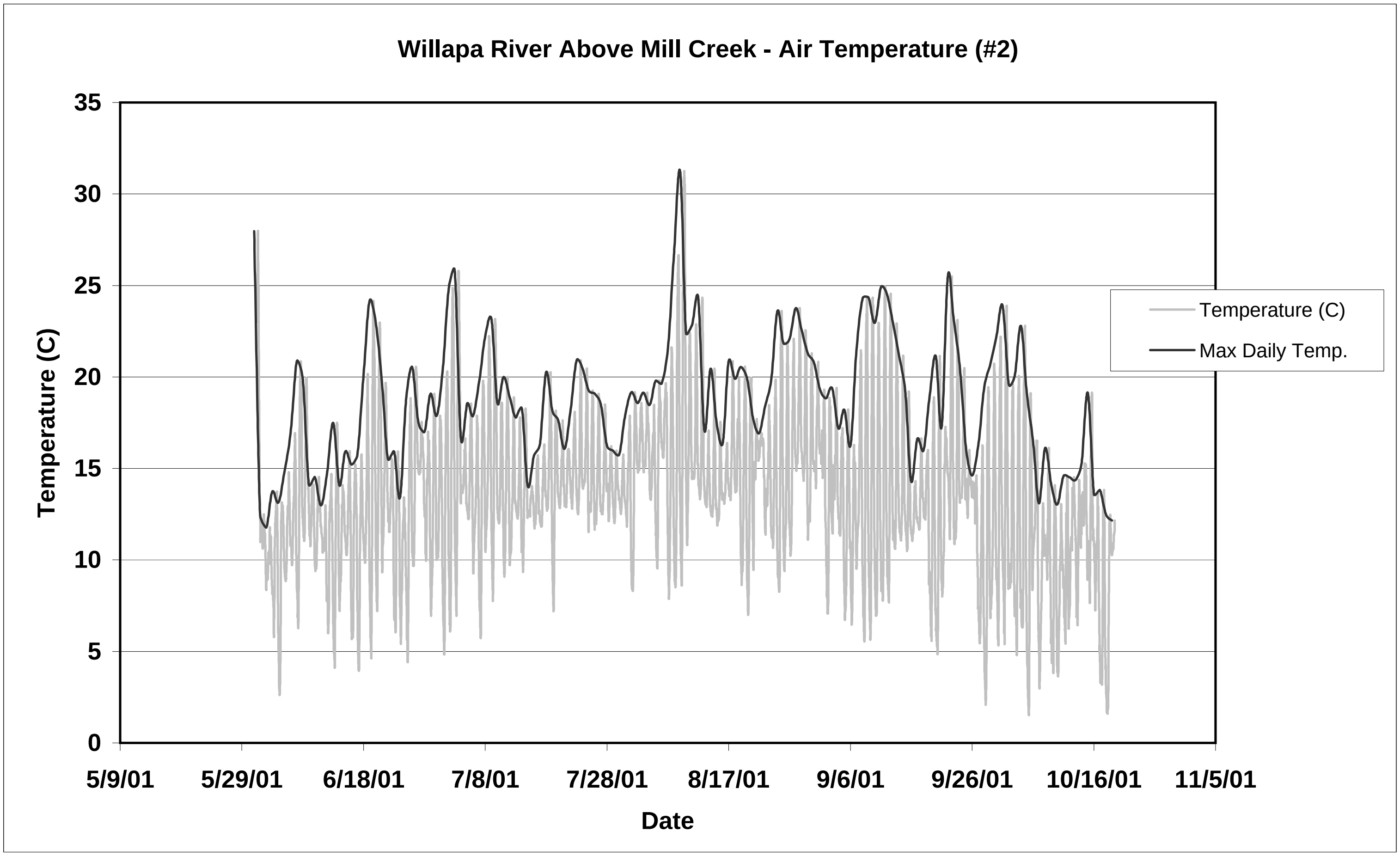
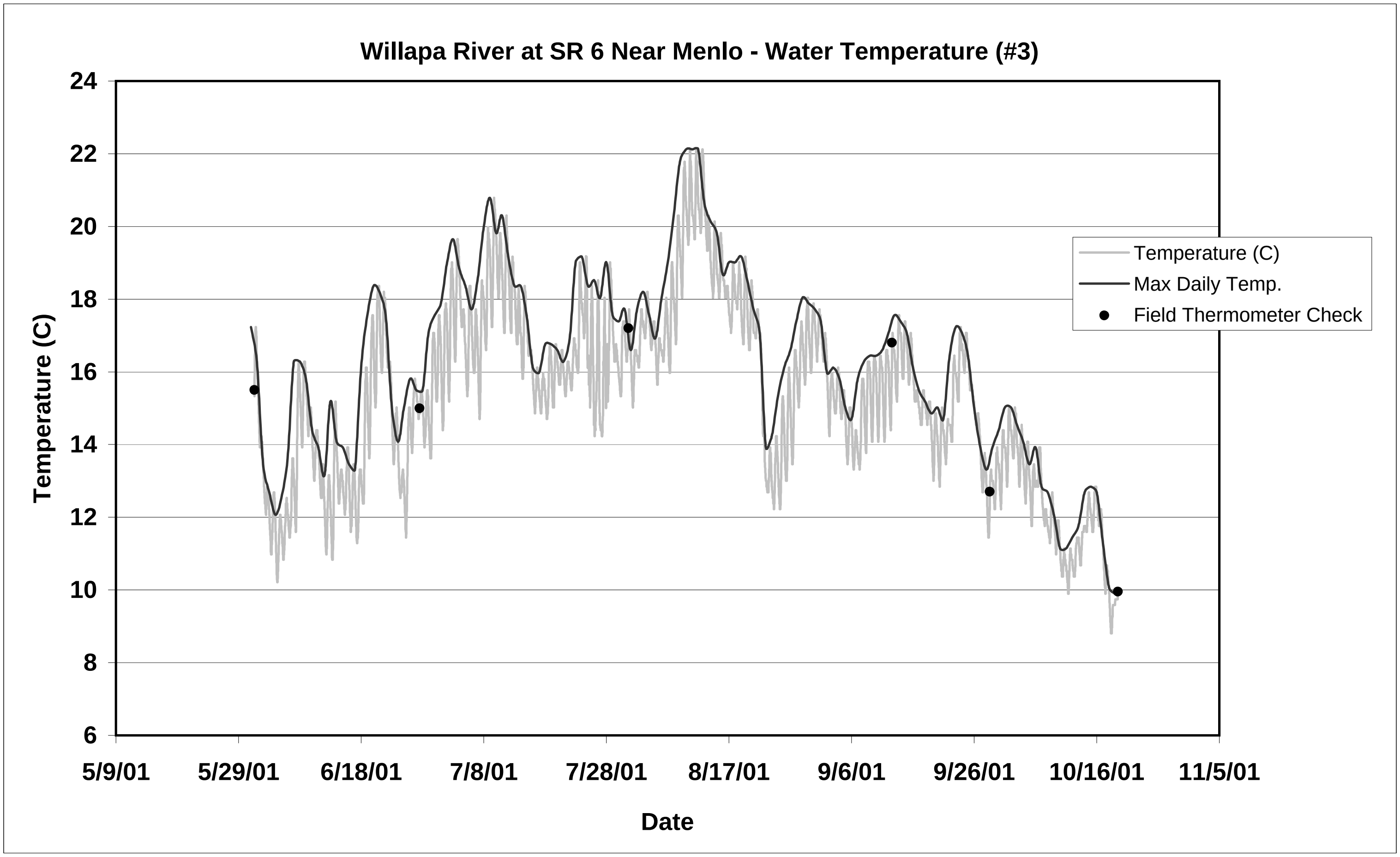
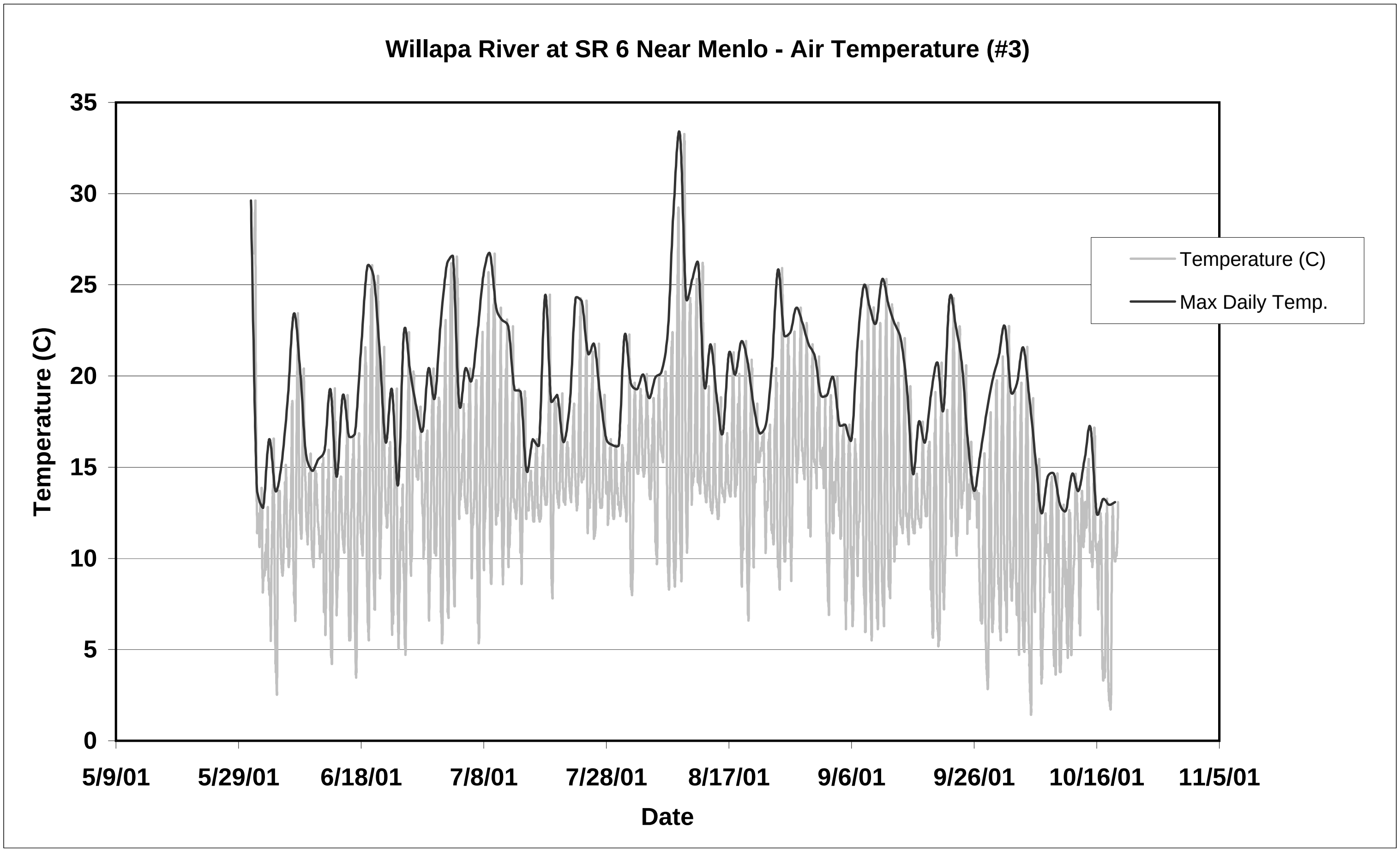

Willapa River at Camp One Road - Water Temperature (#1)
Temperature (C)
26
24
22
20
18
16
14
12
10
8
6
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
● Field Thermometer Check

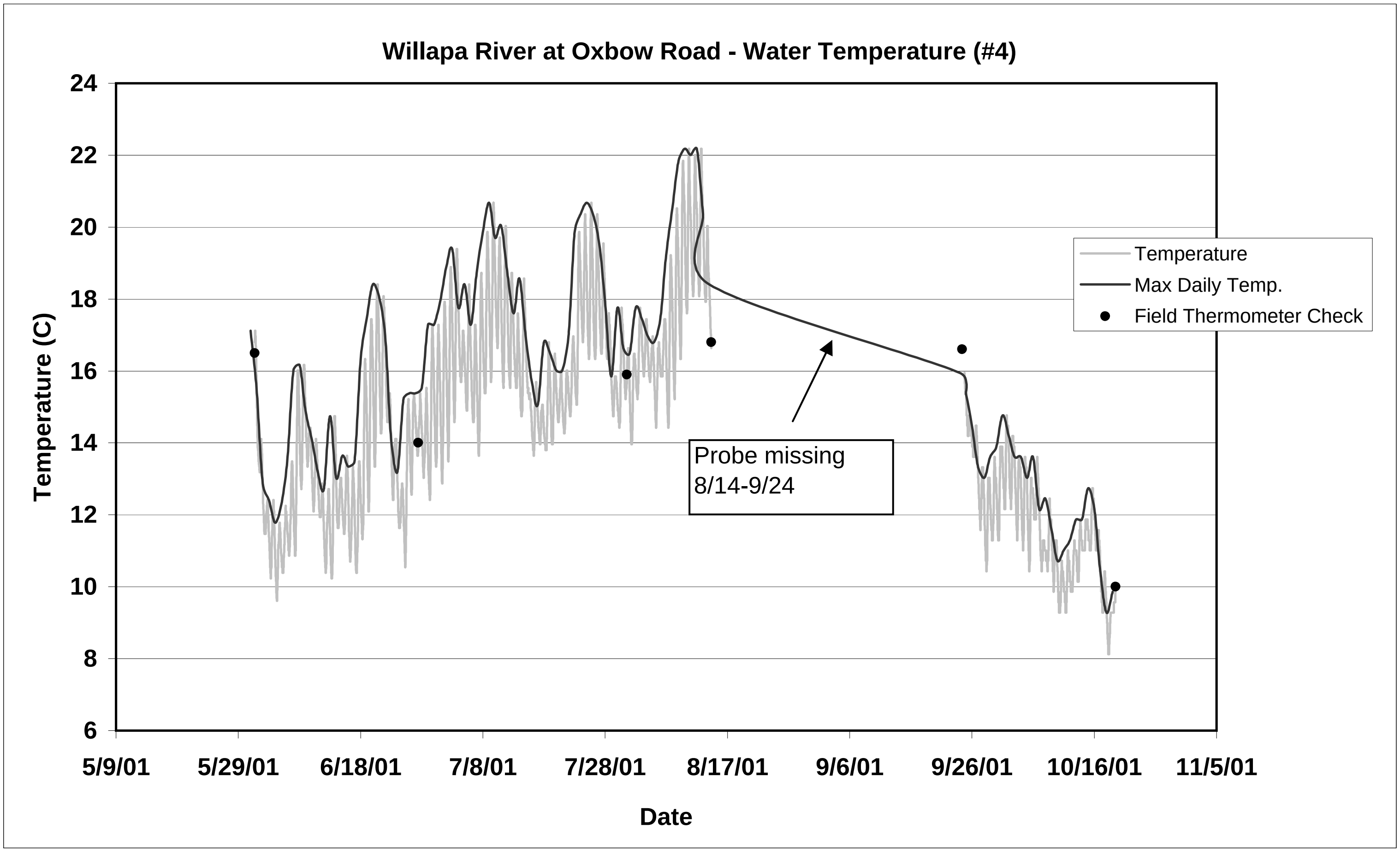

Willapa River at Camp One Road - Air Temperature (#1)
Temperature (C)
35
30
25
20
15
10
5
0
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max. Daily Temp.

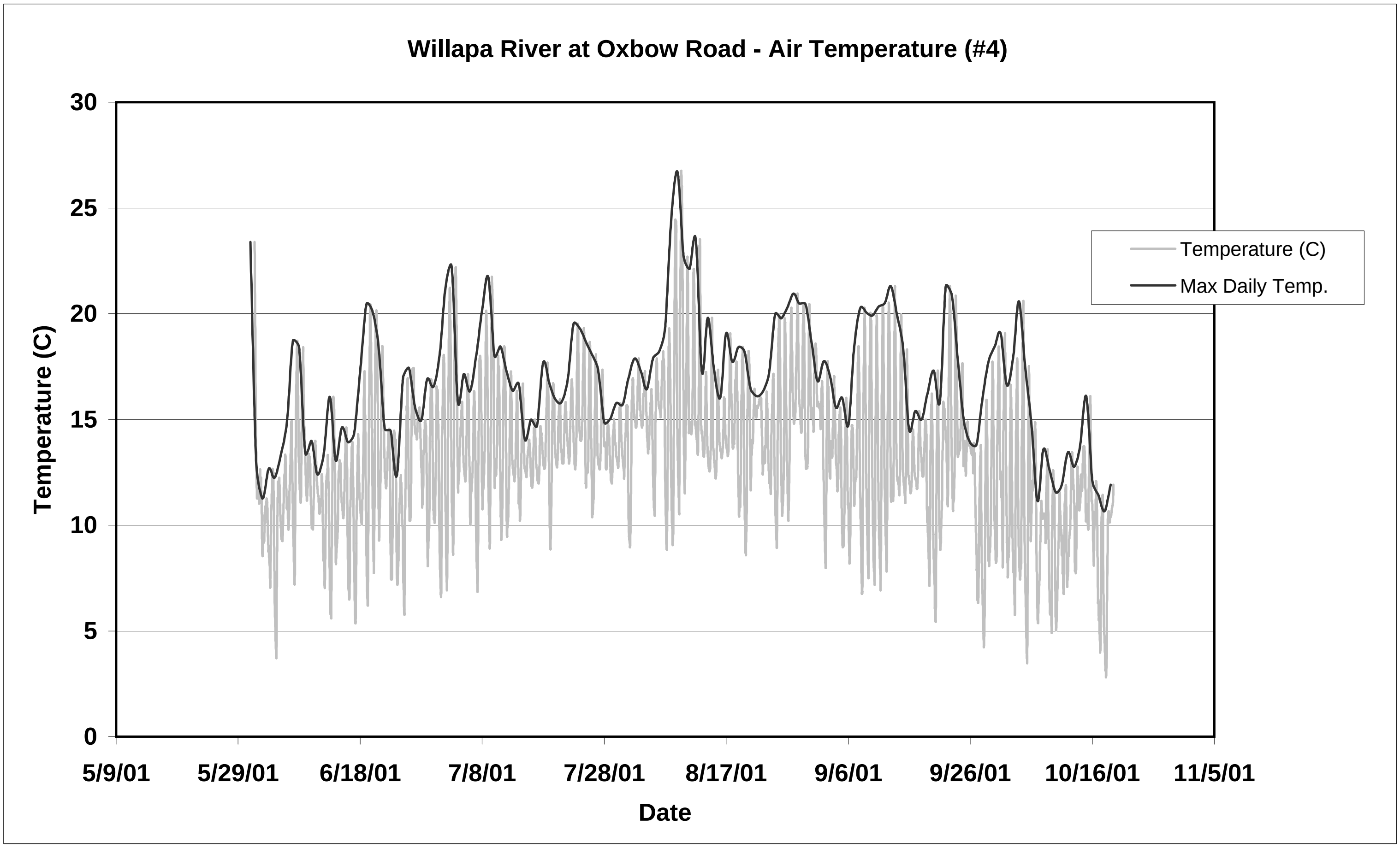

Willapa River Above Mill Creek - Water Temperature (#2)
Temperature (C)
26
24
22
20
18
16
14
12
10
8
6
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
● Field Thermometer Check

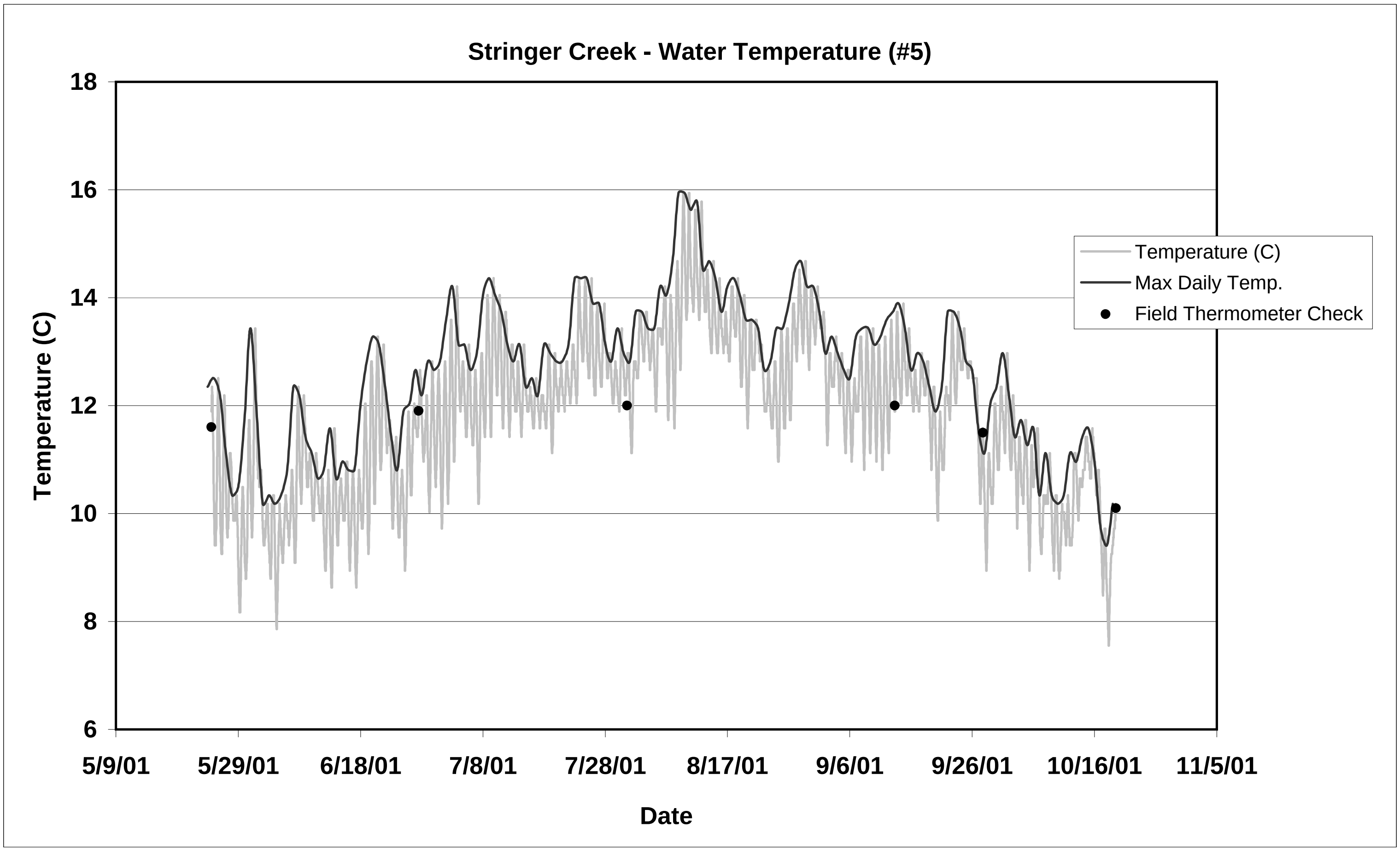

Willapa River Above Mill Creek - Air Temperature (#2)
Temperature (C)
35
30
25
20
15
10
5
0
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.

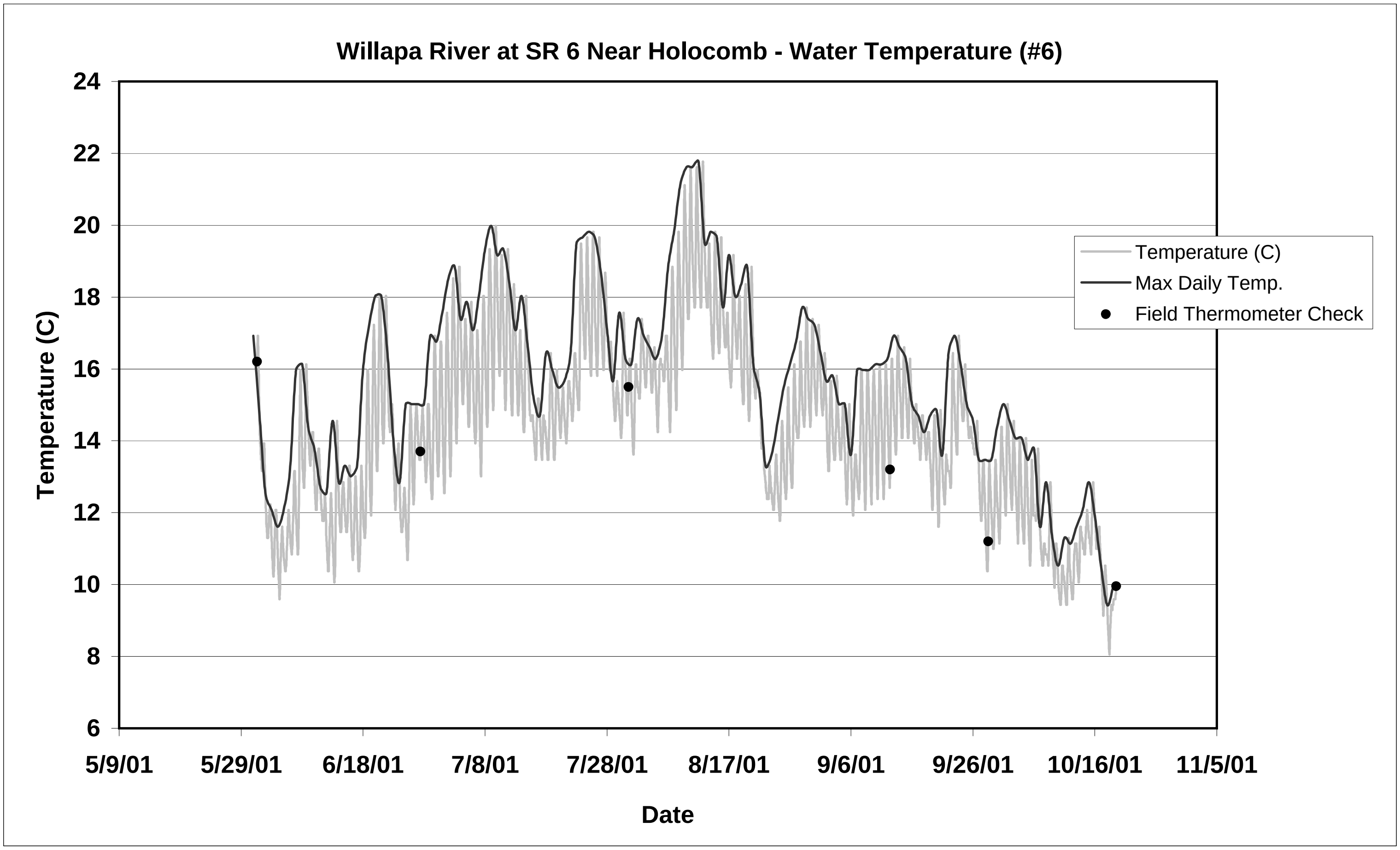

Willapa River at SR 6 Near Menlo - Water Temperature (#3)
Temperature (C)
24
22
20
18
16
14
12
10
8
6
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
● Field Thermometer Check

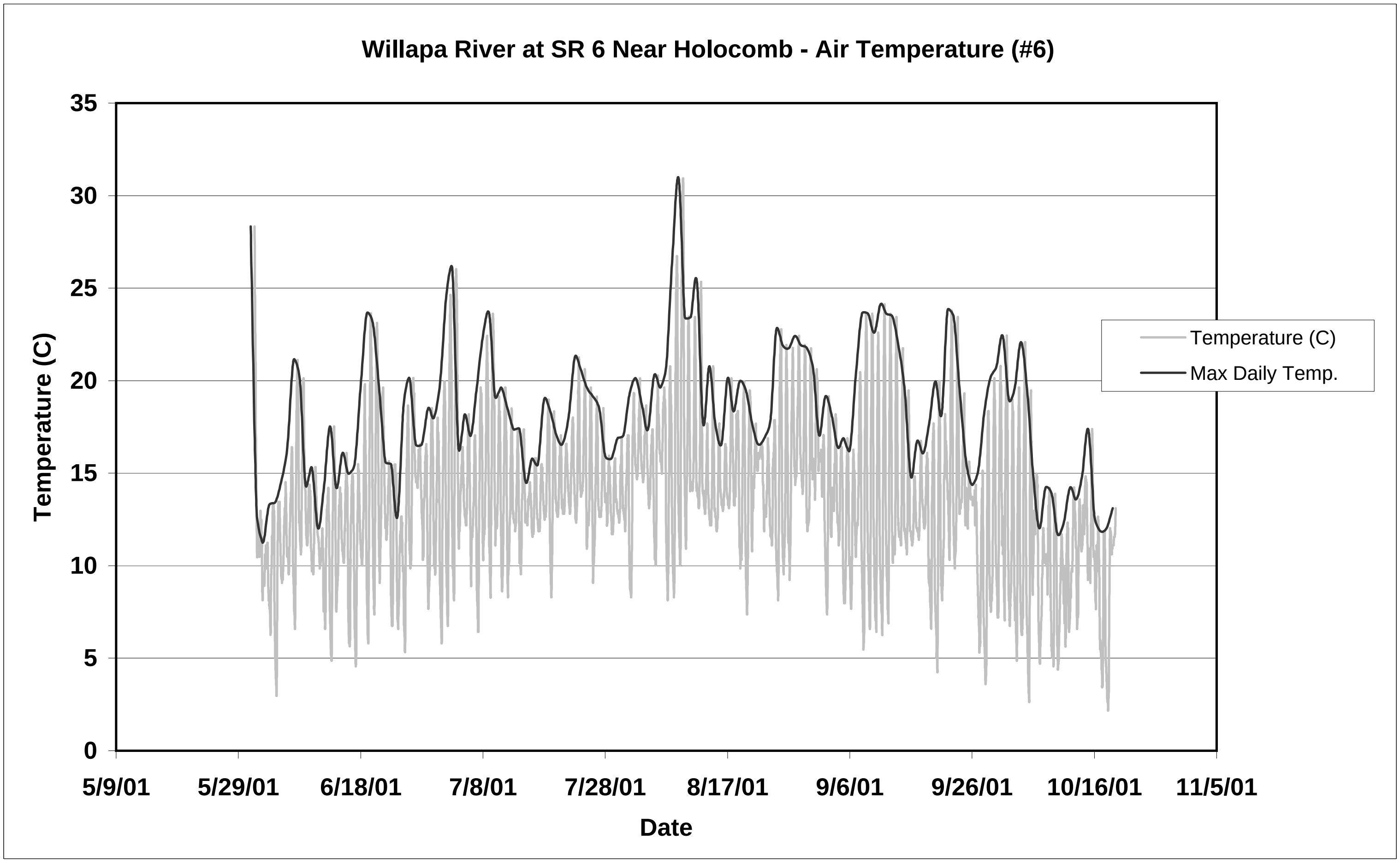

Willapa River at SR 6 Near Menlo - Air Temperature (#3)
Temperature (C)
35
30
25
20
15
10
5
0
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.

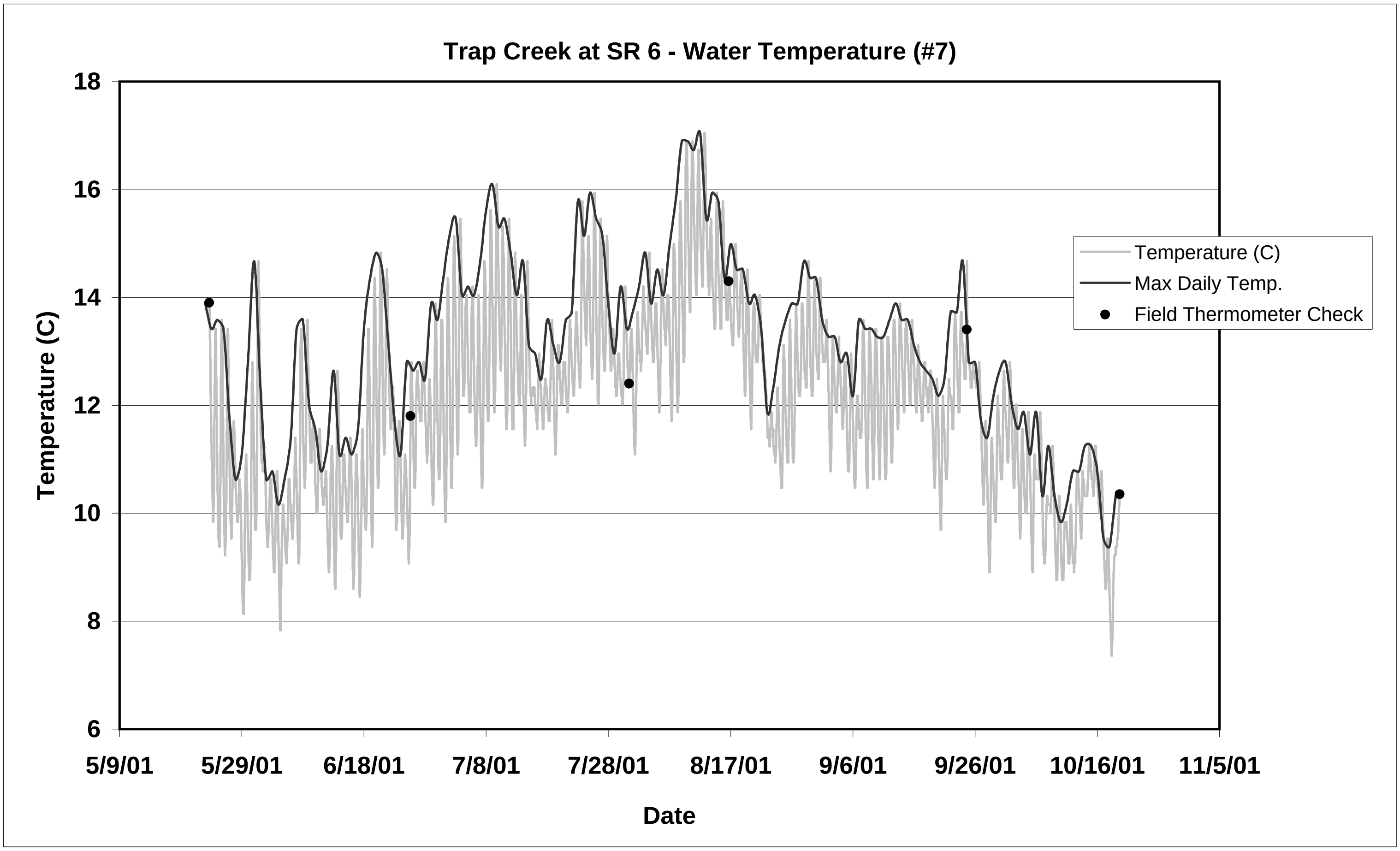

Willapa River at Oxbow Road - Water Temperature (#4)
Temperature (C)
24
22
20
18
16
14
12
10
8
6
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature
Max Daily Temp.
● Field Thermometer Check
Probe missing
8/14-9/24

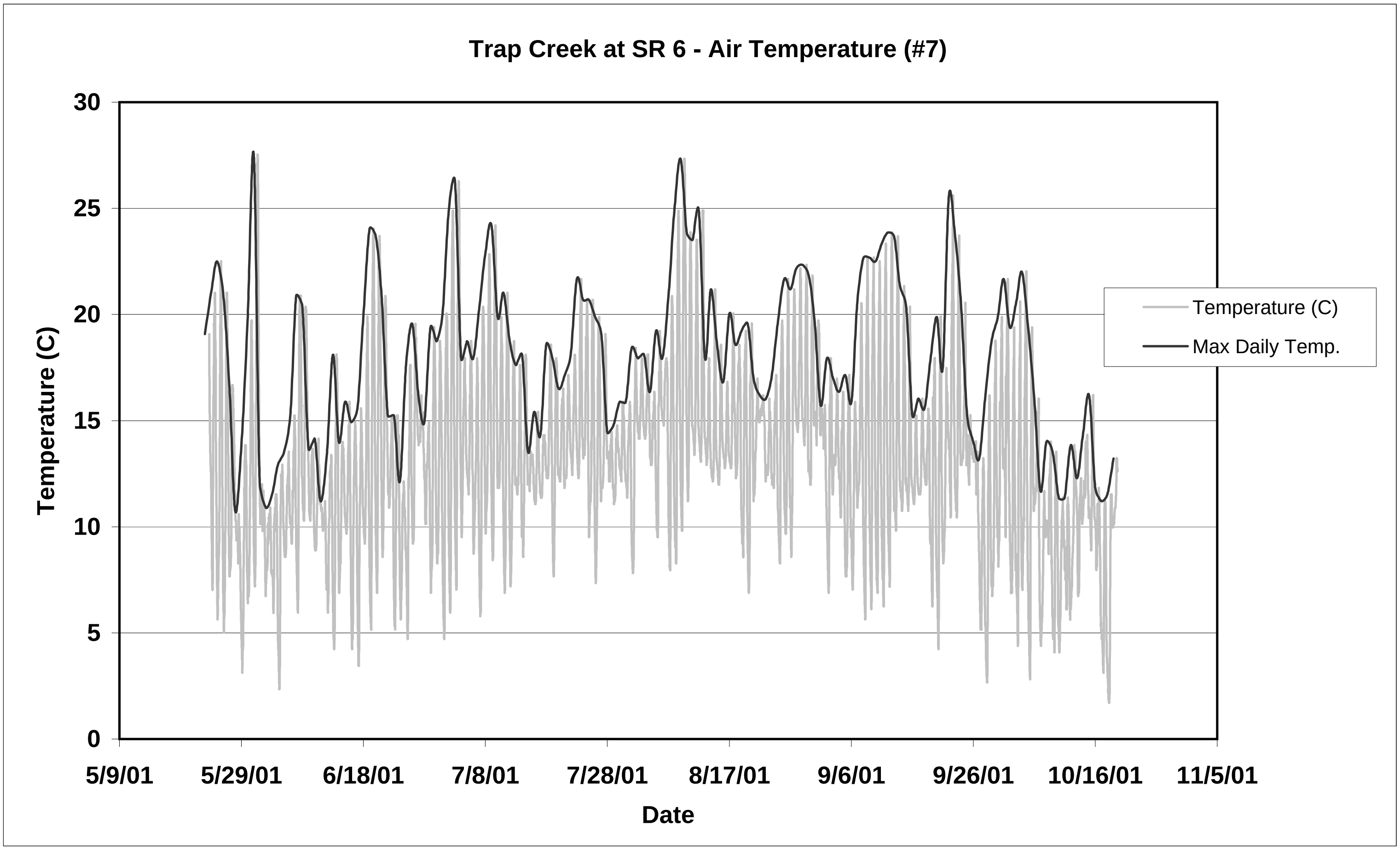

Willapa River at Oxbow Road - Air Temperature (#4)
Temperature (C)
30
25
20
15
10
5
0
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.

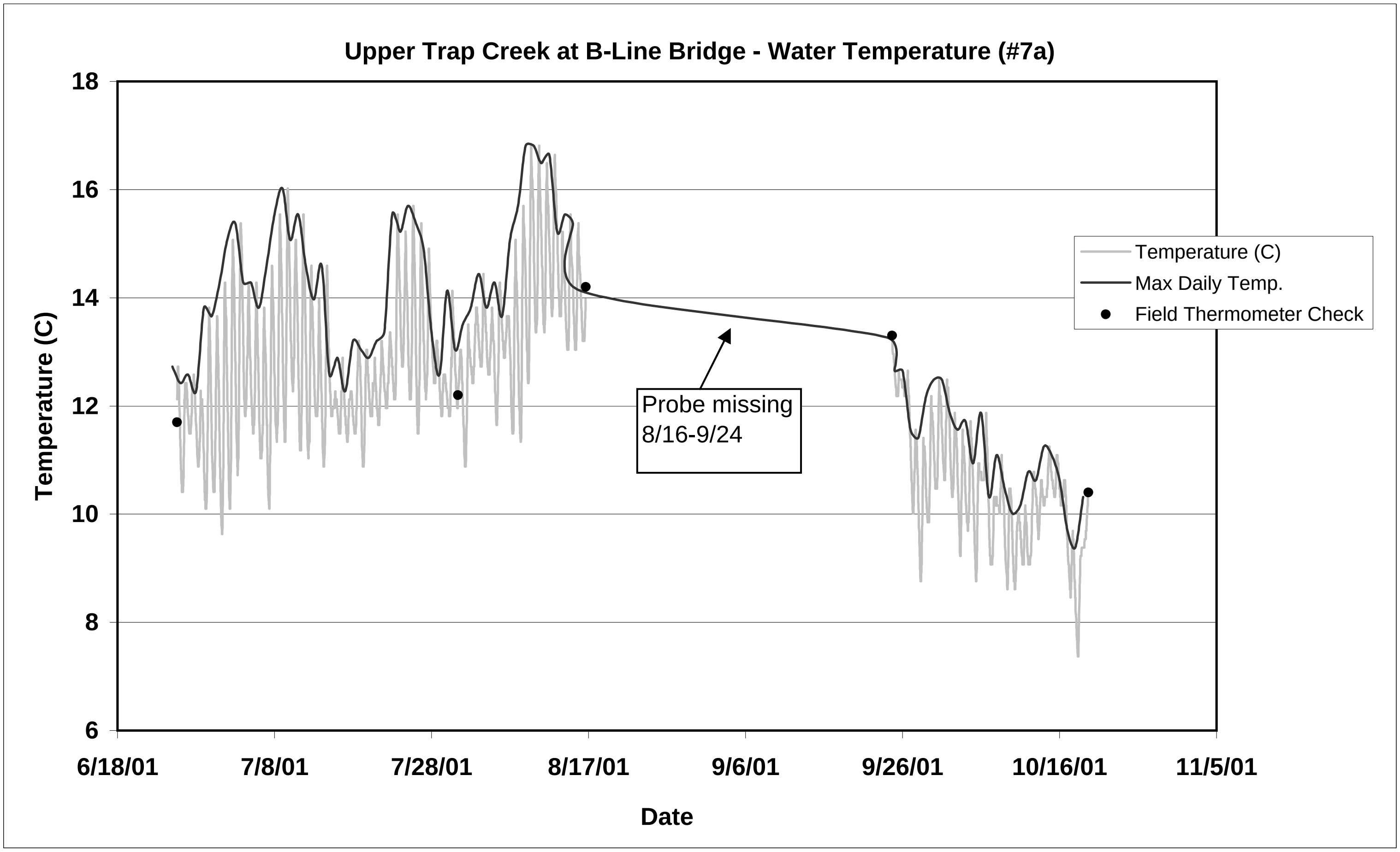

Stringer Creek - Water Temperature (#5)
18
16
14
12
10
8
6
Temperature (C)
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
Field Thermometer Check

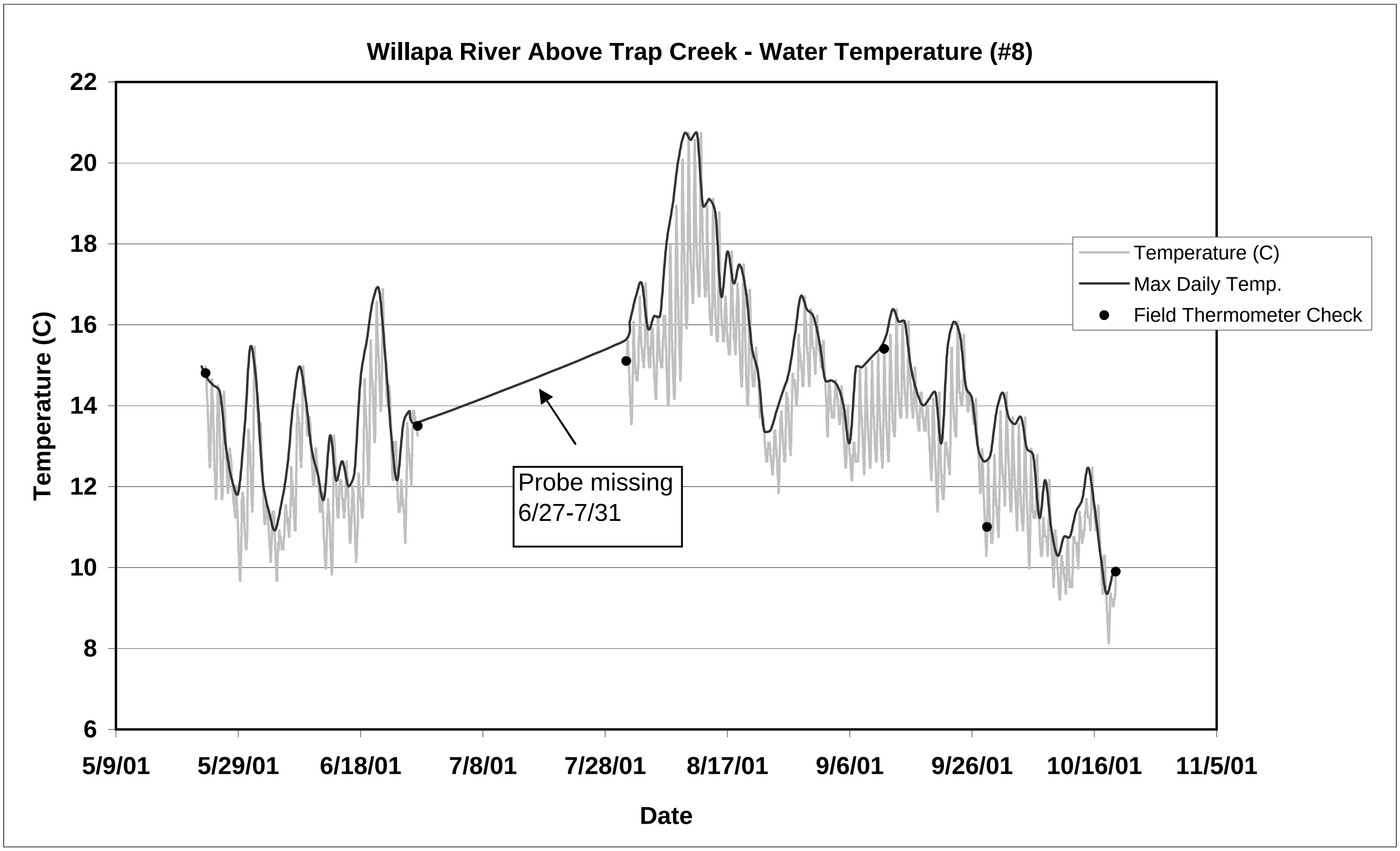

Willapa River at SR 6 Near Holocomb - Water Temperature (#6)
Temperature (C)
24
22
20
18
16
14
12
10
8
6
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
● Field Thermometer Check


Willapa River at SR 6 Near Holocomb - Air Temperature (#6)
Temperature (C)
35
30
25
20
15
10
5
0
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.

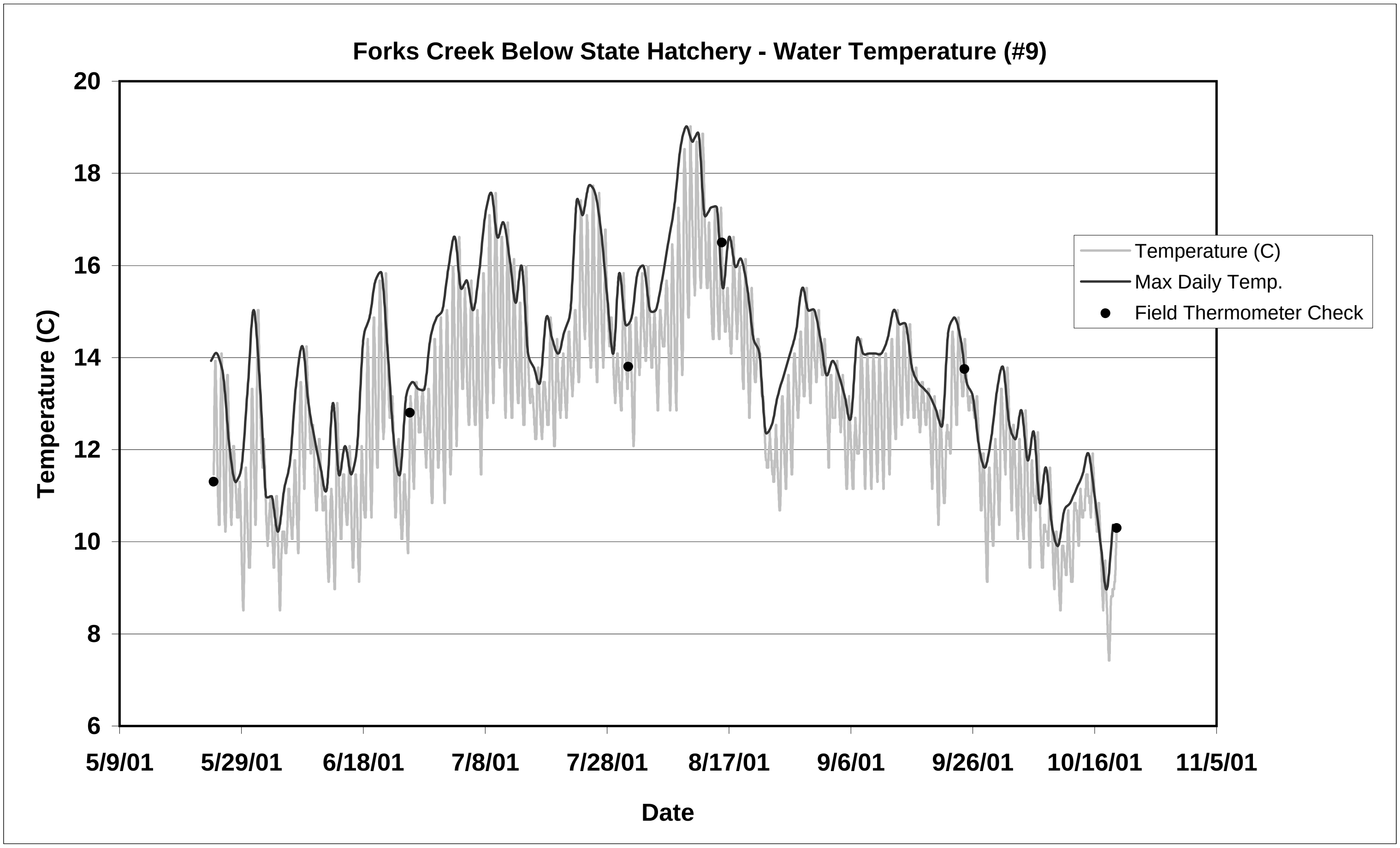

Trap Creek at SR 6 - Water Temperature (#7)
Temperature (C)
18
16
14
12
10
8
6
Date
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Temperature (C)
Max Daily Temp.
● Field Thermometer Check

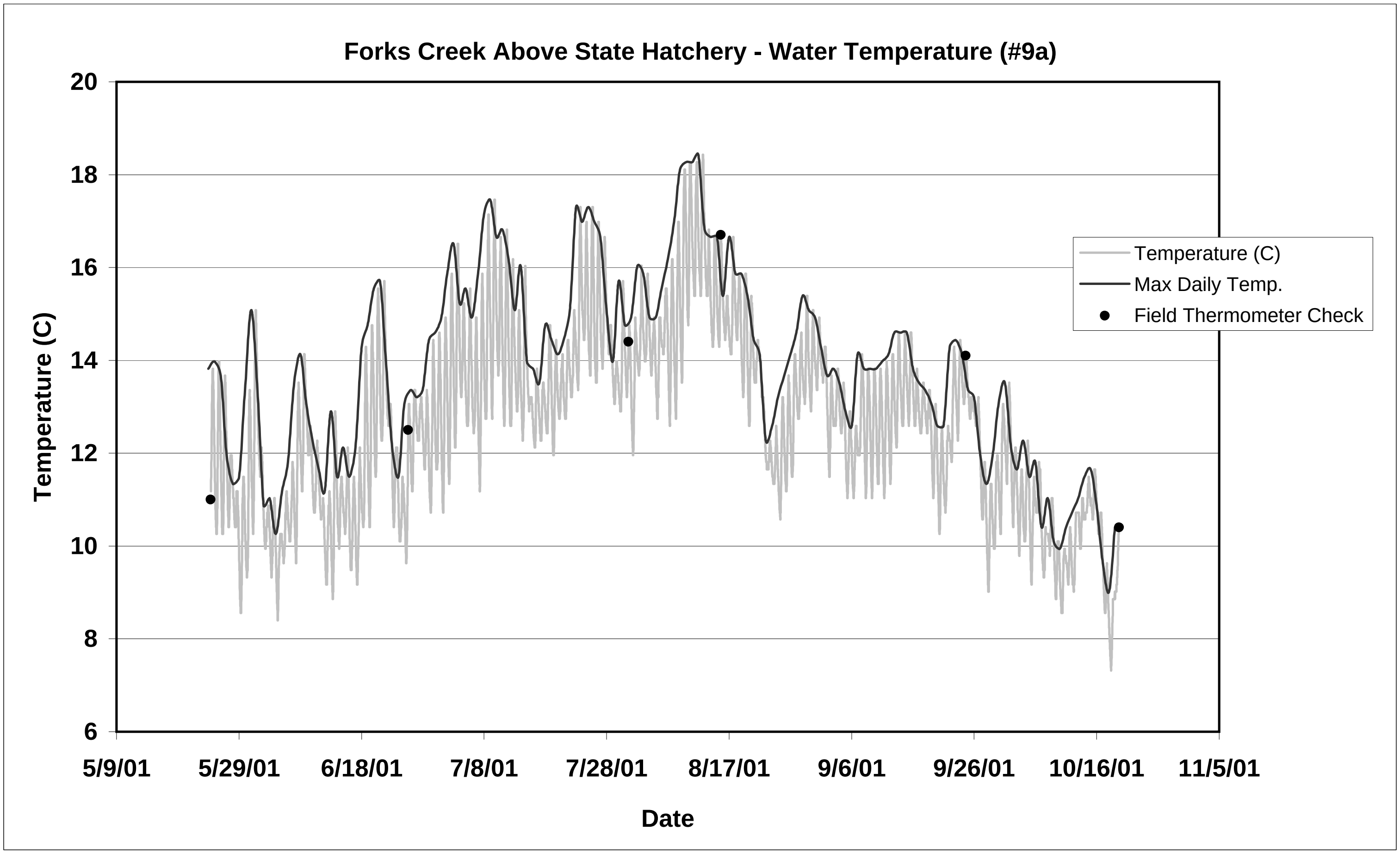

Trap Creek at SR 6 - Air Temperature (#7)
Temperature (C)
30
25
20
15
10
5
0
Date
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Temperature (C)
Max Daily Temp.

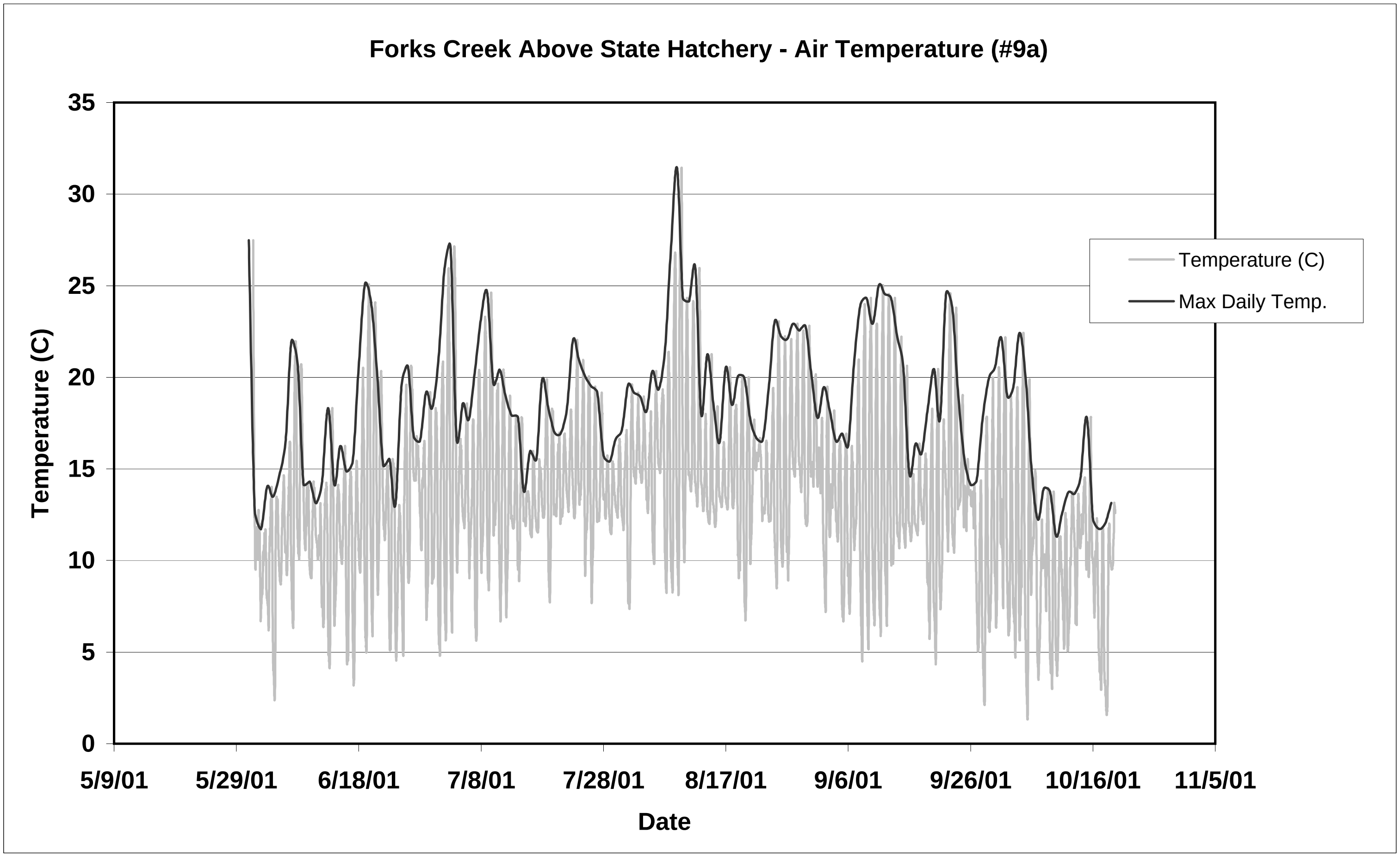
Upper Trap Creek at B-Line Bridge - Water Temperature (#7a)
Temperature (C)
18
16
14
12
10
8
6
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
● Field Thermometer Check
Probe missing
8/16-9/24

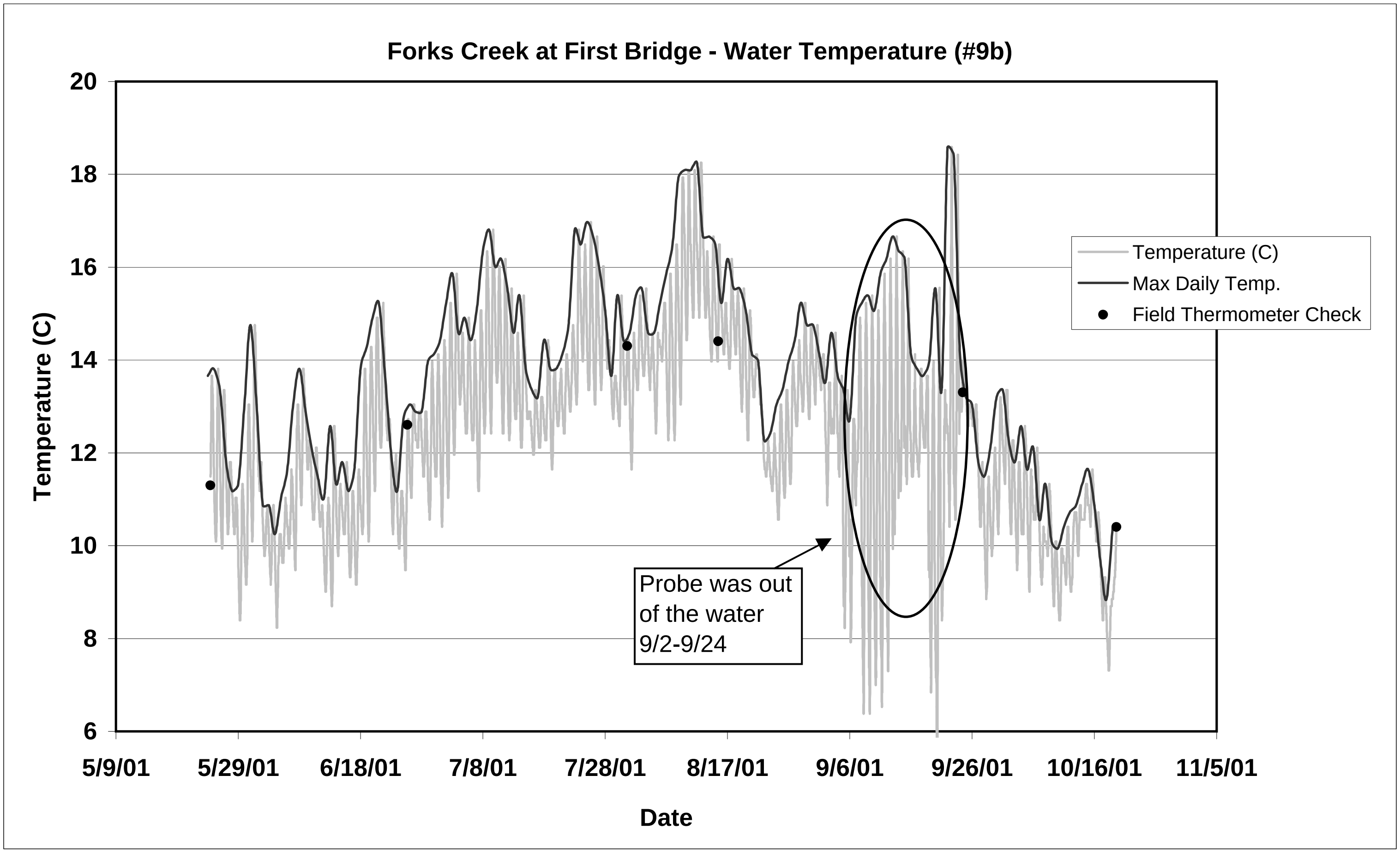


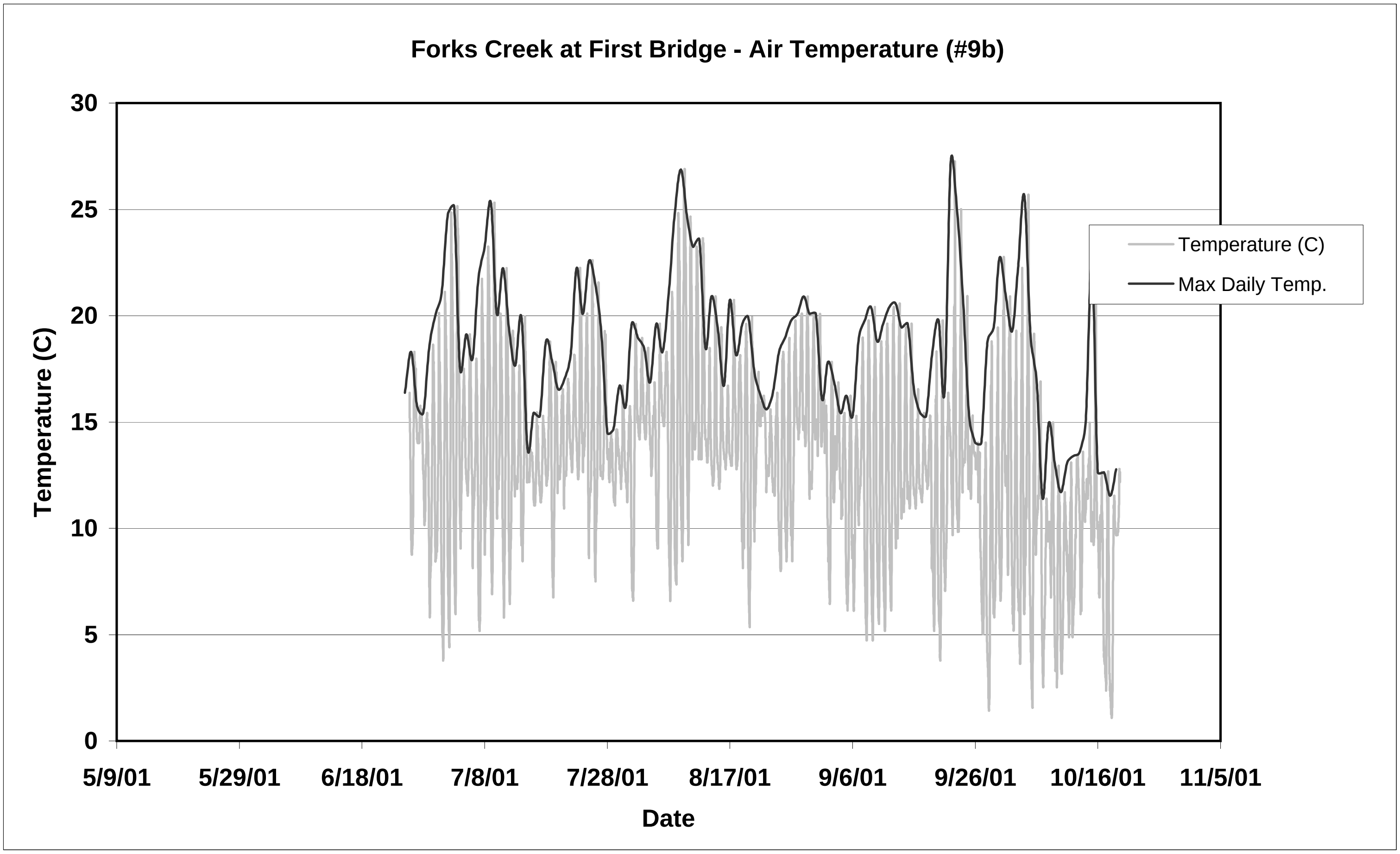
Willapa River Above Trap Creek - Water Temperature (#8)
Temperature (C)
22
20
18
16
14
12
10
8
6
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
Field Thermometer Check
Probe missing
6/27-7/31

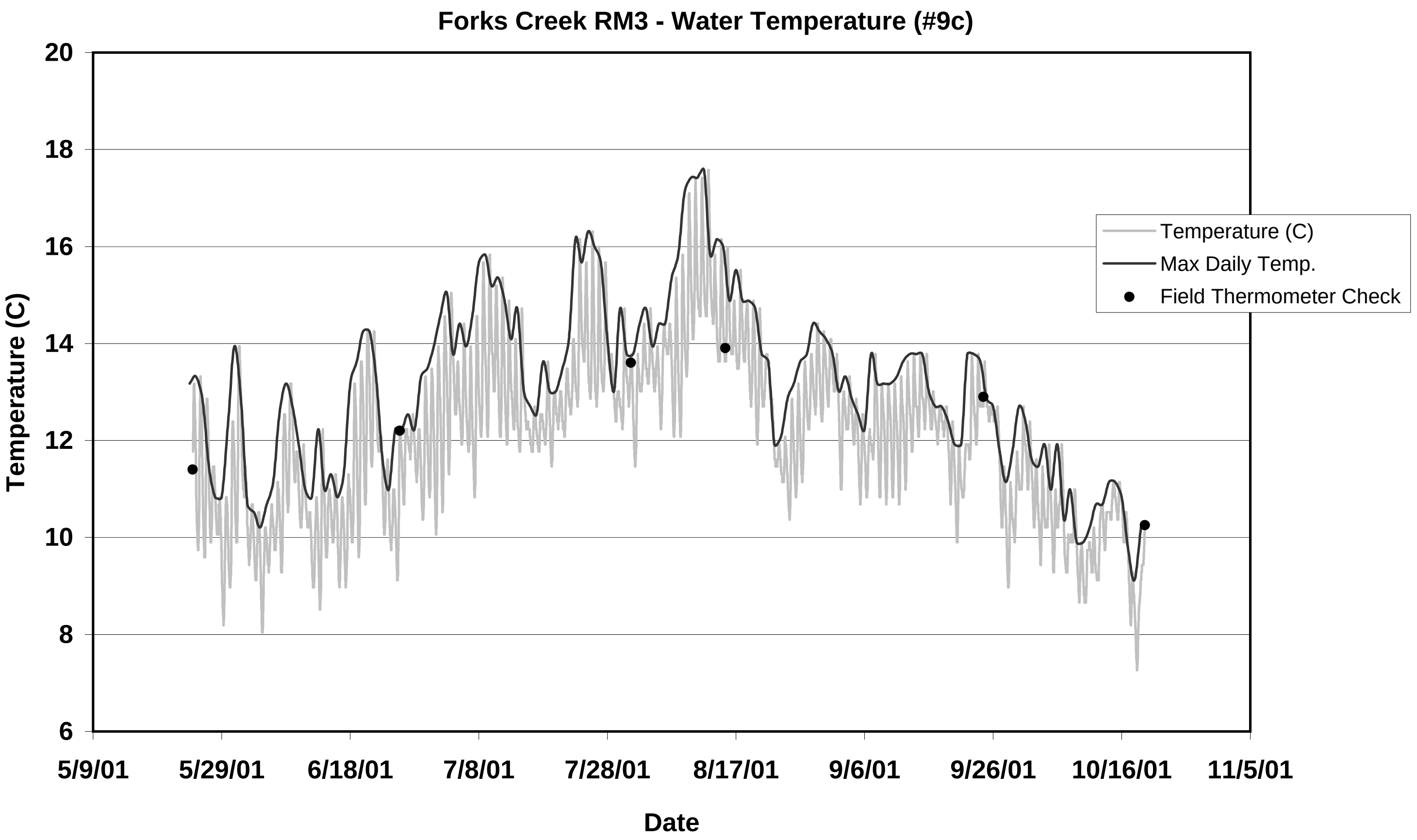

Forks Creek Below State Hatchery - Water Temperature (#9)
Temperature (C)
20
18
16
14
12
10
8
6
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
● Field Thermometer Check

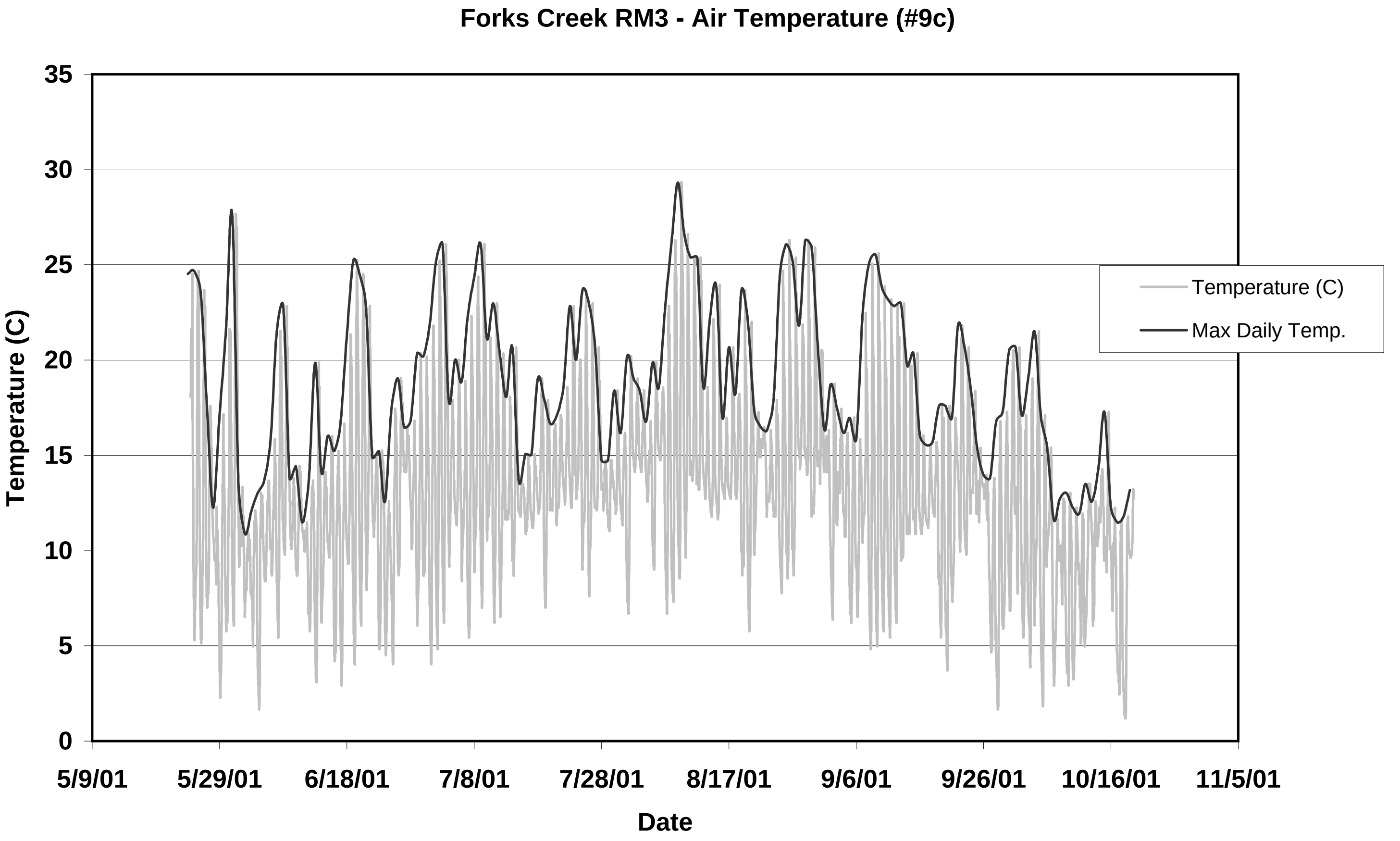

Forks Creek Above State Hatchery - Water Temperature (#9a)
Temperature (C)
20
18
16
14
12
10
8
6
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
● Field Thermometer Check

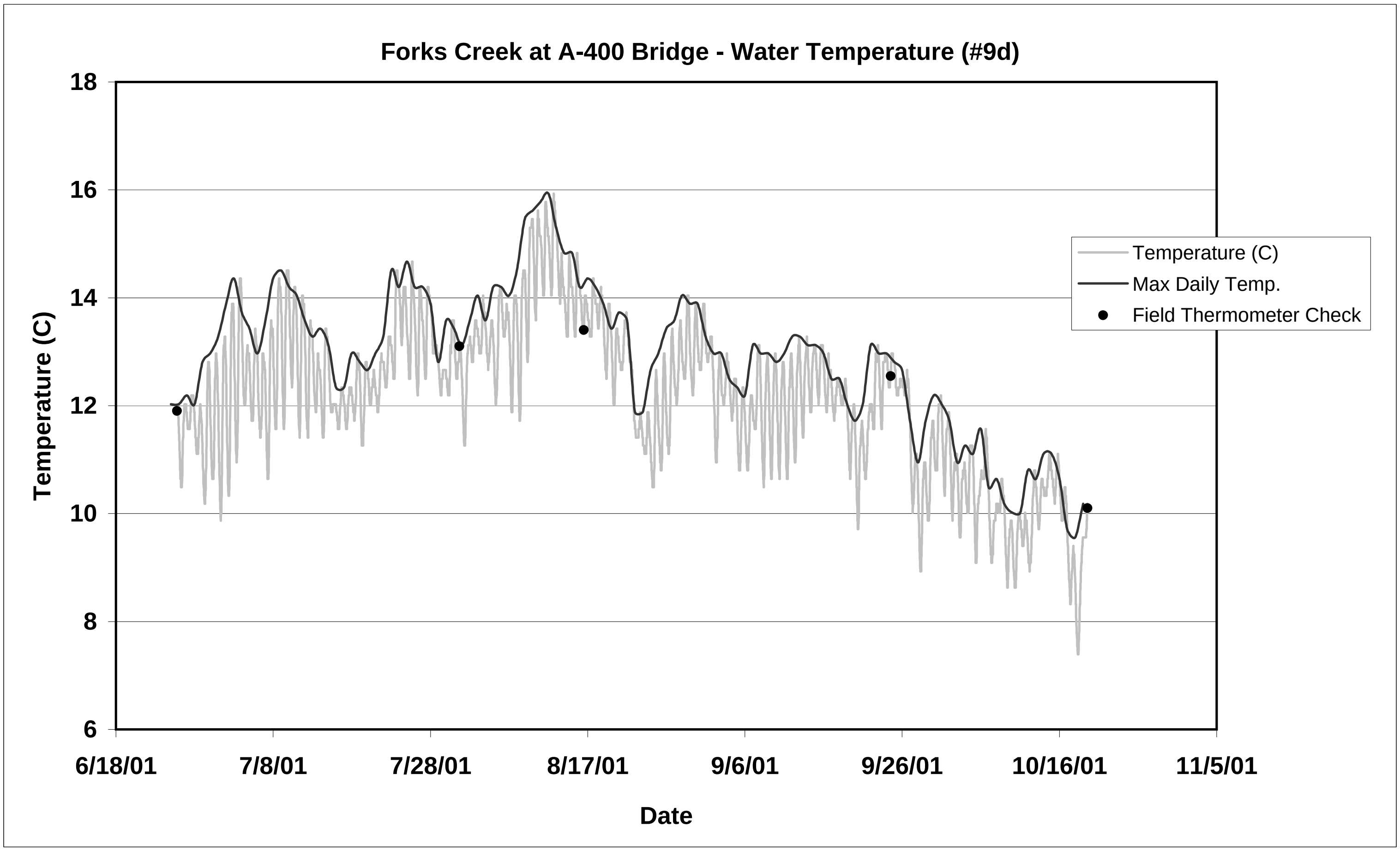

Forks Creek Above State Hatchery - Air Temperature (#9a)
Temperature (C)
35
30
25
20
15
10
5
0
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.

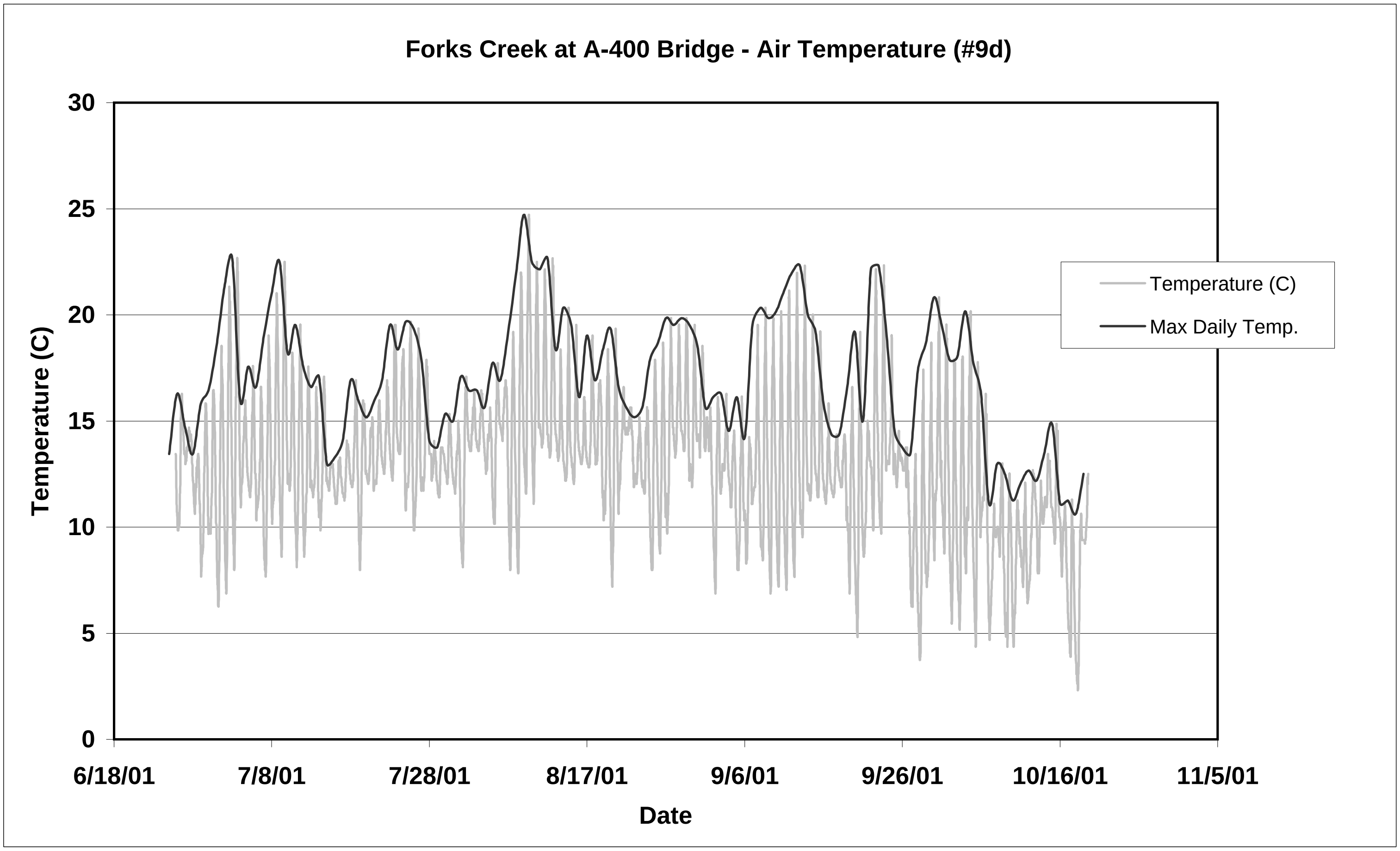

Forks Creek at First Bridge - Water Temperature (#9b)
20
18
16
14
12
10
8
6
Temperature (C)
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
● Field Thermometer Check
Probe was out of the water 9/2-9/24

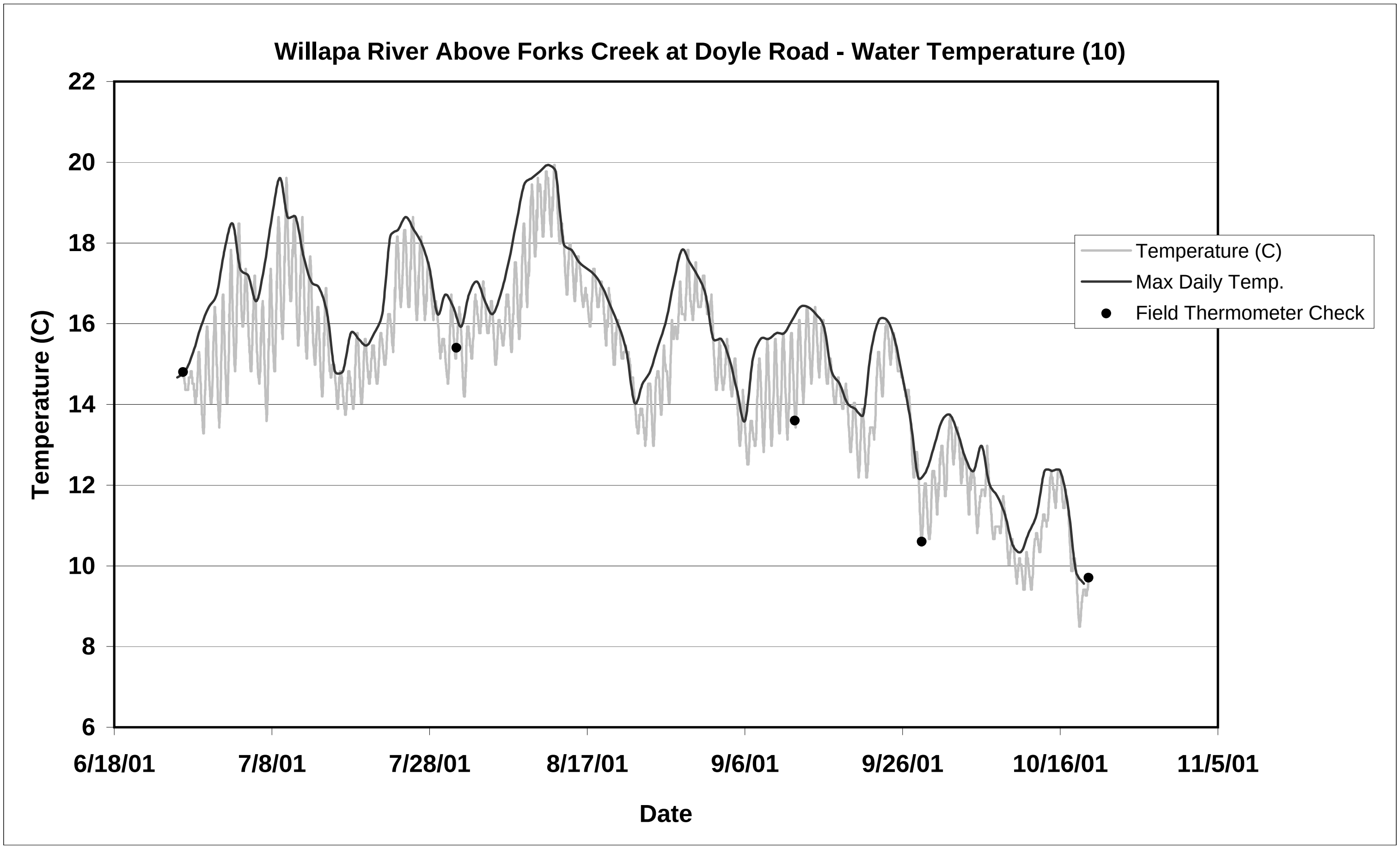

Forks Creek at First Bridge - Air Temperature (#9b)
30
25
20
15
10
5
0
Temperature (C)
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.

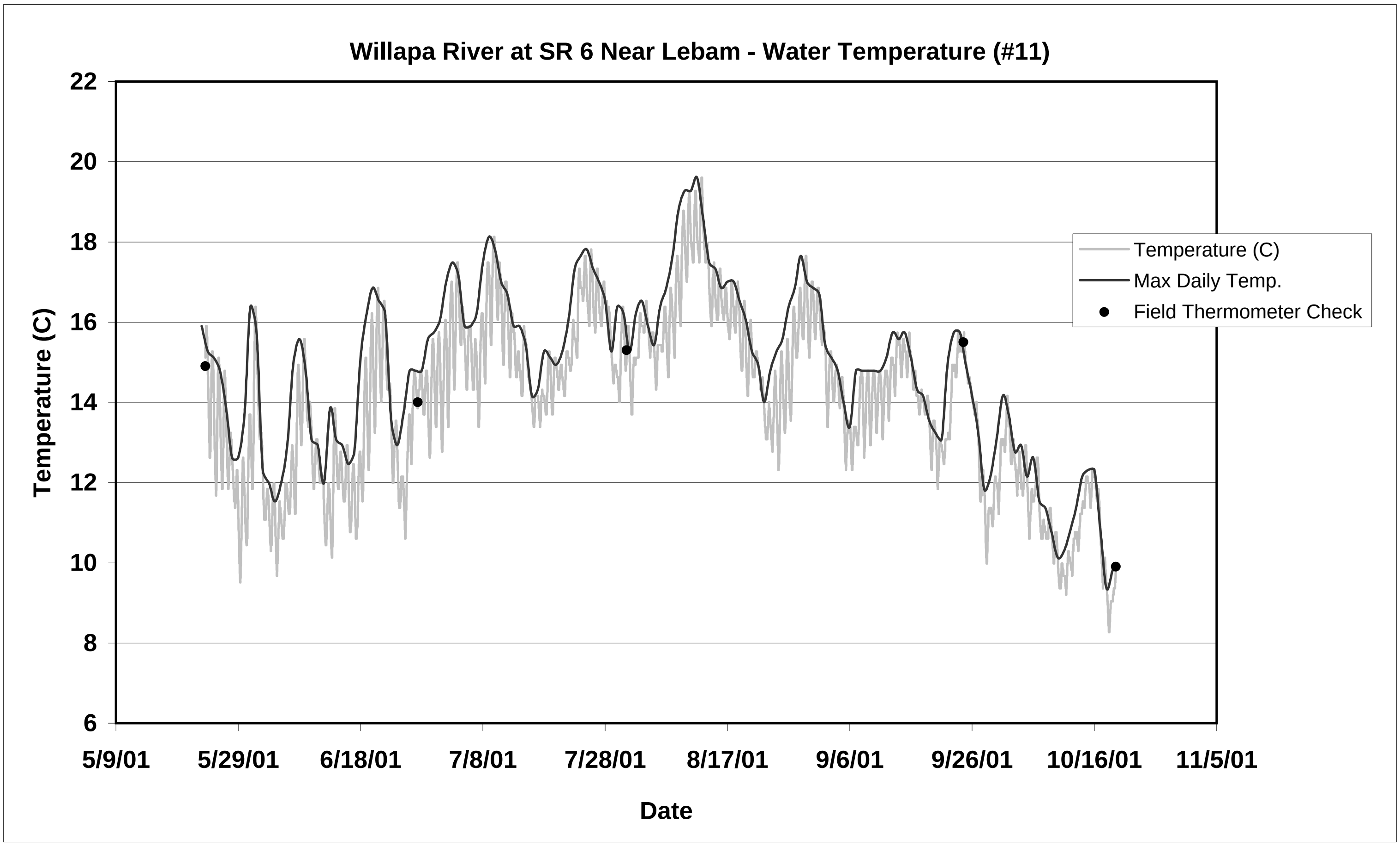

Forks Creek RM3 - Water Temperature (#9c)
Temperature (C)
20
18
16
14
12
10
8
6
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
● Field Thermometer Check

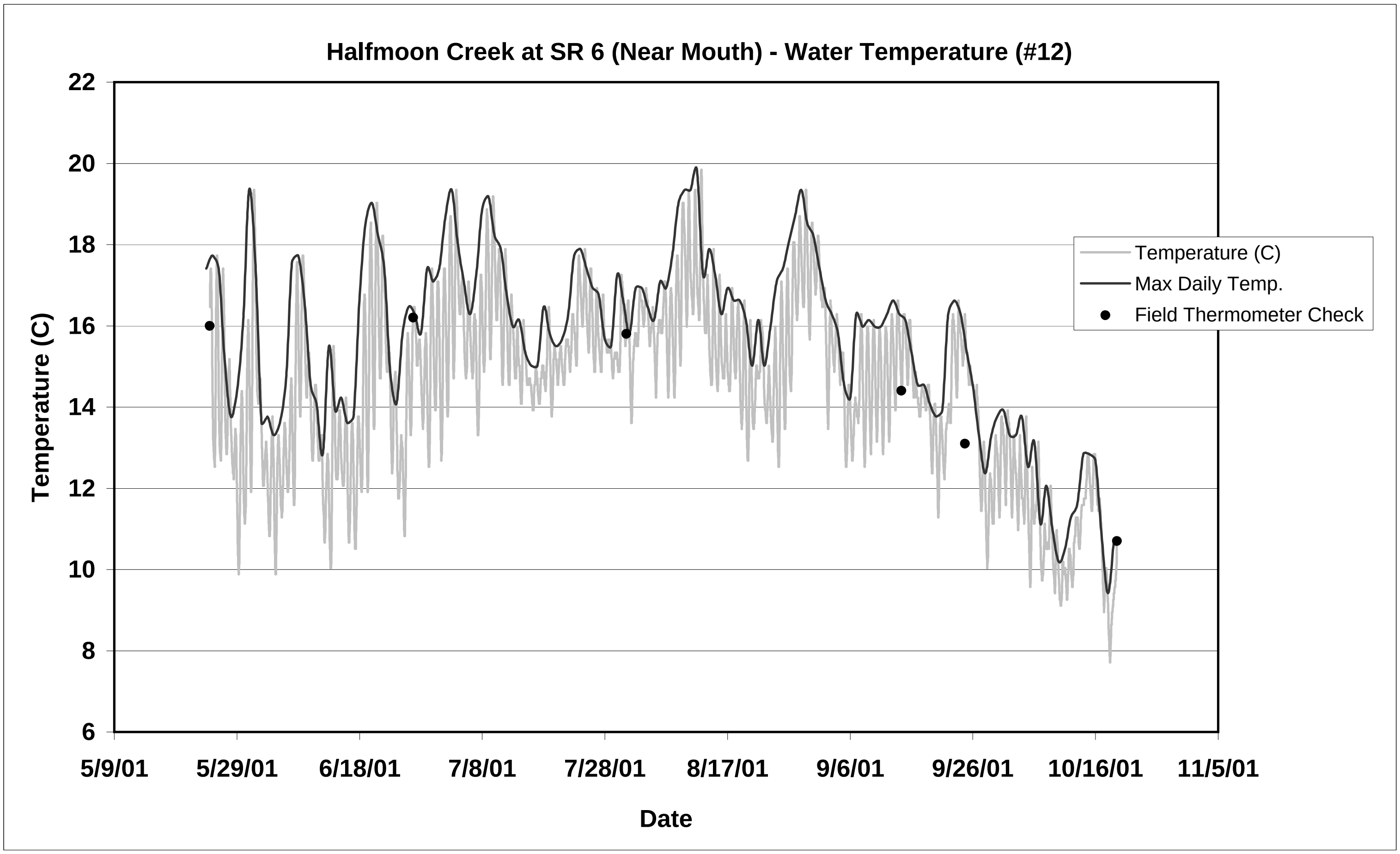

Forks Creek RM3 - Air Temperature (#9c)
Temperature (C)
35
30
25
20
15
10
5
0
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.

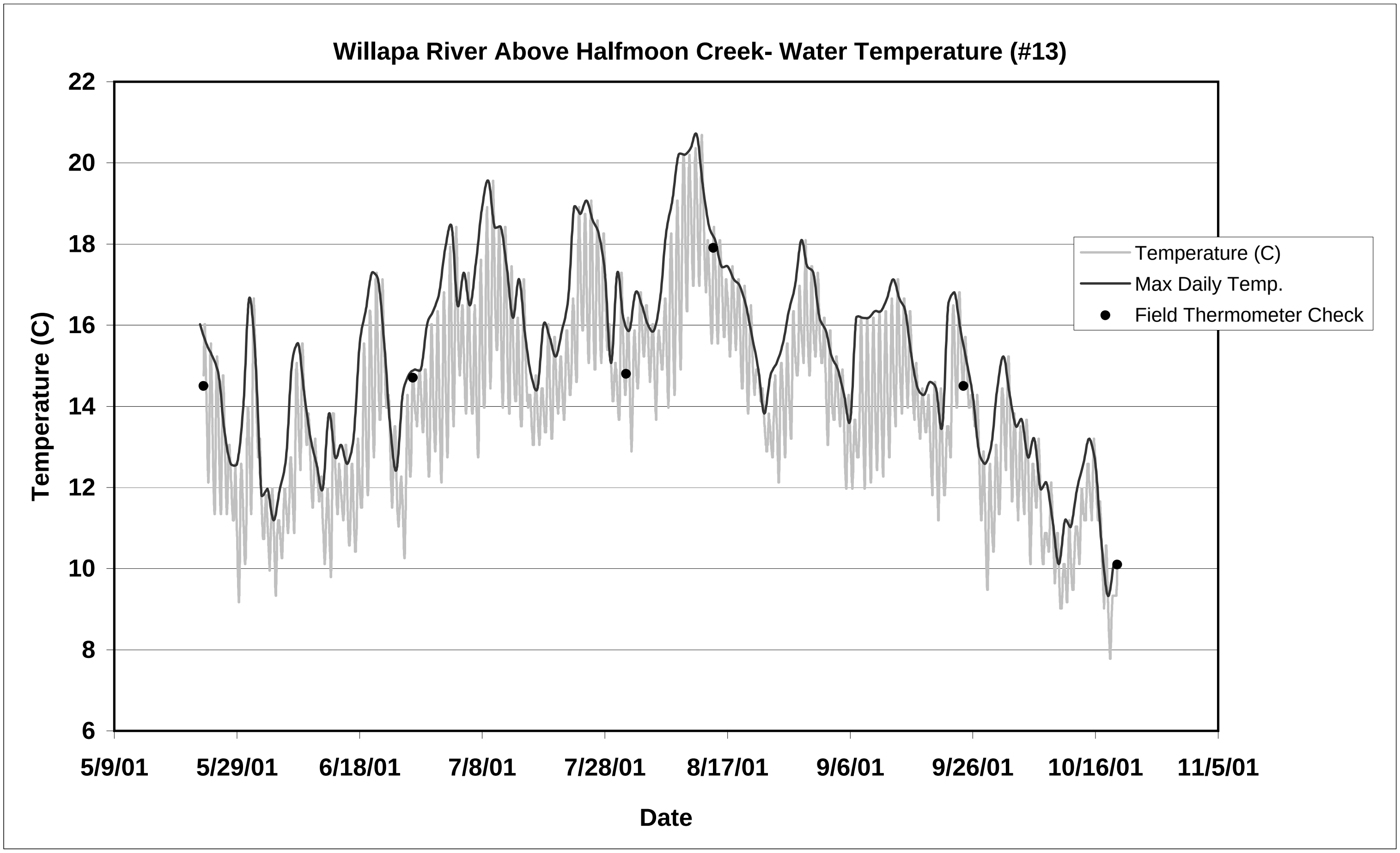

Forks Creek at A-400 Bridge - Water Temperature (#9d)
Temperature (C)
18
16
14
12
10
8
6
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
Field Thermometer Check


Forks Creek at A-400 Bridge - Air Temperature (#9d)
Temperature (C)
30
25
20
15
10
5
0
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.

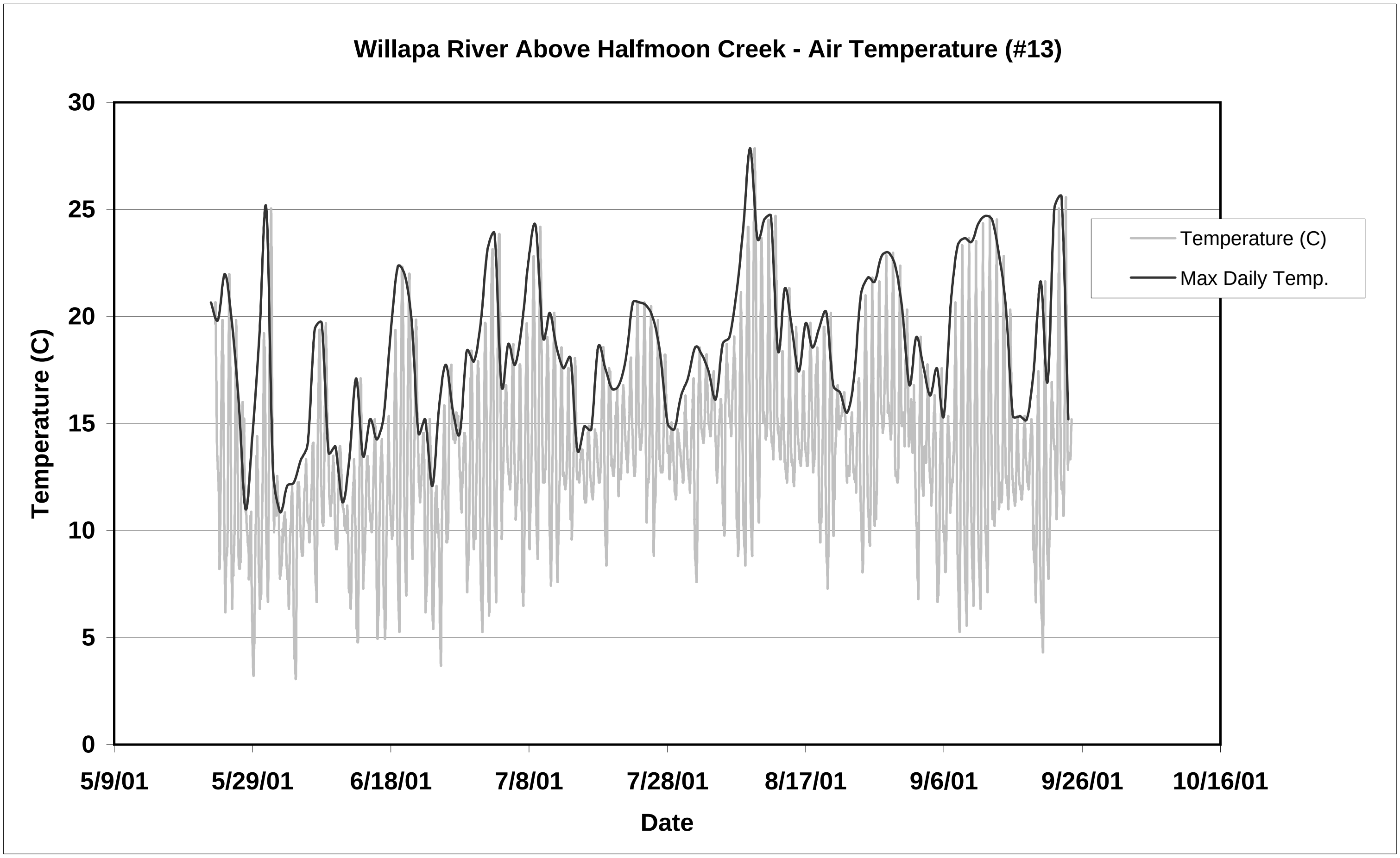

Willapa River Above Forks Creek at Doyle Road - Water Temperature (10)
22
20
18
16
14
12
10
8
6
Temperature (C)
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
● Field Thermometer Check


Willapa River at SR 6 Near Lebam - Water Temperature (#11)
Temperature (C)
22
20
18
16
14
12
10
8
6
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
● Field Thermometer Check

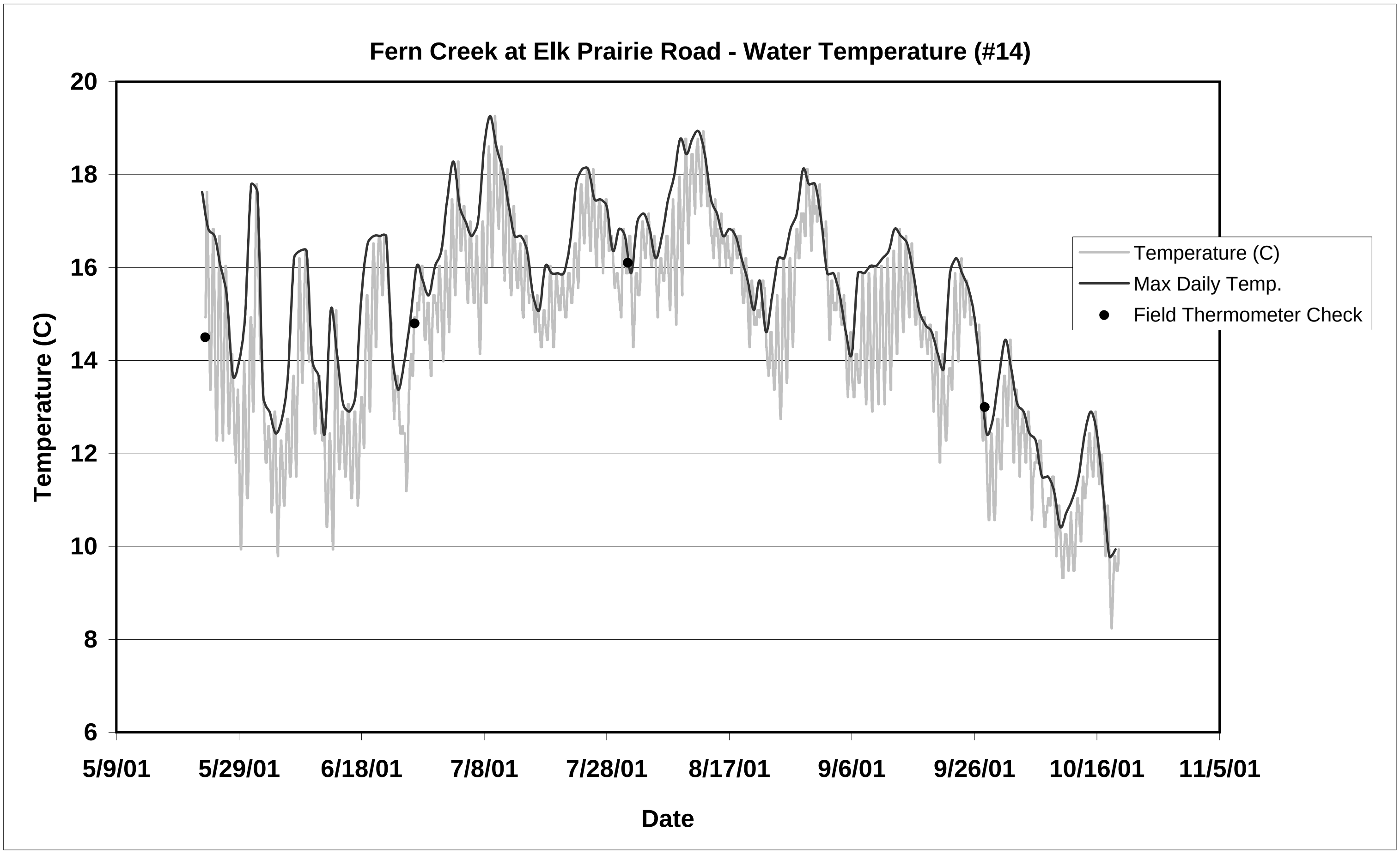

Halfmoon Creek at SR 6 (Near Mouth) - Water Temperature (#12)
22
20
18
16
14
12
10
8
6
Temperature (C)
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
● Field Thermometer Check

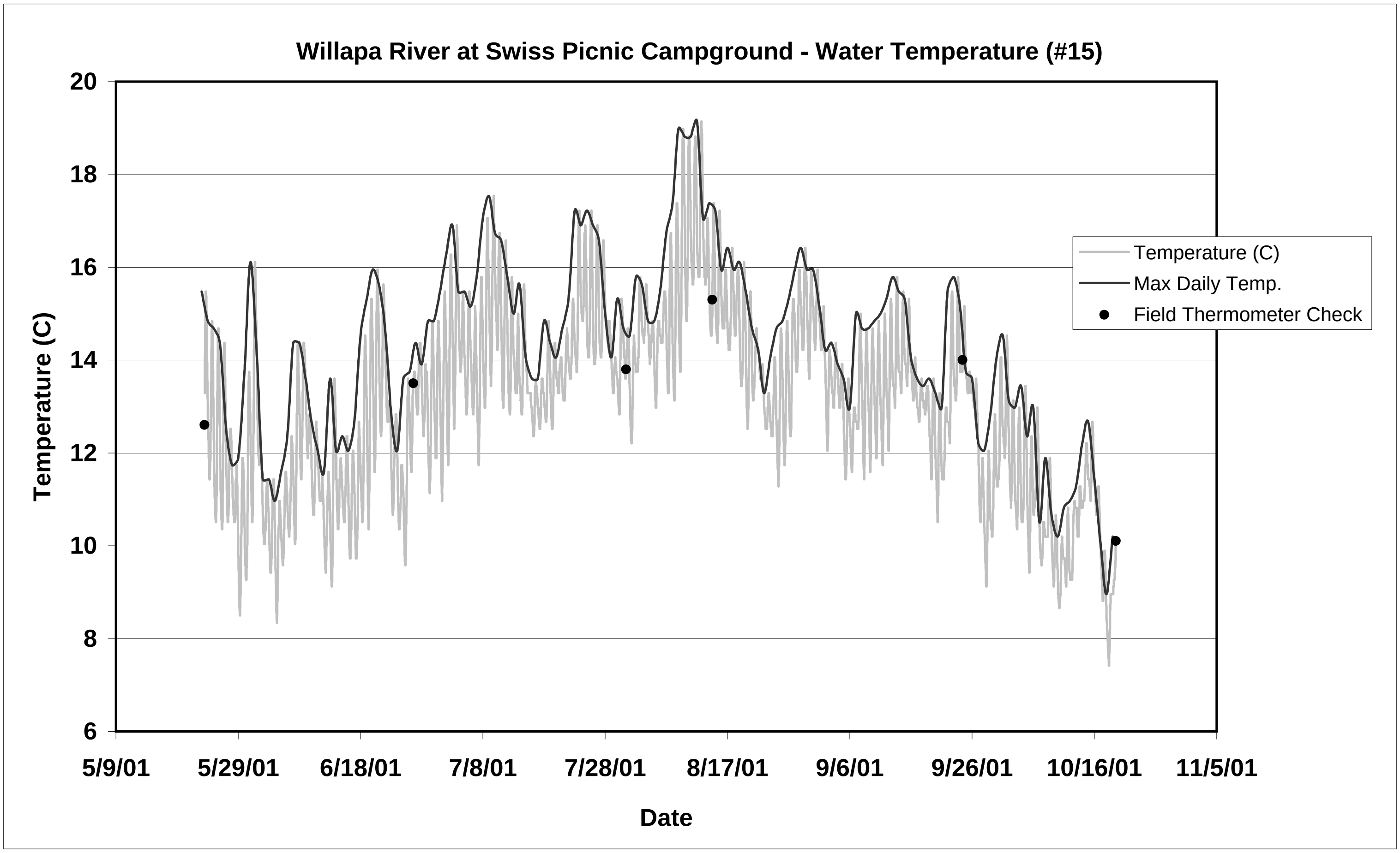


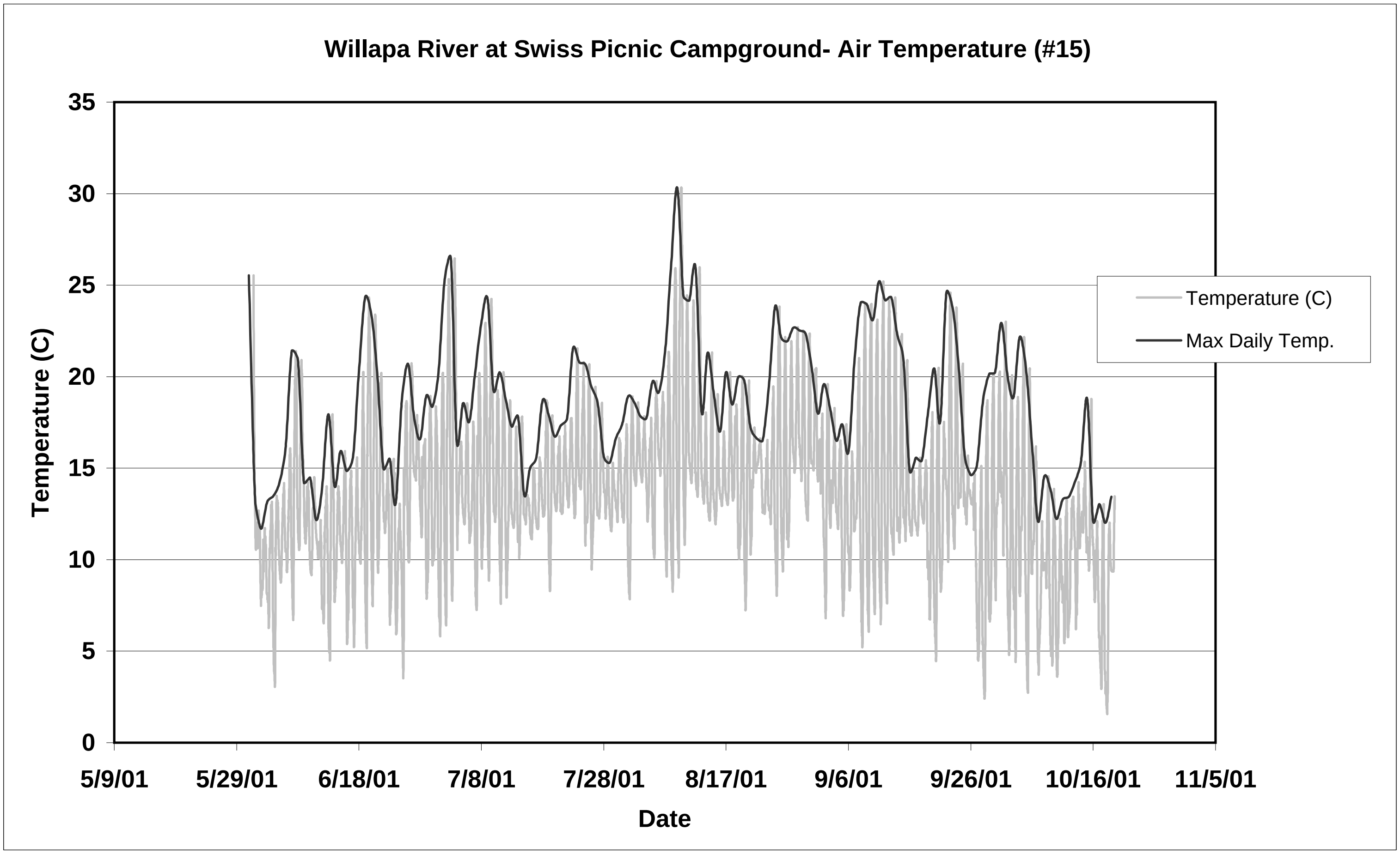
Willapa River Above Halfmoon Creek- Water Temperature (#13)
Temperature (C)
22
20
18
16
14
12
10
8
6
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
● Field Thermometer Check

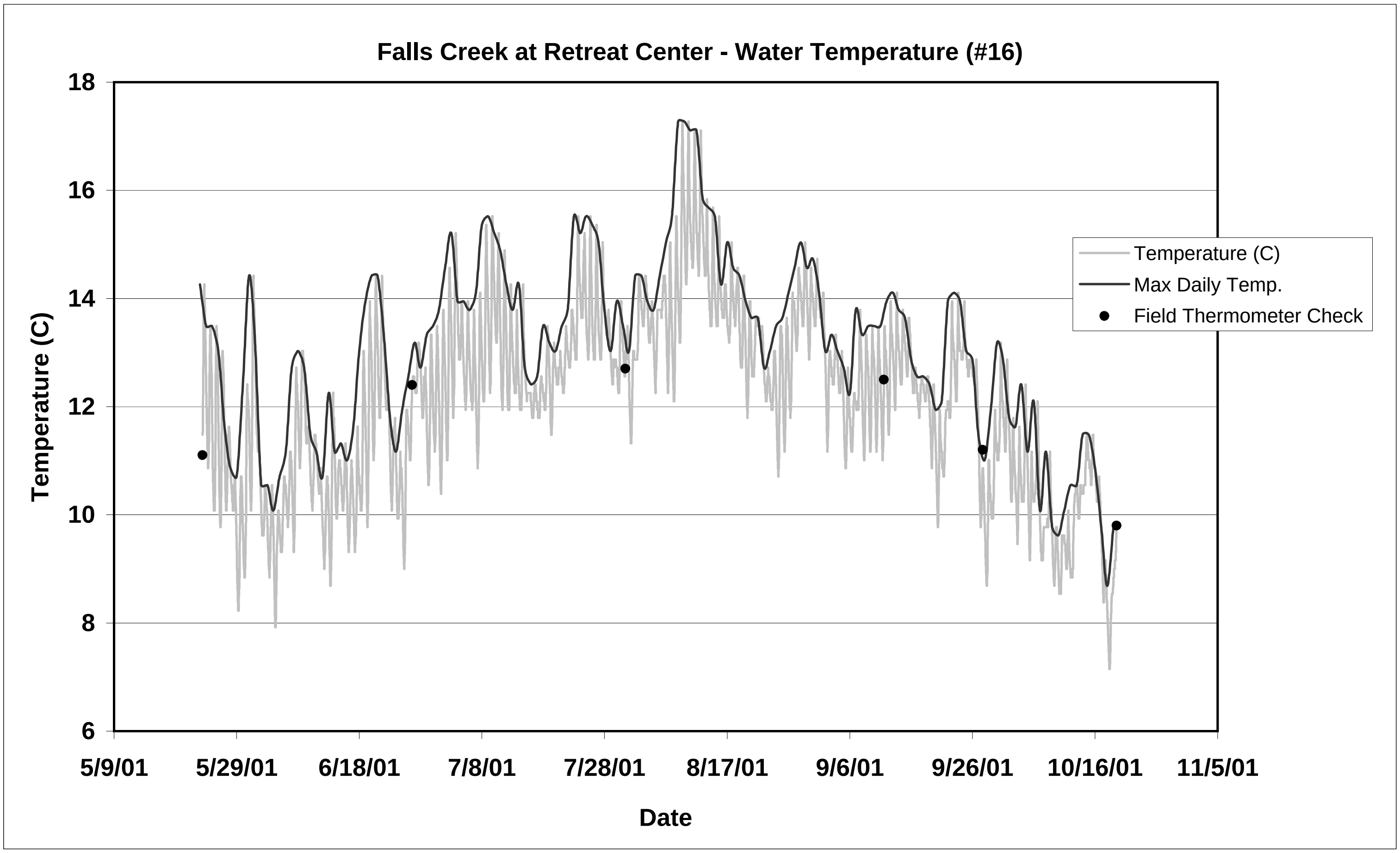


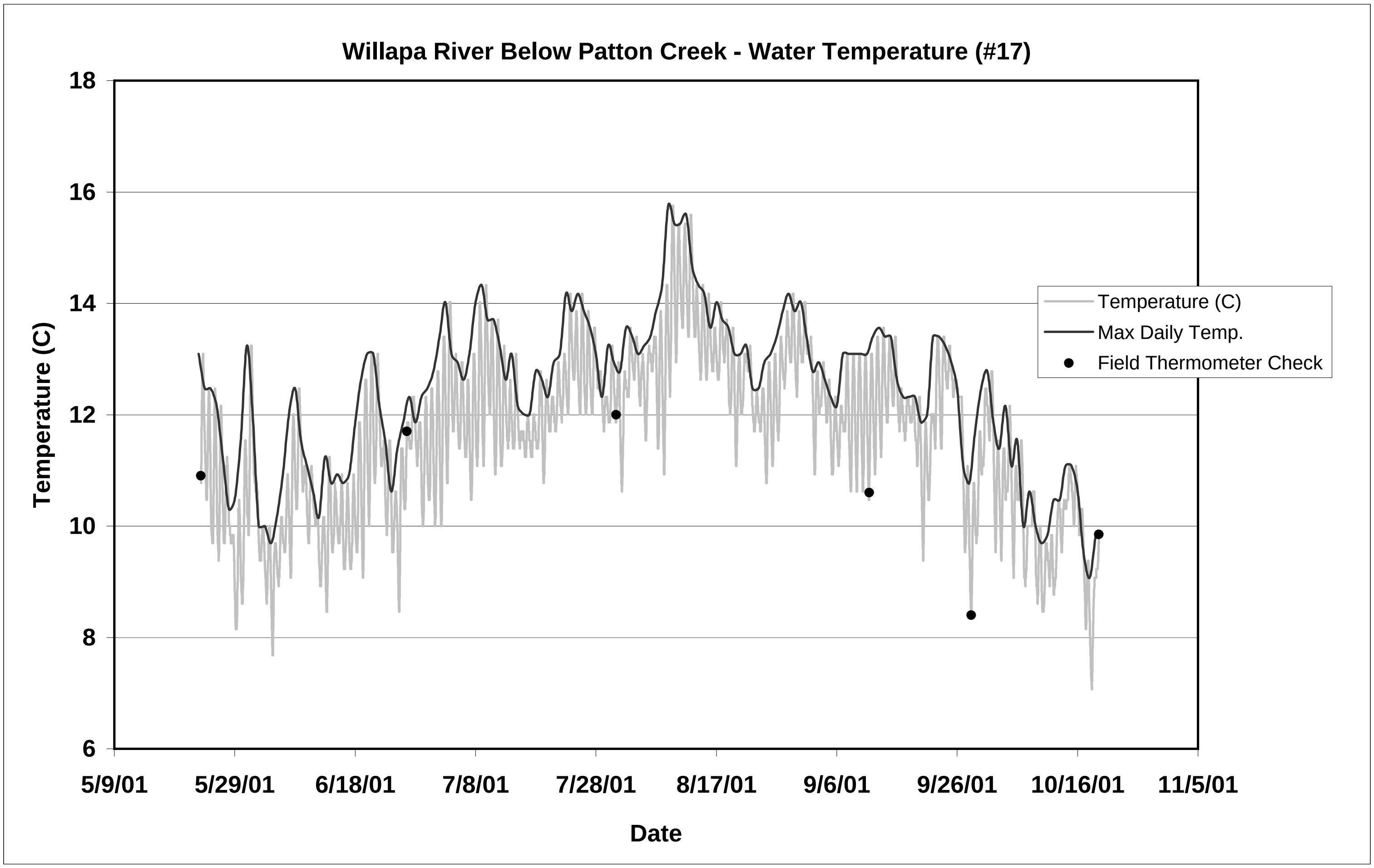
Willapa River Above Halfmoon Creek - Air Temperature (#13)
Temperature (C)
30
25
20
15
10
5
0
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
Date
Temperature (C)
Max Daily Temp.

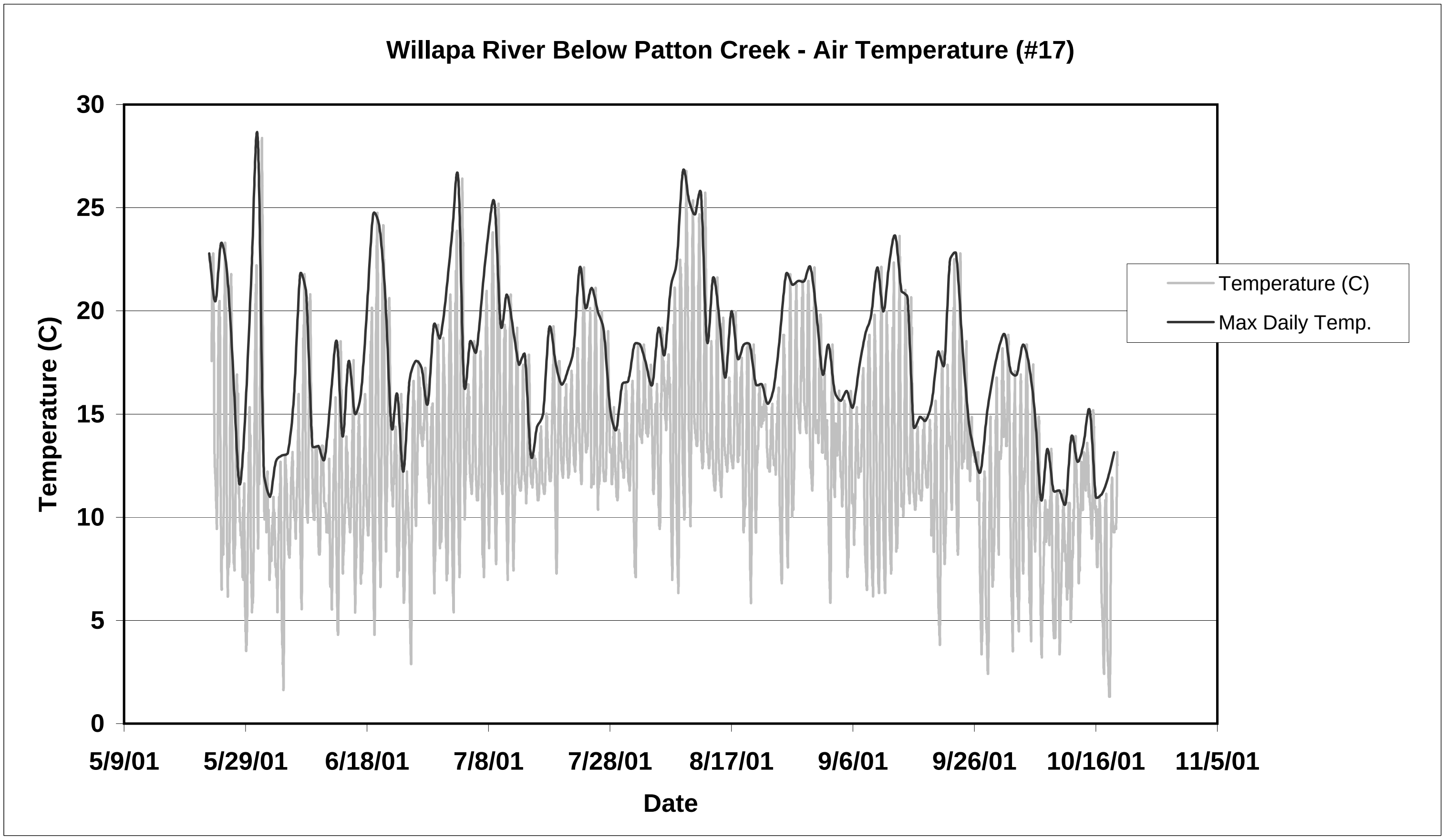

Fern Creek at Elk Prairie Road - Water Temperature (#14)
20
18
16
14
12
10
8
6
Temperature (C)
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
● Field Thermometer Check

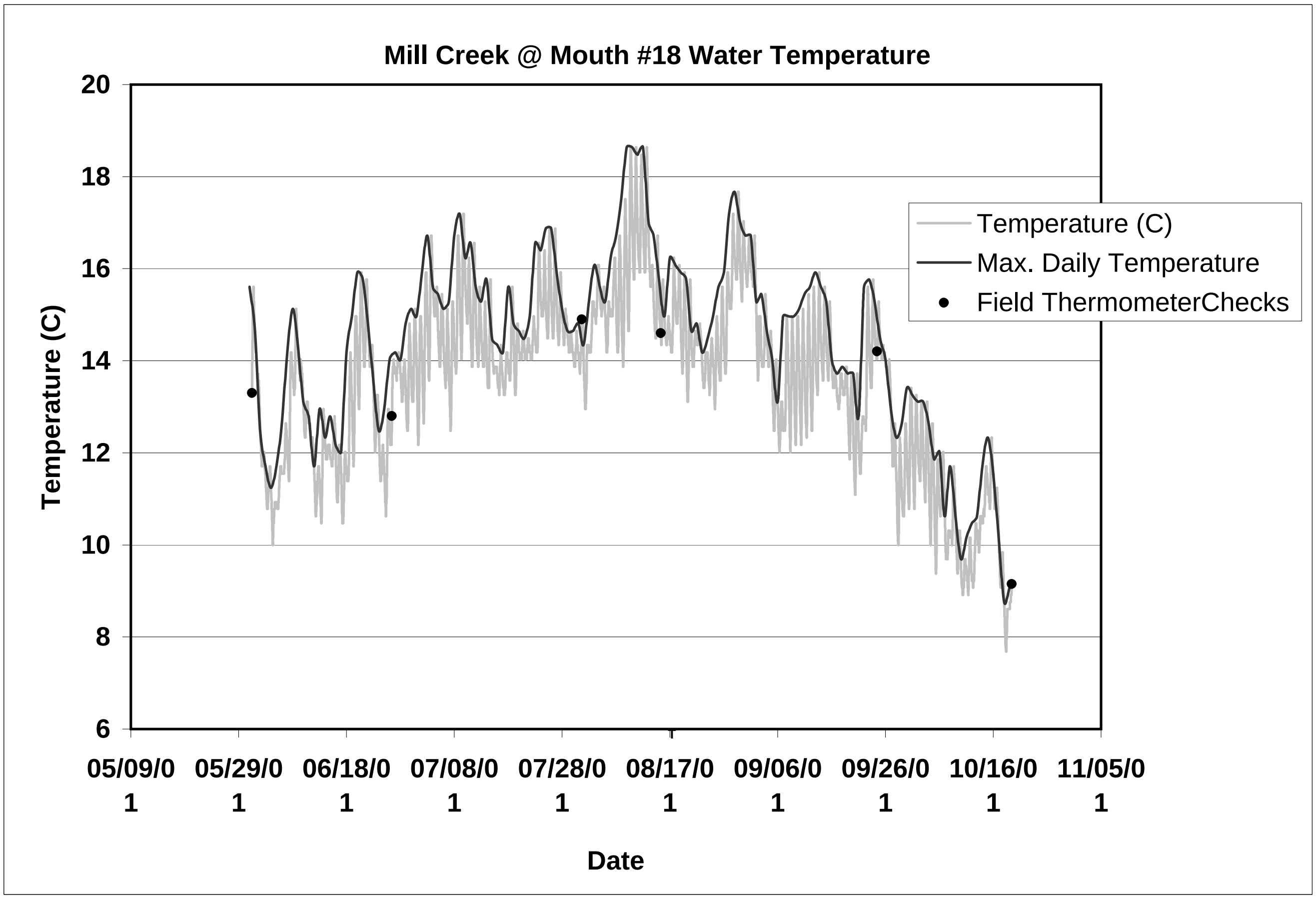

Willapa River at Swiss Picnic Campground - Water Temperature (#15)
Temperature (C)
20
18
16
14
12
10
8
6
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
Field Thermometer Check

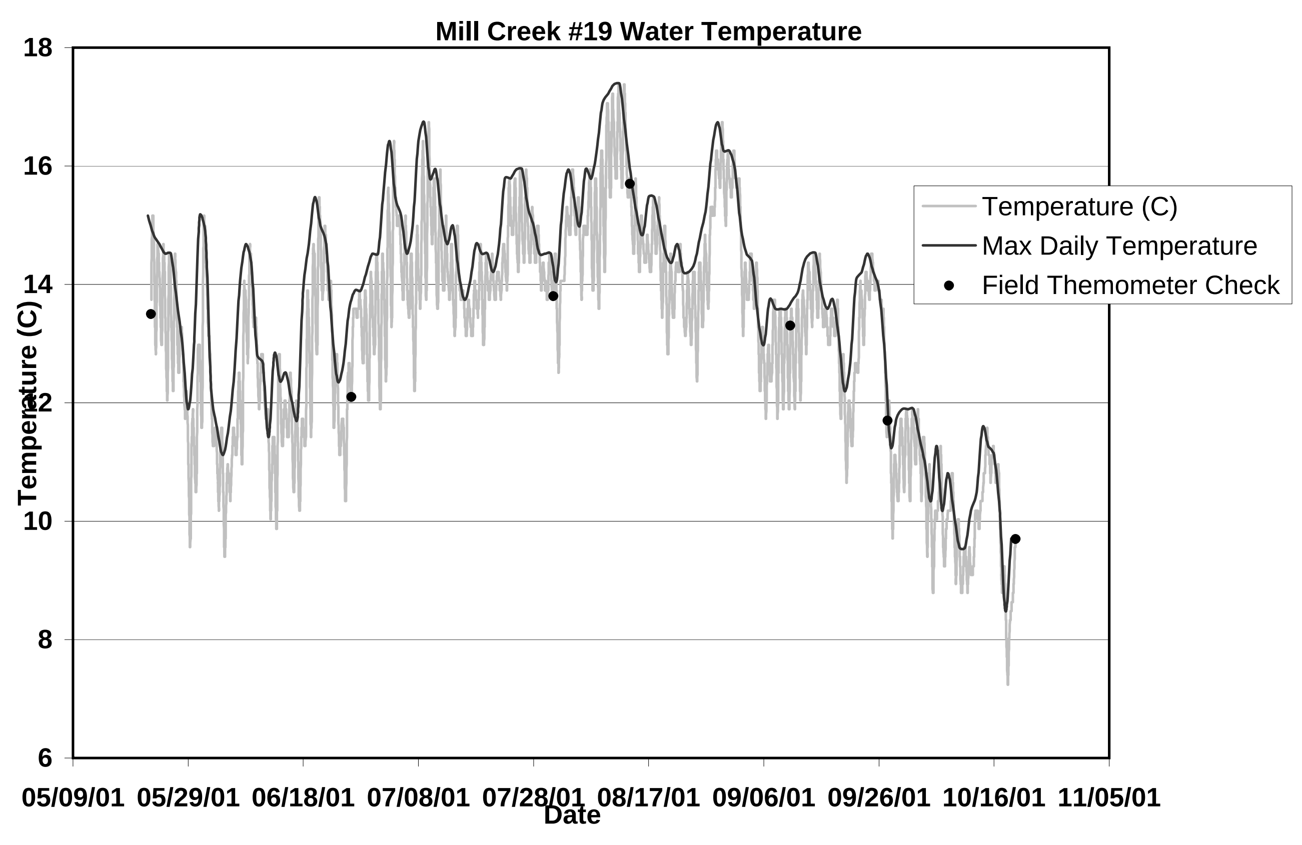

Willapa River at Swiss Picnic Campground- Air Temperature (#15)
Temperature (C)
35
30
25
20
15
10
5
0
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.

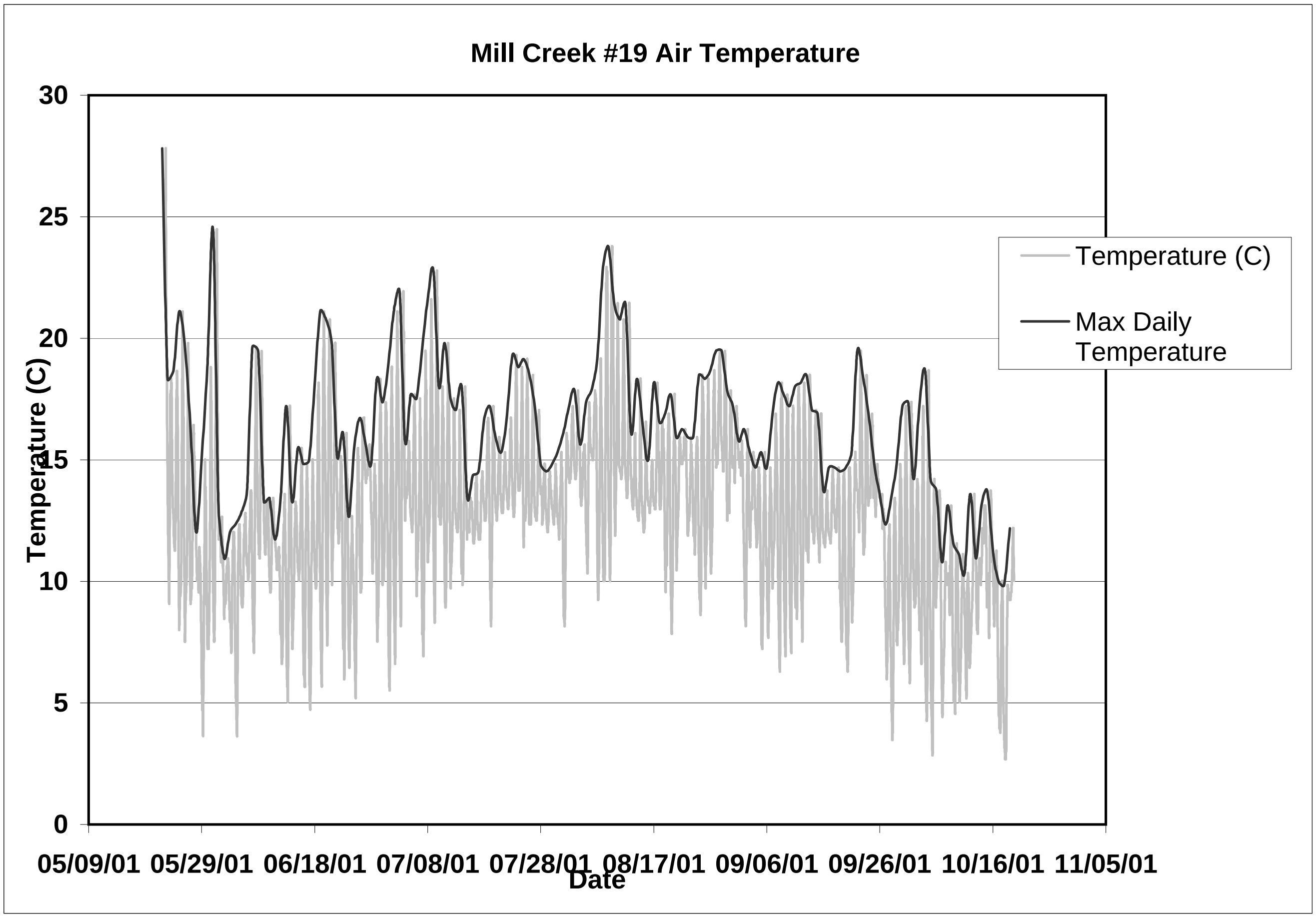

Falls Creek at Retreat Center - Water Temperature (#16)
Temperature (C)
18
16
14
12
10
8
6
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
● Field Thermometer Check

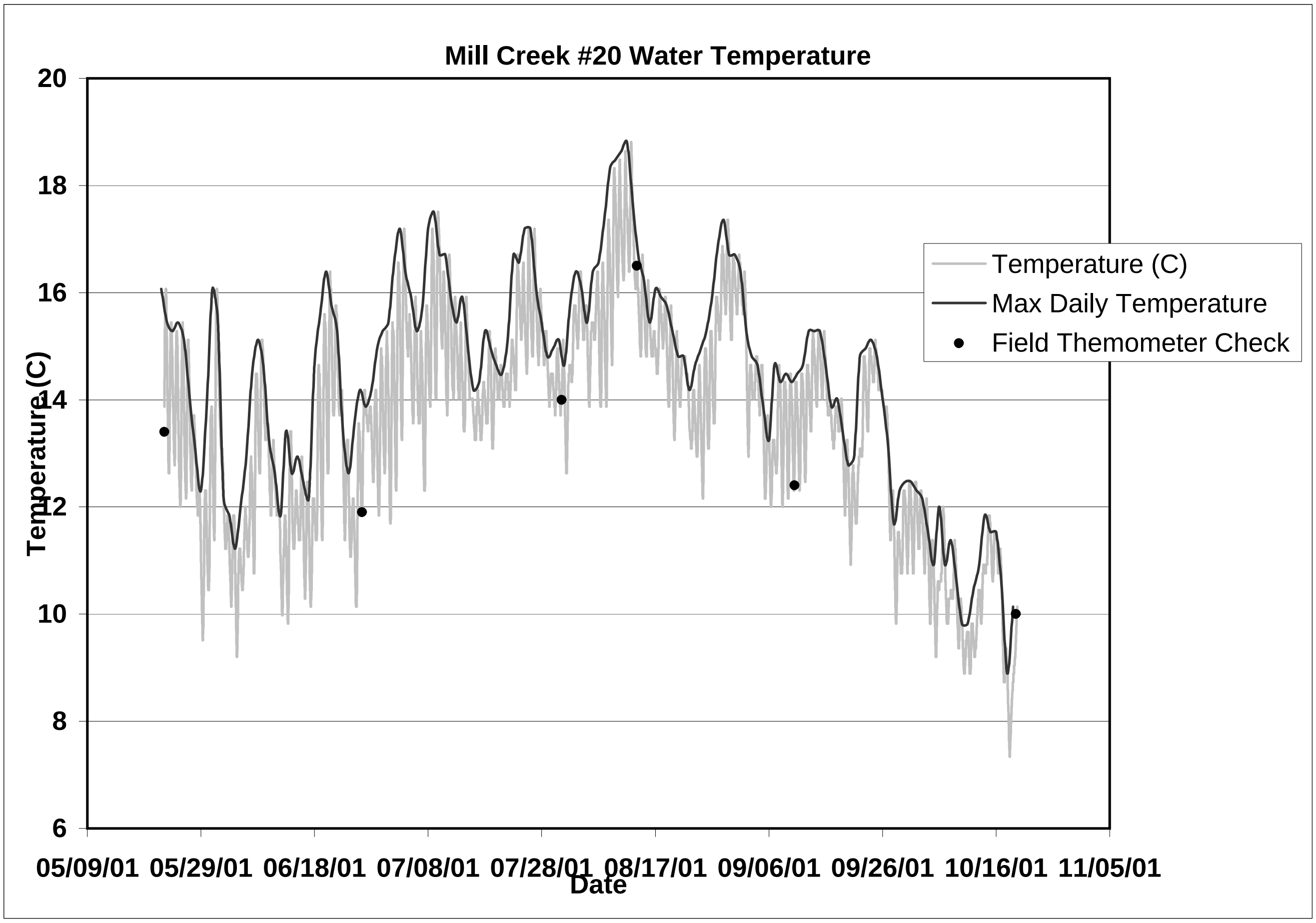

Willapa River Below Patton Creek - Water Temperature (#17)
Temperature (C)
18
16
14
12
10
8
6
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.
Field Thermometer Check

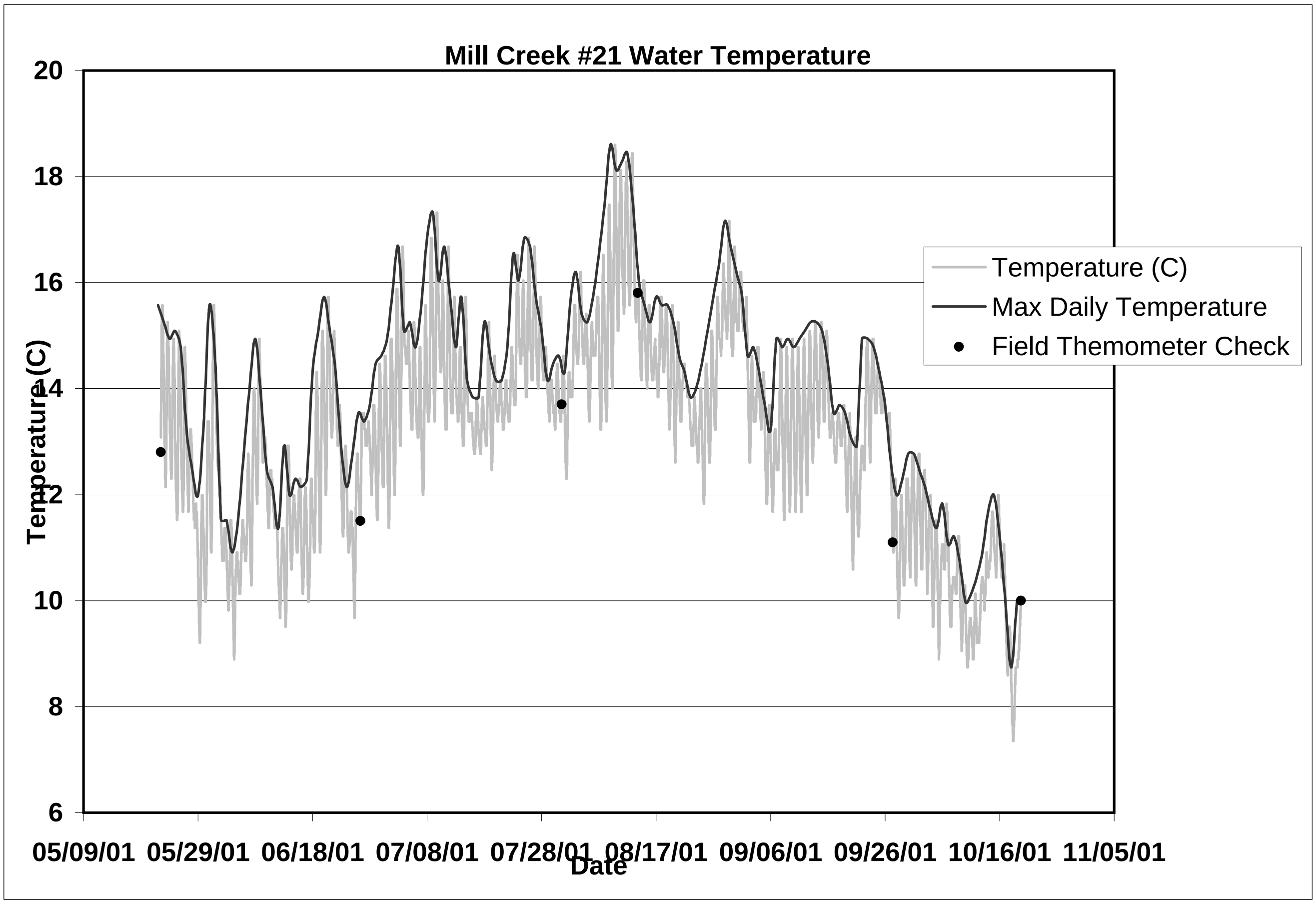

Willapa River Below Patton Creek - Air Temperature (#17)
Temperature (C)
30
25
20
15
10
5
0
5/9/01
5/29/01
6/18/01
7/8/01
7/28/01
8/17/01
9/6/01
9/26/01
10/16/01
11/5/01
Date
Temperature (C)
Max Daily Temp.

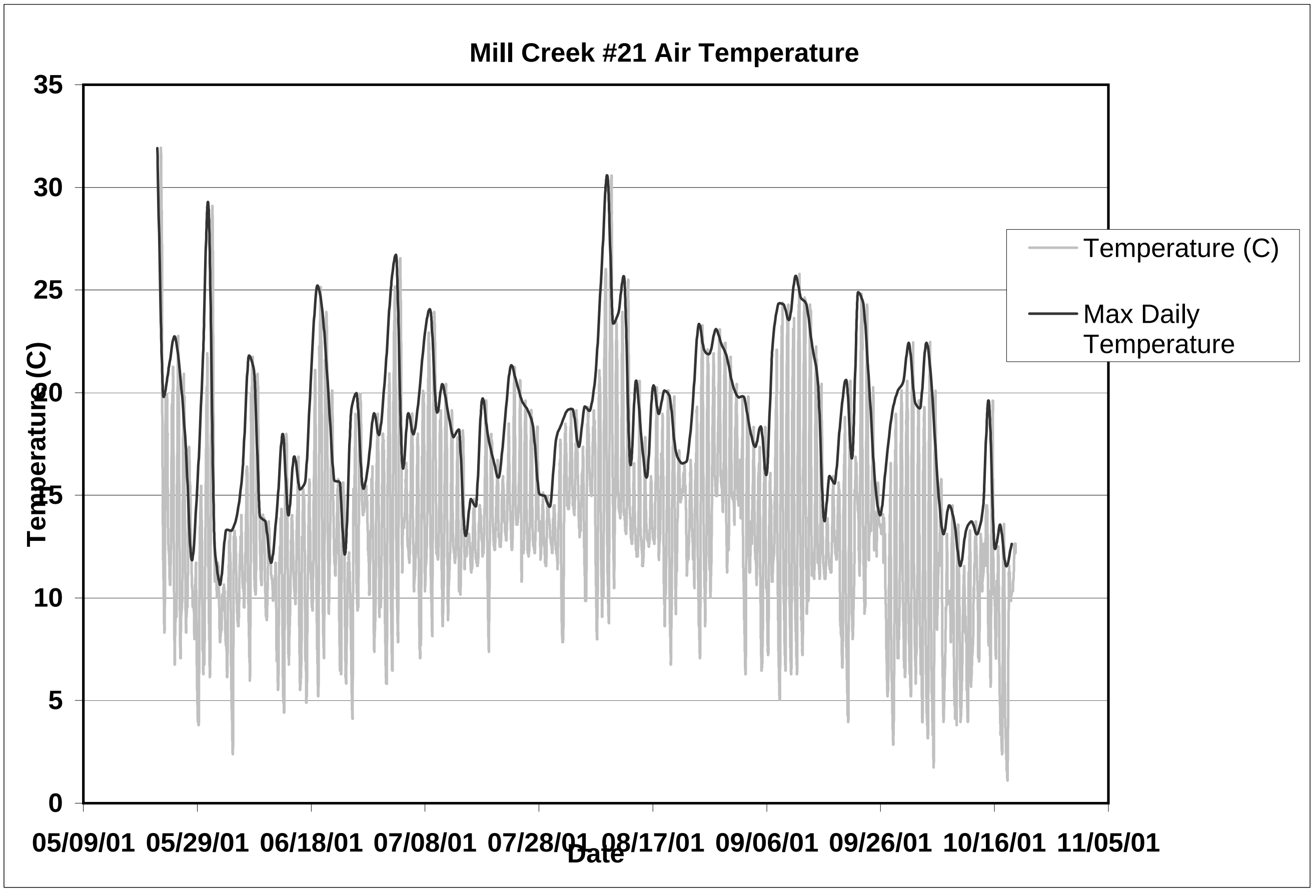

Mill Creek @ Mouth #18 Water Temperature
20
18
16
14
12
10
8
6
Temperature (C)
05/09/01
05/29/01
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max. Daily Temperature
Field ThermometerChecks

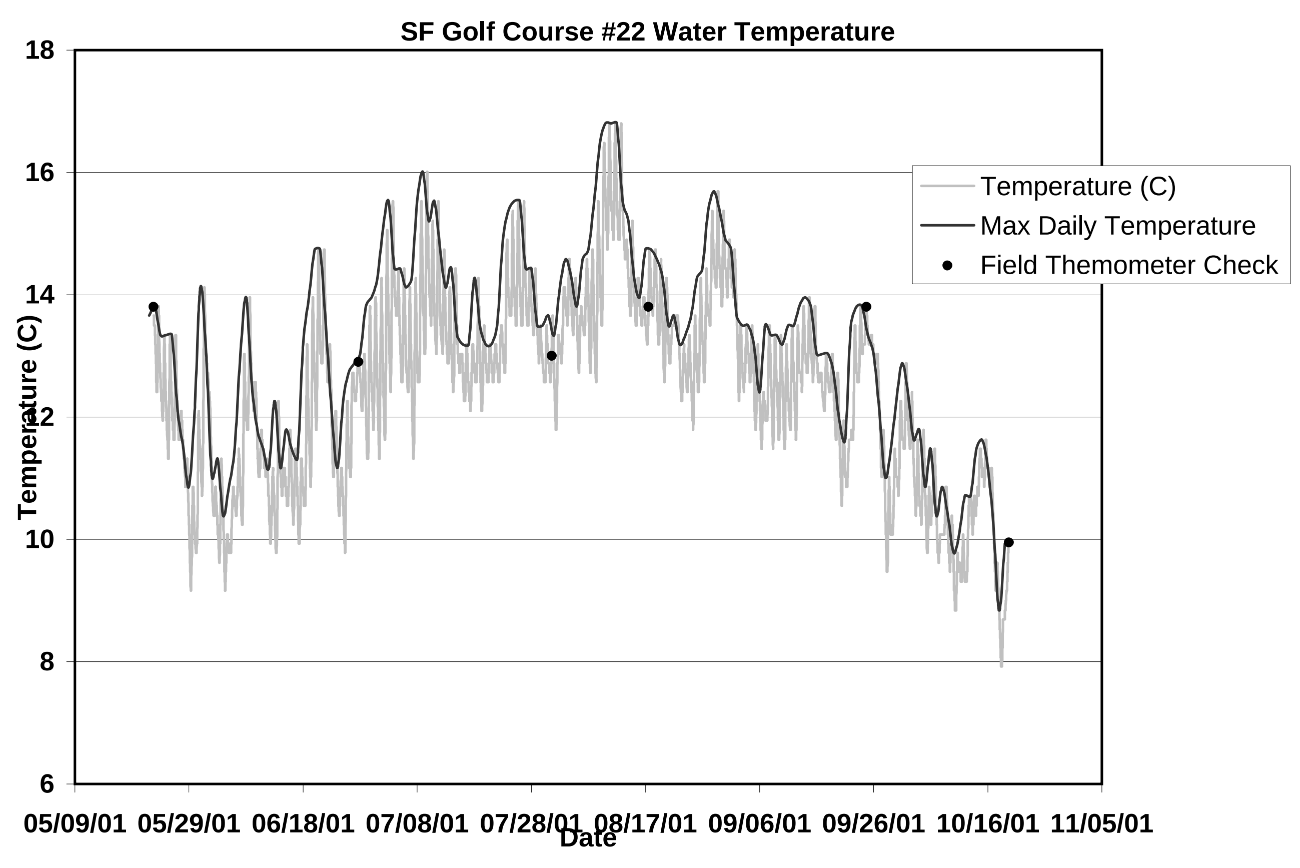

Mill Creek #19 Water Temperature
18
16
14
12
10
8
6
Temperature (C)
05/09/01
05/29/01
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature
Field Themometer Check

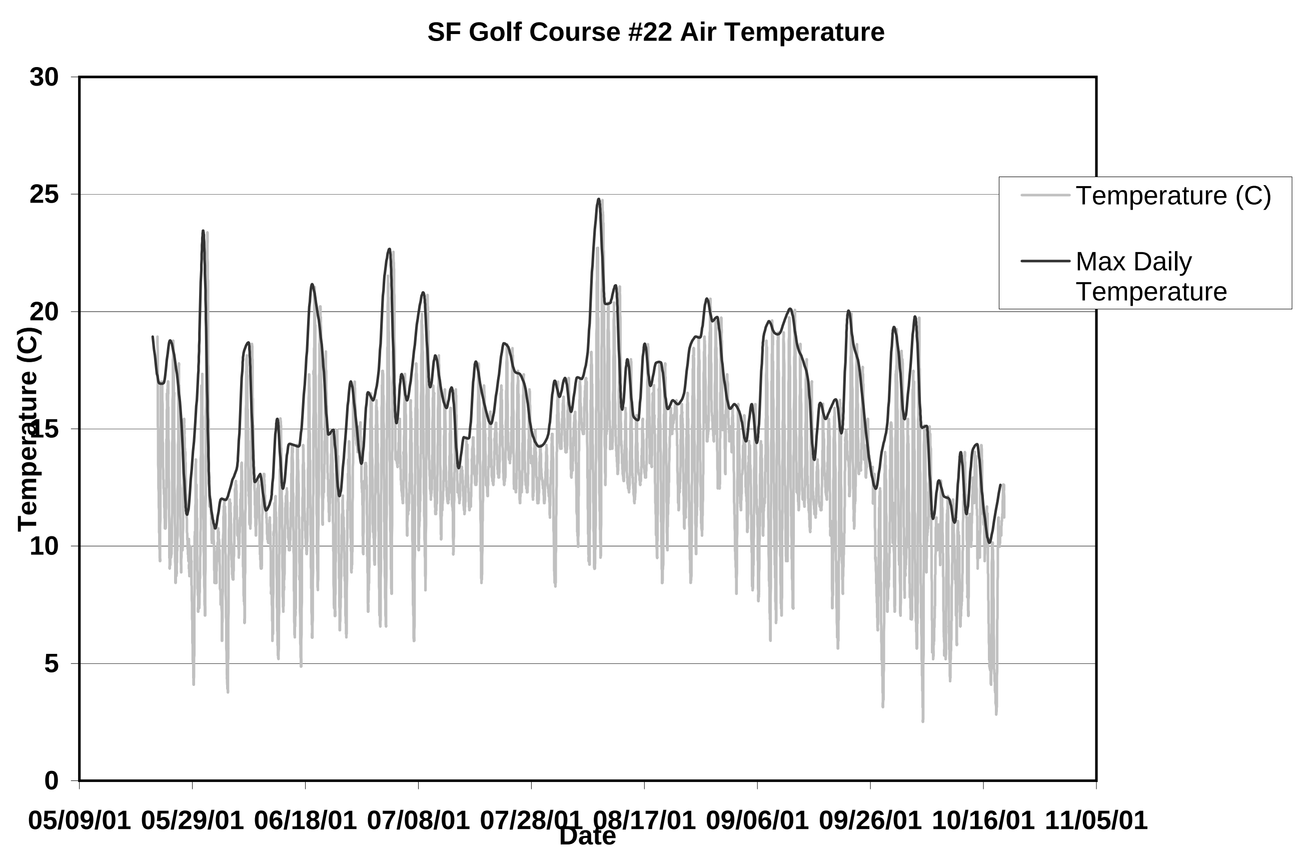

Mill Creek #19 Air Temperature
30
25
20
15
10
5
0
Temperature (C)
05/09/01
05/29/01
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature

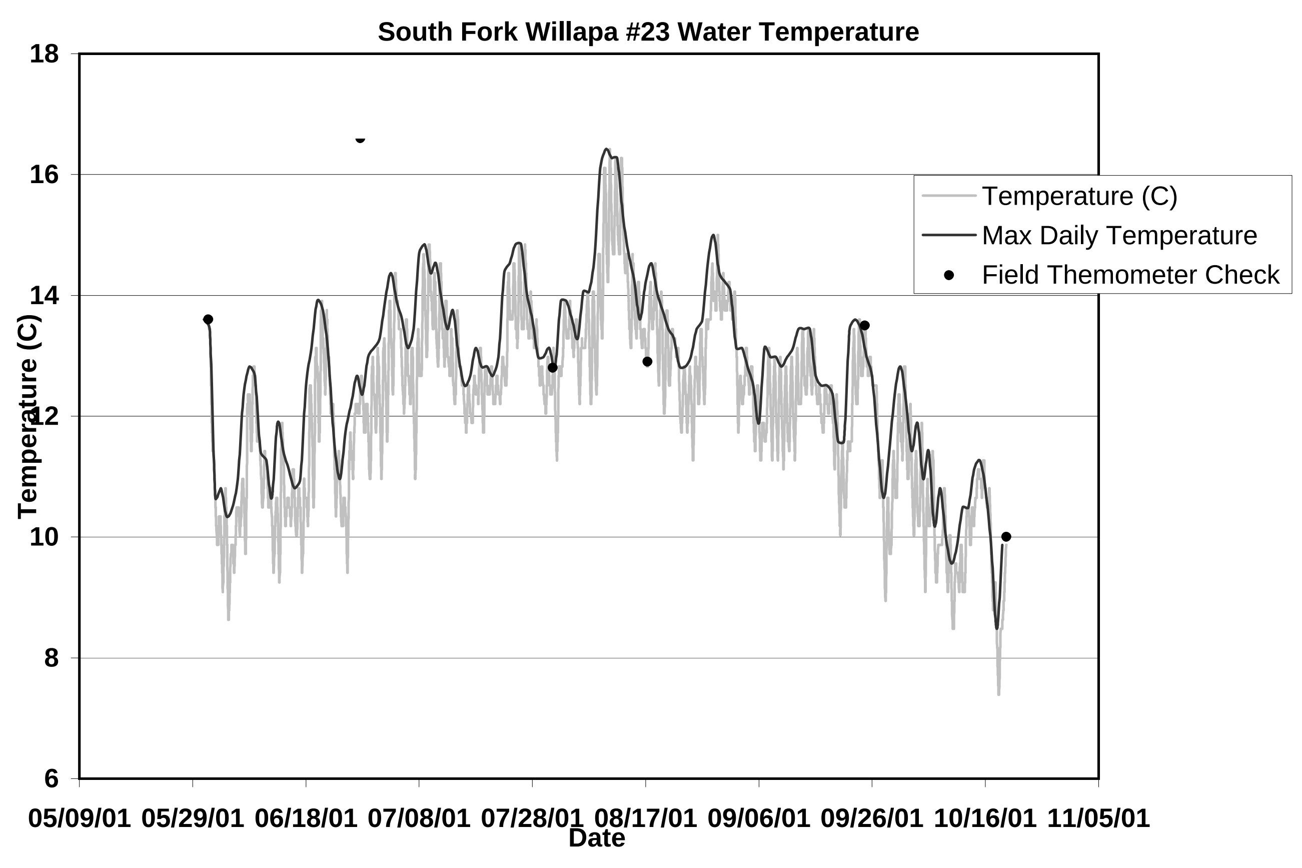

Mill Creek #20 Water Temperature
20
18
16
14
12
10
8
6
Temperature (C)
05/09/01
05/29/01
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature
Field Themometer Check

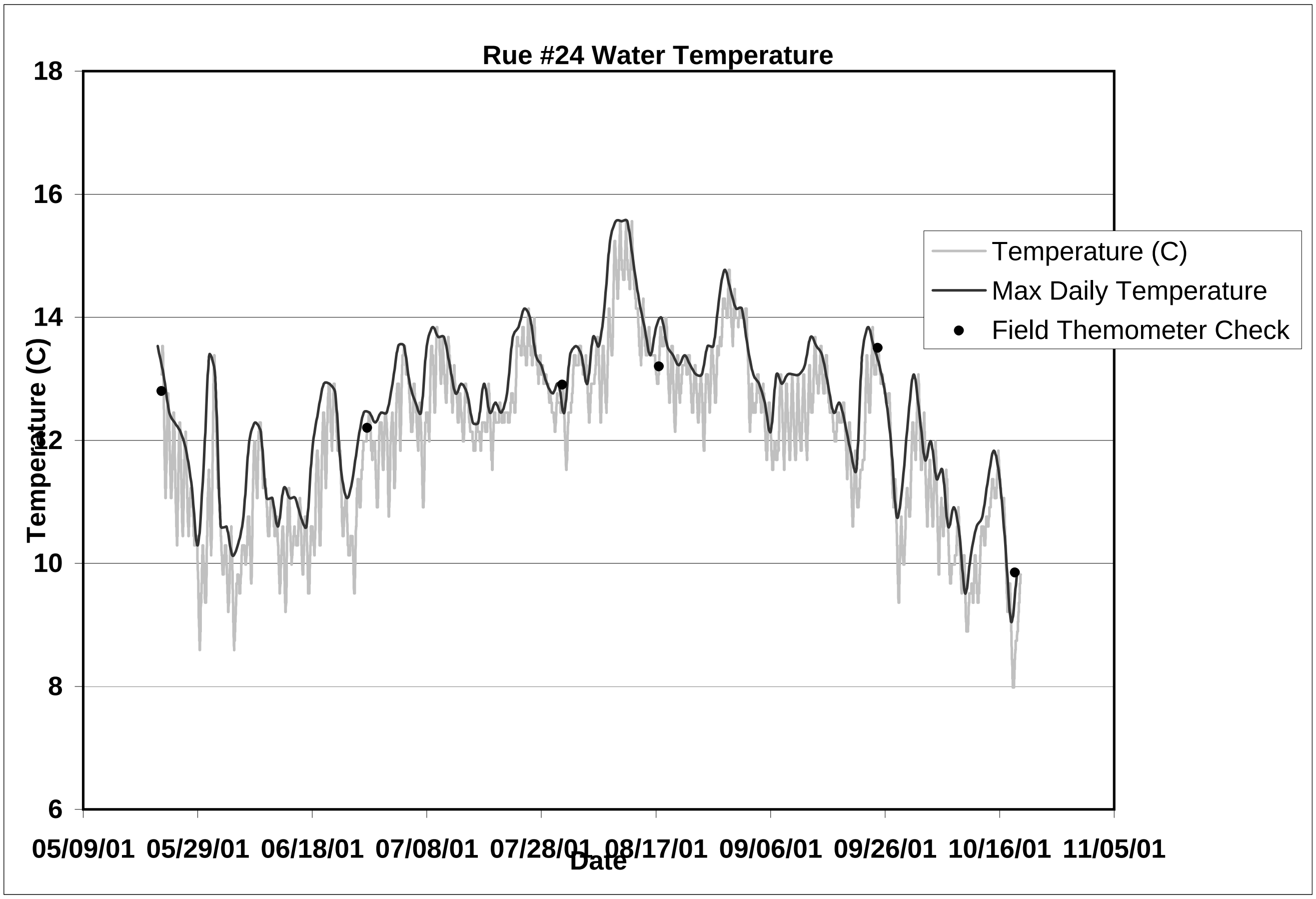

Mill Creek #21 Water Temperature
20
18
16
14
12
10
8
6
Temperature (C)
05/09/01
05/29/01
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature
Field Themometer Check

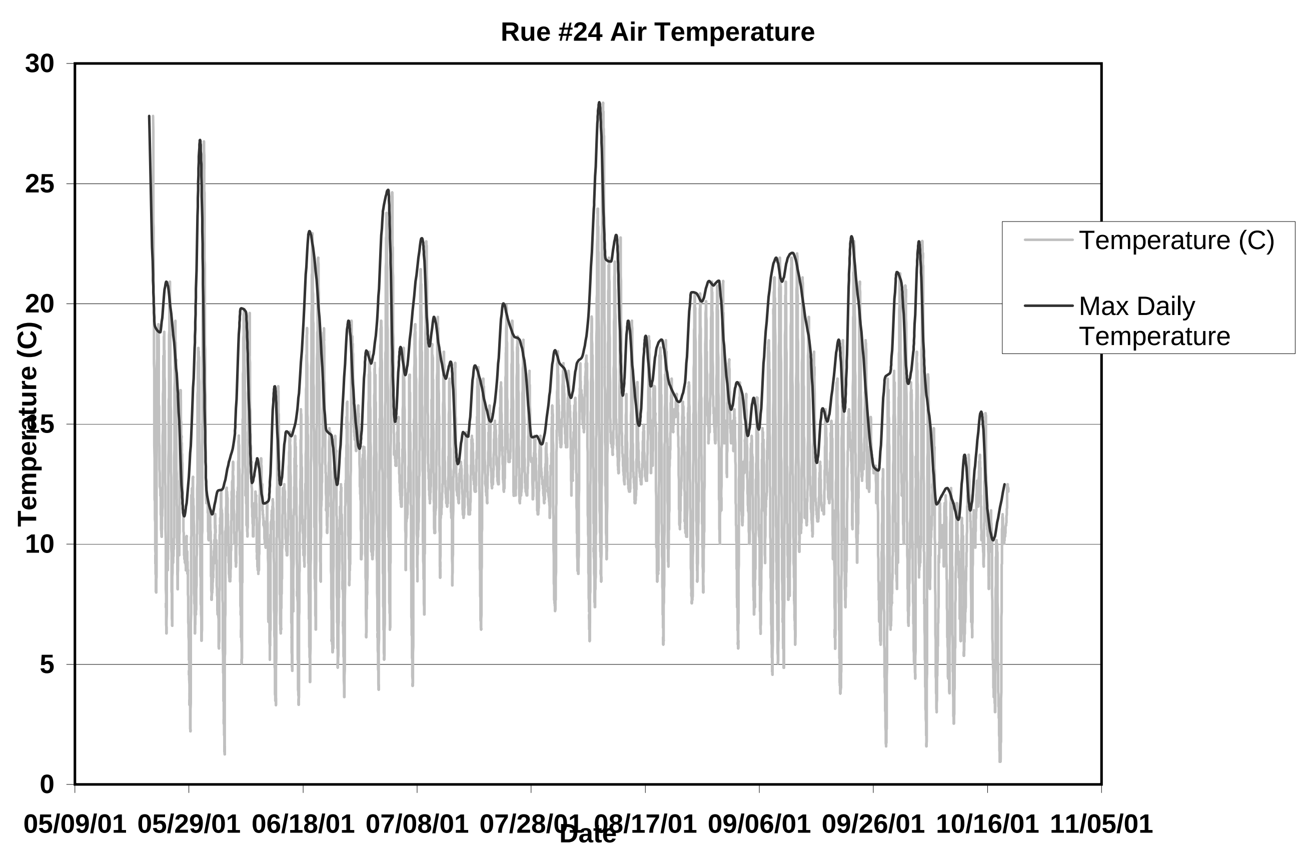

Mill Creek #21 Air Temperature
35
30
25
20
15
10
5
0
Temperature (C)
05/09/01
05/29/01
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature

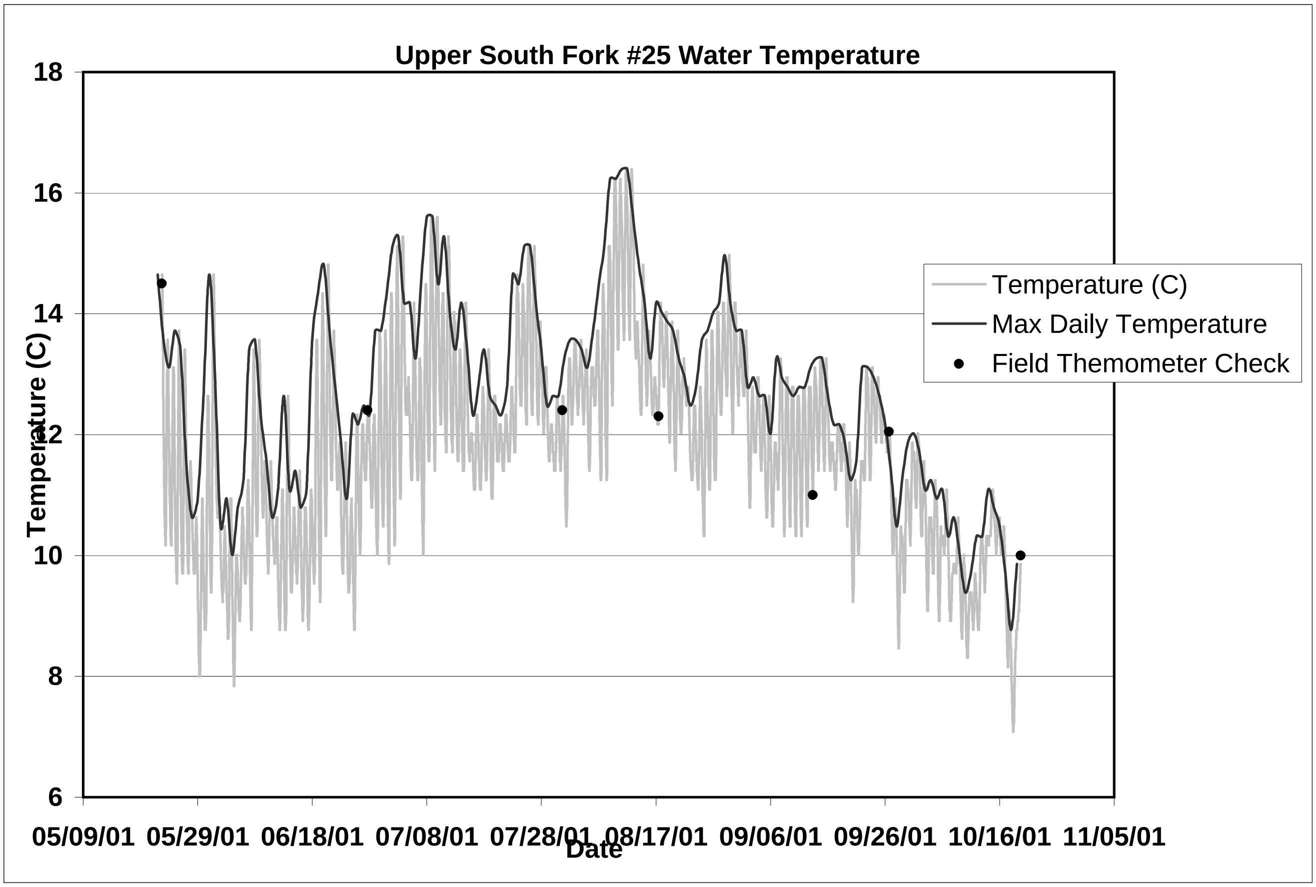

SF Golf Course #22 Water Temperature
Temperature (C)
18
16
14
12
10
8
6
05/09/01
05/29/01
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature
● Field Themometer Check

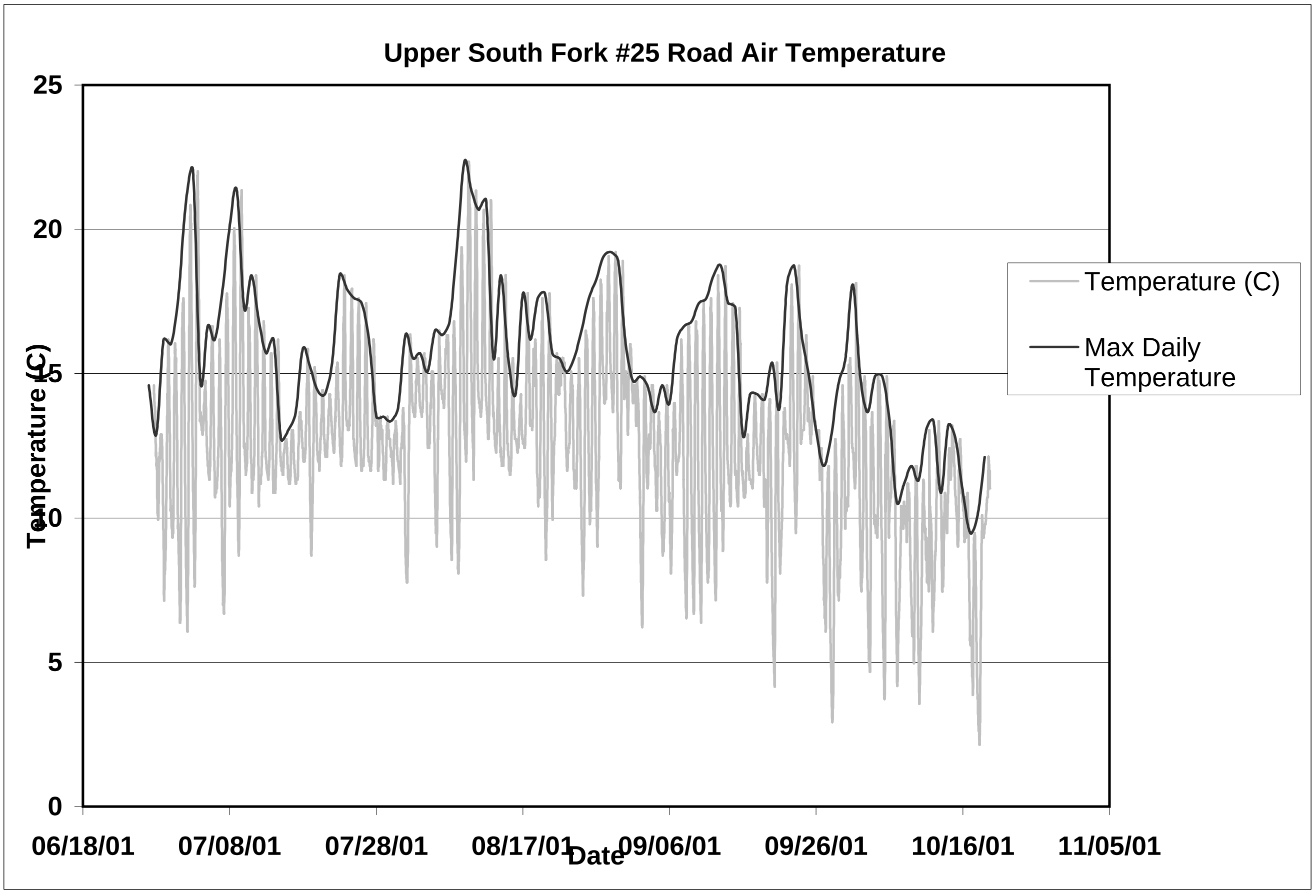

SF Golf Course #22 Air Temperature
Temperature (C)
30
25
20
15
10
5
0
05/09/01
05/29/01
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature

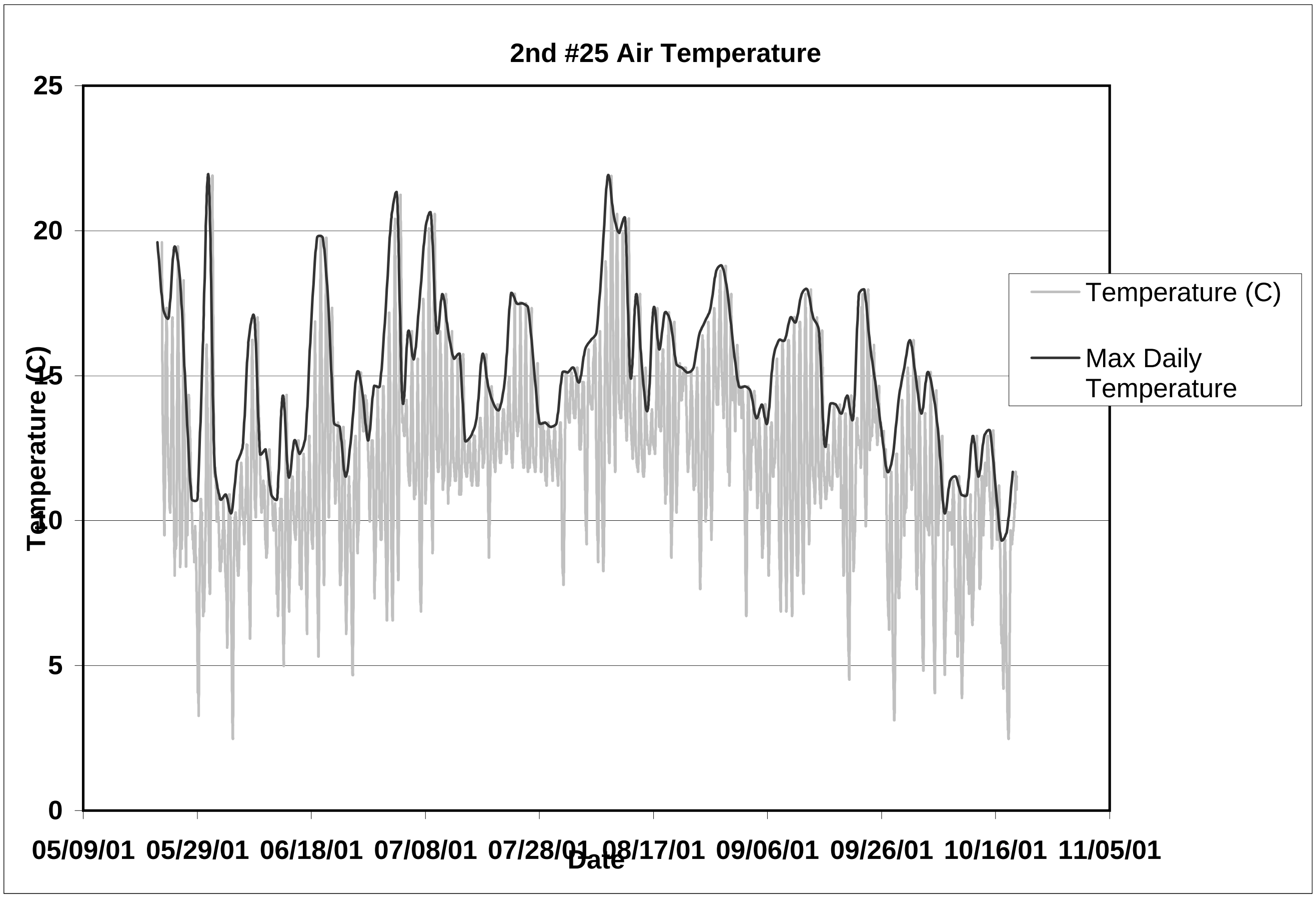

South Fork Willapa #23 Water Temperature
18
16
14
12
10
8
6
Temperature (C)
05/09/01
05/29/01
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature
Field Themometer Check

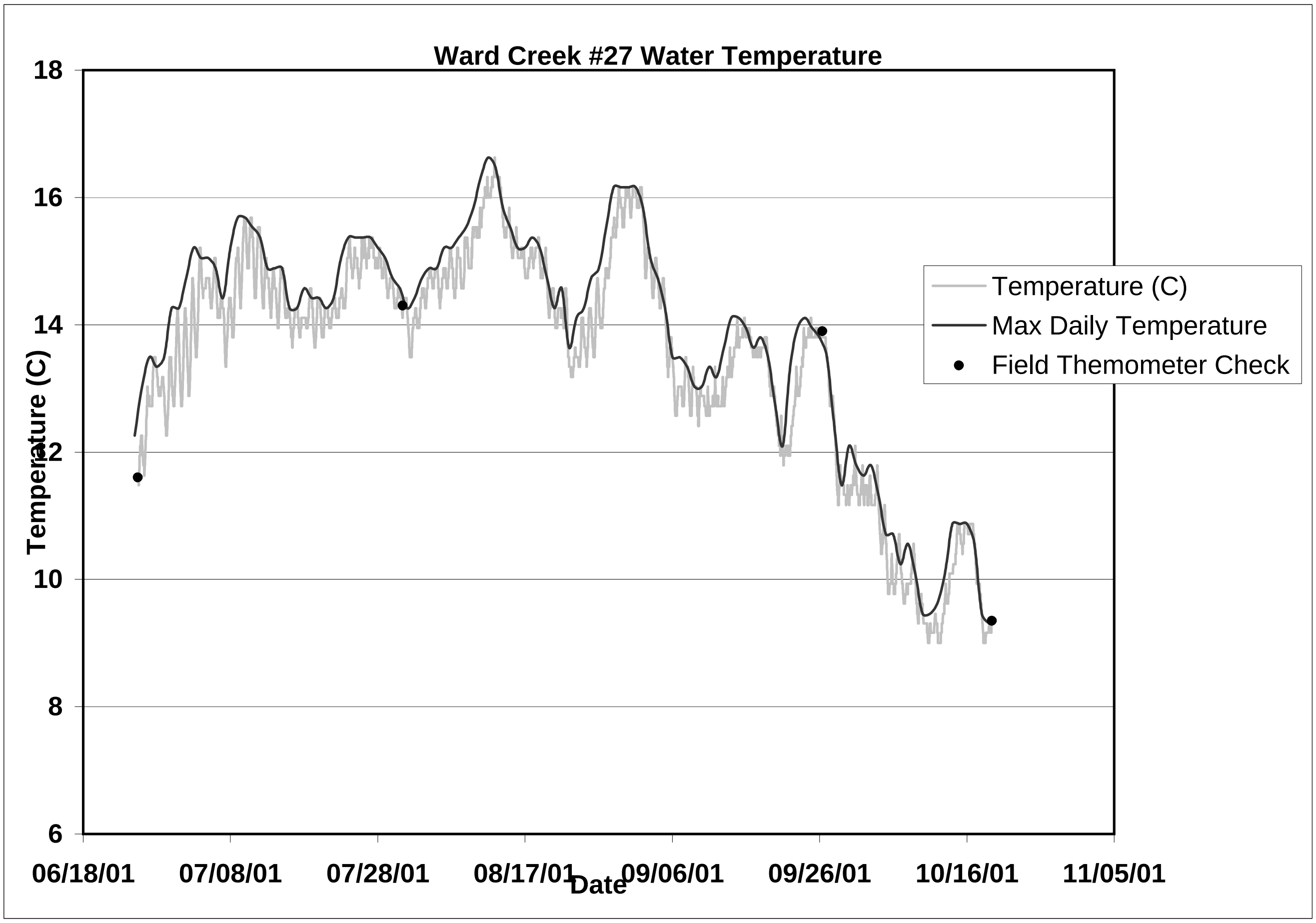

Rue #24 Water Temperature
18
16
14
12
10
8
6
Temperature (C)
05/09/01
05/29/01
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature
Field Themometer Check

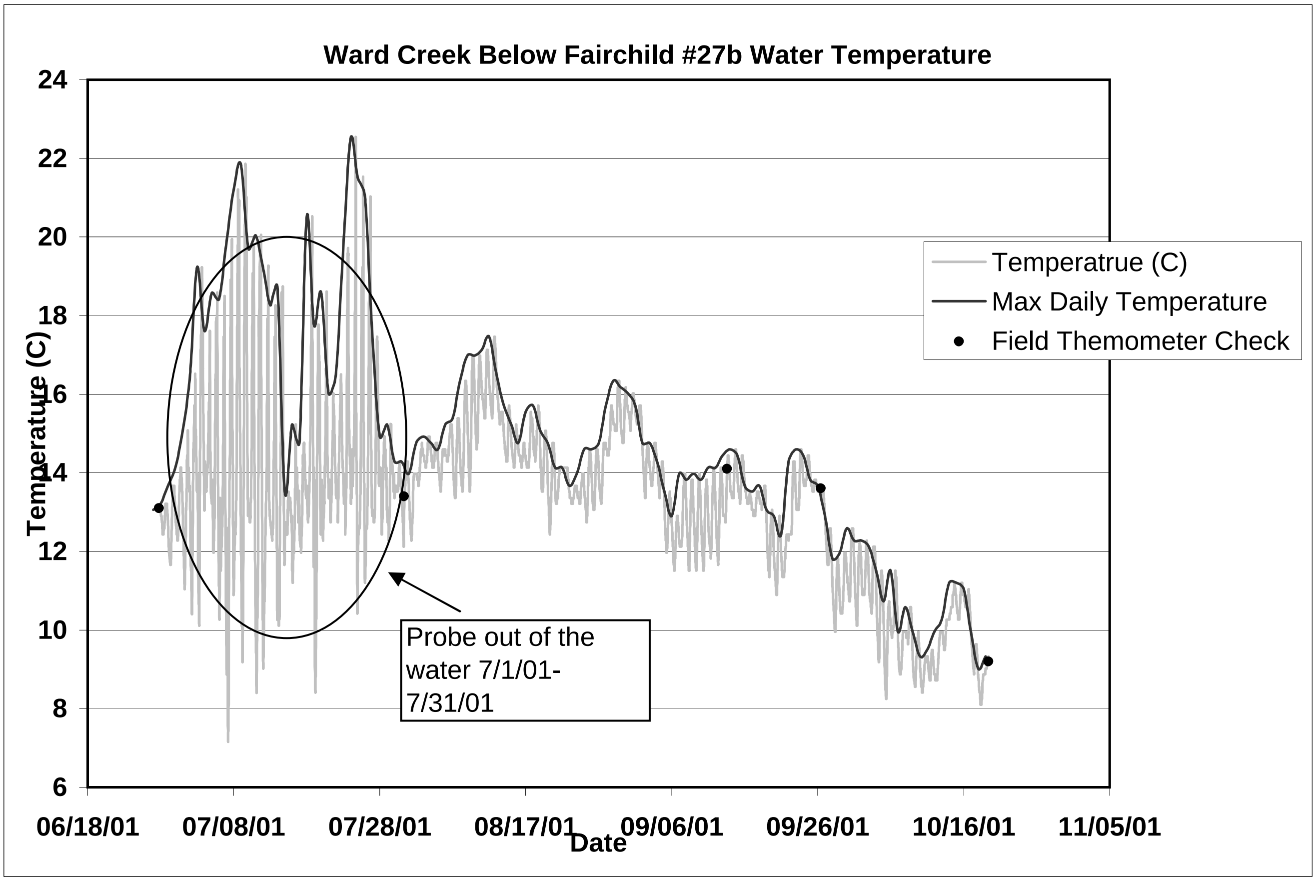

Rue #24 Air Temperature
30
25
20
15
10
5
0
Temperature (C)
05/09/01
05/29/01
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature

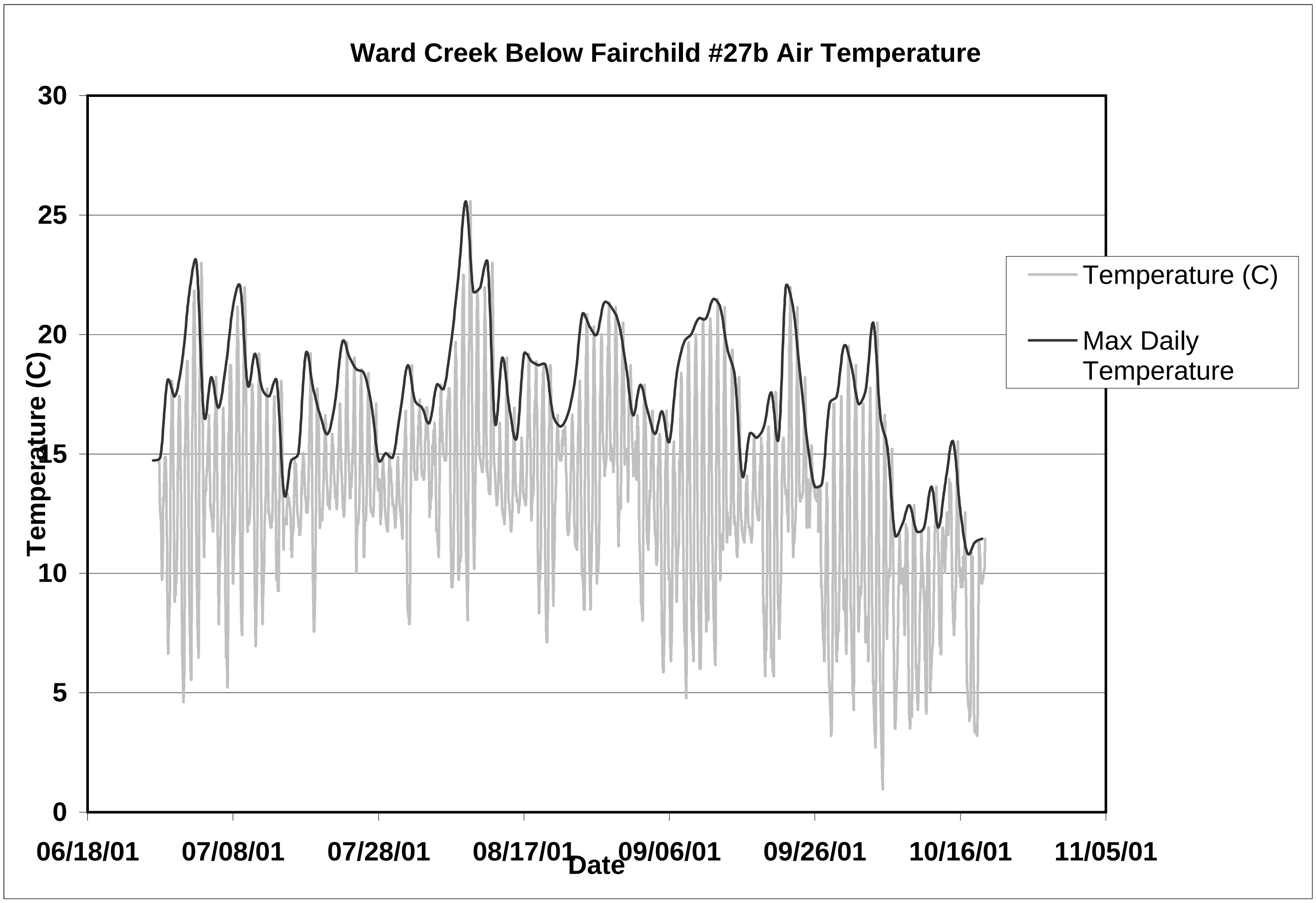

Upper South Fork #25 Water Temperature
18
16
14
12
10
8
6
Temperature (C)
05/09/01
05/29/01
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature
Field Themometer Check

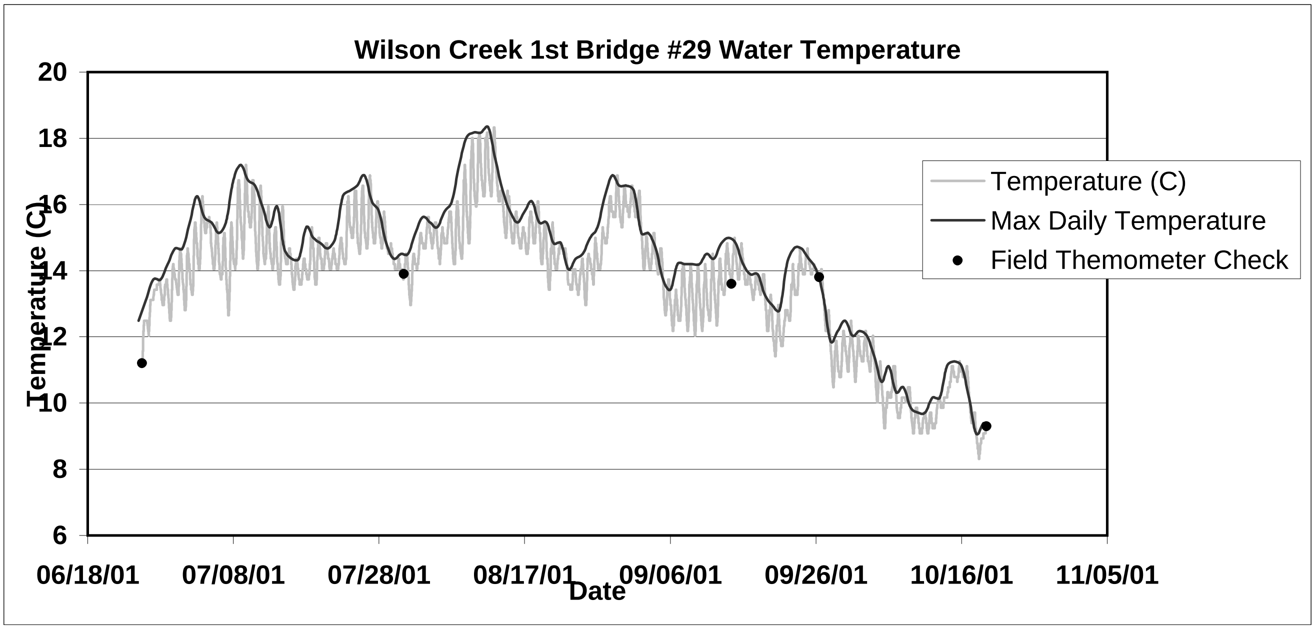

Upper South Fork #25 Road Air Temperature
25
20
15
10
5
0
Temperature (C)
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature

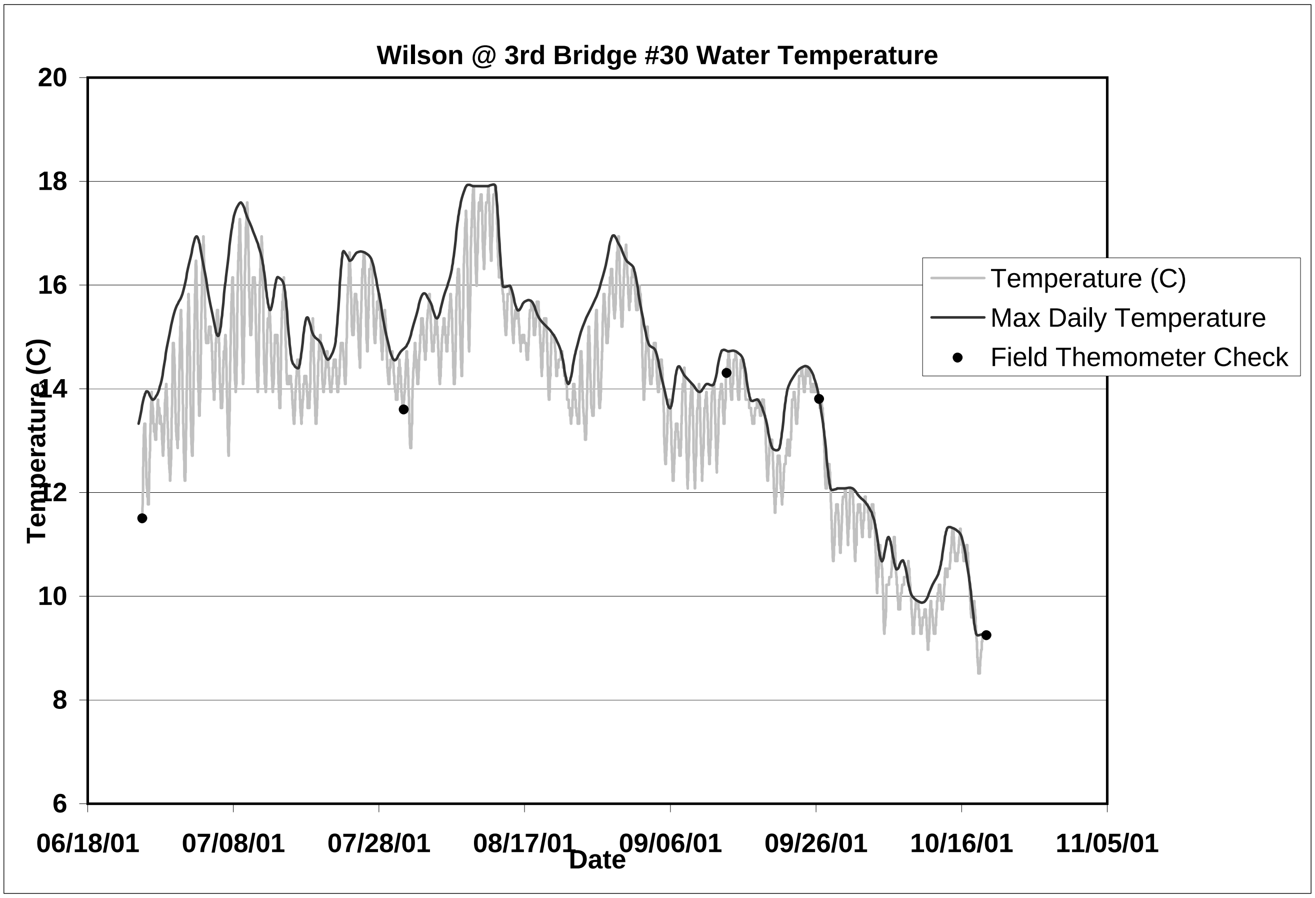

2nd #25 Air Temperature
25
20
15
10
5
0
Temperature (C)
05/09/01
05/29/01
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature

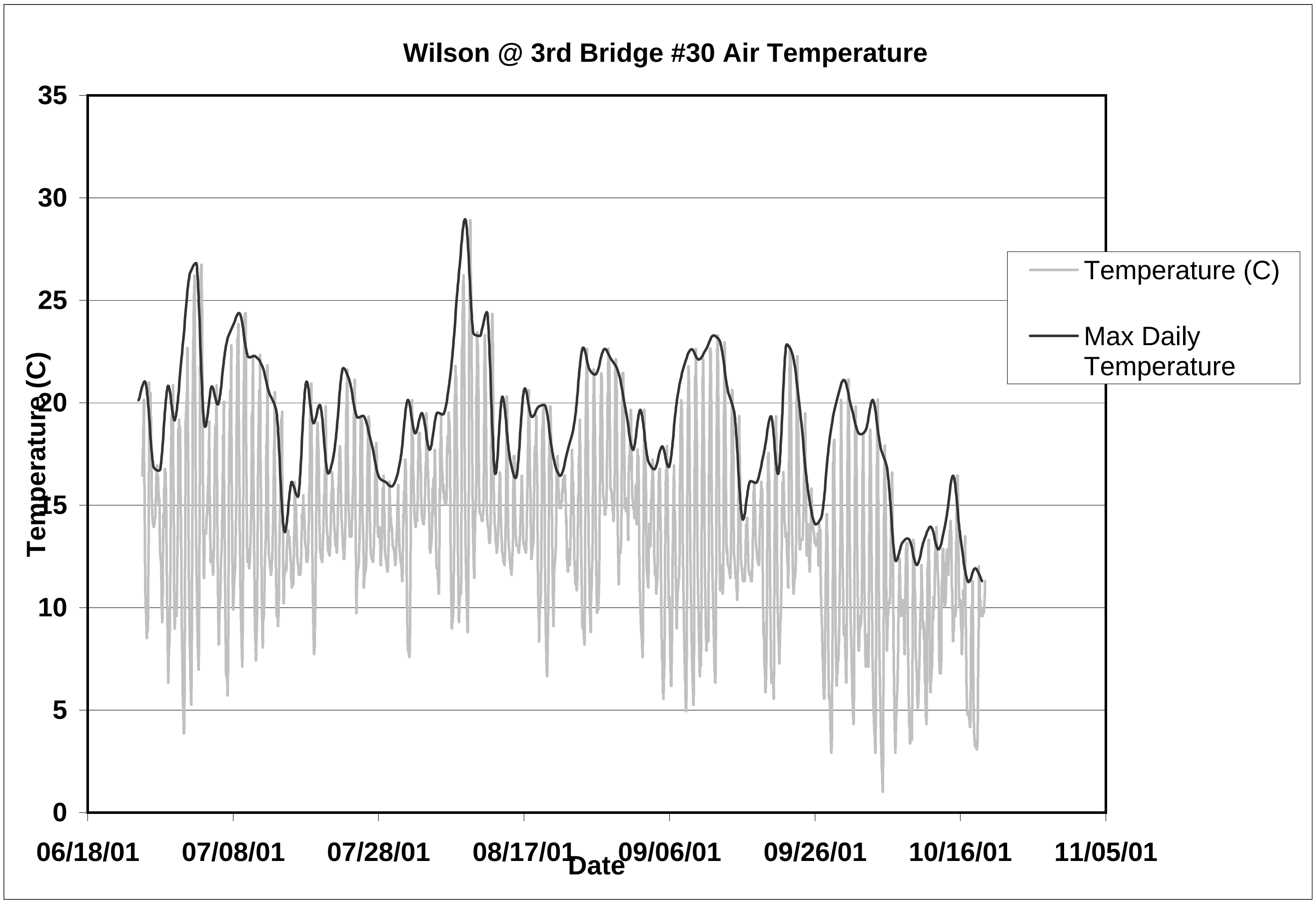

Ward Creek #27 Water Temperature
Temperature (C)
18
16
14
12
10
8
6
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature
Field Themometer Check


Ward Creek Below Fairchild #27b Water Temperature
Temperature (C)
24
22
20
18
16
14
12
10
8
6
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperatrue (C)
Max Daily Temperature
Field Themometer Check
Probe out of the water 7/1/01-7/31/01


Ward Creek Below Fairchild #27b Air Temperature
Temperature (C)
30
25
20
15
10
5
0
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature


Wilson Creek 1st Bridge #29 Water Temperature
Temperature (C)
20
18
16
14
12
10
8
6
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature
Field Themometer Check


Wilson @ 3rd Bridge #30 Water Temperature
20
18
16
14
12
10
8
6
Temperature (C)
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature
● Field Themometer Check


Wilson @ 3rd Bridge #30 Air Temperature
35
30
25
20
15
10
5
0
Temperature (C)
06/18/01
07/08/01
07/28/01
08/17/01
09/06/01
09/26/01
10/16/01
11/05/01
Date
Temperature (C)
Max Daily Temperature

Appendix B

Flow data from Ecology's field surveys

Table B-1. Individual Flow Measurements from Surveys.

Station	Flow (Q) (cfs)	Number of velocity readings	Channel Area (sq ft)	Wetted Perimeter (feet)	Average Velocity (fps)	Wetted Width (feet)	Average Depth (feet)	Time	Date
Willapa 1	62.30	26	121.64	71.28	0.51	70.10	1.74	1450	9/28/01
Willapa 2	154.22	17	183.66	76.51	0.84	75.40	2.44	1030	5/31/01
Willapa 2	103.47	27	171.33	84.24	0.60	82.40	2.08	1025	6/26/01
Willapa 2	46.78	29	104.44	76.61	0.45	74.90	1.39	1550	7/31/01
Willapa 2	32.46	24	101.39	72.98	0.32	72.40	1.40	1230	8/13/01
Willapa 2	55.92	34	110.40	77.35	0.51	75.50	1.46	1425	9/28/01
Willapa 3	147.09	19	144.31	66.35	1.02	65.50	2.20	1415	5/31/01
Willapa 3	134.33	20	135.20	72.70	0.99	71.50	1.89	1240	6/27/01
Willapa 3	56.18	23	103.14	65.26	0.54	64.20	1.61	1500	7/31/01
Willapa 3	60.36	19	106.04	68.62	0.57	68.20	1.55	15:00	9/12/01
Willapa 3	54.01	31	89.23	67.68	0.61	65.30	1.37	1315	9/28/01
Willapa 4	139.07	17	88.21	71.62	1.58	70.70	1.25	1630	5/31/01
Willapa 4	132.88	22	84.70	80.01	1.57	79.30	1.07	1050	6/27/01
Willapa 4	49.23	29	56.73	76.07	0.87	74.90	0.76	1335	7/31/01
Willapa 4	35.67	16	27.38	44.42	1.30	44.10	0.62	735	8/14/01
Willapa 4	55.34	27	71.57	79.59	0.77	78.10	0.92	1235	9/28/01
Stringer 5	10.30	17	6.74	15.89	1.53	15.70	0.43	1435	5/24/01
Stringer 5	6.71	17	4.81	8.79	1.40	8.10	0.59	1125	6/27/01
Stringer 5	2.13	17	3.02	12.15	0.71	12.00	0.25	1415	7/31/01
Stringer 5	2.41	23	3.62	11.78	0.67	11.50	0.31	750	9/13/01
Stringer 5	1.68	23	2.92	10.64	0.58	10.90	0.27	1800	9/27/01
Willapa 6	126.97	19	111.07	67.59	1.14	67.00	1.66	1530	5/31/01
Willapa 6	121.72	24	116.54	71.40	1.04	70.90	1.64	945	6/27/01
Willapa 6	48.28	18	93.19	68.13	0.52	67.90	1.37	1255	7/31/01
Willapa 6	51.11	16	92.69	68.04	0.55	67.80	1.37	1025	9/12/01
Willapa 6	48.39	26	87.44	67.68	0.55	67.00	1.31	1205	9/28/01
Trap 7	52.51	17	19.94	33.44	2.63	33.30	0.60	1645	5/23/01
Trap 7	24.93	16	11.42	28.07	2.18	28.00	0.41	1445	6/25/01
Trap 7	16.54	17	8.61	25.57	1.92	25.50	0.34	930	7/31/01
Trap 7	10.56	13	7.77	24.35	1.36	24.30	0.32	1635	8/16/01
Trap 7	14.94	18	7.62	23.88	1.96	23.80	0.32	1545	9/24/01
Trap 7	25.01	14	10.76	24.67	2.32	24.60	0.44	1545	9/26/01
Trap 7a	19.31	19	23.96	21.55	0.81	20.50	1.17	1405	6/25/01
Trap 7a	12.96	21	21.96	22.07	0.59	21.40	1.03	900	7/31/01
Trap 7a	8.71	11	18.56	21.53	0.47	21.20	0.88	1600	8/16/01
Trap 7a	22.78	18	16.72	24.67	1.36	24.15	0.69	1515	9/26/01
Willapa 8	32.22	26	23.22	26.60	1.39	25.20	0.92	1155	7/31/01
Willapa 8	36.86	24	17.12	39.25	2.15	39.00	0.44	1630	9/11/01
Willapa 8	36.05	27	23.82	24.74	1.51	24.90	0.96	1105	9/28/01

Station	Flow (Q) (cfs)	Number of velocity readings	Channel Area (sq ft)	Wetted Perimeter (feet)	Average Velocity (fps)	Wetted Width (feet)	Average Depth (feet)	Time	Date
Fork 9	29.32	26	39.61	34.54	0.74	33.80	1.17	1555	6/25/01
Fork 9	19.47	16	29.69	26.31	0.66	25.80	1.15	1110	7/31/01
Fork 9	13.12	23	8.49	12.50	1.55	11.80	0.72	2000	8/15/01
Fork 9	14.05	20	12.96	19.37	1.08	18.50	0.70	1440	9/24/01
Fork 9	31.51	26	20.91	25.09	1.51	31.30	0.67	1415	9/26/01
Fork 9a	56.00	18	34.98	32.30	1.60	31.50	1.11	943	5/24/01
Fork 9a	23.74	19	28.23	32.11	0.84	31.70	0.89	1510	6/25/01
Fork 9a	8.57	17	19.89	28.88	0.43	28.30	0.70	1410	7/31/01
Fork 9a	5.50	14	16.61	25.82	0.33	25.40	0.65	1625	8/15/01
Fork 9a	25.05	18	29.98	32.25	0.84	31.80	0.94	1445	9/26/01
Fork 9b	60.28	18	55.02	49.43	1.10	49.00	1.12	1040	5/24/01
Fork 9b	25.62	16	54.74	39.07	0.47	38.10	1.44	1650	6/25/01
Fork 9b	6.82	17	53.61	31.87	0.13	31.10	1.72	1040	7/31/01
Fork 9b	6.41	20	42.28	39.93	0.15	39.20	1.08	1200	8/15/01
Fork 9b	22.10	18	45.44	38.16	0.49	37.20	1.22	1340	9/26/01
Fork 9c	57.25	22	54.39	41.57	1.05	40.70	1.34	1240	5/24/01
Fork 9c	25.89	17	44.83	38.99	0.58	38.50	1.16	1750	6/25/01
Fork 9c	14.25	20	34.58	37.36	0.41	36.90	0.94	1555	7/31/01
Fork 9c	9.84	19	39.03	37.26	0.25	36.60	1.07	830	8/16/01
Fork 9c	25.72	22	41.75	40.15	0.62	39.50	1.06	1235	9/26/01
Fork 9d	26.59	18	42.39	34.96	0.63	34.40	1.23	1850	6/25/01
Fork 9d	14.31	21	22.53	38.22	0.63	38.00	0.59	1645	7/31/01
Fork 9d	10.09	18	18.62	35.92	0.54	35.60	0.52	1210	8/16/01
Fork 9d	27.28	22	25.04	41.68	1.09	41.50	0.60	1205	9/26/01
Willapa 10	17.18	21	175.37	58.70	0.10	55.00	3.19	1025	7/31/01
Willapa 10	13.45	20	162.16	55.98	0.08	52.60	3.08	1015	9/28/01
Willapa 11	15.07	18	42.18	26.24	0.36	24.90	1.69	1330	7/31/01
Willapa 11	15.94	29	36.69	29.10	0.43	27.30	1.34	930	9/28/01
Halfmoon 12	7.75	16	4.42	14.56	1.75	14.40	0.31	1355	5/24/01
Halfmoon 12	2.65	13	3.44	12.10	0.77	12.00	0.29	1745	6/26/01
Halfmoon 12	0.83	17	2.57	8.41	0.32	8.00	0.32	1241	7/31/01
Halfmoon 12	0.52	18	2.32	8.91	0.22	8.80	0.26	750	9/14/01
Halfmoon 12	1.30	23	2.65	10.76	0.49	10.70	0.25	1730	9/27/01
Willapa 13	73.69	22	44.18	58.00	1.67	57.50	0.77	1340	5/23/01
Willapa 13	27.04	21	48.55	54.71	0.56	54.40	0.89	1655	6/26/01
Willapa 13	15.61	19	51.65	53.26	0.30	52.90	0.98	1151	7/31/01
Willapa 13	6.94	18	47.42	52.50	0.15	52.30	0.91	1530	8/14/01
Willapa 13	14.04	21	46.89	53.57	0.30	53.20	0.88	915	9/28/01
Fern 14	11.50	15	14.48	14.66	0.79	14.00	1.03	1250	5/23/01
Fern 14	3.64	14	6.00	11.06	0.61	10.70	0.56	1630	6/26/01
Fern 14	1.66	15	5.50	12.05	0.30	11.80	0.47	1117	7/31/01
Fern 14	1.17	18	2.53	9.19	0.46	9.00	0.28	1500	9/11/01
Fern 14	2.35	18	5.86	9.30	0.40	8.50	0.69	1708	9/27/01
Willapa 15	58.81	19	19.79	34.62	2.97	34.20	0.58	1140	5/23/01
Willapa 15	19.30	24	16.27	38.48	1.19	38.40	0.42	1600	6/26/01
Willapa 15	13.95	18	9.91	34.26	1.41	34.20	0.29	1045	7/31/01
Willapa 15	6.45	14	12.57	19.26	0.51	18.90	0.66	1250	8/14/01

Station	Flow (Q) (cfs)	Number of velocity readings	Channel Area (sq ft)	Wetted Perimeter (feet)	Average Velocity (fps)	Wetted Width (feet)	Average Depth (feet)	Time	Date
Willapa 15	11.67	18	23.37	22.97	0.50	22.60	1.03	850	9/28/01
Falls 16	24.59	17	12.29	30.47	2.00	30.20	0.41	1030	5/23/01
Falls 16	7.98	21	17.39	38.02	0.46	37.30	0.47	1525	6/26/01
Falls 16	7.61	18	4.04	9.12	1.88	8.80	0.46	1005	7/31/01
Falls 16	6.61	19	4.67	10.44	1.42	10.20	0.46	1330	9/11/01
Falls 16	6.80	18	21.43	30.55	0.32	30.30	0.71	1620	9/27/01
Willapa 17	20.31	19	16.93	26.74	1.20	26.30	0.64	925	5/23/01
Willapa 17	8.24	19	10.80	16.65	0.76	16.30	0.66	1420	6/26/01
Willapa 17	4.87	16	8.79	15.69	0.55	15.40	0.57	924	7/31/01
Willapa 17	4.22	18	9.78	17.01	0.43	16.70	0.59	913	9/11/01
Willapa 17	4.31	15	6.44	13.13	0.67	12.70	0.51	815	9/28/01
Mill 18	19.00	16	20.19	28.79	0.94	28.60	0.71	1200	5/31/01
Mill 18	14.31	14	17.35	28.82	0.82	28.50	0.61	1040	6/26/01
Mill 18	9.56	15	16.23	27.83	0.59	27.70	0.59	1200	7/31/01
Mill 18	4.62	13	13.64	25.56	0.34	25.40	0.54	800	8/15/01
Mill 18	4.25	21	18.50	28.68	0.23	28.50	0.65	1040	9/24/01
Mill 18	9.07	16	21.21	29.37	0.43	29.20	0.73	1540	9/27/01
Mill 19	28.16	17	21.71	30.69	1.30	30.20	0.72	1410	5/22/01
Mill 19	12.75	17	13.91	24.14	0.92	23.90	0.58	945	6/26/01
Mill 19	7.17	22	12.33	22.39	0.58	22.20	0.56	1135	7/31/01
Mill 19	4.99	15	9.96	20.15	0.50	20.00	0.50	1515	9/10/01
Mill 19	7.61	17	12.74	22.40	0.60	22.20	0.57	1245	9/27/01
Mill 20	24.79	17	14.77	22.11	1.68	21.90	0.67	1305	5/22/01
Mill 20	11.04	14	12.42	18.41	0.89	18.10	0.69	925	6/26/01
Mill 20	7.06	18	6.15	18.10	1.15	18.00	0.34	1210	7/31/01
Mill 20	4.37	16	9.86	22.10	0.44	21.90	0.45	1105	9/10/01
Mill 20	7.46	19	11.56	17.67	0.65	17.30	0.67	1200	9/27/01
Mill 21	14.76	22	16.66	42.08	0.89	42.00	0.40	1205	5/22/01
Mill 21	7.58	17	12.34	39.56	0.61	39.50	0.31	850	6/26/01
Mill 21	4.81	20	12.14	39.06	0.40	39.00	0.31	1253	7/31/01
Mill 21	3.96	16	22.76	22.47	0.17	21.80	1.04	950	9/10/01
Mill 21	6.37	19	28.02	23.05	0.23	22.30	1.26	800	9/27/01
SF 22	124.57	19	57.94	49.44	2.15	48.90	1.18	1910	5/22/01
SF 22	73.63	20	57.14	49.92	1.29	49.30	1.16	1700	6/27/01
SF 22	37.54	24	50.01	46.03	0.75	45.60	1.10	1415	7/31/01
SF 22	32.81	16	58.44	47.22	0.56	46.90	1.25	1340	8/17/01
SF 22	29.63	17	54.22	45.20	0.55	44.90	1.21	1836	9/24/01
SF 22	33.94	18	60.26	47.40	0.56	47.00	1.28	1755	9/26/01
SF 23	67.64	22	54.37	41.39	1.24	40.50	1.34	1830	5/31/01
SF 23	59.87	18	53.11	41.47	1.13	40.40	1.31	1430	6/27/01
SF 23	31.47	21	43.04	40.01	0.73	39.20	1.10	1830	7/31/01
SF 23	27.85	14	28.72	38.84	0.97	38.70	0.74	800	8/17/01
SF 23	36.92	21	44.59	38.56	0.83	37.70	1.18	1725	9/26/01
Rue 24	23.54	15	15.52	20.35	1.52	20.10	0.77	1630	5/22/01
Rue 24	14.31	17	10.74	24.72	1.33	24.60	0.44	1350	6/27/01
Rue 24	7.55	24	7.69	23.70	0.98	23.60	0.33	1640	7/31/01
Rue 24	5.30	20	4.23	10.29	1.25	10.00	0.42	1220	8/17/01

Station	Flow (Q) (cfs)	Number of velocity readings	Channel Area (sq ft)	Wetted Perimeter (feet)	Average Velocity (fps)	Wetted Width (feet)	Average Depth (feet)	Time	Date
Rue 24	6.71	19	9.83	17.75	0.68	17.60	0.56	1620	9/26/01
SF 25	64.10	17	47.88	46.81	1.34	46.50	1.03	1745	5/22/01
SF 25	38.95	23	33.80	44.55	1.15	44.30	0.76	1520	6/27/01
SF 25	21.49	17	26.67	43.63	0.81	43.40	0.61	1555	7/31/01
SF 25	19.36	16	26.76	43.48	0.72	43.30	0.62	1120	8/17/01
SF 25	29.51	19	32.17	45.42	0.92	45.20	0.71	1650	9/26/01
Ward 27b	35.80	17	36.42	23.90	0.98	23.10	1.58	1835	6/27/01
Ward 27b	7.00	18	13.93	18.32	0.50	17.80	0.78	840	7/31/01
Ward 27b	5.70	19	16.53	19.38	0.35	18.90	0.87	1440	9/13/01
Ward 27b	5.69	15	19.28	19.71	0.30	19.20	1.00	1000	9/26/01
Wilson 29	29.65	21	13.83	20.18	2.14	19.90	0.69	1115	6/25/01
Wilson 29	13.07	20	7.66	18.91	1.71	18.80	0.41	945	7/31/01
Wilson 29	5.88	18	6.49	16.08	0.91	15.90	0.41	930	9/14/01
Wilson 29	5.88	18	6.49	16.08	0.91	15.90	0.41	1115	9/26/01
Wilson 30	7.89	16	20.34	20.45	0.39	19.40	1.05	1200	6/25/01
Wilson 30	11.94	16	14.64	15.26	0.82	18.80	0.78	1035	7/31/01
Wilson 30	5.22	17	11.34	15.73	0.46	15.30	0.74	1745	9/13/01
Wilson 30	7.11	16	11.03	14.80	0.64	14.50	0.76	1030	9/26/01

Appendix C

Channel geometry and substrate summary from stream surveys in the Willapa River basin

Table C-1. Channel Geometry Summary.

Data from shaded surveys below may not be representative of a typical reach because of a low number of transects measured or because of issues described under * and ** below.

site	Wetted width (ft)	Bankfull width (ft)	NSDZ (ft)	Wetted depth (ft)	Bankfull depth (ft)	Number of transects averaged
1	66.65	79.85	88.59	2.62	4.17	10
2	59.85	86.64		1.52	4.52	10
3	66.67	85.78	90.80	1.47	3.13	10
4	53.45	87.84	99.90	1.66	3.16	10
5	11.50	22.00	22.00	0.31	1.33	1
6	78.32	91.02	112.29	1.26	2.91	10
7	31.88	51.04	71.78	0.71	1.77	10
7a	21.20	36.40	57.00	0.88	1.46	1
8	52.44	86.95	91.05	0.98	2.14	10
10	51.16	54.76	57.88	3.67	4.64	7
12	11.80	15.90		0.43	1.69	1
13	38.12	45.81	55.16	1.20	2.89	10
14	9.00	12.00	32.00	0.28	1.34	1
15	28.36	46.24	58.48	1.15	2.27	9
16	36.50	38.70	36.00	0.54	1.58	1
17	18.64	33.34	35.21	0.38	1.58	10
18	32.54	41.73	47.84	0.87	2.56	10
19	30.44	40.04	50.32	0.55	2.31	10
20	29.37	44.21	51.90	0.66	2.37	10
21	30.45	40.20	47.16	1.49	2.79	10*
9a	28.26	55.92	92.52	0.69	2.20	10**
9b	36.18	69.41	93.10	0.69	2.12	10
9c	38.69	63.10	73.96	0.68	2.37	10
9d	48.48	62.07	65.65	0.94	2.23	10
22	42.89	52.64	75.20	1.41	2.81	10
23	46.29	60.00	64.67	1.30	2.46	10
24	10.00	25.20	41.50	0.42	1.69	1
25	31.75	47.64	61.95	0.84	2.07	10
27	22.50	26.50	28.50	3.19	3.76	1
29	28.12	35.53	47.68	1.36	2.63	10
30	15.30	21.00		0.74	1.77	1
27b	25.07	30.78	34.24	0.79	2.65	10

* - beaver dam series

** - some bank hardening near hatchery

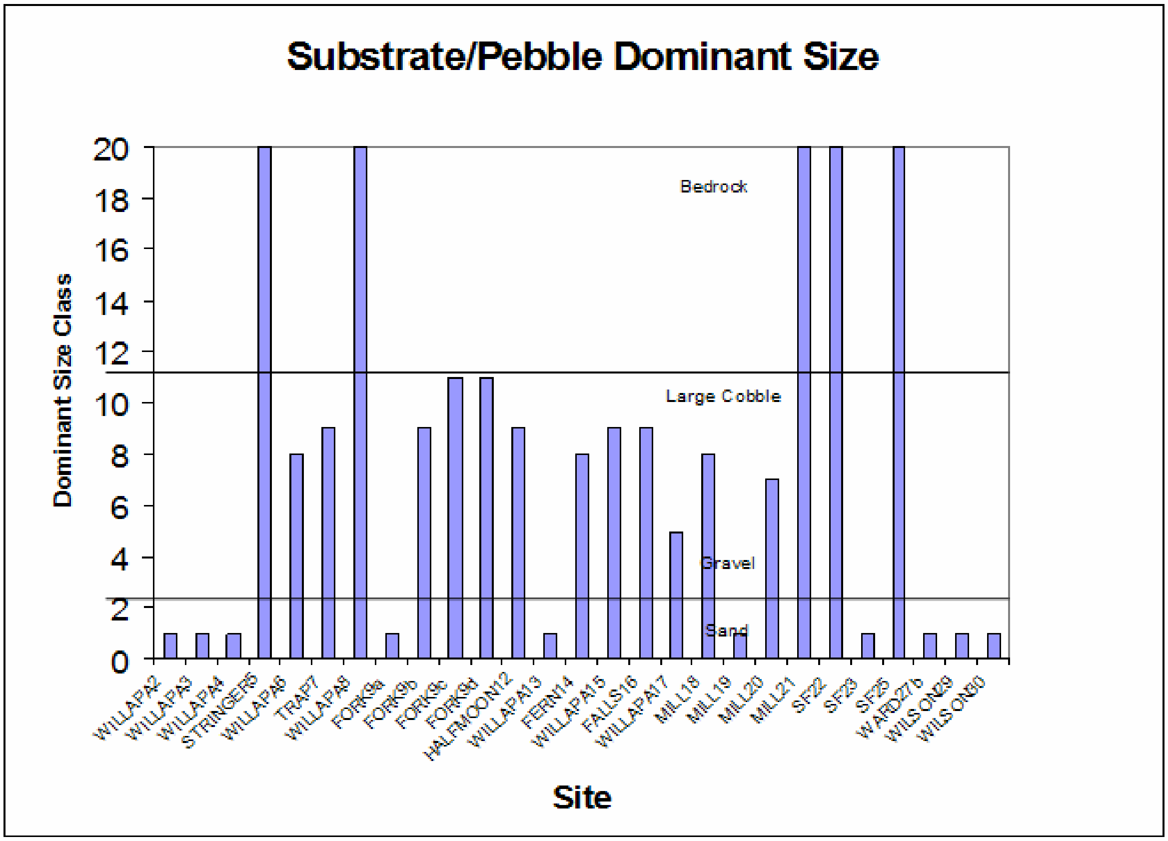


Figure C-1. Wolman Pebble Dominant Size Class Data.

Appendix D
Willapa River groundwater temperature assessment

This appendix contains the groundwater temperature results table and a summary of findings from Denis Erickson's memorandum of November 5, 2001. The complete text of the memorandum is available upon request from the author of this TMDL report.

Sample results and summary statistics are listed in Table D-1. Well water temperatures ranged from 10.1 to 13.1°C with a mean of 11.3°C. Temperatures show little variability but, in general, lower temperatures appear to occur in the uplands, and higher temperatures occur in the lower valleys. The 13.1°C temperature appears to be an outlier. The water system for that well has a filter but reportedly does not have a treatment system.

Table D-1. Sample Results and Summary Statistics.

Well ID	Temperature (°C)	pH (Std Units)	Specific Conductance (µmhos/cm)
Mainstem Willapa			
13/7-33R1	11.7	4.9	72
13/7-33R2	11.1	5.4	63
13/7-33Q	11.1	7.0	197
13/7-33D	10.4	7.0	307
13/7-32M	11.2	8.1	75
12/7-06L	11.3	8.4	270
12/8-01C	11.5	7.8	480
13/8-36D	10.1	8.0	200
13/8-36B	11.6	9.3	71
South Fork Willapa			
13/8-16H	11.4	8.3	305
13/8-09M	11.5	7.0	78
13/8-08G	13.1	8.3	520
14/8-32G	10.7	6.4	170
Mean=	11.3		216
Median=	11.3		197
Minimum=	10.1	4.9	63
Maximum=	13.1	9.3	520
Standard Deviation=	0.72		155
Number of Samples=	13	13	13

The pH ranged from 4.9 to 9.3. Alkaline pHs (pHs >7) in groundwater are somewhat unusual for western Washington State, but in this case are probably related to the presence of carbonate minerals associated with the sedimentary rocks in which the wells were completed. Specific conductance ranged from 63 to 520 µmhos/cm, with a mean of 216 µmhos/cm.

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Appendix E

Load allocations for effective shade for the Willapa River watershed

Table E-1. Load allocations for effective shade in the mainstem Willapa River.

Distance from Patton Creek confluence to upstream segment boundary (Km)	Distance from Patton Creek confluence 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)	Percent effective shade increase required over current conditions	Landmark/ Tributary Name
0	0	96%	13	2.4%	
0.00	0.30	96%	13	0.5%	Patton Creek
0.30	0.61	93%	20	0.0%	
0.61	0.91	94%	18	0.0%	
0.91	1.22	94%	17	9.5%	
1.22	1.52	94%	19	59.3%	
1.52	1.83	94%	18	42.6%	
1.83	2.13	92%	24	75.6%	
2.13	2.44	93%	22	9.8%	
2.44	2.74	93%	22	37.9%	
2.74	3.05	93%	22	65.5%	
3.05	3.35	93%	22	58.4%	
3.35	3.66	92%	24	93.1%	
3.66	3.96	93%	21	33.7%	
3.96	4.27	91%	27	84.7%	
4.27	4.57	92%	25	21.5%	
4.57	4.88	92%	23	35.2%	
4.88	5.18	91%	26	5.1%	
5.18	5.49	91%	26	55.2%	
5.49	5.79	91%	28	95.3%	
5.79	6.10	92%	24	33.6%	
6.10	6.40	91%	28	72.7%	
6.40	6.71	91%	28	66.1%	Falls Creek
6.71	7.01	87%	41	61.7%	
7.01	7.32	86%	43	41.1%	
7.32	7.62	86%	43	0.0%	
7.62	7.92	88%	36	15.9%	
7.92	8.23	87%	40	61.9%	
8.23	8.53	87%	41	54.0%	
8.53	8.84	82%	56	70.0%	
8.84	9.14	82%	54	77.8%	Fern Creek
9.14	9.45	81%	58	55.8%	
9.45	9.75	77%	68	78.0%	
9.75	10.06	82%	56	69.0%	
10.06	10.36	81%	56	55.3%	

Distance from Patton Creek confluence to upstream segment boundary (Km)	Distance from Patton Creek confluence 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)	Percent effective shade increase required over current conditions	Landmark/ Tributary Name
10.36	10.67	81%	59	61.5%	
10.67	10.97	79%	64	48.3%	
10.97	11.28	79%	63	24.6%	
11.28	11.58	77%	68	60.8%	
11.58	11.89	79%	62	26.8%	
11.89	12.19	79%	62	16.8%	
12.19	12.50	80%	60	33.4%	
12.50	12.80	79%	63	62.6%	Half Moon Creek
12.80	13.11	81%	58	6.7%	
13.11	13.41	82%	55	12.4%	
13.41	13.72	76%	72	32.2%	
13.72	14.02	76%	73	66.8%	
14.02	14.33	67%	100	46.4%	
14.33	14.63	67%	99	51.2%	
14.63	14.94	75%	75	18.8%	
14.94	15.24	75%	77	38.1%	
15.24	15.54	74%	77	60.8%	
15.54	15.85	74%	78	63.1%	
15.85	16.15	75%	77	54.0%	
16.15	16.46	74%	79	17.4%	
16.46	16.76	73%	80	33.0%	
16.76	17.07	83%	51	56.1%	
17.07	17.37	78%	66	71.3%	
17.37	17.68	78%	66	70.3%	
17.68	17.98	76%	74	80.5%	
17.98	18.29	76%	74	83.9%	Doyle Road
18.29	18.59	86%	43	39.1%	
18.59	18.90	77%	71	47.5%	
18.90	19.20	77%	69	36.5%	
19.20	19.51	78%	65	34.5%	
19.51	19.81	68%	98	37.4%	Fork Creek
19.81	20.12	78%	67	13.4%	
20.12	20.42	68%	97	46.3%	
20.42	20.73	70%	92	39.9%	Trap Creek
20.73	21.03	67%	99	15.6%	
21.03	21.34	65%	104	75.5%	
21.34	21.64	66%	103	65.5%	
21.64	21.95	67%	101	41.4%	
21.95	22.25	78%	67	33.4%	
22.25	22.56	65%	105	52.9%	
22.56	22.86	67%	101	56.1%	
22.86	23.16	71%	89	40.6%	
23.16	23.47	68%	96	52.3%	
23.47	23.77	76%	73	68.5%	
23.77	24.08	74%	79	43.5%	

Distance from Patton Creek confluence to upstream segment boundary (Km)	Distance from Patton Creek confluence 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)	Percent effective shade increase required over current conditions	Landmark/ Tributary Name
24.08	24.38	76%	74	72.3%	
24.38	24.69	74%	78	80.1%	
24.69	24.99	70%	92	73.4%	
24.99	25.30	78%	65	82.6%	
25.30	25.60	68%	97	86.1%	
25.60	25.91	74%	78	93.8%	
25.91	26.21	57%	131	96.1%	
26.21	26.52	71%	88	81.1%	
26.52	26.82	80%	62	27.8%	
26.82	27.13	77%	69	21.2%	
27.13	27.43	75%	76	28.8%	Oxbow Cr.
27.43	27.74	77%	71	57.9%	
27.74	28.04	73%	81	75.5%	
28.04	28.35	76%	73	76.6%	
28.35	28.65	71%	88	71.3%	
28.65	28.96	74%	79	50.4%	
28.96	29.26	73%	82	42.7%	
29.26	29.57	72%	85	47.1%	
29.57	29.87	73%	80	60.0%	
29.87	30.18	69%	94	67.1%	
30.18	30.48	66%	101	79.7%	
30.48	30.78	67%	98	67.3%	
30.78	31.09	75%	76	54.1%	Stringer Cr.
31.09	31.39	74%	80	60.5%	
31.39	31.70	76%	73	71.9%	
31.70	32.00	68%	97	84.5%	
32.00	32.31	76%	71	66.9%	
32.31	32.61	73%	82	72.9%	
32.61	32.92	68%	97	77.0%	
32.92	33.22	65%	106	80.6%	
33.22	33.53	78%	66	67.2%	
33.53	33.83	69%	93	64.0%	
33.83	34.14	71%	89	58.0%	
34.14	34.44	65%	106	82.3%	
34.44	34.75	73%	80	66.2%	
34.75	35.05	82%	54	64.8%	
35.05	35.36	73%	81	32.0%	
35.36	35.66	72%	85	65.1%	
35.66	35.97	77%	69	78.7%	Rt 6 crossing near Menlo
35.97	36.27	79%	64	41.4%	
36.27	36.58	73%	82	32.7%	
36.58	36.88	70%	92	35.2%	
36.88	37.19	72%	84	25.9%	
37.19	37.49	70%	90	23.9%	

Distance from Patton Creek confluence to upstream segment boundary (Km)	Distance from Patton Creek confluence 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)	Percent effective shade increase required over current conditions	Landmark/ Tributary Name
37.49	37.80	73%	81	60.8%	
37.80	38.10	64%	109	84.4%	
38.10	38.40	66%	102	92.3%	
38.40	38.71	72%	85	88.1%	
38.71	39.01	62%	114	57.4%	
39.01	39.32	66%	104	42.1%	
39.32	39.62	66%	101	95.6%	
39.62	39.93	58%	127	93.0%	
39.93	40.23	64%	110	57.2%	
40.23	40.54	64%	108	94.2%	
40.54	40.84	72%	85	72.0%	
40.84	41.15	65%	104	42.3%	
41.15	41.45	62%	116	89.9%	
41.45	41.76	65%	105	89.5%	Mill Creek
41.76	42.06	65%	107	87.8%	
42.06	42.37	58%	127	85.6%	
42.37	42.67	66%	102	76.2%	
42.67	42.98	62%	116	51.9%	
42.98	43.16	67%	98	40.2%	

The line in the middle of page 130 is the division point along the mainstem between load allocations of 50-year vegetation and 100-year vegetation.

Table E-2. Load allocations for effective shade in the Fork Creek tributary to the Willapa River.

Distance from boundary condition at A-400 road to upstream segment boundary (Km)	Distance from boundary condition at A-400 road 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)	Percent effective shade increase required over current conditions	Landmark
0	0	85.3%	45	31.1%	A-400 road
0.00	0.30	82.1%	54	23.5%	
0.30	0.61	79.1%	63	15.5%	
0.61	0.91	78.8%	64	14.7%	
0.91	1.22	79.9%	61	15.7%	
1.22	1.52	80.8%	58	5.2%	
1.52	1.83	81.6%	56	2.2%	
1.83	2.13	78.2%	66	17.1%	
2.13	2.44	77.8%	67	11.7%	
2.44	2.74	81.0%	57	21.5%	
2.74	3.05	80.0%	60	18.7%	
3.05	3.35	81.4%	56	21.0%	
3.35	3.66	78.7%	65	15.0%	
3.66	3.96	78.2%	66	21.6%	
3.96	4.27	81.4%	56	56.6%	Hatchery intake and dam
4.27	4.57	75.0%	76	33.6%	
4.57	4.88	78.0%	66	33.2%	
4.88	5.18	78.7%	64	25.1%	
5.18	5.49	76.9%	70	47.2%	
5.49	5.79	73.9%	79	53.0%	
5.79	6.10	75.7%	74	56.8%	Mouth at Km 6.16

Table E-3. Load allocations for effective shade for miscellaneous perennial streams in the Willapa River watershed based on bankfull width and stream aspect.

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
1	90.0%	90.0%	90.0%	6	6	6
2	90.0%	90.0%	90.0%	6	6	6
3	90.0%	90.0%	90.0%	7	7	7
4	90.0%	90.0%	90.0%	8	8	8
5	90.0%	90.0%	90.0%	11	11	10
6	90.0%	90.0%	90.0%	14	14	12
7	90.0%	90.0%	90.0%	18	18	15
8	90.0%	90.0%	90.0%	22	22	18
9	90.0%	90.0%	90.0%	25	25	21
10	90.0%	90.0%	90.0%	29	29	24
12	89.1%	89.0%	90.0%	37	37	31
14	86.8%	86.5%	87.9%	45	46	39
16	84.5%	84.0%	84.7%	53	54	49
18	82.2%	81.5%	80.1%	61	62	62
20	79.4%	78.5%	73.3%	70	72	82
25	72.9%	71.4%	60.6%	93	97	128
30	67.5%	65.3%	51.9%	111	117	160
35	62.9%	60.0%	45.5%	127	136	183
40	58.8%	55.4%	40.6%	142	152	201