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Teanaway River Basin Temperature Pilot Technical Assessment

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Teanaway River Basin Temperature Pilot Technical Assessment

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by
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Water Body Numbers (see Table 1)

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Abstract

The Teanaway River basin drains to the upper reaches of the Yakima River on the east slope of the Cascade mountain range. The basin experiences high stream temperatures detrimental to threatened salmonids. This report summarizes an approach for developing a temperature Total Maximum Daily Load (TMDL), applied on a pilot basis to the Teanaway River basin. The project objectives were to (1) determine potential solutions to the high stream temperature problems, and (2) pilot the use of Geographic Information System techniques for more effective collection and analysis of temperature data.

Continuous water temperature data gathered from July 1 to October 8, 1998 show that the middle and lower basin exceeds the 18ºC water quality standard in over 75% of the days monitored. Analysis and stream temperature modeling with Stream Segment Temperature Model (SSTEMP) show that improvements in riparian shade, active channel width, and flow can lower these temperatures. Estimates made with the best available data are that a 1.5ºC to 3ºC reduction in mean daily water temperature could be realized with a mature riparian buffer, sediment controls for roads, and streamflow increases. The reduction in maximum daily water temperature would be approximately 3ºC to 6ºC under the most favorable simulated conditions. These estimates are made for a *critical condition*, which for stream temperature is a time of low flow and high air temperature.

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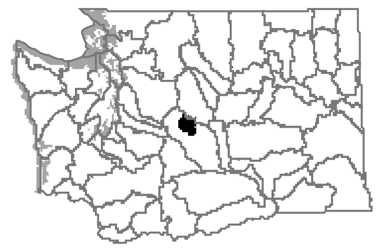
Executive Summary

Teanaway River Sub-basin at a Glance

Basin: Upper Yakima
Sub-basin: Teanaway
Key Impaired Resources: Chinook Salmon
Resident Rainbow Trout
Steelhead Trout
Uses Affected: Salmonid Fish Spawning and Rearing
Type of Impairment: Water Temperature Increases
Pollutant: Heat (Solar Radiation)



Technical Assessment Summary

This report summarizes an approach for developing a temperature Total Maximum Daily Load (TMDL), applied on a pilot basis to the Teanaway River basin. When a stream surface is exposed to midday solar radiation, large quantities of heat are delivered to the stream system (Brown, 1969, Beschta et al., 1987). When shaded throughout the entire duration of the daily solar cycle, far less heat energy is transferred to the stream. The assessment is designed to (1) address impairments due to surface water temperature increases on eight water quality-limited stream segments located in the watershed and (2) provide goals for protection of all remaining streams. Streamside shade is used as a surrogate to address these water temperature increases as allowed per federal regulations.

Analysis and stream temperature modeling with the Stream Segment Temperature Model (SSTEMP) show that increases in riparian shade, reduction in active channel width, and increases in streamflow can lower stream temperatures. Estimates made with the best available data are that a 1.5ºC to 3ºC reduction in mean daily water temperature could be realized with a mature riparian buffer, sediment controls for roads, and streamflow increases. The reduction in maximum daily water temperature would be approximately 3ºC to 6ºC under the most favorable simulated conditions. These estimates are made for a *critical condition*, which for stream temperature is a time of low flow and high air temperature. The summer of 1998 had good conditions for a critical analysis.

At critical low-flow and high-temperature conditions, establishment of a full mature riparian stream corridor will result in shading that produces a 35-62% reduction in solar radiation load. This solar load reduction correlates to an estimated 1.5ºC reduction in mean daily temperature and a 3ºC reduction in maximum daily temperature. Sediment load reductions resulting from an established mature riparian corridor and improved road maintenance, as recommended in the North Fork and West Fork Teanaway Watershed Analysis Reports, are estimated to reduce the width of in the active channel zone and the channel width-to-depth ratio. An additional 10% reduction in solar radiation load, and a 0.5ºC reduction in mean daily temperature (0.5ºC to 1ºC reduction in the maximum daily temperature), are expected to be realized through sediment control. Doubling the flow in the lower segment of the North Fork from 20 to 40 cubic feet per second (cfs) and in the mainstem from 27 to 50 cfs, using existing riparian shade, decreases the mean daily temperature by 1ºC (and the maximum daily temperature by 2ºC).

In addition to providing shading, a mature riparian corridor is expected to allow growth of vegetation that can stabilize the bank during high flows, dissipate stream energy, and reduce the amount of bank cutting. It is also expected that restricting the access of cattle and other animals to the stream will be necessary to encourage riparian growth and thus reduce damage to banks. There are additional unquantifiable benefits to stream temperature that have not been addressed in this study, but are possible as a mature riparian buffer becomes established. Some of these are:

- Increase of large woody debris to the stream – providing salmon habitat, pool-forming, and sediment-trapping.
- Additional support for smaller vegetation – providing stream shading.
- Gravel bed shading – resulting in cooler conditions for water moving under or through those gravels.
- Cooling of ambient air temperature (because air temperature under a mature canopy is usually lower than that over bare or sparsely covered ground) – causing a further reduction in heat transfer to the stream.

Long-term monitoring would be required to determine actual temperature reductions realized.

When natural conditions exceed the numeric water temperature standards of 16ºC for Class AA streams and 18ºC for Class A streams, no temperature increase will be allowed which will raise the water temperature by greater than 0.3ºC (Chapter 173-201A WAC). Because of the unquantifiable benefits described above and the uncertainty associated with any model, this study does not attempt to specify what stream temperatures constitute *natural conditions*. Natural conditions in the Washington State water quality standards means conditions prior to human influence. Stream temperature is determined by a complex interaction of external influences and stream specific, internal hydrologic processes (Poole and Berman, 2000). The modeling approach used in the Teanaway Temperature TMDL analyses considers some of these factors, but available information is insufficient to estimate what temperatures may have existed in this watershed prior to anthropogenic influences.

The intent of this pilot approach is to identify some of the major human impacts on stream temperature, in the hope of identifying actions that can help the stream temperature more closely approach natural temperatures. Some areas of the watershed that have not been heavily harvested and do not contain roads, specifically the upper Middle Fork of the Teanaway, may already be approaching their natural condition. Further monitoring upstream of human impacts would be necessary to make this determination.

Because a larger volume of water cannot be heated as quickly as a smaller one, and because a larger volume can assimilate more heat load for the same rise in temperature as a smaller one, it is important to continue water right buyback efforts in the basin. It is also important to be aware of the negative impacts of withdrawing groundwater that potentially could cool the stream during summer months.

The five elements of a TMDL, as required by federal statute and regulation, are summarized below:

1. Loading capacity

The loading capacity is determined specifically for the eight streams on the 303(d) list located in this basin and generally for the remaining perennial streams based on Rosgen channel type. In most cases, the achievable shade was less than the total shade needed to meet the State's surface water quality temperature criteria. Therefore, the loading capacity is based on the estimated shade that would be provided by a mature riparian forest. For segments determined to have a high stream width-to-depth ratio, the loading capacity is determined using a mature riparian forest and a 30% reduction in the width of the active channel zone. The solar radiation loading capacities generally range from 93-189 joules per square meter of water surface area per second.

2. Wasteload allocation

Since there are no permitted thermal discharges within the Teanaway River basin, the wasteload allocation for solar radiation is zero.

3. Load allocations

Allocations are summarized using riparian shade as a surrogate for solar radiation. The allocations range from 33% shade for the segment above 3,500 feet in elevation and 52% shade (154 $j/m^2/s$) to 71% shade (93 $j/m^2/s$) for the remaining segments. Shade allocations in stream segments that do not meet the numeric 16°C or 18°C standards for the critical conditions modeled are generally calculated using site potential size trees growing at the edge of the active channel zone and setting the stream azimuth equal to the average for that segment.

4. Margin of safety

The margin of safety is implicit by using an extreme climatic condition in the modeling analysis. Climatic conditions measured on July 28, 1998 were used in this analysis. The air temperature measured on this day is the 95^{th} percentile of maximum July and August air temperatures in Cle Elum, Washington.

5. Seasonal variation

Monitoring data show that the majority of temperature measurements exceeding the criteria occur in July and August. Since it is not possible to change allocations of shade over a season, they were set based on this critical summer period. The modeling analysis used climatic conditions collected on July 28, which was the high for both air and water temperatures during 1998.

Pilot Techniques Summary

The Teanaway temperature assessment provided the opportunity to develop and apply landscape evaluation techniques in an area where field data were being collected. Many future TMDL studies will occur in areas where few data are available. Monitoring segments were selected based on geology, soils, slope, land use, and tributary confluence as identified in Geographic Information System (GIS) coverages and aerial photos. Protocols established for the Wenatchee National Forest study and approved by EPA were followed for thermograph and field data collection. This data collection included channel morphology, slope, flow, riparian shade, primary riparian species, and air and water temperatures. Rosgen (level 2) channel type was identified and used to define primary model segments. SSTEMP, a U.S. Geological Survey (USGS) Biological Resources Division stream segment temperature modeling software, was employed to evaluate riparian shade, channel width/depth characteristics, and some streamflow and groundwater effects on stream temperature. Further streamflow and groundwater information was evaluated using the USGS Hydrograph Separation (HYSEP) model.

Rosgen classification

Because the Rosgen classification is based primarily on slope, geology and channel confinement, the GIS techniques proved to be very successful in delineating monitoring segments that complied with this classification. The SSTEMP A and B channel terms and the Manning's n term were independently calculated, when possible, for each monitoring reach. The resulting values showed that that the B channel term and Manning's n should be kept constant within a Rosgen stream type in this basin.

Aerial photos and shade

Timber, Fish and Wildlife (TFW) protocols for estimating riparian shade from aerial photos (Washington DNR, 1997) produced similar estimates to those gathered in the field with a densiometer. The goal of the aerial photo protocol is to place segments into general shade percentile categories of 0-20%, 20-40%, 40-70%, and 70-90%. These categories may be sufficient in some water quality studies, especially if there is a large discrepancy between the existing condition and the desired condition. A process under development using digital orthophotos to assess current riparian shade holds promise but has not been fully analyzed.

Some map-collected and field-collected variables were compared. As expected, stream surface slope, stream aspect, and location coordinates can be collected from maps as well as they can in the field. Channel width and depth information and entrenchment values from temperature limited streams should be collected in the field as necessary.

A GIS tool using Digital Elevation Model (DEM) data, sub-basin area, and average precipitation data was successful in helping explain streamflow in the basin.

Introduction

Objectives

The objectives of this study were to:

- Evaluate the causes and extent of stream temperature heating in the Teanaway River basin.
- Incorporate the use of spatial analysis and landscape methods in the evaluation of stream temperature factors in the Teanaway River basin

There is great interest in developing methods for assessing water quality conditions using the large quantities of land-based information that are becoming available through aerial photos, satellite remote sensing, and Geographic Information System (GIS) layer development. This land-based information is suited to non-point source Total Maximum Daily Loads (TMDLs). This study combines both map and field collected data to evaluate stream temperatures. The intent was to determine which data pieces can successfully be gathered from readily available GIS coverages and photos, and which need to be collected in the field.

This study was undertaken through cooperation with the U.S. Environmental Protection Agency (EPA) Region 10 and the Wenatchee National Forest. EPA provided partial funding to this project for piloting landscape temperature TMDL methods. Because the U.S. Forest Service (USFS) had initiated a large stream temperature collection project for the summer of 1998, Ecology cooperated by following their EPA-approved data collection protocols and by providing Ecology data to the USFS. This allows Ecology's Teanaway data to be incorporated into the USFS study, and should facilitate Ecology's use of data collected by the USFS in other Wenatchee National Forest watersheds.

Land Use and Basin Characterization

The Teanaway River basin drains an area of 207 square miles and is located east of the Cascade crest near the town of Cle Elum, Washington. The Teanaway, considered a 5^{th} code Hydrologic Unit (HUC) by EPA, lies in the upper reaches of the larger Yakima River watershed. Topography and location of this Kittitas County watershed are displayed in Figure 1.

The climate consists of warm, dry summers and cold, snowy winters. Annual precipitation ranges from 20 inches near the mouth of the Teanaway River (elevation 1,800 feet) to 90 inches in the high mountains (elevation 6,000 feet). Peak runoff events are of two kinds: rain-on-snow precipitation events between November and February, and high flows associated with spring snowmelt in April and May (NFTWA, 1996). Streamflow information is available for the U.S. Bureau of Reclamation (USBR) gage located on the Teanaway River below the confluence of the three major forks. The gage is upstream of major irrigation diversions, and drains approximately 172 square miles. The 1971 - 1998 period of records show a peak flow of 8,000 cfs and a low flow of 6 cfs, with an average annual peak of 1000 cfs and an average annual 7-day low of 15 cfs.

Major land uses (Figure 2) and ownership can generally be described by dividing the watershed into thirds. The upper one-third of the watershed lies in the Wenatchee National Forest and is managed by the USFS. Much of the middle one-third of the watershed is owned and managed by private timber companies, with land adjacent to the Middle and North forks often in light agricultural or range land. The lower one-third of the watershed, below the West, Middle, and North forks, contains hay, feed crops, and horses near the mainstem, and timber management in the surrounding hills.

Forestry practices

Plummer (1902) describes the Teanaway River basin as dominated by yellow pine and red fir. All of the forest stands in the Teanaway basin below the USFS boundary have been harvested at least once and many areas have been logged two or three times since 1903 (NFTWA, 1996). Past logging practices have included the use of splash dams and the construction of railroads parallel to or in the streambeds themselves. Timber owners in the basin at the time of this study were Boise-Cascade and Plum Creek Timber companies (NFTWA, 1996).

Agriculture and range land

The Teanaway River basin has been used for agriculture since the early 1900s. Beginning in 1920, Cascade Lumber leased land for cattle and sheep in the North Fork Teanaway basin. The cattle herd ranged from 400 to several thousand through 1993. Today approximately 230 head of cattle are raised in the North Fork basin, with a small number of additional cattle grazing in the West Fork basin. Feed crops and hay are grown adjacent to the Teanaway River and its tributaries. Domestic water use is supplied by wells, and irrigation is provided by surface water withdrawals.

Fish

Anadromous species that occur in the basin include spring-run chinook salmon (*Oncorhynchus tshawytscha*) and steelhead trout (*O. mykiss*). Resident species include brook trout (*Salvelinus fontinalis*), rainbow trout (*O. mykiss*), cutthroat trout (*O. clarki*), and bull trout (*S. confluentus*). Washington Department of Fish and Wildlife (WDFW) manages the Teanaway basin primarily for anadromous species (NFTWA, 1996). The Bonneville Power Administration (BPA) is presently building ponds for chinook salmon just above the confluence with Jack Creek on the North Fork Teanaway River. The six acclimation ponds are immediately downstream of the 29 Pines Campground. Jack Creek will be the water source for this facility. Very low numbers of anadromous fish now reach the forks of the Teanaway. This facility hopes to boost these numbers.

Geology, soils, and roads

Surface erosion occurs when soil from steep slopes is exposed to precipitation, and the subsequent overland flow can detach soil particles and carry them to streams where the typically fine-grained soil has the potential to impact water quality and fish spawning habitat. Deposits

Figure 1
The Teanaway River Basin: Topography and Location

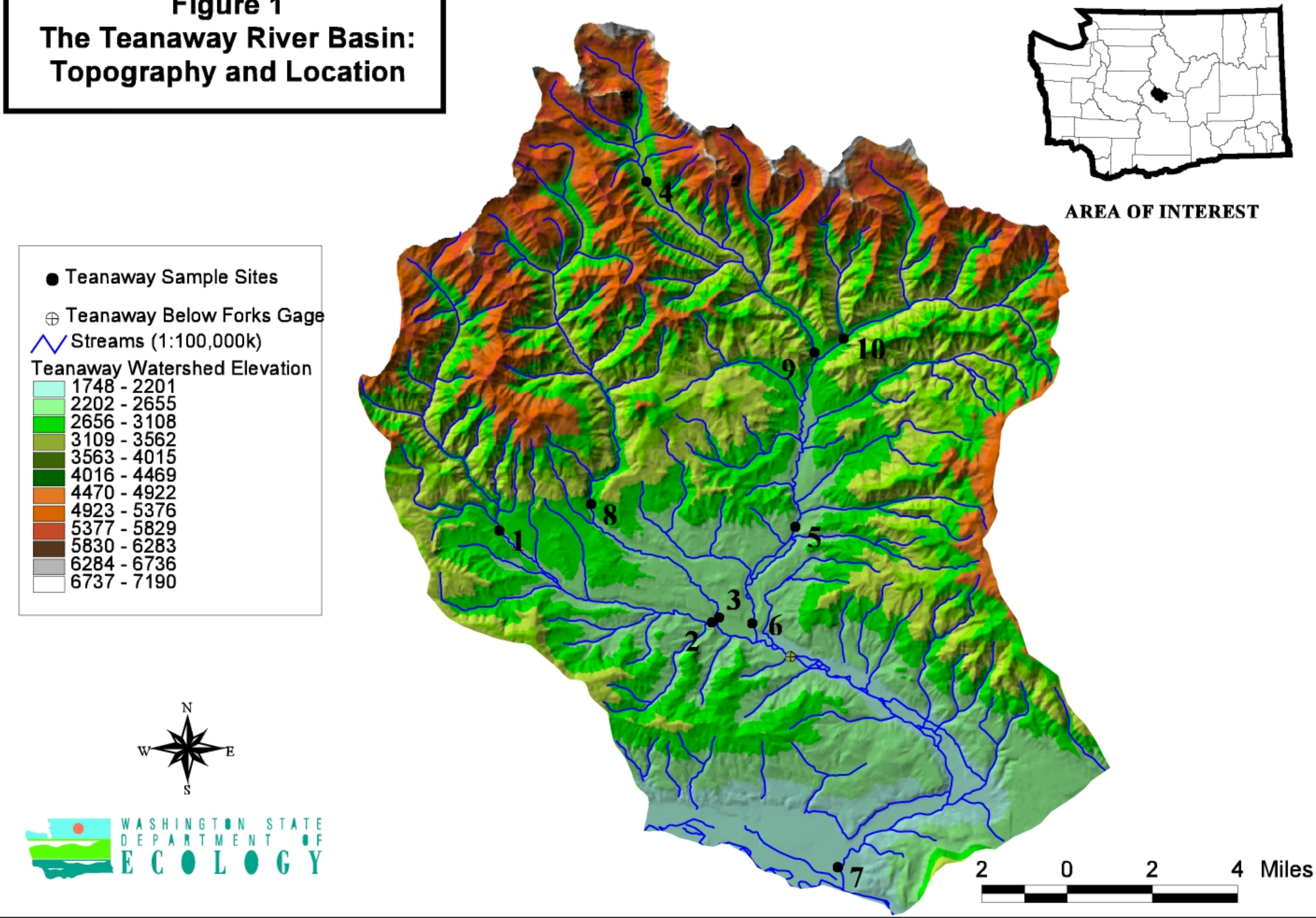


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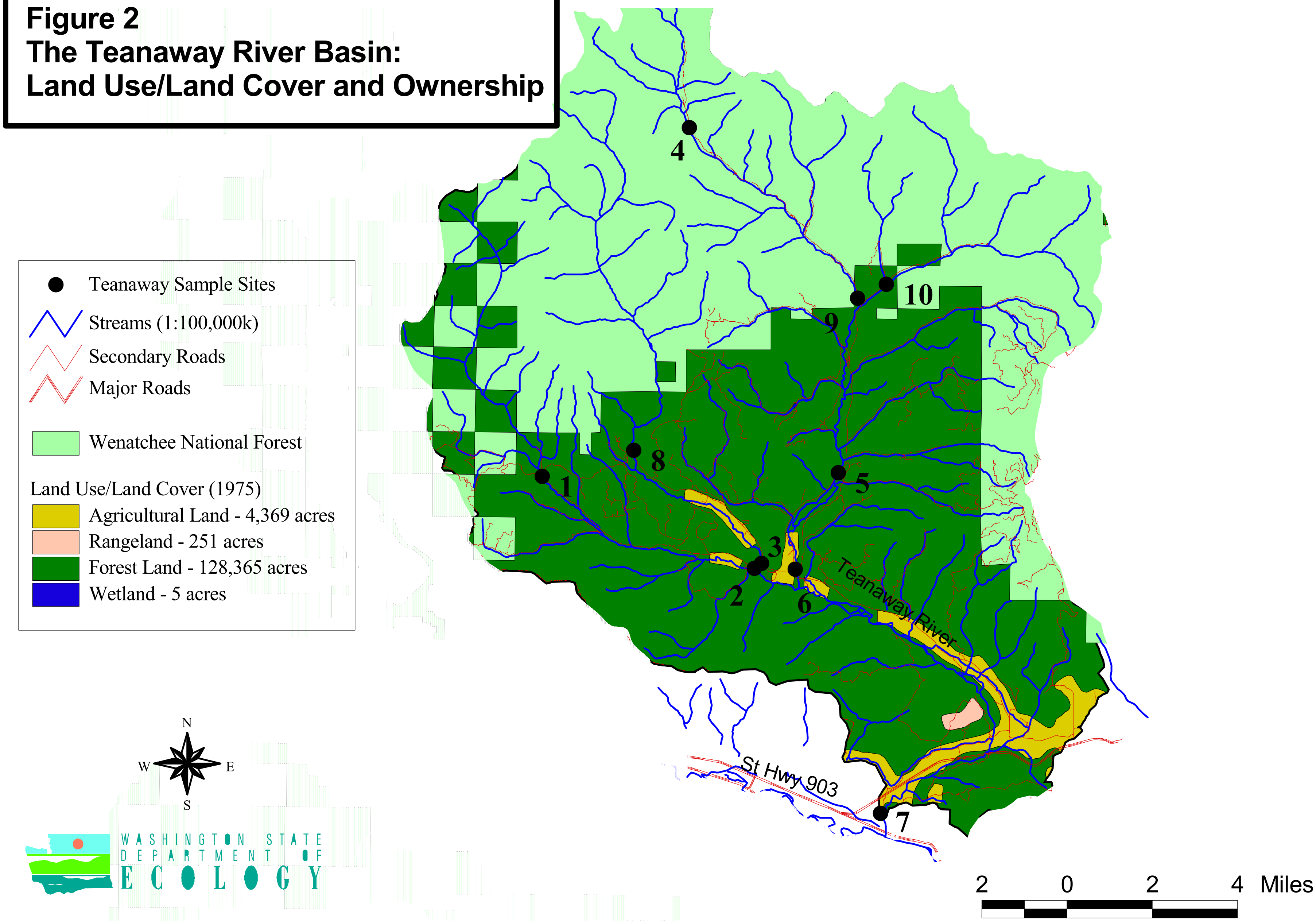
Figure 2
The Teanaway River Basin:
Land Use/Land Cover and Ownership



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of fine sediment to streams also affects stream temperature by contributing to the widening and shallowing of a stream; this makes the stream more vulnerable to heating, due to solar radiation and a larger water surface to air interface.

Sediment sources in the basin are from roads, logging and agriculture practices, landslides, and natural conditions. The North Fork Teanaway Watershed Analysis (1996) reports that, for the lower North Fork watershed, the background sediment yield is about 1,454 tons per year, of which 810 tons is fine sediment. The estimated total amount of delivered sediment from roads is approximately 4% of the estimated total background yield, and 7% of the background fine sediment yield. The West Fork Teanaway Watershed Analysis (1997) estimates a background fine sediment load of 205 tons year, and a road sediment delivery of 252 tons per year, for the lower West Fork watershed. Both the North Fork and West Fork Watershed Analysis Reports propose an increase in road maintenance, especially on unpaved roads.

Figures 3 and 4 show the geology and soil properties of the Teanaway River basin. A more detailed discussion can be found in Appendix F.

Problem Definition

The streams in the Teanaway River basin are prone to excessive heating, due to low flows, hot weather, and wide shallow streams with low riparian shade. In addition, many of the channels are scoured to bedrock substrate which tends to retain heat.

The high stream temperatures measured in the Teanaway River are detrimental to adult chinook salmon that are migrating and holding during the hot period. Hicks (1999) recommended that for chinook salmon, the upper limit of optimal temperature for juvenile rearing or adult migration was 17°C, and that the single daily maximum for adult migration was 22.5°C. At the beginning of spawning season, usually September, the temperature needs to be less than 15°C before adults will begin to spawn. By the midpoint of spawning, the 7-day average of the daily maximum temperature should be at or below 13.5°C. Juvenile chinook and steelhead rear for a minimum of one year in the system before out-migration and have summer rearing upper 7-day limits of 17°C and 16°C, respectively. Bull trout requirements for migration are similar to those for chinook but spawning, which would presumably occur in the upper watershed, requires temperatures to be at or below 7.5°C. Scouring from high winter streamflows is also detrimental to redds.

The West Fork Teanaway Causal Mechanism and Prescriptions Report (WFTWA, 1997) states for the lower West Fork Teanaway, that *"the combined effects of logging, grazing and agriculture have probably reduced the age, size and density of forest stands in and adjacent to parts of the channel migration zones, resulting in a decline in size and abundance of tree shading to the stream channels. Because channel locations have varied over time, past harvest of the CMZ has contributed to existing low shade." Because of this change in channel migration, "trees within the CMZ (or associated buffer) which do not currently provide shade to the channel may do so at some time in the future."* An increase of riparian vegetation, to provide both shade and large woody debris, is suggested in both the North Fork and West Fork Watershed Analyses.

Existing Water Quality Programs

U.S. Forest Service

The Aquatic Conservation Strategy for federal forest lands has several objectives for management of the riparian forest (USFS, 1994), two of which are:

- Maintain and restore the physical integrity of the aquatic system, including shorelines, banks, and bottom configurations.
- Maintain and restore the species composition and structural diversity of plant communities in riparian areas and wetlands to provide adequate summer and winter thermal regulation, nutrient filtering, appropriate rates of surface erosion, bank erosion, and channel migration and to supply amounts and distributions of coarse woody debris sufficient to sustain physical complexity and stability.

The Aquatic Conservation Strategy contains detailed standards for maintaining and restoring riparian reserves. As a general rule, these standards prohibit or regulate activities within the riparian reserves that retard or prevent the attainment of the objectives in the Aquatic Conservation Strategy.

Watershed analysis for forest practices

Private landowners can conduct a special watershed assessment under State rule (Chapter 222-22 WAC) to obtain relief from other requirements under the State Environmental Policy Act. In these watershed analyses, riparian conditions are assessed and specific prescriptions are established based on this assessment governing allowable forest practices. Generally, more restrictive conditions are placed on sensitive riparian areas than are allowed under standard forest practice rules. To date, watershed analyses have been completed on two sub-basins, the North Fork Teanaway River from the mouth to the junction with Stafford Creek, and the West Fork Teanaway River from the mouth to the headwaters.

Kittitas County

Kittitas County is the major local government in the Teanaway River basin.

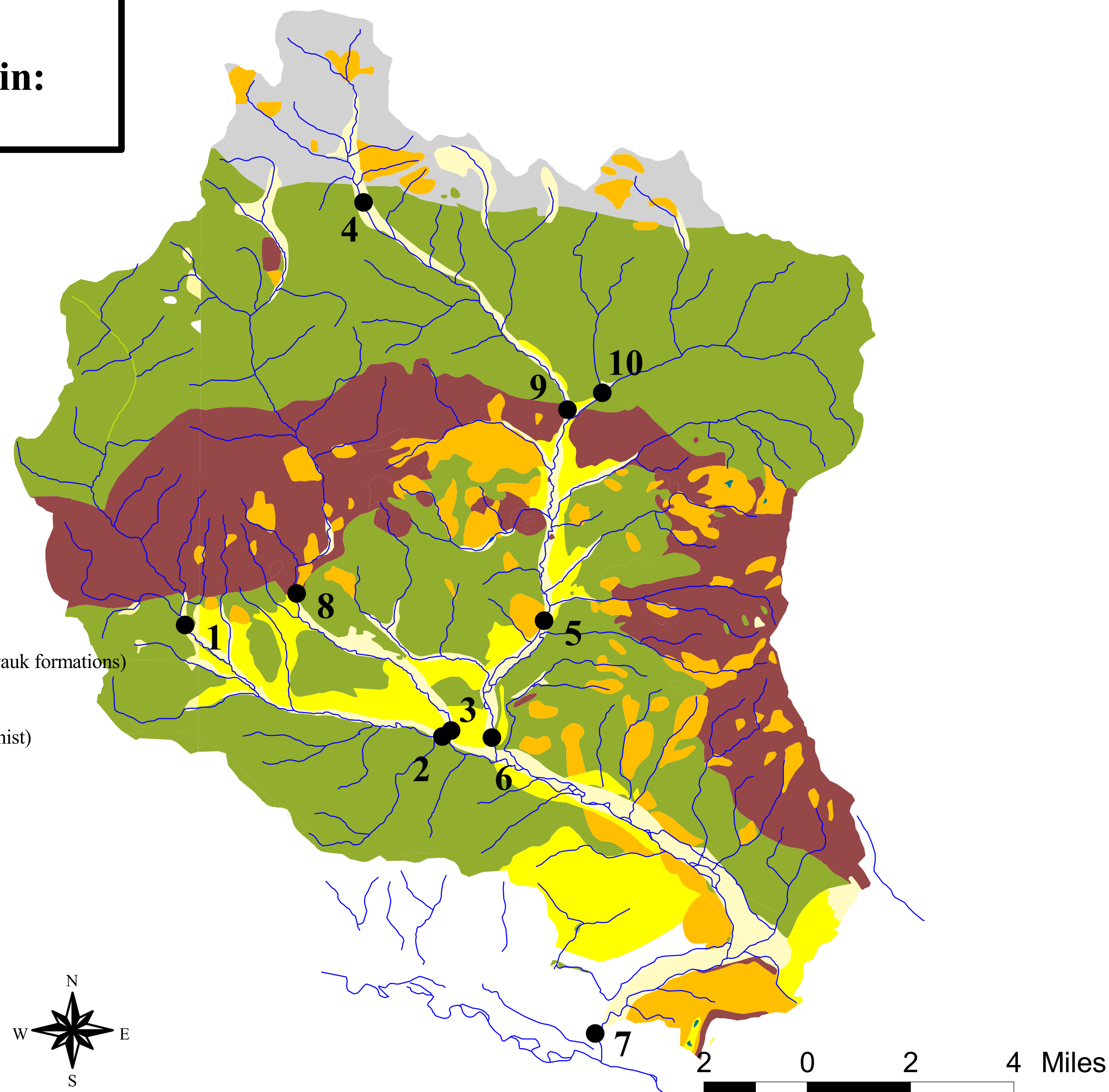
Yakama Tribe

The Yakama Tribe is interested in restoring fish runs to the upper Yakima watersheds. The Tribe has successfully initiated an instream flow project, and has been active in water temperature monitoring and habitat assessment in the basin.

U.S. Bureau of Reclamation

The U.S. Bureau of Reclamation is active in this basin with fish restoration projects, instream flow monitoring, and management of the irrigation system.

Figure 3
The Teanaway River Basin: Geology



Teanaway Sample Sites

Streams (1:100,000k)

Geology Legend

- Nonglacial Alluvium
- Sedimentary - Bedrock units (Eocene Roslyn and Swauk formations)
- Loess - Landslide deposits(silt and fine sand)
- Metamorphic (Jurassic - Mount Stewart batholith, schist)
- Alluvial outwash deposits (sand, gravel, & silt)
- Volcanic (Teanaway formation)

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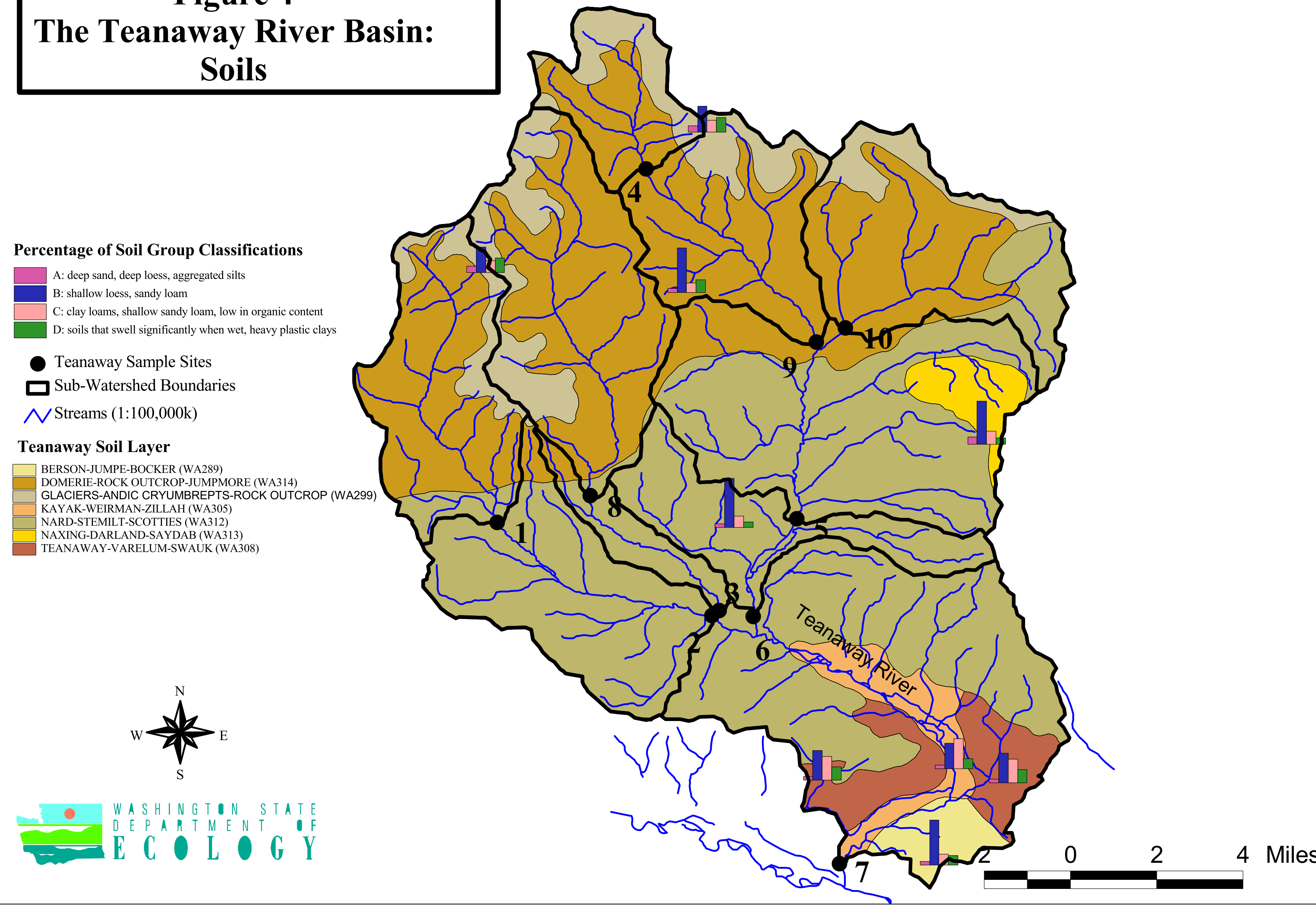
Figure 4
The Teanaway River Basin: Soils



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Applicable Water Quality Criteria

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

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

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

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 Teanaway 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 Teanaway River basin are designated as either Class AA or Class A. These classes have different temperature criteria to protect the characteristic uses.

For Class AA waters:

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

For Class A waters:

"Temperature shall not exceed 18.0°C…due to human activities. When natural conditions exceed 18.0°C…, no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3°C."

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

"Whenever the natural conditions of said waters are of a lower quality than the criteria assigned, the natural conditions shall constitute the water quality criteria."

Water Quality Impairments

As a result of data showing temperature criteria are exceeded, the segments listed in Table 1 are included on Washington State's 1998 Section 303(d) list.

Table 1. Teanaway basin section 303(d) stream segments listed for temperature

Section 303(d) Listed Segments	*Water Class*	***Water Body ID***	
		1996 ID	***1998 ID***
Mainstem Teanaway River	A	WA-39-2000	ZH39IA
Lower Middle Fork Teanaway River	A	WA-39-2200	KB710Y
Lower West Fork Teanaway River	A	WA-39-2300	OD70SN
Lower North Fork Teanaway River	A	WA-39-2100	TI29YR
Upper North Fork Teanaway River	AA	WA-39-2150	TI29YR
Upper West Fork Teanaway River	AA	WA-39-2350	OD70SN
Upper Middle Fork Teanaway River	AA	WA-39-2250	KB710Y
Stafford Creek	AA	WA-39-2155	IY03YA

Methods

Pollutants and Surrogate Measures

The Teanaway River basin TMDL will be developed for heat (i.e., incoming solar radiation). Heat is considered a pollutant under Section 502(6) of the Clean Water Act. Heat generated by solar radiation reaching the stream provides energy to raise water temperatures. Elevated summertime stream temperatures due to anthropogenic causes (Figure 5) in the Teanaway Watershed result from the following conditions:

- Channel widening (increased width-to-depth ratios) that increases the stream surface area exposed to energy processes, namely solar radiation;
- Riparian vegetation disturbance that compromises stream surface shading, through reductions in riparian vegetation height and density (shade is commonly measured as percent effective shade); and
- Reduced summertime baseflows that result from instream withdrawals or from wells in hydraulic continuity with the stream.

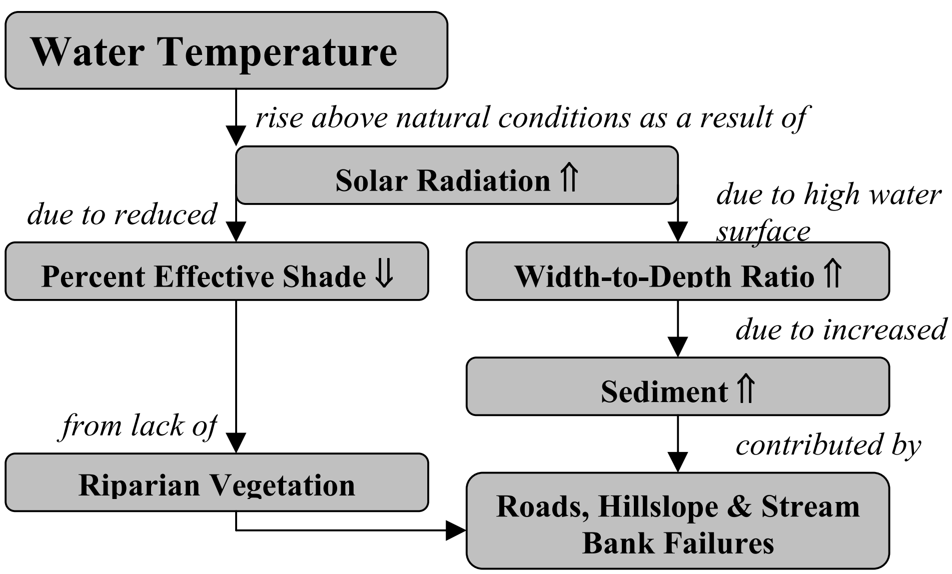

Figure 5. Shade and channel characteristics that impact water temperature (Boyd and Park, 1998)

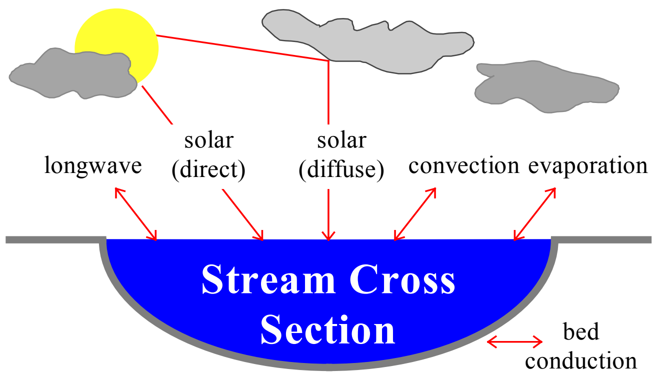

Figure 6. Heat transfer processes that affect water temperature (Cleland, 1999)

Figure 6 shows heat energy processes that control heat energy transfer to and from a given volume of water, and Figure 7 shows the relative importance of these in heating a typical unshaded stream. As discussed in numerous studies, the daily profile for water temperature increases typically follows the same pattern as solar radiation delivered to an unshaded stream. Other processes, such as longwave radiation and convection, also introduce energy into a stream but at much smaller rates when compared to solar radiation (Beschta and Weatherred, 1984; Boyd, 1996). If streamflow increased the volume of water available, these same heat processes would be in place but would result in a smaller temperature gain to the stream.

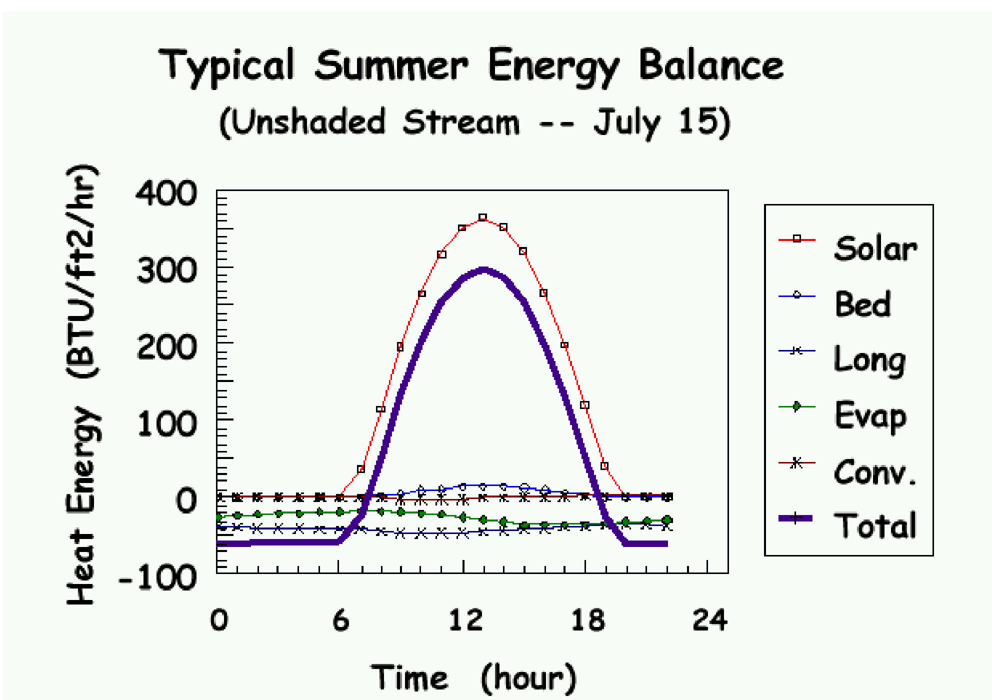

Figure 7. Typical summer energy balance for unshaded stream (Cleland, 1999)

The Teanaway River basin technical assessment uses both heat *loads* and a surrogate measure (shade) to fulfill requirements of Section 303(d). Heat loads are derived and allocated (in units of joules per square meters per second); however, they are of limited value in guiding management activities needed to solve identified water quality problems. The Teanaway River basin technical assessment also expresses, in terms of shade, the size of tree necessary in the riparian zone to produce that shade. Shade is used as a surrogate to thermal load as allowed under EPA regulations [defined as *other appropriate measure* in 40 CFR §130.2(i)]. A decrease in shade due to inadequate riparian vegetation causes an increase in solar radiation and thermal load upon the affected stream section. Human-caused activities that contribute to lack of shade include livestock grazing, recreation, agriculture, and logging. Other factors influencing the distribution of the solar heat load have also been assessed, including increases in the wetted width-to-depth ratios of stream channels and instream flow.

Site Selection

Temperature monitoring stream segments were selected based on geology, soils, slope, land use, and tributary confluence as identified in GIS coverages and aerial photos. One monitoring segment was located in a relatively natural setting, with little impact by humans. Two other segments were located in low impact areas. All streams listed under Section 303(d) were monitored. Sites monitored near the mouths of the main forks generally had more riparian vegetation, as shown on aerial photos, than in much of the upstream areas. Four of the ten sites had been monitored for several years by the USFS (Sites 1, 8, 9, 10) and were generally at the Wenatchee National Forest boundary. Sub-basin watersheds were delineated for each sample site and are shown in Figure 4.

Data Collection Methods

The following summarizes the data collected for this project. Detailed descriptions can be found in Appendix B.

Air temperature

Air temperature was monitored hourly at the six Ecology sites from July 1 to October 6, 1998. Air temperature was also monitored daily at the U.S. Bureau of Reclamation gage just below the confluence of the West, Middle, and North forks. Air temperatures were checked by thermometer during field visits to the sites.

Water temperature

Water temperature was monitored hourly at five of the six Ecology sites from July 1 to October 6. Water temperature was monitored every 30 minutes at three of the four USFS sites from June 15 to October 6. Water temperatures were also taken by thermometer during field visits to all sites. The probes at Sites 1 and 2 disappeared during the monitoring season.

Streamflow

The U.S. Bureau of Reclamation measured streamflow at two gages. A long-term station located just below the confluence of the three forks measures average daily flow. A second flow gage, located closer to the mouth of the mainstem Teanaway River, was in operation during much of 1998. Instantaneous streamflow was measured at each Ecology thermograph site in July (except Site 7), and was measured at all ten sites in August and October.

Shade

Shade was measured with a densiometer at ten locations in the thermal reach above each site. A thermal reach is 300 meters for smaller streams and 600 meters for larger ones. Data used to supplement this collection consisted of:

- TFW watershed analysis completed for the West Fork by the Plum Creek Timber Company and for the North Fork by the Boise Cascade Timber Company;
- TFW survey data collected in 1989 and 1990 for the West and Middle forks; and
- Aerial and orthophotos, which are evaluated using spatial and imaging tools to explore methods of estimating shade or riparian cover.

Channel morphology

Channel types are usually defined by substrate, channel confinement, slope, sinuosity, and width-to-depth ratios. Knowledge of morphology is important for evaluation of water quality, restoration options, and stream function. The Rosgen channel classification system is used by this study. Data were gathered to allow this classification and for SSTEMP modeling. Physical bankfull width and depth, and wetted width and depth, were measured at each site. Active channel width was estimated from aerial photos and compared to estimates as available in the North Fork and West Fork Watershed Analysis Reports. Stream surface slope was measured in the field with a clinometer and from GIS coverages. A Wohman pebble count was done at each site to get a frequency distribution of the size of the substrate.

Groundwater

The Teanaway River system contains an abundance of bedrock. Bedrock systems traditionally produce less groundwater inflow, or have very irregular inflow emerging from cracks in the bed. Instantaneous streamflow measurements taken in the watershed were used to calculate gain from groundwater in the downstream direction. Estimates from Ecology's baseflow project provided a rough percent contribution from groundwater by month for this study. The baseflow project estimated a percentage monthly groundwater contribution to each USGS long-term gage statewide (Sinclair and Pitz, 1999).

Additional data

Additional data included stream location, basin area, stream elevation at monitoring site, thermal reach length, precipitation zone, distance to divide, Rosgen stream class, stream azimuth, and number of road miles within 200 feet of a perennial stream.

Model Selection

SSTEMP (Stream Segment Temperature Model), a one-dimensional steady-state stream temperature model, was chosen for use in this study. SSTEMP is a scaled down version of the Stream Network Temperature Model written by Theurer et al. (1984). SSTEMP may be used to evaluate the effects of riparian shade, stream withdrawals and returns, channel morphology, and reservoir release on instream temperature (Bartholow, 1997).

Criteria for model selection were ease of use, data requirements, availability to the public, reliability of predictions, and use by others for temperature TMDL work. Of the models considered, SSTEMP was mid-range for data input requirements. The TFW temperature model was likely the easiest to use and required only elevation and shade. While this model may work well in forested areas with little flow modification, it was desirable to have a model with the capability to evaluate flow and stream widening. The high end for data requirements was HSPF-Shade, which required more information than was available for this study. The Heat Source model, under development in Oregon, was also considered but was not available to Ecology or the public at this time. EPA is currently using SSTEMP in several temperature TMDLs, and a project to model the lower Yakima Basin using the full SNTEMP model is likely to take place within the next two years (Barwin, 1998). Because the Teanaway River lies in the upper Yakima Basin, this future work was a consideration.

SSTEMP is a well-documented model maintained by the Biological Research Division of the U.S. Geological Survey (USGS). SSTEMP is known to be very good at predicting mean daily temperature and is less reliable at predicting maximum daily temperature (Sullivan et al., 1990). SSTEMP handles a single stream segment at a time. The program requires inputs describing the average stream geometry, as well as (steady-state) hydrology and meteorology; and the program predicts the minimum, mean, and maximum daily water temperatures at some specified distance(s) downstream. SSTEMP is in the public domain and may be copied and distributed freely. The website address for this software and documentation is http://www.mesc.nbs.gov/rsm/rsm_software.html.

Quality Assurance

Water temperature data gathered at Site 8 after August 8, 1998 was not used because it is likely that this thermograph was out of the water for much of the remainder of the year. Quality control procedures using comparisons with air temperature thermographs and comparisons with water temperature at other sites show that the seasonal high for both air and water temperatures at all sites was between July 27 and July 29. Site 8 water temperatures followed similar patterns to those measured at other sites until around August 8, 1998 when the water temperature probe began following air temperature patterns.

Water temperature readings taken with a thermometer during field visits were found to be identical to those recorded by the continuous probes.

The densiometer shade reading for Site 1 (upper West Fork) may be underestimated. The same sampler took all shade readings at Sites 2 through 10, using ten readings per thermal reach. A second sampler took the shade readings for Site 1 and used just five readings for this reach. Site 8 (upper Middle Fork) data were used to calculate riparian goals for Site 1.

The water thermographs installed at Sites 1 and 2 on the West Fork Teanaway were both physically lost during the sampling season. Because Site 8 (upper Middle Fork) and Site 1 (upper West Fork) are at similar elevations, have similar channel and flow characteristics, and are in similar geology and soils, the Site 8 data are used to model Site 1. Thermograph data collected in 1996 by the USFS also verified that these two sites show similar water temperatures.

Water Temperature Condition Results

Water Temperature

Table 2 and Figure 8 show the percentage of days exceeding the Washington State water quality numerical standard as measured July 1 to October 6, 1998. The water quality standard is 18°C for sites 3, 5, 6, and 7, and 16°C for sites 4, 8, 9, and 10. Data show that, except for the highest altitude site, all measured sites exceed these values. Data also show that the entire summer is of concern, with the lower altitude sites exceeding 18°C in over 75% of the days monitored. Appendix A shows complete graphs for water and air temperature data gathered in the Teanaway River basin during the summer of 1998.

Table 2. Water temperature summary from Hobo thermographs (June 30 - October 7, 1998) Teanaway basin

Monitoring Site	Water Quality Standard (degrees C)	Maximum Seasonal Temperature (degrees C)	Minimum Seasonal Temperature (degrees C)	Average Seasonal Temperature (degrees C)	No. of days over 18°C or 16°C standard (total= 96)	Percent of days exceeding WQ Standard	Number of days exceeding 18°C.	Percent of days exceeding 18°C.
3	18	26.3	9.2	16.7	89	93%	89	93%
4	16	13.3	5.8	9.0	0	0%	0	0%
5	18	24.4	8.0	15.6	74	77%	74	77%
6	18	25.3	8.0	16.5	79	82%	79	82%
7	18	28.5	8.6	18.0	82	85%	82	85%
8*	16	21.9	11.1	15.8	28	90%	17	55%
9	16	19.8	3.8	12.6	46	48%	10	10%
10	16	19.4	5.7	12.0	30	31%	7	7%

All maximum water temperatures were achieved on July 28, 1998. Air temperatures were at the maximum on either July 27 or 28. Air temperatures measured in Cle Elum were at the seasonal high of 102ºF on July 27.

* Site 8 data reported in this table are for the 31 days in July because the monitor came out of the water around August 8, 1998.

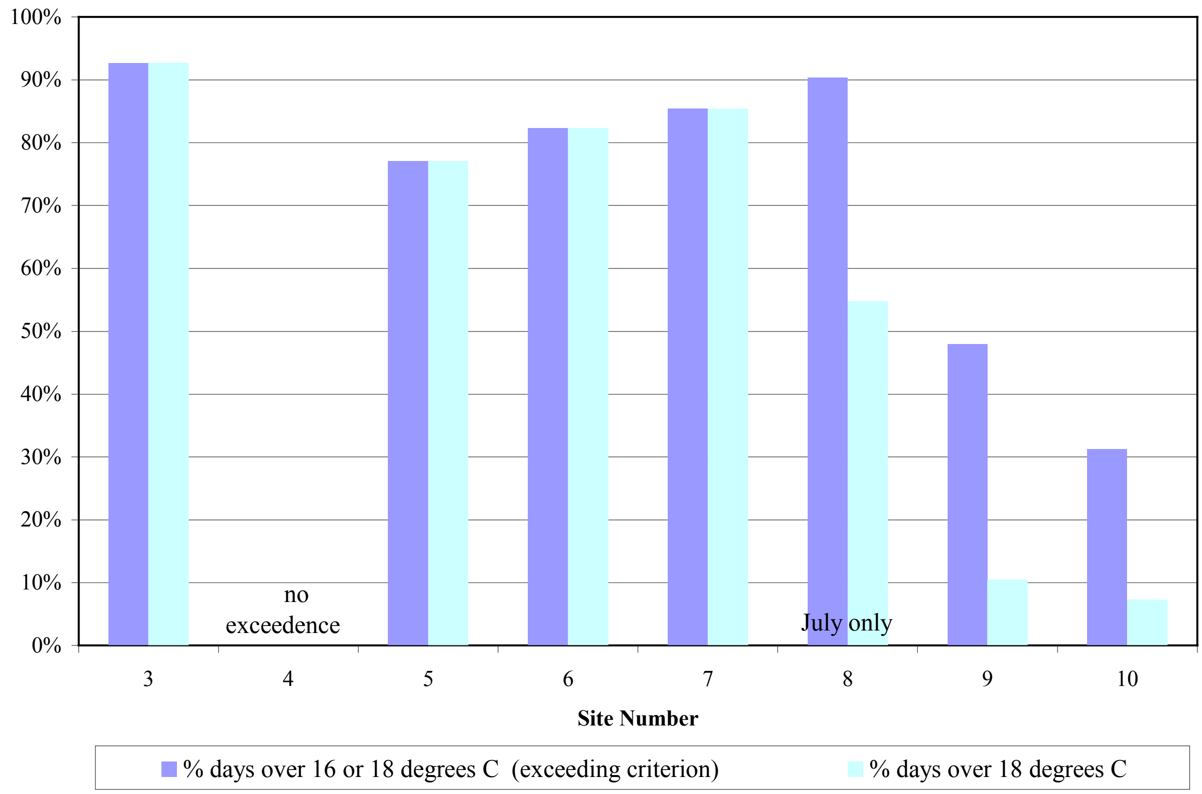

Figure 8. Percent of days from July 1 to October 6, 1998 that temperature criteria were exceeded

Streamflows are generally high in May, but begin rapidly decreasing in June until very low flows are reached in August and September. Thermograph data measured during the 1996 season by the USFS show peak water temperatures occurring in late July, as they did in 1998. Although temperatures are hot, temperatures at the USFS boundary (Sites 8, 9, 10) show that water delivery to the Class A segments downstream is generally at or below the state water quality standard of 18°C. Figure 9 shows the average daily maximum water temperature for July 22 to August 11, 1998. This three-week period was selected because it is the period that on average has the highest maximum daily air temperature (greater than 81ºF) as measured in Cle Elum, Washington over the last 60 years.

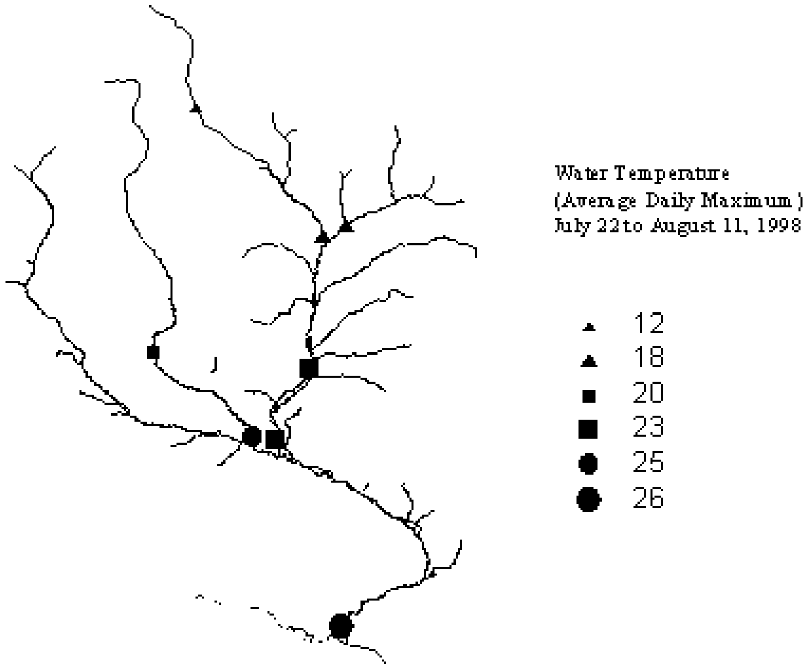

Figure 9. Average daily maximum water temperature, July 22 to August 11, 1998

Air Temperature

Air temperature data were gathered at six locations in the watershed. Mean daily air temperature is required by SSTEMP as an input parameter. Statistical Package Software (SYSTAT) was used to develop a regression to predict mean daily air temperature at sites where data were not collected. Sullivan et al. (1990) developed an *air temperature vs. altitude* relationship using temperature at sea level as a dependent variable. The site nearest Cle Elum was used as a dependent variable, because air temperature data is more likely to be collected there on an annual basis and be available for future temperature studies.

The resulting equation was:

$$T(x) = 3.106 + .919\,(T(c) - .002\,(x))$$

Where: $T(x)$ = mean daily air temperature at elevation x
x = site elevation in feet
$T(c)$ = mean daily air temperature at Site 7 (elevation 1,840) near Cle Elum

This relationship had a correlation coefficient, r^2, of .93

This equation tended to predict temperature accurately at all sites, but did slightly underestimate mean daily air temperature at Ecology's upper elevation site of 3,500 ft. It was also not significantly different than using an average of mean daily air temperatures from Sites 4 and 5 to determine the temperature for Sites 1, 8, 9, and 10.

Because the methods of collecting mean air temperature can differ, a regression using the maximum daily temperature as a dependant variable may be a better predictor of site air temperature in future studies.

Seasonal Variation

Stream temperature in the Teanaway basin follows a definite pattern of seasonal variation. The months of June, July, August, and September are hot. In October, as days get shorter and cooler and autumn rains begin, stream temperatures rapidly cool. Data collected near the mouth of the Teanaway River from July 1998 through May 1999 (Figure 10) show that November through May temperatures are very low. Water temperature data collected annually since 1996 by the USFS support this pattern. Peak stream temperatures typically occur in July or August. To ensure capture of the seasonal high temperature, thermographs should be placed in this basin no later than June 20.

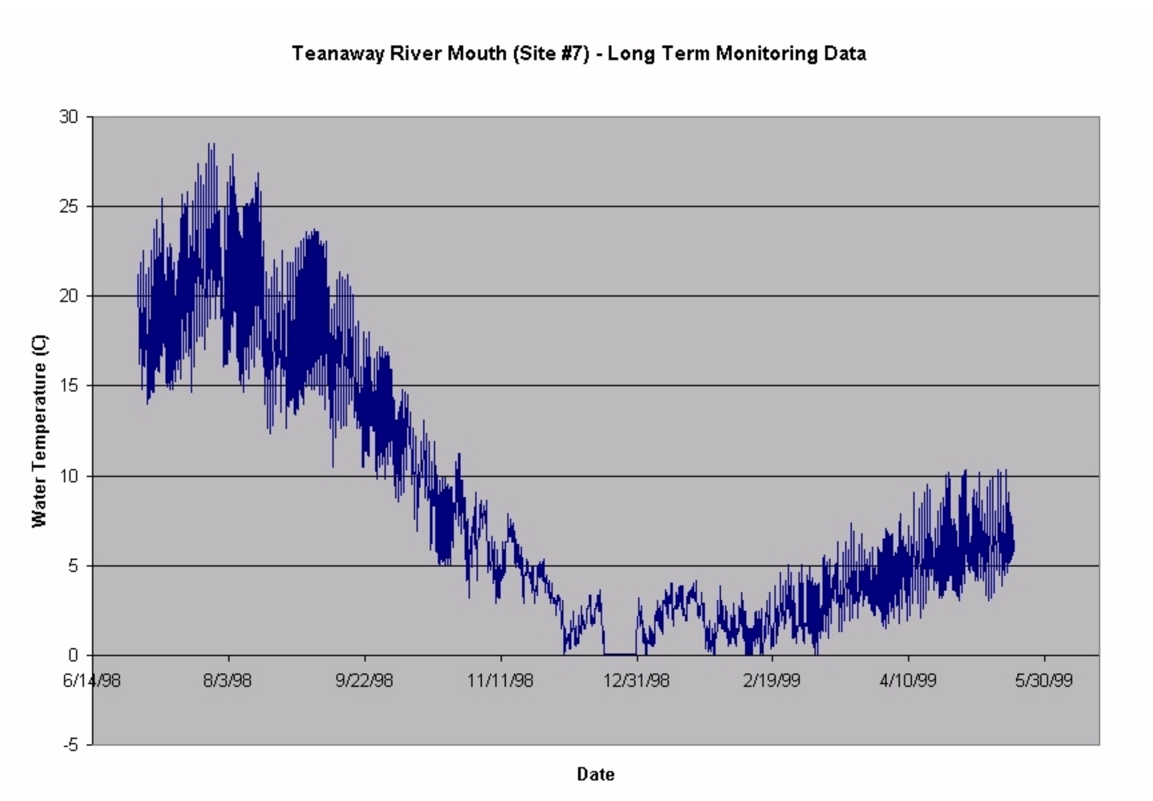

Figure 10. Water temperature data showing seasonal variation

Temperature Modeling and Analysis

Streams in the Teanaway River basin were categorized to address the response of stream temperature to different channel effects, according to Rosgen (1996). Rosgen primarily uses slope, surficial geology, stream width-to-depth ratios, and substrate to categorize streams. Field data collected at thermograph sites allowed this categorization. GIS coverages and USGS quad maps were used along with the field data to verify the applicable Rosgen classifications. Appendix table G-1 summarizes the basic characteristics for each modeled stream segment.

Stream Segment Temperature Model (SSTEMP) Input Parameters

SSTEMP requires input data for 19 variables, ranging from channel conditions to climate. Many of these were kept constant for all model runs. Several parameters were varied to assess the sensitivity of the results to that factor. The model input parameters used are listed below.

Segment Length: Two types of model runs were made in this study:

- A longer segment length, representing the distance between temperature monitoring sites (ranging from 3.4 to 10 miles), was used to assist in calibration and verification of the SSTEMP model for prediction of mean and maximum daily water temperatures. In these cases, hobo thermographs had been placed at each end of the stream segment.
- A shorter, one-mile segment was used in modeling and heat load calculations for which an upstream hobo site was not available. A one-mile segment was chosen for ease of display and because it was the standard used in the Simpson (EPA, 1999) and Sucker-Grayback (Boyd, 1998) TMDLs. Sullivan et al. (1990) recommend a minimum thermal reach length of 600 meters in streams with bankfull widths greater than 40 feet, and 300 meters in length for streams with bankfull widths less than 40 feet.

Segment Inflow and Segment Outflow: Actual streamflow measured at the upstream and downstream ends of each segment was used for calibration and verification model runs using July 1 and August 17-21 conditions. The percent change in flow observed at the 'Teanaway below Forks' gage from July 28 to August 18 was used to back calculate likely flows for the extreme condition on July 28. In all model segments below the USFS boundary, segment inflow was equal to segment outflow (details in Table 5 streamflow analysis section). For the one-mile segments above Sites 1, 8, and 10, the percent flow gain per mile was assumed to be the same as that measured between Sites 4 and 9.

Inflow Temperature: For stream segments with thermographs at each end, the measured 24-hour mean water temperature from the upstream site was used. One-mile segments used the measured 24-hour mean water temperature from the downstream hobo site.

Lateral and Ground Temperature: 7.2°C is the mean annual air temperature measured in Cle Elum, Washington.

Air Temperature: For calibration and verification, the model used actual air temperatures measured at six thermograph sites in the basin during the summer of 1998. These sites covered the entire range of elevation in the basin. For sites with no air temperature monitoring, a linear relationship was established to predict air temperatures by elevation from the data gathered.

Wind Speed: 2 mps was the mean daily wind speed measured July 28, 1998 at the USFS weather station located at Liberty (near Blewett Pass) at an elevation of 2,434 feet.

Relative Humidity: The relative humidity was 35% for June and August model runs. This was the usual daily mean for daytime temperatures. A relative humidity of 30% was measured on July 28, 1998 and was used to model the critical conditioning. Relative humidity measurements were available from the USFS weather station at Liberty; these measurements were determined to be representative of the Teanaway River basin. The Bureau of Commerce relative humidity maps also verified 35% as appropriate for this basin.

Possible Sun: 90% was used.

Solar Radiation: Solar radiation for July 2-6 model runs, 333j/m^2/s; for July 27-29, 320 j/m^2/s; and for August 17-21, 258 j/m^2/s. These values were calculated with the solar model portion of SSTEMP (SSSolar), using a latitude of 47 degrees 17 minutes and an elevation of 2,400 feet.

Thermal Gradient: 1.65 j/m^2/s/°C was used, based on recommended default from the model user documentation (Bartholow, 1997).

Daylight Length: Values calculated with SSSolar were based on the Teanaway River basin's latitude and elevation. For July 2-6 model runs, 15.88 hours; for July 27-29, 14.9 hours; and for August 17-21, 13.83 hours.

Percent Shade:

- Existing shade values were measured with a forest densiometer and verified against aerial photos and information from the North Fork and West Fork Watershed Analysis Reports.
- Attainable shade for a mature riparian forest was calculated using the SSShade module of SSTEMP. This calculation used mature tree heights and crowns provided by the Cle Elum Ranger Station, a channel width equal to the active channel zone, and the average azimuth for the segment measured from quad maps.

Manning's n (resistance to flow): 0.08. Manning's n is not a sensitive parameter for prediction of the daily mean water temperature; however, it is very sensitive for prediction of the daily maximum temperature (Bartholow, 1997). Because the maximum is the critical value for this study, extensive research was done on selecting an appropriate Manning's n. Rosgen and other sources usually recommend a Manning's n ranging from .035 to .05. However, these recommendations are based on resistance to flow at bankfull stage. Because the Teanaway basin has such a large variation in flow, these are not appropriate for modeling summer low-flow situations. A low-flow stream with many boulders will experience much more contact and resistance from the stream bottom than a filled stream. Bovee and Milhous (1978) give data from a gravel-bed stream in Oregon, demonstrating a variation in Manning's n from .05 for flows greater than .84 cubic meters per second (cms), to .35 for flows less than .03 cms. Calculations of Manning's n using the Chezy-Manning equation, and limited velocity data gathered at the sites, indicated that a higher n was appropriate for this basin. Using calculations and test calibrations on the Sites 5-6 segment, 0.08 seemed to be reasonable and was still within Rosgen's recommended range for some channel types.

Elevation Downstream: The elevation of the downstream hobo thermograph site for each segment modeled was taken from the Digital Elevation Model GIS data layer. This layer was found to be slightly more accurate than the 1:24,000 quad map and much more accurate than Ecology's GPS reading.

Elevation Upstream: Elevation upstream was **c**alculated from the slope of the stream segment being modeled, the stream segment length, and the downstream elevation.

Stream Width Coefficient and Exponent: These values, also known as the Width A Term and the Width B Term, can be derived using the relationship between channel width and streamflow. The purpose of these terms is to determine channel width and depth at various streamflows.

- *Width B Term:* A value of 0.15 was used for Rosgen type B streams and 0.20 for Rosgen type C streams based on their respective channel geometry and flow calculations. The user documentation recommends a default of 0.20 in the absence of channel data or a value of 0 if stream width but not depth is known (Bartholow, 1997).
- *Width A Term:* Values ranging from 8 to 20 were used. This value was input so that the model width-to-depth ratio was accurate. Wider streams had a larger A term, smaller streams with less flow had a smaller A term. This parameter was also varied to assess temperature effects on the estimated range of width-to-depth ratios.

Model Performance

Model performance is summarized in Table 3 and Figures 11 and 12. The SSTEMP model was calibrated with segment 5-6 (i.e., the model segment that starts at the Site 5 thermograph and ends at the Site 6 thermograph) data for June and August. Primary calibration parameters were Manning's n and the channel A and B terms. Other model runs were made by applying the best available field measured or acquired data as described in the model input section.

Four statistical tests were applied to model results:

1. *Mean deviation* is simply the average deviation between the predicted and actual water temperature.
2. *Median absolute deviation* describes the central tendency of model performance.
3. *Root mean square error* presents an estimate of the variation in the same units as the measurement (e.g., ºC).
4. *Relative error* presents this variation as a percentage of the measurement mean. The relative error for predicting daily mean temperature was 5.0% and for maximum temperature was 7.8%.

Table 3. Performance of the Teanaway major segment stream temperature model									
		Input Temperatures		Output Water Temperatures					
		Mean	Mean	Predicted	Predicted	Actual	Actual		
	Stream	24 hour	24 hour	Mean 24h	Maximum	Mean 24h	Maximum	Error	Error
Date	Segment	Water (C)	Air (C)	Water (C)	Water (C)	Water (C)	Water (C)	Mean	Maximum
07/02/98	5-6	14.10	17.71	15.36	19.43	15.37	19.11	-0.01	0.32
07/03/98	5-6	14.09	16.11	15.19	19.16	15.22	18.47	-0.03	0.69
07/04/98	5-6	13.53	14.62	14.56	18.51	14.68	18.63	-0.12	-0.12
07/05/98	5-6	14.01	16.09	15.01	19.07	15.41	20.08	-0.40	-1.01
07/06/98	5-6	14.66	18.45	15.88	19.91	15.94	20.73	-0.06	-0.82
08/17/98	5-6	14.84	10.84	14.71	19.95	15.38	18.63	-0.67	1.32
08/19/98	5-6	15.26	14.34	15.75	21.09	15.96	20.08	-0.21	1.01
08/20/98	5-6	15.80	16.79	16.67	22.04	16.47	20.40	0.20	1.64
08/21/98	5-6	15.78	15.94	16.45	21.79	16.50	18.95	-0.05	2.84
7/27/98	5-6	19.36	26.05	22.07	27.67	20.69	24.78	1.38	2.89
7/28/98	5-6	19.95	26.82	22.64	28.17	21.43	25.3	1.21	2.87
7/29/98	5-6	19.30	24.36	21.58	27.12	20.67	24.43	0.91	2.69
07/02/98	9/10 - 5	11.6	17.36	13.81	18.46	14.10	17.66	-0.29	0.80
07/03/98	9/10 - 5	11.5	15.80	13.53	18.1	14.09	17.82	-0.56	0.28
07/04/98	9/10 - 5	10.8	14.14	12.74	17.31	13.53	17.50	-0.79	-0.19
07/05/98	9/10 - 5	11	15.42	13.07	17.68	14.01	19.11	-0.94	-1.43
07/06/98	9/10 - 5	11.7	17.81	13.95	18.61	14.66	19.59	-0.71	-0.98
08/17/98	9/10 - 5	11.7	10.41	13.14	19.06	14.84	18.79	-1.70	0.27
08/19/98	9/10 - 5	12	14.19	14.44	20.45	15.26	20.24	-0.82	0.21
08/20/98	9/10 - 5	12	16.62	15.22	21.32	15.80	19.92	-0.57	1.40
08/21/98	9/10 - 5	12.5	15.86	15.23	21.24	15.78	18.95	-0.55	2.29
7/27/98	9/10 - 5	16.18	25.40	21.12	27.25	19.36	24.09	1.76	3.16
7/28/98	9/10 - 5	15.76	26.11	21.17	27.37	19.95	24.43	1.22	2.94
7/29/98	9/10 - 5	14.90	24.04	20	26.29	19.30	23.57	0.70	2.72
07/02/98	4-9	8.49	16.97	12.26	16.06	11.6	14.49	0.66	1.57
07/03/98	4-9	8.04	15.14	11.55	15.31	11.5	14.49	0.05	0.82
07/04/98	4-9	7.74	13.09	10.86	14.57	10.8	13.25	0.06	1.32
07/05/98	4-9	8.28	14.92	11.58	15.32	11	13.56	0.58	1.76
07/06/98	4-9	8.49	16.85	12.22	16.02	11.7	15.27	0.52	0.75
08/17/98	4-9	8.62	9.99	9.81	14.17	11.7	13.87	-1.89	0.30
08/19/98	4-9	8.88	13.26	11.11	15.54	12	15.27	-0.89	0.27
08/20/98	4-9	9.10	15.70	12.14	16.61	12	15.75	0.14	0.86
08/21/98	4-9	9.14	15.27	11.97	16.43	12.5	14.64	-0.53	1.79
7/27/98	4-9	10.57	24.25	16.35	21.09	16.18	19.43	0.17	1.66
7/28/98	4-9	10.89	24.97	16.72	21.46	15.76	19.76	0.96	1.70
7/29/98	4-9	10.65	23.13	15.87	20.59	14.90	18.95	0.97	1.64
07/02/98	6-7	15.63	21.26	17.15	21.13	18.45	22.56	-1.30	-1.43
07/03/98	6-7	15.47	18.73	16.75	20.61	18.12	21.23	-1.37	-0.62
07/04/98	6-7	14.99	17.18	16.19	20.02	17.15	21.56	-0.96	-1.54
07/05/98	6-7	15.69	18.86	16.95	20.8	17.96	22.56	-1.01	-1.76
07/06/98	6-7	16.22	22.23	17.76	21.72	18.85	23.74	-1.09	-2.02

Table 3 (cont.). Performance of the Teanaway major segment stream temperature model									
		Input Temperatures		Output Water Temperatures					
		Mean	Mean	Predicted	Predicted	Actual	Actual		
	Stream	24 hour	24 hour	Mean 24h	Maximum	Mean 24h	Maximum	Error	Error
Date	Segment*	Water (C)	Air (C)	Water (C)	Water (C)	Water (C)	Water (C)	Mean	Maximum
08/17/98	6-7	15.38	14.51	16.33	21.72	16.29	20.40	0.04	1.32
08/19/98	6-7	15.96	16.85	17.29	22.70	17.17	22.06	0.12	0.64
08/20/98	6-7	16.47	19.25	18.24	23.68	17.90	21.56	0.34	2.12
08/21/98	6-7	16.50	18.80	18.13	23.55	17.69	20.24	0.44	3.31
7/27/98	6-7	20.69	28.75	23.39	28.54	23.12	28.13	0.27	0.41
7/28/98	6-7	21.43	29.60	24.08	29.16	23.76	28.49	0.32	0.67
7/29/98	6-7	20.67	27.19	23.00	28.08	22.88	27.23	0.12	0.85
			Mean	Maximum					
Statistics									
Mean Deviation			-0.02ºC	0.83ºC					
Median Absolute Deviation			0.57ºC	1.32ºC					
Root Mean Square Error			0.81ºC	1.64ºC					
Relative Error			5.0%	7.8%					

* The stream model segment naming convention for segments with a hobo thermograph at each end is "upstream site - downstream site" (e.g., 5-6: 5 is the site number for the upstream hobo, and 6 is the site number for the downstream hobo).

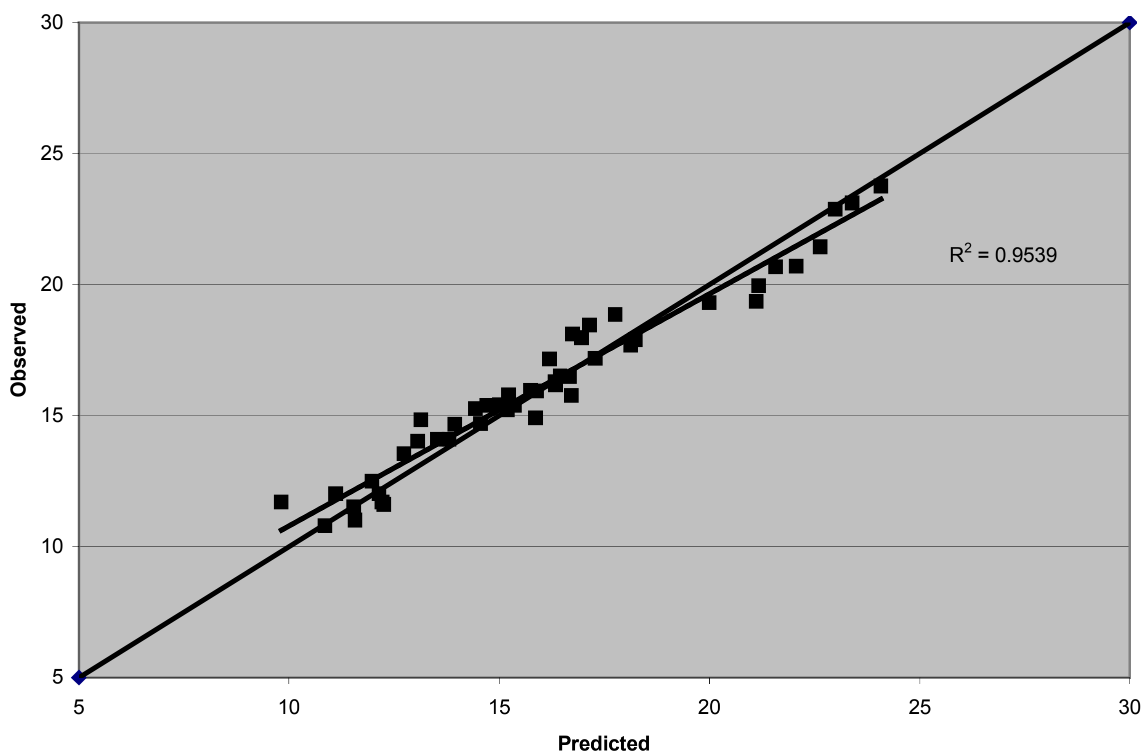

Figure 11. Observed vs. predicted mean daily water temperature

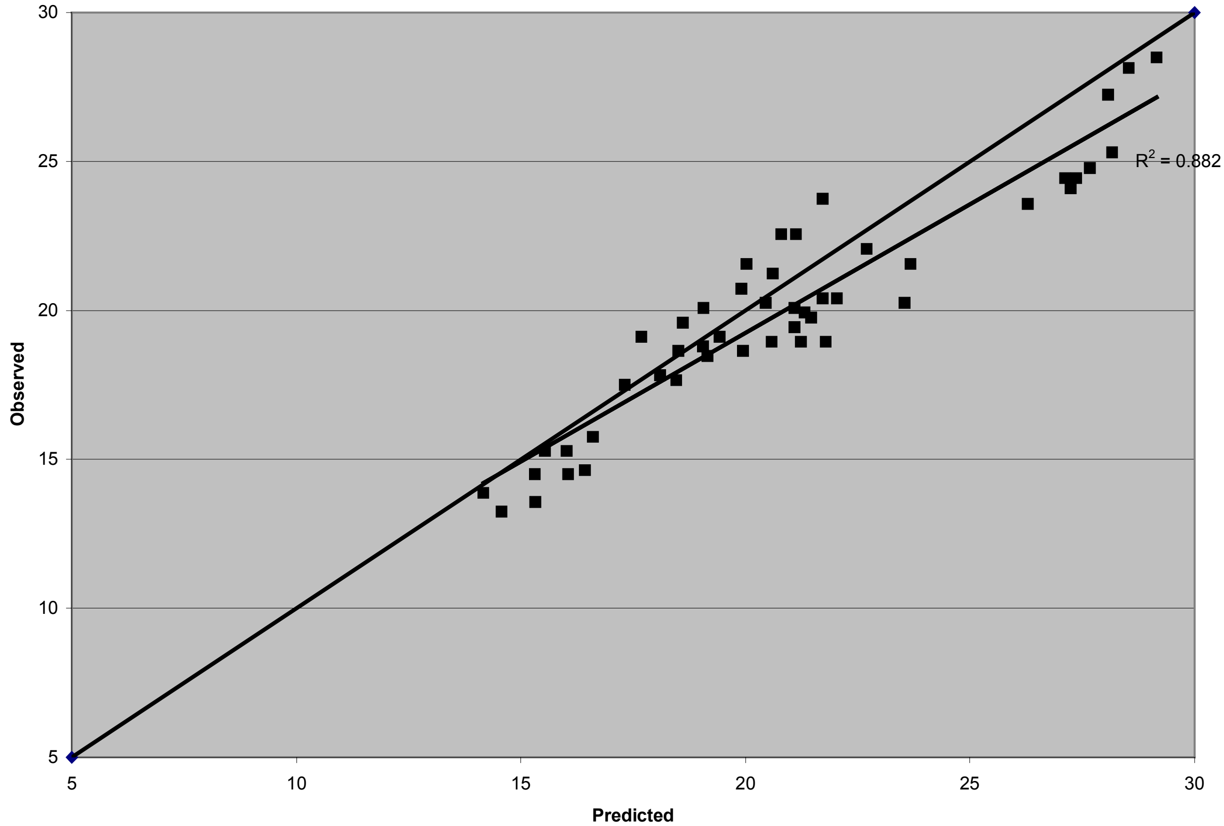

Figure 12. Observed vs. predicted maximum daily water temperature

These error measures indicate that the model predicted mean and maximum daily temperatures well.

Each figure shows two lines: one shows the relationship between the observed and predicted temperatures, and the other shows the line of one-to-one correspondence. During the extreme condition, the maximum daily water temperature is somewhat over-predicted and may serve as a margin of safety.

Analysis of Factors Affecting Temperature

Three management related factors that influence stream temperatures were assessed using the SSTEMP model: instream flow, wetted width-to-depth ratios of stream channels, and riparian shade. Climate related factors, such as air temperature and relative humidity, were used to help define critical conditions for this study.

Flow

Increasing streamflow was evaluated as a possible method of cooling the Teanaway River. Evaluation shows that this method can improve temperatures, but not significantly enough to be a complete solution for the Teanaway. The Teanaway routinely experiences extremely low flows in August, September, and October. Doubling the flow in the lower portion of the basin by not diverting stream water can expect to produce a 1°C reduction in the mean daily water temperature, if all other factors including riparian shade are held to 1998 conditions. Increasing the streamflow will be important for salmonids that are spawning, migrating, holding, or rearing. Current summer conditions leave the stream so dry that impedance to salmonid migration seems certain, and both the North Fork and West Fork Watershed Analyses report that pool-to-riffle ratios have dropped over time. If flow gains could be made by increasing the amount of cool groundwater available to the stream, the temperature reduction could be greater.

The theory behind increasing streamflow to decrease water temperature is that a larger mass of water will take longer to heat and cool through the water surface to air interchange. The larger mass of water can also assimilate more heat load for the same raise in temperature as a smaller one and thus will moderate the heating effect. In the Teanaway basin, the existing stream width-to-depth ratios are high, ranging from 18 to 70 during some low-flow conditions. With stream depths usually in the 0.5- to 1-foot range during summer low flows, the stream has a large surface area exposed and will rapidly heat and cool, as evidenced by the large fluctuation in water temperature (Figure A-1) over a typical diurnal cycle. Even if summer streamflow were doubled, the water surface area will still be large relative to its mass, and will rapidly heat and cool with exposure to solar radiation.

Groundwater stored during winter rains and released during the summer can have a large cooling effect on a stream. If cool groundwater inflows to the stream creating a gaining reach as it mixes with the already warmed stream water, temperatures can be reduced. This is different from increasing the streamflow by simply not diverting the already warmed water in the stream. Both will effect a change, but adding 7.2°C water can reduce temperatures more than leaving in 16°C water.

Several information sources and methods were combined to assess the effect of streamflow on water temperatures in the Teanaway basin. These were:

- The period of recorded gage information
- Streamflow analysis with HYSEP, a USGS streamflow hydrograph separation model
- SSTEMP model results for the basin
- GIS-based hydrologic analysis of streamflow patterns

The first step in the analysis was to compare the 1998 flow year with the period of record, to determine what flow increases could be likely on a long-term basis if management controls were in place. The second step was to use SSTEMP to bracket the decreases in temperature that could be expected if these gains in flow were realized. The third step was to explore groundwater issues.

The Teanaway River has been gauged continuously since 1968. The Teanaway below Forks gage was monitored initially by the USGS and more recently by the U.S. Bureau of Reclamation. Some records for 1915-1918 and 1948-1950 also exist, but may have been taken lower in the basin. This gage information shows a definite seasonal pattern of very low flows during the summer and very high scouring flows during the winter or spring (Figure 13). Examination of flow data from 1915-1919 also shows extremely low summer flows comparable to those seen today. However, these early flows cannot be used to simulate natural conditions, because the basin was used for agriculture and animal farming at that time.

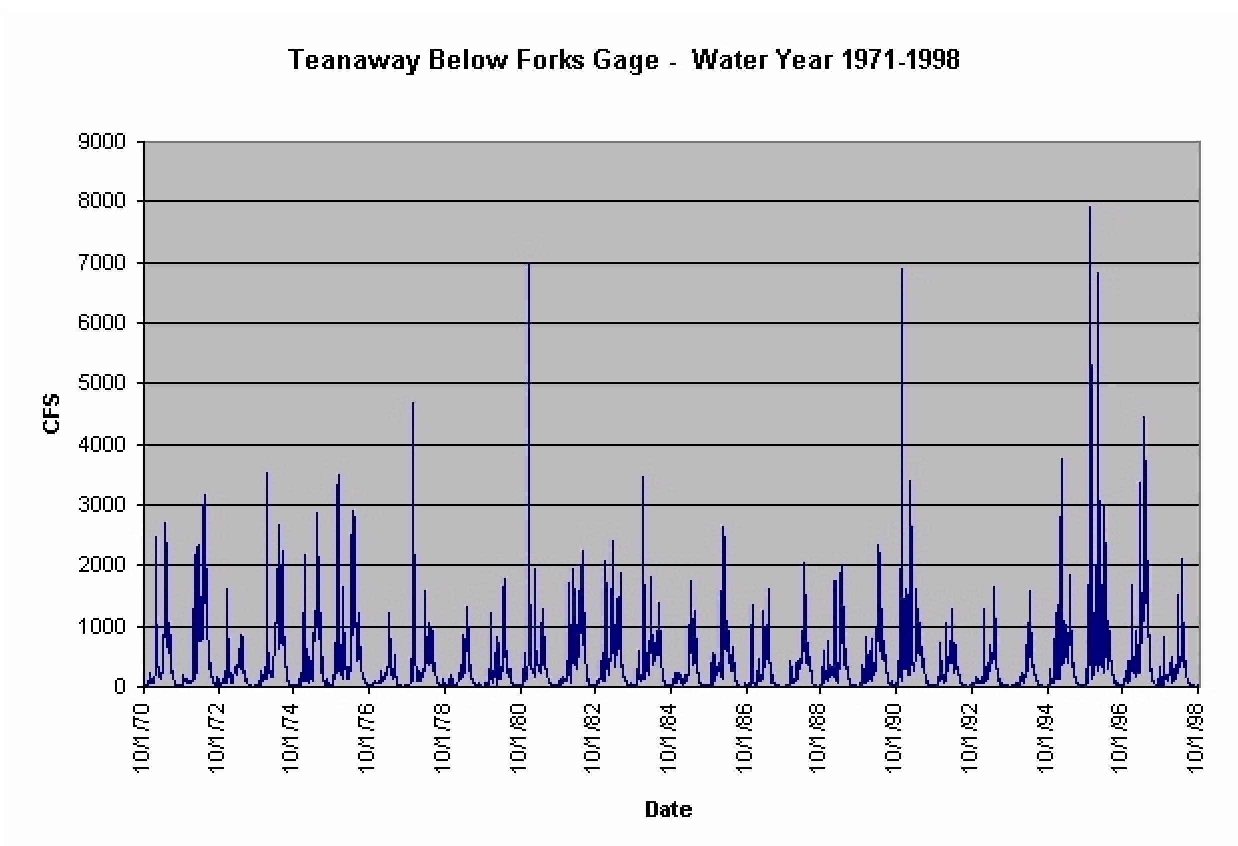

Figure 13. Flow from Teanaway below Forks gage, water year 1971-1998

The continuously monitored period was processed with HYSEP, a USGS model for evaluating streamflows (Sinclair and Pitz, 1999). HYSEP is a hydrograph separation software and can be used to separate surface runoff from baseflow (Sloto and Crouse, 1996). The model was used to estimate the percent of summer streamflow in the basin from groundwater baseflow and from surface runoff (on average). HYSEP also produces average annual flow statistics.

Figure 14 compares water year 1998 streamflows with monthly average flows as calculated by HYSEP. Figure 15 shows summer averages for total streamflow, baseflow, and surface flow and compares these against 1998 total streamflow. Comparison of 1998 against the average continuous monitored period shows that 1998 had generally lower streamflow than average but was not an extreme or abnormal condition. Although 1998 was considered a low-flow year in many Washington State streams, the Teanaway basin did not have as many active instream water rights that year. No permitted instream withdrawals were in operation above the Teanaway at Forks gage during the summer, and only three water rights were active in the lower basin (Barwin, 1998).

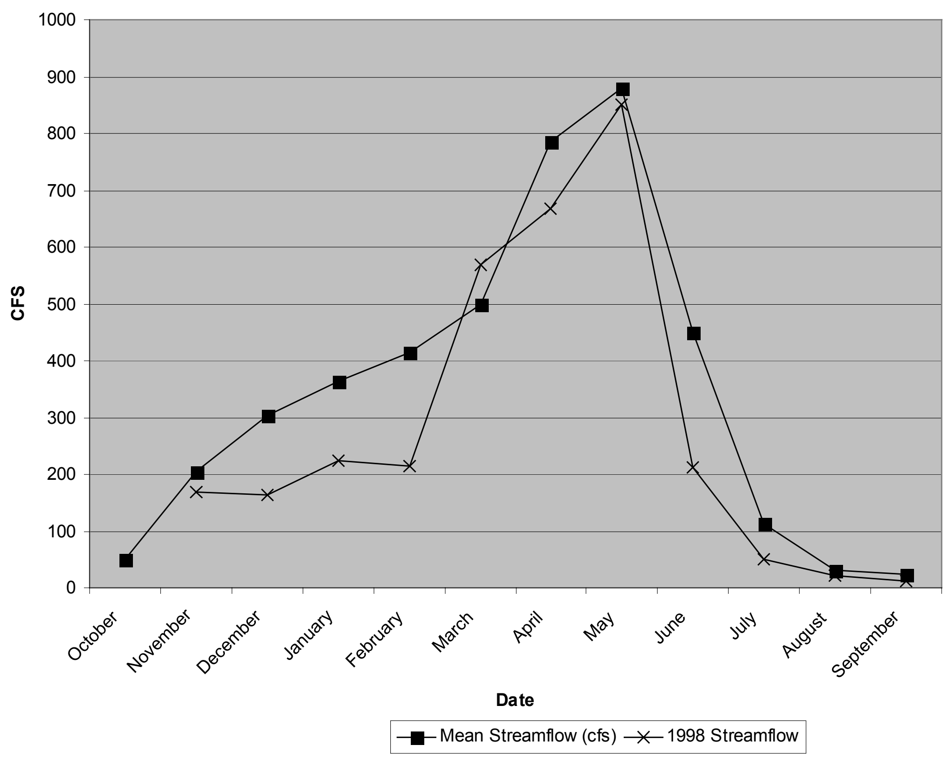

Figure 14. Teanaway below Forks gage, monthly averages for 1998 vs. monthly averages for 1968-1998 as calculated by HYSEP

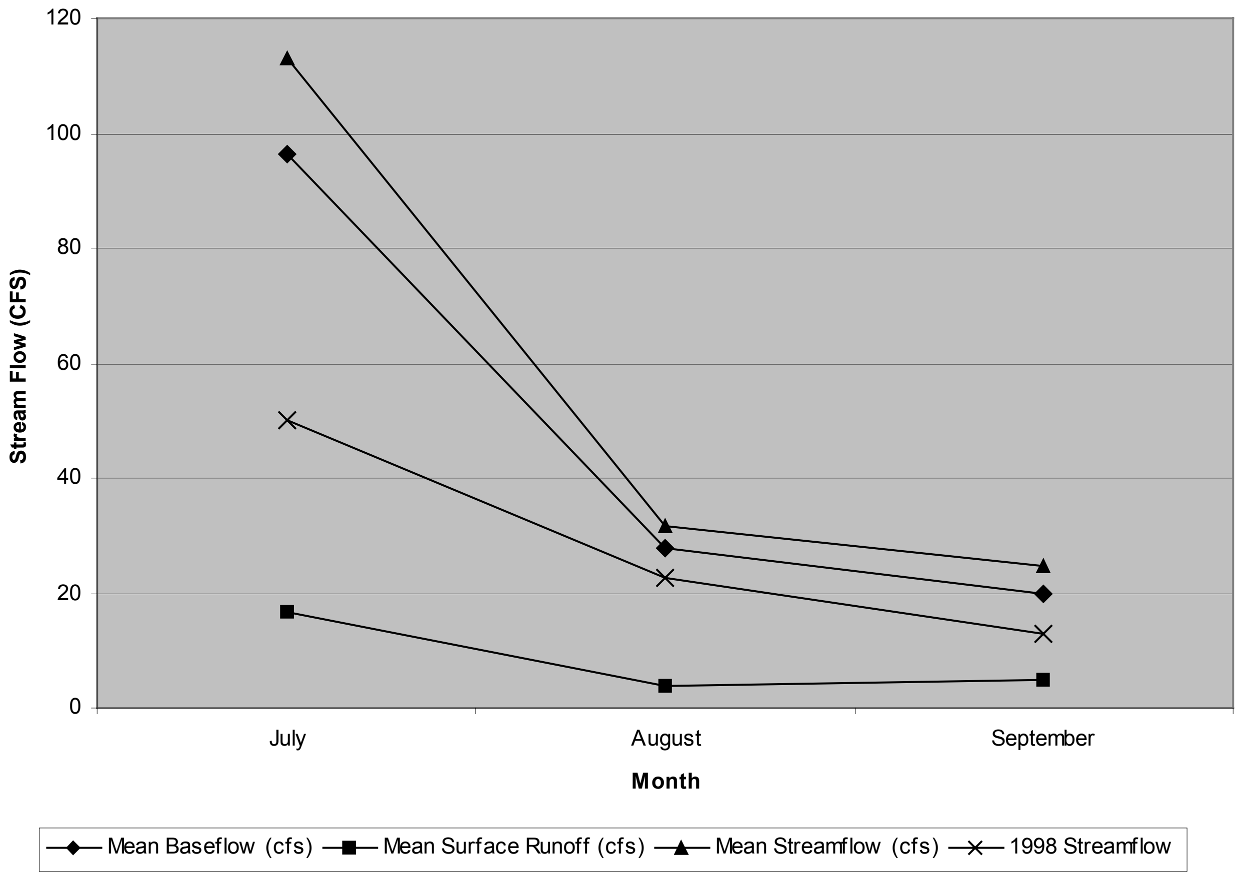

Figure 15. Teanaway below Forks gage, summer monthly averages for 1998 vs. 1968-1998 as calculated by HYSEP

Average long-term streamflow for August and September are 27.8 cfs and 19.7 cfs, respectively, comparable to the 22.8 cfs and 13.0 cfs measured in 1998. The lowest recorded flow during this period was 6 cfs measured in September 1990, and the highest flow was 7,911 cfs measured in November 1995.

Table 4 shows flow statistics calculated using the 1968-1998 period of record. Observation of these flow statistics and best judgment determined that a doubling of the 1998 flow was the most that could reasonably be expected through management actions, and serves as an upper bracket to modeling scenarios. This doubling corresponds to increasing a median annual 7-day low flow of 15 cfs to a maximum annual 7-day low flow of 27 cfs. Because the critical condition was July 28, SSTEMP modeling artificially doubled the July 28 flow in the Site 5 to 6 segment from 20 cfs to 40 cfs, and in the Site 6 to 7 segment from 27 to 50 cfs. These flow increases resulted in a mean daily water temperature reduction of 1.0°C in each of the modeled segments.

Because no water withdrawals were in place upstream of these two segments, it is unlikely that flow gains in other parts of the basin could be guaranteed.

Table 4. Miscellaneous streamflow statistics

Flow Statistic	Flow (cfs)
Median Annual 7-day Low flow 1968-1998	15
Minimum Annual 7-day Low flow 1968-1998	6.7
Maximum Annual 7-day Low flow 1968-1998	27
7Q10 Annual	8.7
7Q10 July + August	10.7
7Q10 July only	18.7
7Q2	14.6

Groundwater

SSTEMP accounts for groundwater by using the difference between streamflow entering the model segment and exiting the model segment, and assigning this flow a temperature of 7.2ºC. Where there is no difference, there is no groundwater inflow. Flow estimates at all sites for July 28 and an estimation of groundwater inflow were necessary for SSTEMP modeling of the critical period. As part of field data collection, Ecology measured streamflow with a Marsh-McBurney flowmeter two or three times at each site. These estimates are shown in Table 5.

Table 5 shows streamflow tends to stay the same or decrease slightly in the downstream direction. This was true for all major stream forks measured except for the North Fork between Sites 4 and 9, which showed significant gain. Because there is no gain, the model applies no groundwater input except for areas upstream from the USFS boundary. Model results closely approximated actual measured water temperatures at all sites, indicating assumptions about groundwater contribution were correct and that the upper basin sites had a larger proportion of groundwater.

Groundwater inflow is keeping the upper basin cooler. Observation of stream temperature at Site 4 supports this by showing that, although solar loads and air temperature (94ºF on July 27) climb very high, stream temperature stays constant.

Table 5. Streamflow estimates for Teanaway basin thermograph sites - summer 1998

Station #	Measured August Flow	Estimated July 28 Flow	Measured June Flow	Measured October Flow
West Fork Sites				
1- Upper WF Teanaway (USFS)	3.13	4	-	2.30
2- Lower WF Teanaway	2.54	4	8.73	1.11
Middle Fork Sites				
8- Upper MF Teanaway (USFS)	3.40	4	-	3.80
3- Lower MF Teanaway	2.08	4	16.48	1.72
4- Upper NF Teanaway, below De Rue Cr.	5.72	7	26.93	7.32
North Fork Sites				
9 + 10 NF Teanaway+Stafford Creek	21.13	20	-	18.74
5- NF Teanaway, between Middle and Dickey Cr.	18.35	20	69.64	16.05
6- NF Teanaway, near mouth	17.61	20	56.13	8.58
Mainstem Sites				
Teanaway below Forks gage	26.00		90.00	16.00
7- Mainstem Teanaway, near mouth	16.93	27	-	15.94
Streamflow recorded at the Teanaway below Forks gage on July 28, 1998 was 27 cfs				

Groundwater in the lower basin is either not available or is being intercepted by wells and/or vegetation. Because the long-term flow record shows low flows almost every year and because no water rights were being exercised in the middle watershed during 1998, it seems unlikely to be able to realize large gains in groundwater contribution in the future. In fact, further development on the forks resulting in larger well-water withdrawals will have a detrimental effect on stream temperature. Housing and other development is close to the river, and well water is likely in hydraulic continuity with the river.

A GIS landscape tool to estimate continuous streamflow at various points in a watershed was developed during this assessment project and is documented in Appendix E. This GIS methodology was unsuccessful for flow reconstruction in the Teanaway basin, because flow does not increase in a downstream direction during the summer. The GIS tool was successful in confirming that groundwater contribution to streamflow in the upper watershed is greater than that in the lower watershed.

Channel width and depth

Channel width and channel width-to-depth ratios are important to stream temperature, because a wide, shallow stream will absorb heat much quicker than a deeper narrower channel. The PACFISH/INFISH reports (USDA, 1995) suggest channel width-to-depth ratios of 10 or less as ideal for salmon. The channel width-to-depth ratios in the Teanaway are much larger, ranging from 18 to 70 (in some low-flow situations). The INFISH goals are likely not appropriate for the Teanaway, since even streams relatively unimpacted by sediment have channel width-to-depth ratios in the 20 range. A sensitivity analysis was performed on the channel width-to-depth ratio using SSTEMP and a range of shade values. This sensitivity analysis was performed using June conditions in the Site 5-6 segment and a base condition of width-to-depth equal to 36. Figure 16 demonstrates the change in temperature estimated by SSTEMP over the range of likely width-to-depth ratios and levels of riparian shade.

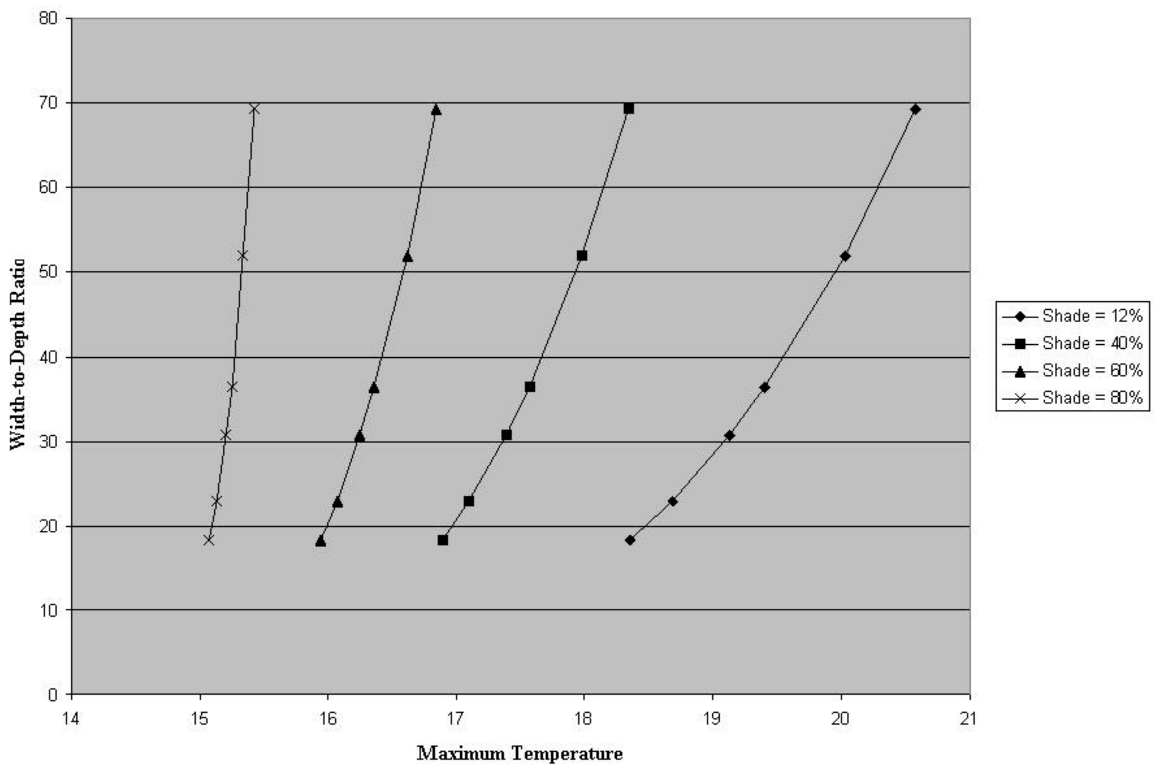

Figure 16. Change in maximum stream temperature as a function of channel width-to-depth ratio and riparian shade (sensitivity analysis using June 30 conditions)

This example shows that in a relatively unshaded stream, the width-to-depth ratio has a much greater influence on the maximum stream temperature than in a highly shaded stream. With the current shade of 12%, this segment can be expected to see an increase of 1.18°C if the channel width-to-depth ratio were increased to 69, and a decrease of 1.05°C if the ratio were decreased to 18. At a riparian shade of 80%, the channel width-to-depth ratio does not markedly affect the maximum daily temperature, resulting in 0.18 and - 0.18°C changes for width-to-depth equal to 69 and 18, respectively. July flow and weather conditions will likely produce a larger effect than the June conditions modeled. As indicated later in this report, a reasonable shade goal for this segment is 50%. In this range the channel width-to-depth ratio is a significant factor in stream temperature. This sensitivity analysis was done holding all input parameters constant. The sensitivity analysis does not take into account that as the channel becomes narrower the same size trees were providing more shade.

A portion of the large width-to-depth ratios seen in the Teanaway River basin can be attributed to widening and shallowing of streams due to sediment input. Much of the sediment in the Teanaway basin comes from natural sources such as landslides and soil erosion. However, some sediment input is due to road building and maintenance, cattle grazing, and agricultural and recreation activities near the streams. These activities discourage the growth of riparian vegetation, causing additional bank erosion. A stream channel assessment of lower McDonald Creek (Rashin, 2000), conducted to evaluate stream channel conditions before and after timber harvest activities, showed extensive streambed scour and deposition of materials transported from upstream erosion sites, as well as an almost doubling of the average active channel width.

Several methods were used to estimate the maximum channel width-to-depth ratio reduction that could be expected if the stream were to return to natural conditions. These methods were:

- Compared field measured bankfull and low-flow channel width-to-depth ratios to average channel width-to-depth ratios as reported in Rosgen (1996).
- Compared measured wetted and bankfull widths to expected widths calculated from an empirical relationship derived by Sullivan et al. (1990) for eastern Washington. This relationship, based on distance to the divide, was established with only five data points, so it should be interpreted only as an indicator.
- Compared sediment index values using the methods outlined in Oregon's North Fork Siuslaw River Water Quality Management Plan (Siuslaw National Forest, 1998) and in Fitzgerald (1997). These index values were calculated using GIS coverages to find miles of road within 200 feet of the channel, and dividing by watershed area, to get an indicator of road sedimentation risk at each site.
- Used the BLM/USFS Proper Functioning Condition (PFC) method to evaluate all sites. Sites showing erosion and sediment deposition problems should be expected to reduce their width-to-depth ratio as sites return to a more natural condition (Appendix H).

Methods 1 and 2 both indicated 30% reductions as the maximum possible in the middle and lower basin streams. Methods 3 and 4, which were more qualitative than quantitative, supported that human caused sediment loading was likely very low in the upper basin. A 30% decrease in channel was applied to SSShade to calculate riparian shade values that could be attained if this full reduction occurred. These shade values were then modeled to show the resulting solar loading, and the temperature reductions that could be realized if these ideal channel widths were realized. The results are reported in the Loading Capacity Analysis section of this report.

Figure 17 shows the road sediment index values. The sediment risk from roads is low in Sites 3, 4, and 8; moderate in Sites 1, 9, and 10; and high in Sites 2, 5, 6, and 7. The PFC analysis identifies Sites 1, 8, 4, and 10 as in *Proper Functioning Condition*. Site 9 was *Functional-At-Risk*, and the others were *Nonfunctional* primarily because of sedimentation, bank erosion, and downcutting.

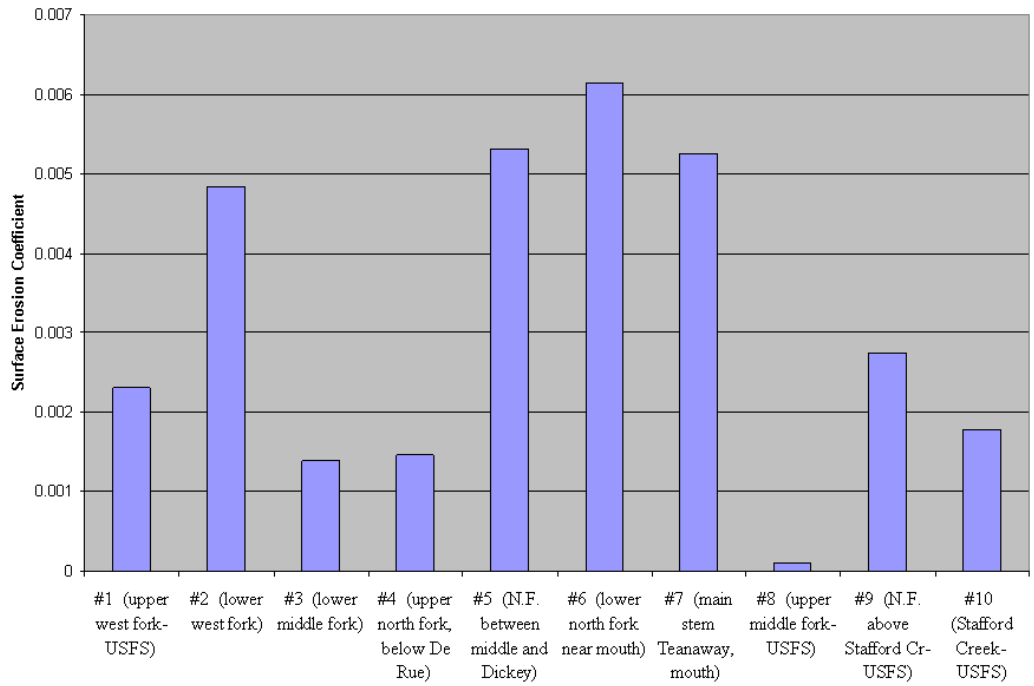

Figure 17. Road sediment risk index

Site 2 is impacted from logging roads; Sites 5, 6, and 7 from logging, recreation, agriculture, and animal access to streams; and Site 9 from recreation. In these areas, improving road maintenance, restricting animal access, and creating and maintaining buffers (as supported in the North Fork and West Fork Watershed Analysis Reports) would reduce sediment input and should be implemented.

Streamside buffers (Riparian Management Zones and Riparian Leave Tree Areas) were generally found to be effective at preventing sediment delivery and direct physical disturbances to streams (Rashin et al., 1999). Road drainage best management practices specify practices for installing relief culverts and were found to be effective for reducing sediment delivery in over half of the road sites evaluated by Rashin.

Riparian shade

Riparian shade acts to intercept solar radiation before it reaches the stream surface and can be very effective in preventing water temperature increases. Observations in the field, during download of hobo thermographs, indicated 4-5^{o}C air temperature differences between shaded hobos and hobos placed 15 feet away in the sun. This portion of the study had three goals: (1) estimation of the existing shade, (2) estimation of the maximum attainable shade that could be reached, and (3) estimation of the shade needed to meet water quality standards.

Existing riparian shade

Three methods were used to quantify the current riparian shade condition in the basin. The first of these was field collection of shade information using a forest densiometer and TFW protocols. The second and third methods used aerial and orthophotos to estimate current shade. These latter methods were attractive, because the cost of field sampling is high and photos are becoming readily available. The aerial photo method used was in accordance with TFW protocols; details are presented in Appendix C. The orthophoto method was developed under this study and has not been completely evaluated, but shows promise; it is outlined in Appendix D. Table C-2 shows a comparison of shade values collected using a densiometer, 1:15,840 color aerial photos, 1:12,000 black and white aerial photos, as well as shade values reported in the Teanaway North Fork and West Fork Watershed Analyses. For the most part, all methods estimated existing shade in the same general range. Ecology did, however, have much more confidence using 1:12,000 scale photos than using the 1:15,840 photos. Ecology proceeded with further analysis using the field collected densiometer readings.

Attainable riparian shade values for the Teanaway basin

Attainable riparian shade is defined for this study as the maximum shade that can be realized with a mature forest canopy. Attainable shade is calculated for each model reach and is reported in Table 6. The SSShade module of SSTEMP was used to calculate these shade values. Inputs to the shade calculation are:

- channel width
- vegetation offset from channel
- date
- latitude
- vegetation density
- vegetation height
- vegetation crown
- topographic shading
- stream azimuth

The following discussion covers selection and justification of the SSShade model input values.

Channel width: The active channel zone (ACZ) width as measured from aerial photos (Appendix C) and compared with field collected bankfull widths was used as the input for channel width. The active channel zone is readily identified from aerial photographs. The ACZ is defined as the water surface width plus adjacent dry channel bed, and unvegetated bars and/or low terraces. Generally the active channel is wider than the bankfull channel but smaller than the entire channel migration zone.

Table 6. Estimated attainable shade values for the Teanaway basin sample sites

Site Name	Site Number	Approximate Mean/Max ACZ Width	Existing Shade Average 0-2000' Upstream of Hobo	ACZ Width Used in Attainable Shade Calculation	Azimuth of Thermal Reach	Azimuth of Major Segment	Attainable Shade Estimate with Mature Tree Size A	Attainable Shade Estimate with Mature Tree Size B	Attainable Shade Estimate with Tree Size B and 30% Reduction in ACZ
Upper West Fork	1	40/75'	13.1%	60	-29	-35	62%	67%	NA
Lower West Fork	2	50/100'	29.0%	75	-78	-70	50%	61%	68%
Lower Middle Fork	3	75/150'	10.7%	100	2	-45	49%	57%	64%
Upper North Fork below De Rue Creek	4	40/75'	33.4%	60	-28	-25	63%	NA	NA
N.F. between Middle and Dickey Creeks	5	100/250'	10.6%	175	12	12	38%	46%	55%
North Fork near mouth	6	100/225'	13.0%	175	-9	30	36%	44%	54%
Mainstem Teanaway	7	125/250'	3.2%	180	21	45	32%	41%	52%
Upper Middle Fork	8	40/150'	27.7%	60	-41	30	62%	67%	NA
North Fork above Stafford Creek	9	40/90'	46.4%	65	-26	25	61%	66%	71%
Stafford Creek	10	30/60'	33.1%	45	47	60	67%	70%	NA

Mature tree size A is 90’ tall, has a crown of 25’, and a density of 75%

Mature tree size B is 125’ tall, has a crown of 30’, and a density of 75%

ACZ = the Active Channel Zone is defined as the water surface width plus adjacent dry channel bed, and unvegetated bars and/or low terraces

Existing shade is that measured with a densiometer during 1998

Vegetation offset from channel: A vegetation offset of zero was used, because Ecology assumes that trees will be growing at the edge of the ACZ. Similar assumptions were applied to the Simpson temperature TMDL when making shade calculations with the Shadow model (Cleland, 1999).

Date: June 22 was used as the date because it is the longest day of the year. Since June 22 also would have the least shade, using this date may underestimate the shade that could be produced later in the summer.

Latitude: A latitude of 47 degrees 17 minutes was used, which was average for the Teanaway basin.

Vegetation density: The vegetation density was assumed to be 75%. A tree density of 100% is not possible and could be interpreted as a total block of solar radiation. Cleland (1999) uses a density value of 80% for the Simpson TMDL, and Steve Butkus (1998) uses 85% for the Snohomish basin, both in western Washington. Eastern Cascade slope forests are typically less dense than those in western Washington. The significance of the density value is that the maximum shade that will result from this analysis is 75%.

Vegetation height and crown: Vegetation height and crown information was collected by personal correspondence (Trowbridge, 1999) from the Cle Elum Ranger District. These data are estimates for mature trees commonly found in this region, and consider climatic and soil conditions. Shade values have been calculated using two sizes of mature trees to allow flexibility in any restoration work. The size A tree (Table 6) has a feet height of 90 feet, and a crown of 25 feet and the size B tree has a height of 125 feet and a crown of 30 feet.

Stream azimuth: The stream azimuth was the average for the model reach as estimated from USGS quad maps. SSShade calculations, using the azimuth of the thermal reach measured in the field, produced almost identical attainable shade values as those using the entire model reach. The largest difference was 2%.

Stream orientation (azimuth) is an important factor to consider when calculating attainable shade. Figure 18 shows percent of the stream that is shaded on a monthly basis, holding tree size and channel width constant but varying the stream azimuth. A stream flowing due east (azimuth –90) or due west (azimuth 90) would need larger trees to attain the same summertime shade value as a stream flowing due south (azimuth 0). Because the sun is over the Northern Hemisphere in the summer, streams oriented in an east-west direction may see direct sunlight very early in the day. Site 2, with an azimuth of -78 and thus an east-west type orientation, was generally much warmer when measured at the same time with a thermometer than was Site 3, located less than ½ mile away but with an azimuth of 2 degrees.

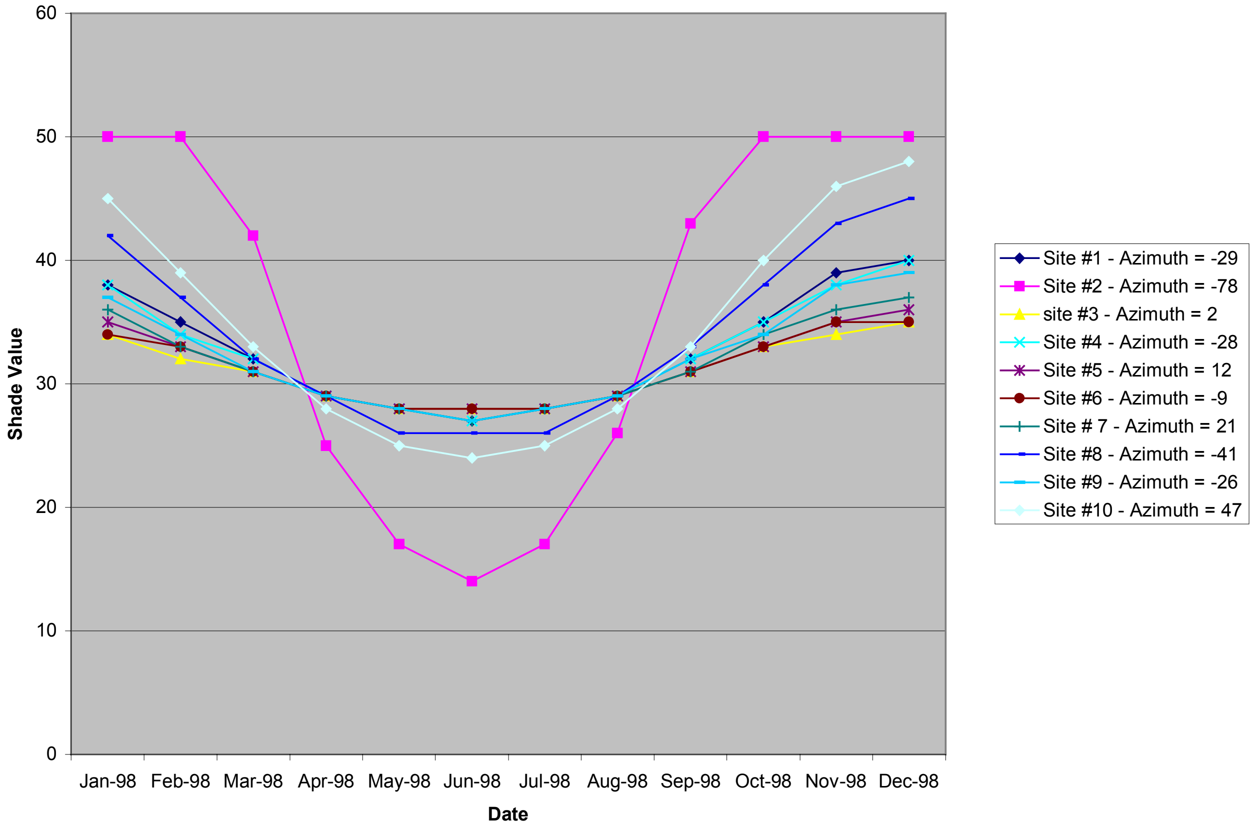

Figure 18. Sensitivity analysis – effect of stream azimuth on stream shade by month

Because streams with wide active channels cannot meet the maximum of 75% shade, further calculations assumed that the maximum channel width reduction that could be achieved with sediment reduction is 30%. Table 6 shows that the wider type C and D channels found on the mainstem and the North Fork can be expected to produce 50% shade. Current shade values range from 3-12% in these reaches. The mouths of the West and Middle Fork could attain 60% shade at maximum canopy, and the upper stations are capable of 65% shade. Smaller forks can all be expected to approach 70-75%. Ecology expects that these estimates accurately portray the maximum attainable shade expected in this basin.

Loading Capacity Analysis

Determination of the loading capacity requires defining the critical conditions, which is when pollutant loading has the greatest potential for exceeding the state water quality standards. For this analysis, the peak three-day air temperature period for 1998, which also coincided with the peak water temperature for this year, was selected as critical conditions. This period was July 26, 27, and 28, with the peak day being July 28, 1998. The Teanaway below Forks gage data show that July 28 is the 95th percentile for air temperature, based on the period 1995 – 1998. July 28, 1998 was also used for critical conditions in the draft Snohomish Temperature TMDL (1998).

Loading capacities are based on the temperature water quality standards that give an upper criterion that may not be exceeded (16 or 18°C, depending on classification), and a limit of 0.3°C when natural conditions exceed the criterion. Thermal loading capacities for streams in the Teanaway River Basin Temperature Assessment are presented in units of energy per time (joules/m^2/second). However, these values are of little use for stream management. The loading capacities and the TMDL allocations are also expressed as targets for percent shade, as allowed by federal regulations. Because these shade estimates were made using trees in the riparian buffer of a definite height and crown, allocations can also be expressed in terms of size of tree in the buffer that is necessary to ensure these shade values. The change in temperature, amount of shade required to achieve the criteria, and the thermal loads were determined for each of the modeled stream segment categories (Tables 7 and 8).

In Table 7 loading estimates were calculated with SSTEMP using the model parameterization as described earlier in this report. "Current condition" shows the amount of solar load currently being applied to the stream. The "shade required to meet the 16°C or 18°C temperature criteria" column shows the amount of shade needed for the stream to achieve the criteria during the critical conditions set in this analysis. The "site potential or achievable shade" column shows in its upper part, the shade that is achievable with a mature riparian forest. The lower portion of the column shows, for those segments determined to have sediment loading, the amount of shade achievable with a mature riparian forest and a 30% reduction in the active channel zone width.

Except for the Headwaters to Site 4 segment, the shade required is more than can be achieved through growth of site potential trees and through a 30% reduction in the ACZ width. Because Ecology is unable to quantify all potential benefits to water temperature through restoration, determination of the water temperature of the natural condition would be made after the watershed is well into restoration. Required solar load decrease is calculated using the loading capacity attainable with both the sediment and harvest reductions.

For all segments, a significant reduction in mean daily temperature can be realized. Water temperature decreases are expressed in terms of the mean daily temperature, because the SSTEMP model was a better predictor of the mean. The expected decreases in the maximum daily water temperature would be greater. Model results and a linear relationship between the mean and maximum water temperatures at each site show that the average 1.5°C reduction in the mean daily water temperature due to riparian shade corresponds to a 3°C reduction in the maximum daily water temperature. The additional 0.5°C reduction due to sediment reduction corresponds to a further reduction in the maximum of 0.5 to 1.0°C. For Site 7, the expected 1.67°C reduction in the mean daily temperature would be accompanied by a 3°C reduction in the maximum daily temperature.

The predictions of temperature reductions presented in this report assume that background conditions stay constant, especially those affecting volume of surface water or groundwater. The analysis assumes that, as in 1998, water rights upstream of the forks gage are bought back and are not withdrawing surface water. It further assumes that groundwater withdrawals in continuity with the stream are in the same amounts and locations as in 1998 and that upland land management practices such as clearing, which have the potential to alter flow patterns, are as in 1998.

Table 7. Loading capacity of modeled stream segments

Perennial Stream Reach	Existing Shade Condition (%)	Current Condition Solar Load (j/m2/s)	Shade Required to Meet 16°C or 18°C Temperature Criteria	**Site Potential Achievable Shade** (riparian/ riparian & sediment)	Solar Loading Capacity Site Potential Shade (j/m2/s)	Nonpoint Source of Pollutant	Decrease in Current Mean Temperature with Achievable Shade (°C)	Required Solar Load Decrease (%)
Headwaters to Site 4	33	213	33 (16°C)	63	122	Harvest		0
Sites 4 to 9	46	173	85 (16°C)	66 71	109 93	Harvest H + Sediment	1.50 1.86	46
Sites 9/10 to 5	11	285	93 (18°C)	46 55	173 144	Harvest H +Sediment	1.87 2.36	50
Sites 5 to 6	12	282	100+ (18°C)	44 54	179 147	Harvest H +Sediment	1.34 1.75	48
Sites 6 to 7	3	310	100+ (18°C)	41 52	189 154	Harvest H +Sediment	1.3 1.67	50

Table 8. Loading capacity of one-mile modeled stream segments

Perennial Stream Reach	Existing Shade Condition (%)	Current Condition Solar Load (j/m2/s)	Shade Required for no temperature gain/mile Criteria	**Site Potential Achievable Shade** (riparian/ riparian & sediment)	Loading Capacity Site Potential Shade	Nonpoint Source of Pollutant	Gain for One mile segment at existing conditions	Water Temperature gain for one mile segment at goal conditions	Required Solar Load Decrease (%)
Site 10	27	233	73	70	96	Harvest	NA	.05ºC	59
Site 8	28*	233	55	67	105	Harvest	0.71C	-.34ºC	35
Site 3	11	284	80	57 64	138 115	Harvest Sediment	1.71	.40ºC	59
Site 1	13*	278	55	67	105	Harvest	1.08C	-.29ºC	62
Site 2	29	228	80	61 68	124 102	Harvest Sediment	Similar to Site 3	.31ºC	55
Other Rosgen B Segments	N/A	N/A		70					
Other Rosgen C Segments	N/A	N/A		60					
All Other Tributaries*	N/A	N/A		70					

* Confidence in existing shade estimates for these segments are lower because (1) of discrepancies with aerial photos and (2) only five densiometer readings were taken on segment 1 instead of the standard ten.

Segment 2 is possibly warmer than shown here. Hand thermometer readings taken on this east-west orientation stream are warmer .

Shade requirements for Sites 1 and 8 for no temperature gain may be underestimated. The estimate for groundwater inflow was calculated using the same percent per mile gain as in the Site 4 - 9 segment (because of their similar elevation and placement in the watershed). However, because the stream flow is much lower and the water temperatures are high, the riparian shade and sediment controls should be the best possible.

Margin of Safety

Margin of safety is incorporated in three ways:

- Conditions measured on the same day as the 95th percentile maximum July and August air temperature were used as the basis for the temperature assessment calculations.
- SSTEMP tended to over predict maximum daily water temperature during the critical condition, which results in conservative required shade values being set.
- No 0.3°C temperature increase over natural conditions is allowed per state statute.

Actual streamflow measured on July 28 was used to model the critical condition. This represented the 7-day median low-flow value or 7Q2. This should represent all flow available in a typical low-flow year, since no water rights were active above the gage. Using a 7Q10 value would lower the modeled flow by a factor of ½.

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Conclusions

- Analysis and stream temperature modeling with the Stream Segment Temperature Model (SSTEMP) show that increases in riparian shade, reduction in active channel width, and increases in streamflow can lower stream temperatures. Estimates made with the best available data are that a 1.5ºC to 3ºC reduction in mean daily water temperature could be realized with a mature riparian buffer, sediment controls for roads, and streamflow increases. The reduction in maximum daily water temperature would be approximately 3ºC to 6ºC under the most favorable simulated conditions. These estimates are made for a *critical condition*, which for stream temperature is a time of low flow and high air temperature. The summer of 1998 had good conditions for a critical analysis.

- At critical low-flow and high-temperature conditions, establishment of a full mature riparian stream corridor will result in shading that produces a 35 to 62% reduction in solar radiation load. This solar load reduction correlates to an estimated 1.5ºC reduction in mean daily temperature and a 3ºC reduction in maximum daily temperature. Sediment load reductions resulting from an established mature riparian corridor and improved road maintenance, as recommended in the North Fork and West Fork Teanaway Watershed Analysis Reports, are estimated to reduce the width of in the active channel zone and the channel width-to-depth ratio. An additional 10% reduction in solar radiation load, and a 0.5ºC reduction in mean daily temperature (0.5 to 1ºC reduction in the maximum daily temperature), are expected to be realized through sediment control. Doubling the flow in the lower segment of the North Fork from 20 to 40 cubic feet per second (cfs) and in the mainstem from 27 to 50 cfs, using existing riparian shade, decreases the mean daily temperature by 1ºC (and the maximum daily temperature by 2ºC).

- In addition to providing shading, a mature riparian corridor is expected to allow growth of vegetation that can stabilize the bank during high flows, dissipate stream energy, and reduce the amount of bank cutting. It is also expected that restricting the access of cattle and other animals to the stream will be necessary to encourage riparian growth and thus reduce damage to banks. There are additional unquantifiable benefits to stream temperature that have not been addressed in this study, but are possible as a mature riparian buffer becomes established. Some of these are:

  ◊ Increase of large woody debris to the stream – providing salmon habitat, pool-forming, and sediment-trapping.

  ◊ Additional support for smaller vegetation – providing stream shading.

  ◊ Gravel bed shading – resulting in cooler conditions for water moving under or through those gravels.

  ◊ Cooling of ambient air temperature (because air temperature under a mature canopy is usually lower than that over bare or sparsely covered ground) – causing a further reduction in heat transfer to the stream.

  Long-term monitoring would be required to determine actual temperature reductions realized.

- When natural conditions exceed the numeric water temperature standards of 16ºC for Class AA streams and 18ºC for Class A streams, no temperature increase will be allowed which will raise the water temperature by greater than 0.3ºC (Chapter 173-201A WAC). Because of the unquantifiable benefits described above and the uncertainty associated with any model, this study does not attempt to specify what stream temperatures constitute *natural conditions*. Natural conditions in the Washington State water quality standards means conditions prior to human influence. The intent of this pilot approach is to identify some of the major human impacts on stream temperature, in the hope of identifying actions that will cause the stream temperature to more closely approach natural temperatures. Some areas of the watershed that have not been heavily harvested and do not contain roads (e.g., the upper Middle Fork of the Teanaway) may already be approaching their natural condition. Further monitoring of that sub-basin, upstream of human impacts, would be necessary to make this determination.

Recommendations

- Restore a full mature riparian buffer to provide shade, stabilize banks, provide large woody debris, and provide other stream habitat benefits.

- Reduce sediment input to streams through improvements in road maintenance, as described in the North Fork and West Fork Watershed Analysis Reports.

- Implement other methods of reducing sediment input to the streams, such as fencing and restricting animal access.

- Continue water right buyback transactions that have occurred to date. A larger volume of water cannot be heated as quickly as a smaller one, and a larger volume can assimilate more heat load for the same rise in temperature than a smaller one. Streamflow levels in the basin will be an important component of temperature control.

- When making water permitting and development decisions, consider the negative impacts of withdrawing groundwater that may otherwise be cooling the stream during the summer.

- Use local agency and landowner expertise, along with data gathered in the North Fork and West Fork Watershed Analysis Reports, to prioritize areas for restoration.

- Develop further the method of using orthophotos to estimate riparian shade.

- Gather stream slope, aspect, and elevation information using GIS and other mapping techniques, instead of gathering information in the field.

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Appendices

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Appendix A

Graphical Presentation of Air and Water Temperature Data Collected in the Teanaway Basin, July 1 – October 7, 1998

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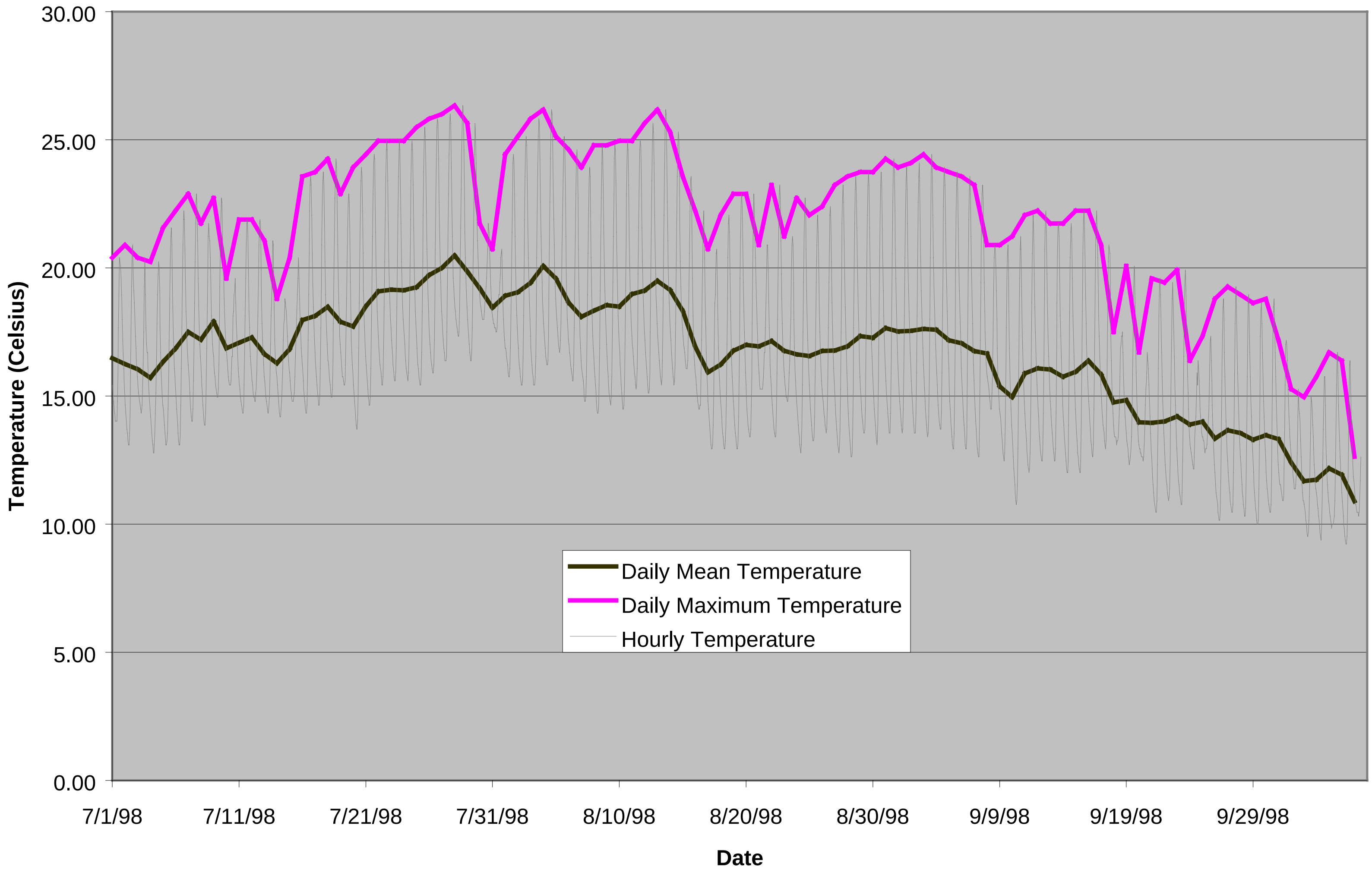
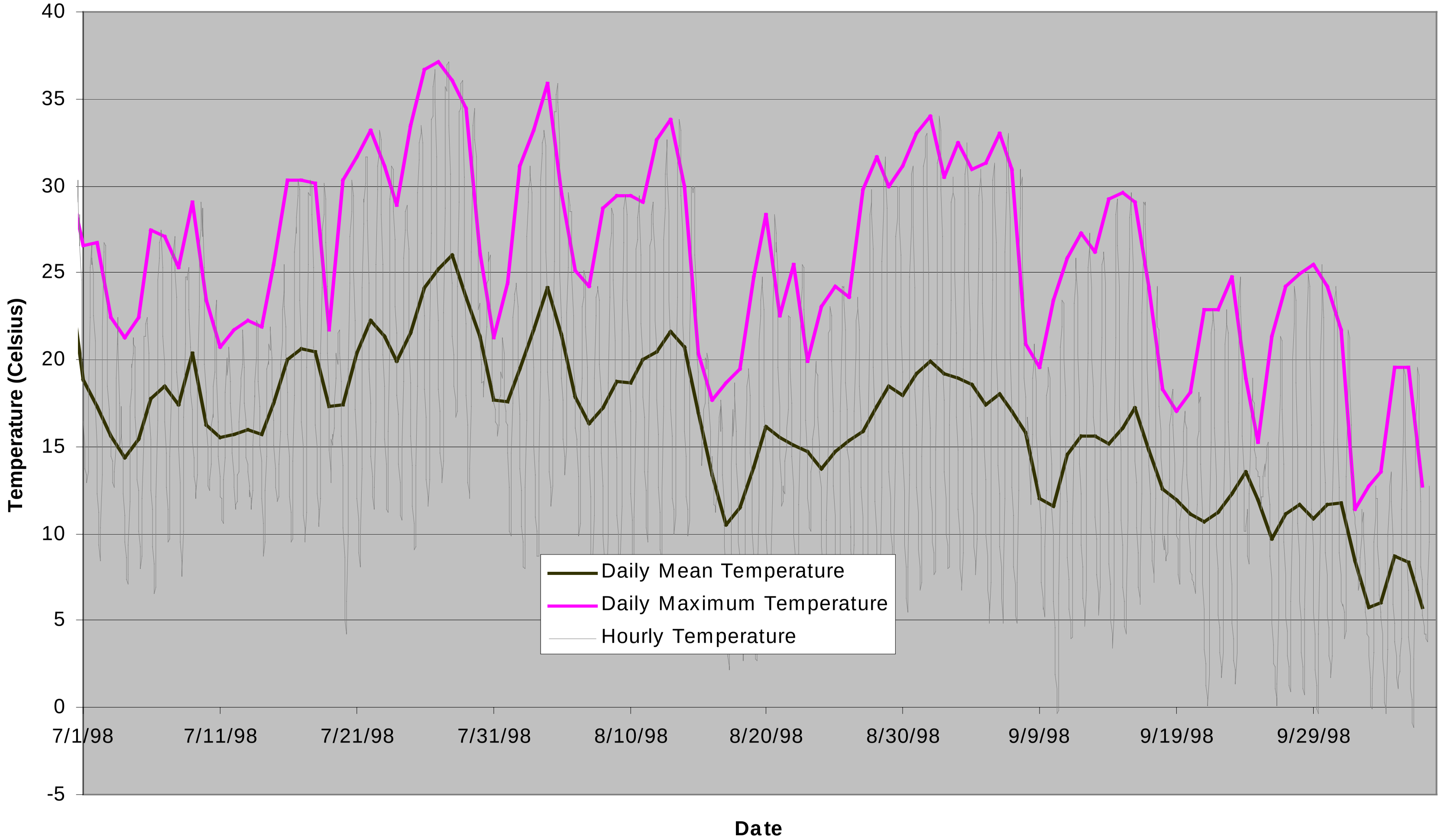
Figure A-1.

Maximum, Mean, and Hourly Water Temperature for the Lower Middle Fork Teanaway River (Site #3) from 7/1/98 to 10/7/98



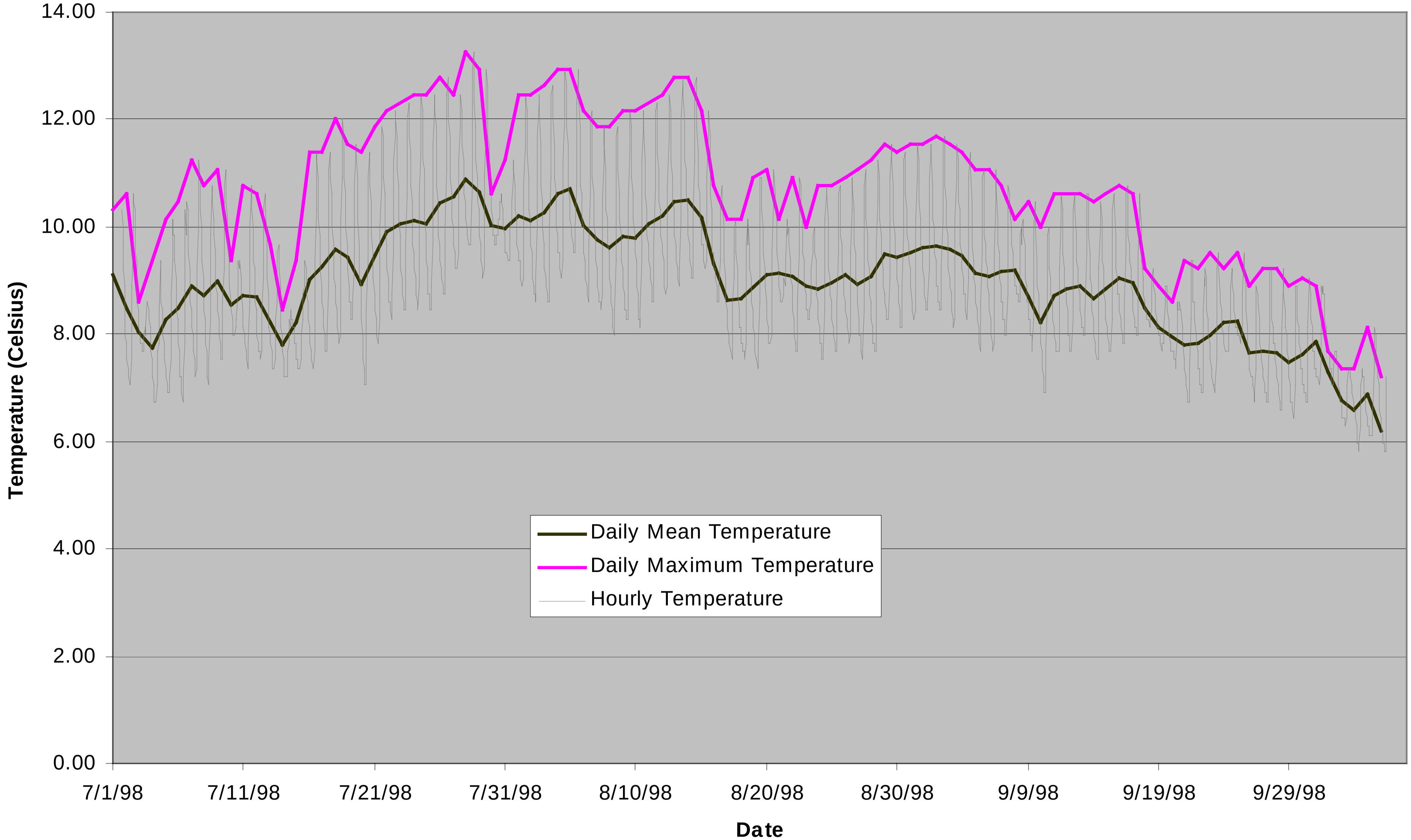
NOTE: Some values for 8/18/98 may be missing because of thermograph download and relaunch

Figure A-2.
Maximum, Mean, and Hourly Air Temperature for the Lower Middle Fork Teanaway River (Site #3) from 7/1/98 to 10/7/98



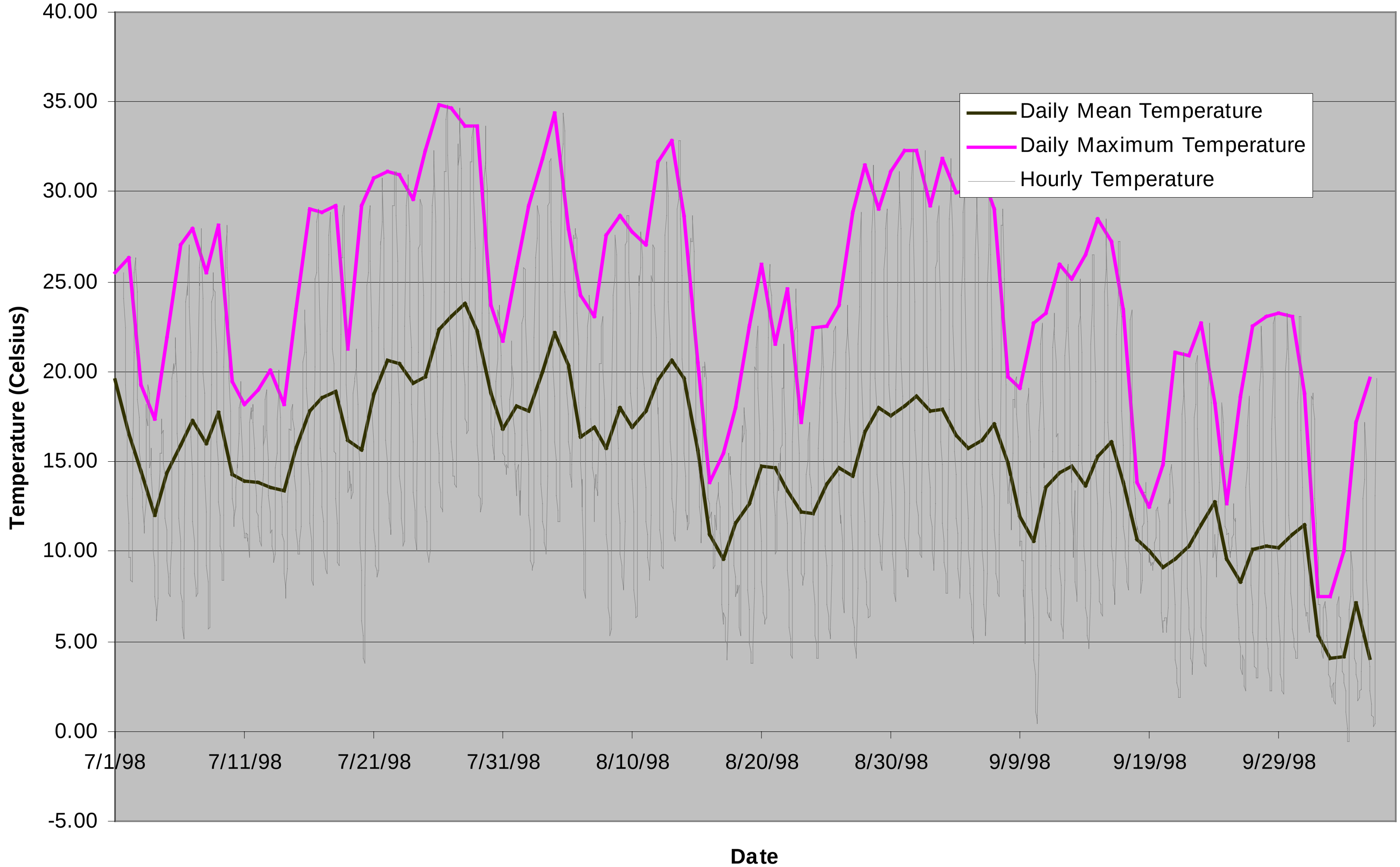
NOTE: Some values for 8/18/98 may be missing because of thermograph download and relaunch

Figure A-3.
Maximum, Mean, and Hourly Water Temperature for the Upper North Fork Teanaway River, below De Rue Creek (Site #4) from 7/1/98 to 10/7/98



NOTE: Some values for 8/18/98 may be missing because of thermograph download and relaunch

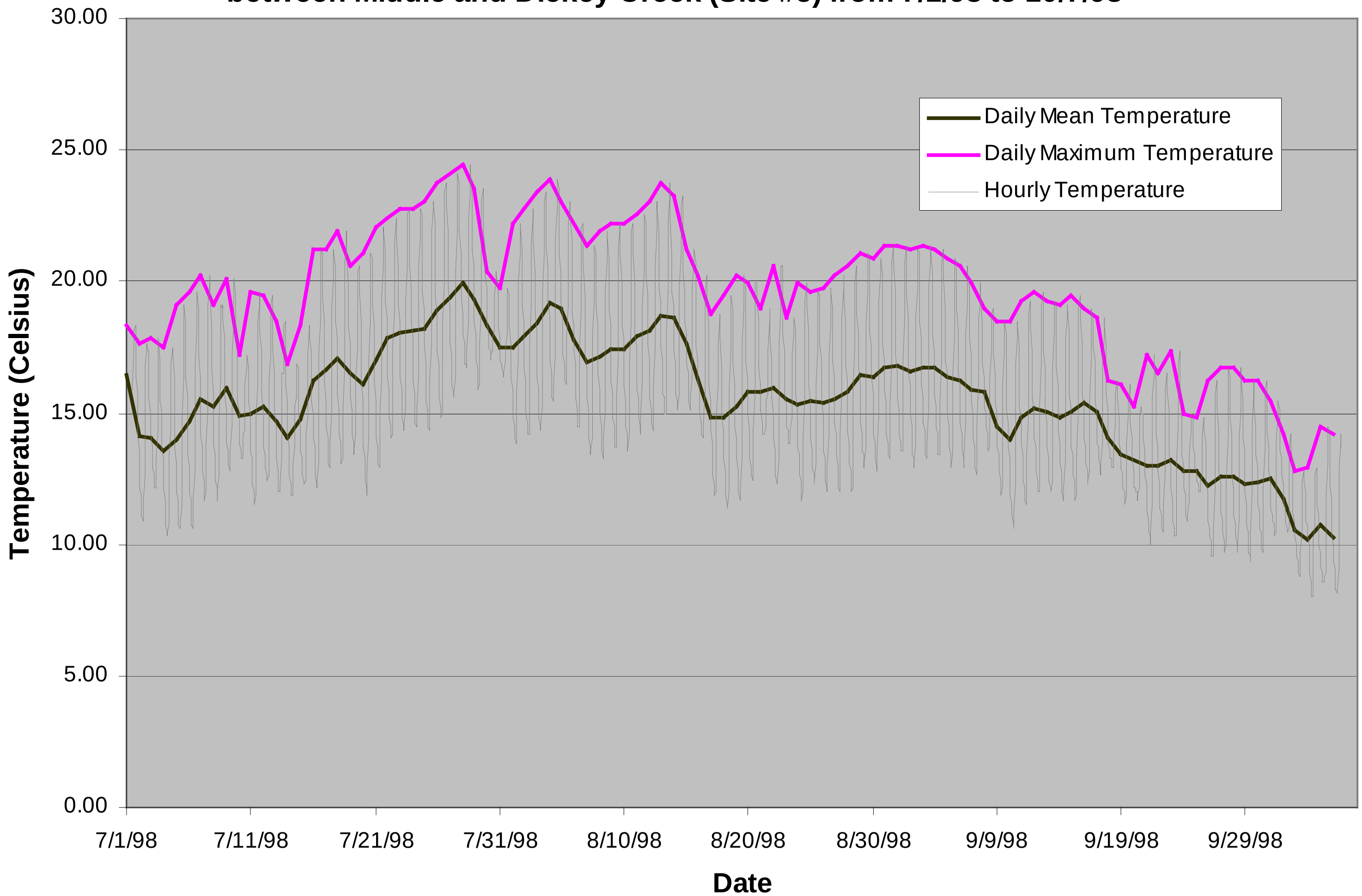
Figure A-4.
Maximum, Mean, and Hourly Air Temperature for the North Fork Teanaway River, below De Rue Creek (Site #4) from 7/1/98 to 10/7/98



NOTE: Some values for 8/18/98 may be missing because of thermograph download and relaunch

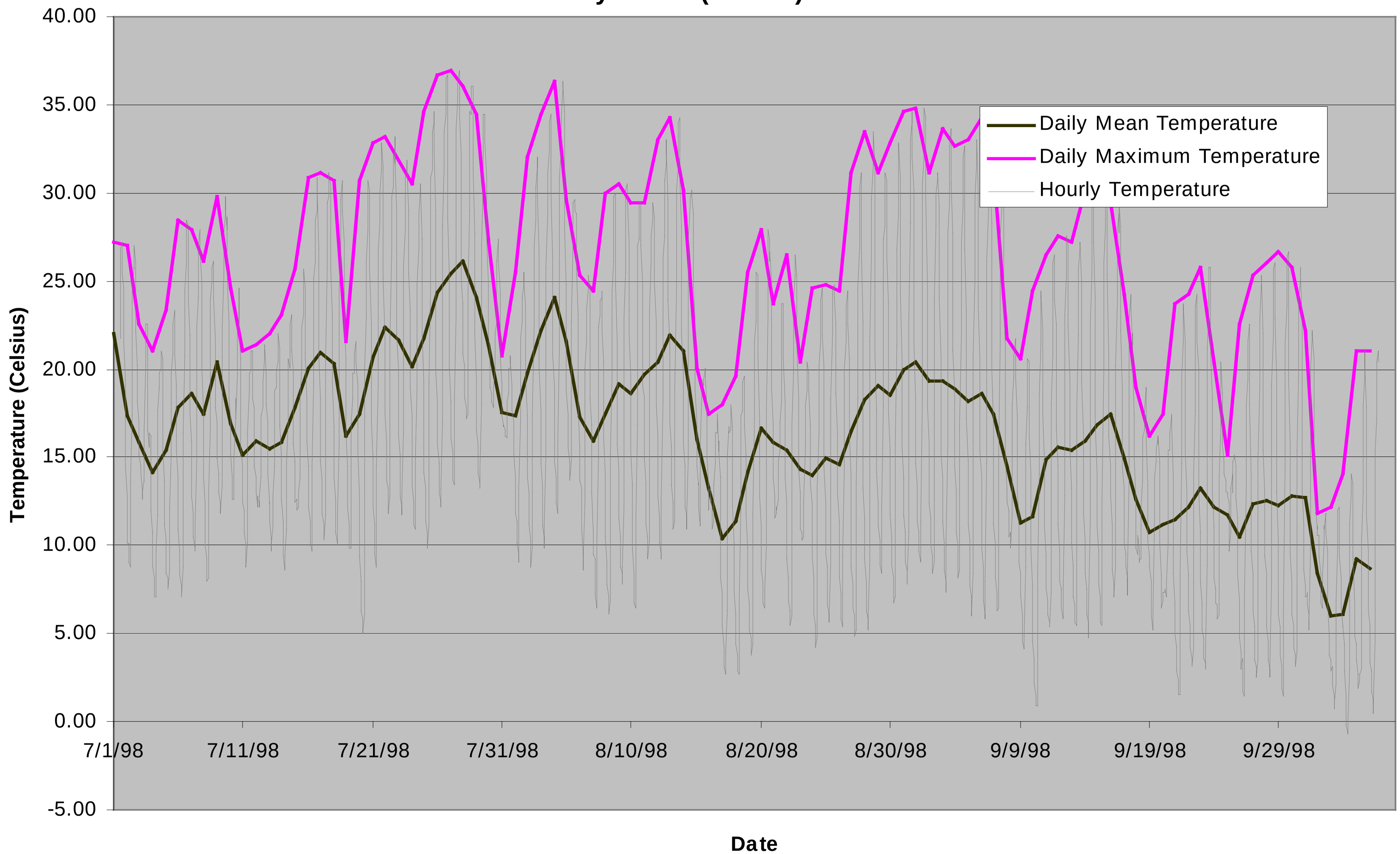
Figure A-5.

Maximum, Mean, and Hourly Water Temperature for the North Fork Teanaway River, between Middle and Dickey Creek (Site #5) from 7/1/98 to 10/7/98



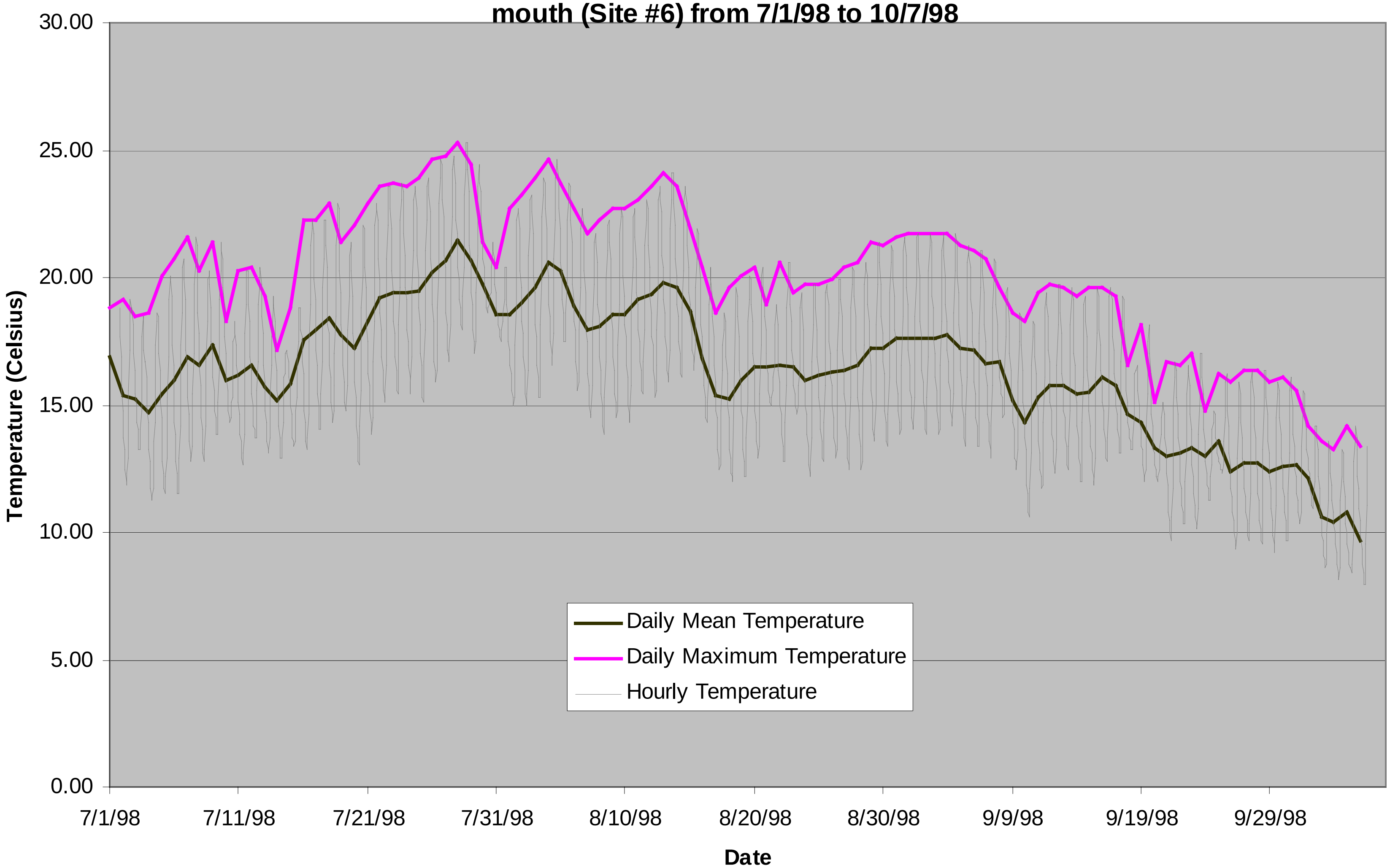
NOTE: Some values for 8/18/98 may be missing because of thermograph download and relaunch

Figure A-6.
Maximum, Mean, and Hourly Air Temperature for the North Fork Teanaway River, between Middle and Dickey Creek (Site #5) from 7/1/98 to 10/7/98



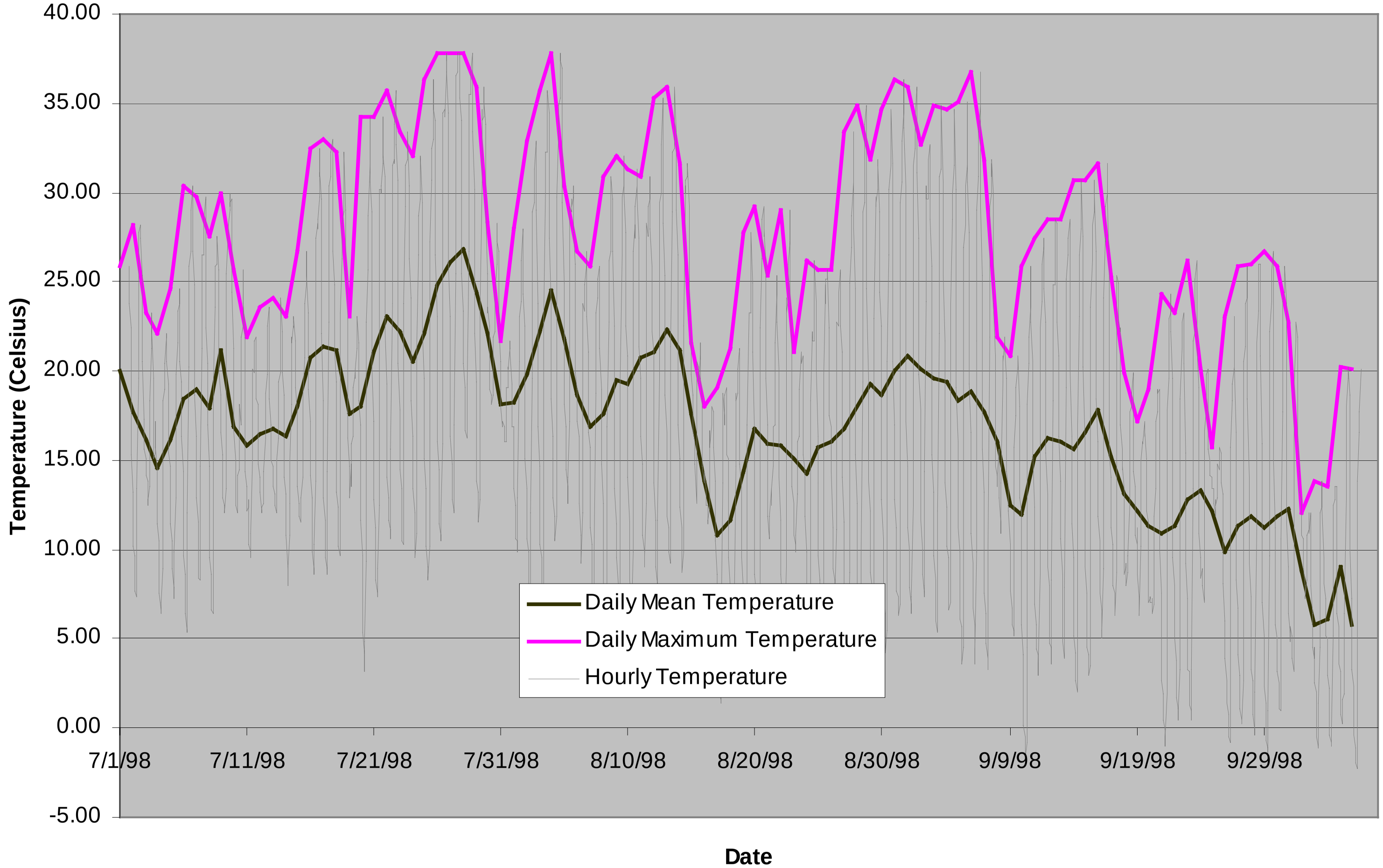
NOTE: Some values for 8/18/98 may be missing because of thermograph download and relaunch

Figure A-7.
Maximum, Mean, and Hourly Water Temperature for the North Fork Teanaway River, near mouth (Site #6) from 7/1/98 to 10/7/98



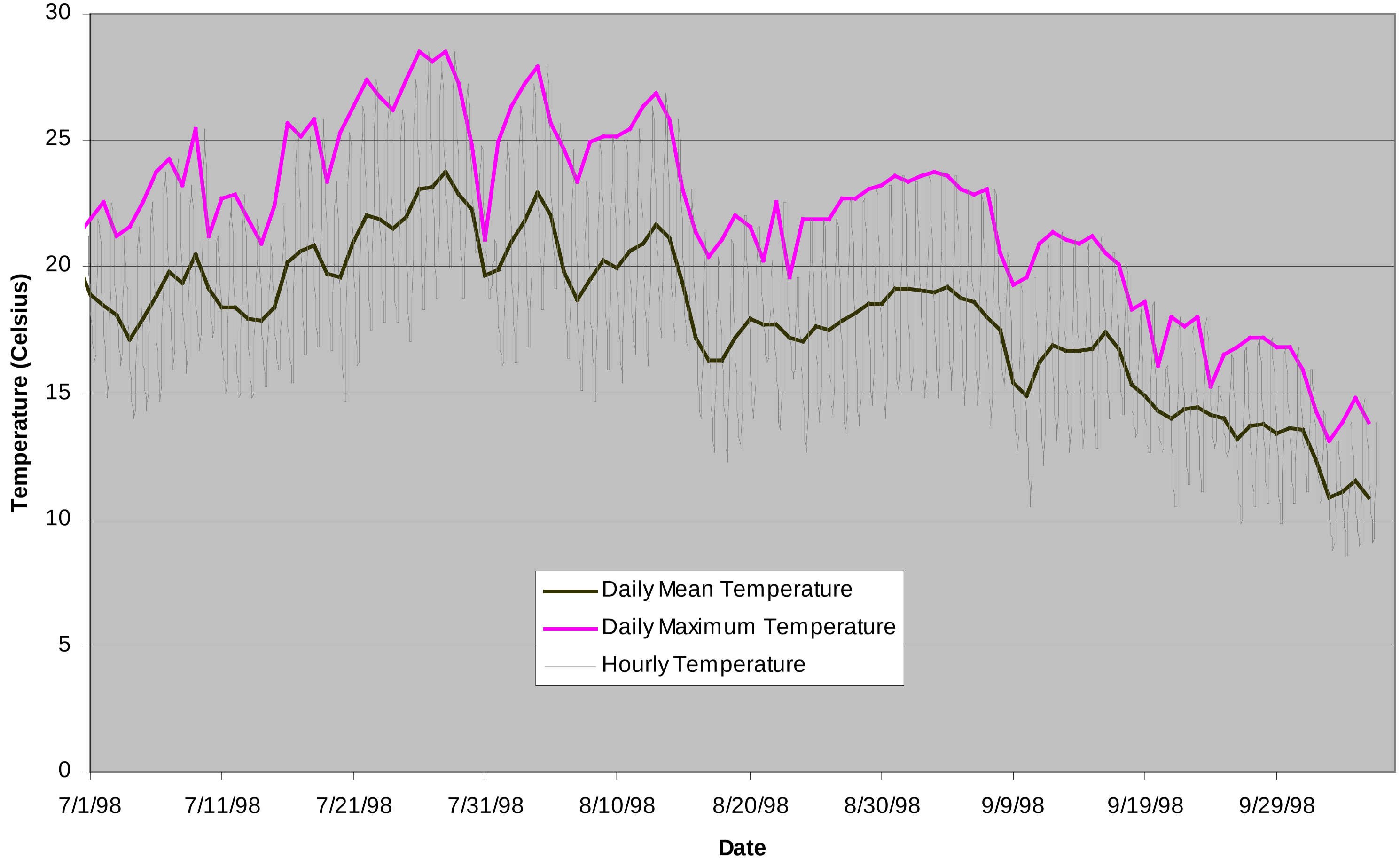
NOTE: Some values for 8/18/98 may be missing because of thermograph download and relaunch

Figure A-8.
Maximum, Mean, and Hourly Air Temperature for the North Fork Teanaway River, near mouth (Site #6) from 7/1/98 to 10/7/98



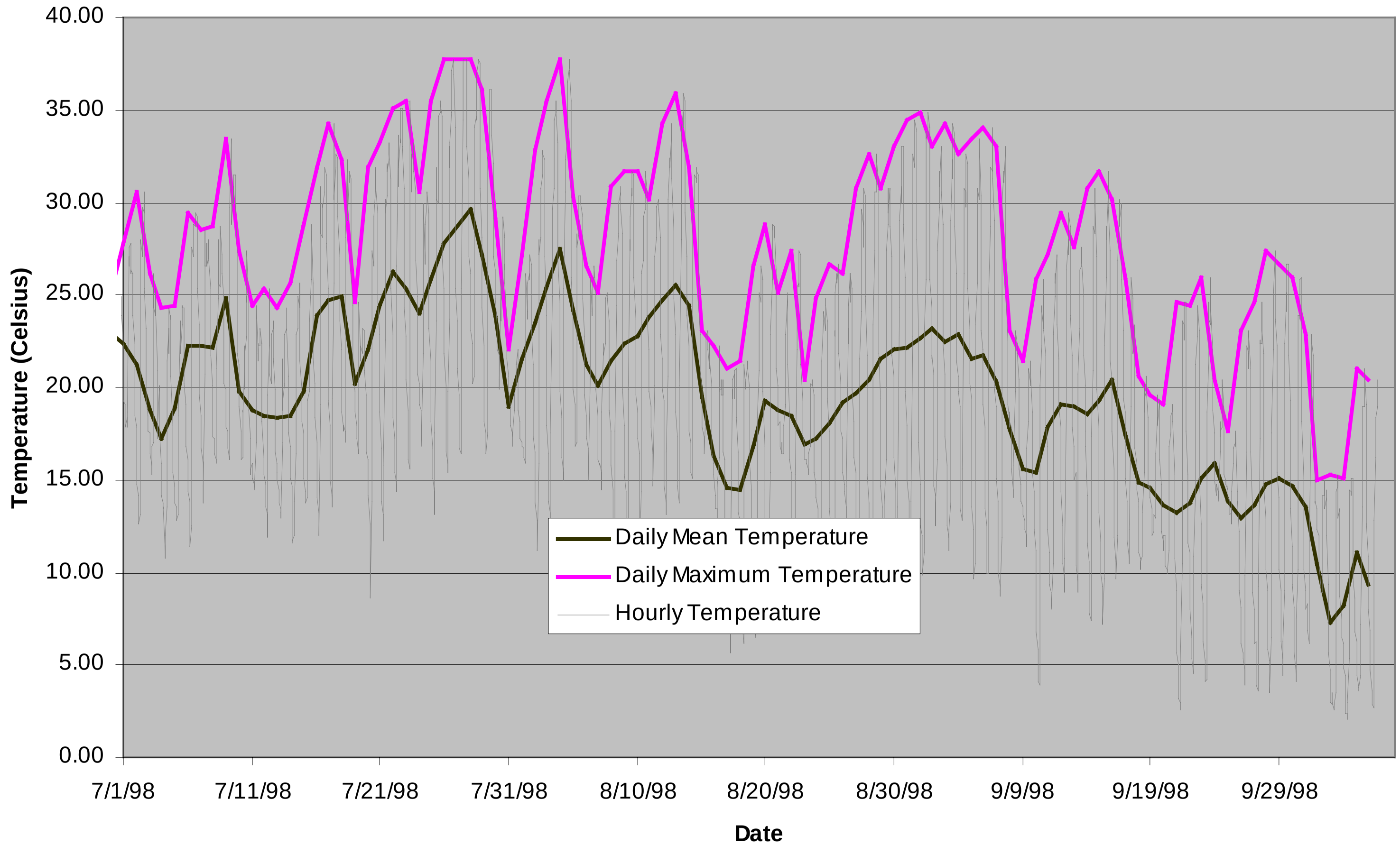
NOTE: Some values for 8/18/98 may be missing because of thermograph download and relaunch

Figure A-9.
Maximum, Mean, and Hourly Water Temperature for the Main Stem Teanaway River, near mouth (Site #7) from 7/1/98 to 10/6/98



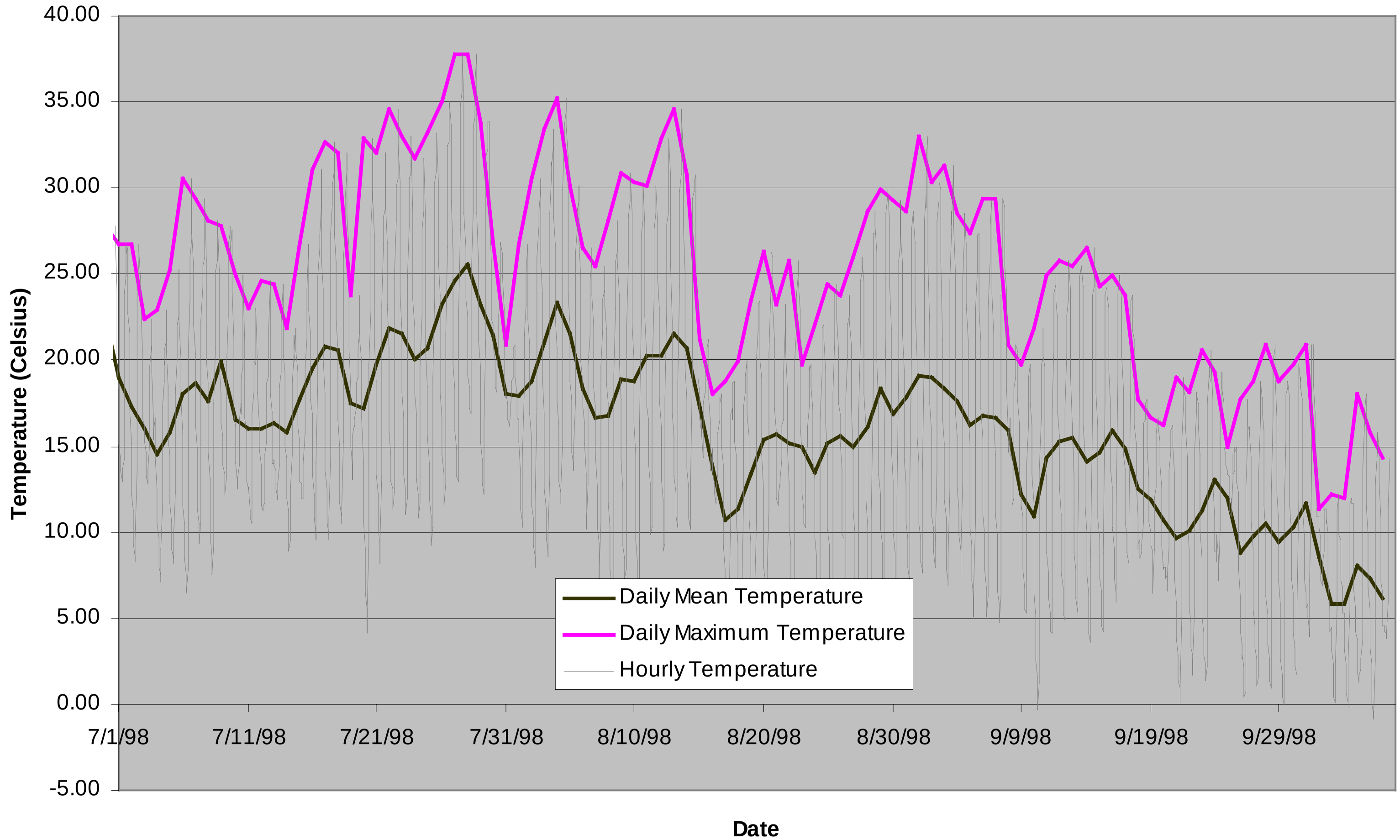
NOTE: Some values for 8/18/98 may be missing because of thermograph download and relaunch

Figure A-10.
Maximum, Mean, and Hourly Air Temperature for the Main Stem Teanaway River, near mouth (Site #7) from 7/1/98 to 10/6/98



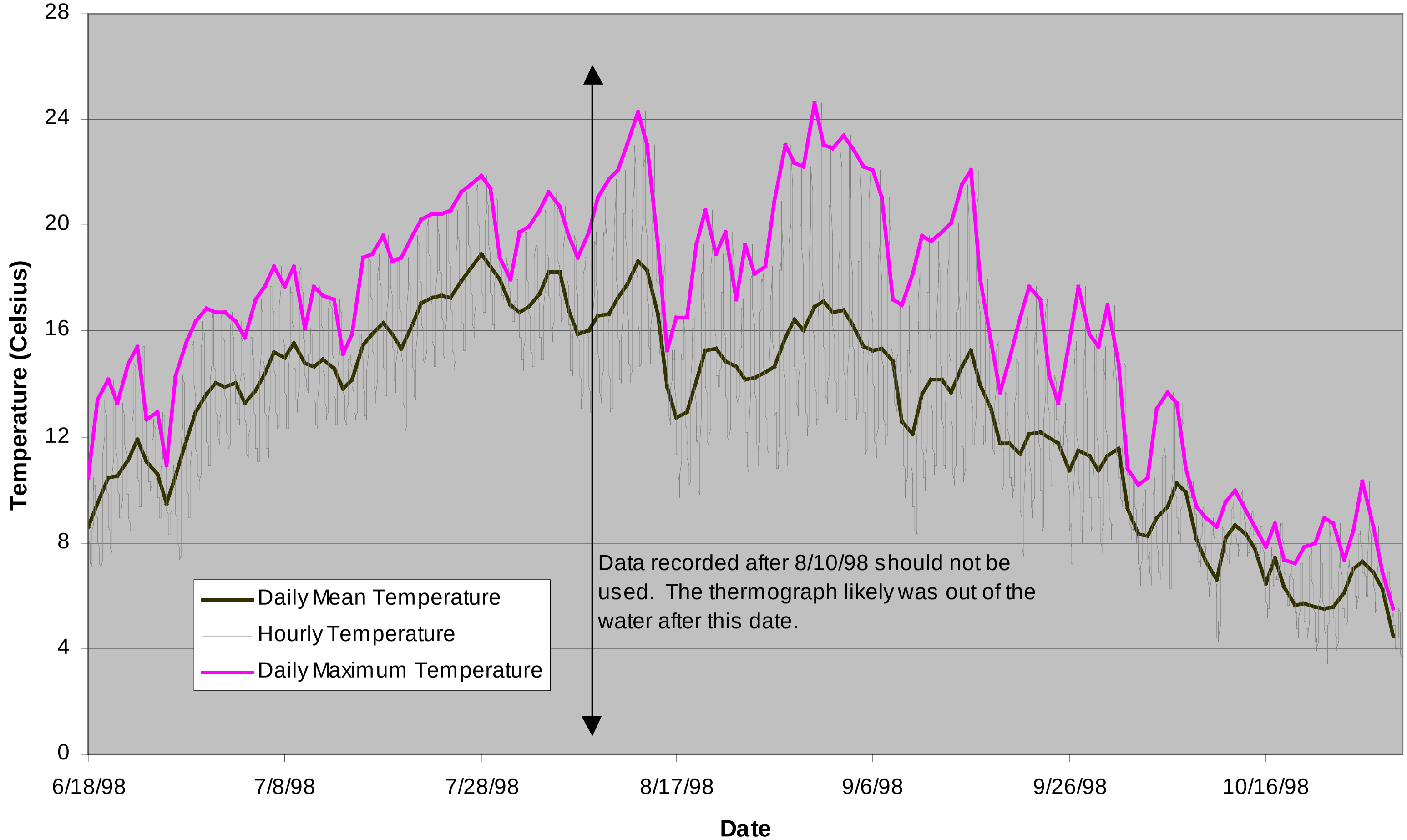
NOTE: Some values for 8/18/98 may be missing because of thermograph download and relaunch

Figure A-11.
Maximum, Mean, and Hourly Air Temperature for the Lower West Fork Teanaway River, near mouth (Site #2) from 7/1/98 to 10/7/98



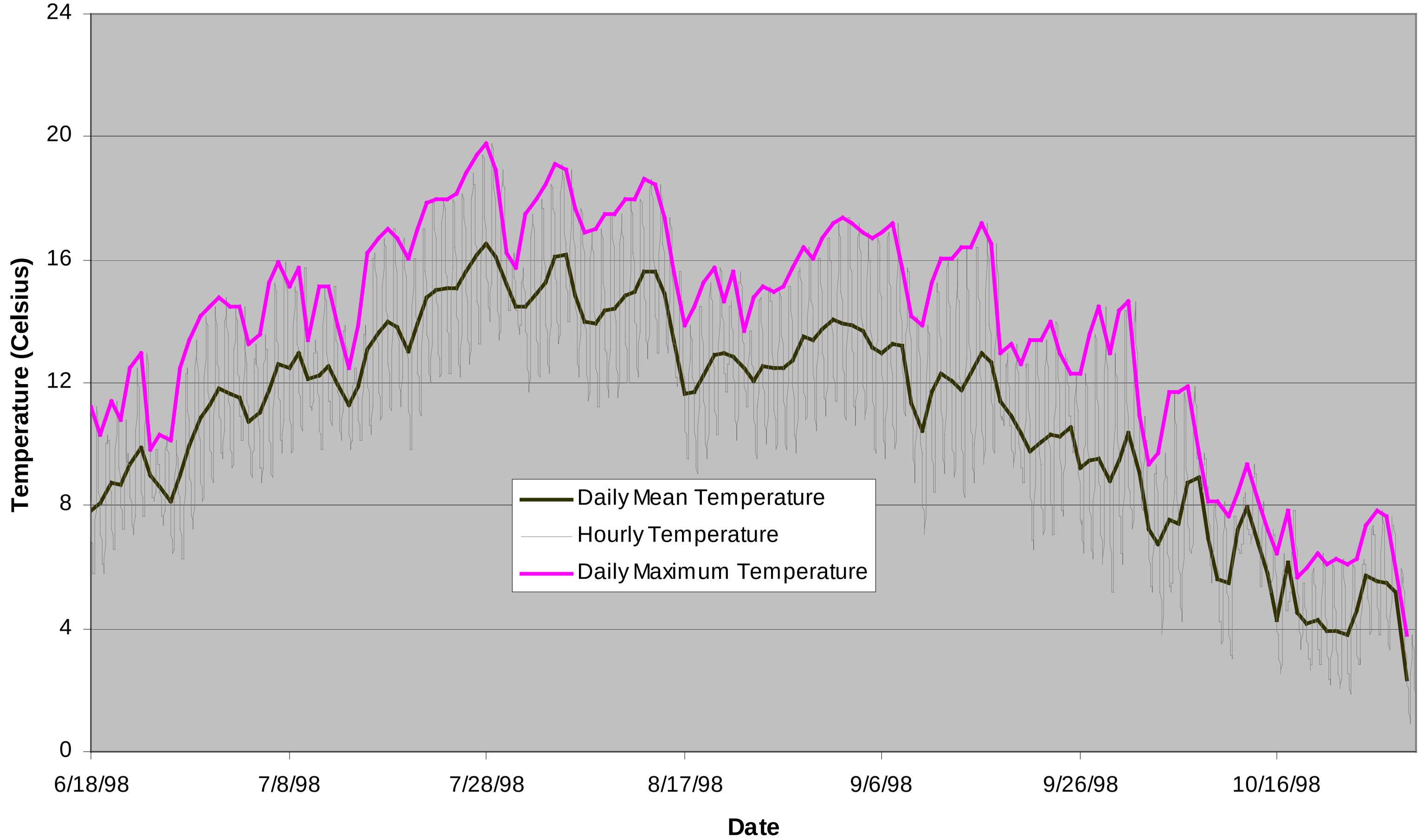
NOTE: Some values for 8/18/98 may be missing because of thermograph download and relaunch

Figure A-12.
Maximum, Mean, and Hourly Water Temperature for the Upper Middle Fork Teanaway River (USFS - Site #8) from 6/16/98 to 10/29/98



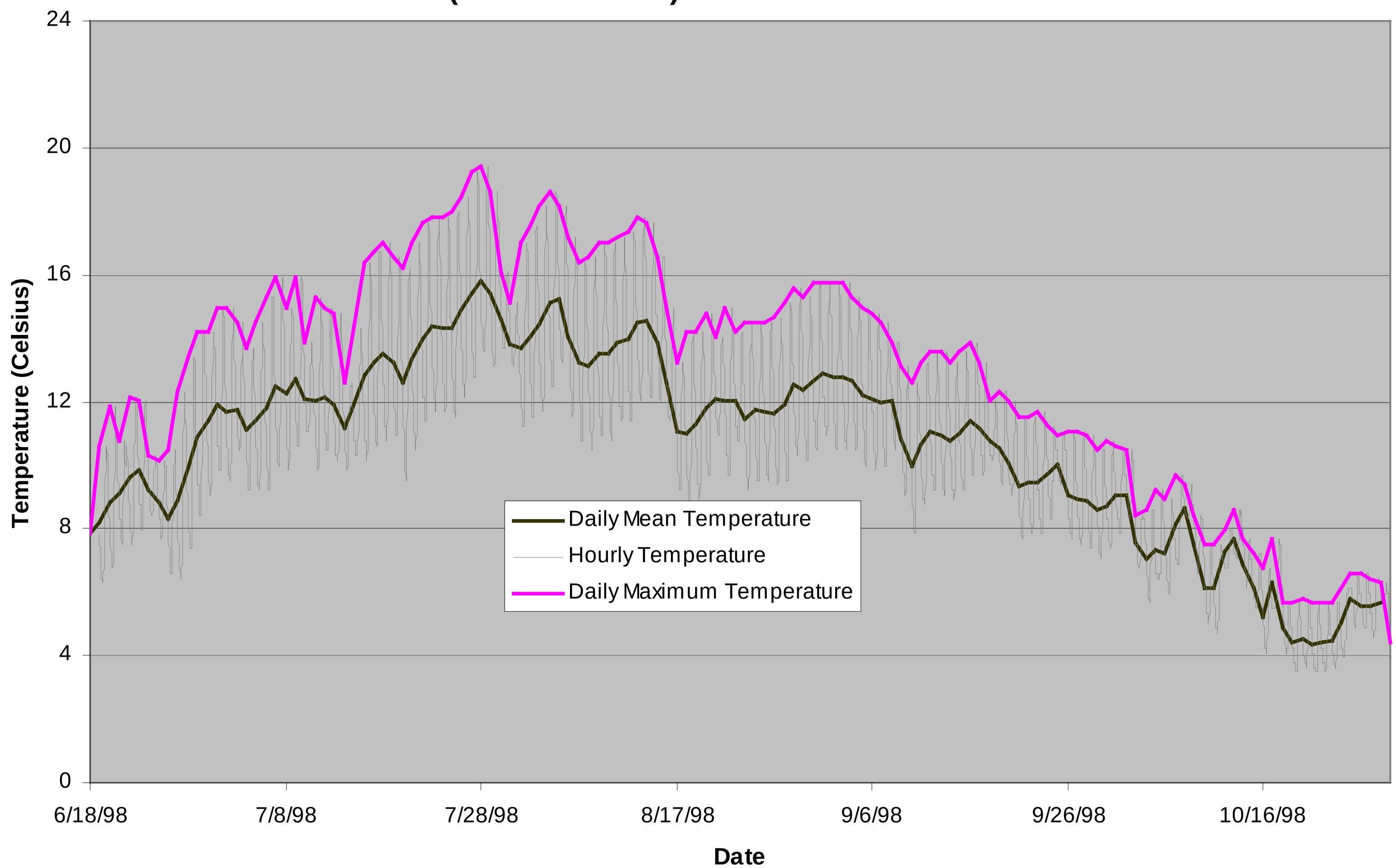
NOTE: Some values for 8/18/98 may be missing because of thermograph download and relaunch

Figure A-13.
Maximum, Mean, and Hourly Water Temperature for the North Fork Teanaway River, above Stafford Creek (USFS - Site #9) from 6/18/98 to 10/29/98



NOTE: Some values for 8/18/98 may be missing because of thermograph download and relaunch

Figure A-14.
Maximum, Mean, and Hourly Water Temperature for Stafford Creek
(USFS - Site #10) from 6/18/98 to 10/29/98



NOTE: Some values for 8/18/98 may be missing because of thermograph download and relaunch

Appendix B

Stream Temperature Protocol

Calibration and Placement of Temperature Monitoring Equipment and Field Data Collection in the Teanaway River Basin, June 30 – October 6, 1998

The following protocol was drafted for use in the *Eastern Cascades Stream Temperature Evaluation Project, Wenatchee National Forest* for the 1998 sampling season. This project was supported by USEPA, Region 10, USEPA Office of Research and Development, Landscape Ecology Branch, National Exposure Research Laboratory, and the USDA Forest Service. Ecology was a cooperator in this project and used this draft protocol for collection of stream temperature data in the Teanaway basin, June – October 1998.

The protocol was written by the Project Team:

- Jenna Scholz, Aquatic Biologist and Principal Investigator, USEPA/USFS Consultant
- Tom Robison, Forest Hydrologist, Wenatchee National Forest
- Iris Goodman, Landscape Ecologist, USEPA Office of Research and Development

Introduction

This document presents stream temperature protocols for the Eastern Cascades Stream Temperature Evaluation Project 1998 field season. These protocols are based, in part, on those outlined in the draft Stream Temperature Protocol (Forest Science Project 1998), and the draft Timber Fish and Wildlife Ambient Monitoring Manual (TFW 1998). Field methods described in this protocol are for obtaining representative stream temperatures from perennial streams for both trend and compliance monitoring within the Wenatchee National Forest. Field methods discussed include calibration, deployment, maintenance, and recovery of continuous recording temperature sensors (e.g., Hobo Temps, Stowaways).

Methodology

The protocols for stream temperature monitoring outlined below include methods for calibration, site installation, data downloading, and site-specific data collection. These protocols are designed to ensure accurate and consistent monitoring efforts throughout the Wenatchee National Forest.

Items proceeded by ** note where Ecology either collected additional data or will likely use a change in protocol for future studies.

Calibration

Calibration of temperature sensors is required to ensure equipment reliability and provide quality assurance documentation. Calibration must be conducted both pre- and post-monitoring. The following outlines the protocols for calibration and standardization of stream temperature monitoring equipment.

- A National Institute of Standards and Technology (NIST) traceable thermometer must be used to test the accuracy and precision of the temperature sensors. The NIST-traceable thermometer should be calibrated annually, with at least two calibration points between 10°C and 25°C. Calibration should be performed using a thermally stable mass of water, such as an ice bath at a testing laboratory. The stable temperature of the insulated water mass allows direct comparison of the unit's readout with that of the NIST-traceable thermometer. Accuracy of the NIST thermometer must be within +/- 0.5°C.

- Prior to use, all continuous monitoring devices must be calibrated at both room temperature and in an ice bath, to ensure they are operating accurately within the manufacture's specified temperature range. Calibrate all continuous stream temperature monitoring sensors against a NIST-traceable thermometer at two temperatures, room temperature (25°C) and near freezing. A logbook must be kept documenting each unit's serial number, calibration date, calibration test results, and the reference thermometer used. Sensors not meeting precision and accuracy data quality objectives should not be used.

  ◊ To calibrate the temperature sensors at room temperature, fill a container with water and allow it to sit overnight within a controlled environment (a room in which temperature is relatively constant). When the temperature bath is ready, mix the bath to avoid stratification, and continue mixing throughout calibration.

  ◊ To calibrate the temperature sensors at temperatures near freezing, fill a container 3/4 full of ice and add water to cover completely. Mix the water bath constantly until a uniform water temperature near 0°C is reached. Ice must always be present in the bath to maintain equilibrium. Gently agitate the bath during calibration to avoid stratification.

  ◊ During both calibration procedures, launch the temperature sensors and place them into the respective baths along with the NIST-traceable thermometer. Allow the sensors to stabilize for 10 minutes. Once stabilized, record the time and NIST thermometer temperature in the logbook at 1 minute intervals for 10 consecutive minutes. Download temperature sensor data.

  ◊ After completing the readings, determine the difference between the NIST readings and the data collected by the temperature sensors during the same time period. Calculate the mean difference between the NIST thermometer and the temperature sensors over the complete calibration period. Any instruments that vary by more than 0.2°C should not be used.

  Temperature difference = (NIST reading/10 - Sensor reading/10)

- **Using a voltage meter, individually check the battery within the sensor assemblage. Confirm that thermograph batteries have sufficient charges for the entire monitoring period. Also, have extra batteries on hand in the event of failure. *New thermograph batteries were purchased and installed in all Ecology owned thermographs.*

- Temperature monitoring equipment must be audited during the field season. Each sensor will be compared against measurements taken using a hand-held reference thermometer. Hand-held measurements will be taken at the time of deployment and retrieval, and any other time the sensor is moved (such as during data download or in the event of dewatering). All hand-held reference thermometers must be calibrated using a NIST thermometer prior to use in the field. In addition, reference thermometers must have an accuracy of +/- 0.5°C, and a resolution of 0.1°C.

Sampling Frequency and Duration

- Temperature sensors recording both air and water temperature should collect readings hourly. Hourly measurements will ensure that the maximum daily temperature is recorded.

- **Temperature monitoring should include the warmest period during the field season. Probes should be placed in the stream no later than June 20, and monitoring should continue until September 30. *Ecology probes were in place July 1- October 6 and did capture the warmest period which was July 27,28,29.*

Site Installation

- The stream temperature sensors should be placed at the downstream end of the thermal reach in a location representative of average conditions. Areas of cold water refugia or isolated hot spots should be avoided. Monitoring locations should avoid or account for confounding factors that influence stream temperature such as:
  - ◊ confluence of tributaries
  - ◊ groundwater inflow
  - ◊ channel morphology (e.g., isolated pools or stream segments)
  - ◊ hydrologic factors (e.g., wetlands and water withdrawals)
  - ◊ lakes, reservoirs, beaver ponds, and other impoundments

- Sensors should be placed in a well-mixed zone (e.g., at the end of a run, riffle, or cascade). In addition, sensors should be placed in the thalweg of the channel to avoid dewatering during the summer low flow months.

- Monitoring devices should be installed such that they are completely submerged. However, if possible, sensors should not be placed in direct contact with the channel bottom as substrate can serve as a heat sink.

- Sensors should be secured using aircraft cable, surgical tubing, rebar, or diver's weights.

- Where possible, sensors should be placed in a shaded location. Shade can be provided directly by tree canopy cover, large woody debris, or overhanging banks.

- Record the serial number of each sensor/data logger combination at each monitoring site. Do not move the sensor to another location during the monitoring period. In the event that the sensor is dewatered, it can be moved into the active channel adjacent to its original installation point. If this occurs, note the adjustment in the field notebook and collect a hand-held reference temperature at the new location.

- Use a geographic positioning system (GPS) to determine the stream temperature monitoring station location, or mark the site location on a USGS topographic map.

Data Downloading

Although the equipment used for temperature monitoring contains an 8k memory capacity, it is necessary to download stream and air temperature data at least once during the monitoring period. Downloading data at the midpoint of the monitoring period will ensure that the probe is recording properly.

- Record the date and time the sensor was removed from the stream as well as the date and time it was returned to the monitoring location.
- Return the sensor to the same location and depth after downloading.
- Record the condition of the sensor (e.g., normal, exposed to air, or vandalism).
- Collect a hand-held reference temperature (both air and water) to be used for field data calibration.
- Make a duplicate copy of the data file for each site and store these backup files in a fireproof location.

Site-Specific Data Collection

In addition to stream temperature, other site-specific data should be collected at each monitoring site. These data include attributes important to status and trend analysis of stream temperature patterns.

- Air temperature will be monitored at selected longitudinal profile sites. Install calibrated temperature sensors approximately 1-3 meters into the riparian zone from the edge of the bankfull channel about 1 meter above the ground. Be sure the instruments are shaded from direct and indirect sunlight throughout the day and protected from precipitation if possible. Place the sensor in an area representing temperatures immediately adjacent to the stream.

- The physical length of the thermal reach should be recorded at each site. In general, stream reaches should be between 300 meters in smaller streams, and 600 meters in larger streams. Where possible, measure the reach length using a hip chain. The portion of the active channel containing the majority of streamflow should be measured. In cases where the reach length exceeds 600 meters, measure the distance on a 1:24,000 scale USGS topographic map.

- Canopy closure should be measured every 100 feet for a total of not less than 10 bankfull widths to determine the average canopy closure within the thermal reach. Measurements should be collected upstream of the monitoring location using a spherical densiometer. See the TFW Monitoring Reference Point Survey Method for complete details on collecting canopy closure data.

- Bankfull width and depth should be measured at the stream temperature monitoring site. Bankfull height is defined as that point where water spills out of the channel and onto the floodplain. Specific indices used to find bankfull level are changes in cross section slope, size distribution of surface material and vegetation, location of the maximum height of point bars, and the location of the floodplain surface above the channel. Detailed methods are referenced in Harrison et al. (1994). The identification of bankfull level at one specific cross section is sometimes difficult. Therefore, the reach should be walked to confirm positive identification of all valley bottom surfaces including terraces, if present, and the floodplain surface.

  ◊ Stream bankfull width will be measured with a distance tape by locating bankfull level on one or both banks, and stretching the tape horizontally and perpendicular to the direction of streamflow. Measurements should be made at a riffle on a straight stream reach. If the temperature sensor is not located within a riffle, collect bankfull information within the riffle closest to the stream monitoring location.

  ◊ **Stream bankfull depth will be calculated as the arithmetic average of vertical measurements from the channel bottom to the bankfull tape. Vertical measurements should be taken at any point where there is a break in slope in the cross-sectional profile. A minimum of six measurements should be made. *Ecology took a minimum of 10 depth measurements to establish the bankfull depth.*

- **Average channel aspect should be measured at each canopy closure measurement point. Take a compass reading of the flow direction at bankfull flow at each of these points and record the average channel aspect in degrees for each thermal reach. *Ecology took these measurements but it is likely that Aspect from GIS or Quad maps may be sufficient.*

- Habitat type should be recorded at the location of the temperature sensor. Use the following codes to determine habitat type:

  Riffle - Shallow reaches with swiftly flowing, turbulent water
  Run - Relatively uniform flowing reaches with little surface agitation
  Pool - Shallow pools (probes should not be placed in pools deeper than 2 feet)

- Channel type of the thermal reach should be determined using the Montgomery and Buffington (1993) classification system. Substantial channel modification by aggradation, debris flow, fire, beaver activity, etc., should be noted. *The Rosgen channel classification was later established as the standard for this study.*

- **Discharge flow measurements should be made at one cross section location at the time of the survey using methods outlined by Locke and Bowers 1990. *Ecology took three flow measurements at each site: One during thermograph installation on June 30 or July 1, one during the mid-season thermograph download in late August, and one October 6 or 7 when the thermographs were removed.*

  Staff gages at adjacent streamflow stations should be read and recorded in the field noting the time and day that the discharge measurements are taken.

- A Wolman pebble count should be made at the point of flow measurement. A minimum of 100 particles of substrate material within bankfull width will be measured (Wolman, 1994; King and Potyondy, 1993)

- Photographs should be taken to include each cross section and each stream temperature monitoring site. The photographic record should include the stretched distance tape at bankfull elevation, and the thermograph location.

- Weather conditions at the time of the survey should be noted.

- **Water surface slope will be measured at the point of cross section measurement using a hand held clinometer or abney and measuring from the upstream to downstream ends of the riffle. *Ecology made slope measurements with a clinometer, but determined that this information could be sufficiently gathered from GIS Digital Elevation data or from a USGS Quad map.*

- Riparian vegetation should be documented within the thermal reach. Vegetation information should be collected using the protocol developed by ECADS (Iris Goodman, pers. comm.)

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Appendix C

Aerial Photo Interpretation

Remote Sensing has been shown to be an effective technique for many monitoring and inventory purposes, particularly for forest and land use determination. The handbook of Remote Sensing in Fish and Wildlife management (1979) concludes that remote sensing is a viable tool for riparian area monitoring and inventory. Culpin et al. (1985) suggest that aerial photos combined with ground data can be used for riparian baseline inventory, including identification of stream/riparian segments and existing conditions of stream/riparian areas.

Canopy cover (shade) is an important factor governing stream heating and cooling. Remote Sensing can be used to compare estimates of riparian conditions providing shade, to the minimum shade values needed to meet state water quality criteria for maximum stream temperature. These minimum shade values can be derived from photo-shade interpretation using aerial photos verified with field measurements (densiometer) and ground-truthing (WDNR 1997).

Valley bottom width, active channel zone, topography, land use, wetlands, characterization of geomorphology, Riparian Condition Units, and "areas of interest" can also be assessed and verified through aerial photographic interpretation.

Methods and Materials

The training and methods used for the Teanaway River Basin Technical Assessment are in accordance with Washington Department of Natural Resources (WDNR) Watershed Analysis Appendices: Riparian Function, Version 4.0.

Two different sets of aerial photos are available for the Teanaway River Basin, due to the USFS boundary. The USFS provided (free of charge) 1992 color 1:15,840 aerial photos of the upper portions of the watershed. These photos were used to study sample sites 1, 8, 4, 9, & 10. WDNR provided ($8.64 per photo) 1998 Black & White 1:12,000 aerial photos for the lower portion of the watershed. These photos were used on sample sites 2, 3, 5, 6, & 7 and provided a higher degree of resolution and accuracy

The same methodology is applied for each sample site. Riparian Condition Units (RCUs) are defined for each stream reach (stream reaches sampled varied between 900 –2000 feet, depending on stream width). Each RCU is unique in that it differs from adjacent RCUs in the type, size, and/or density of riparian vegetation. Riparian areas on opposite sides of the stream are treated as separate RCUs. The length of each RCU should be a minimum of 2,000 feet (1 inch on 1:24,000 scale map). RCU codes use the "CMD" system where:

C = Vegetation type (Conifer or Hardwood)
M = Tree Size (Small, Medium, or Large)
D = Stand density (Dense or Sparse)

The level of canopy closure is estimated at each point along the stream reach where the field densiometer reading was recorded. These levels of canopy closure are then averaged to provide a shade measurement for the reach and compared to the average shade value derived from the densiometer readings. A canopy closure value is also estimated for a 5,000-foot reach upstream to further characterize the riparian area of the sample site. Table C-1 lists the canopy closure categories for aerial photo interpretation.

Table C-1 Estimated Levels of Canopy Closure (Shade) from Aerial Photos

Stream surface not visible	>90% shade
Stream surface slightly visible or visible in patches	70-90% shade
Stream surface visible but banks are not visible	40-70% shade
Stream surface visible and banks visible at times	20-40% shade
Stream surface and banks visible	0-20% shade

The aerial photos are also used to gather information on conditions that limit vegetative growth – "Areas of Interest" (e.g., talus slopes, bedrock outcrops, mass-wasting areas, wetlands, roads, annual floodplains, powerlines, agriculture, housing). Physical constraints such as closed canopy, slope, canyons, angle of sun, and other factors may limit the ability to detect features of interest, and thus should be noted and taken into account when performing the analysis.

Accuracy and Cost

Ground truthing, field measurements (densiometer readings), and training assist in verifying canopy closure estimates and achieving the most reliable results. Greater confidence in the accuracy of aerial photographic interpretation is achieved with the interpreter's experience and familiarity with the region and process, and with 1:12,000 black & white photos. It is also recommended that the same person that participated in field sampling do the photo analysis; this further reinforces the ground-truthing process.

Cost will usually depend on the scale and availability of the aerial photos required for the region of interest. Studies generally have concluded that the cost of remote sensing will usually be less than ground survey data (Lillesand and Kieffer, 1987; Janza, 1975). Incorporating remote sensing into existing and future watershed management programs could greatly enhance our ability and accuracy to inventory and monitor aquatic and riparian habitat.

Results

Table C-2 shows a comparison of shade values collected using a densiometer, 1:15,840 color aerial photos, 1:12,000 black and white aerial photos, and those reported in the Teanaway North and West Forks Watershed Analyses. For the most part, all methods estimated existing shade values within the same general range. Ecology did, however, have much more confidence using 1:12,000 scale photos than the 1:15,840 photos.

Table C-2. Estimated shade values for the Teanaway basin sample

Site Name	Site Number	Dominant RCU	Approx. Mean/ Max ACZ	Average Shade of Reach: 0-2000' Upstream (Densiometer field measurement)	Canopy Closure estimates of 0 -2,000' Reach Upstream (Aerial Photos - USFS color 1:15840, 1992)	Canopy Closure estimate of 5,000' Reach Upstream (Aerial Photos - USFS color 1:15840, 1992)	Canopy Closure estimates of 0 -2,000' Reach Upstream (Aerial Photos - DNR B&W 1:12000, 1998)	Canopy Closure estimate of 5,000' Reach Upstream (Aerial Photos - DNR B&W 1:12000, 1998)	Teanaway Watershed Analysis
Upper West Fork	Site 1	CMD (right bank) CSS (left bank)	40/75'	13.13% ***	20-40%	20-40%	0-20%	20-40%	33.7%**
Lower West. Fork	Site 2	CMS	50/100'	28.98%			20-40%	20-40%	21.5%**
Lower Middle Fork	Site 3	MMD (> 2400' upstream MMS)	75/150'	10.26%			0-20%	0-20%	
Upper N. F. below De Rue Cr.	Site 4	CMD	40/75'	33.37%	40-70%	20-40%			
N. F. between Middle and Dickey Cr.	Site 5	CMD (right bank) CSS (left bank)	100/250'	10.57%			0-20%	0-20%	16%*
North Fork near mouth	Site 6	MMS	100/225'	12.91%			0-20%	0-20%	16%*
Mainstem Teanaway	Site 7	MMS	125/250'	3.21%			0-20%	0-20%	
Upper Middle Fork	Site 8	CMD (>2000' upstream - CSS, right bank)	40/150'	27.70%	70-90%	70-90% (first 900') 20-40% for remaining 4100'	40-70%	20-40%	
North Fork above Stafford Cr.	Site 9	CMD (right bank) CSS (left bank)	40/90'	46.42%	20-40%	40-70% (left bank less shade)	20-40%	20-40%	
Stafford Cr.	Site 10	CMD (left bank) CSS (right bank)	30/60'	33.11%	20-40%	20-40%			

* Boise Cascade Co., 1996. Teanaway Watershed Analysis: Resource Assessment Report covering the watershed area south of Stafford Creek to the mouth of the North Fork Teanaway

** Connor, M., 1997. Riparian Function Assessment as part of the West Fork Teanaway Watershed Analysis (DNR Review Draft)

*** Because only 5 readings were taken upstream of this reach (instead of the 10 used for all other reaches), the accuracy of this reading is likely to be less

Appendix D

Using Digital Orthophotos to Estimate Canopy Cover/Riparian Shade

There was insufficient time to completely develop the process of estimating riparian shade from digital orthophotos. However this method holds significant promise and is important to document progress to date. Because shade is so important to stream temperature, it is always a factor needing evaluation in this type of study. Field staff are likely to be able to visit and evaluate riparian vegetation in just portions of a watershed, when in fact knowing shade or riparian density values throughout a watershed is important to a landscape or basin wide study.

Digital orthophotos covering the entire Teanaway basin were made available by the Wenatchee National Forest. These were converted to an ArcInfo grid with a cell size of 13 feet and gray scale pixel values ranging from 0 to 256. Darker cells, for the most part, show denser vegetation and the lightest cells are often pavement or clearing. Ecology's goal was to see if we could find a correlation between the shade value collected in the field and the average pixel value from the photo for a buffered region around the stream reach. The 10 sites where riparian shade values had been collected were to be used to set up and test this correlation.

Because some photos are darker than others (shadowing, clouds, photos taken earlier or later in the day), we decided to proceed using just one orthophoto quad containing four of the field sites.

Process Steps. The following is a fairly technical documentation of the steps taken during this portion of the project. Some of it may be easier to understand by first looking at Figure D-2.

Using ESRI Arcview and the Arcview Spatial Analyst Extension

- The WDNR 1:24,000 stream layer was overlaid on the orthophoto image grid.
- The stream layer was buffered using a distance of 100 feet
- Four reaches, that had been surveyed for riparian shade, were selected to create a separate shape file. These reaches were 1000 to 2000 feet in length depending on stream size.
- The reach shape file was also buffered by 100 feet and converted to a grid.
- Using the Arcview Spatial Analyst map calculator, the orthophoto pixel value grid was multiplied by the reach survey grid. This produced a new grid containing the orthophoto image and values for each survey reach buffer area.
- The orthophoto pixel values were averaged for each survey reach buffer area.

In Microsoft Excel

- Performed a linear regression of average pixel value and densiometer reading. Figure D-1 shows the results of this regression.

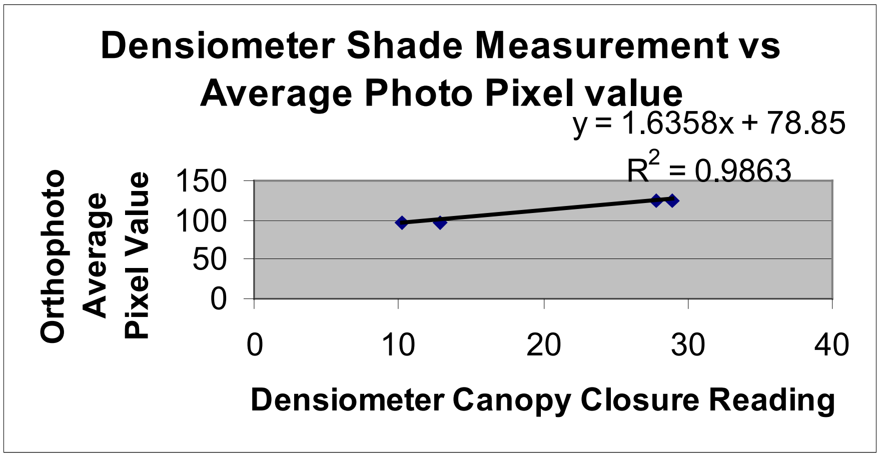


Figure D-1. Riparian Shade relationship. Average orthophoto pixel value for the surveyed stream reach vs. densiometer reading for the surveyed stream reach

In Arcview

- Create a grid from the buffered basin stream layer and multiply it by the orthophoto grid in the map calculator. This will result in an orthophoto riparian buffer.
- Apply the regression to the buffered stream layer to get an Arc/Info grid showing riparian shade for the basin.
- Use neighborhood statistics or some other grouping method to generalize the riparian shade grid as desired.

Discussion

Explanations of the above process:

- 100-foot buffer. 100 feet was chosen because I wanted to get the entire stream plus approximately 25 feet into the vegetation on either bank. 100 feet was determined to be a reasonable-sized buffer for this watershed. For future work using a buffer that varies with stream size or stream type may be more appropriate
- Using the 1:24K stream coverage as a base. This was convenient, but because streams migrate over time, if the date of the photo is much different from the date of the base data for the stream layer, streams may not line up correctly with the riparian vegetation. Options are:
  (1) Use software that allows you to select the stream from the orthophoto itself; and
  (2) Choose field densiometer sites where the photo and stream coverages line up well to establish the regression. Then apply the regression to the watershed knowing that some stream migration error will be involved.

  A potential method of dealing with differences in lighter exposure when using multiple photos is to use the overlap area to correct. Most adjacent orthophotos have an area of overlap. These areas may be used to calculate average pixel value differences when moving from one photo to the next.

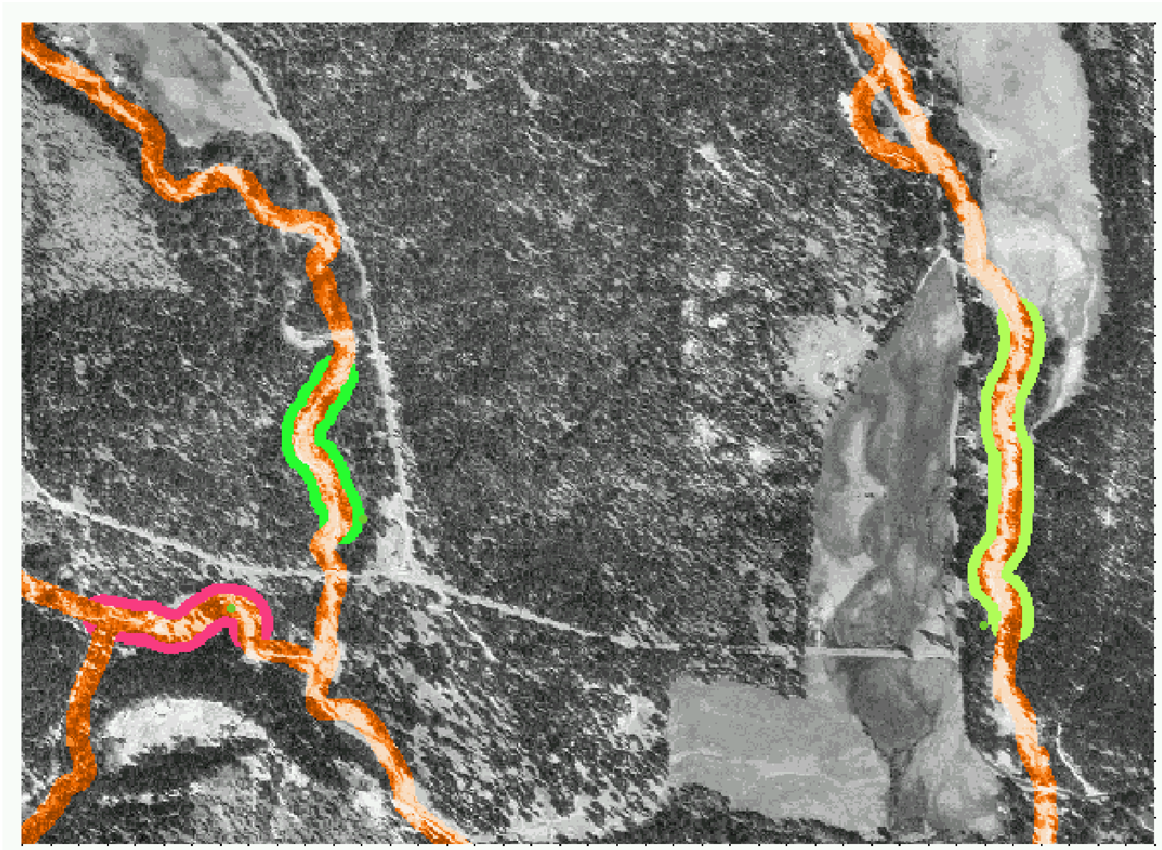


Figure D-2. Orthophoto showing three of the surveyed stream reach areas

Appendix E

GIS Analysis of Streamflow

The streamflow analysis uses watershed area, average annual precipitation information, and one continuous gage to estimate streamflow at points throughout the watershed. This analysis is based on methods developed by the University of Texas Center for Research in Water Resources described on their website, http://www.ce.utexas.edu/prof/maidment/ce397/urubamba/peru.htm. It was further developed at Ecology to accumulate precipitation across the landscape.

Ecology has been fairly successful using this method to estimate daily streamflow in basins that do not use extensive water withdrawals and that have a continuous stream gage in the basin for calibration. The method assumes that soil types and other parameters affecting delivery of precipitation to streamflow are similar across the watershed. In both the Willapa and Chehalis basins, this method produced tributary flow estimates that closely approximated actual measured flow.

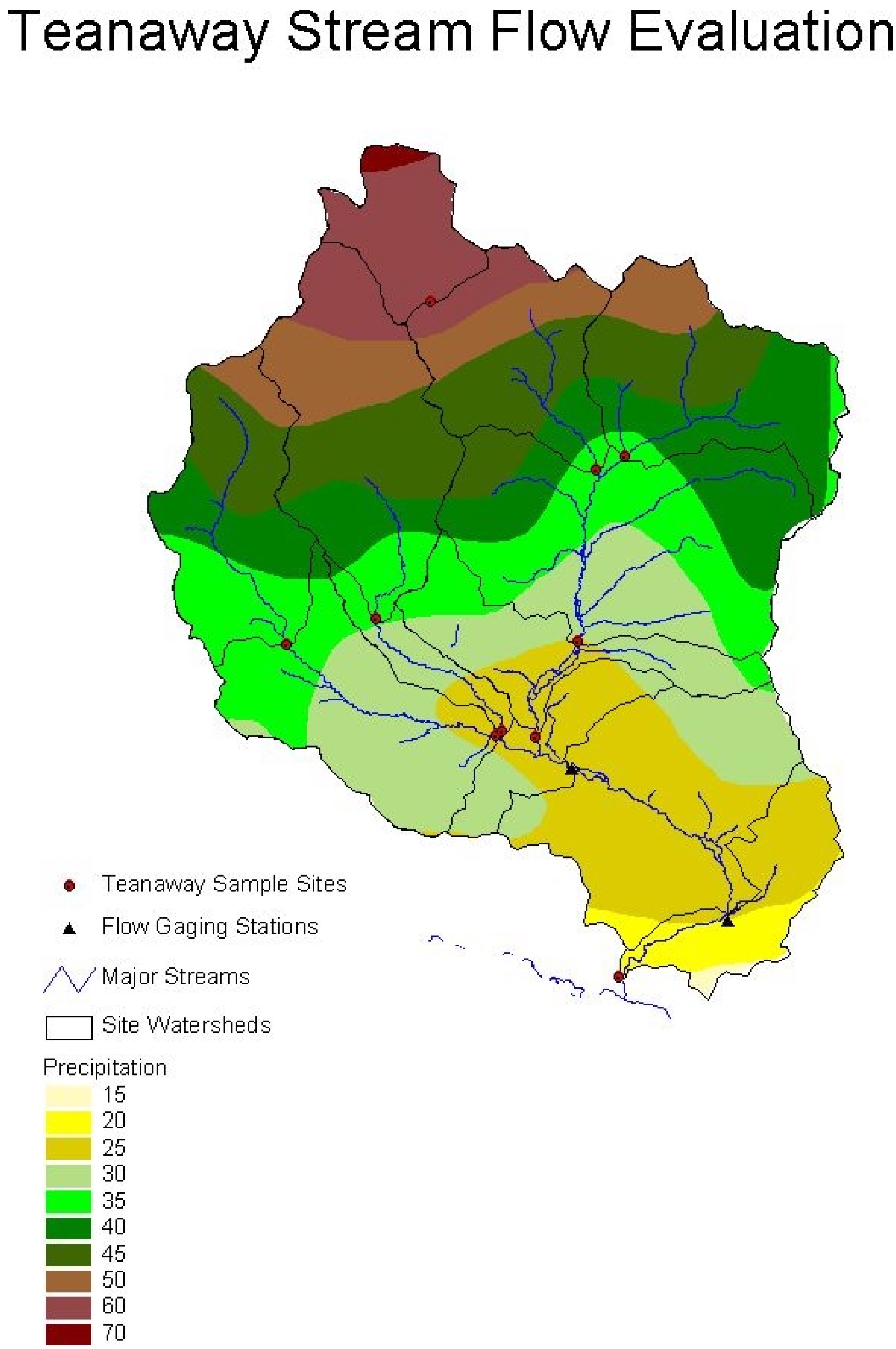
Hydrogeologists have used sub-watershed area to estimate flow for many years (e.g., a sub-watershed with an area that is 10% of the total watershed should have 10% of the flow). The GIS method automates the area calculation and allows sub-watersheds with heavier precipitation to receive a larger proportion of the flow. Often precipitation varies dramatically across a watershed, especially at the higher elevations.

Briefly, watershed area above each of the sample sites was calculated using the grid-based Spatial Analyst extension to ESRI Arcview. These areas were then weighted using an annual precipitation grid (Figure E-1). The precipitation-weighted area above the continuous gage is calculated and becomes the value representing 100% of the streamflow (the denominator value). The weighted area above each major sub-basin pour point is calculated and divided by the denominator to produce the fraction of the streamflow delivered to that point. This fraction can then be multiplied by the daily continuous flow record to produce a synthetic hydrograph for each of the sub-basin pour points.

- When calculating expected streamflow using the area-weighting method and the Teanaway at the Forks gage as the basin calibration point, flow was underestimated in the upper watershed. Because of the small watershed area above Site 4 in relation to the whole, the August flow for that site was estimated at 0.5cfs instead of the actual 7 cfs. The method also expected the upper West (Site 1) and upper Middle (Site 8) Fork sites to have less flow than their mouth site (Sites 2 and 3) flows. This was not true.
- Further observation of field data showed that flows were increasing from the top of the watershed to Sites 4 and 9. The flows on all forks did not increase between the USFS sites at the forest service boundary to the mouth sites established by Ecology (e.g., flows in August and October for all West and Middle Fork sites approximated 3 cfs); while flows in the North Fork and mainstem were approximately 16 cfs from the confluence of Stafford Creek and the North Fork through Sites 5 and 6 to the mouth of the mainstem at Site 7.

In conclusion, this method of flow reconstruction cannot be used in most of the Teanaway basin because streamflow does not increase as the basin drainage area increases.

Figure E-1


Teanaway Stream Flow Evaluation
Teanaway Sample Sites
Flow Gaging Stations
Major Streams
Site Watersheds
Precipitation
15
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25
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Appendix F

Geology and Soils

There are four geologic and topographic areas within the basin (Figure 3):

1. *The Mount Stewart batholith and schist* – a metamorphic formation occupying the northern region of the watershed (headwaters of the North Fork and Middle Fork Teanaway Rivers) with steep headwalls and glacially carved hollows or cirques.
2. *The Swauk Sandstone* – a sedimentary formation resistant in the upper basin.
3. *The Teanaway Basalt* – a volcanic resistant unit of basalt, basaltic tuff, and breccia layers in the middle of the basin. The West Fork Teanaway forms a deep rock gorge in this area.
4. *The Roslyn Sandstone* – a sedimentary, easily weathered unit in most of the lower basin.

Ancient, large-scale mass wasting features and landslide deposits of silt and fine sand occur throughout the basin. The North, Middle, and West Fork Teanaway Rivers down-cut to bedrock in places through glacial and recent floodplain alluvium (Tabor et al., 1982). The mainstem of the North Fork Teanaway occupies a broad (900 to 1,500 feet wide), glacially-carved valley. Lining the mainstem valley, and to some extent up tributary valleys, are remnants of moraine terraces composed of sand and gravel deposited between the ice and the valley side walls during two separate glacial advances (NFTWA, 1996).

The underlying geologic parent material determines the characteristics of the overlying soils, i.e., whether it is predominantly fine-grained (silt and clay) or coarse-grained (sand and gravel). The strength of the parent material usually determines the hillslope characteristics, with strong material resulting in steep slopes and weak material forming flatter slopes (NFTWA, 1996). Figure 4 shows the soil units that occur in the Teanaway River basin and graphs of their associated permeability (NRCS, 1994). To assess their potential for surface erosion, the following soil characteristics are important.

Permeability	Low values of permeability indicate an increased potential for generation of overland flow.
Size gradation	Soil size gradation is indicative because finer-grained soil particles can be more easily entrained by flowing water than coarser particles.
Percent clay	The greater amount of clay, the less potential for erosion due to the cohesive properties of clay particles.
Erosion factor K	Can vary from 0.02 to 0.69; the higher the value, the greater the erosion potential.

The soil types in the upper half of the watershed consist primarily of residuum and colluvium from Swauk sandstone and Teanaway basalt with an admixture of volcanic ash in the top soil layers. The soil texture is generally very gravelly to gravelly sandy loam with a large percentage of rack fragments. Soils derived from volcanic bedrock have low erosion potential. These soils can be over 5 feet in depth, have permeability rates exceeding 2.0 inches per hour, and have K values between 0.10 and 0.25. These soils generally occur on the higher slopes and ridges in the watershed.

Soil types consisting primarily of residuum and colluvium from highly weathered Roslyn sandstone with an admixture of volcanic ash occupy the lower half of the Teanaway River watershed. These soils also occur from scattered glacio-fluvial terrace deposits. The soil texture is typically loam to sandy or silt loam with few rock fragments. The soil depth is generally between 4 to 5 feet, has permeability rates between 0.06 and 0.6 inches per hour, and has K values greater than 0.25. These soil units have a high potential for soil erosion and usually occur on slopes with gradients less than 25 percent.

Surface Erosion

Surface erosion occurs when soil from sufficiently steep slopes is exposed to precipitation, and the subsequent overland flow can detach soil particles and eventually carry them to streams where the typically fine-grained soil has the potential to impact water quality and fish spawning habitat. Inputs of fine sediment to streams also affects stream temperature by contributing to the widening and shallowing of a stream, which makes it more vulnerable to heating due to solar radiation and a larger water surface to air interface.

Surface erosion assessment focuses on identifying land use activities, areas that have a high potential for soil erosion, and locations that deliver fine-grained sediment to streams with vulnerable public resources (NFTWA, 1996). While the steep, sparsely vegetated, mountainous terrain can be prone to soil erosion, land-use activities that remove the protective duff layer, compact the soil, and/or increase the slope angle can greatly increase the rate of erosion. Additionally, increasing or concentrating the flow of water over the soil can increase the amount of erosion and the likelihood of delivering sediment to streams. Forest management activities that can increase surface erosion include road construction, poor road maintenance, ground and cable yarding, and site preparation such as broadcast burning (WFTWA 1997).

Natural surface erosion is rare in forested areas where water infiltration capacity is high. Areas with little vegetative cover, particularly on steep slopes, may be prone to sheetwash erosion, freeze/thaw processes, and dry ravel. These areas tend to have shallow soil without a protective duff layer allowing exposed soil particles to be easily detached (WFTWA 1997). The easily compacted soils of the Roslyn formation in the lower half of the watershed are naturally prone to erosion.

Soil disturbance from management activities predominantly occurs in the lower half of the watershed. Areas of more poorly drained or easily eroded soils could contribute sediment to the drainage system if they were disturbed by ground-based harvesting equipment, or road building and maintenance during wet-ground conditions. Water that has been concentrated on roads and skid trails and is discharged onto erodible soils could cause gullying and sediment delivery.

Excessive numbers of cattle in the watershed can also contribute significantly to erosion of stream banks that are composed of weak soils.

Surface Erosion from Roads

Major roads in this basin are the Teanaway, North, South, and Middle Fork Roads maintained by Kittitas County, U.S. Forest Service (USFS) roads, Washington State Department of Natural Resource (WDNR) roads and accompanying bridges and culverts. WDNR roads are used for forestry purposes only, and USFS roads are available for forestry and recreational use.

Most roads in the Teanaway River watershed are at least 20 years old, and many of the roads that parallel the tributary streams have been rebuilt from existing railroad grades that were originally constructed in the 1900s. The soil derived from the Roslyn sandstone is easily compacted, and once tires create even a small channel, gully erosion can progress quickly. Once these soils are compacted for roads, they require frequent maintenance and more runoff control measures such as waterbars (WFTWA, 1997).

The North Fork Teanaway Watershed Analysis (1996) reports that for the lower North Fork watershed the background sediment yield is about 1,454 tons per year, while the fine sediment portion is estimated at 810 tons per year. The estimated total amount of delivered sediment from roads is approximately 4 percent of the estimated total background yield, and 7 percent of the background fine sediment yield. The West Fork Teanaway Watershed Analysis (1997) estimates a background fine sediment load of 205 tons year and a road sediment delivery of 252 tons per year for the lower West Fork watershed. Both the West Fork and North Fork Watershed Analysis Reports propose an increase in road maintenance, especially on unpaved roads

Appendix G. Characteristics of Modeled Stream Segments

Sample Sites	Elevation (feet)	Size of Sub-basin Watershed (acres)	Slope	Average Shade % for Reach	Approximate Mean/Max of Active Channel Zone (feet)
1 Upper West Fork - USFS	2,680	11,998	2.0%	13*	40/75'
2 Lower West Fork	2,280	24,752	1.1%	29	50/100'
3 Lower Middle Fork	2,280	19,111	1.2%	10	75/150'
4 Upper North Fork, below De Rue	3,760	6,047	2.5%	33	40/75'
5 N.F. between Middle Fork and Dickey Cr.	2,400	52,579	1.3%	11	100/250'
6 Lower North Fork near mouth	2,240	60,488	1.0%	13	100/225'
7 Mainstem Teanaway, mouth	1,840	132,989	0.5%	3	125/250'
8 Upper Middle Fork - USFS	2,680	16,409	2.8%	28	40/150'
9 North Fork above Stafford Cr.- USFS	2,760	16,684	2.2%	46	40/90'
10 Stafford Creek - USFS	2,800	13,757	3.0%	33	30/60'

	Bankfull W/D Ratio	Dominant Channel Material	Rosgen Channel**	Dominant Underlying Geologic Parent Material
1 Upper West Fork - USFS	44	cobble	B3	Roslyn Sandstone
2 Lower West Fork	37	coarse gravel/bedrock	C4/C1	Roslyn Sandstone
3 Lower Middle Fork	25	bedrock/cobble	C1/C3	Roslyn Sandstone
4 Upper North Fork, below De Rue Cr.	18	cobble/boulder	B2	Swauk Sandstone
5 N.F. between Middle Fork and Dickey Cr.	43	cobble	C3	Roslyn Sandstone
6 Lower North Fork near mouth	43	bedrock/cobble	C1/C3	Roslyn Sandstone
7 Mainstem Teanaway, mouth	32***	cobble	D3	Roslyn Sandstone
8 Upper Middle Fork - USFS	36	cobble	B2/B3	Teanaway Basalt
9 North Fork above Stafford Cr.- USFS	49	cobble	C3	Teanaway Basalt
10 Stafford Creek - USFS	26	cobble/boulder	B2	Swauk Sandstone

* Shade in this reach may be underestimated. Fewer densiometer readings were taken along this segment.

** Entrenchment values were not measured. Some channels classified as Rosgen type C could be classified as type F, if in an entrenched/degraded condition.

*** Site 7 bankfull measurements were taken at a narrow place in the channel, and are not representative of the modeled stream segment.

Appendix H

Proper Functioning Condition

The Revised 1998 Lotic Checklist was used to evaluate the condition of the thermal reach above each site. The purpose was to assess the general condition of the stream in a consistent manner for each site and to initiate thoughts on management actions that may be needed to restore the stream. Stream reaches were placed into three categories as described in U.S. Dept. Interior (1995): Proper Functioning Condition, Functional-At Risk, and Nonfunctional.

They are defined as follows:

Proper functioning condition

Riparian-wetland areas are functioning properly when adequate vegetation, landform, or large woody debris is present to dissipate stream energy associated with high waterflows, thereby reducing erosion and improving water quality; filter sediment, capture bedload, and aid floodplain development; improve flood-water retention and ground-water recharge; develop root masses that stabilize streambanks against cutting action; develop diverse ponding and channel characteristics to provide the habitat and the water depth, duration, and temperature necessary for fish production, waterfowl breeding, and other uses; and support greater biodiversity**.** The functioning condition of riparian-wetland areas is a result of interaction among geology, soil, water, and vegetation.

Functional-at-risk

Riparian-wetland areas that are in functional condition, but an existing soil, water, or vegetation attribute makes them susceptible to degradation.

Nonfunctional

Riparian-wetland areas that clearly are not providing adequate vegetation, landform, or large woody debris to dissipate stream energy associated with high flows and thus are not reducing erosion, improving water quality, etc., as listed above. The absence of certain physical attributes such as a floodplain, where one should be, is an indicator of nonfunctioning conditions.

Lotic Checklist

Name of Riparian-Wetland Area: ____________________
Date:__________ Segment/Reach ID:__________
Miles:__________ Acres:__________
ID Team Observers:____________________

Yes	No	N/A	HYDROLOGIC
			1) Floodplain above bankfull is inundated in "relatively frequent" events
			2) Where beaver dams are present are they active and stable
			3) Sinuosity, width/depth ratio, and gradient are in balance with the landscape setting (i.e., landform, geology, and bioclimatic region)
			4) Riparian-wetland area is widening or has achieved potential extent
			5) Upland watershed is not contributing to riparian-wetland degradation

Yes	No	N/A	VEGETATION
			6) Diverse age-class distribution of riparian-wetland vegetation (recruitment for maintenance/recovery)
			7) Diverse composition of riparian-wetland vegetation (for maintenance/recovery)
			8) Species present indicate maintenance of riparian-wetland soil moisture characteristics
			9) Streambank vegetation is comprised of those plants or plant communities that have root masses capable of withstanding high streamflow events
			10) Riparian-wetland plants exhibit high vigor
			11) Adequate riparian-wetland vegetative cover present to protect banks and dissipate energy during high flows
			12) Plant communities are an adequate source of coarse and/or large woody material (for maintenance/recovery)

Yes	No	N/A	EROSION DEPOSITION
			13) Floodplain and channel characteristics (i.e., rocks, overflow channels, coarse and/or large woody material) adequate to dissipate energy
			14) Point bars are revegetating with riparian-wetland vegetation
			15) Lateral stream movement is associated with natural sinuosity
			16) System is vertically stable
			17) Stream is in balance with the water and sediment being supplied by the watershed (i.e., no excessive erosion or deposition)

Remarks (Rationale for Rating)

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Summary Determination

Functional Rating:

___ **Proper Functioning Condition**

___ **Functional - At Risk**

___ **Nonfunctional**

___ **Unknown**

Trend for Functional - At Risk:

___ **Upward**
___ **Downward**
___ **Not Apparent**

Are factors contributing to unacceptable conditions outside the control of the manager?

Yes ___
No ___

If yes, what are those factors?

___ **Flow regulations**
___ **Mining activities**
___ **Upstream channel conditions**
___ **Channelization**
___ **Road encroachment**
___ **Oil field water discharge**
___ **Augmented flows**
___ **Other (specify)** ____________________

(Revised 1998)