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Wenatchee National Forest Water Temperature Total Maximum Daily Load

Technical Report

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Executive Summary

Chronically elevated water temperatures, observed at 18 separate water segments within the Wenatchee National Forest, located in central Washington, resulted in their inclusion on Washington State's 1998 303(d) list. Section 303, part d of the Clean Water Act requires that states compile a list of waters that are not achieving water quality standards. Once a water body is included on the list, a TMDL study is required to address the water quality problem. The primary objectives of the TMDL study are to examine pollutant sources and determine the pollutant reductions (allocations) necessary to achieve the water quality standard.

Washington State's water quality standard for temperature that applies to surface waters within the Wenatchee National Forest is that the maximum temperature must not exceed 60.8°F (16°C).

This study established allocations based on effective shade, a surrogate measure of heat flux. Effective shade is the fraction of incoming solar shortwave radiation above the vegetation and topography that is blocked from reaching the surface of the stream.

In addition to the 18 listed water segments, water temperature data collected by the United States Forest Service indicated that a further 46 water segments within the forest were impaired, with maximum water temperatures exceeding the water quality standard.

This TMDL established the effective shade levels necessary for these temperature impaired waters to achieve the standard. In addition, the analysis methods, which utilized a stream classification system, allow for the extrapolation of effective shade levels necessary to meet the water quality standard for surface waters throughout the forest. Additional analysis methods examined site potential shade, or the maximum amount of effective shade provided by late-successional vegetation. The determination of site potential shade for the Wenatchee National Forest was a critical element of the analysis due to the presence of naturally occurring limitations to vegetative growth. For the arid portions of the forest, these limitations result in site potential effective shade levels that are lower than those required to achieve the temperature standard.

Introduction

Total Maximum Daily Load Background

Section 303(d) of the federal Clean Water Act requires that states establish Total Maximum Daily Loads (TMDLs) for surface waters that do not meet water quality standards following the application of technology-based pollution controls. The U.S. Environmental Protection Agency (EPA) has promulgated regulations (40 CFR 130) and developed guidance (EPA, 1991) for establishing TMDLs.

Under the Clean Water Act, each state has water quality standards designed to protect, restore, and preserve water quality. Water quality standards are usually in the form of numeric criteria established to achieve beneficial uses, such as protection of cold water biota or drinking water supplies. When a lake, river, or stream fails to meet water quality standards after application of required technology-based controls, the Clean Water Act requires the state to place it on a list of "impaired" water bodies (known as the "303(d) list") and to prepare an analysis called a **Total Maximum Daily Load (TMDL)**.

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

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

<u>Wenatchee National Forest TMDL</u>

This TMDL is being established for the pollutant, heat (solar radiation). Excessive heat loads to surface waters within Wenatchee National Forest have resulted in water temperatures exceeding the state water quality standard. Washington State's water temperature standard that applies to surface waters within the Wenatchee National Forest is that the maximum temperature must not exceed 60.8 degrees Fahrenheit (^{o}F) (16 degrees Celsius (^{o}C)).

Washington State's 1998 303(d) list contains 18 individual water body segments within the Wenatchee National Forest where water temperature has been observed exceeding the temperature standard. More recent data, collected by the United States Forest Service (USFS) in 2001, indicates that there are an additional 46 locations with temperature exceedances.

A TMDL that solely addresses the impaired (listed and unlisted) stream segments could be completed. Because of the large amount of data that are available for the greater Wenatchee National Forest, it is more efficient and relevant to develop the analysis to address water temperature in perennial streams throughout the forest. For this reason, this TMDL uses broader resource functions and conditions to develop appropriate allocations across a diversity of streams within the forest. With this approach, the TMDL allocations that result will help guide future restoration activities.

TMDL Report Elements

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

Loading Capacity: The loading capacity for heat (or solar radiation) is based on achieving effective shade levels (in the riparian corridor) needed to meet state water quality standards for temperature. Using a stream channel classification system that incorporates information - for instance, on geologic setting, drainage area, active channel width, and flow, effective shade - targets were developed. (Effective shade is defined as the fraction of the potential solar shortwave radiation that is blocked by vegetation and topography before it reaches the stream surface.) The classification system recognized the variability in channel and riparian characteristics that occur across the landscape and grouped streams that shared common water temperature influences such as shade, ground water, or channel morphology.

Load Allocations: Allocations in this TMDL are based on percent effective shade and apply only to surface waters within the Wenatchee National Forest. Effective shade can be linked to source areas and, thus, to actions (specifically riparian management) needed to address processes which influence water temperature.

Wasteload Allocation: There are no permitted discharges within the area covered by the TMDL, therefore, the wasteload allocation is zero.

Margin of Safety: The margin of safety was determined to be the difference between the load allocation, or percent effective shade required to meet the temperature water quality standard, and the load capacity, represented by the effective shade generated by the natural potential vegetation. In addition, the analysis was based on data collected during critical conditions. The summer of 2001 was unusually hot and dry.

Seasonal Variation: Existing conditions for stream temperatures in the Wenatchee National Forest reflect seasonal variation. The warmest water temperatures typically occur between mid-July and mid-August. This time frame was used as the critical period for the development and analysis of allocations.

Surrogate Measures – Effective Shade

This TMDL assessment uses riparian shade as a surrogate measure of heat flux to fulfill the requirements of Section 303 part (d) of the Clean Water Act. Effective shade is defined as the fraction of the potential solar shortwave radiation that is blocked by vegetation and topography before it reaches the stream surface.

Heat loads to streams were calculated in this TMDL through the use of a numeric model (in units of calories per square centimeter per day or cal/cm^2-day). However, heat loads are of less relevance in guiding management activities needed to solve identified water quality problems. For this reason, shade is used as a surrogate to the thermal load as allowed under EPA regulations (defined as “other appropriate measure” in 40 CFR §130.2(i)).

Overview of Heating Processes

While climate and geographic location are outside of human control, riparian condition, channel morphology, and hydrology are affected by land use activities. The following processes affect water temperatures in the Wenatchee National Forest:

- Riparian vegetation disturbance reduces stream surface shading through decreased riparian vegetation height, width, and/or density, thus increasing the amount of solar radiation reaching the stream surface.
- Channel widening (increased width to depth ratios), the result of elevated sediment loading, increases the stream surface area exposed to solar radiation.
- Summertime base flows are reduced from both in-stream and hydraulically connected groundwater withdrawals resulting in increased stream temperature.

Figure 1 provides the major pathways that allow excessive solar radiation to reach a stream and are among the factors considered in this analysis. The amount of solar radiation that reaches a stream surface is a primary factor in the maximum water temperature that is realized (Figure 1, 1). The amount of the solar load delivered to a stream is in turn determined by two pathways, a vegetation-related component (2) and the other sediment-related (3). Effective shade is determined primarily by the height and density of riparian vegetation (4). The width-to-depth ratio determines the potential stream surface area exposed to solar radiation and is determined by the amount of bedload within the channel (5). The amount of sediment delivered to a stream is a function of the erosion-related activities present within a particular drainage area such as existing roads (and those under construction), and hillslope failures (7). Excessive delivery of sediment to channels can also affect riparian vegetation through compensating channel morphological changes that result in streambank failure (6).

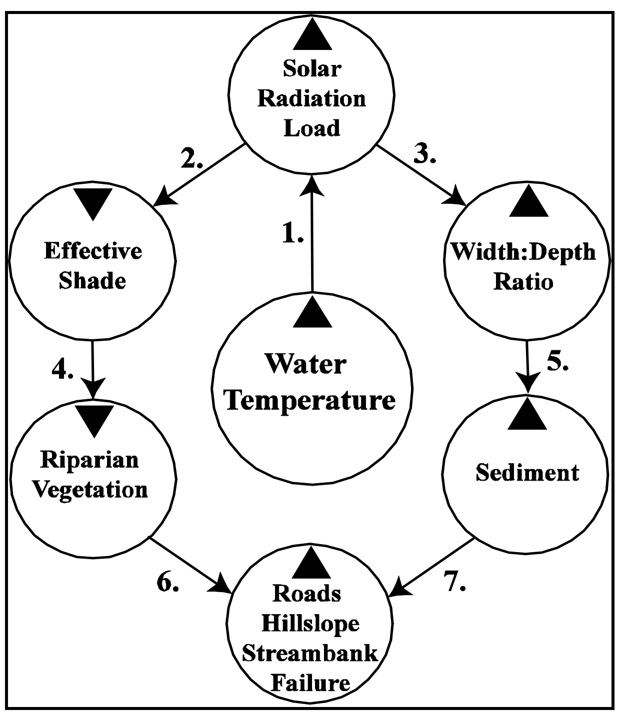

Figure 1. Shade and channel characteristics and their effects on water temperature.

Heat Budget - Framework for Linking Water Temperature and Shade

Water temperature is related to the heat content of water but is actually a measure of the intensity or concentration of stored heat within a given volume. Riparian vegetation, stream morphology, hydrology, climate, and geographic location influence stream temperature and, therefore, the heat flux. For this reason, in order to understand the changes in temperature of water, a budget, or an accounting of the major gains and losses of heat must be considered.

A heat budget expresses this in mathematical form:

$$J_{net} = J_{longwave} + J_{solar} + J_{convection} + J_{evaporation} + J_{bed} + J_{hyporheic} + J_{in\ (surface\ or\ ground)} + J_{out}$$

"J" represents the flux, or flow of heat, of each component and can be positive or negative (units in calories per square centimeter per day). Objects emit absorbed heat in the form of long-wave radiation ($J_{longwave}$)(Figure 2, 1). The atmosphere provides some long-wave radiation to water bodies, but more tends to be emitted by the water bodies, generally resulting in a net loss of heat. Solar, or short-wave radiation, (J_{solar}) tends to dominate the heat budget where effective shade is low (2). Solar radiation inputs peak at mid-day and do not occur at night. Important, in terms of this TMDL, is that the solar shortwave flux to a stream can be controlled (depending on the stream width and vegetation growing conditions) by managing riparian vegetation. Riparian vegetation blocks the total potential short-wave radiation load from entering the stream, limiting potential temperature increases. This is the reason why the percent effective shade, or the fraction of the potential solar shortwave radiation that is blocked by vegetation and topography before it reaches the stream surface, is used as the principal management parameter in this TMDL.

Heat can be transferred through convection ($J_{convection}$) (3). If a stream is hotter than the air temperature above it, heat is transferred from the stream to the air, resulting in a decreased water temperature. Wind transfers heat horizontally, dissipating air temperature gains next to the stream surface. This process maintains a temperature gradient, driving convection losses from the stream. If air temperature exceeds water temperature, heat is transferred into the stream. However, this term tends to be small relative to other heat fluxes.

Evaporation ($J_{evaporation}$) results in a transfer of latent heat from the water body to the air, although it is small relative to other terms in the heat budget equation (4). Finally, heat can be transferred to or from the bed through advective exchange of water containing heat ($J_{hyporheic}$) or by conduction (J_{bed}) with the sediments (Beschta et al., 1987) (5). In addition, heat is advected in (J_{in}) and out (J_{out}) of a reach via surface water transport (6). As it will be discussed later in this report, groundwater inflow can have a significant cooling effect on stream temperature during warm summer months. Subsurface flow, surface water inflow, and rain are the primary advective sources. The role of advection depends on the volume of groundwater or tributary inputs relative to the total stream discharge, for this reason, the influence of groundwater cooling diminishes in a downstream direction.

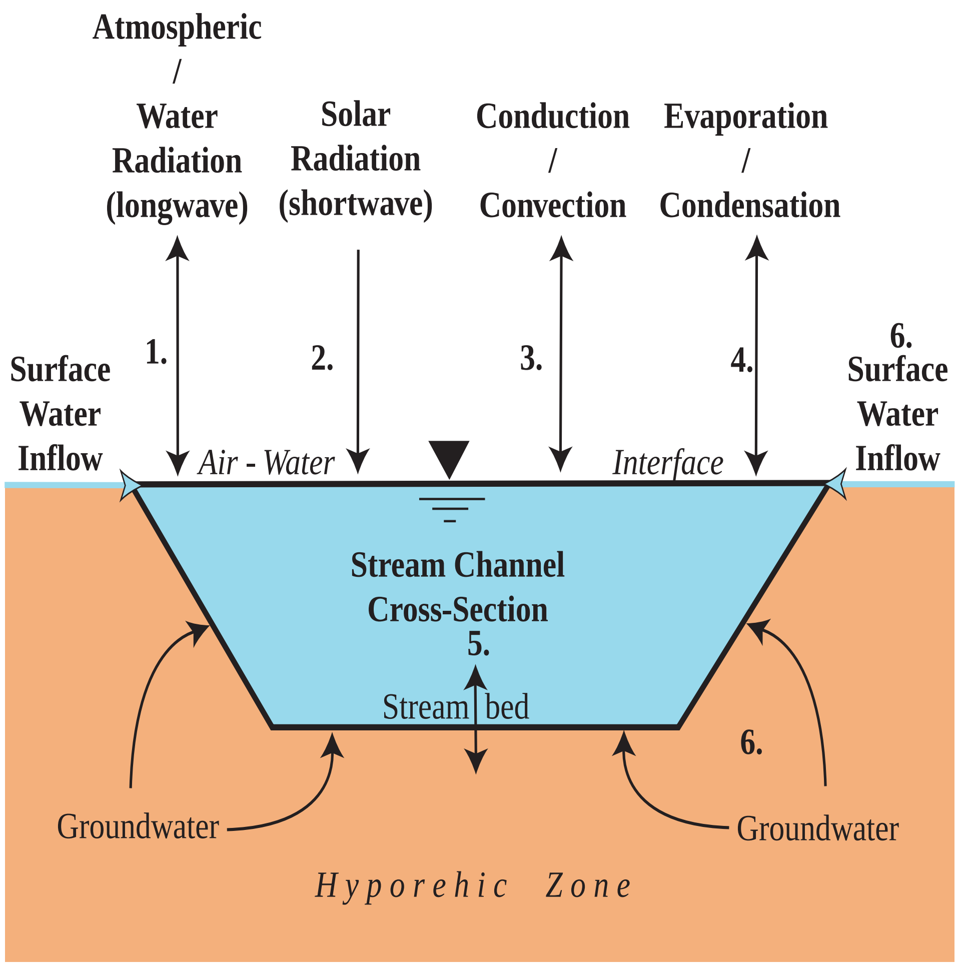

Figure 2. The heat energy processes that effect water temperature.

<u>Heat Equation</u>

A loading capacity for heat (expressed as British Thermal Units (BTU)/square foot per day) can be derived using an analysis of heat transfer processes in water. One of the most basic forms of a heat transfer analysis is the fundamental equation applied by Brown (1969) for forest streams .

$$\Delta T = (\Delta H * A) \; / \; (V * \rho * c_p)$$

ΔT	Temperature change (°F / hour)
ΔH	Rate that heat is received (BTU / hour)
A	Surface area (ft^2)
V	Volume (ft^3)
ρ	Density of water (62.4 lb / ft^3)
c_p	Specific heat of water (BTU/ lb - °F)

The calculation of water temperature by a mechanistic model follows the basic relationship described by the equation above. A mechanistic model is essentially a bookkeeping of different heat transfer processes to determine potential water temperature changes.

The heat budget technique utilizes six variables (solar radiation, long wave radiation, evaporation, convection, bed conduction, and advection) to determine the net gain or loss of stored heat (ΔH) in a known volume of water. The change in ΔH is then converted to a water temperature change.

An advantage of the heat budget approach is that it goes beyond a narrow focus on maximum water temperatures. Maximum water temperatures simply reflect symptoms when criteria values are exceeded. Because the TMDL is designed to decrease the pollutant load during a critical time frame, the analysis of heat transfer processes allows a more direct assessment of causes. The daily profile for water temperature increases typically follows the same pattern of solar radiation delivered to an un-shaded stream. Thus, two critical time frames for development of loading capacity targets are the period of the day when the solar radiation flux has the greatest potential to deliver large quantities of heat energy to the stream and the diurnal range.

Background

Description of Study Area

The 3480 square mile Wenatchee National Forest is located on the east slope of the Cascade Range in central Washington State. The dimensions of the forest from north to south are approximately 140 miles and range between 30 to 50 miles east to west. Five river subbasins are found within the forest, in order from north to south, they include: the Chelan (17 percent of forest area), Entiat (11 percent), Wenatchee (33 percent), upper Yakima (18 percent), and Naches (22 percent).

The crests of the Cascade Mountains form much of the forest's western boundary while to its eastern edge is the Columbia River. Between the two, elevations range from approximately 9000 feet within the common ice fields of the upper Entiat and Chelan basins (Mount Stuart, within the Wenatchee basin, has a peak elevation of approximately 9400 feet) to approximately 1000 feet in lower Entiat, Wenatchee, and Chelan basins, near the Columbia River (Figure 3).

Corresponding with these elevation extremes are similar levels of change in precipitation. The upper elevations of the Cascade Range have annual precipitation levels of approximately 130 inches (most falling as snow from November to April) to approximately 10 inches near the Columbia River (Figure 4). The west-to-east transition from maritime to arid conditions is the result of a rain-shadow effect of the Cascade Range. With prevailing winter storms from the Pacific Ocean approaching the Cascades from the southwest, the majority of the precipitation associated with storm events falls to the west and at the mountain crests. This rain-shadow effect results in large variations in the type and distribution of vegetation within the forest. A mountain hemlock and silver fir environment occurs within the moist maritime conditions along the slopes of the Cascades while a shrub-steppe environment is present in the lower elevations of the Entiat and Wenatchee basins (Lillybridge, 1995).

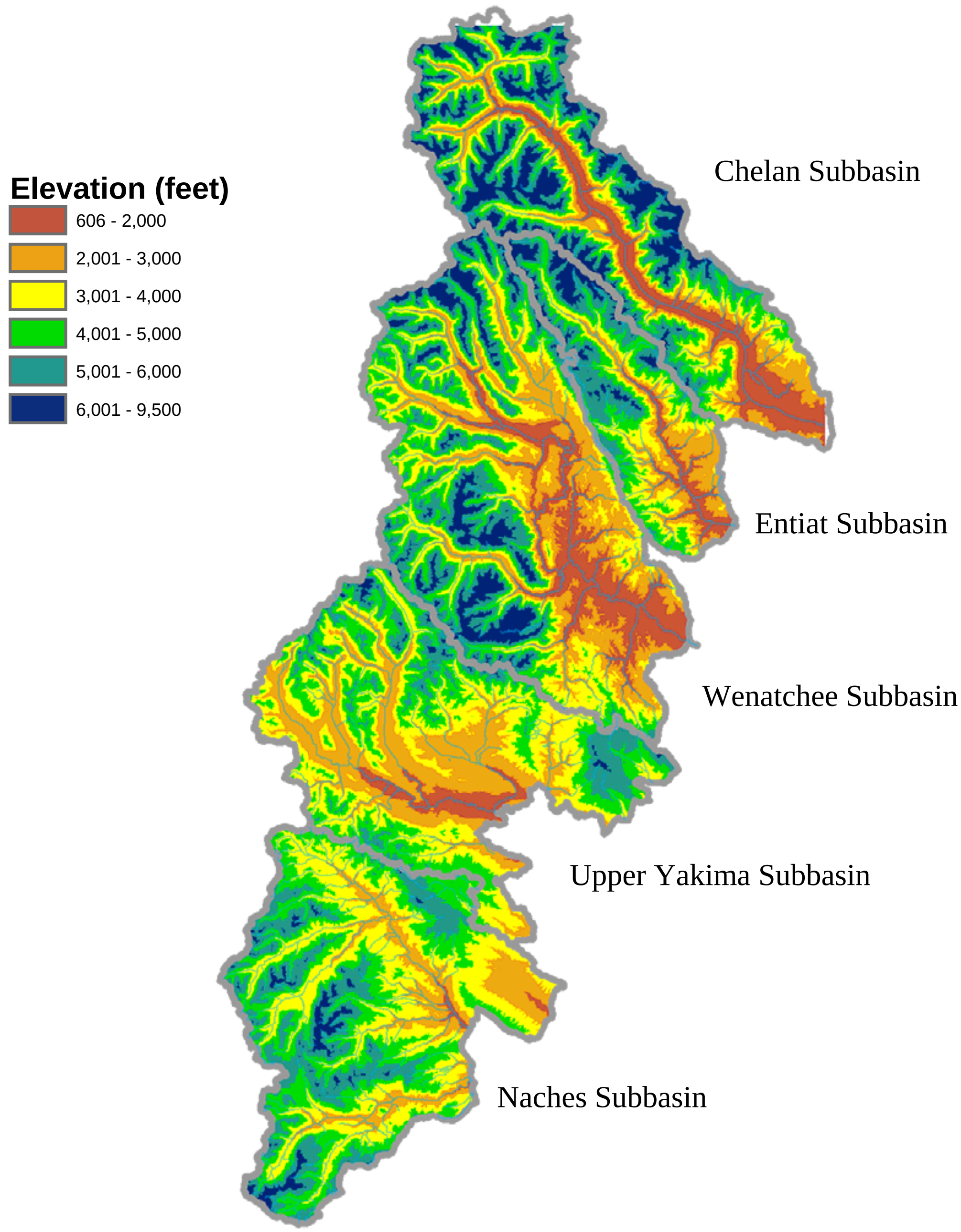

Figure 3. The range in elevation (mean sea level) within the Wenatchee National Forest.

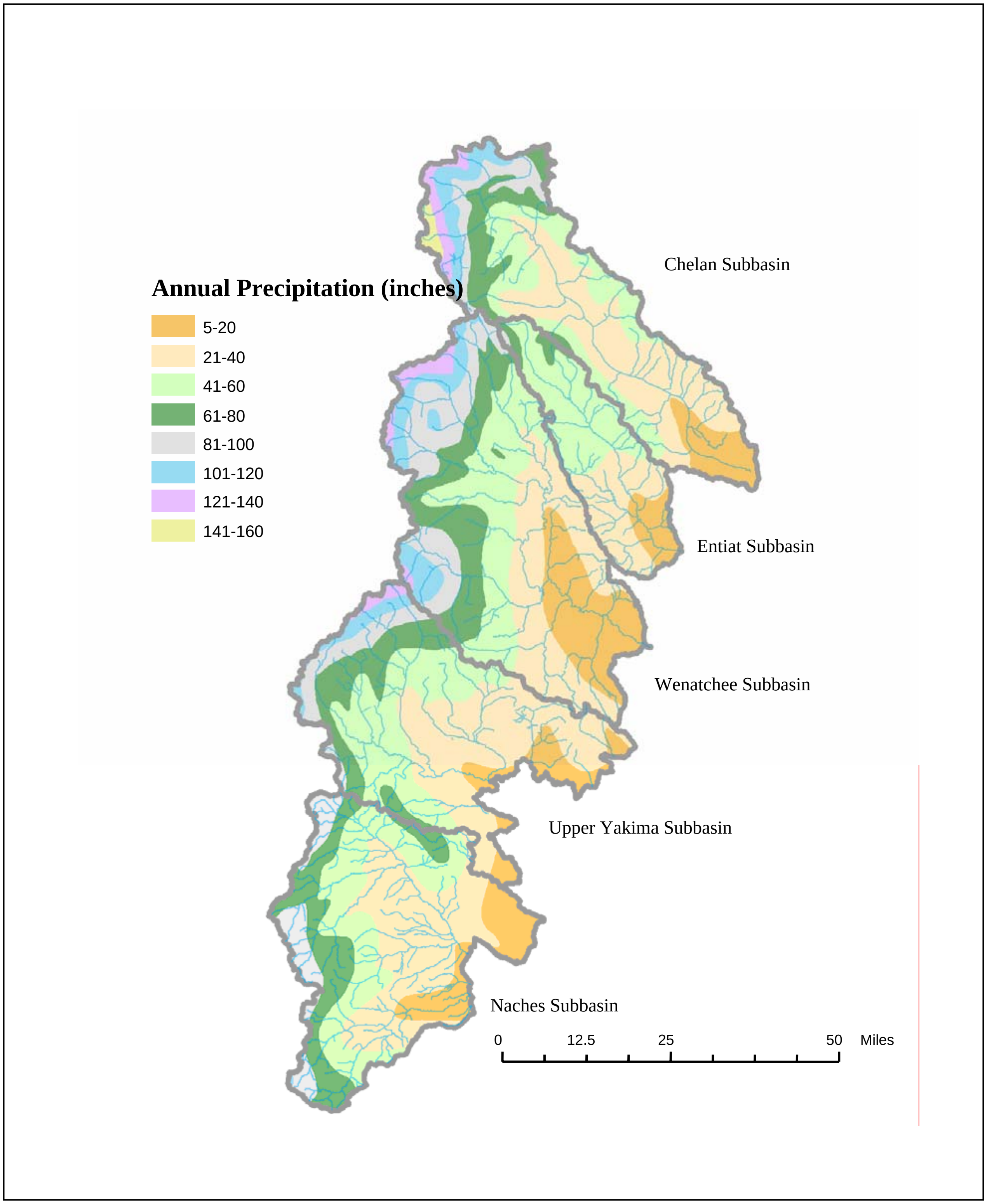

Figure 4. The range in annual precipitation observed in the Wenatchee National Forest.

Statement of Problem

Chronically elevated water temperatures have been observed at numerous locations throughout the Wenatchee National Forest based on data collected since 1995 by the USFS. Washington State's water quality standard for temperature that applies to surface waters within the Wenatchee National Forest (which are classified as AA) is that the maximum water temperature must not exceed 60.8°F (16°C). Much of the USFS water temperature data, along with additional data submitted by the Yakama Indian Nation, has been used by the Washington State Department of Ecology to include 18 separate water segments within the forest on the state's 1998 303(d) list of impaired waters (Figure 5). In addition, data collected by the USFS as part of routine temperature monitoring at 137 stations in 2001 indicates that a further 46 water bodies are impaired, with maximum water temperatures exceeding the standard.

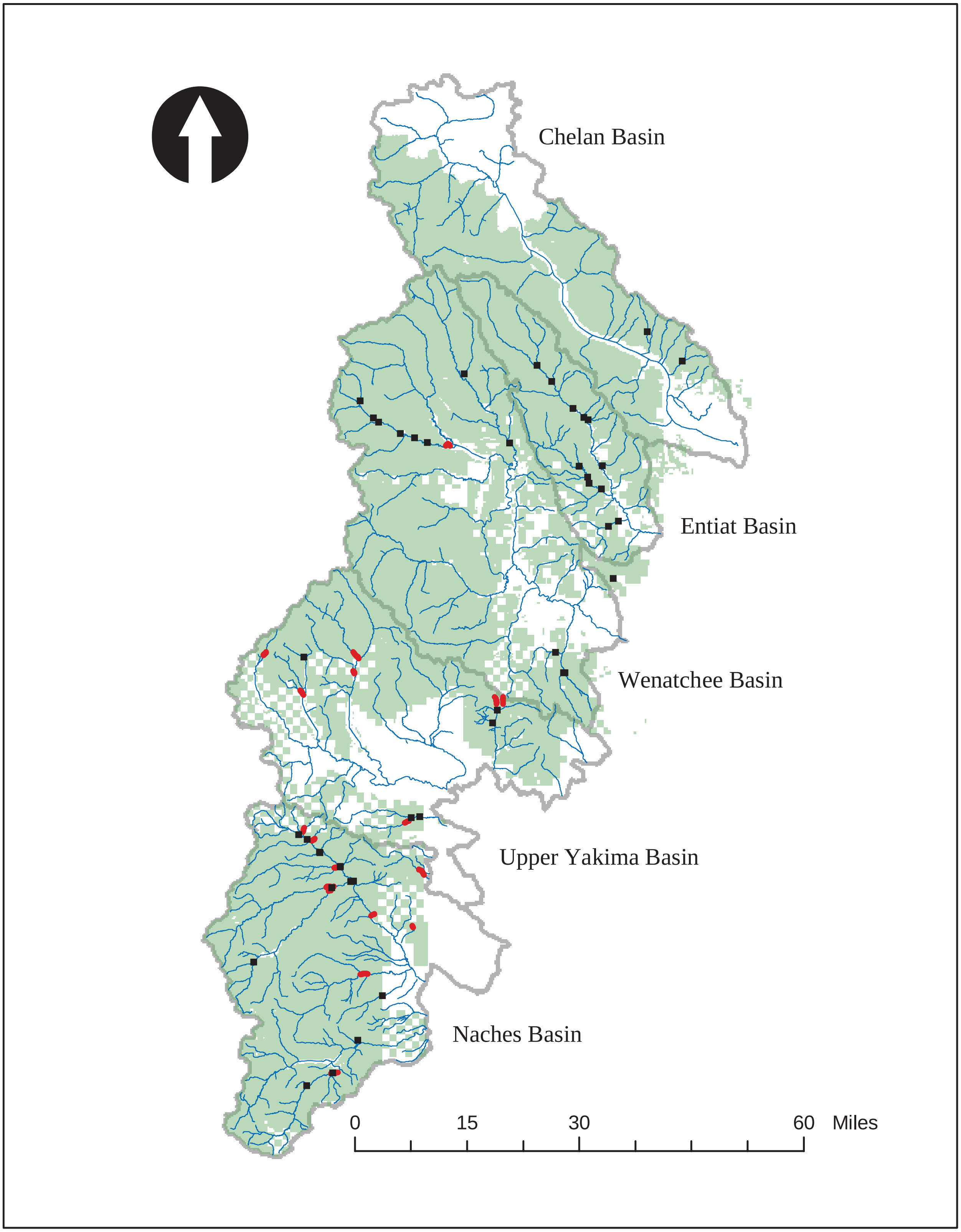

***Figure 5. Listed (red) and impaired (black) surface waters within the Wenatchee National Forest*.**

Applicable Criteria

This TMDL analysis is designed to address impairment of characteristic uses caused by elevated water temperatures. The water quality standards, set forth in Chapter 173-201A of the Washington Administrative Code (WAC), include designated beneficial uses, classifications, numeric criteria, and narrative standards for surface waters of the state. The characteristic uses designated for protection in the Wenatchee National Forest 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 Wenatchee National Forest are designated as Class AA (waters of extraordinary quality).

The temperature criteria for Class AA waters are as follows:

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

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

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

Water Quality and Resource Impairments

Water bodies located within the Wenatchee National Forest that are included on Washington State's most current (1998) 303(d) list for temperature are included in table 1. In Table 1, the water segments are located by township/range/section and by Ecology's water resource inventory area (WRIA) and the agency's 1996 and 1998 303(d) water body identification numbering system (WBID). The water temperature of many of these 18 streams was monitored in 2001 as part of a USFS expanded monitoring effort. That data indicates that the majority of these sites continue to experience maximum water temperatures exceeding the standard.

Table 1. Water bodies within the Wenatchee National Forest included on the 1996 and 1998 303(d) lists for water temperature.

Water Body	*WRIA*	*1996 WBID*	*1998 WBID*	*Township, Range, Section*
Cooper R.	*39*	*WA-39-1055*	*WX84IT*	*22N,14E,16*
Gale Ck.	*39*	*WA-39-1300*	*RZ54RL*	*22N,13E,32*
Gold Ck.	*39*	*WA-39-1390*	*ZS28LG*	*22N,11E,01*
Iron Ck.	*39*	*WA-39-1440*	*YW62RW*	*21N,17E,03*
SF Manastash Ck.	*39*	*WA-39-3025*	*WW44PW*	*18N,15E,36*
SF Taneum Ck.	*39*	*WA-39-1570*	*WJ69FI*	*19N,15E,27*
Waptus R.	*39*	*WA-39-1057*	*XB92PJ*	*22N,14E,04*
Blue Ck.	*39*	*WA-39-1435*	*BU07PV*	*21N,17E,02*
American R.	*38*	*WA-38-1060*	*QX86IU*	*17N,13E,12*
Bear Ck.	*38*	*WA-38-1088*	*JJ42VM*	*19N,13E,32*
NF Nile Ck.	*38*	*WA-38-2110*	*IN37QB*	*16N,15E,03*
Bumping R.	*38*	*WA-38-1070*	*XR40PP*	*17N,13E,12*
Crow Ck.	*38*	*WA-38-1081*	*TL45HC*	*18N,14E,30*
Gold Ck.	*38*	*WA-38-1041*	*CR82VL*	*17N,14E,36*
Mathew Ck.	*38*	*WA-38-1086*	*LW85BJ*	*18N,13E,10*
SF Tieton R.	*38*	*WA-38-3000*	*NV27KW*	*13N,13E,13*
Rattlesnake Ck.	*38*	*WA-38-1035*	*MB08QY*	*15N,14E,10*
Little Wenatchee R.	*45*	*WA-45-4000*	*DS66LF*	*27N,16E,15*

Based on the 2001 water temperature monitoring data from 137 locations throughout the forest, an additional 46 sites had maximum water temperatures that exceeded 60.8°F (16°C), the state temperature standard. At many of these sites, water temperatures were chronically elevated throughout the summer. These impaired sites are listed in Table 2**.**

Table 2. Water bodies where water temperatures were observed at levels exceeding the 60.8°F water quality standard in 2001.

Stream Name	USFS Monitoring Site	WRIA	Township, Range, Section	2001 Max. Temperature
Hause Ck.	HAUS_01	38	14N, 14E, 21	64.4
South Fork Tieton	SFTI_01	38	13N, 13E, 13	65.0
Little Rattlesnake Ck.	LTRA_02	38	15N, 14E, 25	63.8
Little Naches R.	LTNA_01	38	17N, 14E, 4	69.8
Little Naches R.	LTNA_02	38	18N, 14E, 30	68.7
Little Naches R.	LTNA_04	38	18N, 13E, 14	67.0
Little Naches R.	LTNA_05	38	18N, 13E, 9	64.9
Little Naches R.	LTNA_06	38	18N, 13E, 5	64.8
Sand Ck.	SANDN_01	38	18N, 13E, 14	62.8
Bumping R.	BUMP_01	38	17N, 14E, 4	70.5
Bumping R.	BUMP_03	38	17N, 13E, 12	72.0
Bumping R.	BUMP_06	38	16N, 11E, 36	64.9
Quartz Ck.	QUAR_01	38	18N, 14E, 30	61.2
Grey Ck.	GREY_01	38	13N, 13E, 29	62.7
Entiat R.	ENTI_12	46	28N, 19E, 33	67.5
Entiat R.	ENTI_13	46	28N, 19E, 29	65.4
Entiat	ENTI_14	46	28N, 18E, 2	61.7
North Fork Entiat	NFEN_01	46	29N, 18E, 27	61.5
Swakane Ck.	SWAKANE	46	24N, 20E, 16	75.5
Roaring Ck.	ROAR_01	46	25N, 20E, 8	70.1
Roaring Ck.	ROAR_02	46	25N, 20E, 7	65.3
Potato Ck.	POTA_01	46	27N, 19E, 36	69.7
Preston Ck.	PRES_01	46	28N, 19E, 34	63.8
Mitchel Ck.	MITC_01	46	29N, 21E, 24	61.2
Mad R.	MADR_01	46	26N, 19E, 13	70.1
Mad R.	MADR_02	46	26N, 19E, 15	69.3
Mad R.	MADR_03	46	26N, 19E, 10	68.4
Mad R.	MADR_04	46	27N, 19E, 33	68.9
Grade Ck.	GRAD_02	47	30N, 21E, 31	61.0
Little Wenatchee R.	LTWE_02	45	27N, 16E, 18	68.1
Little Wenatchee R.	LTWE_03	45	27N, 15E, 11	65.5
Little Wenatchee R.	LTWE_05	45	27N, 15E, 10	65.9
Little Wenatchee R.	LTWE_07	45	28N, 14E, 36	64.7
Little Wenatchee R.	LWTE_09	45	28N, 13E, 14	62.6
Lake Ck.	LAKEW_01	45	28N, 15E, 31	64.8
Chiwawa R.	CHWA_01	45	27N, 18E, 30	64.0
Chiwawa R.	CHWA_02	45	27N, 17E, 13	64.9
Rock Ck.	ROCK_01	45	29N, 17E, 31	61.1
Sand Ck.	SANDW_01	45	22N, 18E, 1	64.3
East Fork Mission	EFMI_01	45	22N, 19E, 18	72.0
Devils Gulch	DEVI_01	45	22N, 19E, 18	68.9
Iron Ck.	IRON_01	39	21N, 17E, 10	64.1
Mineral Ck.	MINE_01	39	22N, 13E, 5	66.2
Blue Ck.	BLUE_01	39	21N, 17E, 22	63.0
Taneum Ck.	TANE_01	39	19N, 15E, 25	68.5
North Fork Taneum Ck.	NFTA_01	39	19N, 15E, 26	63.4

Overview of Wenatchee National Forest Water Temperature Data

The goal of this TMDL is to establish forest-wide riparian shade levels (in terms of percent effective shade) to maintain maximum water temperatures at, or below, the water quality

standard. An overview of the data used to make these determinations provides a useful foundation for explaining water temperature variability across the forest and some of the analysis considerations used to determine the load allocations.
In 2001, water temperature was measured at 137 locations distributed throughout the Wenatchee National Forest (Figure 6). The monitoring sites covered a variety of channel types, drainage areas, geologic settings, elevations, and vegetative communities. (Additional information on each monitoring stations is included in Appendix A.) In some cases, surface waters outside of the forest were also monitored. Typically, these locations were part of a network of monitoring sites located on larger river systems. (A larger network of temperature probes was deployed on the Entiat, Mad, Chiwawa, Little Wenatchee, and Naches Rivers as part of the thermal infrared remote sensing conducted in August of 2001 by the USFS.)

For most of the monitoring sites, water temperatures were recorded every 30 minutes from June though September, bracketing the period when the most elevated water temperatures occur. In 2001, the majority of the stations recorded peak water temperatures on August 12. For this reason, and to provide a common information base, the observations presented in this section are based on data collected on that day.

The elevations where monitoring stations were located ranged between 782 feet (msl) at the Entiat River station 1, to 4300 feet at the Mad River station 7. The median elevation for the monitoring stations was 2504 feet. The median drainage area above the monitoring locations was 22 square miles but ranged between 1 and 418 square miles.

<u>Minimum and maximum water temperatures</u>

For the majority of the monitoring stations, there is some commonality in the relationship between the minimum and maximum water temperature recorded on August 12 (Figure 7). As observed, streams with lower maximum water temperatures also tended to have lower minimums whereas those that have the most elevated daily maximums also had corresponding elevated minimums.

Streams with the coldest water temperatures tend to be those that have greater groundwater inflow comprising the majority of their flow, typified by the higher elevation first and second order streams. (The temperature of ground water within the greater Wenatchee National Forest is approximately 50^{o}F (10^{o}C).) For those streams that experience the upper temperature extreme, a greater variety of influences are likely present among them: low riparian shade levels, low groundwater inflow in relation to the total stream flow, storage (thermally stratified inflow from lakes and reservoirs), and flow diversion.

Based on the relationship between minimum and maximum water temperatures, the minimum water temperature typically observed for those stations that remained at or below the water temperature standard of 60.8^{o}F (16^{o}C) was approximately 53^{o}F. Overall, median temperatures for the monitoring stations were a maximum of 61.2^{o}F, a minimum of 53.5^{o}F, and a diurnal range of 7.7^{o}F.

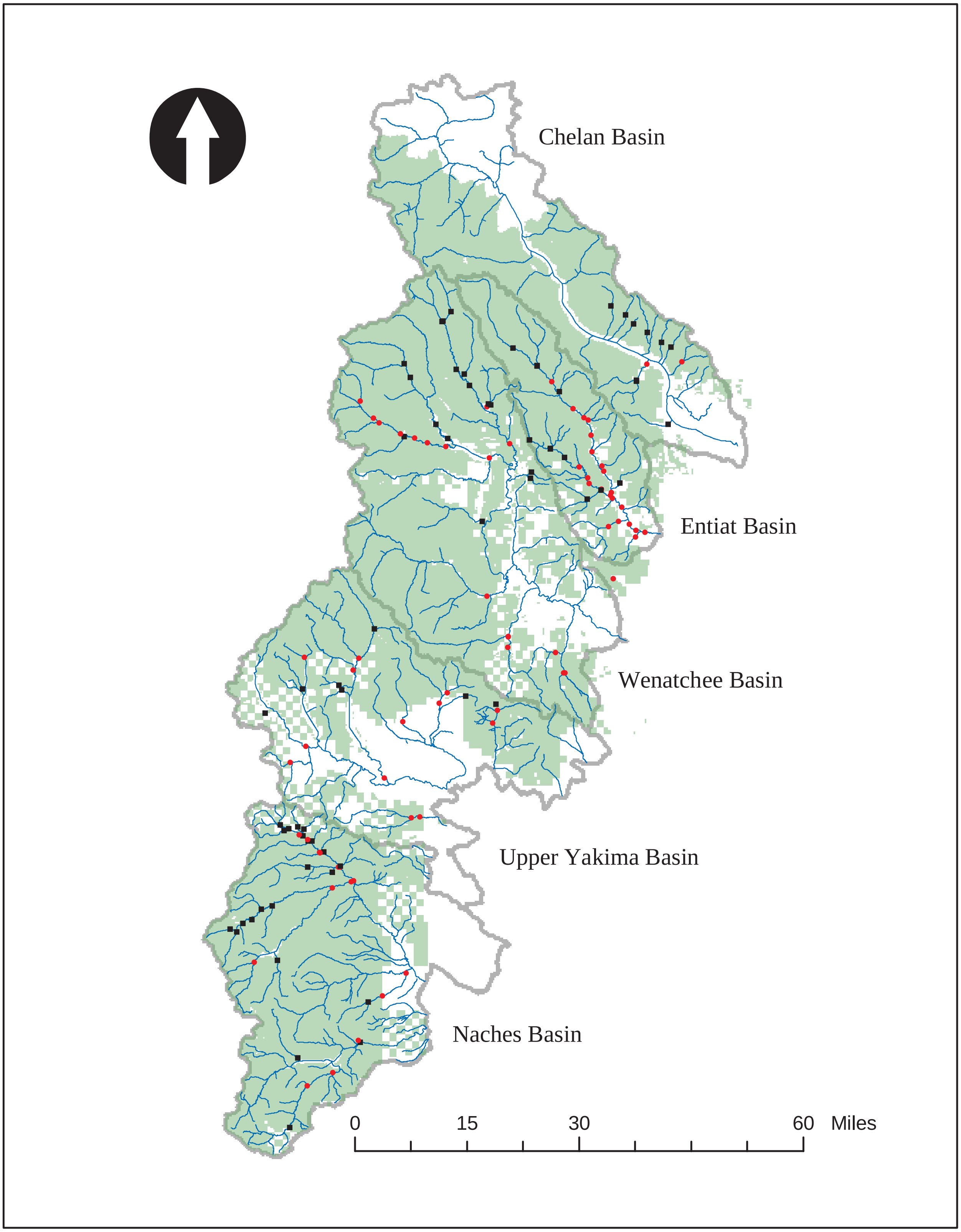

Figure 6. 2001 USFS water temperature monitoring locations. Stations with maximum temperatures above and below the standard are depicted in red and black, respectively.

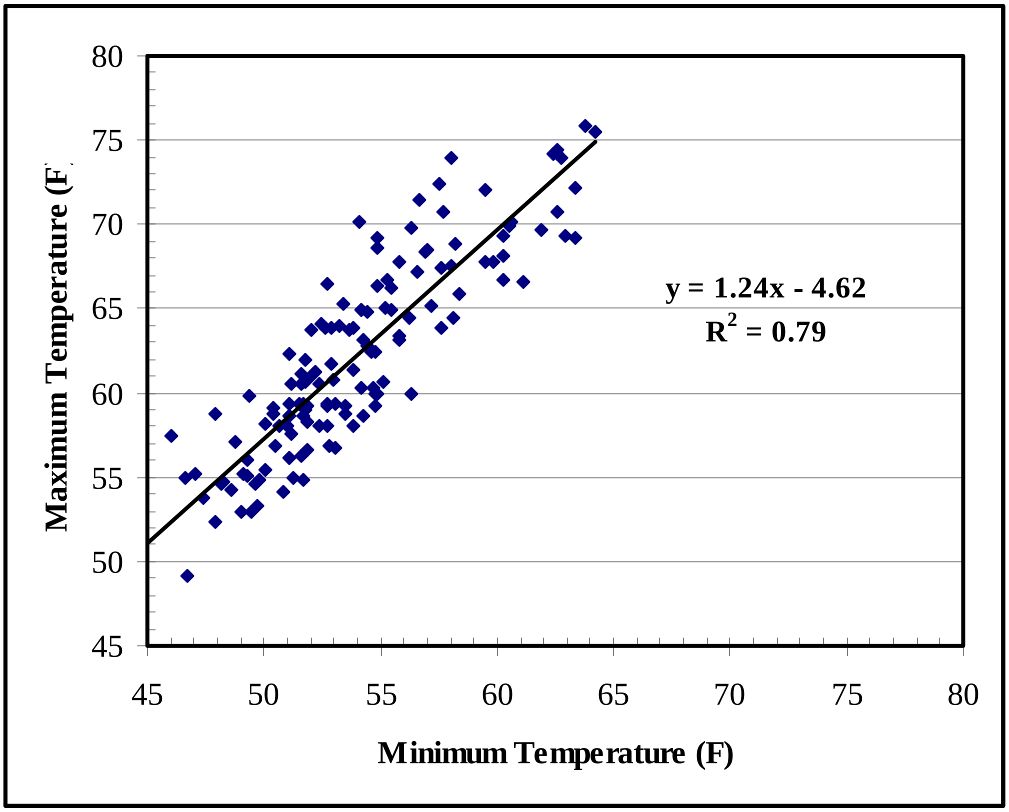

Figure 7. The relationship between the minimum and maximum water temperature observed on August 12, 2001 at the Wenatchee USFS monitoring stations.

Diurnal Range

Table 3 provides a statistical overview of the diurnal range (maximum minus minimum on August 12) observed for various ranges of maximum water temperature. As expected, the coldest monitoring sites, the 50 to 55°F range, have the lowest median diurnal temperature variation (approximately 5°F). Again, these streams likely have groundwater discharge comprising the majority of the in-stream flow and are, therefore, buffered from wide variations in temperature. In contrast, for the 65°F+ monitoring sites, the overall median temperature range is approximately 10°F. These streams experience chronically elevated water temperatures for a variety of reasons but the lack of riparian shade is likely a common one.

Table 3. Statistical overview of the diurnal range (°F) observed for several maximum water temperature ranges.

Maximum Temperature Range	*N*	*Median Range*	*Max Range*	*Min Range*	*75th Percentile Range*	*25th Percentile Range*	*Temp. Max Median*	*Temp. Min Median*
50 – 55	*16*	*4.6*	*8.4*	*2.5*	*5.8*	*3.6*	*54.2*	*48.8*
56 – 60	*44*	*6.4*	*11.5*	*3.6*	*7.6*	*5.1*	*58.5*	*51.6*
61 – 65	*36*	*8.9*	*11.8*	*5.6*	*10.3*	*7.8*	*62.7*	*53.8*
66 – 70	*29*	*9.8*	*14.3*	*5.5*	*11.5*	*8.0*	*67.8*	*57.6*
70 – 75	*15*	*11.8*	*16.0*	*8.2*	*13.9*	*11.3*	*72.4*	*62.4*

Excluding monitoring stations highly influenced by groundwater inflow (50-55°F), the temperatures characteristics of stations where the maximum water temperature remained below the standard are represented by the range 55 – 60°F. Within this range the median maximum temperature was 58.5°F with a median diurnal range of 6.4°F. The 75th and 25th percentiles of the diurnal range are 7.6 and 5.1°F, respectively. Based on these results, it can be extrapolated that for streams to achieve an annual maximum at the water quality standard (60.8° F) they should have a diurnal range of approximately 5 to 8 degrees resulting in a low of between 53 to 56 degrees on the day the maximum water temperature is observed.

While a significant relationship between the minimum and maximum water temperatures was observed for the monitoring stations, the diurnal range has a lower correlation with the maximum water temperature (Figure 8).

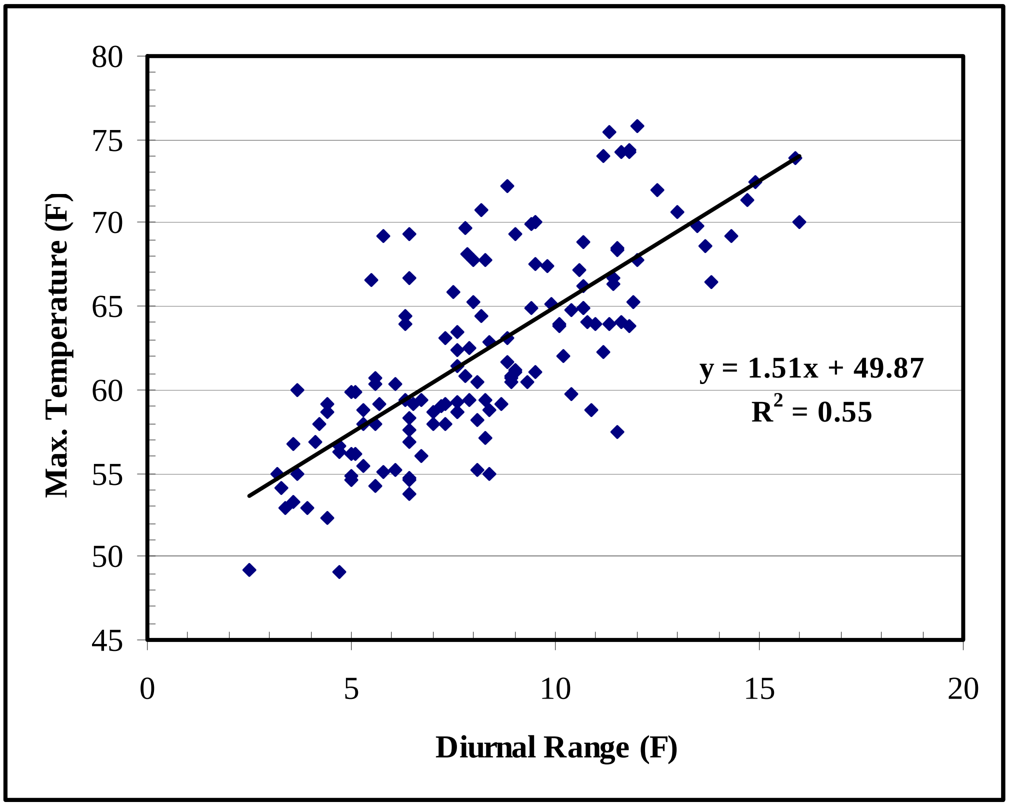

Figure 8. The relationship between the diurnal temperature range and the maximum water temperature observed on August 12, 2001 at the Wenatchee USFS monitoring stations.

The scatter in the relationship between the diurnal range and the maximum water temperature was examined closer to determine if there are certain characteristics shared for those stations on the upper and lower extremes. These data outliers were divided into two groups depicted in Figure 9 by the squares (warm-water stations) and diamonds (cold-water stations). As observed, in comparison to the majority of the monitoring stations, the warm-water stations have greater maximum water temperatures, and the cold-water stations have colder maximum temperatures for their respective diurnal ranges.

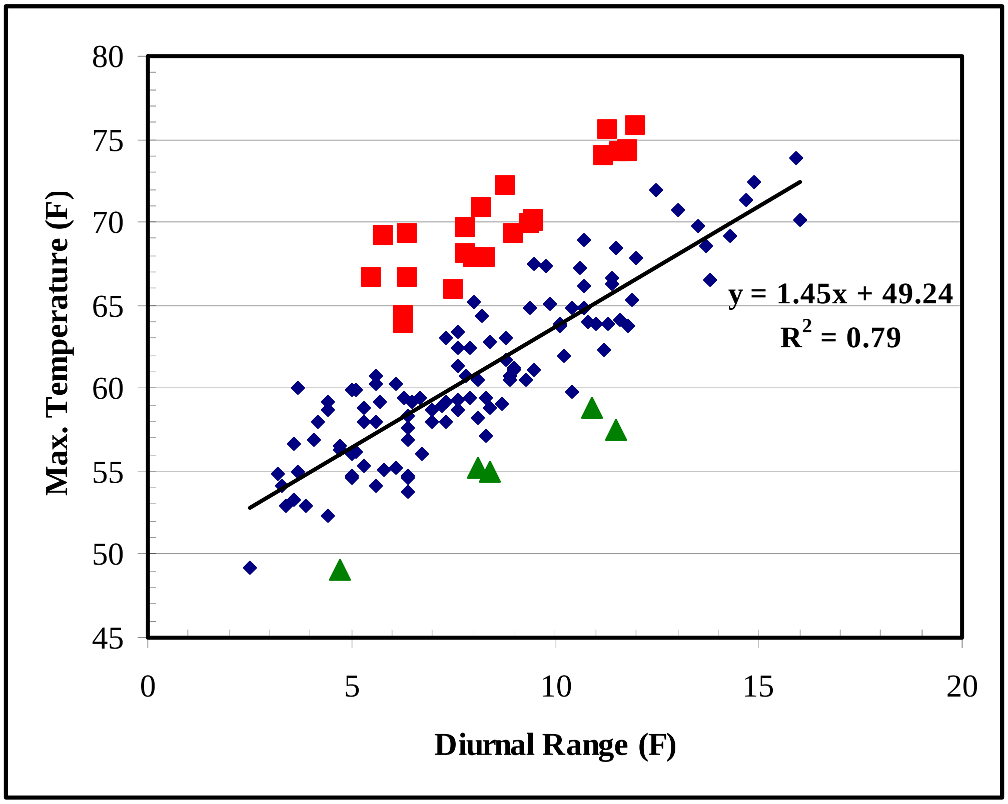

Figure 9. The relationship between the diurnal range (°F) and the maximum water temperature based on three subgroups: squares represent warm-water outliers and the triangles represent cold-water outliers in relation to the main dataset (diamonds).

Warm-water Stations

A common characteristic for many of the warm-water stations is having a significant amount of water storage in the form of natural lakes or impoundments that contribute to flow passing the monitoring locations. Included in this grouping are the monitoring stations located on Lake Creek (Little Wenatchee River), Yakima River, Cle Elum River, Cooper River, Waptus River, lower Bumping River, Little Wenatchee River (below Lake Creek and at Wenatchee Lake), and Icicle Creek. The storage of heat within these impoundments has the effect of modifying water temperatures by maintaining more elevated minimum water temperatures at downstream locations. For this reason, streams that receive outflow from lakes or reservoirs experience higher minimum water temperatures and, with all other heating factors equal, will experience greater maximum water temperatures.

Also, included among the warm-water sites are Mad River stations (0 through 3), Entiat River (1 through 9), and Nason Creek. These stations, while having a similar heating pattern as observed for the monitoring stations with water storage do not share that characteristic. Instead, these streams likely have greater storage of heat within their channels due to common characteristics like long flow paths (Entiat), flow through lower elevations with higher minimum air temperatures reducing the potential for night-time cooling, storage within pools (Mad River), conductive heating from bedrock (Mad River), as well as low groundwater inflow and high exposure. Another common characteristic of the warm-water stations without storage is that they are situated in the lowest elevations among the monitoring stations. The lower elevations within the forest receive significantly lower precipitation levels resulting in lower tree height and canopy density levels which in turn reduces the potential stream shade that can be produced. The average elevation for these stations is 1301 feet in comparison to the overall average of 2485 feet. In particular, the elevations of the Entiat River stations (1 through 9) are low with an overall average of 1092 feet, with a range from 782 feet at the lowest station (1) to 1462 feet (9). In a sense, elevation is a surrogate for many of the characteristics mentioned above. These warm-water stations at the lower elevations tend to be higher order streams with greater width to depth ratios (higher exposure), lower levels of effective shade, with groundwater inflow comprising a lower percentage of the total flow, reducing this potential source of cooling.

<u>Cold-water Stations</u>

The cold-water stations are represented by Deep Creek (Naches), Indian Creek (Entiat), Phelps Creek (Wenatchee), American River above the Rainier Fork (Naches), and the South Fork Tieton at the Forest Service Road 1070 crossing. The characteristic these stations share is that the maximum water temperature remains lower than expected (in comparison to the majority of the monitoring stations) given their respective diurnal range. In direct contrast to the warm-water monitoring stations (those without storage), these stations are situated in the highest elevations of the monitoring sites. The average elevation for these sites is 3517 feet with a range between 2958 feet for Indian Creek (Naches) to 3950 feet for the South Fork Tieton (3). (In comparison, the average elevation for all the monitoring stations is 2485 feet.) Given the high elevation, night-time cooling is significant. In fact, these stations had among the lowest minimum water temperatures of the monitoring sites, with an average minimum of 46.4^{o}F. (In comparison, the average minimum for all of the monitoring stations was 54.1^{o}F)

Again, elevation is a surrogate of other heating characteristics. In the case of the cold-water stations, the overwhelming influence on water temperature is ground water. At all of these stations groundwater discharge likely comprises the majority of the flow and, therefore, has a moderating influencing on the maximum water temperatures observed. For instance, the South Fork Tieton station (3) is located in Conrad Meadows with naturally low effective shade levels. Low shade levels result in this station having a diurnal range of approximately 11^{o}F. For the majority of the stations, this large a temperature range would result in maximum water temperature of approximately 65^{o}F, exceeding the water quality standard. However, a maximum temperature of only 58.8^{o}F was recorded.

The warm-water (those with storage) and cold-water sites are functioning in a similar way; both have a heat reservoir that has a moderating effect on the diurnal temperature range. The cold-water stations have ground water serving as their heat reservoir (reducing heat) and the warm-water stations have lake or reservoir storage (supplying heat).

<u>Diurnal Heating Patterns</u>

To examine differences in diurnal heating, the monitoring stations were divided into several groups: the warm-water stations, cold-water stations, groundwater-dominated stations (where the maximum water temperature remained below 55^{o}F). The remainder of the stations were divided into those that remained below the water quality standard ($x<=60.8^{o}$F) and those that exceeded it ($x>60.8^{o}$F). The median hourly (bi-hourly) water temperatures observed on August 12 for these groups are presented in Figure 10. As observed, each of these groups displays a different heating pattern. The warm-water stations have a median minimum water temperature of 61^{o}F, in contrast, the cold-water and groundwater-dominated stations have a median low of

49°F and 46°F, respectively. As discussed earlier, the cold-water and warm-water stations share a similar heating pattern, both with an approximately 9°F diurnal range. But because they have significantly different minimum temperatures, they also have equally separated maximum water temperatures.

The groundwater-dominated and cold-water stations only differ in the magnitude of their minimum temperatures. For reasons discussed earlier, the cold-water stations have an approximately 3°F lower minimum temperature than observed for the groundwater-dominated stations. However, the maximum temperature between these two groups is the same at 55°F. For this reason, the diurnal range of the cold-water stations is 9°F while for the groundwater-dominated stations is 6°F.

The group of monitoring stations with maximum water temperatures below the water quality standard (x<=60.8°F) had a low of 52°F and a maximum of 58°F resulting in a diurnal range of 6°F. In contrast, the stations that exceeded the standard (x>60.8°F) had a diurnal range of 10°F. So while this group shared a similar minimum as the stations that met the standard (53°F as opposed to 52°F) the elevated diurnal range results in a maximum of 63°F. For this reason, in addition to examining the heating of streams based on the maximum annual temperatures achieved, they can also be examined based on the diurnal range and the pattern of heating.

Based on the median diurnal range observed for stations meeting the water quality standard (6°F) it can be extrapolated that the warm-water sites with storage will likely never meet the standard while the cold-water and groundwater sites will likely always meet it despite widely varying shade levels.

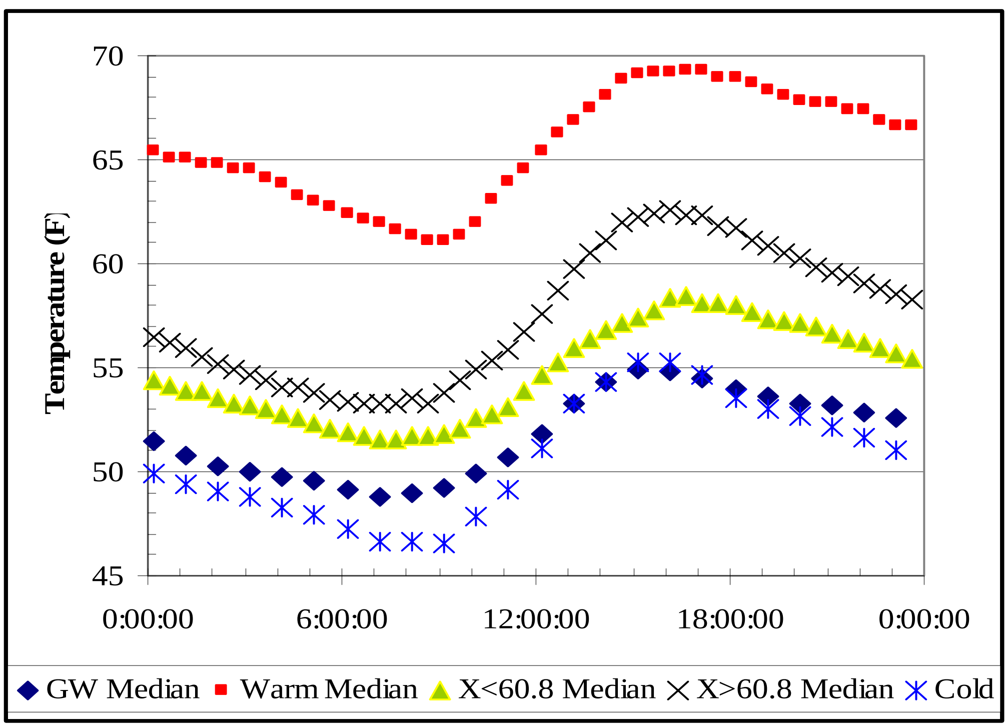

Figure 10. The water temperature heating pattern observed on August 12, 2001 for several groups of monitoring sites.

Geology – The influence of elevation and ground water on water temperature

Based on the previous discussion, it is apparent that there are landforms or areas within the forest where, due to geological characteristics, greater groundwater storage and supply occur resulting in colder water temperatures. The association between the monitoring sites that met the temperature standard and geologic setting was examined to identify situations where greater storage and discharge of ground water are present.

Land-type associations (LTA), or areas that share common topographic, geologic, and potential natural vegetation characteristics were delineated for the Wenatchee National Forest (Davis, 1994). Integrated within the LTA is a qualitative assessment of the aquifer recharge potential associated with each land-type based on the depth and texture of the overburden (material residing above bedrock), landform shape, exposure, gradients, geologic fracturing and structure, annual precipitation, and surface drainage configurations. A high, moderate, and low recharge potential was associated with each of the 18 land-types identified for the forest. This information is particularly useful for determining, on a landscape basis, what surface waters have high groundwater discharge and, therefore, likely have colder water temperatures.

The association between land-type and monitoring stations where maximum water temperatures remained below the standard was examined. The results of this analysis identified certain land-types associated with colder streams, indicative of higher groundwater inflow. They include: scoured glaciated mountain slopes (G), glaciated mountain slopes (I), glacial troughs (K), glacial moraines (L), landslides (T), and moderately steep volcanic flows (X). All of these landforms have a high to moderate groundwater recharge potential associated with them. An additional land-type associated with colder water is scoured glacial troughs (F). While this land-type has a low recharge potential it is situated in the highest elevations of the landforms in the forest (Figure 11).

The association between these landforms and colder water is due to their higher elevation and groundwater storage. The majority of the monitoring stations located with these landforms had maximum water temperatures that remained below the water quality standard despite having variable shade levels. However, there are streams situated within these landforms that have abnormally elevated water temperatures. Some of these stations, located within the upper Yakima subbasin, such as the Cooper River, Mineral Creek, and the Waptus River experience water temperatures above expected levels due to heat storage within their drainages in the form of lakes. The same is true for the lower Bumping River (due to Bumping Lake reservoir) in the Naches drainage and Lake Creek in the Wenatchee drainage.

For others, such as the Little Wenatchee River, the Little Naches River, and the lower South Fork Tieton, channel morphological changes (wide, shallow channels) due to high sediment loading combined with low shade levels have resulted in elevated water temperatures. The lower reaches of Sand Creek and Crow Creek, two tributaries to the Little Naches River, also display similarly elevated water temperatures despite proximity within these colder water landforms, again the reason is likely the result of low shade levels. So proximity within these landforms does not preclude streams from experiencing warmer water temperatures. However, elevated water temperatures within these landforms, given the associated conditions of high groundwater inflow, are indicative of low shade characteristics, the result of sediment-related channel widening and (or) loss of a shade producing riparian vegetative buffer.

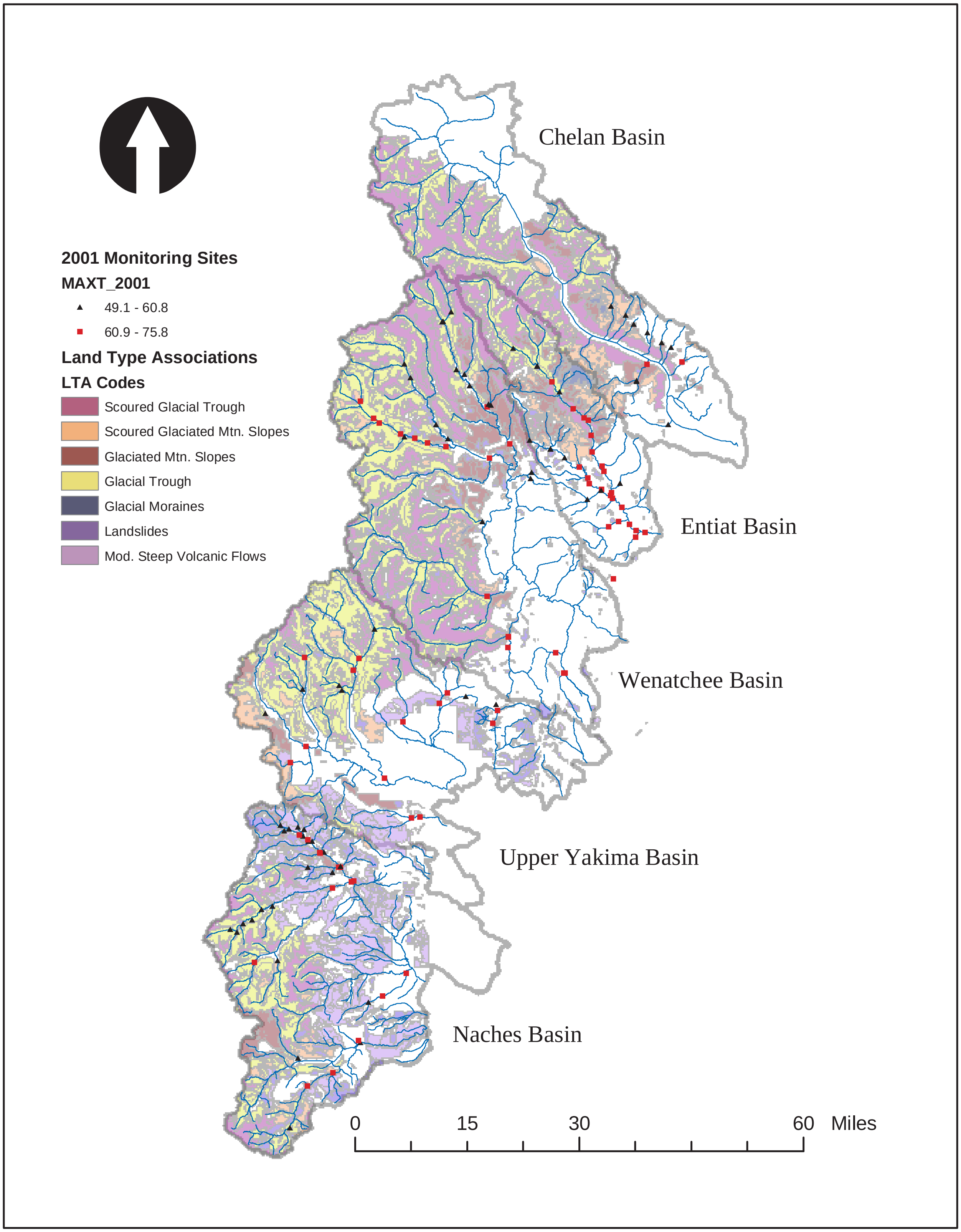

Figure 11. Landforms associated with cooler streams.

Seasonal Variation

Clean Water Act Section 303(d)(1) requires that TMDLs "be established at levels necessary to implement the applicable water quality standards with seasonal variations".

Existing conditions for stream temperatures throughout the Wenatchee National Forest reflect seasonal variation. Cooler temperatures occur in the winter, while warmer temperatures are observed in the summer. The highest water temperatures typically occur from July through August. This time frame was used as the critical period for development of this TMDL.

Seasonal estimates for stream flow, solar flux, and climatic variables were considered in developing critical conditions for TMDL model assumptions. The critical period for evaluation of solar flux and effective shade was assumed to be August 1 because it is the mid-point of the period when water temperatures are typically at their seasonal peak coincident with low flow levels.

Technical Analysis

Landscape Scale Analyses

TMDL development for non-point pollution sources presents some inherent challenges. Diffuse, or nonpoint sources, are often associated with watershed scale features and processes occurring over time. Consequently, addressing non-point water quality concerns requires a different approach from traditional point source problems.

Classification systems have been developed to better understand the characteristics and sensitivities of diverse landscapes, and how long-term land management plans interact with them. They are designed to account for the essential influences (e.g. geologic setting, climatic factors) that are largely responsible for much of the natural variation in habitat types at various spatial and temporal scales.

A classification system was developed for the Wenatchee National Forest based on three attributes: geologic setting, drainage area, and channel morphological characteristics. This classification framework, combined with information compiled in its development, provided a technical basis to support assumptions used in the heat budget analysis.

<u>Geologic Setting</u>

Stratifying the landscape into Subsection Mapping Units (SMU) captures influences of geologic setting and associated physical processes within the Wenatchee National Forest. In 1994, the Wenatchee N.F. completed a subsection level of ecological stratification intended for subregional planning, which is explained in the *"National Hierarchical Framework for Ecological Units"*. Subsection Mapping Units are designed to contain broad areas with similar geomorphic history and expression (landforms), potential natural vegetation patterns, climatic conditions, and soil development. The Wenatchee National Forest includes nine SMUs described in Table 4 and Figure 12.

Table 4. Description of subsection codes.

Subsection Code	***Description***
M242 – Ca *Wenatchee Highlands*	*Elevation Range – 2500 – 9500'* *Precipitation – 50 – 160"* *Primary Landscape Setting* *Glacial Cirques* *Natural Vegetation = Alpine meadows, Mountain Hemlock* *Trough Walls* *Natural Vegetation = Mountain Hemlock, Silver Fir series* *Trough Bottoms* *Natural Vegetation = Pacific Silver Fir, Western Hemlock series, wet meadows*
M242 – Cb *Chelan and Sawtooth Highlands*	*Elevation Range – 1100 – 8000'* *Precipitation – 15 – 55"* *Primary Landscape Setting* *Glacial Cirques (above 6500')* *Natural Vegetation = Alpine meadows, subalpine larch, whitebark pine, subalpine fir* *Glacial Trough Walls (1100 – 6500')* *Natural Vegetation = Doug. Fir, Grand Fir, subalpine fir series (high elevations). Ponderosa pine series, grassland shrub steppe (lower elevations)* *Trough Bottoms (lower elevations)* *Natural Vegetation = Doug. Fir, Ponderosa Pine series associated with shrub-steppe*
M242 – Cq *Entiat – Chelan Hills*	*Elevation Range – 1000 – 6700'* *Precipitation – 15 – 59"* *Primary Landscape Setting* *Glacial Moraines (5000'+)* *Natural Vegetation = Subalpine fir, Grand Fir series* *Highly Dissected Hill Slopes (1000 – 5000')* *Natural Vegetation = Ponderosa Pine within shrub-steppe at lower elevations, Doug. Fir and grand fir in the upper elevations.*

Subsection Code	Description
M242 – Ci *Cle Elum / Lake Wenatchee Mountain Valleys*	*Elevation Range – 1900 – 4200'* *Precipitation – 30 – 80"* *Primary Landscape Setting* *Valley Bottoms (low to mid-elevations)* *Natural Vegetation = Doug. Fir, Grand Fir, W. Hemlock, sedge/willow meadows* *Glacial Moraines (mid to high elevations)* *Natural Vegetation = Doug. Fir, grand fir, W Hemlock*
M242 – Cm *Wenatchee – Swauk Sandstone Hills*	*Elevation Range – 1000 – 5000'* *Precipitation – 15 – 49"* *Stream flows are usually intermittent or perennial streams have interrupted flows* *Primary Landscape Setting* *Dissected Sandstone Hills* *Natural Vegetation = Ponderosa Pine associated with shrub-steepe (lower elevations), Doug. Fir series (mid to upper elevations).*
M242 – Cn *Upper Yakima – Swauk Sandstone Hills*	*Elevation Range – 2500 – 7000'* *Precipitation – 30 – 50"* *Primary Landscape Setting* *Dissected Sandstone Hills* *Natural Vegetation = W. Hemlock, Grand Fir (western portion), Grand Fir, subalpine fir (eastern portion).*
M242 – Co *Upper Yakima Basin*	*Elevation Range – 2500 – 9500'* *Precipitation – 50 – 160"* *Near surface ground water, seeps, and springs on lower slopes helps to maintain base flows and low stream temperatures.* *Primary Landscape Setting* *Glacial Mountains (upper elevations)* *Natural Vegetation = W. Hemlock, Pac. Silver Fir, Mountain Hemlock.* *Dissected Ridges (low to mid elevations)* *Natural Vegetation = W. Hemlock, Pac. Silver Fir and Grand Fir (eastern portion)*

Subsection Code	Description
M242 – Cp *Naches Mountains*	*Elevation Range – 2500 – 7700'* *Precipitation – 40 – 99"* *Near surface ground water, seeps, and springs on lower slopes helps to maintain base flows and low stream temperatures.* *Primary Landscape Setting* *Glacial Mountains (upper elevations)* *Natural Vegetation = Pac. Silver Fir and Mtn. Hemlock* *Volcanic & Pyroclastic Flows* *Natural Vegetation = Subalpine Fir (upper elevations), Grand Fir (mid elevations), Doug. Fir (lower elevations).* *Dissected Mountain Slopes* *Natural Vegetation = Silver Fir (W. portion), Grand Fir (E. Portion, low elevation), Subalpine Fir (E. portion, upper elevation)*
M242 – Cc ***Cascade Mountains, Non-glaciated***	***Elevation Range – 2000 – 6000'*** ***Precipitation – 10 – 50"*** ***Primary Landscape Setting*** ***Plateaus and Mountain Slopes*** ***Natural Vegetation = Ponderosa Pine associated with shrub-steppe***
M242 – Cc ***Cascade Mountains, Non-glaciated***	***Elevation Range – 2000 – 6000'*** ***Precipitation – 10 – 50"*** ***Primary Landscape Setting*** ***Plateaus and Mountain Slopes*** ***Natural Vegetation = Ponderosa Pine associated with shrub-steppe***

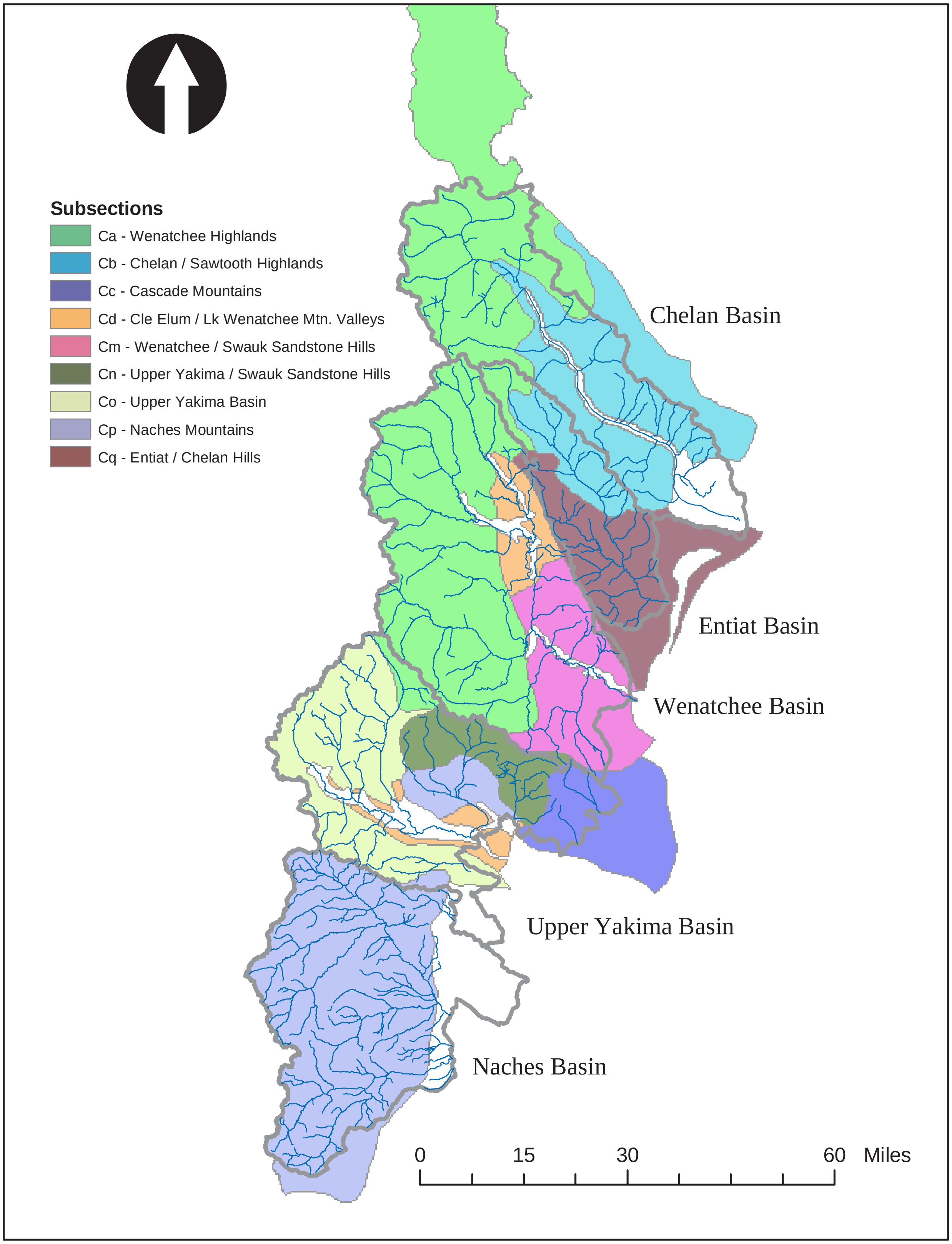

Figure 12. Subsections within the Wenatchee National Forest.

Drainage Area

Both watershed size and stream order are important in assessing water temperature. Hydraulic geometry relationships should be stratified not only by stream type, but also by watershed size (Rosgen, 1996). Stream order has long been used by hydrologists to develop quantitative relationships and is often used to describe stream size.

A 1:24,000 scale digitized stream layer covering the Wenatchee National Forest was used to develop a relationship between relative stream size and drainage area at each water temperature monitoring location. A geometric progression in drainage area size that captured the greatest number of orders was determined for the forest (Table 5). The bankfull width presented in Table 5 was determined based on an evaluation of drainage area to bankfull width observed at USGS gauging stations in proximity to the Wenatchee National Forest (Figure 13).

Table 5. Relationship between stream size and drainage area (acres) observed at monitoring locations.

Relative Size	*Drainage Area (acres)*	*Bankfull Width (ft)*
1	*X<=2000*	*16*
2	*2000<x<=5000*	*20*
3	*5000<x<=12500*	*31*
4	*12500<x<=31250*	*47*
5	*31250<x<=78125*	*70*
6	*78125<x<=195313*	*106*
7	*195313<x<=488281*	*160*

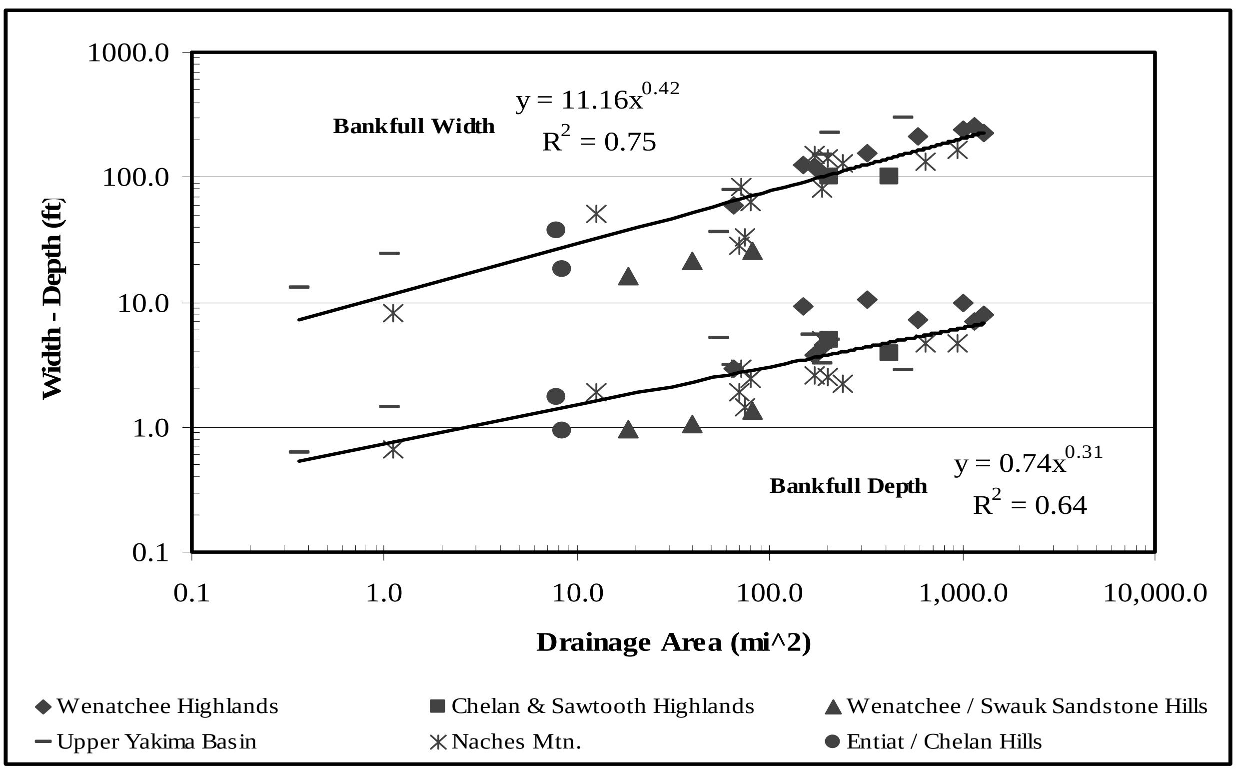

Figure 13. The relationship between drainage area and bankfull width and depth observed at historic and current USGS gauging stations within, and proximal to, the Wenatchee National Forest (note log scale) .

Channel Classification

Methods exist to assess the condition of a stream as well as departure from its potential (Rosgen, 1996). These methods, built around channel classification, are useful to develop specific TMDL surrogate measures for streams in the Wenatchee National Forest. Consequently, a second lower level of stratification consists of classifying stream segments of the channel network within each of the subsections.

Rosgen has developed a broad-level delineation system, which allows for a rapid initial morphological classification of stream types that are typically encountered within watersheds. The system provides a framework for organizing and assessing information within each Subsection Map Unit. Table 6 describes the major stream types used in development of this TMDL.

Table 6. Stream-type descriptions (Rosgen, 1996).

Stream Type	*General Description*	*Bankfull W:D Ratio*	*Slope (%)*	*Landform / Soils / Features*
A	*Steep, entrenched, cascading step/pool streams. High energy/debris transport associated with depositional soils. Very stable if bedrock or boulder dominated channel*	*<12*	*4 – 10*	*High relief. Erosional or depositional and bedrock forms. Entrenched and confined streams with cascading reaches. Frequently spaced, deep pools in associated step/pool bed morphology.*
B	*Moderately entrenched, moderate gradient, riffle dominated channel, with infrequently spaced pools. Very stable plan and profile. Stable banks.*	*>12*	*2-4*	*Moderate relief, colluvial deposition, and/or structural. Moderate entrenchment and w/d ratio. Narrow, gently sloping valleys. Rapids predominate with scour pools.*
C	*Low gradient, meandering, point-bar, riffle/pool, alluvial channels with broad, well defined floodplains.*	*>12*	*<2*	*Broad valleys with terraces, in association with floodplains, alluvial soils. Slightly entrenched with well-defined meandering channels. Riffle/pool bed morophology.*
E	*Low gradient, meandering riffle/pool stream with w/d ratio and little deposition. Very efficient and stable. High meander width ratio.*	*<12*	*<2*	*Broad valley/meadows. Alluvial materials with floodplains. Highly sinuous with stable, well vegetated banks. Riffle/pool morphology with very low w/d ratios.*

Mechanistic Water Temperature Models

Mechanistic models have been developed, based on a heat budget approach, which estimate water temperature under different heat balance and flow conditions. Brown (1969) was the first to apply a heat budget to estimate water temperatures on small streams affected by timber harvest. Using mathematical relationships to describe heat transfer processes, the rate of change in water temperature on a summer day can be estimated. Relationships include both the total energy transfer rate to the stream (i.e. the sum of individual processes) and the response of water temperature to heat energy absorbed. Heat transfer processes considered in the analysis include solar radiation, longwave radiation, convection, evaporation, and bed conduction (Wunderlich 1972, Jobson and Keefer 1979, Beschta and Weatherred 1984, Sinokrot and Stefan 1993).

Solar radiation is the predominant energy transfer process that contributes to water temperature increases. A general relationship between solar radiation loads and stream temperature can be developed by quantifying heat transfer processes, providing a starting point to defining a loading capacity (i.e. the greatest amount of loading that a water-body can receive without exceeding water quality standards).

QUAL2K and Response Temperature Model

QUAL2K (Chapra, 1997) and the Response Temperature models were used to calculate the components of the heat budget and to simulate water temperatures. QUAL2K, a Visual Basic application in a Microsoft Excel® environment, uses the kinetic formulations for the surface water heat budget described earlier. In summary, QUAL2K is a steady-state, one-dimensional model that simulates diurnally varying water temperature using a finite-difference numerical method. Therefore, a single flow condition is selected to represent a given condition, such as a seven-day average flow. For temperature simulation, solar radiation, air temperature, relative humidity, headwater temperature, and point source/tributary water temperatures are specified as diurnally varying functions with a minimum and maximum value and time of the maximum value.

The concept of response temperature was originally proposed by J.E. Edinger Associates. Response temperature is defined as the temperature that a column of fully mixed water would have if heat fluxes across the surface were the only heat transfer processes. In other words, the water temperature is assumed to be responding only to those heat fluxes.

The rate of surface heat exchange can be calculated from meteorological data (e.g. air and dew point temperature, wind speed, cloud cover, solar radiation). Edinger et al (1974) provides a review of the methods that can be used to estimate heat fluxes. Because meteorological data are available for long periods, this simple model provides the basis to estimate long-term, frequency of occurrence statistics for natural water temperatures.

The Department of Ecology has extended this concept to include the response to heat flux between the water and the stream bed, groundwater inflow, and hyporheic exchange. The rate of change of response temperature can be written in terms of the net rate of surface heat exchange as:

dT/dt = Jnet / (d*rho*Cp)

dT/dt	The rate of change of water temperature with time (^{o}C per second)
Jnet	The net rate of surface heat exchange (solar shortwave, longwave atmospheric, longwave back, convection, evaporation, streambed conduction, hyporheic exchange, groundwater inflow) (calories/square-centimeter-second)
d	The mean depth of the water column (centimeters)
Rho	The density of water (1 gram/cubic-centimeter)
Cp	The specific heat of water at constant pressure (calorie/gram-^{o}C)

A similar expression can also be written for the change in temperature of the surface layer of the bottom sediment underlying the stream bed in response to the heat flux from hyporheic exchange and conduction between the water and sediment.

Site Potential Shade

The effective shade produced by late-successional, or site potential growth, was estimated for the forest. Site potential vegetation is defined by the maximum tree height and canopy density (principal shade producing attributes) that can be expected for a particular area. Therefore, the shade produced by site potential vegetation represents the maximum that can be produced naturally. This calculation served as the load allocation in this TMDL.

Seven forested groups have been delineated within the Wenatchee National Forest (Lillybridge, 1995). These groups represent the climax, or late-successional species likely to dominate following an extended disturbance-free period. They include: ponderosa pine/shrub-steppe, Douglas fir, Douglas fir/grand fir, grand fir/western hemlock, western hemlock, Pacific silver fir/ mountain hemlock, and sub-alpine fir. In order to determine the effective shade likely to be generated within these groups it is necessary to make an estimate on their optimal (old growth) tree height and canopy density, two physical characteristics critical to calculating effective shade. An overview of this analysis process is provided below.

<u>Tree Height</u>

Old growth characteristics for the major late-successional trees have been defined for the Pacific Northwest Region of the Forest Service (Interim Old Growth Definitions,1992). One of these characteristics, diameter at breast height (DBH), was used to calculate the tree height associated with old growth by species.

Old growth tree height was determined for each of the seven forested vegetation groups by relating DBH to height. To examine this relationship, a Wenatchee National Forest database of vegetative plot information was used. The database contains information on the major tree species growing throughout the forest under a variety of environmental conditions and growth stages. Among the data collected at the vegetative plots were tree height and DBH by species. Based on this information, a power-type regression equation was determined for each of the major tree types (Table 7). Applying these relationships to the old growth DBH results in an estimate of tree height (Table 7). Old growth tree heights ranged between approximately 100 feet for ponderosa pine, Douglas fir, western hemlock, mountain hemlock, and sub-alpine fir to 120 feet for Pacific silver fir and grand fir.

Table 7. The power function relationship between diameter at breast height (DBH, inches) and tree height (feet) by species.

	n	*Equation*	r^2	*Old Growth DBH (inches)*	*Resultant Tree Height (ft)*
All Species	*3829*	*Tree Height = 17.65* $(dbh)^{0.59}$	*0.56*	*-*	*-*
Ponderosa Pine	*391*	*Tree Height = 10.58* $(dbh)^{0.72}$	*0.63*	*21*	*95*
Douglas Fir	*1537*	*Tree Height = 18.57* $(dbh)^{0.57}$	*0.53*	*21*	*105*
Grand Fir	*423*	*Tree Height = 17.55* $(dbh)^{0.63}$	*0.70*	*21*	*120*
W. Hemlock	*261*	*Tree Height = 20.68* $(dbh)^{0.55}$	*0.65*	*21*	*110*
Mtn. Hemlock	*90*	*Tree Height = 17.11* $(dbh)^{0.55}$	*0.63*	*25*	*100*
Sub-Alpine Fir	*156*	*Tree Height = 8.87* $(dbh)^{0.79}$	*0.51*	*21*	*98*
P. Silver Fir	*305*	*Tree Height = 17.40* $(dbh)^{0.61}$	*0.67*	*26*	*127*

Canopy Density

Areas within the forest that define the seven plant groups have been digitized into a geographic information system (GIS) polygon cover. In addition, canopy density has been evaluated throughout the forest resulting in a GIS grid cover (based on a 25 m^2 resolution) using the following ranges of canopy density: 0-10 percent, 10-40 percent, 40-70 percent and 70-100 percent.

An evaluation of riparian canopy density, based on the vegetation groups was conducted using the following methods.

- Surface waters within the Wenatchee National Forest were separated by their intersection (or enclosure) within each of the groups. (A 1:24,000 scale digitized stream layer was used to identify surface waters throughout the forest.)
- Following the separation of surface waters by group, a 150-foot buffer (each side or 300-foot total) was then placed around the streams.
- Each of the seven buffered stream layers was then used to clip the canopy density grid.
- For each of the seven clipped grids (one for each plant group), the percent of the total area represented by the various canopy density ranges were determined. (The total area, for each group, is equivalent to the area enclosed within a 150-foot buffer along the entire length of streams specific to each group.) The results of this analysis are provided in Table 8.

Table 8. Percent of the riparian area, within each vegetative group, represented by the various canopy density ranges.

Vegetative Group	*Forest Canopy Density*				*Non-forest Canopy Density*		
	0 to 10%	*10 to 40%*	*40 to 70%*	*70 to 100%*	*Shrub-Steppe*	*Open S. Face / Meadows/ Rock*	*Rock / Glacier*
Ponderosa Pine	*26*	*15*	*14*	*13*	*15*	*17*	*-*
Douglas Fir	*24*	*20*	*18*	*25*	*2*	*11*	*-*
Douglas Fir / Grand Fir	*14*	*14*	*26*	*36*	*2*	*7*	*-*
Grand Fir/ W. Hemlock	*11*	*10*	*20*	*55*	*-*	*4*	*-*
W. Hemlock	*10*	*11*	*17*	*56*	*-*	*6*	*-*
P. Silver Fir/ Mtn. Hemlock	*14*	*8*	*14*	*56*	*-*	*8*	*-*
Sub-Alpine Fir	*12*	*9*	*15*	*49*	*-*	*12*	*3*

Grouping

Based on the analysis results (Table 8) it is apparent that certain vegetative groups share similar canopy density levels. For instance, the lower elevation, drier, ponderosa pine and Douglas fir groups have a greater representation of the lower canopy densities ranges (0 - 10 percent, 10 - 40 percent) while the other five vegetative groups, located in higher elevations and wetter growing conditions, have a greater representation of the higher canopy density ranges (40 – 70 percent, 70 – 100 percent). In particular, the canopy density ranges within vegetative groups: grand fir/western hemlock, western hemlock, Pacific silver fir/mountain hemlock, and sub-alpine fir are all represented at similar levels (Table 8). The Douglas fir/grand fir vegetative group is transitional between the ponderosa pine/Douglas fir and those located at higher elevations.

Based on these similarities, the seven vegetative groups were placed into three new groups for this TMDL analysis. Group-a comprises the ponderosa pine and Douglas fir. The Douglas fir/grand fir vegetative group comprises group-b. The other vegetative groups including: grand fir/western hemlock, western hemlock, Pacific silver fir/mountain hemlock, and sub-alpine fir comprise group-c. Figure 14 presents the extent of each group within the Wenatchee National Forest

Determination of Optimal Canopy Density and Tree Height Levels

The canopy density grid values reflect current (1997) levels throughout the Wenatchee National Forest from highly disturbed (clear cut, fire) to old growth conditions. For the majority of the forest, riparian canopy density levels are optimal. This is reflected in the results of the riparian canopy density analysis where the majority of the canopy density for group-c is at the highest levels, 70 to 100 percent. Within group-c, the percent representation of the various ranges of canopy density, by vegetative group, are also similarly distributed. A highly fractured representation of canopy density levels between vegetative groups would be indicative of large scale riparian disturbance. However, based on the analysis results, that is not the case within the Wenatchee National Forest. Optimal canopy density levels were determined for groups a, b, and c using the following method.

- Based on the percent representation within each canopy density range (refer to Table 8), a weighted average was calculated. (The percent representation applied to the forested and non-forested landscape.) The canopy density value used within each of the ranges was the maximum one. For instance, if 26 percent of the streamside area for a particular vegetative group was represented by the 0 to 10 percent canopy density range, then a value of 2.6 percent was calculated (0.26 * 10 percent). The reason for the use of the highest range value is because this analysis is directed toward determining optimal canopy density levels.

Although the use of the weighted average as a means of calculating optimal canopy density includes observations from impacted areas, it is assumed that the overall extent of the impacted areas is relatively minor in comparison to the total analysis area for each plant association group. The results of this analysis are presented in Table 9 along with the optimal tree heights. Tree heights were calculated for each vegetative group by averaging the old growth tree heights (presented in Table 7) among the species that are associated with each group. These tree heights and canopy density levels then served as input for calculating the effective shade for each vegetative group.

Table 9. Optimal tree height and canopy density by vegetative group.

	Tree Height (feet)	***Canopy Density (%)***
Group a	*100*	*47*
Group b	*113*	*62*
Group c	*111*	*71*

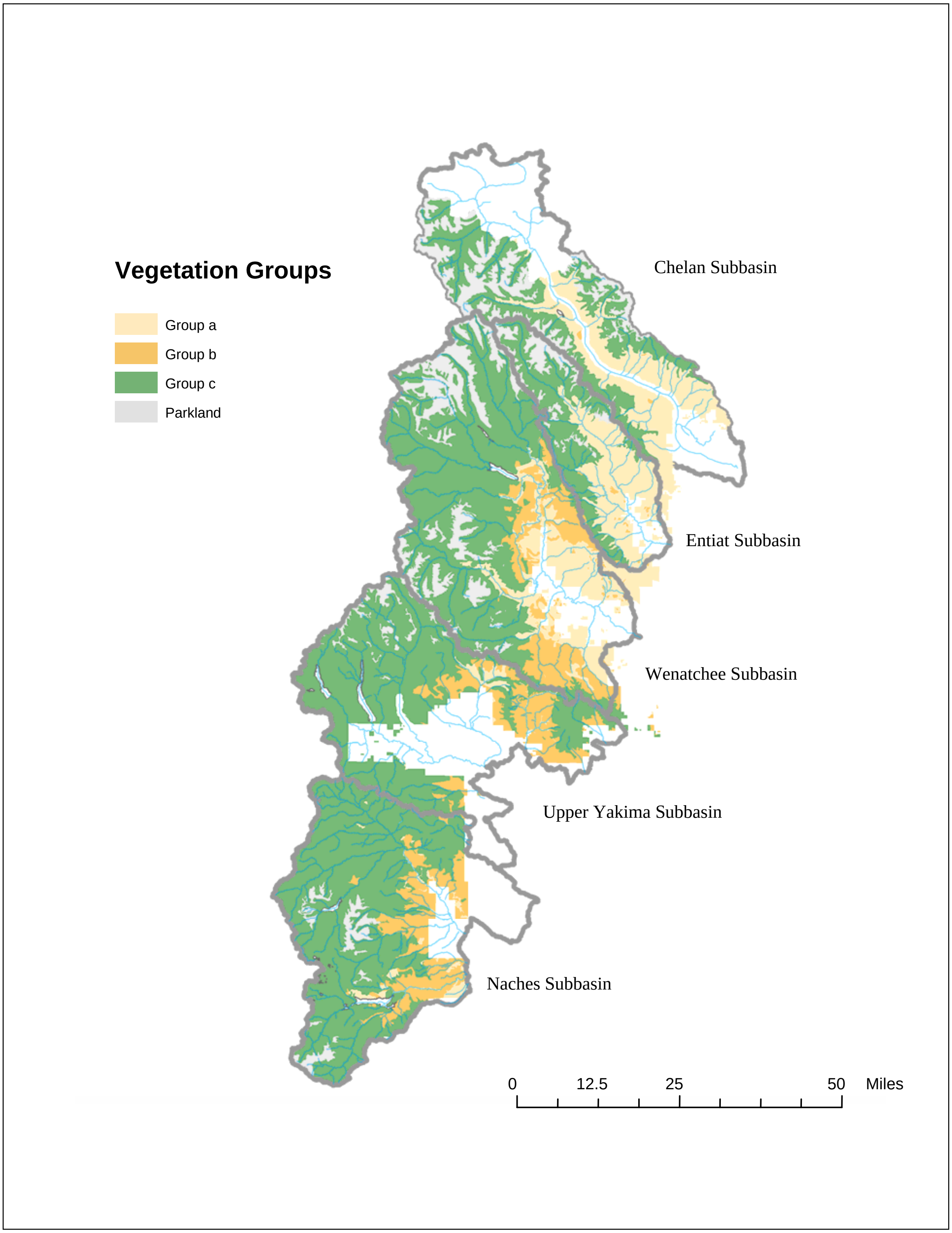

Figure 14. The extent of the three vegetative groups within the Wenatchee National Forest.

Loading Capacity

Regulatory Framework

The foundation of a TMDL analysis is the water quality standard. It provides the basis from which the fundamental TMDL calculations are made, among them, the load capacity and load allocation. (For surface waters within the Wenatchee National Forest, the temperature standard is 60.8^{o}F (16^{o}C).)

Under the current regulatory framework for development of TMDLs, identification of the loading capacity is an important first step. The loading capacity provides a reference for calculating the amount of pollutant reduction needed to bring an impaired water into compliance with standards. EPA's current regulation defines loading capacity as *"the greatest amount of loading that a water can receive without violating water quality standards"*. Allocations are defined as the portion of a receiving water's loading capacity that is allocated to point or nonpoint sources and natural background. By definition, TMDLs are the sum of the allocations *[40 CFR §130.2(i)]*.

Heat is the pollutant for this TMDL. As a result, the load capacity is based on determining what level reduction in heat is necessary to achieve the standard for temperature impaired surface waters. As discussed earlier, rather than setting the load capacity based on heat, the surrogate measure, percent effective shade, has been used.

Within this analysis, the TMDL allocation is the percent effective shade necessary to reduce water temperatures to the water quality standard while the load allocation is the percent effective shade provided by site potential vegetation.

<u>Channel Class Target Development</u>

Identification of loading capacity targets utilizes the landscape stratification system developed specifically for this TMDL analysis. The loading capacities reflect the range variation in geologic setting and associated physical processes that occur across the Wenatchee National Forest. Channel classes are based on three attributes, which include:

- Subsection Mapping Units (SMU) that reflect the geologic setting
- Watershed size
- Channel morophology

Existing data collected by the USFS was used in a heat budget analysis to determine loading capacity targets. The Response Temperature Model (RTM), described earlier, was well suited for this analysis. RTM allows examination of processes that affect water temperature and can be run in a single reach mode for comparison with actual data. Key factors used in the analysis, which vary by channel class, include:

- Flow
- Channel depth
- Channel slope
- Manning's n

Table 10 summarizes results of the loading analysis. TMDL targets are organized by geologic setting and channel classes within each SMU.

Natural Conditions

A complication in using mechanistic models to develop load allocations (in terms of effective shade) is that the result may not be achievable. This occurs when the vegetative height associated with a mature riparian area is not tall enough or of sufficient density to shade the entire active channel. For such cases, and for cases where the numeric criteria is naturally exceeded, the natural conditions clause of Washington's water quality standards is applied [WAC 173-201A-070(2)]. This means that the temperature that results from shade provided by mature riparian vegetation becomes the standard and the effective shade level associated with these conditions becomes the loading capacity.

Thus, the analysis process looks at the effective shade that results from the potential natural vegetation for each channel type. Using the Response Temperature Model, this level is compared to the effective shade needed to meet the water quality critieria. The effective shade needed to meet the diurnal range target is also considered in the analysis.

To better quantify the linkage between effective shade associated with natural conditions and the anticipated effect on water temperatures, diurnal variation was also considered. As discussed earlier, diurnal variation in water temperature occurs naturally in stream systems. The magnitude of the temperature change (e.g. the diurnal range) has greater meaning in TMDL development for nonpoint sources than a "no threshold" criteria (e.g. 16^{o}C). This is because a TMDL is designed to decrease the pollutant load. Assessing the diurnal range as a result of load reduction is much more straightforward than predicting attainment of an absolute water temperature. This approach incorporates consideration of natural conditions by looking at the temperature patterns from a base condition (as opposed to engaging in a debate about the level of the base temperature).

Because of the structure of this analysis, the TMDL and load allocations will be presented in the following section.

Load Allocations

Under the current regulatory framework for development of TMDLs, flexibility is allowed for specifying allocations. TMDLs can be expressed in terms of either mass per time, toxicity, or other appropriate measures. This TMDL assessment uses percent effective shade as a surrogate measure of heat flux to fulfill the requirements of Section 303 part (d) of the Clean Water Act. Effective shade is defined as the fraction of the potential solar shortwave radiation that is blocked by vegetation and topography before it reaches the stream surface. In contrast, allocations could have taken the form of energy per unit area (heat load), however, that measure is less relevant in guiding management activities needed to solve identified water quality problems. Percent effective shade can be linked to specific source areas, and thus to actions (specifically riparian management) needed to solve problems that cause water temperature increases. For this reason, shade is used as a surrogate to the thermal load as allowed under EPA regulations (defined as "other appropriate measure" in 40 CFR §130.2(i)).

This TMDL develops load allocations based on a channel classification system developed for surface waters within the Wenatchee National Forest. Table 10 outlines the TMDL load allocations, or the effective shade levels required to meet the temperature standard, and the load allocation, or the effective shade level provided by site potential vegetation. (Refer to the technical analysis section for a complete explanation of the classification system and its development.)

Table 10. The TMDL and load allocation by channel class.

Classification	*Flow (cfs)*	*W:D (wetted)*	*TMDL Allocation Effective Shade (%)*	*Load Allocation (Site Potential) Effective Shade (%)*		
				Group a	*Group b*	*Group c*
M242Ca Wenatchee Highlands						
Ca-3C	*4*	*30*	*65*	*46*	*58*	*67*
Ca-4C	*8*	*35*	*60*	*43*	*55*	*63*
Ca-5C	*16*	*40*	*55*	*39*	*51*	*58*
Ca-6C	*32*	*45*	*50*	*33*	*44*	*51*
M242Cb Chelan & Sawtooth Highlands						
Cb-1A	*1*	*10*	*70*	*48*	*61*	*70*
Cb-2A	*2*	*10*	*70*	*47*	*61*	*69*
Cb-3C	*4*	*30*	*65*	*46*	*58*	*67*
Cb-4C	*8*	*35*	*60*	*43*	*55*	*63*
Cb-5C	*16*	*40*	*55*	*39*	*51*	*58*
Cb-6C	*32*	*45*	*50*	*33*	*44*	*51*
M242Cd Cle Elum / Lake Wenatchee Mountain Valleys						
Cd-1A	*1*	*10*	*70*	*48*	*61*	*70*
Cd-2B	*2*	*15*	*70*	*47*	*61*	*69*
Cd-5C	*16*	*40*	*55*	*39*	*51*	*58*
Cd-6C	*32*	*45*	*50*	*33*	*44*	*51*
M242Cm Wenatchee / Swauk Sandstone Hills						
Cm-3C	*4*	*30*	*65*	*46*	*58*	*67*
Cm-4C	*8*	*35*	*60*	*43*	*55*	*63*
Cm-5C	*16*	*40*	*55*	*39*	*51*	*58*
M242Cn Upper Yakima / Swauk Sandstone Hills						
Cn-1A	*1*	*10*	*70*	*48*	*61*	*70*
Cn-2B	*2*	*15*	*70*	*47*	*61*	*69*
Cn-4C	*8*	*30*	*60*	*43*	*55*	*63*

Classification	Flow (cfs)	W:D (wetted)	TMDL Allocation Effective Shade (%)	Load Allocation (Site Potential) Effective Shade (%)		
				Group a	Group b	Group c
M242Co Upper Yakima Basin						
Co-2B	2	15	70	47	61	69
Co-3C	4	30	65	46	58	67
Co-4C	8	35	60	43	55	63
Co-5C	16	40	55	39	51	58
M242Cp Naches Mountains						
Cp-1A	1	10	70	48	61	70
Cp-1B	1	15	70	48	61	70
Cp-2B	2	15	70	47	61	69
Cp-2C	2	25	70	47	61	69
Cp-3B	4	20	60	46	58	67
Cp-3C	4	30	65	46	58	67
Cp-4C	8	35	60	43	55	63
Cp-5C	16	40	55	39	51	58
Cp-6C	32	45	50	33	44	51
M242Cq Entiat / Chelan Hills						
Cq-2B	2	15	70	47	61	69
Cq-3C	4	30	65	46	58	67
Cq-4C	8	35	60	43	55	63
Cq-5C	16	40	55	39	51	58
Cq-6C	32	45	50	33	44	51
Cq-7C	64		45	27	35	41
M242Cc Cascade Mountain: Non-glaciated						
Cc-1A	1	10	70	48	61	70
Cc-2B	2	15	70	47	61	69
Cc-4C	8	35	60	43	55	63
Cc-5C	16	40	55	39	51	58
Cc-6C	32	45	50	33	44	51

Based on the classification scheme presented in Table 10, along with associated allocations, the percent effective shade applicable for streams throughout the forest can be extrapolated.

The Cooper River provides an example of how Table 10 is applied. In order to use Table 10, the classification appropriate to a particular stream section of interest must first be determined. In review, the classification system is based on three attributes: subsection, stream size (based on drainage area), and Rosgen channel class. For instance, the Cooper River which has a classification of Co-4C, is located within the upper Yakima basin (subsection Co), has a stream size of 4, with a Rosgen channel class of C.

The first step in determining the TMDL allocation appropriate to a particular stream section is to identify what subsection it lies within. Figure 12 provides a map of the subsections within the Wenatchee Forest. Referring to Figure 12, the Cooper River, which discharges to the Cle Elum River above Kachess Lake, is located in the upper Yakima basin subsection (Co).

The next step is to determine the drainage area (in acres) located above the stream section. Table 5 provides a breakdown of the relationship between drainage area and stream size. Based on its drainage area, in reference to the 2001 monitoring location (approximately 24,000 acres), and referring to Table 5, it is a stream size 4.

Table 6 provides general descriptions and channel characteristics (bankfull width to depth ratios, channel slope) by channel class (refer to Rosgen, 1996 for additional channel class attributes). The lower Cooper River with bankfull width to depth ratio greater than 12 and a slope less than 2, place it as a C-type channel. Based on these attributes, the Cooper River, at the monitoring location, has a channel classification of Co-4C. Referring to Table 10, a Co-4C has a TMDL allocation of 60 percent effective shade.

The next step is to determine what vegetative group applies to the Cooper River. Referring to Figure 14, a map of the extent of the three vegetative groups within the Wenatchee Forest, the Cooper River, at the monitoring location, is situated in group c. Referring to Table 10, the site potential shade level for group c, given the Cooper Rivers classification of Co-4c, is 63 percent. In this case because the site potential shade allocation is greater than the TMDL allocation, the TMDL allocation is the applicable one. In review, the TMDL allocation is the percent effective shade necessary to reduce water temperatures to the water quality standard. In comparison, the load allocation is the percent effective shade provided by site potential vegetation. Site potential vegetation has maximum tree height and canopy density (principal shade producing attributes) expected for a particular area. As observed from Table 10, for stream reaches located within groups a and b, the majority of the allocations will default to the site potential allocation. (The allocation for shade cannot go beyond what can be produced naturally.) However, in the case of the Cooper River, the temperature standard will be met at an effective shade level below that provided by site potential vegetation. For this reason, the TMDL allocation is 60 percent.

Direct application of Table 10 to the listed and impaired streams is provided in Tables 11 and 12.

Table 11. Allocations (as percent effective shade) for water bodies within the Wenatchee National Forest included on the 1996 and 1998 303(d) lists for water temperature.

Water Body	*1996 WBID*	*Township, Range, Section*	*Stream Classification*	*TMDL Allocation Effective Shade (%)*	*Load Allocation Effective Shade (%)*
Cooper R.	*WA-39-1055*	*22N,14E,16*	*Co-4Cc*	*60*	*63*
Gale Ck.	*WA-39-1300*	*22N,13E,32*	*Co-2Bc*	*70*	***69***
Gold Ck.	*WA-39-1390*	*22N,11E,01*	*Cb-3Cc*	*65*	*67*
Iron Ck.	*WA-39-1440*	*21N,17E,03*	*Cn-2Ba*	*70*	***47***
SF Manastash Ck.	*WA-39-3025*	*18N,15E,36*	*Cc-4Cc*	*60*	*63*
SF Taneum Ck.	*WA-39-1570*	*19N,15E,27*	*Co-4Cc*	*60*	*63*
Waptus R.	*WA-39-1057*	*22N,14E,04*	*Co-5Cc*	*55*	*58*
Blue Ck.	*WA-39-1435*	*21N,17E,02*	*Cn-1Ac*	*70*	*70*
American R.	*WA-38-1060*	*17N,13E,12*	*Cp-5Cc*	*55*	*58*
Bear Ck.	*WA-38-1088*	*19N,13E,32*	*Cp-2Bc*	*70*	***69***
NF Nile Ck. (Benton)	*WA-38-2110*	*16N,15E,03*	*Cp-1Ab*	*70*	***61***
Bumping R.	*WA-38-1070*	*17N,13E,12*	*Cp-5Cc*	*55*	*58*
Crow Ck.	*WA-38-1081*	*18N,14E,30*	*Cp-4Cc*	*60*	*63*
Gold Ck.	*WA-38-1041*	*17N,14E,36*	*Cb-2Aa*	*70*	***47***
Mathew Ck.	*WA-38-1086*	*18N,13E,10*	*Cp-2Bc*	*70*	***69***
SF Tieton R.	*WA-38-3000*	*13N,13E,13*	*Cp-5Cc*	*55*	*58*
Rattlesnake Ck.	*WA-38-1035*	*15N,14E,10*	*Cp-5Cb*	*55*	***51***
Little Wenatchee R.	*WA-45-4000*	*27N,16E,15*	*Ca-5Cc*	*55*	*58*

Bold - TMDL allocation defaults to the load allocation (site potential vegetation).

Table 12. Allocations (as percent effective shade) for water bodies where water temperatures were observed at levels exceeding the 60.8°F water quality standard in 2001.

Water Body	*Stream Name*	*Township, Range, Section*	*Stream Classification*	*TMDL Allocation Effective Shade (%)*	*Load Allocation Effective Shade (%)*
HAUS_01	*Hause Ck.*	*14N, 14E, 21*	*Cp-2Bb*	*70*	***61***
LTRA_02	*Little Rattlesnake Ck.*	*15N, 14E, 25*	*Cp-3Cb*	*65*	***58***
LTNA_01	*Little Naches R.*	*17N, 14E, 4*	*Cp-6Cc*	*50*	*51*
LTNA_02	*Little Naches R.*	*18N, 14E, 30*	*Cp-5Cc*	*55*	*58*
LTNA_04	*Little Naches R.*	*18N, 13E, 14*	*Cp-5Cc*	*55*	*58*
LTNA_05	*Little Naches R.*	*18N, 13E, 9*	*Cp-4Cc*	*60*	*63*
LTNA_06	*Little Naches R.*	*18N, 13E, 5*	*Cp-4Cc*	*60*	*63*
SANDN_01	*Sand Ck.*	*18N, 13E, 14*	*Cp-2Bc*	*70*	***69***
BUMP_01	*Bumping R.*	*17N, 14E, 4*	*Cp-6Cc*	*50*	*51*
BUMP_06	*Bumping R.*	*16N, 11E, 36*	*Cp-4Cc*	*60*	*63*
QUAR_01	*Quartz Ck.*	*18N, 14E, 30*	*Cp-3Cc*	*65*	*67*
GREY_01	*Grey Ck.*	*13N, 13E, 29*	*Cp-1Ab*	*70*	***61***
ENTI_12	*Entiat R.*	*28N, 19E, 33*	*Cb-6Ca*	*50*	***33***
ENTI_13	*Entiat R.*	*28N, 19E, 29*	*Cb-6Ca*	*50*	***33***
ENTI_14	*Entiat R.*	*28N, 18E, 2*	*Cb-6Ca*	*50*	***33***
NFEN_01	*North Fork Entiat*	*29N, 18E, 27*	*Cb-4Ca*	*60*	***43***
SWAKANE	*Swakane Ck.*	*24N, 20E, 16*	*Cq-3Ca*	*65*	***46***
ROAR_01	*Roaring Ck.*	*25N, 20E, 8*	*Cq-4Ca*	*60*	***43***
ROAR_02	*Roaring Ck.*	*25N, 20E, 7*	*Cq-4Ca*	*60*	***43***
POTA_01	*Potato Ck.*	*27N, 19E, 36*	*Cq-3Ca*	*65*	***46***
PRES_01	*Preston Ck.*	*28N, 19E, 34*	*Cb-2Aa*	*70*	***47***
MITC_01	*Mitchel Ck.*	*29N, 21E, 24*	*Cb-2Aa*	*70*	***47***
MADR_01	*Mad R.*	*26N, 19E, 13*	*Cq-5Ca*	*55*	***39***
MADR_02	*Mad R.*	*26N, 19E, 15*	*Cq-5Ca*	*55*	***39***
MADR_03	*Mad R.*	*26N, 19E, 10*	*Cq-5Ca*	*55*	***39***
MADR_04	*Mad R.*	*27N, 19E, 33*	*Cq-4Ca*	*60*	***43***
GRAD_02	*Grade Ck.*	*30N, 21E, 31*	*Cb-3Ca*	*65*	***46***
LTWE_02	*Little Wenatchee R.*	*27N, 16E, 18*	*Ca-5Cc*	*55*	*58*
LTWE_03	*Little Wenatchee R.*	*27N, 15E, 11*	*Ca-5Cc*	*55*	*58*
LTWE_05	*Little Wenatchee R.*	*27N, 15E, 10*	*Ca-5Cc*	*55*	*58*
LTWE_07	*Little Wenatchee R.*	*28N, 14E, 36*	*Ca-4Cc*	*60*	*63*
LWTE_09	*Little Wenatchee R.*	*28N, 13E, 14*	*Ca-3Cc*	*65*	*67*
LAKEW_01	*Lake Ck.*	*28N, 15E, 31*	*Ca-3Cc*	*65*	*67*
CHWA_02	*Chiwawa R.*	*27N, 17E, 13*	*Cd-6Ca*	*50*	***33***
ROCK_01	*Rock Ck.*	*29N, 17E, 31*	*Cd-4Cc*	*60*	*63*
SANDW_01	*Sand Ck.*	*22N, 18E, 1*	*Cm-3Cb*	*65*	***58***
EFMI_01	*East Fork Mission*	*22N, 19E, 18*	*Cm-4Cb*	*60*	***55***
DEVI_01	*Devils Gulch*	*22N, 19E, 18*	*Cm-3Cb*	*65*	***58***
IRON_01	*Iron Ck.*	*21N, 17E, 10*	*Cn-2Ba*	*70*	***47***
MINE_01	*Mineral Ck.*	*22N, 13E, 5*	*Co-2Bc*	*70*	***69***
BLUE_01	*Blue Ck.*	*21N, 17E, 22*	*Cn-2Ba*	*70*	***47***
TANE_01	*Taneum Ck.*	*19N, 15E, 25*	*Co-5Cc*	*55*	*58*
NFTA_01	*North Fork Taneum Ck.*	*19N, 15E, 26*	*Co-4Cc*	*60*	*63*

Bold - TMDL allocation defaults to the load allocation (site potential vegetation).

Margin of Safety

The Clean Water Act requires that each TMDL have some margin of safety (MOS) to account for analysis uncertainty occurring, for instance, from a lack of available data, error involved in pollutant loading calculations, or in the effect best management practice implementation will have on loading reductions and receiving water quality. A margin of safety can be expressed as an unallocated assimilative capacity or through the use of conservative analytical assumptions used in establishing the TMDL (e.g., derivation of numeric targets, modeling assumptions or effectiveness of proposed management actions).

Much of the data used in this analysis is based on the monitoring data collected by the USFS during the summer of 2001. Physical conditions represented by both air temperature and stream flow indicate that 2001 was unusual: air temperatures were at historic highs and stream flows at historic lows. These conditions, along with other factors, provided for warmer water temperatures particularly for those water bodies with low effective shade levels. Because of these critical conditions, the analysis results based on the 2001 data provides a high margin of safety.

A discussion of air temperatures and flow levels observed within, and proximal to, the Wenatchee National Forest during the summer of 2001 is provided below.

Air Temperature – Historic to 2001

Based on air temperature monitoring data collected at stations located within the Wenatchee National Forest, the average maximum and minimum August air temperatures in 2001 were 76.2°F and 47.9°F, respectively. August 12 was among the warmest days of the summer for most of the sites with average maximum and minimum air temperatures of 90.0°F and 51.5°F, respectively. On August 12, peak air temperature occurred at approximately 3:00 PM and the minimum occurred at approximately 6:30 AM (Table 13).

Table 13. Average maximum air temperatures (^{o}F) observed at several of the Wenatchee monitoring stations during August, 2001 along with the maximum and minimum observed on August 12, 2001.

Monitoring Station	Elevation (feet)	8 / 2001 Max	8 / 2001 Min	8-12-01 Max	Time Max	8-12-01 Min	Time Min
Bearn_01	3133	72.7	46.3	86.1	15:00	49.1	6:00
LTNA_01	2547	77.1	47.5	92.3	14:00	51.8	6:00
LTNA_02	2716	78.2	45.7	92.4	14:00	49.5	6:00
LTNA_03	-	78.1	49.4	89.7	14:00	53.0	7:00
LTNA_04	2930	79.2	46.7	94.6	14:00	49.9	7:00
LTNA_06	3135	71.8	45.3	86.2	15:00	48.2	6:00
MFLN	3363	75.4	44.9	90.5	13:00	47.2	6:00
NFLN	3253	76.8	43.9	93.9	13:00	45.8	6:00
Bump_01	2561	81.6	50.1	94.9	15:00	54.2	6:00
Bump_06	3474	76.6	45.9	94.0	15:00	50.2	7:00
Amer_01	-	77.5	46.9	90.5	14:00	51.8	5:00
Amer_02	-	72.5	45.6	84.8	15:00	51.5	6:30
Amer_04	3630	71.4	44.4	86.9	16:00	48.5	7:00
Amer_05	3655	74.1	43.3	90.1	16:00	47.1	7:00
White_01	1869	73.8	54.1	85.2	18:00	56.7	7:00
LTWE_01	1877	78.4	54.5	87.2	17:30	57.2	6:00
Chwa_01	1768	77.6	51.3	90.3	16:30	55.5	7:00
Chwa_05	2781	75.5	46.7	88.2	15:30	48.6	6:00
Nason_01	1866	79.1	53.8	92.4	15:30	57.1	6:30
Yaki_01	2200	75.2	49.6	90.6	15:00	51.5	6:30
Teanaway	-	76.9	46.8	89.5	14:00	51.5	6:00
Tane_01	2720	71.6	52.6	84.5	14:30	56.6	6:00
Swak_01	-	81.4	46.3	94.2	14:30	51.6	6:00

A comparison was made between air temperatures observed during the study period (summer, 2001) with those observed historically. Several weather stations were chosen for this analysis based both on their proximity to the forest and having a sufficient data record. Additionally, weather stations were selected that represented a variety of elevations and subsections (Table 14). All of the stations, except the Entiat weather station, have a record of daily air temperatures of over 40 years with the Cle Elum and Stehekin stations having recorded data since 1931, a record of 71 years.

From the full data record, the average August maximum and minimum air temperatures were calculated for each year. (The month of August was chosen because air temperatures tend to peak then and in 2001 peak air and water temperatures occurred in mid-August.) Percentiles were then determined from the full record of annual average August maximum and minimum values. This information is presented in Table 14 along with the average August maximum and minimum temperatures observed in 2001. (The 2001 data were compared to the historic record based on their percentile position. The 2001 percentile is included in Table 14 in parentheses.)

As observed, August 2001 had above average maximum and minimum air temperatures. For Stehekin and Cle Elum, the average August 2001 maximum represented the 87th and 81st percentiles, respectively. (Both of these stations have over a 70 year data record.) Similarly, minimum August air temperatures were also above average in 2001 in comparison to the historic record. The 2001 August average minimum represented the 97th and 92nd percentile for Stehekin and Cle Elum, respectively. (A more elevated minimum air temperature has the effect of reducing the night-time cooling potential of surface waters.)

Table 14. Percentiles of average maximum and minimum (italics) air temperatures (oF) for the month of August observed at weather stations within proximity to the Wenatchee National Forest in comparison to those observed in 2001.

Weather Station	*Elevation (ft)*	*Period of Record*	*Max*	*Min*	*75^{th}*	*25^{th}*	*Median*	*2001*
Entiat	*960*	*1989-*	*89.3*	*79.8*	*87.6*	*84.7*	*86.3*	*88.5 (92^{nd})*
		Present	55.5	47.7	54.2	52.1	53.4	53.9 (60^{th})
Chelan	*1120*	*1958-*	*91.7*	*77.9*	*87.0*	*83.0*	*84.2*	*88.2 (83^{rd})*
		Present	64.1	51.5	61.3	57.6	59.4	61.9 (85^{th})
Stehekin	*1270*	*1931-*	*89.9*	*73.5*	*83.4*	*78.5*	*81.3*	*85.8 (87^{th})*
		Present	57.9	46.7	54.3	50.0	51.6	57.8 (97^{th})
Cle Elum	*1920*	*1931-*	*90.0*	*73.1*	*83.3*	*77.8*	*80.6*	*83.7 (81^{st})*
		Present	55.3	44.8	51.3	47.6	49.9	53.0 (92^{nd})
Stampede Pass	*3958*	*1944-*	*75.1*	*56.6*	*67.0*	*62.0*	*64.4*	*66.6 (67^{th})*
		Present	54.5	43.2	48.9	45.5	47.2	49.4 (81^{st})

Discharge Analysis – Historic to 2001

Discharge levels during the 2001 summer period were at historic low levels. (The level of discharge is an important factor in determining a particular stream's susceptibility to heating.) For this reason, the summer of 2001 provides an excellent baseline for examining the extreme condition leading to conservative assumptions in the analysis process.

To provide some perspective between the flow levels observed in 2001 to those observed historically, the flow record of United States Geological Survey (USGS) gauging stations in proximity to the Wenatchee Forest were examined. Table 15 provides a list of these gauging stations and their period of record. Because typically, the month of August is when the warmest water temperatures occur (and this was the case in 2001), an examination of the average annual August flow level for the period of record was made. Table 16 provides an overview of this analysis based on percentiles of average annual August flow levels covering the period of record.

As observed, for the streams with no diversions, American and Stehekin Rivers, the August 2001 flow levels were at the 12^{th} percentile in comparison to historic average August flow levels. Stated another way, among the August flows that have been measured historically, and for American and Stehekin Rivers this is 66 and 80 years, respectively, 88 percent have been greater. For those streams with more diversions present, in-stream flows were lower. For the Wenatchee River at Monitor, the average August 2001 flow of 581 represented the 3^{rd} percentile (97 percent of average August flows were greater). Flows in the Chiwawa River were less impacted by the unusually low precipitation conditions in 2000/2001 due to contributions from high elevation snow and glacial melt (Figure 15).

Table 15. Background information on USGS gauging stations in proximity to the Wenatchee National Forest.

USGS Station	Station Number	Drainage Area (mi^2)	Period of Record	Diversion
Stehekin	12451000	321	1911-15, 1927-Present (n=80)	No known regulation or diversion
Chiwawa	12456500	170	1911-14, 1936-49, 1954-57, 1993-Present (n=30)	Single irrigation diversion (approx. 20 cfs)
Icicle	12458000	193	1936-71, 1993-Present (n=43)	Regulation in headwater lakes. No diversion
American (Nile)	12488500	79	1909-11, 1913-15, 1939-Present (n=66)	No known regulation or diversion
Entiat (Ardenvoir)	12452800	203	1957-Present (n=44)	Numerous diversions
Entiat (Entiat)	12452990	419	1996-Present (n=6)	Numerous diversions
Wenatchee (Monitor)	12462500	1301	1962-Present (n=39)	Numerous diversions
Wenatchee (Peshastin)	12459000	1000	1929-Present (n=72)	Numerous diversions

Table 16. Average August flow (cubic feet per second) percentiles for several USGS gauging stations covering the flow record along with levels observed in 2001.

Station	Maximum	75th Percentile	50th Percentile	25th Percentile	Minimum	8- 2001 Median (percentile)
Stehekin	2716	1397	1206	935	681	816 (12th)
Chiwawa	899	355	251	169	106	168 (25th)
Icicle	764	330	229	180	121	141 (8th)
American (Nile)	343	104	78	59	41	50 (12th)
Entiat (Ardenvoir)	577	261	188	139	99	107 (2nd)
Entiat (Entiat)	655	353	287	230	123	122 (-)
Wenatchee (Monitor)	3985	1822	1287	810	457	581 (3rd)
Wenatchee (Peshastin)	3969	1790	1301	944	675	712 (7th)

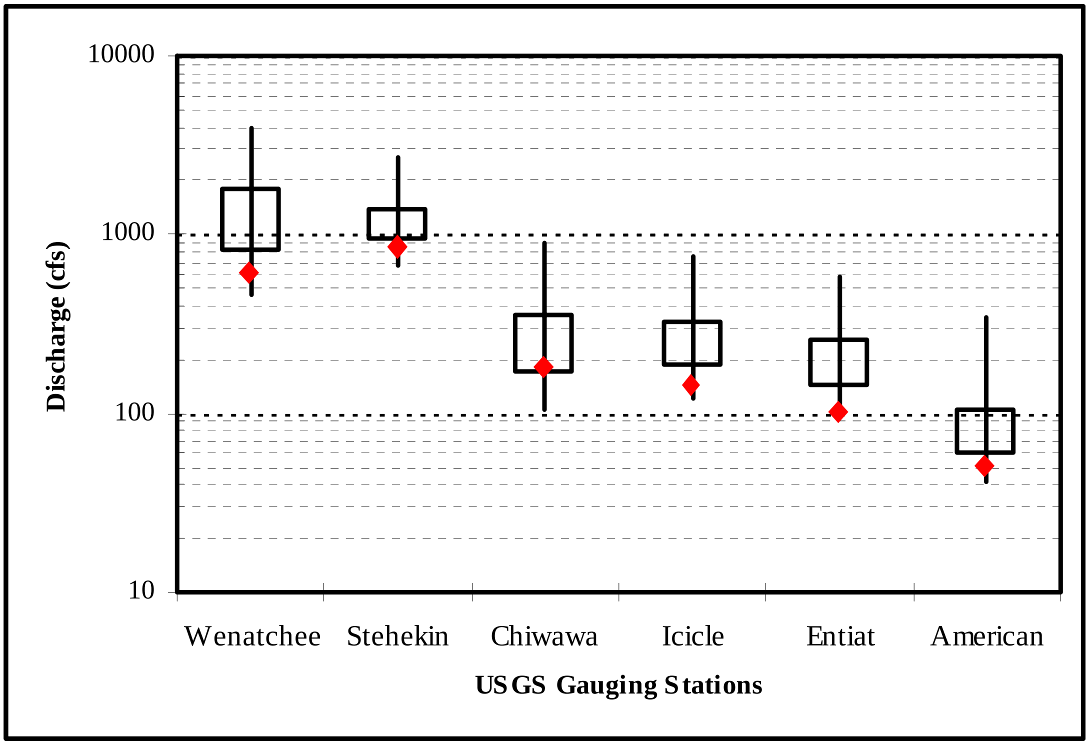

Figure 15. Box plots of average annual August flow levels (cfs) observed at USGS gauging stations in proximity to the Wenatchee National Forest for their respective period of record. Diamonds represent the median August flow for 2001. Endpoints on vertical lines represent the maximum and minimum flows. The top and bottom of boxes represent the 75th and 25th percentiles.)

Summary Implementation Strategy

Introduction: (Refer to page 1 of this document)

Overview

In practical application, the determination of load allocations and load capacities, the primary objectives of TMDLs, really only provide a bare framework, a target, to base implementation activities on. For this reason, this section summarizes the strategy of how the USFS and Ecology will work together, and the elements of that work, to ensure effective actions towards meeting the established targets and restoring compliance with the temperature standard. It is anticipated that with the exercise of due care and protection, water quality standards for temperature should be met by 2045.

Implementation Plan Development

The USFS and Ecology are the two principal agencies involved in this TMDL and with its subsequent implementation and monitoring activities. Establishing this partnership is a joint memorandum of agreement signed in 2000. In addition, and crucial to the implementation of this TMDL, is current direction under the Wenatchee National Forest Plan (as amended by the Northwest Forest Plan) regarding riparian vegetation throughout the Wenatchee National Forest.

The framework for the implementation of this TMDL is based on the amended Wenatchee National Forest Plan specifically the Aquatic Conservation Strategy, a major component of the plan that applies to all riparian reserves on National Forest System lands. Forest plan standards and associated riparian protection levels contained within the plan, serve as a benchmark for design of the TMDL assessments and are fundamental components of the TMDL implementation.

Reasonable Assurance

Assurance that allocations are met rely on standards and guidelines as they apply to riparian reserves designated within the amended Wenatchee Land and Resource Management Plan, and the cooperative partnership between Ecology and the USFS.

<u>Ecology / USFS Memorandum of Agreement (MOA)</u>

This TMDL analysis is a cooperative effort between the Washington State Department of Ecology and the United States Forest Service. The partnership was formed through a 2000 memorandum of agreement (MOA). The initial impetus for the MOA was a joint recognition that inadequately maintained roads on USFS lands were resulting in significant water quality problems throughout the state. For this reason, the agreement established a schedule for planning and implementation of road maintenance and abandonment.

Importantly, in terms of this TMDL, is that the MOA also recognized the USFS as the Designated Management Agency for meeting Clean Water Act requirements on National Forest System lands and the Forest Service agreed to meet or exceed the water quality requirements in state and federal law. To meet this goal, the MOA recognized the necessity that the Forest Service and Ecology share responsibility for developing TMDLs on Forest System lands.

Ecology and the USFS meet annually to determine compliance with the MOA. These programs provide reasonable assurance for TMDL implementation and restoration of water quality for federal lands.

United States Forest Service (USFS) – Northwest Forest Plan

Forest plans are required by the National Forest Management Act (NFMA) for each National Forest. These plans establish land allocations, goals and objectives, and standards and guidelines that direct how National Forest System lands are managed.

The Aquatic Conservation Strategy, a component of the amended forest plan, is designed to protect and restore the ecological health of the aquatic system and its dependent species. Restoration priorities are based on watershed analysis and planning which will help to determine areas where the greatest benefits can be achieved along with the likelihood of success. In general, watersheds that currently have the best habitat, or those with the greatest potential for recovery, are priority areas for increased protection and for restoration treatments. The conservation strategy aims to maintain the natural disturbance regime. Components of the Aquatic Conservation Strategy include:

Riparian Reserves: Lands along streams, wetlands, ponds, lakes, and unstable and potentially unstable areas where special standards and guidelines direct land use. Riparian reserves are designed to maintain and restore the ecological health of watersheds and aquatic ecosystems. Interim widths for Riparian Reserves are established based on ecological, hydrologic, and geomorphic factors. Interim Riparian Reserves for federal lands are delineated as part of the watershed analysis process based on identification and evaluation of critical hillslope, riparian, and channel processes. Final Riparian Reserve boundaries are determined at the site-specific level during the appropriate National Environmental Policy Act analysis.

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

- Fish-bearing streams - Riparian Reserves consist of the stream and the area on each side of the stream extending from the edges of the active stream channel to the top of the inner gorge, or to the outer edges of the 100-year flood plain, or to the outer edges of riparian vegetation, or to a slope distance equal to the height of two site-potential trees, or 300 feet slope distance (600 feet total, including both sides of the stream channel), whichever is greatest.

- Permanently flowing non-fish bearing streams - Riparian Reserves consist of the stream and the area on each side of the stream extending from the edges of the active stream channel to the top of the inner gorge, or to the outer edges of the 100-year flood plain, or to the outer edges of riparian vegetation, or to a slope distance equal to the height of one site-potential tree, or 150 feet slope distance (300 feet total, including both sides of the stream channel), whichever is greatest.

- Specific riparian reserves ranging from 100 to 300 feet of slope distance are also specified for the following categories of riparian areas: constructed ponds and reservoirs; wetlands (greater than one acre), lakes, and natural ponds; seasonally flowing or intermittent streams; wetlands less than one acre, and unstable and potentially unstable areas.

Key Watersheds: A system of refugia comprising watersheds crucial to at-risk fish species and stocks while also providing high quality habitat. Key Watersheds are generally those identified as having the best habitat or those with the greatest potential for recovery. Key watersheds are priority areas for increased protection and for restoration treatments. Activities to protect and restore aquatic habitat in Key Watersheds are a higher priority than similar activities in other watersheds.

Watershed Analysis: An on-going, iterative analysis procedure for characterizing watershed and ecological processes to meet specific management objectives within the subject watershed. This analysis should enable watershed planning that achieves Aquatic Conservation Strategy objectives. Watershed analysis provides the basis for monitoring and restoration programs and the foundation from which the Riparian Reserves can be delineated.

Watershed Restoration: A comprehensive, long-term program of watershed restoration to restore watershed health and aquatic ecosystems, including habitats supporting fish and other aquatic and riparian-dependent organisms.

Further implementation assurance is provided through provisions that require the USFS consult with the U.S. Environmental Protection Agency as part of the NEPA process for revisions to the Forest Land and Resource Management Plan. These consultations will include any plan revisions that may affect TMDL implementation.

Additional implementation measures are being undertaken within the Wenatchee Forest through a roads analysis. The objective of the roads analysis is to provide critical information needed to identify and manage a minimum road system that is safe and responsive to public needs while having minimal adverse effects on ecological processes and health. This planning action is being accomplished with public and agency (federal and state) input.

Water Quality Restoration Plans are Forest Service planning documents that identify Best Management Practice actions appropriate to correct water quality issues within defined drainage areas. These plans will enhance and focus activities and improve shade levels in areas where the plans are developed.

Ecology staff will review USFS planning and implementation activities to ensure that state water quality laws and regulations are being met or exceeded. This includes the responsibility to certify that general water quality Best Management Practices (BMPs) and current Forest Plans are consistent with the CWA. The certification process includes the comparison of state BMPs and USFS BMPs. If Ecology or the USFS determines that USFS BMPs provide less resource protection than state BMPs, the USFS will review the BMPs for amendment.

Adaptive Management

Ecology will utilize its existing resources and authorities under RCW 90.48 to implement this TMDL. Working closely with the Forest Service, Ecology will set reasonable, achievable, and effective strategies for meeting the targets (load allocations) established in this TMDL and will include these activities in the Detailed Implementation Plan. If water quality standards for temperature are met without meeting the target load allocations then the objectives of this TMDL are met and no further Best Management Practices (BMPs) are needed. If the target load allocations are met, but the stream still does not meet water quality standards for temperature, then BMPs established in the Detailed Implementation Plan shall be made more stringent or revised. It is anticipated that the direction of implementation activities will allow for change based on new information or conditions.

If implementation activities are not producing expected or required results, Ecology may choose to conduct additional studies to identify the significant sources of heat input to the river system. If the causes can be determined, additional implementation measures may be needed. The USFS has a policy of adaptive management. Re-evaluation is anticipated to occur at five to ten year intervals and the TMDL may be modified as a result. Additional events that would require a review and subsequent TMDL revision, include: new Endangered Species Act listings, new water quality standards that apply to the Wenatchee Forest, or some unforeseen event affecting the landscape.

Monitoring Strategy

Following the approval of this TMDL by the United States Environmental Protection Agency, Ecology will develop, with assistance of the USFS, a Detailed Implementation Plan (DIP). The DIP will provide greater detail to all of the elements presented in this section (Strategic Implementation Strategy) and will contain a monitoring plan, used to evaluate implementation measures. The monitoring strategy will include the following measures: 1) the USFS will continue to monitor water temperatures throughout the forest annually (summer period) at established locations (compliance monitoring); 2) Ecology and USFS will jointly review that information, along with other aspects of the TMDL implementation, and 3) effectiveness monitoring of shade levels by Ecology will occur within an appropriate timeframe.

Potential Funding Sources

The Wenatchee National Forest has funded restoration activities implemented on lands it administers. The types of restoration activities include road decommissioning, road stabilization and riparian plantings. The types of funds used to complete this work include Emergency Repair for Federally-Owned Roads, Supplemental Emergency Flood, and Appropriated funds.

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Appendix A
Monitoring Data

Stream Name	Station Name	Subbasin	Elevation (ft)	Drainage Area (acres)	Max. Temperature ^oF
Chelan Subbasin					
Coyote	COYO_01	Chelan	4046	667	55.0
First	FIRS_01	Chelan	1205	11621	55.4
Gold	GOLD_02	Chelan	2976		52.0
Mitchel	MITC_01	Chelan	2632	4045	61.2
NF Twenty-five	NF25_01	Chelan	1876	12512	52.3
Poison	POIS_01	Chelan	3150	3774	55.2
Safety	SAFE_02	Chelan	4025	5470	54.6
SF Twenty-five	SF25_01	Chelan	1903	11102	56.1
Twenty	TWEN_01	Chelan	1219	26611	63.4
Entiat Subbasin					
Cougar	COUG_01	Entiat	3365	8351	58.0
Entiat River	ENTI_01	Entiat	782	267646	75.5
Entiat River	ENTI_02	Entiat	857	254212	75.8
Entiat River	ENTI_03	Entiat	931	250741	74.2
Entiat River	ENTI_05	Entiat	1107	224426	74.4
Entiat River	ENTI_06	Entiat	1225	219022	74.2
Entiat River	ENTI_07	Entiat	1279	160582	74.0
Entiat River	ENTI_09	Entiat	1462	141123	69.7
Entiat	ENTI_11	Entiat	1614	119949	68.9
Entiat River	ENTI_12	Entiat	1690	109646	67.2
Entiat	ENTI_13	Entiat	1737	102845	65.1
Entiat River	ENTI_14	Entiat	2372	91998	61.7
Entiat	ENTI_15	Entiat	2659	47786	58.7
Entiat River	ENTI_16	Entiat	3097	34684	56.0
Fall	FALL_01	Entiat	4161	3114	54.2
Grade	GRAD_02	Entiat	3484	5513	60.5
Indian	INDIE_01	Entiat	2045	3677	56.7
Lake	LAKEE_01	Entiat	2289	8934	58.8
Mad River	MADR_00	Entiat	1262	58440	70.0
Mad River	MADR_01	Entiat	1400	56760	70.1
Mad River	MADR_03	Entiat	1834	32999	67.8
Mad River	MADR_04	Entiat	2440	31050	68.6
Mad River	MADR_05	Entiat	2912	27826	60.5
Mad River	MADR_06	Entiat	3359	14260	57.6
Mad River	MADR_07	Entiat	4576	6333	58.0
Mad River	MADR_O2	Entiat	1668	40378	69.3
Mill	MILL_01	Entiat	1107	7328	69.2
Mud	MUDD_01	Entiat	1701	14385	59.0
NF Entiat	NFEN_01	Entiat	2680	17653	60.7
Potato	POTA_01	Entiat	1576	6587	66.5
Preston	PRES_01	Entiat	1735	4645	63.8
Roaring	ROAR_01	Entiat	1248	15827	70.1
Roaring	ROAR_02	Entiat	1546	13449	65.3
Stormy	STOR_01	Entiat	1579	5435	63.9
Swakane	SWAKE_01	Entiat	1491	8666	73.9
Tillicum	TILL_01	Entiat	1420	14566	58.0

Stream Name	Station Name	Subbasin	Elevation (ft)	Drainage Area (acres)	Max. Temperature ^oF
Naches Subbasin					
American River	AMER_04	Naches	3630	12281	59.2
American River	AMER_05	Naches	3655	4993	57.5
Bear	BEAR_01	Naches	3133	7700	60.7
Bear	BEAR_02	Naches	3170	3640	58.7
Blow	BLOW_01	Naches	3366	2776	56.2
Bumping River	BUMP_01	Naches	2560	124378	69.9
Bumping River	BUMP_03	Naches	2756	71019	70.8
Bumping River	BUMP_06	Naches	3474	16541	64.9
Crow	CROW_01	Naches	2756		61.4
Crow	CROW_02	Naches	3217	18759	59.4
Deep	DEEP_01	Naches	3498	15271	49.1
Grey	GREY_01	Naches	3401		62.7
Hause	HAUS_01	Naches	2716	2224	64.4
Indian	INDIT_01	Naches	2958	12658	55.0
Kettle	KETT_01	Naches	3356	3926	53.3
Little Naches	LTNA_01	Naches	2547	95540	69.8
Little Naches	LTNA_02	Naches	2716	59047	68.4
Little Naches	LTNA_04	Naches	2930	40744	66.7
Little Naches	LTNA_05	Naches	3103	27323	64.9
Little Naches	LTNA_06	Naches	3135	18835	64.8
Little Rattlesnake	LTRA_01	Naches	2100	16228	63.9
Little Rattlesnake	LTRA_02	Naches	3104	11239	63.8
Little Rattlesnake	LTRA_03	Naches	3667	7268	58.3
Mathew	MATH_01	Naches	3087	2069	59.4
MF Little Naches	MFLN_01	Naches	3363	4560	59.4
NF Little Naches	NFLN_01	Naches	3253	11940	58.8
Pileup	PILE_01	Naches	2877	5579	58.0
Pine	PINE_01	Naches	2535	1544	59.9
Quartz	QUAR_01	Naches	2706	10364	59.3
Rainier Fork	RANI_01	Naches	3853	4631	55.1
Sand	SANDN_01	Naches	2918	4107	62.5
SF Little Naches	SFLN_01	Naches	3080	9711	59.2
SF Tieton	SFTI_01	Naches	3015		63.1
SF Tieton	SFTI_03	Naches	3950	16240	58.8
Timber	TIMB_01	Naches	3576	1832	52.9
Union	UNIO_01	Naches	3401	7256	54.6
West Fork Bear	WFBE_01	Naches	3377	3256	56.9
West Fork Quartz	WFQU_01	Naches	3205	2746	54.9
Wenatchee Subbasin					
Beaver	BEAV_01	Wenatchee	2395	3323	56.6
Beaver	BEAV_02	Wenatchee	2387	1059	58.7
Chikamin	CHIK_01	Wenatchee	2407	13943	61.1
Chiwaukum	CHIW_01	Wenatchee	1768	25830	60.3
Chiwawa	CHWA_02	Wenatchee	2084	110566	64.9
Chiwawa	CHWA_03	Wenatchee	2415	62946	59.4
Chiwawa	CHWA_04	Wenatchee	2465	43605	58.7
Chiwawa	CHWA_05	Wenatchee	2781	15753	59.1
Devils Gulch	DEVI_01	Wenatchee	1772	10399	67.8

Stream Name	Station Name	Subbasin	Elevation (ft)	Drainage Area (acres)	Max. Temperature °F
EF Mission	EFMI_01	Wenatchee	1749	13046	71.4
Icicle	ICIC_01	Wenatchee	1246	131408	66.7
Lake	LAKEW_01	Wenatchee	2333	11014	63.9
Little Wenatchee	LTWE_01	Wenatchee	1877	65001	66.6
Little Wenatchee	LTWE_02	Wenatchee	1912	60722	67.5
Little Wenatchee	LTWE_03	Wenatchee	1954	55011	65.2
Little Wenatchee	LTWE_05	Wenatchee	2117	41337	65.9
Little Wenatchee	LTWE_07	Wenatchee	2431	21138	64.4
Little Wenatchee	LTWE_09	Wenatchee	2935	6961	62.3
Marble	MARB_01	Wenatchee	2470	2558	54.1
Minnow	MINN_01	Wenatchee	2462	2008	56.9
Nason	NASO_01	Wenatchee	1866	68162	72.2
Peshastin	PESH_01	Wenatchee	1801	61957	62.4
Peshstin	PESH_02	Wenatchee	1813	38328	66.2
Peshastin	PESH_03	Wenatchee	2156	34208	72.0
Phelps	PHEL_01	Wenatchee	2809	11407	58.2
Phelps	PHEL_02	Wenatchee	3525	9464	55.2
Rainy	RAIN_01	Wenatchee	2159	10862	59.2
Rock	ROCK_01	Wenatchee	2504	13817	60.5
Sand	SANDW_01	Wenatchee	1426	11941	63.1
White	WHIT_01	Wenatchee	1869	73809	60.0
White	WHIT_02	Wenatchee	1877	95842	59.2
White	WHIT_03	Wenatchee	2302	42614	60.8
White	WHIT_04	Wenatchee	2378	26258	60.8
Yakima	YAKI_01	Wenatchee	2200	52936	69.3
Yakima Subbasin					
Blue	BLUE_01	Yakima	2833	2294	61.8
Box Canyon	BOXC_01	Yakima	2273	7743	59.9
Cabin	CABI_03	Yakima	2910		64.0
Cle Elum	CLEE_01	Yakima	1975	141996	67.8
Cooper	COOP_01	Yakima	2360	23862	69.2
Fortune	FORT_01	Yakima	3221	6379	54.8
French Cabin	FRCA_01	Yakima	3153	4496	58.0
Iron	IRON_01	Yakima	2944	3876	64.1
Jack	JACK_01	Yakima	3127	2372	53.8
Jungle	JUNGY_01	Yakima	2617	3924	62.8
Meadow	MEAD_01	Yakima	2527	5395	60.3
MF Tenaway	MFTE_01	Yakima	2656	16554	67.4
Mineral	MINE_01	Yakima	2482	3656	66.2
NF Taneum	NFTA_01	Yakima	2818	15293	62.8
Stafford	STAF_01	Yakima	2795	14240	63.9
Taneum	TANE_01	Yakima	2720	31563	68.5
Thorp	THOR_01	Yakima	3241	2938	56.3
Waptus	WAPT_01	Yakima	2508	33814	68.1
West Fork Iron	WFIR_01	Yakima	3074	809	52.9