Tieton River and Lower Naches River Temperature Study, 2004 and 2015

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Cover photo: Confluence of the Tieton and Naches Rivers, facing downstream.
(Photo by Evan Newell)

Tieton River and Lower Naches River Temperature Study, 2004 and 2015

by

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Water Resource Inventory Area (WRIA) and 8-digit Hydrologic Unit Code (HUC) numbers for the study area:

- WRIA: 38 (Naches Watershed)
- HUC number: 17030002 (Naches Watershed)

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Abstract

This study presents a scientific analysis of water temperature in the Tieton River and the lower Naches River (below the confluence with the Tieton River). It presents results from continuous monitoring of temperature in the river using data loggers in 2004 and 2015. It also presents results from a deterministic, finite-difference model, QUAL2Kw, to simulate water temperature in these rivers during 2015.

This study addresses two portions of the Naches River basin (WRIA[1] 38) which were not addressed in a previous study, *Upper Naches River Temperature Total Maximum Daily Load Volume 1*. (Brock, 2008):

- Tieton River, which includes the mainstem Tieton River and all tributaries to the headwaters.
- Lower Naches River, which includes the mainstem Naches River from the confluence with the Tieton River (RM 17.6) to the confluence with the Yakima River (RM 0) and all tributaries along this reach, except Cowiche Creek.

This study differs from Brock (2008) because this study does not (1) estimate system potential shade conditions for these rivers, or (2) assign load or wasteload allocations to these rivers.

During 2004 and 2015, monitored water temperature for all sites (except one) in both rivers exceeded (did not meet) current freshwater temperature criteria for aquatic life uses. The single exception was a site immediately downstream of Tieton Dam. During 2015, water temperature in the Naches River exceeded supplemental spawning temperature criteria, in applicable portions of the river.

Model temperature simulation results indicate that summer time water temperature in the Tieton River is controlled by environmental warming of cold water which flows out of Tieton Dam. The Tieton River has a significant cooling effect on the Naches River, as indicated by model simulation and thermal aerial imaging. Water temperature in the Naches River is controlled by this mixing of water from the Tieton River with the upper Naches River, plus a relatively small temperature influence from groundwater and relatively minor shading of the river by vegetation as the river water warms in a downstream direction.

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[1] Water Resource Inventory Area

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Introduction

This study presents an analysis of water temperature in the Tieton River (between Tieton Dam and the river's mouth) and the lower Naches River (between the confluence with the Tieton River and its mouth). It presents results from continuous monitoring of temperature in the river using data loggers in 2004 and 2015. This study also presents results from QUAL2Kw modeling software, which was used to simulate water temperature in these rivers. It is a continuation of a previous study in the Naches River basin (Brock, 2008).

This study differs from Brock (2008) because it does not estimate system potential mature riparian shade conditions for these rivers, nor does it assign load allocations (LAs) or wasteload allocations (WLAs). Future work by Ecology may assign LAs and WLAs to these rivers based on the results presented in this report, possibly combined with any future analysis (for example, system potential mature riparian vegetation shade analysis). This work was performed under two Quality Assurance Project Plans (LeMoine and Brock, 2004; Urmos-Berry, 2015).

Study Area

The Naches River basin is the land area where all tributaries drain into the Naches River. It is designated by the Washington State Department of Ecology (Ecology) as Water Resource Inventory Area (WRIA) 38. Ecology and other Washington State natural resources agencies have divided the state into 62 WRIAs to delineate the state's major watersheds. WRIA 38 is part of the Yakima River drainage basin.

The Naches River basin is divided into four distinct subbasins (Figure 1):

- Upper Naches River, which consists of the mainstem Naches River from the confluence with the Tieton River at river mile (RM) 17.6 to the headwaters and all tributaries along this reach.
- Lower Naches River, which includes the mainstem Naches River from RM 17.6 to the confluence with the Yakima River (RM 0) and all tributaries along this reach, except Cowiche Creek.
- Cowiche Creek, which includes the creek and all tributaries.
- Tieton River, which includes the mainstem Tieton River and all tributaries to the headwaters.

Two of these subbasins, upper Naches River and Cowiche Creek, were addressed in two previous studies:

- *Upper Naches River Temperature Total Maximum Daily Load, Volume 1, Water Quality Study Findings* (Brock, 2008).
- *Upper Naches River and Cowiche Creek Temperature Total Maximum Daily Load, Volume 2, Implementation Strategy* (Peterschmidt, 2010).

The present study addresses two of these subbasins which were not completely addressed as part of Brock (2008) and Peterschmidt (2010): the Tieton River and lower Naches River subbasins. The original study was designed to address all four subbasins at once, but this plan was changed due to the complex management of Tieton River and lower Naches River flows by the U.S. Bureau of Reclamation (USBR).

The current study does not address surface water on lands owned by the National Forest Service in the Tieton River subbasin (Figure 1). Water temperature in surface waters on those lands were addressed in the *Wenatchee National Forest Water Temperature TMDL Technical Report* (Whiley and Cleland, 2003).

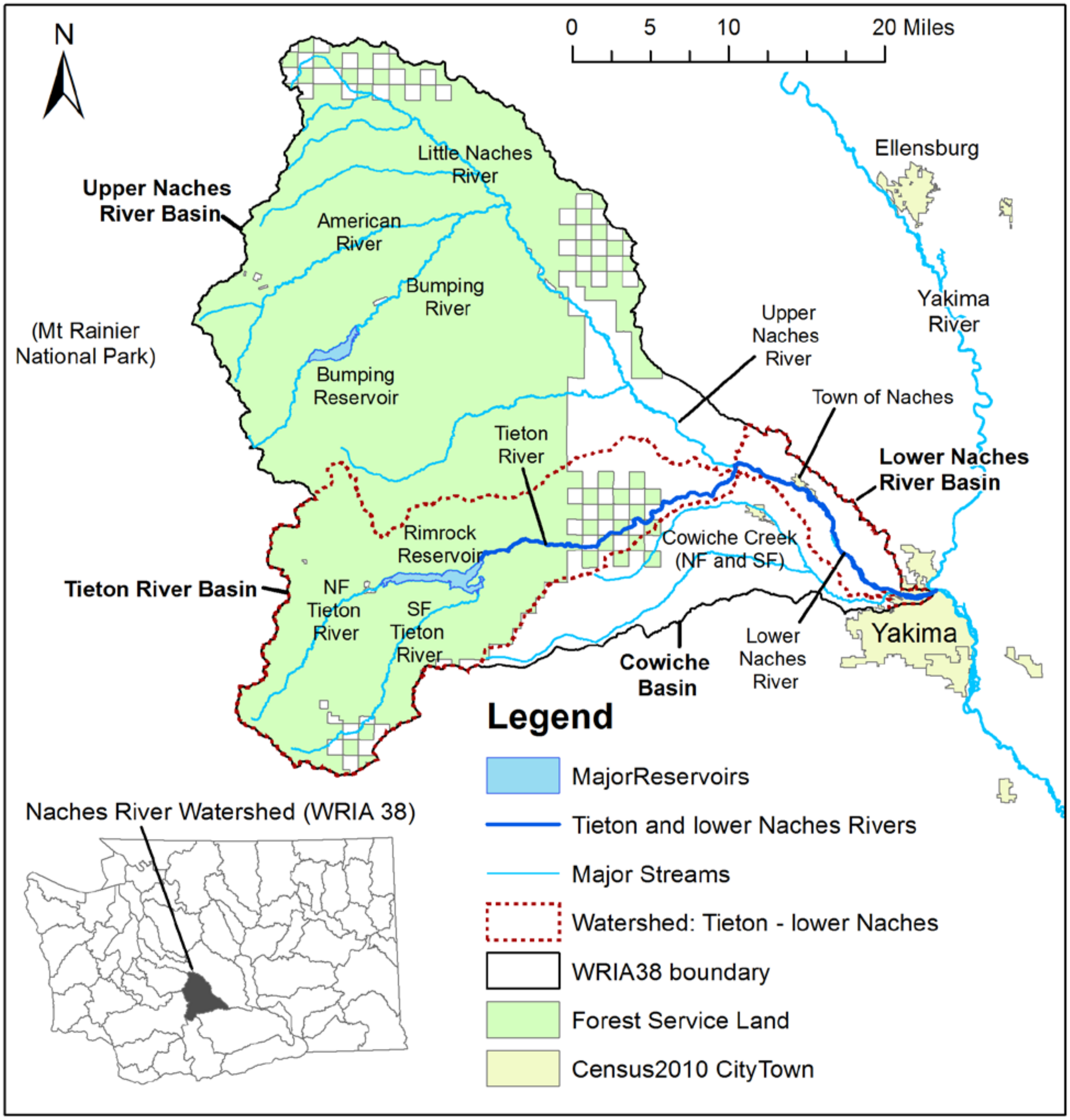

Figure 1. Study area for the *Tieton River and Lower Naches River Temperature Study.*

Two major waterbodies in the Naches River basin, Watershed Resource Inventory Area (WRIA) 38, and their major tributaries, are included in this assessment:

- Naches River, from its mouth at the Yakima River to its confluence with the Tieton River at RM 17.5.
- Tieton River, from its mouth at the Naches River to just below Tieton Dam at Rimrock Reservoir. Part of this river lies on National Forest Service land; this portion of the river was included in the study to develop a predictive temperature model for the remainder of the river.

A total maximum daily load (TMDL) on the studied surface water bodies may be developed in a future TMDL project, but this will not include river segments which lie on U.S. Forest Service (USFS) land. On the Tieton River, the contiguous USFS boundary occurs near RM 13.7, although there are also patches of USFS land downstream of this location.

The Naches River has four major tributaries: Bumping, American, Little Naches, and Tieton Rivers. Above the confluence with the Tieton River it is referred to as the *upper* Naches River; below the confluence as the *lower* Naches River. The upper Naches River flows southeast from the Cascade Mountains until it converges with the Tieton River. The upper Naches River was previously studied in Brock (2008).

The Tieton River flows east from Tieton Dam (outlet for Rimrock Reservoir) through the Tieton River Canyon until it converges with the Naches River. Land ownership in the Tieton subbasin is predominantly public. The USFS (Wenatchee National Forest) owns and manages the majority of land in the basin. The Washington State Department of Natural Resources (WDNR) and Washington Department of Fish and Wildlife (WDFW) own and manage the next largest proportion of public lands. The private lands consist of small recreational cabins and small resorts.

The lower Naches River flows southeast from the confluence of the Tieton River to the city of Yakima, where it converges with the Yakima River. The lower Naches River subbasin predominantly supports irrigated agriculture croplands. The major crops raised in the basin are apples, pears, and cherries. There are two municipalities located within the lower Naches River basin: Naches and Yakima.

Flow in the Tieton and lower Naches Rivers is strongly influenced by USBR operation of two major water storage reservoirs in the basin: Rimrock Reservoir (approximately 198,000 acre-feet) which is located on the Tieton River, and Bumping Reservoir (approximately 33,700 acre-feet) which is located on the Bumping River. Water collected in these reservoirs is released seasonally to meet demands for irrigation water supply, flood control, and instream flows for fish.

Flow in the Tieton and lower Naches Rivers is also influenced by a number of diversions of water away from, and sometimes back into, the river from irrigation canals and ditches.

The vegetation of the Naches River basin is a complex blend of forest, shrub steppe, and grasslands. The forests are located in the mountainous areas where precipitation is greater, and also along the riparian edges of streams and rivers. Ponderosa pine, douglas fir, and grand and noble fir form the majority of complex heterogeneous forests at the higher elevations (Haring, 2001). Oregon white oak, cottonwood, birch, and alder are found along the riparian zones in the valleys (Haring, 2001). Most of the land in the lower reaches is populated with shrub and grassland that is highly susceptible to erosion if disturbed.

According to WDFW's Salmon Scape application (http://apps.wdfw.wa.gov/salmonscape/, accessed 10/24/2017), spring and fall Chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*Oncorhynchus kisutch*), steelhead (resident form: rainbow trout. *Oncorhynchus mykiss*), and bull trout (resident form: Dolly Varden. *Salvelinus confluentus*) comprise the cold water fish species present in the Naches River basin. Pacific lamprey, cutthroat trout, and mountain whitefish have also been documented within the basin (YSFWPB, 2004).

The climate of the Naches River basin ranges from cool and moist in the mountains to warm and dry in the valleys. Most of the precipitation falls during November to February. Annual precipitation in the mountains is from 70 to 140 inches at the Cascade crest and less than 10 inches in the eastern part of the basin (Figure 2). Average summertime temperature ranges from 55°F in the mountains to 85°F in the valleys. These conditions are formed by predominately westerly winds coming over the Cascade crest and also the rain shadow effect in the valleys below.

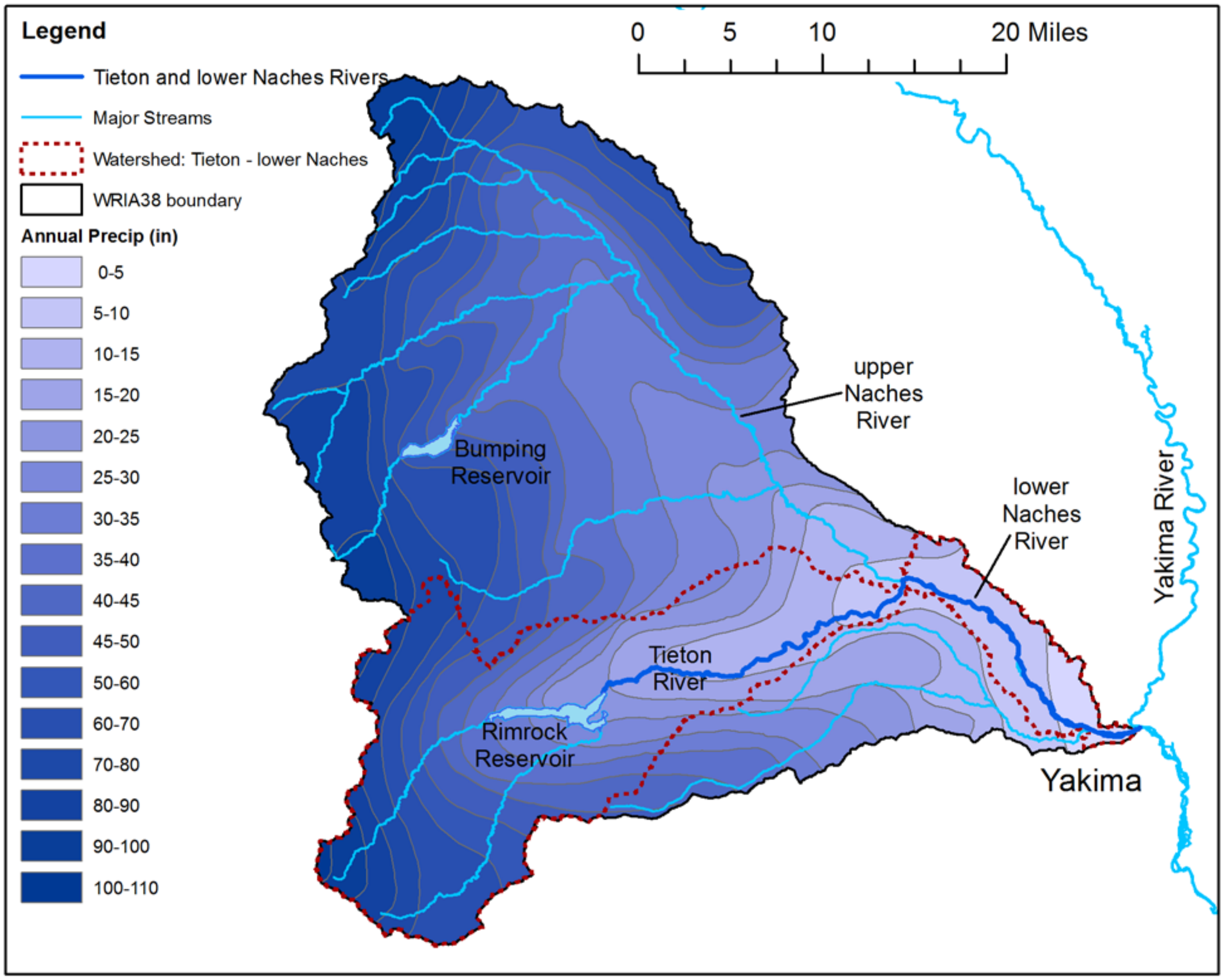

Figure 2. Average annual precipitation (inches) within the Naches River basin.

Precipitation data shown in Figure 2 are from National Oceanic and Atmospheric Administration (NOAA) Precipitation Frequency Atlas of the Western United States Volume IX.

Drought of 2015

The temperature monitoring studies in 2004 and 2015 were designed without any prior expectation of upcoming flow or temperature conditions. For example, planning for the 2015 study began early in 2014, and the QAPP (Urmos-Berry, 2015) for this study does not discuss expected flow conditions in these rivers because this was an unknown factor at the time of planning.

During 2015, a drought was declared for all of Washington State. Unlike classic droughts, characterized by precipitation deficits, 2015 began with a “snowpack drought” due to warm temperature during the winter of 2014-15 and near normal precipitation. Washington experienced record low snowpack because mountain precipitation that would normally fall as snow instead fell as rain (Andersen et al., 2016).

The snowpack deficit then was compounded as precipitation began to lag behind normal levels in early spring and into the summer. With record spring and summer temperatures, and little to no precipitation over much of the state, the snowpack drought morphed into a traditional precipitation drought. Many rivers and streams experienced record low flows (Andersen et al., 2016).

The drought of 2015 was directly responsible for widespread fish die-offs and impacts to wildlife, and it also resulted in the worst wildfire season in state history (Andersen et al., 2016). It caused agricultural losses estimated between $633 and $773 million (McLain et al., 2017).

The situation in the winter of 2014-15 sets an example for the known effect of atmospheric warming on reducing mountain snowpack in the Pacific Northwest, a known risk that has been reported by a sizable body of research (Fosu et al., 2016; Stoelinga et al., 2010; Mote et al., 2014; Abatzoglou et al., 2014). Planning for the future should use the lessons learned from the 2015 drought to identify potential impacts, needs, and uncertainties, because successfully adapting to changes may be required to protect our state’s farms, communities, and natural environment (Andersen et al., 2016).

Because of the coincidental drought conditions, the 2015 temperature study provides an opportunity to examine both a “worst case scenario” for river temperature, as well as a wide range of more typical river temperature during the cooler periods. Model simulated water temperature successfully calibrated against a wide range of observed conditions in 2015 (from June 1 to October 31). This allows for model simulation of a wide range of water temperature, which may be useful for possible future development of a TMDL in this study area.

Possible future development of a TMDL based on the 2004 and 2015 temperature study should take into account both the unusually high water temperatures observed during 2015 as well as water temperatures which represent more typical present day conditions.

Rimrock Reservoir and Tieton Dam

Immediately upstream of the study reach on the Tieton River is Rimrock Reservoir, which is maintained by the Tieton Dam. This dam was built in 1925 and has no fish passage facilities (USBR, 2002).

Rimrock Reservoir is one part of a system of reservoirs that USBR manages in the Yakima River basin. Water from the reservoir is used to meet irrigation demands, flood control, and instream flow for fish (USBR, 2002). Water released from this reservoir enters the Tieton River and flows through the Tieton River Canyon until it enters the Naches River near the junction of State Highway 410 and U.S. Highway 12.

Rimrock Reservoir was created by inundating McAllister Meadows, and is not associated with a natural lake (USBR, 2002). It therefore lacks a minimum conservation pool (historical lake bed). To maintain fish habitat, Rimrock Reservoir has not been drafted below 21,988 acre-feet (at the end of September) or 10,730 acre-feet (at the end of October) since 1987 (USBR, 2002). At low reservoir levels, fish are more vulnerable to being entrained through the outlet works.

When the reservoir is full, the outlet from Tieton Dam releases water from approximately 200 ft below water surface. This is based on the Tieton Dam outlet invert elevation of 2722 ft with a normal reservoir elevation of 2926 ft (USBR, 2002). By the end of October, the outlet is shallower due to reservoir draw down. For example, according to the USBR website, the outlet appeared to be approximately 100 ft below the surface of the reservoir by the end of October, 2015. Water released from Tieton Dam increases in temperature over the summer, due in part to this draw down.

The USBR manages water releases from Rimrock Reservoir as part of a management strategy descriptively termed the “flip-flop.” In practice, flip-flop, which was conceived and initiated in 1981, consists of releasing most of the water needed to supply the Yakima Basin’s irrigation needs from reservoirs in the upper Yakima basin until about September 1 each year. During this time, releases of storage water from Rimrock and Kachess Reservoirs are minimized. In early September, the release pattern reverses: the majority of the flow needed to satisfy Yakima Basin irrigation demand is provided by storage water releases from Rimrock and Kachess Reservoirs, and the other upper Yakima releases are substantially curtailed (YSFWPB, 2004 and personal communication Chris Lynch, USBR).

The purpose of the flip-flop operation is to encourage spring Chinook salmon, returning to the upper Yakima River in the summer and spawning in September and early October, to spawn at lower river flow and water levels. This minimizes the flows required to keep the salmon redds (fish nests) watered and protected during the incubation period (November through March), while still allowing USBR to refill its upper Yakima basin storage reservoirs for the next year’s irrigation season; it is also consistent with the “normative” flow concept for the upper Yakima arm of the Yakima River basin (USBR, 2004).

The hydrograph of the Tieton River represents the most extreme alteration of the natural hydrograph of any location within the Yakima River Basin (USBR, 2002). The flip-flop operation drastically increases flow during a period in which the river would normally be at its lowest level (September to mid-October). Due to USBR storage operations at Rimrock Reservoir (i.e., refilling the reservoir during the winter and spring), winter flows on the Tieton River are frequently less than 30 cfs for extended periods, and on numerous occasions have dropped below 20 cfs (USBR, 2002). These winter flows are much lower than would occur under unregulated conditions. Peak spring runoff flow is also substantially reduced, approximately 33% (USBR, 2002).

According to USBR (2002), the regulated flow regime has had the following impacts on the Tieton River:

- It has depressed the aquatic invertebrate community due to dewatering in the winter.
- For decades, no spawning has been observed of anadromous and resident salmonids.
- Spawning gravels in this river have been washed downstream with no source for replacement.
- Lack of bedload recruitment from above the dam has affected the channel morphology, causing a decline in habitat complexity.

Previous Temperature Studies

Wenatchee National Forest Stream Analysis

The portion of the Naches River watershed that lies within USFS land (Wenatchee National Forest) was analyzed in the *Wenatchee National Forest TMDL Water Temperature Total Maximum Daily Load Technical Report* (Whiley and Cleland, 2003). The USFS boundary lies at RM 13.7 on the Tieton River and RM 38.8 on the Naches River.

This technical report included:

- Analysis methods using a stream classification system to estimate effective shade levels necessary to meet the water quality standard for surface waters throughout the forest.
- Other analysis methods that examined site potential shade, or the maximum amount of effective shade provided by late-succession vegetation.
- Findings that due to naturally-occurring limitations to vegetative growth, site potential effective shade levels in some portions of the forest are less than what is needed to achieve the numeric temperature standard.

Upper Naches River Water Quality Study Findings

The water quality study findings report (Brock, 2008) presents results for the Naches River from the USFS boundary at RM 38.8 to its confluence with the Tieton River at RM 17.6. Brock's report also presents study information on Cowiche Creek. Study results include:

- Temperature monitoring at 8 sites on the upper Naches River, 5 sites on the lower Naches River, 4 sites on the Tieton River, 8 sites on Cowiche Creek, and monitoring of several other tributaries: Little Naches River, American River, Rattlesnake Creek, Nile Creek, and Reynolds Creek.
- Model simulations for the mainstem Naches River performed at a 7-day average temperature, occurring once in a 10-year return period, designated as 7Q10 critical flow conditions showing that water temperature decreases may be attained with future improvements towards mature riparian vegetation compared with current conditions.
- Thermal infrared aerial surveys of approximately 45 miles of the Naches River on 8/14/2004. Thermal imagery was calibrated to measured water temperatures. These surveys documented the cooling impact that the Tieton River has on the Naches River during flip-flop. They also identified the cooling impact of springs on the Naches River.
- Findings that under *critical* conditions (low flow / hot weather), potential temperature reductions should prevent water temperatures from exceeding the threshold for fish lethality (23ºC). However, at least in some cases, water temperature during critical conditions will likely still exceed numeric criteria despite potential temperature reductions.
- Recommendations that a buffer of mature riparian vegetation along the banks of rivers and streams, and improvements in microclimate and channel width, are expected to decrease the average daily maximum water temperatures.
- Increasing streamflows will also improve water temperature.

Tieton River and Lower Naches River Temperature Study

Ecology studied water temperature in the Tieton River and lower Naches River within the Naches River basin during a year with a declared drought (Urmos-Berry, 2015). Temperature loggers were used to continuously monitor the temperature at multiple locations along the Tieton River, lower Naches River, and key water inflows. Also, streamflow was monitored at selected locations. Data collection occurred during May-October 2015, and final data were submitted to Ecology's Environmental Information Management (EIM) database.

In addition to the above studies, a list of earlier studies can be found in Appendix A to the Naches Basin Bibliography, found in the *Quality Assurance Project Plan for the Naches River Temperature Total Maximum Daily Load (TMDL) study* (LeMoine and Brock, 2004).
In addition to the above studies, Ecology reviewed historical information related to temperature, dissolved oxygen, and pH for the Yakima River Basin, which included the Naches River Basin as well (Pickett, 2016).

Climate Change

Changes in climate are expected to affect both water quantity and quality in the Pacific Northwest (Snover et al., 2013; Mote et al., 2014). Factors affecting these changes include natural climate variability, which influences regional climate on annual and decadal scales, and long-term increases in air temperature due to rising greenhouse gas emissions. Chapter 21 of the U.S. National Climate Assessment report, *Climate Change Impacts in the United States* (Mote et al., 2014), described observed and projected changes in air temperatures across the region:

- *"[Air]Temperatures increased across the region from 1895 to 2011, with a regionally averaged warming of about 1.3°F."*
- *"An increase in average annual [air]temperature of 3.3°F to 9.7°F is projected by 2070 to 2099 (compared to the period 1970 to 1999), depending largely on total global emissions of heat-trapping gases. The increases are projected to be largest in summer."*

A warming climate affects snowpack and hydrology in important ways. Washington's spring snowpack is projected to decline -38% to -46% by the 2040s and -56% to -70% by the 2080s under low and moderate warming scenarios (Snover et al., 2013). The impact of this snow loss on hydrology will vary by basin, as noted in Mote et al. (2014):

> *"Hydrologic response to climate change will depend upon the dominant form of precipitation in a particular watershed, as well as other local characteristics including elevation, aspect, geology, vegetation, and changing land use. The largest responses are expected to occur in basins with significant snow accumulation, where warming increases winter flows and advances the timing of spring melt. By 2050, snowmelt is projected to shift three to four weeks earlier than the 20th century average, and summer flows are projected to be substantially lower, even for an emissions scenario that assumes substantial emissions reductions…"*

By the 2040s, summer flows are projected to decrease by 30% to more than 50% in rivers draining the Cascade Mountains, Olympic Mountains, and western front of the Rocky Mountains in Washington. These lower flows, combined with rising air temperatures, are expected to cause increased summer stream temperatures. Mantua et al. (2010) presented climate change model scenarios that projected annual maximum weekly average water temperatures that by the 2080s are from 1 to 6°C higher than 1980s conditions. Higher stream temperature degrades or eliminates habitat for salmonids and also can increase salmonid disease and predation, decrease dissolved oxygen levels, and increase the impacts of pollutants on receiving waters.

Water quality can also be affected by an expected increase in extreme precipitation events. According to Mote et al. (2014):

> *"Averaged over the region, the number of days with more than one inch of precipitation is projected to increase 13% in 2041 to 2070 compared with 1971 to 2000 under a scenario that assumes a continuation of current rising emissions trends, though these projections are not consistent across models."*

More extreme precipitation events, combined with warming winter temperature, increases the risk of winter flooding in mixed rain-snow and rain-dominant watersheds. This will likely increase stormwater management challenges in urban areas. Increased erosion and pollutant runoff is also an expected consequence of more intense storms.

Other climate change impacts identified by Mote et al. (2014) that may result in degraded water quality in rivers and streams include:

- Increasing wildfires, resulting in increased post-fire erosion and pollutant loading
- Changes to watershed vegetation from changes to temperature, moisture, and fire regimes
- Increased agricultural pesticide use to control increased disease, pests, and weeds

In 2015, the University of Washington Climate Impacts Group published *State of Knowledge: Climate Change in Puget Sound* (Mauger et al., 2015). This report summarized current research on the impacts of climate change in the Puget Sound region for issues ranging from snowpack to human health. It identified numerous likely changes in freshwater quality and marine water quality. These changes include:

- Decreased summer freshwater flows
- Increased sediment loads in winter and spring
- Warmer freshwater and marine water temperatures
- Decreased dissolved oxygen levels
- Changes in estuarine circulation
- Increased harmful algal blooms
- Increased acidification (lower marine pH levels)
- Rising sea levels and increased coastal erosion

Information on climate change in Washington State is available from:

- University of Washington Climate Impacts Group website: https://cig.uw.edu/
- Ecology's Climate Change website: https://ecology.wa.gov/Air-Climate/Climate-change

Water Quality Standards and Beneficial Uses

Designated Freshwater Aquatic Life Uses and Water Temperature Criteria

The main beneficial use addressed by this study is aquatic life use. Aquatic life uses are protected in part by water temperature criteria associated with key species uses (Washington State Administrative Code, Section 173-201A-600; Table 604). Water temperature levels fluctuate over the day and night in response to changes in weather conditions and river flows. Since the health of aquatic species is tied predominantly to the pattern of maximum temperature, the criteria are measured by the 7-day average of the daily maximum temperatures (7-DADMax). Temperatures are not to exceed the criteria at a probability frequency of more than once every ten years on average.

Water temperatures measured during 2004 and 2015 were compared against the *Water Quality Standards for Surface Waters of the State of Washington* (Ecology, 2012). Because water quality standards have changed over time, the criteria used in this report may differ from criteria used in previous reports. Chapter 173-201A WAC of these standards designates aquatic life uses based on the presence of, or the intent to provide protection for, key species uses listed below. In addition to the key species, it is required that all indigenous fish and nonfish aquatic species be protected.

The following key aquatic life uses and associated water temperature criteria are included within the current study area:

- **Core summer salmonid habitat (16°C Highest 7-DADMax)**: The key identifying characteristics of this use are summer salmonid spawning or emergence, or adult holding; use as important summer rearing habitat by one or more salmonids; or foraging by adult and subadult native char. Other common characteristic aquatic life uses include spawning outside of the summer season, rearing, and migration by salmonids.
- **Salmonid spawning, rearing and migration (17.5°C Highest 7-DADMax)**: The key identifying characteristic of this use is salmon or trout spawning and emergence that only occurs outside of the summer season. Other common characteristic aquatic life uses include rearing and migration by salmonids.

Washington State uses the criteria described above to ensure that where a waterbody is naturally capable of providing full support for its designated aquatic life uses, that condition will be maintained. The standards recognize, however, that not all waters are naturally capable of staying below the fully protective temperature criteria. When a waterbody is naturally warmer than the above described criteria, the state provides an allowance for additional warming due to human activities. In this case, the combined effects of all human activities must also not cause more than a 0.3°C (0.54°F) increase above the naturally higher (inferior) temperature condition.

In addition to the temperature criteria listed above, some waterbodies require special protection for spawning and incubation periods. These waterbodies are protected by supplemental temperature criteria (Ecology, 2011). Some waterbodies in this study fall under the supplemental spawning temperature criterion of 13°C highest 7-DADMax from February 15 to June 15.

Table 1 summarizes the designated aquatic life uses and water temperature criteria for the major waterbodies in this study.

Table 1. Aquatic life uses for major waterbodies in this study.
(Adapted from Table 604, Chapter 172-201A WAC)

Water Body	Core summer habitat	Salmonid spawning, rearing, and migration	Supplemental spawning protection
Tieton River and all tributaries (from Rimrock Reservoir to mouth)	X		
Lower Naches River (from Tieton River confluence to Cowiche Creek confluence)		X	X
Lower Naches River (from Cowiche Creek confluence to mouth)		X	
Oak Creek (tributary to Tieton River)		X	X
Buckskin Slough (tributary to lower Naches River)		X	X

Water Quality Assessment and the 303(d) List

The Clean Water Act (CWA) established a process to identify and clean up polluted waters. The CWA requires each state to have its own water quality standards designed to protect, restore, and preserve water quality. Water quality standards consist of (1) designated uses for protection, such as aquatic life uses, and (2) criteria, usually numeric criteria, to achieve those uses.

Every two years, states are required to prepare a list of waterbodies that do not meet water quality standards. This list is called the CWA 303(d) list. In Washington State, this list is part of the Water Quality Assessment (WQA) process.

To develop the WQA, Ecology compiles its own water quality data along with data from local, state, and federal governments; tribes; industries; and citizen monitoring groups. All data in this WQA are reviewed to ensure they were collected using appropriate scientific methods before they are used to develop the assessment.

The WQA divides waterbodies into five categories. Those not meeting standards are given a Category 5 designation, which collectively becomes the 303(d) list.

Category 1 – Meets standards for parameter(s) for which it has been tested.
Category 2 – Waters of concern.
Category 3 – Waters with no data or insufficient data available.
Category 4 – Polluted waters that do not require a TMDL because they:
  4a – Have an approved TMDL project being implemented.
  4b – Have a pollution control program in place that should solve the problem.
  4c – Are impaired by a non-pollutant such as low water flow, dams, or culverts.
Category 5 – Polluted waters that require a TMDL – the 303(d) list.

Further information is available at Ecology’s Water Quality Assessment website: wq303dindex.

Waterbodies within the study area for this report that are included on the 303(d) list are presented in Table 2. The CWA requires that a TMDL be developed for each of the waterbodies on the 303(d) list.

Table 2. Waterbodies in the study area on the 303[d] list for temperature.

Waterbody	Listing ID	Reach code	Category	2014 List	2012 List	2008 List	2004 List
Naches River	8336	17030002006948	5	Y	Y	Y	N
	48443	17030002000024	5	Y	Y	Y	N
	48444	17030002001307	5	Y	Y	Y	N
	48445	17030002001319	5	Y	Y	Y	N
	48446	17030002001336	5	Y	Y	Y	N
Tieton River	48471	17030002000305	5	Y	Y	Y	N
	48472	17030002000306	5	Y	Y	Y	N
	48474	17030002000310	5	Y	Y	Y	N
Oak Creek	73003	17030002000494	5	Y	N	N	N

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Goals and Objectives

Project Goals

1. Characterize summer (June-October) water temperature of the Tieton River, the lower Naches River (below confluence with the Tieton River), and selected tributaries.
2. Develop a predictive computer temperature model for the Tieton River (from the Wenatchee National Forest Boundary) and the lower Naches River.

Project Objectives

1. Compile existing data for current and historical river and meteorological conditions. Sources include Ecology, USBR, NOAA, and WSU.
2. Create a predictive water temperature model for the Tieton and lower Naches Rivers to match observed conditions seen in the compiled data.
3. Assess sensitivity of the predictive water temperature model.
4. Use the model to simulate water temperature changes in response to hypothetical changes in the basin environment.
5. Provide quality data and models that can be used for future work, such as a TMDL, for temperature or regional modeling.

Methods

Water Temperature Data

The types of water temperature measurements compiled for this study are described below.

- **Water and air temperature data loggers (Ecology)**: The purpose of the data loggers was to provide a continuous (30 minute interval) record of water temperatures at selected sites in the study area. Water temperature in mainstem rivers and tributaries was monitored using data loggers during 2015 and also the 2004 TMDL study (Brock, 2008). Methods for data collection and quality assurance are described in the respective QAPPs (Urmos-Berry, 2015 and LeMoine and Brock, 2004). The data were assessed for quality assurance and stored in Ecology's Environmental Information (EIM) database.
- **Continuous water temperature gage (USBR)**: USBR temperature data is not collected under a QAPP and the quality is highly uncertain. For 2015, Ecology verified the accuracy of this gage using a data logger at the same location. The purpose of the gage was to provide a historical context (at a coarse screening level) for water temperatures observed in 2004 and 2015. Data were downloaded from the USBR website for gage NACW below the Wapatox diversion dam (https://www.usbr.gov/pn/hydromet/yakima/).

Ecology water temperature measurement locations are shown in Figure 3.

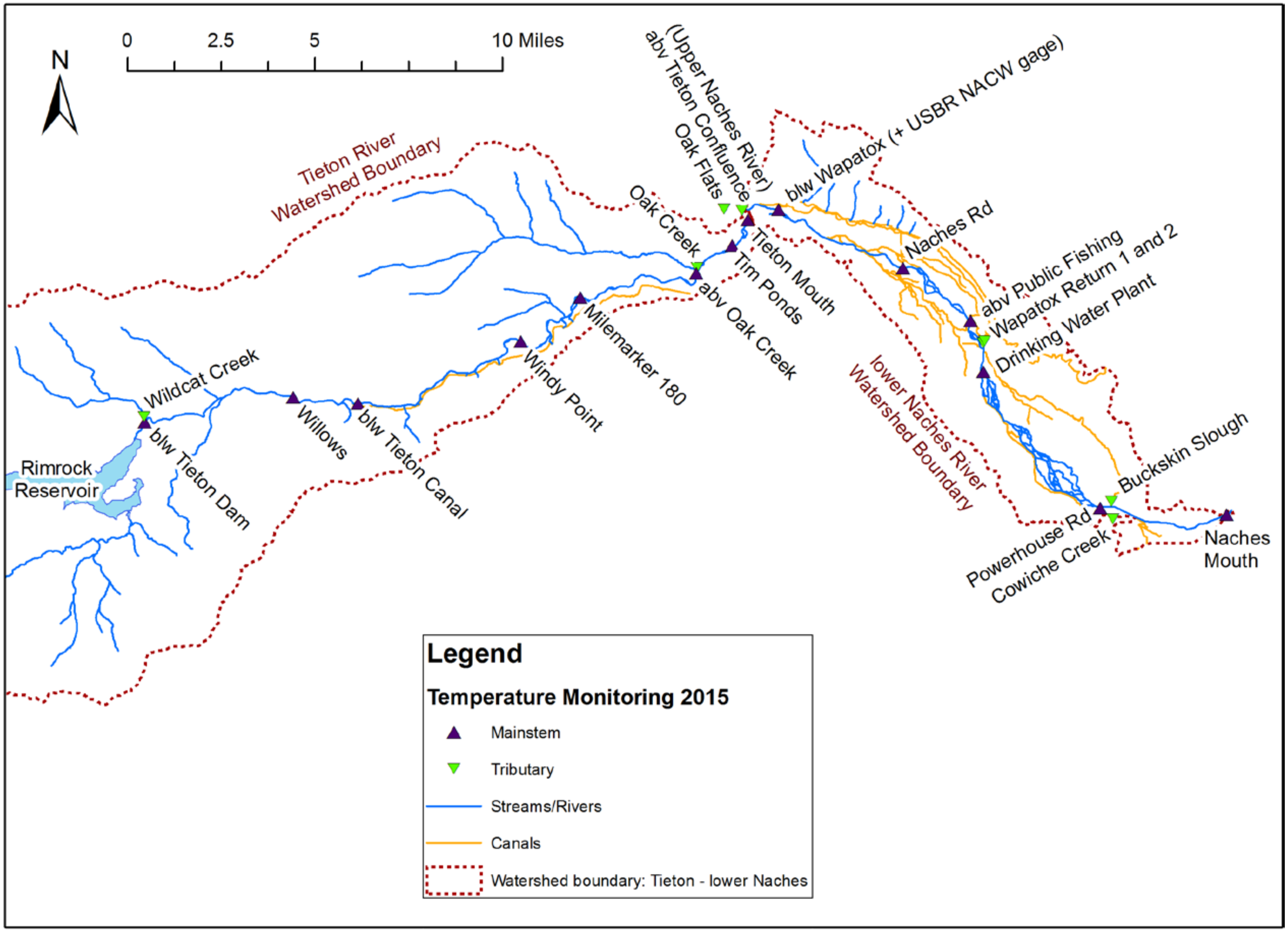

Figure 3. Water temperature sampling locations.

Streamflow Data

The types of streamflow measurements compiled for this study are described below.

- **Flow measurements (Ecology)**: The purpose of these measurements was to monitor (1) tributary flows into the Tieton and Naches Rivers (mainstem) and (2) two minor canal withdrawals from the mainstem Naches River. Measurements were collected twice monthly during June through October 2015. Methods for data collection are described in the Quality Assurance Project Plan (Urmos-Berry, 2015). Results are available through Ecology's EIM database.
- **Continuous flow gage (Ecology)**: The purpose of the gage was to measure the amount of Naches River water mixing with the Tieton River water at the confluence. The flow gage was installed in the Naches River near Oak Flats and measured streamflow at 15 minute intervals. Ecology's Stream Hydrology Unit installed and operated the gage in accordance with standard protocols established by the unit. The gage started to collect data on 8/11/2015 and continued through the end of the study (early November, 2015).
- **Continuous flow gages (USBR)**: The purpose of these gages was to measure flows in the mainstem rivers and the canals diverting water from the mainstem. Where available, continuous 15-minute or hourly streamflow data were downloaded from the USBR website: https://www.usbr.gov/pn/hydromet/yakima/yakwebdayread.html. For those canals where online data were unavailable in 2015, historical data averages (2001-04) were used as estimates of 2015 canal withdrawal amounts, based on data provided to Ecology by USBR as part of the 2004 TMDL study (Brock, 2008).
- **Groundwater seepage investigation (Ecology and USGS)**: Previously reported groundwater flow estimates along the Tieton and Naches Rivers were used in this study. These estimates were based on differential flow measurements collected by Ecology and USGS (Brock, 2008; Vaccaro, 2011).

Streamflow locations are shown in Figure 4, and data types are listed by location in Table 3.

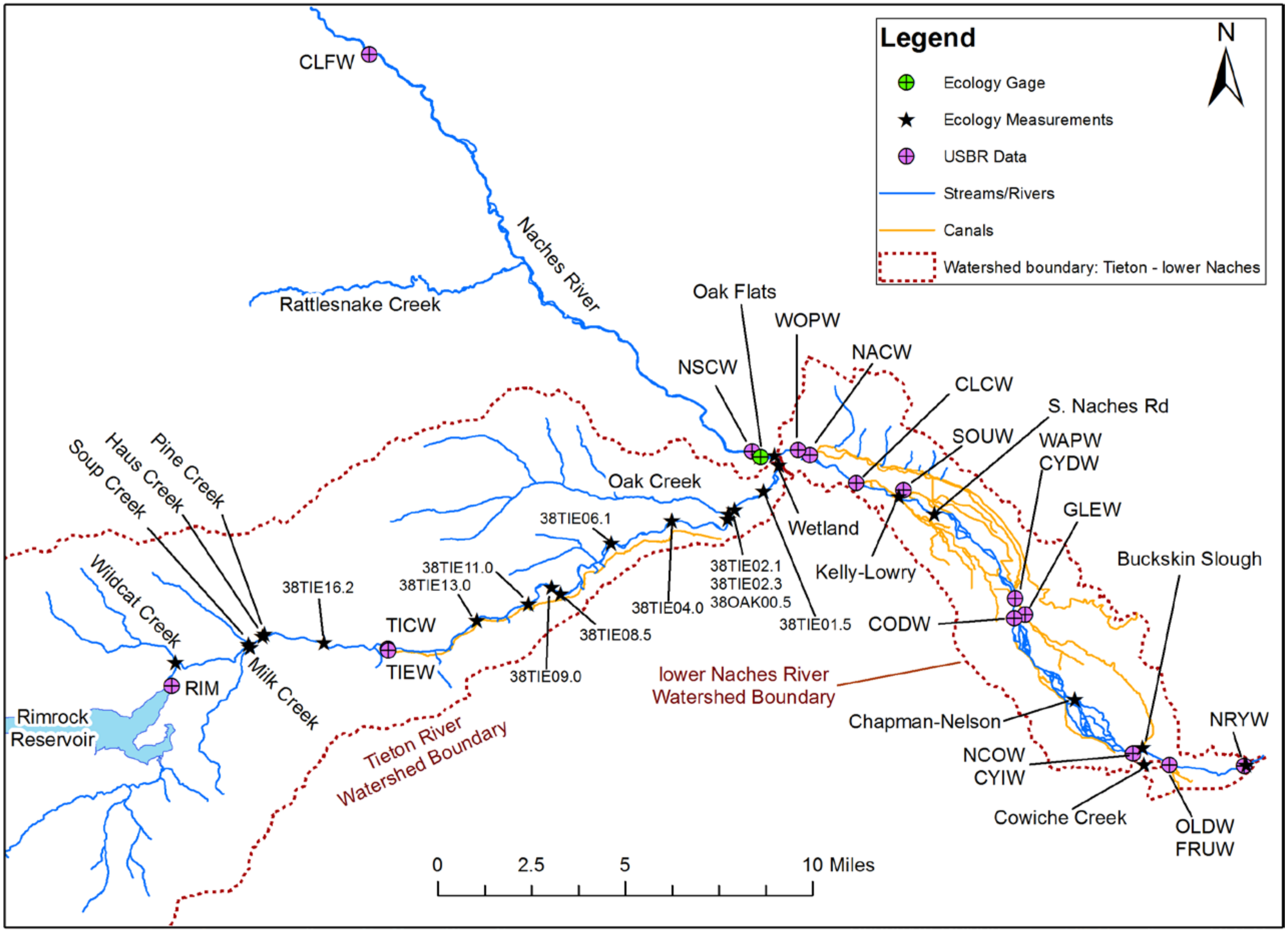

Figure 4. Streamflow sampling locations.

Table 3. Locations and associated type of streamflow data used in this study.

Location	ID	Calendar Year		
		2015	1983-2014	2001-04
Pine Creek	38PINE0.05	M		
Soup Creek	38SOUP0.05	M		
Wildcat Creek	38WILD0.05	M		
Milk Creek	38MILK0.05	M		
Hause Creek	38HAUS0.05	M		
Oak Creek	38OAK0.05	M		
Buckskin Slough	38BINW	M		
Cowiche Creek	38COW00.5	M		
Naches River at Oak Flats	38NAC18.0	G/M		
Chapman-Nelson Canal	38CHFW	M		
Kelly-Lowry Canal	38KLYW	M		
Tieton River - Rimrock Reservoir Outflow	RIM	USBR		
Tieton Canal Diversion	TIEW	USBR		
Naches River below Tieton Canal Diversion	TICW	USBR	USBR	
Naches River near Cliffdell	CLFW	USBR		
Naches-Selah Canal Diversion	NSCW	USBR		
Wapatox Power Canal Diversion	WOPW	USBR		
Naches River below Wapatox Canal Diversion	NACW	USBR	USBR	
South Naches Canal Diversion	SOUW	USBR		
Naches River near Yakima	NRYW	USBR / M	USBR	
Wapatox Power Canal Return Flow	WAPW	USBR		
Clark Ditch Diversion	CLCW			USBR
Yakima Valley Canal Diversion	CODW	USBR		
Yakima City Irrigation Diversion	CYIW	USBR		
Fruitvale Power Canal Diversion	FRUW			USBR
Gleed Canal Diversion	GLEW	USBR		
Naches-Cowiche Canal Diversion	NCOW	USBR		
Old Union Canal Diversion	OLDW			USBR
Yakima M&I Diversion	CYOW	City of Yakima		

M = Ecology measurement, G = Ecology gage, USBR = USBR online or historical data.
M&I = Municipal and Industrial

Meteorological Data

Several meteorological measurements (air temperature, dew point temperature, wind speed, cloud cover, and solar radiation) are input parameters needed for the QUAL2Kw water temperature model. Model input data compiled for these parameters are listed and described below.

- **Air temperature data loggers (Ecology):** Urmos-Berry (2015) used data loggers to collect air temperature data in 2015. The purpose of these data loggers was to provide a continuous (30-minute interval) record of air temperatures at selected sites in the study area.
- **Relative humidity data loggers (Ecology):** Urmos-Berry (2015) also used data loggers to collect relative humidity data in 2015. The purpose of these data loggers was to provide a continuous (30 minute interval) record of relative humidity at selected sites in the study area. Relative humidity was combined with air temperature to calculate dew point, described below.
- **Weather station Naches (Washington State University):** Online data for the following meteorological measurements were downloaded from the WSU AgWeatherNet website (http://www.weather.wsu.edu/): solar shortwave radiation, air temperature, and wind speed. In addition, cloud cover for the model was calculated based on changes in solar radiation, described below. This gage is located approximately one mile upstream of the City of Yakima drinking water treatment plant.
- **Weather station KYKM-Yakima airport (National Oceanic and Atmospheric Administration / National Weather Service):** Online data for the following meteorological measurements were downloaded from the MesoWest website (http://mesowest.utah.edu/): air temperature and wind speed.
- **Weather station RIM-Tieton Dam (USBR):** Online data for wind speed measurements were downloaded from the USBR website: https://www.usbr.gov/pn/hydromet/yakima/yakwebdayread.html.
- **Weather station at Sawmill Flats (RAWS):** Online data for temperature and dew point.

Calculations using Meteorological Data

Dew point temperature was calculated for the QUAL2Kw model based on relative humidity and air temperature near the river. Relative humidity was measured using data loggers at several locations along the river.

Dew point temperatures were calculated using the formulas below, which are rearranged versions of equations 30.15-30.17 in Chapra (1997). Calculated dew points were compared against those calculated by the relative humidity gages as well as nearby weather stations. Variables in the formulas below are vapor pressure of the air in mmHg (e_{air}), percent relative humidity (R_h), air temperature in Celsius (T), and dew point temperature in Celsius (T_{dew}).

$$e_{air} = \frac{R_h}{100} 4.596\, exp\left(\frac{17.27\, T}{237.3 + T}\right)$$

$$T_{dew} = \frac{237.3 \ln\left(\frac{e_{air}}{4.596}\right)}{17.27 - ln\left(\frac{e_{air}}{4.596}\right)}$$

Dew point temperatures were calculated at three locations using the following measurement points:

- **Near Tieton Dam**: Relative humidity gage near the dam (Ecology) and air temperature near the dam (Ecology). Prior to operation of the relative humidity gage on 7/14/2015, dew point temperatures reported at the Sawmill Flats (RAWS) station were used.
- **Near City of Yakima drinking water treatment plant**: Relative humidity gage near the plant (Ecology) and air temperature at the Naches Weather Station (WSU). Prior to operation of the relative humidity gage on 7/14/2015, dew point temperatures from the Naches Weather Station (WSU) were used. (Distance between the weather station and the relative humidity gage ~ 2 miles.)
- **Near Naches River mouth**: Relative humidity gage near the mouth (Ecology) and air temperature from the Yakima airport (NOAA). Prior to operation of the relative humidity gage on 7/14/2015, dew point temperatures from the Yakima airport (KYKM) were used. (Distance between the airport and the relative humidity gage ~ 4 miles.)

For dew point temperatures used in future model simulations or modifications to this model, Ecology notes that the dew point temperatures calculated near the mouth of the Naches River appear to show a wider range (minimum/maximum) from temperatures reported at the Yakima airport. Average dew point temperatures agree with the airport. This could potentially affect the lower portion of the model between the City of Yakima Drinking water treatment plant (WTP) and the mouth of the Naches River. Dew point temperatures at this location were not calculated prior to 7/14/2015, so this does not affect maximum simulated water temperatures in early July.

Cloud cover for the model was calculated by calculating attenuation factors for each day based on the ratio of maximum solar radiation at the Naches weather station versus expected maximum solar radiation for that day. Expected radiation was calculated by fitting a loess smoothing curve to the maximum radiation observed on clear days. The amount of cloud cover required to create the needed attenuation factor was calculated using the formula implemented in QUAL2Kw:

$$CL = \left[\frac{1 - ac}{KCL1}\right]^{\frac{1}{KCL2}}$$

Where CL is the fraction of sky covered by clouds, KCL1 and KCL2 are constants which were set to the default values in QUAL2Kw of KCL1=0.65 and KCL2=2; ac=attenuation factor based on observed maximum solar radiation divided by expected maximum solar radiation.

For the water temperature model inputs, the following meteorological parameters were interpolated based on elevation: air temperature, dew point temperature, and wind speed. This is because these parameters change significantly between the beginning of the model near Tieton Dam (elevation 2716 ft) and the mouth of the Naches River (elevation 1079 ft).

Air temperature locations used in the interpolation were near Tieton Dam (Ecology), milemarker 180 (Ecology), Naches weather station (WSU), and Yakima airport (NOAA). Dew point temperature locations used are listed in the Dew Point Calculation section above. Wind speed locations used were Tieton Dam weather station (USBR), Naches weather station (WSU), and Yakima airport (NOAA). Yakima airport measurements were taken to represent conditions at the mouth of the Naches River. Naches weather station measurements were taken to represent conditions near the public fishing area on the Naches River.

Hydrogeometry Data

A stream's hydrogeometry consists of its hydrologic characteristics (velocity, flow, dispersion) and its geometry (depth, width, cross-sectional area, slope) (Chapra, 1997). These factors affect the amount of stream surface area exposed to meteorological conditions such as sunlight, longwave radiation, and other weather conditions. These factors also determine the length of time that the stream water will be exposed to these conditions.

The following measurements were used to calculate hydrogeometry for use in the QUAL2Kw model:

Water Velocity: Reach average water velocity was calculated based on rhodamine dye tracer studies on September 11-12 and October 19-20, 2015. Dye studies are used to estimate travel times by measuring the time it takes for a slug of dye to reach specific downstream locations.

The two dye studies began in the Tieton River just below the diversion for the Tieton Canal and ended near 16th Avenue, just upstream of the mouth of the Naches River. The mainstem Tieton and Naches Rivers were broken into four reaches for these studies.

A slug of dye was added to the river at the upper end of each reach. Dye arrival times were measured at the end of each reach using Hydrolab® Datasondes® equipped with rhodamine sensors. Maximum observed concentration arrival times were chosen as average arrival times for each reach. Average reach velocities were then calculated as reach length divided by travel time. Both dye studies were conducted using standard operating procedures (Ecology, 2015b).

Wetted Width: River widths were calculated based on GIS analysis of aerial photos. For this study, aerial photo surveys of the river were obtained for August 20 and September 19, 2015. In addition, aerial photos of the river were available for July 3 and 19, 2015 in GIS through the United States Department of Agriculture's National Agriculture Imagery Program (NAIP).

River widths were calculated from aerial photos by digitizing lines to mark the water boundary along both banks of the river using GIS software (ArcMap) and then measuring the distance between these lines at regular intervals using Ttools software (Ecology, 2015).

Water Depth: Water depths were continuously measured along a profile of more than 17 miles of the Naches River on August 12-13, 2015. The profile began below the Wapatox diversion dam and ended at the railroad trellis near the river mouth.

Profile data collection followed standard operating procedures (Ecology, 2015c). Depths were measured using a Hydrolab® Minisonde® equipped with a depth probe, mounted inside a length of PVC pipe and dragged along the channel bottom behind a canoe. Canoe location was continuously monitored via global positioning system (GPS). Locations and depths were logged and stored electronically as the canoe travelled downstream. The minisonde also recorded specific conductance, pH, dissolved oxygen (DO), and water temperature. Calibrations and post-checks of specific conductance, pH, and DO were performed in accordance with standard operating procedures (Ecology, 2016).

Slope: Channel slope was calculated using Ttools software. See Model Software section below.

Calculations using Hydrogeometry Data

Hydrogeometry has an important influence on the sensitivity of water temperature to the influence of meteorological conditions. River water velocity, depth, and width all respond to changes in river flow. The QUAL2Kw model uses power curves to calculate flow related changes to velocity and depth (Pelletier and Chapra, 2008). The power curves used for velocity and depth both have the same form:

$$X = aQ^b$$

Where X represents either velocity or depth, Q = flow, and a, b represent empirical coefficients determined from velocity-discharge and depth-discharge rating curves. These empirical coefficients are set for each reach of the model and determine the velocity and depth of water in that reach under all flow conditions.

The empirical coefficients used for water velocity in the model were calculated based on water velocities measured by the two dye studies. Coefficients were calculated using the following formula (Thomann and Mueller, 1987):

$$b = \frac{\log(u_2) - \log(u_1)}{\log(Q_2) - \log(Q_1)}$$

$$a = \frac{u_1}{Q_1^b}$$

Where Q_1, Q_2 are the flows observed during the two different dye studies, and u_2 and u_1 are the average velocities observed during the two different dye studies. From the formula above, it is apparent that b represents the slope of a line on a log-log plot of velocity versus flow. Because each segment of the dye studies spanned multiple reaches within the model, calculated empirical coefficients were applied to all model reaches within each dye study segment.

The empirical coefficients for water depth used the identical equation above, substituting *observed* depths in place of *observed*. Empirical depth coefficients were calculated individually for each model reach. Observed depths for this calculation did not use depths measured during the hydrolab profile because the date of the profile did not correspond to the dye study dates; therefore, flow and water depth also differ between the dye studies and hydrolab profiles, especially during flip-flop. Additionally, the hydrolab profile did not measure depth in the Tieton River.

Observed depths used for calculating depth coefficients were instead calculated using the following equation:

$$depth = \frac{Volume}{length * width}$$

Volume was calculated within QUAL2Kw based on simulated flows on the date of each dye study. Width was estimated based on aerial photographs. The length of each model reach was 1 km.

Vegetation and Shade Data

In addition to hydrogeometry, shade from near-stream vegetation represents one of the most important factors influencing water temperature. These data were obtained from a vegetation analysis created during the 2004 TMDL study (Brock, 2008).

The original 2004 vegetation analysis used aerial photo interpretation and GIS analysis to map vegetation type along both banks of the Tieton and Naches Rivers. Vegetation type was interpreted using aerial photos at 100-meter intervals along the river. Three zones (0:50, 50:100, and 100:150 ft) along both river banks were digitized in GIS as lines on these photos. Vegetation types were interpreted and recorded by hand for each interval/zone.

Riparian vegetation was classified into current vegetation categories:

- Conifer trees (small/medium/large and sparse/medium/dense)
- Deciduous trees (small/medium/large and sparse/medium/dense)
- Mixed trees (small/medium/large and sparse/medium/dense)
- Scrub/shrub
- Grass/rush/sedge
- Orchard
- Additional categories for features such as water, roads, pasture, etc.

Each vegetation category was assigned three characteristic attributes: height, average canopy density, and streambank overhang. Vegetation categories and attributes are listed in Appendix C, Table C-2.

Effective shade on the Tieton River and lower Naches River was estimated using hemispherical photographs collected as part of the Upper Naches River TMDL study (Brock, 2008).

Model Construction Software

Three specialized software tools listed below were used to create a water temperature model for the Tieton and lower Naches Rivers. Measurement data collected using the above methods were utilized as inputs to these software tools.

1. The Oregon Department of Environmental Quality (ODEQ) and Ecology's Ttools extension for ArcMap (Ecology, 2015) was used to sample and process GIS data for input to the QUAL2Kw model. The mainstem Tieton and lower Naches Rivers were segmented into 1000-meter intervals using this tool. These segments were based on the river position in 2015 NAIP aerial photography. Slopes for these segments was calculated using a 10-meter DEM (USGS, 2009). River widths on three different dates were also measured based on aerial photographs of the river water's edge along the full length of the Tieton and lower Naches Rivers.

2. Ecology's Shade.xls model (Ecology, 2013) was used to calculate effective shade along the river reaches. Effective shade is defined as the fraction of incoming solar shortwave radiation above the vegetation and topography that is blocked from reaching the surface of the stream. Vegetation shade was calculated based on the 2004 vegetation analysis. Topographic shade was

calculated by sampling a 10 meter digital elevation model (DEM) using Ttools software. Shade values were calculated every hour at 100-meter intervals along the streams and then averaged over 1000-meter intervals for input to the QUAL2Kw model. The Shade model was adapted from a program also originally developed by the ODEQ as part of the HeatSource model. The Shade model uses mathematical simulations to quantify potential daily solar load and generate percent effective shade values.

3. Ecology used the dynamic flow version of QUAL2Kw (Pelletier et al., 2006; Chapra et al., 2008) to simulate water temperature. QUAL2Kw is a finite difference numerical model which uses a kinematic wave method for dynamic flow routing. The kinematic wave equation is used to drive advective transport through free-flowing segments and to calculate flows, volumes, depths, and velocities resulting from variable upstream inflow. In addition, the QUAL2Kw framework allows input of continuous changes in boundary loads and meteorology. Among other inputs, this model uses the effective shade calculated by Shade.xls. Previous versions of QUAL2Kw were limited to steady-state, single-day solutions.

Study Quality Assurance Evaluation

Different types of data from both Ecology and external sources were used in this study. Table 4 indicates which data sets have established quality assurance/quality control (QA/QC) programs to ensure data reliability. Website links to either QA/QC information or data sources, as noted, are provided.

Table 4. Quality assurance check of data used in this study.

Agency	Data	Established QA/QC Program?	Accredited Laboratories, SOPs & Equipment?	QA/QC Documentation or Publications Readily Available?	Link to QA/QC Information (or data sources, as noted)
Ecology	Flow	Yes	Yes	Yes	Quality Assurance at Ecology
Ecology	Temperature	Yes	Yes	Yes	Quality Assurance at Ecology
Ecology	Travel time	Yes	Yes	Yes	Quality Assurance at Ecology
Ecology	River widths	Yes	Yes	No	Unknown
Ecology	River depths	Yes	Yes	No	Published SOPs
USBR	Flow	Yes	Yes	No	https://www.usbr.gov/main/qoi/
USBR	Temperature	No	No	No	Not available
NOAA	Meteorological	Yes	Yes	Yes	http://www.cio.noaa.gov/services_programs/IQ_Guidelines_011812.html
WSU	Meteorological	Yes	Yes	No	Data Source: http://www.weather.wsu.edu/

Bias and Precision

For temperature and flow data collected by Ecology in 2004, QA is documented in Brock (2008) and LeMoine and Brock (2004). Pre- and post-checks of temperature loggers against constant temperature baths were reported to meet manufacturer specifications. Field checks with a thermometer averaged 0.2°C difference relative to data loggers. Average differences in flow replicates during field work in 2004 were reported to be 4.3%. No flow replicates were collected during 2015 field work.

For temperature and flow data collected by Ecology in 2015, QA is documented in Urmos-Berry (2015) and Appendix D of this report. All of the post-check temperature bath results for the data loggers in 2015 were close to manufacturer-stated accuracy (±0.2°C). The maximum difference observed during the post-check results was 0.23°C, which represents an average absolute difference between the data logger and ten measurements using a National Institute of Standards

(NIST) certified thermometer. Several temperature data loggers in 2015 did not meet pre-check temperature bath results, especially in the ice bath (likely due to non-uniform bath temperature). Room temperature bath pre-check results were close to manufacturer stated accuracy in 2015, with a maximum difference of 0.24°C. The bath at room temperature is closest to the target temperature for this study. Therefore, water temperature data-logger results from both 2004 and 2015 are considered reliable for this study.

Water temperature data downloaded from USBR were verified by comparing results at station NACW against an adjacent temperature logger deployed by Ecology in 2015. The NACW temperatures were found to be slightly warmer than Ecology's logger (Bias +0.4°C) and RMSE 0.38°C.

No estimates of bias or precision are available for the flows measured at USBR gages. For comparison, Ecology performed two flow measurements at USBR gage NRYW to check for agreement between the gage and Ecology's results. On 8/18/2015, Ecology measured flow = 240 cfs, which compares closely (<1% RPD[2]) to the downloaded daily average flow at NRYW = 239 cfs. On 10/22/2015, Ecology measured flow = 354 cfs, compared to the downloaded daily average flow for that day at NRYW = 275 cfs, a difference of 22% RPD. Rating curves are not maintained by USBR for this gage, and this particular gage is likely not reliable at higher flows. Rating curves for the other gages used in this study are maintained by USBR.

No estimates of bias or precision are available for downloaded meteorological data, river widths from aerial photography, and dye-study travel times.

Completeness

Completeness is a measure of the amount of valid data needed to meet the goals defined for the uses of the data. In the case of water temperature, this includes both adequate seasonal and spatial coverage of the rivers (Table 5).

Table 5. Completeness of water temperature data collected in 2015 and 2004.

Water Body	2015 (Jun-Oct)		2004 (Jun-Oct)	
	Average # days per month	Number of sites	Average # days per month	Number of sites
Lower Naches River	27.5	8	20.6	4
Tieton River	27.7	8	18.5	4
Oak Creek	30.6	1	---	0
Buckskin Slough	28.8	1	---	0

---

[2] relative percent difference

For water temperature, 2015 had better spatial and temporal/seasonal coverage:

- Spatial: There were twice as many mainstem river sites in 2015. Also, more tributaries were monitored in 2015.
- Temporal/seasonal coverage: This coverage was also better in 2015 because half of the temperature loggers in 2004 on the Tieton and lower Naches Rivers did not record temperature during June or July; the warmest water temperatures of 2004 occurred in late July.

Tributary flow coverage is better in 2015, with flows measured monthly in several waterbodies which were not monitored in 2004: Oak Creek, Buckskin Slough, Wildcat Creek, Milk Creek, Soup Creek, and Hause Creek. Two canal withdrawals were also monitored in 2015: Chapman-Nelson and Kelly-Lowry.

Mainstem river flows were monitored similarly by USBR for both 2004 and 2015. Ecology measured mainstem river flows in 2004 primarily during a groundwater seepage study in July of that year.

Overall flow and water temperature for both the 2004 and 2015 studies are considered representative for these rivers. Both the Tieton and lower Naches Rivers are well mixed systems which can be adequately monitored for temperature using the measurement techniques in the 2004 and 2015 studies. Because some of the measurements for both studies were made at the same locations using similar techniques, data between the two studies can be compared at appropriate locations. For water temperature simulation in QUAL2Kw, measurements made in 2015 provide better spatial and temporal coverage for model calibration.

Flow and water temperature data for the 2004 and 2015 studies are credible data as described in Ecology’s Water Quality Policy 1-11:

- Data were collected under appropriate quality assurance and quality control procedures.
- Data are representative of the water quality conditions at the time the data were collected.
- Data consist of an adequate number of samples.
- Data collection methods conform to generally accepted methods and protocols in the scientific community.
- Data interpretation, statistical, and modeling methods are also generally acceptable in the scientific community as appropriate for use in assessing the condition of the water.

Evaluating Model Performance

Model performance was evaluated by comparing model simulated temperature data against in-stream observed measurements.

There are two general approaches for assessing the quality of a calibration: subjective and objective. Subjective assessment is based on a visual comparison (plots) between the simulated and observed data. In contrast, objective approaches hinge on developing some quantitative measures of the quality of the fit (Chapra, 1997).

Both subjective and objective approaches were used for this study. Subjective assessment relied on time series and longitudinal plots. Objective assessment relied on two measures of fit: root mean squared error (RMSE) and bias. These two measures complement each other as follows:

- RMSE provides a measurement of total error that will be zero only when the simulated and observed data match exactly. RMSE is always a positive number.
- Bias is the average difference between the simulated and observed data. It indicates whether the model tends to over- or under-predict. If bias is positive, the model is over-predicting observed data; if bias is negative, the model is under-predicting observed data. Bias is zero when all differences average out (highs and lows cancel each other). At zero bias, there may still be non-zero total error (RMSE > 0).

The RMSE and overall bias (for n = number of field observations) were calculated as:

$$RMSE = \sqrt{\frac{\Sigma(T_{\text{simulated}} - T_{\text{observed}})^2}{n}}$$

$$Bias = \frac{\sum (T_{\text{simulated}} - T_{\text{observed}})}{n}$$

Results

Table 6 present the site list of locations used for this technical temperature study.

Table 6. Study sites used in this temperature study.

Short Name	EIM Location ID	River Mile	Description	Water Temperature	Flow Measurements	Continuous Flow Gage	Air Temperature	Relative Humidity
Tieton River Sites								
blw Tieton Dam	38TIE20.8	20.8	Tieton River below Dam	X			X	X
Willows	38TIE16.2	16.2	Tieton River at Willows campground	X				
blw Tieton Canal	38TICW	14.4	Tieton River near USBR flow station	X				
Windy Point	38TIE09.0	9.0	Tieton River at Hwy 12 near Windy Point Campground	X				
Milemarker 180	38TIE06.1	6.1	Tieton River upstream of mile marker 180	X			X	
abv Oak Creek	38TIE02.3	2.3	Tieton River at Hwy 12 upstream of Oak Creek	X				
Tom's Pond	38TIE01.5	1.5	Tieton River at Tom's Pond	X				
Tieton Mouth	38TIE00.4	0.4	Tieton River near mouth	X				
Naches River Sites								
Oak Flats	38NAC18.0	18.0	Naches River below Naches Selah Canal	X	X	X		
abv Tieton Confluence	38NAC17.6	17.6	Naches River near Confluence with Tieton Y	X				
blw Wapatox	38NACW	16.6	Naches River below Hwy 12-410 at USBR Station	X				
Naches Rd	38NAC12.8	12.8	Naches River at S Naches Rd Bridge	X				
abv Public Fishing	38NAC10.5B	10.5	Naches River upstream of Naches at Public Fishing	X				
Drinking water plant	38NAC9.0	9.0	Naches River at City of Yakima water treatment plant	X				X
Powerhouse Rd	38NAC03.84	3.84	Naches River at Powerhouse Road	X				
NRYW	38NAC00.5	0.5	Naches River near Yakima USBR Gage		X			
Naches Mouth	38NAC0.18	0.18	Naches River near mouth	X				X
Tributary and Canal Sites								
Wildcat Creek	38WILD0.05	0.05	Wildcat Creek near mouth	X	X			
Soup Creek	38SOUP0.05	0.05	Soup Creek near mouth		X			
Milk Creek	38MILK0.05	0.05	Milk Creek near mouth		X			
Hause Creek	38HAUS0.05	0.05	Hause Creek near mouth		X			
Pine Creek	38PINE0.05	0.05	Pine Creek near mouth		X			
Oak Creek	38OAK0.05	0.05	Oak Creek near mouth	X	X			
Wetland	38OUT17.6	17.6	Outflow to Naches R from Wetland near Hwy 12-410		X			
Kelly Lowry	38KLYW	13.7	Kelly Lowry Diversion		X			
WAPW	38WAPW2	9.7	Wapatox Canal Return 1 and 2	X				
Chapman Nelson	38CHFW	6.1	Chapman Nelson Diversion		X			
Buckskin Slough	38BINW	0.1	Buckskin Slough near Naches River 1	X	X			
Cowiche Creek	38COW00.5	0.5	Cowiche Creek at Powerhouse Road	X	X			

Streamflow Conditions

Five continuous flow gages were available on the mainstem Tieton and Naches Rivers to assess flow conditions:

- Tieton River below Tieton Dam (RIM).
- Tieton River below the Tieton Canal Diversion (TICW).
- Naches River (upper) at Oak Flats in 2015 (Ecology gage 38A140).
- Naches River (lower) below the Wapatox Power Canal (NACW).
- Naches River (lower) near the mouth (NRYW).

Based on Ecology measurements and communication with USBR, gage NRYW may be sufficiently reliable for low flows in 2015, but is likely unreliable at higher flows. Verbal communication from Chris Lynch (USBR) indicates that the rating curve for gage NRYW is no longer fully maintained and therefore reported flows from the gage may be inaccurate at times. Two types of observations support this assessment:

- Two flow measurements in 2015 by Ecology indicated that gage NRYW may be sufficiently reliable for model simulation purposes at low flows. To evaluate NRYW gage reliability, Ecology measured flow twice during 2015 at the gage site. On 8/18/2015 Ecology measured flow (240 cfs) was within 1% of the gage-reported flow (239 cfs). On 10/22/2015 Ecology measured flow (354 cfs) differed by 22% (RPD) from the gage reported flow (276 cfs).
- Comparisons of flow between gages NACW and NRYW indicate that gage NRYW is likely unreliable at high flow. For example, on 9/14/15 gage NACW reported daily average flow of 2335 cfs while gage NRYW reported only 853 cfs. Even with canal diversions, it is unlikely that Naches River flow decreased by such a large amount between these two gages. (Flows at gage NACW reasonably match the combined flows from Ecology's gage at Oak Flats and gage TICW.)

Flows for the Naches River below Wapatox (NACW) in 2004 and 2015

Because gage NRYW may be unreliable except during low-flow conditions, gage NACW was chosen as the best available gage to represent Naches River flow conditions in 2015. With the exception of water diverted to the Wapatox canal, this location represents the combined flow entering the lower Naches River watershed from both the upper Naches River watershed and the Tieton River watershed.

Overall flow conditions in 2015 are shown in Figure 5 as 7-day flow averages at NACW. Also shown in Figure 5 are 7-day flow averages from 2004 and the overall average of 7-day flow averages from 2000-2014. From this figure, it is apparent that flows at NACW were lower than average early in 2015, but returned to normal after the flip-flop began in early September. Early low flows in 2015 were likely due to warm air temperature and low snow pack. Releases of water from Rimrock Reservoir starting in September (flip-flop) increased flow levels for all years. This reflects the fact that this river system is highly managed; therefore, relatively uniform conditions exist during managed releases of water.

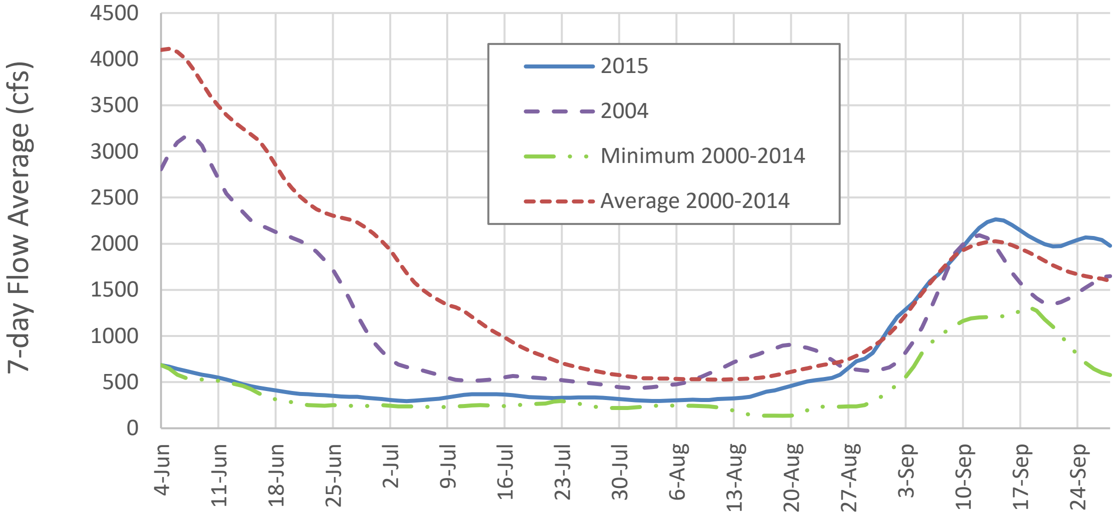

Figure 5. 7-day flow averages for 2004 and 2015 at USBR gage NACW, compared to minimum and average 7-day flows during 2000-2014.

Flow Diversions

Water is diverted from the Tieton and Naches Rivers by a system of canals operated by USBR. Diverted water is primarily used for irrigation. Average withdrawal rates during the June through mid-October portion of the irrigation season are listed in Table 7. Canal flows for 2015 were downloaded from the USBR website, except for the Chapman-Nelson canal which was measured by Ecology. Many of these canals did not have published flows on the USBR website in 2015. But historical flow data during 2001-04 were available for these canals, previously provided by USBR to Ecology during the 2004 TMDL study (Brock, 2008).

Table 7. Average flow rates (Jun 1-Oct 1) reported by USBR for canals in the Tieton and lower Naches River watersheds.

Location	Average Flow (cfs)	
	2015	2001-04
Tieton Diversion	261	---
Wapatox Power Diversion	55	---
South Naches Diversion	55	---
Clark Diversion	---	3
Yakima Valley Canal Diversion	42	44
Yakima City Irrigation Diversion	8.4	20
Fruitvale Power Diversion	---	22
Gleed Diversion	30	33
Chapman-Nelson Diversion	2	---
Naches-Cowiche Diversion	20	19
Old Union Diversion	13	13
Yakima M&I Diversion	18	21

Since 2003, a change in water management operations resulted in increased flows in the Naches River along a 7.4 mile reach beginning at the Wapatox diversion (which includes gage NACW). The change in water management operations occurred when USBR purchased the former Wapatox Power Plant property from PacifiCorp, retired the plant, and transferred the water right into a water trust program (Isley, 2017). This resulted in more water remaining in the Naches River (reported to be approximately 300-450 cfs) instead of being diverted from the river to the Wapatox Power canal. Currently, smaller flows are still diverted to the Wapatox canal to meet contractual obligations for water delivery to individual irrigators (Isley, 2017).

Diversion to the Wapatox Power Canal occurs just upstream of the NACW gage. Below NACW, additional water is diverted to the South-Naches Canal. The change in operations affected measured flows at all three locations. Decreased diversions to the Wapatox Canal increased flow at NACW. As part of this change, flow was increased to the South-Naches Canal downstream of NACW (Isley, 2017).

Figure 6 illustrates the relationship between flows in the Naches River (NACW), the Wapatox Power Canal (WOPW), and South-Naches Canal (SOUW). Since 2003, a change in flow can be seen at all three gages (labelled “pre” vs “post” in Figure 6). The top part of this figure shows that mainstem river flow (NACW) has increased since 2003 due to the reduction in water diverted to WOPW. The bottom part of this figure shows an increase in canal flows measured at gages WOPW and SOUW (plotted as average flow during July-August).

Annual 7-day low flows in the Naches River (NACW) have increased significantly since 2003, due to decreases in diversions to the Wapatox Power Canal (WOPW). Flows in the Wapatox Power Canal continued to decrease over time 2003, likely due to USBR adjustments in canal flows. It is not clear from Figure 6, but a slight increase in canal flow for the South Naches Canal (SOUW) occurred after 2003. There was a median decrease of 296 cfs for the Wapatox Canal and a 7.9 cfs median increase for the South-Naches Canal.

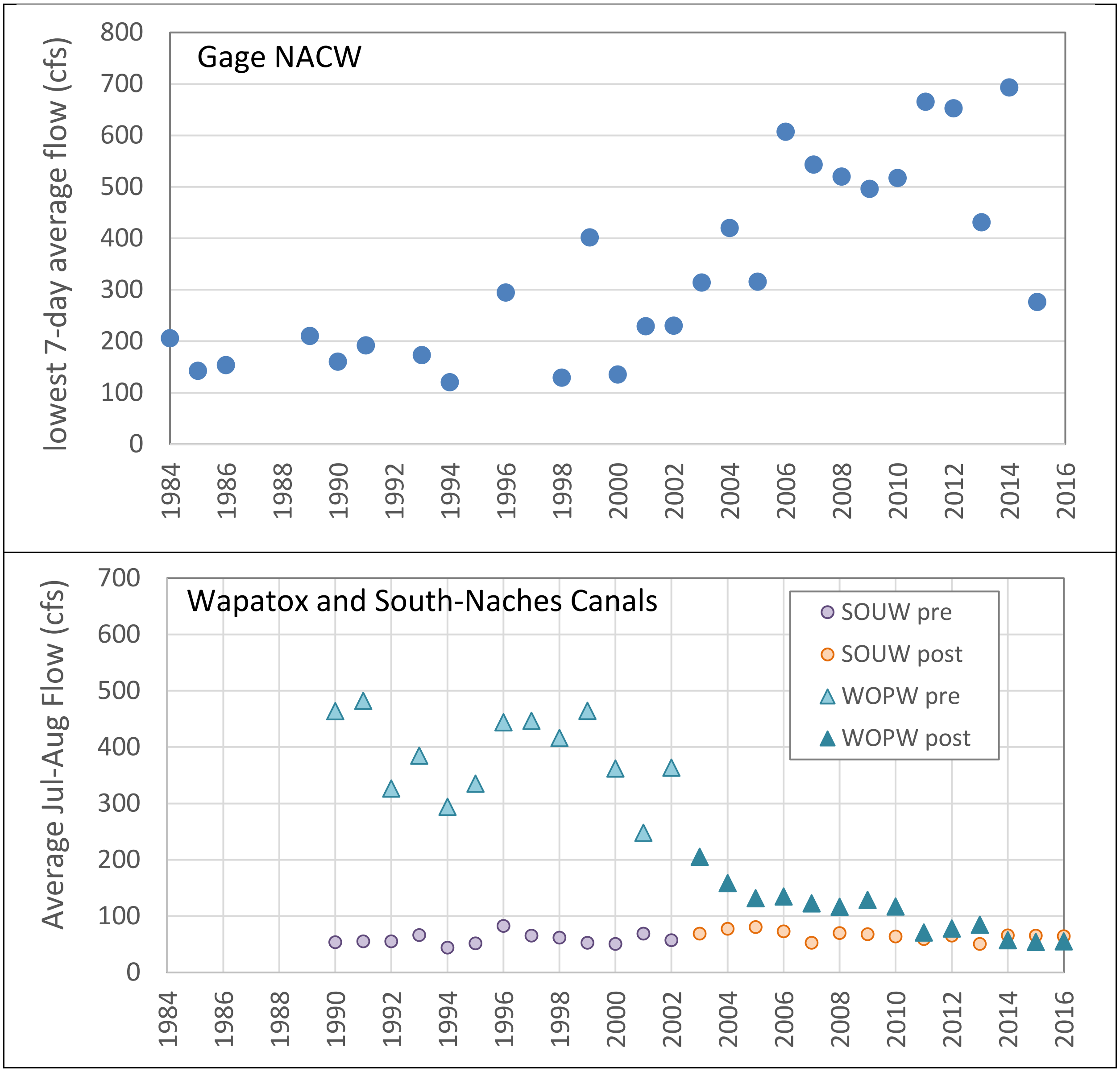

Figure 6. *Top:* Lowest 7-day average flows by year for the USBR gage below Wapatox (Jun-Oct). *Bottom:* Average Jul-Aug flows by year for USBR gages on the Wapatox Power Canal (WOPW) and South-Naches Canal (SOUW).

Flow Statistics

Flow statistics are important for assessing water temperature because reducing the water level in a river can cause it to be more prone to heating. In other words, the highest water temperatures tend to occur during periods of low flow. This is because low flows can produce significantly increased surface-area-to-volume ratios, which accelerate the rate of convective, conductive, and radiant heating (USBR, 2002).

Because the Tieton and lower Naches Rivers are highly regulated flow systems, flow statistics for these rivers can change as a result of changes in operating policies in flow regulation. Flow statistics for these rivers reflect both natural hydrological fluctuations and operating policies at the flow regulating agency (USBR, 2002).

The low-flow statistics at USBR gage NACW (below the Wapatox Canal) have changed since 2003. This is due to less water being diverted into the Wapatox Canal, as described above and shown in Figure 6. More water is now kept in the river at this location (approximately 300-450 cfs on average). Flow statistics at this location must take into account the additional flow in the river that exists today, rather than relying on past conditions.

Due to flow regulation by USBR, low-flow statistics for these rivers differ between the irrigation season and non-irrigation season. The lowest flow on these rivers tends to occur during the non-irrigation season, when the reservoirs are being filled. Irrigation season low-flow statistics tend to be higher than non-irrigation season low-flow statistics, because water is being released from the reservoirs during the irrigation season.

For assessing the highest water temperature conditions, irrigation season low-flow statistics are more relevant than non-irrigation season low-flow statistics. This is because hot weather occurs during irrigation season. Low flows during the non-irrigation season may have other impacts on aquatic life, but will not likely create the highest water temperature conditions since the weather is cool at this time of year.

Change to Previously Published Flow Statistics

Brock (2008) published 7Q10 flow statistics for July-August on the Tieton River and lower Naches Rivers. The 7Q10 statistic is the lowest annual 7-day average flow with a 10-year recurrence interval. These statistics are reproduced in Table 8 for two locations in the current study area. In addition to the 7Q10 statistics, Brock also calculated statistics for typical low flows during July-August, represented by 7Q2 flows. The 7Q2 statistic is the lowest annual 7-day average flow with a 2-year recurrence interval.

Due to changes in operation of the Wapatox Canal discussed above, the previously published low-flow statistics are “outdated” at one of the locations in Table 8 (gage NACW - Naches River near Town of Naches). This is because more water is now kept in the river, and less water is diverted to the canal. The affected statistics are marked with an asterisk (*) on the table. Low-flow statistics presented below are for reference only and were not used as inputs to any modeling scenarios or analysis as part of this study. Table 8 also presents the measured lowest 7-day average flows which occurred during June-August 2004 and 2015 at these two locations.

Table 8. Low-flow statistics during July-August (Brock, 2008).

Location	Gage ID	Period of record	Statistics (Brock, 2008)		Lowest observed 7-day flow average	
			Jul-Aug 7Q10 (cfs)	Jul-Aug 7Q2 (cfs)	Jun-Aug 2004 (cfs)	Jun-Aug 2015 (cfs)
Tieton River below Tieton Canal Diversion (RM 14.2)	TICW	1977-2005	92	174	268 (Jul-13)	131 (Jun-20)
Naches River near Town of Naches (RM 16.8)	NACW	1977-2005	122 *****	191 *****	426 (Aug-1)	294 (Jul-4)

***** Published low-flow statistics at this location are outdated due to changes in Wapatox Canal operations.

Low-flow statistics (7Q10 and 7Q2) at gage NACW were *not* recalculated for present-day conditions for two reasons:

- There is only a relatively short flow record since changes were made at the Wapatox Canal, during which time the amount of water diverted into the canal appears to have been gradually adjusted. This would introduce uncertainty into any statistical calculation due to the short record and changing canal operations.
- Because 2015 conditions included low flow and high temperature, no additional model scenarios based on flow statistics were performed as part of this study to represent critical temperature conditions.

To provide a long-term historical perspective to recent low-flow conditions, the observed 7-day low flows during June-August 2003-2017 are shown in Figure 7.

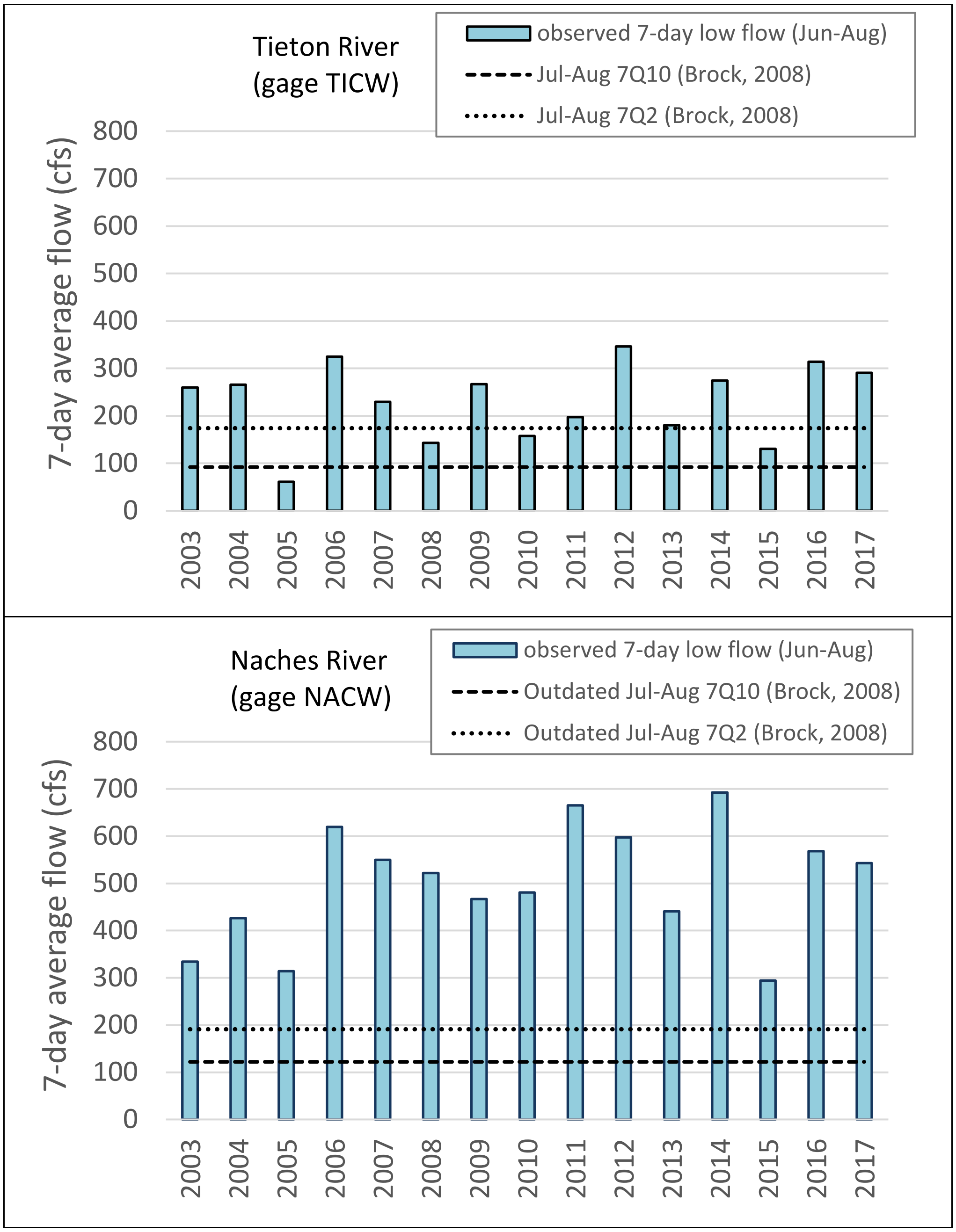

Figure 7. Lowest 7-day flow averages during June-August (2003-2017) at gages TICW (top) and NACW (bottom).

Dashed lines show the low-flow statistics from Brock (2008). Statistics at gage NACW are noted as "outdated" in this figure due to operational changes at Wapatox Canal since 2003.

Streamflows during Non-Irrigation Season

During the non-irrigation season, flow is reduced for the Tieton River while Rimrock Reservoir is being recharged. These lower flows during winter can affect aquatic life due to dewatering (USBR, 2002) but should not affect critical temperature conditions during warm weather periods (late spring through early fall) when water is being released from the reservoirs.

Sometimes Ecology protects specific flow amounts by regulation, called instream flows. There are no instream flows set by Ecology within the Naches basin, according to webpage Instream Flow & Water Management Rule, accessed 10/19/2017.

However, federal streamflow targets exist in the Naches Basin and are under USBR jurisdiction for implementation. There are two locations within the Naches basin which have federal streamflow targets for the non-irrigation season (USBR, 2002):

- Rimrock Reservoir outflow at USBR gage RIM (Oct 21-Mar 31): 15-50 cfs. Supports general aquatic needs.
- Naches River near Naches at USBR gage NACW (Oct 21-Mar 31): 100-125 cfs. Supports fish passage and general aquatic needs.

The operating flows to meet these targets are negotiated on an annual basis between USBR and an advisory board called the System Operations Advisory Committee (SOAC) (USBR, 2002). This board consists of fishery biologists representing the U.S. Fish and Wildlife Service, the Yakama Nation, the Washington Department of Fish and Wildlife, and irrigation entities represented by the Yakima Basin Joint Board (USBR, 2002).

According to flow data downloaded from the USBR website, the lowest 7-day flow average during non-irrigation season during the years 2003-2016 for these two gages were:

- Rimrock Reservoir outflow (gage RIM) = 30.4 cfs in 2006
- Naches River near Naches (gage NACW) = 276 cfs in 2015

Historical non-irrigation season low-flow statistics for these gages during the period 1910-1979 are also available in Williams and Pearson (1985).

Water Temperature Conditions

Water Temperature Monitoring Results

In 2015, Ecology monitored water temperature at eight locations on the Tieton River, six locations on the Naches River, and one location on each of three tributaries: Wildcat Creek, Oak Creek, and Buckskin Slough. Monitoring in 2004 occurred at four locations on the Tieton River and four locations on the Naches River. Monitoring results from 2004 were previously reported in Brock (2008), and therefore this report focuses on 2015.

The annual highest 7-DADMax temperatures recorded at these locations are shown in Table 9, along with the dates of observation.

Due to data gaps or installation dates, some of the data loggers did not record water temperatures during the hottest part of the year. In these cases, the highest 7-DADMax values are marked with an asterisk (*) in Table 9, since the recorded temperatures do not represent the highest annual value at that location. Water temperature criteria (excluding supplemental criteria) are also shown in this table. Brock (2008) reported the highest *recorded* 7-DADMax temperatures at all locations in 2004, without noting which data loggers did or did not operate during the hottest part of the year.

All locations, except one, in Table 9 did not meet (exceeded) water temperature criteria during 2004 and 2015. The one exception was the site below Tieton Dam, which was just under the temperature criterion of 16°C in 2015. Without exception, the highest annual 7-DADMax water temperatures at each station in this table increase in a downstream direction for the Tieton and Naches Rivers. Generally speaking, cold water is released from the dam and heats as it travels downstream from the dam.

Table 9. Analysis of 7-DADMax water temperature data from studies in 2004 and 2015.

	Highest annual 7-DADMax (°C)		Criterion (°C)	Date of observation		River Mile	Waterbody
Site	2015	2004		2015	2004		
blw Tieton Dam	16.0	---	16	14-Sep	---	20.8	Tieton R
Willows	16.2	---	16	13-Sep	---	16.2	Tieton R
blw Tieton Canal	16.4	---	16	13-Sep	---	14.4	Tieton R
Windy Point	19.3	*	16	2-Jul	---	9.0	Tieton R
Milemarker 180	*	19.4	16	---	23-Jul	6.1	Tieton R
abv Oak Creek	22.2	*	16	2-Jul	---	2.3	Tieton R
Tom's Pond	22.5	---	16	3-Jul	---	1.5	Tieton R
Tieton Mouth	22.7	20.7	16	3-Jul	23-Jul	0.4	Tieton R
blw Wapatox	24.4	---	17.5	3-Jul	---	16.6	Naches R
Naches Rd	24.7	*	17.5	3-Jul	---	12.8	Naches R
abv Public Fishing	24.9	---	17.5	2-Jul	---	10.5	Naches R
Drinking water plant	25.0	*	17.5	1-Jul	---	9.0	Naches R
Powerhouse Rd	26.5	23.7	17.5	1-Jul	31-Jul	3.84	Naches R
Naches Mouth	28.2	23.9	17.5	2-Jul	30-Jul	0.5	Naches R
Wildcat Creek	20.2	---	16	1-Jul	---	0.05	Wildcat Creek
Oak Creek	27.7	---	16	4-Jul	---	0.05	Oak Creek
Buckskin Slough	21.2	---	17.5	7-Jul	---	0.1	Buckskin Slough

* Indicates data logger did not operate during hottest part of the year.

For *air* temperature, the highest 7-DADMax at various weather stations in the area occurred during June 29 - July 1. The highest 7-DADMax air temperature was 100.1°F at the Naches weather station (WSU) and 103.8°F at the Yakima airport (NWS).

For those locations that had a suitable record when supplemental water temperature criteria apply, the highest 7-DADMax temperatures during June 1 to June 15 are shown in Table 10. None of the observed highest 7-DADMax temperatures in either 2015 or 2004 met (did not exceed) criteria.

Table 10. Water temperature data analysis during supplemental criteria time period.

	Highest (Jun 1-15) 7-DADMax		Suppl. Criterion	Date of Observation		River Mile	Waterbody
Site	2015	2004		2015	2004		
blw Wapatox	21.1	---	13	8-Jun	---	16.6	Naches R
Naches Rd	21.6	14.9	13	8-Jun	15-Jun	12.8	Naches R
abv Public Fishing	*	*	13	---	---	10.5	Naches R
Drinking water plant	21.7	*	13	8-Jun	---	9.0	Naches R
Powerhouse Rd	22.0	*	13	9-Jun	---	3.84	Naches R
Oak Creek	23.6	---	13	9-Jun	---	0.05	Oak Creek
Buckskin Slough	18.7	---	13	14-Jun	---	0.1	Buckskin Slough

* Data logger did not operate during the supplemental period.

Tables 9 and 10 show that water temperatures during 2015 were warmer than during 2004. The 2015 highest 7-DADMax, at the mouth of the Naches River, was more than 4°C warmer than the 2004 value. Similarly, the 2015 highest 7-DADMax at the mouth of the Tieton River was 2°C warmer than the 2004 value.

Plots of the 7-DADMax water temperature along the Tieton and Naches Rivers is shown for 2015 in Figure 8 and 2004 in Figure 9. Water temperature criteria are also shown on these plots. The plots for 2004 also show the 2015 temperature at the mouth of each river, for reference. Gaps in the 2015 data beginning in late August are due to intentional removal of data loggers prior to the start of flip-flop in order to prevent lost data loggers. Gaps in the 2004 data are also visible. Additional plots of the 2004 data are available in Brock (2008).

The overall pattern of water temperature increasing in a downstream direction is visible on both plots. At the mouth of the Tieton River the 7-DADMax water temperature remained above (not meeting) the criterion from June 1 until almost the beginning of October. At the mouth of the Naches River, the 7-DADMax water temperature remained above the criterion from the time the logger began operating in mid-June until almost the end of September. At Powerhouse Road, 7-DADMax water temperature remained above the supplemental criteria from the time the logger began operating until the June 15 cutoff date.

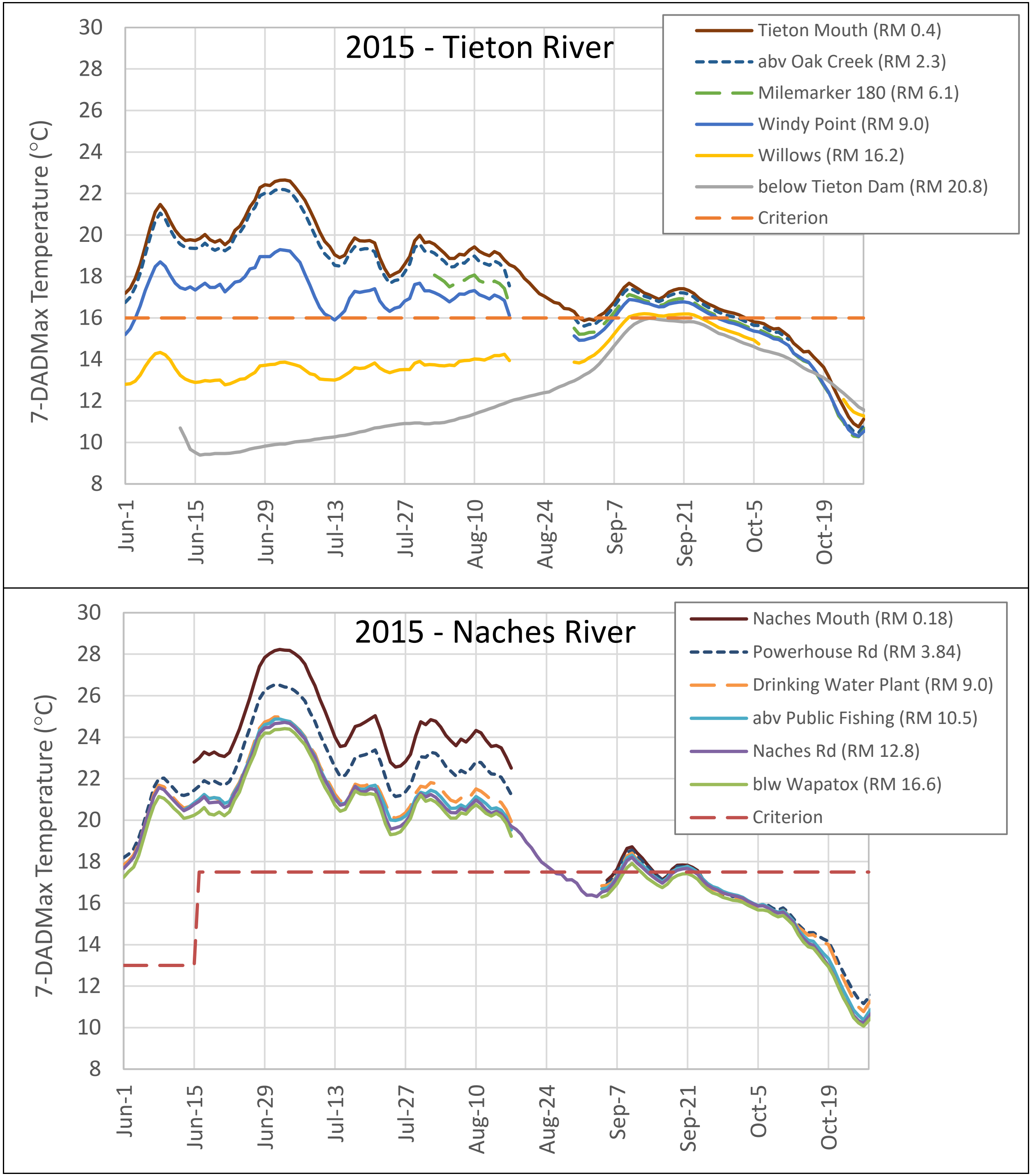

Figure 8. 7-DADMax water temperature in 2015 along the Tieton River *(top plot)* and Naches River *(bottom plot)*.

Water temperature criterion are included on the above plots.

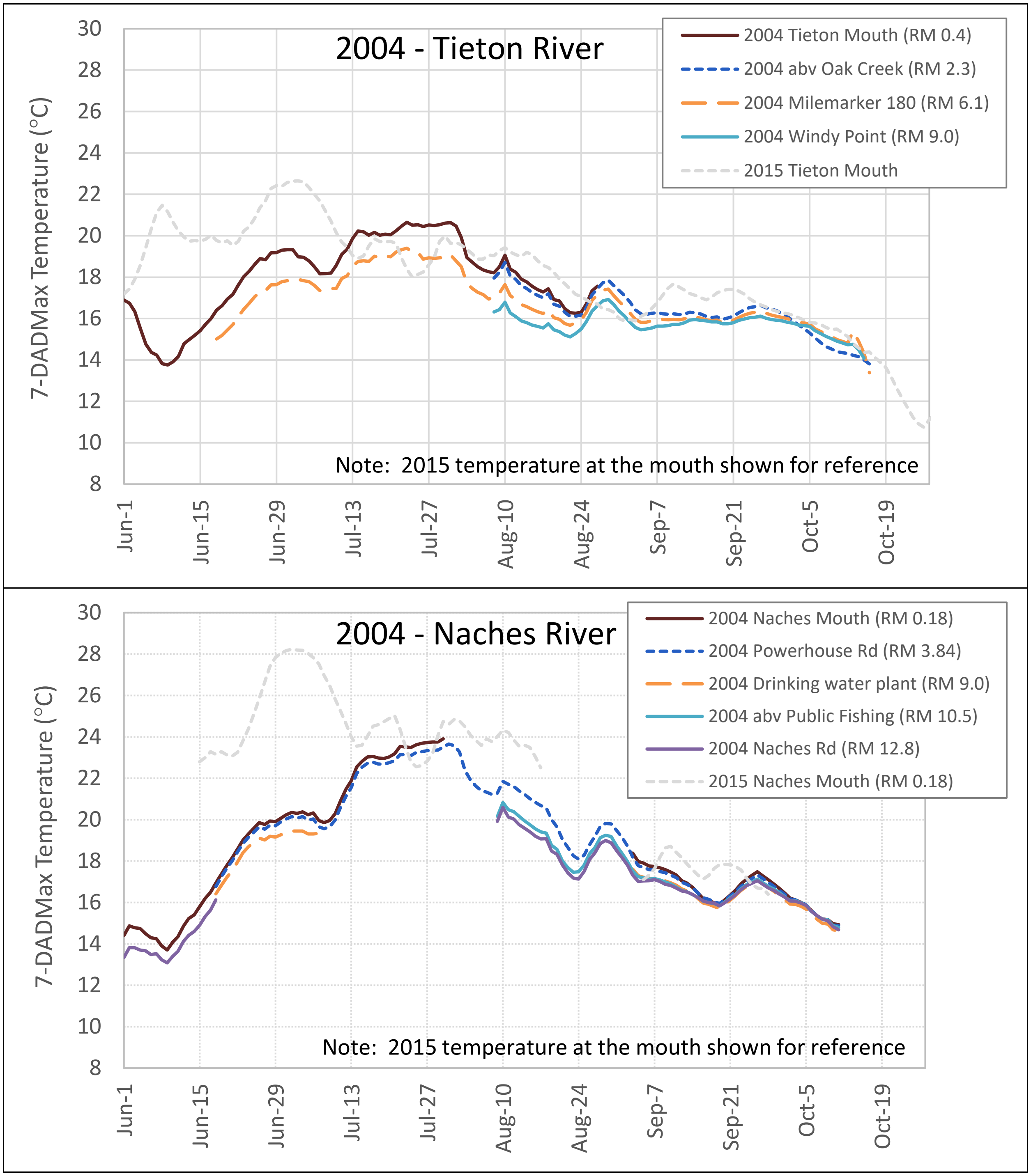

Figure 9. 7-DADMax water temperature in 2004 along the Tieton River *(top plot)* and Naches River *(bottom plot)*.

For reference, the above plots also include the 2015 water temperature (7-DADMax) at the mouth of each river.

Historical Water Temperature Monitoring at Gage NACW

To allow a historical perspective of water temperature in 2015, Ecology calculated the highest 7-DADMax water temperatures (2000-2015) at this gage location using data downloaded from the USBR website. Water temperature results on the USBR website extend back to 1984, but as described above, changes in water management operations affected flow since 2003, which likely had a strong influence on water temperature as well. Therefore, this analysis extended back just before the change in water management.

To verify whether water temperature results from this gage were reliable, Ecology installed a water temperature data logger at the gage site in 2015 to allow comparison of results. The NACW gage from June 1 to October 1 showed a good overall fit to Ecology's data logger (Bias +0.4°C and RMSE 0.38°C). To be clear, temperatures in 2015 at the NACW tended to be 0.4°C higher than the Ecology results as an overall average. The bias was relatively consistent through this time period. The largest observed hourly temperature difference at NACW was +0.54°C warmer than the Ecology data logger.

The highest 7-DADMax temperature in 2015 at NACW is also reasonably close to the value recorded by Ecology's data logger. The highest 7-DADMax for 2015 at NACW was 24.90°C, while the Ecology data logger recorded 24.41°C (both on 7/3/2015). This is a bias of +0.49°C, consistent with the hourly average bias.

No direct comparison between NACW and an Ecology data logger is available in 2004, but comparison with a data logger 6.4 km downstream (S. Naches Rd) provides an indication that 2004 7-DADMax temperatures at NACW were in reasonable agreement with Ecology's results. This is based on relative increases in temperature between these two locations which appear consistent between 2004 and 2015. An increase of +0.31°C in the 7-DADMax was seen between two Ecology data loggers at these locations on 7/3/2015, which is nearly identical to the increase of +0.28°C between gage NACW and the Ecology data logger at Naches Rd on 8/10/2004. The warmest date recorded by this data logger was 8/10/2004, which had a 7-DADMax of 20.59°C; the 7-DADMax at NACW on this date was 20.31°C.

The highest 7-DADMaxs observed at NACW during both the supplemental period (Feb 15 – Jun 15) and annually for years 2000-2015 are listed in Table 11. The highest 7-DADMax water temperature at this gage in 2015 was biased +0.49°C compared to the Ecology data logger. It is unknown whether previous years experienced a similar bias.

Table 11 indicates that water temperatures were high in 2015 compared to past years. The highest annual 7-DADMax temperature in 2015 was 24.9°C, which exceeds the next highest value (in year 2000) by more than 2°C. The highest supplemental period 7-DADMax temperature in 2015 was 21.4°C, which exceeds the next highest value (in year 2005) by nearly 5°C.

Temperatures in Table 11 often exceed (do not meet) present-day water quality criteria by more than the +0.4°C of bias observed at this gage in 2015. This indicates that even if the gage has a persistent bias, present-day annual water quality standards (7-DADMax of 17.5°C) would likely have been exceeded for all years in this table at this location on the Naches River. Present-day supplemental water quality standards (7-DADMax of 13°C) would likely have been exceeded for about half of the years in this table at this location on the Naches River.

The timing of the highest 7-DADMax is also of interest in Table 11. The highest annual 7-DADMax temperature occurred earlier for 2015 compared to previous years (early July 2015 compared with late July to mid-August for most other years). For the supplemental criteria period (Feb 15 to Jun 15), the highest 7-DADMax for all years occurred during June.

Table 11. Highest 7-DADMax temperatures observed at gage NACW for years 2000-2015.

	Supplemental (Feb 15 – Jun 15)			Annual		
Year	Highest 7-DADMax (°C)	Date	Present-day Criterion	Highest 7-DADMax (°C)	Date	Present-day Criterion
2000	12.9	Jun-15	13	**22.5**	Jul-31	17.5
2001	**15.4**	Jun-15	13	**22.1**	Aug-13	17.5
2002	12.8	Jun-15	13	**20.5**	Aug-12	17.5
2003	**14.5**	Jun-15	13	**21.9**	Jul-29	17.5
2004	**14.4**	Jun-15	13	**21.8**	Jul-31	17.5
2005	**16.6**	Jun-14	13	**21.8**	Jul-28	17.5
2006	12.6	Jun-8	13	**21.9**	Jul-24	17.5
2007	**14.1**	Jun-15	13	**21.1**	Jul-12	17.5
2008	12.9	Jun-15	13	**21.1**	Aug-14	17.5
2009	**13.5**	Jun-15	13	**22.1**	Jul-30	17.5
2010	11.9	Jun-15	13	**20.9**	Aug-15	17.5
2011	11.6	Jun-14	13	**20.2**	Aug-26	17.5
2012	12.9	Jun-14	13	**20.7**	Aug-16	17.5
2013	**14.5**	Jun-15	13	**22.4**	Jul-24	17.5
2014	**14.0**	Jun-15	13	**21.7**	Jul-31	17.5
2015	**21.4**	Jun-8	13	**24.9**	Jul-3	17.5

Model Simulation Analyses for Water Temperature

Monitoring data collected and downloaded for the 2015 study were used to simulate water temperature along the Tieton and lower Naches Rivers, beginning just below Tieton Dam and ending at the mouth of the Naches River. Temperature was continuously simulated from June 1 to October 31 using QUAL2Kw software (Pelletier et al., 2006; Pelletier and Chapra, 2008). See the Model Construction Software section above for details on all software used.

The river centerline was digitized in GIS (ArcMap version 10.2.2) using 2015 NAIP aerial photography (Figure 10). The centerline was segmented into 1000-meter reaches using Ttools software extension for ArcMap. Total model length was 65.5 km, composed of 65 reaches of 1-km length plus a final reach of length 0.5 km at the mouth of the Naches River. Slopes were specified within each reach based on sampling a 10-m resolution digital elevation model (DEM) using Ttools software. Overall, reaches near Tieton Dam had slopes of approximately 1% which gradually decrease downstream to around 0.5% near the City of Yakima.

Water temperatures and flows were specified at the model headwater just below Tieton Dam based on data logger temperatures and flow gage RIM. Additional sources and abstractions (diversions) were specified along the length of the model using available flow and water temperature monitoring data.

An important tributary source for this model is the upper Naches River which enters into the model at the confluence of the Tieton River and the lower Naches River. Flows for this source were obtained using two different techniques.

- Flows were monitored using an Ecology gage near Oak Flats, which began recording flow data on 8/11/2015.
- Prior to the start of gage operation, flows were estimated using the USBR flow gage on the Naches River at Cliffdell minus the USBR flow gage on the South Naches Canal, plus an estimate of other combined sources such as Rattlesnake Creek and stream gains/losses to alluvium. Using this technique matched Ecology’s flow gage data at Oak Flats with 11% average absolute RPD, which is an acceptable fit to measured flows. Early season flow estimates for the upper Naches River allowed successful calibration of the model prior to operation of the Ecology gage.

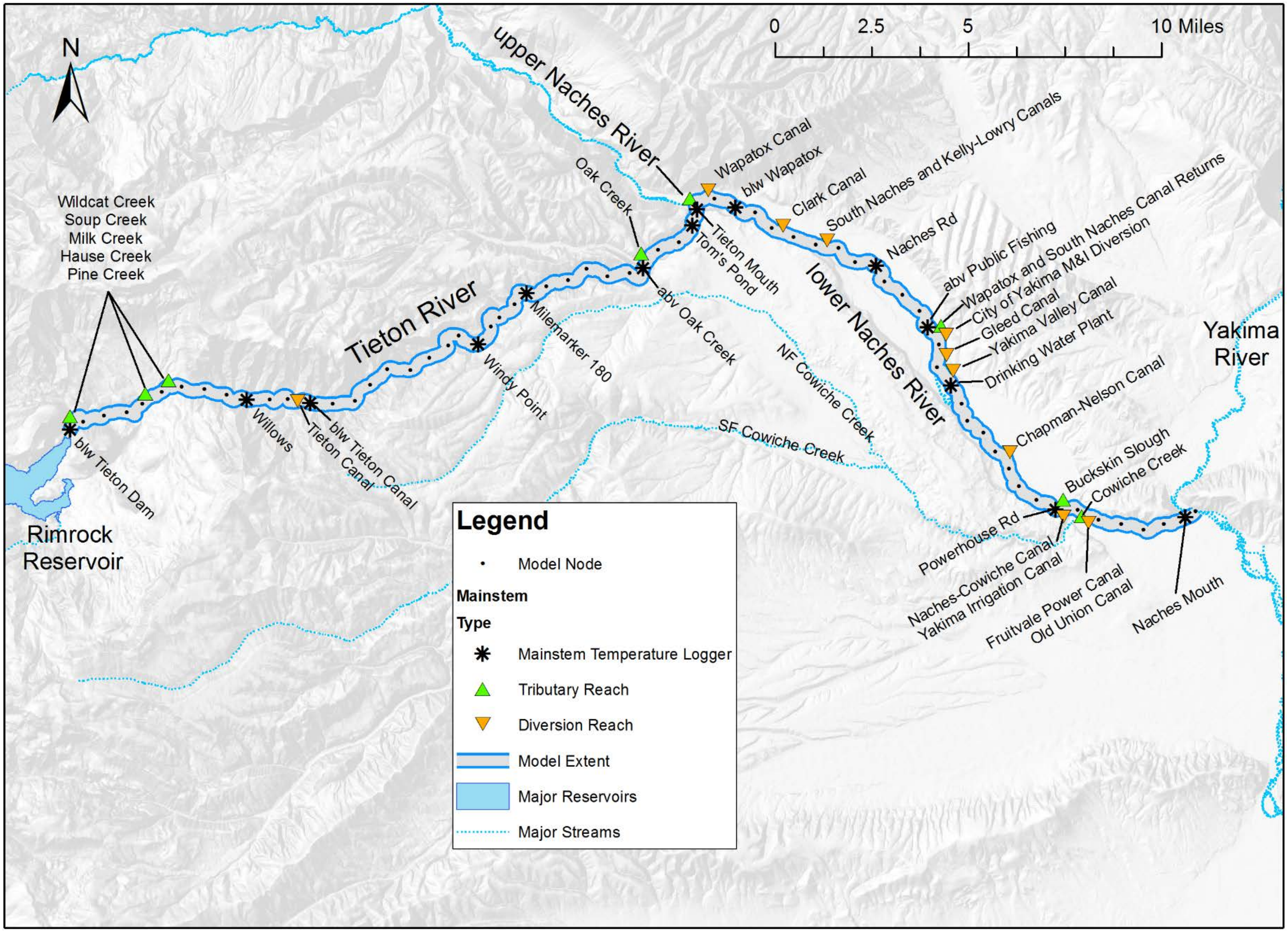

Figure 10. Model schematic.

Channel Hydrogeometry Results

Velocity

As discussed in the Methods section above, water velocity measurements were made using dye tracer studies on September 11-12 and October 19-20, 2015 (Table 12). Flows were high during September due to the flip-flop and were lower in October. Average water velocities were measured along four segments of the rivers starting below the Tieton Canal Diversion and ending at 16th Ave (close to the mouth of the Naches). For the portion of the model lying upstream of the dye study, velocity rating coefficients reported in Brock (2008) were used (coef=0.28, exp=0.49).

Table 12. Results of the time of travel study conducted in 2015.

		September				October				Velocity Rating	
Segment	Segment Length (km)	Flow (cfs)	Time (hr)	Total Time (hr)	Vel (m/s)	Flow (cfs)	Time (hr)	Total Time (hr)	Vel (m/s)	coef	exp
Tieton - MP180	13.54	1791	2.08	2.08	1.81	143	6.18	6.18	0.61	0.333	0.430
MP180-Wapatox	10.93	1791	1.50	3.58	2.02	143	4.95	11.13	0.61	0.317	0.472
Wapatox-WTP	14.33	2222	2.85	6.43	1.40	308	5.73	16.86	0.69	0.323	0.353
WTP-16th Ave	13.82	2255	3.00	9.43	1.28	298	6.72	23.58	0.57	0.245	0.398

Total travel times in this table differ from model travel times because the dye study did not start at model headwater.

Width and Depth

As discussed in the Methods section above, river widths were measured using aerial photographs from July, August, and September 2015 (Figure 11, upper). Widths were measured at 50 m intervals and then averaged over each model reach. Average depths were calculated based on average widths (Figure 11, lower). Average depths also depend on the volume of water within a reach.

Figure 11 shows that the Naches River (0-30.4 km) tends to be wider and slightly shallower than the Tieton River (30.4-65.5 km). High flows in September due to flip-flop resulted in wider and deeper rivers than the other two months.

Widths in the Naches River are more variable than the Tieton River in part due to river splitting or braiding. Braids in the river are not directly modeled in QUAL2Kw, so effort was made during aerial photo interpretation to assign a single channel width to the river which approximately matched the combined width of all river braids. This was done along approximately 20% of the length of the Naches River and 7% of the Tieton River.

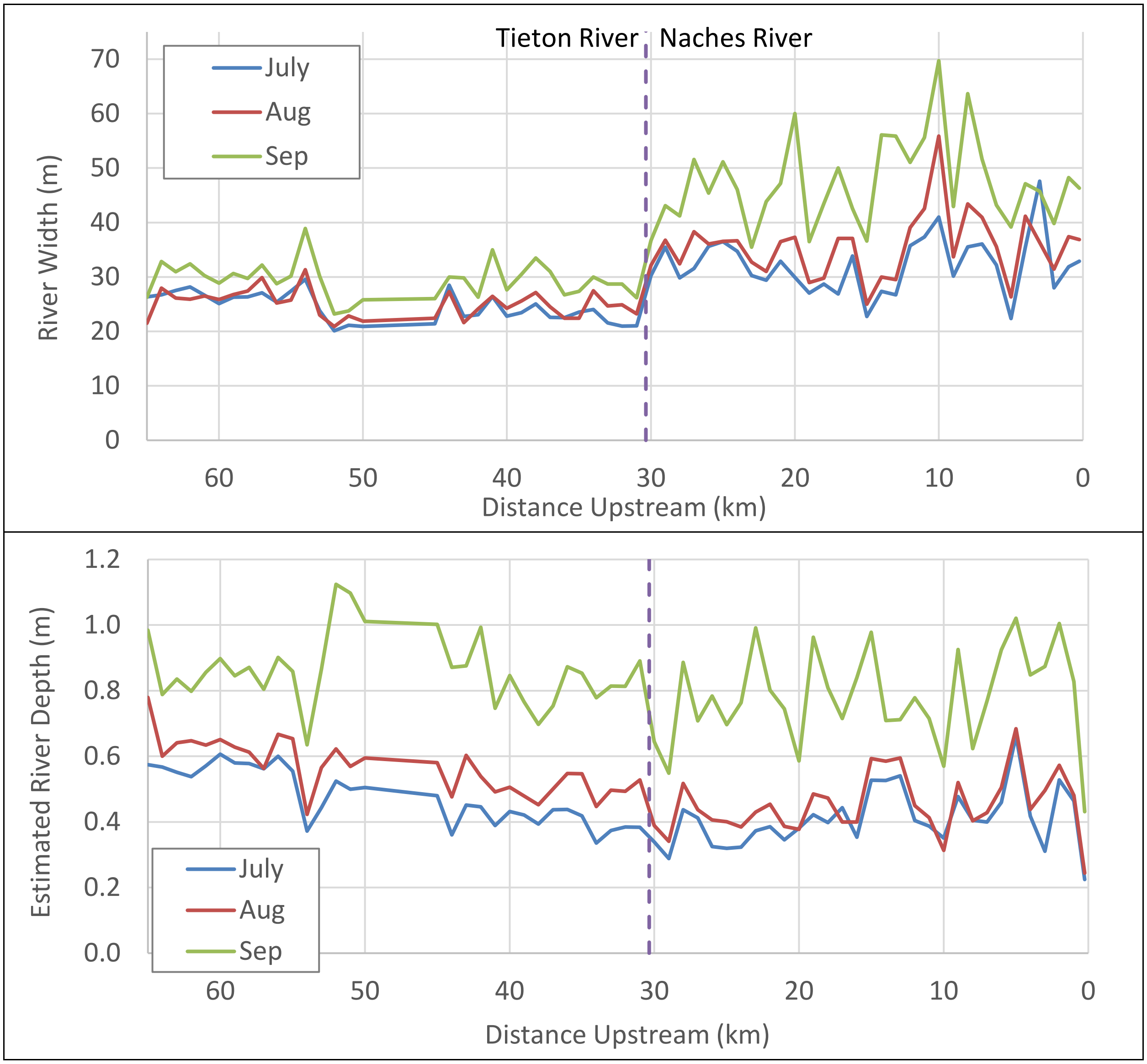

Figure 11. Measured river widths from aerial photography (upper plot) and calculated river depths (lower plot).

Vegetation and Shade Results

As discussed in the Methods section above, the vegetation analysis from the 2004 study was used to calculate effective shade for the QUAL2Kw model. Shade modeling used in this report represents present day conditions and does *not* represent system potential mature riparian vegetation shade.

Overall averages of vegetation type and shade characteristics used in the Shade model are presented in Table 13. Vegetation types were originally assigned to zones 0:50, 50:100, and 100:150 feet on either side of the Tieton and Naches Rivers. For use in the Shade model, these zones were converted to 9 zones at 6-meter spacing, for a vegetation width of 54 meters along each side of the river.

The vegetation analysis presented below represents 2004 conditions. It was prepared based on the vegetation analysis described in Brock (2008). The 2004 analysis is considered preliminary and can be updated if future vegetation analysis is performed along the Tieton and lower Naches Rivers. No analysis was performed regarding the potential improvement of shade along either river.

Table 13. Types of vegetation used in the Shade model and average characteristics.

Vegetation Type	Total fraction	Average height (m)	Average density (%)	Average overhang (m)	Examples
Conifers	11%	25.6	49%	2.3	Ponderosa Pine, Grand Fir, Western Hemlock
Deciduous	38%	17.1	47%	1.8	Cottonwood, Willow, Alder, Aspen
Mixed	19%	20.8	51%	2.0	Mix of conifer and deciduous
Scrub/shrub	9%	2.0	46%	0.2	Red-osier dogwood, Sedge, Prickly Currant, Wood's Rose
Barren	21%	0.0	0%	0.0	Dry fields, Roadway
Other	2%	2.0	100%	0.1	Reed Canary grass, Sedge, other grasses

Due to minor changes in river course between 2004 and 2015, upstream distances were adjusted as necessary to match the model node spacing for 2015. Effective shade was calculated using 100-meter spacing and then averaged by model reach (1000 m) for use in QUAL2Kw. Wetted river widths in the model were interpreted from July 2015 NAIP aerial photos in ArcMap.

One important factor in the Shade model is the near-stream disturbance zone widths (NSDZ). For this model, NSDZ widths exceeded wetted width by an average 2.4 meters (Tieton River) and 7.8 meters (Naches River). The Shade model appears sensitive to NSDZ widths. If future analysis of vegetation and shade is performed on these rivers, field measurements or additional GIS analysis of NSDZ widths might help refine the Shade model.

The Shade model does *not* assess potential beneficial impacts of riparian vegetation to the river such as river bank stabilization.

As a preliminary check on the Shade model, effective shade was calculated for 7/27/2004 and compared against hemispherical photographs taken on 7/23/2004 and 7/31/2004 (Figure 12, upper). Predicted shade values are shown at 100-m intervals (small points) and 1000-m reach averaged values (line). Hemispherical photo measurements agree well overall, with the exception of one measurement at approximately 15 km upstream (near the City of Yakima Drinking water treatment plant). The high value of effective shade here appears to be due to a single large tree overhanging the southeast portion of the photograph location, and probably did not represent average conditions of the reach.

Hourly values of effective shade were then calculated for 2015, June 1 to October 31. These values were used as inputs to the water temperature model in QUAL2Kw.

Although the Tieton River tends to have slightly more shade than the Naches River, both rivers have low shade (<20%) during the hottest part of the year. This is in part due to river width (over 20 meters). As discussed in the preceding section, for braided portions river width is slightly overestimated due to combining river braids into a single channel. This may result in slightly underestimating the actual shade to the braided channels from riparian vegetation.

The width of both rivers helps explain why shade is low (Figure 12, lower). These curves indicate that shade decreases as the river widens, and that shade will likely be limited for a wide river, regardless of the type of vegetation along the river bank. These idealized shade curves were calculated using the Shade model with average vegetation height and density for each river separately, combined with the average topographic shading for these rivers. Values used in the Shade model: vegetation height=13.9/12.1 m; density=0.5; aspect=110°; topo=14.8°/6.6°.

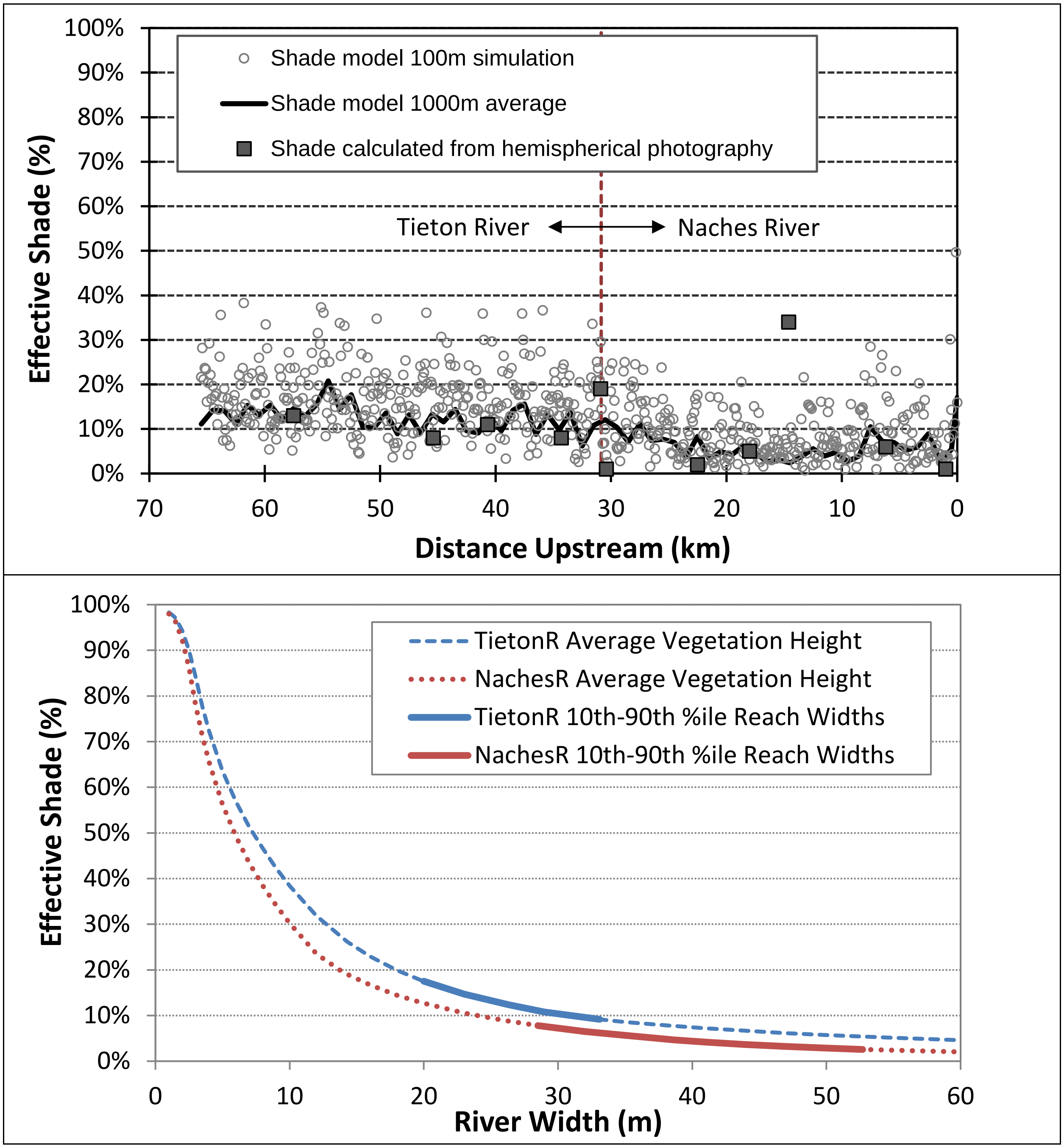

Figure 12. *Top:* Shade model simulation compared to measured shade using hemispherical photography; *Bottom:* Relation between effective shade and river width for idealized shade based on average height/density vegetation along the Tieton and Naches Rivers.

Model Calibration

Mass Balance (Flow) Calibration

To check mass balance in the QUAL2Kw model, simulated flows were compared against three USBR gages (Figure 13):

- One in the mainstem Tieton River, below Tieton Canal (TICW).
- Two in the mainstem lower Naches River, below Wapatox (NACW) and near Yakima (NRYW).

Some flow data from two gages were excluded from the comparison against the model (identified as qualified in Figure 13).

- Flows over 350 cfs at the gage near Yakima were qualified as unusable for model comparison. This was based on communication by USBR that the rating curves are not well maintained for this gage. This value was chosen because Ecology measured a flow near 350 cfs at this gage, as discussed above. The lower flows are most important for simulating temperature under low-flow conditions in the river.
- Flows over 1500 cfs at the gage below the Wapatox Canal diversion were also qualified, which occurred during flip-flop. This was done because at these high flows there was a discrepancy between this gage and the sum of flows from the upper Naches River (Ecology gage 38A140) plus the Tieton River below the Tieton Canal (TICW). Because this condition occurs during flip-flop, it does not affect temperature simulations during low-flow conditions.

After qualifying these data, the flow balance in the model was adequate for the upper two gages: below Tieton Canal and below Wapatox Canal. Simulated flows are biased slightly low part of the season for the gage near Yakima, which could be due to either gage error or possibly overestimating canal withdrawals in the model. To keep flow estimates conservative, Ecology decided to not reduce the canal withdrawals in the model based on this gage due to the known issues at this gage.

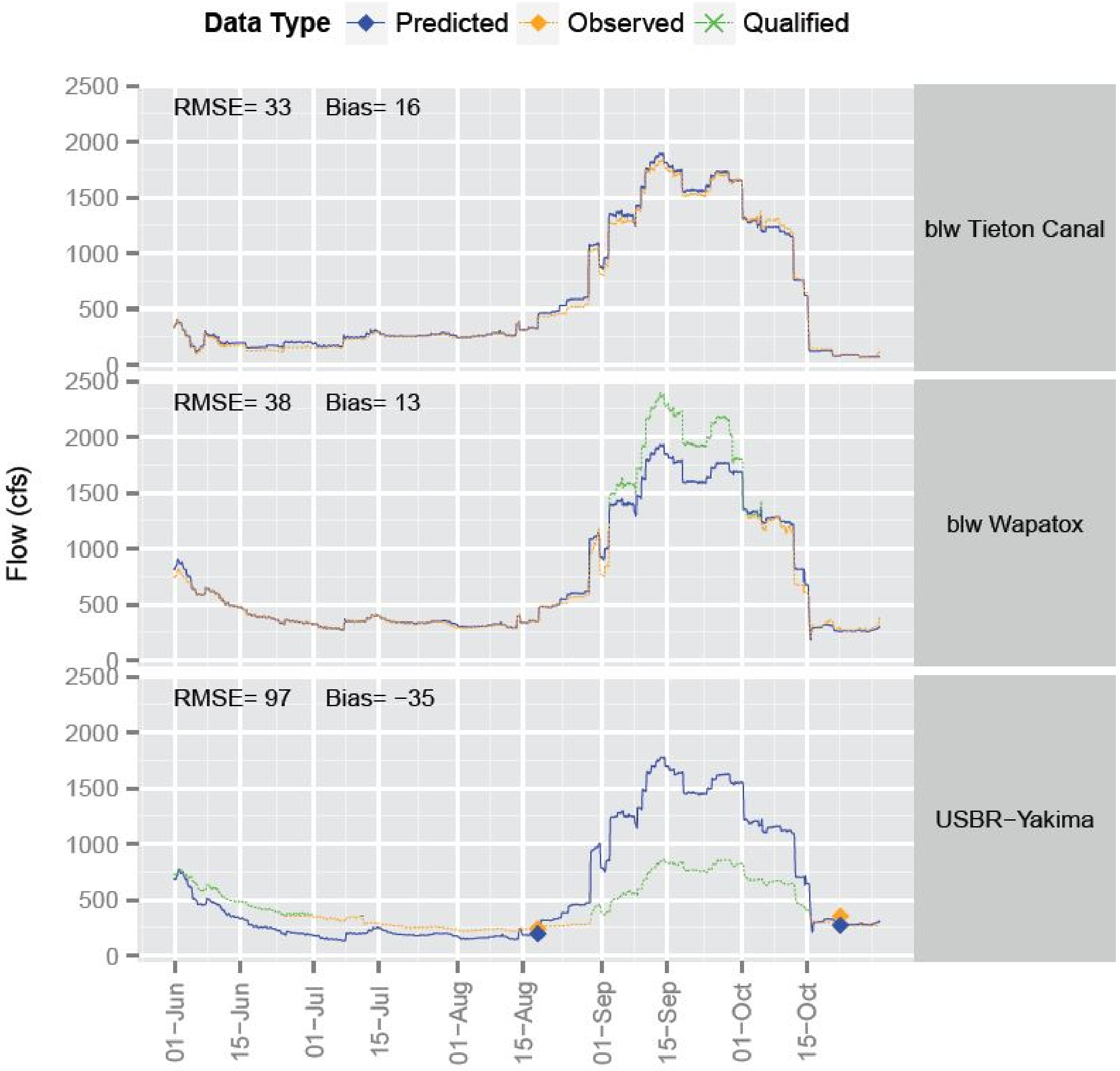

Figure 13. Comparison of simulated mainstem flows against three USBR gages.

Travel Time Check

Simulated water travel times (Figure 14) from Tieton Dam to the mouth of the Yakima River were shorter (11.5 hr) during high flows (Sept 12). Travel times were longer (30.5 hr) during low flows (Oct 19). Because empirical velocity coefficients were calculated directly from the dye study results, no calibration was necessary for travel time. Instead, a check was made to ensure that simulated travel times agreed with dye-study results, as shown on the figure.

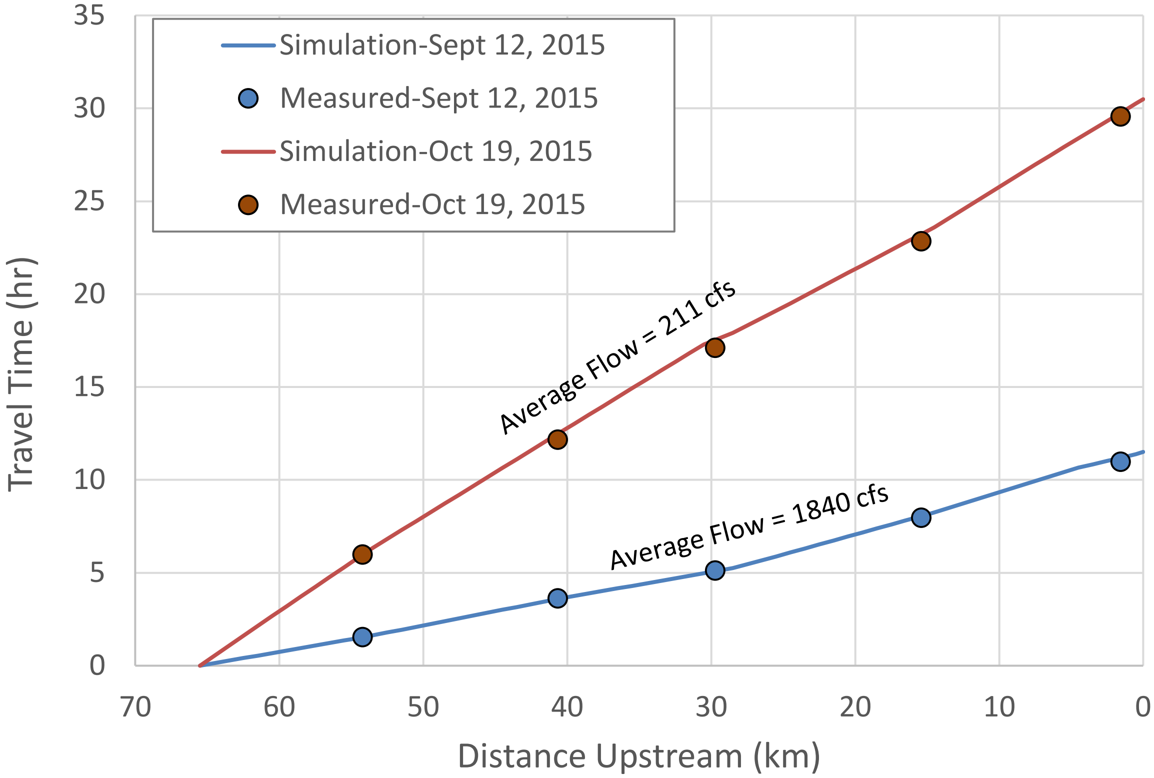

Figure 14. Model simulated versus measured travel times for two different dates.

Preliminary Temperature Calibration

QUAL2Kw model calibration for water temperature was performed by manually adjusting parameters to obtain a best fit between simulated water temperatures versus observations. As noted by Chapra (1997), there are two general approaches to assessment of the quality of a calibration: subjective and objective. The subjective approach compares plots of simulation results against measured data. The objective approach focuses on quantitative measurements of fit (e.g., bias and RMSE). While both approaches were used for this study, emphasis was placed on minimizing bias and RMSE for 7-DADMax water temperature during the hottest portion of the year (June 15 to August 15).

Prior to calibration, an adjustment was made to the shortwave solar radiation used in the model. The model was initially set to use observed solar radiation downloaded from weather station Naches (WSU). However, Ecology noted that solar radiation data downloaded from this weather station appears biased low in June when compared against solar radiation models which fit the remainder of the model simulation season. The issue was resolved by allowing the QUAL2Kw model to calculate solar radiation using the Ryan-Stolzenbach solar radiation model with an atmospheric attenuation coefficient of 0.8. The Naches weather station solar radiation data were used for calculating cloud cover to attenuate solar radiation on cloudy days, as described in the Methods section above. This improved model fit during June.

A preliminary calibration of the QUAL2Kw model was performed without any groundwater inflow to the model. The calibration was performed by multiplying depth rating curves by a dimensionless factor, with a multiplier of 1 representing the original starting value. Multipliers greater than 1.0 represented deeper water relative to starting values and multipliers less than 1.0 represented shallower water. While a satisfactory calibration was achieved using this method, it required depth multipliers in the lower Naches River of up to 1.6 times the original depth value (≤ 60% increase in water depth). The large increase in depth needed to calibrate this model indicated a possible need for a groundwater component in the model for the Naches River. On the other hand, groundwater appears less important for the Tieton River, since calibration multipliers for water depth were 1.2 or less (≤ 20% increase in depth).

Groundwater

Groundwater inputs to the model can be interpreted to represent a combination of hyporheic flow and groundwater. Hyporheic flow represents the interface between surface water and groundwater flow that occurs in the upper, shallow part of the subsurface (the upper river bed). Hyporheic flow was not simulated separately because no measurements of hyporheic flow were found for these rivers and also because uncertainty exists regarding the total amount and distribution of groundwater inflow. Therefore, Ecology chose to keep the model as simple as possible during calibration.

No groundwater inflow for the Tieton River was included in the model. Ecology's seepage investigation in July 2004 found a gaining reach between RM 1.5 to RM 0.4, but notes that triplicate flow measurements at RM 1.5 indicated that measurement variability exceeded the gain/loss value at this site and perhaps at other sites along the Tieton River (Carey, 2007). The lack of groundwater inflow seems geologically plausible for much of the Tieton River, which overlies a thin layer of alluvium within a deep, narrow valley of volcanic rock (Kinnison and Sceva, 1963). Calibration of the Tieton River portion of the model was successful without specifically accounting for groundwater inflow.

Total groundwater inflow of 35 cfs was added to the model for the lower Naches River based on the net gain reported for the entire lower Naches River from the July 2004 seepage study (Carey, 2007). This net gain represents the sum of two losing reaches and one gaining reach in the Carey report. No stream losses were included in the model for the lower Naches River. There is uncertainty regarding groundwater inflow and loss rates for the Naches River. See Appendix E for further information.

The model distributes groundwater inflow uniformly along the Naches River between RM 17.1 and RM 3.4. This distribution differs from the seepage study in Carey (2007) which measured a gaining reach along RM 12.8-0.5 and two losing reaches along RM 17.6-12.8. The model distribution of inflowing groundwater was based on a gradual increase in specific conductivity measured in the 2015 river profile. This rise in specific conductivity, from approximately 70 to 95 uS/cm, was measured along the river between from just below the Wapatox Canal (RM 17.1) to just above Buckskin Slough (RM 3.3).

Groundwater inflow temperature was set to 15.9°C based on Figure 6 and Table 5 in Carey (2007), as well as temperatures from piezometer AHT082 in a 2013-14 Ecology study on Wide Hollow Creek near Union Gap (EIM study ID JICA0002). There is uncertainty regarding groundwater inflow temperature. Further details and sensitivity to groundwater temperature is shown in Appendix E.

The groundwater inflow for the Naches River portion of the model differs significantly from Vaccaro (2011) and Magirl et al. (2009). However, errors were found in the USGS spreadsheet calculations for these publications; see Appendix E for details. Because of this issue, Dr. Magirl of the USGS recommended via email that it is appropriate for Ecology to rely on the values published in Carey (2007) rather than the USGS publications above.

Final Temperature Calibration

After adding groundwater inflows to the QUAL2Kw model, a final calibration was performed using the same technique of multiplying rating curves by dimensionless factors. To avoid unrealistic depths, multiplication factors were kept at 1.2 or less (≤ 20% increase in depth relative to starting values). The empirical coefficient values used in the calibrated 2015 model for depth rating curves are listed in Appendix C, Table C-3.

As a check on the calibrated depth rating curves, simulated model depths were compared against water depth measurements obtained along a 17-mile profile in the Naches River on Aug 12-13, 2015. Profile measurements showed an average river depth of 0.42 m with a standard deviation of 0.08 m. When compared against these measurements, the model simulation had a nearly identical average depth of 0.42 m (Bias < 0.001 m) with a standard deviation of 0.10 m and RMSE of 0.11 m. Profile measurements may tend to be biased deeper than the average stream-bed, since the profile measurements tend to occur in the deepest part of the river (thalweg).

Statistics for the final model calibration are listed in Table 14. The fit to the data is excellent considering that target RMSE was ≤ 1°C. For the 7-DADMax, RMSE was at most 0.56° for Jun-15 to Aug-15. Hourly RMSE was at most 0.84° for the same period. Bias is generally close to zero, except for some reaches of the Naches River. Slight positive bias was seen in the model (up to +0.41°C compared to the data logger near the drinking water plant). Adjustments to the model were not made to remove this small bias since no evidence was available to determine the source of the bias (e.g., groundwater, water depth, shade, or some other factor). The small negative bias in the hourly data was primarily due to night-time temperature being too cool in the model.

Table 14. Statistics of fit for the calibrated 2015 water temperature model.

	7-DADMax Fit				**Hourly Fit**			
	Jun15-Aug15		Jun1-Oct31		Jun15-Aug15		Jun1-Oct31	
Site	Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE
blw Tieton Dam	-0.02	0.02	-0.02	0.03	0.00	0.03	0.00	0.03
Willows	0.01	0.12	0.08	0.15	0.11	0.31	0.05	0.31
Windy Point	0.04	0.36	0.03	0.27	-0.13	0.53	-0.15	0.46
Milemarker 180	0.00	0.18	0.06	0.16	-0.16	0.49	-0.15	0.36
abv Oak Creek	0.02	0.29	0.00	0.25	-0.41	0.84	-0.32	0.68
Tom's Pond	0.01	0.30	-0.06	0.27	-0.30	0.80	-0.29	0.66
Tieton Mouth	0.04	0.29	-0.06	0.26	-0.32	0.79	-0.29	0.64
blw Wapatox	-0.08	0.21	-0.14	0.29	-0.27	0.50	-0.26	0.48
Naches Rd	0.26	0.34	0.05	0.27	0.07	0.51	-0.10	0.47
abv Public Fishing	0.38	0.46	0.12	0.37	0.03	0.61	-0.13	0.53
Drinking water plant	0.41	0.56	0.12	0.45	0.13	0.65	-0.04	0.60
Powerhouse Rd	0.01	0.34	-0.11	0.33	-0.14	0.77	-0.24	0.71
Naches Mouth	-0.01	0.33	-0.12	0.37	0.08	0.68	-0.11	0.65
AVERAGE FIT	0.08	0.30	-0.01	0.27	-0.10	0.58	-0.16	0.51

Plots showing the simulated water temperatures versus the observed (data logger) temperatures are shown in Figures 15 and 16.

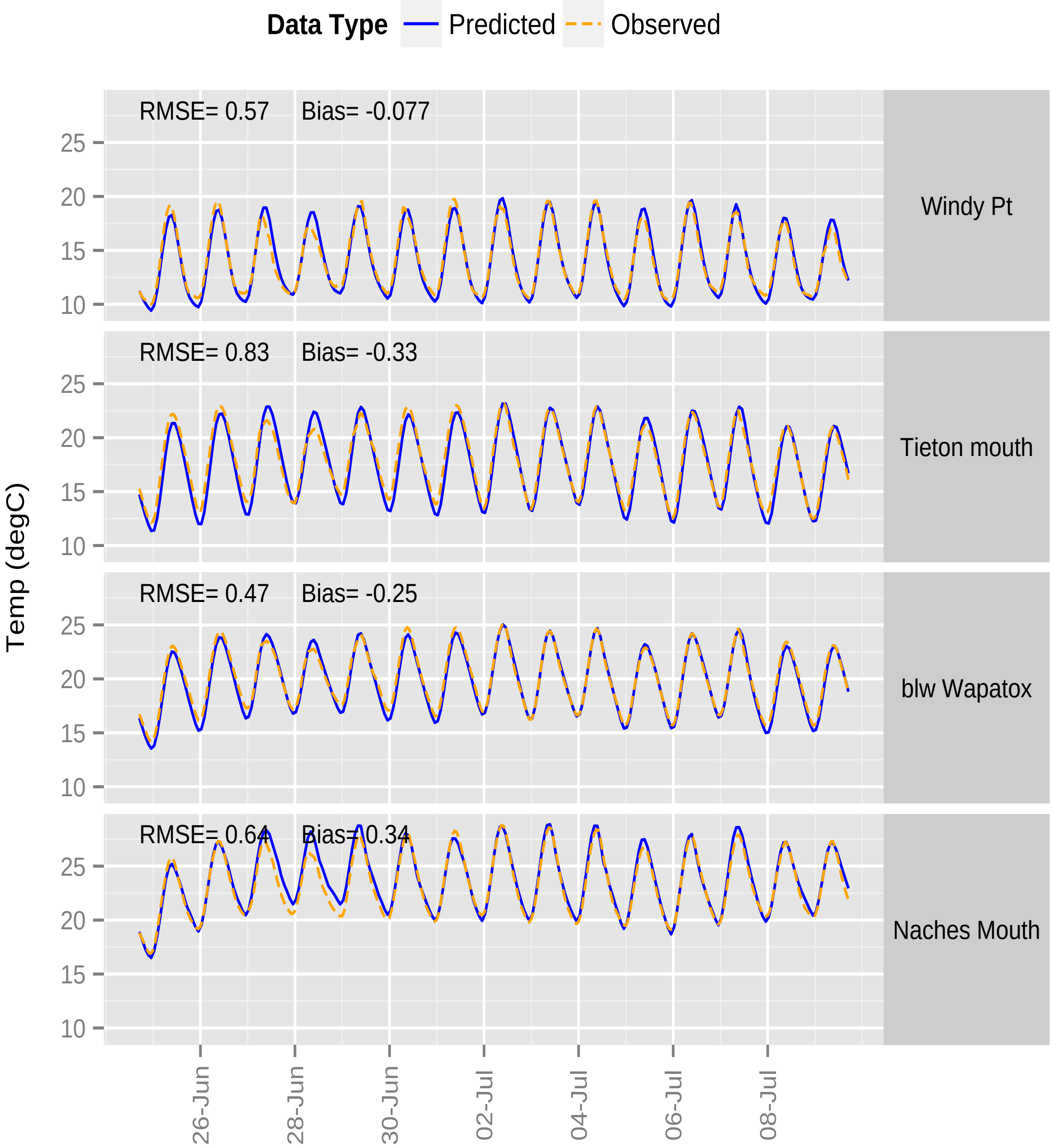

Figure 15. Plot and statistics of fit for simulated versus observed water temperature during the high temperature period of 2015 (June 25 to July 10).

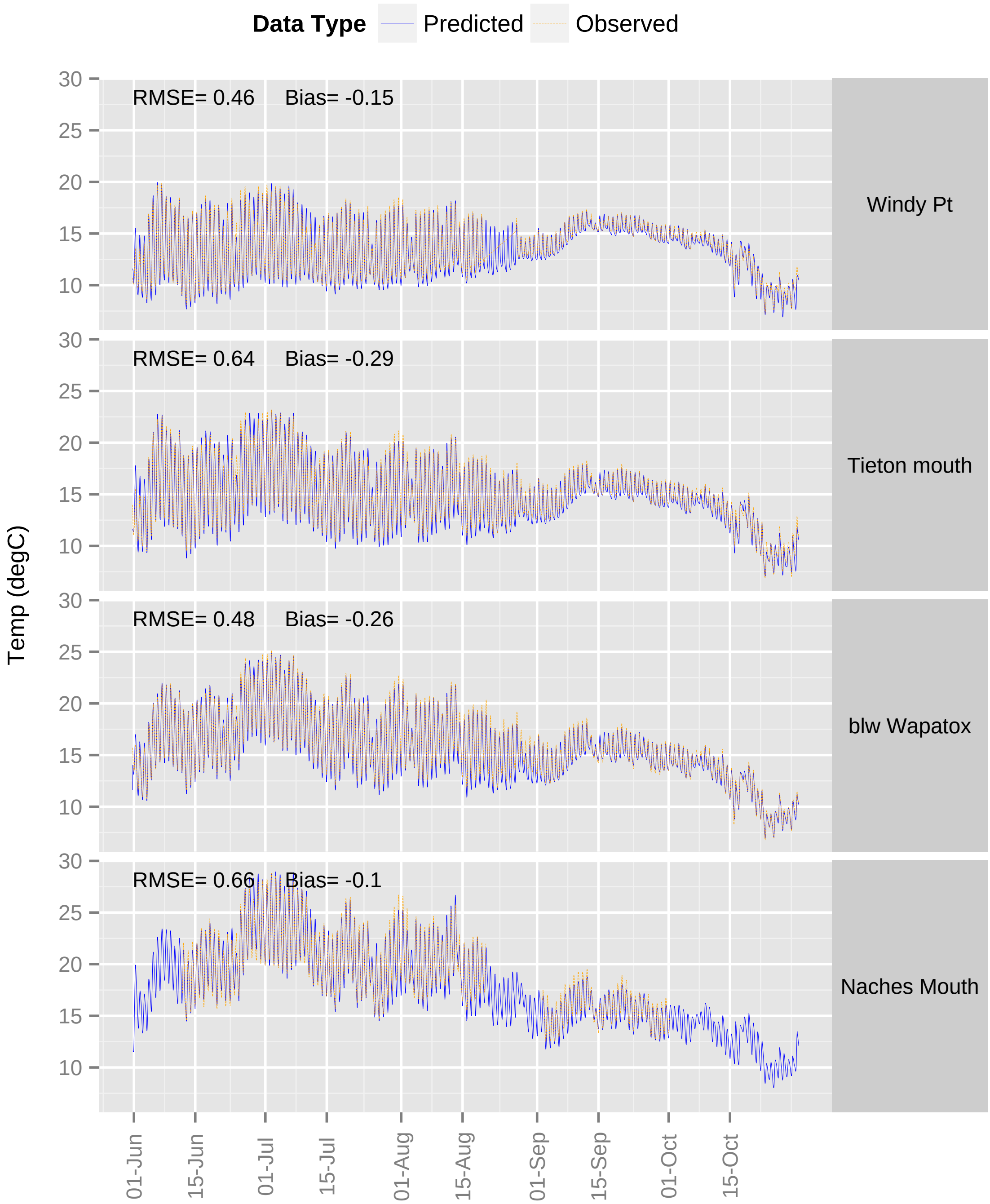

Figure 16. Plot and statistics of fit for simulated versus observed water temperature during the full modeled season in 2015 (June 1 to October 31).

Discussion

Differences between 2015 and Recent Years

This section examines differences between temperatures observed in 2015, and temperatures recorded in recent years to look for explanations for the unusually high water temperatures observed in 2015. Water temperature was remarkably warm for the studied rivers in 2015; this was primarily due to severe drought and hot weather conditions during that year.

The study in 2015 was not planned with any expectation of unusual conditions. However, any future decisions based on the results of 2015 should bear in mind that temperatures were unusually high during part of the study that year. During other parts of 2015, temperatures were more typical.

As discussed above, observed water temperatures in 2015 were unusually high for the Tieton and lower Naches Rivers, compared to any of the years since 2000. The highest annual 7-DADMax temperature in 2015 exceeded other years by more than 2°C. The highest supplemental period (measured June 1-15) 7-DADMax temperature in 2015 exceeded other years by more than 5°C.

One difference between 2015 and the other years is timing: high temperatures occurred much earlier in 2015 compared to other years. In 2015, maximum temperatures occurred in early July, compared to late July through mid-August for other years examined. This was due to a combination of low flow and a heat wave during late June to early July, 2015. At the Yakima airport, daily maximum air temperatures exceeded 100°F every day from June 26 to July 9. On July 3, 2015 (the date of maximum water temperature at NACW), air temperature exceeded 107°F at the Yakima airport. Ecology's data logger for air temperature near the Tieton River exceeded 106°F on the same date.

Another difference between 2015 and normal years was lack of snow accumulation (called snowpack drought). This resulted in lower flows earlier than normal in the season, because the Tieton and Naches Rivers are fed by melt-water from snowpack. According to the Natural Resources Conservation Service website, the snow water equivalent for the Naches River Basin on May 1, 2015 was 20% of the 1981-2010 median.

The warm weather and low snowpack in 2015 resemble what climate model projections indicate to be expected normal conditions by the middle of this century (Dalton et al., 2017). More precipitation fell as rain instead of snow in 2015, which resulted in lower snowpack. Overall measurements of snowpack in the Cascades taken on April 1 (when snowpack is usually at its peak) have decreased by about 20% since the 1950s (Mote et al., 2014). Spring snowmelt is projected by climate change models to occur three to four weeks earlier by mid-century, and summer streamflows are likely to decline (Mote et al., 2014).

To provide perspective for 2015 against other recent years, Figure 17 plots the number of hot days, the median river flows, and the highest 7-DADMax temperature for 2000-2015. The top plot shows the number of days each year exceeding 98°F (at the Yakima airport). The center plot shows the median daily flow at gage NACW (during the June 1 to October 1 period). The bottom plot shows highest annual 7-DADMax water temperature recorded (at gage NACW). From this figure, 2015 had more hot days than any year since 2000, combined with low median flow. Previous years do not appear to have experienced the same combination of a large number of hot days combined with low flows.

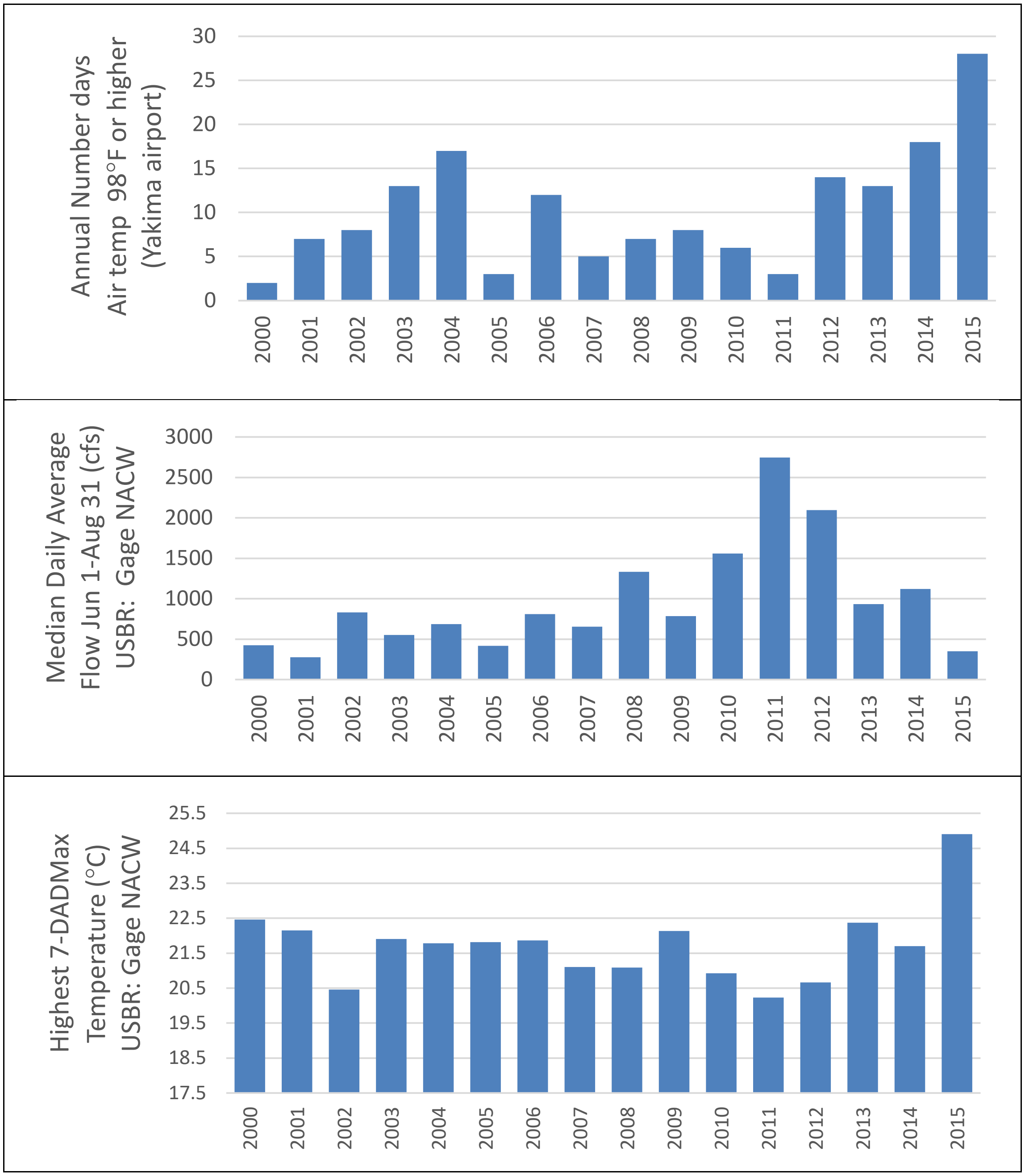

Figure 17. *Top*: Historical (2000-2015) number of hot days at the Yakima airport, *Middle*: median Naches River flow at gage NACW, and *Bottom*: highest 7-DADMax temperature at gage NACW.

Despite possible bias in water temperature at gage NACW, historical temperature data at this gage indicate the criterion of 17.5°C highest 7-DADMax temperature was exceeded for each year during 2000-2015. The lowest value on Figure 17 is 20.23°C in 2011. This figure is primarily intended to lend a valuable historical perspective to the water temperatures at the gage location over the years. According to the USBR, the temperature gage at this station is not calibrated or checked on a regular basis. In 2015, it appeared to be biased high relative to an Ecology temperature logger, but was off by less than half a degree Celsius.

Water temperatures in 2015 returned to roughly normal values after mid-July. Figure 18 compares 7-DADMax temperatures and 7-day average flows between 2015 and 2004. From April to mid-July, water temperature is higher and flow is lower in 2015. After this, the two years become similar in temperature and flow. Flows during the flip-flop in 2015 were actually higher than in 2004.

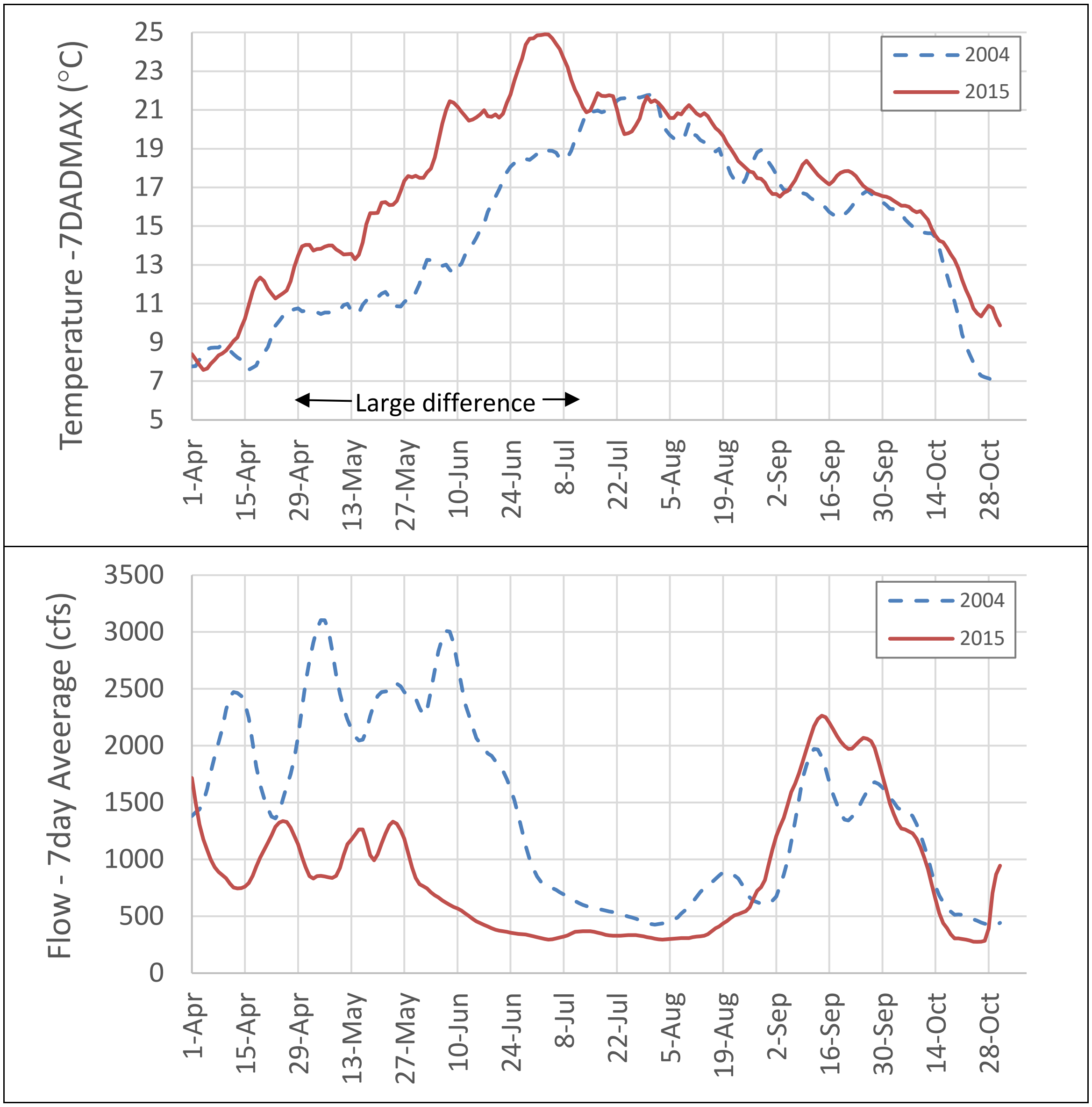

Figure 18. Water temperature (7-DADMax) and flow (7-day average) at gage NACW during 2004 and 2015.

Influence of Water Released from Tieton Dam (Rimrock Reservoir)

At full reservoir capacity, the outlet from Tieton Dam lies approximately 200 ft below the water surface. This means that the water released from this dam tends to be pulled from the cooler, stagnant layer of water near the bottom of the reservoir (hypolimnion), rather than the warm, well mixed layer of water at the surface (epilimnion).

Cold water released from the dam gradually warms up over the summer as the reservoir level drops. This warming accelerates during flip-flop. For example, in 2015 water temperature just below the dam was ~10°C prior to flip-flop (July 1). It warmed to ~13°C at the beginning of flip-flop (Sept 1). It then rapidly warmed to ~16°C in the middle of flip-flop (Sept 13). After flip-flop ended, the water cooled off once again ~11°C (Oct 31).

Prior to the start of flip-flop, during hot weather, the cold water released from Rimrock Reservoir heats rapidly as it travels downstream along the Tieton and lower Naches Rivers. It heats due to weather conditions such as air temperature, sunlight (shortwave radiation), longwave radiation, and other processes. See Appendix A for a detailed description of factors influencing water temperature.

During flip-flop the water released from the dam is heated much less as it travels downstream. The reduced heating is primarily due to increased flow volume: there is much more water which moves faster. It takes more energy to heat the larger mass of water, and there is less time to heat it since it is moving faster.

To illustrate the difference in heating before and during flip-flop, water temperature on two different dates in 2015 are compared in Figure 19. The top plot of this figure shows the warming on July 2 (prior to flip-flop), while the lower plot shows the warming on September 13 (during flip-flop). July 2 was chosen because most temperature loggers in 2015 recorded their highest temperature during July 1-3. September 13 was chosen because temperature loggers in the upper part of the Tieton River (just below the dam) recorded their highest temperature on this date. Model-predicted temperature ranges are shown as blue shading in Figure 19, with a dashed line to indicate mean daily temperature. Temperature ranges measured by data loggers are shown as blue vertical lines in this figure, with a circle/cross indicating mean temperature recorded by the logger.

The upper plot in Figure 19 shows that when less water is released during hot weather, the water warms rapidly as it travels downstream. Water temperature just below the dam is nearly uniform, less than 10°C. Average flow and travel time are 250 cfs and 28.5 hours, respectively. A jump in water temperature occurs just below the mouth of the Tieton River, due to the confluence with the Naches River. Warming in the Tieton River is rapid because the cold water is far out of equilibrium relative to environmental conditions. Warming continues in the Naches River, which is even more exposed to environmental conditions due to its width. Shade is low in both rivers.

The lower plot in Figure 19 shows that when more water is released during cool weather, water temperature remains fairly constant. On this date (Sept 13), the water temperature immediately below the dam is warmer (~16°C) than in early July (~10°C), due to seasonal warming in Rimrock Reservoir during drawdown. Average flow and travel time on this date are 1890 cfs and 11.6 hours, respectively. The large volume of water released from the dam has little time to be influenced by weather conditions as it travels rapidly downstream, especially since air temperature tends to be cooler, and there is less sunlight plus increased shade due to the season.

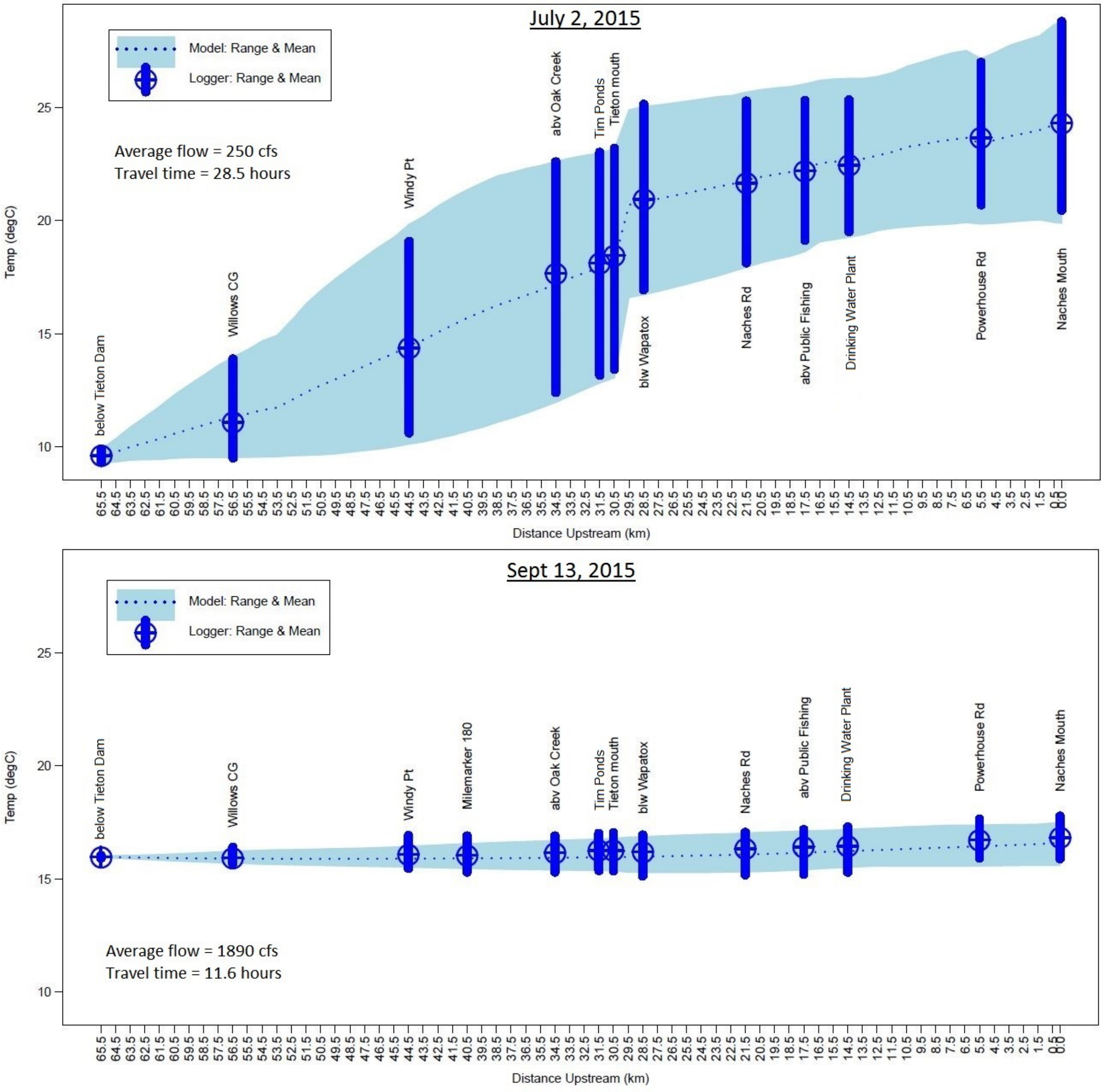

Figure 19. Warming of water as it moves downstream after being released from Tieton Dam on the hottest date (7/2/2015, *top*) and during flip-flop (9/13/2015, *bottom*).

Model Sensitivity

The general behavior of the calibrated 2015 QUAL2Kw model was evaluated through a sensitivity analysis using simple parameter perturbation (Chapra, 1997). This method raises/lowers a single model parameter to evaluate the effect on simulated daily maximum water temperature. Parameter perturbation was applied for the following model parameters:

- headwater temperature (Tieton Dam ±2°C)
- tributary temperature (upper Naches River ±2°C)
- headwater flow (Tieton Dam ±50 cfs)
- tributary flow (upper Naches River ±50 cfs)
- air temperature (±2°C)
- effective shade (±10%)
- water depth (±10%)
- water velocity (±10%)

Water temperature simulations with a single perturbed parameter were compared against the calibrated 2015 simulation (which is referred to in this report as the ***baseline model***) in order to quantify the sensitivity of the model for each of the above parameters. Changes were assessed for daily maximum water temperature on 7/2/2015, the date of maximum water temperatures.

Because the perturbation amounts were chosen arbitrarily, they cannot be ranked in importance against a different type of perturbation. Details on the sensitivity analysis are provided in Appendix B. Results are summarized in Table 15 below:

Table 15. Sensitivity analysis: impacts on simulated temperatures for July 2, 2015.

Perturbed parameter	Perturbed portion of model	Perturbation amount	Maximum impact to a single reach (°C)	Median impact on all reaches (°C)	Impacted Waterbody
Water temp.	Headwater (dam)	+2°C / -2°C	1.98 / -1.98	1.56 / -1.58	Tieton River
Flow rate	Headwater (dam)	-50 cfs / + 50 cfs	1.80 / -1.26	1.39 / -0.93	
Effective shade	Full model	-10% / +10%	1.12 / -1.13	0.75 / -0.76	
Water depth	Full model	-10% / +10%	1.02 / -0.87	0.78 / -0.66	
Water velocity	Full model	-10% / +10%	0.60 / -0.55	0.39 / -0.36	
Air temp.	Full model	+2°C / -2°C	0.44 / -0.43	0.22 / -0.21	
Flow rate	Headwater (dam)	-50 cfs / +50 cfs	1.31 / -1.18	1.19 / -1.03	Naches River
Water temp.	Upper Naches River	+2°C / -2°C	1.02 / -1.02	0.64 / -0.65	
Flow rate	Upper Naches River	-50 cfs / +50 cfs	1.01 / -0.69	0.31 / -0.20	
Effective shade	Full model	-10% / +10%	0.93 / -1.05	0.74 / -0.85	
Water depth	Full model	-10% / +10%	0.82 / -0.73	0.75 / -0.65	
Water velocity	Full model	-10% / +10%	0.53 / -0.47	0.40 / -0.31	
Water temp.	Headwater (dam)	+2°C / -2°C	0.51 / -0.53	0.33 / -0.34	
Air temp.	Full model	+2°C	0.47 / -0.47	0.34 / -0.34	

Model Scenarios

To evaluate how hypothetical changes in river conditions affect simulated water temperature, several model scenarios are evaluated below. These scenarios were developed collaboratively between Ecology's Water Quality Program and Environmental Assessment Program. Scenario results below present simulated temperature impacts only, without any consideration of other factors such as water availability or any other issues.

Most of the scenarios below examine the sensitivity of the model to important environmental factors, rather than reflecting specific project proposals. The one exception is the scenario simulating the temperature impact of hypothetically relocating the outfall for the Naches Publicly Owned Treatment Works (POTW), which might potentially occur sometime in the future.

Temperature impacts from these scenarios were created by changing specific inputs of the 2015 calibrated QUAL2Kw model to reflect the hypothetical changes. The calibrated 2015 model is referred to in this report as the "*baseline model*" for purposes of the discussion below. The impact of the scenario conditions to water temperature in the river was assessed by comparing water temperatures simulated by the scenario model against those simulated by the baseline model.

List of scenarios

#1a	Increased flow (+200 cfs) from Rimrock Reservoir
#1b	Increased flow (+400 cfs) from Rimrock Reservoir
#2	Reduction in upper Naches River Temperature
#3a	Increase effective shade by +10%
#3b	Increase effective shade by +20%
#4	Impact of Town of Naches Publicly Owned Treatment Works (POTW) outfall

Scenario results are presented in different formats as needed:

- For scenarios #1a, #1b, #2, #3a and #3b, the temperature impacts are shown longitudinally for a single day: July 2, 2015. This date was chosen because it had the highest water temperature in the Tieton and lower Naches Rivers.
- Scenario #4 shows daily maximum water temperature impacts within a 300-ft reach of the Naches River at the location of a hypothetical POTW outfall (between the dates of June 1 to October 31, 2015).

Scenario #1a and #1b: Increased flow from Rimrock Reservoir

Water flowing out of Rimrock Reservoir (at Tieton Dam) was increased by an arbitrary amount of +200 and +400 cfs for scenarios #1a and #1b, respectively. No changes were made to the water temperature flowing out of Rimrock Reservoir. Flows were increased for the entire duration of the model (June 1 to October 31). Impacts were assessed on July 2, 2015 (the date of highest water temperature).

The longitudinal impact of this scenario on water temperature is shown in Figure 20.

- Orange lines = simulated daily maximum temperature on 7/2/2015
    - solid orange line = baseline model maximum temperature
    - dashed orange line = +200 cfs scenario maximum temperature
    - dash-dot orange line = +400 cfs scenario maximum temperature
- Blue lines = simulated daily minimum temperature on 7/2/2015
    - solid blue line = baseline model minimum temperature
    - dashed blue line = +200 cfs scenario minimum temperature
    - dash-dot blue line = +400 cfs scenario minimum temperature

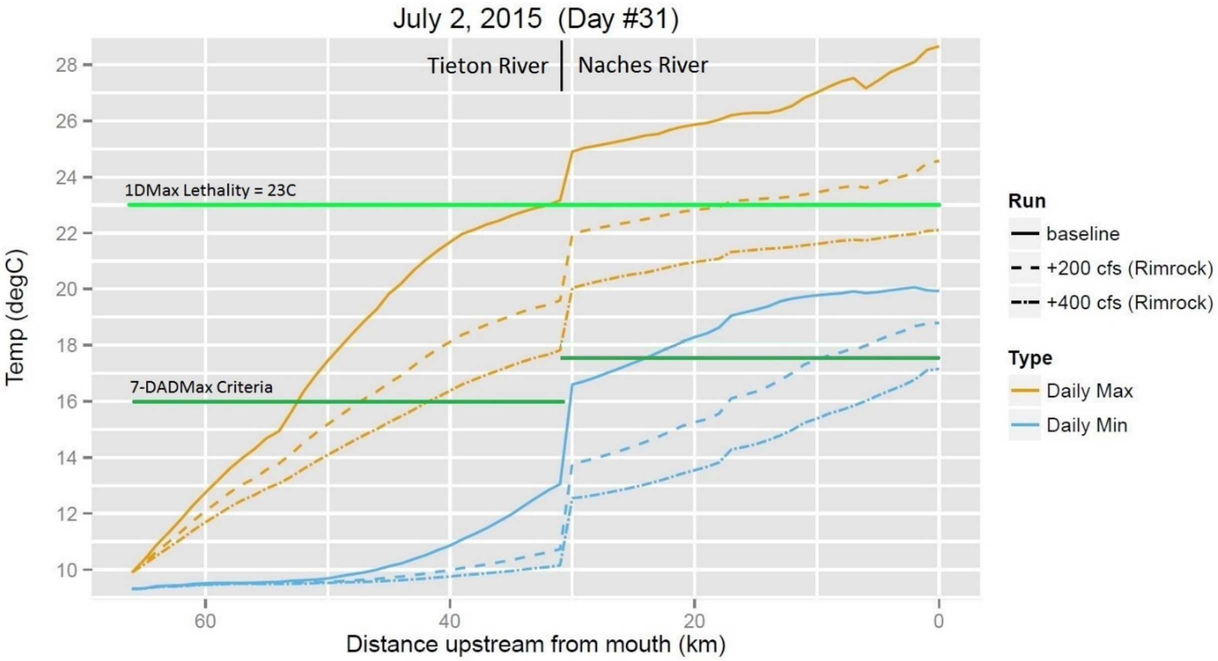

Figure 20. Simulated longitudinal water temperature in the baseline and scenario #1a (+200 cfs) and #1b (+400 cfs) models on 7/2/2015.

Simulated water temperatures in scenarios #1a and #1b decreased due to the following factors:

- Extra water mass: keeps the water cooler because it takes more energy to heat a larger mass of water.
- Faster water velocity: reduces travel time which means reduced exposure time to weather conditions.
- Deeper water: reduces ratio of surface area to volume, which results in less efficient heating of the water due to weather.

Neither scenarios #1a nor #1b cooled daily maximum temperature below the 7-DADMax criteria for the entire length of either river. Daily *minimum* temperature lies mostly below the 7-DADMax criteria for both rivers in scenario #1a, and also scenario #1b except near the mouth of the Naches River.

Scenario #1a cooled water temperature below the 23°C lethality limit for approximately 10 km of the lower Naches River, from the confluence at ~30 km down to ~20 km. In scenario #1b, the entire length of the lower Naches River is cooled below 23°C.

Scenario #2: Reduction in Upper Naches River Temperature

Water temperature in the upper Naches River was reduced by 2.7°C for this scenario. The reduction was applied equally to both daytime and nighttime hourly temperatures. The amount of temperature reduction was based on the *Upper Naches River Temperature TMDL* report which states that "the best estimate of potential summertime stream temperature reductions for the upper Naches River (RM 38.8 to 17.6) is 2.7°C" (Brock, 2008).

Figure 21 shows the impact of this scenario on simulated water temperature, longitudinally on 7/2/2015. The upper Naches River enters the model near km 31 in this figure. The upper Naches River is represented as a tributary in the model, with assigned hourly temperatures and flows. No model simulation or analysis was performed on the upper Naches River for the current study.

Scenario #2 cools daily maximum and daily minimum temperatures by a little over 1°C below the confluence of the Tieton and Naches Rivers, and approximately 0.5°C near the mouth of the Naches River. Daily maximum temperature remains above the lethality and 7-DADMax criteria.

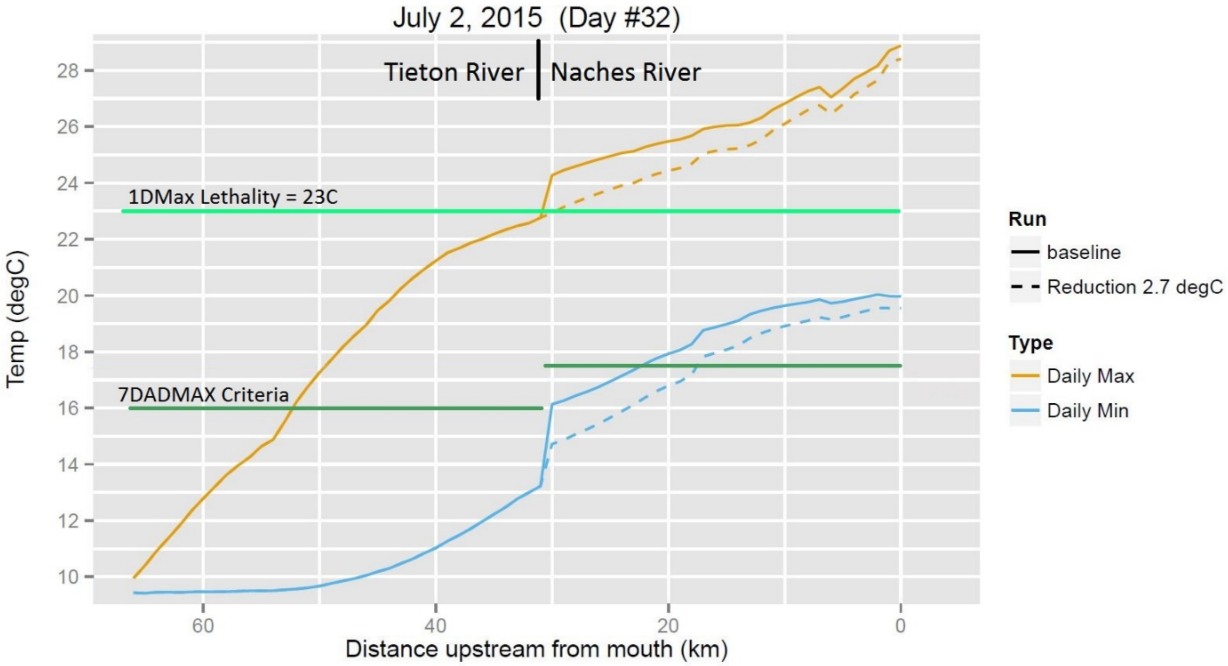

Figure 21. Simulated longitudinal water temperature in the baseline and scenario #2 on 7/2/2015, in which water temperature was reduced for the upper Naches River.

Scenario #3a and #3b: Arbitrary Increases in Effective Shade

For this scenario, effective shade was increased by two arbitrary amounts: +10% and +20% for scenario #3a and #3b, respectively. These increases to shade do not provide any implications regarding the potential for shade improvement along either river. Shade was increased along the entire length of the model for both simulations.

Figure 22 shows the impacts of these shade increases on simulated water temperatures, longitudinally on 7/2/2015. Reductions in water temperature are small near Tieton Dam, and increase downstream. Daily minimum temperatures were not strongly impacted by effective shade, especially near Tieton Dam.

Scenarios #3a and #3b impact daily maximum temperatures by cooling approximately 1°C and 2°C, respectively, along portions of the Tieton River and the entire length of the lower Naches River. The entire length of the lower Naches River remains above both the lethality limit and 7-DADMax criteria on the simulation date. Scenario impacts to daily minimum temperature are smaller than impacts to daily maximum temperature.

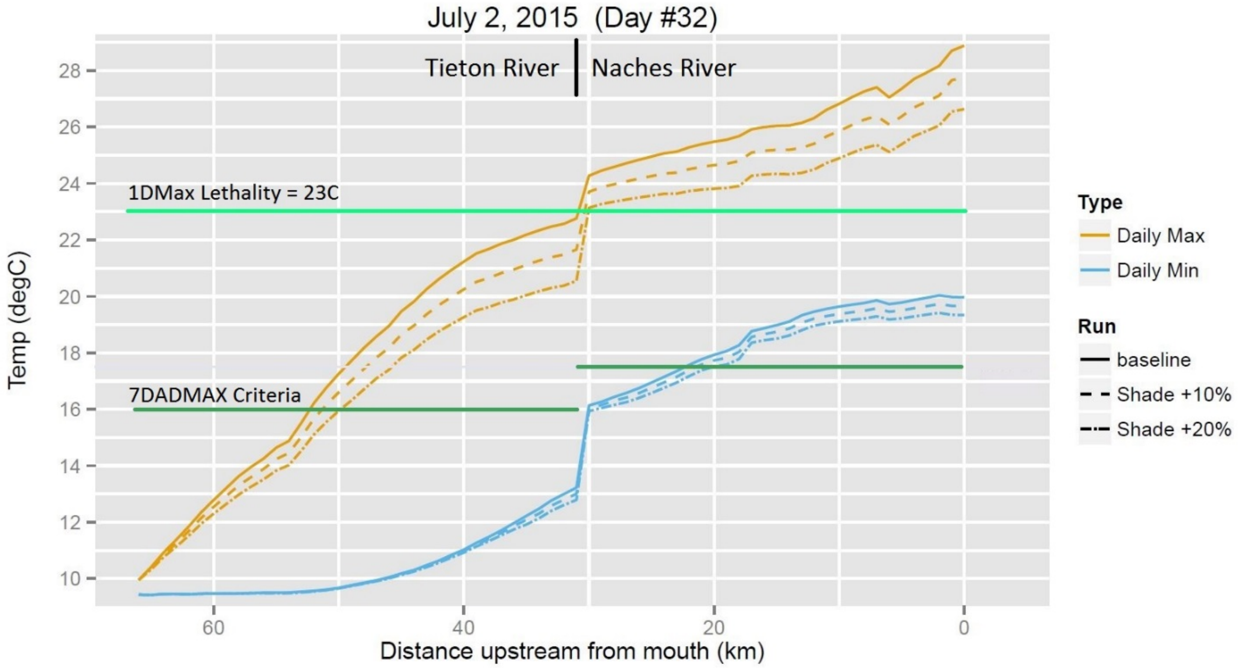

Figure 22. Simulated longitudinal water temperature in the baseline and scenario #3a and #3b on 7/2/2015, showing temperature impacts of increased effective shade.

Scenario #4: Impact of Town of Naches POTW Outfall

This scenario evaluates the impact of a hypothetical discharge directly to the Naches River from the town of Naches Publicly Owned Treatment Works (POTW). This scenario is hypothetical because currently treatment plant effluent is discharged into a side channel of the Naches River, which is separated from the main channel by flood levees (Ecology, 2007). This channel flows about 1,000 feet southeast of the outfall to a 48-inch culvert through the flood levee into the main channel of the Naches River (Huibregtse, Louman, 2001).

To create this scenario, the baseline (2015) model was altered as follows: the length of the reach where the POTW discharges to the river was shortened from 1 km to 300 feet (0.091 km). Simulated water temperature in this reach should change slightly due to the reduced travel time of water in the shorter reach, relative to the longer reach used for the baseline (2015) model. The scenario with this shortened reach and no flow from the POTW is referred to below as the zero-flow-POTW model.

A scenario which includes POTW flow was then created by assigning a constant flow rate and temperature to hypothetical discharge, into the shortened model reach, from the POTW. A constant flow rate was set to 0.18 million gallons per day (MGD), which is the design criteria "Monthly Average for the Maximum Month" on the fact sheet for this POTW (Ecology, 2007).

The flow rate of 0.18 MGD assigned to the POTW is a conservatively high estimate which exceeds the 95th percentile of 0.11 MGD of recently monitored flows. The 95th percentile statistic was calculated from discharge monitoring data reports in Ecology's Water Quality Permitting and Reporting Information System (PARIS) (Jim Leier - Ecology, personal communication).

A constant water temperature of 23.7°C was assigned to the hypothetical POTW discharge, which is the highest observed 7-day average of daily maximum temperatures at the POTW based on PARIS discharge monitoring data (statistic provided by Jim Leier - Ecology, personal communication).

The impact of the POTW on the shortened discharge reach was evaluated by comparing simulated daily maximum temperature between the zero-flow-POTW model and the scenario which includes POTW flow. To allow evaluation of impacts across a variety of flow and temperature conditions, the comparison ran from June 1 to October 31. Flow and temperature from the POTW remained constant during the entire simulation.

QUAL2Kw simulated impacts to daily maximum temperature within the 300-ft reach from June 1 to October 31, 2015 are shown in the top portion of Figure 23. Also shown in the top graph is the predicted impact to the reach based on a mass balance approach, which is described below. The lower portion of this figure also is described below.

In fact, during cooler months, the POTW effluent would not remain a constant 23.7°C (as assumed for this exercise). Because of this assumption, maximum simulated temperature impacts to the 300-ft reach occur during late October when the river is cold (9.4°C) and flow is low (240 cfs), after flip-flop. The actual impact in October would be lower because the POTW effluent would be cooler than the assumed temperature. The maximum daily temperature recorded in October (2012-16) was actually 19.0°C, based on PARIS discharge monitoring data.

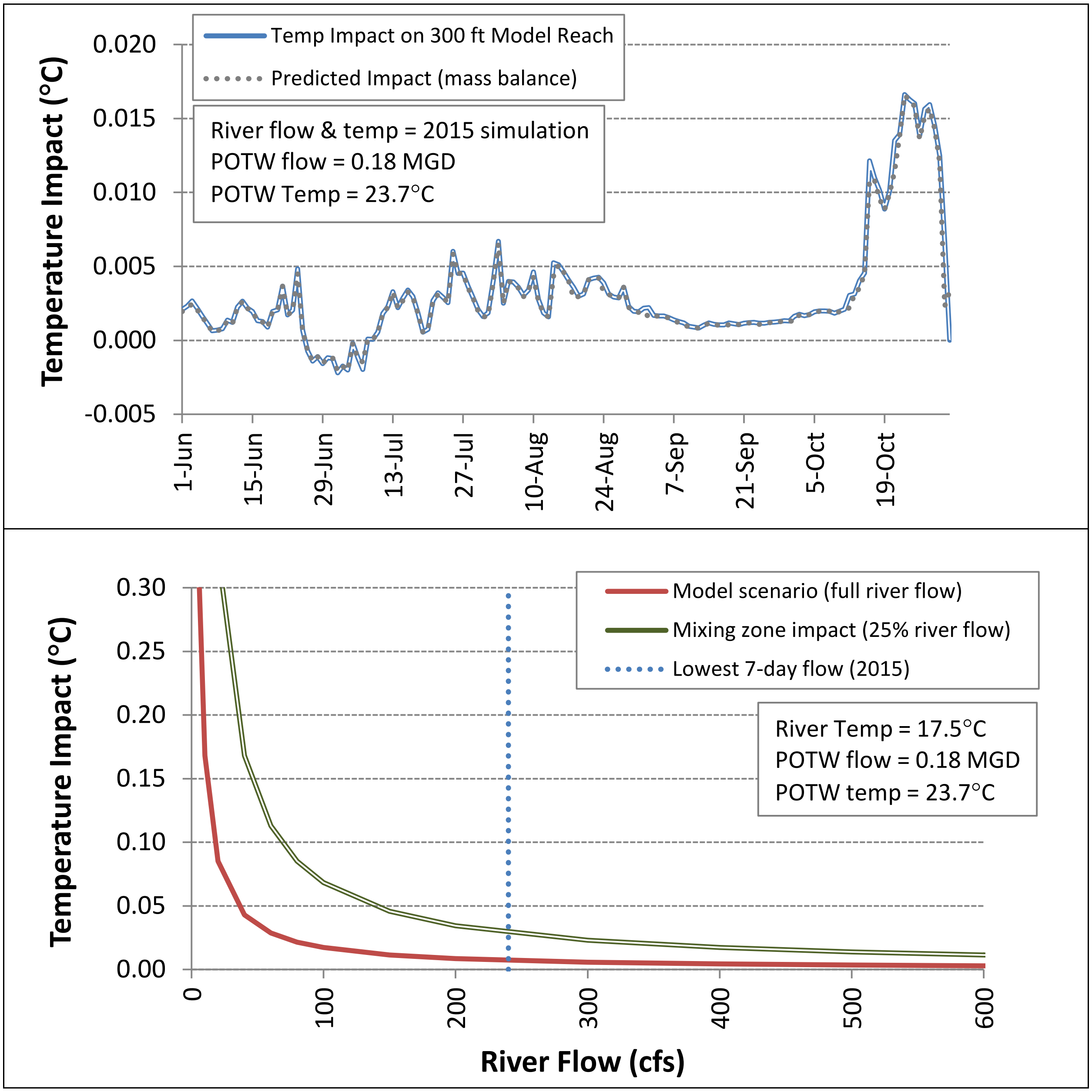

Figure 23. *Top:* QUAL2Kw and mass balance simulated temperature impact to a 300-ft reach of the Naches River due to hypothetical flow from the Naches POTW. *Bottom:* Mass balance temperature impact to a 300-ft reach of the Naches River from the Naches POTW at varying river flows.

A mass balance approach was used to check the QUAL2Kw output, and also to make further predictions regarding temperature impacts to the river. Equations used in this approach are derived below:

Ti = Temperature in river reach without POTW flow
Tf = Temperature in river reach with POTW flow
Tp = Temperature of POTW water
Qr = Flow in the river
Qp = Flow from POTW
T_{impact} = Tf - Ti

$$Tf = \frac{TrQr + TpQp}{Qr + Qp}$$

$$T_{impact} = \frac{TiQr + TpQp}{Qr + Qp} - Ti$$

$$T_{impact} = \frac{TpQp - TiQp}{Qr + Qp}$$

$$T_{impact} = \frac{Qp}{Qr + Qp}(Tp - Ti)$$

Using these equations, mass balance predicted temperature impacts were then calculated and plotted in the top portion of Figure 23. A close match was found between QUAL2Kw simulated temperature impacts and the mass balance approach. These calculations used QUAL2Kw output values for average daily flow and maximum daily river temperature, combined with the assumed POTW flow and temperature given above.

The mass balance equations were next used to predict the temperature impact to the 300-ft reach of the Naches River for varying river flows under an assumption of 17.5°C initial river temperature (bottom portion of Figure 23). As can be seen in this figure, temperature impacts drop below 0.05°C at river flows approximately over 40 cfs, and continue to drop as flow increases.

By using 25% of the river flow instead of the full flow, the temperature impact on a 300-ft mixing zone was also calculated and included in the bottom portion of Figure 23.

Critical flow conditions at the hypothetical POTW outfall location were represented in this scenario by using the lowest 7-day flow average for this reach from the 2015 baseline model (240 cfs). This value was used because no recent 7Q10 flow statistic was available at this location due to recent changes and adjustments to Wapatox Canal operations. Flows in 2015 represented critical conditions for the river because the low flows and hot weather resulted in high water temperatures for these rivers. According to Ecology (2012), critical conditions for temperature exist when there is the greatest potential to produce high water temperature which adversely impacts aquatic biota.

In 2015, the lowest 7-day averaged flow in the model reach where the hypothetical POTW discharge occurs was 240 cfs. This flow value differs from the lowest 7-day average flow value at the USBR gage NACW because additional canal diversions lie between gage NACW and the hypothetical POTW outfall location.

To calculate the temperature impact on the Naches River from a hypothetical outfall at the Naches POTW under critical low-flow conditions in the river:

- Critical flow in the Naches River at this location = 240 cfs
- Assume river temperature = 17.5°C
- POTW outfall flow = 0.18 MGD
- POTW outfall temperature = 23.7°C

Under these conditions (full river flow), the temperature impact to a 300-ft reach of the Naches River is 0.007°C. This represents the temperature impact of the Naches POTW to the Naches River under critical low-flow conditions.

Under a 25% river flow condition, such as typically used in a mixing zone calculation, the temperature impact under these conditions is 0.029°C.

Conclusions and Recommendations

Summary and Conclusions

- During 2004, water temperatures in the Tieton River and the lower Naches River did not meet (exceeded) present-day freshwater temperature criteria for aquatic life uses set by law in Washington State.
- During 2015, water temperatures did not meet freshwater temperature criteria for aquatic life uses set by law in Washington State for nearly all monitored sites. These sites include the Tieton River (except immediately below Tieton Dam), the lower Naches River, Oak Creek, and Buckskin Slough.
- During 2015, water temperature in the Naches River did not meet supplemental spawning temperature criteria, for applicable reaches.
- During 2004 and 2015, measurements of daily maximum water temperatures in the Tieton and lower Naches Rivers increased in a downstream direction towards the river mouths.
- Based on historical water temperature records at the USBR gage NACW, water temperature in the Naches River was unusually high in 2015 during late June and early July compared to all years since 2000. Water temperature in 2015 returned to more typical values after mid-July.
- The Tieton and lower Naches Rivers are highly regulated systems due to reservoir releases, diversions of water into canals and ditches, and return flows. Flow statistics for these rivers reflect both natural hydrological fluctuations and operating policies. If changes are made in the future to these policies, then flow statistics for these rivers will change in accordance.
- Due to changes in Wapatox Canal operations since 2003, minimum flow during the irrigation season has increased by approximately 300-450 cfs in the Naches River for the reach between this canal diversion (Naches RM 17.1) and the canal return (Naches RM 9.7). Due to this change, low-flow statistics at the USBR gage NACW have also changed since 2003.
- Due to reduced snowpack in the Naches River basin, flows in the Tieton and lower Naches Rivers were low during June-August 2015.
- Depending on flow conditions in the rivers, typical travel times from Tieton Dam to the mouth of the Naches River were between 11-29 hours in 2015, based on dye studies.
- Water temperature in the Tieton River is controlled by environmental warming of cold water which flows out of Rimrock Reservoir. The warming is primarily due to factors such as weather and is influenced by flow conditions. The cold water is initially far below equilibrium temperature with the environment and typically does not reach equilibrium temperature before entering the Naches River, due to short travel times.

- Based on model simulations of water temperature, the Tieton River has a significant cooling effect on the Naches River for some distance below the confluence. This agrees with previous study results mentioned above for aerial thermal infrared imaging performed in 2004 (Brock, 2008).
- Based on model simulations of water temperature, water temperature in the Naches River is controlled primarily by upstream water temperature and flow from the Tieton River and also by weather. A small temperature influence on the river exists due to groundwater or hyporheic flow entering the river along a reach of the river below the Town of Naches and extending downstream to just outside the City of Yakima (near the twin bridges on Hwy 12).
- Riparian shade is low in both the Tieton and lower Naches Rivers. The width of these rivers is a significant factor limiting shade.
- Based on model simulations of water temperature (and mass balance equations), the impact of a hypothetical outfall from the Naches Publicly Owned Treatment Works (POTW) was below 0.007°C during the warm months of 2015. This impact increased in late October as river temperatures became low. The scenario used conservatively high-flow and constant high temperature estimates for the POTW outfall.
- Based on mass balance equations, the impact of a hypothetical outfall from the Naches POTW on a mixing zone (using 25% of 2015 low-flow conditions) was 0.029°C. The modeled 7-day averaged low flow of 240 cfs in 2015 is the best available estimate of 7Q10 flow conditions at the hypothetical Naches POTW outfall location.

Recommendations

- Because the maximum annual temperatures in both the Tieton and lower Naches Rivers occur near the mouths, these locations make effective monitoring sites for maximum river temperatures. For supplemental water temperature criteria, the Naches River should be monitored just upstream of the Cowiche Creek confluence, since the supplemental criteria do not apply at the mouth of the Naches River.
- Future studies of the Naches River should consider improving continuous flow monitoring near the Naches River mouth. This improvement would address the uncertainty in flow encountered at this location during calibration of the QUAL2Kw model for 2015.
- Measuring the specific conductivity and temperature of groundwater during future studies may improve estimates of groundwater flux.
- Discuss flow management with USBR to see if additional water could be available for release from Tieton Dam during periods of hot weather and low flow. Based on model simulation scenarios, extra water released from Tieton Dam would reduce water temperature in the Tieton and lower Naches Rivers during the hottest parts of the year. This could help fish survive lethal temperature conditions.
- Ecology should continue working with partners in the Yakima Basin Integrated Plan, possibly investigating temperature model scenarios in order to gain insight into temperature impacts of any future projects in the lower Naches and Tieton River basins.

References

Abatzoglou, J. T., D. E. Rupp, and P. W. Mote, 2014: Seasonal climate variability and change in the Pacific Northwest of the United States. J. Climate, 27, 2125–2142, doi:10.1175/JCLI-D-13-00218.1.

Brock, S.E., 2008. Upper Naches River Temperature Total Maximum Daily Load Volume 1. Water Quality Findings. Washington State Department of Ecology, Olympia, WA. https://fortress.wa.gov/ecy/publications/SummaryPages/0803036.html

Carey, B., 2007. Groundwater-Surface Water Interactions Along the Naches and Tieton Rivers, Summer and Fall 2004. Washington State Department of Ecology, Olympia, WA. Publication No. 06-03-003. https://fortress.wa.gov/ecy/publications/SummaryPages/0603003.html

Chapra, S.C., 1997. Surface Water-Quality Modeling. McGraw-Hill, New York, N.Y.

Chapra, S.C., Pelletier, G.J., and Tao, H., 2008. QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality, Version 2.11: Documentation and Users Manual. Civil and Environmental Engineering Dept., Tufts University, Medford, MA.

Dalton, M.M., K.D. Dello, L. Hawkins, P.W. Mote, and D.E. Rupp, 2017. *The Third Oregon Climate Assessment Report*, Oregon Climate Change Research Institute, College of Earth, Ocean and Atmospheric Sciences, Oregon State University, Corvallis, OR.

Ecology, 2007. Fact Sheet for NPDES Permit No. WA 002258-6 Town of Naches Publicly Owned Treatment Works. Washington State Department of Ecology, Olympia, WA.

Ecology, 2011. Waters Requiring Supplemental Spawning and Incubation Protection for Salmonid Species. Washington State Department of Ecology, Olympia, WA. Publication No. 06-10-038. https://fortress.wa.gov/ecy/publications/SummaryPages/0610038.html

Ecology, 2012. Water Quality Standards for Surface Waters of the State of Washington, Chapter 173-201A WAC. Washington State Department of Ecology, Olympia, WA. Publication No. 06-10-091. https://fortress.wa.gov/ecy/publications/SummaryPages/0610091.html

Ecology, 2013. Shade.xls - a tool for estimating shade from riparian vegetation. Washington State Department of Ecology, Olympia, WA. Models and Tools

Ecology, 2015. TTools User Guide - Python Add-in for ArcMap. Washington State Department of Ecology, Olympia, WA.

Ecology, 2015b. Standard Operating Procedure for Time of Travel Studies in Freshwater Using a Dye Tracer. Washington State Department of Ecology, Olympia, WA. SOP No. EAP037. Published SOPs

Ecology, 2015c. Standard Operating Procedure for Collection of Longitudinal Stream Depth Profiles. Washington State Department of Ecology, Olympia, WA. SOP No. EAP097. Published SOPs

Ecology, 2016. Standard Operating Procedures for Hydrolab® Datasonde®, MiniSonde®, and HL4 Multiprobes. Washington State Department of Ecology, Olympia, WA. SOP No. EAP033. Published SOPs

EPA, 2016. Climate Change Indicators in the United States: *Trends in April Snowpack in the Western United States, 1955-2016*. https://www.epa.gov/climate-indicators/climate-change-indicators-snowpack Accessed 3/24/2017. United States Environmental Protection Agency.

Fosu, B.O., S.Y. Simon Wang, and Jin-Ho Yoon, 2016: The 2014/15 Snowpack Drought in Washington State and its Climate Forcing [in "Explaining Extremes of 2015 from a Climate Perspective"]. Bull. Amer. Meteor. Soc., 97 (12), S14–S18, doi:10.1175/BAMS-D-16-0149.

Haring, D., 2001. Habitat Limiting Factors: Yakima River Watershed, Water Resource Inventory Areas 37-39 Final Report, Washington State Conservation Commission.

Huibregtse, Louman, 2001. Town of Naches Wastewater Treatment Facilities Engineering Report. Huibregtse, Louman Associates, Inc., Yakima, WA. December 2001.

Isley, S., 2017. Water transfer working group project description application no CS4-0496CTCLsb19. U.S. Bureau of Reclamation, Yakima, WA.

Kinnison, H., and J. Sceva, 1963. Effects of hydraulic and geologic factors on streamflow of the Yakima River basin, Washington: U.S. Geological Survey Water-Supply Paper 1595.

Leier, J., 2017. Personal communication with Jim Leier, Water Quality Program Technical Unit, Washington State Department of Ecology, Olympia, WA.

LeMoine, M. and Brock, S.E., 2004. Quality Assurance Project Plan: Naches River Temperature Total Maximum Daily Load. Washington State Department of Ecology, Olympia, WA. https://fortress.wa.gov/ecy/publications/summarypages/0403110.html

Lynch, C., 2018. Email correspondence on 7/24/2018 from Christopher Lynch, U.S. Bureau of Reclamation, Yakima Field Office, Yakima, WA.

Magirl, C.S., Julich, R.J., Welch, W.B., Curran, C.R., Mastin, M.C., and Vaccaro, J.J., 2009, Summary of seepage investigations in the Yakima River basin, Washington: U.S. Geological Survey Data Series 473.

Mantua, N., I. Tover, and A. Hamlet, 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. *Climatic Change*, Vol. 102, Nos. 1-2, September 2010.

Mauger, G.S., J.H. Casola, H.A. Morgan, R.L. Strauch, B. Jones, B. Curry, T.M. Busch Isaksen, L. Whitely Binder, M.B. Krosby, and A.K. Snover, 2015. State of Knowledge: Climate Change in Puget Sound. Report prepared for the Puget Sound Partnership and the National Oceanic and Atmospheric Administration. Climate Impacts Group, University of Washington, Seattle, WA.

McLain, K., J. Hancock, and M. Drennan, 2017. 2015 Drought and Agriculture, A Study by the Washington State Department of Agriculture. Washington State Department of Agriculture, Olympia, WA.

Mote, P.W., A.K. Snover, S.M. Capalbo, S. Eigenbrode, P. Glick, J.S. Littell, R. Raymondi, S. Reeder, 2014. Chapter 21 in *Climate Change Impacts in the United States: The Third U.S. National Climate Assessment*, J. Melillo, Terese (T.C.) Richmond, and G.W. Yohe, Eds., U.S. Global Change Research Program.

Pelletier, G., S. Chapra, and H. Tao, 2006. QUAL2Kw – A framework for modeling water quality in streams and rivers using a genetic algorithm for calibration. Environmental Modelling and Software 21 (2006) 419-425.

Pelletier, G. and S. Chapra, 2008. QUAL2Kw theory and documentation (version 5.1) A modeling framework for simulating river and stream water quality. Washington State Department of Ecology, Olympia, WA.

Peterschmidt, M., 2010. Upper Naches River and Cowiche Creek Temperature Total Maximum Daily Load, Volume 2. Implementation Strategy. Washington State Department of Ecology, Water Quality Program, Olympia, WA.
https://fortress.wa.gov/ecy/publications/SummaryPages/1010068.html

Pickett, P., 2016. Yakima River Preliminary Assessment of Temperature, Dissolved Oxygen, and pH. Washington State Department of Ecology, Olympia, WA.
https://fortress.wa.gov/ecy/publications/SummaryPages/1603048.html

Snover, A.K., G.S. Mauger, L.C. Whitely Binder, M. Krosby, and I. Tohver, 2013. *Climate Change Impacts and Adaptation in Washington State: Technical Summaries for Decision Makers*. State of Knowledge Report prepared for the Washington State Department of Ecology. Climate Impacts Group, University of Washington, Seattle, WA.

Stoelinga, M. T., M. D. Albright, and C. F. Mass, 2010: A new look at snowpack trends in the Cascade Mountains. J. Climate, 23, 2473–2491, doi: 10.1175/2009JCLI2911.1.

Thomann, R.V. and J.A. Mueller, 1987. Principles of surface water quality modeling and control. Harper and Row publishers.

Urmos-Berry, E., 2015. Quality Assurance Project Plan Tieton River and Lower Naches River Temperature Study. Washington State Department of Ecology, Olympia, WA. Publication No. 15-03-112.
https://fortress.wa.gov/ecy/publications/SummaryPages/1503112.html

USBR (U.S. Bureau of Reclamation), 2002. Interim Comprehensive Basin Operating Plan.

USBR (U.S. Bureau of Reclamation), 2004. Yakima Field Office Project Operations Outlook 2004 Irrigation Season. Yakima Field Office, Yakima, WA. June.

USBR (U.S. Bureau of Reclamation), 2017. Online publication summarizing major storage reservoirs in the Yakima River Basin. https://www.usbr.gov/pn/hydromet/yakima/yaktea.html

USGS, 2009. 1/3-Arc Second National Elevation Dataset, National Elevation Data. United States Geological Survey, Reston, Virginia.

Vaccaro, J.J., 2011. River-Aquifer Exchanges in the Yakima River Basin, Washington. Scientific Investigations Report 2011-5026. United States Geological Survey, Reston, Virginia.

Ward, W., 2011. Standard Operating Procedures for Continuous Monitoring of Fresh Water Rivers and Streams, Version 1.0. Washington State Department of Ecology, Olympia, WA. SOP No. EAP080. Published SOPs

Whiley, A.J. and Cleland, B., 2003. Wenatchee National Forest Water Temperature Total Maximum Daily Load Technical Report. Washington State Department of Ecology, Water Quality Program, Olympia, WA. Publication No. 03-10-063. https://fortress.wa.gov/ecy/publications/SummaryPages/0310063.html

Williams, J. and Pearson, H., 1985. Streamflow statistics and drainage basin characteristics for the southwestern and eastern regions, Washington. Volume II. Eastern Washington. United States Geological Survey Open File Report 84-145-B. Tacoma, WA.

Yakima Subbasin Fish and Wildlife Planning Board (YSFWPB). 2004. Yakima Subbasin Plan, Yakima, Washington. May. http://www.nwcouncil.org/fw/subbasinplanning/yakima/plan/.

Appendices

Appendix A. Overview of Stream Heating Processes

This appendix provides a general explanation of the physical mechanisms impacting water temperature in surface water bodies. Ecology has published this material for similar purposes in several other temperature-related reports. The illustrative examples shown below are not specifically taken from the Tieton and lower Naches Rivers, although the same general principles apply to all surface water bodies.

The temperature of a stream reflects the amount of heat energy in the water. Changes in water temperature within a particular segment of a stream are induced by the balance of the heat exchange between the water and the surrounding environment during transport through the segment. If there is more heat energy entering the water in a stream segment than there is leaving, the temperature will increase. If there is less heat energy entering the water in a stream segment than there is leaving, then the temperature will decrease. The general relationships between stream parameters, thermodynamic processes (heat and mass transfer), and stream temperature change is outlined in Figure A-1.

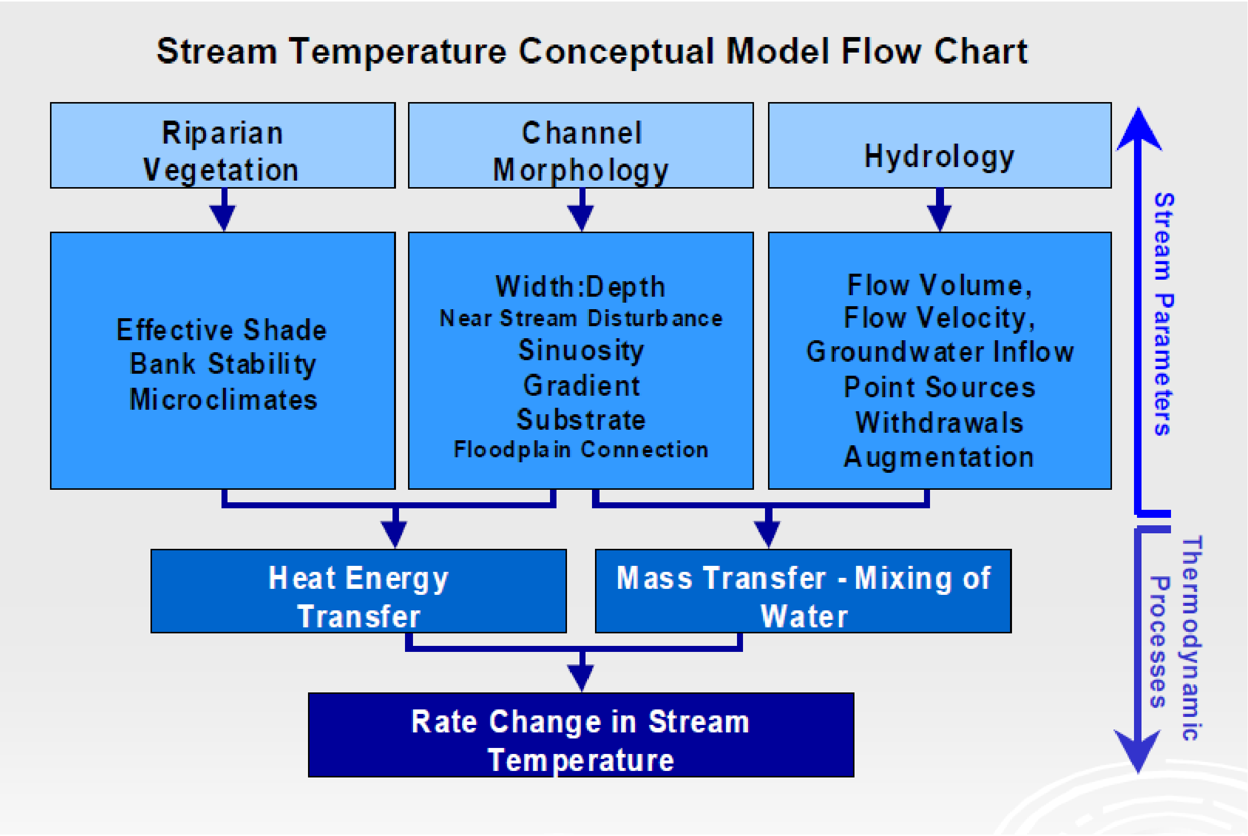

Figure A-1. Conceptual model of factors that affect stream temperature.

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

- **Stream depth.** Stream depth affects both the magnitude of the stream temperature fluctuations and the response time of the stream to changes in environmental conditions.
- **Air temperature.** Daily average stream temperatures and daily average air temperatures are both highly influenced by incoming solar radiation (Johnson, 2004). When the sun is not shining, the temperature in a volume of water tends toward the dew-point temperature (Edinger et al., 1974).
- **Solar radiation and riparian vegetation.** The daily maximum temperatures in a stream are strongly influenced by removal of riparian vegetation because of diurnal patterns of solar heat flux. Daily average temperatures are less affected by removal of riparian vegetation.
- **Groundwater.** Inflows of groundwater can have an important cooling effect on stream temperature. This effect will depend on the rate of groundwater inflow relative to the flow in the stream and the difference in temperatures between the groundwater and the stream.

Water temperature can also be strongly affected by tributaries and human discharges, depending on their temperature. In lakes and reservoirs, water temperatures can be affected by thermal stratification and wind.

Heat budgets and temperature prediction

Heat exchange processes occur between the water body and the surrounding environment, and these processes control stream temperature. Edinger et al. (1974) and Chapra (1997) provide thorough descriptions of the physical processes involved. Figure A-2 shows the major heat energy processes or fluxes across the water surface or streambed.

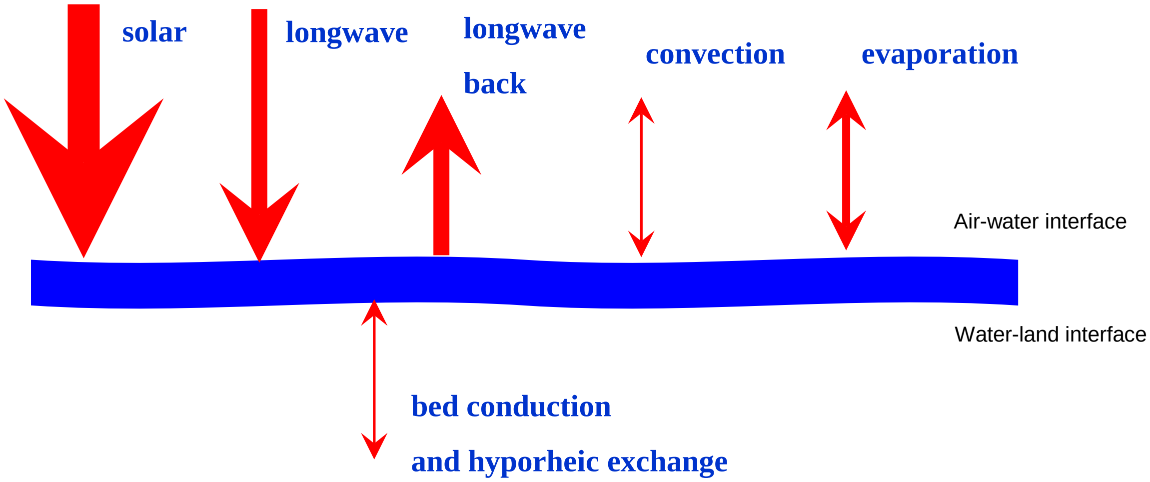

Figure A-2. Surface heat exchange processes that affect water temperature (net heat flux = solar + longwave atmosphere + longwave back + convection + evaporation + bed). Heat flux between the water and streambed occurs through conduction and hyporheic exchange.

The heat exchange processes with the greatest magnitude are as follows (Edinger et al., 1974):

- **Shortwave solar radiation**. Shortwave solar radiation is the radiant energy which passes directly from the sun to the earth. Shortwave solar radiation is contained in a wavelength range from 0.14 um to about 4 um. At Ecology's weather station on the Palouse River near the mouth of Union Flat Creek (34PAL33.4), the daily average global shortwave solar radiation for July-August 2007 was 271 W/m^2. The peak values during daylight hours are typically about 3 times higher than the daily average. Shortwave solar radiation constitutes the major thermal input to an unshaded body of water during the day when the sky is clear. Solar exposure was identified as the most influential factor in stream heating processes (Sinokrot and Stefan, 1993; Johnson and Jones, 2000; Danehy, 2005).
- **Longwave atmospheric radiation.** The longwave radiation from the atmosphere ranges in wavelength from about 4 to 120 um. Longwave atmospheric radiation depends primarily on air temperature and humidity, and increases as both of those increase. It constitutes the major thermal input to a body of water at night and on warm, cloudy days. The daily average heat flux from longwave atmospheric radiation typically ranges from about 300 to 450 W/m^2 at mid latitudes (Edinger et al., 1974).
- **Longwave back radiation from the water to the atmosphere.** Water sends heat energy back to the atmosphere in the form of longwave radiation in the wavelength range from about 4 to 120 um. Back radiation accounts for a major portion of the heat loss from a body of water. Back radiation increases as water temperature increases. The daily average heat flux out of the water from longwave back radiation typically ranges from about 300 to 500 W/m^2 (Edinger et al., 1974).

The remaining heat exchange processes generally have less magnitude and are as follows:

- **Evaporation flux at the air-water interface** is influenced mostly by wind speed and the vapor pressure gradient between the water surface and the air. When the air is saturated, the evaporation stops. When the gradient is negative (vapor pressure at the water surface is less than the vapor pressure of the air), condensation, the reversal of evaporation takes place; this term then becomes a gaining component in the heat balance.
- **Convection flux at the air-water interface** is driven by the temperature difference between water and air and by wind speed. Heat is transferred in the direction of decreasing temperature.
- **Streambed conduction flux and hyporheic exchange** component of the heat budget represents the heat exchange through conduction between the bed and the water body and the influence of hyporheic exchange. The magnitude of streambed conduction is driven by the size and conductance properties of the substrate. The heat transfer through conduction is more pronounced when thermal differences between the substrate and water column are higher. This heat transfer usually affects the temperature diel profile, rather than the magnitude of the maximum daily water temperature.

  Hyporheic exchange can be an important mechanism for stream cooling in some basins (Johnson and Jones, 2000; Poole and Berman, 2000; Johnson, 2004). The hyporheic zone is defined as the region of saturated substrate located beneath the channel characterized by complex hydrodynamic processes that combine stream water and groundwater. The resulting fluxes can have significant implications for stream temperature at different spatial and temporal scales. For example, studies in the Walla Walla River in Oregon have shown water temperatures declining downstream in a section of the river as hyporheic interstitial flow cools in a riffle reach and then remixes into the stream in a pool reach.

Figures A-3 and A-4 show surface heat flux in a relatively unshaded stream reach and in a more heavily shaded stream reach, respectively.

Figure A-3 shows an example of the estimated diurnal pattern of the surface heat fluxes in one of Washington's coastal rivers for the week of August 8-14, 2001. The daily maximum temperatures in a stream are strongly influenced by removal of riparian vegetation because of diurnal patterns of solar shortwave heat flux (Adams and Sullivan, 1989). The solar shortwave flux can be controlled by managing vegetation in the riparian areas adjacent to the stream.

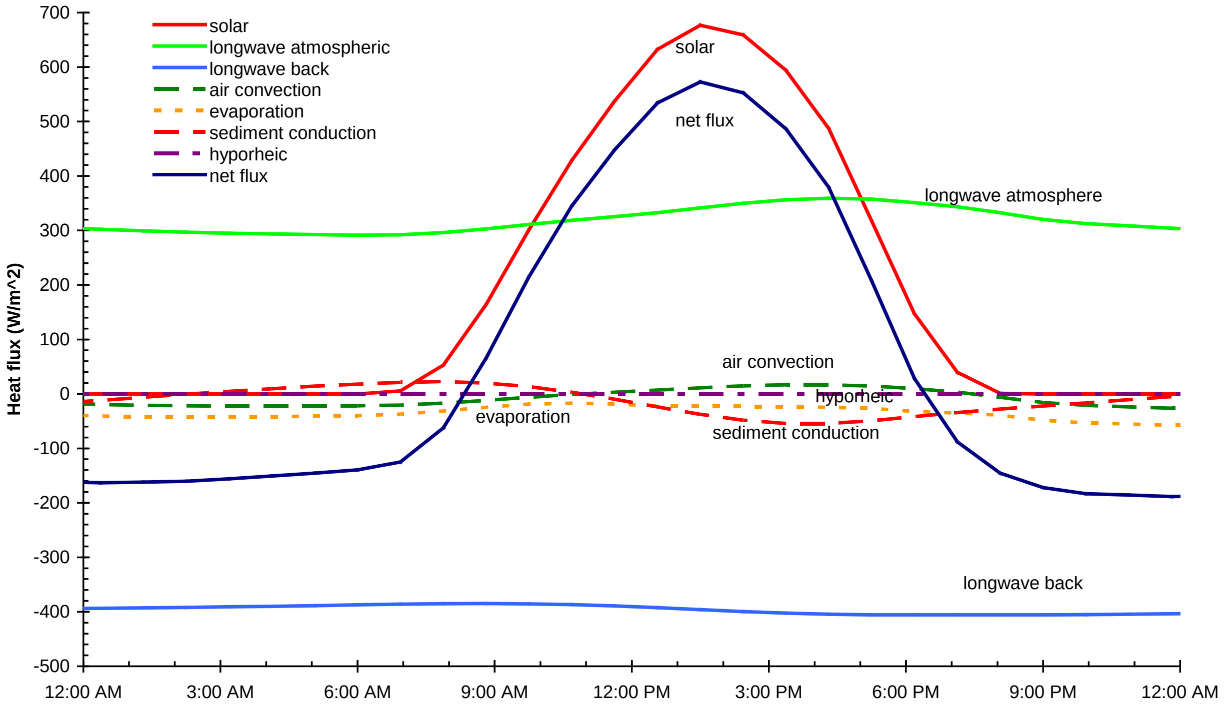

Figure A-3. Estimated heat fluxes in a river during August 8-14, 2001.

Net heat flux = solar + longwave atmosphere + longwave back + air convection + evaporation + sediment conduction + hyporheic.

Figure A-4 shows an example of the estimated diurnal pattern of the surface heat fluxes in a more heavily shaded location in the same river. Shade that is produced by riparian vegetation or topography can reduce the solar shortwave flux. Other processes – such as longwave radiation, convection, evaporation, bed conduction, or hyporheic exchange – also influence the net heat flux into or out of a stream.

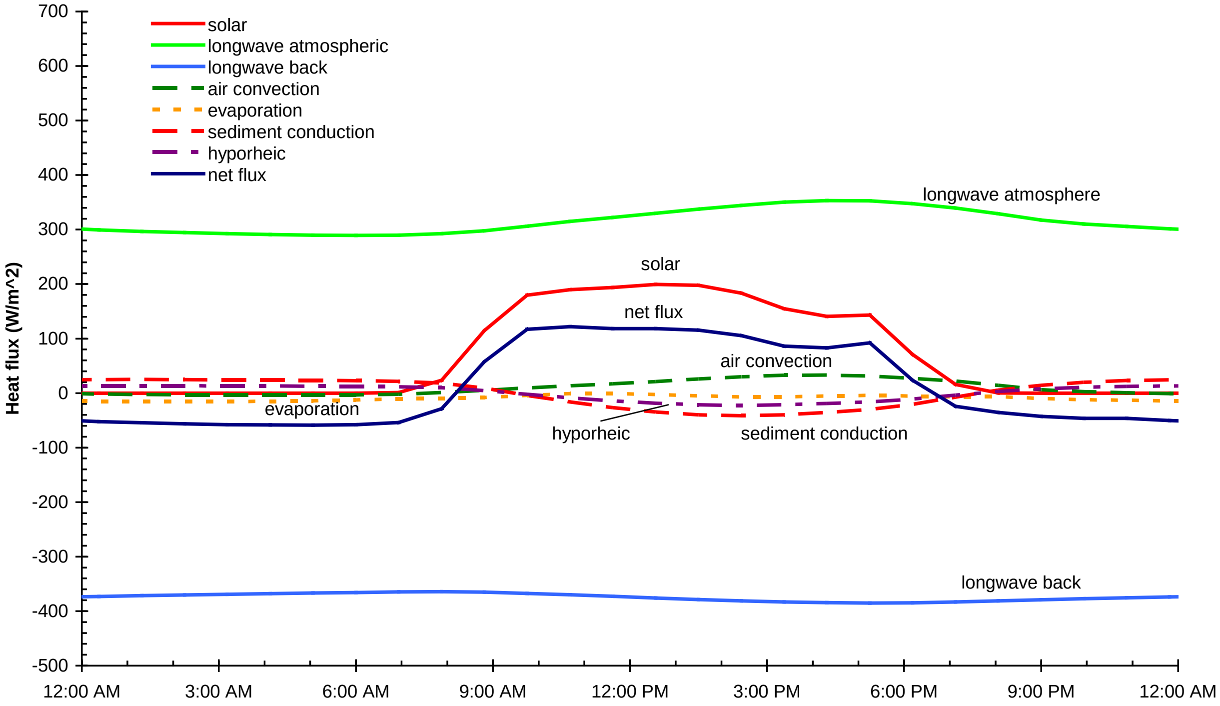

Figure A-4. Estimated heat fluxes in a more shaded section of a river during August 8-14, 2001.

Net heat flux = solar + longwave atmosphere + longwave back + air convection + evaporation + sediment conduction + hyporheic.

Heat exchange between the stream and the streambed has an important influence on water temperature. The temperature of the streambed is typically warmer than the overlying water at night and cooler than the water during the day (Figure A-5). Heat is typically transferred from the water into the streambed during the day, then back into the stream during the night (Adams and Sullivan, 1989). This has the effect of dampening the diurnal range of stream temperature variations without affecting the daily average stream temperature.

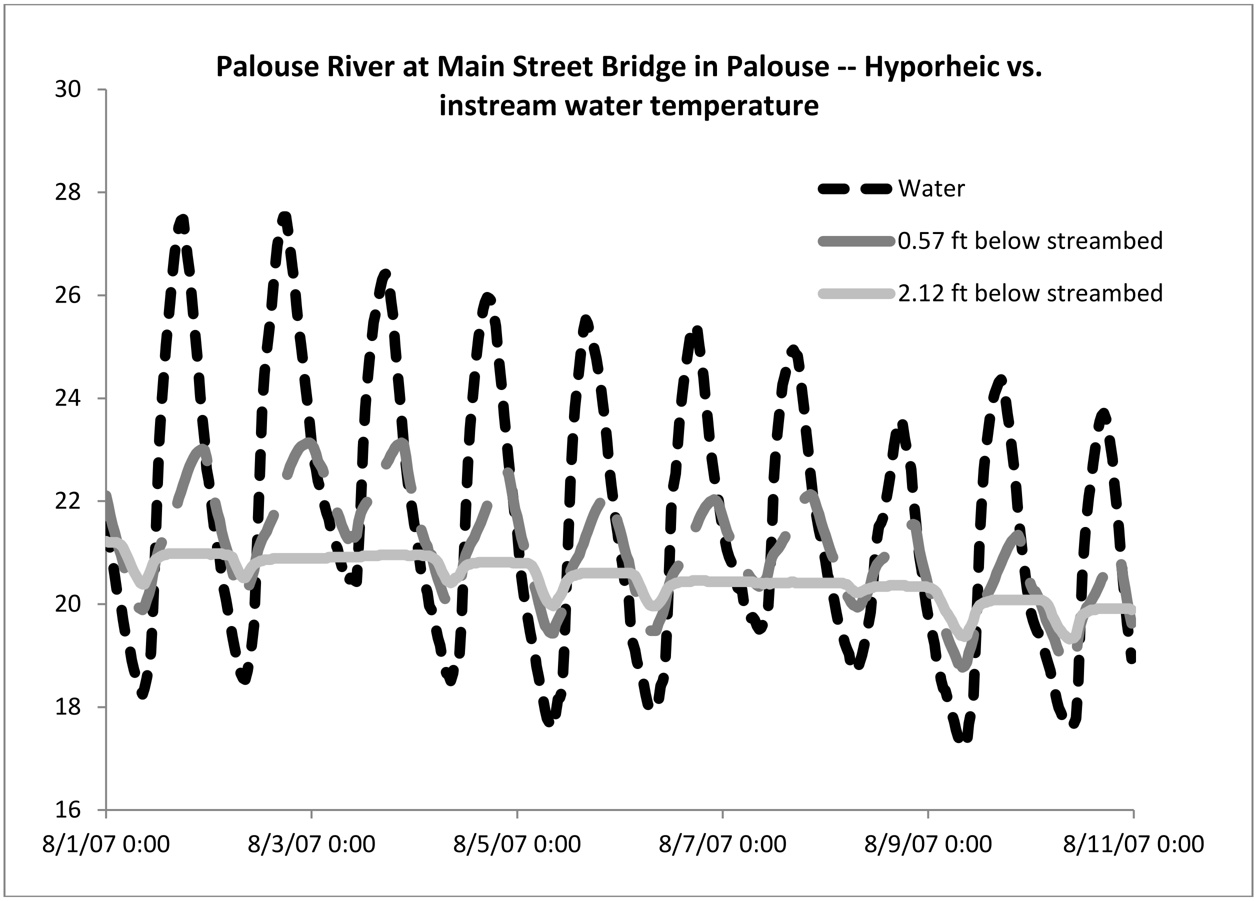

Figure A-5. Water and streambed temperatures in early August 2007 in the Palouse River at Main Street Bridge in Palouse (station 34PAL120.0).

The bulk temperature of a vertically mixed volume of water in a stream segment under natural conditions tends to increase or decrease with time during the day according to whether the net heat flux is either positive or negative. When the sun is not shining, the water temperature tends toward the dew-point temperature (Edinger et al., 1974; Brady et al., 1969). The equilibrium temperature of a natural body of water is defined as the temperature at which the water is in equilibrium with its surrounding environment and the net rate of surface heat exchange would be zero (Edinger et al., 1968; 1974).

The dominant contribution to the seasonal variations in the equilibrium temperature of water is from seasonal variations in the dew-point temperature (Edinger et al., 1974). The main source of hourly fluctuations in water temperature during the day is solar radiation. Solar radiation generally reaches a maximum during the day when the sun is highest in the sky unless cloud cover or shade from vegetation interferes.

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

Thermal role of riparian vegetation

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

Summaries of the scientific literature on the thermal role of riparian vegetation in forested and agricultural areas are provided by Belt et al., 1992; Beschta et al., 1987; Bolton and Monahan, 2001; Castelle and Johnson, 2000; CH2M Hill, 2000; GEI, 2002; Ice, 2001; and Wenger, 1999. All of these summaries recognize that the scientific literature indicates that riparian vegetation plays an important role in controlling stream temperature. Important benefits that riparian vegetation has upon the stream temperature include:

- Near-stream vegetation height, width, and density combine to produce shadows that can reduce solar heat flux to the surface of the water.
- Riparian vegetation creates a thermal microclimate that generally maintains cooler air temperatures, higher relative humidity, lower wind speeds, and cooler ground temperatures along stream corridors.
- Channel morphology can be strongly affected by near-stream vegetation. Specifically, stream vegetation is often part of human impacts on land-cover type and condition, which can affect flood plain and instream roughness, the contribution of coarse woody debris, sedimentation, stream substrate composition, and streambank stability.

Although the warming of water temperatures as a streamflows downstream can be a natural process, the rates of heating can be dramatically lower when high levels of shade exist and heat flux from solar radiation is minimized. There is a natural maximum potential level of vegetation and associated shade that a given stream is capable of attaining in an undisturbed situation. In general, the importance of shade decreases as the width of a stream increases.

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

Effective shade

Stream shade may be measured or calculated using a variety of methods (Chen, 1996; Chen et al., 1998; Ice, 2001; OWEB, 1999; Teti, 2001; Teti and Pike, 2005). Effective shade is defined as the fraction or percentage of the total possible solar radiation heat energy that is prevented from reaching the surface of the water:

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

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

Canopy cover is the percent of sky covered by vegetation and topography at a given point. Shade is influenced by cover but changes throughout each day, as the position of the sun changes spatially and temporally with respect to the canopy cover (Kelley and Krueger, 2005).

In the Northern Hemisphere, the earth tilts on its axis toward the sun during the summer, allowing longer day length and higher solar altitude. Both are functions of solar declination, a measure of the earth's tilt toward the sun (Figure A-6). Latitude and longitude positions fix the stream to a position on the globe, while aspect provides the direction of streamflow. Near-stream vegetation height, width, and density describe the physical barriers between the stream and sun that can attenuate and scatter incoming solar radiation, producing shade (Table A-1). The solar position has a vertical component – solar altitude – and a horizontal component – solar azimuth – that are both functions of time, date, and the earth's rotation.

While the interaction of these shade variables may seem complex, the mathematics that describes them is relatively straightforward geometry. Using solar tables or mathematical simulations, the potential daily solar load can be quantified. The shade from riparian vegetation can be measured with a variety of methods, including:

- Hemispherical photography
- Angular canopy densiometer
- Solar pathfinder

(Ice, 2001; OWEB, 1999; Boyd, 1996; Teti, 2001; Teti and Pike, 2005.)

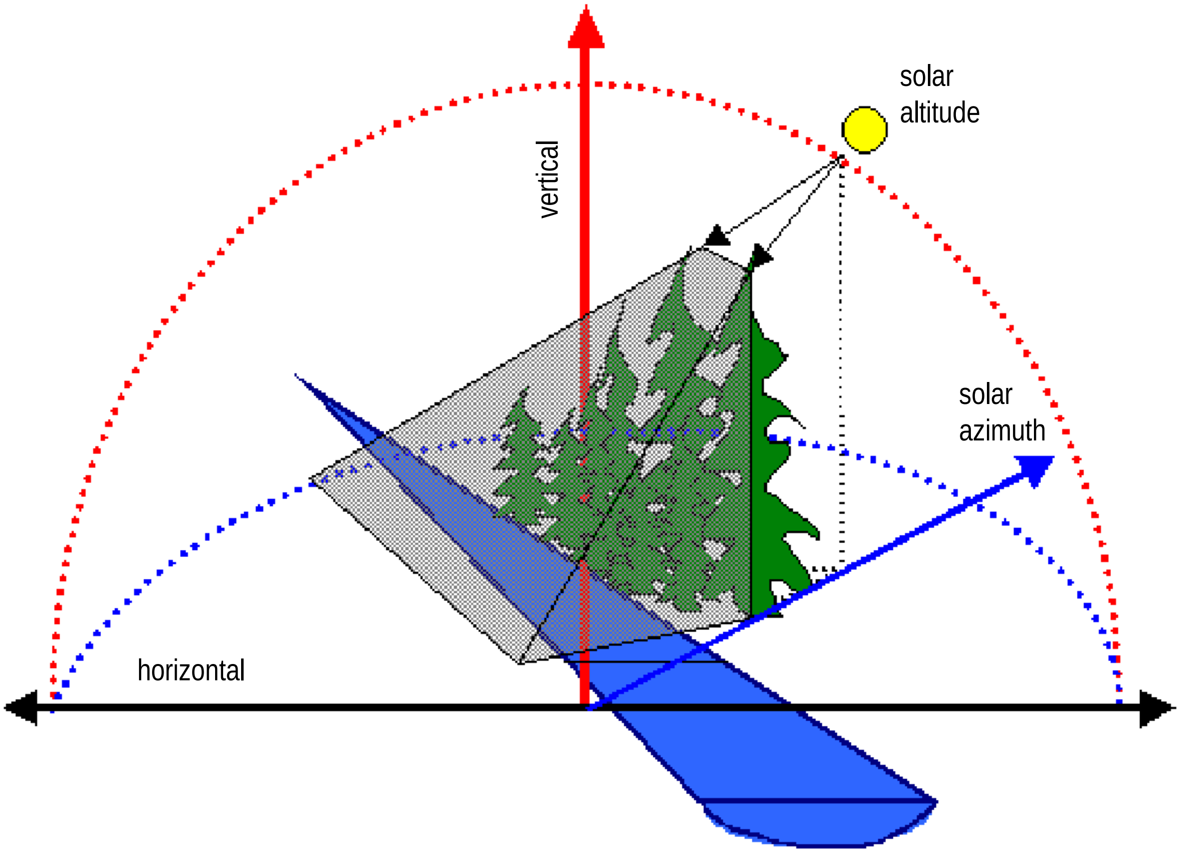

Figure A-6. Parameters that affect shade and geometric relationships. *Solar altitude* is a measure of the vertical angle of the sun's position relative to the horizon. *Solar azimuth* is a measure of the horizontal angle of the sun's position relative to north. (Boyd and Kasper, 2003.)

Hemispherical photography is generally regarded as the most accurate method for measuring shade, although the equipment that is required is significantly more expensive compared with other methods. Angular canopy densiometers (ACD) and solar pathfinders provide a good balance of cost and accuracy for measuring the importance of riparian vegetation for preventing increases in stream temperature (Beschta et al., 1987; Teti, 2001, 2005). Whereas canopy density is usually expressed as a vertical projection of the canopy onto a horizontal surface, the ACD is a projection of the canopy measured at an angle above the horizon at which direct beam solar radiation passes through the canopy. This angle is typically determined by the position of the sun above the horizon during that portion of the day (usually between 10 A.M. and 2 P.M. in mid to late summer) when the potential solar heat flux is most significant. Typical values of the ACD for old-growth stands in western Oregon have been reported to range from 80% to 90%. (Brazier and Brown, 1973; Steinblums et al., 1984).

Computer programs for the mathematical simulation of shade may also be used to estimate shade from measurements or estimates of the key parameters listed in Table A-1 (Ecology 2003; Chen, 1996; Chen et al., 1998; Boyd, 1996; Boyd and Park, 1998).

Table A-1. Factors that influence stream shade.

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

Bold indicates influenced by human activities.

Riparian buffers and effective shade

Trees in riparian areas provide shade to streams and minimize undesirable water temperature changes (Brazier and Brown 1973; Steinblums et al., 1984). The shading effectiveness of riparian vegetation is correlated to riparian area width (Figure A-7). The shade as represented by angular canopy density (ACD) for a given riparian buffer width varies over space and time because of differences among site potential vegetation, and forest development stages (e.g., height and density, and stream width). For example, a 50-foot-wide riparian area with fully developed trees could provide from 45% to 72% of the potential shade in the two studies shown in Figure A-7.

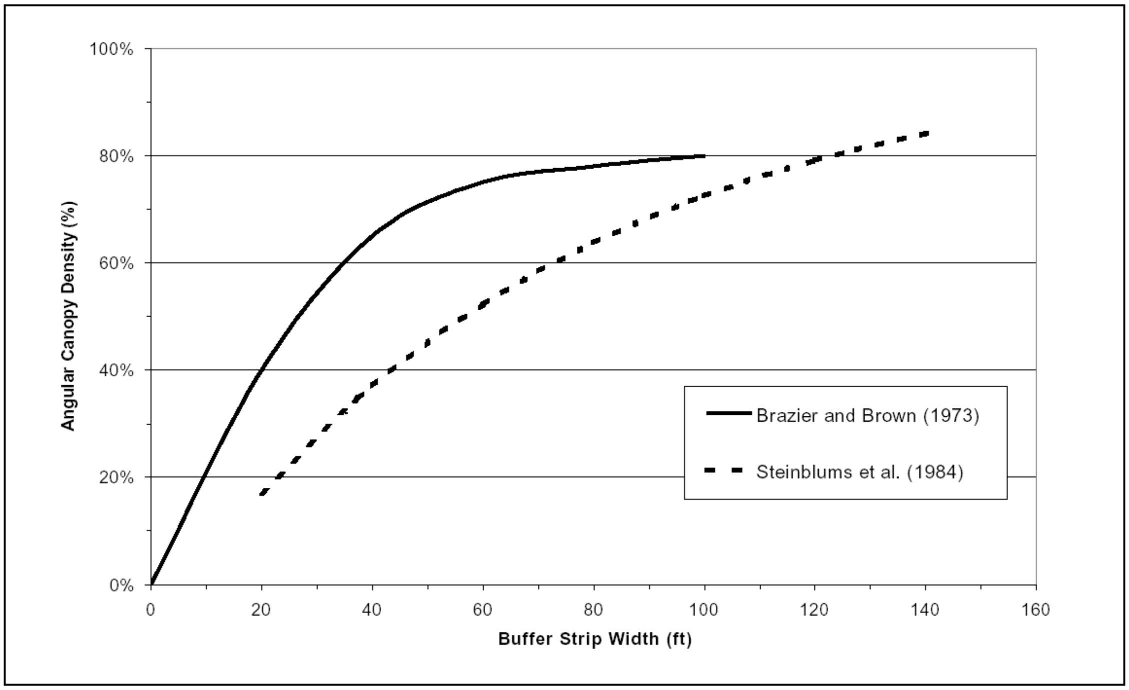

Figure A-7. Relationship between angular canopy density and riparian buffer width for small streams in old-growth riparian stands (after Beschta et al., 1987; and CH2M Hill, 2000).

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

Several studies of stream shading report that most of the potential shade comes from the riparian area within about 75 feet (23 m) of the channel (CH2M Hill, 2000; Castelle and Johnson, 2000):

- Beschta et al. (1987) report that a 98-foot-wide (30-m) buffer provides the same level of shading as that of an old-growth stand.
- Brazier and Brown (1973) found that a 79-foot (24-m) buffer provides maximum shade to streams.
- Steinblums et al. (1984) concluded that a 56-foot (17-m) buffer provides 90% of the maximum ACD.
- Corbett and Lynch (1985) concluded that a 39-foot (12-m) buffer should adequately protect small streams from large temperature changes following logging.
- Broderson (1973) reported that a 49-foot-wide (15-m) buffer provides 85% of the maximum shade for small streams.
- Lynch et al. (1984) found that a 98-foot-wide (30-m) buffer maintains water temperatures within 2°F (1°C) of their former average temperature in small streams (channel width less than 3 m).

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

Steinblums et al. (1984) concluded that shade could be delivered to forest streams from beyond 75 feet (22 m) and potentially out to 140 feet (43 m). In some site-specific cases, forest practices between 75 and 140 feet from the channel have the potential to reduce shade delivery by up to 25% of maximum. However, any reduction in shade beyond 75 feet would probably be relatively low on the horizon, and the impact on stream heating would be relatively minimal because the potential solar radiation decreases significantly as solar elevation decreases.

Microclimate - surrounding thermal environment

A secondary consequence of near-stream vegetation is its effect on the riparian microclimate. Riparian corridors often produce a microclimate that surrounds the stream where cooler air temperatures, higher relative humidity, and lower wind speeds are characteristic. Riparian microclimates tend to moderate daily air temperatures. Evapotranspiration by riparian plant communities increases relative humidity. Physical blockage by riparian vegetation reduces wind speed.

Riparian buffers commonly occur on both sides of the stream, compounding the edge influence on the microclimate. Brosofske et al. (1997) reported that a buffer width of at least 150 feet (45 m) on each side of the stream was required to maintain a natural riparian microclimate environment in small forest streams (channel width less than 4 m) in the foothills of the western slope of the Cascade Mountains in Western Washington with predominantly Douglas-fir and western hemlock.

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

- **Air temperature**. Edgerton and McConnell (1976) showed that removing all or a portion of the tree canopy resulted in cooler terrestrial air temperatures at night and warmer temperatures during the day, enough to influence thermal cover sought by elk (*Cervus canadensis*) on their eastern Oregon summer range. Increases in maximum air temperature varied from 5 to 7°C for the hottest days (estimate). However, the mean daily air temperature did not appear to have changed substantially since the maximum temperatures were offset by almost equal changes to the minima.

  Similar temperatures have been commonly reported (Childs and Flint, 1987; Fowler et al., 1987), even with extensive clearcuts (Holtby, 1988). In an evaluation of buffer strip width, Brosofske et al. (1997) found that air temperatures immediately adjacent to the ground increased 4.5°C during the day and about 0.5°C at night (estimate). Fowler and Anderson (1987) measured a 0.9°C air temperature increase in clearcut areas, but temperatures were also 3°C higher in the adjacent forest. Chen et al. (1993) found similar (2.1°C) increases.

  All measurements reported here were made over land instead of water, but in aggregate support about a 2°C increase in ambient mean daily air temperature resulting from extensive clearcutting.

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

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

Thermal role of channel morphology

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

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

Channel modification usually occurs during high-flow events. Land uses that affect the magnitude and timing of high-flow events may negatively impact channel width and depth. Channel straightening can increase flow velocities and lead to deeply incised streambanks and washout of gravel and cobble substrate. Riparian vegetation conditions will affect the resilience of the streambanks/flood plain during periods of sediment introduction and high flow. Disturbance processes may have differing results depending on the ability of riparian vegetation to shape and protect channels.

Channel morphology can also be the result of upland land practices or disconnection of the flood plain. Erosion in the watershed can result in high bed load and shallower, wider channels downstream. The separation of the flood plain from the main channel of a river can result in sediment being carried in the channel that would otherwise be deposited in the flood plain. It can also increase velocities and bank erosion.

Channel morphology is related to riparian vegetation composition and condition by:

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

References for Appendix A

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

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

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

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

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

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

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

Boyd, M. and B. Kasper, 2003. Analytical methods for dynamic open channel heat and mass transfer: Methodology for heat source model Version 7.0. www.deq.state.or.us/wq/TMDLs/tools.htm

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

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

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

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

Brown, G.W. and J.T. Krygier, 1970. Effects of clear-cutting on stream temperature. Water Resources Research 6(4):1133-1140.

Brown, G.W., G.W. Swank, and J. Rothacher, 1971. Water temperature in the Steamboat drainage. U.S. Department of Agriculture Forest Service, Research Paper PNW-119, Portland, OR. 17 p.

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

CH2M Hill, 2000. Review of the scientific foundations of the forests and fish plan. Prepared for the Washington Forest Protection Association. www.wfpa.org/

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

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

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

Chen, Y.D., R.F. Carsel, S.C. McCutcheon, and W.L Nutter, 1998. Stream temperature simulation of forested riparian areas: I. watershed-scale model development; II. model application. Journal of Environmental Engineering. April 1998. pp 304-328.

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

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

Danehy, R.J., C.G. Colson, K.B. Parrett, and S.D. Duke, 2005. Patterns and sources of thermal heterogeneity in small mountain streams within a forested setting. Forest Ecology and Management, 2005. 208(1-3): p. 287-302.

Ecology, 2003. Shade.xls - a tool for estimating shade from riparian vegetation. Washington State Department of Ecology, Olympia, WA. Models and Tools

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

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

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

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

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

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

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

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

Johnson, S.L., 2004. Factors influencing stream temperatures in small streams: substrate effects and a shading experiment. Canadian Journal of Fisheries and Aquatic Sciences 61:913-923.

Johnson, S.L. and J.A. Jones, 2000. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. Canadian Journal of Fisheries and Aquatic Sciences. Vol. 57 (2): 30-39.

Kelley, C.E., Krueger, 2005. Canopy Cover and Shade Determinations in Riparian Zones. Journal of the American Water Resources Association, 41 (1): 37-46.

Levno, A. and J. Rothacher, 1967. Increases in maximum stream temperatures after logging in old growth Douglas-fir watersheds. U.S. Department of Agriculture, Forest Service PNW-65, Portland, OR. 12 pp.

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

OWEB, 1999. Water quality monitoring technical guidebook: chapter 14, stream shade and canopy cover monitoring methods. Oregon Watershed Enhancement Board.

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

Poole, G.C. and C.H. Berman, 2000. Pathways of Human Influence on Water Temperature Dynamics in Stream Channels. U.S. Environmental Protection Agency, Region 10, Seattle, WA. 20 pp. www.krisweb.com/biblio/gen_usepa_pooleetal_2000_pathways.pdf.

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

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

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

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

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

Teti, P.A., 2001. A new instrument for measuring shade provided by overhead vegetation. Cariboo Forest Region Research Section, British Columbia Ministry of Forests, Extension note No. 34.

Teti, P.A. and R.G. Pike, 2005. Selecting and testing an instrument for surveying stream shade. BC Journal of Ecosystems and Management 6(2):1-16. www.forrex.org/jem/2005/vol6_no2_art1.pdf

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

Appendix B. Analysis of Model Sensitivity

The general behavior of the calibrated 2015 QUAL2Kw model was evaluated through a sensitivity analysis using simple parameter perturbation (Chapra, 1997). This method raises/lowers a single model parameter to evaluate the effect on simulated daily maximum water temperature. Parameter perturbation was applied for the following model parameters:

- meteorological values (air temperature)
- channel geometry (water depth and water velocity)
- effective shade
- tributary/headwater flow and temperature (Tieton Dam and upper Naches River at the confluence with the Tieton River)

Water temperatures simulated with a single perturbed parameter were compared against the calibrated 2015 model (baseline) to quantify the sensitivity of the model for each of the above parameters. Changes were assessed for daily maximum water temperature on 7/2/2015 because that date had the highest water temperature.

Changes in simulated daily maximum water temperature are shown as boxplots in Figures B-1 to B-3. The boxplots are separated by river to represent the changes along each modeled reach of the Tieton River (35 reaches) and the lower Naches River (31 reaches). Perturbations to the upper Naches River (at the Tieton River confluence) have no effect on the Tieton River since the perturbation occurs downstream of the Tieton River mouth. These boxplots show the range from the most-impacted reach versus the least-impacted reach.

In Figure B-1, altering effective shade, water depth, and water velocity (±10%) has an impact of typically less than 1°C. This perturbation occurs along the entire length of both rivers, and the magnitude of the effect is similar in both rivers. Reaches of the Tieton River close to the headwater (Tieton Dam) are less affected by the change since it takes time for the cold water exiting the dam to experience changes. Shade and depth have larger impacts overall than does velocity.

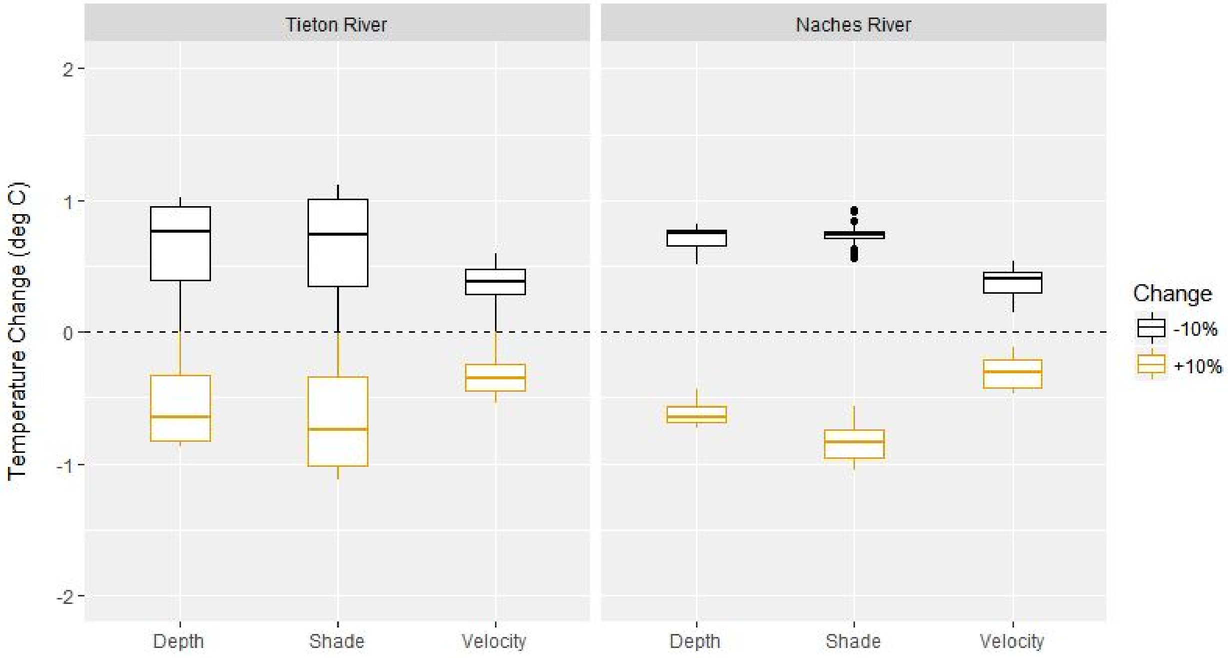

Figure B-1. Boxplots showing change in daily maximum water temperature on 7/2/2015 relative to the baseline model due to altering effective shade, water depth, and water velocity.

In Figure B-2, altering flow (±50 cfs) from the Tieton Dam (model headwater) has a strong influence on daily maximum water temperature, >1°C at the mouth of both rivers. This is consistent with results in the Model Scenarios section above. Altering flow (±50 cfs) from the upper Naches River has less effect on water temperature: <1°C on the lower Naches River and no effect on the Tieton River. This is because water from the upper Naches River is warmer than water from the Tieton River. Increasing flow from the upper Naches River still has an overall cooling effect on the lower Naches River, except for a small amount of warming which occurs near the Tieton River confluence, where the warmer water mixes with the cooler water entering from the Tieton River.

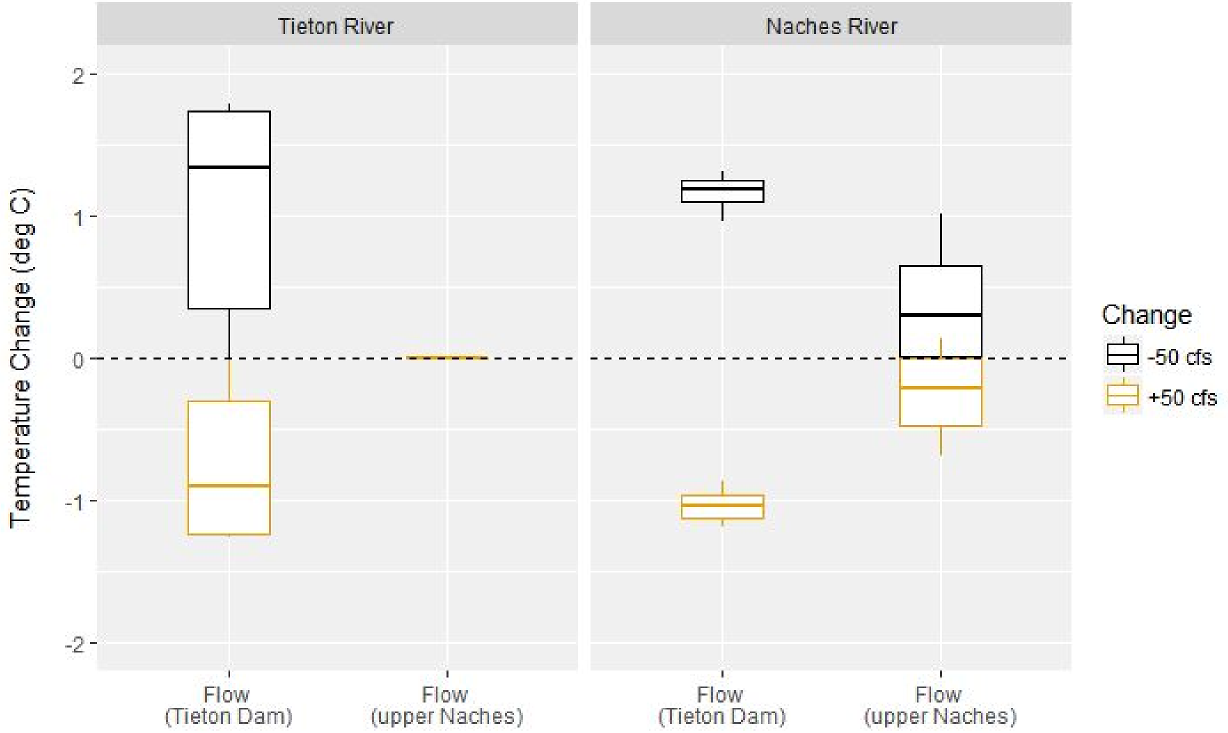

Figure B-2. Boxplots showing change in daily maximum water temperature on 7/2/2015 relative to the baseline model due to altering flow at the Tieton Dam (headwater) and the upper Naches River (at the Tieton River confluence).

In Figure B-3, altering air temperature (±2°C) has relatively little impact on water temperature, due to the short amount of time the water is exposed to the air in the simulation. Note that the simulation of air temperature did not include changes to the water temperature entering from the upper Naches River.

Altering water temperature at the Tieton Dam has a strong impact on simulated water temperature in the Tieton River; it has less impact on water in the lower Naches River. The lower Naches River is more impacted when alterations are made to water temperature from the upper Naches River.

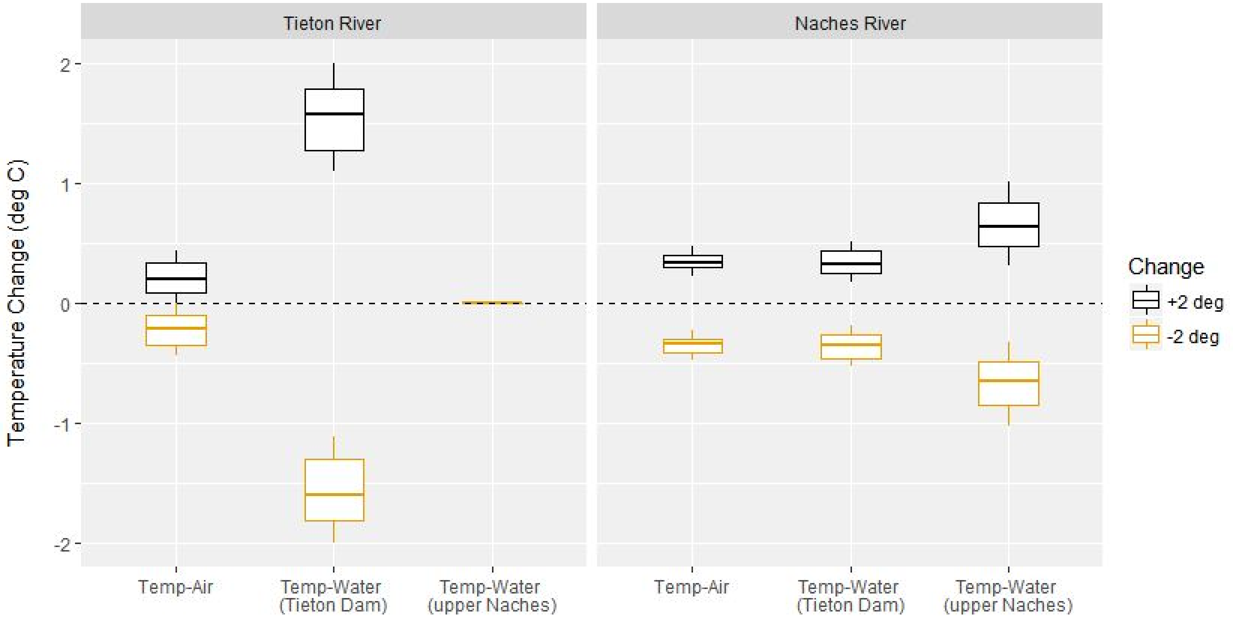

Figure B-3. Boxplots showing change in daily maximum water temperature on 7/2/2015 relative to the baseline model due to altering air temperature, water temperature at Tieton Dam (headwater), and water temperature in the upper Naches River at the Tieton River confluence.

Sensitivity Analysis Summary

Simulated maximum daily water temperatures on 7/2/2015 in the Tieton and lower Naches Rivers are sensitive to several model parameters:

- The most sensitive parameter was the amount of flow from Tieton Dam.
- The least sensitive parameter was air temperature, due to short travel times in this system.
- Water velocity was not a sensitive parameter, again due to short travel times in this system.
- Shade and water depth both had moderate impact on temperature.
- Water temperature from the upper Naches River had a moderate impact on temperature in the lower Naches River.

Appendix C. Tables

Table C-1. Types and sources of data used in the QUAL2Kw model.

Parameter	Location	Source Agency	Description
Air Temperature	Tieton Dam Milepost 180 above Fishing Area mouth - Naches R	Ecology Ecology WSU NOAA	Temperature logger Temperature logger Naches weather station Yakima airport weather station
Dew Point	Tieton Dam Drinking water treatment plant mouth - Naches R	Ecology Ecology / WSU Ecology / NOAA	Relative humidity gage + air temperature logger Relative humidity gage + Naches weather station air temp Relative humidity gage + airport air temperature
Wind Speed	Tieton Dam above Fishing Area mouth - Naches R	USBR WSU NOAA	Weather station Naches weather station Yakima airport weather station
Cloud Cover	All stations	WSU	Calculated using Naches weather station solar attenuation
Shortwave Radiation	All stations	(model)	Ryan-Stolzenbach (0.8)
Down-welling Longwave Radiation	All stations	(model)	Satterlund
Water Temperature	All major sources	Ecology	Temperature logger (EIM)
Flow Rate	Tieton Dam Wildcat Creek Soup Creek Milk Creek Hause Creek Pine Creek Tieton Canal diversion Oak Creek upper Naches River Wapatox diversion Clark diversion Kelly-Lowry diversion South Naches diversion Wapatox return flow Yakima City M&I diversion South Naches return flow Gleed diversion Yakima Valley Canal diversion Chapman-Nelson diversion Naches-Cowiche diversion Yakima City Irrigation diversion Buckskin Slough Fruitvale diversion Old Union diversion Cowiche Creek	USBR Ecology Ecology Ecology Ecology Ecology USBR Ecology Ecology / USBR USBR USBR Ecology USBR USBR USBR no data avail USBR USBR Ecology USBR USBR Ecology USBR USBR Ecology	RIM gage Discrete flow measurements Discrete flow measurements Discrete flow measurements Discrete flow measurements Discrete flow measurements TIEW gage Discrete flow measurements Oak Flats gage (ECY) / CLFW and NSCW gages (USBR) WOPW gage Average reported flow (2001-04) Discrete flow measurements SOUW gage WAPW gage Average reported flow (2001-04) Set to 50% of diversion flow Average reported flow (2001-04) Average reported flow (2001-04) Discrete flow measurements Average reported flow (2001-04) Average reported flow (2001-04) Discrete flow measurements Average reported flow (2001-04) Average reported flow (2001-04) Discrete flow measurements

Table C-2. Vegetation codes used in the Shade model.

Code	Description	Height (m)	Density (%)	Overhang (m)
111	conifer, small, sparse	9.0	25%	1.0
112	conifer, small, dense	9.0	75%	1.0
113	conifer, small, medium	9.0	50%	1.0
131	conifer, medium, sparse	20.0	25%	1.5
132	conifer, medium, dense	20.0	75%	1.5
133	conifer, medium, medium	20.0	50%	1.5
121	conifer, large, sparse	30.5	25%	3.0
122	conifer, large, dense	30.5	75%	3.0
123	conifer, large, medium	30.5	50%	3.0
211	deciduous, small, sparse	9.0	25%	1.0
212	deciduous, small, dense	9.0	75%	1.0
213	deciduous, small, medium	9.0	50%	1.0
231	deciduous, medium, sparse	22.0	25%	2.0
232	deciduous, medium, dense	22.0	75%	2.0
233	deciduous, medium, medium	22.0	50%	2.0
221	deciduous, large, sparse	32.0	25%	4.0
222	deciduous, large, dense	32.0	75%	4.0
223	deciduous, large, medium	32.0	50%	4.0
311	mixed, small, sparse	9.0	25%	1.0
312	mixed, small, dense	9.0	75%	1.0
313	mixed, small, medium	9.0	50%	1.0
331	mixed, medium, sparse	22.0	25%	2.0
332	mixed, medium, dense	22.0	75%	2.0
333	mixed, medium, medium	22.0	50%	2.0
321	mixed, large, sparse	32.0	25%	3.0
322	mixed, large, dense	32.0	75%	3.0
323	mixed, large, medium	32.0	50%	3.0
400	riparian scrub/ shrub	2.0	75%	0.2
401	scrub/ shrub upland	2.0	25%	0.2
500	grass/ rush/ sedge riparian	0.5	75%	0.1
600	barren	0.0	100%	0.0
700	water	0.0	100%	0.0
800	developed	6.1	100%	0.6
850	pastures, cultivated--lawn	0.0	100%	0.0
870	orchard	3.0	75%	0.0
1000	water flows under bridge	50.0	100%	0.0
2000	water flows under road, through culvert		100%	0.0

Table C-3. Velocity and depth rating coefficients used in the QUAL2Kw model.

Site	Reach #	Rating Curves			
		Velocity		Depth	
		coef	exp	coef	exp
	0	0.280	0.490	0.227	0.321
TietonR below Dam	1	0.280	0.490	0.204	0.321
	2	0.280	0.490	0.225	0.311
	3	0.280	0.490	0.277	0.246
	4	0.280	0.490	0.195	0.354
	5	0.280	0.490	0.184	0.380
	6	0.280	0.490	0.195	0.351
	7	0.280	0.490	0.156	0.415
	8	0.280	0.490	0.141	0.422
TietonR at Willows CG	9	0.280	0.490	0.204	0.355
	10	0.280	0.490	0.270	0.323
	11	0.280	0.490	0.198	0.333
TietonR near USBR	12	0.280	0.490	0.255	0.347
	13	0.333	0.430	0.152	0.586
	14	0.333	0.430	0.157	0.537
	15	0.333	0.430	0.214	0.434
	16	0.333	0.430	0.214	0.434
	17	0.333	0.430	0.214	0.434
	18	0.333	0.430	0.202	0.448
	19	0.333	0.430	0.202	0.448
	20	0.333	0.430	0.202	0.448
TietonR at Windy Point	21	0.333	0.430	0.147	0.495
	22	0.333	0.430	0.266	0.307
	23	0.333	0.430	0.143	0.503
	24	0.333	0.430	0.197	0.343
TietonR abv MM180	25	0.333	0.430	0.166	0.422
	26	0.317	0.472	0.204	0.386
	27	0.317	0.472	0.208	0.357
	28	0.317	0.472	0.242	0.340
	29	0.317	0.472	0.235	0.383
	30	0.317	0.472	0.246	0.365
TietonR abv Oak Creek	31	0.317	0.472	0.159	0.456
	32	0.317	0.472	0.210	0.405
	33	0.317	0.472	0.206	0.411
TietonR at Tom's Pond	34	0.317	0.472	0.210	0.429
TietonR near mouth	35	0.317	0.472	0.157	0.418
	36	0.317	0.472	0.115	0.395

Site	Reach #	Rating Curves			
		Velocity		Depth	
		coef	exp	coef	exp
NachesR at upper USBR	37	0.317	0.472	0.153	0.446
	38	0.323	0.353	0.185	0.399
	39	0.323	0.353	0.155	0.478
	40	0.323	0.353	0.183	0.402
	41	0.323	0.353	0.148	0.485
	42	0.323	0.353	0.130	0.590
	43	0.323	0.353	0.213	0.402
NachesR at Naches Road	44	0.323	0.353	0.156	0.465
	45	0.323	0.353	0.218	0.311
	46	0.323	0.353	0.187	0.485
	47	0.323	0.353	0.233	0.381
NachesR abv fishing area	48	0.323	0.353	0.169	0.429
	49	0.323	0.353	0.127	0.548
	50	0.323	0.353	0.290	0.370
NachesR at Water Plant	51	0.323	0.353	0.498	0.141
	52	0.245	0.398	0.518	0.132
	53	0.245	0.398	0.201	0.406
	54	0.245	0.398	0.185	0.406
	55	0.245	0.398	0.129	0.441
	56	0.245	0.398	0.223	0.425
	57	0.245	0.398	0.222	0.321
	58	0.245	0.398	0.181	0.432
	59	0.245	0.398	0.197	0.456
NachesR at N-C diversion	60	0.245	0.398	0.390	0.302
	61	0.245	0.398	0.154	0.499
	62	0.245	0.398	0.207	0.428
	63	0.245	0.398	0.242	0.424
16th Ave	64	0.245	0.398	0.211	0.410
NachesR at lower USBR	65	0.245	0.398	0.102	0.429
NachesR near mouth	66	0.245	0.398	0.203	0.430

Appendix D. Quality Assurance Evaluation for 2015 Data Collection

Ecology studied water temperatures in the Tieton River and lower Naches River within the Naches River basin during 2005, a year with a declared drought (Urmos-Berry, 2015). Temperature loggers were used to continuously monitor the temperature at multiple locations along the Tieton River, lower Naches River, and key water inflows. Also, streamflow was monitored at selected locations. No replicate flow measurements were collected.

Data collection occurred during May-October 2015, and final data were submitted to Ecology's Environmental Information Management (EIM) database.

Temperature

The accuracy and instrument bias measurement quality objectives (MQOs) of each temperature logger was verified through both pre- and post-deployment calibration checks following the *Standard Operating Procedures for Continuous Temperature Monitoring of Fresh Water Rivers and Streams* (Ward, 2011). The procedures require the temperature loggers be tested in controlled water temperature baths that bracket the expected monitoring range (near 0ºC and near 20ºC).

In accordance with Ward (2011), for each water bath, ten water temperature readings were recorded using a NIST-certified thermometer. The average absolute difference between data logger values and these readings was calculated (Table D-1).

Post-check results were good for all 27 temperature loggers used in this study, within manufacturer-stated accuracy (±0.2°C).

Many of the data loggers (Tidbit V2) used for the 2015 study did not pass the pre-check requirements for water tidbits indicated in the SOP (Ward, 2011), especially for the ice bath. This was likely due to issues maintaining uniform temperatures in the water bath, rather than issues with the temperature loggers. According to the SOP, tidbits that have a mean difference of 0.2°C in one or both baths should not be deployed for water temperature monitoring unless the tidbits pass a follow-up test.

Some of these temperature loggers were accidentally deployed due to mixing two groups of data loggers: those from this pre-check bath, along with another set of data loggers which had also failed this pre-check but had passed a follow-up test. It was known that issues occurred during the initial pre-check, so a follow-up test was performed. Both the initial pre-check and follow-up test included more temperature loggers than shown in Table D-1. Some of the loggers were omitted from the follow-up test by accident, and the two groups of data loggers later became mixed.

Sampling bias was minimized by following data logger deployment procedures described in Ward (2011). These procedures specify site selection and deployment methods designed to ensure that the temperature logger results are representative of stream conditions throughout the entire 2015 monitoring period and not biased by the effects of solar radiation or low streamflow conditions.

Table D-1. Mean absolute difference of temperature loggers versus ten NIST thermometer readings.

Pre-check average diff (deg C)			Site	Serial #	Post-check average diff (deg C)		
ice bath	mid-range	room temp			ice bath	mid-range	room temp
0.35	0.20	0.19	TietonR below Dam	10221701	0.12	0.19	0.16
0.03	0.08	0.15	Wapatox return1	10225285	0.12	0.21	0.18
0.44	0.07	0.14	NachesR near mouth	10227096	0.20	0.13	0.12
0.03	0.22	0.17	Wapatox return2	10227100	0.12	0.20	0.19
0.12	0.10	0.04	Wapatox return / Water Plant diversion	10227105	0.23	0.07	0.07
0.20	0.15	0.21	NachesR at Powerhouse Rd	10227109	0.15	0.19	0.19
0.39	0.25	0.20	TietonR at Tom's Pond	10227110	0.09	0.21	0.19
0.35	0.18	0.21	Cowiche Creek	10227111	0.15	0.19	0.17
0.03	0.10	0.14	NachesR at Water Plant and Buckskin1	10227112	0.23	0.11	0.09
0.03	0.06	0.09	TietonR abv MM180	10227113	0.20	0.12	0.12
0.41	0.25	0.19	Wildcat Creek	10227121	0.12	0.20	0.18
0.23	0.11	0.13	Cowiche Creek	10227123	0.20	0.12	0.12
0.27	0.19	0.19	TietonR near USBR	10227124	0.12	0.19	0.19
0.19	0.19	0.22	NachesR near mouth	10227125	0.20	0.19	0.20
0.52	0.23	0.24	TietonR near mouth	10227126	0.12	0.19	0.16
0.19	0.20	0.23	Air06.1	10227128	0.09	0.22	0.21
0.65	0.25	0.21	TietonR at Windy Point	10227129	0.13	0.19	0.00
0.30	0.17	0.19	NachesR abv fishing area	10227133	0.17	0.16	0.16
0.40	0.16	0.14	Air20.8	10227134	0.18	0.16	0.15
0.19	0.14	0.14	NachesR below Naches Selah Canal	10227137	0.15	0.17	0.14
0.23	0.21	0.19	NachesR abv Tieton conf and Buckskin2	10227138	0.12	0.21	0.19
0.26	0.09	0.17	NachesR at upper USBR	10227139	0.12	0.12	0.20
0.04	0.14	0.14	TietonR abv Oak Creek	10227140	0.17	0.14	0.14
0.03	0.07	0.11	NachesR abv Tieton conf and Oak Creek	10227141	0.21	0.12	0.03
0.51	0.24	0.12	TietonR at Willows CG	10227142	0.21	0.12	0.12
0.23	0.20	0.24	TietonR near mouth and NachesR abv confluence	10227143	0.00	0.00	0.21
0.10	0.13	0.17	NachesR at Naches Road	10227144	0.12	0.19	0.17

Flow

At the beginning of each week in the field, the Marsh-McBirney FlowMate® was zeroed out to ensure accurate measurements. The expected accuracy and reporting limits are found in Urmos-Berry (2015).

No replicate flow measurements were collected in 2015.

Appendix E. Groundwater Inflow - Lower Naches River

This appendix provides additional information about groundwater inflow distribution and temperature used in the model for the lower Naches River. A calculation error in USGS analysis of groundwater inflow along the lower Naches River is also documented.

Distribution of groundwater inflow

As noted in the body of this report, the model distributes groundwater inflow uniformly along the Naches River between RM 17.1 and RM 3.4. The model distribution of inflowing groundwater was based on a gradual increase in specific conductivity measured in the 2015 river profile. This profile is shown in Figure E-1.

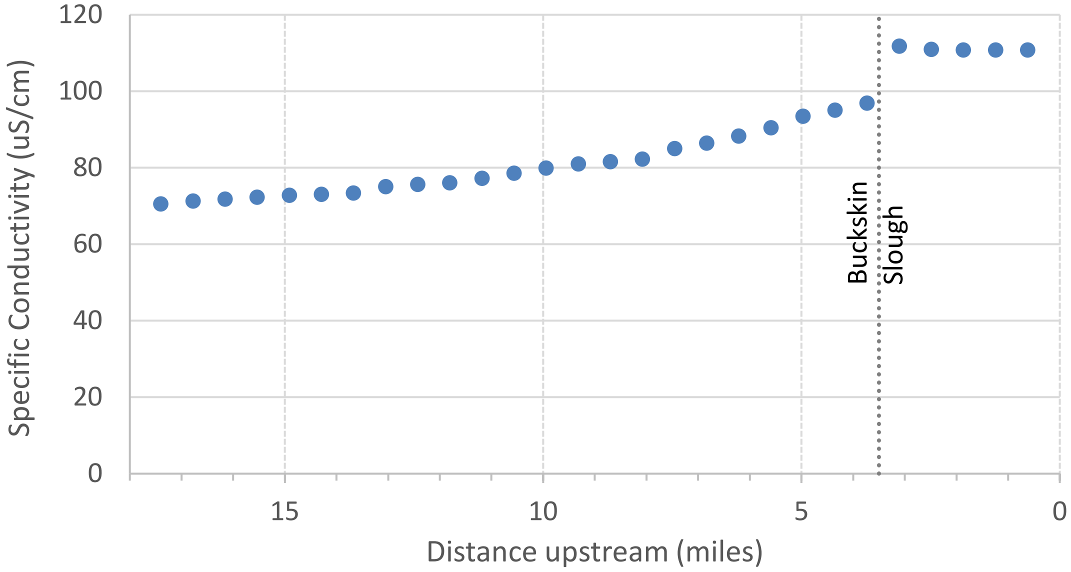

Figure E-1. Specific conductivity profile measured in the Naches River on 8/14/2015, averaged along 1 kilometer model reaches.

There is a change in slope near RM 8 for the specific conductivity profile above, which may be due to changes in groundwater inflow rate, changes in specific conductivity of the groundwater, or changes in the river volume due to irrigation diversions. For the model, the groundwater inflow was set at a constant rate due to insufficient information to determine the exact distribution of groundwater inflow for the Naches River.

Besides groundwater, other sources of surface water to the river could contribute to the observed rise in specific conductivity along the river. However, any large sources would be expected to create sudden jumps in the profile, similar to the jump at Buckskin Slough in Figure E-1. Apart from this one jump, the overall pattern of increasing conductivity is relatively smooth.

Specific conductivity of groundwater near the Naches River was not measured in 2004 or 2015. For future studies, measuring the specific conductivity of groundwater might improve estimates of groundwater flux along the lower Naches River, because the observed rise in conductivity along the river could then be simulated in the model.

Groundwater inflow temperature

As noted above, groundwater temperature in the calibrated model was set to a constant value of 15.9°C. The actual temperature of inflowing groundwater during 2015 is uncertain because no groundwater monitoring was performed along the lower Naches River that year. It is likely that the actual groundwater temperature varies seasonally (Carey, 2007). A constant temperature value was used in the model due to lack of information regarding seasonal variation during 2015.

The temperature used in the model was based on the following sources of information:

- Figure 6 (Carey, 2007) at RM 3.7 which shows a seasonal hyporheic temperature that appears independent of river temperature and has a range of approximately 14-17°C.
- Table 5 (Carey, 2007) at RM 8.5 which lists a piezometer temperature of 15.9°C for Aug 3-9, 2004.
- Piezometer AHT082 (EIM) temperature measurement of 15.8°C during August 2013 along Wide Hollow Creek near Union Gap, WA.

Because the temperature of inflowing groundwater is uncertain, model sensitivity to this parameter is shown in Figure E-2. Decreasing groundwater temperature to 13.9°C (change of -2°C) simulated daily maximum temperature decreased ≤ 0.2°C. Decreasing groundwater temperature to 11.9°C (change of -4°C) simulated daily maximum temperature decreased ≤ 0.4°C.

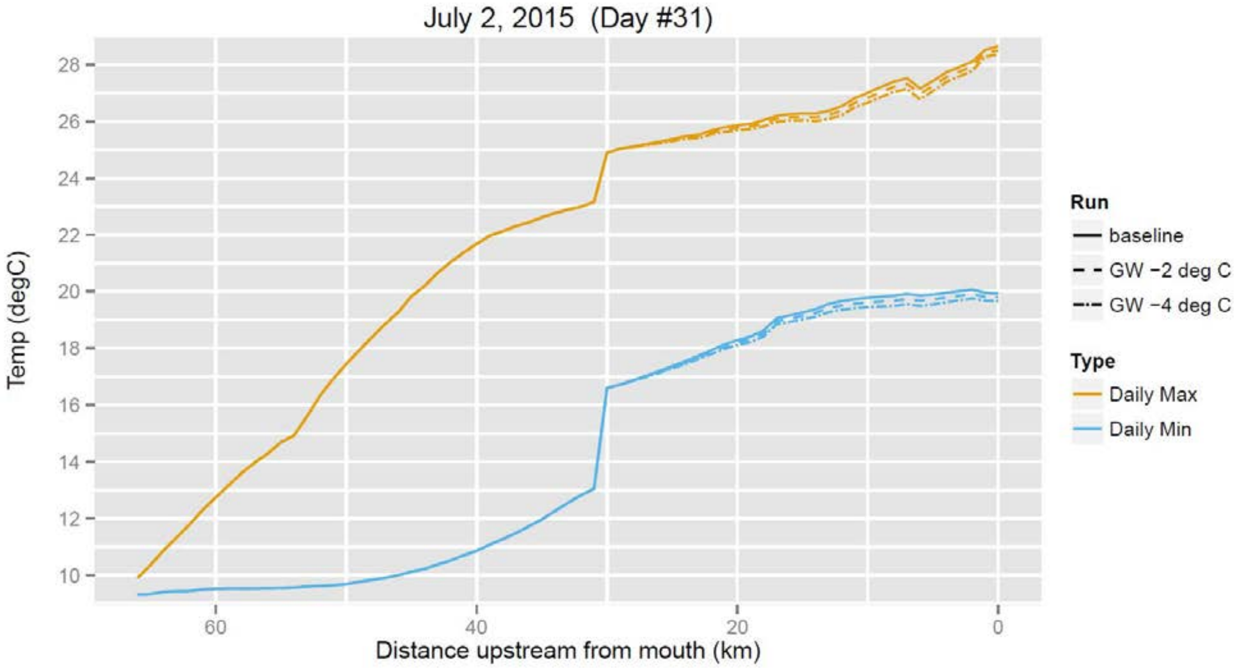

Figure E-2. Sensitivity of simulated temperature to groundwater temperature on one of the hottest days (7/2/2015).

USGS Calculation Error

The USGS published a data summary which included Ecology's original seepage study data from Carey (2007) but which calculated different gain and loss rates for the lower Naches River (Table 13 in Magirl et al., 2009). Differences between values found in Table 13 of the USGS data summary and the original values published in Carey (2007) for the lower Naches River are partially documented in Table E-1 below.

Based on correspondence with Dr. Christopher Magirl (USGS), there appears to be a bug or error (maybe as many as 4) in Table 13 of the USGS data summary. This indicates that Figure 18 of Vaccaro et al. (2011), which utilizes the USGS data summary, is also possibly incorrect for the lower Naches River. Because the reliability of Table 13 in the USGS data summary is questionable, Dr. Magirl believes that referring back to the original data in Carey (2007) is appropriate for Ecology's modeling analysis.

Ecology also noted discrepancies between tributary inflow and diversion outflow between Carey (2007) and Table 13 of the USGS data summary. These are listed in Table E-2 below. Based on these values, it appears that Table 13 of the USGS data summary categorized two of the return flows to the Naches River listed in Carey (2007) as diversions: the Wapatox Canal return at RM 9.7 and the Kelley Ditch return at RM 10 (see Appendix B of Carey, 2007).

References for Appendix E

Carey, B., 2007. Groundwater-surface water interactions along the Naches and Tieton Rivers, summer and fall 2004. Washington State Department of Ecology, Olympia, WA. Publication No. 06-03-003. https://fortress.wa.gov/ecy/publications/SummaryPages/0603003.html

Magirl, C.S., Julich, R.J., Welch, W.B., Curran, C.R., Mastin, M.C., and Vaccaro, J.J., 2009. Summary of seepage investigations in the Yakima River basin, Washington: U.S. Geological Survey Data Series 473. https://pubs.usgs.gov/ds/473/

Table E-1. Comparison of net seepage gain or loss between the original seepage study (Appendix B in Carey, 2007) and the data summary of that study (Table 13 in Magirl et al., 2009).

			Values in Agreement			**Values in Disagreement**	
						Appendix B Carey (2007)	Table 13 Magirl et al. (2009)
Location Description	Site ID	River Mile	Mean Discharge (cfs)	Change from upstream (cfs)	Reach length (miles)	Net Seepage Gain or Loss (cfs/mile)	Net Seepage Gain or Loss (cfs/mile)
Naches River above Tieton River	38-NAC-17.6	17.6	369	---	---	---	---
Naches River below Tieton River	38-NAC-16	16	467	-34	1.6	-21	-31
Naches River at South Naches Road	38-NAC-12.8	12.8	367	-26	3.2	-8.0	-22
Naches River at USBR gage NRYW	38-NAC-0.5	0.5	432	95	12.3	7.7	41

Table E-2. Comparison of tributary inflow and diversion outflow between the original seepage study (Appendix B in Carey, 2007) and the data summary of that study (Table 13 in Magirl et al., 2009).

Naches River Reach	**Tributary Inflow** (cfs)		**Diversion Outflow** (cfs)	
	Carey (2007)	Magirl et al. (2009)	Carey (2007)	Magirl et al. (2009)
RM 17.6-16	287	287	155	155
RM 16-12.8	0	0	74	74
RM 12.8-0.5	138	22	168	284

Appendix F. Glossary, Acronyms, and Abbreviations

Glossary

1-DMax or 1-day maximum temperature: The highest water temperature reached on any given day. This measure can be obtained using calibrated maximum and minimum thermometers or continuous monitoring probes having sampling intervals of 30 minutes or less.

7-DADMax or 7-day average of the daily maximum temperatures: The arithmetic average of seven consecutive measures of daily maximum temperatures. The 7-DADMax for any individual day is calculated by averaging that day's daily maximum temperature with the daily maximum temperatures of the three days prior and the three days after that date.

7Q10 flow: A critical low-flow condition. The 7Q10 is a statistical estimate of the lowest 7-day average flow that can be expected to occur once every 10 years on average. The 7Q10 flow is commonly used to represent the critical flow condition in a water body and is typically calculated from long-term flow data collected in each basin. For temperature TMDL work, the 7Q10 is usually calculated for the months of July and August as these typically represent the critical months for temperature in our state.

303(d) List: Section 303(d) of the federal Clean Water Act requires Washington State periodically to prepare a list of all surface waters in the state for which beneficial uses of the water – such as for drinking, recreation, aquatic habitat, and industrial use – are impaired by pollutants. These are water quality-limited waterbodies (ocean waters, estuaries, lakes, and streams) that fall short of state surface water quality standards and are not expected to improve within the next two years.

Clean Water Act: A federal act passed in 1972 that contains provisions to restore and maintain the quality of the nation’s waters. Section 303(d) of the Clean Water Act establishes the TMDL program.

Conductivity: A measure of water’s ability to conduct an electrical current. Conductivity is related to the concentration and charge of dissolved ions in water.

Critical condition: When the physical, chemical, and biological characteristics of the receiving water environment interact with the effluent to produce the greatest potential adverse impact on aquatic biota and existing or designated water uses. For steady-state discharges to riverine systems, the critical condition may be assumed to be equal to the 7Q10 (see definition) flow event unless determined otherwise by the department.

Designated uses: Those uses specified in Chapter 173-201A WAC (Water Quality Standards for Surface Waters of the State of Washington) for each water body or segment, regardless of whether or not the uses are currently attained.

Diel: Of, or pertaining to, a 24-hour period.

Diurnal: Of, or pertaining to, a day or each day; daily. (1) Occurring during the daytime only, as different from nocturnal or crepuscular, or (2) Daily; related to actions which are completed in the course of a calendar day, and which typically recur every calendar day (for example, diurnal temperature rises during the day and falls during the night.)

Effective shade: The fraction of incoming solar shortwave radiation that is blocked from reaching the surface of a stream or other defined area.

Effluent: An outflowing of water from a natural body of water or from a man-made structure. For example, the treated outflow from a wastewater treatment plant.

Exceeded criteria: Did not meet criteria.

Hyporheic: The area beneath and adjacent to a stream where surface water and groundwater intermix.

Load allocation: The portion of a receiving water's loading capacity attributed to one or more of its existing or future sources of nonpoint pollution or to natural background sources.

Margin of safety: Required component of TMDLs that accounts for uncertainty about the relationship between pollutant loads and quality of the receiving water body.

National Pollutant Discharge Elimination System (NPDES): National program for issuing, modifying, revoking and reissuing, terminating, monitoring, and enforcing permits, and imposing and enforcing pretreatment requirements under the Clean Water Act. The NPDES program regulates discharges from wastewater treatment plants, large factories, and other facilities that use, process, and discharge water back into lakes, streams, rivers, bays, and oceans.

Near-stream disturbance zone (NSDZ): The active channel area without riparian vegetation that includes features such as gravel bars.

Nonpoint source: Pollution that enters any waters of the state from any dispersed land-based or water-based activities, including but not limited to atmospheric deposition, surface-water runoff from agricultural lands, urban areas, or forest lands, subsurface or underground sources, or discharges from boats or marine vessels not otherwise regulated under the NPDES program. Generally, any unconfined and diffuse source of contamination. Legally, any source of water pollution that does not meet the legal definition of "point source" in section 502(14) of the Clean Water Act.

Parameter: Water quality constituent being measured (analyte). A physical, chemical, or biological property whose values determine environmental characteristics or behavior.

Point source: Sources of pollution that discharge at a specific location from pipes, outfalls, and conveyance channels to a surface water. Examples of point source discharges include municipal wastewater treatment plants, municipal stormwater systems, industrial waste treatment facilities, and construction sites where more than 5 acres of land have been cleared.

Pollution: Contamination or other alteration of the physical, chemical, or biological properties of any waters of the state. This includes change in temperature, taste, color, turbidity, or odor of the waters. It also includes discharge of any liquid, gaseous, solid, radioactive, or other substance into any waters of the state. This definition assumes that these changes will, or are likely to, create a nuisance or render such waters harmful, detrimental, or injurious to (1) public health, safety, or welfare, or (2) domestic, commercial, industrial, agricultural, recreational, or other legitimate beneficial uses, or (3) livestock, wild animals, birds, fish, or other aquatic life.

Reach: A specific portion or segment of a stream.

Riparian: Relating to the banks along a natural course of water.

Salmonid: Fish that belong to the family *Salmonidae*. Species of salmon, trout, or char.

Stormwater: The portion of precipitation that does not naturally percolate into the ground or evaporate but instead runs off roads, pavement, and roofs during rainfall or snow melt. Stormwater can also come from hard or saturated grass surfaces such as lawns, pastures, playfields, and from gravel roads and parking lots.

Surface waters of the state: Lakes, rivers, ponds, streams, inland waters, salt waters, wetlands and all other surface waters and water courses within the jurisdiction of Washington State.

System potential: The design condition used for TMDL analysis.

S**ystem-potential mature riparian vegetation:** Vegetation which can grow and reproduce on a site, given climate, elevation, soil properties, plant biology, and hydrologic processes.

System-potential temperature: An approximation of the temperatures that would occur under natural conditions. System potential is our best understanding of natural conditions that can be supported by available analytical methods. The simulation of the system-potential condition uses best estimates of *mature riparian vegetation, system-potential channel morphology, and system-potential riparian microclimate* that would occur absent any human alteration.

Total Maximum Daily Load (TMDL): Water cleanup plan. A distribution of a substance in a waterbody designed to protect it from not meeting (exceeding) water quality standards. A TMDL is equal to the sum of all of the following: (1) individual wasteload allocations for point sources, (2) the load allocations for nonpoint sources, (3) the contribution of natural sources, and (4) a Margin of Safety to allow for uncertainty in the wasteload determination. A reserve for future growth is also generally provided.

Wasteload allocation: The portion of a receiving water’s loading capacity allocated to existing or future point sources of pollution. Wasteload allocations constitute one type of water quality-based effluent limitation.

Watershed: A drainage area or basin in which all land and water areas drain or flow toward a central collector such as a stream, river, or lake at a lower elevation.

Acronyms and Abbreviations

CWA	Clean Water Act
DEM	digital elevation model
Ecology	Washington State Department of Ecology
EIM	Environmental Information Management
EPA	U.S. Environmental Protection Agency
GIS	Geographic Information System software
GPS	global positioning system

M&I	Municipal and Industrial
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NSDZ	near-stream disturbance zone
ODEQ	Oregon Department of Environmental Quality
POTW	publicly owned treatment works
RM	river mile
RMSE	root mean squared error
RPD	relative percent difference
SOP	standard operating procedure
TMDL	total maximum daily load (water cleanup plan)
USBR	U.S. Bureau of Reclamation
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WAC	Washington Administrative Code
WLA	wasteload allocation
WQA	water quality assessment
WRIA	water resources inventory area
WSU	Washington State University
WTP	water treatment plant

Units of Measurement

°C	degrees centigrade
cfs	cubic feet per second
°F	degrees Fahrenheit
ft	feet
ft/s	feet per second
in	inch
km	kilometer, a unit of length equal to 1,000 meters.
m	meter
mi	mile
mgd	million gallons per day
s	second
um	micrometer
uS/cm	microsiemens per centimeter
W/m^2	watts per square meter