Whatcom, Squalicum, and Padden Creeks Temperature

Total Maximum Daily Load

Water Quality Improvement Report

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Cover photo: Pixi Falls in Whatcom Falls Park.

Project Codes and 1996 303(d) Water-body ID Numbers

Data for this project are available at Ecology's Environmental Information Management (EIM) website at www.ecy.wa.gov/eim/index.htm. Search User Study ID, NCRI0002.

Activity Tracker Codes (Environmental Assessment Program) are 04-040 and 09-183.

TMDL Study Code (Water Quality Program) is WhaC01TM. The Squalicum/Padden Innovative project does not have a separate code.

Water-body Numbers: WA-01-1622, WA-01-3110, WA-01-3200, WA-01-3210, WA-01-3215, WA-01-3220, WA-01-3225

Whatcom, Squalicum, and Padden Creeks
Temperature
Total Maximum Daily Load

Water Quality Improvement Report

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Abstract

Whatcom, Squalicum, and Padden Creeks are on the 303(d) list for impaired waters for temperature in the state of Washington.

As part of the Whatcom, Squalicum, and Padden Creeks total maximum daily load (TMDL) study for temperature, the city of Bellingham conducted fieldwork during the summer of 2002. This report presents an analysis of the spatial and temporal temperature patterns of Whatcom Creek and its tributaries. QUAL2Kw, a stream temperature model, was used to investigate possible thermal behaviors of Whatcom Creek for different meteorological, shade, and headwater boundary conditions. The Whatcom Creek analysis was expanded to include the Squalicum and Padden Creek watersheds because of similar soils, vegetation, landscape, and local management.

The observed stream temperatures in the Whatcom Creek watershed during 2002 showed that most locations are warmer than the Washington State water quality criteria. In general, although the tributaries were also found to exceed the 16°C numeric criterion, they are slightly cooler than the mainstem Whatcom Creek.

Whatcom Creek headwater temperatures are affected by the temperatures in Lake Whatcom, as well as by the streamflows released in the channel at the control dam.

Reductions in water temperature are predicted for hypothetical conditions with mature riparian vegetation and improvements in riparian microclimate. Model simulations performed at critical low-flow and meteorological conditions show that an average reduction of 2.0ºC is expected compared with the current conditions.

This technical assessment uses effective shade as a surrogate measure of heat flux to fulfill the requirements of Section 303(d) for a temperature TMDL. Effective shade is defined as the fraction of incoming solar short wave radiation that is blocked by vegetation and topography from reaching the surface of the stream.

In addition to load allocations for effective shade, other management activities are recommended for compliance with the Washington State water quality standards for water temperature.

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    - Water Quality Program clerical staff for formatting and editing the final report.

Executive Summary

Introduction

Whatcom, Squalicum, and Padden Creeks are on Washington State's 303(d) list of water quality impaired waters because of high temperatures (Figure ES-1). The federal Clean Water Act requires that a total maximum daily load (TMDL) be developed for each of the water bodies on the 303(d) list. The TMDL study identifies pollution problems in the watershed, and specifies how much pollution needs to be reduced or eliminated to achieve clean water.

In accordance with this requirement, the Washington State Department of Ecology (Ecology) and the city of Bellingham initiated a cooperative effort to develop a temperature TMDL for the creeks that run through the city of Bellingham. Sampling was conducted by Bellingham during the summer of 2002. This water quality improvement report contains the study, along with recommendations for cleaning up the water bodies, and an implementation strategy that lays out roles and responsibilities for the cleanup process.

Figure ES-1. Location of Whatcom, Squalicum, and Padden Creeks in Washington State.

QUAL2Kw, a stream water quality model, was calibrated using collected field data and then used to investigate the response of Whatcom Creek under different meteorological, shade and headwater boundary conditions. The Whatcom Creek analysis was expanded to include the Squalicum and Padden Creek watersheds because of similar soils, vegetation, landscape, and local management (Stohr, 2009).

Effective shade was used as a surrogate measure of heat flux to fulfill the requirements of Section 303(d) of the Clean Water Act for a temperature TMDL. Effective shade is defined as the fraction of incoming solar shortwave radiation that is blocked from reaching the surface of the stream by vegetation and topography.

Whatcom Creek watershed

The Whatcom Creek watershed runs west from Lake Whatcom into Bellingham Bay within Water Resources Inventory Area (WRIA) 1 in the northwestern corner of Washington State. The 6.7 km creek includes four tributaries (Hanna, Cemetery, Fever, and Lincoln Creeks) and drains a total area of 23 km^2 (5680 acres). The upper third of the creek lies within a park, while the lower two-thirds flow through developed sections of the city of Bellingham before emptying into Bellingham Bay.

Although relatively short in length, Whatcom Creek has a complex riparian ecosystem and anadromous fisheries, as well as recreational activities including fishing, boating, and swimming. Land use in the watershed is a mix of parkland, industrial, and residential areas. The creek houses two hatcheries: the Whatcom Creek Hatchery located near the mouth of the creek, and the Bellingham Hatchery located in Whatcom Falls Park.

Streamflow in Whatcom Creek is heavily controlled by the water level management of Lake Whatcom, which is regulated by a control dam at the outlet of Lake Whatcom. The creek's urban setting makes it subject to other impacts including channelization, flood control projects, loss of riparian vegetation, and stormwater runoff.

Padden and Squalicum Creek watersheds

Squalicum and Padden Creeks are the remaining larger streams running through the city of Bellingham.

The Squalicum Creek watershed includes most of northern Bellingham, beginning at Squalicum and Toad Lakes, and stretching west to Bellingham Bay. Tributaries to this 24-square-mile (15,097 acre) watershed include Baker, Spring, and McCormick Creeks. Squalicum Creek and its tributaries provide habitat for several salmonid species including coho, chum, sea-run steelhead, and cutthroat trout.

The Padden Creek watershed drains about 3,830 acres in the south end of Bellingham and includes the sub-basins of Lake Padden and Connelly Creek. The Padden Creek watershed elevation ranges from sea level to 985 feet. The upper watershed consists of several unnamed tributaries that flow through forested parks into Lake Padden. The lower portion is drained by Padden Creek as it meanders 2.9 miles from Lake Padden to Bellingham Bay, through residential development and city parks. The Padden Creek watershed includes moderate-density residential use, forested parks, a golf course, a commercial garden, and a retail area.

Washington State water quality standards

The main beneficial uses to be protected by this TMDL are aquatic life uses, including *core summer salmonid habitat* and *salmonid spawning, rearing, and migration*. Washington State water quality standards for temperature state that the 7-day average of daily maximum temperatures (7-DADMax) in core summer salmonid habitat should not exceed 16°C. Areas designated as salmonid spawning, rearing, and migration habitat should not exceed a 7-DADMax of 17.5°C. (Figure ES-2.)

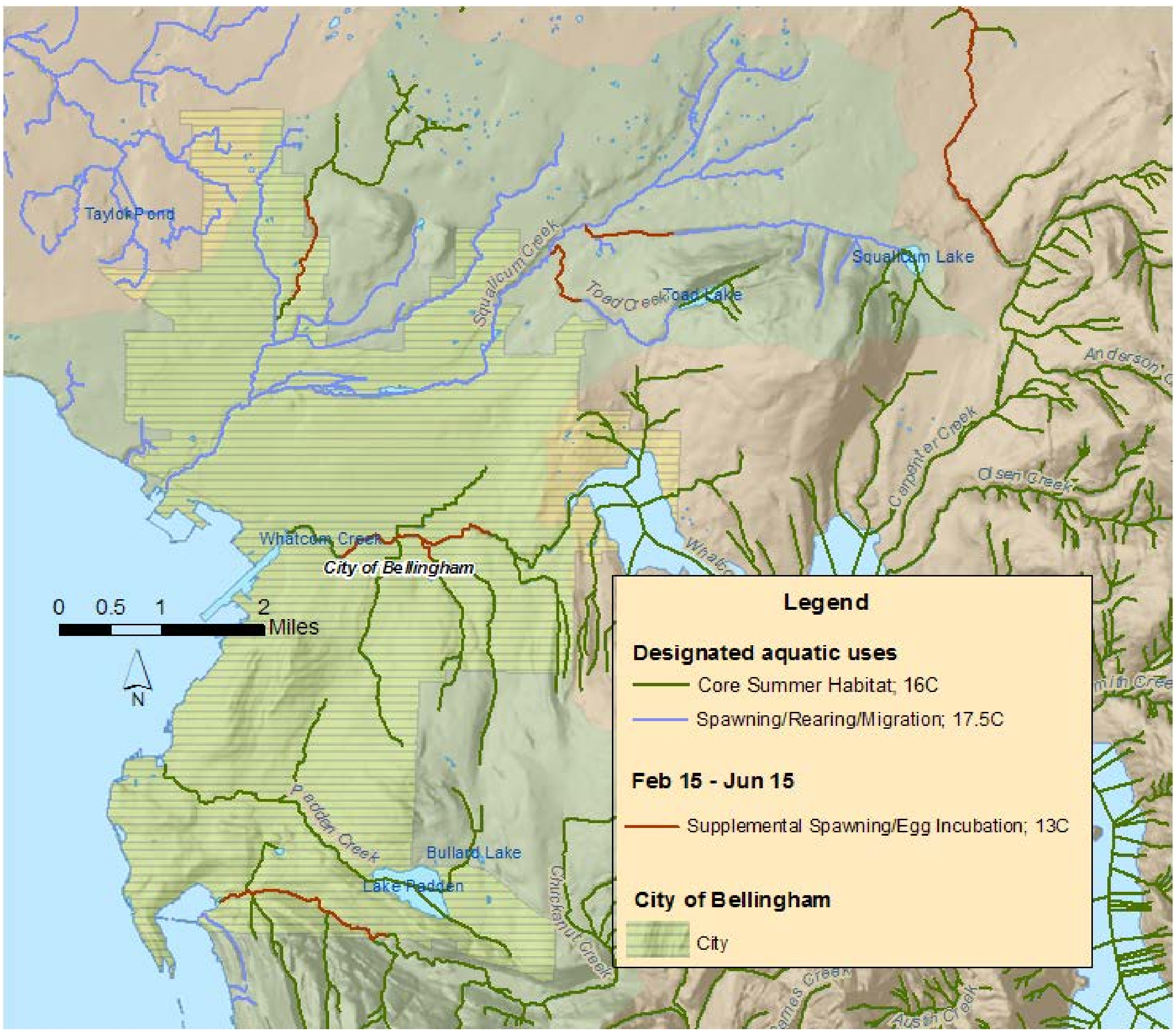

Figure ES-2. Water Quality Standards for Whatcom, Squalicum, and Padden Creeks.

Washington State uses the criteria described previously to ensure that where a water body 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 water body is naturally warmer than the previously-described criteria, the state provides a small allowance for additional warming due to human activities. In this case, the combined effects of all human activities must not cause more than a 0.3°C (0.54°F) increase above the naturally higher (inferior) temperature condition.

Stream water quality monitoring

Field data collection from summer 2002 included:

- The installation of continuous temperature data loggers to record air temperature, dewpoint temperature, and instream temperatures.
- Continuous and instantaneous flow measurements.
- Riparian canopy shade measurements.
- Stream channel measurements.

Water temperature data showed that:

- Whatcom Creek temperature exceeded the 16°C numeric criterion from May through October.
- Warmest temperatures were recorded at the outlet of Lake Whatcom at the control dam. Whatcom Creek cools as it moves downstream through the forested reaches, then gradually warms up again as it flows through developed areas.
- Tributaries to Whatcom Creek are generally cooler than the mainstem except for Hannah Creek, which is the smallest, and the warmest creek in the watershed.

Water quality modeling

Ecology developed a steady-flow stream and river water quality model, QUAL2Kw, for Whatcom Creek to evaluate its capacity to assimilate heat loads. After calibrated and validated to summer 2002 instream data, the model was used to determine the loading capacity in Whatcom Creek. This was based on a prediction of water temperatures under low-flow and 90th percentile (1 in 10 years) climate conditions, combined with a range of effective shade conditions.

The modeling predicted that the implementation of mature riparian vegetation within a 45-meter (150-ft) buffer along the banks of the creek could reduce the daily maximum temperature across the stream length by about 1.8^{o}C compared to current conditions. Changes in microclimate associated with mature riparian vegetation could further lower the daily average maximum water temperature by about 0.2^{o}C.

Load and wasteload allocations

Load allocations for effective shade are prescribed to address temperature impairments in Whatcom, Squalicum, and Padden Creeks and their tributaries. The load allocations are expected to re-establish mature riparian vegetation, eventually providing a functioning riparian zone and resulting in water temperatures equivalent to those that would occur under natural conditions.

In Whatcom Creek, system potential temperatures resulting from implementing system potential mature riparian vegetation are predicted to be higher than the 16°C water quality criterion during the hottest period of the year. However, WAC 173-201A-200(1)(c)(i) states: When a water body's temperature is warmer than the criteria in Table 200 (1)(c) (or within 0.3°C (0.54°F) of the criteria) and that condition is due to natural conditions, then human actions, considered cumulatively, may not cause the 7-DADMax temperature of that water body to increase more than 0.3°C (0.54°F).

The Bellingham Creek Hatchery is the only NPDES discharge to Whatcom Creek. The hatchery intake pipe is located at the Whatcom Lake control dam, and the water coming into the hatchery is considered to be at natural conditions because there is little or no human control over the lake temperature. The maximum allowable effluent temperature for the Bellingham Creek Hatchery NPDES discharge is not to exceed the temperature of the intake water by more than 0.3°C.

Stormwater from the city of Bellingham and Washington State Department of Transportation Municipal Separate Storm Systems (MS4s) are also regulated by the NPDES permit program. However, MS4 permits are different from all other NPDES permits in two significant ways. The first difference is that the permits do not require monitoring of each outfall, but instead require a program that limits what enters the system, and to a much smaller extent, how stormwater is handled once in the system. The second difference is that wasteload allocations do not need to be included in the permit as a numeric limit, but can be translated to best management practices (BMPs). Because the MS4s only discharge after rainfall they tend to cool the stream and so no BMPs will be required to implement their wasteload allocation.

Recommendations

In addition to the load allocations for effective shade in the study area, the following management activities are recommendations for implementation:

- For privately-owned forest land, the riparian vegetation prescriptions in the Forests and Fish Report (DNR, 1999) are recommended for all perennial streams. Load allocations are included in this TMDL for forest lands in accordance with the section of the Forests and Fish Report entitled "*TMDLs produced prior to 2009 in mixed use watersheds*."
- Instream flows and water withdrawals are managed through regulatory avenues separate from TMDLs. However, stream temperature is related to the amount of instream flow, and increases in flow generally result in decreases in maximum temperatures. The stream is closed for additional appropriation, and there do not appear to be any active surface water

withdrawals. Projects that have the potential to increase groundwater inflows to streams in the watershed should be encouraged.

- Hyporheic exchange flows and groundwater discharges are important to maintain the current temperature regime and reduce maximum daily instream temperatures. Factors that influence hyporheic exchange flow include the vertical hydraulic gradient between surface and subsurface waters, as well as the hydraulic conductivity of streambed sediments. Activities that reduce the hydraulic conductivity of streambed sediments could increase stream temperatures. Management activities should reduce upland and channel erosion, and avoid sedimentation of fine materials in the stream substrate.
- Riparian vegetation buffers should be restored and managed in accordance with the urban setting of the watershed. These actions include, but are not limited to, increasing forest cover in the urban watershed, conserving and planting trees at development sites, and planting trees along local streams and roads and in parking lots.
- Interim monitoring of water temperatures during summer is recommended, perhaps at 5-year intervals. Continuously-recording water temperature monitors should be deployed from July through August to capture the critical conditions.
- Interim monitoring of the composition and extent of riparian vegetation is also recommended (for example, by using photogrammetry or remote sensing methods, hemispherical photography, densiometers, or solar pathfinder instruments).

Implementation strategy

The primary means of implementing the TMDL are through the city's Shoreline Master Program and Critical Areas Ordinances. Both of these programs put limits on what can happen in the riparian areas. Both include protection of riparian vegetation.

A secondary level of protection is provided by the city's stormwater management program as required by the NPDES permit for discharge of water from their MS4. The requirements for all new development to use on-site stormwater management as a first approach to addressing new development, and to a more modest extent in redevelopment, will reduce stormwater discharges during times of critical temperature.

What is a Total Maximum Daily Load (TMDL)

Federal Clean Water Act requirements

The Clean Water Act established a process to identify and clean up polluted waters. The Clean Water Act 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 cold water biota and drinking water supply, and (2) criteria, usually numeric criteria, to achieve those uses.

Every two years, states are required to prepare a list of water bodies – lakes, rivers, streams, or marine waters – that do not meet water quality standards. This list is called the 303(d) list. To develop the list, Ecology compiles its own water quality data along with data from local, state, and federal governments, tribes, industries, and citizen monitoring groups. All data are reviewed to ensure that they were collected using appropriate scientific methods before the data are used to develop the 303(d) list. The 303(d) list is part of the larger Water Quality Assessment.

The Water Quality Assessment is a list that tells a more complete story about the condition of Washington's water. This list divides water bodies into five categories:

Category 1 – Meets standards for parameter(s) for which it has been tested.

Category 2 – Waters of concern.

Category 3 – Waters with insufficient data available.

Category 4 – Polluted waters that do not require a TMDL because:

- 4a. – Has an approved TMDL and it is being implemented.
- 4b. – Has a pollution control program in place that should solve the problem.
- 4c. – Is impaired by a non-pollutant such as low water flow, dams, culverts.

Category 5 – Polluted waters that require a TMDL – the 303(d) list.

TMDL process overview

The Clean Water Act requires that a TMDL be developed for each of the water bodies on the 303(d) list. The TMDL identifies pollution problems in the watershed and then specifies how much pollution needs to be reduced or eliminated to achieve clean water. Ecology then works with the local community to develop (1) an overall approach to control the pollution, called the *implementation strategy*, and (2) a monitoring plan to assess effectiveness of the water quality improvement activities.

Once EPA approves the TMDL, a *water quality implementation plan* must be developed within one year. This plan identifies specific tasks, responsible parties, and timelines for achieving clean water.

Who should participate in this TMDL?

The city of Bellingham regulates land use for most of the length of Squalicum and the entire length of Whatcom and Padden Creeks. Whatcom County regulates land use on the headwaters of Squalicum Creek. The city and Whatcom County will need to work with the citizens that own riparian land to meet effective shade targets.

Elements the Clean Water Act requires in a TMDL

The goal of a TMDL is to ensure that impaired water will attain water quality standards. A TMDL includes a written, quantitative assessment of the water quality problems and of the pollutant sources that cause the problem, if known. The TMDL determines the amount of a given pollutant that can be discharged to the water body and still meet standards (the *loading capacity*), and allocates that load among the various sources.

Identifying the pollutant loading capacity for a water body is an important step in developing a TMDL. EPA defines the loading capacity as "*the greatest amount of loading that a water body can receive without violating water quality standards.*" The loading capacity provides a reference for calculating the amount of pollution reduction needed to bring a water body into compliance with the standards.

The portion of the receiving water's loading capacity assigned to a particular source is a *wasteload* or *load* allocation. If the pollutant comes from a discrete (point) source, such as a municipal or industrial facility's discharge pipe, that facility's share of the loading capacity is called a *wasteload allocation*. If the pollutant comes from a set of diffuse (nonpoint) sources such as general urban, residential, or farm runoff, the cumulative share is called a *load allocation*.

The TMDL must also consider seasonal variations, and include a *margin of safety* that takes into account any lack of knowledge about the causes of the water quality problem or its loading capacity. A *reserve capacity* for future loads from growth pressures is sometimes included as well. By definition, a TMDL is the sum of the allocations, which must not exceed the loading capacity. The sum of the wasteload and load allocations, the margin of safety, and any reserve capacity must be equal to or less than the loading capacity.

TMDL = Loading Capacity = sum of all wasteload allocations + sum of all load allocations + margin of safety.

Why Ecology is Conducting a TMDL Study in this Watershed

Overview

Monitoring data from Ecology's ambient station (station 01E050) indicate that Whatcom Creek does not meet (exceeds) criteria from the Washington State water quality standards for temperature. This resulted in the creek's inclusion on the 1996 303(d) list. In response to this listing, Ecology is required to conduct a TMDL study for Whatcom Creek. Subsequent monitoring by the city of Bellingham and others show that temperatures exceeding criteria were found in other nearby streams. The TMDL study for Whatcom, Squalicum, and Padden Creek watersheds began in 2002, and is summarized in this report.

The evaluation process includes a water quality technical study to determine the capacity of the water body to absorb pollutants and still meet water quality standards currently in effect. The study also evaluates the likely sources of those pollutants, and the specific amount of pollution (the pollutant load) that needs to be reduced to meet water quality standards.

The goal of the *Whatcom, Squalicum, and Padden Creeks Temperature TMDL* study is to (1) characterize the water temperature in the Whatcom Creek basin, and (2) establish load and wasteload allocations for the heat sources to meet water quality standards for surface water temperature in the study area.

During and after the technical study, Ecology works with other agencies and local citizens to identify pollution controls based on the study findings.

Study area

Figure 1 shows a map of the study area. Whatcom, Squalicum, and Padden Creeks are in Water Resource Inventory Area (WRIA) 1, in northwest Washington State. The creeks generally run from east to west flowing into Bellingham Bay.

- Whatcom Creek starts at Lake Whatcom and lies primarily within the Bellingham city limits. It includes four tributaries: Hanna, Cemetery, Fever, and Lincoln Creeks. The headwaters of Hanna, Cemetery, and a portion of Lincoln Creek are in unincorporated Whatcom County.

- The Squalicum Creek watershed includes most of northern Bellingham, beginning at Squalicum and Toad Lakes, stretching west to Bellingham Bay. Its major tributaries are Baker, Spring, and McCormick Creeks.

- The Padden Creek watershed lies in the south end of Bellingham and includes the sub-basins of Lake Padden and Connelly Creek. The upper watershed consists of several unnamed tributaries that flow through forested parks into Lake Padden. The lower portion meanders through residential development and city parks before emptying into Bellingham Bay.

Figure 1. Location of Whatcom, Squalicum, and Padden Creeks in Washington State.

Pollutants addressed by this TMDL

This TMDL addresses temperature impairments in Whatcom, Squalicum, and Padden Creeks and their tributaries.

Pollutant sources

Anthropogenic heat sources include:

- Increased levels of solar radiation reaching the stream surface from loss of natural shade.
- Effluent discharges to surface waters. Effluent is an outflowing of water from a natural water body or from a man-made structure.
- Increased heating and decreased cooling of the stream due to flow and channel alterations.

The pollutants targeted in this TMDL are heat from human-caused loss of shade, which results in increased solar radiation loading to the stream network, and heat from warm-water discharges of human origin.

Heat loading from point sources occurs when effluent with a higher temperature enters the stream. Low summertime flows decrease the thermal assimilative capacity of streams. Heat loading causes larger temperature increases in stream segments where flows are lower.

Riparian vegetation; stream morphology; hydrology; climate; and geographic location influence stream temperature. While climate and geographic location are outside of human control, riparian condition, channel morphology, and hydrology are affected by land use and water management activities. Specifically, the elevated summertime stream temperatures attributed to anthropogenic sources in the study area result from the following:

- Whatcom Creek temperatures influenced by water temperatures in Lake Whatcom, the source of Whatcom Creek, as well as water management decisions taken to control lake levels.
- Riparian vegetation disturbances reducing stream surface shading via decreased riparian vegetation height, width, and/or density, thus increasing the amount of solar radiation reaching the stream surface. The loss of riparian vegetation was mainly due to:
  - Removal of riparian vegetation for urban development.
  - Conversion of land from forest to residential/industrial areas.
  - The 1999 Whatcom Creek fuel spill and fire that affected a significant portion of the Whatcom Creek riparian corridor.
- Channel morphology alterations due to the urban setting of the watershed by:
  - Increased sediment loading from urban development.
  - Channelization and flood control projects.
  - Channel restrictions from road crossings.

- Altered exchange of water between the water column and hyporheic zone due to changes in the sediment balance in the stream and watershed.
- Altered natural hydrology due to:
  - The addition of many point sources for stormwater runoff.
  - Increased urbanized impervious drainage surfaces augmenting spring, fall, and winter runoff and decreasing summertime base flows.
  - Changes in groundwater inflow from withdrawals and reduced infiltration.
  - Altered flows controlled by management of lake levels through use of the control dam.

Pollutants and surrogate measures

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

This TMDL incorporates measures other than "daily loads" to fulfill the requirements of Section 303(d). This TMDL allocates other appropriate measures, or "surrogate measures" as provided under EPA regulations [40 CFR 130.2(i)]. The "Report of the Federal Advisory Committee on the Total Maximum Daily Load (TMDL) Program" (EPA, 1998) includes the following guidance on the use of surrogate measures for TMDL development:

> *When the impairment is tied to a pollutant for which a numeric criterion is not possible, or where the impairment is identified but cannot be attributed to a single traditional "pollutant," the state should try to identify another (surrogate) environmental indicator that can be used to develop a quantified TMDL, using numeric analytical techniques where they are available, and best professional judgment (BPJ) where they are not.*

Water temperature increases as a result of increased heat flux loads. A loading capacity for radiant heat energy (e.g., incoming solar radiation) can be used to define a reduction target that forms the basis for identifying a surrogate for heat loading from solar radiation. This technical assessment for the *Whatcom, Squalicum, and Padden Creek Temperature TMDL* uses effective shade as a surrogate measure of heat flux from solar radiation to fulfill the requirements of Section 303(d). Effective shade is defined as the fraction of the potential solar short-wave radiation that is blocked by vegetation and topography before it reaches the stream surface. The definition of effective shade allows direct translation of the solar radiation loading capacity.

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

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.

Impaired designated uses and water bodies on Ecology's 303(d) list of impaired waters

The main beneficial uses to be protected by this TMDL are aquatic life uses, including *core summer salmonid habitat* and *salmonid spawning, rearing, and migration*. In addition, these water bodies are to be protected for primary contact recreation and for domestic, industrial, and agricultural water supply.

Washington State has established water quality standards to protect these beneficial uses. Table 1 and Figure 2 include listings for temperature that violate these standards within the study area.

Table 1. Study area water bodies on the 2008 303(d) list for temperature.

Water-body Name	Listing ID	Parameter	Township	Range	Section
Whatcom Creek	36841	Temperature	38N	03E	28
Whatcom Creek	36842	Temperature	38N	03E	30
Whatcom Creek	36843	Temperature	38N	03E	29
Lincoln Creek	39202	Temperature	38N	03E	29
Fever Creek	39185	Temperature	38N	03E	29
Hanna Creek	48648	Temperature	38N	03E	28
Cemetery Creek	39178	Temperature	38N	03E	29
Connelly Creek	39181	Temperature	37N	03E	06
Padden Creek	39223	Temperature	37N	03E	07
Squalicum Creek	39239	Temperature	38N	03E	09
Squalicum Creek	39241	Temperature	38N	03E	18

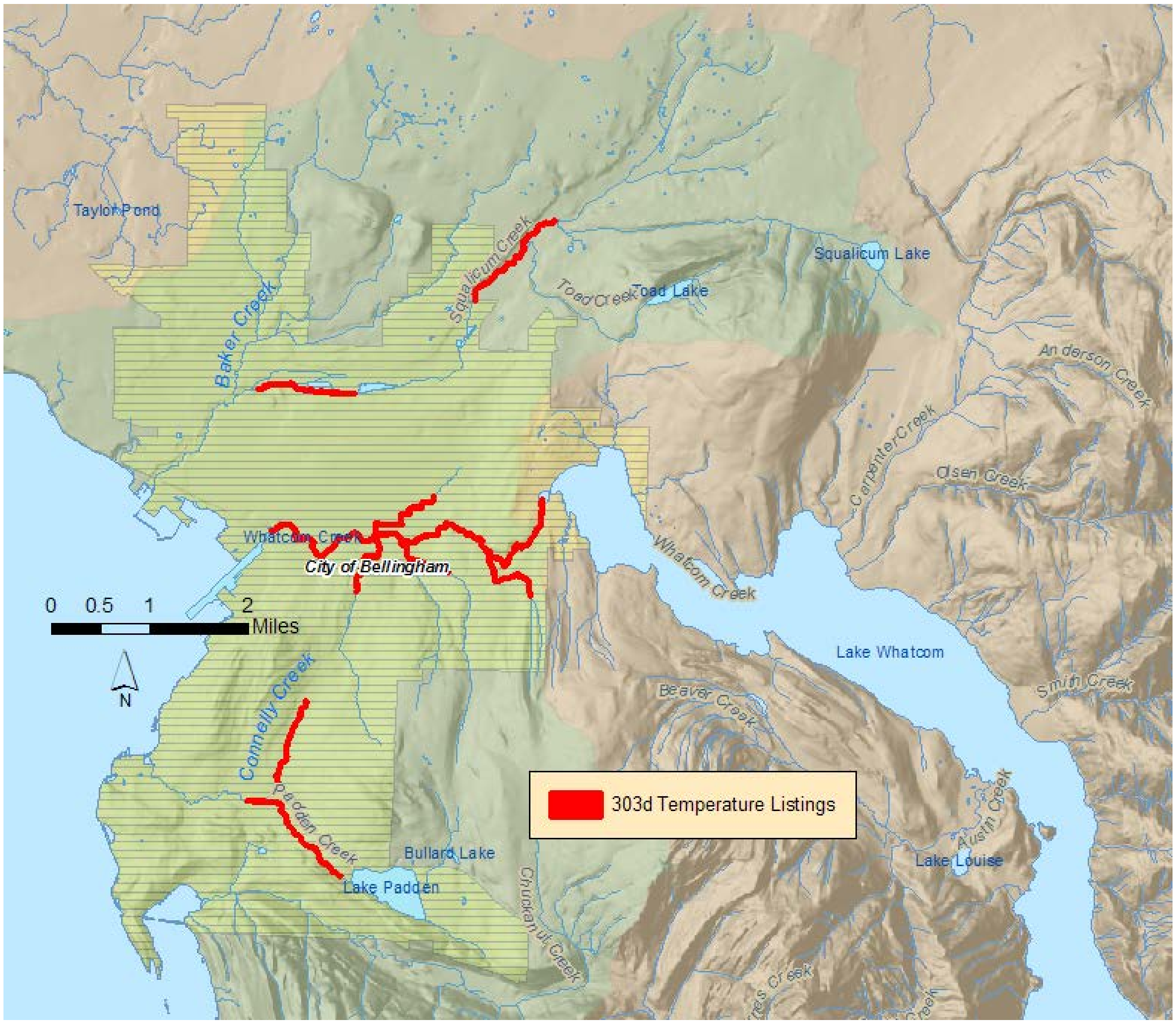

Figure 2. Map of study area stream segments listed for temperature.

This watershed has other water quality issues that will not be addressed in this TMDL. In particular, the following additional 303(d) listings for parameters other than temperature (Table 2) occur in the study area, but are not addressed in this report.

The fecal coliform listings in the Whatcom Creek watershed are addressed in a separate report, *Whatcom Creek Fecal Coliform Total Maximum Daily Load Report* (Shannahan et al., 2004; and Hood, 2007). Dissolved oxygen levels should improve with lower stream temperatures.

Table 2. Additional 303(d) listings not addressed by this report.

Water-body Name	Medium	Listing ID	Parameter	Township	Range	Section
Whatcom Creek *	Water	16408	Fecal Coliform	38N	03E	30
Whatcom Creek	Water	39033	Dissolved Oxygen	38N	03E	28
Whatcom Creek	Water	39034	Dissolved Oxygen	38N	03E	30
Whatcom Creek	Water	39035	Dissolved Oxygen	38N	03E	29
Whatcom Creek *	Water	39160	Fecal Coliform	38N	03E	28
Whatcom Creek *	Water	39162	Fecal Coliform	38N	03E	29
Lincoln Creek	Water	38981	Dissolved Oxygen	38N	03E	29
Lincoln Creek *	Water	39112	Fecal Coliform	38N	03E	29
Fever Creek	Water	9106	Zinc	38N	03E	29
Fever Creek	Water	38963	Dissolved Oxygen	38N	03E	21
Fever Creek	Water	38964	Dissolved Oxygen	38N	03E	29
Fever Creek *	Water	39089	Fecal Coliform	38N	03E	21
Fever Creek *	Water	39090	Fecal Coliform	38N	03E	29
Hanna Creek *	Water	45565	Fecal Coliform	38N	03E	28
Cemetery Creek	Water	38957	Dissolved Oxygen	38N	03E	29
Cemetery Creek *	Water	39061	Fecal Coliform	38N	03E	29
Baker Creek	Water	38950	Dissolved Oxygen	38N	02E	24
Baker Creek	Water	39037	Fecal Coliform	38N	02E	13
Baker Creek	Water	39038	Fecal Coliform	38N	02E	24
Connelly Creek	Water	38960	Dissolved Oxygen	37N	03E	06
Connelly Creek	Water	39068	Fecal Coliform	37N	03E	06

Water-body Name	Medium	Listing ID	Parameter	Township	Range	Section
Padden Creek	Water	39003	Dissolved Oxygen	37N	03E	07
Padden Creek	Water	39005	Dissolved Oxygen	37N	02E	01
Padden Creek	Water	39130	Fecal Coliform	37N	02E	12
Padden Creek	Water	39133	Fecal Coliform	37N	02E	01
Squalicum Creek	Water	39019	Dissolved Oxygen	38N	03E	09
Squalicum Creek	Water	39020	Dissolved Oxygen	38N	03E	16
Squalicum Creek	Water	39021	Dissolved Oxygen	38N	03E	18
Squalicum Creek	Water	39150	Fecal Coliform	38N	03E	09
Squalicum Creek	Water	39151	Fecal Coliform	38N	03E	16
Squalicum Creek	Water	39152	Fecal Coliform	38N	02E	13
Squalicum Creek	Water	39153	Fecal Coliform	38N	02E	43

Fecal coliform listings with an * are being addressed in a separate TMDL study (Shannahan et al., 2004; and Hood, 2007).

Why are we doing this TMDL now?

This TMDL was initiated in 2001 as a temperature TMDL for Whatcom Creek. The city of Bellingham coordinated data collection for model calibration, and Ecology calibrated a water quality model for Whatcom Creek. Due to shifting resources, the report was not completed.

As a result of the partially complete report, it became clear that the approach to implementing the temperature TMDL for Whatcom Creek would be applicable to Squalicum and Padden Creeks as well. Additional work was done to extend the model to cover all three major urban streams.

Water Quality Standards and Numeric Targets

Washington State Water Quality Standards, set forth in Chapter 173-201A of the Washington Administrative Code (WAC; Ecology, 2006), include designated beneficial uses, water-body classifications, and numeric and narrative water quality criteria for surface waters of the state.

The designated aquatic life uses for Whatcom, Squalicum, and Padden Creeks and tributaries (Figure 3) include (WAC 173-201A-200):

- *Core summer salmonid habitat*. This use protects summer season (June 15 through September 15) salmonid spawning or emergence, or adult holding; summer rearing habitat by one or more salmonids; or foraging by adult and sub-adult native char. Other protected uses include spawning outside of the summer season, rearing, and migration by salmonids.

- *Salmonid spawning, rearing, and migration.* This use protects salmon or trout spawning and emergence that only occur outside of the summer season (September 16 – June 14). Other uses include rearing and migration by salmonids.

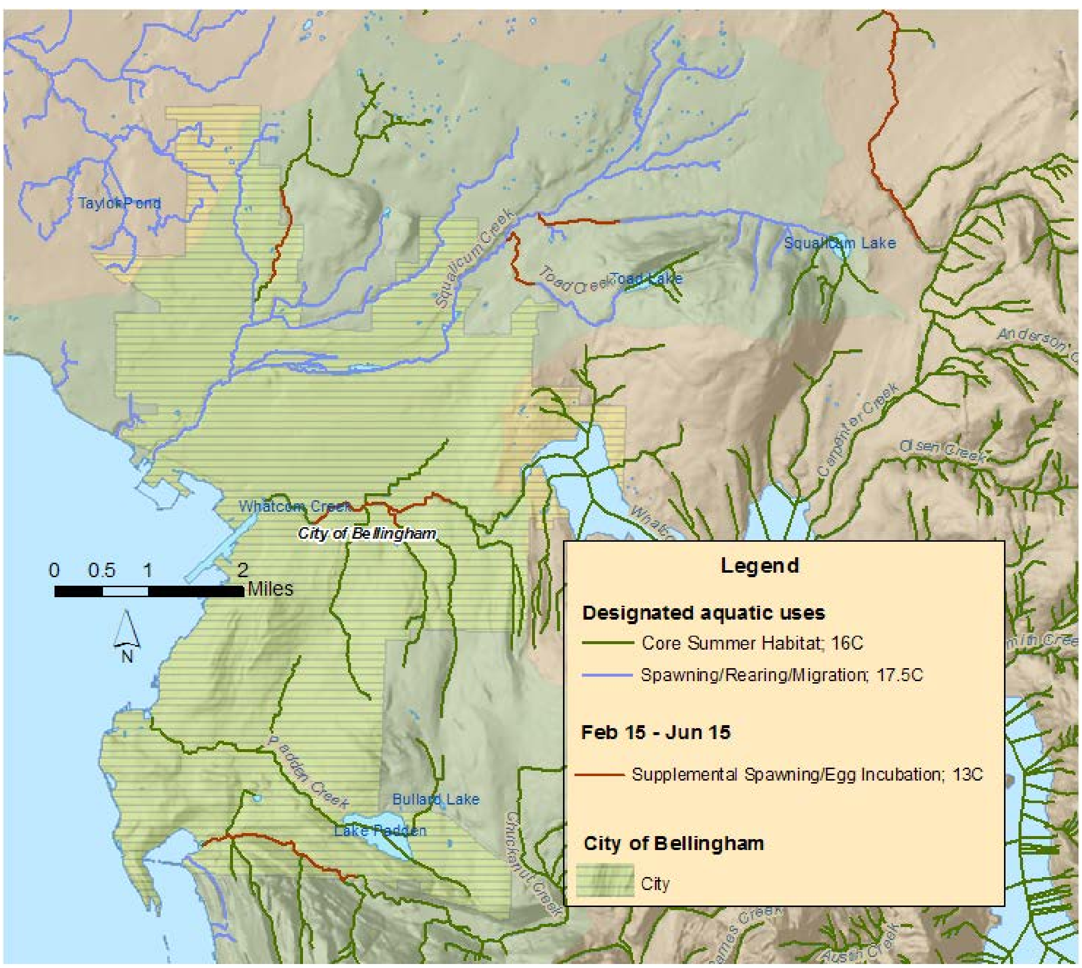

Figure 3. Water Quality Standards for Whatcom, Squalicum, and Padden Creeks.

Other non-aquatic life uses include water supply (domestic, industrial, and agricultural), stock watering, fish and shellfish harvesting, wildlife habitat, recreation (primary contact recreation, sport fishing, boating, and aesthetic enjoyment), and commerce and navigation. Numeric criteria for specific water quality parameters are intended to protect these designated uses.

Ecology revised the state water quality standards in July 2003 and in 2006. EPA approved these changes in February 2008.

Each beneficial use designation described previously has associated water quality criteria. The relevant temperature criteria that apply are detailed below.

Temperature

Fresh waters

Temperature affects the physiology and behavior of fish and other aquatic life. Temperature may be the most influential factor limiting the distribution and health of aquatic life and can be greatly influenced by human activities.

Temperature levels fluctuate over the day and night in response to changes in climatic conditions and river flows. Since the health of aquatic species is tied predominantly to the pattern of maximum temperatures, the criteria are expressed as the highest 7-day average of the daily maximum temperatures (7-DADMax) occurring in a water body.

In the Washington State water quality standards, aquatic life use categories are described using key species (salmon versus warm-water species) and life-stage conditions (spawning versus rearing) [WAC 173-201A-200; 2003 edition].

The beneficial uses to be protected within the Whatcom, Squalicum, and Padden Creek watersheds include (1) Core Summer Salmonid Habitat and (2) Salmonid Spawning, Rearing, and Migration. The applicable temperature criteria for these designated uses are contained in 173-201A-200(c) as:

(1) To protect the designated aquatic life uses of "*Core Summer Salmonid Habitat*," the highest 7-DADMax temperature must not exceed 16°C (60.8°F) more than once every ten years on average.

(2) To protect the designated aquatic life uses of "*Salmonid, Spawning, Rearing, and Migration, and Salmonid Rearing and Migration Only*," the highest 7-DADMax temperature must not exceed 17.5°C (63.5°F) more than once every ten years on average.

Special consideration is also required to protect spawning and incubation of salmonid species. Where Ecology determines that the temperature criteria established for a water body would likely not result in protective spawning and incubation temperatures, the following criteria apply: (A) Maximum 7-DADMax temperatures of 9°C (48.2°F) at the initiation of spawning and at fry emergence for char; and (B) Maximum 7-DADMax temperatures of 13°C (55.4°F) at the initiation of spawning for salmon and at fry emergence for salmon and trout.

Areas with special consideration in this study are portions of the Whatcom and Squalicum Creek drainages (Figure 3). These areas have additional protection for the period of February 15-June 15, when waters must not exceed 13°C.

Washington State uses the criteria described previously to ensure that where a water body 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 water body is naturally warmer than the above-described criteria, the state provides a small allowance for additional warming due to human activities. In this case, the combined effects of all human activities must not cause more than a 0.3°C (0.54°F) increase above the naturally higher (inferior) temperature condition.

Whether or not the water body is naturally high in temperature is determined using a model. The model roughly approximates natural conditions, and is appropriate for determining the implementation of the temperature criteria. This model results in what is called the *system thermal potential* or *system potential* of the water body.

The water quality standards contain a default that would allow the numeric criteria to be modified to reflect the natural condition, if the natural condition is a higher temperature than the numeric criteria. However, the modeling approximation done for this TMDL does not give an estimate of the historic natural condition that is accurate enough to support rule-making to change the temperature criteria.

While the criteria generally apply throughout a water body, they are not intended to apply to discretely anomalous areas such as in shallow stagnant eddy pools where natural features unrelated to human influences are the cause of not meeting the criteria. For this reason, the standards direct that one take measurements from well-mixed portions of rivers and streams. For similar reasons, one does not take samples from anomalously cold areas such as at discrete points where cold groundwaters flow into the water body.

Global climate change

Changes in climate are expected to affect both water quantity and quality in the Pacific Northwest (Casola et al., 2005). Whatcom, Squalicum, and Padden Creeks are fed by stored groundwater, which is influenced by winter precipitation. Increases in air temperatures result in more precipitation falling as rain rather than snow and earlier melting of the winter snowpack. Changes to timing of precipitation or changes to quantities falling as snow or rain could affect summer streamflows.

Ten climate change models were used to predict the average rate of climatic warming in the Pacific Northwest (Mote et al., 2005). The average warming rate is expected to be in the range of 0.1-0.6°C (0.2-1.0°F) per decade, with a best estimate of 0.3°C (0.5°F) (Mote et al., 2005). Eight of the ten models predicted proportionately higher summer temperatures, with three indicating summer temperature increases at least two times higher than winter increases. Summer streamflows are also predicted to decrease as a consequence of global climate change (Hamlet and Lettenmaier, 1999).

The expected changes coming to our region's climate highlight the importance of protecting and restoring the mechanisms that help keep stream temperatures cool. Stream temperature improvements obtained by growing mature riparian vegetation corridors along streambanks, reducing channel widths, and enhancing summer baseflows may all help offset the changes expected from global climate change – keeping conditions from getting worse. It will take considerable time, however, to reverse those human actions that contribute to excess stream warming. The sooner such restoration actions begin and the more complete they are, the more effective we will be in offsetting some of the detrimental effects on our stream resources.

These efforts may not cause streams to meet the numeric temperature criteria everywhere or in all years. However, they will maximize the extent and frequency of healthy temperature conditions, creating long-term and crucial benefits for fish and other aquatic species. As global climate change progresses, the thermal regime of the stream itself will change due to reduced summer streamflows and increased air temperatures.

The state is writing this TMDL to meet Washington State's water quality standards based on current and historic patterns of climate. Changes in stream temperature associated with global climate change may require further modifications to the human-source allocations at some time in the future. However, the best way to preserve our aquatic resources and to minimize future disturbance to human industry would be to begin now to protect as much of the thermal health of our streams as possible.

Overview of Stream Heating Processes

Introduction

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 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 leaving, the temperature will decrease. The general relationships between stream parameters, thermodynamic processes (heat and mass transfer), and stream temperature change are outlined in Figure 4.

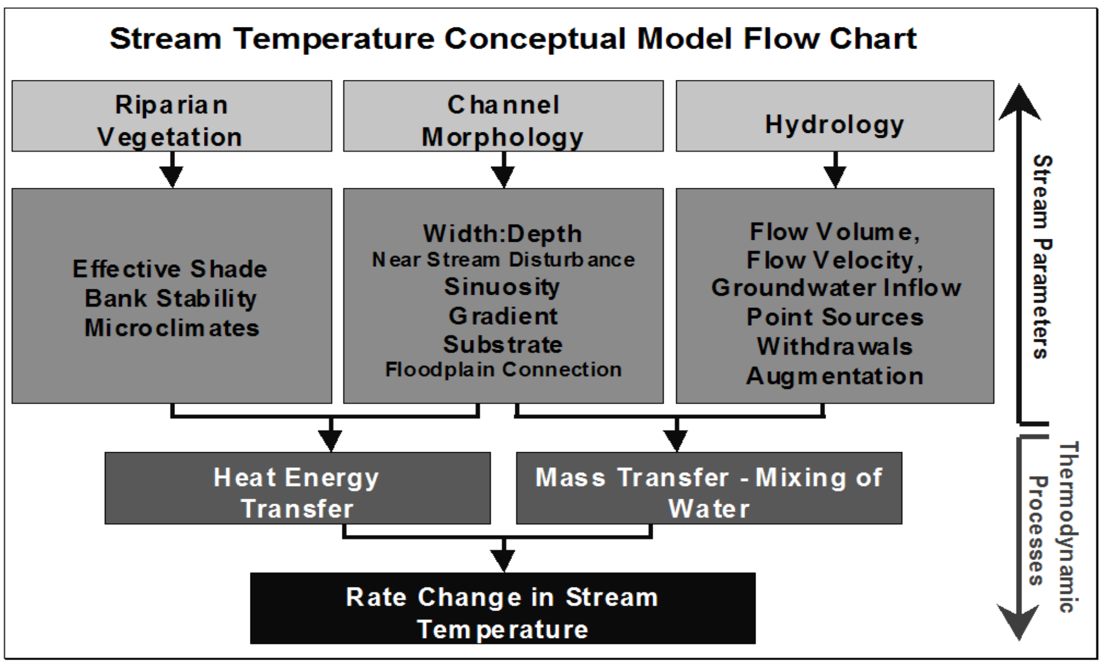

Figure 4. Conceptual model of factors that affect stream temperature.

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 water temperature in a volume of water tends toward the dew-point temperature (Edinger et al., 1974).

- **Solar radiation and riparian vegetation.** The daily maximum temperatures in a stream are strongly influenced by removal of riparian vegetation because of diurnal patterns of solar heat flux. Daily average temperatures are less affected by removal of riparian vegetation.

- **Groundwater.** Inflows of groundwater can have an important cooling effect on stream temperature. This effect will depend on the rate of groundwater inflow relative to the flow in the stream and the difference in temperatures between the groundwater and the stream.

Heat budgets and temperature prediction

The heat exchange processes occur between the water body and the surrounding environment and control stream temperature. Edinger et al. (1974) and Chapra (1997) provide thorough descriptions of the physical processes involved. Figure 5 shows the major heat energy processes or fluxes across the water surface or streambed (net heat flux = solar + long-wave atmosphere + long-wave back +± convection +± evaporation +± bed). Heat flux between the water and streambed occurs through conduction and hyporheic exchange.

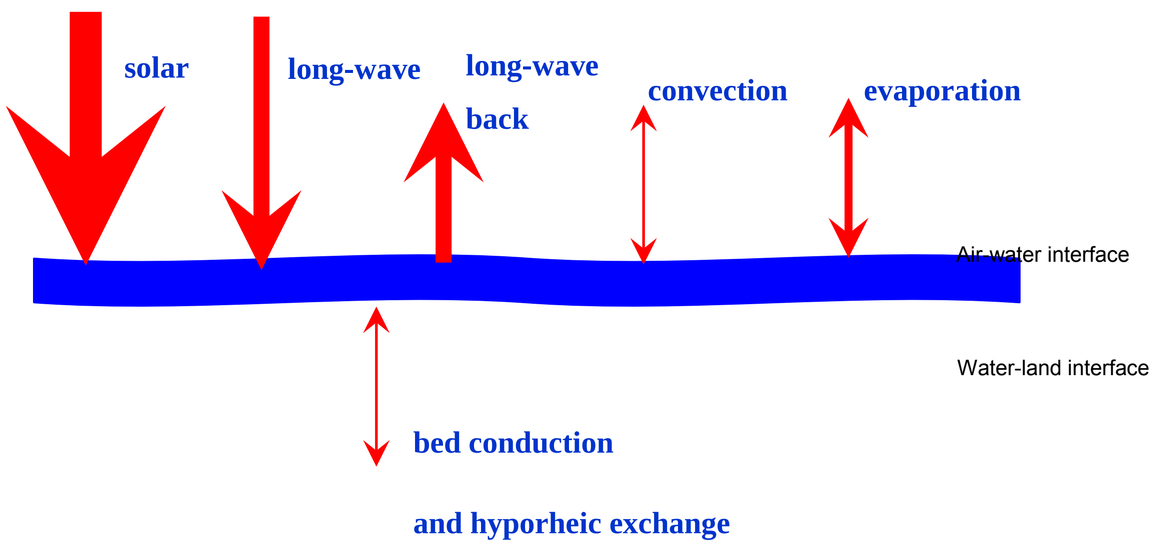

Figure 5. Surface heat exchange processes that affect water temperature.

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

- **Short-wave solar radiation** is the difference between the energy that comes directly from the sun and that reflected by the water body. Short-wave solar radiation is the most significant input in the heat balance during the day when the sky is clear. However, the surrounding physical features such as vegetation and topography can significantly reduce the amount of short-wave radiation received at a particular location. Vegetation and topography that is completely opaque will reduce short-wave radiation by 100%. Solar exposure was identified as the most influential factor in stream heating processes (Sinokrot and Stefan, 1993; Johnson and Jones; 2000, Danehy et al., 2005).

- **Long-wave atmospheric radiation**. The amount of long-wave radiation is determined by a series of atmospheric components such as water vapor, carbon dioxide, ozone, and air temperature. This heat budget component is most significant during warm cloudy conditions and at night. The long-wave radiation from the atmosphere ranges in wavelength range from about 4 μm to 120 μm. Long-wave atmospheric radiation depends primarily on air temperature and humidity and increases as both of those increase. The daily average heat flux from long-wave atmospheric radiation typically ranges from about 300 to 450 W/m^2 at mid latitudes (Edinger et al., 1974).

- **Long-wave back radiation from the water** is the radiation emitted by the water body to the atmosphere. This is an important component among the processes that define energy loss. Its mathematical description is based on the Stefan-Boltzmann fourth power radiation law for a blackbody as a function of the water emissivity and temperature. Water sends heat energy back to the atmosphere in the form of long-wave radiation in the wavelength range of about 4 μm to 120 μm. Back radiation accounts for a major portion of the heat loss from a body of water. Back radiation increases as water temperature increases. The daily average heat flux out of the water from long-wave 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:

- **Convection flux at the air-water interface** is driven by the temperature difference between water and air and by the wind speed. It is related to evaporation flux through the Bowen ratio. Heat is transferred in the direction of decreasing temperature.

- **Evaporation flux at the air-water interface** is influenced mostly by the 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 gain component in the heat balance.

- **The bed conduction flux and hyporheic exchange** components of the heat budget represent the heat exchange through conduction between the bed and the water body and the influence of hyporheic exchange. The magnitude of bed 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, and usually affects the temperature diel profile, rather than affecting the magnitude of the maximum daily water temperature. Hyporheic exchange recently received increased attention as a possible important mechanism for stream cooling (Johnson and Jones, 2000; Poole and Berman, 2000; Johnson, 2004). The hyporheic zone is defined as the region 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.

An example of the estimated surface heat fluxes in Whatcom Creek from August 22 to the end of September 2002 is shown in Figure 6.

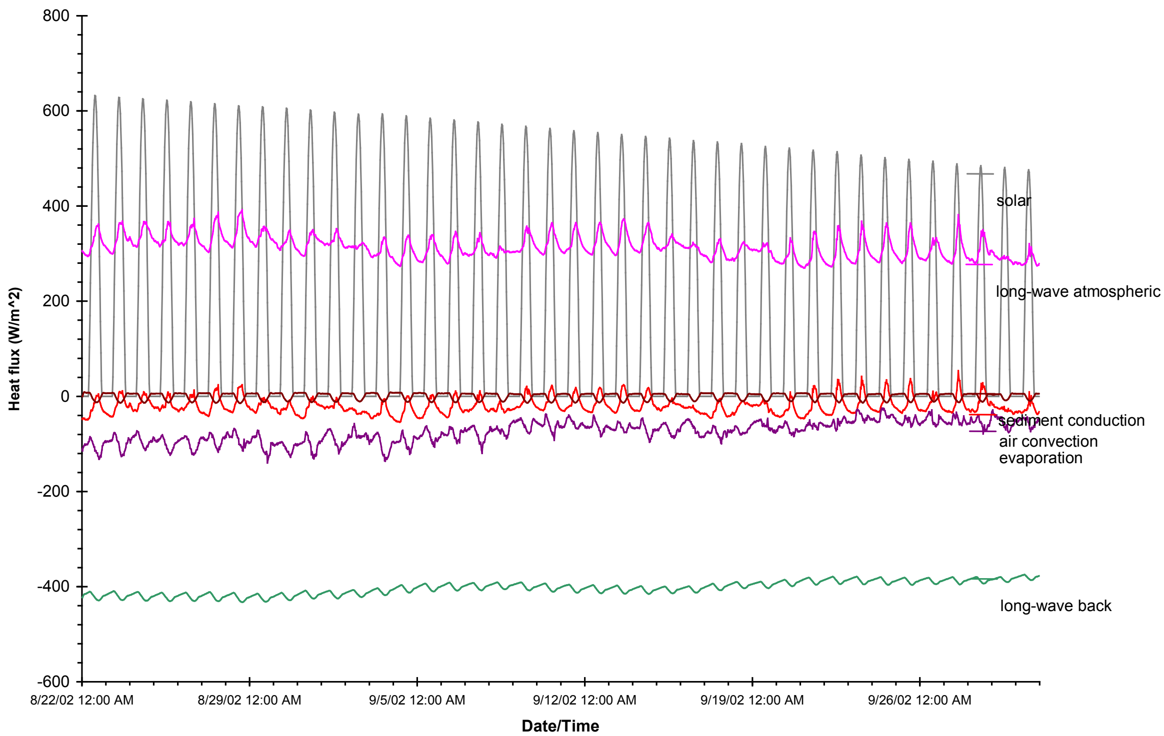

Figure 6. Estimated surface heat fluxes in Whatcom Creek from August 22 to the end of September 2002.

(net heat flux = solar + long-wave atmosphere + long-wave back + air convection + evaporation + sediment conduction). Note: hyporheic exchange was not simulated. Modeling software: Ecology rTemp model (www.ecy.wa.gov/programs/eap/models/).

Heat exchange between the stream and the streambed has an important influence on water temperature. The temperature of the streambed is typically warmer than the overlying water at night and cooler than the water during the daylight hours (Figure 7). 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.

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

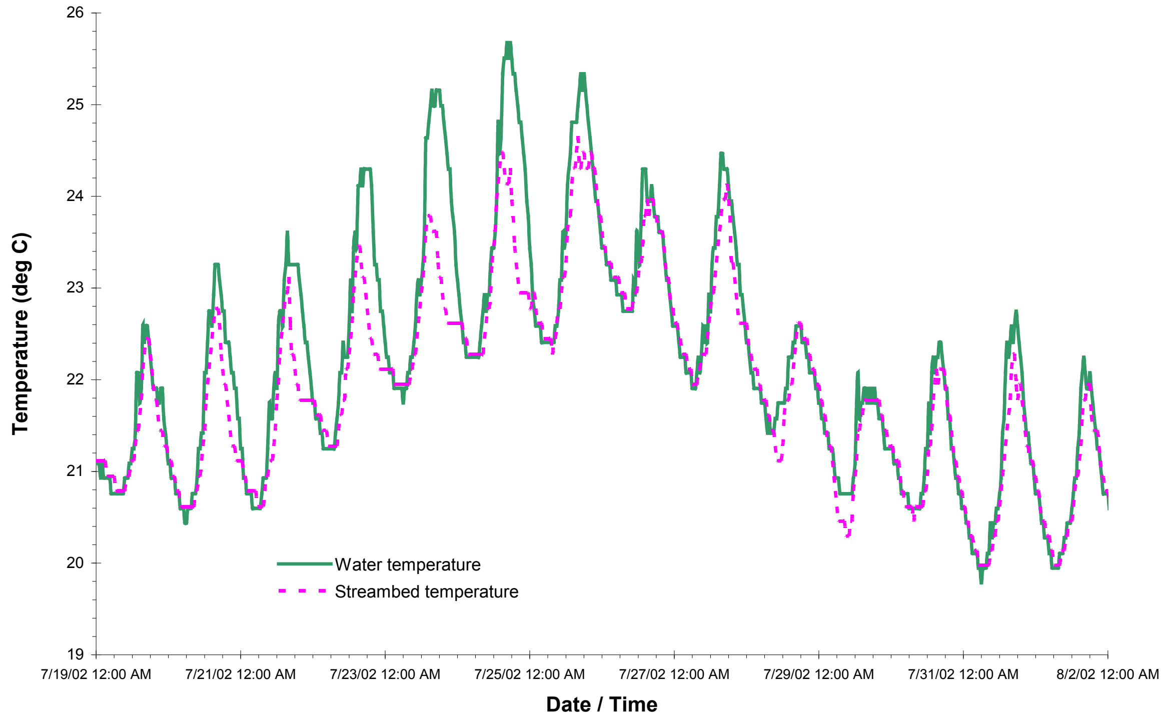

Figure 7. Measured water and streambed temperatures from July 19 to August 2, 2002 at Whatcom Creek at the pond above the control dam.

Thermal role of riparian vegetation

Riparian vegetation may act as an efficient insulating barrier, where the vegetation influences heat exchange rates with the atmosphere and the surrounding environment. Riparian vegetation may also cause changes in microclimatic conditions; decreasing air temperature, ground temperatures, and wind speeds; and increasing the relative humidity. It also plays an important role in bank stability and channel morphology. As the river enlarges and widens, riparian vegetation influences in controlling stream temperatures become less important (Poole and Berman, 2000).

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

Riparian vegetation restoration was identified as one of the most important management steps that may improve stream temperatures (Johnson and Jones, 2000; Blann et al., 2002). The net heat flux into a stream can be managed by increasing the shade from vegetation, which reduces the short-wave solar flux, the most significant component of a stream heat budget. Other processes, such as long-wave radiation, convection, evaporation, bed conduction, or hyporheic exchange, also influence the net heat flux into or out of a stream.

Effective shade

Shade is an important parameter that controls the stream heating derived from solar radiation. Solar radiation has the potential to be one of the largest heat transfer mechanisms in a stream system. Human activities can degrade near-stream vegetation and/or channel morphology, and in turn, affect shade. Reductions in shade have the potential to cause significant increases in heat delivery to a stream system. Stream shade is an important factor in describing the heat budget for the present analysis. Stream shade may be measured or calculated using a variety of methods (Chen, 1996; Chen et al., 1998a,b; Ice, 2001; OWEB, 1999; Teti, 2001; Teti and Pike, 2005).

Shade is the amount of solar energy that is obscured or reflected by vegetation or topography above a stream. Effective shade is defined as the fraction or percentage of the total possible solar radiation heat energy that is prevented from reaching the surface of the water:

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

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

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 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 summer months, allowing longer day length and higher solar altitude, both of which are functions of solar declination (i.e., a measure of the earth’s tilt toward the sun) (Figure 8). Geographic position fixes the stream to a position on the globe, while aspect provides the stream/riparian orientation (direction of streamflow). Near-stream vegetation height, width, and density describe the physical barriers between the stream and sun that can attenuate and scatter incoming solar radiation (i.e., produce shade) (Table 3). The solar position has a vertical component (i.e., solar altitude) and a horizontal component (i.e., solar azimuth) that are both functions of time/date (i.e., solar declination) and the earth’s rotation.

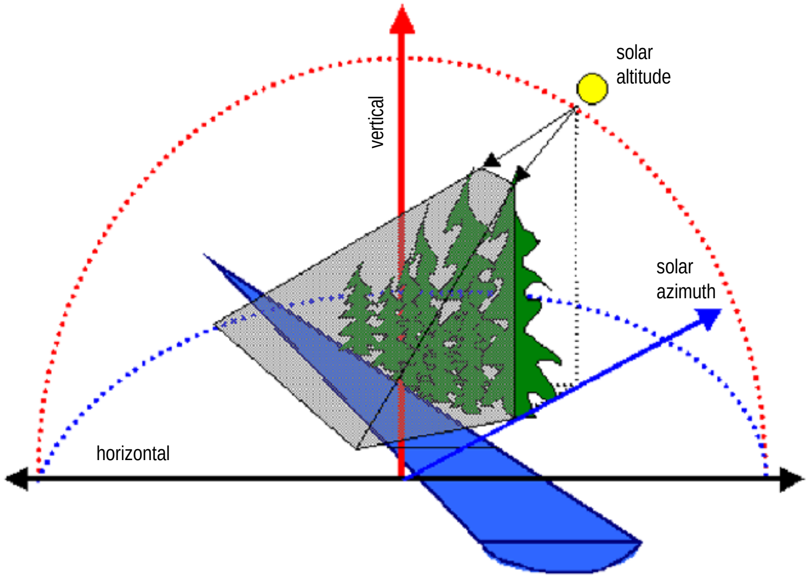

Figure 8. Parameters that affect shade and geometric relationships.

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.)

Table 3. 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

Italics indicate influenced by human activities.

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 and solar pathfinder.

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 3 (Ecology, 2003; Chen, 1996; Chen et al., 1998a and 1998b; Boyd, 1996; Boyd and Park, 1998).

Microclimate - surrounding thermal environment

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

Riparian buffers commonly occur on both 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 meters) 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 degrees 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 degrees C during the day and about 0.5 degrees C at night (estimate). Fowler and Anderson (1987) measured a 0.9 degrees C air temperature increase in clearcut areas. Chen et al. (1993) found similar (2.1 degrees C) increases.

  Ledwith (1996) evaluated buffer widths of 150m, 90m, 60m, 30m, 15m, and 0m, finding that a minimum buffer width of 30m (100 feet) was necessary to avoid significantly impacting the riparian microclimate. All measurements reported here were made over land instead of water, but in aggregate support about a 2 degrees C increase in ambient mean daily air temperature resulting from loss of riparian vegetation.

- **Relative humidity**. Brosofske et al. (1997) examined changes in relative humidity within 17 to 72 m buffer strips. The focus of their study was to document changes along the gradient from forested to clearcut areas, so they did not explicitly report pre- to post-harvest changes at the stream. However, there appeared to be a reduction in relative humidity at the stream of

7% during the day and 6% at night (estimate). Relative humidity at stream sites increased exponentially with buffer width. Similarly, a study by Chen et al. (1993) showed a decrease of about 11% in mean daily relative humidity on clear days at the edges of clearcuts.

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

Thermal role of channel morphology

Changes in channel morphology, primarily widening, affect 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 straightening can increase flow velocities and lead to deeply incised streambanks and washout of gravel and cobble substrate.

Channel modification usually occurs during high-flow events. Land uses that affect the magnitude and timing of high-flow events may negatively impact channel width and depth. Riparian vegetation conditions will affect the resilience of the 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. Riparian vegetation affects channel morphology by:

- **Building streambanks**. Riparian vegetation trap suspended sediments, encouraging deposition of sediment in the flood plain (instead of the streambed) and reducing incoming sources of sediment.
- **Maintaining stable streambanks**. High rooting strength and high streambank and flood plain roughness prevents streambank erosion.
- **Reducing flow velocity** (erosive kinetic energy). Riparian vegetation supplies large woody debris to the active channel, increases the pool/riffle ratio, and adds channel complexity that reduces shear stress exposure to streambank soil particles.

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Watershed Description

The Whatcom, Squalicum, and Padden Creek watersheds are part of WRIA 1 located in the northwestern corner of Washington State.

The study area climate is typically maritime Pacific Northwest, with cool, wet winters and mild summers. Precipitation and streamflows are highest in winter as a result of rainstorms and drainage from Lake Whatcom. Annual average precipitation throughout WRIA 1 ranges from about 85-125 cm (33-50 in) in its most western part to about 405-445 cm (160-175 in) in the central and southeastern areas (Figure 9). The lowest flows usually occur from July through September during the summer dry period (City of Bellingham, 2001).

Whatcom Creek

Whatcom Creek is 6.7 km long, beginning with its headwaters as the only natural outlet of Lake Whatcom (Figure 1). From Lake Whatcom, the creek flows downstream through a forested park before entering the developed sections of the city of Bellingham and ultimately emptying into Bellingham Bay. Whatcom Creek drains an area of about 23 km^2 (5680 acres) in addition to the 1259 km^2 (31,180 acres) watershed of the lake. This creek has an average gradient of 18.9 m/km and four tributaries: Hanna, Cemetery, Fever, and Lincoln Creeks.

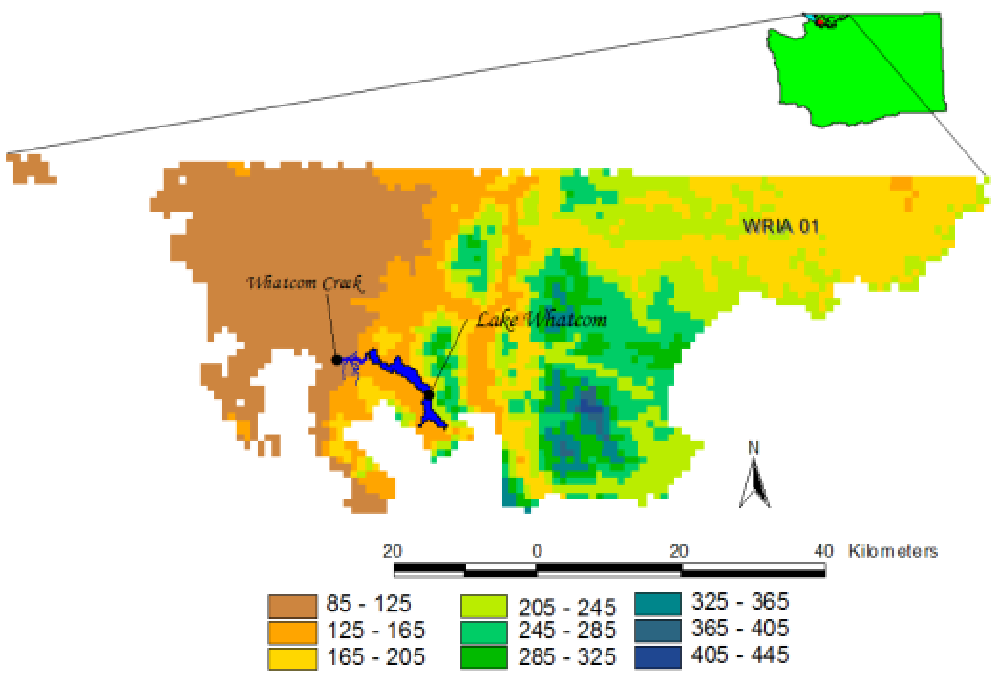

Figure 9. Annual precipitation (cm) distribution in WRIA 1.
Data from www.daymet.com based on 18 years of records (1980-1997).

The 20.3 km^2 Lake Whatcom (19.2 km long and about 46 m average depth) is a source of drinking water for more than 86,000 residents in the city of Bellingham and Whatcom County Water District No. 10. Additionally, it provides water for various active industries in the area. The lake is structurally divided by two sills into three basins. Basin 1 (2.12×10^7 m^2 surface area, 9 m average depth), located in the northwest section of the lake and source for Whatcom Creek, and Basin 2 (1.61×10^7 m^2 surface area, 9 m average depth) each comprise 2% of the water volume in the lake. The remaining 96% of water volume is contained by Basin 3 (1.66×10^8 m^2 surface area, 54 m average depth).

In the Lake Whatcom watershed, Basins 1 and 2 are mostly dominated by residential development while Basin 3 is dominated by forestry. All the major streams and many intermittent streams (about 87% of the watershed drainage area) empty into the lake in Basin 3. The rest of the watershed is drained by direct runoff or intermittent streams. The city of Bellingham diverts water from the Middle Fork of the Nooksack River into Basin 3 in order to increase water availability to the city (Cusimano et al., 2002).

Although relatively short in length, Whatcom Creek has complex riparian ecosystems and anadromous fisheries, as well as recreational activities including fishing, boating, and swimming.

Land use in the Whatcom Creek watershed is a mix of parkland, industrial, and residential areas. The upper watershed is dominated by Whatcom Falls Park and adjacent residential areas. The lower watershed is characterized by commercial and industrial areas (Serdar et al., 1999). Fever Creek (5.1 km^2) drains a mix of industrial and urban residential areas, whereas Lincoln Creek (3.2 km^2) drains commercial and residential areas. Cemetery Creek (6.6 km^2) drains public (undeveloped) and urban residential areas (Serdar, 1999).

The forested areas of the Whatcom Creek watershed are dominated by flora and fauna similar to the forested areas of the Lake Whatcom watershed. The stream exits the lake near Bloedel-Donovan Park and enters Whatcom Falls Park (Figure 10). Whatcom Creek cuts through sandstone formations, particularly in these upper reaches, creating six waterfalls along the creek (Friday, 1999). When the creek leaves the park and enters a lower gradient area, its flow begins to slow as it winds its way through thickets of various shrubs and blackberries between Civic Field complex and Iowa Street (Friday, 1999). Taller trees, such as cottonwoods, can be seen along this reach.

As Whatcom Creek approaches Interstate 5, it enters a highly urban and industrialized area. From the City Hall to Bellingham Bay the stream covers its final reach and then empties into an estuary of mixed salt and freshwater. This site of the relatively new Maritime Heritage Park has walking trails amid native plants and trees (Friday, 1999). A nearby former sewage plant was converted into a salmon hatchery in 1978. The hatchery plants fish in local streams including Whatcom Creek. Recreational activities follow, as fish return to spawn in Whatcom Creek. At present, the Whatcom Creek Hatchery is the largest chum salmon egg take facility in North Puget Sound. In addition to the fish hatchery located near the mouth of Whatcom Creek, there is a rainbow trout hatchery (Bellingham Hatchery) located upstream near the lake outlet.

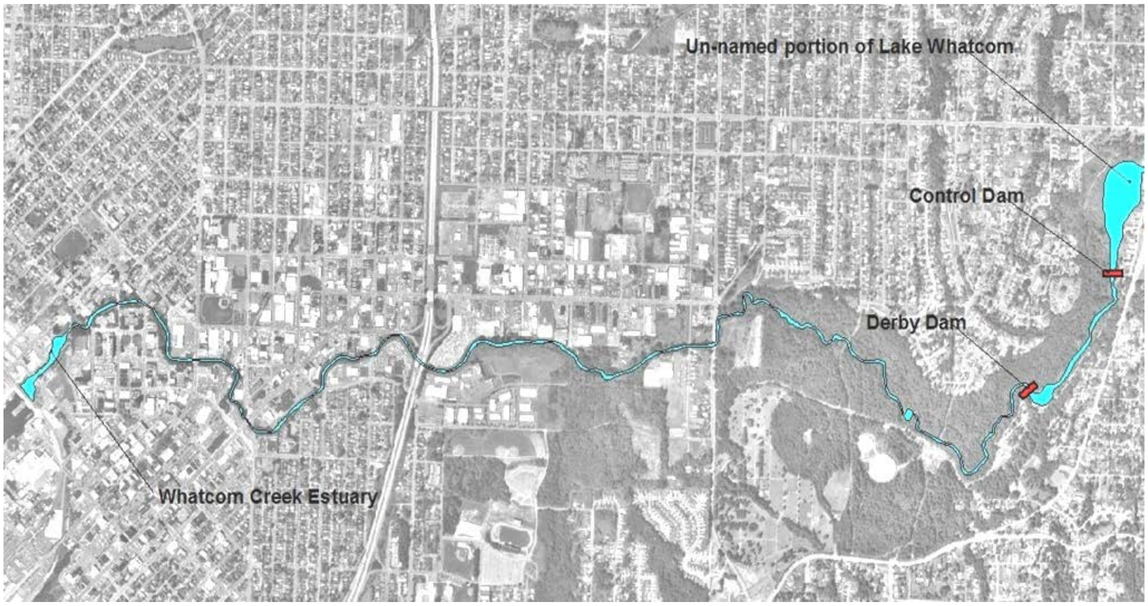

Figure 10. Whatcom Creek riparian corridor.

Whatcom Creek streamflow is heavily controlled by the water level management of Lake Whatcom. A control dam, built at the outlet of Lake Whatcom in 1938, is used to regulate the volumes of water entering Whatcom Creek. The city operates the dam to provide additional water storage and prevent flooding. Flow into Whatcom Creek can be reduced if water supply is low (Cusimano et al., 2002). In order to protect lakefront properties against flooding, the city does not restrict the outflow of the lake when the lake elevation is above approximately 96 m above mean sea level (City of Bellingham, 2001). A second dam is in place downstream of the control dam at the outlet of Lake Whatcom, forming a 0.7 km-long Derby Pond. The streamflow in Whatcom Creek is, however, mostly regulated by the control dam at the outlet of the lake.

Besides the controlled streamflow, the stream hydrology is also affected by its urban setting that often results in channelization and flood control projects, loss of riparian vegetation, and channel restrictions from road crossings, as well as the addition of many point sources of stormwater runoff (Shannahan et al., 2004). Cemetery Creek and its four tributaries drain residential areas and small wetlands. Fever, Lincoln, and Cemetery Creeks are perennial streams that have summer flows with less than one cubic foot per second. Hanna Creek is an intermittent stream that usually goes dry during August and September (Shannahan et al., 2004).

Squalicum and Padden Creeks are the remaining larger streams running through the city of Bellingham.

Squalicum Creek

The Squalicum Creek watershed includes most of northern Bellingham, beginning at Squalicum and Toad Lakes with sub-basin areas of 2.3 and 2.6 km^2 respectively, and stretching west to Bellingham Bay. This 61 km^2 (15,097 acre) watershed encompasses Baker Creek (11 km^2), which joins Squalicum near Meridian Street. Baker Creek is the largest of the tributaries. Other tributaries include Spring (12 km^2) and McCormick Creeks (14 km^2). Squalicum Creek and its tributaries provide habitat for several salmonid species including coho, chum, sea-run steelhead, and cutthroat trout.

Land use within the Squalicum Creek watershed includes residential, forestry, commercial, agricultural, light industrial, and some mining. The watershed lies partially within the city of Bellingham with its headwaters in the unincorporated area of Whatcom County. As it makes its way towards Bellingham Bay, Squalicum Creek receives runoff from many areas, including the parking lots at Bellis Fair Mall, Meridian Shopping Center, and the Albertson Center. The largest tributary of Squalicum Creek is Baker Creek. At least 62 animal species inhabit Squalicum Creek watershed, including 36 types of birds, as well as 15 mammal, 6 fish, 3 amphibian, and 2 reptile species (NSEA, 2009).

Padden Creek

The Padden Creek watershed drains about 15 km^2 (3,830 acres) in the south end of Bellingham and includes the 7 km^2 sub-basin of Lake Padden and 3 km^2 sub-basin of Connelly Creek. The Padden Creek watershed elevation ranges from sea level to 985 feet. The upper watershed consists of several unnamed tributaries that flow through forested parks into Lake Padden. The outlet of the lake is controlled by a dam with a sutro weir. During the summer the lake level is below the dam. No water flows from the lake to the creek from midsummer until late fall when winter rains again raise the lake level. The lower portion of the lake is drained by Padden Creek as it meanders 2.9 miles from Lake Padden to Bellingham Bay, through residential development and city parks. The Padden Creek watershed includes moderate-density residential use, forested parks, a golf course, a commercial garden, and a retail area.

Land use within the Padden Creek watershed includes residential, forestry, agricultural, commercial, and industrial. Padden Creek flows entirely within the Bellingham city limits, from Lake Padden to Bellingham Bay. It flows through the Fairhaven, Happy Valley, and Samish neighborhoods and drains 6 square miles of land. Parks in the Padden Creek watershed include Fairhaven Park and Lake Padden Park. Padden Creek provides good habitat for chinook, chum, coho, steelhead, and resident trout (NSEA, 2009).

Goals and Objectives

Project goals

The project goals are to (1) conduct a TMDL study on temperature in the Whatcom, Squalicum, and Padden Creek watersheds during critical low-flow conditions, and (2) establish an implementation strategy to meet water quality standards for temperature in this area.

Study objectives

The objectives for the TMDL study are as follows:

- Characterize stream temperatures and processes governing the thermal regime in Whatcom Creek during critical conditions.
- Develop a predictive temperature model of the Whatcom Creek basin under critical conditions. Apply the model to determine load allocations for effective shade and other surrogate measures to meet temperature water quality standards. Identify the areas influenced by lakes or wetlands.
- Develop shade curves for the Squalicum and Padden Creek watersheds and for tributaries to Whatcom Creek. Shade curves show the expected effective shade for each location on a stream depending on its channel width and stream aspect. Shade curves are developed at the assumed maximum riparian vegetation condition for the basin depending on climate and soil types.

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Field Data Collection

Study methods and study quality assurance evaluation

The study methods and study quality assurance (QA) evaluation for field data collection followed the protocols documented in the Whatcom Creek Temperature Total Maximum Daily Load QA Project Plan (City of Bellingham, 2002).

As reported in the QA Project Plan, instream flow monitoring and QA followed standard U.S. Geological Survey protocols. Riparian and channel surveys followed Timber-Fish-Wildlife (TFW) Stream Temperature Survey Methods (Schuett-Hames et al., 1999). Temperature monitoring followed protocols that have been adapted from TFW for use by Ecology in temperature TMDLs. Temperature monitoring and QA protocols are documented in Bilhimer and Stohr (2008).

Data used in this study met or exceeded the data quality objectives established for this project. The quality of project data is adequate to support the TMDL analysis.

Temperature monitoring data are available in Ecology's EIM system at www.ecy.wa.gov/eim/index.htm, under Study ID NCRI0002.

Results and discussion

Temperature data for the Whatcom Creek watershed

A network of continuous temperature dataloggers was installed in the Whatcom Creek watershed by the city of Bellingham to monitor stream temperatures during the dry season (May-October) of 2002. The locations of stream temperature sensors along Whatcom Creek and its tributaries are shown in Figure 11.

Figures 12 and 13 show continuous daily maximum water temperatures during May-October at each of the sampling stations during the 2002 stream temperature monitoring period. Table 4 summarizes the highest daily maximum and the highest 7-day average maximum water temperatures for 2002.

Stream temperature data from 2002 show that water temperatures in excess of the 16°C 7-day average of the daily maximum temperatures (7-DADMax) are common in the Whatcom Creek watershed (Table 4, Figures 12 and 13). Water temperature exceedances in Whatcom Creek were recorded as early as late May and continued until about the beginning of October.

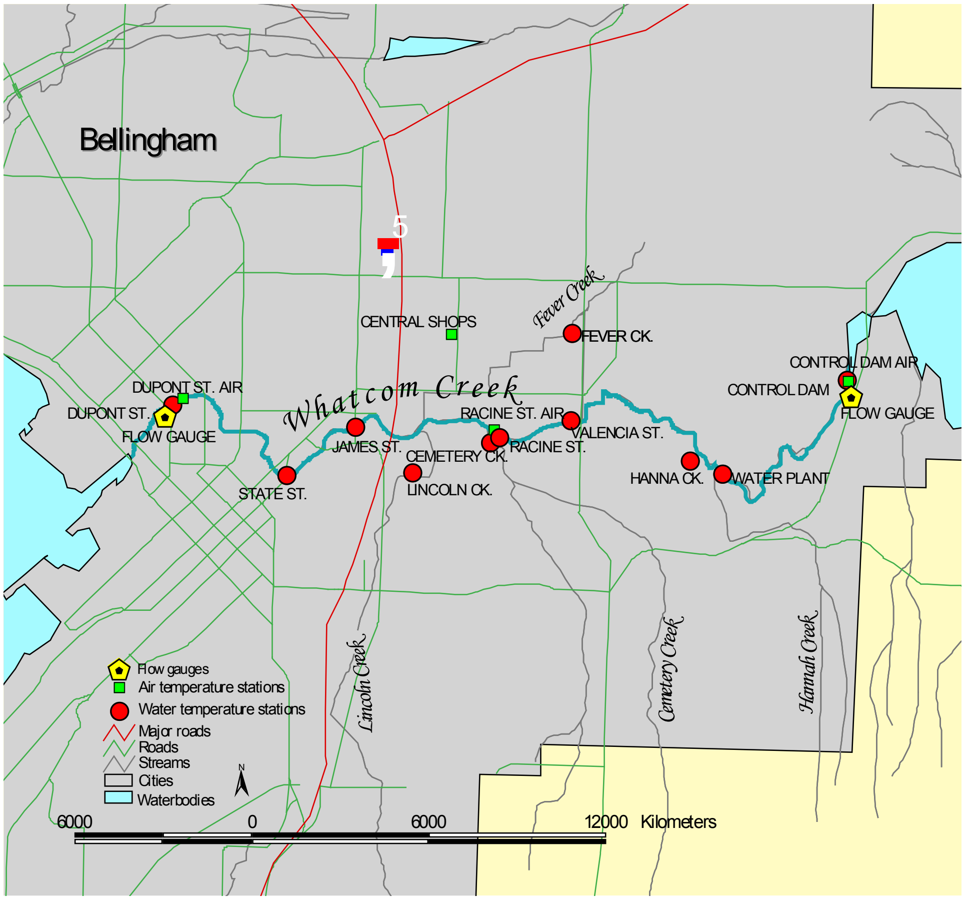


Figure 11. Stream temperature sensor locations in Whatcom Creek during the 2002 monitoring period.

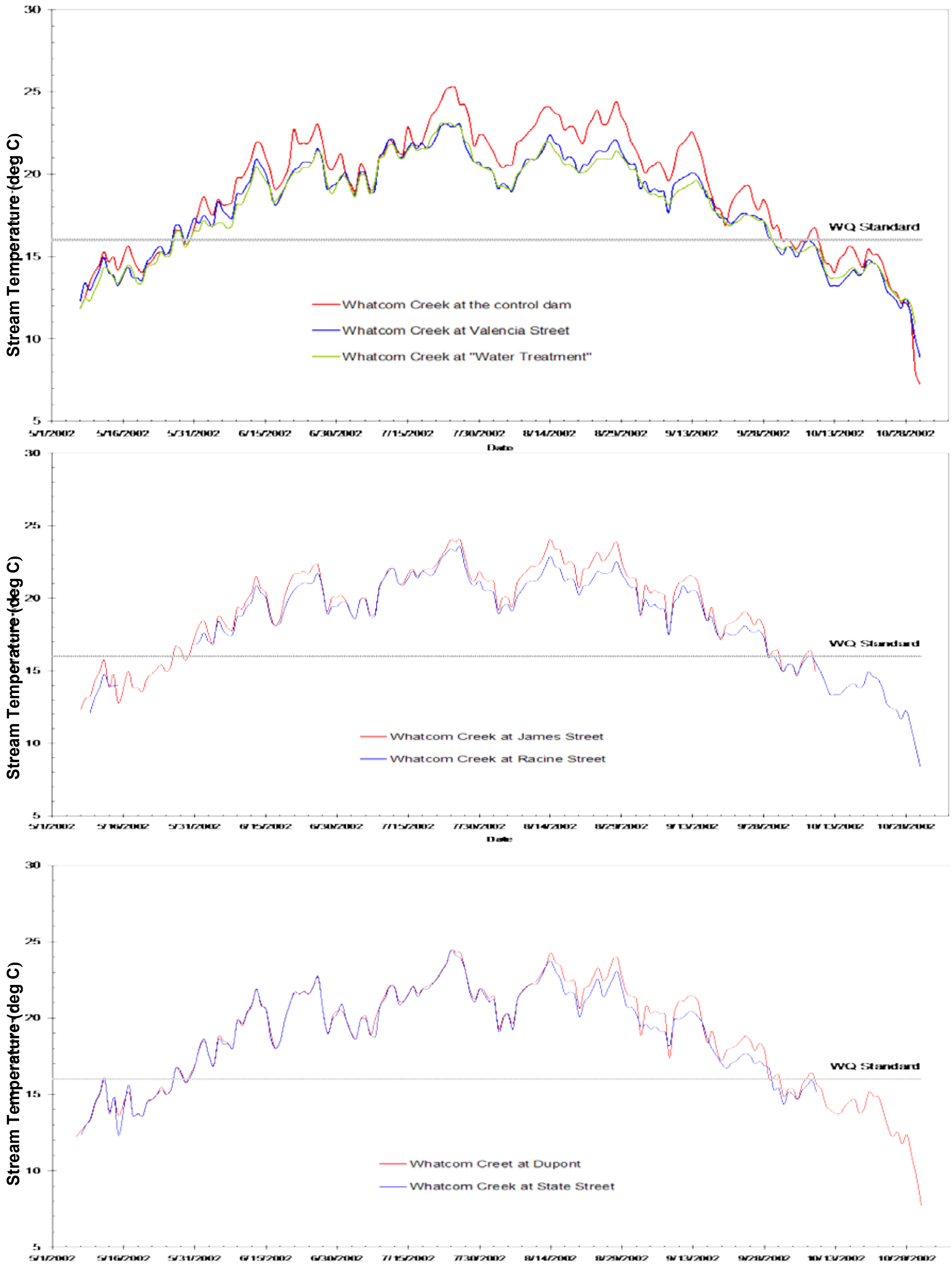


Figure 12. Daily maximum water temperatures in Whatcom Creek from May to October 2002.

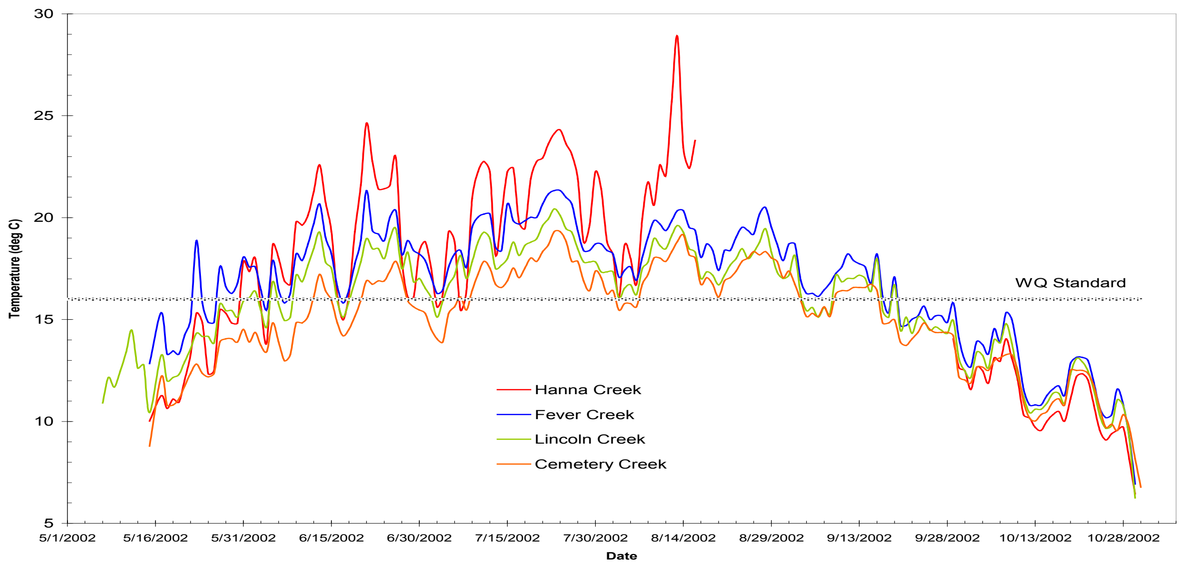


Figure 13. Daily maximum water temperatures in Whatcom Creek tributaries from May to October 2002.

Table 4. Summary of the highest daily maximum water temperatures in Whatcom Creek watershed, 2002.

ID Number	Station	Description	River (creek kilometer)	Highest 7-day-average daily maximum water temperature during 2002 (deg C)	Highest daily maximum water temperature during 2002 (deg C)
521498	Hanna Creek	Hanna Creek at mouth	At mouth	24.1	28.9
531540	Control Dam	Whatcom Creek at headwaters	6.7	24.6	25.3
531532	State Street	Whatcom Creek at State Street	1.5	23.6	24.5
521497	Dupont Street	Whatcom Creek at Dupont Street	0.4	23.5	24.4
531535	James Street	Whatcom Creek at James Street	2.1	23.7	24
483462	Racine Street	Whatcom Creek at Racine Street	3.3	22.9	23.6
531531	Valencia Street	Whatcom Creek at Valencia Street	3.8	22.7	23
483460	Water Plant	Whatcom Creek at the Water Plant	5.3	22.9	23
483461	Fever Creek	Fever Creek at mouth	At mouth	20.9	21.3
512712	Lincoln Creek	Lincoln Creek at mouth	At mouth	19.7	20.4
531538	Cemetery Creek	Cemetery Creek at mouth	At mouth	18.6	19.3

Figure 12 and Table 4 indicate that daily maximum water temperatures at the Control Dam station at the outlet of Lake Whatcom are the highest in Whatcom Creek. Water tends to cool down as is passes through the Derby Pond and the shaded reach below it. Daily maximum temperatures recorded at the Water Plant station are about 0.5°C to 2.2°C cooler than at the Control Dam station, with an average of 1.3°C in the May through October 2002 period (Figure 12). The Water Plant station recorded the coolest daily maximum temperatures, followed by the next downstream station, Valencia St. Whatcom Creek begins to warm up gradually as it leaves the cooler and more humid forested reach and enters the downstream developed area. In this lower section, the warmest stations are James St., State St., and Dupont St., respectively. However, they are not warmer than the headwater Control Dam station.

Whatcom Creek tributaries

Whatcom Creek tributaries are in general cooler than the mainstem, with the exception of Hannah Creek, which is the smallest. The coolest Whatcom Creek tributary is Cemetery Creek. Lincoln Creek is the second coolest, but had many exceedances of the criterion during the June through September 2002 period. Fever Creek is warmer than both Cemetery and Lincoln Creeks, with daily maximum temperatures above the criterion for almost the entire May to September period. Hannah Creek is the warmest creek in the entire watershed, with daily maximum temperatures reaching 25 °C and above (Figure 13).

The high temperatures in Hannah Creek are due mainly to its reduced streamflow that allows the water to warm up more easily. Moreover, Hannah Creek usually goes dry during the summer. Although warm, the Whatcom Creek tributaries, with the exception of Hannah Creek, show fewer exceedances of the criterion than the mainstem. Whatcom Creek and its tributaries were, in general, above the 16°C limit from late May to early October 2002.

The highest daily maximum stream temperatures occurred during the period of relatively high air temperatures at the end of July and in the middle and end of August in 2002 (Figures 12 and 13).

Stream temperature and air temperature

Stream temperature mimics air temperature at some lag time and different magnitudes. Both air and water temperatures respond to the major factor affecting them, the incoming solar radiation. Air temperature was considered as a major factor affecting stream temperatures (Edinger et al., 1968; Sullivan and Adams, 1990), but this statement may be misleading because these correlations do not demonstrate causation (Johnson, 2003).

Air and stream temperature variations during July – September 2002 at Dupont St., Racine St., and Control Dam stations (Figure 11) are shown in Figure 14. Water temperature at the Control Dam station is influenced by the temperature in Basin 1 of Lake Whatcom. The Racine St. station stream temperature measurements show the smallest daily variations, while at the mouth (Dupont St. station) the stream displays the highest daily fluctuations (Figure 14).

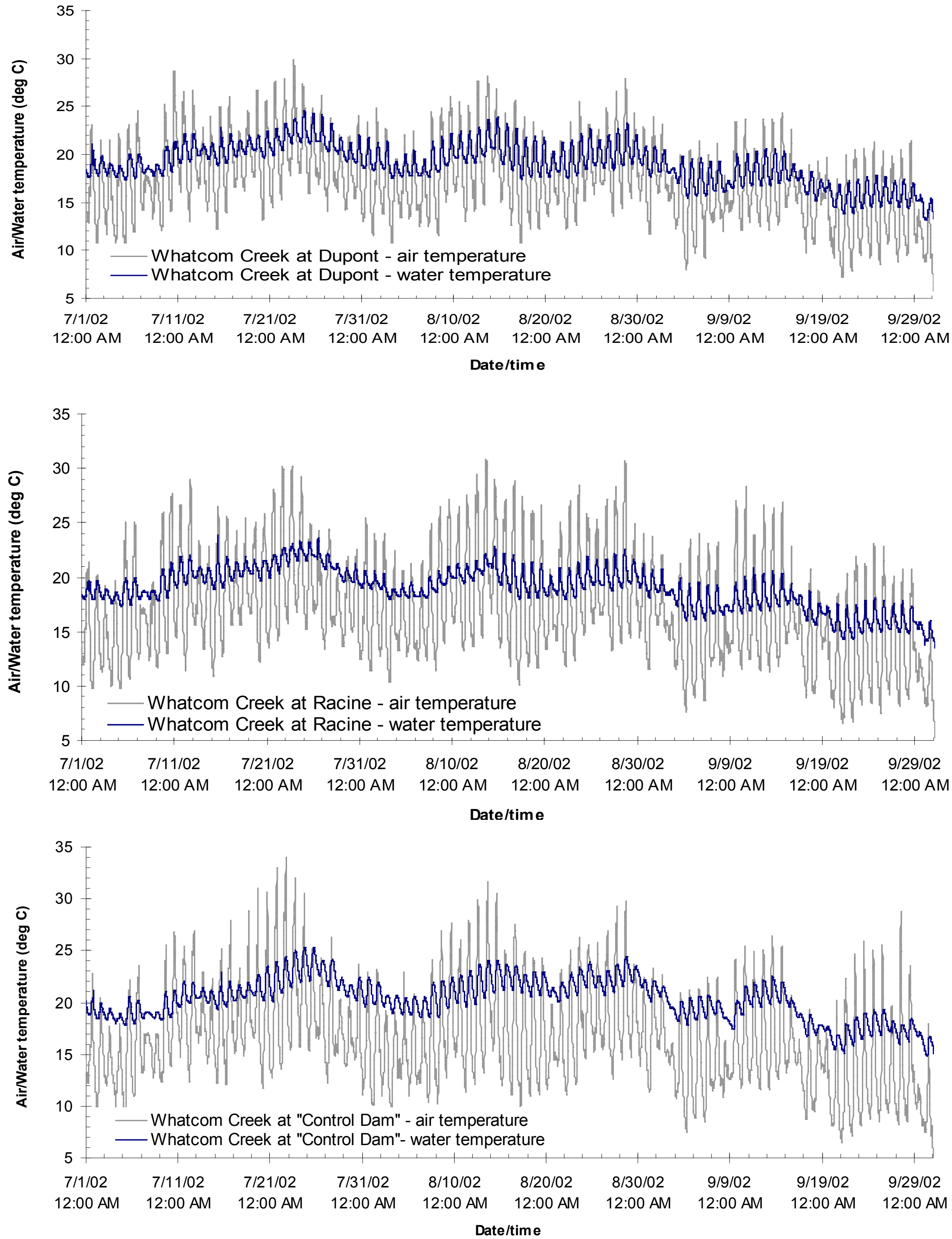


Figure 14. Air and water temperature variations during July to September 2002 at Dupont St., Racine St., and Control Dam stations.

Streamflow data for the Whatcom Creek watershed

Continuous streamflows were recorded at two locations in Whatcom Creek: at the Derby Pond and near the stream mouth at the Dupont St. station (Figure 11). Daily streamflows at the two stations for May-October 2002 are shown in Figure 15. Water discharges in Whatcom Creek are largely controlled by the control dam placed at the outlet of Lake Whatcom. The flow measurements at the two stations are close due to the relatively small size of the watershed and small tributary inputs. Additionally, instantaneous flow measurements on Whatcom Creek tributaries were taken during the dry season of 2002 (Table 5). Tributary inflows are often about an order of magnitude lower than flows in Whatcom Creek.

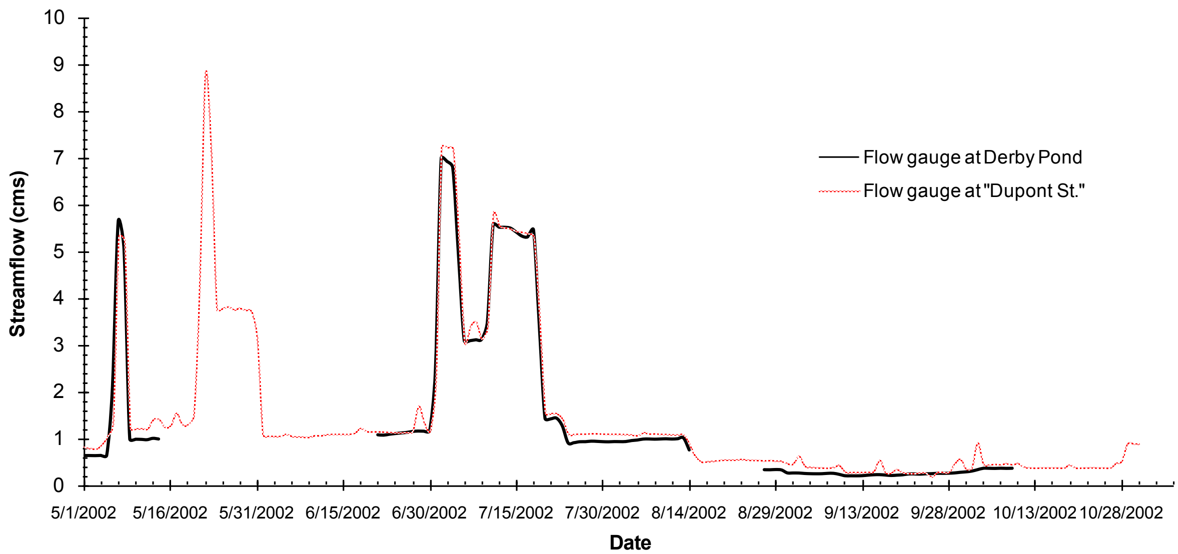


Figure 15. Daily streamflows in Whatcom Creek at the Derby Pond (upstream) and Dupont St. (downstream) stations during the dry season of 2002.

Table 5. Instantaneous streamflow measurements in Whatcom Creek tributaries from May to October 2002.

Watercourse	Date	Q(cfs)
Cemetery Creek	5/7/2002	0.57
	5/21/2002	0.67
	6/4/2002	0.19
	6/18/2002	0.21
	7/3/2002	0.11
	7/17/2002	0.04
	8/7/2002	0.01
	10/8/2002	0.03
Fever Creek	5/7/2002	0.32
	5/21/2002	0.34
	6/4/2002	0.1
	6/18/2002	0.19
	7/3/2002	0.07
	7/17/2002	1.3
	8/7/2002	0.04
	8/27/2002	0.03
	10/8/2002	0.07
Hannah Creek	5/7/2002	0.51
	5/21/2002	0.54
	6/4/2002	0.09
	7/3/2002	0
Lincoln Creek	7/3/2002	0.14
	7/17/2002	0.12
	8/7/2002	0.07
	8/27/2002	0.06
	9/10/2002	0.07
	9/24/2002	0.05
	10/8/2002	0.12

Meteorology/Climate data

Regional meteorological parameters are routinely recorded at the Bellingham International Airport weather station (Figure 16). Additionally an air temperature/relative humidity probe was placed at Central Shops, and three air temperature sensors were placed at the Dupont St., Racine St., and Control Dam stations.

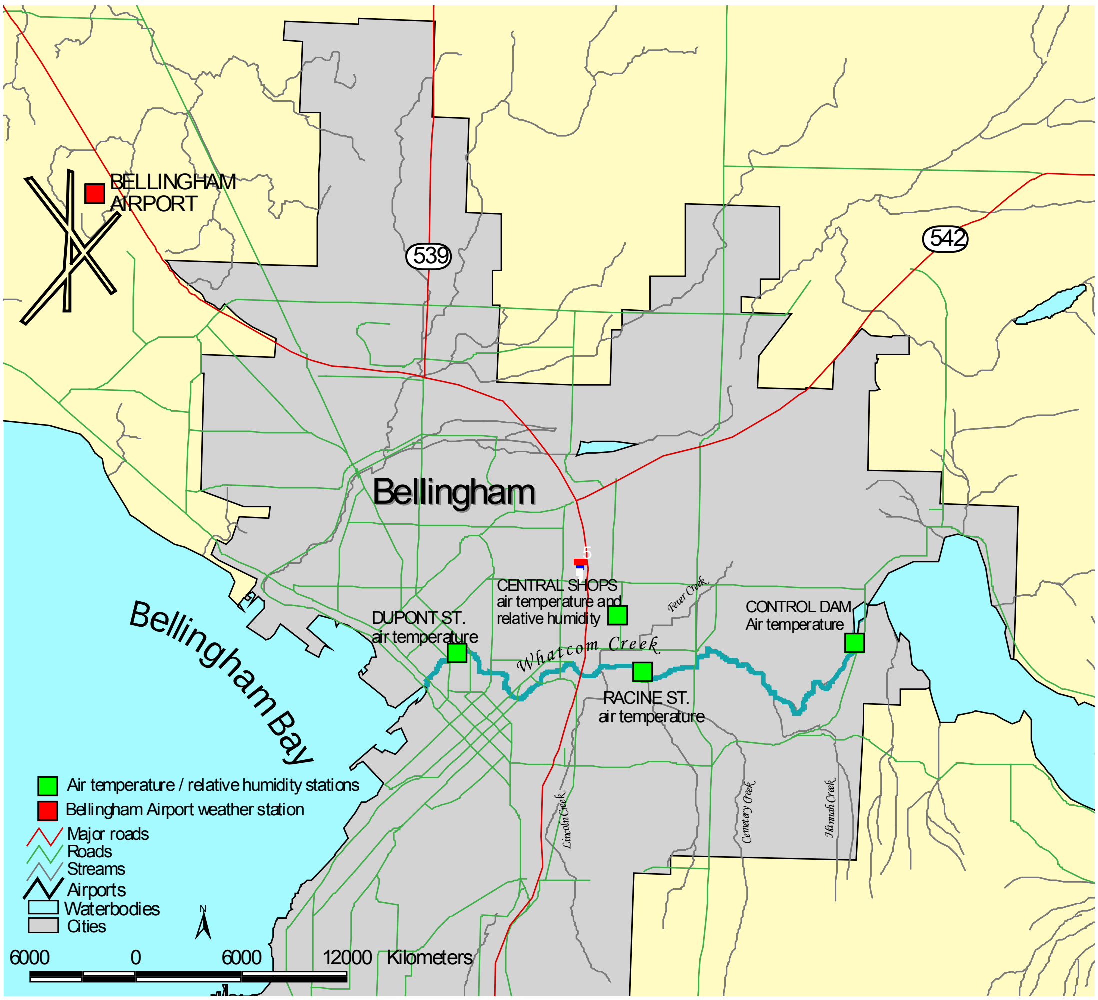


Figure 16. Bellingham Airport weather station and Ecology air temperature / relative humidity probe stations during the 2002 monitoring period.

Air temperature and dewpoint temperature variations during May to October 2002 recorded at the Central Shops station and Bellingham Airport meteorological station are shown in Figure 17. The dewpoint temperature is the temperature at which water vapor condenses in cooling air at the existing atmospheric pressure and vapor content.

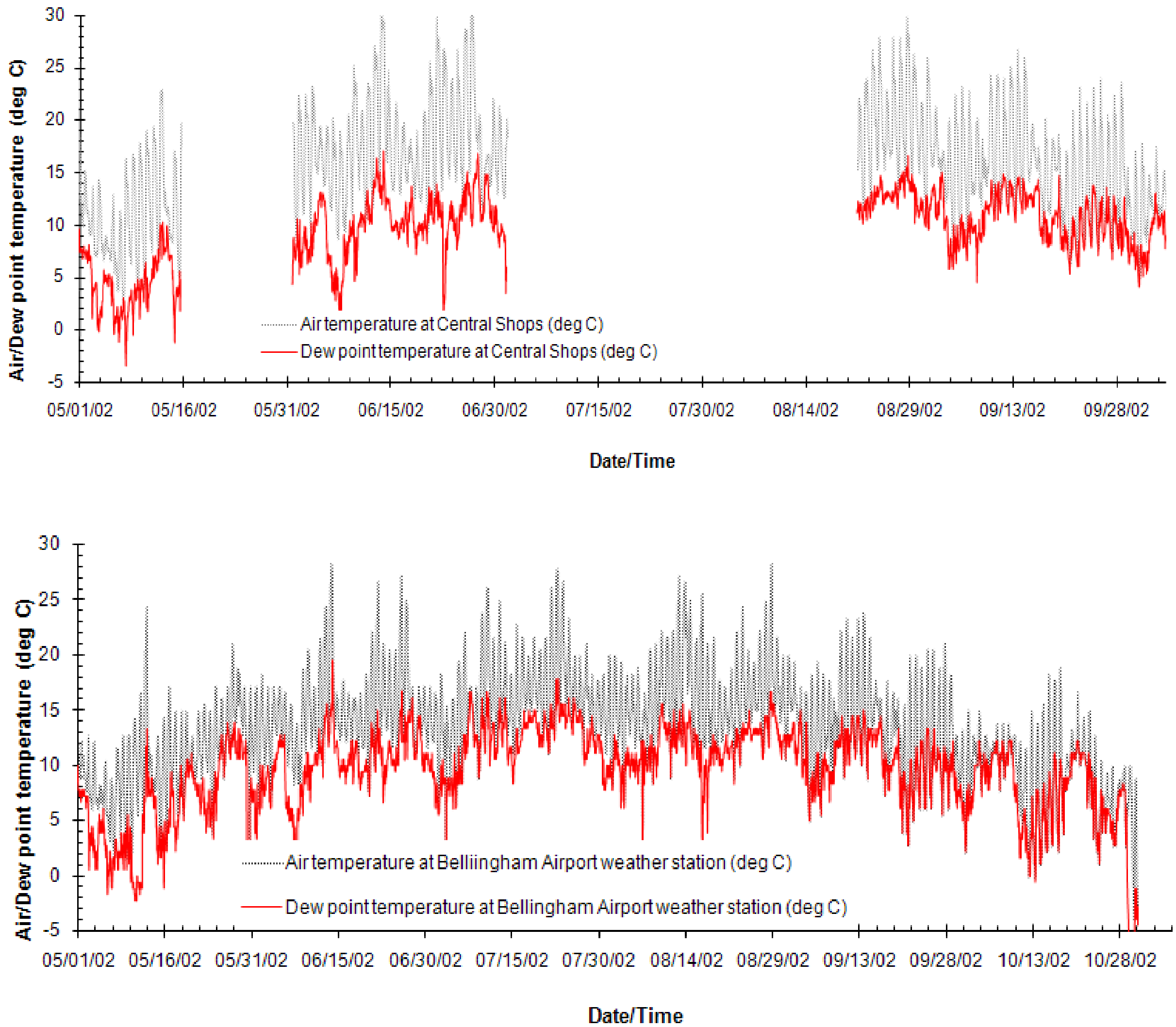


Figure 17. Air and dewpoint temperature during May to October 2002 recorded at Central Shops and Bellingham Airport meteorological stations.

Figure 18 shows the air temperature variations between the Central Shops station and the Bellingham Airport station. Lower daily extremes are recorded at the airport than at the Central Shops station. The differences between daily minimum and maxima at the two stations average roughly between 2°C and 4°C.

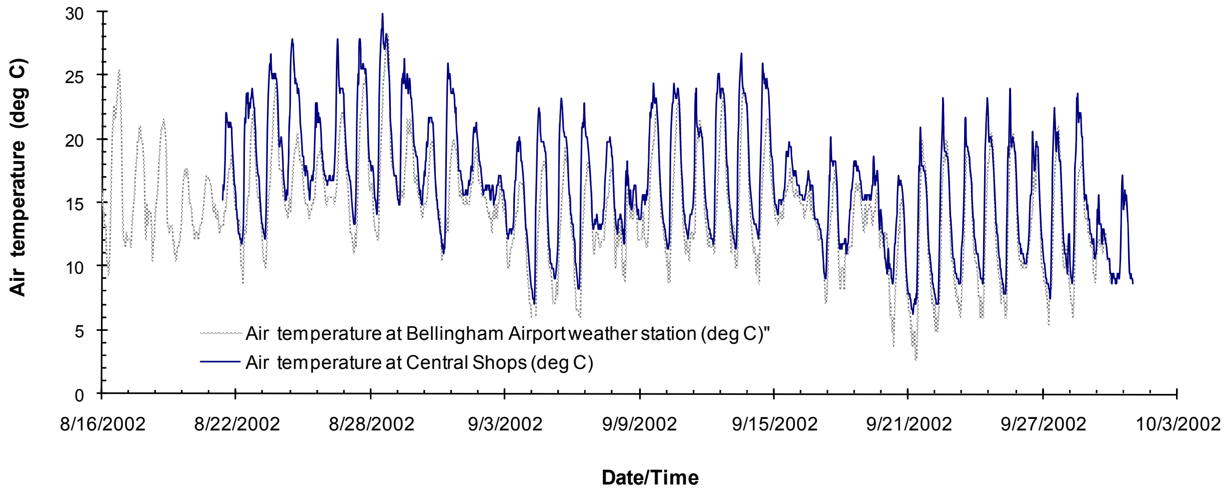


Figure 18. Air temperature at the Central Shops station and at the Bellingham Airport meteorological station during end of August to September 2002.

Meteorological data relevant to the Whatcom Creek stream temperature model were investigated for long-term statistics. Data used for this analysis were from the Bellingham Airport weather station (data available: 01/1949 – 01/2004). Sources of the data were Pacific Northwest EarthInfo Inc. meteorological data CD purchased by Ecology (data from 01/1949 to 06/2001), and the University of Washington Atmospheric Sciences Department webpage (data from 06/2001 to 01/2004), www-k12.atmos.washington.edu/k12/grayskies/nw_weather.html.

The highest daily maximum temperature and the highest 7-day average of daily maximum air temperature were selected for each year and were used to determine the median and the 90th percentile conditions. Fifty-six years of data were used for this statistical analysis summarized in Table 6.

Table 6. Estimated daily maximum and minimum air temperatures on days and weeks with the highest daily maximum temperatures for a median year and 90th percentile year.

Station	Years of data	Air temperature	7 – day averages		1 – day statistics	
			Median year hottest week	90th percentile hottest week	Median year hottest day	90th percentile hottest day
			8/2-8/1990	8/12-18/1977	7/24/2004	7/25/1988
Bellingham Airport weather station	56 (1949 - 2004)	Maximum air temperature on the hottest day/week (deg C)	25.8	28.1	30.0	33.3
		Minimum air temperature on the hottest day/week (deg C)	*13.7*	*15.6*	*13.9*	*13.3*

TMDL Analyses

Analytical framework

Data collected during this TMDL effort have been used to simulate water temperature in Whatcom Creek with a model that is both spatially continuous and which spans full-day lengths using steady flow and a dynamic heat budget. The GIS and modeling analyses were conducted using these specialized software tools:

- The Oregon Department of Environmental Quality's (ODEQ's) Ttools extension for ArcView (ODEQ, 2001) was used to sample and process GIS data for input to the Shade and QUAL2Kw models.
- Ecology's Shade model (Ecology, 2003) was used to estimate effective shade along the mainstem of the major tributaries in the Whatcom Creek watershed. Effective shade was calculated at fixed intervals along the stream, and data were input to the QUAL2Kw model.
- The QUAL2Kw model (Pelletier and Chapra, 2008; Chapra and Pelletier, 2003) was used to calculate the components of the heat budget and to simulate water temperatures. QUAL2Kw simulates diurnal variations in stream temperature for a steady-flow condition. QUAL2Kw was applied by assuming that flow remains constant for a given condition such as a 7-day or 1-day period, but key variables are allowed to vary with time over the course of a day. For temperature simulation, the solar radiation, air temperature, relative humidity, headwater temperature, and tributary water temperatures were specified or simulated as diurnally varying functions. QUAL2Kw uses the kinetic formulations for the components of the surface water heat budget that are shown in Figures 5 and 6 and described in Chapra (1997).
- All input data for the Shade and QUAL2Kw models are longitudinally referenced, allowing spatial and/or continuous inputs to apply to certain zones or specific river segments. Model input data were determined from available GIS coverages using the Ttools extension for ArcView, or from data collected by Ecology or other data sources. Detailed spatial data sets were developed for the following parameters for model calibration and verification.
    - Near-stream disturbance zone (NSDZ) widths were digitized at 1:3000 scale.
    - West, east, and south topographic shade angle calculations were made from the 10-meter DEM grid using ODEQ's Ttools extension for ArcView.
    - Stream elevation and gradient were sampled from the 10-meter DEM grid with the ArcView Ttools extension. Gradient was calculated from the longitudinal profiles of elevation from the 10-meter DEM.
    - Aspect (streamflow direction in decimal degrees from north) was calculated by the Ttools extension for ArcView.

- The daily minimum and maximum observed temperatures for the boundary conditions at the headwaters and tributaries were used as input to the QUAL2Kw model for the calibration and verification periods.

- The temperature of groundwater is often assumed to be similar to the mean annual air temperature (Theurer et al., 1984). Calibration of the QUAL2Kw model involved selection of the temperature of diffuse inflows ranging from the estimated temperature of groundwater temperature as measured in nearby wells to observed temperatures of surface water tributaries.

- Ecology's rTemp simple model (www.ecy.wa.gov/programs/eap/models/index.html) was used to simulate Whatcom Creek temperature daily variations. rTemp is a temperature model that solves the heat balance equation assuming a column of completely mixed water. Advection and dispersion are neglected. This simple model is used for the purpose of showing more detailed information for particular locations and for showing temperatures over a several week period. Load allocations are established based on the Shade and QUAL2Kw model results.

Seasonal variation

Clean Water Act Section 303(d)(1) requires that TMDLs "*be established at the level necessary to implement the applicable water quality standards with seasonal variations*," The current regulation also states that determination of "*TMDLs shall take into account critical conditions for streamflow, loading, and water quality parameters*" [40 CFR 130.7(c)(2)]. Finally, Section 303(d)(1)(D) suggests consideration of normal conditions, flows, and dissipative capacity.

Existing conditions for stream temperatures in Whatcom Creek reflect seasonal variation. Cooler temperatures occur in the winter, while warmer temperatures are observed in the summer. The highest temperatures typically occur from mid-July through mid-August. This timeframe is used as the critical period for development of the TMDL.

Seasonal estimates for streamflow, solar flux, and climatic variables for the TMDL are taken into account to develop critical conditions for the TMDL model. The critical period for evaluation of solar flux and effective shade will be assumed to be August 1 because it is the mid-point of the period when water temperatures are typically at their seasonal peak.

Since streamflow in Whatcom Creek is heavily regulated by the control dam placed at the outlet of Lake Whatcom, a typical low-flow analysis (a 7-day average, 2-year recurrence interval (7Q2) and/or a 7-day average 10-year recurrence interval (7Q10) for the months of July and August) would not apply. Therefore, a reasonable low-flow condition for Whatcom Creek was chosen to be represented by the 90th percentile low flow for July and August 2002, for which the flow was continuously monitored at both "headwater" and "mouth" stations.

Riparian vegetation and effective shade

Mapping the near-stream vegetation cover at current conditions

Near-stream vegetation cover, along with channel morphology and stream hydrology, represents the most important factors that influence stream temperature. To obtain a detailed description of the existing riparian conditions of Whatcom Creek, a combination of field observations and GIS analysis was used.

A 300-foot buffer from each bank of Whatcom Creek (Figure 19) was defined along both sides of the stream in a GIS environment. Vegetation polygons were mapped at a 1:3000 scale within the stream buffer. A vegetation type code that combines information about the average tree height and canopy density was assigned to each delineated polygon using orthophoto quadrangles (DOQs), as represented in Figure 19. To increase the accuracy of the image interpretation (riparian vegetation type, height, and density), field observations of vegetation type, height, and density were compared against the digitized GIS data.

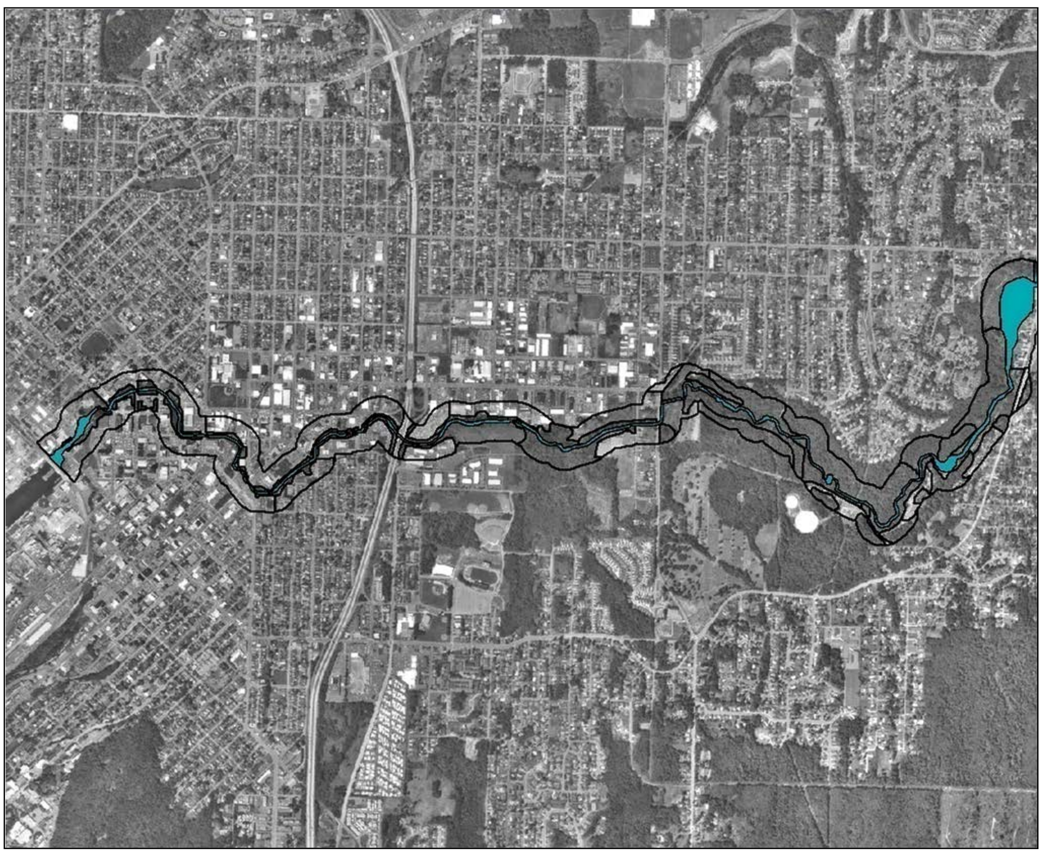


Figure 19. Digitized channel geometry and delineated vegetation polygons in a 300-foot buffer along Whatcom Creek.

Vegetation codes used in the riparian vegetation mapping processes are presented in Table 7.

Table 7. Riparian vegetation classification scheme.

Code	Description	Height (meters)	Density (%)	Overhang (meters)
301	Water	0.0	0%	0.0
307	Barren gravel	0.0	0%	0.0
400	Barren road	0.0	0%	0.0
800	Dense shrubs	2.4	50%	0.2
850	Sparse shrubs	2.7	10%	0.3
900	Grasses	1.2	75%	0.1
3248	Developed residential buildings	9.1	100%	0.9
3249	Developed industrial buildings	15.2	100%	1.5
3250	Developed mixed commercial & residential	12.2	100%	1.2
3251	Car parking lot	0.0	0%	0.0
3252	Developed with no trees	9.1	0%	0.9
111	Conifer small sparse	21.9	25%	2.2
112	Conifer small dense	21.9	75%	2.2
121	Conifer medium sparse	35.7	25%	3.6
122	Conifer medium dense	35.7	75%	3.6
131	Conifer large sparse	42.1	25%	4.2
132	Conifer large dense	42.1	85%	4.2
211	Deciduous small sparse	10.7	25%	1.1
212	Deciduous small dense	10.7	75%	1.1
221	Deciduous medium sparse	17.4	25%	1.7
222	Deciduous medium dense	17.4	75%	1.7
231	Deciduous large sparse	22.3	25%	2.2
232	Deciduous large dense	22.3	75%	2.2
311	Mixed small sparse	6.4	25%	0.6
312	Mixed small dense	6.4	75%	0.6
321	Mixed medium sparse	16.8	25%	1.7
322	Mixed medium dense	16.8	75%	1.7
331	Mixed large sparse	33.2	25%	3.3
332	Mixed large dense	33.2	75%	3.3
234	Deciduous large sparse	22.3	35%	2.2

Near-stream land cover along Whatcom Creek in a 300-foot buffer along its banks is represented in Figure 20. The Whatcom Creek riparian buffer is dominated by industrial buildings located mostly in the downstream area (23%), followed by developed areas with no trees (10.5%), mixed (conifer and hardwood) large dense vegetation present mostly in the upstream reaches (8.4%), and residential buildings downstream (8%).

(a)

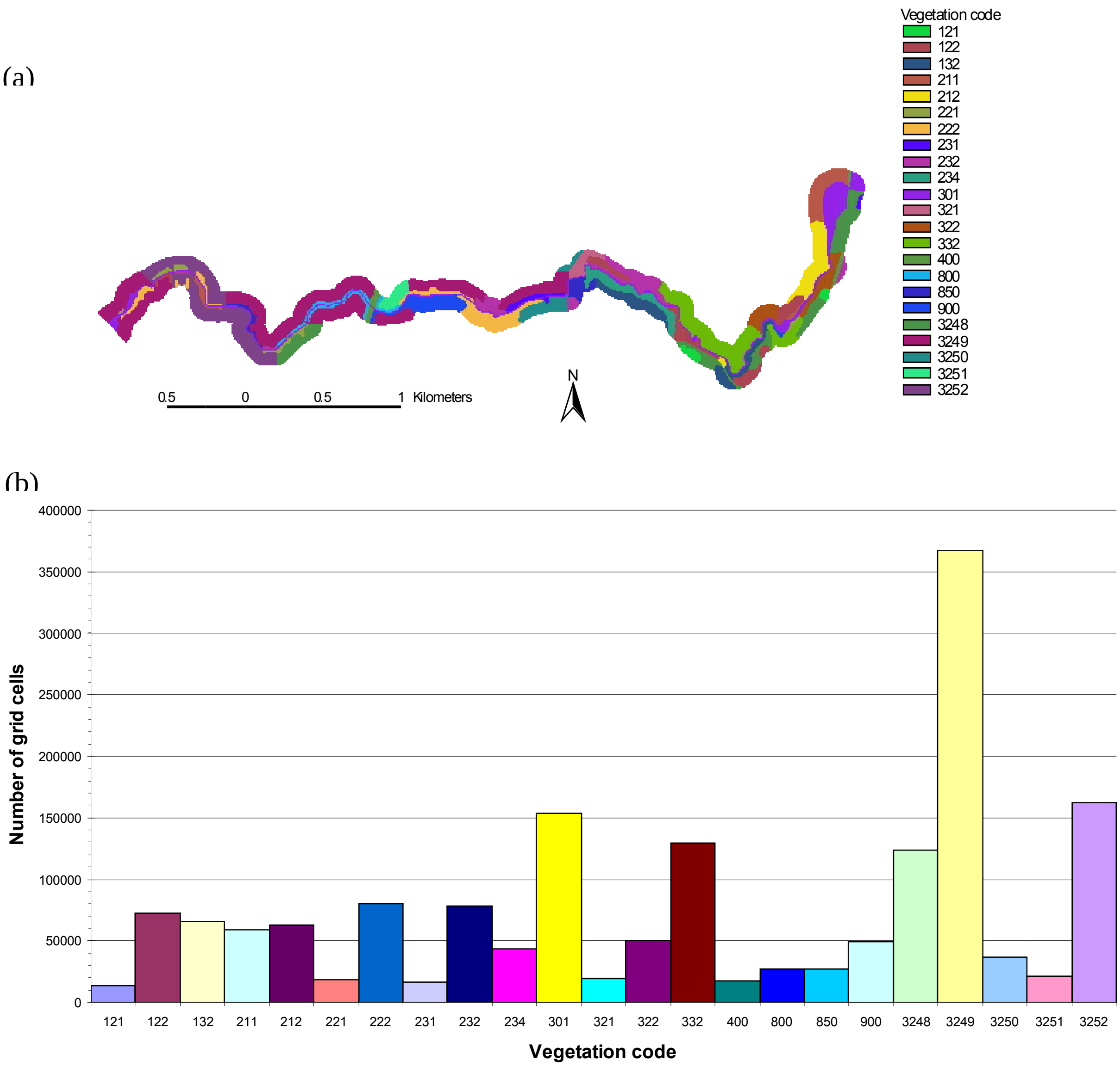


Figure 20. (a) Near-stream land cover along Whatcom Creek. (b) Vegetation type distribution in the Whatcom Creek 300-foot riparian corridor.

Immediately after leaving the lake, the creek enters Whatcom Falls Park, an undeveloped forested area with many 100+ year old Douglas-firs and western red cedars. Hanna Creek joins the mainstem just as Whatcom Creek enters a deeply incised bedrock gorge. This section of Whatcom Creek is the only freshwater shoreline in Bellingham designated as natural under the city's Shoreline Management Master Program. As the creek leaves the gorge, it flows over Middle Falls, a natural barrier to migration of adult and juvenile salmonids. The section from Middle Falls to the mouth of Whatcom Creek provides habitat for cutthroat trout (*Oncorhynchus clarki)*, chinook salmon (*O. tshawytscha)*, coho salmon (*O. kisutch)*, chum salmon (*O. keta)*, pink salmon (*O. gorbuscha)*, and steelhead and rainbow trout (*O. mykiss)*. (City of Bellingham, 2001.)

On June 10, 1999, the upper part of the watershed was heavily affected by a gasoline leak explosion that incinerated a one-and-one-half-mile stretch of Whatcom Creek and Hannah Creek. Figure 21 presents an aerial picture taken after the explosion, showing the affected stretch of the Whatcom Creek riparian corridor. The Whatcom Creek Unified Command immediately began creek restoration work in several important areas: streambed remediation, erosion control, habitat, and riparian vegetation restoration. The majority of this work has now been completed.

Figure 21. The Whatcom Creek riparian corridor after the June 10, 1999 gasoline explosion. ***Photo source: City of Bellingham.***

Hanna Creek drains off Galbraith Mountain and flows through a single-family residential neighborhood before entering Whatcom Falls Park. Much of the riparian zone is intact, and many large conifer trees are present. The creek is well-shaded for most of its length, although the riparian vegetation in the lower end was impacted by the fuel spill and fire in June 1999 (City of Bellingham, 2001).

The upper reaches of Cemetery Creek are relatively undeveloped, while the lower reaches are subject to a combination of commercial, undeveloped, and cemetery land uses. Substrate consists of fine gravel, fine silt, and muck. Riparian vegetation consists of a dense understory dominated by salmonberry (*Rubus spectabilis*) and Himalayan blackberry (*Rubus discolor*). Alder (*Alnus rubra*) dominates the upper canopy cover. Streamflow is slow, and many pools become isolated in the forested wetland near the confluence with the mainstem. The city's sewer and water lines cross the creek bed near the confluence with the mainstem (City of Bellingham, 2001).

Fever Creek is a small creek draining from older single- and multiple-family residences on Alabama Hill. Fever Creek is above ground until it crosses Valencia Street, where it enters two underground pipes. One pipe contains the majority of flow and drains to Whatcom Creek under the Valencia Street Bridge. The second pipe contains a small proportion of the flow and continues underground through a light-industrial area, collecting stormwater runoff and joining Whatcom Creek just upstream of Interstate 5 (I-5) (City of Bellingham, 2001).

Lincoln Creek is heavily impacted by urban development and associated impervious surfaces. It flows through and under several large shopping centers, parking lots, and a high-density residential area before being piped underground through a light-industrial area and joining Whatcom Creek just above the I-5 crossing. Lincoln Creek receives stormwater from the majority of the nearby impervious areas (City of Bellingham, 2001).

Potential near-stream vegetation cover

System potential effective shade is the natural maximum level of shade that a given stream is capable of attaining with the growth of "system potential mature riparian vegetation," defined as *that vegetation which can grow and reproduce on a site, given climate, elevation, soil properties, plant biology, and hydrologic processes.*

Tree heights are specific to an area and dependent on several variables including soils, climate, elevation, and hydrologic processes. GIS soils datasets are often linked to an index with values of 50- or 100-year tree heights that the soils in the area can support. Generally west of the Cascade Range site conditions are estimated by using an index age of 50 years, while eastside site conditions are estimated by using an index age of 100 years. Both the Natural Resources Conservation Service Soil Survey Geographic Database (SSURGO) and the Washington State Department of Natural Resources (DNR) provide soils coverage for the State of Washington.

For Whatcom Creek, system potential vegetation height was estimated based on the DNR soils polygon coverage (http://fortress.wa.gov/dnr/app1/dataweb/metadata/soils.htm). DNR soils data were available for the upper reaches of Whatcom Creek and the forested areas of its tributaries. The mean site index tree height at 50 years for this area was 35.5 m (116 ft).

After completing analysis and modeling for Whatcom Creek, the study area was expanded to include Squalicum and Padden Creeks and their tributaries. Because the DNR soil survey covered only portions of these creeks, the Whatcom County Soil Survey (USDA, 1992) was also consulted. The Whatcom County survey is available in GIS layers (SSURGO) and covers the entire county, including the urban areas (Figure 22). Both soils layers use the same base information, but the DNR soil survey is much easier to work with. This is because the tree index information is directly attached to the soil polygon, while the SSURGO information involves more database and calculation work.

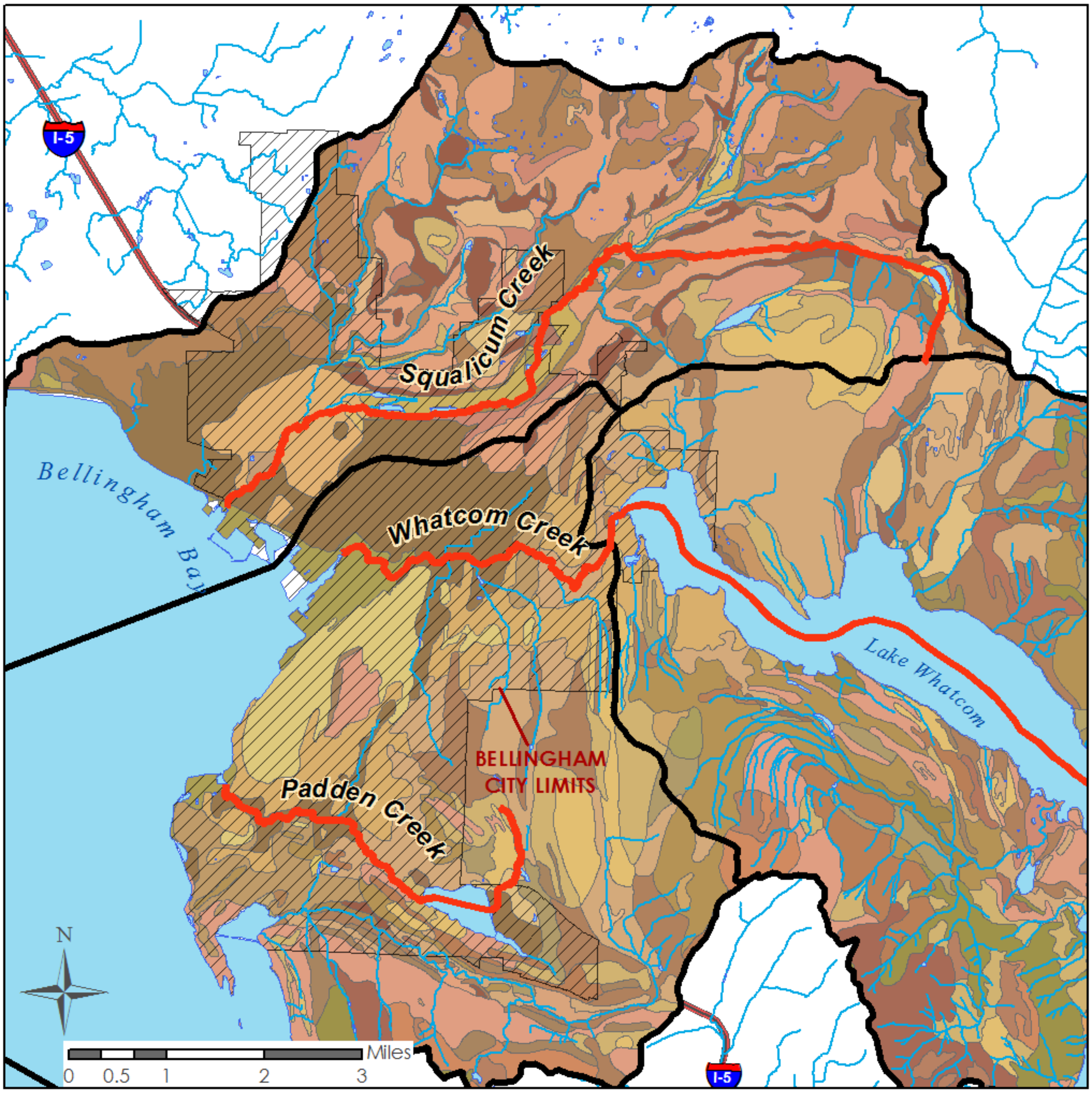


Figure 22. Soil detail available from the USDA Soil Survey Geographic Database (SSURGO) and the Whatcom County Soil Survey.

Complete listing of near-stream soil information is available in Appendix D.

All soils within 500 feet of Padden and Squalicum Creeks were evaluated. The average tree height values for near-stream soils in these areas are shown in Table 8. Height is weighted appropriately for the size of the area occupied by that soil type. Some portions of the urban area do not have index values so these were not used in the calculations. Complete listings of the soil information used are in Appendix D.

Table 8. Index tree heights from SSURGO for the Squalicum and Padden Creek watersheds.

Watershed	50- year heights (feet)
Squalicum Creek	113 (34.4 meters)
Padden Creek	124 (37.8 meters)
Squalicum and Padden combined	117.1 (35.7 meters)

Note: Heights are weighted by area occupied by each soil type.

The index tree height for the combined Squalicum Creek and Padden Creek near-stream area was almost identical to that used for Whatcom Creek, 117.1 feet versus 116 feet respectively. Therefore the value of 116 feet used in the Whatcom Creek analysis was expanded to the entire Whatcom, Padden, and Squalicum Creek study area.

For many temperature projects, a system potential height of 100 years is used because that is a better estimate of the ultimate tree height in the watershed. For this project, a height of 50 years was used because the stream channel widths are narrow and a sensitivity analysis shows that the taller tree height does not measurably change the shade value. Whatcom Creek has an average channel width of 10.4 meters between the control dam and the mouth at Bellingham Bay. Padden and Squalicum Creeks are also narrow enough to be well shaded with 50-year index size vegetation.

Effective shade calculations

Whatcom Creek vegetation data were input into a Shade model (Ecology, 2003). The vegetation codes required for input in this model were sampled with Ttools 3.3 ArcView extension developed by the Oregon Department of Environmental Quality (ODEQ, 2001) at 25-meter intervals. The shade calculation method chosen was the method developed by Chen (1996) and implemented in the Ecology Shade model. Other data required by the Shade model include stream aspect and topographic shade angles to the west, south, and east. The shade levels are determined mostly by the time of the year, solar position, geographic position, stream geomorphology, and riparian vegetation.

Effective shade corresponding to site potential vegetation was estimated assuming a 45-m (150-ft) wide riparian buffer and riparian vegetation at mature stages with an average height of 35.5 m and 85% canopy cover. The 150-ft wide buffer width is considered to provide the maximum achievable shade from the near-stream vegetation (estimate, Brazier and Brown, 1973; Steinblums et al., 1984). In the 45-m (150-ft) riparian buffer, only the current vegetated areas were assumed to represent the site-potential mature vegetation. Areas presently occupied by roads and urban development mapped for the current condition Shade model were assumed the same in the site-potential Shade model. The Shade model was not used to evaluate a buffer of less than 150 feet because of limitations in simulating the loss of other riparian functions (e.g., microclimate improvements, erosion control, and channel stability).

Effective shade levels provided by vegetation and topography (Figure 23) were estimated for the Whatcom Creek corridor for three scenarios:

- Topography only.
- Current vegetation and topography.
- Mature riparian vegetation and topography.

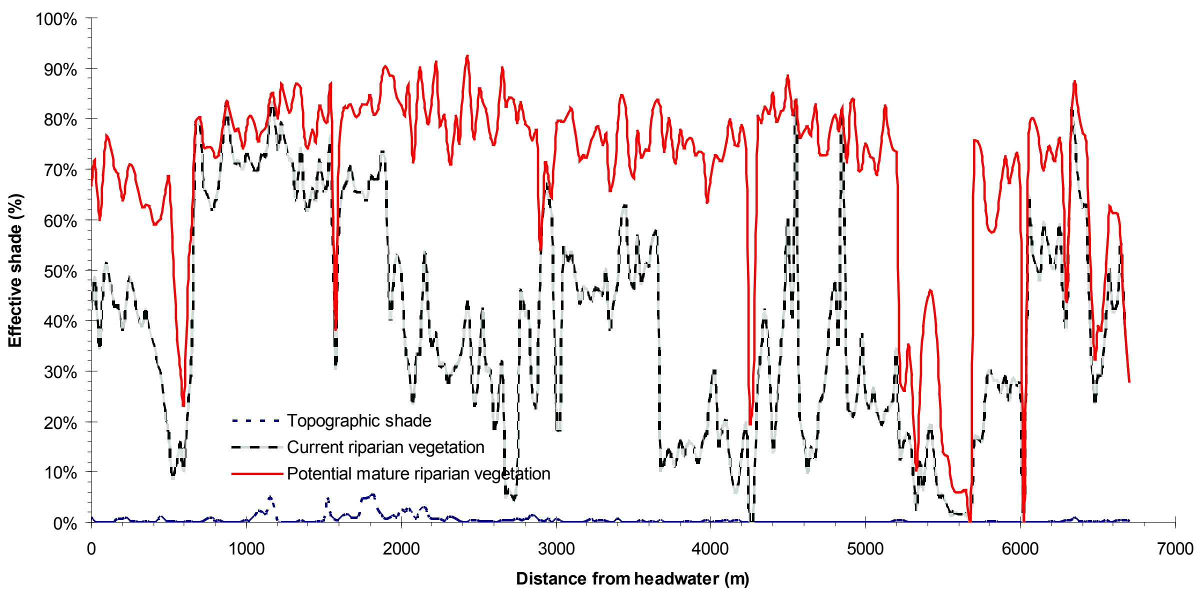


Figure 23. Effective shade from topography, current riparian vegetation, and potential mature vegetation in the Whatcom Creek corridor.

Calibration and confirmation of the QUAL2Kw model

The July 11-17, 2002 period, corresponding to a condition of relatively high streamflow (about 5.3 m^3/s) in Whatcom Creek, was used to calibrate the QUAL2Kw water quality model. A different period, August 5-7, 2002, with similar meteorological conditions but a significantly lower discharge (about 1 m^3/s), was used to confirm the stream temperature model.

The goodness-of-fit for both calibration and confirmation periods was summarized using the root mean square error (RMSE), as a measure of the deviation of model-predicted stream temperature from the measured values. The RMSE represents an estimation of the overall model performance and was calculated as:

$$RMSE = \sqrt{\sum \frac{(T_{measured} - T_{calculated})^2}{n}}$$

The measurement location at the lake control dam was not used in the computation because it influenced the model prediction as an upstream boundary condition. The RMSE were calculated for maximum and minimum predicted temperatures for both calibration and confirmation periods (Table 9). The Whatcom Creek predicted and measured maximum and minimum stream water temperature longitudinal profiles for the calibration and confirmation periods are presented in Figure 24.

Table 9. Summary of RMSE (deg C) of differences between the predicted and observed daily maximum and minimum temperatures in Whatcom Creek.

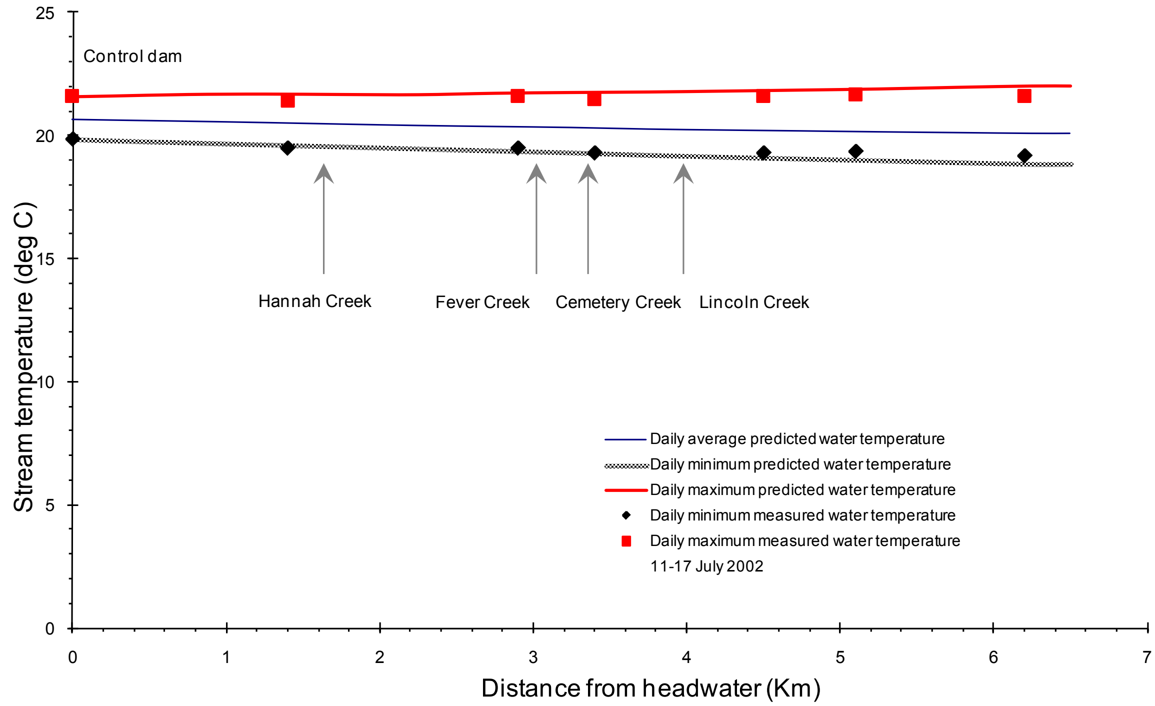
Watercourse	Model Calibration		Model Confirmation	
Whatcom Creek	Minimum 0.22	July 11-17, 2002	Minimum 0.37	Aug 5-7, 2002
	Maximum 0.28		Maximum 0.73	

The model fit, for the calibration period (July 11-17, 2005) is better (lower RMSE) than that for the confirmation period. The lower streamflow of the August 5-7 period increased the creek sensitivity to the heat exchange processes and made them more difficult to be simulated in the model. Also, the transition between the Derby Pond reach to the regular channel was not accurately modeled at low flow.

Ecology's rTemp simple model was used to demonstrate daily temperature variations in Whatcom Creek. Although the QUAL2Kw model is used to set load allocations based on a critical one-week period, it was considered instructive to also look at daily water temperature variations during the low-flow period from the end of August through the end of September 2002. The rTemp simple model was used to predict daily variations of water temperature in Whatcom Creek during this period (RMSE = 1.3°C). Figure 25 shows the rTemp water temperature model predictions and the measured air and water temperatures at the Control Dam station.

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

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



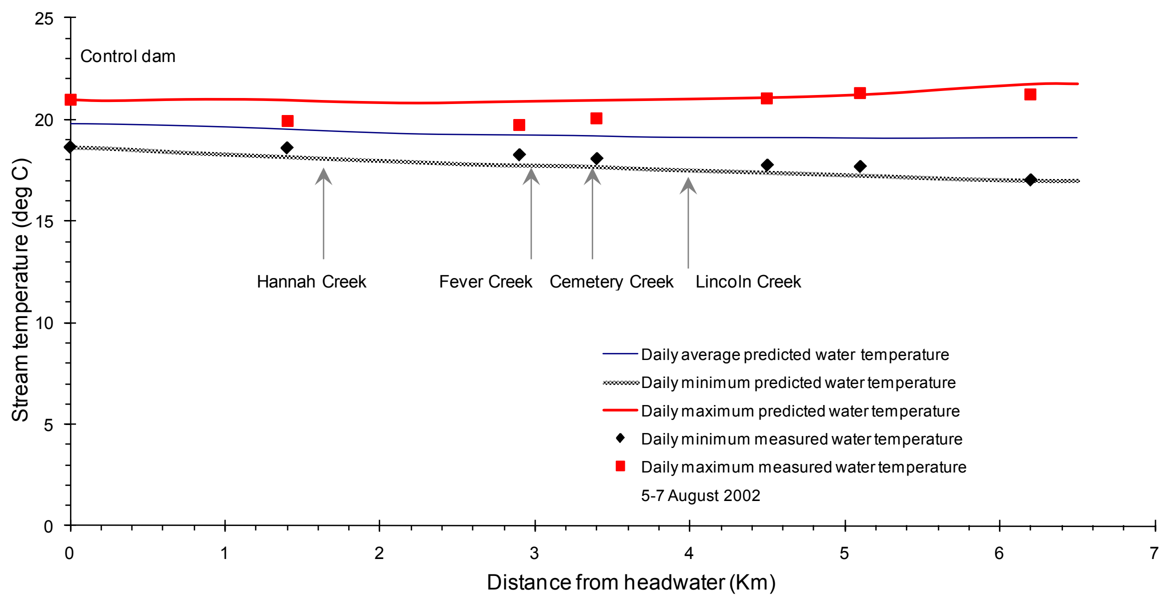


Figure 24. Predicted and observed water temperatures in Whatcom Creek at model calibration (July 11-17, 2002) and model confirmation (August 5-7, 2002).

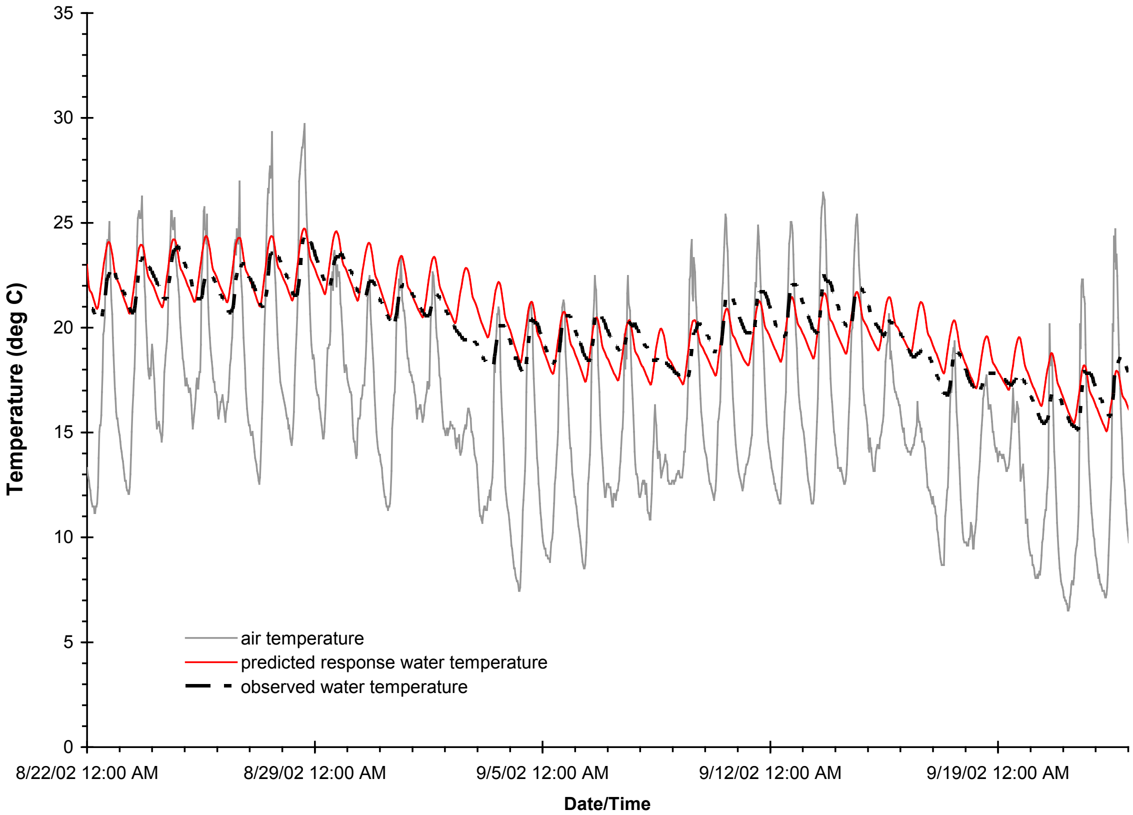


Figure 25. Predicted and observed water temperatures in Whatcom Creek from August 22 to September 22, 2002 at the Control Dam station.

Ecology has extended this concept to also include the response to heat flux between the water and the streambed, groundwater inflow, and hyporheic exchange.

The rate of change of response temperature can be written in terms of the net rate of surface heat exchange as

$$\frac{dT}{dt} = \frac{J_{net}}{D\rho_w C_{pw}}$$

where:

$\frac{dT}{dt}$ is the rate of change of water temperature with time (e.g., deg C per second).

D is the mean depth of the water column (e.g., cm).

J_{net} is the net rate of surface heat exchange (solar short-wave, long-wave atmospheric, long-wave back, convection, evaporation, streambed conduction, hyporheic exchange, groundwater inflow) (e.g., cal/cm^2/sec).

ρ is the density of water (e.g., g/cm^3).

C_{pw} is the specific heat of water at constant pressure (e.g., cal/g/deg C).

A similar expression was used in the rTemp model for the change in temperature of the surface layer of the bottom sediment underlying the streambed in response to the heat flux from hyporheic exchange and conduction between the water and sediment.

Loading capacity

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

This TMDL uses the modeled system potential temperature as an approximation of the natural temperature *during critical high air temperatures and low-flow conditions.* TMDL load allocations are supposed to be set for the critical condition in order to be protective of the stream during most of the year. The modeled system potential condition uses best estimates of potential mature riparian vegetation and riparian microclimate. The TMDL design condition is the system potential condition with "minimized human disturbance." The human modifications that affect the system include the control dam placed at the outlet of Lake Whatcom, the modified channel morphology, and the riparian areas affected by the presence of the city of Bellingham infrastructure and buildings.

The calibrated QUAL2Kw model was used to determine the loading capacity in Whatcom Creek. Loading capacity was determined based on prediction of water temperatures under a low-flow and 90^{th} percentile (1 in 10 year) climate conditions combined with a range of effective shade conditions.

Streamflows in Whatcom Creek are regulated by the control dam placed at the outlet of Lake Whatcom. Therefore, the amount of water in the channel is dependent on the water planning decisions and flood management strategies. The 90^{th} percentile low-flow condition (ranked from the lowest to highest, about 0.55 m^3/s, approximately half of the value for the August 5-7 confirmation period) for July-August 2002 was considered a critical low-flow condition for load allocations estimates in Whatcom Creek.

Air temperatures associated with the critical flow conditions were assumed to be represented by the August 12-18, 1977 week. This week corresponds to the historic 90^{th} percentile air temperature condition at the Bellingham International Airport meteorological station.

A series of scenarios that are expected to reduce the Whatcom Creek water temperature were evaluated as follows:

- **Maximum potential shade** that would be provided by 150-ft wide buffers of system potential mature riparian vegetation (less areas covered by infrastructure and buildings).

- **Microclimate improvements.** The presence of mature riparian vegetation is expected to induce changes in microclimate conditions along the stream. The air temperature and the wind speed would decrease, and the relative humidity would increase. Bartholow (2000) summarized possible changes in microclimate due to the presence of mature riparian vegetation based on relevant literature review, and indicated possible average decreases in air temperature of about 2^{o}C and average increases in relative humidity of approximately 10%. These values were used to simulate possible water temperature response due to microclimate changes.

The results of the model runs for critical conditions are presented in Table 10 and Figure 26.

Table 10. Summary of predicted daily maximum water temperatures at critical conditions in Whatcom Creek.

Model Scenario	Average predicted daily maximum temperatures across all reaches Tmax (degrees C)
Current condition	22.4
Mature riparian vegetation	20.6
Plus microclimate improvement	20.4

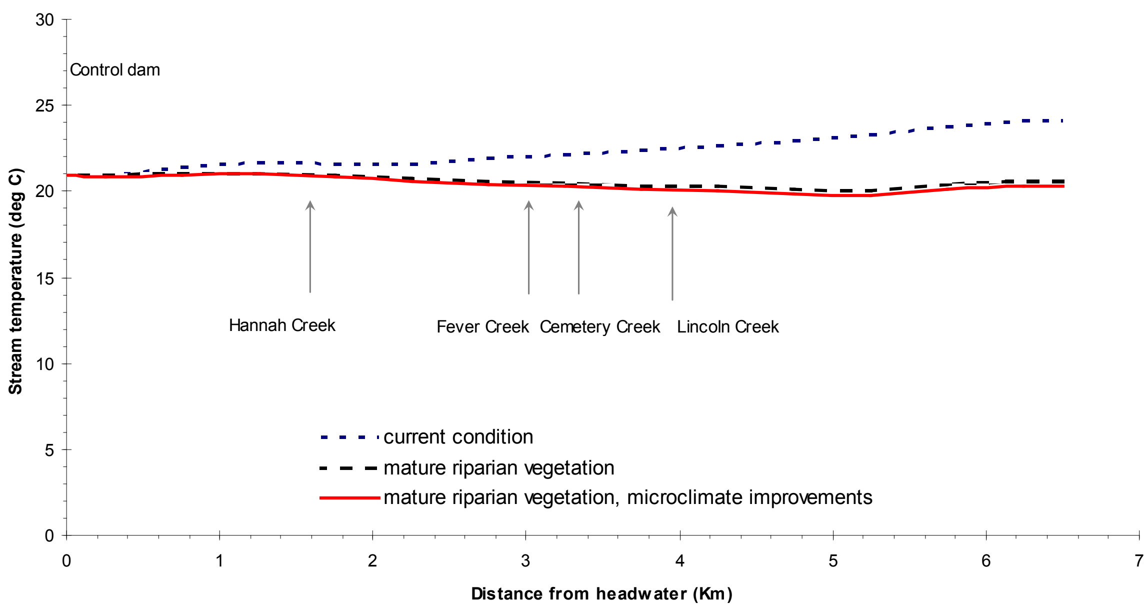


Figure 26. Predicted daily maximum water temperatures in Whatcom Creek for critical flow and meteorological conditions.

The QUAL2Kw model simulations indicated that:

1. A buffer of mature riparian vegetation along the banks of Whatcom Creek is expected to decrease its average daily maximum temperature. For the critical low-flow scenario, the daily maximum temperature across the stream length could be decreased by about 1.8 ºC compared to current conditions.

2. The changes in microclimate associated with mature riparian vegetation could further lower the daily average maximum water temperature by about 0.2ºC.

Figure 27 presents the time variation of temperature in Whatcom Creek assuming the current and increased riparian shade levels. The simulations were performed using the simple, single-reach rTemp model. This simulation was done for illustrative purposes. The load allocations are assigned based on QUAL2Kw model simulations.

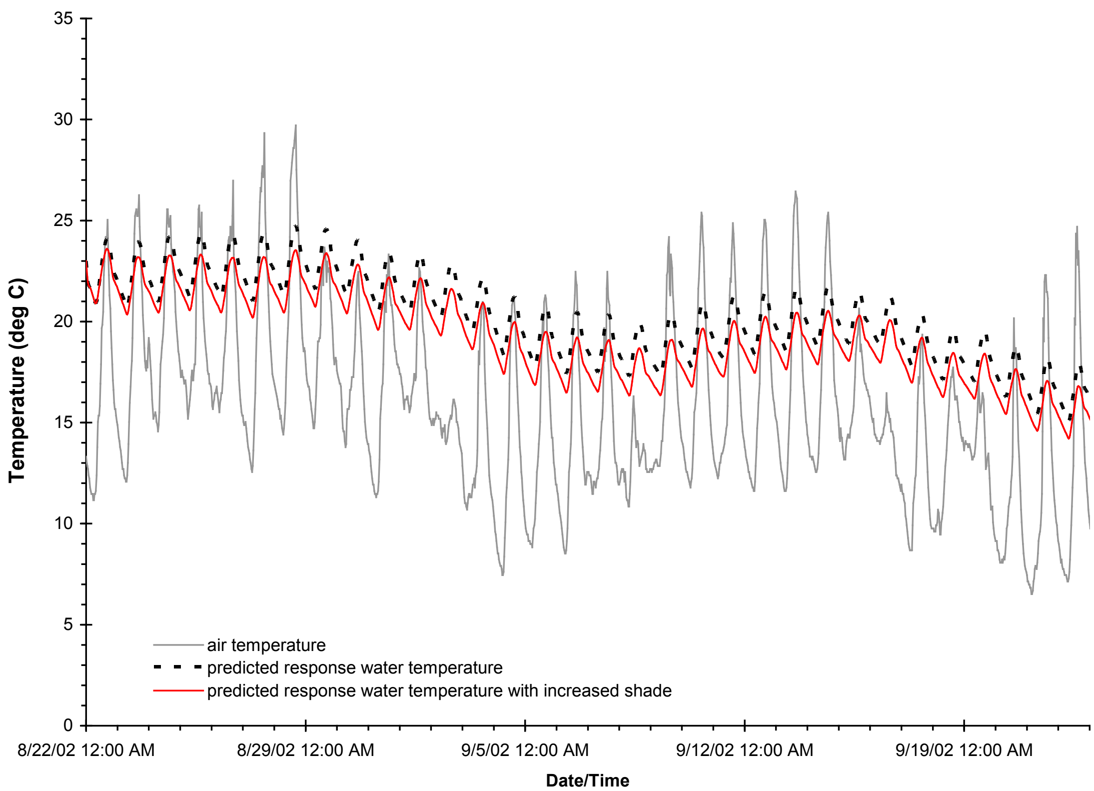


Figure 27. Predicted daily variations of water temperatures in Whatcom Creek for critical flow conditions for current and increased effective shade levels.

Lowland western Washington streams typically have a critical period in the late summer when ground water inflow is low, days are long and the sun is high, and air temperatures are warm. The result is that almost all streams exceed the criteria for a short period even when there is full shade. The only exceptions to this have been higher elevation areas in the Cascade Range and areas with a very high inflow of groundwater . Even in these cases, the majority of the study area had load-allocation targets that were at system-potential. There is no additional loading capacity available for heat in the Whatcom, Squalicum, and Padden Creek Watersheds. Therefore, as discussed for Whatcom Creek the criteria becomes the natural condition and the load allocation is the amount of shade predicted under natural riparian conditions.

Load allocations

Load allocations for effective shade are quantified specifically for each reach in Whatcom Creek. The Whatcom Creek tributaries and all streams in the Squalicum and Padden Creek drainages are assigned effective shade load allocations based on channel width and stream aspect (direction). Load allocations for Whatcom Creek begin at the control dam located at the outlet of the lake and go downstream every 25 meters until reaching Bellingham Bay. These allocations are shown in Appendix B and Figure 28. Segments showing load allocations in the 0-20% range are located near bridges or other existing urban structures that are expected to remain without riparian vegetation.

The load allocations are expected to re-establish mature riparian vegetation, eventually providing a functioning riparian zone. This will result in water temperatures that are equivalent to the temperatures that would occur under natural conditions. At that point in time, either the stream will have cooled to meet or be cooler than the numeric criterion, or the stream will have cooled to its natural temperature, which may be higher than the numeric criterion. In either case, the standard will be met, based on the natural conditions provision of the water quality standards. WAC 173-201A-200(1)(c)(i) states: *When a water body's temperature is warmer than the criteria (or within 0.3^{o}C (0.54^{o}F) of the criteria) and that condition is due to natural conditions, then human actions considered cumulatively may not cause the temperature of that water body to increase more than 0.3^{o}C (0.54^{o}F).*

Establishing mature riparian vegetation is expected to have a secondary benefit of improving microclimate conditions. Management actions that control other influences on stream temperature, such as sediment loading, groundwater inflows, and hyporheic exchange, are also recommended.

For the Whatcom Creek tributaries and for all streams in the Padden and Squalicum Creek watersheds, the load allocations for effective shade are represented in Figure 29 and Appendix C. The allocations are based on the estimated relationship between shade, channel width, and stream aspect at the assumed maximum riparian vegetation condition: 85% density and 35.5 meter tree height.

Figure 29 shows that the importance of shade decreases as the width of the channel increases. Topographic shade was assumed equal to zero. Instructions for determining site-specific load allocations using a shade curve (Figure 29) can be found in Appendix C.

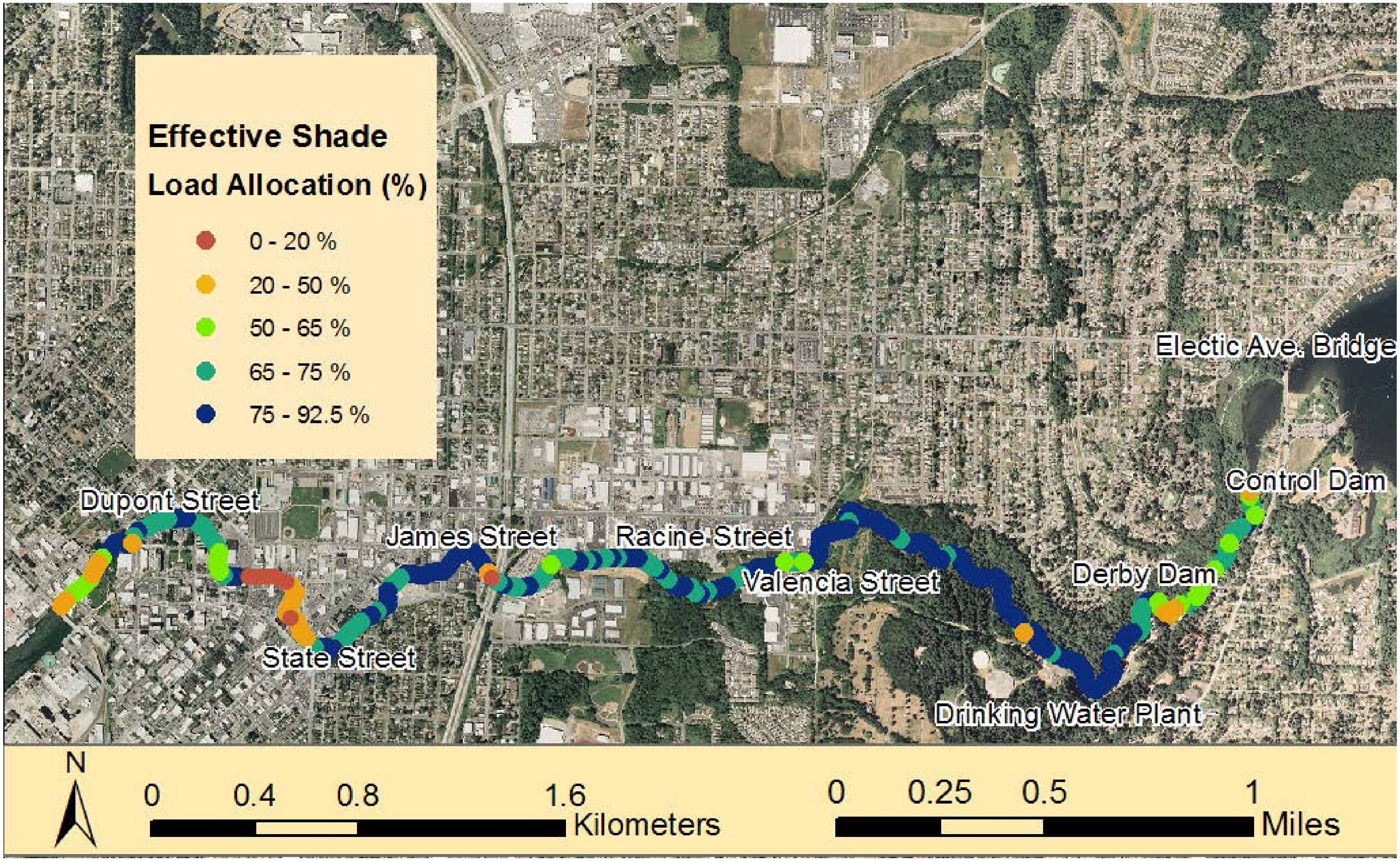


Figure 28. Effective shade load allocations for Whatcom Creek. (For color version, see Appendix B)

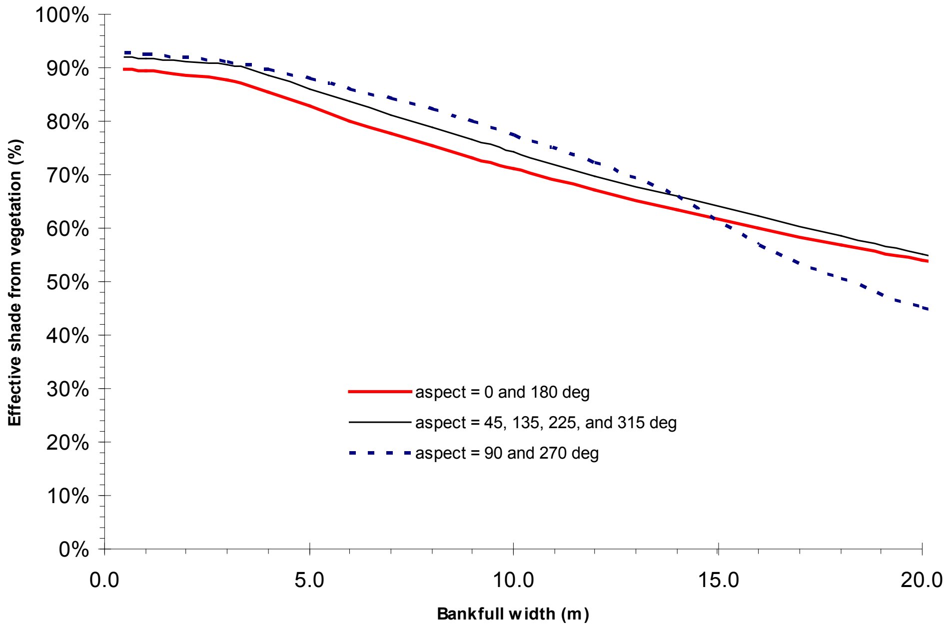


Figure 29. Load allocations for effective shade for various bankfull width and aspect of streams in the Whatcom, Squalicum, and Padden Creek watersheds assuming a riparian vegetation height of 35.5 meters, a canopy density of 85%, and 3.6-meter overhang.

Wasteload allocations

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

The only NPDES permit that requires monitoring at the outfall is the permit, WA-003150-0, assigned to the Bellingham Hatchery located at Whatcom Falls park. The facility draws its water from Lake Whatcom. Because of the large area of the lake exposed to solar radiation without an opportunity for shading even under natural conditions, the temperature of the lake water is considered a natural condition. The hatchery only adds a small amount of heat as the water flows through the hatchery. The hatchery has no way to reduce heat inputs so to require discharging at a temperature below the intake temperature would require halting the discharge. This would be disastrous to the fish at the hatchery. The discharge to the creek is very near the outlet from the lake where the creek is naturally warm. Shortly after the discharge, the creek enters the gorge in Whatcom Falls Park, which provides significant cooling to the creek. Therefore an incremental increase of 0.3 ºC above the intake temperature is allowed and no reasonable assurance is necessary.

Stormwater sources of thermal pollution in the watershed are assigned a wasteload allocation, based on the current water quality standards for freshwater systems and location of the stormwater source within the Whatcom Creek watershed. These wasteload allocations only apply to stormwater discharges that may occur during the critical summer low flow period.

The water temperature measurements in Whatcom Creek in 2002 have shown that the stream does not meet the current water quality numeric criterion of 16°C for most of the summer (June-September) season. Lake Whatcom, the headwater of the system, influences the temperature regime in Whatcom Creek and causes exceedances of the numeric criteria of 16°C. At current conditions, the stream shows little potential for downstream cooling in its upper vegetated region, and a slight tendency for downstream heating in the lower, less vegetated urbanized areas. Whatcom Creek tributaries also have shown multiple exceedances during the summer season of 2002.

The thermal influences of the tributaries on Whatcom Creek are very small, given their relatively small size and the reduced temperature differences between the mainstem and the tributaries. Therefore, the system has no capacity for additional heat loads generated from existing and future stormwater sources during the critical summer low-flow period. Although stormwater discharges were not sampled for this study, based on temperature data collected on the mainstem, the wasteload allocation for all municipal stormwater sources from new developments and redevelopments in the urbanized region of Whatcom Creek watershed is a cumulative 0.3°C incremental temperature increase above 16°C during summer low-flow periods.

Stormwater best management practices (BMPs)

The expectation is that stormwater best management practices (BMPs; Ecology, 2005) and/or treatment will be installed concurrent with new development and redevelopment so that discharges from these sources will not contribute to existing water quality problems. The same wasteload allocation also applies to existing stormwater discharges. However, Ecology intends to work with affected municipalities to establish a schedule for implementing any needed stormwater controls determined necessary to meet the wasteload allocation. State law authorizes establishing schedules of compliance to meet water-quality-based effluent limits within the shortest reasonable time, not to exceed 10 years.

BMPs for treating municipal stormwater runoff, which include infiltration basins, have been applied to many of the developed areas that drain to Whatcom Creek. The use of stormwater BMPs, such as stormwater infiltration, is anticipated to be adequate to protect water quality during the critical season because direct surface discharge from the basins does not typically occur during summer rain events. Summer storm events, which exceed the design storm for the BMPs, could result in a direct surface discharge to Whatcom Creek. However, these events are expected to be infrequent and are not expected to result in exceedances of the wasteload allocation.

The wasteload allocation applies during the critical summer low-flow period, typically occurring from June through September. The same wasteload allocation applies to existing stormwater discharges. As stated above, Ecology may establish a compliance schedule for the municipality to install appropriate BMPs or treatment if determined necessary to meet the wasteload allocations. Stormwater infiltration basins combined with other BMPs are anticipated to meet these wasteload allocations.

Margin of safety

The margin of safety accounts for uncertainty about pollutant loading and water-body response. In this TMDL, the margin of safety is addressed by using critical conditions in the modeling analysis. The margin of safety in this TMDL is implicit because of the following:

- The 90th percentile of the highest 7-day averages of daily maximum air temperature was used as a worst-case condition for model simulations, coupled with a low-flow condition in Whatcom Creek.
- Model uncertainty for prediction of water temperature was assessed by estimating the RMSE of model predictions compared with observed temperatures. The average RMSE for model calibration and confirmation of maximum temperatures was 0.5ºC.
- The load allocations are set to the effective shade provided by full mature riparian vegetation, which are the maximum values achievable in the Whatcom, Squalicum, and Padden Creek watersheds.

Reasonable assurances

When establishing a TMDL, reductions of a particular pollutant are allocated among the pollutant sources (both point and nonpoint sources) in the water body. For the Whatcom, Squalicum, and Padden Creek Temperatures TMDL, both point and nonpoint sources exist. TMDLs (and related action plans) must show "reasonable assurance" that these sources will be reduced to their allocated amount. Education, outreach, technical and financial assistance, permit administration, and enforcement will all be used to ensure that the goals of this water cleanup plan are met.

Ecology believes that the following activities already support this TMDL and add to the assurance that temperature in Whatcom, Squalicum, and Padden Creeks will meet conditions provided by Washington State water quality standards. This assumes that the following activities are continued and maintained.

The goal of the Whatcom, Squalicum, and Padden Creek Water Quality Improvement Plan for temperature is to help the waters of the basin meet the state's water quality standards. There is considerable interest and local involvement toward resolving the water quality problems in Whatcom, Squalicum, and Padden Creeks. Numerous organizations and agencies are already engaged in stream restoration and source correction actions that will help resolve the temperature problem. The following rationale helps provide reasonable assurance that the Whatcom, Squalicum, and Padden Creeks nonpoint source TMDL goals will be met by 2015.

The city of Bellingham has an active program to restore and maintain riparian vegetation along Whatcom Creek with long term funding as part of the Natural Resource Damage Assessment from the Whatcom Creek Pipeline Explosion. Since the TMDL study, 60 acres of riparian vegetation have been established mostly along Whatcom Creek.

The Shoreline Master Program for the city of Bellingham regulates activities within 200 feet of the shore line. This affects Padden Creek below the McKenzie Ave. right of way and all of Whatcom and Squalicum Creeks. After a lengthy process, the city is currently proposing adoption of revisions to the program. Under the proposed revisions, the shorelines are designated either Natural or Urban Conservancy. Riparian buffers of at least 100 feet on the upper reaches of Whatcom and Squalicum Creeks and 150 feet for the remaining length are protected. A 200-foot riparian buffer is protected in the shoreline for Padden Creek. Redevelopment within the shoreline can also trigger reestablishment of riparian vegetation within those buffers.

The city also has a critical areas ordinance that protects existing riparian vegetation outside of the shoreline jurisdiction. In those cases, at least 75 feet is protected.

When the Shoreline Master Program and Critical Areas ordinances are next revised, we expect the city of Bellingham to examine them to see if additional requirements are necessary to protect the temperature of the urban streams.

While Ecology is authorized under RCW Chapter 90.48 to impose strict requirements or issue enforcement actions to achieve compliance with state water quality standards, it is the goal of all participants in the Whatcom, Padden and Squalicum Temperature TMDL process to achieve clean water through voluntary control actions.

Ecology will consider and issue notices of noncompliance, in accordance with the Regulatory Reform Act, in situations where the cause or contribution to the cause of noncompliance with load allocations can be established.

Conclusions and Recommendations

As a result of this study, the following recommendations are made.

1. Whatcom Creek headwater temperature is determined by the temperature in Lake Whatcom as well as by the streamflows released in the channel at the control dam.

2. During 2002, the observed stream temperatures in the Whatcom Creek watershed showed that current conditions at most of the locations are warmer than the current water quality criteria. In general, tributaries are cooler than the mainstem. Hanna Creek, the smallest among Whatcom Creek tributaries, is also the warmest in the watershed due to its low summer flow. In the summer of 2002, Whatcom Creek was found to exceed the 16°C limit continuously from the beginning of June until the end of September.

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

   - For privately-owned forest land, the riparian vegetation prescriptions in the Forests and Fish Report (DNR, 1999) are recommended for all perennial streams. Load allocations are included in this TMDL for forest lands in accordance with the section of the Forests and Fish Report entitled, *TMDLs produced prior to 2009 in mixed use watersheds*.

   - Instream flows and water withdrawals are managed through regulatory avenues separate from TMDLs. However, stream temperature is related to the amount of instream flow, and increases in flow generally result in decreases in maximum temperatures. The stream is closed for additional appropriation, and there do not appear to be any active surface water withdrawals. Future projects that have the potential to increase groundwater inflows to streams in the watershed should be encouraged.

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

   - Riparian vegetation buffers should be restored and managed in accordance with the urban setting of the watershed. These actions include, but are not limited to, increasing forest cover in the urban watershed, conserving and planting trees at development sites, as well as planting trees along local streams and roads and in parking lots.

4. To determine the effects of management strategies within the Whatcom, Squalicum, and Padden Creek watersheds, interim monitoring of water temperatures during summer is

recommended, perhaps at 5-year intervals. Continuously-recording water temperature monitors should be deployed from July through August to capture the critical conditions. The following locations are suggested for a minimal sampling program:

- Whatcom Creek near mouth.
- Whatcom Creek at Racine St.
- Whatcom Creek below the control dam.

5. Interim monitoring of the composition and extent of riparian vegetation is also recommended (for example, by using photogrammetry or remote sensing methods, hemispherical photography, densiometers, or solar pathfinder instruments).

Implementation Strategy

Introduction

This implementation strategy describes what will be done to improve water quality. It describes the roles and authorities of cleanup partners (that is, those organizations with jurisdiction, authority, or direct responsibility for cleanup) and the programs or other means through which they will address these water quality issues.

After the U.S. Environmental Protection Agency (EPA) approves this TMDL, interested and responsible parties will work together to develop a *water quality implementation plan*. The plan will describe and prioritize specific actions planned to improve water quality and achieve water quality standards.

What needs to be done?

The city of Bellingham and Whatcom County protect riparian vegetation through their critical areas ordinances. This protects the riparian area from removal of riparian vegetation and encourages growth of additional vegetation over time. Implementation of both of the city and county Critical Areas Ordinances over time will ensure shade is attained on the creeks. As the requirements of those regulations are reviewed, the ability to meet the shade targets should be part of the analysis of any proposed revisions.

The process of establishing new vegetation is accelerated with focused efforts on riparian planting activities. The city of Bellingham and the Nooksack Enhancement Association have been successful at securing grants to help cover the cost of the plantings. These activities should be continued.

The state's forest practices regulations will be relied upon to bring waters into compliance with the load allocations established in this TMDL on private and state forest lands. This strategy, referred to as the Clean Water Act Assurances, was established as a formal agreement to the 1999 Forests and Fish Report (www.dnr.wa.gov/Publications/fp_rules_forestsandfish.pdf).

The state's forest practices rules were developed with the expectation that the stream buffers and harvest management prescriptions were stringent enough to meet state water quality standards for temperature and turbidity, and provide protection equal to what would be required under a TMDL. As part of the 1999 agreement, new forest practices rules for roads were also established. These new road construction and maintenance standards are intended to provide better control of road-related sediments, provide better stream bank stability protection, and meet current best management practices.

To ensure the rules are as effective as assumed, a formal adaptive management program was established to assess and revise the forest practices rules, as needed. The agreement to rely on the forest practices rules in lieu of developing separate TMDL load allocations or implementation requirements for forestry is conditioned on maintaining an effective adaptive management program.

Consistent with the directives of the 1999 Forests and Fish agreement, Ecology conducted a formal 10-year review of the forest practices and adaptive management programs in 2009:

www.ecy.wa.gov/programs/wq/nonpoint/ForestPractices/CWAassurances-FinalRevPaper071509-W97.pdf

Ecology noted numerous areas where improvements were needed, but also recognized the state's forest practices program provides a substantial framework for bringing the forest practices rules and activities into full compliance with the water quality standards. Therefore, Ecology decided to conditionally extend the CWA assurances with the intent to stimulate the needed improvements. Ecology, in consultation with key stakeholders, established specific milestones for program accomplishment and improvement. These milestones were designed to provide Ecology and the public with confidence that forest practices in the state will be conducted in a manner that does not cause or contribute to a violation of the state water quality standards.

The success of this TMDL project will be assessed using monitoring data from streams in the watershed.

Who needs to participate?

The city of Bellingham and Whatcom County have regulations that protect riparian corridors. The enforcement of those regulations is believed to be the actions that are needed to ensure that shade targets are met. Specifically, the buffer widths for riparian protection specified in Bellingham Municipal Code (BMC) 16.55.500.D and Whatcom County Code (WCC) 16.16.740 appear to be adequate to meet shade targets. If discretionary clauses allowing buffer averaging are exercised, the ability to meet shade targets should be considered. If unusual conditions raise doubts that the shade targets will be met, the local jurisdiction is the appropriate entity to consider if wider buffers should be applied based on site-specific conditions. If the ordinances are amended, proposed buffers should be evaluated for their ability to meet shade targets.

Additionally, the city of Bellingham Public Works Operations Lab staff will continue to conduct routine monitoring of each system through the Urban Stream Monitoring Program, and select one of the creek systems for longer-term monitoring each year from 2010 to 2014.

What is the schedule for achieving water quality standards?

In the short term, woody vegetation will be established in the riparian buffers and will grow to provide shade. It is estimated that the areas that are already vegetated will provide the target shade over several decades.

In the longer term, redevelopment of paved areas will be exploited to reestablish shade along the remaining creek. It is anticipated that the incremental change through redevelopment may take several additional decades.

Adaptive management

TMDL reductions should be achieved by 2100. The *water quality implementation plan* will identify interim targets. These targets will be described in terms of concentrations and/or loads, as well as in terms of implemented cleanup actions. Partners will work together to monitor progress towards these goals to evaluate successes, obstacles, and changing needs, and make adjustments to the cleanup strategy as needed.

It is ultimately Ecology's responsibility to assure that cleanup is being actively pursued and water standards are achieved.

Monitoring progress

Local governments evaluate the Critical Areas Ordinance that regulates the riparian corridors every five years. It is expected that the shade targets established in this TMDL will help inform their decision-making on the updates to those regulations. Periodically it would be helpful to survey the streams to monitor progress toward meeting shade targets to help with the reevaluation.

Monitoring implementation actions and how they will be maintained

Compliance monitoring will be needed when water quality standards are believed to be achieved.

Entities with enforcement authority are responsible for following up on any enforcement actions. Stormwater permittees are responsible for meeting the requirements of their permits. Those conducting restoration projects or installing best management practices (BMPs) are responsible for monitoring plant survival rates and maintenance of improvements, structures and fencing.

The *water quality implementation plan* will describe the coordinated monitoring strategy.

That plan will include a commitment by the city of Bellingham Public Works Operations staff to conduct monthly water quality samples from various long term monitoring locations at Whatcom, Squalicum, and Padden Creeks. Sampling will also occur on the major tributaries to this systems (Hanna, Fever, Valencia, Cemetery, Baker and Connelly Creeks). Samples will be collected for temperature, fecal coliform, turbidity, conductivity, pH and dissolved oxygen. In-situ water quality water quality probes (data sonde) will be deployed on one of the three creeks during the critical summer period (identified in the report as July and August) each year to collect a more robust dataset to characterize the temperature conditions in each creek. As resources allow, more than one station may be employed per system. An ambient temperature thermister will be utilized to help assess the data.

The city of Bellingham Public Works Operations staff will also continue to maintain a flow gauging station at Whatcom (2 stations), Squalicum (1 station) and Padden (1 station) creeks.

These long term monitoring stations help assess the hydrologic condition in these TMDL listed creeks.

Potential funding sources

The following sources of funding may be appropriate to help meet the shade targets by providing funding to local government or landowners.

Sponsoring Entity	Funding Source	Uses to be Made of Funds
Department of Ecology, WQP	Centennial Clean Water Fund, Section 319, and State Revolving Fund www.ecy.wa.gov/programs/wq/funding/	Facilities and water pollution control-related activities; implementation, design, acquisition, construction, and improvement of water pollution control. Priorities include implementing water cleanup plans; keeping pollution out of streams and aquifers; modernizing aging wastewater treatment facilities; reclaiming and reusing waste water.
Puget Sound Action Team	Public Involvement and Education grants www.psat.wa.gov/Programs/Pie_Ed/round_14/02_intro_funding.htm	Project priorities include: reduce harmful impacts from stormwater; prevent contamination from public/private sewer systems and other nonpoint sources.
County Conservation District	Federal Conservation Reserve Enhancement Program www.snohomishcd.org/crep.htm	Conservation easements; cost-share for implementing agricultural/riparian best management practices (BMPs).
Natural Resources Conservation Service	Environmental Quality Incentive Program www.nrcs.usda.gov/programs/eqip/	Voluntary conservation program for farmers and ranchers that promotes agricultural production and environmental quality as compatible national goals; includes cost-share funds for farm BMPs.
Department of Ecology, SEA	Coastal Zone Protection Fund	Some funding is available through a program that taps into penalty monies collected by the WQP.
Office of Interagency Committee, Salmon Recovery Board	Salmon Recovery Funding Board www.iac.wa.gov/srfb/grants.asp	Provides grants for habitat restoration, land acquisition and habitat assessment.
Natural Resources Conservation Service	Wetland Reserve Program www.wa.nrcs.usda.gov/programs/wrp/wrp.html	Landowners may receive incentives to enhance wetlands in exchange for retiring marginal agricultural land.

Summary of public involvement methods

This section will be completed after the public has reviewed this draft and included in the final document.

Next steps

Once EPA approves the TMDL, a *water quality implementation plan* must be developed within one year. Ecology will work with local people to create this plan, choosing the combination of possible solutions they think will be most effective in their watershed. Elements of this plan include:

- Who will commit to do what?
- How to determine if the implementation plan works.
- What to do if the implementation plan doesn’t work.
- Potential funding sources.

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References

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.

Bilhimer, D. and A. Stohr, 2008. EAP044 - Standard Operating Procedures for continuous temperature monitoring of fresh water rivers and streams conducted in a Total Maximum Daily Load (TMDL) project for stream temperature. Washington State Department of Ecology, Olympia WA.
www.ecy.wa.gov/programs/eap/qa/docs/ECY_EAP_SOP_044Cont_Temp_Monit_TMDL.pdf

Blann, K., J.F. Nerbonne, and B. Vondracek, 2002. Relationship of riparian buffer type to water temperature in the driftless area ecoregion of Minnesota. NAJFM. 22:441-451.

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

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.

Boyd, M. and C. Park, 1998. Sucker-Grayback Total Daily Maximum Load. Oregon

Department of Environmental Quality and U.S. Forest Service.

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.

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

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

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

Casola, J.H., J.E. Kay, A.K. Snover, R.A. Norheim, L.C. Whitely Binder, and the Climate Impacts Group, 2005. Climate Impacts on Washington's Hydropower, Water Supply, Forests, Fish, and Agriculture. A report prepared for King County (Washington) by the Climate Impacts Group (Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle).

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

Chapra, S.C. and G.J. Pelletier, 2003. QUAL2K: A Modeling Framework for Simulating Riverand Stream Water Quality: Documentation and Users Manual. Civil and Environmental Engineering Dept., Tufts University, Medford, MA. Steven.Chapra@tufts.edu.

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, 1998a. Stream temperature simulation of forested riparian areas: I. watershed-scale model development. Journal of Environmental Engineering. April 1998. pp 304-315.

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

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

City of Bellingham, 2001. Whatcom Creek Temperature Total Maximum Daily Load: Quality Assurance Project Plan.

Cusimano, R.F., Hood, S., and Liu, J., 2002. Quality Assurance Project Plan: Lake Whatcom TMDL Study. Washington State Department of Ecology. Publication No. 02-03-74. www.ecy.wa.gov/pubs/0203074.pdf.

Danehy, R.J., Colson, C.G., Parett, and K.B., Duke, S.D. 2005. Patterns and sources of thermal heterogeneity in small mountain streams within a forested setting. For Ecol Manag 208:287–302.

DNR, 1999. Forests and fish report. Washington State Department of Natural Resources, April 29, 1999. www.dnr.wa.gov/Publications/fp_rules_forestsandfish.pdf.

Dunne and Leopold, 1978. Water in Environmental Planning. W.H. Freeman and Company, New York.

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

Ecology, 2005. Stormwater Management Manual for Western Washington. Water Quality Program, Washington State Department of Ecology, Olympia, WA. Publication No. 05-10-029. www.ecy.wa.gov/biblio/0510029.html.

Ecology, 2006. Water Quality Standards for Surface Waters of the State of Washington, Chapter 173-201A WAC. Washington State Department of Ecology, Olympia, WA. www.ecy.wa.gov/pubs/0610091.pdf.

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

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

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

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

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.

Friday, C., 1999. Whatcom Creek: A History of a Place. www.acadweb.wwu.edu/cpnws/rwc/Draftnar.htm Last accessed on July 18, 2005.

Hamlet A.F. and D.P. Lettenmaier, 1999. Effects of climate change on hydrology and water resources in the Columbia River Basin. Journal of the American Water Resources Association, 35(6):1597- 1623.

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.

Hood, S., 2007. Whatcom Creek Fecal Coliform Total Maximum Daily Load Report: Water Quality Improvement Plan – DRAFT. Washington State Department of Ecology. Publication No. 06-10-041. www.ecy.wa.gov/biblio/0610041.html.

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., 2003. Stream temperature: scaling of observations and issues for modeling. Hydrological Processes 17:497-499.

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 debrisflows in western Cascades, Oregon. Canadian Journal of Fisheries and Aquatic Sciences 57 (Suppl. 2): 30-39.

Ledwith, Tyler, 1996. The effects of Buffer Strip Width on Air Temperature and Relative Humidity in a Stream Riparian Zone. URL: watershed.org/news.sum_96/buffer.html.

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

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

Mote, P.W., E. Salathé, and C. Peacock, 2005. Scenarios of future climate for the Pacific Northwest, Climate Impacts Group, University of Washington, Seattle, WA. 13 pp.

NSEA, 2009. Nooksack Salmon Enhancement Association. https://secure.vq-opensite.com/nsea/index.cfm.

ODEQ, 2001. Ttools 3.0 User Manual. Oregon Department of Environmental Quality. Portland OR.

OWEB, 1999. Water quality monitoring technical guidebook: chapter 14, stream shade and canopy cover monitoring methods. Oregon Watershed Enhancement Board. http://egov.oregon.gov/ODF/privateforests/docs/ShadeProt.pdf.

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

Pelletier, G. and S. Chapra, 2008 (draft). QUAL2Kw: Theory and Documentation for A Modeling Framework to Simulate River and Stream Water Quality. Washington State Department of Ecology, Olympia, WA. www.ecy.wa.gov/programs/eap/models.html.

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 p. 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.

Schuett-Hames, D., A. Pleus, E. Rashin, and J. Matthews, 1999. TFW Monitoring Program Method Manual for the Stream Temperature Survey. Prepared for the Washington State Department of Natural Resources under the Timber, Fish, and Wildlife Agreement. TFW-AM9-99-005. DNR # 107. June.

Serdar, D., Davis D., and Hirsch J., 1999. Lake Whatcom Watershed Cooperative Drinking Water Protection Project: Results of 1998 Water, Sediment and Fish Tissue Sampling. Washington State Department of Ecology. Publication No. 99-337. www.ecy.wa.gov/biblio/99337.html.

Shannahan J.P., LaCroix R., Cusimano, B., and Hood, S., 2004. Whatcom Creek Fecal Coliform Total Maximum Daily Load Study. Washington State Department of Ecology. Publication No. 04-03-015. www.ecy.wa.gov/pubs/0403015.pdf.

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

Steinblums, I.J., H.A. Froehlich, and J.K. Lyons, 1984. Designing stable buffer strips for stream protection. J. For. 82(1):49-52.

Stohr, A., 2009. Quality Assurance Project Plan: Innovative Temperature Total Maximum Daily Load Pilot Study. Washington State Department of Ecology. Publication No. 09-03-105. www.ecy.wa.gov/biblio/0903105.html.

Sullivan K. and T.A. Adams, 1990. The physics of stream heating: an analysis of temperature patterns in stream environments based on physical principles and field data. Weyerhaeuser Technical Report. 044–5002·90/2. Technology Center, Tacoma, WA 98477.

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

Teti, P., 2001. A new instrument for measuring shade provided by overhead vegetation. Cariboo Forest Region Research Section, British Columbia Ministry of Forests, Extension note No. 34. www.for.gov.bc.ca/rsi/research/cextnotes/extnot34.pdf.

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.

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

USDA, 1992. Soil Survey of Whatcom County Area, Washington. Soil Conservation Service, U.S. Department of Agriculture.

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Appendices

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Appendix A. Glossary, acronyms, and abbreviations

Glossary

Anadromous: Sea-run.

Anthropogenic: Human-caused.

Best management practices (BMPs): Physical, structural, and/or operational practices that, when used singularly or in combination, prevent or reduce pollutant discharges.

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.

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 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 (e.g., diurnal temperature rises during the day, and falls during the night).

Effective shade: The fraction of incoming solar short-wave 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 sewage treatment system.

Hydraulic gradient: The difference in hydraulic head between two measuring points, divided by the distance between the two points.

Hyporheic: The area under and along the river channel where surface water and groundwater meet

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

Loading capacity: The greatest amount of a substance that a water body can receive and still meet water quality standards.

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

Municipal separate storm sewer systems (MS4): A conveyance or system of conveyances (including roads with drainage systems, municipal streets, catch basins, curbs, gutters, ditches, manmade channels, or storm drains): (1) owned or operated by a state, city, town, borough, county, parish, district, association, or other public body having jurisdiction over disposal of wastes, storm water, or other wastes and (2) designed or used for collecting or conveying stormwater; (3) which is not a combined sewer; and (4) which is not part of a Publicly Owned Treatment Works (POTW) as defined in the Code of Federal Regulations at 40 CFR 122.2.

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 National Pollutant Discharge Elimination System 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.

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 that clear more than 5 acres of land.

Pollution: Such 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 is 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: Any fish that belong to the family *Salmonidae*. Basically, any species of salmon, trout, or char. www.fws.gov/le/ImpExp/FactSheetSalmonids.htm.

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 watercourses within the jurisdiction of Washington State.

System potential channel morphology: The more stable configuration that would occur with less human disturbance.

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

System potential riparian microclimate: The best estimate of air temperature reductions that are expected under mature riparian vegetation. System potential riparian microclimate can also include expected changes to wind speed and relative humidity.

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.

System potential: The design condition used for TMDL analysis.

Total maximum daily load (TMDL): A distribution of a substance in a water body designed to protect it from 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.

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

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

7Q2 flow: A typical low-flow condition. The 7Q2 is a statistical estimate of the lowest 7-day average flow that can be expected to occur once every other year on average. The 7Q2 flow is commonly used to represent the average low-flow condition in a water body and is typically calculated from long-term flow data collected in each basin. For temperature TMDL work, the 7Q2 is usually calculated for the months of July and August as these typically represent the critical months for temperature in our state.

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 ten 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.

90th percentile: A statistical number obtained from a distribution of a data set, above which 10% of the data exists and below which 90% of the data exists.

Acronyms and abbreviations

Following are acronyms and abbreviations used frequently in this report.

BMP	best management practices
cfs	cubic feet per second
Ecology	Washington State Department of Ecology
EIM	Environmental Information Management database
EPA	U.S. Environmental Protection Agency
GIS	Geographic Information System software
km	Kilometer
m	Meter
NPDES	(See Glossary above)
NSDZ	(See Glossary above)

QA	Quality assurance
RMSE	Root mean square error
SSURGO	Natural Resources Conservation Service Soil Survey Geographic Database
TMDL	(See Glossary above)
USDA	United States Department of Agriculture
WRIA	Water Resources Inventory Area

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Appendix B. Load allocations for effective shade for Whatcom Creek

Load allocations were calculated for every 25-meter reach. These load allocations were averaged for every 400 meters for ease of reporting in Table B-1.

Table B-1. Load allocations for effective shade in Whatcom Creek for the condition of mature riparian vegetation.

Distance from mouth to upstream segment boundary (km)	Distance from mouth to downstream segment boundary (km)	Load allocation for daily average shortwave solar radiation on August 1 (W/m2)	Load allocation for effective shade on August 1 (percent)	Landmarks/Comments
6.7	6.4	94	69%	0.3 km segment with control dam as the upper boundary
6.4	6	131	57%	Derby Dam is at downstream end of this segment
6	5.6	69	77%	
5.6	5.2	57	81%	Drinking water plant at downstream end of segment
5.2	4.8	63	79%	
4.8	4.4	49	84%	
4.4	4	58	81%	
4	3.6	72	76%	Valencia Street
3.6	3.2	73	76%	
3.2	2.8	72	76%	Racine Street
2.8	2.4	100	67%	
2.4	2	57	81%	James Street
2	1.6	75	75%	
1.6	1.2	164	46%	State Street
1.2	0.8	190	37%	
0.8	0.4	96	68%	Dupont Street at downstream end of segment
0.4	0	124	59%	

Load allocations are defined as the system potential maximum achievable effective shade (fraction of the incoming solar radiation blocked by vegetation and topography).

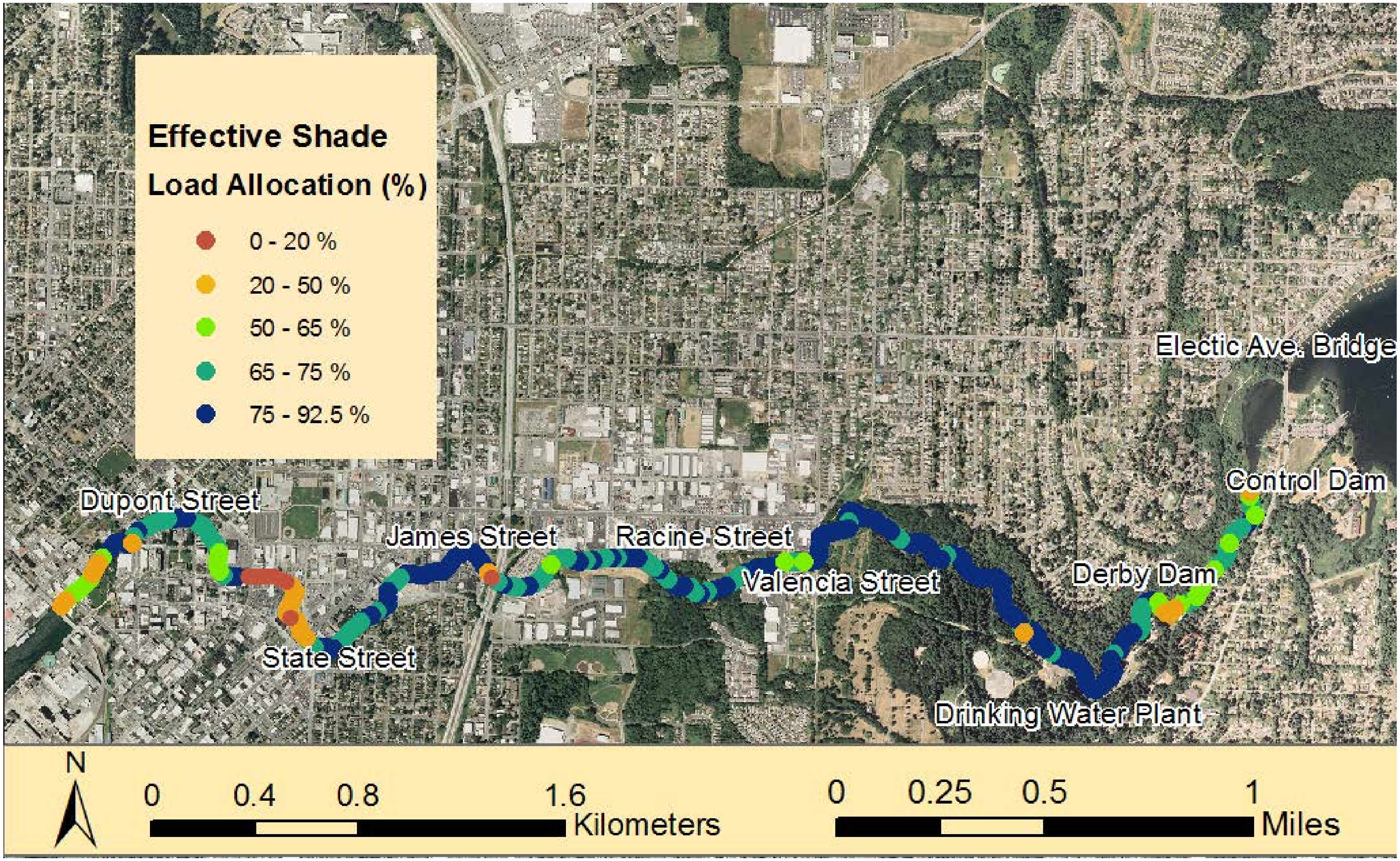

Figure B-1. Effective Shade load allocations for Whatcom Creek.

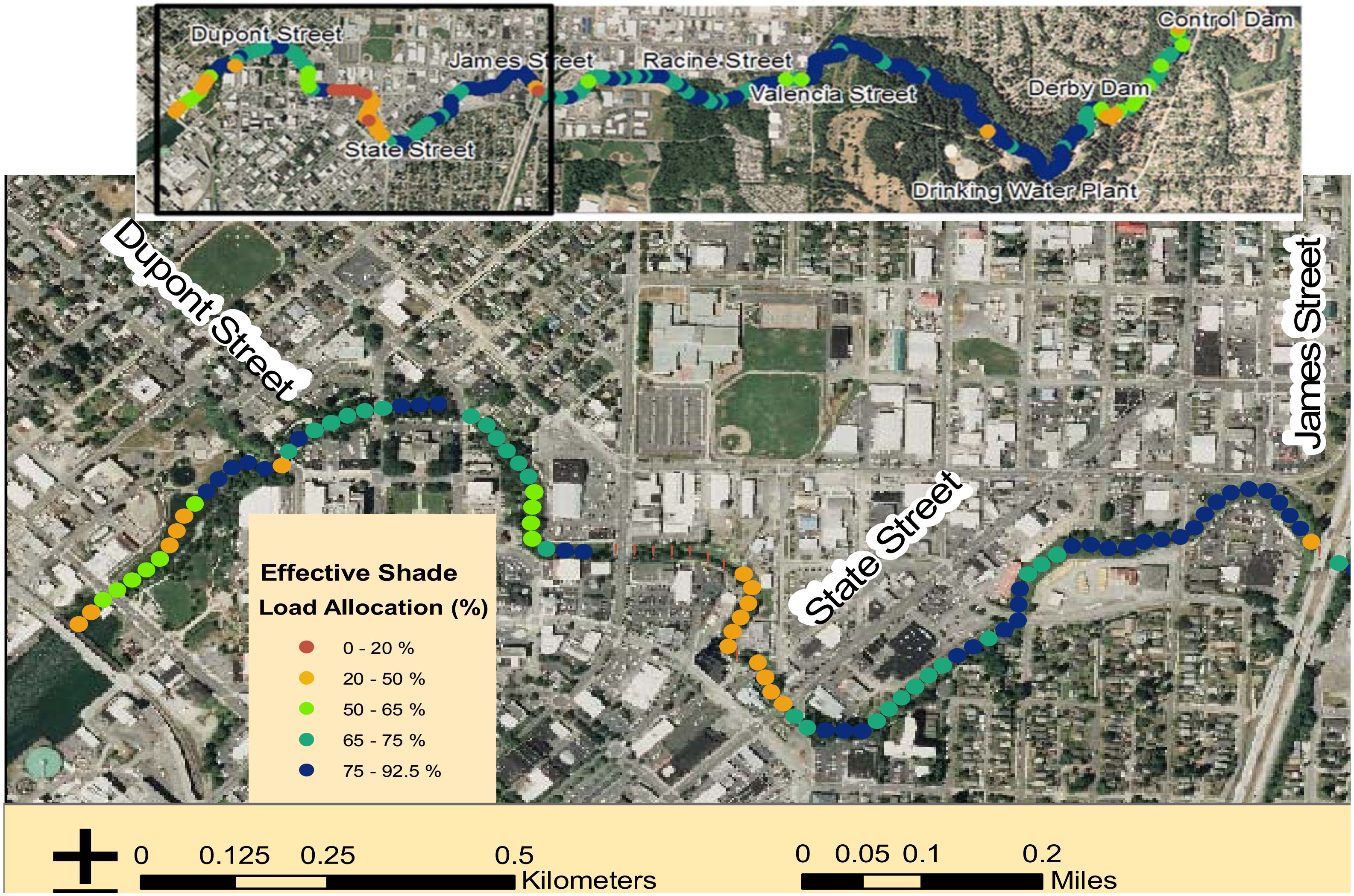

Figure B-2. Effective Shade load allocations for Whatcom Creek: Mouth to James Street.

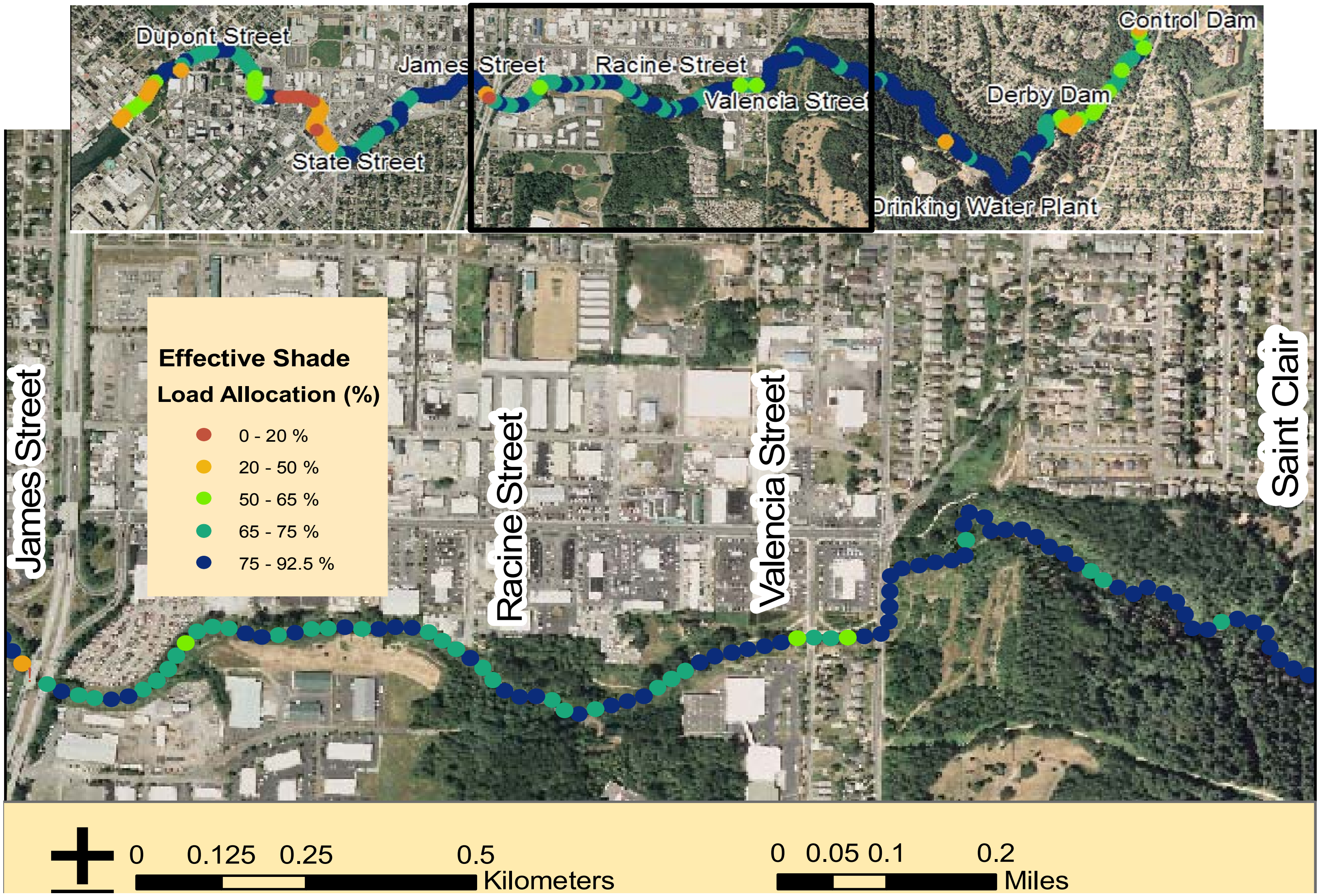

Figure B-3. Effective Shade load allocations for Whatcom Creek: James Street to Saint Clair.

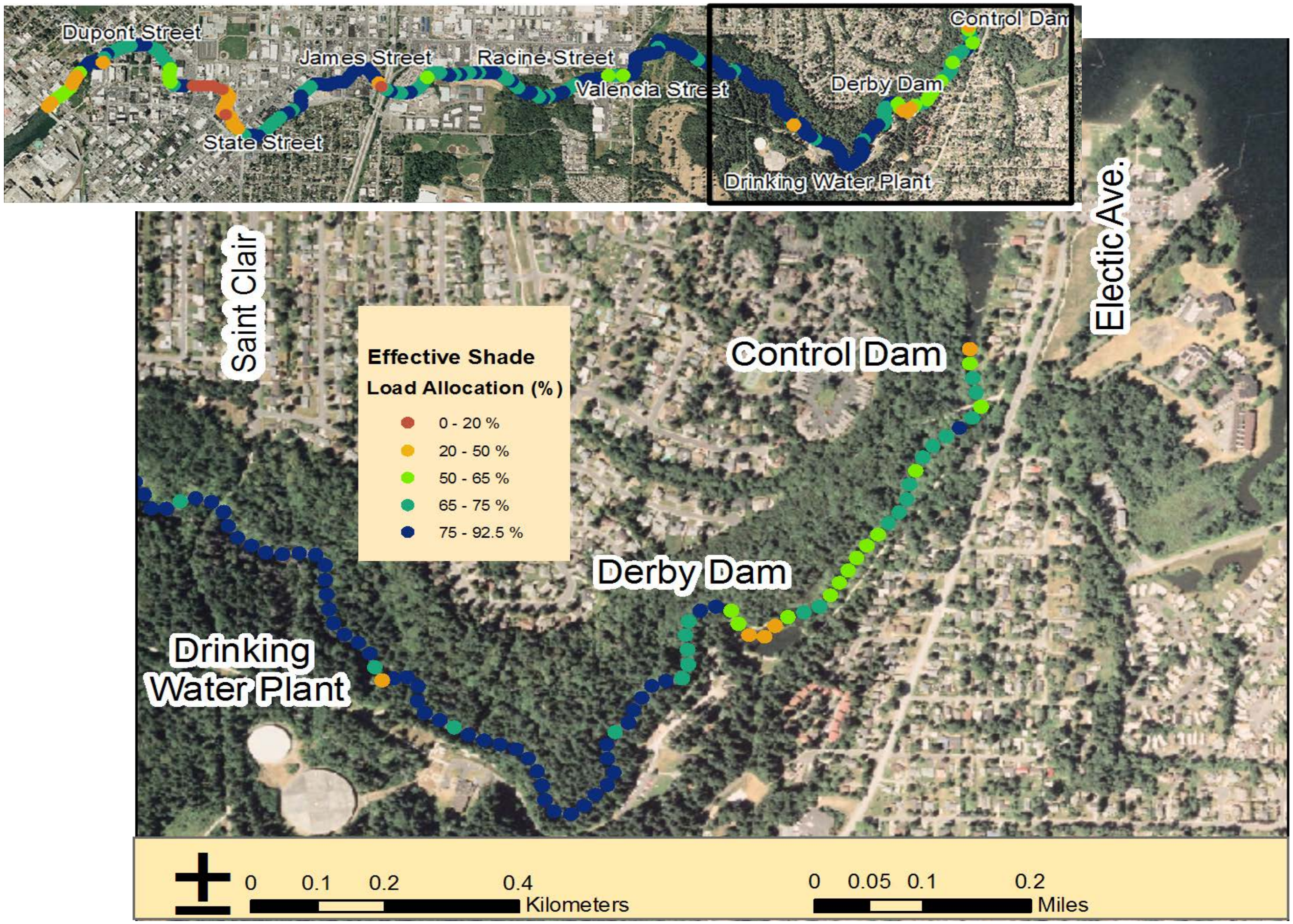

Figure B-4. Effective Shade load allocations for Whatcom Creek: Saint Clair to Control Dam.

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Appendix C. Load allocations

For effective shade for the Whatcom Creek tributaries and all streams in the Padden and Squalicum Creek watersheds based on bankfull width and stream aspect.

Table C-1. Load allocations for effective shade for the Whatcom Creek tributaries and the Padden and Squalicum Creek watersheds.

Bankfull width (meters)	Effective shade from vegetation (percent) at the stream center at various stream aspects (degrees from N)			Daily average global solar short-wave radiation (W/m2) at the stream center at various stream aspects (degrees from N)		
	90 and 270 deg aspect	0 and 180 deg aspect	45, 135, 225, and 315 deg aspect	90 and 270 deg aspect	0 and 180 deg aspect	45, 135, 225, and 315 deg aspect
0.5	93%	90%	92%	22	31	24
1.0	92%	89%	92%	23	32	25
1.5	92%	89%	91%	24	34	26
2.0	92%	89%	91%	25	35	27
2.5	91%	88%	91%	26	36	28
3.0	91%	88%	91%	27	37	28
3.5	91%	87%	90%	28	38	29
4.0	90%	85%	89%	31	45	34
4.5	89%	84%	87%	34	49	39
5.0	88%	83%	86%	37	52	42
5.5	87%	81%	85%	39	57	46
6.0	86%	80%	84%	42	60	50
6.5	85%	79%	83%	45	64	53
7.0	84%	78%	81%	48	67	57
7.5	83%	77%	80%	51	71	61
8.0	82%	75%	79%	54	74	64
8.5	81%	74%	78%	57	78	68
9.0	80%	73%	77%	61	81	71
9.5	79%	72%	75%	64	85	75
10.0	78%	71%	74%	68	87	78
10.5	76%	70%	73%	72	90	81
11.0	75%	69%	72%	76	94	85
11.5	74%	68%	71%	80	97	88
12.0	72%	67%	70%	84	100	91
12.5	71%	66%	69%	88	102	94
13.0	69%	65%	68%	94	106	98
13.5	68%	64%	67%	98	108	100
14.0	66%	64%	66%	103	111	103
14.5	64%	63%	65%	109	114	107
15.0	62%	62%	64%	116	116	109
15.5	58%	61%	63%	126	119	112
16.0	57%	60%	62%	131	121	115
16.5	55%	59%	61%	136	124	118
17.0	54%	58%	60%	141	126	121
17.5	52%	58%	59%	145	128	123
18.0	51%	57%	59%	150	130	126
18.5	49%	56%	58%	154	133	128
19.0	48%	55%	57%	159	135	131
19.5	46%	55%	56%	163	137	133
20.0	45%	54%	55%	166	139	136

How to determine the effective shade load allocation for a specific site using a curve

Shade curves show load allocations for perennial streams when specific reach-by-reach modeling was not applied to that stream. Shade curves are based on the estimated relationship between riparian shade, channel width, and stream aspect at the assumed maximum riparian vegetation condition.

Figure C-1 shows an example shade curve to use as a reference for these instructions. The specific shade curve for this basin is Figure 29 in the body of the report. The specific shade table for this basin is presented in Table C-1 above.

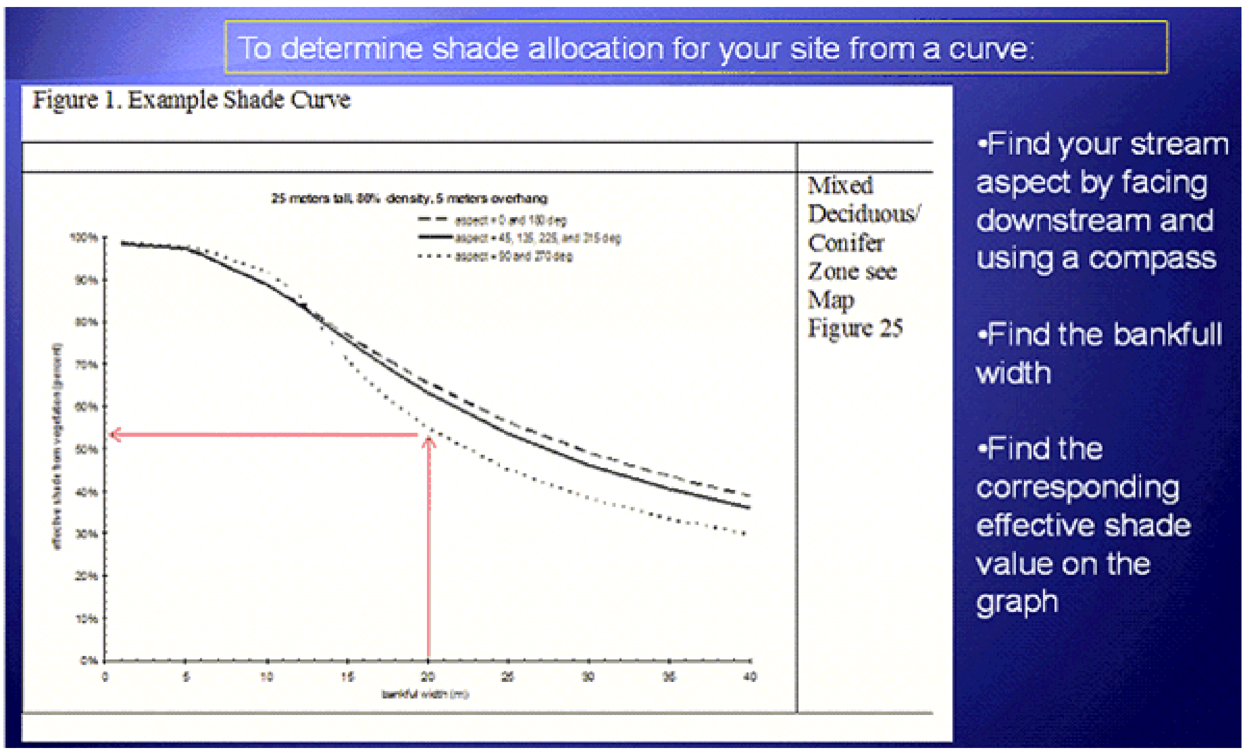

Figure C-1. Example Shade Curve.

There are three steps to determine the shade prescription for a specific site.

1. Find the stream aspect by facing downstream and using a compass to determine the general direction of streamflow in degrees.

   The categories are:

   Stream aspect = 0° and 180° (North and South).

Stream aspect = 45º, 135º, 225º, and 315º (Northeast, Southeast, Southwest, and Northwest).

Stream aspect = 90º and 270º (East and West).

For example: you are standing in the middle of the stream (when the stream can be safely waded) facing downstream holding a compass in your hand. You read your compass and get 50º. The 45º aspect line on the shade curve is the line you will use to determine effective shade.

2. Determine the bankfull width of the stream (in meters) that you are examining.

3. Look at the shade curve or table:
   - Find the correct aspect line for your stream.
   - Find the bankfull width for your stream.
   - Follow the graph straight up from the corresponding bankfull width until you "hit" the correct aspect line.
   - Follow the graph directly to the left and you will find your corresponding effective shade.

The effective shade value you use from the graph is the estimated site potential (or maximum) riparian shade target for restoration efforts. Local site conditions may preclude the site potential vegetation from reaching the estimated effective shade. Please consult with your Ecology TMDL contact if you have questions or concerns.

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Appendix D. Soil survey for Whatcom County

Table D-1. Soil properties for land within 500 feet of Squalicum Creek.

Map Unit Symbol	Soil Name	50-year Site Index (ft)	% of Area	Species
3	Chuckanut loam, bedrock substratum, 5 to 15 percent slopes	119	3.6	Douglas-fir, red alder
27	Chuckanut loam, bedrock substratum, 30 to 60 percent slopes	119	4.9	Douglas-fir, red alder
29	Chuckanut-Urban land complex, 5 to 20 percent slopes	130	0.8	Douglas-fir, red alder
51	Everett complex, 2 to 8 percent slopes	95	2.0	Red alder, western red cedar
52	Everett-Urban land complex, 5 to 20 percent slopes	106	16.0	Douglas-fir, red alder
108	Nati loam, 5 to 15 percent slopes	121	2.1	Douglas-fir, western hemlock, red alder
109	Nati loam, 15 to 30 percent slopes	121	4.9	Douglas-fir, western hemlock, red alder
110	Nati loam, 30 to 60 percent slopes	98	1.0	Douglas-fir, red alder
156	Squalicum gravelly loam, 5 to 15 percent slopes	132	30.0	Douglas-fir, red alder
159	Squalicum-Urban land complex, 5 to 20 percent slopes	132	20.4	Douglas-fir, red alder
171	Urban land	132	2.3	Douglas-fir, red alder
172	Urban land-Whatcom-Labounty complex, 0 to 8 percent slopes	no height	12.0	Urban land, (likely average soil properties)
	Average 50-year Site Index height weighted by area (exclude unit 172)	124		
	Total Padden Creek Area (excluding unit 172) units ft²	150764487		

Table D-2. Soil properties for land within 500 feet of Padden Creek.

Map Unit Symbol	Soil Name	50-year Site Index (ft)	% of Area	Species
11	Bellingham silty clay loam, 0 to 2 percent slopes	86	5.4	Red alder, western red cedar
22	Briscot silt loam, drained, 0 to 2 percent slopes	95	0.6	Red alder, western red cedar, western hemlock
31	Clipper silt loam, drained, 0 to 2 percent slopes	95	0.2	Red alder, western red cedar
82	Kickerville-Urban land complex, 0 to 3 percent slopes	119	9.6	Douglas-fir, red alder
93	Labounty silt loam, 0 to 2 percent slopes	90	1.5	Red alder, western red cedar
94	Labounty silt loam, drained, 0 to 2 percent slopes	90	3.3	Red alder, western red cedar
108	Nati loam, 5 to 15 percent slopes	121	0.2	Douglas-fir, western hemlock, red alder
110	Nati loam, 30 to 60 percent slopes	98	3.5	Douglas-fir, red alder
116	Pangborn muck, drained, 0 to 2 percent slopes	85	0.9	Red alder, western red cedar
120	Pits, gravel	0	0.5	Gravel pits
143	Shalcar muck, drained, 0 to 2 percent	85	0.1	Red alder, western red cedar
157	Squalicum gravelly loam, 15 to 30 percent slopes	132	6.5	Douglas-fir, red alder
171	Urban land	132	6.8	Douglas-fir, red alder
172	Urban land-Whatcom-Labounty complex, 0 to 8 percent slopes	no height	37.9	Urban land, (likely average soil properties)
178	Whatcom silt loam, 0 to 3 percent slopes	116	2.4	Douglas-fir, red alder
179	Whatcom silt loam, 3 to 8 percent slopes	116	11.8	Douglas-fir, red alder
180	Whatcom silt loam, 8 to 15 percent slopes	116	1.5	Douglas-fir, red alder
181	Whatcom silt loam, 30 to 60 percent slopes	116	3.0	Douglas-fir, red alder
182	Whatcom-Labounty silt loams, 0 to 8 percent slopes	116	4.3	Douglas-fir, red alder
	Average 50-year Site Index height weighted by area (exclude unit 172)	113		
	Total Squalicum Creek Area (excluding unit 172) units ft²	226540462		
	Grand 50-year Site Index average for Squalicum and Padden together	117		

Legend

SOIL_NM

- Andic Xerochrepts, 60 to 90 percent slopes
- Andic Xerochrepts, cool-Rock outcrop complex, 60 to 90 percent slopes
- Andic Xerochrepts-Rock outcrop complex, 60 to 90 percent slopes
- Bameston gravelly loam, 0 to 8 percent slopes
- Bameston very gravelly loam, 15 to 30 percent slopes
- Bameston very gravelly loam, 30 to 60 percent slopes
- Bameston very gravelly loam, 8 to 15 percent slopes
- Bellingham silty clay loam, 0 to 2 percent slopes
- Briscot silt loam, drained, 0 to 2 percent slopes
- Briscot, Oridia, and Sumas soils, 0 to 2 percent slopes
- Chuckanut loam, bedrock substratum, 15 to 30 percent slopes
- Chuckanut loam, bedrock substratum, 30 to 60 percent slopes
- Chuckanut loam, bedrock substratum, 5 to 15 percent slopes
- Chuckanut-Urban land complex, 5 to 20 percent slopes
- Clipper silt loam, drained, 0 to 2 percent slopes
- Comar silt loam, 15 to 30 percent slopes
- Comar silt loam, 5 to 15 percent slopes
- Crinker-Rock outcrop complex, 3 to 30 percent slopes
- Crinker-Rock outcrop complex, 30 to 65 percent slopes
- Diobsud gravelly silt loam, 3 to 30 percent slopes
- Diobsud gravelly silt loam, 30 to 65 percent slopes
- Eliza-Tacoma silt loams, 0 to 1 percent slopes
- Everett complex, 2 to 8 percent slopes
- Everett gravelly sandy loam, hard substratum, 2 to 8 percent slopes
- Everett very gravelly sandy loam, 15 to 35 percent slopes
- Everett very gravelly sandy loam, 8 to 15 percent slopes
- Everett-Urban land complex, 5 to 20 percent slopes
- Fishtrap muck, drained, 0 to 2 percent slopes
- Getchell loam, 3 to 30 percent slopes
- Getchell loam, 3 to 30 percent slopes
- Getchell loam, 30 to 60 percent slopes
- Histosols, ponded, 0 to 1 percent slopes
- Hydraquents, tidal, 0 to 1 percent slopes
- Kickerville-Urban land complex, 0 to 3 percent slopes
- Kline gravelly sandy loam, 2 to 8 percent slopes
- Labounty silt loam, 0 to 2 percent slopes
- Labounty silt loam, drained, 0 to 2 percent slopes
- Montborne gravelly loam, 5 to 30 percent slopes
- Montborne very gravelly silt loam, 3 to 30 percent slopes
- Montborne-Rinker complex, 30 to 60 percent slopes
- Montborne-Rinker complex, 30 to 65 percent slopes
- Mt. Vernon fine sandy loam, 0 to 2 percent slopes
- Mukilteo muck
- Nati loam, 15 to 30 percent slopes
- Nati loam, 30 to 60 percent slopes
- Nati loam, 5 to 15 percent slopes
- Pangbom muck, drained, 0 to 2 percent slopes
- Pits, gravel
- Potchub loam, 8 to 30 percent slopes
- Puyallup fine sandy loam, 0 to 2 percent slopes
- Revel loam, 30 to 60 percent slopes
- Revel loam, 5 to 30 percent slopes
- Revel-Welcome-Rock outcrop complex, 30 to 60 percent slopes
- Rinker very channery loam, 30 to 65 percent slopes
- Rock outcrop
- Sehome gravelly loam, 15 to 30 percent slopes
- Sehome gravelly loam, 30 to 60 percent slopes
- Sehome loam, 2 to 8 percent slopes
- Sehome loam, 8 to 15 percent slopes
- Shalcar and Fishtrap soils, 0 to 2 percent slopes
- Shalcar muck, drained, 0 to 2 percent
- Springsteen very gravelly loam, 30 to 60 percent slopes
- Springsteen very gravelly loam, 30 to 65 percent slopes
- Squalicum gravelly loam, 15 to 30 percent slopes
- Squalicum gravelly loam, 30 to 60 percent slopes
- Squalicum gravelly loam, 5 to 15 percent slopes
- Squalicum-Urban land complex, 5 to 20 percent slopes
- Squires very channery loam, 30 to 60 percent slopes
- Squires very channery loam, 5 to 30 percent slopes
- Tromp loam, 0 to 2 percent slopes
- Typic Cryorthods, 60 to 90 percent slopes
- Typic Cryorthods-Rock outcrop complex, 65 to 90 percent slopes
- Urban land
- Urban land-Whatcom-Labounty complex, 0 to 8 percent slopes
- Vanzandt very gravelly loam, 0 to 15 percent slopes
- Vanzandt very gravelly loam, 15 to 30 percent slopes
- Vanzandt very gravelly loam, 30 to 60 percent slopes
- Vanzandt very gravelly loam, 30 to 65 percent slopes
- Vanzandt very gravelly loam, 5 to 15 percent slopes
- Water
- Whatcom silt loam, 0 to 3 percent slopes
- Whatcom silt loam, 3 to 8 percent slopes
- Whatcom silt loam, 30 to 60 percent slopes
- Whatcom silt loam, 8 to 15 percent slopes
- Whatcom-Labounty silt loams, 0 to 15 percent slopes
- Whatcom-Labounty silt loams, 0 to 8 percent slopes
- Whitehorn silt loam, 0 to 2 percent slopes
- Wickersham channery silt loam, 0 to 8 percent slopes
- Winston loam, 3 to 15 percent slopes
- Wollard gravelly silt loam, 3 to 30 percent slopes
- Wollard gravelly silt loam, 30 to 60 percent slopes
- Yelm-Urban land complex, 0 to 3 percent slopes

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Appendix E. Record of public participation

Introduction

Public participation was modest. Because this TMDL identified the appropriate actions are taking place and the appropriate protections are in place, there was little interest.

Summary of comments and responses

Several requests for more information were received and fulfilled. Two written comment letters were received.

Comments identified a need to better address wasteload allocations for permitted Municipal Separate Storm Systems.

The comments and responses are in Appendix F.

List of public meetings

The city of Bellingham City Council received a summary of the findings in a work session on May 9. The Whatcom County Council was advised of the release of the draft TMDL at the council meeting on May 10.

Outreach and announcements

Include the following, if applicable:

A 30-day public comment period for this report was held through June 8, 2011. A news release was sent to all local media in the Whatcom, Squalicum, Padden watershed area. Radio station KGMI ran a story on May 9, which is available at http:/podcast.kgmi.com/kgmi/2927208.MP3.

Advertisements were placed in the following publications:

- Bellingham Herald, published on May 7, 2011

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Appendix F. Response to public comments

Comment: Two comments addressed clarification on the WLA for regulated stormwater discharges. One expressed concern that there is no monitoring information on the regulated stormwater discharges and one expressed concern that that the translation of the numeric WLA of the TMDL into BMPs in the permit did not provide assurance that the water quality standard would be met, especially when no BMPs were identified.   A third comment questioned the evaluation of stormwater thermal discharges.

> **Response:** *In Bellingham's climate, rain does not typically fall on hot days. The critical season for* ***s****tream temperature is characterized by several days of clear dry air with no precipitation, followed by moist air from the ocean that cools temperatures for a day or more prior to rainfall. Figure 1 shows this pattern based on examining the relationship between cloud cover and rainfall for the period July 1996 through September 2010.   We do not have stream temperature data for the dates that are highlighted.   Figures 2,3 and 4 show the time series of air temperature and rainfall for the months containing the data points with relatively light cloud cover on the day of the rainfall and the previous day. As can be seen the pattern is quite consistent. Rainfall is not the short duration summer thunderstorm type rainfall that typically causes stormwater related temperature problems, but represents a period where we can expect stream temperatures to be dropping. A time series of stream temperature, cloud cover and rainfall displaying a moving seven-day window can be viewed. It also shows the pattern that summer rainfall is accompanied by a slowing of the rate of stream warming or a cooling trend.*
>
> *Stormwater temperature was not monitored during the study, but based on the pattern we observed above we feel confident that stormwater will not contribute to increasing the 7DAD temperature, but rather will contribute to decreasing the 7DAD temperature. The temperature of the stormwater is expected to be lower than the naturally occurring stream temperature and so no BMPs are necessary*.

Comment: WSDOT is not mentioned on xv as a NPDES MS4 permitted discharge.

> **Response:** *WSDOT added.*

Comment: Suggests adding key to Figure 22 on page 50.

> **Response:** *A key has been added to the end of Appendix D. It is recommended that the soil data be downloaded from the source if identification is critical.*

Comment: It is not appropriate to assign a WLA to sources that Ecology did not characterize.

> **Response:** *In a fully allocated TMDL, the unassigned WLA is zero. For a temperature TMDL, this would result in ridiculous situation of requiring any discharges to have a temperature of zero Kelvin, an unattainable temperature even in a laboratory. Instead, we have assigned a WLA equal to the numeric criterion. This means that no mixing zone*

is necessary to meet the water quality standards. And, as has been noted above we believe this WLA is already being met by the stormwater dischargers.

Comment: Compliance with WSDOT MS4 permit should be satisfactory to meet the TMDL as not particular sources in the WSDOT MS4 have been identified.

Response: *Ecology concurs.*

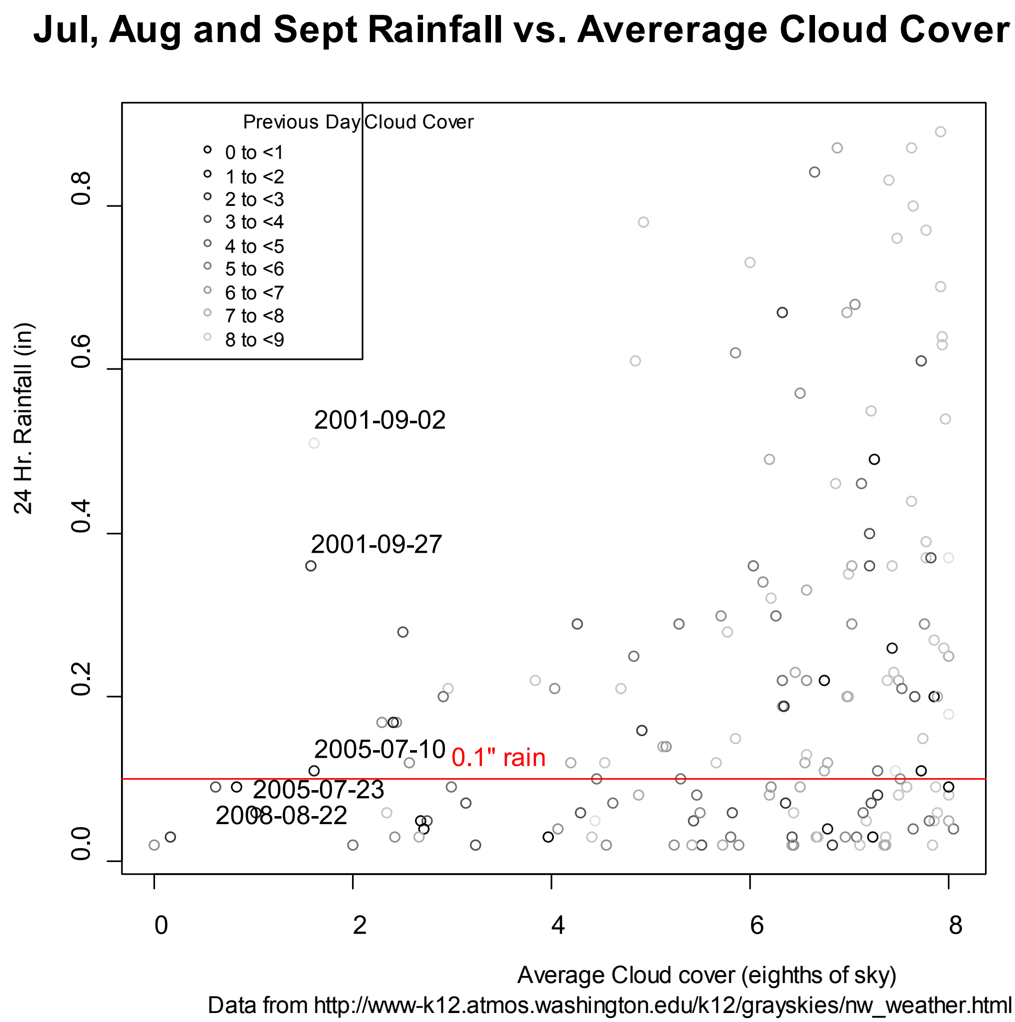

Figure 1. Relationship between summer rainfall and cloud cover

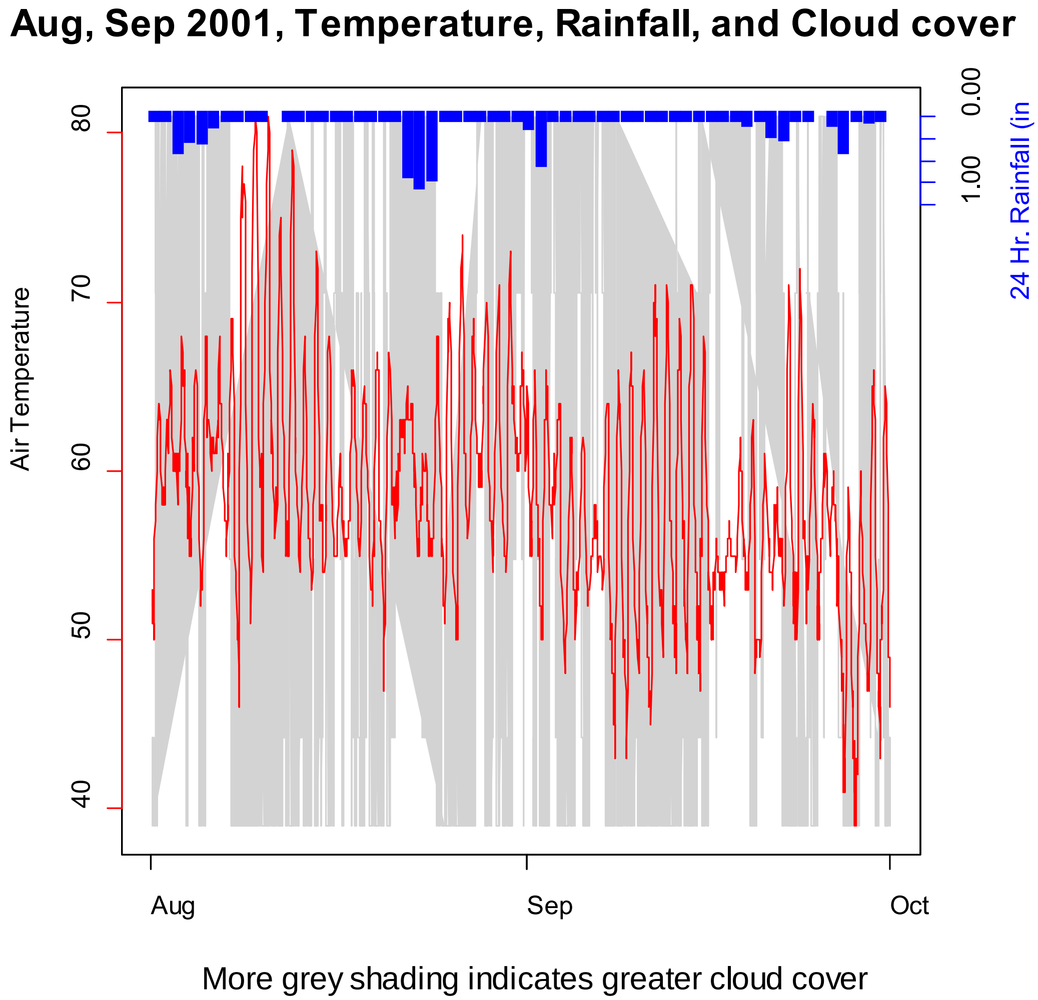

Figure 2. August, September 2001 time series

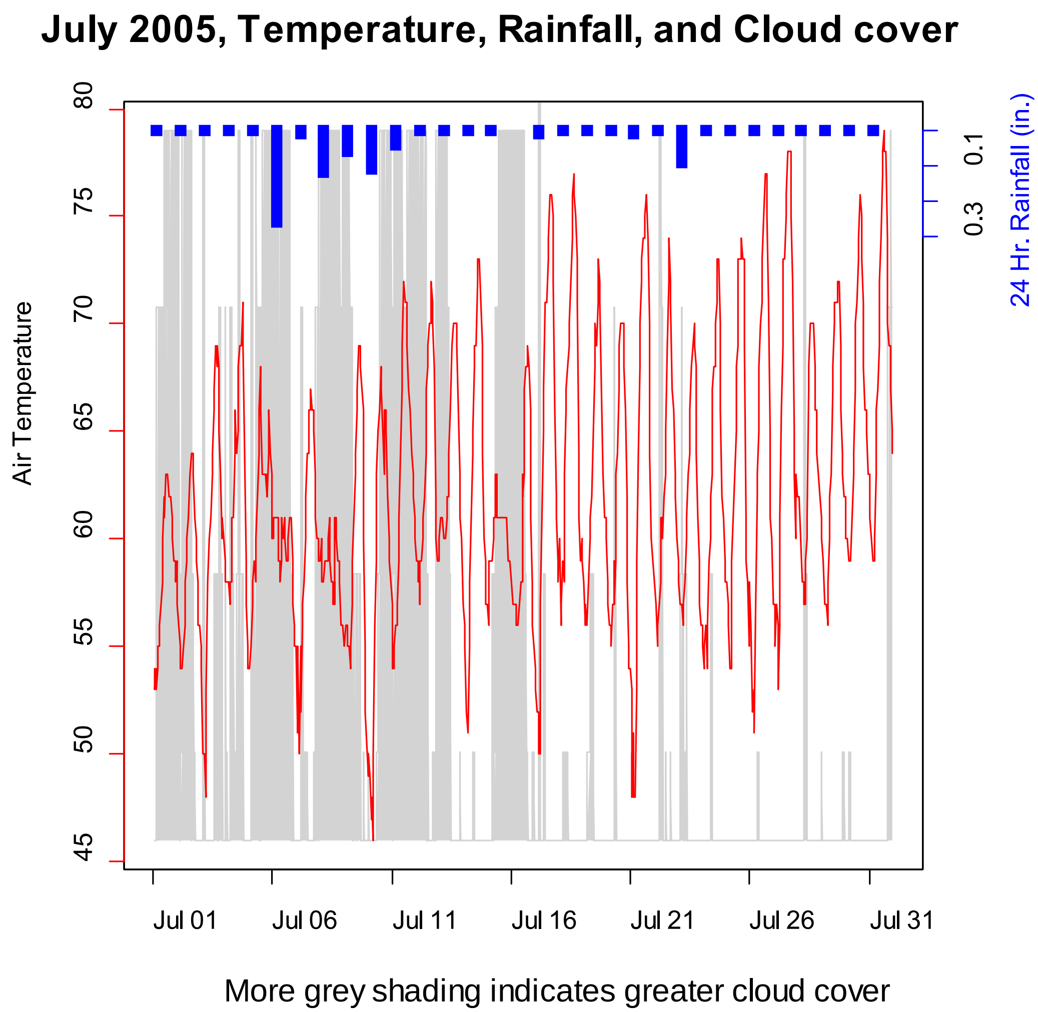

Figure 3. July 2005 time series

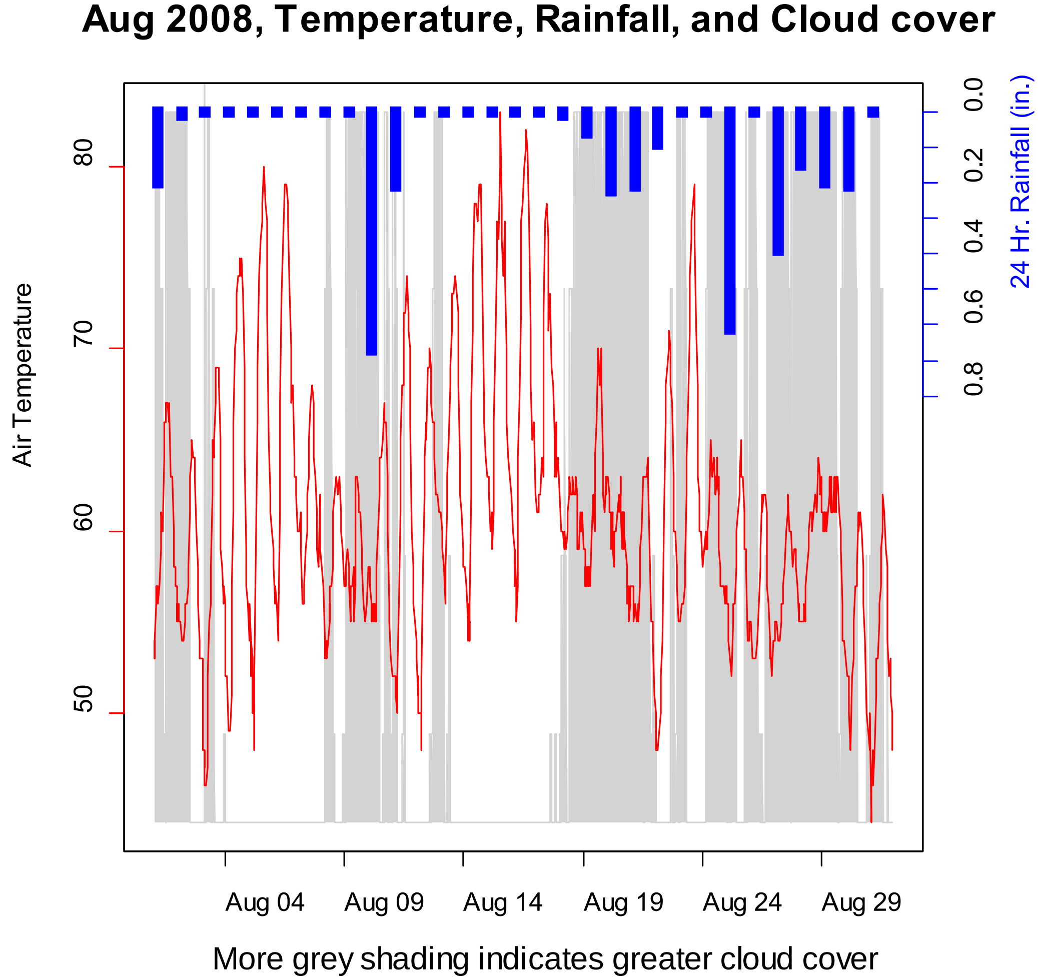

Figure 4. August 2008 time series