DEPARTMENT OF
ECOLOGY
State of Washington

Cranberry, Johns, and Mill Creeks Temperature Characterization Study

Three Creeks in Mason County

June 2018

Publication No. 18-10-022

Publication and Contact Information

This report is available on the Department of Ecology's web site at
https://fortress.wa.gov/ecy/publications/SummaryPages/1810022.html

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• Eastern Regional Office, Spokane	509-329-3400

Water Resource Inventory Area (WRIA)

- WRIA 14

8-digit Hydrologic Unit Code (HUC) numbers:

- 17110017

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, AAHM0004.

Cranberry, Johns, and Mill Creeks Temperature Characterization Study

Three Creeks in Mason County

by

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Acknowledgements

The authors of this report thank everyone for contributions made to this study and report.

In particular we are grateful for participating members of the:

- The Squaxin Island Tribe
- Oakland Bay-Hammersly Inlet Advisory Group

Preface

In 2005, the Department of Ecology (Ecology) intended this research to be a total maximum daily load (TMDL) for temperature. However, additional information would be needed to meet that objective at this time. Therefore, the data are being summarized in a temperature characterization study. Regardless of the type of document, the need to cool the water in these creeks and improve riparian buffers remain. These creeks will stay on the 303(d) list of impaired waters until they meet water quality standards. If standards are not met, Ecology is required by the Clean Water Act to write a TMDL in the future.

Abstract

Cranberry, Johns, and Mill Creeks are located near the city of Shelton in Mason County, Washington. Cranberry and Johns Creeks are tributaries to Oakland Bay; Mill Creek is a tributary to Hammersley Inlet (Figure 1). All are in the Kennedy-Goldsborough watershed (Water Resource Inventory Area (WRIA) 14). Scientists with the Squaxin Island Tribe had been collecting temperature data in these three creeks and identified temperature impairments. The waterbodies were placed on the 2004 303(d) list for temperature. A water quality study was designed (Ahmed and Lawrence, 2005) and conducted in 2005 to obtain new and more intensive water quality.

The 2005 data were used to calibrate and validate the QUAL2Kw water quality model. The study described in this report is based on modeling the heat sources and sinks using the data from 2005. The model was then used to simulate stream temperatures under critical meteorological and streamflow conditions with existing and full system-potential riparian vegetation. Reduction in the riparian condition, changes in land use, and lake management issues may contribute to current high water temperatures. The large areas of surface area exposed to solar radiation may be a key factor. However, the natural condition of these headwater wetlands and lakes is unknown. The creeks remain on the 2016 303(d) list for temperature.

Data suggests that the elevated stream temperatures may be attributed to the current condition of headwater wetlands or lakes with large water surface areas exposed to sunlight. Increased stream temperature resulting from anthropogenic activities can be slowed and prevented by

reversing the process over time. The reversal can be accomplished by increasing riparian shade through improved riparian vegetation, preventing or minimizing impacts of land-use activities on stream hydrology/morphology and by using selective withdrawal of lake water at depth using an outlet structure.

Generally, the water cools as it flows downstream. Groundwater contribution may be a factor that explains the downstream cooling in these waterbodies. Protection of thermal refugia, provided with the groundwater inputs, is a key strategy to protect aquatic life and survival strategies. Effective shade[1] was calculated with the goal of determining the shade required to bring the streams to within Washington State water quality standards for temperature or to the system-potential temperatures of the waterbodies.

Sources of anthropogenic heat can be slowed and/or prevented by increasing riparian shade through improved riparian vegetation, preventing or minimizing impacts of land-use activities on stream hydrology/morphology and by using selective withdrawal of lake water at depth using an outlet structure.

Introduction

Cranberry, Johns, and Mill Creeks are located near the city of Shelton in Mason County, Washington (Figure 1). Land use is mostly commercial forest and rural residential. All three creeks are characterized by lakes or large wetlands at headwaters. The relatively high water temperatures most likely result from large areas of water exposed to sunlight.

Cranberry and Johns Creeks are tributaries to Oakland Bay. Oakland Bay is a short, narrow bay that angles abruptly northeast from its connection with Hammersley Inlet to the south. The Bay ranges in width from 1000 feet to near one mile and covers an area of approximately 5.4 square miles. Mill Creek is a tributary to Hammersley Inlet which is one of the shallowest and narrowest of all inlets in South Puget Sound. The inlet is six miles long with an estimated surface area of 2.2 square miles.

The Squaxin Island Tribe (Tribe) had been collecting temperature data in these creeks and found that Washington State water quality standards for temperature were not being met. The Tribe documented longitudinal temperature profiles obtained through a thermal infrared (TIR) survey conducted in 2003. The TIR suggested that temperatures drop significantly in all three creeks in the downstream direction. The drop in temperatures along these creeks is presumed to be a result of cooler groundwater inflow together with heat exchange between warmer water and cooler soil (stream bed) and/or cooler air (resulting from shade from riparian vegetation).

The waterbodies were placed on the 2004 303(d) list. Further data collection was conducted in 2005 in order to model (using QUAL2Kw) the streams and understand the impacts of different variables for elevated stream temperatures.

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[1] Effective shade is the fraction of incoming solar shortwave radiation above the vegetation and topography that is blocked from reaching the surface of the stream. Effective shade was used as a surrogate measure of heat flux.

The QUAL2Kw model was calibrated and validated using 2005 field data. The model was then used to simulate stream temperatures under critical meteorological and streamflow conditions with existing and full system-potential riparian vegetation. The effective shade (a surrogate measure of heat flux) necessary to bring the stream temperatures to within the system-potential temperature or the water quality standards was established. Because of the time needed to grow trees and establish self-sustaining riparian areas, percent effective shade values were determined for stream reaches.

Beneficial Uses

Cranberry, Johns, and Mill Creeks remain on Washington State's 2016 303(d) list of waterbodies for not meeting temperature water quality standards. 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 flow. 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 waterbody. Appendix A describes the water quality standards for temperature. Appendix B describes some physical and biological factors that effect stream temperature.

Documented anadromous (sea-run) salmon species in the tributaries to Oakland Bay/Hammersley Inlet watershed include chum, coho, steelhead, sea-run (coastal) cutthroat, rainbow trout, and incidental reports of pink and sockeye (WDFW, 1993). The critical species are summer chum that spawn from early September to late October.

Water Quality Criteria

Aquatic life use categories are described using key species and life-stage conditions as per WAC 173-201A-200 (Ecology, 2017).

The aquatic life use designation for Cranberry, Johns, and Mill Creeks and their tributaries is "core summer salmonid habitat". The key identifying characteristics for this use are: summer (June 15 – September 15) salmonid spawning or emergence, adult holding; use as important summer rearing habitat by one or more salmonids; or foraging by adult and subadult native char. Other common characteristic aquatic life uses for waters in this category include spawning outside of the summer season, rearing, and migration by salmonids. 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 waterbody.

The applicable temperature criteria for the designated uses are summarized below in Table 1 and further described in Appendix A.

Table 1. Aquatic life temperature criteria (Ecology, 2017).

Waterbody	Aquatic Life Use Designation	Temperature Criteria (7-DADMax)	Supplemental Criteria Spawning/Incubation (7-DADMax)
Cranberry Creek	Core Summer Salmonid Habitat	**16 °C**	**13 °C** (Sept 15 - May 15)
Johns Creek	Core Summer Salmonid Habitat	**16 °C**	**13 °C** (Sept 1 - May 15)
Mill Creek	Core Summer Salmonid Habitat	**16 °C**	na

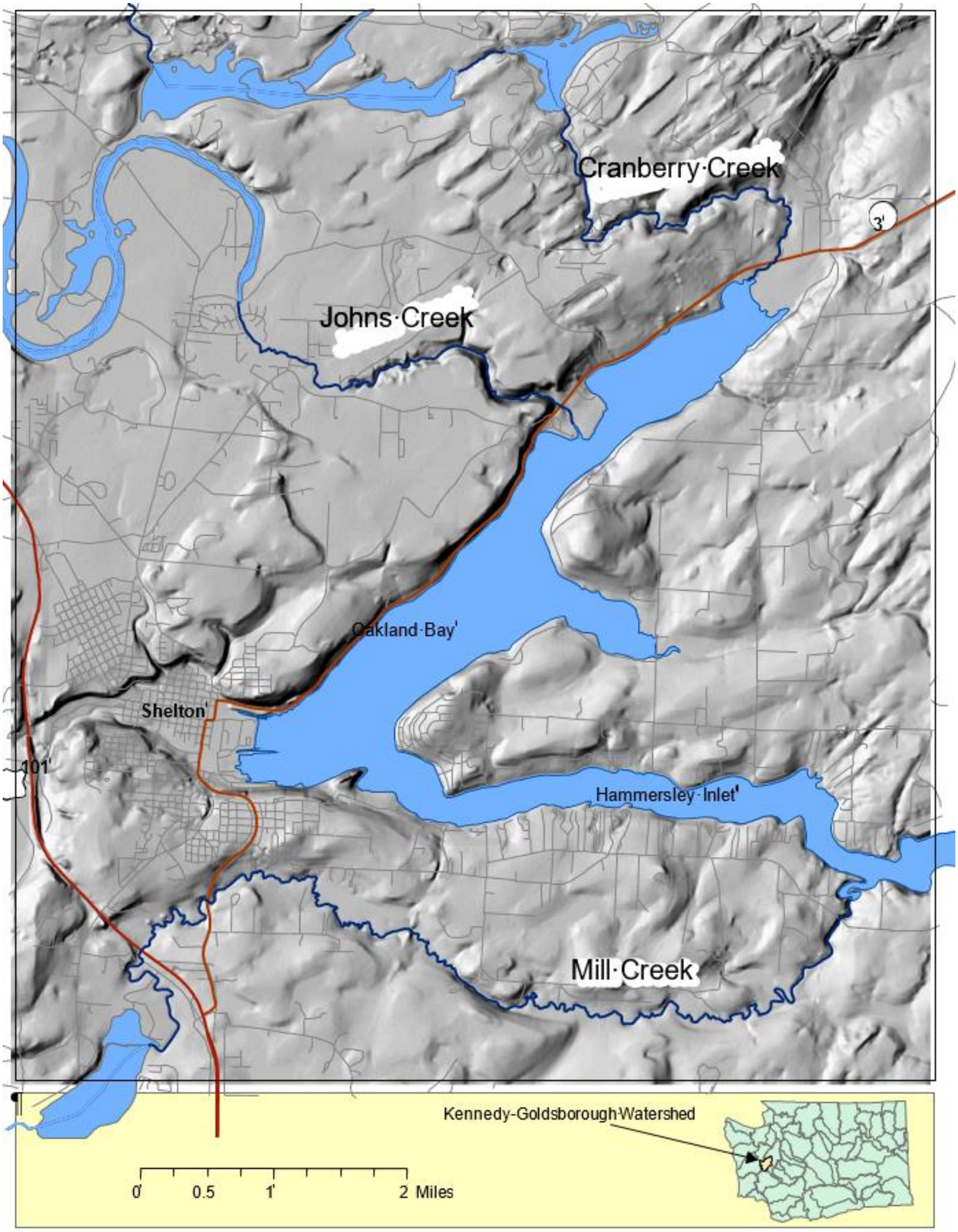


Figure 1. Location of Cranberry, Johns, and Mill Creeks.

Goals and Objectives

Project goals

The goal of the temperature study for Cranberry, Johns, and Mill Creeks is to protect the designated aquatic life uses for salmonid spawning, rearing, and migration.

Study objectives

Specific objectives include:

1. Gather sufficient continuous stream temperature data to enable analytical modeling to be performed.
2. Gather stream temperature data and microclimate information.
3. Establish stream flow dynamics and critical periods.
4. Determine groundwater temperature influences and gradients.
5. Establish stream morphology characteristics.
6. Develop and calibrate a temperature and shade model for each stream.
7. Determine effective shade targets to achieve healthy water temperatures.

Watershed Descriptions

Cranberry Creek

Cranberry Creek originates from the NE cove of Cranberry Lake, a natural lake, and flows a short distance before entering Lake Limerrick (Figure 1) a constructed lake. The creek then leaves the SE corner of Lake Limerrick and flows generally southeast to Oakland Bay

Cranberry lake is a natural lake with a surface area of 73 hectares. Lake Limerick is a 52-hectare manmade lake created in 1966 by damming a wetland (Smith and Rector, 1994). It discharges into Cranberry Creek via an outlet structure.

Cranberry Creek drains approximately 39 Km^2 (Brown and Caldwell, 1990). The maximum elevation of the creek is 154.5 m (Schuett-Hames, et al., 1996). Historical mean annual discharge was estimated at 1.5 cms (Williams et al., 1975). In the last three years the mean annual discharge has been estimated at 1.33 cms (Konovsky, 2008). The reach of the creek between the mouth in Oakland Bay and below Lake Limerick is approximately 5.6 Km long. The distance between Lake Limerick and Cranberry Lake is approximately 0.8 Km. However, the actual stream segment is much smaller (0.45 Km) from below the culvert below Cranberry Lake to the gaging station above the culvert above Lake Limerick. The 2005 temperature profiles and hydraulic gradients for Cranberry Creek can be found in Appendix C.

Johns Creek

Johns Creek (Figure 1) begins at a eight-kilometer-long wetland system and then follows a low-gradient, meandering course through glacial outwash before descending through a deep canyon at a gradient of approximately two to three percent to enter Oakland Bay through a wide delta. Johns Creek is 13 Km long (Williams et al., 1975) and drains an area of approximately 34 Km^2. The maximum elevation of Johns is 104 m (Schuett-Hames et al., 1996).

The historical mean annual discharge has been reported as 1 cms (35 cfs) (Williams et al., 1975). However, based on most recent three years of data, the mean annual average flow has been estimated at 0.7 cms (Konovsky, 2008). Some of the most productive shellfish beds in the bay are located at the mouth of Johns Creek. Most of the channel is accessible to fish. The stream hosts coho, steelhead, cutthroat, and two chum runs.

A groundwater-fed tributary discharges cold water into the creek at approximately a mile above the mouth of the creek. The water in this tributary is cold year-round. In the summer of 2005, the temperature in this tributary was consistently at 9°C (see Appendix D, Figure D-4).

Mill Creek

Mill Creek originates as the outflow of Lake Isabella and then flows easterly into Hammersley Inlet (Figure 1) The stretch from Lake Isabella to the mouth of the creek at Hammersley Inlet (east of Walker Park) is approximately 15.4 Km and drains an area of approximately 75 Km^2 . The major flow volumn of Mill Creek comes from Gosnell Creek which originates about 3.9 miles above Lake Isabella (Williams et al., 1975).

Forbes Lake, a 15.8-hectare lake about 2.4 Km west of the unincorporated area of Arcadia, also drains into Mill Creek (Brown and Caldwell, 1990). This small tributary enters Mill Creek close to the confluence with the the Inlet, however, it offers a small percentage of Mill Creek flow (Williams et al., 1975).

The maximum elevation of Mill Creek is 370 m (Schuett-Hames et al., 1996). Land use along Mill Creek and lower Gosnell Creek is primarily agricultural and residential, while upper Gosnell and its largest tributary, Rock Creek, are surrounded by commercial timberlands. The historical mean annual discharge of Mill Creek is approximately 1.67 cms (Ecology, 1983). The recent last three years of data show that the mean annual discharge has stayed the same (Konovsky, 2008).

Methods

Field data on temperatures and flows for all three creeks were gathered in the summer of 2005 by Ecology and Squaxin Island Tribal staff. Data were collected in accordance with the Quality Assurance Project Plan (QAPP) (Ahmed and Sullivan, 2005) written for this project.

Continuous temperature monitoring devices were installed along the mainstem of each creek at selected locations by the Squaxin Island Tribe. The tribe also installed piezometers at these locations with continuous temperature monitoring devices at three depths within the piezometer. The construction of the piezometers and the locations of temperature devices within the piezometer are similar to that in Ahmed and Hempleman (2006). Flows were measured at these locations on a monthly basis during summer 2005. In addition, thermal infrared (TIR) surveys were conducted by the Squaxin Island Tribe in 2003.

Data quality

Prior to the initiation of field sampling, Ecology developed a project QAPP in May 2005 (Ahmed and Lawrence 2005). Data quality objectives were determined including target accuracy or reporting values and quality control procedures. All analyses were performed in accordance with the QAPP and accepted data were used for model calibration.

Sampling Locations

Figure 2 shows the locations of the temperature monitoring stations in Cranberry Creek. Temperature data loggers were installed at six stations (CRA1, CRA1.4, CRA1.7, CRA2, CRA2.5, and CRA3) in Cranberry Creek in summer 2005 between the headwaters at Lake Limerick and the mouth of the creek at Oakland Bay. Another temperature data logger was installed at station CRA4 between Cranberry Lake and Lake Limerick. Groundwater temperatures and elevations were also measured in piezometers constructed at these locations.

Local air temperatures and relative humidity were measured at a midway location (station CRA1.7) between Lake Limerick and Oakland Bay. Streamflows were measured at all the monitoring stations. In addition, continuous flow was recorded at station CRA4 and CRA1 with stream gages maintained by the Squaxin Island Tribe. Although temperature measuring devices were planned to be installed in Cranberry Lake and Lake Limerick near the outlet, due to access issues, a temperature profile of Cranberry Lake could not be obtained during the field investigations of summer 2005.

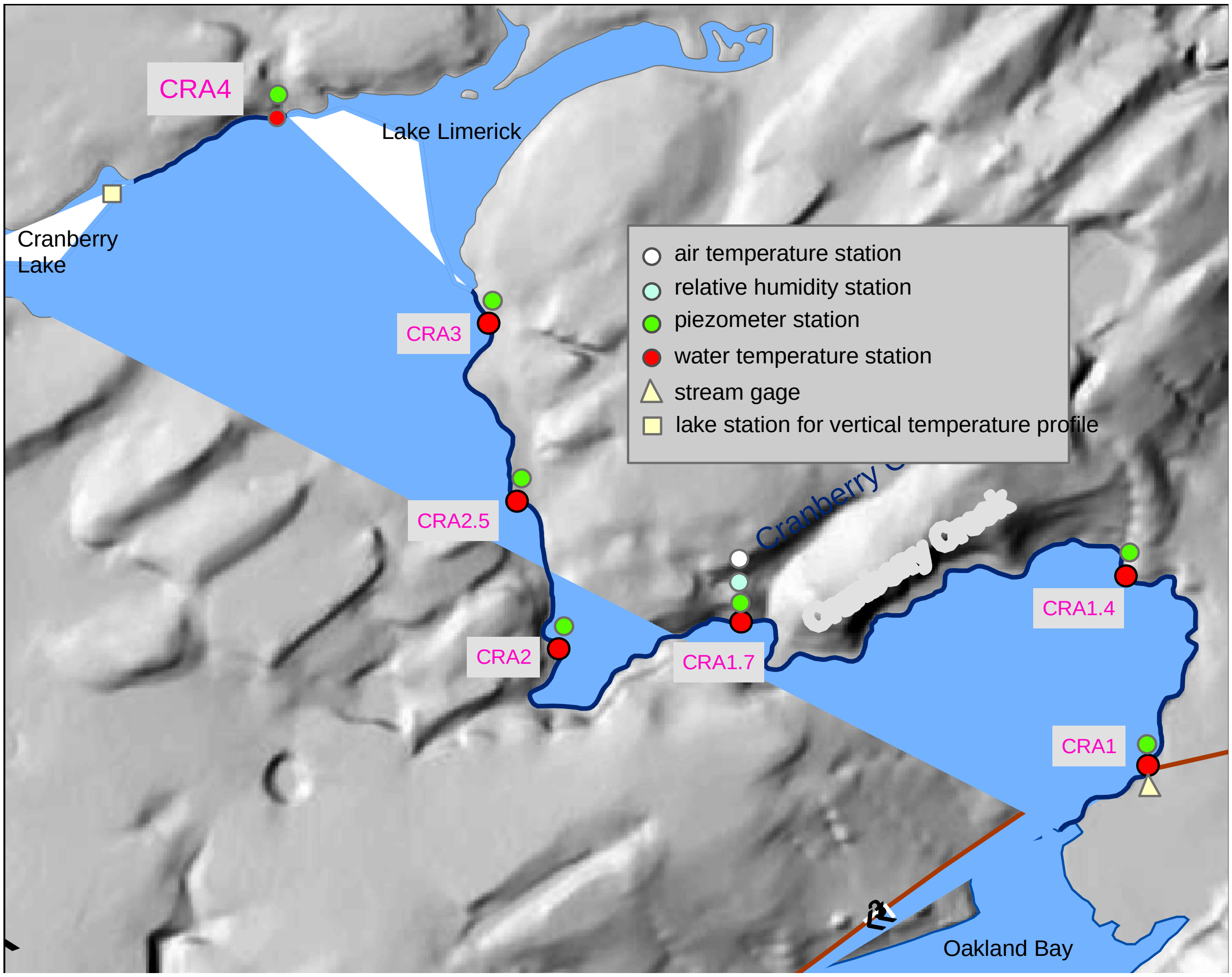


Figure 2. Monitoring stations in Cranberry Creek.

Figure 3 shows the locations of the temperature monitoring stations in Johns Creek. Temperature data loggers were installed at eight stations (JOH1, JOH1.1, JOH1.3, JOHTO, JOH1.4, JOH1.7, JOH2, and JOH2.5) in Johns Creek in summer 2005 between the headwaters (below the wetlands) and the mouth of the creek at Oakland Bay. Groundwater temperatures and elevations were also measured in piezometers constructed at these locations. Local air temperatures and relative humidity were measured at two locations (stations JOH1.1 and JOH2). Streamflows were measured at all the monitoring stations. In addition, continuous flow was recorded at station JOH1 and JOH2 with stream gages maintained by the Squaxin Island Tribe.

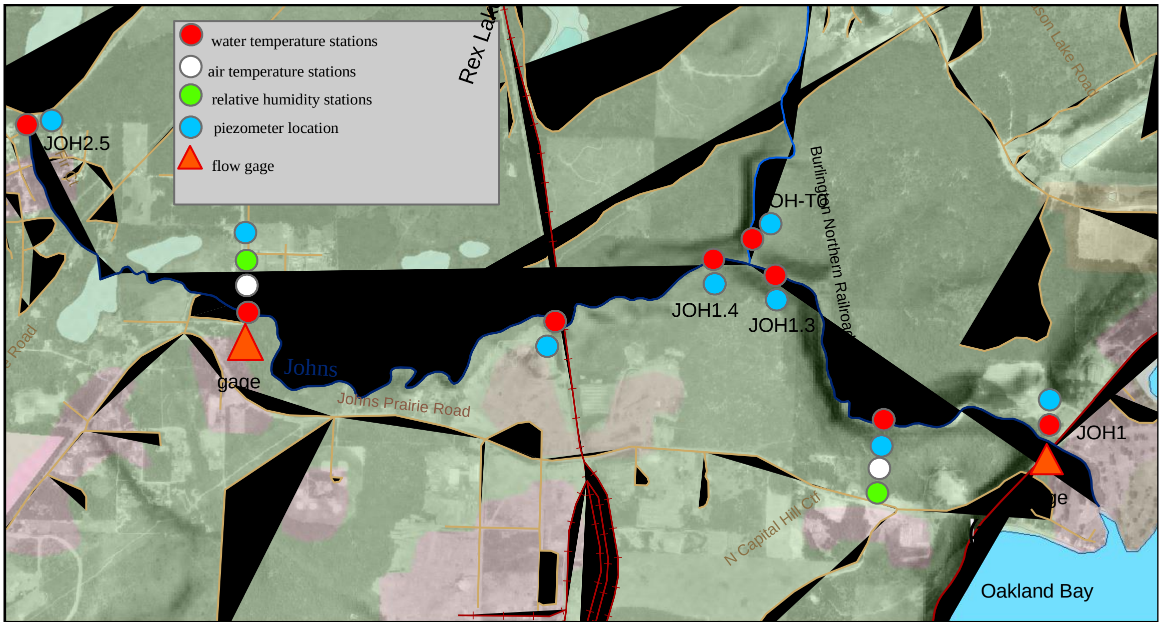


Figure 3. Monitoring stations in Johns Creek.

Figure 4 shows the locations of the temperature monitoring stations in Mill Creek. Temperature data loggers were installed at five stations (MIL1, MIL1.5, MIL1.75, MIL2, and MIL3) in Mill Creek in summer 2005 between the headwaters (below Lake Isabella) and the mouth of the creek at Oakland Bay. Groundwater temperatures and elevations were also measured in piezometers constructed at these locations. Local air temperatures and relative humidity were measured at two locations (MIL1 and MIL2). Streamflows were measured at all the monitoring stations. In addition, continuous flow was recorded at station MIL2 with a stream gage maintained by the Squaxin Island Tribe.

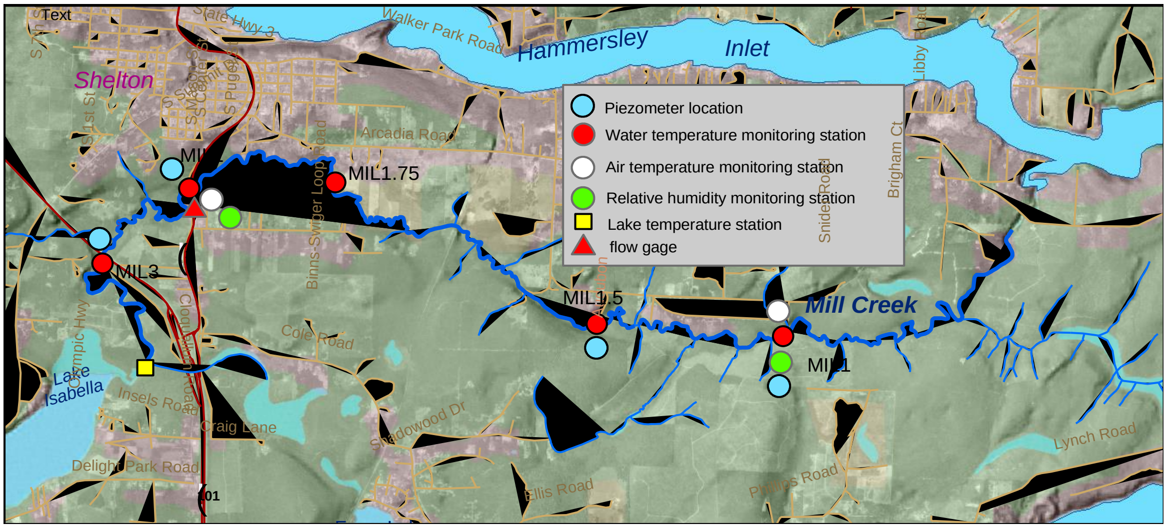


Figure 4. Monitoring stations in Mill Creek.

Existing Riparian Conditions

To obtain a detailed description of existing riparian conditions, a combination of field data on tree heights and species, interpretation of aerial photography, and GIS analysis were used. Vegetative polygons made up of stream segment lengths and the buffers were mapped at a 1:3000 scale. Thermal infrared (TIR) surveys were completed by the Squaxin Island Tribe for Cranberry, Johns, and Mill Creeks in August 2003.

A vegetation type code was assigned to each delineated polygon using black-and-white digital orthophoto quadrangles (DOQs). The original DOQs have a resolution of 3 ft pixel size. No color DOQs were available for the creeks.

To supplement the black-and-white photos and to increase the accuracy of image interpretation (riparian vegetation type and density), digital photographs acquired during the TIR survey were used. These digital images (about 1020 images) were taken from low altitude (about 366 m) and collected sequentially with about 40 percent overlap with a ground width of approximately 130 meters.

The survey was conducted on August 18, 2003. The TIR images were more accurate, and specific details such as tree shadows helped in deciphering the species composition and relative heights. Field surveys on August 16, 2004 and April 28, 2005 of vegetation type and density were also compared against digitized GIS data.

The assigned vegetation code for each vegetation polygon then represented four attributes: tree height, type (e.g., conifers, deciduous, mixed, grass, barren), percent vegetation overhang, and average canopy density. Although nearshore densitometer readings were taken by the Squaxin Island Tribe in summer 2005 (Appendix F), the above procedure was deemed more accurate and efficient compared to using spot densitometer readings (Cristea, 2004).

Critical streamflows

The lowest minimum instream flows (cfs) as per WAC 173-514-030(1) are shown in Table 2. These flows are limited to the dates and locations indicated. The critical low flows 7Q2 and 7Q20 in the streams were estimated by Taylor et al. (2000). The 7Q10 flows were estimated from these flows and probability ratios as 0.1 cms, 0.09 cms and 0.25 cms for Cranberry, Johns, and Mill Creeks, respectively. It is assumed that the station locations of these flows are the same as those for the “minimum instream flows”.

However, recent 3-year flow data gathered by the Squaxin Island Tribe (Konovsky, 2008) show that the minimum 7-day flow to be in the order of 0.18 cms for Cranberry Creek, 0.13 cms for Johns Creek, and 0.3 cms for Mill Creek. These flows would be the 7Q3 flows. Using the 7Q3 estimate and the 7Q20 estimate, and linear interpolation, the 7Q10 flows would be as shown in Table 2. These values are very close to the 7Q10 flows based on estimates of Taylor et al. (2000).

Table 2. Minimum instream flows for Cranberry, Johns, and Mill Creeks.

Creek	Minimum instream flows, cfs	Dates applicable	Station Location	Station Description	7Q20, cms (cfs)	7Q10 cms (cfs)	7Q3 cms (cfs)
Cranberry	8	July 15 – October 1	KM 0.8	Station CRA1 at Highway 3 bridge	0.099 (3.5)	0.11 (4)	0.18 (6.5)
Johns	7	August 1- October 15	KM 4	Station JOH2 at Johns Creek Drive bridge	0.084 (3)	0.09 (3.3)	0.13 (4.7)
Mill	20	August 1 – October 15	KM 5	Near Audubon Way	0.25 (8.8)	0.026 (9)	0.3 (10.7)

Modeling framework

The QUAL2Kw (Pelletier and Chapra, 2008) water quality model was used. The following sequence reflects the process used to determine model outputs for this study:

1. The model was calibrated and confirmed using observed data.
2. Critical stream temperature under a reasonable worst case scenario of flow and weather conditions, but with existing vegetation, was predicted.
3. System-potential temperatures were predicted with full potential riparian vegetation under critical conditions.
4. System-potential temperatures were estimated as combinations of shade values necessary to bring the stream temperatures to within water quality standards.

The temperature study described in this report is based on modeling the heat sources and sinks along the channel as per the method developed by Chapra (1997) with calibration and confirmation using the data collected in 2005.

Field measurements were taken of bankfull width, wetted width, depth, and incision. Riparian management zone (RMZ) characteristics, such as active channel width, cover, size, density, and bank erosion, were also recorded during the surveys. Information gathered was used in the shade model to predict effective shade along the stream channel.

Groundwater temperatures were continuously measured at three depths within a piezometer established at each monitoring station along the creeks. The bottom temperature device generally showed no diurnal variation during the monitoring period (see Appendices C, D and E). This steady temperature was indicative of the local groundwater temperature, particularly for the gaining segments of the creeks. The difference in measured flows between two adjacent stations was considered as the portion contributed by either groundwater gain or loss.

During model calibration, both the hyporheic depth and flow were varied within the range.

Conservative assumptions made in the model are summarized below.

- system-potential shade values were based on existing average maximum tree height and 85 percent vegetation density.

- The critical conditions for system-potential shade values used the lowest 7-day average flow with a 10-year recurrence interval.
- The critical condition air temperatures were the 90th percentile of the historical 7-day average of daily maximum temperatures.

Results and Discussion

Groundwater and stream temperature profiles and hydraulic gradients for all three creeks can be reviewed in Appendices C, D and E.

Cranberry Creek

Figure 5 shows the gage flows at station CRA1 and the 7-DADMax temperatures at CRA1, CRA3, and CRA4 during June-September 2005. Temperatures at CRA3 and CRA4 were similar. Seepage runs (a method of taking flow measurements to provide estimates of the net gains or losses across broader creek reaches) were conducted on June 23, July 25, July 28, August 24, and September 22, 2005.

The July 28 (bold vertical dotted line in Figure 5) seepage run was used for model calibration for the mainstem segment between Lake Limerick and Oakland Bay. Temperature instruments were removed from the creek prior to the September 22 seepage run. The highest 7-DADMax occurred on July 31. However, no seepage runs were conducted on this day, and the streamflow was relatively unsteady due to a storm event. Model confirmation used August 24 data sets (vertical line in Figure 5), corresponding to another seepage run but during lower peak temperatures and steady flows.

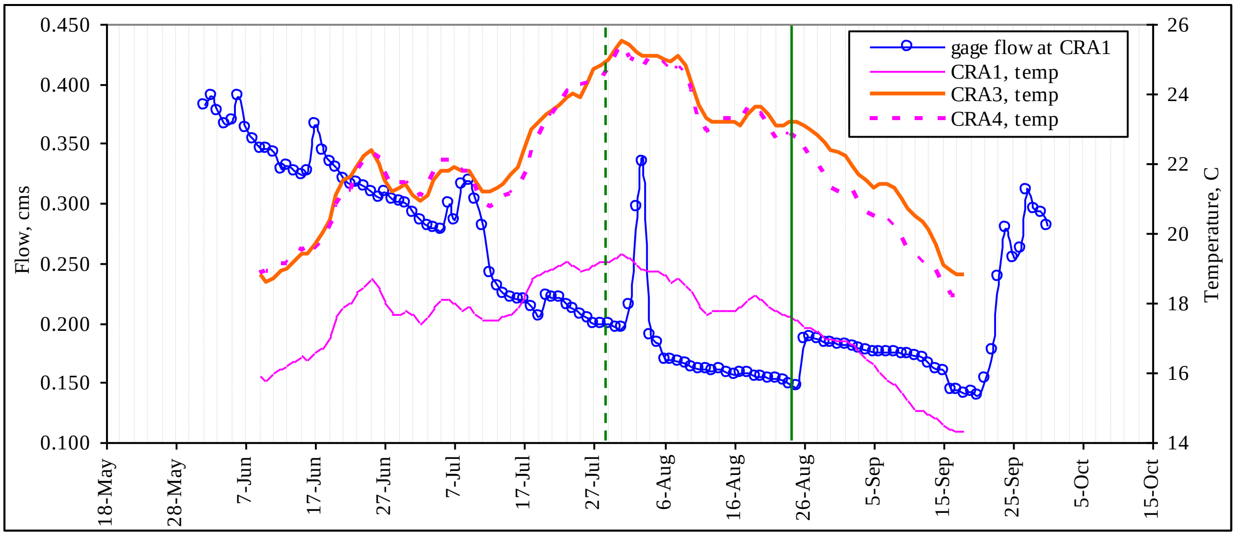


Figure 5. Gage flow at station CRA1 and 7-DADMax temperatures at stations CRA1, CRA3 and CRA4.

Figure 6 shows a longitudinal temperature profile for Cranberry Creek from the thermal infrared (TIR) survey. There was almost an 8˚C drop in water temperature from the outlet at Lake Limerick to the mouth of Cranberry Creek at Oakland Bay. The cooling may be due to riparian shade and/or cooler groundwater inflow. Cooling also takes place in the 2100 feet of the stream stretch between Cranberry and Limerick Lakes. Figure 7 shows a plan view of the TIR survey with cooling temperatures towards the mouth of the creek. The flow at station CRA1, at the mouth of the creek, on the day of the TIR survey was 4.7 cfs.

Figure 6. Longitudinal temperature profile in Cranberry Creek, August 2003.

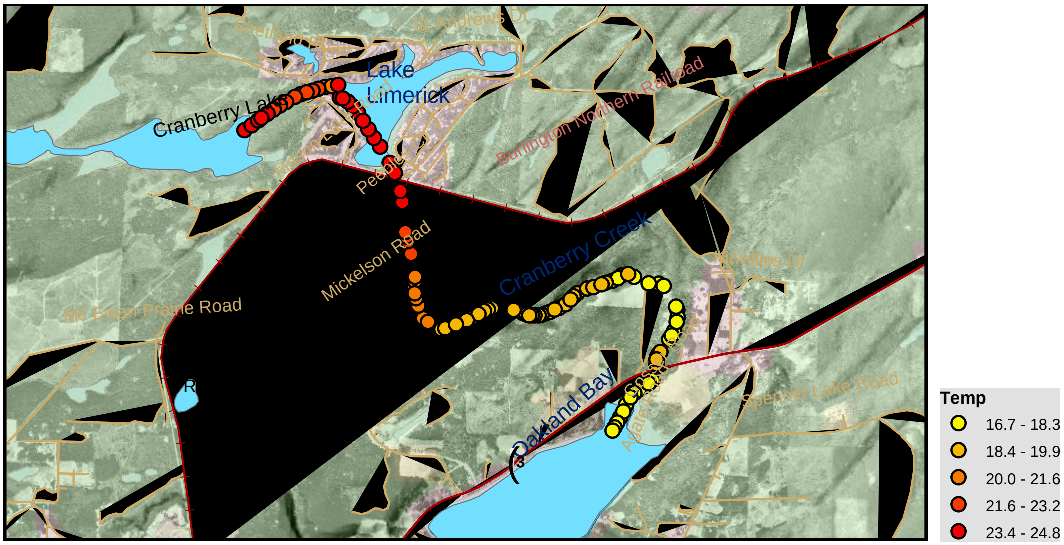


Figure 7. TIR survey of Cranberry Creek showing decreasing temperatures towards the mouth of the creek.

Johns Creek

Figure 8 shows the gage flows and 7-DADMax temperatures at stations JOH1 and JOH2 and JOH2.5, during June-September 2005. Seepage runs were conducted on June 21, July 19, August 23, and September 20. The highest 7-DADMax occurred on July 31, and no seepage runs were conducted on this day. However, July 31 (shown by a vertical dotted line in Figure 8) was chosen for model calibration, and flows at the various stations were estimated based on relationships developed between gaged and ungaged flows. Model confirmation was done for August 23 (vertical line in Figure 8), corresponding to another seepage run but during lower peak temperatures and steady flows.

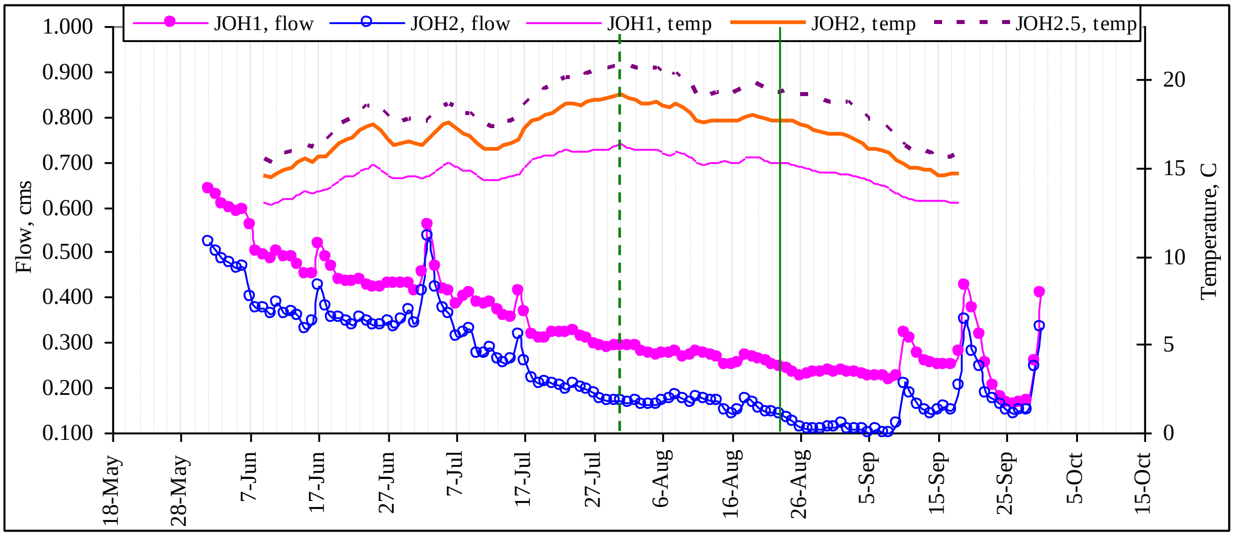


Figure 8. Gage flow and 7-DADMax temperatures at stations JOH1, JOH 2, and JOH2.5.

Figure 9 shows a longitudinal temperature profile from the TIR survey. There is an average 4˚C drop in water temperature from the downstream end of the wetlands at McEwen Prairie Road to the mouth of Johns Creek at Oakland Bay. The cooling may be due to riparian shade and/or cooler groundwater inflow. Significant cooling (6˚C) also takes place in the wetland from river mile 6.9 to the mouth of the wetland at river mile 4.6. Stream temperatures rise slightly after leaving the wetland and then start a significant cooling trend to about river mile 1 that results in a 6˚C temperature reduction. Stream temperatures rise by roughly two degrees between river mile 0.8 and the mouth of the stream at Oakland Bay. Figure 10 shows a plan view of the TIR survey.

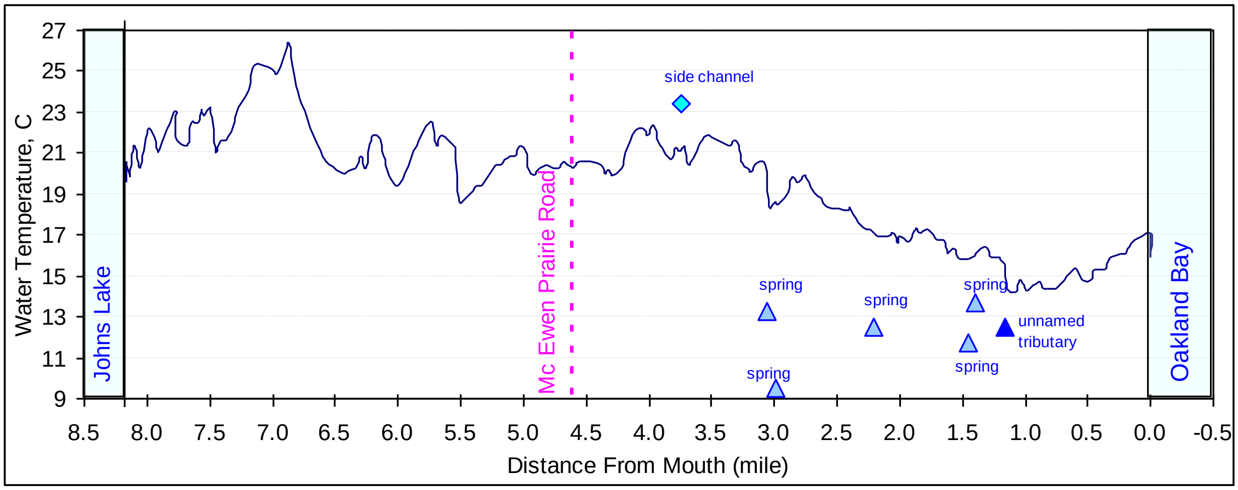


Figure 9. Longitudinal temperature profile in Johns Creek, August 2003.

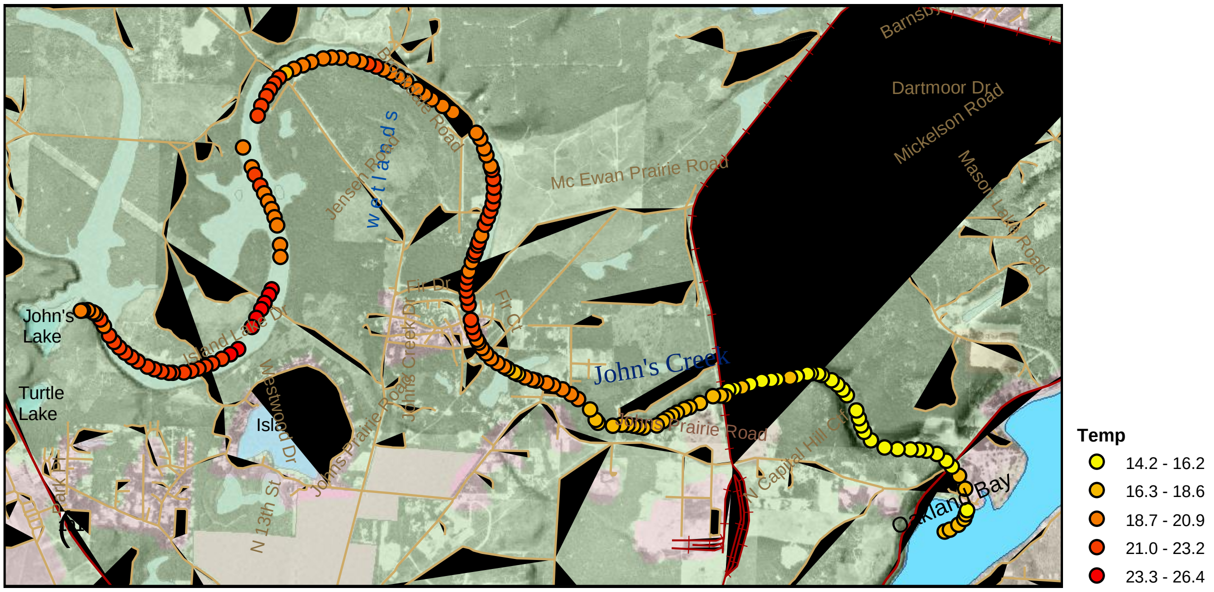


Figure 10. TIR survey of Johns Creek showing decreasing temperatures towards the mouth of the creek.

Mill Creek

Figure 11 shows the gage flows at station MIL2 and 7-DADMax temperatures at MIL1 and MIL3 during June-September 2005. Seepage runs were conducted on June 2, July 29, August 22, and September 16. The highest 7-DADMax occurred on July 31, and no seepage runs were conducted on this day. However, July 29 (vertical dotted line in Figure 11) was chosen for model calibration since this was a seepage-run day and it was fairly close to the peak temperature day. Model confirmation was done for August 22 (vertical bold line in Figure 11), corresponding to another seepage run but during lower peak temperatures and steady flows.

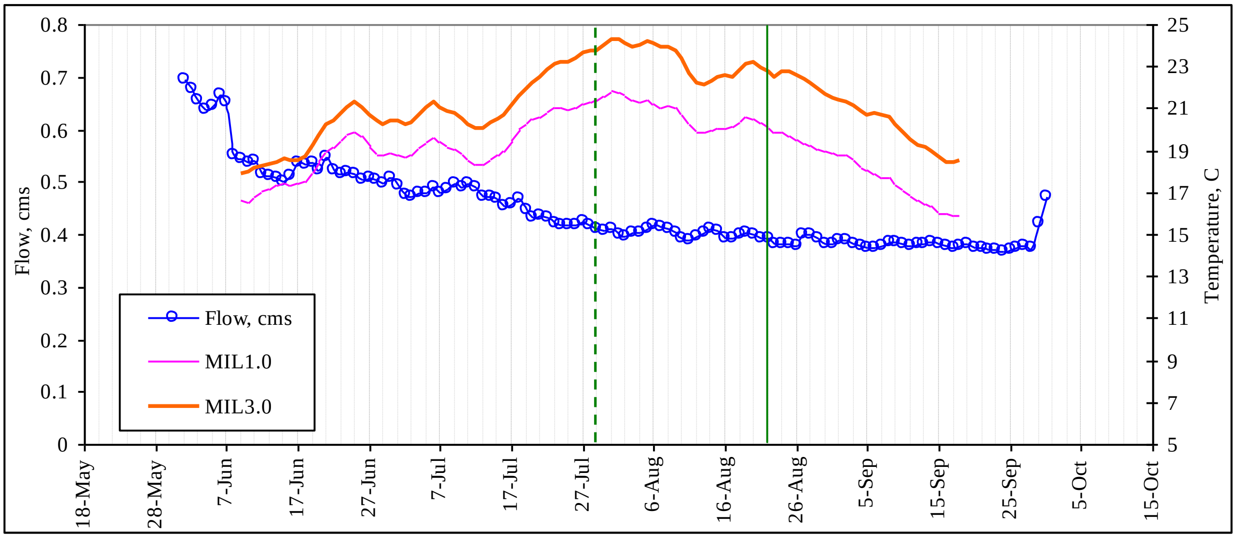


Figure 11. Gage flow at station MIL2, and 7-DADMax temperatures at stations MIL1 and MIL3.

Figure 12 shows a longitudinal temperature profile for Mill Creek from the TIR survey. There is an approximate 3˚C drop in water temperature from the outlet at Lake Isabella to the mouth of Mill Creek at Hammersley Inlet. The cooling may be due to riparian shade and/or cooler groundwater inflow. Figure 13 shows a plan view of the TIR survey with cooling temperatures towards the mouth of the creek.

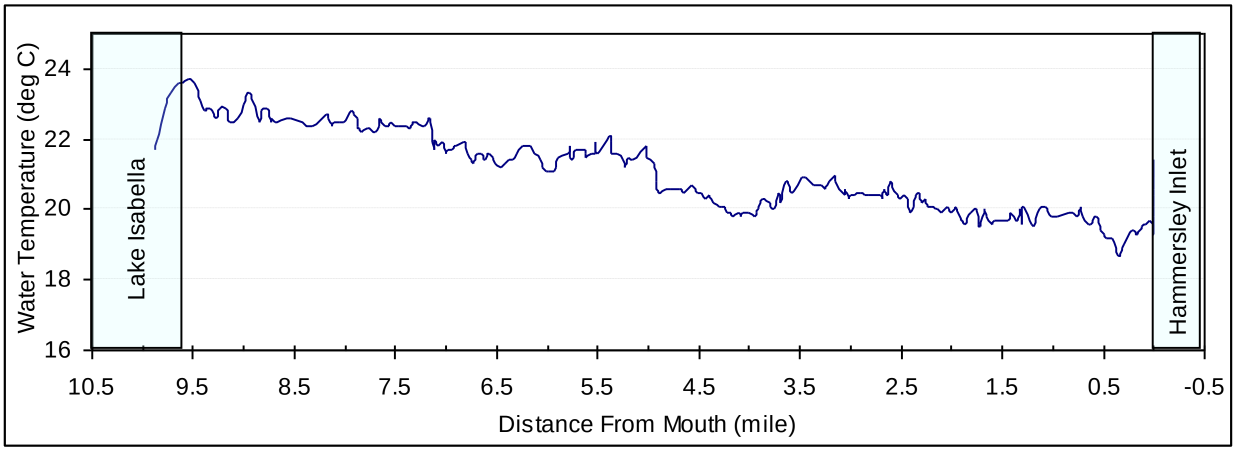


Figure 12. Longitudinal temperature profile in Mill Creek from the mouth at Hammersley Inlet to Lake Isabella outlet, August 2003.

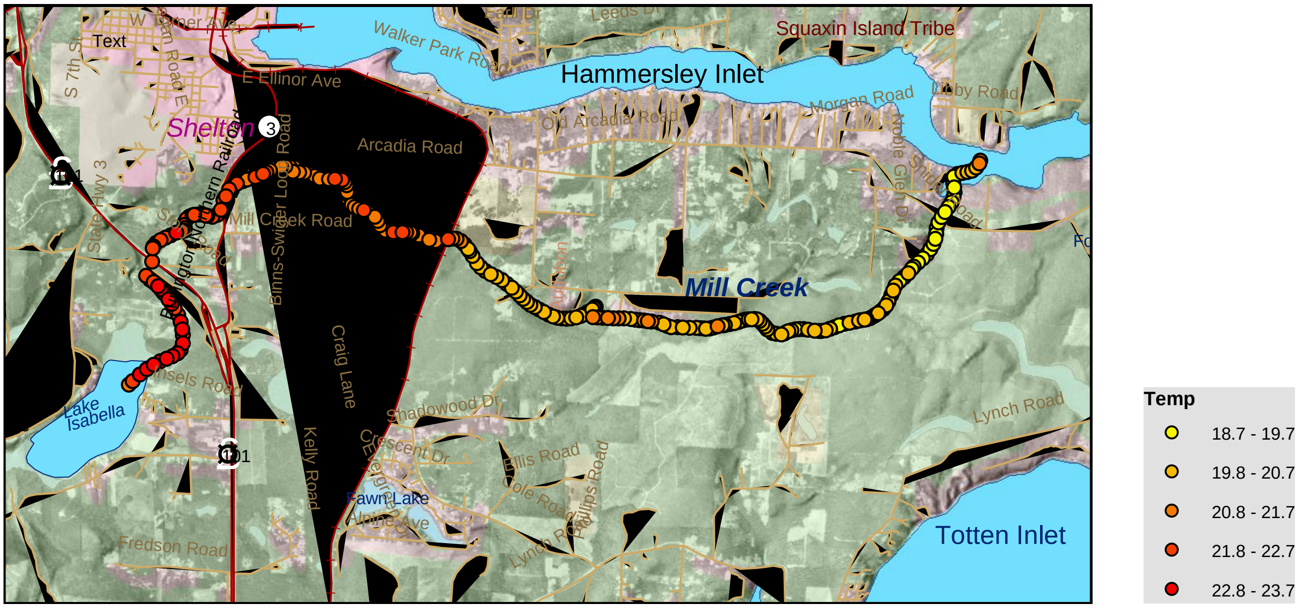


Figure 13. TIR survey of Mill Creek showing decreasing temperatures towards the mouth of the creek.

Stream Hydraulics

Hydraulic power functions (Chapra, 1997) shown in Table 3 were used to establish stream geometry and stream velocity for a given streamflow. These functions were developed for each monitoring station based on velocity and cross-section data gathered during synoptic surveys.

Velocity, $V = aQ^b$

Width, $W= cQ^d$

where "a" and "c" are the coefficients, and "b" and "d" are the exponents of the power functions.

Table 3. Stream power functions for Cranberry, Johns, and Mill Creeks.

Creek	Station	Velocity Function		Width Function	
		Coefficient	Exponent	Coefficient	Exponent*
Cranberry	CRA4	0.554	0.78	Depth: 0.3	Depth: 0.23
	CRA3	0.82	0.65	6.47	0.044
	CRA2.5	0.62	0.79	6.95	0
	CRA2	0.67	0.47	7.35	0
	CRA1.7	0.54	0.66	9.50	0.103
	CRA1.4	0.63	0.17	0.19	0.37
	CRA1	0.73	0.40	6.97	0.065
Johns	JOHTO	3.01	0.88	2.87	0.000
	JOH2.5	0.43	0.40	13.97	0.414
	JOH2	0.62	0.63	4.72	0.005
	JOH1.7	0.73	0.55	4.67	0.145
	JOH1.4	0.63	0.75	7.34	0.171
	JOH1.3	1.66	0.90	5.36	0.000
	JOH1.1	0.49	0.71	6.71	0.000
	JOH1	0.55	0.66	6.80	0.048
Mill	MIL 3.0	0.175	0.871	14.4	0
	MIL 2.0	0.457	0.886	8.5	0.039
	MIL 1.5	0.269	0.845	10.5	0
	MIL 1.0	0.370	0.665	7.0	0.212

* When exponents of the power functions for stream widths are zero, the measured width did not change significantly within the range of flow measured at the station.

The power functions at each station were initially assumed to extend half-way between adjacent stations and used to estimate average velocities and depths for predicted flows along the stream using the QUAL2Kw model. This assumption was adjusted based on riparian stream survey data gathered by the Squaxin Island Tribe. For a given flow, both the velocity and width of the channel were estimated for each of the QUAL2Kw segments. Since a rectangular channel cross- section was assumed, the depth of channel for each segment was obtained from these two parameters as well.

Station flows under 7Q10 flow conditions at the gaging station were estimated based on relationships between station flows and gage flows developed for the synoptic surveys. These are shown in Table 4.

Table 4. Station and gage flow relationships for Cranberry, Johns, and Mills.

Creek	Station	Station-gage flow relationship	R^2
Cranberry (gage at CRA1)	CRA3	0.7226 Qgage + 0.0015	0.999
	CRA2.5	0.8142 Qgage - 0.0093	0.998
	CRA2	0.7314 Qgage + 0.008	0.990
	CRA1.7	0.8292 Qgage + 0.0091	0.999
	CRA1.4	0.8854 Qgage + 0.0334	0.992
Johns (gage at JOH1	JOHTO	0.1029 Qgage + 0.0252	0.600
	JOH2.5	0.4254 Qgage + 0.055	0.600
	JOH2	0.4694 Qgage + 0.0545	0.998
	JOH1.7	1.0615 Qgage - 0.0523	0.967
	JOH1.4	0.7169 Qgage + 0.0661	0.884
	JOH1.3	0.792 Qgage + 0.104	0.966
	JOH1.1	0.774 Qgage + 0.1191	0.978
Mill (gage at MIL2)	MIL1	1.2694x - 0.0369	0.994
	MIL1.5	1.1402x - 0.0496	0.994
	MIL3	1.0925x - 0.0763	0.998

Groundwater hydraulics and temperature

Groundwater temperatures were measured within the groundwater column in piezometers established at various locations along each stream. Water level measurements within the piezometers and the stream indicated the hydraulic gradient between the stream and groundwater table. The hydraulic gradient data are limited. However, in a losing stream, the temperature in the piezometer (as measured by the bottom temperature device) will likely have the same diurnal signal as the temperature of the stream.

Figure 14 shows the groundwater temperatures along various locations in Cranberry, Johns, and Mill Creeks. These temperatures were measured in piezometers installed at the respective locations indicated in Figure 14. Three temperature measuring devices were installed at various depths in the piezometer water column. Figure 14 shows the temperature measured at the bottom of the piezometer. In general, upstream groundwater temperatures are warmer, and downstream groundwater temperatures are cooler.

In Johns Creek, the groundwater temperature near Oak Park (station JOH2.5) showed the highest temperature. However, the diurnal signal seems to be very strong, indicating some impact from surface water. The groundwater temperatures downstream of this station are more stable indicating “true” groundwater temperatures. The downstream stations show cooler groundwater temperatures with the coolest temperature (9.5°C) observed at the coldwater tributary (station JOHTO). This cold groundwater temperature is unique to Johns Creek and was not observed in any of the other streams.

The upper lake system in the Cranberry watershed seems to impact groundwater temperatures with higher groundwater temperatures at stations closer to the lakes.

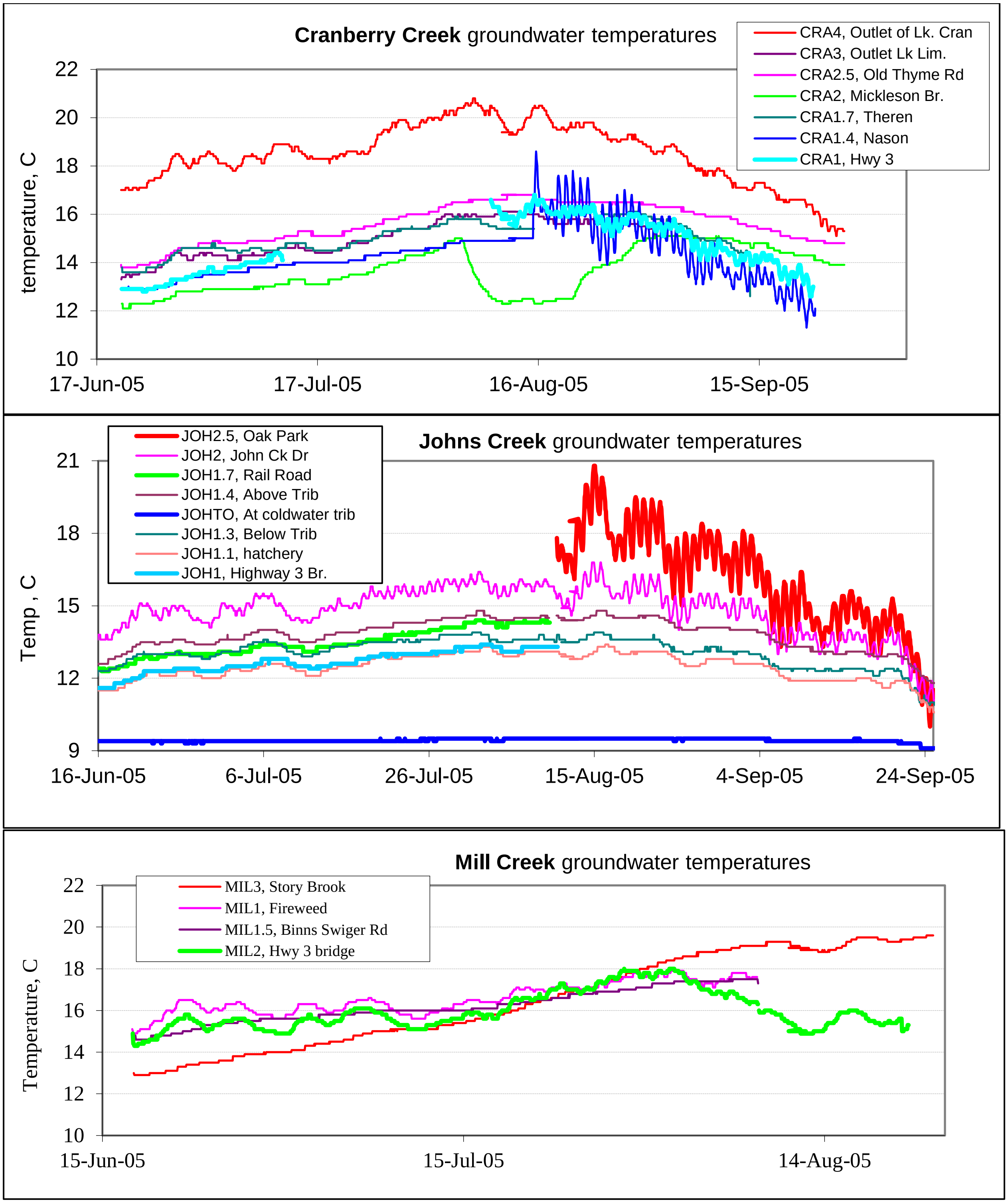


Figure 14. Temperatures at the bottom of piezometers in Cranberry, Johns, Mill Creeks.

The ArcView GIS dynamic segmentation method was used to produce 600 ft (approx. 183 m) stream segments. In addition, a 50 ft (15.2 m), 100 ft (30.5 m), and 150 ft (45.7 m) buffer from each side of a creek was delineated as shown in Figure 15.

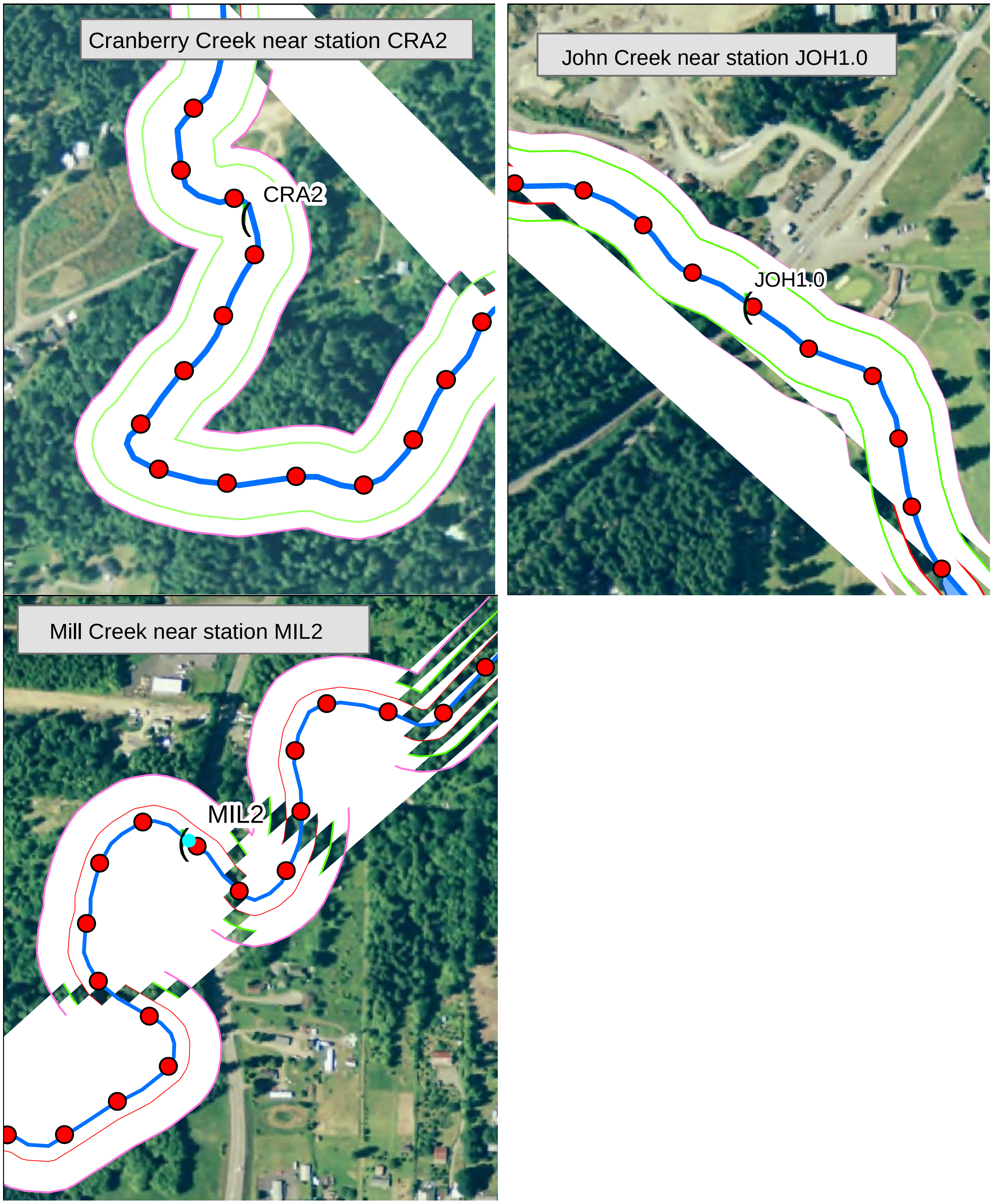


Figure 15. Example of digital ortho quad (DOQ) and digitized channel buffers for Cranberry, Johns, and Mill Creeks.

Model Calibration

Model calibration with different values of parameters within the ranges discussed in this section was accomplished using the genetic algorithm for automatic QUAL2Kw calibration (Pelletier, 2005). During model confirmation, all parameter values were kept the same as for model calibration. However, field and weather data specific to the verification period were used.

Prior to calibration of the QUAL2Kw model, various shortwave solar radiation models were compared to available solar radiation data at a University of Washington (UW) weather station (www-k12.atmos.washington.edu/k12/grayskies/nw_weather.html). The Bras model (Pelletier and Chapra, 2008) with an atmospheric turbidity coefficient of 2.4, and the Ryan-Stolzenbach model (Pelletier and Chapra, 2008) with an atmospheric transmission coefficient of 0.75, calibrated well with the observed UW data under clear skies as shown in Figure 16.

Although there could potentially be differences in the atmospheric turbidity coefficient and the atmospheric transmission coefficient between the University of Washington area (Seattle) and Oakland Bay, these values were used as starting values during model calibration.

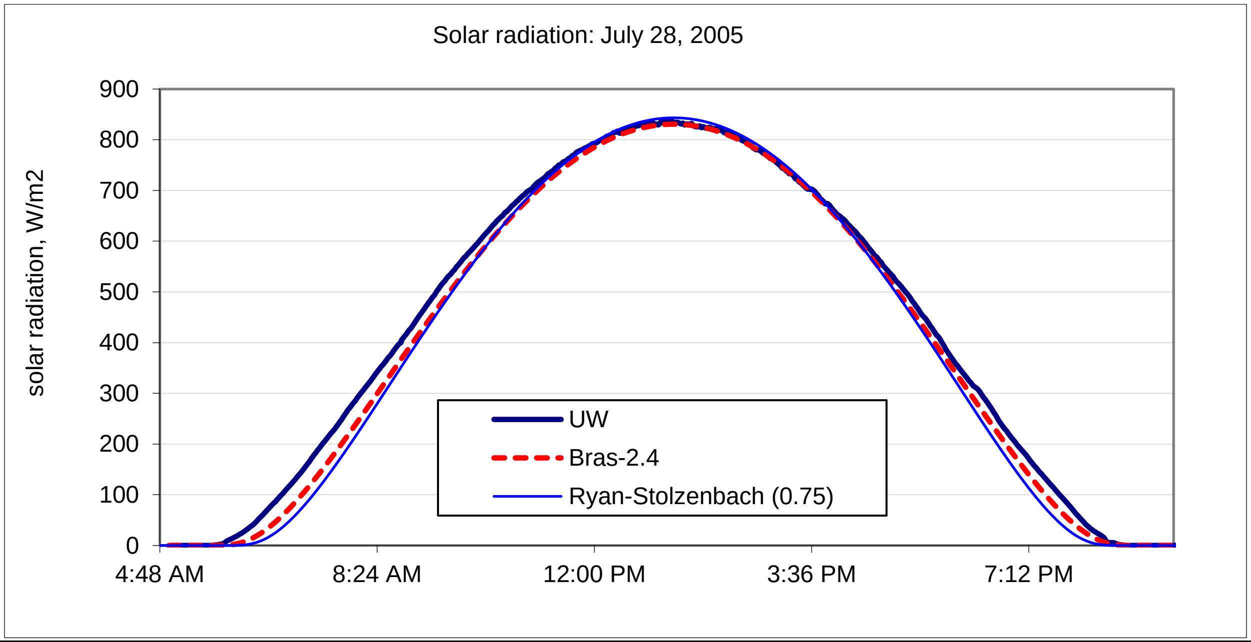


Figure 16. Comparison of global solar radiation measured at the University of Washington and as predicted by the Bras and Ryan-Stolzenbach models.

Weather data, such as wind speed, were reduced by as much as 20 percent to account for topographic and vegetation differences between Shelton's Sanderson Field (where wind data were gathered) and Cranberry, Johns, and Mill Creeks. Cloud cover also varied by 30 percent since there is a range of values associated with each cloud cover datum. For example, for scattered cloud cover, the sky coverage is equal to 2/8 to 4/8. No changes were made for overcast skies or clear skies. As indicated earlier, the hyporheic depth and flow also varied along the stream during model calibration.

Cranberry Creek

Figure 17 shows the model calibration and verification plots with predicted and observed temperatures along mainstem Cranberry Creek from the outlet of Lake Limerick to the mouth at Oakland Bay. The longitudinal thermal infrared (TIR) temperature profile (August 18, 2003) is also included.

Table 5 shows the root mean square error (RMSE) between the observed (7-day averages) and predicted temperatures for both model calibration and verification. The RMSE is close to the instrument error of ±0.4°C. There was good agreement between observed and predicted temperatures during model calibration and verification.

Table 5. RMSE (ºC) between observed and predicted temperatures in Cranberry Creek.

Temperature	Type	
	model calibration	model verification
Maximum	0.3	0.1
Average	0.3	0.3
Minimum	0.4	0.5

No seepage runs were completed in the stretch between Cranberry Lake and Lake Limerick. Flow and temperature were measured at station CRA4 (at the culvert above Lake Limerick). Due to access issues, a temperature profile of the lake could not be obtained during the field investigations. Temperatures observed at station CRA4 were likely reflective of temperatures at the outlet of Cranberry Lake, given the short stretch and intact visible riparian vegetation.

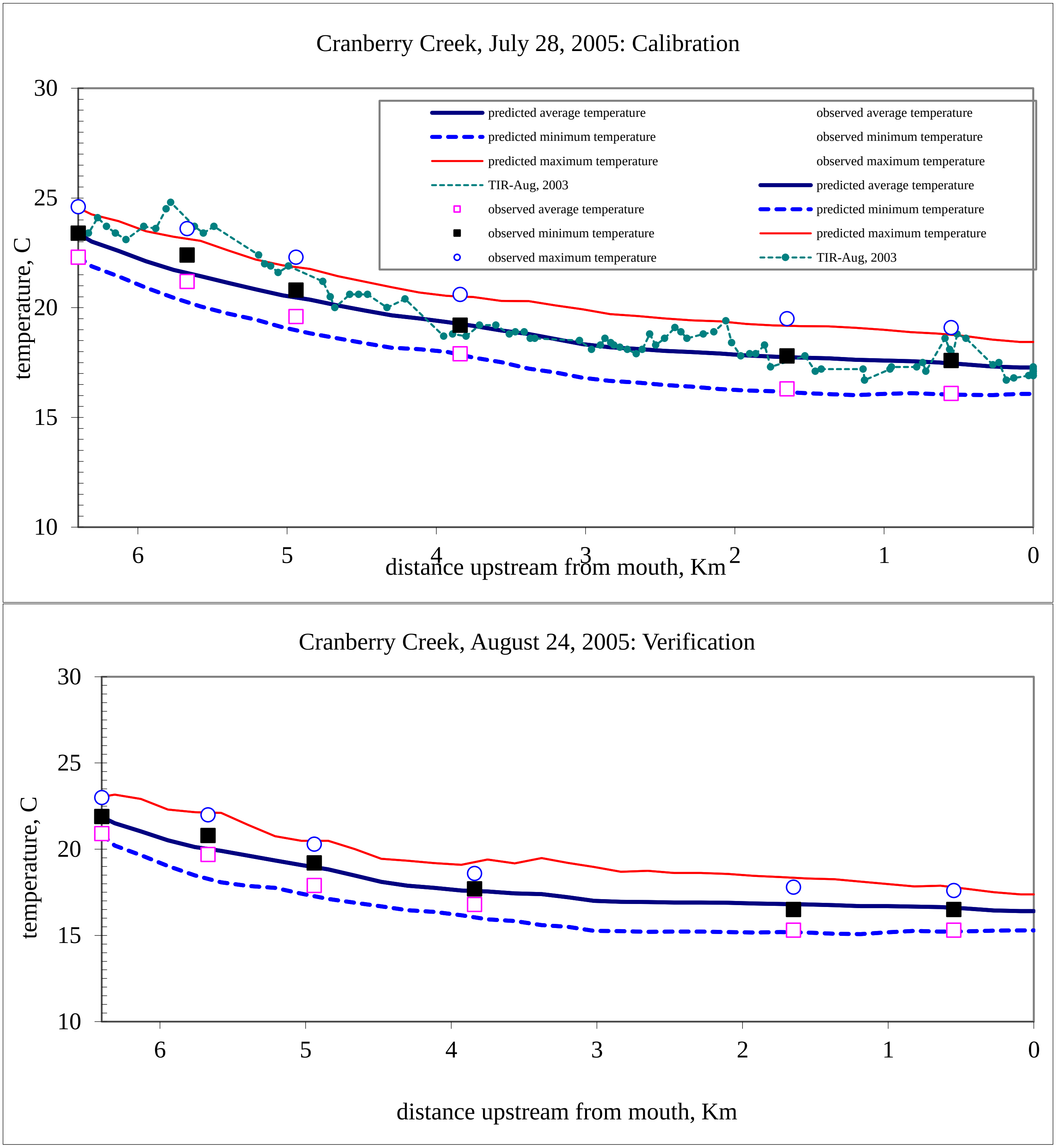


Figure 17. Model calibration (July 28) and verification (August 24) for Cranberry Creek.

Johns Creek

Figure 18 shows the model calibration and verification plot with predicted and observed (7-day average) temperatures along mainstem Johns Creek. The longitudinal TIR temperature profile (August 2003) is also shown in the calibration plot. The TIR plot shows higher surface temperatures near the wetlands at the headwaters.

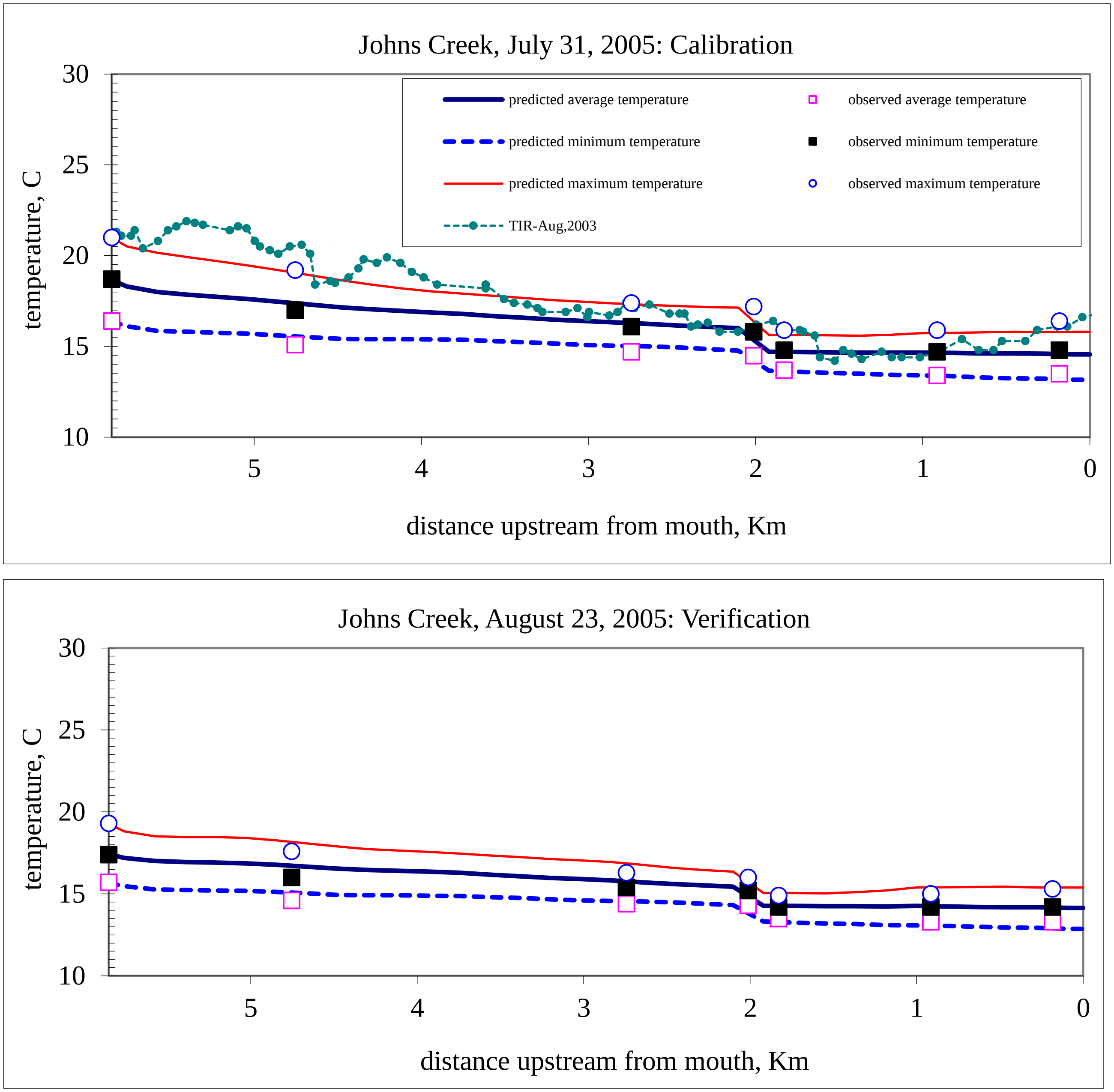


Figure 18. Model calibration (July 31) and verification (August 23) for Johns Creek.

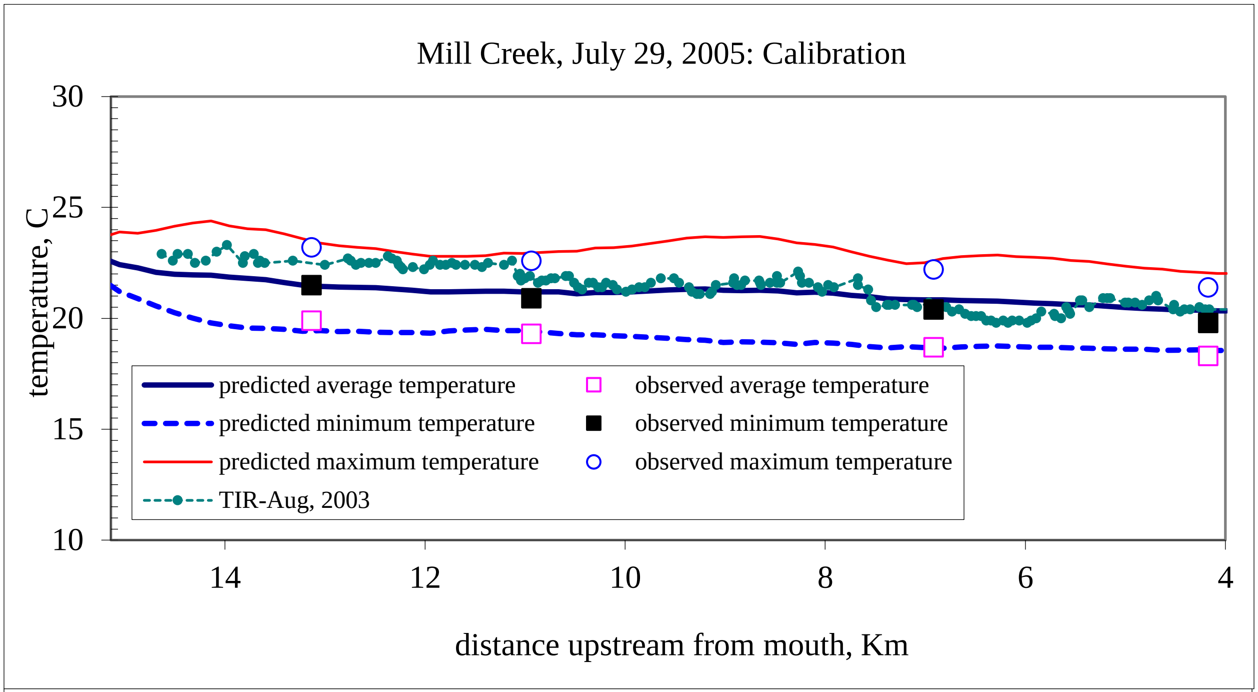
Table 6 shows the root mean square error (RMSE) between the observed and predicted temperatures for both model calibration and verification. The RMSE is close to the instrument error of ±0.4°C. There was good agreement between observed and predicted temperatures during model calibration and verification.

Table 6. RMSE (°C) between observed and predicted temperatures in Johns Creek.

Temperature	Type	
	model calibration	model verification
Maximum	0.3	0.4
Average	0.2	0.3
Minimum	0.3	0.3

Mill Creek

Figure 19 shows the model calibration and verification plot with predicted and observed temperatures along mainstem Mill Creek. The longitudinal TIR temperature profile (August 2003) is also shown in the calibration plot.


Mill Creek, July 29, 2005: Calibration

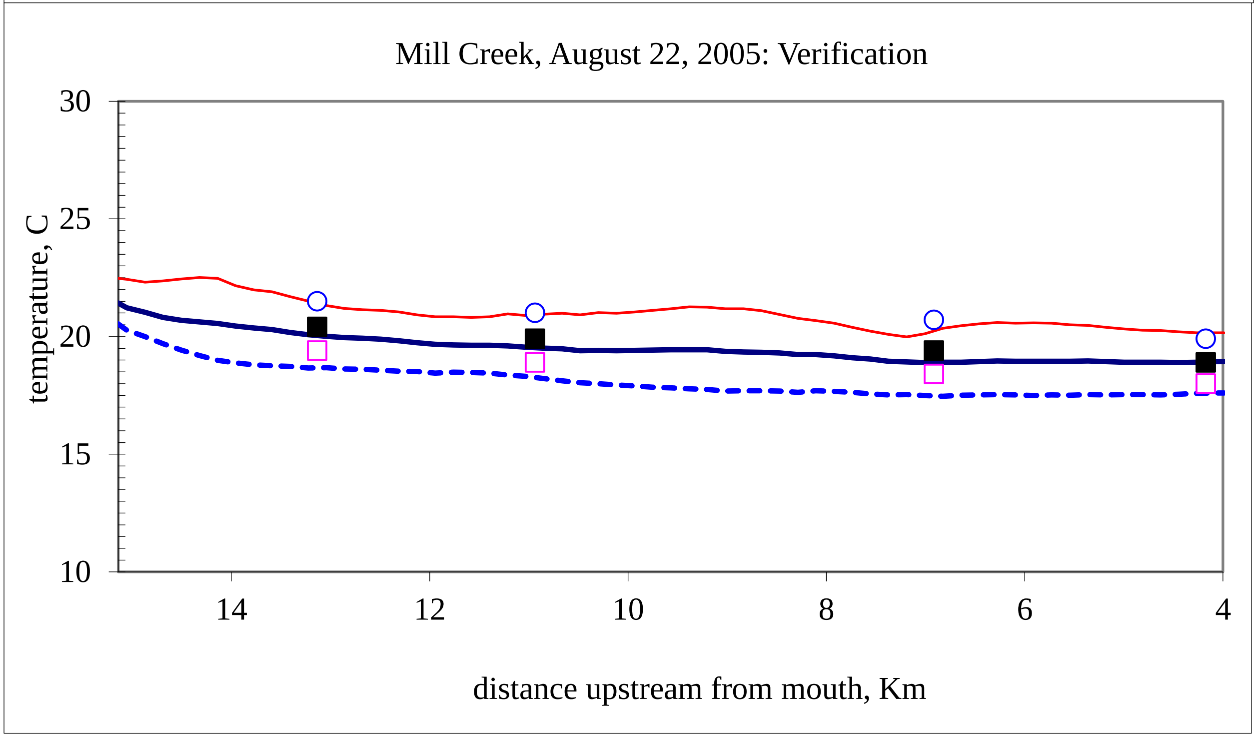

Mill Creek, August 22, 2005: Verification

Figure 19. Model calibration (July 29) and verification (August 22) for Mill Creek.

Table 7 shows the root mean square error (RMSE) between the observed and predicted temperatures for both model calibration and verification. The RMSE is close to the instrument error of ±0.4°C. There was good agreement between observed and predicted temperatures during model calibration and verification.

Table 7. RMSE (ºC) between observed and predicted temperatures in Mill Creek.

Temperature ºC	Type	
	model calibration	model confirmation
Maximum	0.4	0.3
Average	0.3	0.3
Minimum	0.3	0.6

Temperatures under critical conditions

In all three creeks, both calibration and verification model runs show that the highest stream temperatures exist at the headwaters (i.e., just below lake outlets or below wetlands). The purpose of evaluating critical conditions is to see if creek temperatures meet water quality standards during maximum headwater temperatures, critical streamflow, high air temperatures, clear skies, and in the absence of wind under existing riparian vegetation.

Regional air temperature was assumed to be the 90th percentile of the 7-day average of daily maximum (7-DADMax) temperatures. This was 29 ºC measured in August 2002 based on data from the Olympia Airport between 1948 and 2003 (Ahmed and Hempleman, 2006). The data correlated well with air temperature data from Shelton's Sanderson Field. In 2005, Shelton air temperatures reached a 7-DADMax of 29°C on July 31. However, the corresponding study-area air temperatures were lower as shown in Figure 20. Air temperature and dew-point temperature data measured near Cranberry Creek on this day were used for critical conditions.

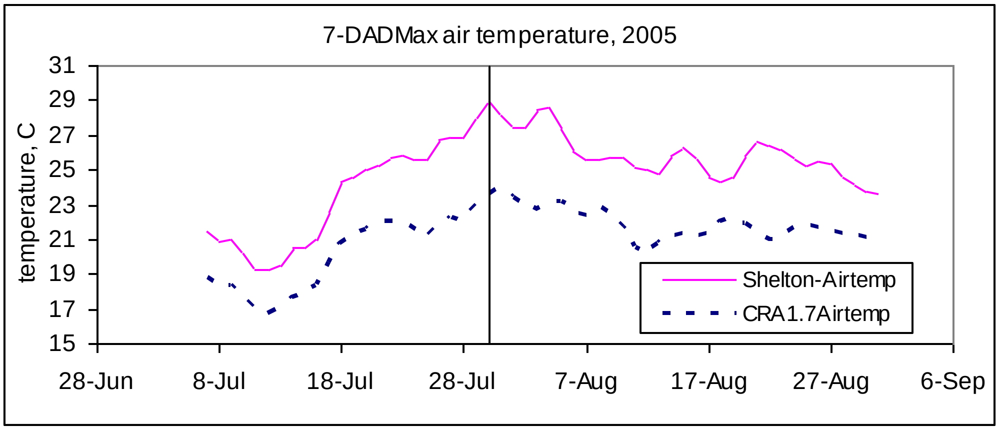


Figure 20. Shelton weather station and a Cranberry Creek station air temperatures, 2005.

Lower Cranberry Creek

For lower Cranberry Creek, the maximum 7-DADMax headwater temperature is approximately 26°C recorded at CRAN3 in 2003. Similar temperatures were measured in 2005. The maximum temperature in Cranberry Creek is at the headwaters and is tied to temperatures in Lake Limerick. Figure 21 shows the stratification in Lake Limerick during July-September 2005. Lake stratification disappears by mid September. The highest outlet temperatures are during the later part of July and early part of August. This is also the period of highest stratification in the lake.

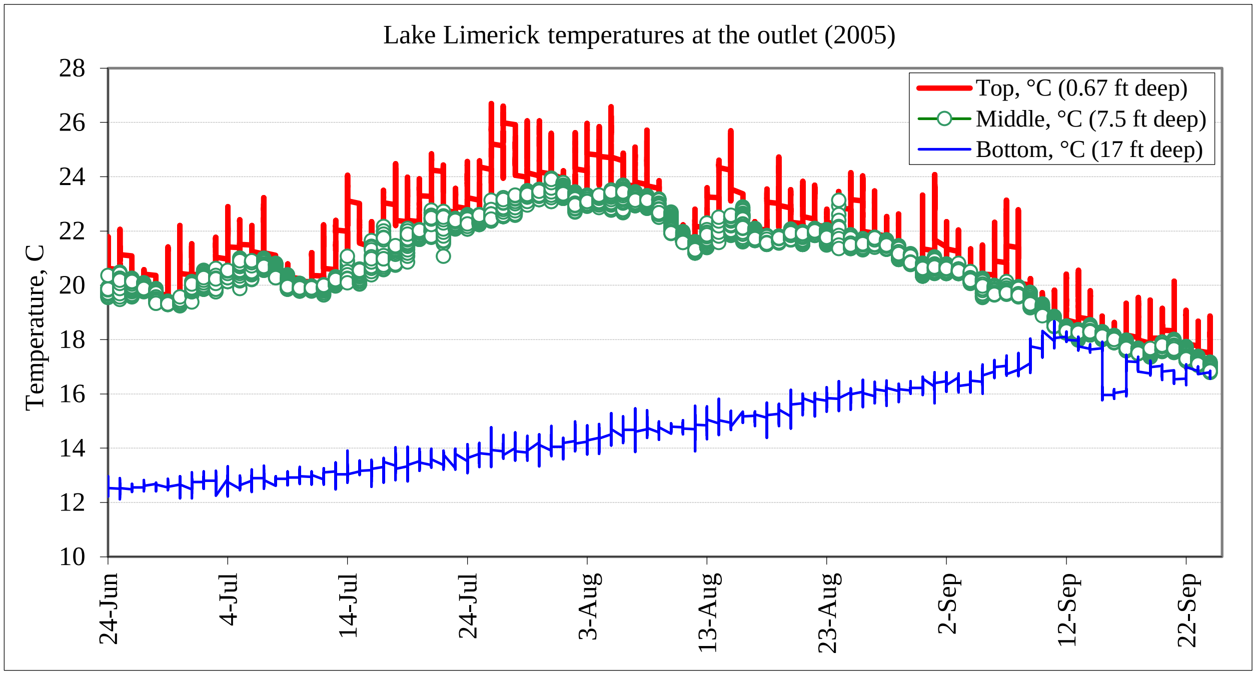


Figure 21. Temperature profile at the outlet of Lake Limerick.

The critical streamflow used is the low 7Q10 flow of 4 cfs (0.113 cms). However, this low flow occurs in September. In order to get a low flow statistic for the critical month of July, a ratio of the lowest 7-day average flow in July and September in 2005 was used, along with the annual 7Q10, to estimate the July 7Q10 flow of 4.5 cfs (0.127 cms).

Under critical conditions of low flow (July 7Q10 flow), high ambient air temperatures, and high lake temperatures (late July), the calibrated QUAL2kw model predicts the headwater temperatures to drop by approximately 7°C downstream to the mouth of Cranberry Creek as shown in Figure 22. However, the numeric water quality criterion of 16°C is not met at any portion of the creek.

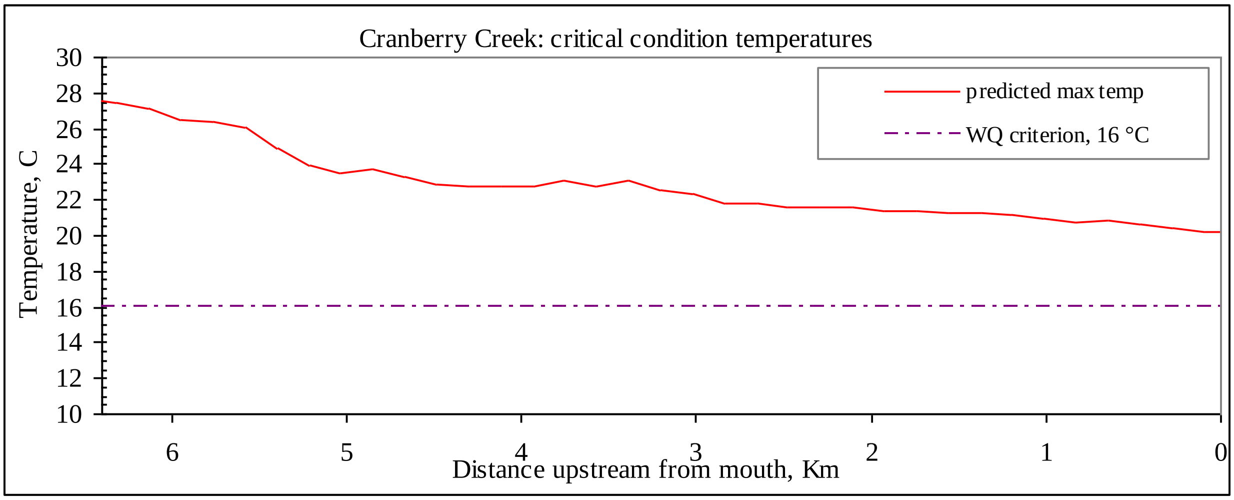


Figure 22. Stream temperatures under critical conditions in Cranberry Creek, July 31, 2005.

The calibrated QUAL2kw model was used to predict downstream temperatures in September when stratification in Lake Limerick disappears (see Figure 21). The low 7Q10 streamflow of 4 cfs was used. September 17 was used as the model day with highest lake outlet temperatures for September. The 90th percentile of 7-DADMax air temperatures for September 17 was 25.6°C as estimated from the 50-year data set obtained from the Olympia Airport following correlation with Shelton's Sanderson Field data (Ahmed and Hempleman, 2006). The 90th percentile was reduced to account for the local stream microclimate based on the relationship between air temperatures at Shelton's Sanderson Field and at station CRAN1.7 for September 17 (Figure 23).

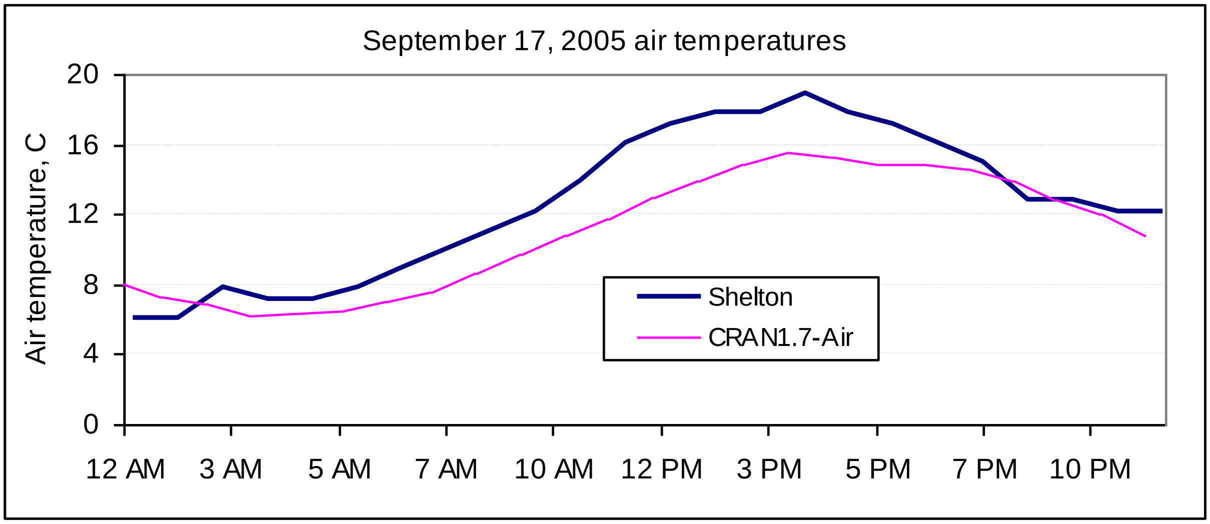


Figure 23. Difference between Shelton air and local stream air temperatures, September 17, 2005.

Figure 24 shows the temperature profile during the September lake turnover period. Lake outlet temperatures are reduced by approximately 4°C near the mouth of Cranberry Creek. Although a portion of the creek is below the water quality criterion of 16°C, the spawning criterion of 13°C was not met at any of the stream segments.

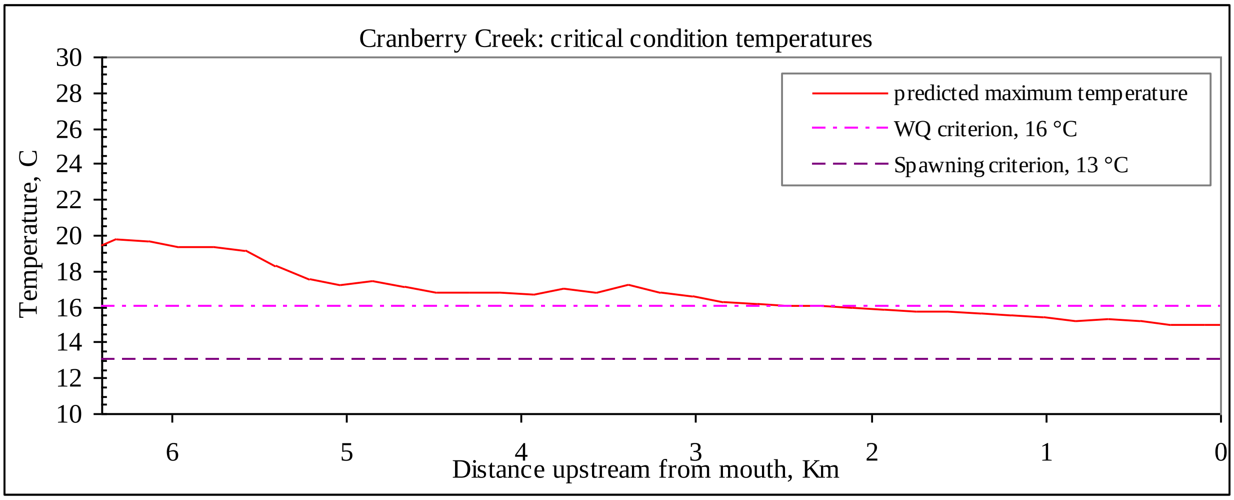


Figure 24. Stream temperatures under critical conditions in Cranberry Creek, September 17, 2005.

Upper Cranberry Creek

Stream temperatures in the upper segment of Cranberry Creek, between Cranberry Lake and Lake Limerick, are impacted by Cranberry Lake which is a natural lake without any outlet structure. Higher flows from Cranberry Lake would likely result in higher temperatures at station CRA4. This reach is very small, and due to lack of upstream data it was not modeled.

Johns Creek

For Johns Creek, the maximum 7-DADMax headwater temperature measured at the end of the wetlands was approximately 22°C recorded on July 31, 2005 at station JOH2.5 in Oak Park. Similar temperatures were measured in 2003 at station JOH3 at the Jensen Road culvert upstream of JOH2.5 and within the wetlands. The maximum temperature in Johns Creek is at the headwaters and is tied to temperatures within the wetlands. The lowest flow in Johns Creek occurs in September. In order to get a low-flow statistic for the critical month of July, a ratio of the lowest 7-day average flow in July and September in 2005 was used, along with the annual 7Q10 (3.3 cfs or 0.093 m^3/s) to estimate the July 7Q10 flow of 5.6 cfs (0.158 m^3/s).

Under critical conditions of flow and ambient air temperature (Figure 25), the numeric water quality criterion of 16°C was not met at any of the stream segments. The temperature reduction along Johns Creek due to existing riparian vegetation during critical flow and ambient air temperatures is almost negligible. The only significant cooling is due to discharge from the coldwater tributary.

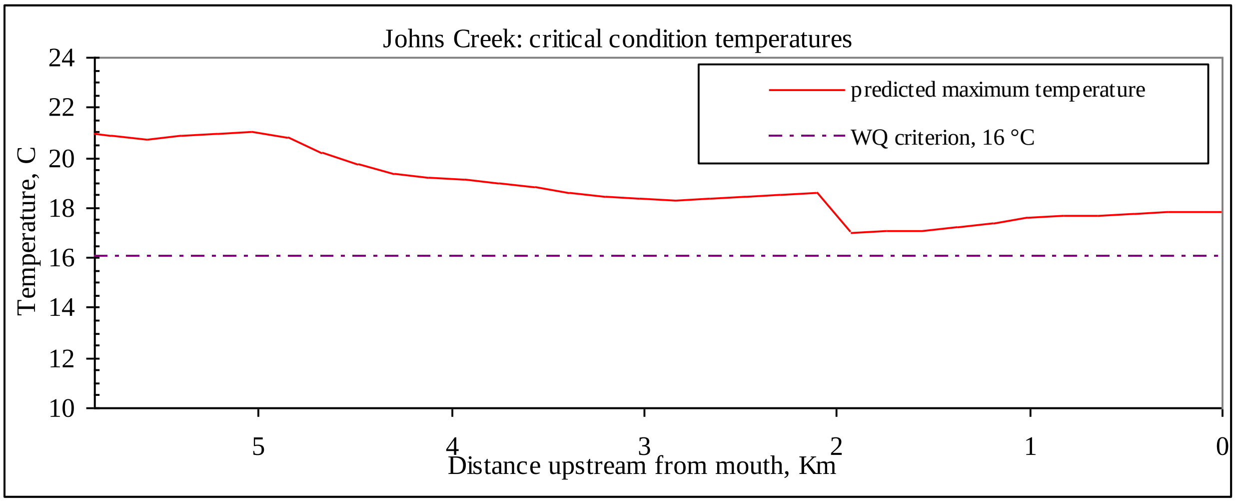


Figure 25. Stream temperatures under critical conditions in Johns Creek, July 31, 2005.

To simulate the summer chum spawning season, September 1 was used as the model day with highest headwater temperatures for September. The 90th percentile of 7-DADMax air temperatures for September 1 was 27.5°C as estimated from the 50-year data set obtained from the Olympia Airport following correlation with Shelton's Sanderson Field data (Ahmed and Hempleman, 2006). The 90th percentile was adjusted to account for local stream microclimate based on the relationship between air temperatures at Shelton's Sanderson Field and that at stations JOH1.1 and JOH2, for September 1 (Figure 26).

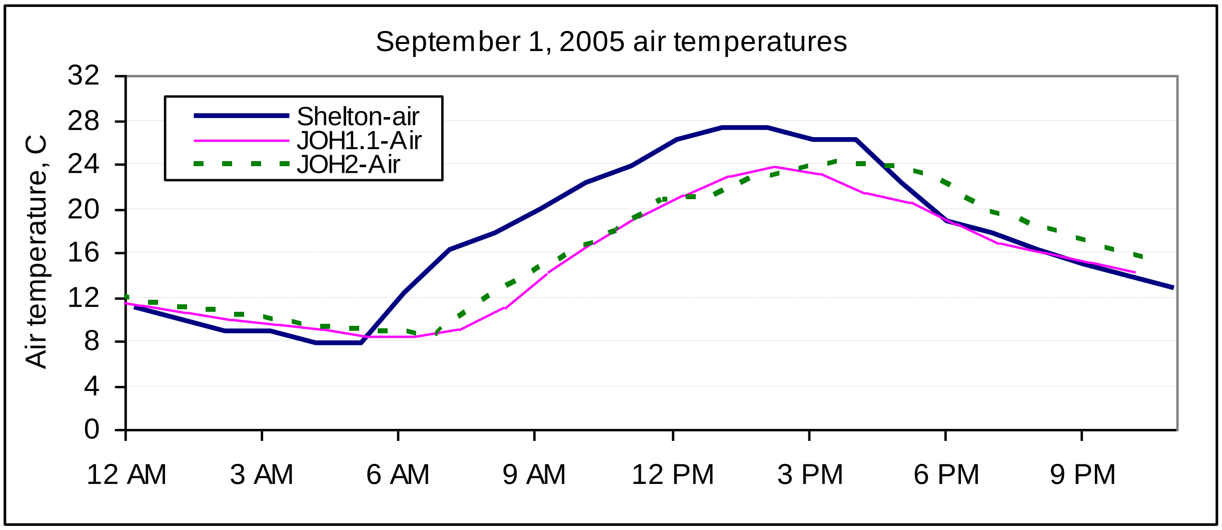


Figure 26. Difference between Shelton air and local stream air temperatures, September 1, 2005.

Figure 27 shows the temperature profile for critical conditions on September 1. A significant reduction in headwater temperature only occurs below the coldwater tributary, below which the temperature criterion of 16°C is met. However, the spawning criterion of 13°C was not met at any of the stream segments.

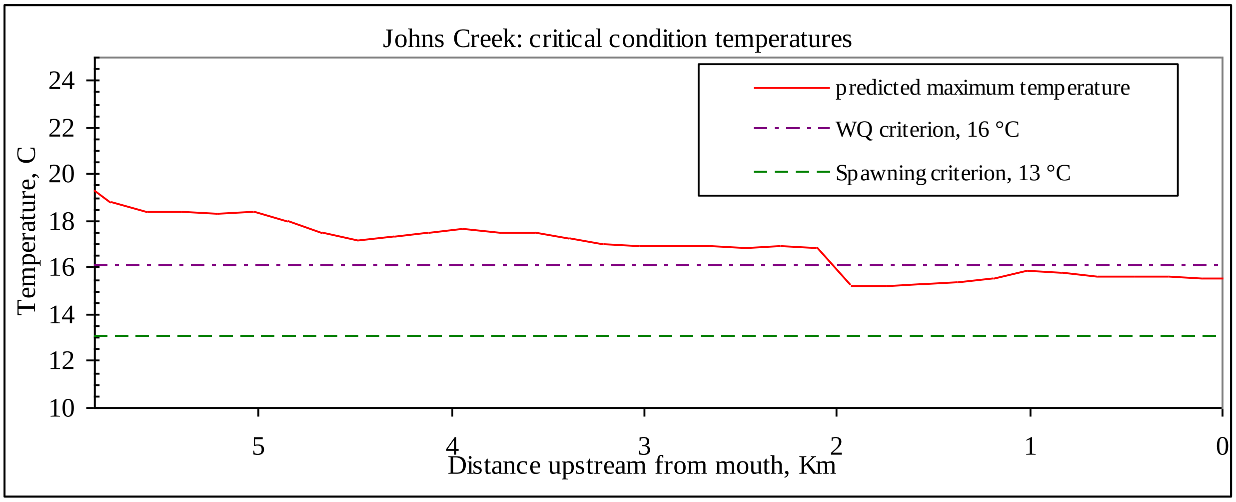


Figure 27. Stream temperatures under critical conditions in Johns Creek, September 1, 2005.

Mill Creek

For Mill Creek, the maximum 7-DADMax headwater temperature is approximately 24°C measured by the Squaxin Island Tribe at MIL3 in 2000 (July 30), 2001 (August 9) and 2003 (July 18 and August 9) (Ahmed and Sullivan, 2005). During the 2005 field study, a 7-DADMax temperature of 24°C was also measured at MIL3 on July 31. The maximum temperature is at the headwaters and is tied to temperatures in Lake Isabella. The lowest 7Q10 flow of 9 cfs (0.255 cms) occurs in September. In order to get a low-flow statistic for the critical month of July, a ratio of lowest 7-day average flow in July and September in 2005 was used along with the annual 7Q10 to estimate the July 7Q10 flow of 9.9 cfs (0.281 cms).

Figure 28 shows the temperature profile at the outlet of Lake Isabella during July-September 2005. The highest outlet temperatures are during the later part of July and early part of August. The outlet of Lake Isabella is fairly shallow (approximately 4 feet deep), with no stratification.

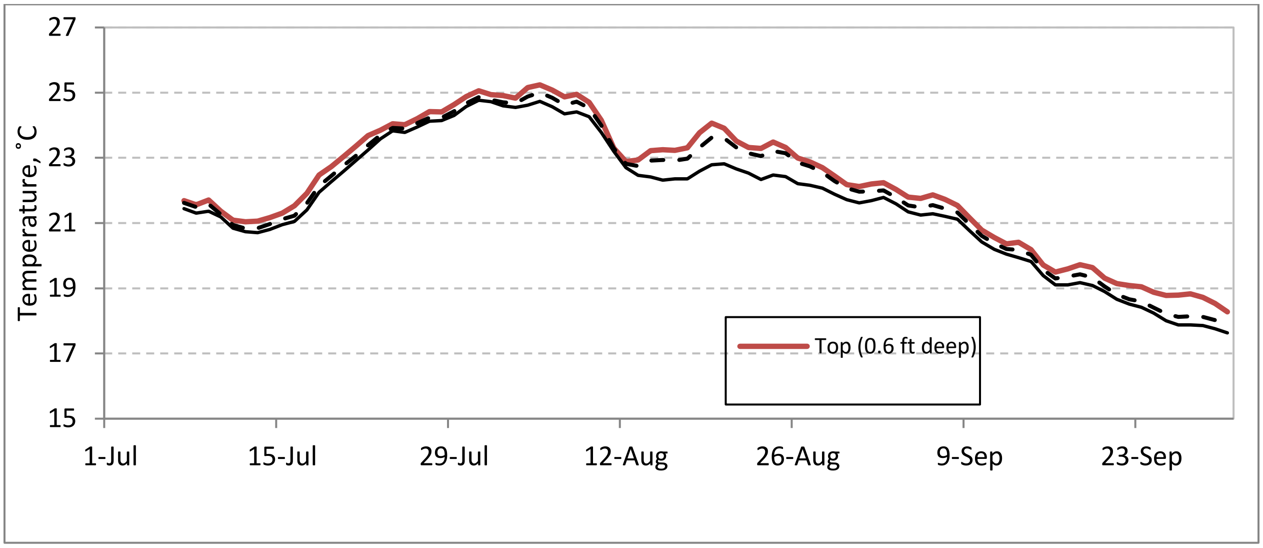


Figure 28. 7-DADMax temperatures at outlet of Lake Isabella.

As shown in Figure 29, under critical conditions of flow and ambient air temperatures, existing riparian vegetation, and high observed headwater temperatures, there is apparently no temperature change along Mill Creek towards Hammersley Inlet.

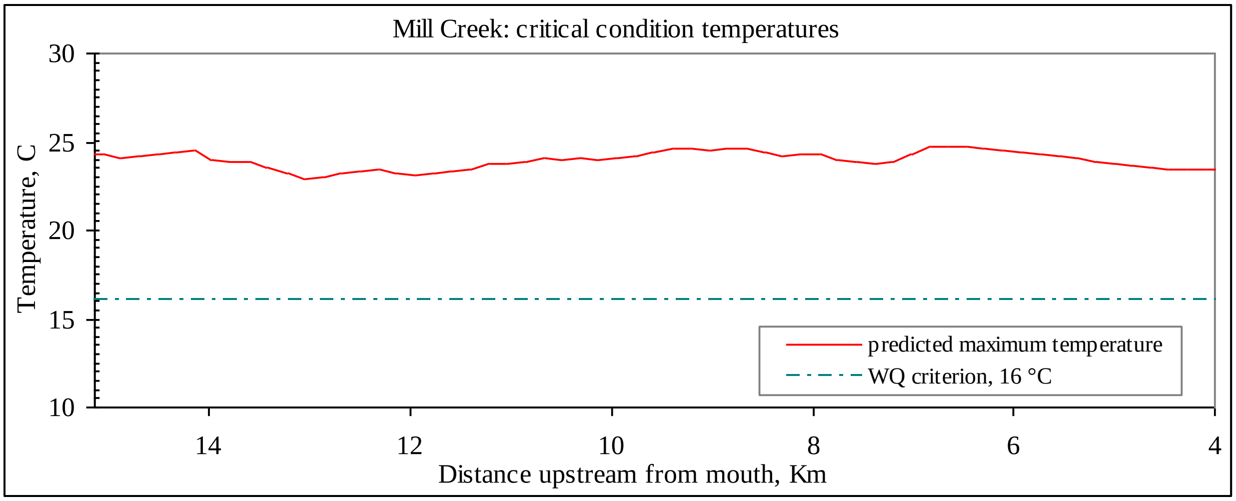


Figure 29. Stream temperatures under critical conditions in Mill Creek, July 31, 2005.

System-Potential Temperatures

In the previous section, a calibrated model was used to predict the maximum temperatures that the stream may attain under critical conditions of flow and ambient air temperatures. In this section, the calibrated model will be used to predict how cool the stream temperatures are likely to get under conditions of full mature riparian vegetation. Impact of other variables such as increased streamflow, reducing stream widths, and increasing groundwater and hyporheic flows will also be considered. System-potential temperatures are stream temperatures that are likely to be attained when these changes are made.

For system potential temperatures due to riparian vegetation, the existing tree species with maximum current tree height was used for each segment. However, for segments with shrubs and grasslands, new conifer trees were assumed. The density of trees was assumed at 85 percent, and the overhang was assumed to be equal to that currently existing for the largest respective tree species.

Site potential riparian vegetation and shade

The riparian vegetation potential was estimated based on expected maximum height of trees (50 years growth) and density. The Washington State Department of Natural Resources provides soil coverage data containing digitized soil delineations and soil attributes. One of the attributes in the soil coverage is site index data which contains information on the height of the dominant tallest trees in a stand. The age of the trees chosen is 50 years for Western Washington.

The soil coverage was used to produce a 150-foot riparian buffer zone along both sides of Cranberry, Johns, and Mill Creeks using ArcView GIS. Soil type within the buffer zone is estimated to produce a Douglas fir with a maximum height of 38.6 meters in 50 years. The maximum average height of trees estimated from field data was 30.5 meters. A tree height of 30 meters was used in estimating system-potential temperature to provide some factor of safety. The maximum potential density of trees along the stream corridor will vary depending primarily on the presence of roads and tributaries.

An 85 percent density was assumed as an estimate of riparian vegetation density potential. The ortho-photographs showed in excess of 95 percent tree density in some areas. In addition, a 1-m overhang for coniferous trees was assumed (the standard overhang for coniferous trees is 3 meters).

Effective shade calculations

The attributes of vegetation in the riparian zone on the right and left banks were sampled from GIS coverages of the riparian vegetation along the stream at 100 meter interval and laterally at 50 ft (15.2 m), 100 ft (30.5 m) to 150 ft (45.7 m) intervals using the Ttools extension foArcView developed by the Oregon Department of Environmental Quality (http://www.oregon.gov/deq/wq/tmdls/Pages/TMDLs-Tools.aspx). The vegetation attributes were codified and entered into the Shade Model (Ecology, 2003). The Shade Model is based on the shade calculation method of Chen (1996).

Other spatial data estimated with Ttools at each transect location included stream aspect (streamflow direction in decimal degrees from north), elevation (sampled from 10-meter digital elevation maps), and topographic shade angles to the west, south, and east. These were also input into the Shade Model.

Effective shade was estimated at 183-meter (600 ft) intervals along the streams for input to the QUAL2Kw model. The Shade Model estimates stream segment shade levels as aerial percent shade, with 100 percent meaning that the whole stream segment is shaded.

Lower Cranberry Creek

Full riparian vegetation will result in an additional 3.3°C reduction in maximum stream temperatures near the mouth of Cranberry Creek, compared to existing vegetation, as shown in Figure 30. The water quality criterion of 16°C will not be met at any segment of the creek.

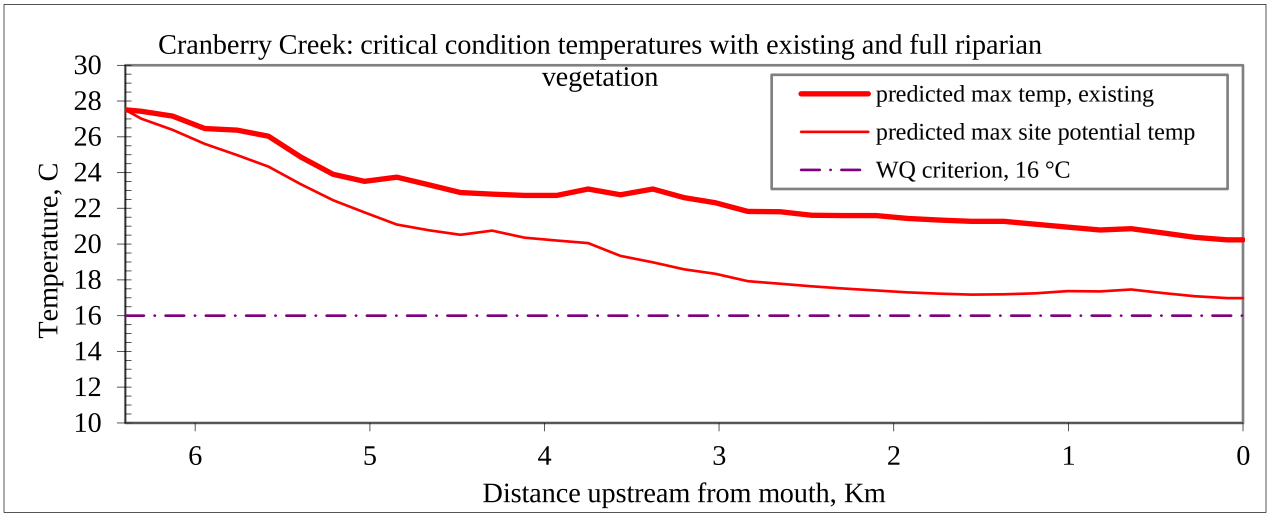


Figure 30. System-potential temperature under critical conditions for Cranberry Creek, July 31, 2005.

Full riparian vegetation will also result in reduction of temperatures during the chum spawning season in September. Figure 31 shows that the predicted downstream maximum stream temperatures would be reduced by as much as 2°C with full riparian vegetation compared to existing vegetation conditions. The spawning criterion of 13°C is met within a one-kilometer stretch at the mouth of the creek. Elevated headwater temperatures observed during the summer chum spawning season are a result of an early fall turnover of Lake Limerick (see Figure 21.)

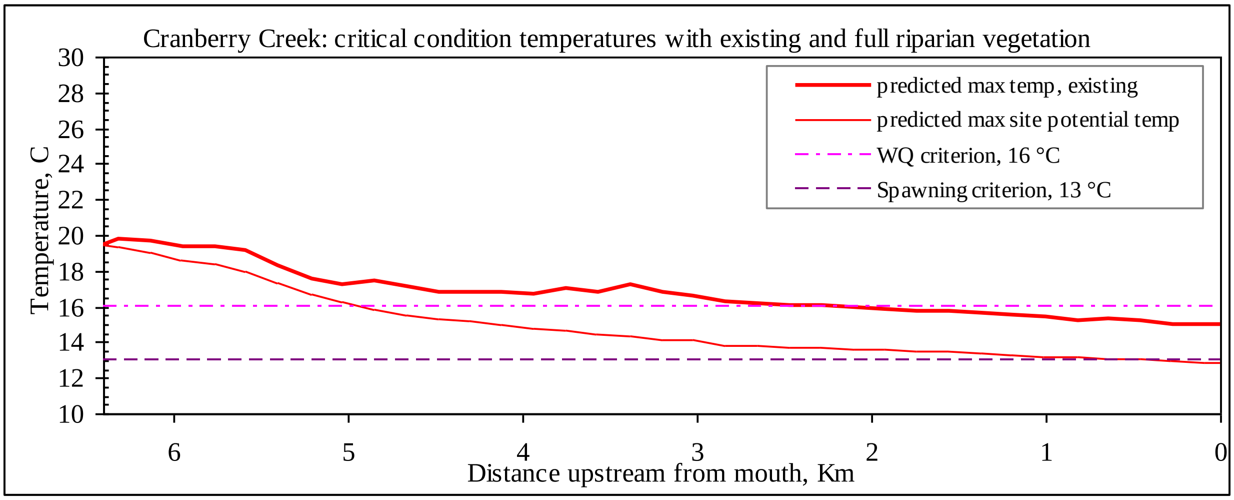


Figure 31. System-potential temperature under critical conditions for Cranberry Creek, September 17, 2005.

Lake Limerick is a manmade lake established by the impoundment of Cranberry Creek in 1966. It is not possible at this time to evaluate the impact of this manmade lake on stream temperatures due to lack of information on whether this was a wetland with no defined stream channel or a defined stream channel. What impact there would be on stream temperatures, if Lake Limerick did not exist, can only be hypothesized and cannot be fully investigated due to lack of historical data.

Out of 12 factors affecting stream temperature, stream width was the sixth most important variable following air temperatures, relative humidity, percent shade, streamflow, and headwater temperature (Bartholow, 1989). Although reducing widths should intuitively lower temperatures, this is only true for streams where headwater temperatures are cooler and the stream gains in temperature downstream. In the case of Cranberry Creek, headwater temperatures are high and net cooling occurs downstream due to shading, groundwater input, hyporheic flow, wind, cloud cover, and evaporation.

The groundwater temperatures are also high, between 14 to 16°C (see Figure 14) during late July and early August, relative to the mean annual air temperature of 11°C measured at the Sanderson Field weather station in Shelton (Ahmed and Hempleman 2006). Incidentally, the temperatures in the bottom layers of Lake Limerick were also in excess of 14°C during this period. There is apparently some warming of local groundwater due to the current configuration of the headwater lakes.

Site potential temperatures are intricately linked to groundwater temperatures beyond any cooling that may be achieved through improved riparian vegetation. Any increase in groundwater inflow or hyporheic enhancements will have little impact, if any, when improved shading would reduce the stream temperatures to near groundwater temperatures.

Upper Cranberry Creek

There is no outlet structure at Cranberry Lake, except for two culverts that drain the lake into Cranberry Creek. Some improvement of stream temperatures, however, may be achieved through improvement of riparian vegetation. The effective length of this reach above CRA4 and below the culverts near Cranberry Lake is approximately 0.3 miles. To what degree the increased vegetation would impact stream temperature would depend on the temperature of water from the lake. However, full riparian vegetation would allow temperatures to be closer to natural conditions. To estimate how much additional shade could be provided, the shade model was run for both existing and system-potential vegetation conditions.

Johns Creek

Full riparian vegetation will result in an additional 3.6°C reduction in maximum stream temperatures near the mouth of Johns Creek, compared to existing vegetation, as shown in Figure 32. In excess of a 3-kilometer stream segment at the mouth is in compliance with the temperature criterion of 16°C under full riparian vegetation conditions.

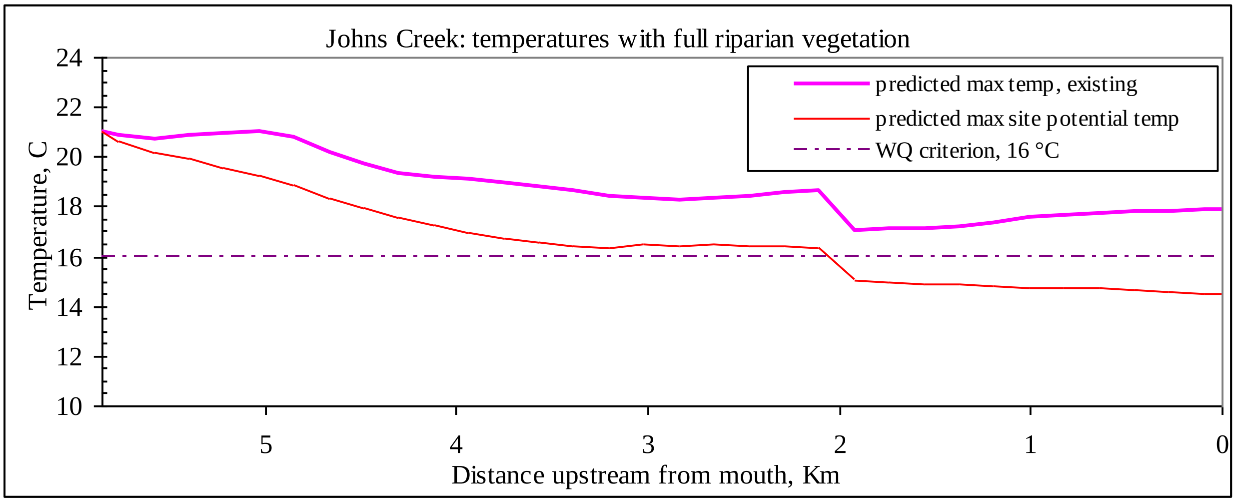


Figure 32. System-potential temperatures for Johns Creek, July 31, 2005.

Full riparian vegetation will also result in reduction of temperatures during the chum spawning season in September. Figure 33 shows that the predicted downstream maximum stream temperatures are reduced by as much as 3.8°C with full riparian vegetation compared to existing vegetation conditions. The spawning criterion of 13°C is met within a 2-kilometer stretch at the mouth of the creek.

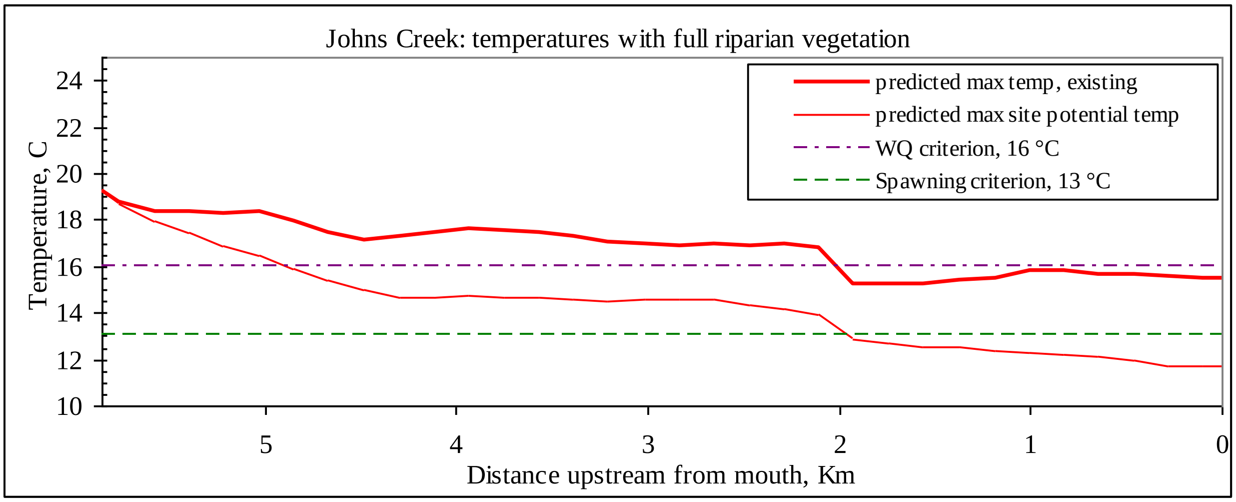


Figure 33. System-potential temperatures for Johns Creek, September 1, 2005.

As shown in the previous model runs, the coldwater tributary plays an important role in reducing the stream temperatures in the lower portion of Johns Creek. The coldwater tributary is fed by groundwater. In order to assess the impact of the coldwater tributary on downstream temperatures, the flow in the tributary was varied as shown in Figure 34. Increased flow does improve the downstream temperatures, although not as significantly within the flow ranges evaluated. However, some control of groundwater withdrawals in this area may be helpful in maintaining or enhancing the flow in the coldwater tributary.

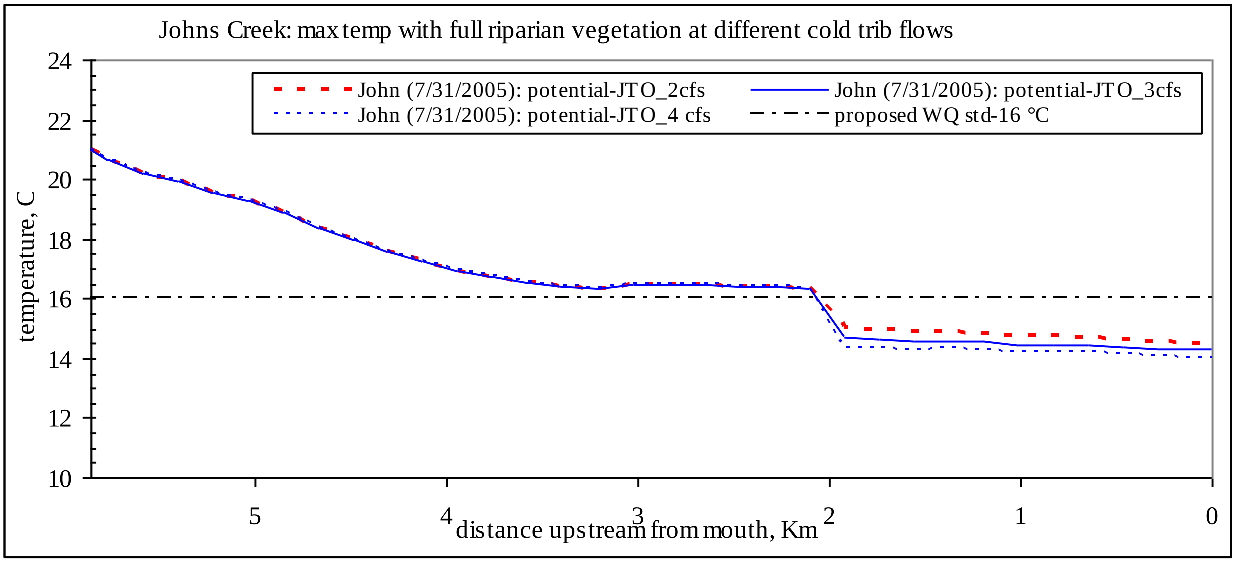


Figure 34. System-potential temperatures for Johns Creek with increased flows in the Cold Creek tributary, July 31, 2005.

While we generally assume that the extensive exposure of wetland surfaces to solar radiation will increase stream water temperatures downstream, the thermal infrared (TIR) data for Johns Creek indicates significant cooling can also occur within a wetland system. Figure 9 demonstrates that the Johns Creek wetland system does not fit a linear model of downstream temperature increases. It includes both areas of cooling (up to 5°C) and warming in an overall pattern of variability. The overall result is a modest increase in temperature. The extent to which such patterns of variability have been lost over time is unknown.

A large wetland exists at the headwaters of Johns Creek. As a result, the warmest temperatures are at the headwaters. Cooling occurs downstream from shade, evaporation, groundwater input, hyporheic flow, etc. Under critical July 7Q10 flow conditions and full riparian vegetation, the temperatures in excess of 16°C cannot be avoided above river mile 2.3 (3.7 Km). Temperatures below 16°C can be achieved only below the coldwater tributary. Full riparian vegetation is needed to achieve system-potential temperatures. During the chum spawning season (beginning September 1), the 13°C criterion is only met below the coldwater tributary (river mile 1.37 (~2 Km)) with full riparian vegetation. Increased flow in the coldwater tributary tends to lower the downstream temperatures.

Mill Creek

Full riparian vegetation will result in an additional 5.4°C reduction in maximum stream temperatures near the mouth of the creek, compared to existing vegetation, as shown in Figure 35. However, even with full riparian vegetation, stream temperatures are above 16°C for the length of the stream.

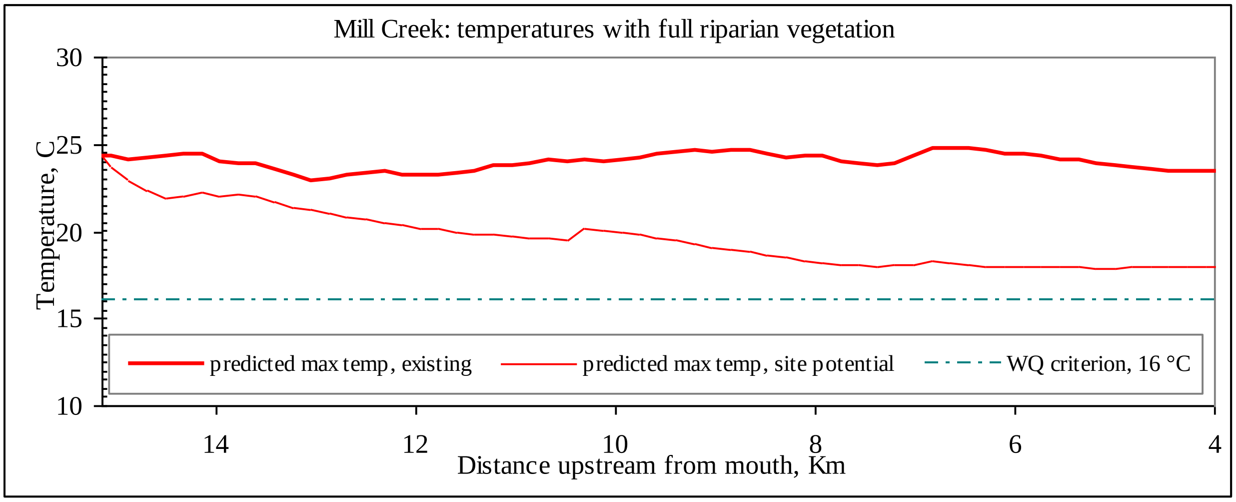


Figure 35. System-potential temperatures for Mill Creek, July 31, 2005.

Figure 36 shows that the lake temperatures are reduced by approximately 0.7°C in the channel between Lake Isabella and Storybrook bridge. This is an approximately 2-kilometer-long channel and is relatively wider than Mill Creek below Storybrook bridge (station MIL3, Figure 4). Cooling of this channel is limited due to its large surface area. However, improved riparian vegetation may help reduce the temperatures somewhat. Heat loads were not evaluated for this reach.

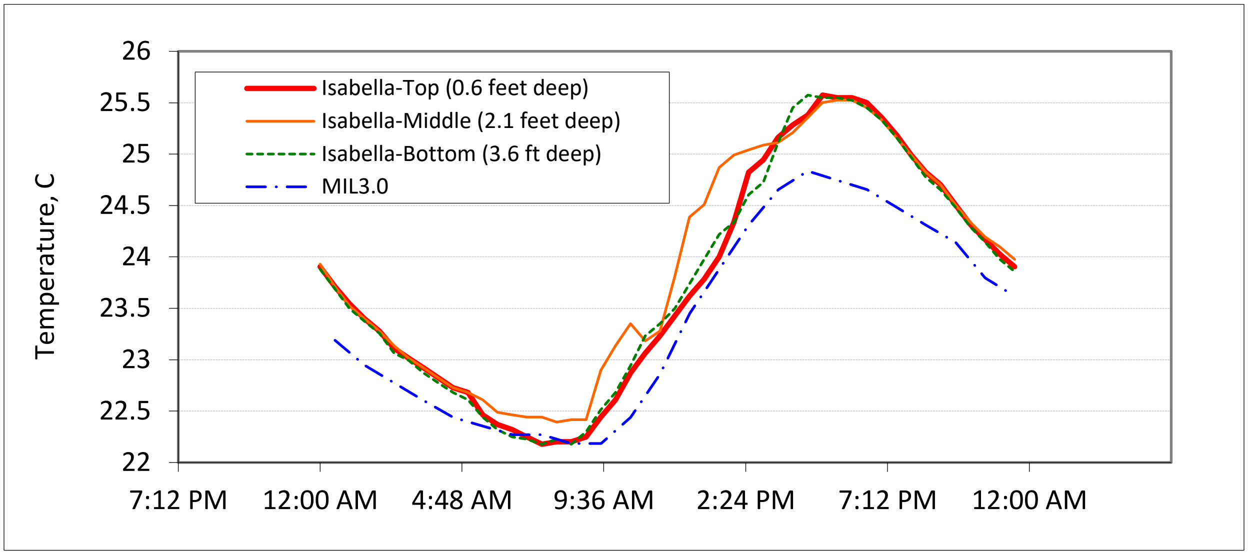


Figure 36. Lake Isabella and Mill Creek station MIL3 critical temperatures.

High instream temperatures are a direct result of warm water from Lake Isabella. With full riparian vegetation, the criterion of 16°C cannot be met at any segment of the stream studied. There is almost no stratification in Lake Isabella near the outlet. Lake Isabella is also a natural lake although there has been significant shoreline development. Predicted temperatures assuming full riparian vegetation may be the best that can be achieved under current conditions. Improving vegetation along the wide channel reach between Lake Isabella and Storybrook bridge may help reduce headwater temperatures. The system-potential temperatures cannot meet the water quality criteria of 16°C.

System-Potential Shade Values

System-potential shade values are the shade values necessary within each segment to minimize stream temperature to the maximum extent possible under critical conditions. Tables 8 and 9 show the shade-capacities for lower and upper Cranberry Creek. Tables 10 and 11 contain the shade capacities for Johns and Mill Creeks, respectively The deficit vegetation is the difference between site-potential and existing vegetation.

These system-potential shade values will achieve the water quality criterion of 13°C during the summer spawning season at the following creeks:

- In Cranberry Creek, after September 15 , below Km 0.5 (river mile 0.3) to the mouth
- In Johns Creek, after September 1, below coldwater tributary (~Km 2, river mile 1.3) to the mouth.

The remainder of the stream segments, where water quality criteria were not met with full riparian vegetation, were considered to achieve site potential conditions under existing headwater lake management and wetland conditions. No comparison of current headwater lake and wetland management with natural background conditions was attempted.

In all three creeks, the upstream sources (lake and wetlands) are a primary cause of high temperatures in the streams under current headwater lake management and wetland conditions. But reductions in groundwater influx may also have at least a minor effect, especially in lower Johns Creek. In addition, the longitudinal temperature profile of Johns Creek suggests that significant cooling of downstream wetland water is possible.

Table 8. System potential value for effective shade for lower Cranberry Creek.

Stations and landmarks	Upstream Km	Downstream Km	Average target effective shade (%)	
			potential	deficit
CRA3 (Km 6.46), below Lake Limerick	6.40	6.22	89%	22%
	6.22	6.04	92%	9%
	6.04	5.85	95%	9%
CRA2.5 (Km 5.61), Olde Tyme Road	5.85	5.67	95%	16%
	5.67	5.49	88%	12%
	5.49	5.30	94%	13%
	5.30	5.12	93%	11%
CRA2 (Km 4.94)	5.12	4.94	96%	15%
	4.94	4.75	92%	33%
	4.75	4.57	90%	14%
	4.57	4.39	80%	6%
	4.39	4.21	86%	15%
	4.21	4.02	87%	23%
CRA1.7 (Km 3.72)	4.02	3.84	89%	19%
	3.84	3.66	91%	23%
	3.66	3.47	95%	23%
	3.47	3.29	95%	27%
	3.29	3.11	96%	15%
	3.11	2.93	96%	11%
	2.93	2.74	95%	22%
	2.74	2.56	95%	29%
	2.56	2.38	93%	20%
	2.38	2.19	93%	26%
	2.19	2.01	93%	28%
	2.01	1.83	91%	13%
CRA1.4 (Km 1.52)	1.83	1.65	86%	18%
	1.65	1.46	89%	10%
	1.46	1.28	92%	13%
	1.28	1.10	89%	9%
	1.10	0.91	90%	18%
	0.91	0.73	90%	17%
CRA1 (Km 0.43)	0.73	0.55	93%	17%
	0.55	0.37	89%	7%
	0.37	0.18	92%	9%
	0.18	0.00	93%	16%

Table 9. System-potential shade values for effective shade for upper Cranberry Creek.

Station and landmark	Upstream Km	Downstream Km	Average target effective shade (%)
Below culvert, below Cranberry Lake	0	61	16%
	61	122	16%
	122	183	15%
	183	244	16%
	244	305	14%
	305	366	15%
CRA4, above culvert, above Lake Limerick	366	427	18%

Table 10. System-potential shade values for effective shade for Johns Creek.

Stations and landmarks	Upstream Km	Downstream Km	Average target effective shade (%)	
			potential	deficit
JOH2.5 (Km 6.1), end of Oak Park	6.04	5.85	94%	16%
	5.85	5.67	94%	18%
	5.67	5.49	94%	48%
	5.49	5.31	93%	52%
	5.31	5.12	93%	48%
JOH2 (Km 4.94), Johns Creek Drive	5.12	4.94	97%	30%
	4.94	4.76	92%	18%
	4.76	4.57	94%	15%
	4.57	4.39	92%	27%
	4.39	4.21	92%	37%
	4.21	4.03	92%	34%
	4.03	3.84	92%	27%
	3.84	3.66	93%	8%
	3.66	3.48	94%	9%
	3.48	3.29	96%	6%
	3.29	3.11	86%	7%
JOH1.7 (Km 3.05), railroad tracks	3.11	2.93	91%	15%
	2.93	2.75	94%	16%
	2.75	2.56	95%	23%
	2.56	2.38	94%	25%
JOH1.4 (2.19), upstream of coldwater tributary	2.38	2.20	95%	29%
JOH1.3 (2.13), downstream of coldwater tributary	2.20	2.01	95%	34%
JOH1.1 (Km 1.22), at hatchery	2.01	1.83	93%	26%
	1.83	1.65	90%	17%
	1.65	1.47	92%	21%
	1.47	1.28	94%	27%
	1.28	1.10	93%	39%
JOH1 (Km 0.49), Highway 3 bridge	1.10	0.92	95%	26%
	0.92	0.73	95%	19%
	0.73	0.55	95%	24%
	0.55	0.37	94%	21%
	0.37	0.18	94%	15%

Table 11. System-potential shade values for effective shade for Mill Creek.

Stations and Landmarks	Upstream Km	Downstream Km	Average target effective	
			potential	deficit
Mill3 (Km 15.45), Storybrook Road	15.54	15.36	92%	26%
	15.36	15.18	94%	21%
	15.18	15	92%	14%
	15	14.81	95%	27%
	14.81	14.63	74%	20%
	14.63	14.45	70%	16%
	14.45	14.26	79%	12%
	14.26	14.08	74%	11%
	14.08	13.9	84%	25%
	13.9	13.72	92%	13%
Mill2 (Km 13.43), diner off Highway 3	13.72	13.53	89%	8%
	13.53	13.35	92%	23%
	13.35	13.17	90%	23%
	13.17	12.98	91%	30%
	12.98	12.8	89%	22%
	12.8	12.62	91%	15%
	12.62	12.44	90%	16%
	12.44	12.25	91%	14%
	12.25	12.07	88%	32%
	12.07	11.89	90%	32%
	11.89	11.7	89%	35%
	11.7	11.52	88%	29%
Mill1.75 (Km 11.21), Arcadia Electric	11.52	11.34	90%	28%
	11.34	11.16	92%	31%
	11.16	10.97	87%	25%
	10.97	10.79	94%	23%
	10.79	10.61	47%	3%
	10.61	10.42	78%	21%
	10.42	10.24	94%	44%
	10.24	10.06	87%	39%
	10.06	9.88	88%	40%
	9.88	9.69	93%	41%
	9.69	9.51	93%	36%
	9.51	9.33	94%	21%
	9.33	9.14	87%	30%
	9.14	8.96	81%	28%
	8.96	8.78	94%	30%
	8.78	8.6	94%	18%
	8.6	8.41	94%	42%
	8.41	8.23	93%	26%
	8.23	8.05	94%	15%
	8.05	7.86	94%	18%
	7.86	7.68	95%	13%
	7.68	7.5	93%	24%
MIL1.5 (Km 7.19), road off of Binswager Loop Road	7.5	7.32	93%	27%
	7.32	7.13	92%	33%
	7.13	6.95	90%	31%
	6.95	6.77	92%	37%
	6.77	6.58	93%	36%
	6.58	6.4	91%	28%
	6.4	6.22	90%	27%
	6.22	6.04	74%	20%
	6.04	5.85	89%	22%
	5.85	5.67	86%	27%
	5.67	5.49	89%	16%
	5.49	5.3	86%	17%
	5.3	5.12	87%	22%
	5.12	4.94	89%	27%
	4.94	4.75	86%	17%
MIL1 (Km 4.45), dirt road off Fireweed	4.75	4.57	89%	30%
	4.57	4.39	87%	32%

Conclusions

In all three creeks, the upstream sources (lake and wetlands) are a primary cause of high temperatures in the streams under current headwater lake management and wetland conditions. But reductions in groundwater influx may also have at least a minor effect, especially in lower Johns Creek.

The relationship between effective shade and mature vegetation is dependent upon the establishment of a sustainable plant community. The system-potential shade values for effective shade under this temperature study are:

- For Cranberry Creek, the system-potential shade values ranges from 6 percent to 33 percent additional effective shade produced by a mature riparian corridor and the existing topography.
- For Johns Creek, the system-potential shade values is 6 percent to 52 percent additional effective shade.
- For Mill Creek, the system-potential shade values is 3 percent to 44 percent additional effective shade.

System-potential shade values will achieve the Washington State water quality criterion of 16°C in the following reaches:

- In Cranberry Creek, no segments meets this criterion during the critical month of July, but this criterion is met below Km 5 (river mile 3) beginning September 1 during the commencement of summer, the chum spawning season.
- In Johns Creek, these criteria are met from the coldwater tributary (~ Km 2, river mile 1.3) to the mouth during July and from Km 5 (river mile 3.1) to the mouth in September.
- In Mill Creek, no segments meet this criterion in the critical month of July.

Even with best management scenarios in the downstream reaches, the stream temperatures cannot be cooled to below water quality standards unless the anthropogenic heat loads from the upstream sources are controlled.

Increased stream temperature resulting from anthropogenic activities can be slowed and or prevented by reversing the process over time. The reversal can be accomplished by increasing riparian shade through improved riparian vegetation, preventing or minimizing impacts of land-use activities on stream hydrology/morphology and by using selective withdrawal of lake water at depth using an outlet structure.

The relatively small size of Cranberry, Johns, and Mill Creeks, and the high rates of groundwater influx, produce very important and highly unique thermal refugia upstream of their mouths for summer chum and overwintering coho species. Protection of these thermal refugia is a key strategy to sustain the life history strategies of these species.

The relatively long period of time needed to establish mature vegetation throughout Cranberry, Johns, and Mill Creek and their tributaries will require interim monitoring to determine the progress being made.

Recommendations

1. Establish a healthy and sustainable riparian corridor along all three creeks. Plant and maintain a riparian buffer with trees of the recommended tree heights in order to achieve the decrease in stream temperatures. Sustainable buffers allow for recruitment and succession and a mixed and heterogeneous plant community that provides for a healthy riparian corridor and habitat values. Buffers should be sufficient to accommodate wind throw and should adjoin wetlands to assure functions of the hyporheic zone, including the groundwater and nutrient relationships important to sustain desired streamside plant communities. Buffer widths should be sufficient to account for stream channel migration, as the three streams in this study will continue to physically move within the respective floodplains. Buffers should be based upon existing regulatory requirements.
2. Specifically, improving vegetation along the wide channel reach between Lake Isabella and Storybrook bridge may help reduce headwater temperatures.
3. Replant riparian areas along each of the streams should consider native vegetation, including but not limited to Douglas fir; western red cedar; western hemlock; dogwood; red alder; black cottonwood; vine maple; salal; Oregon grape; wild cherry; and fern. Individuals should consult with staff from the Mason County/Washington State University Cooperative Extension, Mason Conservation District, Washington State Department of Natural Resources, or other local professionals already engaged in riparian restoration for recommendations on the appropriate species to plant.
4. Interim monitoring is recommended. Continuous-recording temperature devices should be used and measurements made between July 1 and September 15 to capture critical conditions. Interim monitoring should also document physical changes in Cranberry, Johns, and Mill Creeks. As streamside areas are revegetated and riparian canopy is reestablished, documentation of these improvements becomes important for the effective shade assessment.
5. Studies should be undertaken to evaluate how the upstream sources may be managed to minimize the heat load to the streams.
6. Education, outreach, technical and financial assistance, and enforcement should be considered to ensure that temperature goals are met.
7. Implementation activities should be tracked, monitored and maintained to assess effectiveness.
8. If temperatures continue to exceed water quality standards into the future, Ecology will conduct a TMDL.
9. Monitoring should continue after temperature standards are met to ensure implementation measures continue to be effective, especially with the continued impacts of climate change (Appendix G).

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Appendices

Appendix A. Water Quality Standards and Numeric Targets

In the Washington State water quality standards, aquatic life use categories are described using key species (salmon, redband trout, and indigeneous warm water species) and life-stage conditions (ex. spawning, rearing) [WAC 173-201A-200]. The aquatic life use designation for Cranberry, Johns, and Mill Creeks and their tributaries is core summer habitat (16°C) (spawning, emergence, rearing, and migration) (Ecology, 2017). The applicable temperature criteria for the designated use are summarized below: (refer to 173-201A-200(c), Ecology 2017, for all specific criteria).

- Temperature shall not exceed a 7-DADMax temperature of 16°C (60.8°F) for core summer salmonid habitat.
- If the temperature of the water body is warmer than 16°C, or with in 0.3°C of this criteria, and the condition is due to natural conditions, then human actions (considered cumulatively) may not cause the 7-DADMax temperature to increase more than 0.3°C (0.54 °F).
- If the background condition is below the 16°C 7-DADMax temperature, the allowable rate of warming up to, but not exceeding, the numeric criteria from human actions is restricted as follows:
    - Incremental temperature increases resulting from the combined effect of all nonpoint source activities in the waterbody must not, at any time, exceed 2.8 °C (5.04 °F).
    - Point sources shall not increase background temperature by more than 28/(T+7) or bring the stream temperature above the standards established above.
- There are special spawning and incubation protections in Cranberry and Johns Creeks. Temperature shall not exceed a 7-DADMax temperature of 13°C (55.4°F) for salmon and trout spawning. The supplemental criteria for Spawning/Incubation period for Cranberry Creek is September 15 through May 15. The supplemental criteria for Johns Creek Spawning/Incubation period is from September 1 through May 15. Mill Creek does not have any supplemental spawning and incubation criteria.
- Temperatures are not to exceed the criteria at a probability frequency of more than once every ten years on average.
- To protect the stated use of the waterbody, the following temperatures must be maintained to prevent acute lethality and barriers to migration of salmonids:
    - Moderately acclimated (16 - 20 °C, or 60.8 – 68 °F) adult and juvenile salmonids will generally be protected from acute lethality by discrete human actions maintaining the 7-DADMax temperature at or below 22°C (71.6°F) and the 1-day maximum (1-DMax) temperature at or below 23°C (73.4°F).
    - Lethality to developing fish embryos can be expected to occur at a 1-DMax temperature greater than 17.5°C (63.5°F).

  - Barriers to adult salmonid migration are assumed to exist any time the 1-DMax temperature is greater than 22°C (71.6°F) and the adjacent downstream water temperatures are 3°C (5.4°F) or more cooler.
  - Prevent near instantaneous lethality from thermal plumes: prevent fish from being entrained for more than 2 seconds at temperatures above 33°C (91.4°F).

Appendix B. Physical and biological considerations

Since this temperature study is aimed at reducing stream temperatures, it is prudent to discuss briefly the factors that cool streams during summer periods. Figure A-1 shows the factors that influence cooling and the various actions that may facilitate cooling (Konovsky, 2008).

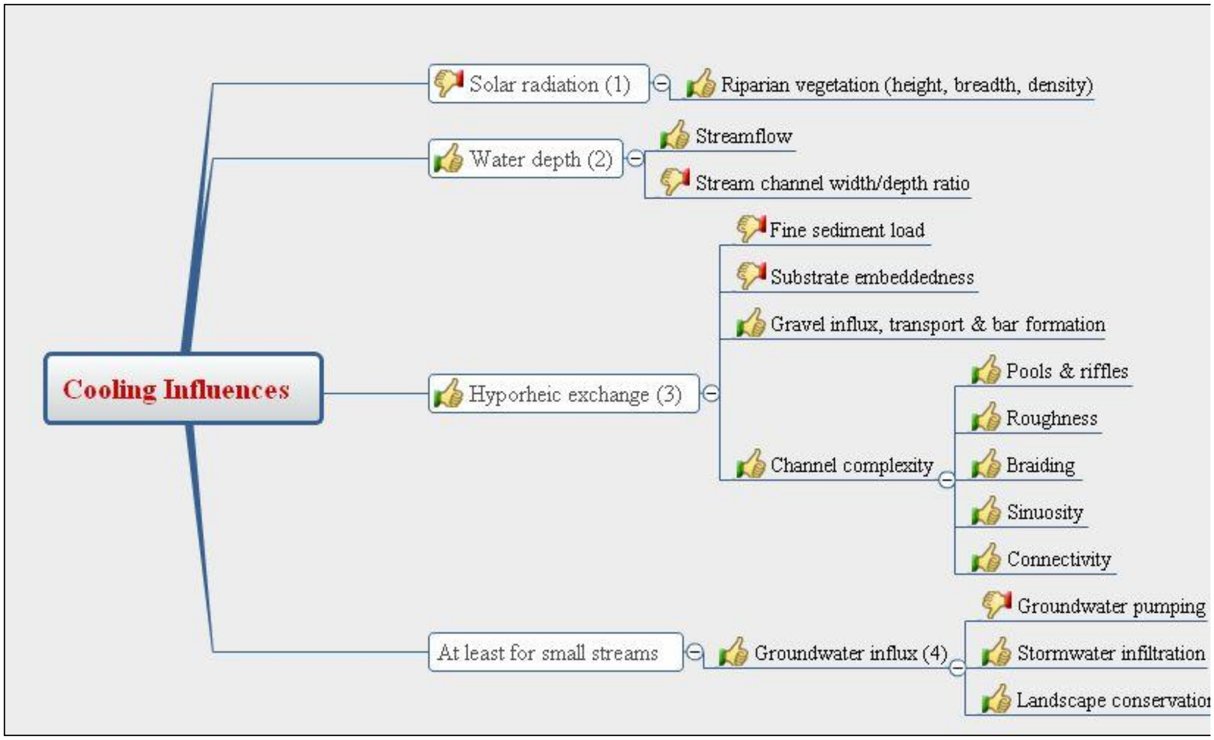

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Figure A-1. **Cooling influences on summer stream temperatures.**

Riparian shade is generally considered to play a key role in reducing stream temperatures because of its role in limiting solar radiation. Stream cooling is improved through habitat restoration activities. However, a number of other activities as shown in Figure A-1, play an important role. Increased streamflow and groundwater inflow, along with increased channel complexity (e.g., pools and riffles, sinuosity) would increase stream cooling. On the other hand, increased width-to-depth ratio, increased fine sediment load, and increased groundwater pumping would tend to reduce cooling.

General processes that elevate water temperatures include: increased solar radiation due to reduced riparian vegetation; widening of channels caused by disruption of geomorphic processes; reduction in groundwater exchanges and low baseflows; presence of altered lakes and wetlands at headwaters; and point sources.

The relationship between effective shade and mature vegetation is dependent upon the establishment of a sustainable plant community, such that the recommended tree heights can be achieved and maintained. Sustainable buffers allow for recruitment and succession and a mixed plant community that provides for a healthy riparian corridor and habitat values. Buffers should be sufficient to accommodate wind throw and should adjoin wetlands to assure functions of the hyporheic zone, including the groundwater and nutrient relationships important to sustain desired streamside plant communities. Buffer widths should be sufficient to account for stream channel migration, as the three streams in this TMDL will continue to physically move within the respective floodplains.

Streambank erosion and liberated sediment can also have an influence on temperatures in the three streams. Dislodged soils can be carried downstream and contribute to stream bed load. Soil particles can also fill interstitial spaces in the hyporheic zone, disrupting water/groundwater movement. By itself, loss of hyporheic exchange can lead to increased stream heating as cooler groundwater inflow becomes reduced.

Soil properties, including soil texture, organic matter content, aspect, moisture content, and structure all affect tree growth and management requirements. Vascular plant species vary by soil type and location. Replanting of riparian areas along each of the streams should consider native vegetation, including but not limited to Douglas fir; western red cedar; western hemlock; dogwood; red alder; black cottonwood; vine maple; salal; Oregon grape; wild cherry; and fern. Individuals should consult with staff from the Mason County/Washington State University Cooperative Extension, Mason Conservation District, Washington State Department of Natural Resources, or other local professionals already engaged in riparian restoration for recommendations on the appropriate species to plant.

Riparian vegetation

Reduction in riparian vegetation (e.g., due to forest and/or agricultural practices) decreases shade and increases the incident shortwave radiation to the stream resulting in increased stream temperatures. This study uses riparian shade as a surrogate measure of solar heat flux to waterbodies. Increases in riparian shade reduce the solar heat flux to the stream. *Effective shade* is defined as the fraction of the potential solar shortwave radiation that is blocked by vegetation and topography before it reaches the stream surface. Since topography is more or less permanent, it will be an increase in riparian shade that will be needed to reduce temperature.

Streamflow

As the amount of water in the stream decreases, the volume of water capable of absorbing the heat decreases, resulting in a rise in stream temperatures. Thus, daytime stream temperatures are higher in shallow water than in deeper water. Shallow waters may be caused either by disruption of stream hydrology (resulting in low flows) or disruption of geomorphic processes (resulting in widening of the stream channel). In stream segments where riparian vegetation density approaches pre-settlement levels, segment width, depth, and length become important in establishing the extent of shading in the stream. Widening and simplifying stream structures into runs and glides, rather than pools and riffles, would result in warmer temperatures.

The capacity for temperature reduction in a stream also decreases if either the volume of groundwater inflow to the stream or the volume of mixed surface/groundwater that re-circulates through the gravel bed is reduced. Reduced groundwater inflow also reduces stream baseflows resulting in shallower streams.

Lakes and wetlands

Stream temperatures may also be high due to the presence of lakes and wetlands at headwaters. These lakes and wetlands provide a large surface area exposed to sunlight. The water column stratifies with warmer water on the top and cooler water at the bottom. A stream fed by water near the surface would be much warmer compared to that fed by deeper water. Cranberry, Johns, and Mill Creeks have lakes or large wetlands at their headwaters and therefore also have relatively high headwater temperatures. Lake Isabella is a natural lake at the headwaters of Mill Creek.

Longitudinal temperature profiles of these creeks show that temperatures drop significantly in all three creeks in the downstream direction. The drop in temperatures along these creeks is presumed to be a result of cooler groundwater inflow together with heat exchange between warmer water and cooler soil (streambed) and/or cooler air (resulting from shade from riparian vegetation). However, the natural conditions pertaining to the cooling processes – and the natural conditions pertaining to the vegetation, hyporheic exchanges, and groundwater influx – are unknown.

Sedimentation

Sedimentation of streams may also contribute to elevated water temperatures. Sediment can fill pools and cause the width-to-depth ratio of a stream to increase, which can facilitate heat exchange (Poole and Berman, 2000). Hagans et al. (1986) reported that sedimentation caused stream temperatures to increase, as dark-colored fine sediment replaced lighter-colored course gravels. The darker sediment stored more solar radiation. Fine sediment may block exchange between surface waters and intra-gravel flows, also contributing to warming.

Hyporheic flow

Changes in pressure head throughout the stream and riparian zone create upwelling of subsurface water into the stream and downwelling of stream water into the subsurface layers. This subsurface zone where the surface and groundwater mix is called the *hyporheic zone* (Reidy and Clinton, 2004).

The effective thickness of the hyporheic zone may typically range from about 20 to 300 percent of the stream depth (Harvey and Wagner, 2000) with higher relative values in smaller streams. Pelletier and Chapra (2004) suggested a hyporheic zone depth of between 10 cm and 100 cm with increasing depths at higher hyporheic flows. Studies conducted in stream headwaters in British Columbia found that a greater hyporheic exchange, relative to surface water flow, existed during low baseflow than high baseflow conditions (Gomi and Moore, 2003).

Groundwater interactions

In general, groundwater influx cools stream temperature, primarily because the groundwater is cooler than the stream. However, for this to happen, there must be a positive hydraulic gradient from the phreatic groundwater to the stream surface. Stormwater infiltration would increase this gradient while pumping would lower the gradient. Preservation of vegetation will allow for prolonged storage and slow release of water into the ground, allowing for prolonged positive hydraulic gradients.

Appendix C. Groundwater and stream temperature profiles, and hydraulic gradients, at stations in Cranberry Creek, 2005

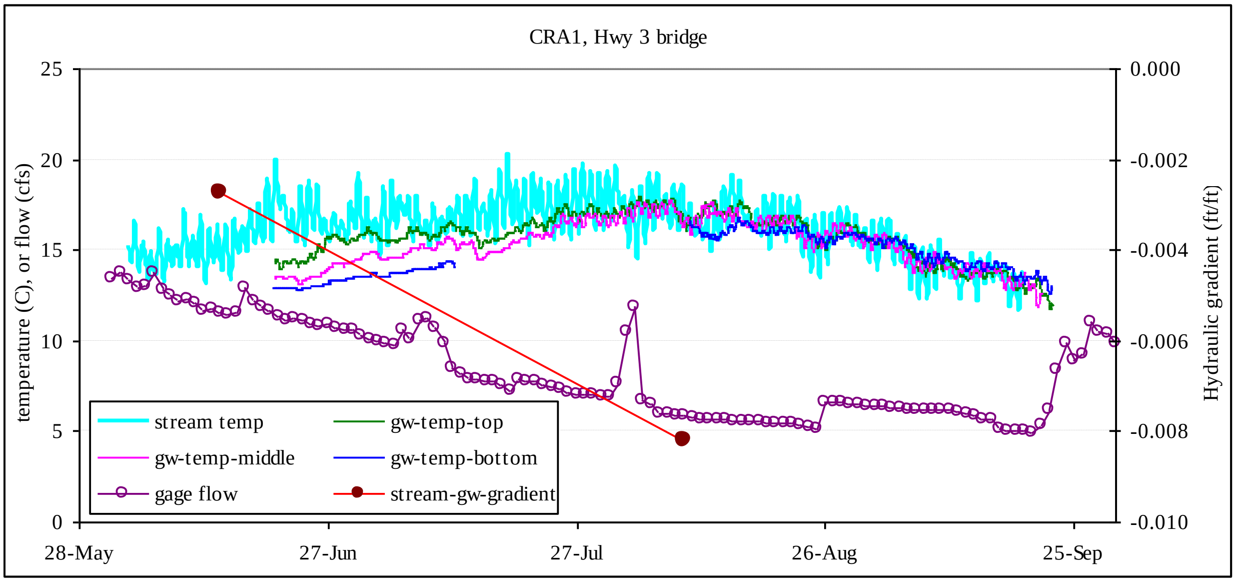

Figure C-1. Groundwater and stream temperature profiles, and hydraulic gradients, at Station CRA1.

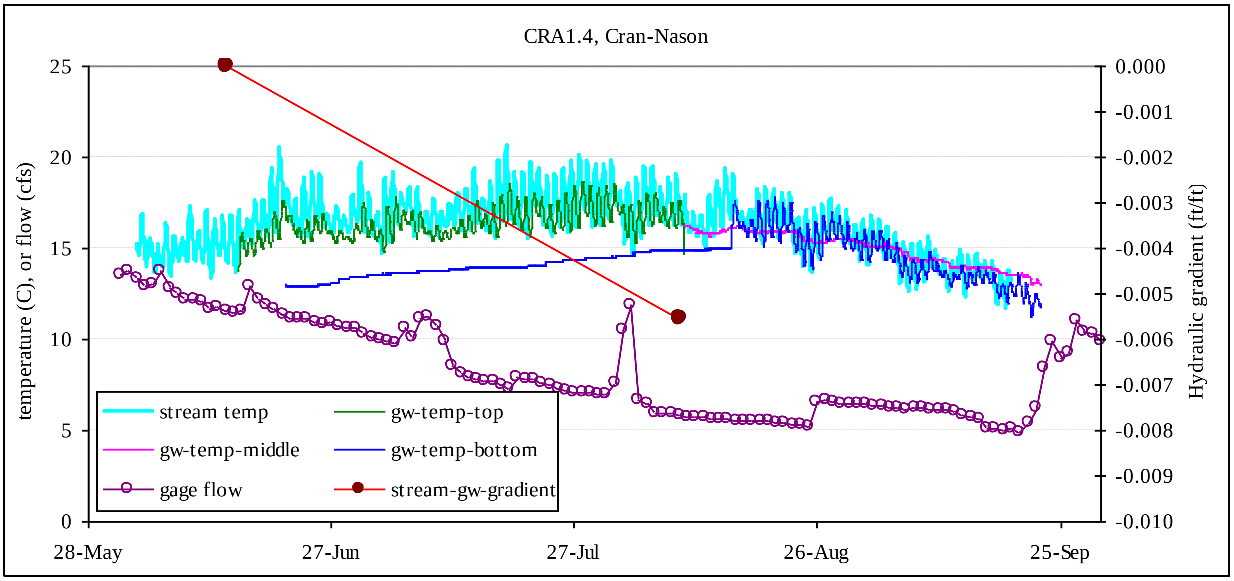

Figure C-2. Groundwater and stream temperature profiles, and hydraulic gradients, at Station CRA1.4.

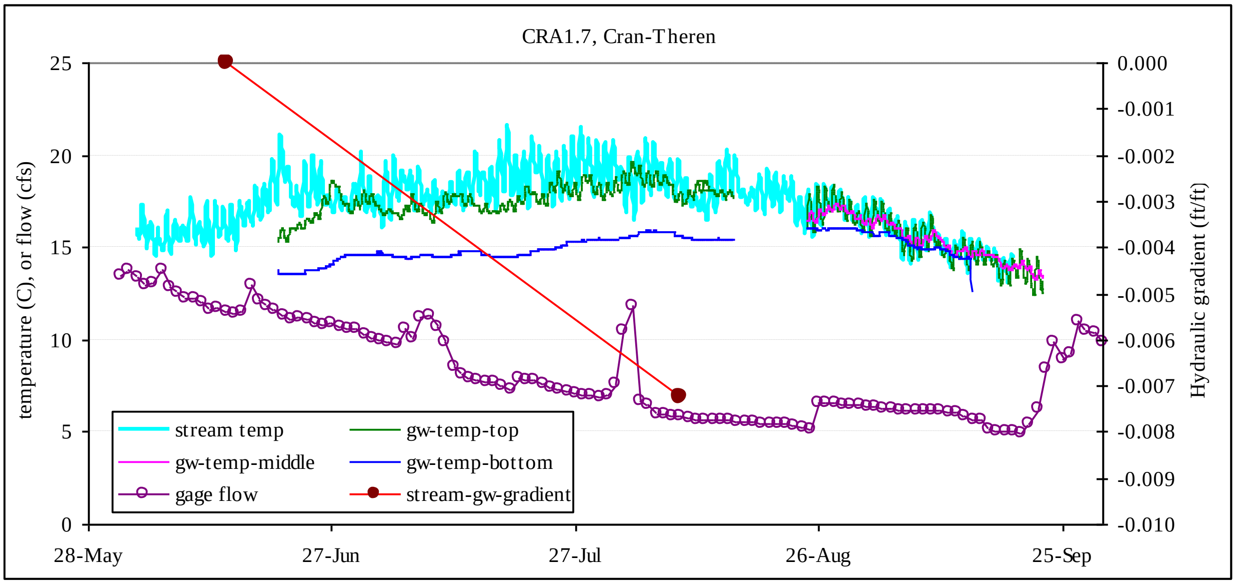

Figure C-3. Groundwater and stream temperature profiles and hydraulic gradients, at Station CRA1.7.

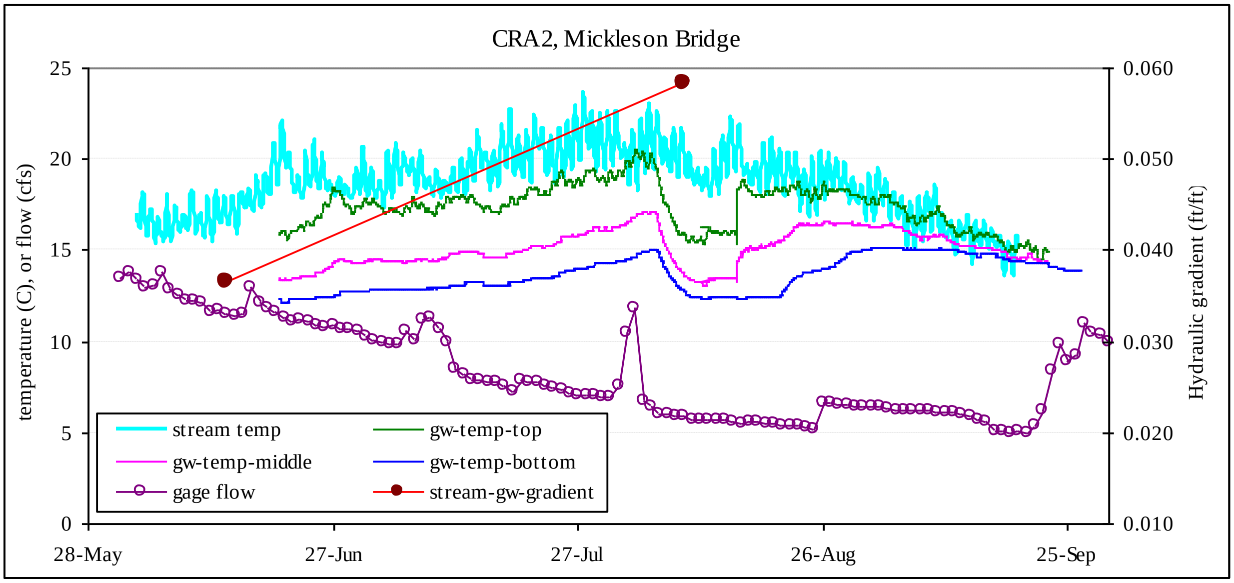

Figure C-4. Groundwater and stream temperature profiles and hydraulic gradients, at Station CRA2.

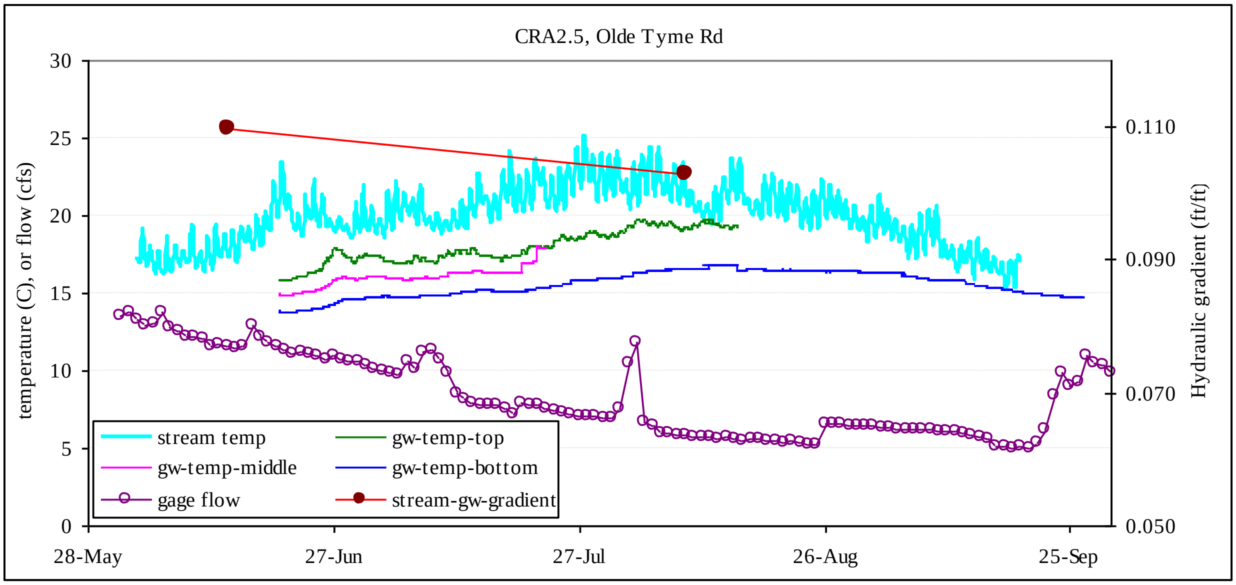

Figure C-5. Groundwater and stream temperature profiles, and hydraulic gradients, at Station CRA2.5.

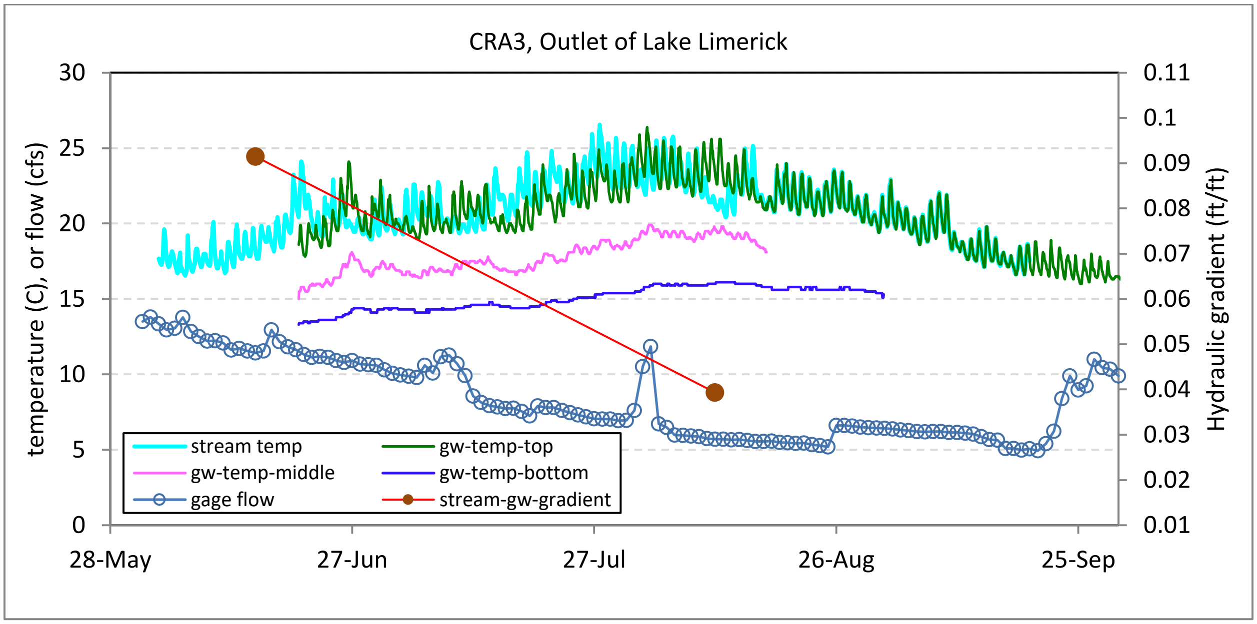

Figure C-6. Groundwater and stream temperature profiles, and hydraulic gradients, at Station CRA3.

Appendix D. Groundwater and stream temperature profiles, and hydraulic gradients, at stations in Johns Creek, 2005

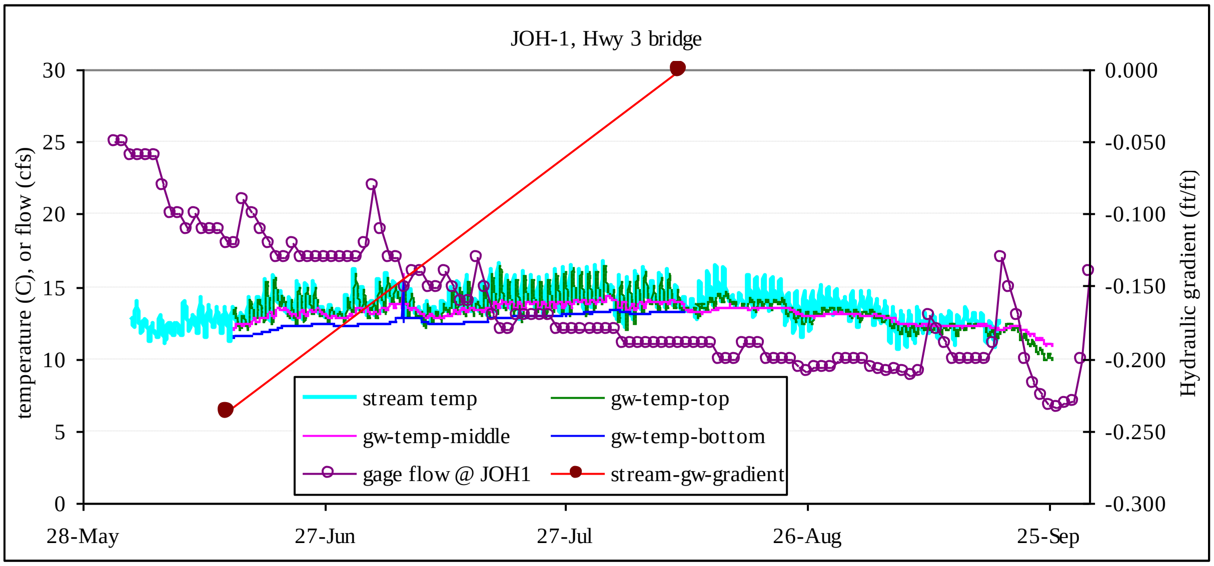

Figure D-1. Groundwater and stream temperature profiles, and hydraulic gradients, at Station JOH1 at Highway 3 bridge.

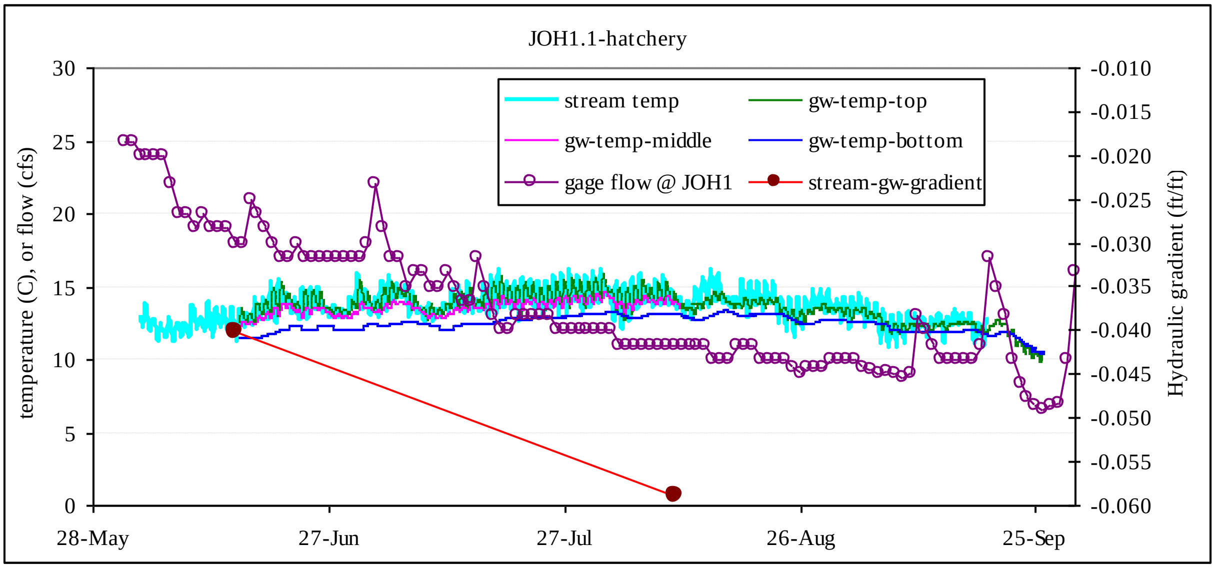

Figure D-2. Groundwater and stream temperature profiles, and hydraulic gradients, at Station JOH1.1 near hatchery.

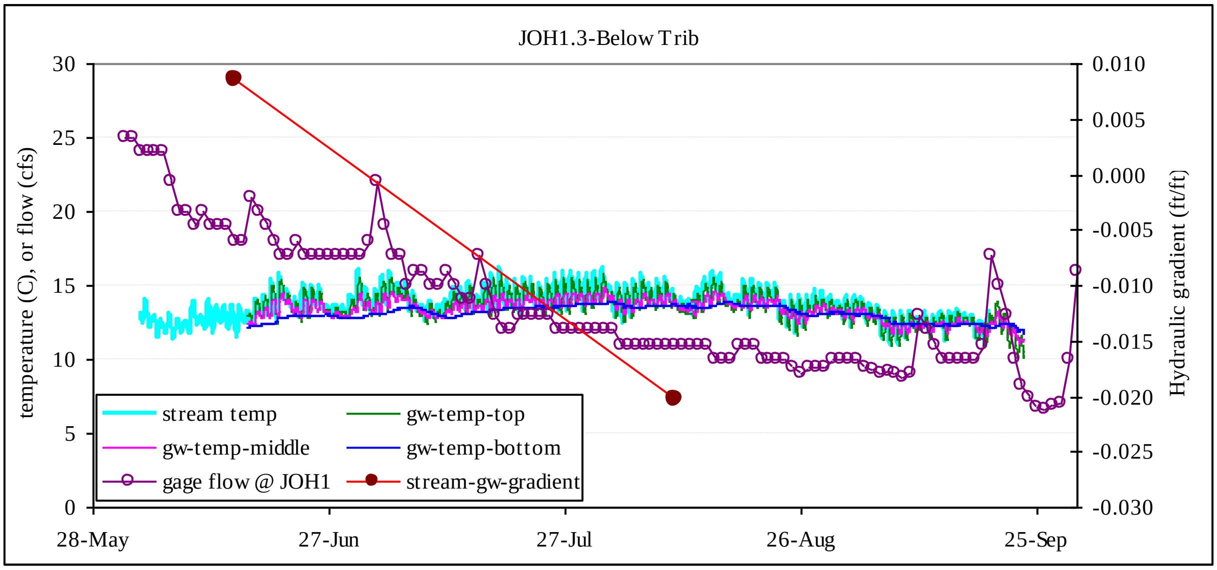

Figure D-3. Groundwater and stream temperature profiles, and hydraulic gradients, at Station JOH1.3 below the coldwater tributary.

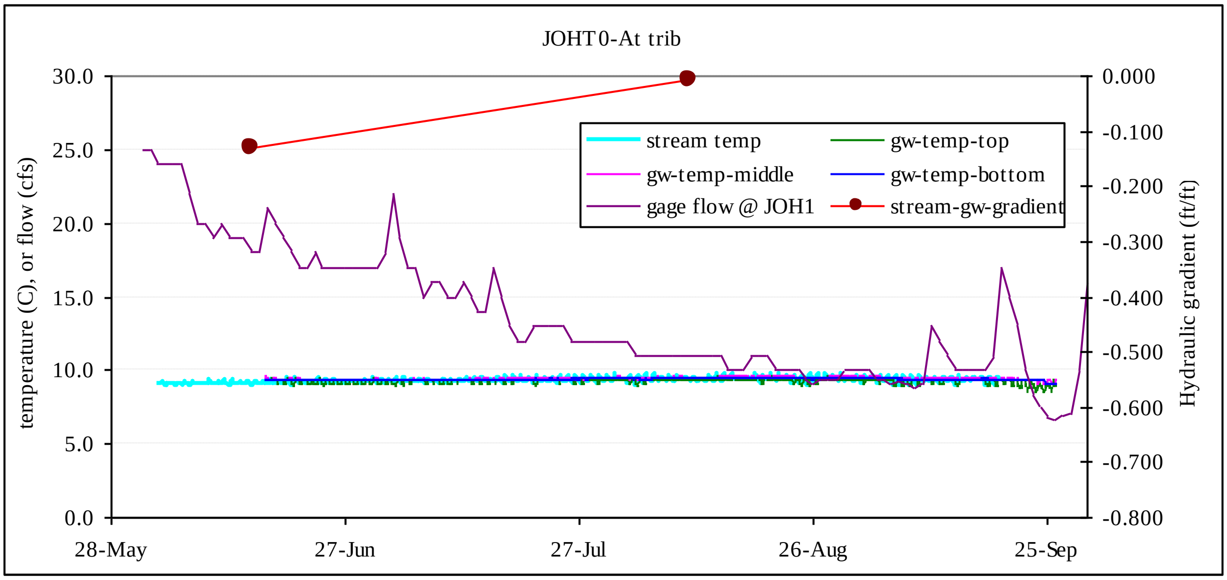

Figure D-4. Groundwater and stream temperature profiles, and hydraulic gradients, at Station JOHT0 on the coldwater tributary.

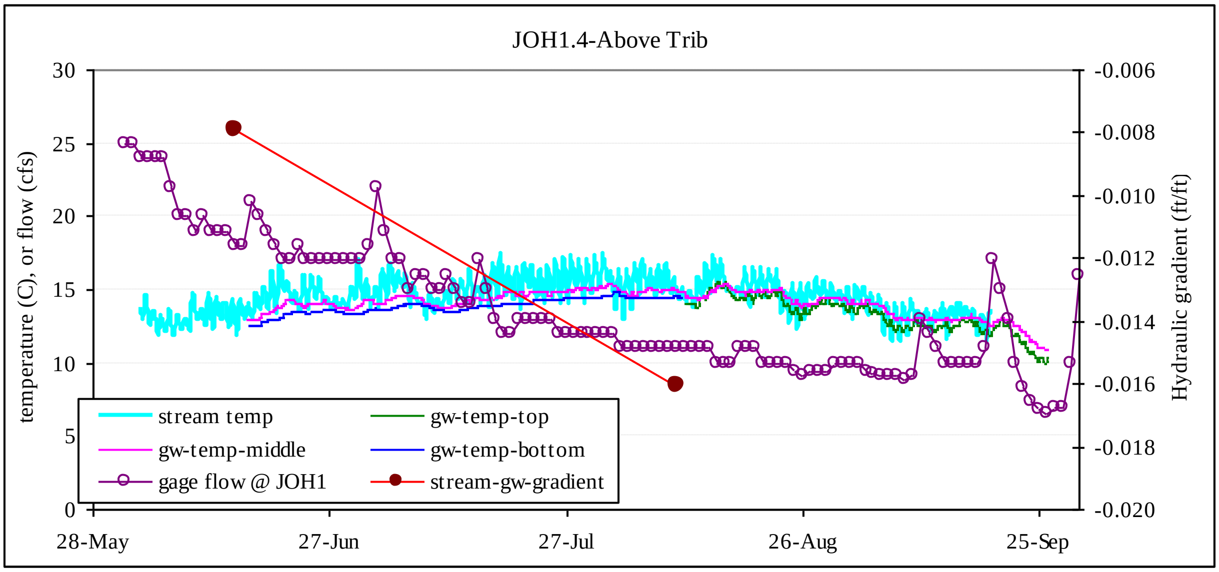

Figure D-5. Groundwater and stream temperature profiles, and hydraulic gradients, at Station JOH1.4 above the coldwater tributary.

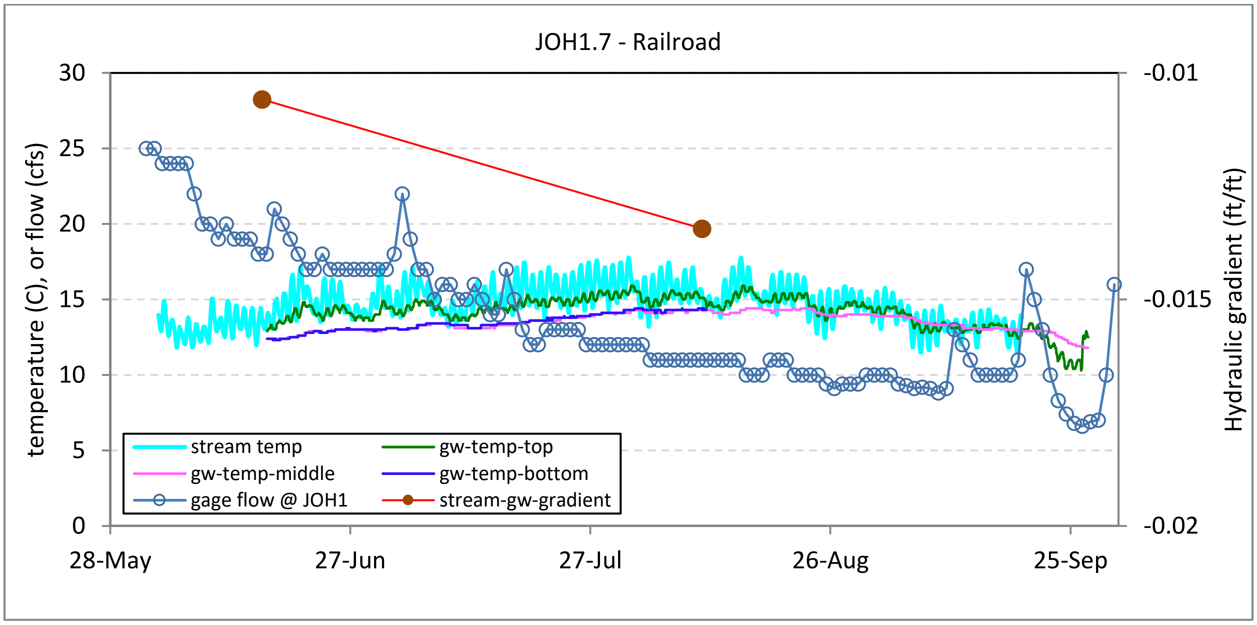

Figure D-6. Groundwater and stream temperature profiles, and hydraulic gradients, at Station JOH1.7 at the railroad.

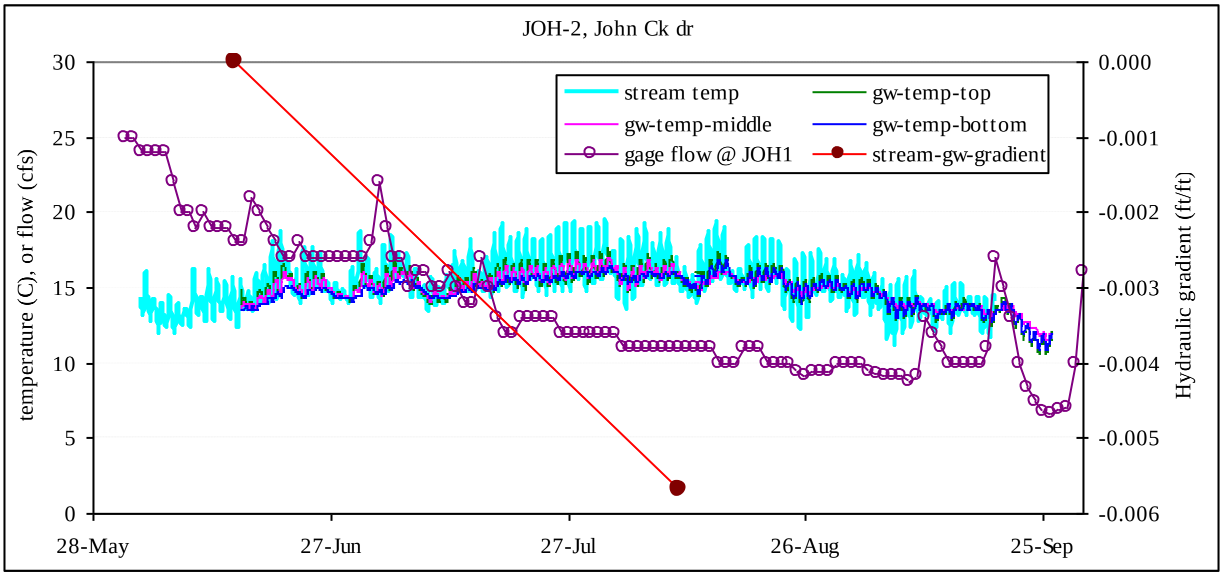

Figure D-7. Groundwater and stream temperature profiles, and hydraulic gradients, at Station JOH2 on Johns Creek Drive.

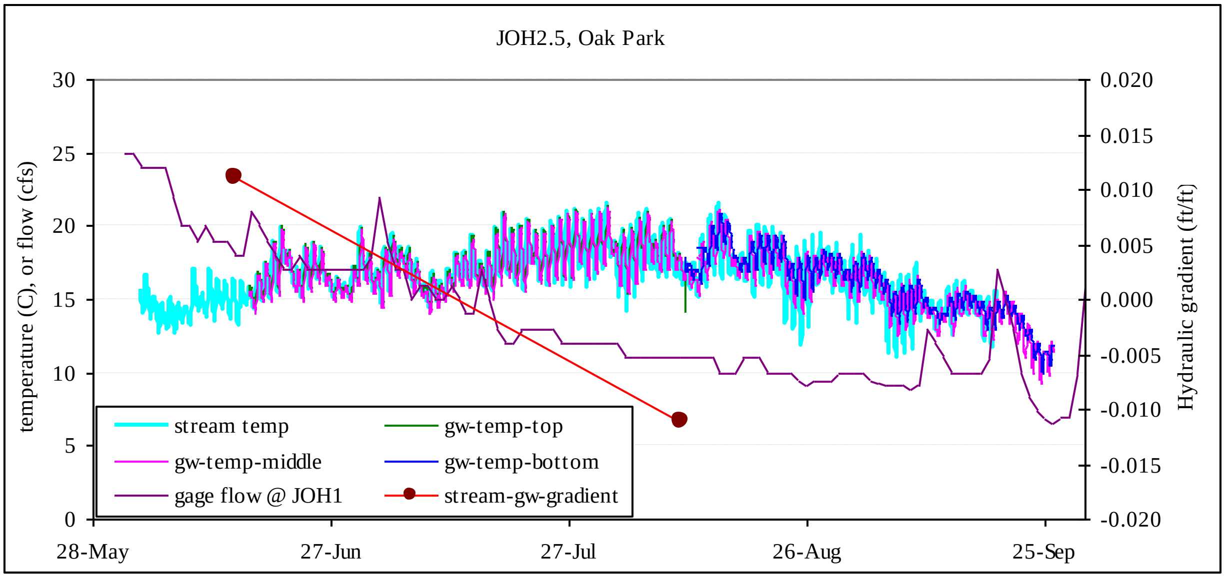

Figure D-8. Groundwater and stream temperature profiles, and hydraulic gradients, at Station JOH2.5 at Oak Park.

Appendix E. Groundwater and stream temperature profiles, and hydraulic gradients, at stations in Mill Creek, 2005

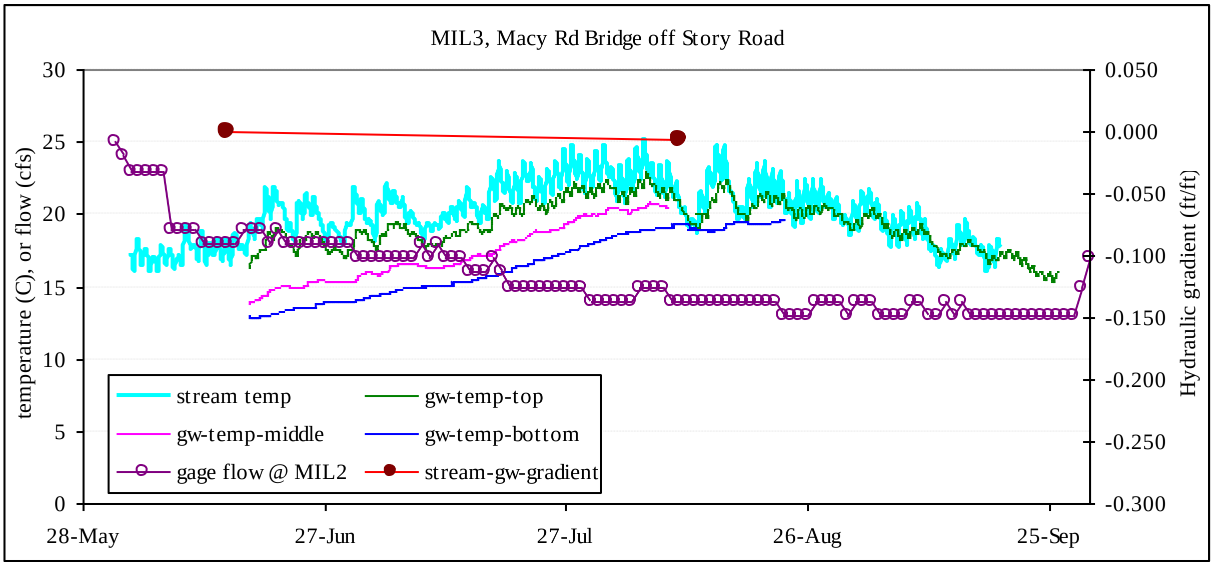

Figure E-1. Groundwater and stream temperature profiles, and hydraulic gradients, at Station MIL3 at Macy Road bridge.

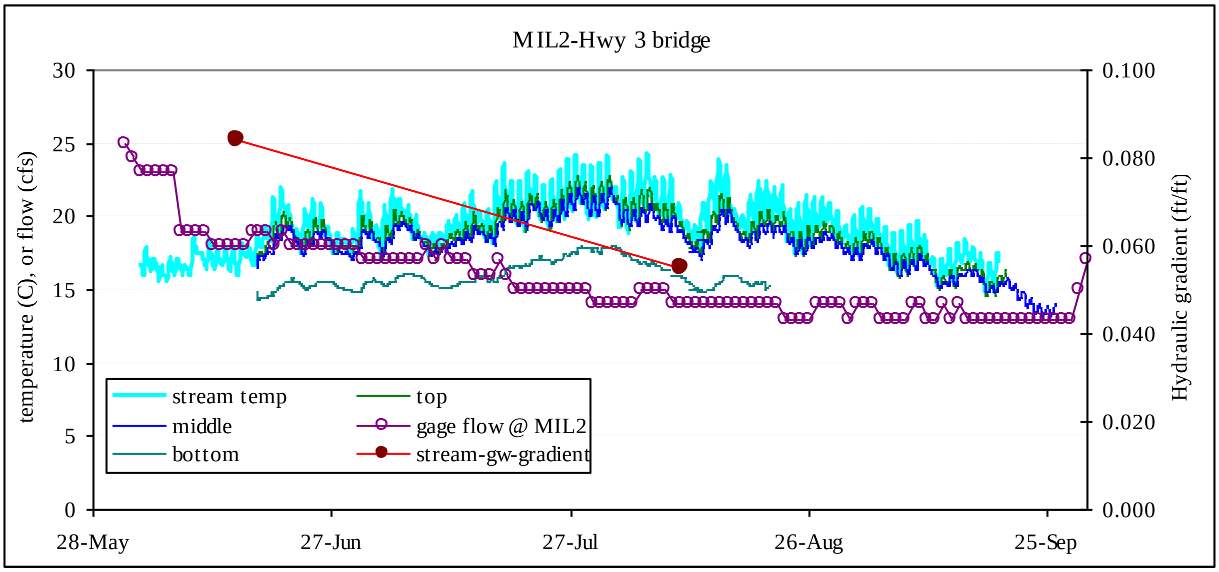

Figure E-2. Groundwater and stream temperature profiles, and hydraulic gradients, at Station MIL2 at Highway 3 bridge.

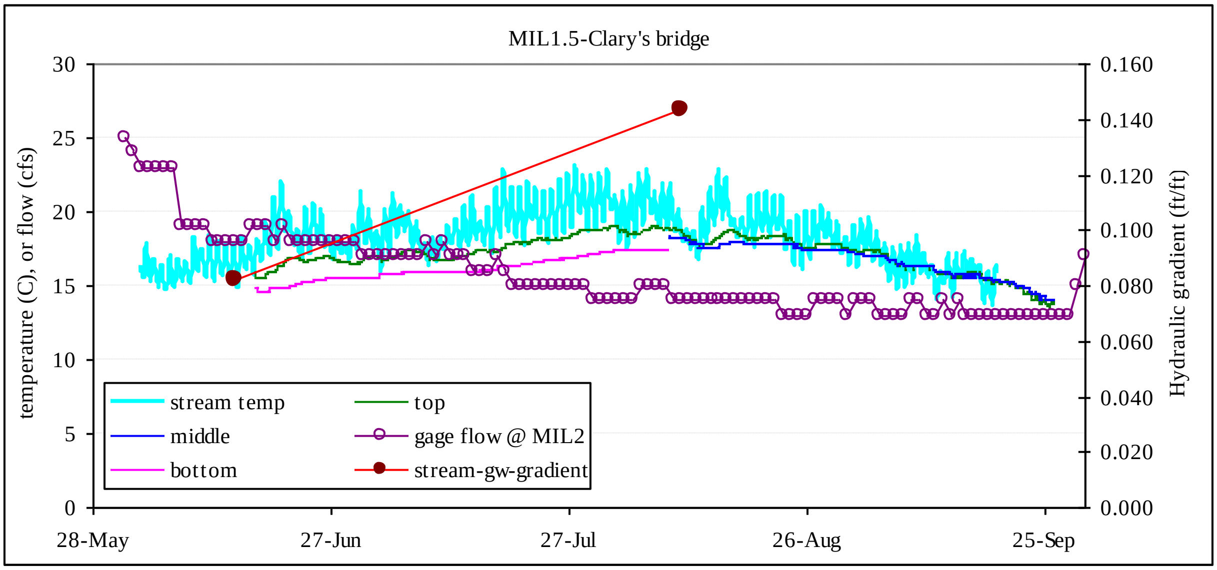

Figure E-3. Groundwater and stream temperature profiles, and hydraulic gradients, at Station MIL1.5 at Clary's bridge.

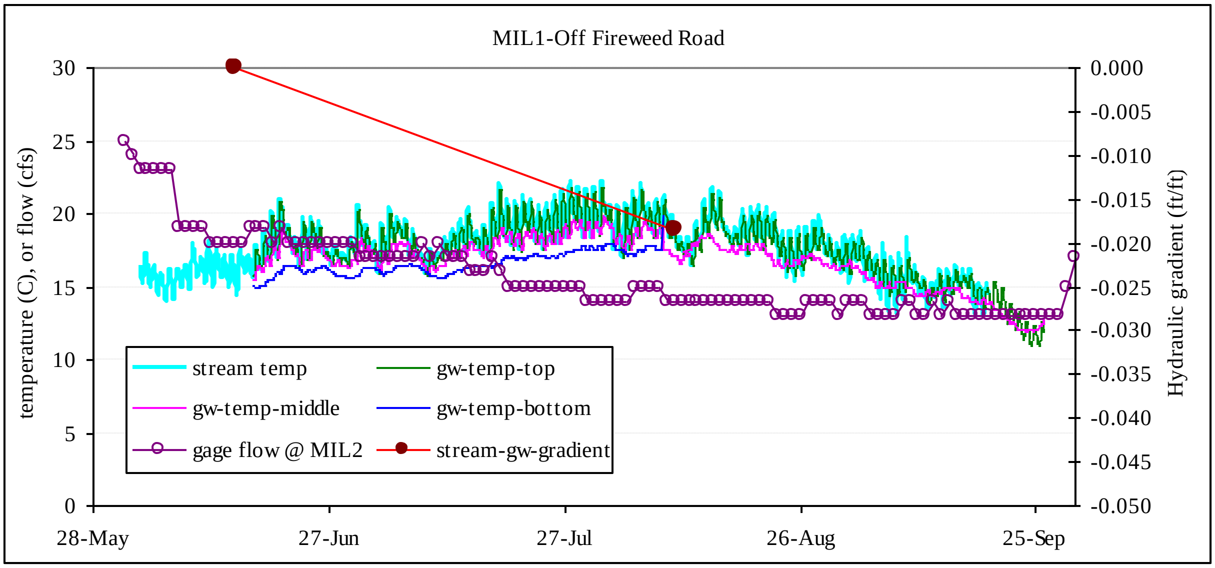

Figure E-4. Groundwater and stream temperature profiles, and hydraulic gradients, at Station MIL1 off Fireweed Road.

Appendix F: Vegetation density data

Creek	Station	Direction	Densiometer, %	Near-stream vegetation cover, %
Cranberry	CRA3	Upstream	88	
		Left bank	96	18
		Downstream	96	
		Right bank	96	8
	CRA2.5	Upstream	60	
		Left bank	96	24
		Downstream	76	
		Right bank	80	34
	CRA2	Upstream	96	
		Left bank	93	100
		Downstream	60	
		Right bank	96	100
	CRA1.7	Upstream	96	
		Left bank	96	100
		Downstream	96	
		Right bank	96	100
	CRA1.4	Upstream	60	
		Left bank	40	5
		Downstream	84	
		Right bank	90	25
	CRA1	Upstream	96	
		Left bank	96	100
		Downstream	96	
		Right bank	96	100
Johns	JOH2.5	Upstream	96	
		Left bank	96	100
		Downstream	96	
		Right bank	96	100
	JOH2	Upstream	60	
		Left bank	84	100
		Downstream	96	
		Right bank	96	100
	JOH1.7	Upstream	90	
		Left bank	80	100
		Downstream	92	
		Right bank	93	100
	JOH1.1	Upstream	96	
		Left bank	96	100
		Downstream	96	
		Right bank	96	100
	JOH1	Upstream	96	
		Left bank	96	100
		Downstream	96	
		Right bank	96	100
Mill	MIL3	Upstream	11	
		Left bank	56	43
		Downstream	42	
		Right bank	46	11
	MIL2	Upstream	56	
		Left bank	88	23
		Downstream	32	
		Right bank	88	14
	MIL1.5	Upstream	60	
		Left bank	58	25
		Downstream	48	
		Right bank	36	4
	MIL1	Upstream	96	
		Left bank	96	100
		Downstream	96	
		Right bank	96	100

Appendix G. Global climate change

Changes in climate are expected to affect both water quantity and quality in the Pacific Northwest (Casola et al., 2005). Summer streamflows in Cranberry, Johns, and Mill Creeks are highly dependent on groundwater influx. This influx, in turn, is dependent on nearby winter rainfall recharging groundwater. Any changes in climate that increase the likelihood of winter stormwater runoff, and decrease rates of precipitation infiltration, will lower summer streamflows.

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 stream banks, 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 temperature study 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.

The relatively small size of Cranberry, Johns, and Mill Creeks, and the high rates of groundwater influx, produce very important and highly unique thermal refugia upstream of their mouths for summer chum and overwintering coho species. Protection of these thermal refugia is a key strategy to sustain the life history strategies of these species.

Appendix H Glossary, acronyms, and abbreviations

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

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

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-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 10 years on average. The 7Q10 flow is commonly used to represent the critical flow condition in a water body and is typically calculated from long-term flow data collected in each basin. For temperature-work, the 7Q10 is usually calculated for the months of July and August as these typically represent the critical months for temperature in our state.

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

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

Ambient: Background or away from point sources of contamination.

Anthropogenic: Human-caused.

Angular canopy density (ACD): The percentage of time that a given point on a stream will be shaded from direct beam solar radiation between 10 a.m. to 2 p.m. local solar time. For example, if a point on a stream is always shaded from 10 a.m. to 2 p.m. in August, then August ACD at that point is 100 percent. If that point is never shaded between 10 a.m. to 2 p.m., then ACD at that point is zero. Average ACD of a stream reach is estimated by sampling it over the width and length of the reach. Typical values of the ACD for old-growth stands in western Oregon have been reported to range from 80 to 90 percent.

Bankfull stage: Formally defined as the stream level that "corresponds to the discharge at which channel maintenance is most effective, that is, the discharge at which moving sediment, forming or removing bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels" (Dunne and Leopold, 1978).

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

Char: Char (genus *Salvelinus*) are distinguished from trout and salmon by the absence of teeth in the roof of the mouth, presence of light colored spots on a dark background, absence of spots on the dorsal fin, small scales, and differences in the structure of their skeleton. (Trout and salmon have dark spots on a lighter background.)

Clean Water Act: 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 waterbody 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 shortwave radiation that is blocked from reaching the surface of a stream or other defined area.

Exceeded criteria: Did not meet criteria.

Hyporheic zone - the area under and along the river channel where surface water and groundwater meet.

Margin of Safety: Accounts for uncertainty about the relationship between pollutant loads and quality of the receiving waterbody.

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.

Root mean square error (RMSE): is a frequently used measure of the differences between values (sample and population values) predicted by a model or an estimator and the values actually observed.

Salmonid: Any fish that belong to the family *Salmonidae*. Basically, any species of salmon, trout, or char.

Seepage Run: A method of taking flow measurements to provide estimates of the net gains or losses across broader creek reaches.

Any fish that belong to the family *Salmonidae*. Basically, any species of salmon, trout, or char..

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

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

Surrogate measures: To provide more meaningful and measurable pollutant targets, EPA regulations [40 CFR 130.2(i)] allow other appropriate measures, or *surrogate* measures.

System potential: The design condition assumed to meet water quality standards.

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

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

System-potential 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.

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.

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

Acronyms and Abbreviations frequently in this report:

BMP	best management practice
Ecology	Washington State Department of Ecology
EPA	Environmental Protection Agency
GIS	Geographic Information Systems
Km	Kilometer
RMSE	Root mean square error
TIR	Thermal infrared
WQ	Water Quality

Units of Measurement

°C	degrees centigrade
°F	degrees ferenheit
cfs	cubic feet per second
cms	cubic meters per second, a unit of flow.
ft	feet
m	meter
mL	milliliters