Final
Water Quality Temperature Modeling
Lake Creek
for
Energy Northwest's
Packwood Lake Hydroelectric Project
FERC No. 2244
Lewis County, Washington

Submitted to

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1.0 INTRODUCTION

Energy Northwest, a municipal corporation and joint operating agency of the State of Washington, operates the Packwood Lake Hydroelectric Project (Project) near the town of Packwood in Lewis County, Washington. The Federal Energy Regulatory Commission (FERC) licensed the Project on July 7, 1960 (effective March 1, 1960), designated as Federal Power Commission License No. 2244. In accordance with the Integrated Licensing Process (ILP) regulations, Energy Northwest filed a Notice of Intent (NOI) to file an application for new license on November 12, 2004. Energy Northwest also concurrently filed with the FERC and the resource agencies, a Pre-Application Document (PAD), containing existing, relevant, and reasonably available information describing the existing environment and the potential effects of the licensee's intended project proposal, including proposed project facilities and operations. The Washington Department of Ecology (WDOE) and the USDA Forest Service filed study requests with FERC that identify water quality issues and related study needs (WDOE 2005, USDA Forest Service 2005).

The Project is located east of the community of Packwood in the Cascade Mountains. Packwood Lake lies within the Gifford Pinchot National Forest. The Project includes: an intake canal; a concrete drop structure and an intake building on Lake Creek located about 424 feet downstream from the outlet to Packwood Lake; a 21,691-foot system of concrete pipe and tunnels; a 5,621 foot-long penstock; a surge tank; and a powerhouse with a 26,126 kW turbine generator. The drop structure that regulates the water level of Packwood Lake was constructed by excavating debris from a natural landslide, which occurred about 1,000 years ago and created the lake. The drop structure located adjacent to the intake structure extends 85 feet in width and is tied into impervious earth fill cutoff walls on each side extending to the natural embankment. The powerhouse is located at the base of the mountain adjacent to the community of Packwood. The powerhouse tailrace flow discharges into a constructed stilling basin and then travels through a lined tailrace channel about 6,690 feet in length to a confluence with the Cowlitz River. The tailrace includes a 200-foot highway culvert and 360-foot flume over Hall Creek.

The total area drained by Lake Creek and Packwood Lake is approximately 19.2 square miles at the drop structure. The total surface area of the lake is 452 acres. The summertime lake elevation (El.) is about 2,857 ft MSL, which is approximately 1,800 ft above the powerhouse. Currently, the FERC license for the Project requires a minimum instream flow of 3 cfs at the drop structure immediately downstream of the outlet of Packwood Lake. There is also an instream flow requirement of 15 cfs at the confluence of Lake Creek with the Cowlitz River. Energy Northwest is not currently required to measure the latter flow. When lake level rises above the drop structure crest elevation (El. 2858.5 ft MSL), the flow passes over the drop structure into Lake Creek downstream of the lake.

1.1 Study Goal and Objectives

The goal of this study is to develop information to support the water quality certification that will be issued by the WDOE, pursuant to Section 401 of the Clean Water Act, for the operation of the Project under a new FERC license. Evaluation of compliance with some water quality standards requires knowing the natural water quality condition for a water body. When the 7-day average of the maximum daily temperature (7-DADMax) exceeds the water quality temperature criteria ($16^{o}C$ for Lake Creek), and that condition is due to natural conditions, then human actions considered cumulatively may not cause the 7-DADMax temperature to increase more than $0.3^{o}C$ (Ecology 2006). Modeling was used to estimate the natural background temperature for Lake Creek since pre-Project temperature data are not available. Modeling for Lake Creek was completed to evaluate water temperatures relative to water quality standards for conditions with and without the Project operating. The results from the Lake Creek model were used in combination with data from the tailrace and Cowlitz River to assess the effects of the Project on summer water temperatures in the Cowlitz River.

2.0 METHODS

The water temperature modeling study for Lake Creek consisted of data collection, model set up, model calibration and model application. Temperature was identified as the key water quality parameter for evaluating Project effects in Lake Creek. Water temperature was the only parameter identified as potentially exceeding water quality standards under different Project operating regimes[1]. Currently water temperature in Lake Creek at its mouth is well below the water quality criteria. Water temperature at the Lake outlet exceeds the criteria due to naturally warm water flowing out of Packwood Lake.

Water temperature in Lake Creek, the Cowlitz River and the Project tailrace were monitored for a two year period. Continuous recording Optic Stowaway™ thermographs were deployed at the locations shown in Figures 2-1 through 2-3. Thermographs were programmed to record hourly temperature. All thermographs were set to real time with data reported on the hour to facilitate analysis among sites. Riverine thermographs were deployed in close proximity to the channel bed at a position that minimizes potential for dewatering.

[1] Summary of consultation record for meeting in Olympia held on January 26, 2007.

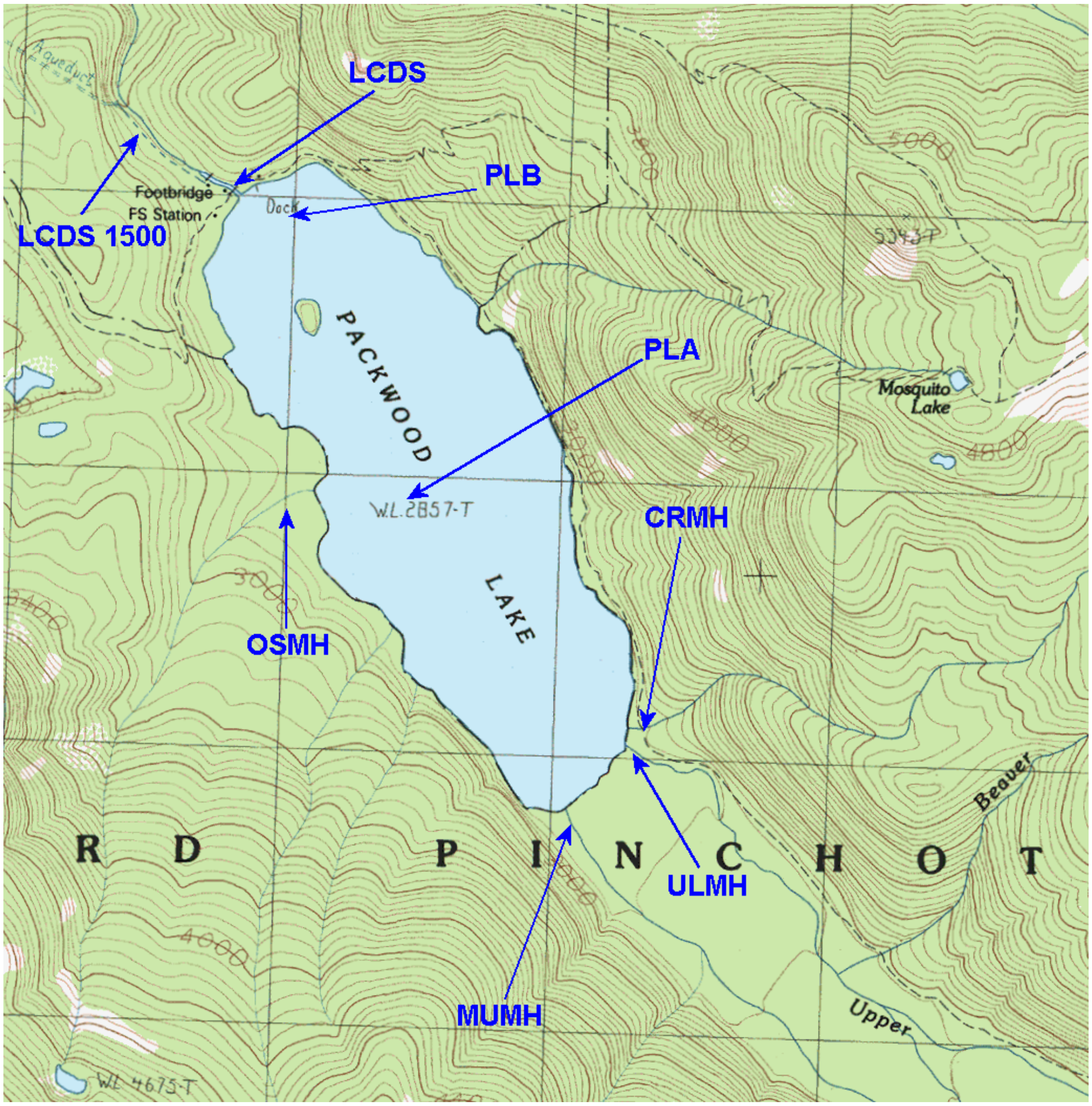

Figure 2-1 Thermograph monitoring locations for Lake Creek below Packwood Lake

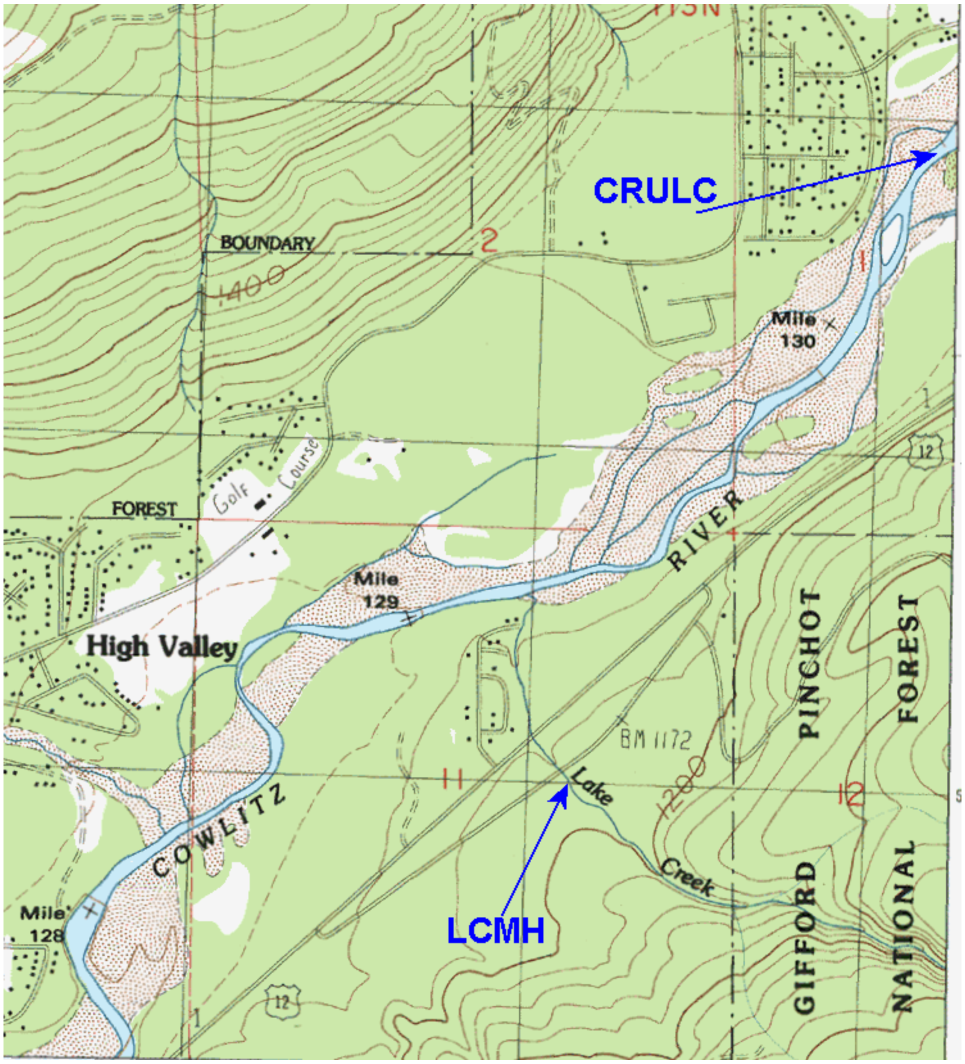

Figure 2-2 Thermograph monitoring locations for Lake Creek near mouth and Cowlitz River and Project tailrace

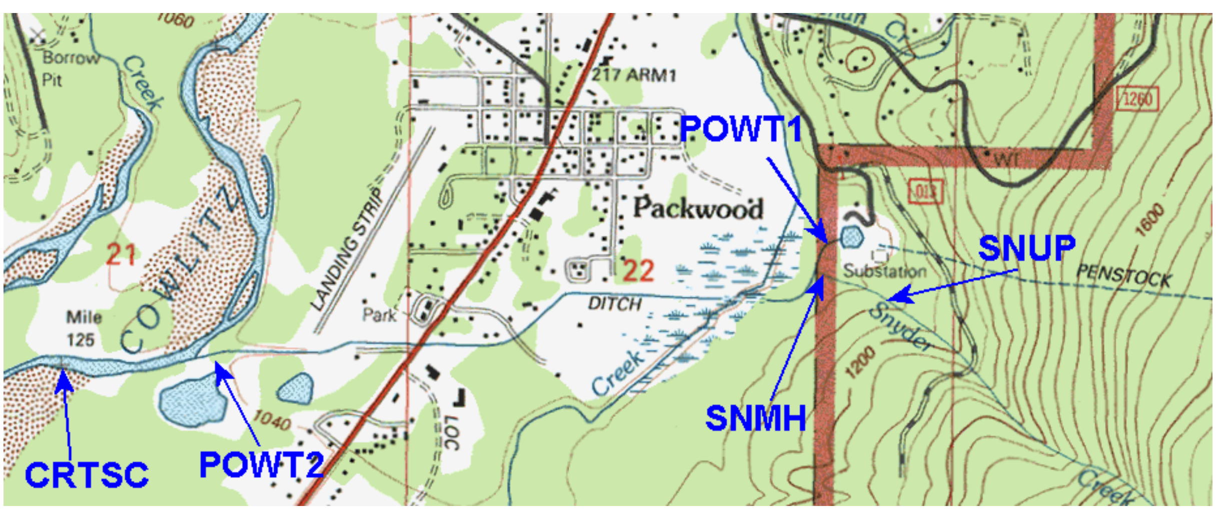

Figure 2-3 Thermograph monitoring locations for Project tailrace

All thermographs were subject to a three-point calibration test prior to deployment. Laboratory calibration of the thermographs was repeated at the end of the study period. The Onset Corporation HOBO thermographs have an accuracy of $\pm$ 0.16°C and a resolution of 0.28°C. All thermographs were within $\pm$0.3°C of the standardized mercury thermometer reading for each of the three laboratory calibration measurements, which indicated that QA/QC standards were satisfied.

Climate data were collected at the Packwood Lake intake and at the powerhouse. At Packwood Lake, an automated climate station was deployed on a tower at a height of approximately 6m. The tower is located adjacent to the drop structure. For this climate station, wind speed, wind direction, air temperature, dewpoint temperature, relative humidity, and solar radiation were measured and recorded at 15-minute intervals.

Air temperature and relative humidity were also monitored at the Packwood Lake powerplant with data recorded at 15-minute intervals.

2.1 Model Selection

The QUAL2Kw model was selected to model water temperatures in Lake Creek. QUAL2Kw is a river and stream water quality model that is intended to represent a modernized version of the QUAL2E model (Brown and Barnwell 1987). QUAL2Kw is adapted from the QUAL2K model that was originally developed by Dr. Steven C. Chapra of Tufts University (Pelletier, Chapra and Tao 2005). QUAL2Kw is similar to QUAL2E in the following respects:

- One dimensional. The channel is well-mixed vertically and laterally.
- Steady state hydraulics. Non-uniform, steady flow is simulated.
- Diel heat budget. The heat budget and temperature are simulated as a function of meteorology on a diel time scale.
- Diel water-quality kinetics. All water quality variables are simulated on a diel time scale.
- Heat and mass inputs. Point and non-point loads and abstractions are simulated.

2.2 Bathymetry and Shading

Channel bathymetry information is required for channel hydraulics calculations. Specifically, stream channel width, depth and velocity relationships to flow are required. Channel orientation data are necessary for calculating channel shading from solar radiation.

Stream Channel

Data for stream channel dimensions were available from the Instream Flow Incremental Method (IFIM) study that was conducted on Lake Creek (EES Consulting 2007d) to assess stream habitat conditions relative to stream flow. Lake Creek downstream of Packwood Lake was partitioned into five distinct reaches based primarily on changes in gradient along the length of the stream. Table 2-1 summarizes reach definition, length, and mean slope for each study reach. Lake Creek is a high gradient, stair-step type creek with a long series of cascades and plunge pools comprising a majority of the habitat.

Table 2-1 Summary of Study Reaches, Lake Creek

Reach	River Mile	River Kilometer	Elevation (ft)	Mean Slope
1	0.0-0.7	0 – 1.13	1,105-1,213	2.9%
2	0.7-1.3	1.13 – 2.09	1,210-1,440	7.3%
3	1.3-3.5	2.09 – 5.6	1,440-2,367	8.0%
4	3.5-4.9	5.6 – 7.89	2,360-2,680	4.3%
5	4.9-5.3	7.89 – 8.5	2,680-2,857	8.4%

The five IFIM study reaches were subsequently consolidated into four study sites where channel hydraulics were measured. A weighted average channel width was computed for each stream reach. The weighted average was based on the proportional weighting assigned to each IFIM cross section. Weighted average channel widths were calculated for a range of flows. A flow to width equation for each stream reach was then estimated (Table 2-2). Equations for the relationship between flow relative to depth and velocity were developed in a similar manner (Table 2-2). The model requires either width or depth as an input. Width functions were used for the Lake Creek model.

Table 2-2 Channel hydraulics equations for Lake Creek QUAL2Kw model

Reach	Study Site	Width Equation	Depth Equation	Velocity Equation
1	1	$W = 6.9046x^{0.1653}$	$D = 0.3366x^{0.2478}$	$V = 0.3961x^{0.4918}$
2-3	2	$W = 7.1368x^{0.1479}$	$D = 0.4095x^{0.1851}$	$V = 0.393x^{0.5170}$
4	3	$W = 6.5942x^{0.2443}$	$D = 0.3647x^{0.2275}$	$V = 0.3561x^{0.3106}$
5	4	$W = 7.4373x^{0.2339}$	$D = 0.3889x^{0.196}$	$V = 0.3319x^{0.4542}$

X = discharge (cms); width, depth and velocity are in metric units; R^2 *for all equations* ≥ 0.99

Topographic Shading

Recent digital orthophotos and DEM data for the study area were used to develop channel orientation and elevation data. Oregon Department of Environmental Quality's (ODEQ) Ttools extension for Arcview (ODEQ 2001) was used to sample and process GIS data for input to the Shade and QUAL2Kw models. West, east and south topographic shade angle calculations were made at 50-meter increments along the channel. Stream elevation, gradient and aspect (stream flow direction in decimals from north) were also calculated by the Ttools extension for Arcview at 50m increments.

Vegetation

Digital, black-and-white orthophotos were combined with existing Forest Service GIS vegetation data (available at http://www.fs.fed.us/gpnf/forest-research/gis/) to create base maps of the study area. Base maps were prepared at a resolution sufficient to show and map major vegetation types (1:6,500). Existing Forest Service vegetation data for the study area provide information on vegetation community or association types. Ground truth surveys of vegetation types were conducted with results reported in DTA (2007). The existing and site potential riparian forest canopy are considered synonymous, because the existing riparian forest canopy is mature (older than 100 years)

Ecology's Shade model (Ecology 2003) was used to estimate effective shade along Lake Creek. Effective shade was calculated at 50m increments along the channel.

2.3 Hydrology

Water temperatures were modeled for existing conditions and critical flow conditions. Model scenarios included with and without the Project operating. Critical flow conditions evaluated were the lowest 7-day average flow with a recurrence interval of two years (7Q2) and a ten year recurrence interval (7Q10) for the month of August. The US Environmental Projection Agency's (EPA) DFLOW 3.1 model was used to calculate the 7Q2 and 7Q10 flows. DFLOW (released March 2006) is a Windows-based tool developed to estimate user selected design stream flows for low flow analysis.

The U.S. Geological Survey (USGS) historically operated two stream gages on Lake Creek and continues to operate a gage on the Cowlitz River at Packwood. The USGS gages include:

- Lake Creek at the outlet of Packwood Lake (immediately downstream of the drop structure [No. 14225500]) period of record 1912 - 1980
- Lake Creek upstream of the confluence with the Cowlitz River (No. 14226000) period of record 1908 - 1977
- Cowlitz River at Packwood, WA (No. 14226500) 1911 - present

EES Consulting has operated a stream gage on Lake Creek at River kilometer (Rkm) 7.9[2] since 2005. This gage is near the location of the historical USGS gage No. 14226000.

Energy Northwest maintains Project operation hydrologic records including daily inflow into Packwood Lake, lake level, minimum release flow (3 cfs), flow overtopping the drop structure, and flow through the powerhouse.

In order to calculate the 7Q2 and 7Q10 flows, daily flow records were analyzed for the period of record from Water Year (WY) 1912 through WY 1962. This is the period of record prior to construction and operation of the Project when all three gages listed above were recording. After Project startup in 1964, the USGS gages remained in operation; however, gage No. 14225500 (lake outlet) only reflects release flows (i.e., instream flows, generally 3 – 5 cfs) plus any overtopping of the drop structure at the top, while the lower gage (No. 14226000) reflects flows at the drop structure plus any accretion in the creek.

[2] The convention used in the QUAL2Kw model for designating longitudinal position on a stream is for the most upstream point in the modeled reach to be designated at Rkm 0.0. For this report, the drop structure at the outlet of Packwood Lake was designated as being at Rkm 0.0 with all locations downstream measured from this reference point.

The model requires an estimate of inflow point sources (tributary) groundwater accretion (diffuse sources). Most of the inflow into Lake Creek is groundwater derived. The model treated all accretion as diffuse inflow with no point source inflows. Both the flow rate and the groundwater temperature are input parameters. Lake Creek has significant and longitudinally variable inflow from the watershed downstream of the Packwood Lake outlet. The measured difference in stream gages at the upper and lower end of the model reach was used for each of the modeled dates. These values were also compared to the difference based on the long term records for 1912 – 1962. The inflow to Lake Creek per square mile of drainage basin was calculated. The USGS quantifies the drainage area at gage 14225500 (lake outlet) as 19.2 square miles, and at gage 14226000 (Lake Creek above mouth) as 26.5 square miles, resulting in an additional drainage area between the two gages of 7.3 square miles. The total drainage area was partitioned into 17 sub-basins so that the inflow could be estimated for points along Lake Creek.

Groundwater temperature was measured monthly as part of the water quality study (EES Consulting 2005 and 2007b) at a location near the upper end of the modeled reach. The groundwater temperature at this location was 4.8^{o}C with minimal variation. While this temperature is representative of the upper end of the modeled reach, a separate estimate of groundwater temperature was necessary for the lower end of the reach. When groundwater temperature data are not available, the temperature is often assumed to be similar to the mean annual air temperature (Theruer et. al. 1984). The mean annual air temperature for the NDCC Coop station at Packwood is 10.7^{o}C. The mean annual air temperature at Packwood was used as the estimate of groundwater temperature for the lower end of the modeled reach. Groundwater temperatures for intermediate points along the model reach were interpolated.

Heat exchange between the water and the streambed is simulated in QUAL2Kw by two processes: (1) conduction according to Fick's law is estimated as a function of the temperature gradient between the water and the surface sediment; and (2) hyporheic exchange that occurs with intergravel flow. No hyporheic exchange was incorporated into the model for Lake Creek.

2.4 Climate

Climate data from the Packwood Lake climate station were used to model the most upstream QUAL2Kw segment. Climate data from the Packwood powerhouse climate station were used to model the most downstream segment. Climate data for all intermediate channel segments were interpolated between values used for the most upstream and downstream segments.

A National Climate Data Center Coop station (No. 456262) has been operative in Packwood since 1924. Data from this station were used to supplement data from the two climate stations operated by Energy Northwest. Data from the Coop station were also used to calculate critical climatic conditions for model scenarios. The median and 10% exceedance daily maximum air temperature values for August were calculated based on the long term data record for the Packwood Coop station.

2.5 Heat Flux

Default values for light and surface heat parameters as specified by the user in the QUAL2Kw model were used. Table 2-3 lists values for light and heat transfer parameters.
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Table 2-3 Light and heat transfer values used in Lake Creek QUAL2Kw model

Parameter	Value	Unit
Photosynthetically available radiation	0.47	
Background light extinction	0.2	/m
Linear chlorophyll light extinction	0.0088	1/m-(ugA/L)
Nonlinear chlorophyll light extinction	0.054	1/m-(ugA/L)$^{2/3}$
ISS light extinction	0.052	1/m-(mgD/L)
Detritus light extinction	0.174	1/m-(mgD/L)
Atmospheric attenuation model for solar	Bras	
Atmospheric turbidity coefficient (2=clear, 5=smoggy, default=2)	2	
Atmospheric transmission coefficient (0.70-0.91, default 0.8)	0.8	
Atmospheric longwave emissivity model	Brunt	
Wind speed function for evaporation and air convection/conduction	Brady-Graves-Geyer	

2.6 Model Calibration

Dates within August 2004 and August 2005 were reviewed to identify those days with climate conditions most similar to the median and 10% exceedance climate criteria; the latter based on the period of record 1924 – 2006. The QUAL2Kw model was then set up to reflect environmental conditions for those dates. The model was calibrated for the existing condition, which had a base flow release of 3 cfs below the drop structure plus measured accretion downstream. Adjustment of the accretion flow was the primary means for calibrating the model. The model showed little sensitivity to climate or shading as groundwater accretion was the largest determinant of downstream water temperature. The model was calibrated for the best fit diurnal pattern, maximum, mean and minimum water temperatures as measured at Rkm 7.9 (monitoring location LCMH near mouth) and Rkm 0.5 (monitoring station LCDS-1500). Note that the QUAL2Kw model treats the upper end of the model reach as Rkm 0. Therefore, the results are presented with the drop structure being at Rkm 0 and the mouth of Lake Creek at Rkm 8.5.

3.0 RESULTS

Lake Creek downstream of the drop structure to the USFS boundary is bordered by mature conifer riparian stands with inclusions of red alder within the channel disturbance zone. Riparian vegetation extending 400 m downstream of the drop structure was mapped as Pacific silver fir and red cedar, 35 m canopy height with a year of origin 1787. Red alder stands dominate closest to the channel for the first 100 m downstream of the drop structure. The riparian stand extending from 400 m downstream of the drop structure to the Forest Service boundary was mapped as large tree, multi storied cedar hemlock with a canopy height of 32 m with 1629 as a year of origin. Downstream of the Forest Service boundary to the mouth, the riparian stands are primarily red alder with a canopy height of 27 m. The density of all riparian stands listed in the model was 75%. The effective shade as computed by the model shade_ver3.0 and inclusive of both topographic and vegetation shading is shown in Figure 3-1. The average effective shade for Lake Creek was 83%.

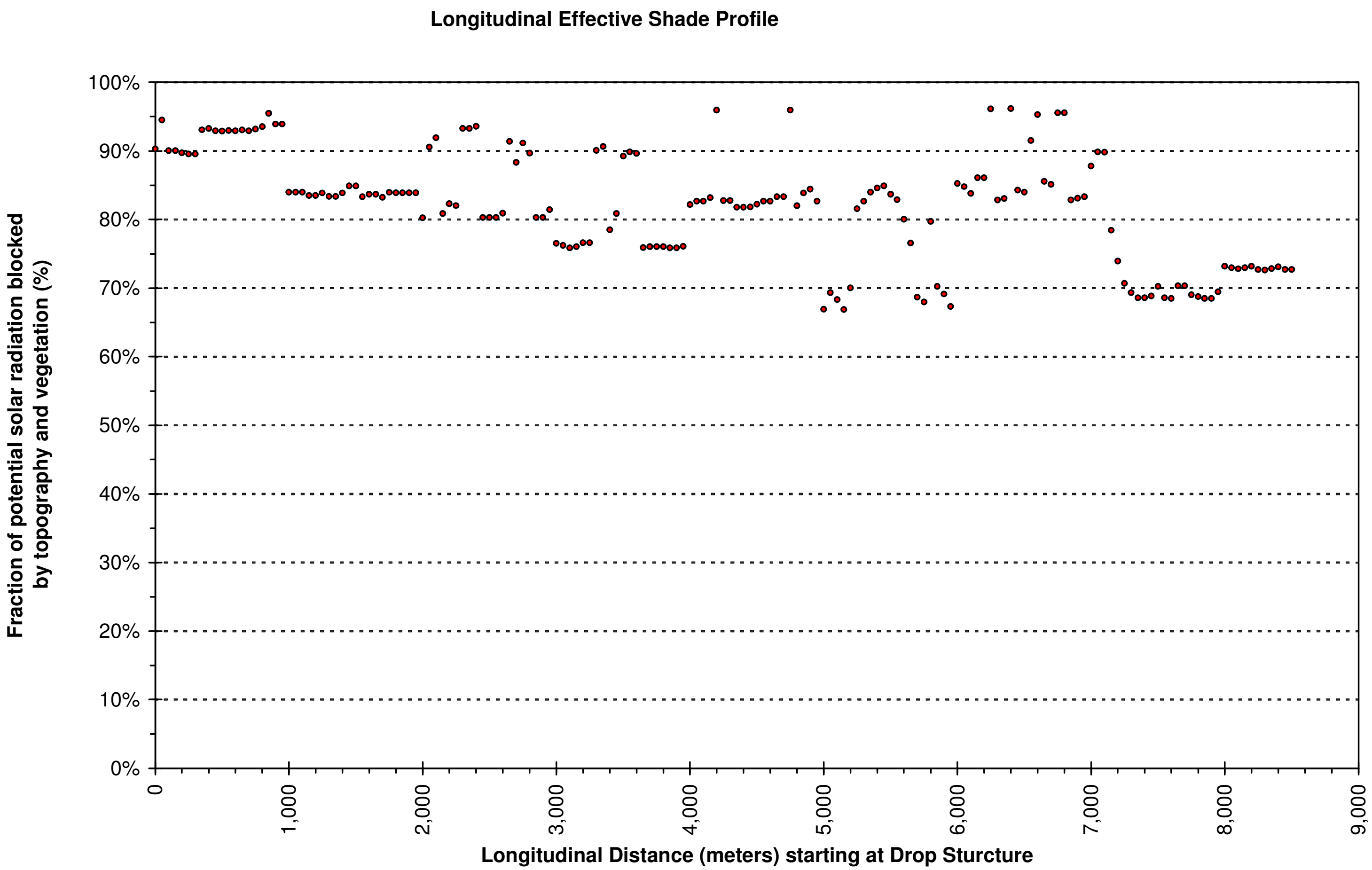

Figure 3-1 Effective shade for Lake Creek

Water quality was monitored at three locations downstream of Packwood Lake; station LCDS is immediately downstream of the drop structure, LCDS-1500 is approximately 0.5 km downstream and station LCMH is near the mouth of Lake Creek at Rkm 7.9. Water quality was also monitored in the Cowlitz River just upstream of the confluence with Lake Creek. When no spill over the drop structure occurs, the flow in lower Lake Creek is primarily from accretion in addition to the minimum 3 cfs flow released from Packwood Lake.

Summer water temperatures decline in a downstream direction within Lake Creek. While the water temperature immediately downstream of the lake commonly exceeds the State water temperature criteria, the water temperature near the mouth never exceeded the criteria. The number of days in 2004 that the 7-DADMax water temperature criteria of 16°C were exceeded is 74 days at LCDS, 54 days at LCDS1500 and 0 days for LCMH. The number of days in 2005 that the water temperature criterion of 16°C was exceeded is 77 days at LCDS, 62 days at LCDS1500 and 0 days for LCMH.

Immediately downstream of the drop structure (LCDS), the water temperature is a function of the lake temperatures at the intake. For the period July through October, the average maximum daily water temperature declines 1°C within approximately 1,500 ft downstream of the drop structure. This decline is attributed to the water temperature responding to ambient conditions within the channel. Riparian shade that is high relative to the lake and cold groundwater inflow are both factors that contribute to the downstream cooling trend in Lake Creek. Figure 3-2 shows the trend in 2004 for the 7-DADMax for Lake Creek and the Cowlitz River upstream of Lake Creek. The pattern was very similar for 2005 with the annual peak occurring slightly earlier. The hottest 7-DADMax at LCMH occurred on August 17 in 2004 and August 10 in 2005.

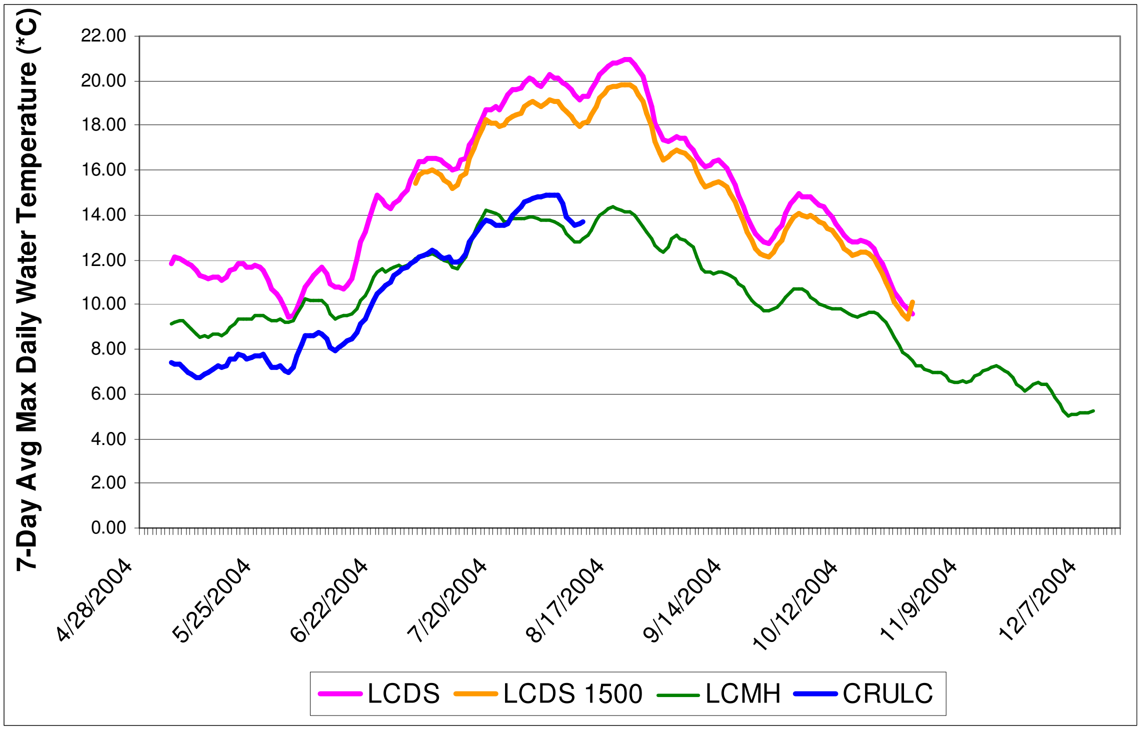

Figure 3-2 7-day average of the maximum daily temperature (7-DADMax) for Lake Creek and the Cowlitz River

The record for the NCDC Coop climate station at Packwood was reviewed to determine the median and 10% exceedance air temperatures. Based on the period of record July and August 1924 – 2006, the median and the 10% exceedance maximum daily air temperature are 26°C and 32.78°C, respectively. The climate data record for August 2004 and August 2005 were reviewed to identify dates when climatic conditions were approximately equal to the median and 10% exceedance conditions. Figure 3-3 shows the maximum daily air temperature data at Packwood for August.

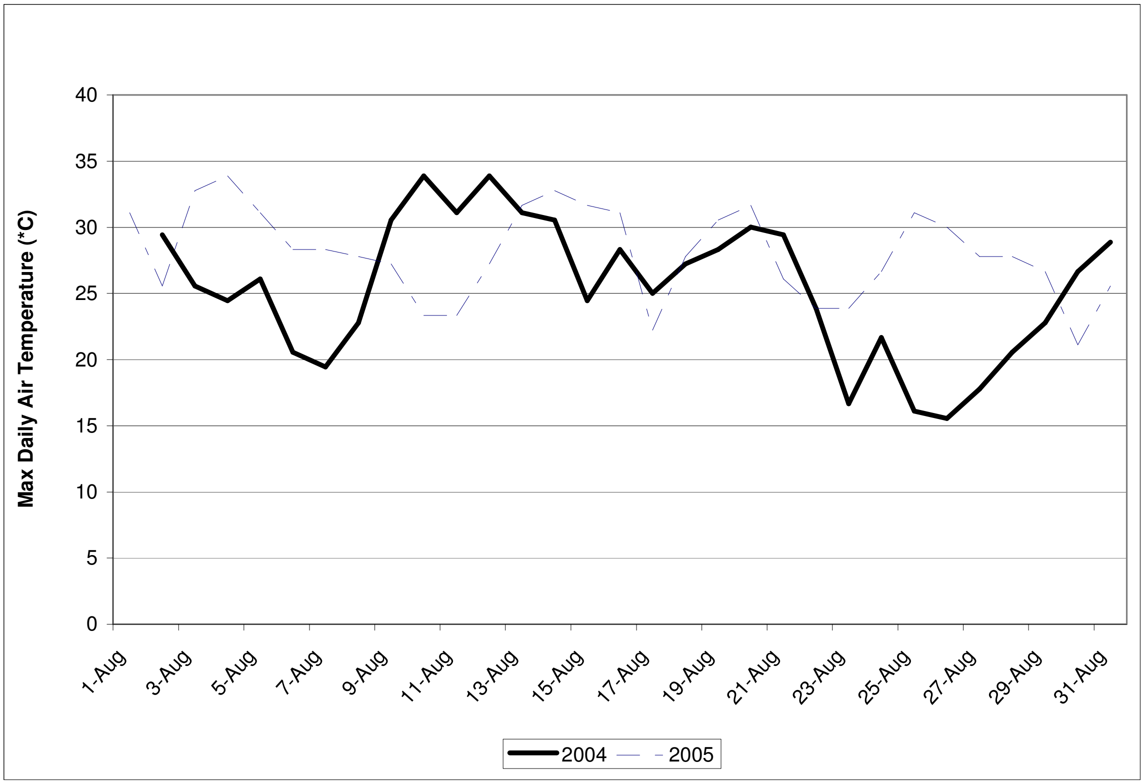

Figure 3-3 Maximum daily air temperature at Packwood

The QUAL2Kw model is a steady state model that is set up to model steady state conditions (steady flow but diurnally variable climate conditions) for a one day period. Table 3-1 lists the dates selected to model water temperature for Lake Creek.

Table 3-1 Water temperature modeling dates for Lake Creek

Date	Air Temp Max (^oC)	Rationale
Aug 5, 2004	26.1	Median climate
Aug 12, 2004	33.89	10% exceedance climate
Aug 14, 2005	32.78	10% exceedance climate
Aug 21, 2005	26.0	Median climate

Hourly climate data for air temperature and dewpoint temperature were used from both the climate station at the powerplant and at the intake. Wind speed data from the station at the intake were used. Solar radiation data from the intake climate station were reviewed to determine appropriate values for hourly cloud cover, which varied between 0 – 25%.

Table 3-2 lists the stream discharges applied in the QUAL2Kw model for each of the modeled dates. The model for the existing condition used the measured discharge at the drop structure and lower gage (Rkm 7.9) with the diffuse groundwater accretion prorated according to basin area. The total accretion is the difference between the measured flow at the upper and lower end of the model reach. The total accretion calculated as the difference between the 7Q2 flow below the drop structure (USGS No 14225500) and near the mouth (USGS No. 14226000) as calculated by Dflow is 0.3596 cms.

Table 3-2 Stream flows for the QUAL2Kw model scenarios for Lake Creek

Date	Scenario	Flow below Drop Structure (cms)	Study Site	Study Site/Reach Accretion[1] (cms)
Aug 5, 2004	Existing	0.085	4	0.0125
	Existing without Project	1.597	3	0.03
	7Q2	1.597	2	0.11
	7Q10	1.1298	1	0.08
Aug 12, 2004	Existing	0.085	4	0.005
	Existing without Project	1.597	3	0.0365
	7Q2	1.597	2	0.11
	7Q10	1.1298	1	0.08
Aug 14, 2005	Existing	0.085	4	0.007
	Existing without Project	0.93445	3	0.0245
	7Q2	1.597	2	0.135
	7Q10	1.1298	1	0.08
Aug 21, 2005	Existing	0.085	4	0.007
	Existing without Project	0.79287	3	0.0245
	7Q2	1.597	2	0.25
	7Q10	1.1298	1	0.1

[1] *Accretion was kept the same for all model scenarios for a given date*

The diffuse inflow rates were adjusted during calibration to achieve a good fit between measured and predicted water temperature. The option for modeling hyporheic flow was not used.

3.1 Model Calibration

Figures 3-4 through 3-7 show the predicted temperature relative to measured water temperatures for the existing conditions for each of the four modeled dates. Table 3-3 lists the measured and predicted temperatures for the existing condition scenarios.

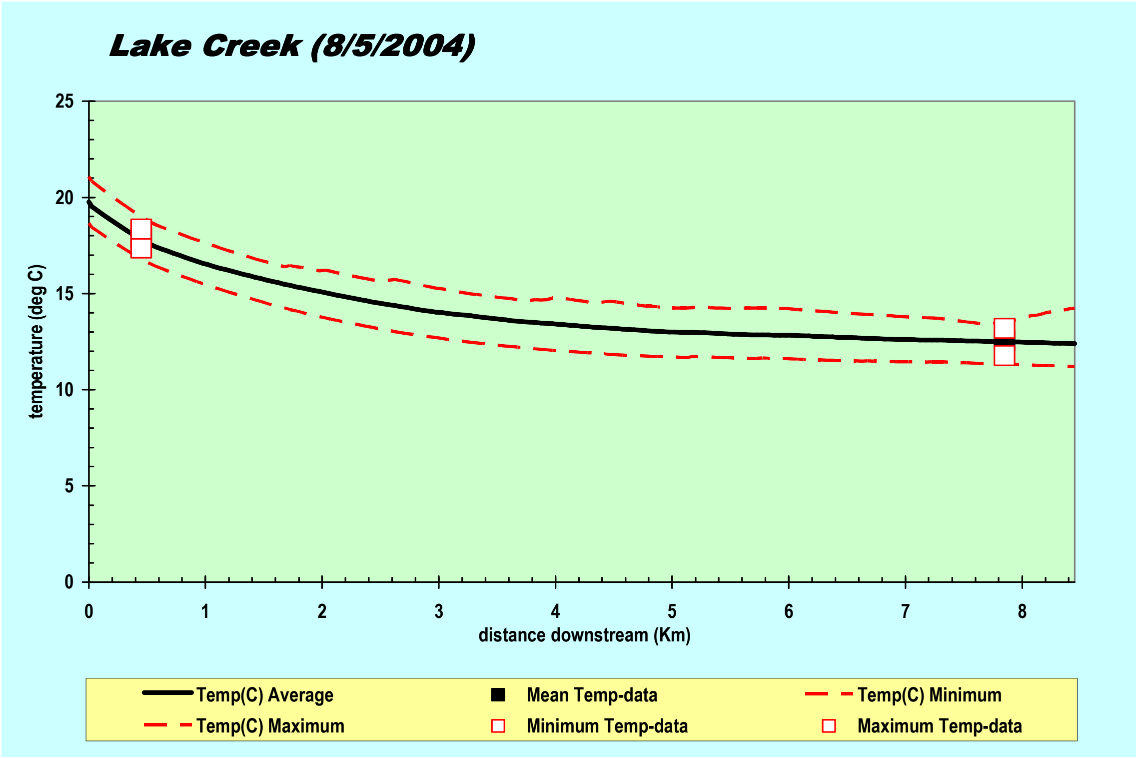

Figure 3-4 Calibration for existing condition Lake Creek August 5, 2004 (Measured temperatures are shown as □. Drop structure is at Rkm 0.0)

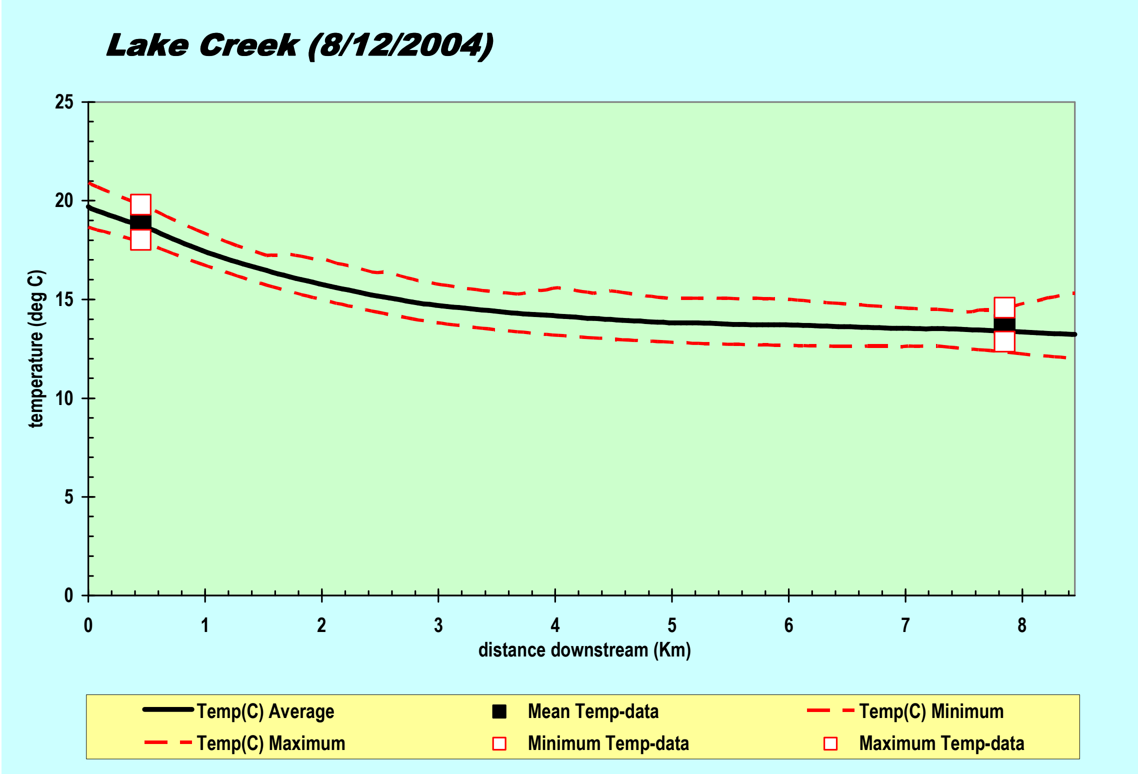

Figure 3-5 Calibration for existing condition Lake Creek August 12, 2004

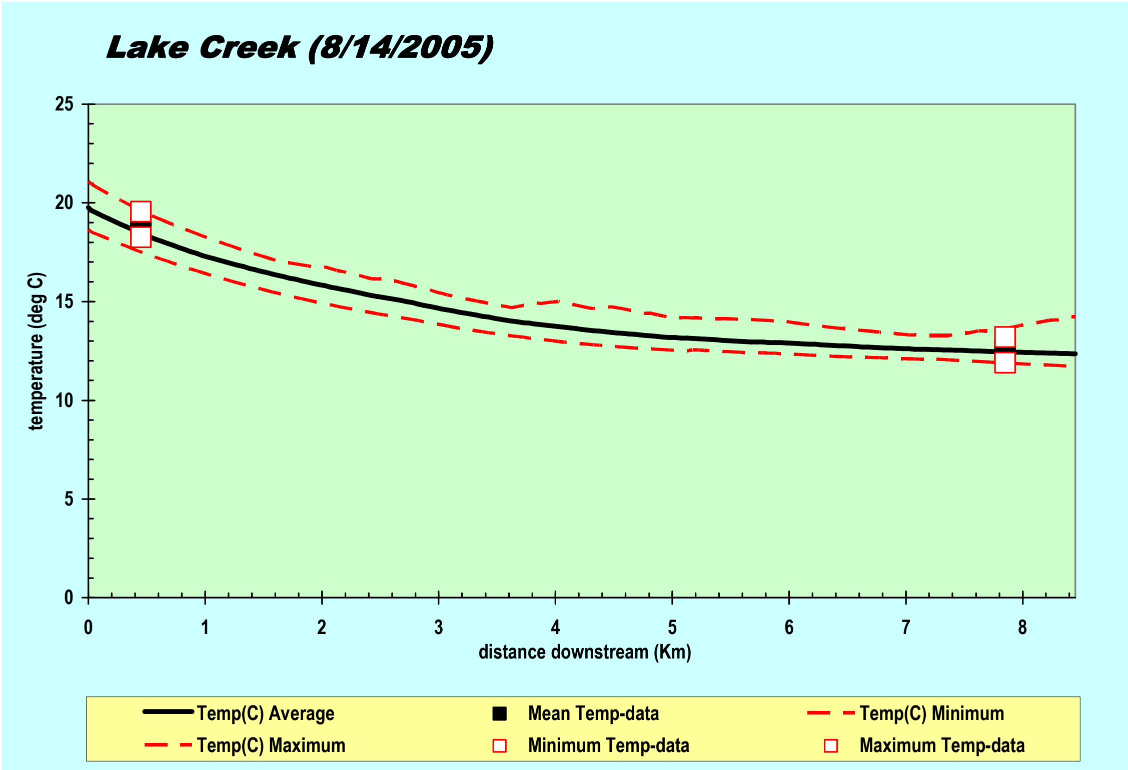

Figure 3-6 Calibration for existing condition Lake Creek August 14, 2005

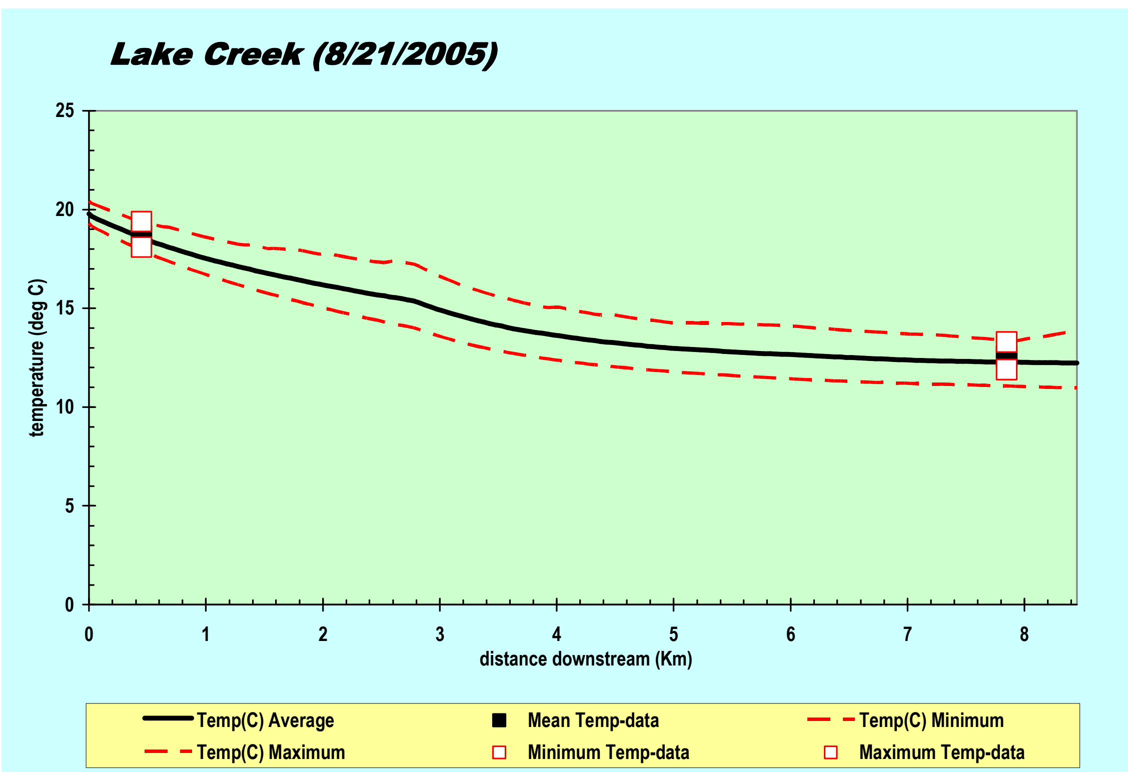

Figure 3-7 Calibration for existing condition Lake Creek August 21, 2005

Table 3-3 Comparison of measured and model predicted water temperature

	Distance Downstream of Lake (km)	Measured Temperature (^oC)			Predicted Temperature (^oC)		
		Mean	Minimum	Maximum	Mean	Minimum	Maximum
8/3/2004	0.00	18.95	18.17	19.30			
	0.50	17.89	17.37	18.34	17.90	16.89	19.09
	7.90	12.55	11.78	13.18	12.48	11.33	13.55
	8.50				12.41	11.21	14.23
8/12/2004	0.00	19.69	18.65	20.92			
	0.50	18.84	18.02	19.80	18.78	17.95	19.85
	7.90	13.73	12.87	14.58	13.38	12.32	14.61
	8.50				13.23	12.03	15.30
8/14/2005	0.00	20.06	19.63	20.76			
	0.50	18.86	18.25	19.56	18.53	17.56	19.69
	7.90	12.60	11.90	13.20	12.45	11.88	13.67
	8.50				12.37	11.73	14.22
8/21/2005	0.00	20.43	19.3	19.75			
	0.50	18.69	18.09	19.39	18.64	18.00	19.41
	7.90	12.56	11.90	13.30	12.28	11.06	13.38
	8.50				12.23	10.97	13.81

The predicted maximum daily temperature was, on average, -0.24^oC cooler than the measured water temperature for the calibration model scenarios. The mean daily predicted temperature was 0.4^oC warmer than the mean daily measured temperature and predicted minimum temperatures were within 0.1^oC of the measured temperatures.

3.2 Model Application

Figures 3-8 through 3-11 show the predicted longitudinal maximum daily water temperatures for all the model scenarios for each of the model dates. Table 3-4 presents the predicted temperatures for each of the modeled scenarios, which include existing conditions with the Project as well as the without Project scenarios for the 7Q2 and 7Q10 flow as measured immediately downstream of the lake. The inflow into the lake for the two modeled dates in 2004 was the equivalent of the 7Q2 flow outflow from the lake so the without Project scenario is the same as the 7Q2 flow.

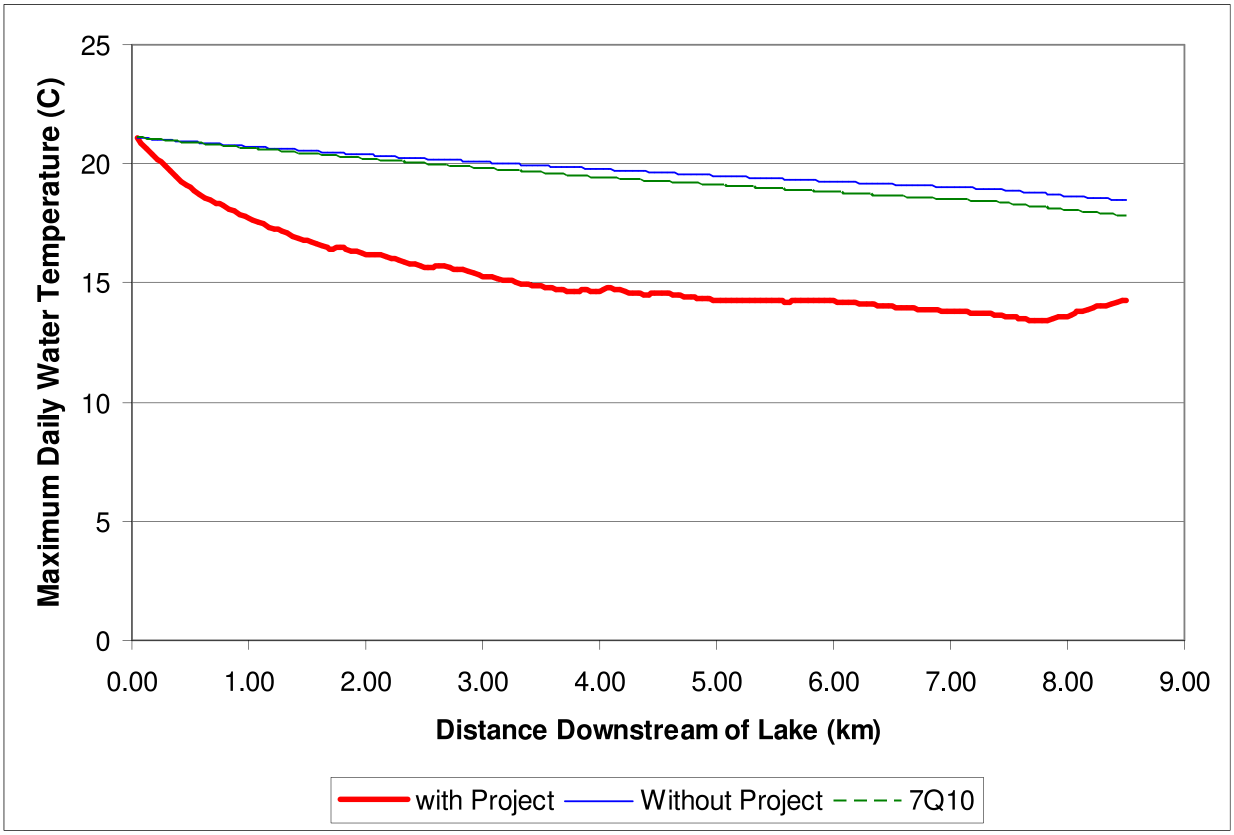

Figure 3-8 Maximum daily water temperatures predicted by QUAL2Kw model for August 5, 2004; median climate conditions. (The without Project flow was equal to the 7Q2 flow)

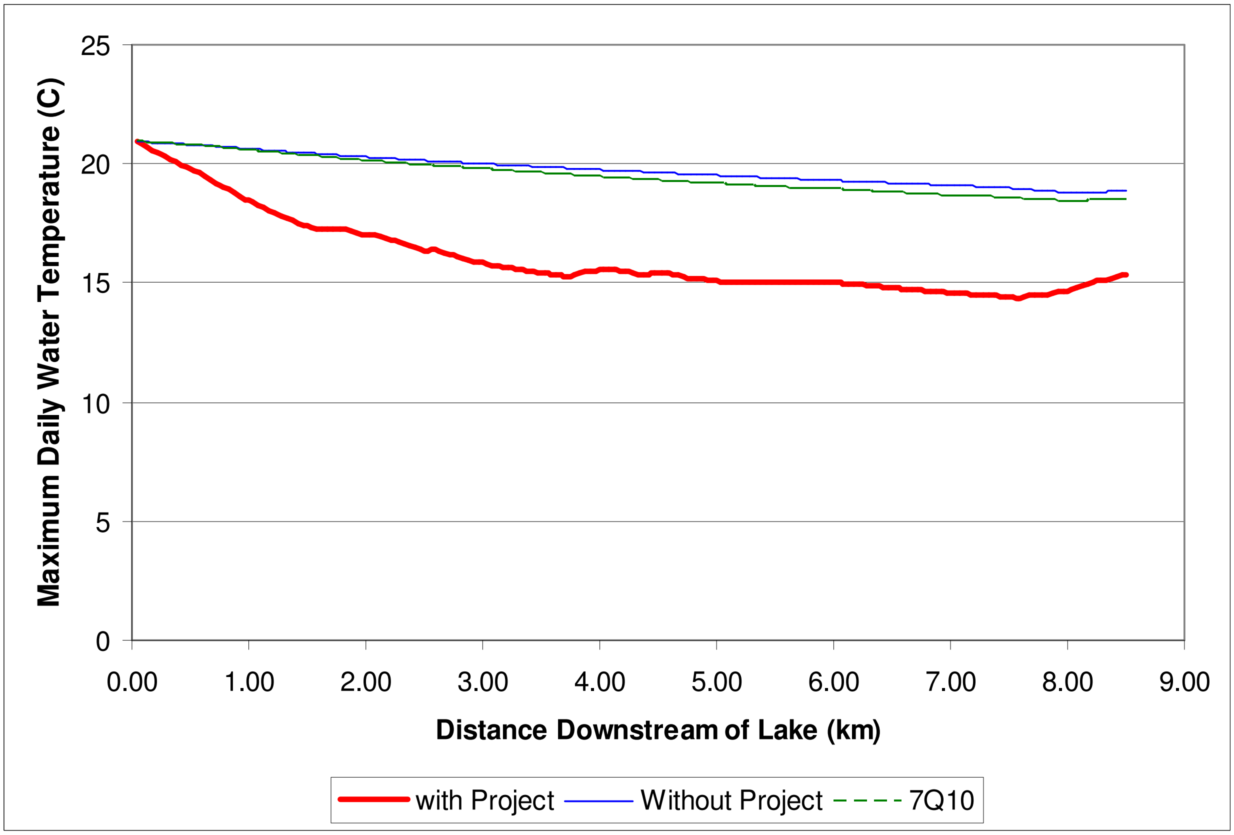

Figure 3-9 Maximum daily water temperatures predicted by QUAL2Kw model for August 12, 2004; 10% exceedance climate conditions. (The without Project flow was equal to the 7Q2 flow)

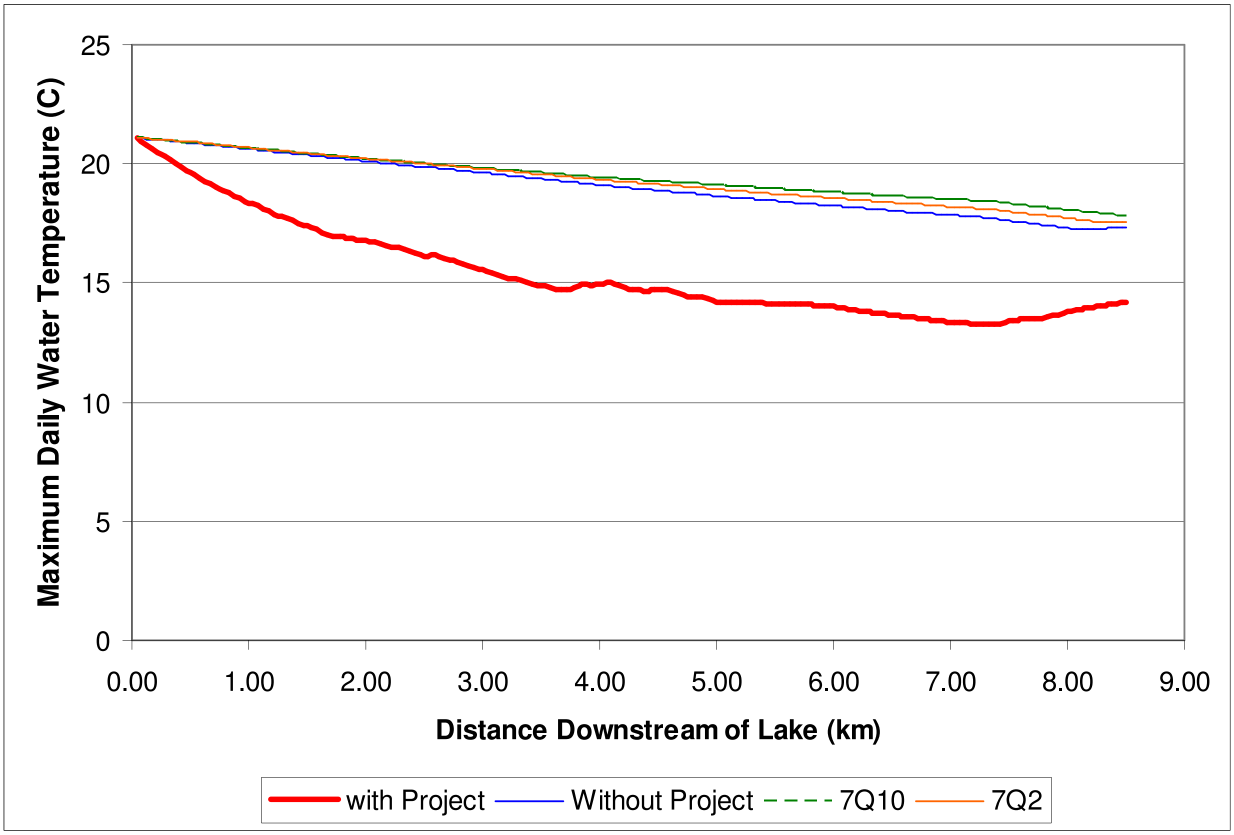

Figure 3-10 Maximum daily water temperatures predicted by QUAL2Kw model for August 14, 2005; 10% exceedance climate conditions

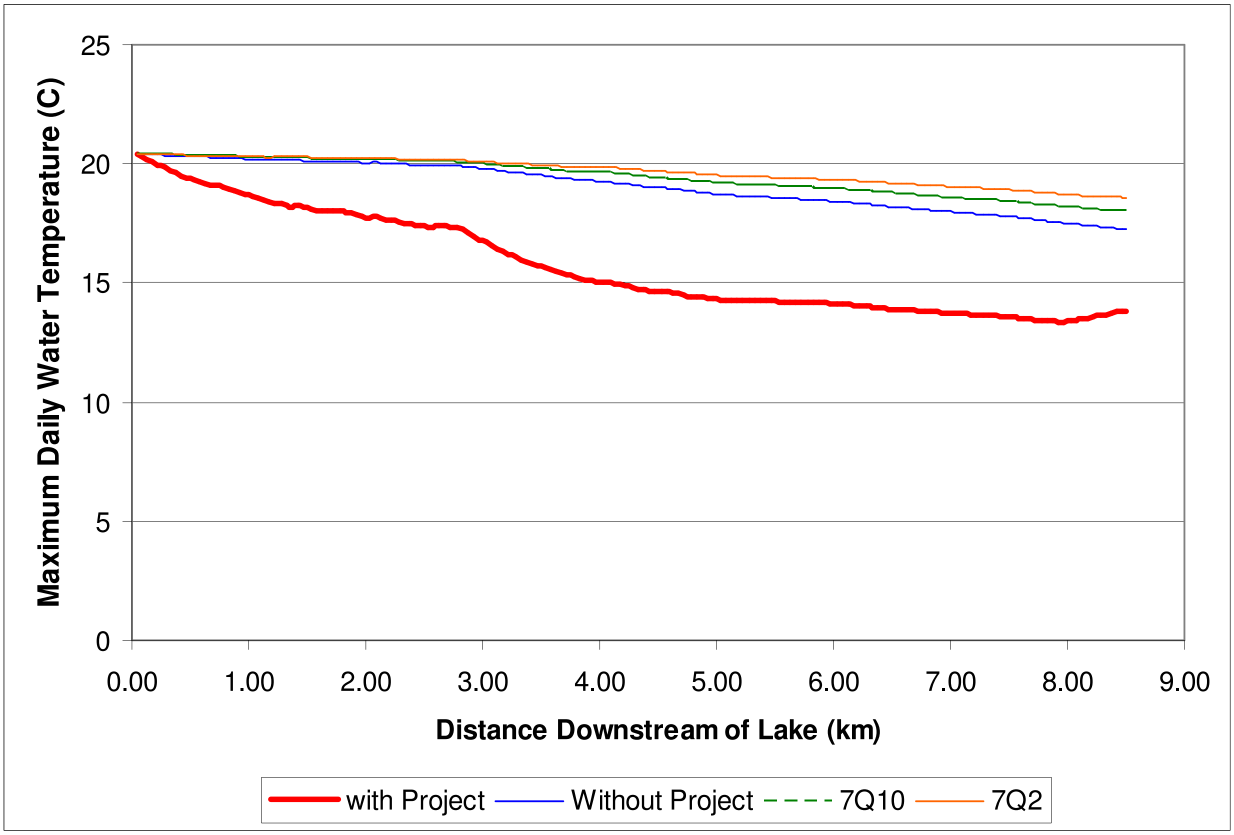

Figure 3-11 Maximum daily water temperatures predicted by QUAL2Kw model for August 21, 2005; median climate conditions

Table 3-4 Water temperatures predicted by QUAL2Kw for Lake Creek

		Predicted Daily Water Temperature		
Scenario	**River km**	**Mean**	**Min**	**Max**
8/5/2004 existing (median climate)	0.48	17.90	16.89	19.09
	7.92	12.48	11.33	13.55
	8.50	12.41	11.21	14.23
8/05/04 7Q2 without Project[1]	0.48	19.60	18.50	20.93
	7.92	17.74	16.45	18.69
	8.50	17.57	16.27	18.46
8/05/04 7Q10 flow	0.48	17.24	15.93	18.06
	7.92	17.24	15.93	18.06
	8.50	17.03	15.71	17.78
8/12/2004 (10% exceedance climate)	0.48	18.78	17.95	19.85
	7.92	13.38	12.32	14.61
	8.50	13.23	12.03	15.30
8/12/2004 7Q2 existing/without Project[1]	0.48	19.61	18.61	20.82
	7.92	18.09	17.13	18.81
	8.50	17.93	16.93	18.84
8/12/2004 7Q10	0.48	19.58	18.59	20.79
	7.92	17.66	16.71	18.44
	8.50	17.46	16.46	18.51
8/14/2005 existing (10% exceedance climate)	0.48	18.53	17.56	19.69
	7.92	12.45	11.88	13.67
	8.50	12.37	11.73	14.22
8/14/2005 without project	0.48	19.58	18.51	20.89
	7.92	16.91	16.07	17.35
	8.50	16.69	15.84	17.31
8/14/2005 7Q2	0.48	19.61	18.53	20.92
	7.92	17.23	16.37	17.76
	8.50	17.02	16.16	17.55
8/14/2005 7Q10	0.48	19.61	18.53	20.92
	7.92	17.23	16.37	17.76
	8.50	17.02	16.16	17.55
8/21/2005 existing (median climate)	0.48	18.64	18.00	19.41
	7.92	12.28	11.06	13.38
	8.50	12.23	10.97	13.81
8/21/2005 existing without project	0.48	19.61	19.08	20.29
	7.92	16.22	15.11	17.54
	8.50	15.99	14.85	17.26
8/21/2005 7Q2	0.48	19.68	19.17	20.36
	7.92	17.48	16.52	18.74
	8.50	17.30	16.30	18.58
8/21/2005 7Q10	0.48	19.65	19.14	20.33
	7.92	16.90	15.86	18.20
	8.50	16.69	15.61	18.00

[1]*The without Project existing flow was equal to the 7Q2 flow for dates in 2004*

3.3 7-DADMax for Lake Creek

The water quality standard for temperature is based on the 7-day average of the maximum daily water temperature (7-DADMax). The highest measured 7-DADMax for Lake Creek immediately below the drop structure (LCDS) occurred for the period ending August 21 for both 2004 and 2005 (EES consulting 2005, 2007b). The 7-DADMax for Lake Creek without the Project was calculated by modeling temperatures for the 7 day period August 15 – 21, 2004. Each day was modeled independently and then the maximum daily temperatures were averaged for the 7-day period. The QUAL2Kw model was first calibrated for the existing conditions. Table 3-5 compares the predicted temperatures to the measured temperatures for the calibration model runs. The absolute mean error in the predicted maximum daily temperature was 0.22^{o}C at Rkm 0.5 (0.5 km downstream of drop the drop structure) and 0.16^{o}C at Rkm 7.9.

Table 3-5 Comparison of measured and model predicted water temperature for August 15-21, 2004

	Distance Downstream of Lake (km)	Measured Temperature (^{o}C)			Predicted Temperature (^{o}C)		
		Mean	Minimum	Maximum	Mean	Minimum	Maximum
8/15/2004	0.00	19.85	18.81	21.09			
	0.50	19.04	18.5	19.96	19.03	18.09	20.29
	7.90	13.54	12.72	14.27	13.38	11.94	14.36
	8.50				13.21	11.79	14.60
8/16/2004	0.00	19.65	18.49	20.59			
	0.50	18.91	18.18	19.8	18.81	17.77	19.77
	7.90	13.77	13.18	14.43	13.39	12.06	14.33
	8.50				13.24	11.91	14.92
8/17/2004	0.00	19.70	19.14	20.76			
	0.50	18.81	18.34	19.47	18.81	18.14	19.83
	7.90	13.66	13.03	14.11	13.06	11.85	14.03
	8.50				12.91	11.67	14.60
8/18/2004	0.00	19.96	19.46	20.92			
	0.50	18.92	18.34	19.8	19.02	18.45	19.97
	7.90	13.34	12.56	13.96	12.91	11.32	14.01
	8.50				12.76	11.17	14.43
8/19/2004	0.00	20.14	19.63	21.25			
	0.50	19.16	18.5	19.96	19.27	18.85	19.94
	7.90	13.54	12.72	14.27	13.30	11.69	14.43
	8.50				13.13	11.53	14.89
8/20/2004	0.00	20.40	19.79	21.42			
	0.50	19.31	18.66	20.12	19.43	18.66	20.52
	7.90	13.58	12.87	14.11	13.10	11.65	14.11
	8.50				12.94	11.48	14.72
8/21/2004	0.00	20.18	19.95	20.59			
	0.50	19.23	18.82	19.64	18.78	17.95	19.85
	7.90	13.50	13.03	13.96	13.38	12.32	14.61
	8.50				13.23	12.03	15.30

The model scenarios for August 15-21, 2004 used the natural inflow to the lake for the flow at the upper end of the modeled reach. The natural inflow range during this period was 1.153 – 2.093 cms (41 - 74 cfs). The median daily lake inflow was 1.302 cms, which is 15% greater than the 7Q10 flow. The flow was approximately equal to the 7Q10 flow on 3 of the 7 days. Groundwater accretion within the modeled reach was kept the same for calibration and without project model runs; accretion rates were only minimally adjusted between days within the modeled period for calibration model runs.

Table 3-6 lists the predicted temperatures for the "without Project" condition. The 7-DADMax for without Project was 19.27°C near the mouth of Lake Creek (Rkm 7.9 LCMH), which compares to a measured 7-DADMax of 14.16°C for the existing condition. The predicted 7-DADMax at the mouth of Lake Creek was 19.09°C; however, no comparable measured data are available at the mouth.

Table 3-6 Predicted without project water temperatures for August 15-21, 2004

	Distance Down-stream of Packwood Lake (km)	Measured Temperature (°C)		
		Mean	Minimum	Maximum
8/15/2004	0.50	19.77	18.75	21.02
	7.90	18.09	16.89	19.29
	8.50	17.90	16.67	19.05
8/16/2004	0.50	19.57	18.42	20.52
	7.90	17.91	16.84	19.24
	8.50	17.72	16.65	19.12
8/17/2004	0.50	19.61	19.02	20.66
	7.90	17.74	16.92	18.74
	8.50	17.55	16.68	18.56
8/18/2004	0.50	19.85	19.33	20.81
	7.90	17.68	16.45	18.92
	8.50	17.47	16.19	18.72
8/19/2004	0.50	20.07	19.81	20.51
	7.90	18.00	16.92	19.44
	8.50	17.78	16.65	19.24
8/20/2004	0.50	20.28	19.64	21.32
	7.90	18.01	16.84	19.41
	8.50	17.78	16.58	19.15
8/21/2004	0.50	20.11	19.87	20.53
	7.90	18.58	17.94	19.85
	8.50	18.43	17.75	19.80
7-DADMax	0.50			20.77
	7.90			19.27
	8.50			19.09

4.0 DISCUSSION

The water temperature for a stream reach is a function of the net balance of heat energy. The energy balance is regulated by the environment surrounding that stream reach. A parcel of water enters a stream reach with a given temperature. If that temperature is higher than the energy balance can maintain, then the water temperature will decrease. If a stream reach with constant environmental conditions is sufficiently long so that the travel time of a parcel of water through the reach is at least as long as the time required to achieve an energy balance to the surrounding conditions, then the temperature is considered to be at equilibrium.

Air temperature, solar shading and stream depth are the most important environmental variables affecting water temperature in a stream (Adams and Sullivan 1989). Higher air temperatures lead to higher water temperatures. The modeling for this study applied the typical (median) air temperature and the extreme (10% exceedance) air temperature regimes based on the daily climate data for the Packwood NCDC coop station. Solar shading is expressed as a percent of the solar radiation that is blocked by physical features. Solar shade can be created by both topographic shading and riparian shading. Topographic shade accounts for about 22% effective shade when averaged for the reaches. Modeling the 7Q2 flow (without Project) for a typical day (August 5, 2004) with only topographic shade (no riparian vegetation) resulted in a maximum daily water temperature at the mouth of Lake Creek that was about 1^{o}C warmer (Figure 4-1). The effect of riparian shade is most pronounced for the first 1.8 km downstream from the lake where the predicted water temperature increased within this reach relative to the lake outflow temperature. The shallow depth in the stream channel relative to the lake provides for higher maximum daily temperatures for a short reach downstream of the lake. Further downstream groundwater influence is more pronounced and the maximum temperature decreases at a similar rate per km for both the shaded and no riparian shade models.

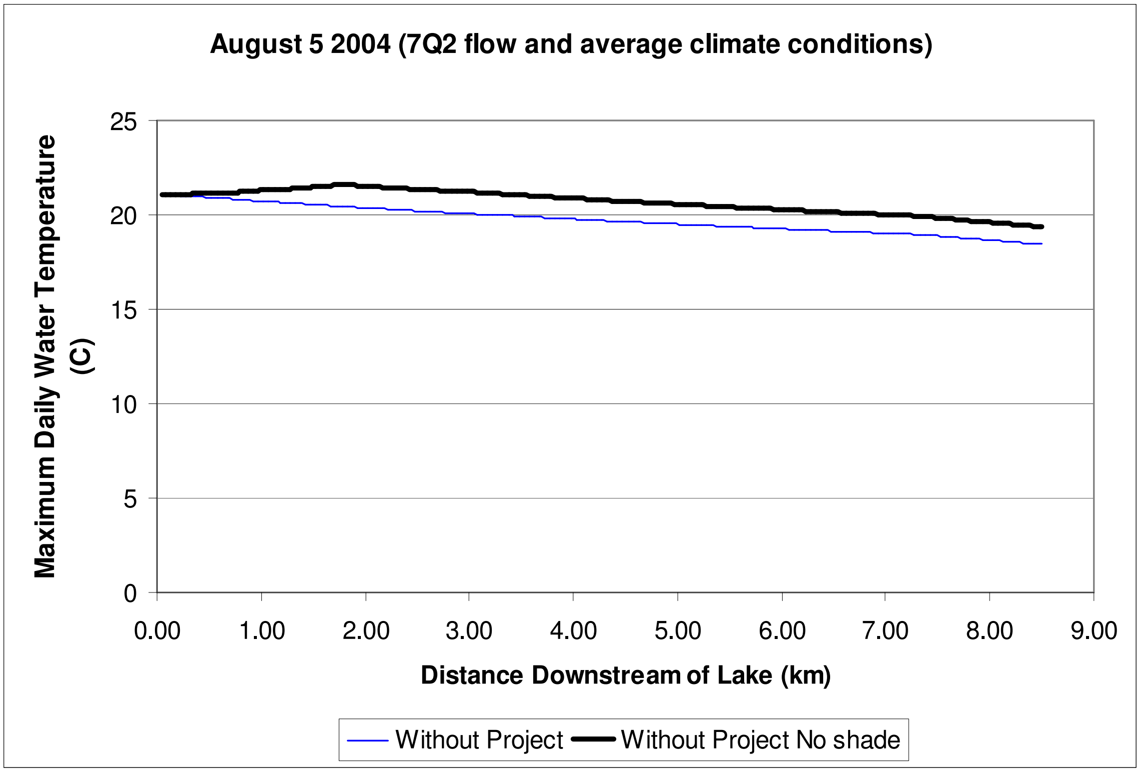

Figure 4-1 Comparison of predicted maximum water temperature for 7Q2 flow with and without riparian shade

Stream depth is a function of flow and channel shape. Greater depth requires a longer time (and distance) to reach equilibrium. A deeper stream has a reduced diurnal temperature fluctuation, but the average temperature when the stream is at equilibrium with surrounding conditions will be the same. The models for Lake Creek were minimally sensitive to stream depth.

The modeled rate and temperature of the groundwater inflow varied for each of the four sub-reaches defined in the model. Groundwater accretion rate and groundwater temperature are the variables that primarily define water temperature for the existing "with Project" model scenarios. The cooling effect of groundwater is less pronounced for the without Project scenarios because the water mass is larger and the groundwater proportion is much less. The majority of the flow in Lake Creek originates as groundwater inflow when the release below the drop structure is the 0.085 cms (3 cfs) minimum release flow.

The transport of heat in a stream has been extensively studied (Edinger et. al. 1974; Theurer 1984). Heat exchange processes include shortwave solar radiation, longwave atmospheric radiation (into the stream and radiated back to the sky), convection, evaporation and conduction. The net effect of these processes determines the water temperature at any given time of day. The relative importance of each process varies diurnally. Figure 4-2 shows the relative importance of heat flux processes for Lake Creek near the mouth (km 7.9).

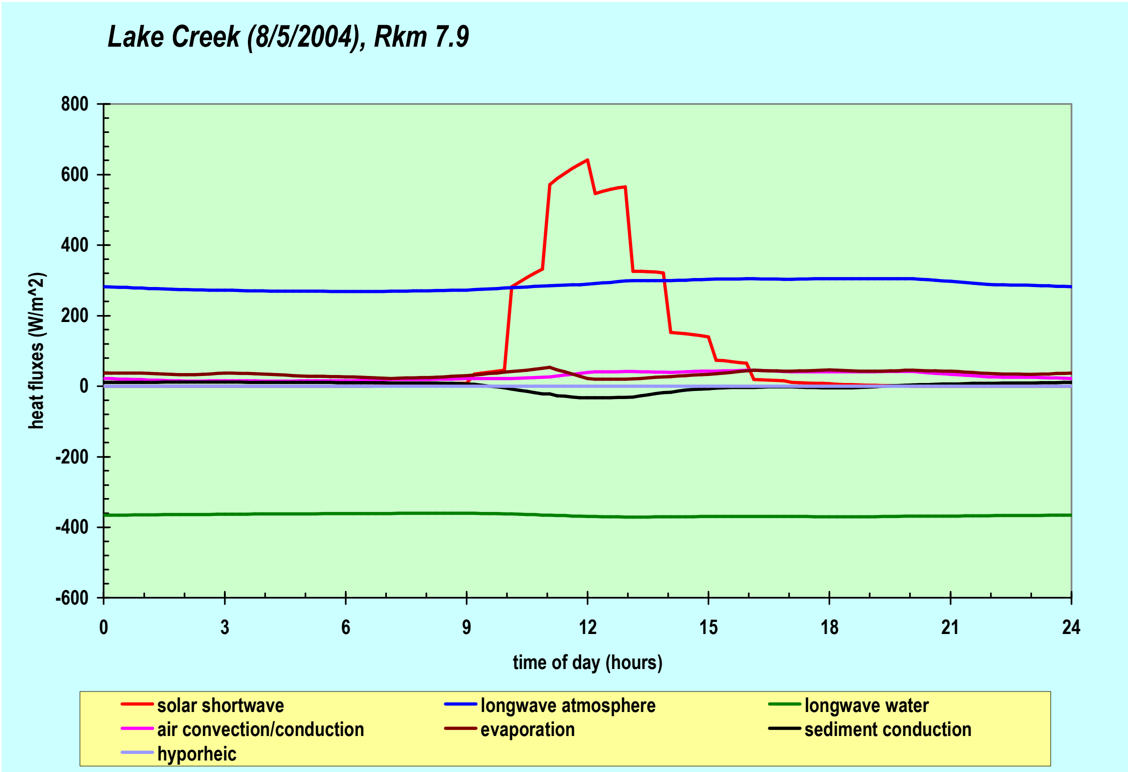

Figure 4-2 Heat flux processes diurnal pattern for Lake Creek August 5, 2004 at Rkm 7.9

Shortwave radiation had the greatest diurnal variation. The high percentage for effective shade reduces the influence of shortwave radiation on water temperature. Shortwave radiation rapidly increased at about 10 am and peaked at noon for the example in Figure 4-2. Figure 4-3 shows the diurnal water temperature pattern for the with-Project and without-Project for a typical day with a 7Q2 flow (August 5, 2004). The stream temperature responded to the increased solar radiation as demonstrated by the increase in temperature between 10 am and about noon. The influence of solar radiation is slightly more pronounced for the without-Project scenario as compared to the influence of groundwater that dominated the with-Project scenario.

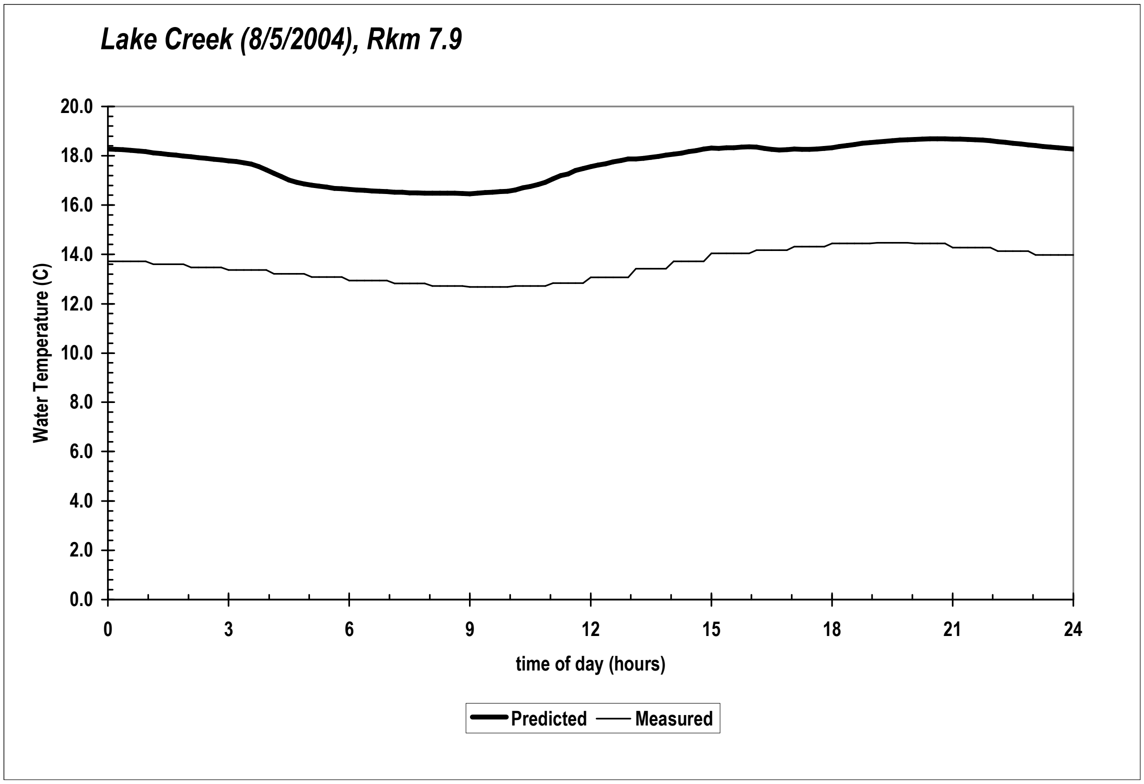

Figure 4-3 Diel water temperature for August 5, 2004: 7Q2 typical climate conditions

Summer water temperatures without the Project are substantially warmer than with the Project. The model scenarios for the 7Q2 on August 5, 2004 and August 21, 2005 represent typical conditions. Maximum daily water temperature at the mouth was 5.27°C cooler with the Project for these two dates.

The model scenario that would be expected to result in the highest stream temperatures is an extremely hot day when flow is at the 7Q10. This condition is represented by the 7Q10 flow model scenarios for August 12, 2004 and August 14, 2005. Maximum daily water temperature at the mouth was 4.2°C and 3.5°C cooler, respectively, for these two dates for the with-Project model scenario. The majority of the flow in Lake Creek is from cool groundwater accretion when there is no spill at the drop structure.

Groundwater accretion for the models was distributed longitudinally according to calculations reported in EES Consulting (2007d). It was assumed that the groundwater accretion in the lower 1.1 km (IFIM Study Site 1) was low. In this area, the Lake Creek stream channel makes the transition from a steep and moderately incised channel to a lower gradient and slightly confined channel as it flows across the floor of the Cowlitz River valley. The effect of specifying minimal groundwater accretion in the lowermost sub-reach is demonstrated by a wider diurnal range at the mouth as shown in Figure 3-4 through Figure 3-6. Water temperature was monitored at Rkm 7.9. It is unknown if the modeled increase in diurnal temperature range for the lower 1.1 km actually occurred or is an artifact of the model specifications for groundwater.

The 7-DADMax temperature was evaluated for with and without the Project. When the Project is operating, water travels downstream from Packwood Lake via two routes; the release flow into Lake Creek below the drop structure and the pipeline/powerhouse tailrace flow. The 7-DADMax temperature near the mouth of Lake Creek for the without Project model is substantially higher than the 7-DADMax for the existing condition. A small amount of cooling occurs for water flowing out of Packwood Lake down Lake Creek due to shading and, more importantly, the addition of cold groundwater accretion. There was no significant difference for measured water temperatures measured at the outlet of the lake and the lower end of the tailrace. The period August 15-21, 2004 represented the highest temperatures for Lake Creek below the drop structure as well as tailrace temperatures recorded in 2004 and 2005. The QUAL2Kw model was applied to existing conditions for each day during this period. The predicted 7-DADMax at the mouth of Lake Creek without the Project was 19.09^{o}C, which compared to a measured 7-DADMax at the lower end of the tailrace of 21.25^{o}C. A similar comparison for the period of highest measured water temperatures in 2005 was not completed since the Project was shut down intermittently in August 2005 without a consecutive 7-day operating period.

Any increase in flow released below the drop structure in the summer results in warmer temperatures throughout lower Lake Creek relative to the existing condition with a 0.085 cms (3 cfs) release below the drop structure. Table 4-1 lists the 7-DADMax at the mouth of Lake Creek associated with various flow releases below the drop structure.

Table 4-1 7-DADMax water temperature at Lake Creek mouth relative to flow below the drop structure

Flow below Drop Structure cms (cfs)	0.085 (3)	0.198 (7)	0.283 (10)	0.425 (15)
7-DADMax (^{o}C)	14.16	15.67	16.20	16.95

Based on August 15-21, 2004, warmest 7-day period for 2-year monitoring period

The effect of Project operations on temperature was identified as a concern for both Lake Creek and the Cowlitz River. A simple mass balance analysis was employed to evaluate Project effects on water temperature in the Cowlitz River. Assuming instantaneous mixing, the downstream temperature was calculated by the following equation.

$$T3 = \frac{T1 * Q1 + T2 * Q2}{(Q1 + Q2)}$$

Where: T1 = maximum temperature water body 1
Q1= discharge water body 1
T2 = maximum temperature water body 2
Q2 = discharge water body 2

Due to the uncertainty of the slight temperature increase downstream of the calibration point at Rkm 7.9 for the existing condition model scenario, the mixed temperature downstream of Lake Creek was calculated with the modeled temperature data at the calibration point instead of the modeled data at the mouth.

For modeled conditions with the Project operating, temperature loading to the Cowlitz River occurs at the mouth of Lake Creek and at the tailrace outlet. In order to calculate the temperature downstream of the tailrace, the mass balance equation was applied using the tailrace flow/temperature regime and the Cowlitz River downstream of Lake Creek flow/temperature regime (i.e., temperature loading from both Lake Creek and the tailrace were considered). It was assumed that the tailrace outflow instantaneously mixed with the Cowlitz River; the tailrace slough was not considered. Table 4-2 lists the temperatures for the mixed flow downstream of Lake Creek for the modeled dates in 2004. Water temperature data were not available for the Cowlitz River in 2005 due to a lost thermograph and the Project was not operating due to insufficient flows for the dates modeled in 2005. Table 4-3 reports the temperature regimes for the modeled dates in 2004 for the mixed flow downstream of the tailrace. For this calculation the mixed flow in the Cowlitz River downstream of Lake Creek was combined with the tailrace flow. A comparison of the Cowlitz river temperature downstream of Lake Creek for without-Project scenarios with the Cowlitz River temperature downstream of the tailrace for the corresponding "with-Project" scenario shows that the Project results in no significant temperature effects to the Cowlitz River. Table 4-3 is color coded to facilitate this comparison.

Table 4-2 Water temperature for mixed flow downstream of Lake Creek in Cowlitz River

			Flow Cowlitz River		Cowlitz River Water Temperature (^oC)			Flow Lake Cr		Lake Creek Water Temperature (^oC)			Cowlitz River Downstream of Lake Creek Water Temperature (^oC)		
	Climate Exceed-ance	Date	(cfs)	(cms)	MAX	MIN	AVG	(cfs)	(cms)	MAX	MIN	AVG	MAX	MIN	AVG
existing with project	10%	8/12/04	702	19.88	14.7	10.98	11.93	9.60	0.27	13.38	12.32	14.61	14.68	11.00	11.97
existing without Project		8/12/04	702	19.88	14.7	10.98	11.93	63.60	1.80	18.83	17.15	18.1	15.04	11.49	12.45
7Q2 flow Lake Creek		8/12/04	702	19.88	14.7	10.98	11.93	63.00	1.78	18.81	17.63	18.09	15.04	11.53	12.44
7Q10 flow Lake Creek		8/12/04	702	19.88	14.7	10.98	11.93	46.50	1.32	18.44	16.71	17.66	14.93	11.34	12.29
existing with project	50%	8/5/2004	762	21.58	14.39	11.84	10.51	9.60	0.27	13.55	11.33	12.48	14.38	11.84	10.53
existing without project		8/5/2004	762	21.58	14.39	11.84	10.51	50.00	1.42	18.49	16.29	17.57	14.64	12.12	10.94
7Q2 flow without Project		8/5/2004	762	21.58	14.39	11.84	10.51	63.00	1.78	18.69	16.45	17.74	14.72	12.20	11.06
7Q2 with Project		8/5/2004	762	21.58	14.39	11.84	10.51	9.60	0.27	13.55	11.33	12.48	14.38	11.84	10.53
7Q10 flow without project		8/5/2004	762	21.58	14.39	11.84	10.51	46.50	1.32	18.06	15.93	17.24	14.60	12.08	10.90
7Q10 with project		8/5/2004	762	21.58	14.39	11.84	10.51	9.60	0.27	13.55	11.33	12.48	14.38	11.84	10.53

Table 4-3 Water temperature for mixed flow downstream of tailrace in Cowlitz River

			Tailrace		Tailrace Water Temperature (°C)			Flow Below Lake Creek		Cowlitz River Downstream of Lake Creek Water Temperature (°C)			Cowlitz River Downstream of Tailrace Water Temperature (°C)		
	Climate Exceed-ance	Date	(cfs)	(cms)	MAX	MIN	AVG	(cfs)	(cms)	MAX	MIN	AVG	MAX	MIN	AVG
existing with project[1]	10%	8/12/04	51	1.44	20.85	19.07	19.88	712	20.15	14.68	11.00	11.97	15.09	11.54	12.50
existing without Project		8/12/04	0	0.00				766	21.68	15.04	11.49	12.45			
7Q10 flow without Project		8/12/04						749	21.20	14.93	11.34	12.29			
7Q10 flow with Project		8/12/04	36.9	1.04	20.85	19.07	19.88	712	20.15	14.68	11.00	11.97	14.96	11.37	12.33
existing with project[1]	50%	8/5/2004	47	1.33	19.39	18.26	19.17	772	21.85	14.38	11.84	10.53	14.67	12.21	11.03
existing without project		8/5/2004	0	0.00				812	22.99	14.64	12.12	10.94			
7Q10 flow without project		8/5/2004	0	0.00				809	22.89	14.60	12.08	10.90			
7Q10 with project		8/5/2004	36.9	1.04	19.39	18.26	19.17	772	21.85	14.38	11.84	10.53	14.61	12.13	10.93

[1]*Existing flow on this date = 7Q2 flow*

In conclusion, the Project reduces flow in Lake Creek downstream of the drop structure. There is a minimum release of 0.085 cms (3 cfs) below the drop structure. The majority of the flow in Lake Creek originates as groundwater accretion, which is relatively cold. This results in maximum daily water temperatures at the mouth of Lake Creek that are well below the water quality criteria. Without the Project, the relative contribution of groundwater to the total stream flow is much less and the stream temperature regime is primarily a function of the warm water flowing out of Packwood Lake. In August, there is about 1°C of cooling for flow out of Packwood Lake by the time it reaches the mouth of Lake Creek. This cooling is due to shading as well as groundwater accretion. The summer maximum daily water temperatures near the mouth of Lake Creek are about 4-5°C cooler with the Project than without the Project. Water routed from Packwood Lake through the powerhouse and then to the Cowlitz River via the Project tailrace does not appreciably change in temperature between the lake and the tailrace outlet (EES Consulting 2005, 2006). The 7-DADMax for the lower end of the tailrace exceeds the 7-DADMax for natural conditions at the mouth of Lake Creek (2.16 °C warmer for the period August 15-21, 2004). The tailrace flow and the cooler water from Lake Creek, when considered in combination, result in no significant temperature change to the Cowlitz River relative to the temperature loading to the Cowlitz River that would occur without the Project.

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