 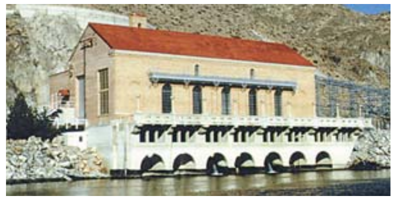 

PUBLIC UTILITY DISTRICT NO. 1 *of* CHELAN COUNTY
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June 1, 2016

Honorable Kimberly D. Bose, Secretary
FEDERAL ENERGY REGULATORY COMMISSION
888 First Street, NE
Washington, DC 20426

VIA ELECTRONIC FILING

Mr. David Bowen
WASHINGTON DEPARTMENT OF ECOLOGY
1250 West Alder Street
Union Gap, WA 98903-0009

Re: **Lake Chelan Hydroelectric Project No. 637**
License Article 401 and Water Quality Certification Condition V.B.
Chelan River Water Temperature Modeling Study Quality Assurance Project Plan Report

Dear Secretary Bose and Mr. Bowen:

On September 4, 2014, the Federal Energy Regulatory Commission (Commission) approved the Public Utility District No. 1 of Chelan County's (Chelan PUD), Chelan River Water Temperature Modeling Study Quality Assurance Project Plan (*Plan*).[1] Pursuant to ordering paragraph (B) of the approving order, Chelan PUD was required to file the Chelan River Water Temperature Modeling Study QAPP Report (*Report*) with the Commission by August 1, 2015.

On April 29, 2015, Chelan PUD filed with the Commission a revised *Plan*, which revised the *Report* filing due February 15, 2016.[2] Subsequently, on May 1, 2015, in a separate filing, Chelan PUD formally requested a time extension to file the *Report* to February 15, 2016, which the Commission granted on June 5, 2015.

On December 3, 2015, Chelan PUD requested a second time extension to file the *Report* by June 1, 2016. The extension was requested in order to assess water temperature model results and finalize the report in consultation with Washington Department of Ecology (Ecology). On

[1] 148 FERC ¶ 62,177.
[2] See page 36, Table 7. Project Milestones. Currently pending Commission approval.

January 14, 2016, the Commission issued its order approving Chelan PUD's request for extending the deadline to June 1, 2016.

Chelan PUD hereby files its final Ecology-reviewed Chelan River Water Temperature Modeling Study QAPP Report, which is now referred to as the "Chelan River Temperature Model Calibration and Initial Results Report." Throughout the collaborative process, discussions centered on the development and calibration of a functional water temperature model as required in the Commission-approved *Plan*, thus the renaming of this report reflects those discussions. On April 22, 2016, a final draft of this report was provided to the resource agencies, Tribes and non-governmental organizations specified for review. Please refer to Appendix 2 for the consultation documentation.

Please contact me or Steven Hays at (509) 661-4181 regarding any questions or comments regarding this submittal.

Sincerely,

Jeffrey G. Osborn
License Compliance Supervisor
jeff.osborn@chelanpud.org
(509) 661-4176

Attachment

cc: Paul Pickett, (Ecology)
Mark Peterschmidt, (Ecology)
Steve Hays, (Chelan PUD)

Public Utility District No. 1 of Chelan County

Wenatchee, Washington

CHELAN RIVER TEMPERATURE MODEL CALIBRATION AND INITIAL RESULTS

FINAL

June 1, 2016

Prepared by WEST Consultants, Inc. under contract SA No. 14 - 111

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1 Introduction

1.1 CWA 401 Certification and FERC License

On June 1, 2004, the Washington State Department of Ecology (Ecology) amended and reissued a 401 water quality certification (Order 1233) to the Public Utility District No. 1 of Chelan County (District) for the Lake Chelan Hydroelectric Project (Project). This water quality certification followed a decision from the Washington State Pollution Control Hearing Board upholding the water quality certification, with the inclusion of nine additional specific clarifications and requirements. On November 6, 2006, the Federal Energy Regulatory Commission (FERC) issued a license to the District to operate the project for 50 years. Additionally, in 2008, under the provisions of 33 USC 1341 (FWPCA § 401), the District submitted an application to Ecology to amend the 401 water quality certification as part of a license amendment to modernize generating units at the Project. In November 2008, Ecology issued a water quality certification (Ecology Order 6215) for the amendment application under Section 401 of the federal Clean Water Act. On May 31, 2012, the District requested an amendment to the 401 water quality certification to modify the hydraulic capacity of the Project. Subsequently, on August 28, 2012, Ecology issued a modified and amended 401 water quality certification, Ecology Order No. 9389.

Under current conditions, which include a minimum flow of 80 cfs, it is not known what level of support for fish, and water temperature for such use, can reasonably be achieved in the Chelan River. To make that determination, the 401 water quality certification for the Project license contains conditions for a ten-year adaptive management plan, which will allow time to determine what level of fish support and water temperature is reasonable and feasible to achieve. The current completion date for determining whether the biological objectives can be met is April 30, 2019. By or before the end of the ten-year adaptive management schedule, the District is to provide Ecology with the information necessary to make a determination on whether the biological objectives in the 401 water quality certification (and CRBEIP) and the state water quality standards have been achieved. Ecology has agreed to review the degree of attainment of the biological objectives and water quality standards and the application of all known, reasonable and feasible measures, and based on the results of the review, initiate a process to modify the applicable standards through rulemaking or such alternative process as may otherwise be authorized under applicable state and federal law (Ecology, 2008).

Under the 401 permit, The District is required to monitor and evaluate conditions in the Chelan River below Lake Chelan. This includes measuring water temperatures, monitoring achievement of biological objectives, recommending and implementing measures to meet biological objectives, and assessing the water quality data collected. There is also a requirement to study the geomorphic influences on water temperatures in the Chelan River in order to address temperature, velocity, depth, and substrate to determine the best methods to achieve the biological objectives for cutthroat trout.

To prepare for these evaluations, as well as for the eventual setting of water quality standards for the Chelan River, the District needs to collect sufficient data to evaluate potential measures that may be suggested for attainment of biological objectives. These could include increased flow releases, riparian vegetation propagation, gravel seeding of streambed, and possible streambed modification to attempt development of thermal refugia areas for cutthroat.

Ultimately, the District intends to develop a numerical temperature model to evaluate the potential effects of different flows, shade, and channel modification on water temperatures in the Chelan River. Several conditions of the 401 water quality certification relate to water temperature. These include requirements that the District:

- Develop a Quality Assurance Project Plan for water quality monitoring and temperature modeling (Order 1233, 5.B);
- Conduct a study to determine the geomorphic influences on water temperatures in the Chelan River in order to address temperature, velocity, depth, and substrate to determine the best methods to achieve the biological objectives for cutthroat trout (Order 1233, 5.B.iv);
- Conduct a riparian feasibility study to better characterize the opportunities for the establishment of riparian vegetation on the banks of the Chelan River (Order 1233, 10.E);
- Collect data on temperatures in the Chelan River and, if appropriate, evaluate its ability to comply with the temperature standards (Order 1233, C).
- FERC issued a license to the District for the Project as described below.

1.2 Description of Study Area and Project

1.2.1 Study Area

The Chelan River is 4.1 miles long from the Lake Chelan Dam to where it discharges to the Columbia River. It can be conceptually divided into four reaches (shown in Figure 1).

1. Reach 1 – Extending 2.29 miles downstream from the Lake Chelan Dam. This reach has a gradient of about one percent. Total length = 2.3 miles.
2. Reach 2 – Between 2.29 and 3.04 miles downstream from the dam, with a lower gradient than Reach 1. Total length = 0.75 miles.
3. Reach 3 – Between 3.04 and 3.53 miles downstream from the dam. This reach is very steep (5-10 percent) and is lined with steep bedrock walls, and is commonly referred to as “The Falls”. Total length = 0.4 miles.

4. Reach 4 – From 3.53 downstream from the dam, to its confluence with the tailrace near the Columbia River. This reach has a gradient of less than two percent. Total length = 0.5 miles (Figure 2).

The climate of the Chelan area is characterized by warm dry summers, and cool winters. The average maximum temperature in the summer is in the mid-80^{o}F (near 30^{o}C) and in the winter is close to freezing (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?wa1350). The climate is semi-arid with an average annual total of about 11 inches of precipitation. More than half of this precipitation occurs during the winter months of November-February.

The Chelan River is the only outflow from Lake Chelan. Flows in the Chelan River (powerhouse plus spill) are measured at the USGS streamflow gauge USGS 12452500 Chelan River at Chelan, WA. Table 1 summarizes these flows by month.

Table 1. Summary of Outflows from Lake Chelan

	Lake Chelan Outflows (cfs)		
	Minimum	**Mean**	**Maximum**
January	31	1660	3651
February	64	1580	4308
March	43	1460	2390
April	16	1430	4416
May	16	2380	7435
June	104	4110	9566
July	967	3530	7479
August	429	1780	3525
September	601	1520	2407
October	388	1740	2850
November	347	1720	3287
December	320	1720	2962
Annual	1133	2048	3139

Notes: USGS 12452500 Chelan River at Chelan, WA (November 1903 – September, 2013)

Figure 1. Chelan River showing study reaches

Figure 2. Chelan River Reach 4 showing habitat channel and structures.

1.2.2 The Project

The Lake Chelan Hydroelectric Project (FERC No. 637) is located on the Chelan River near the City of Chelan in Chelan County, Washington. The Project generates 48 megawatts of hydropower. The Project includes a diversion dam in the upper Chelan River, which is located at the southeast end of Lake Chelan. The dam controls the elevation of Lake Chelan and the flow into the Chelan River. Water flowing through the powerhouse empties into a tailrace about 1,700 feet from the Columbia River (Ecology, 2008).

The Lake Chelan Dam is a steel-reinforced concrete gravity structure. It is approximately 40 feet high and 490 feet long, and contains eight spillway bays and a separate conduit (low-level outlet) to release water collected from the bottom of the forebay. The low-level outlet is used to provide required flows to the Chelan River channel and to release excess water up to about 500 cubic feet per second (cfs). When the spillway gates are open to manage lake levels during periods when inflow to Lake Chelan exceeds the capacity of the powerhouse, as needed from May – August and during fall or winter floods, the excess water is discharged down the Chelan River channel. Lake levels and spillway discharges are managed, to the extent feasible, to limit discharge to the Chelan River channel to no greater than 6,000 cfs during normal operations for control of lake levels. Seiches and extreme inflow conditions may result in spillway flows above 6,000 cfs for lake level control and plant safety.

An underground penstock connecting the dam to the powerhouse delivers water to power the turbine generators (Figure 3). It delivers water from the dam at the southeasterly end of Lake Chelan to the powerhouse at Chelan Falls, a vertical drop of nearly 350 feet. This steel and concrete tunnel is approximately 2.2 miles long. The only visible portion of the tunnel is a 125-foot-high surge tank constructed on the hill above the plant to absorb hydraulic momentum of the water in case of load rejection. The penstock must undergo a federally required inspection every five years. The water is discharged into the tailrace located on the east side of the powerhouse where it flows into the Columbia River.

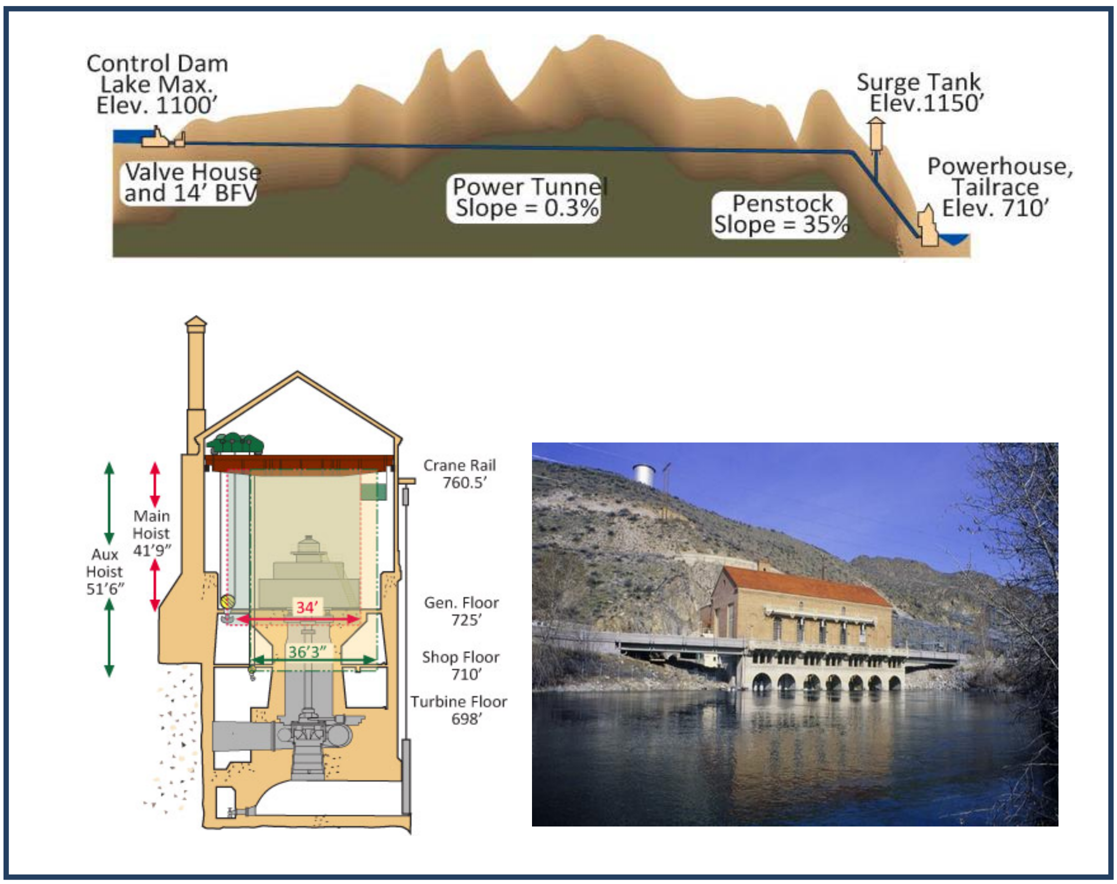


Figure 3. Lake Chelan Hydroelectric Project general views.

1.3 State Water Quality Standards

The goal of the State of Washington is to “maintain the highest possible standards to ensure the purity of all water of the state consistent with public health and public enjoyment thereof, the propagation and protection of wild life, birds, game, fish, and other aquatic life, and the industrial development of the state, and to that end require the use of all known available and reasonable methods by industries and others to prevent and control the pollution of the waters of the state of Washington” (RCW 90.48.010). Under the State’s current water quality standards, approved by the U.S. Environmental Protection Agency in February 2008, the designated uses for the Chelan River include salmonid spawning, rearing, and migration (WAC 173-201A-600(1).)

1.3.1 Numerical Criteria for Temperature

The numerical criterion for temperature for the river and tailrace is a 7-DADMax of 17.5°C, where the 7-DADMax is the average of the daily maximum temperatures of seven consecutive days (WAC 173-201A-200(1)(c)). When the temperature of the waterbody is warmer than this criterion due to natural causes, then human actions should not cause the 7-DADMax to increase by more than 0.3°C. When the natural water conditions are less than the criterion, then human actions should not cause the 7-DADMax to increase by more than 28/(T+7)°C.

The state standards also include specific options for modifying water quality standards by developing site-specific criteria or performing a Use Attainability Analysis (WAC 173-201A-430 and 440.) (Ecology, 2008) within a 10-year compliance schedule (WAC 173-201A-510(5)).

1.3.2 Designated Uses: Fisheries

The current water quality standards for the Chelan River were not attained prior to establishment of minimum flows under the new FERC License for the Lake Chelan Hydroelectric Project. Prior to 2009, in most years the bypassed section of the Chelan River was nearly dry as a result of project operations and lake level management under the previous FERC license. Only during wet years or during project maintenance did the river channel receive substantial flow. When flow was not being released into the river below the dam, fish habitat was restricted to a few isolated pools in the gorge section of the bypassed reach and a short section of river below the powerhouse tailrace. Summer and fall Chinook salmon had been observed using the tailrace and lower river for spawning under the right conditions, while smallmouth bass and suckers used the available habitat for rearing (PUD No. 1 of Chelan County, 2002).

The Chelan River Biological Evaluation and Implementation Plan (Lake Chelan Comprehensive Settlement Agreement, Attachment B, Chapter 7, CRBEIP, October 8, 2003) includes biological objectives to be achieved in the Chelan River. The conditions of the 401 water quality certification require the District to implement minimum instream flows for fish identified in the 401 water quality certification (see 401 water quality certification dated November 19, 2008, Ecology Order No. 6215, paragraph E) and CRBEIP as follows:

Table 2. Water Quality certificate conditions

Reach	Dates	Dry year (cfs)	Average year (cfs)	Wet year (cfs)
1,2,and 3[1]	Jul 16 – May 14	80 all months	80	80
	May 14		Ramp up to 200	Ramp up to 320
	May 15 – Jul 15		200	320
	Jul 16		Ramp down to 80	Ramp down to 80
4[2] Spawning flow	Mar 15 to May 15 and Oct 15 to Nov 30	80 + 240 pumped (320)	320 by combination of spill and pumping Incubation flow, as needed	320 by combination of spill and pumping Incubation flow, as needed

[1] Flows measured at the dam by calibrated gate opening

[2] Flows measured at the dam or through calibrated pump discharge curves

i) The minimum instream flow requirements set forth in the 401 water quality certification are considered minimum values.

ii) Higher flows may be determined to be needed by the Chelan River Fish Forum (CRFF) or by Ecology, as a result of studies performed as part of the CRBEIP.

iii) Ecology retains the right to amend the instream flow requirements specified in this certification to provide adequate habitat and to meet the biological objectives for cutthroat in Reaches 1, 2, and 3 of the Chelan River, or for fall Chinook or steelhead in Reach 4 of the Chelan River, or any species included in the future on a state or federal listing of endangered or threatened species.

iv) With respect to instream flows for spawning in Reach 4, incubation flows are added as needed in all years, including dry years, per Washington State Pollution Control Hearings Board (PCHB) Order dated April 21, 2004 (Confederated Tribes v. Ecology, PCHB No. 03-075.).

1.4 Scope of Work

The goal of the larger study is to develop a water temperature model of the Chelan River, and then use the model to assess various alternatives that might improve use attainment in the river. A previous study (WEST, 2014) recommended that the Department of Ecology temperature model, QUAL2Kw (Pelletier et al., 2006), be used to simulate temperatures in the Chelan River. We also recommended that the temperature routines in HEC-RAS could also be considered as HEC-RAS would be used anyway to develop the hydraulic power functions needed as input to QUAL2Kw. WEST and the PUD next developed a Quality Assurance Project Plan (QAPP) for submittal to Ecology and FERC (WEST and Chelan PUD, revised 2015). That study presented the proposed study design, objectives, quality control procedures, data review, and the technical approach. This report details the development of the hydraulic HEC-RAS model and the development of the QUAL2Kw water temperature model.

1.5 Authorization

WEST Consultants, Inc. (WEST) performed this study under a Services/Independent Contractor Agreement SA No. 14-111 with Chelan PUD. Mr. Steven Hays was Chelan PUD's technical contact.

2 Model Data

The QAPP (WEST and Chelan PUD, 2015) details the data sources and presents some data analyses to identify the influence of various physical processes. Table 3 lists the various types of data proposed to develop and calibrate the models.

Table 3. Summary of data to develop temperature models.

Data Type	Source
Geometry	2009 LiDAR coverage (0.68 points/sq ft and a vertical accuracy of 0.12 ft). If necessary, selected transects will be ground surveyed for confirmation of LiDAR data
Inflows	Project flows known
Downstream	HEC-RAS model of Rocky Reach reservoir
Inflow temperatures	Measured in forebay
Meteorology	Up to five stations available
Water temperature calibration data	7 stations from dam to Columbia River
Shade	LiDAR coverage and estimation of vegetation heights

2.1 Geometry

A LiDAR survey was flown in 2009. These data have been processed and reviewed by the Puget Sound Regional Council, and are accepted for use (USGS, 2009). From the survey, a 3-ft by 3-ft DEM was developed.

Additional in-water geometry was available from an existing HEC-RAS model developed by Chinook Engineers (no citation) and from channel surveys of the habitat channel measured by Ecology in early 2015.

2.2 Flows from Lake Chelan

The District monitors flows into the Chelan River (1) through the low-level outlet, (2) over the spillway, and (3) through the penstock to the powerhouse where it is discharged to the lower river (Reach 4). Flows in the low-level outlet are measured with an ultrasonic flow meter. Spillway flows are calculated from lake level readings and gate settings, for which rating tables exist. This gauging site is known as USGS 12452500 Chelan River and combines powerhouse discharge flows reported by the District with the spillway and low-level outlet flows. Data for this site are reported at http://waterdata.usgs.gov/usa/nwis/nwisman/?site_no=12452500&agency_cd=USGS. The period of record given for this gauge spans from 1903 to present.

2.3 Stage in Columbia River

The Seattle District, Corps of Engineers, developed an HEC-RAS model of the Rocky Reach Pool of the Columbia River between Wells and Rocky Reach Dams. Chelan County PUD measures forebay stages and flows at Rocky Reach Dam (Figure 4). We ran the Rocky Reach

HEC-RAS model for a range of flows up to the 500-year peak discharge and for a range of forebay stages, and noted that the modeled stages at the confluence with the Chelan River were 704.5-713 feet NGVD (or 707.1-716.6 feet NAVD, using a conversion factor between the two vertical datums of 3.6 feet).

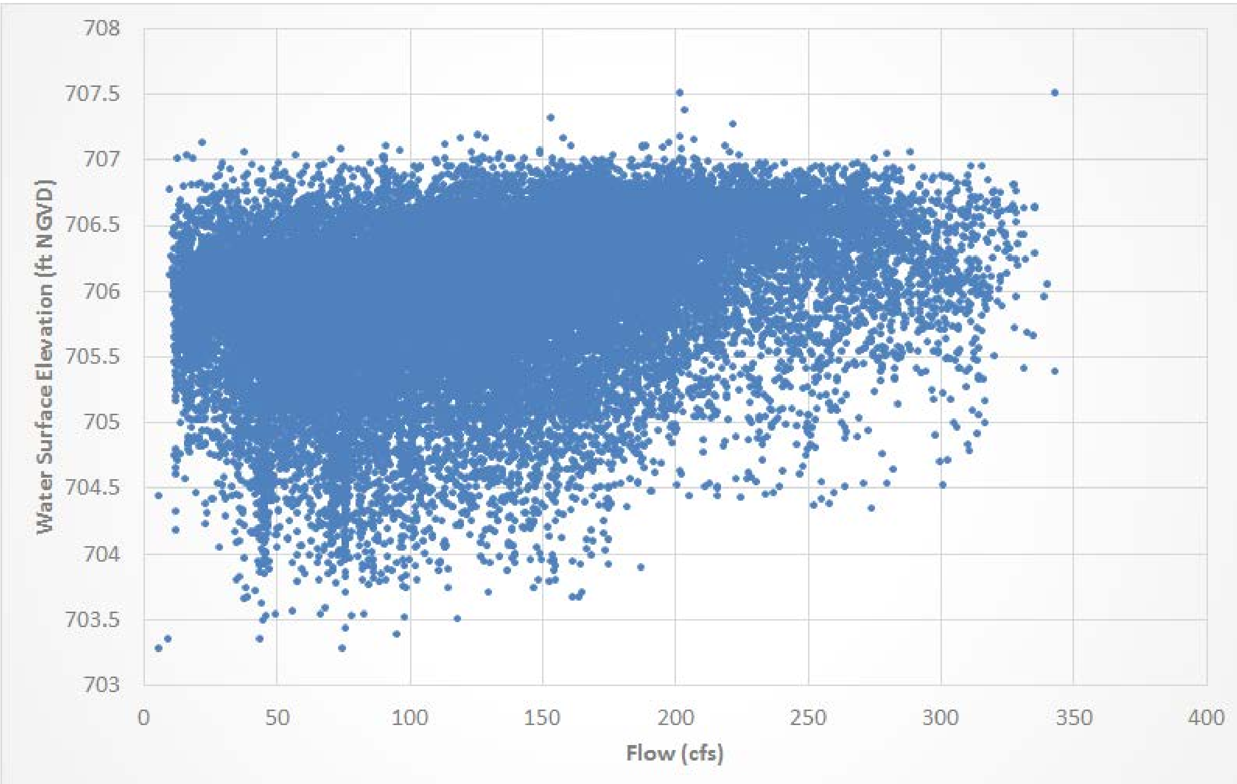


Figure 4. Forebay Water Surface Elevations and Flows at Rocky Reach Dam

We then ran a preliminary HEC-RAS hydraulic model of the Chelan River with low flows from Lake Chelan Dam's low-level outlet of 85, 200, and 350 cfs, supplemented by 1000 cfs through the penstock, using downstream stages of 707.1, 712, and 716.6 feet NAVD. Figure 5 shows that the effect of the Columbia River stage extends upstream only about 1,400 feet (about a quarter mile). Generally, this is downstream of the area of interest for this study, and therefore we chose to use a constant downstream stage of 711 feet NAVD (typical of a level pool behind Rocky Reach Dam under low-to-medium Columbia River flows (from Figure 4) for all hydraulic simulations in the Chelan River.

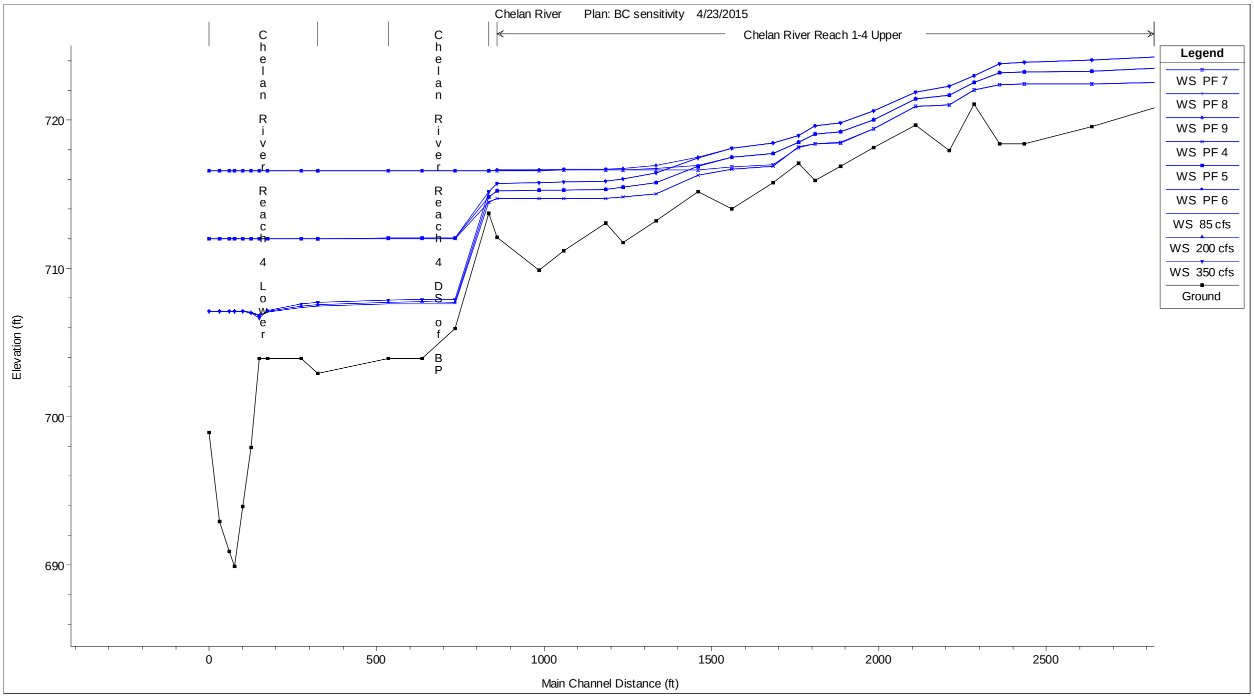


Figure 5. Sensitivity of Columbia River Stage

2.4 Flow Widths in Chelan River

During January 2015, Chelan PUD measured flow widths in part of Reach 1 during low-level release flows of 85, 200 and 350 cfs (Table 4).

2.5 Forebay Temperatures

Chelan County PUD measures temperatures in the Lake Chelan Dam's forebay near the low level outlet, and profiles forebay temperatures using a string of thermistors a small distance upstream of the dam. As we are generally simulating low-flow conditions in the Chelan River, when heat exchange is at its largest, generally we used only temperatures measured just upstream of the low-level outlet for this study. The District provided these temperature data to the study team.

2.6 Meteorology

The majority of the meteorological data used for the QUAL2Kw temperature model were recorded at the Washington State University Chelan South monitoring station, which is located 3.5 miles west of the Lake Chelan Dam (Figure 6). These data include average air temperature, dew point temperature, average wind speed, and solar radiation hourly measurements. Cloud cover data are not recorded at the Chelan South monitoring station, but are available at the NOAA Pangborn (Wenatchee) Airport monitoring station in Wenatchee, WA. This station is approximately 31 miles south of the Lake Chelan (Figure 6).

Table 4. Observed Reach 1 Widths for Various Low-Level Flows

River Station (feet from Columbia River)	350 CFS Width (ft)	200 CFS Width (ft)	85 CFS Width (ft)
19550	94.3	89.8	84.5
19350	83.9	71.2	62.6
19150	99.9	77.5	
18950	80.3	72.2	
18750	95.8	81.9	61.1
18550	101.8	100.8	93.0
18350	88.6	69.7	62.8
18150	108.6	95.2	92.3
17950	79.8	68.1	62.9
17750	89.3	85.8	79.0
17550	100.9	95.9	92.4
17350	121.2	101.7	94.1
17150	165.8	135.9	121.5
16950	159.4	147.9	140.1
16750	109.1	96.9	
16550	146.5	140.1	122.9
16350	164.5	170.5	160.1
16150	174.6	161.1	148.2
15950	127.4	107.8	90.9
15750	79.8	68.6	58.7
15550	162.4	101.0	

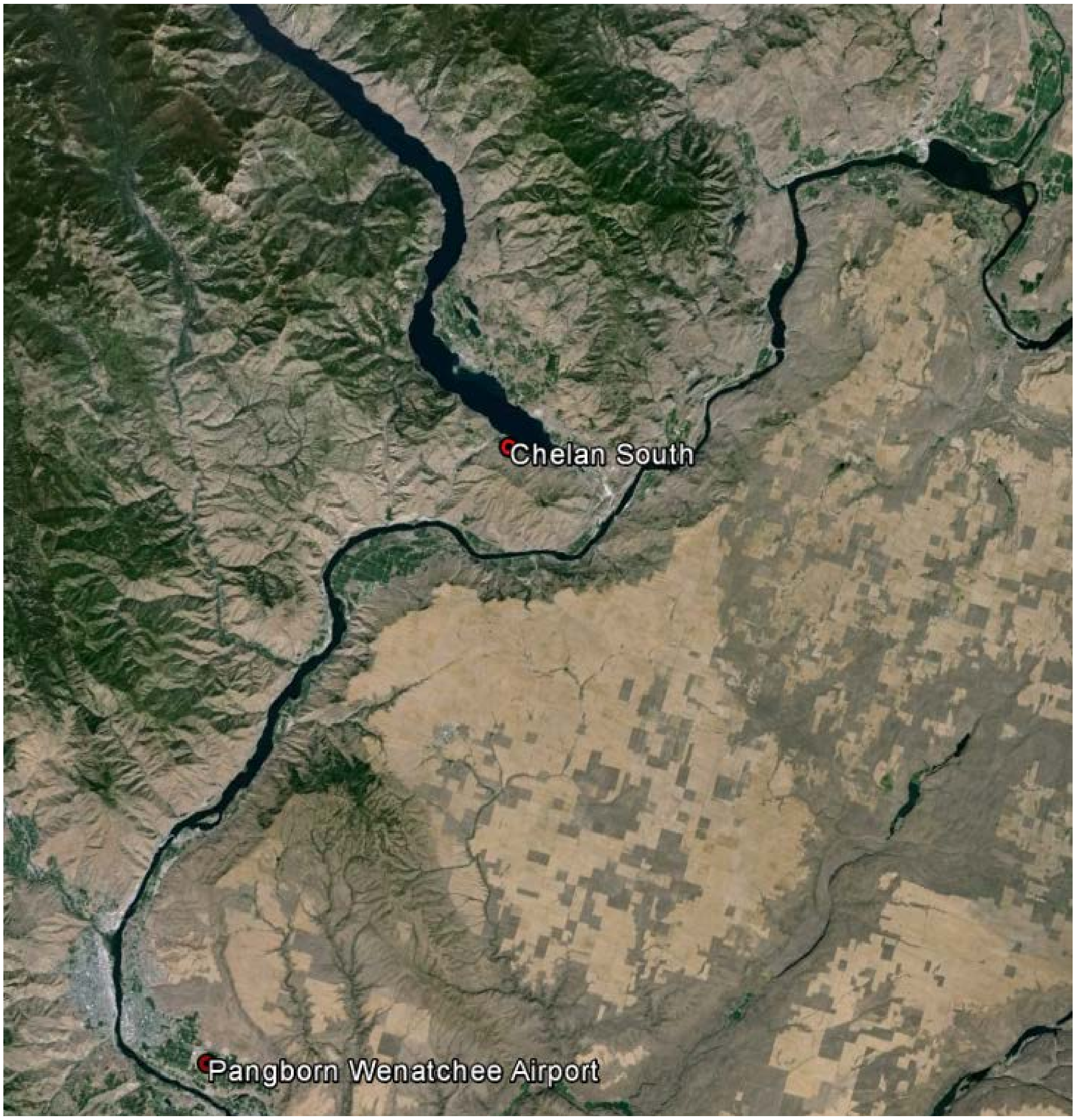


Figure 6. Meteorological Stations near Chelan

2.7 In-Stream Temperatures

The District monitors temperatures in the Chelan River at various locations (Figure 7). These data have been collected as part of the monitoring and evaluation program for the Chelan River, and has been evaluated for quality assurance and quality control. The water temperature data for two sites is collected continuously using 100 ohm platinum RTDs, located in the Low Level Outlet pipeline and from the tailrace at the pump station intake screens. The other sites are monitored with temperature recording data loggers (Onset HOBO Water Temp Pro v2) mounted on fence posts in flowing water.

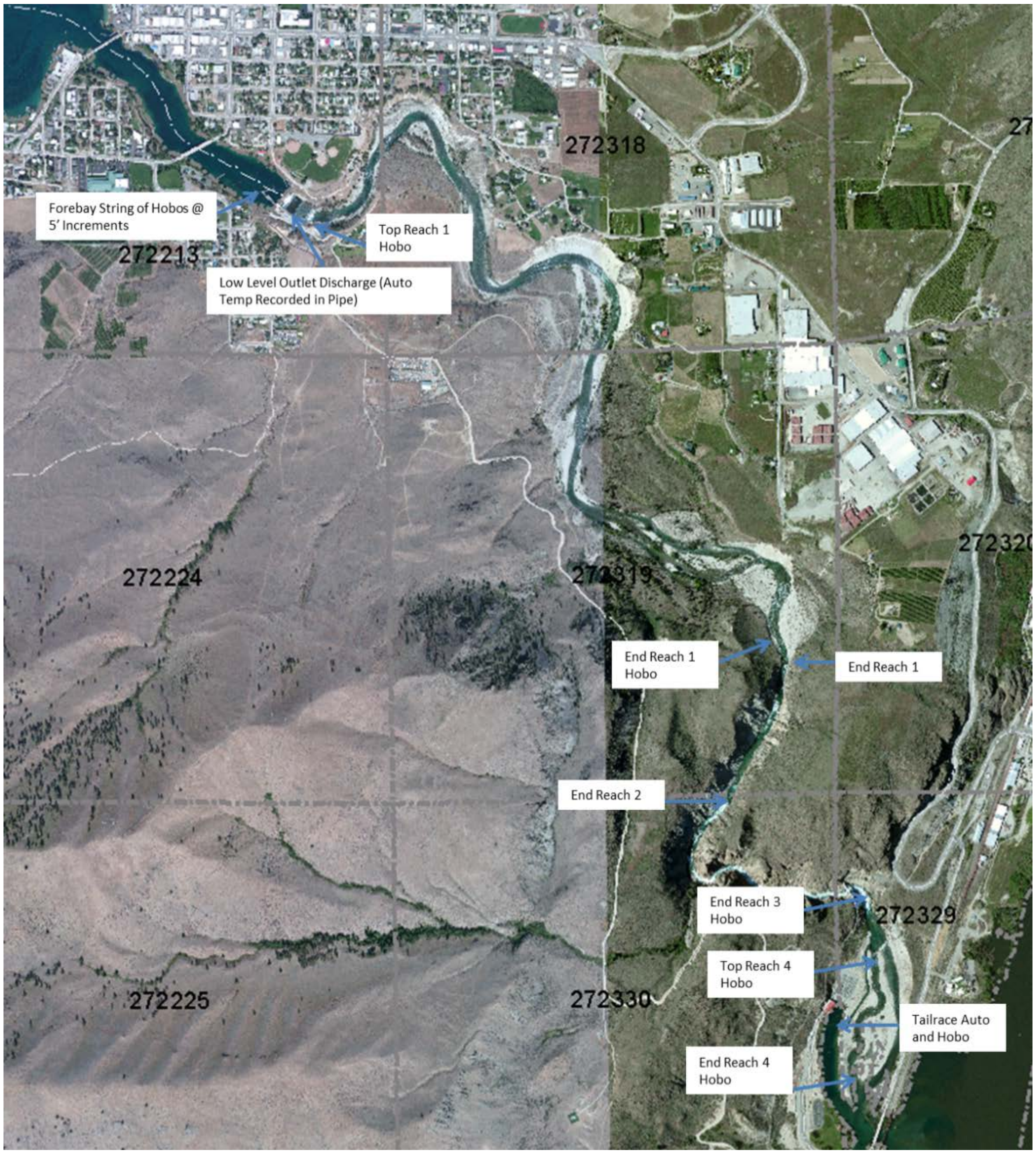


Figure 7. Chelan River in-stream temperature monitoring stations

2.8 Shade

Hourly shade values were calculated using Shade.xls, a tool for estimating shade from riparian vegetation and topography. Shade.xls was adapted from a program developed by the Oregon Department of Environmental Quality (ODEQ) as part of their HeatSource model version 6.

We used the USGS 30-m DEM and GIS tools to determine the east, south, and west vertical topographic angles for each temperature model segment. Shade.xls used these angle to compute hourly shade values, which were then input to the QUAL2Kw temperature model. The shade model was initially developed with topographic shade only, as vegetative shade was considered to be negligible under existing conditions (based on Herrera, 2015). The Shade.xls model was set up with the same segmentation as the QUAL2Kw model, and shade was computed at the center of each reach. Subsequent analysis of existing shade and future potential shade was conducted using the QUAL2Kw model with shade input files prepared by Herrera Environmental Consultants (Herrera).

2.9 Analysis of Data Quality

The empirical flow and temperature data used in the model were collected in accordance with a Quality Assurance Project Plan, which was originally developed in 2007 and recently revised in April 2015 to reflect changes to Washington State surface water quality standards and other factors such as equipment upgrades (Chelan PUD, 2015). The quality assurance measures did not change from the 2007 QAPP. Measurement quality objectives for flow and temperature include bias and accuracy of 5%/200 cfs of flow and ± 0.1 °C, respectively. The sensitivity and resolution of the instrumentation was 1%/100 cfs and 0.01 °C. The temperature loggers were checked prior to and following deployments and all tests met the measurement quality objectives. Flow measurements also met these objectives.

2.10 7-DADMax

The Washington State water quality standard for water temperature in the Chelan River includes the numerical criterion of 7-DADMax of 17.5 °C, where the 7-DADMax is the average of the daily maximum temperatures of seven consecutive days (WAC 173-201A-200(1)(c)). The model is being used to evaluate scenarios that could lead to reductions in the daily maximum water temperature, which over time determines the 7-DADMax. The model has been calibrated and validated with seven day data sets, which included the July 27 – August 2, during which the highest daily maximum temperatures observed in the empirical data set occurred over three consecutive days (July 29-31 each had daily maxima greater than 25 °C). The highest 7-DADMax in 2014 was also during that time period, with the middle day of the highest 7-DADMax (25.0 end Reach 3) occurring on August 1. Future improvements in the model could include comparisons of the simulated to actual daily maximum temperatures over a longer time period, including comparison of the simulated to the actual measured 7-DADMax for longer time periods.

3 Development of Hydraulic Model

3.1 Model Development

A hydraulic model of the Chelan River was developed using the Corps of Engineers model, HEC-RAS (HEC, 2010). We developed the geometry for Reaches 1-3 from existing LiDAR data (flown during near zero flow conditions). We developed the lower Reach 4 geometry using an existing model of the Chelan River (Chinook Engineering, no citation) and replacing the description of the habitat channel with cross sections surveyed by Ecology in early 2015. Figure 8 shows the hydraulic model grid.

Boundary conditions for the hydraulic model included a specified flow through the low-level outlet, additional flows added through the penstock, and a downstream stage of 711 feet NAVD at the confluence with the Columbia River.

3.2 Model Calibration

We calibrated the Chelan River hydraulic model to observed widths in Reach 1 during three low flows (Table 4). The calibration consisted of adjusting main channel Manning's *n* roughness values in the hydraulic model, within realistic bounds, to match the hydraulic model water surface top widths to the observed water surface top widths (Figure 9 to Figure 11). The model was found to consistently underestimate top widths compared to the observed data, especially in areas with significant riffles. Matching observed top widths more closely would require unrealistically large values of Manning's *n*. After investigating site photos and aerial photography, we believe that this underestimation of top widths is caused by the large number of rocks and material that are present in the channel (Figure 12 shows an example). On the upstream portion of the calibration reach, and especially at low flows, these obstructions can fill a significant portion of the cross sectional area of the channel, and are visible above the water surface. As flows increase, the differences between modeled widths and observations decreases (Figure 9 to Figure 11). HEC-RAS assumes freely flowing unobstructed flow, unless modeled otherwise, and these obstructions are simply too small and disordered to be modeled in the 1-D HEC-RAS model.

Below Reach 1, where top widths were measured, Mannings *n* values were assigned based on aerial photographs, and the presence or absence of riffles and pools. In Reach 3, a very steep, boulder-lined channel known as "The Falls", very high values were used. In Reach 4, values were assigned based on the Chinook Engineers hydraulic model values and aerial photographs.

Table 5 shows the final Mannings *n* roughness values.

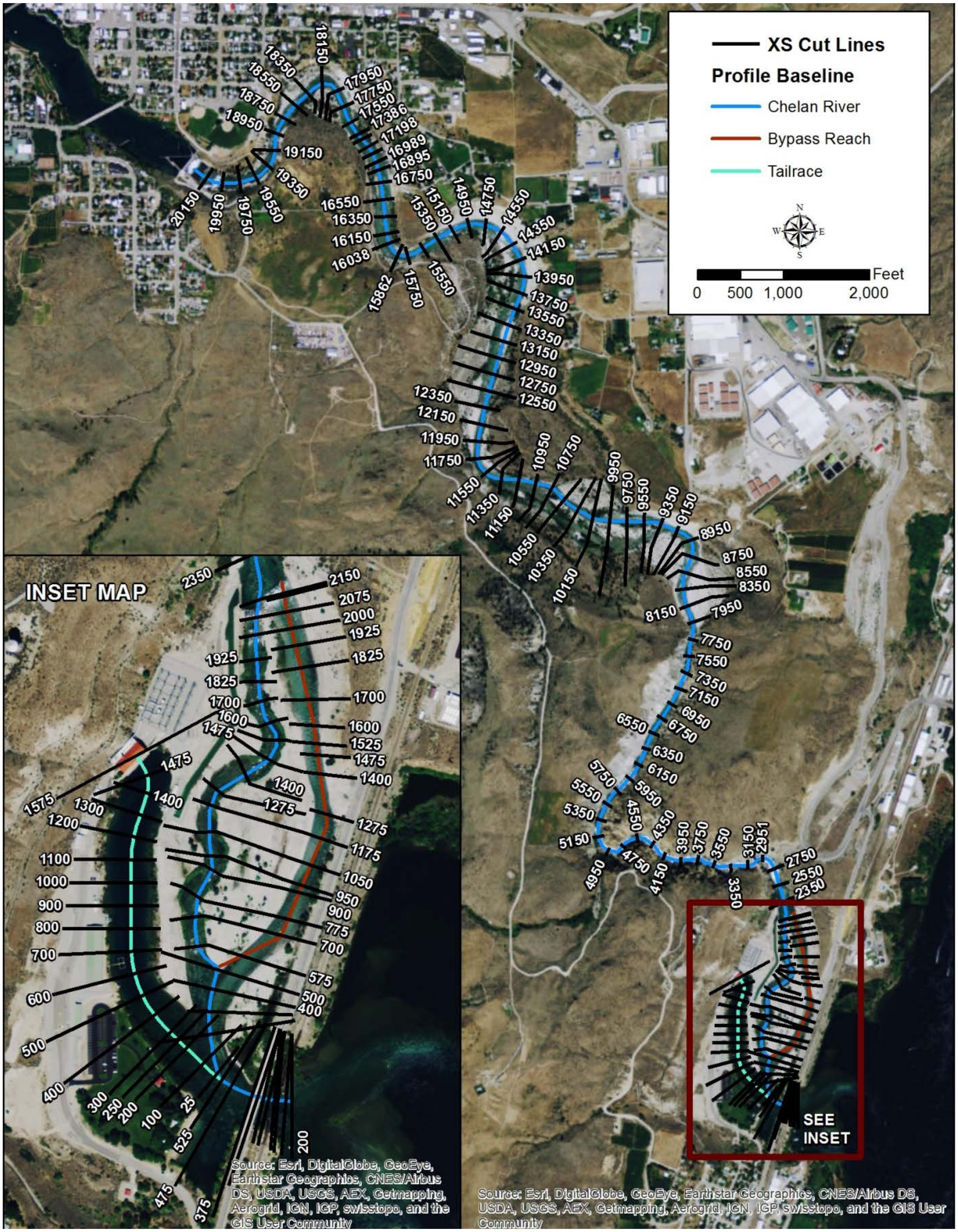


Figure 8. Layout of Chelan River Hydraulic Model

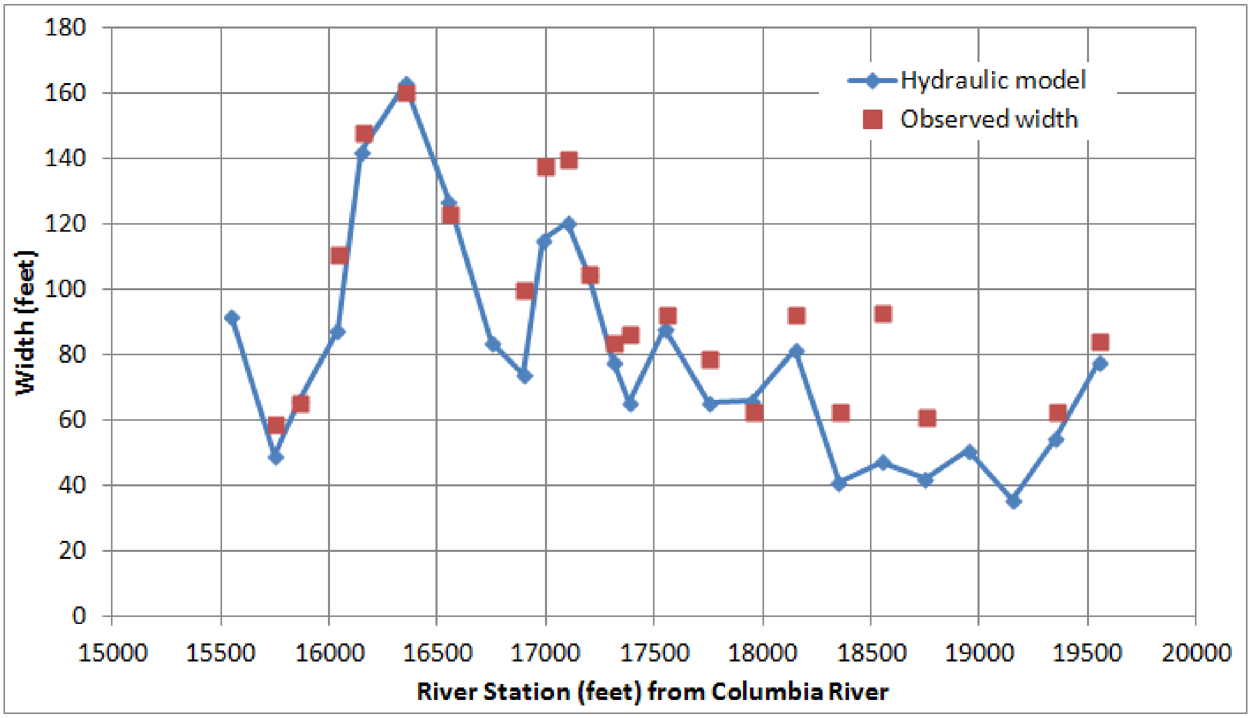


Figure 9. Comparison of Observed and modeled top widths for 85 cfs

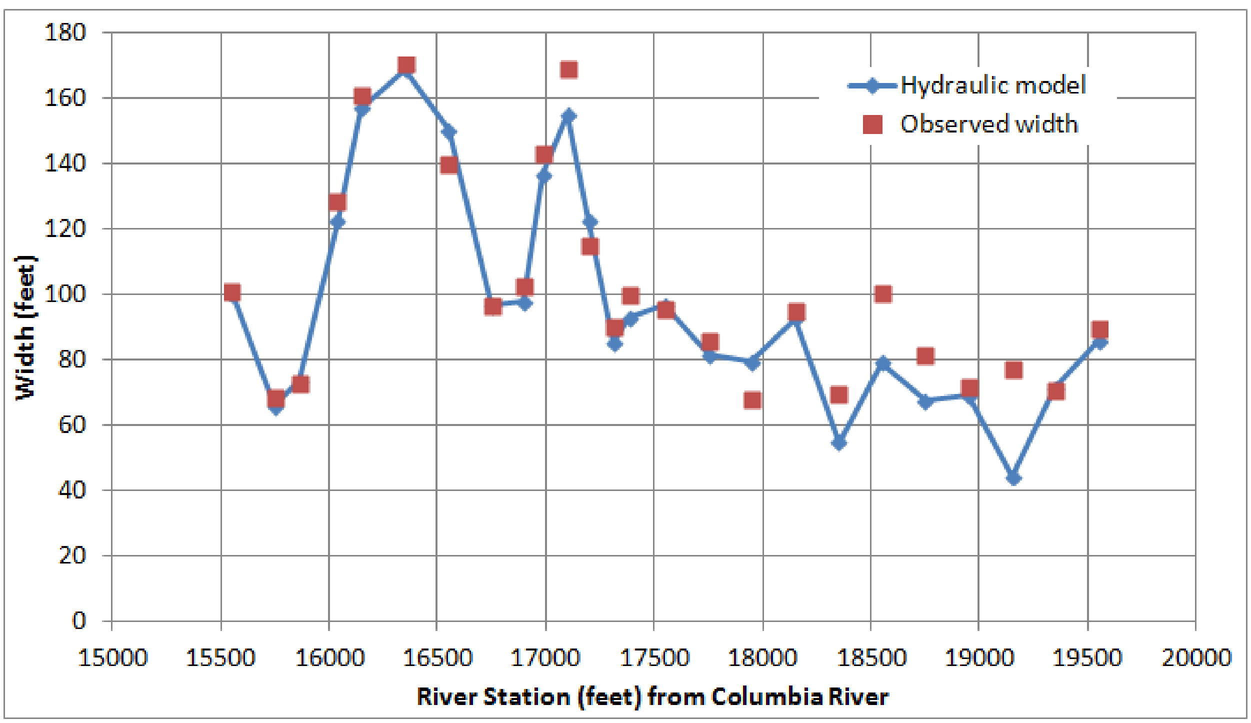


Figure 10. Comparison of Observed and modeled top widths for 200 cfs

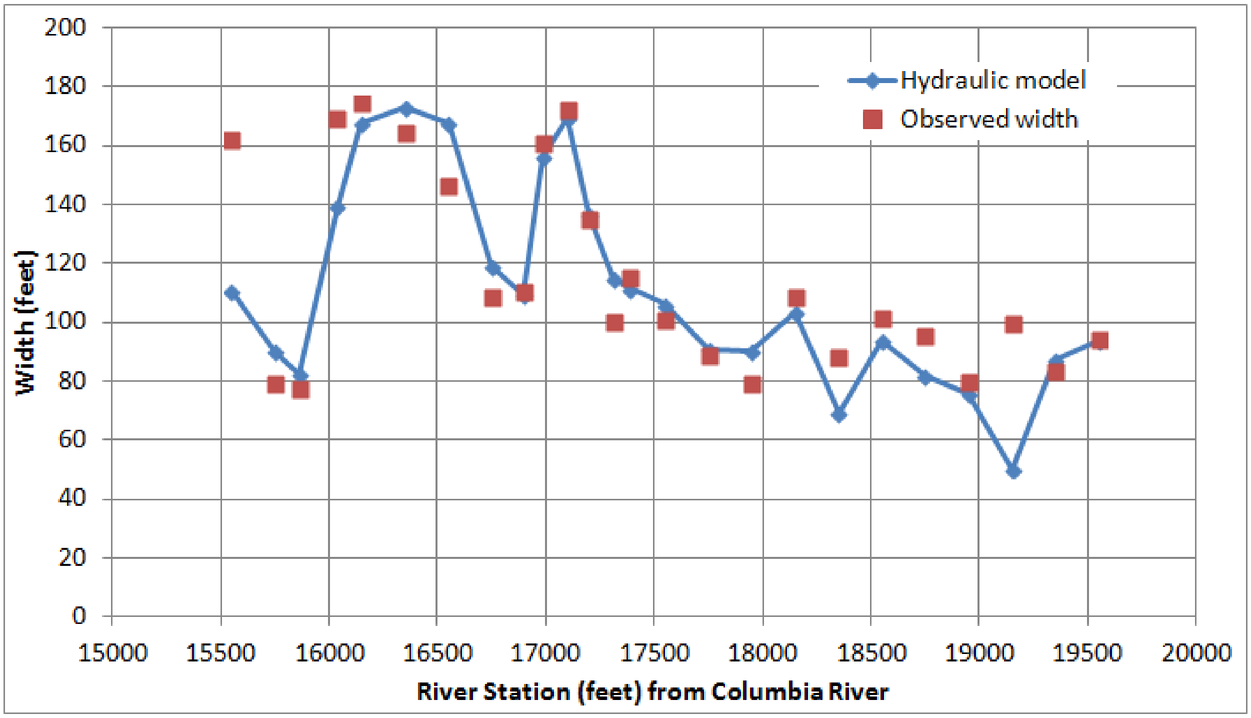


Figure 11. Comparison of Observed and modeled top widths for 350 cfs

Table 5. Hydraulic Model Mannings *n* Roughness Values

River Reach	Channel values	Overbank values
Reach 1	0.07-0.12	0.12
Reach 2	0.07-0.12	0.12
Reach 3 (“The Falls”)	0.15	0.15
Habitat Channel	0.05	0.06
Bypass Reach	0.05	0.07
Tailrace	0.05	0.05
Confluence Reach	0.03	0.06

Figure 12. Example of significant obstruction during low flow

Chelan PUD observed the times of travel for changes in flow at the dam's low-level outlet to the upstream end of the habitat channel in Reach 4. Table 6 shows the "initial" flow before the change and the observed time of travel (Steve Hays, Chelan PUD, personal discussion, February 2015). As the travel times represent the movement of the gravity wave (or wave celerity, not the water speed), the gravity wave travel times were simulated in HEC-RAS using the "subcritical flow regime" option with very low Mannings *n* roughness values that forced conditions everywhere to critical depth (as the stream velocity equals the gravity wave speed at critical depth conditions). The comparisons seen in Table 6 demonstrate that this aspect of the numerical model is working correctly.

Table 6. Comparison of Travel Times (in minutes)

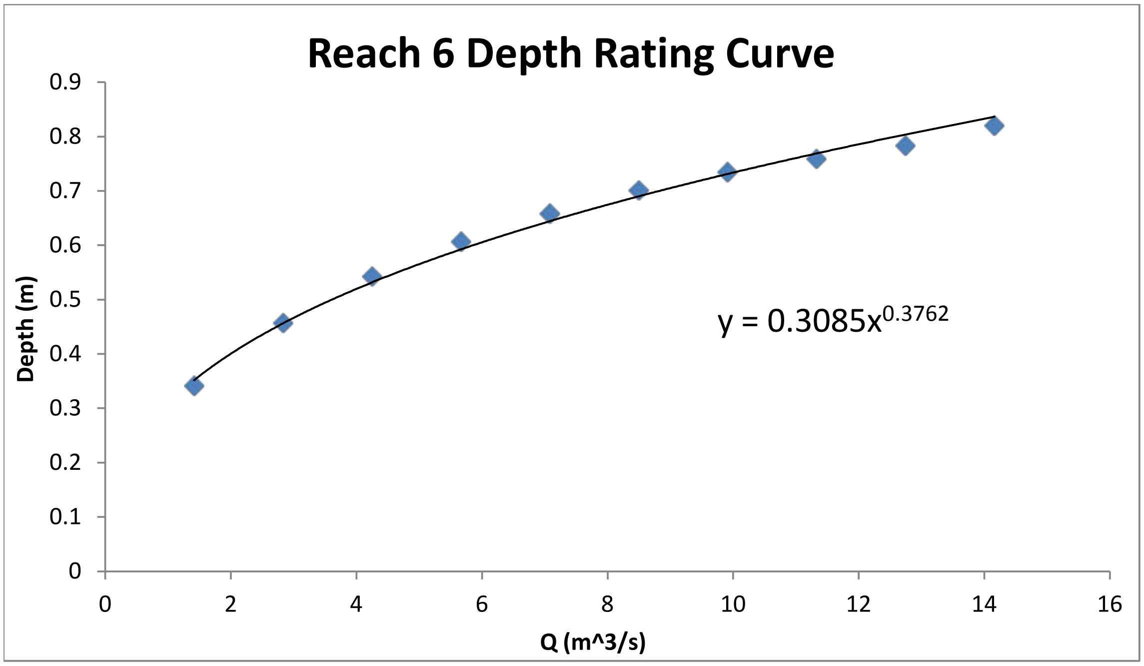
Initial flow (cfs)	Observed (mins)	Modeled (mins)
85	90-100	92
200	80	77
350	60	60

3.3 Development of Power Functions for QUAL2Kw

Of the three available hydraulic calculation methods available in QUAL2Kw, the rating curve method was chosen for the Chelan River. These power function rating curves relate mean velocity, U, and depth, H, to flow, Q, for each QUAL2Kw reach:

$$U = aQ^b \qquad\qquad H = \alpha Q^\beta$$

We ran a range of flows from 50-600 cfs, and exported depth vs. flow and velocity vs. flow data from the calibrated hydraulic (HEC-RAS) model for each QUAL2Kw reach. The results were converted to SI units (used by QUAL2Kw), and power function trendlines created using the trendline option in Microsoft Excel (Figure 13 shows an example). Finally, the coefficients and exponents of these power functions were entered into QUAL2Kw's hydraulic model input.



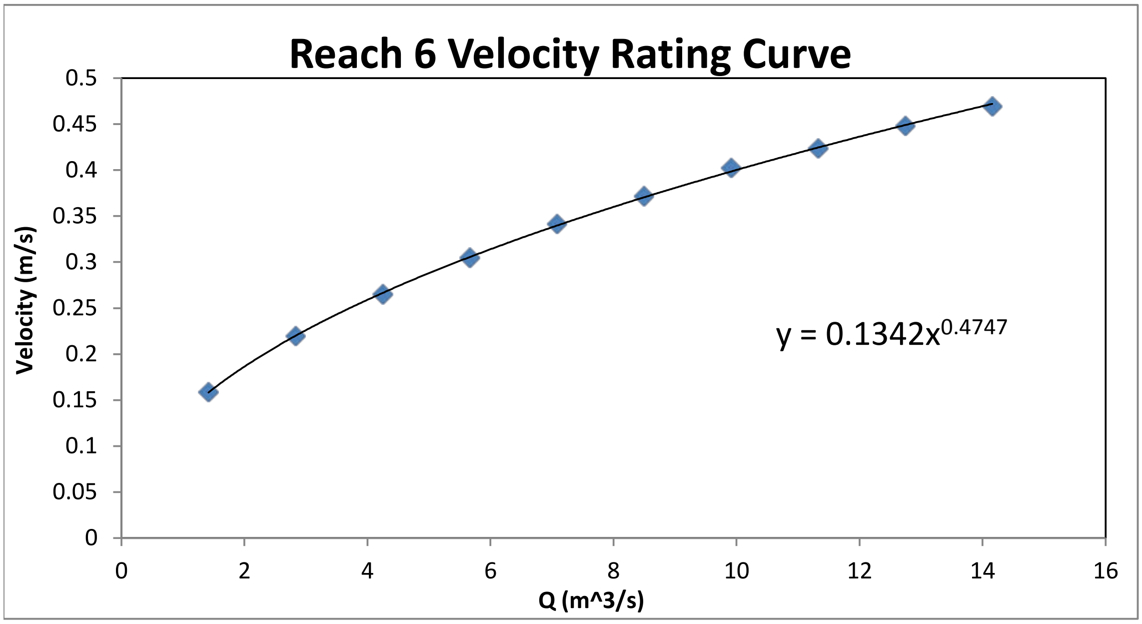


Figure 13. Example rating curve power functions for QUAL2Kw Reach 6

4 Development of Temperature Model

4.1 Model Setup

A temperature model of the main stem of the Chelan River was developed using QUAL2Kw (Pelletier et al., 2006). QUAL2Kw is an excel-based temperature and water quality model. The temperature model solves the one-dimensional thermal mass transport equation for temperature. The mass balance includes inflows, outflows, a comprehensive heat budget module, and water column/hyporheic zone interactions.

We modeled the tailrace reach as a local inflow to the main stem Chelan River temperature model, and did not perform temperature calculations on this reach. The tailrace pump flows were also modeled as inflows to the main stem Chelan River. We divided the main stem of the Chelan River into 23 QUAL2Kw reaches, as QUAL2Kw is a segmented model, and used these same reach definitions in the shade.xls model. These 23 reaches are roughly equal in length, about 1,000 feet, but were adjusted to best fit the channel geometry, essentially looking for fairly straight segments (Figure 14).

4.2 Selection of Calibration and Validation Periods

We chose five model simulation periods to represent a range of conditions in the Chelan River (Table 7). All periods corresponded to low flow in the Chelan River, with no flows over the spillway. We selected these periods to reflect a wide range of conditions on the Chelan River, but with special focus on periods of high temperatures as well as low flows, as seen in Table 7 and Figure 15 through Figure 19. These periods cover a relatively wide range of air temperatures and solar radiation. The September 2013 event was chosen as the calibration event, while the May 2013 event was used for the sensitivity analysis. The March 2015 validation period was chosen specifically to analyze the capability of the temperature model to simulate an unusually warm spring condition. The July 2014 event represented the critical condition for air temperatures, with daily maximum temperatures at or above the 95 percentile for five of those dates for years from 1920 – 2015.

Table 7. Temperature Model Calibration Periods

Simulation Time Period	Simulation Type	Avg. Low Level Outlet Temperature (°C)	Avg. Air Temperature (°C)	Avg. Low Level Outlet Flow (cfs)
April 7-12: 2010	Validation	8.6	6.6	92
May 1-7: 2013	Validation and Sensitivity	13.6	17	126
September 1-7: 2013	Calibration	21.6	21.5	86
July 27 – August 3: 2014	Validation	21.7	27.7	85
March 23-30: 2015	Validation	9.6	11.2	84

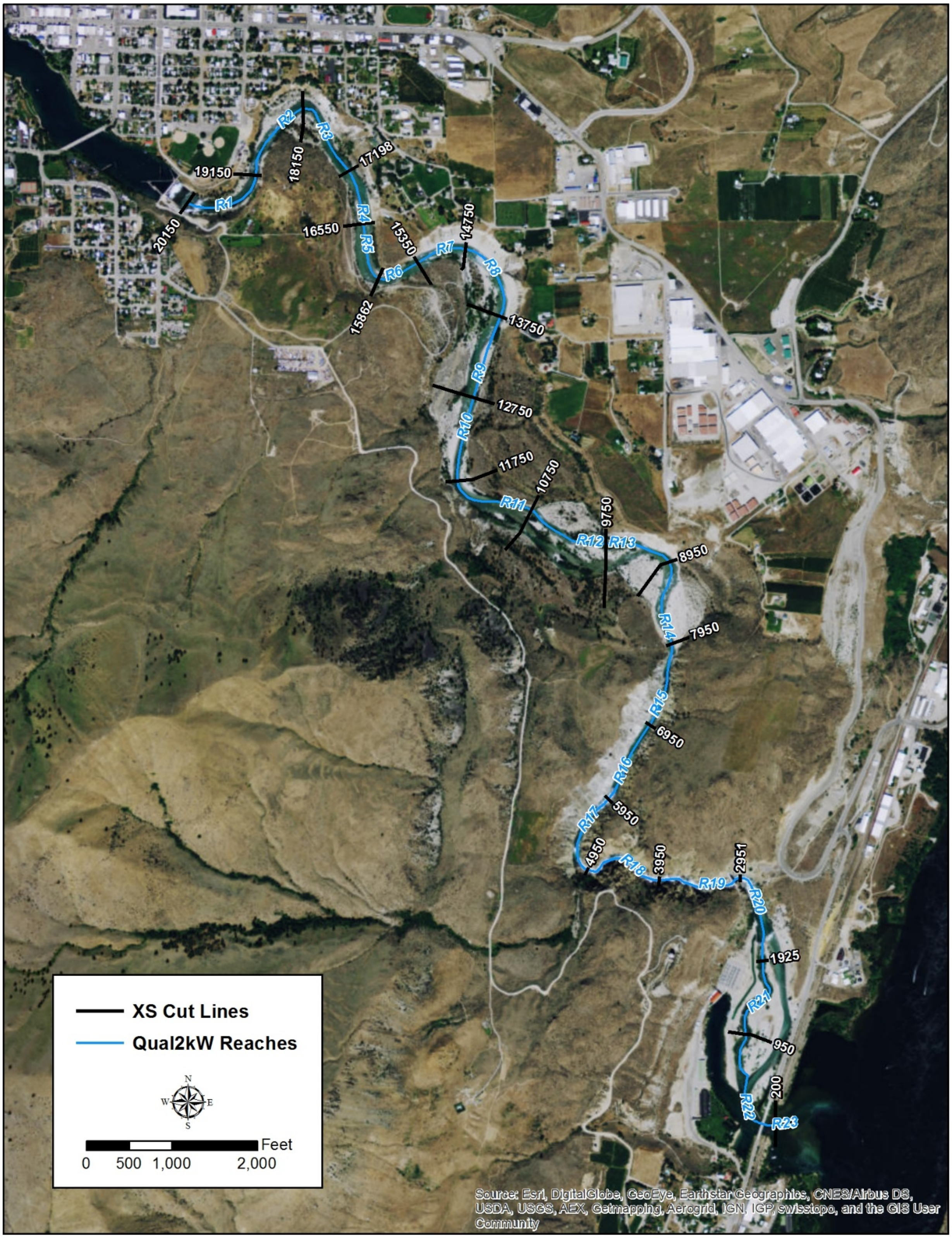


Figure 14. QUAL2Kw temperature model segmentation

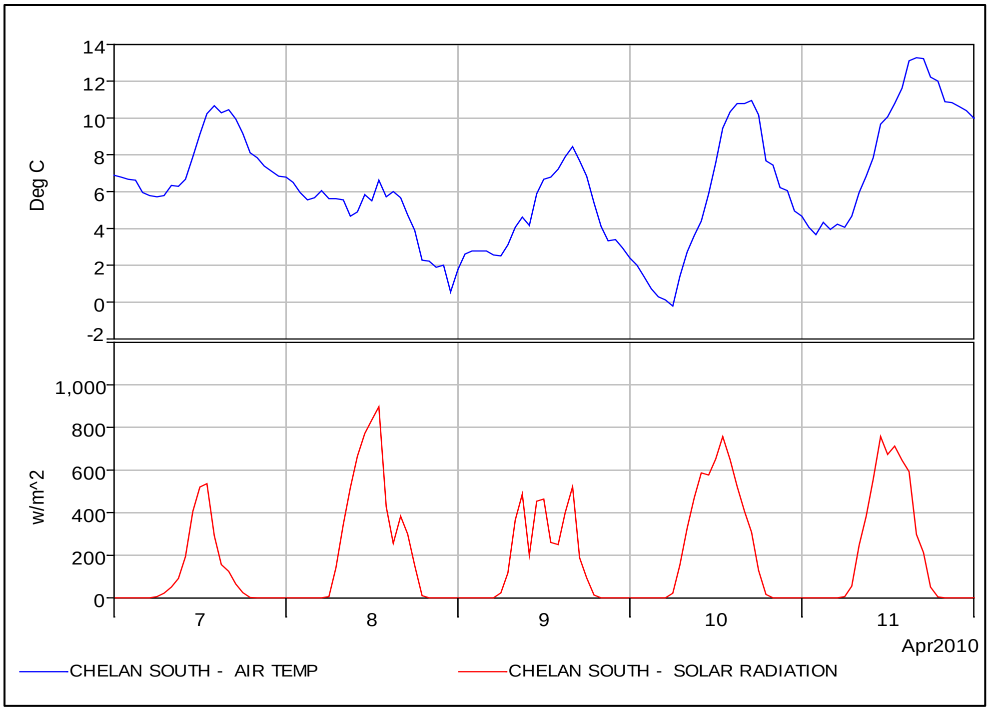


Figure 15. Meteorological variation during the April 2010 event

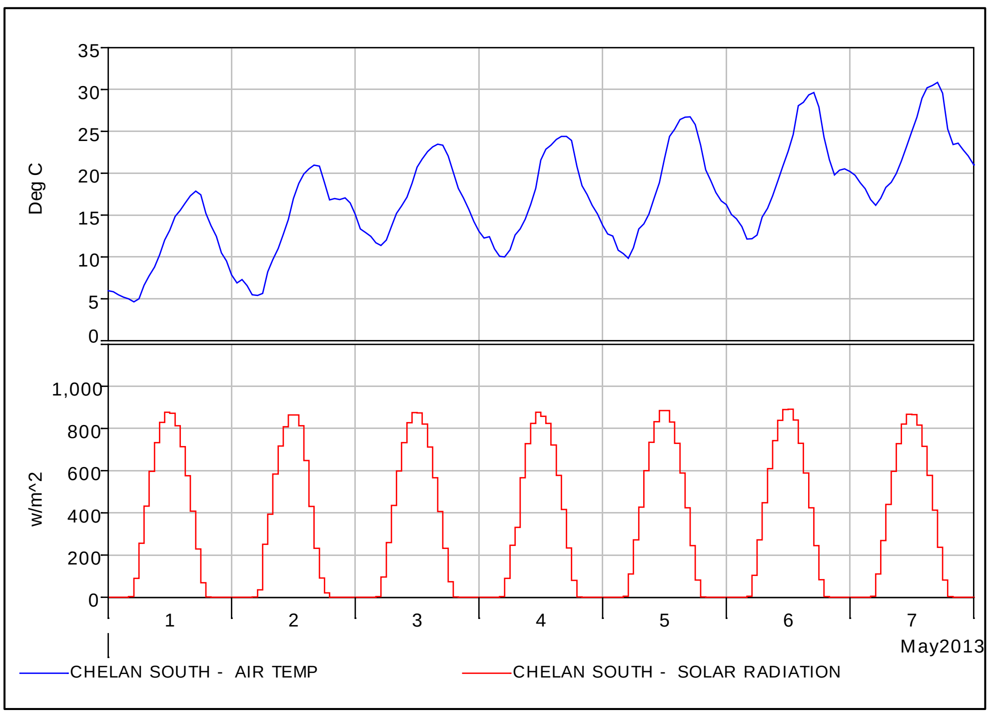


Figure 16. Meteorological variation during the May 2013 event

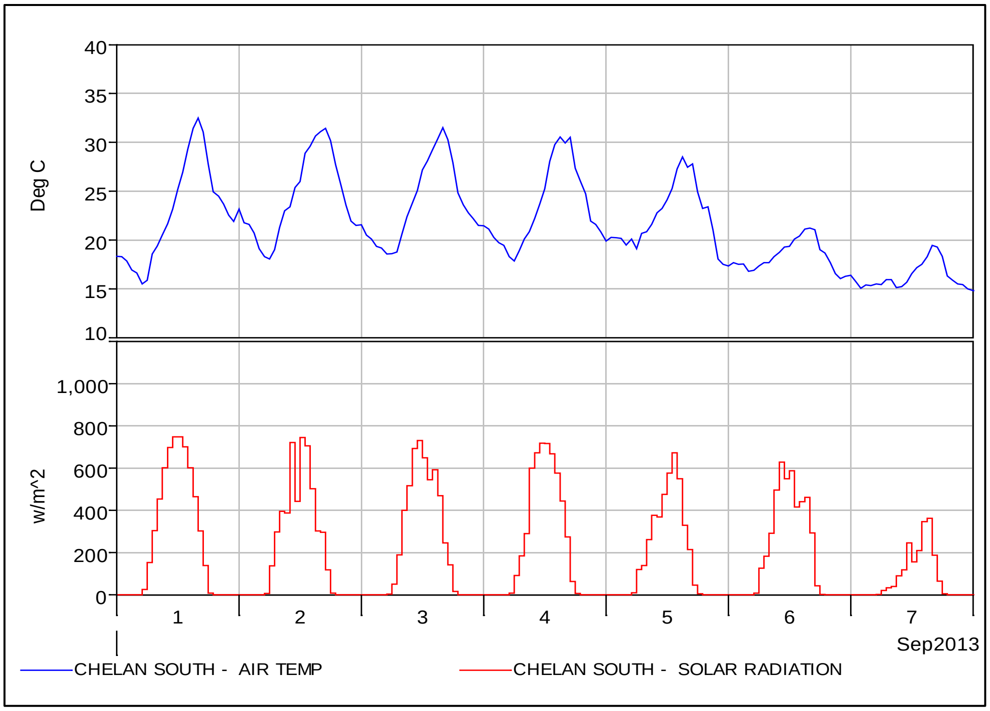


Figure 17. Meteorological variation during the September 2013 event

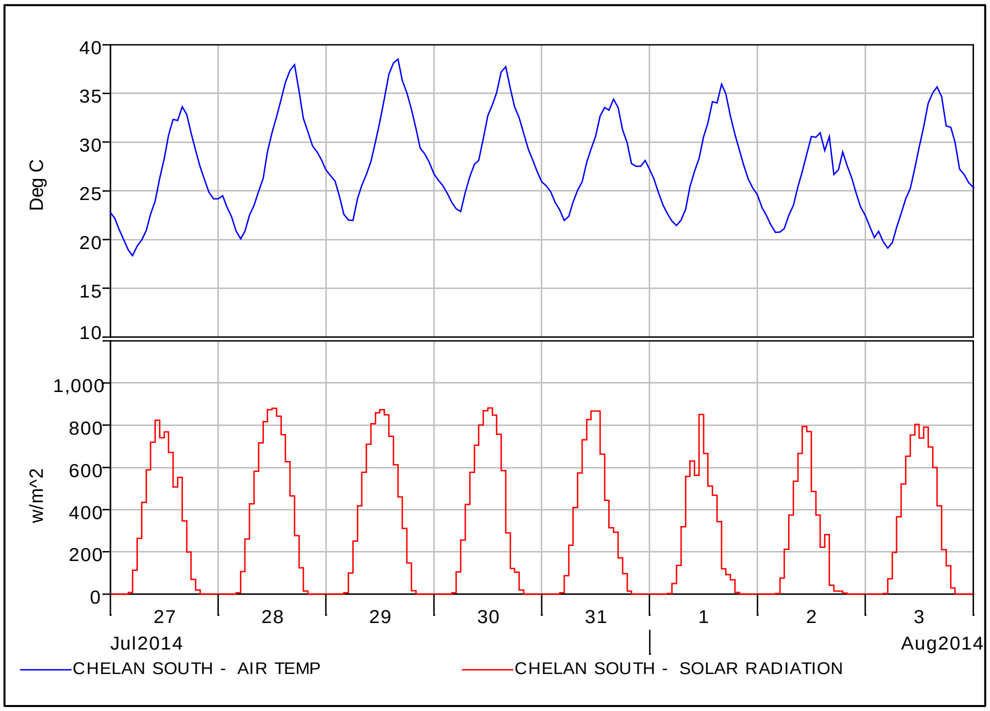


Figure 18. Meteorological variation during the August 2014 event

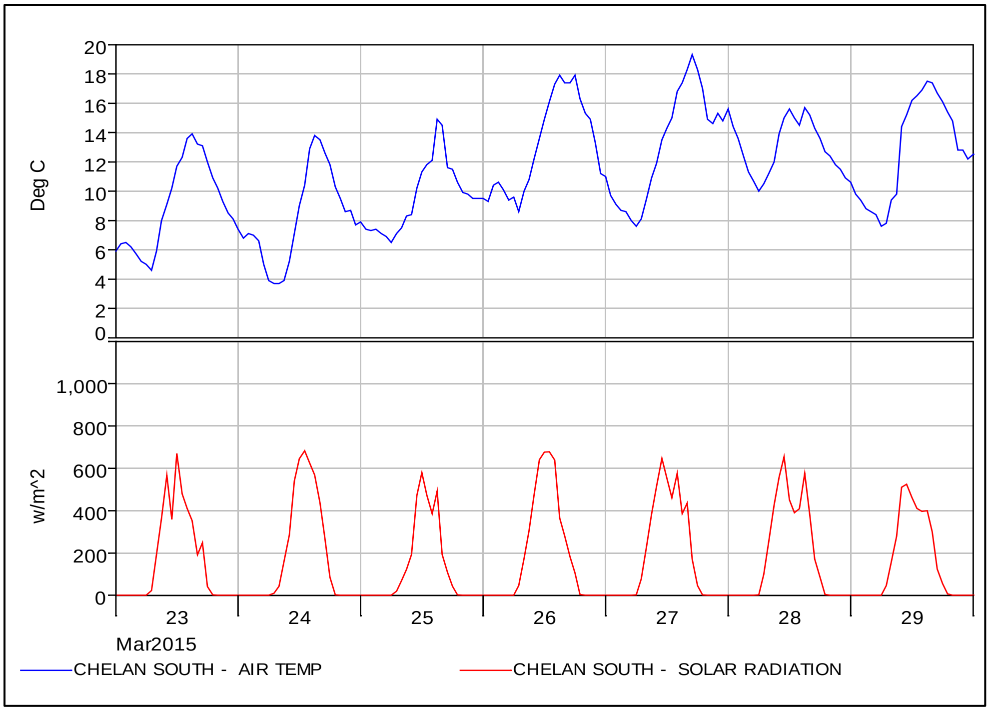


Figure 19. Meteorological variation during the March 2015 event

4.3 Model Sensitivity Analysis

4.3.1 Initial Process Investigation

After obtaining all necessary QUAL2Kw input data, including power functions, meteorological data, flow data, and inflow temperatures, an initial temperature model run was performed for late May 2013. This initial model run used default values for most QUAL2Kw parameters. When run, this model output in-stream temperatures that had significantly higher daily maximum temperatures and significantly lower daily minimum temperatures than observed (Figure 20). We began looking to hyporheic flow as potentially being a source of significant temperature moderation on the Chelan River, as "hyporheic water contains a proportion of groundwater, which is generally constant in temperature relative to stream temperature" (Reidy, 2004). After enabling the hyporheic flow routine in QUAL2Kw, as well as roughly calibrating the parameters that describe hyporheic flow, a significant improvement in temperature model output can be seen (Figure 20).

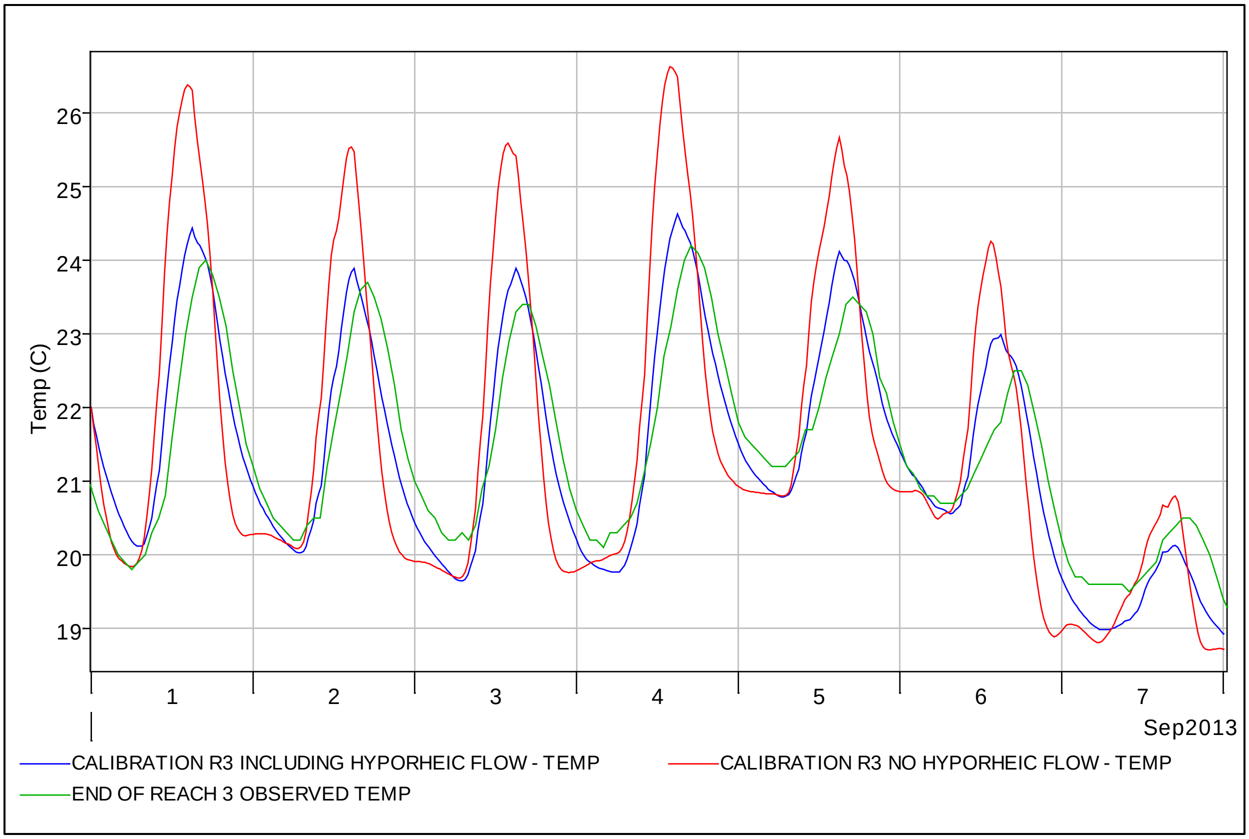


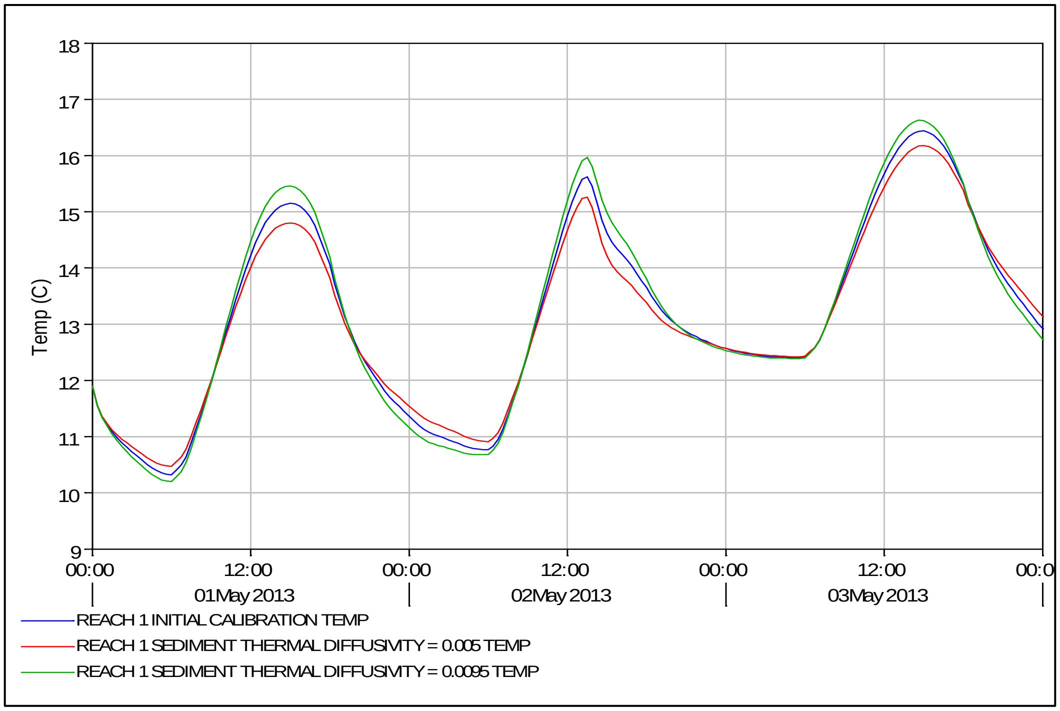
Figure 20. The moderating effects of hyporheic flow on the temperature model

4.3.2 Parameter Sensitivity

We performed a linear parameter sensitivity analysis after initial calibration of the temperature model (Figure 21 through Figure 29). This information was then used to calibrate the temperature model. Sensitivity analysis was performed primarily on parameters that characterize hyporheic flow in QUAL2Kw, including: hyporheic zone thickness, sediment thermal conductivity, sediment thermal diffusivity, hyporheic flow fraction, sediment porosity, and deep sediment temperature. The sensitivity analysis also included incision, which is an input parameter for the Shade.xls model, and light extinction. This analysis was performed for the May 2013 event, and is expected to be representative of any simulation time period. Table 8 below shows statistical parameters describing this sensitivity analysis, with the first 24 hours of QUAL2Kw output data discarded to avoid any initialization error. The statistics compare the results of a change in each model parameter compared to the base case. This analysis shows the model to be significantly sensitive to hyporheic zone thickness, sediment thermal conductivity, and sediment thermal diffusivity. It shows the model to be moderately sensitive to hyporheic flow fraction and deep sediment temperature, while it is relatively insensitive to hyporheic sediment porosity, shade.xls incision, and light extinction.

We also looked at the influence of Mannings *n* roughness values on the hydraulic power functions used in QUAL2Kw, and therefore its influence on water column temperatures. A 20 percent change in Mannings *n* roughness values led to a 90-115 percent average change in stream velocities and a 90-107 percent average change in water depths. We simulated this range of conditions and found (Figure 29) that decreasing Mannings *n* had little effect on stream temperatures and that increasing values had only a moderate effect (less than 0.5^{o}C). As the roughness values are already quite large, overall we believe that the calibrated values are reasonable and will have little effect on model stream temperatures.

Finally, we conducted an abbreviated sensitivity analysis using the March 2015 period. Looking at sediment thermal conductivity (high sensitivity), deep sediment temperatures (moderate sensitivity), and light extinction (low sensitivity), we found very similar levels of parameter sensitivity. This suggests uniformity of parameter response over the various simulations periods chosen (march-September).



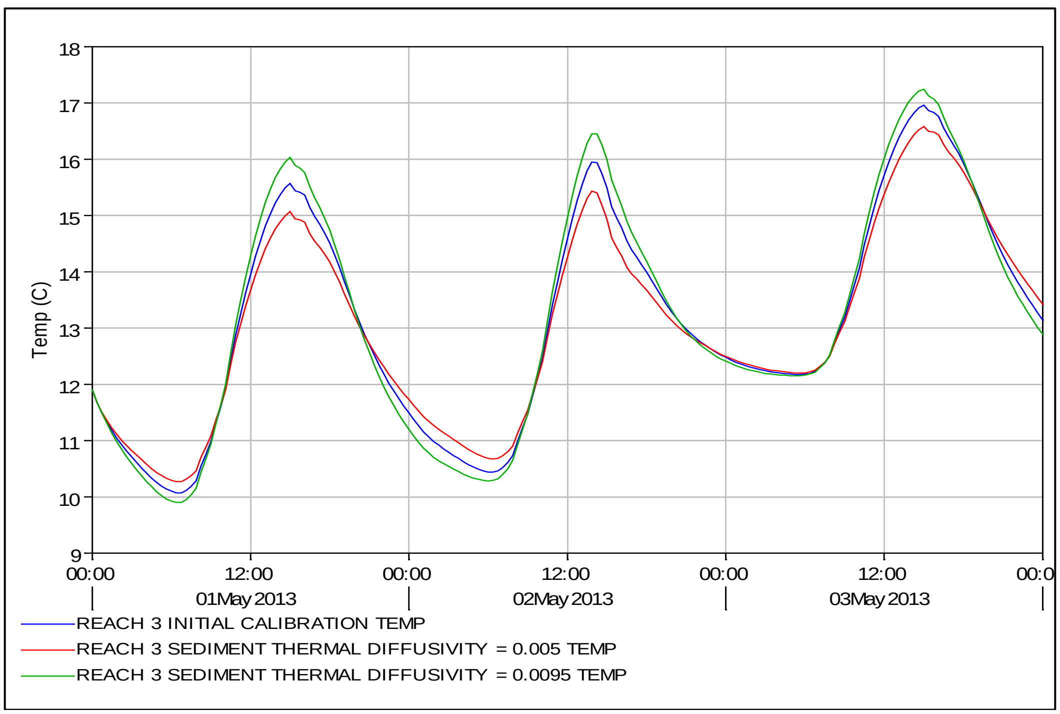


Figure 21. Sediment thermal diffusivity sensitivity analysis (0.005 - 0.0095 cm^2/sec)

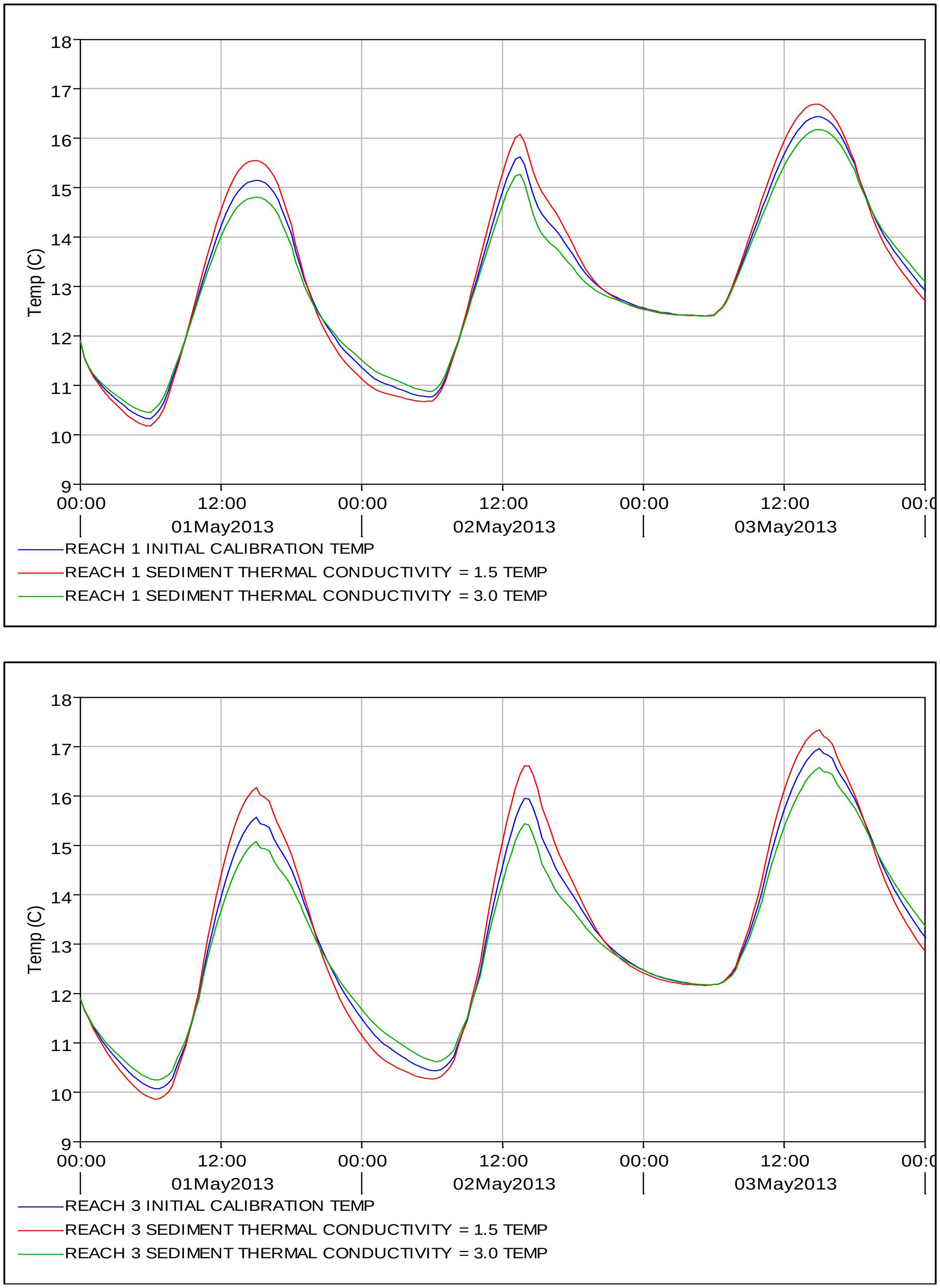
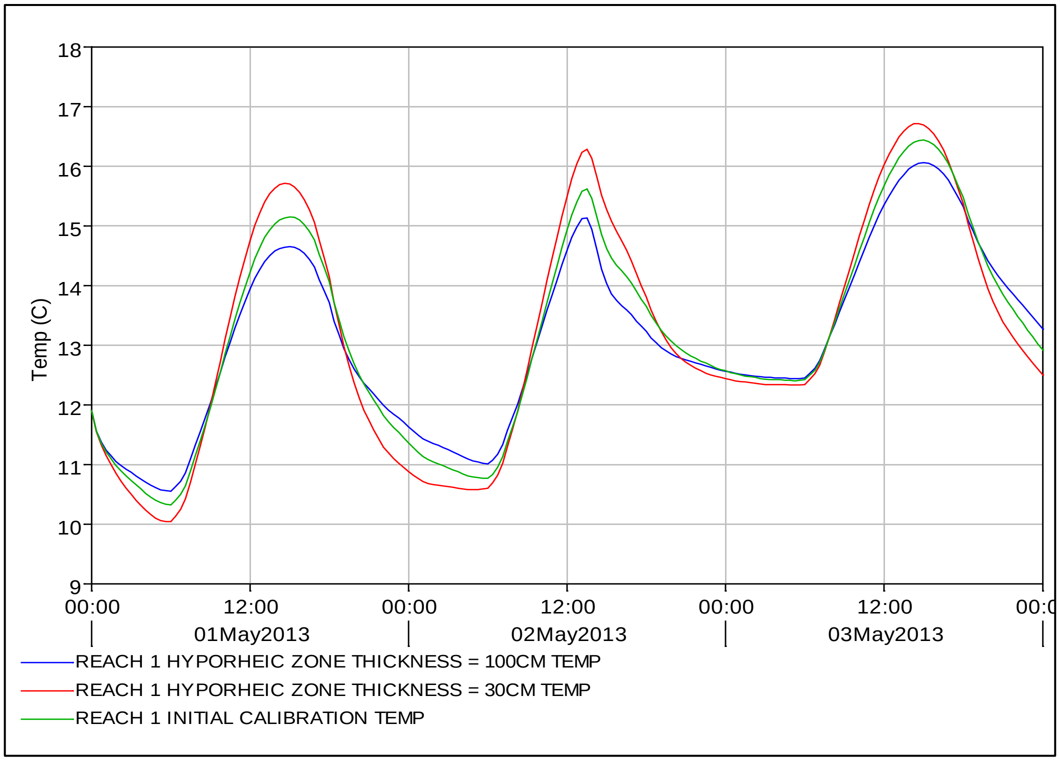


Figure 22. Sediment thermal conductivity sensitivity analysis (1.5 – 3.0 W/m/°C)



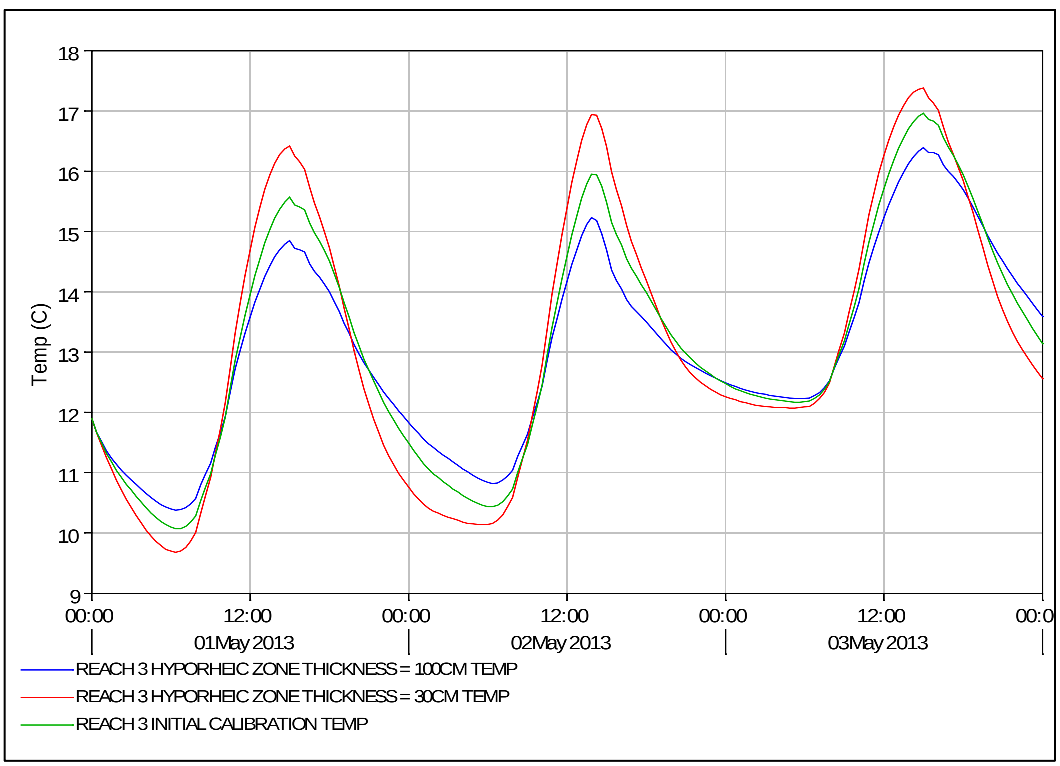


Figure 23. Hyporheic zone thickness sensitivity analysis (30 – 100 cm)

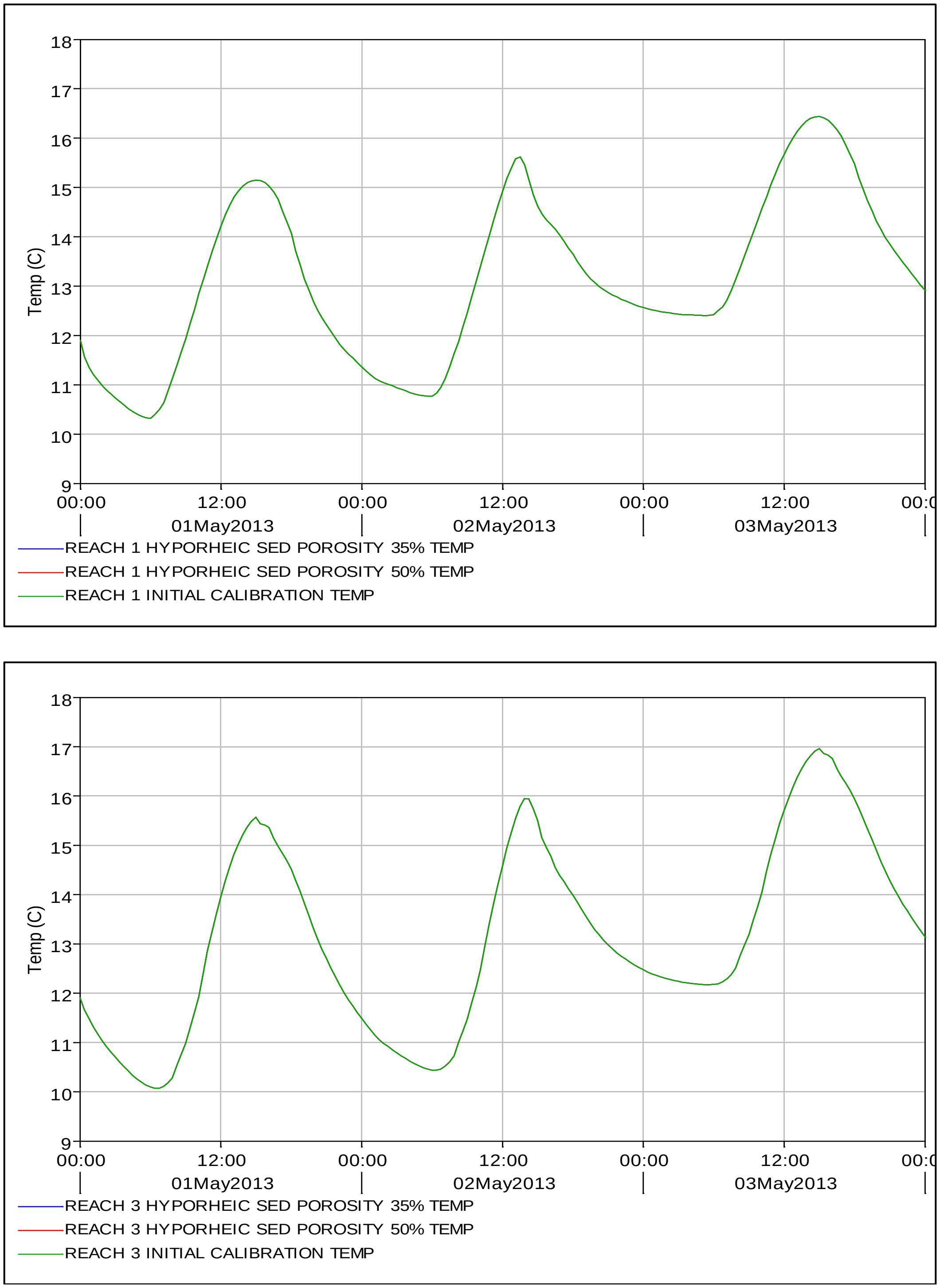
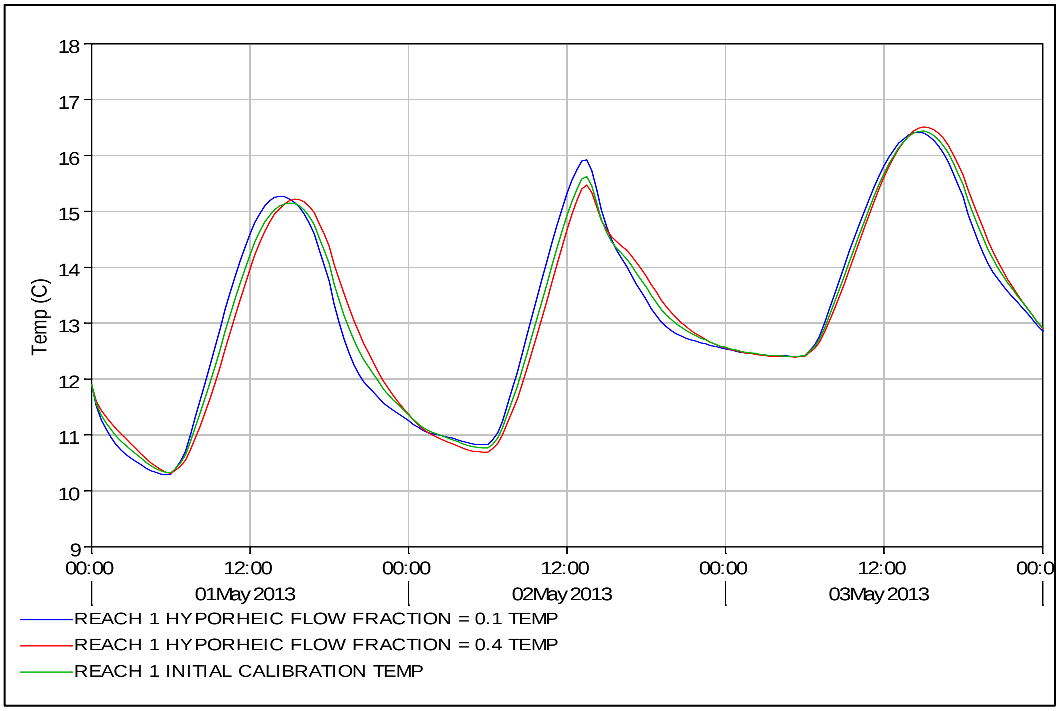


Figure 24. Hyporheic sediment porosity sensitivity analysis (35 – 50%)



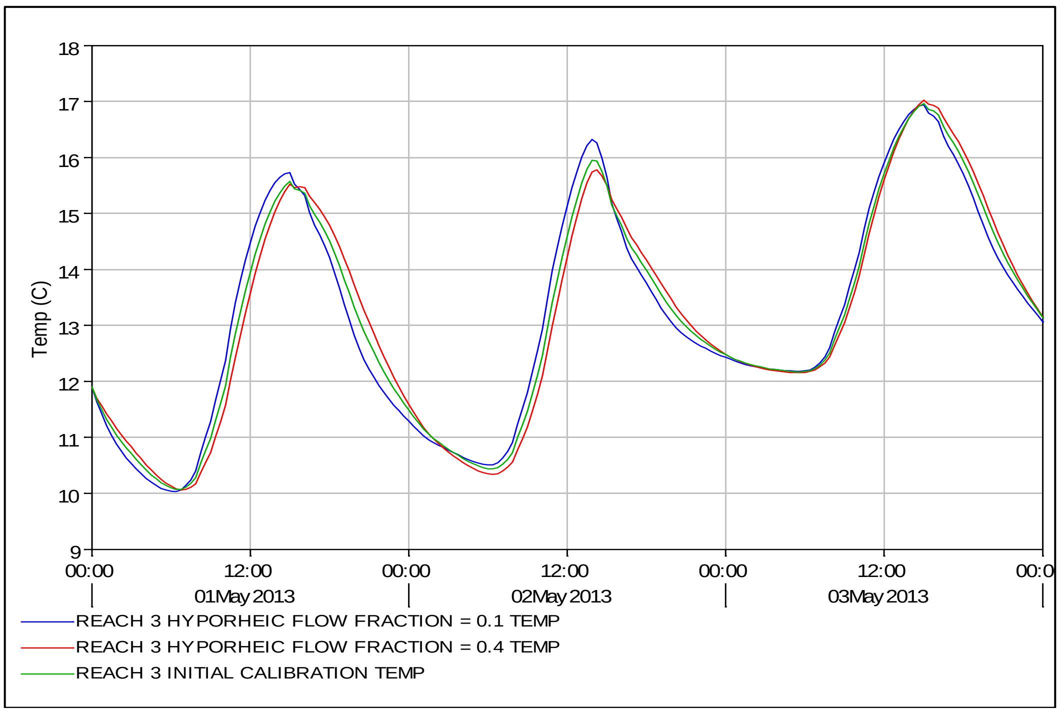
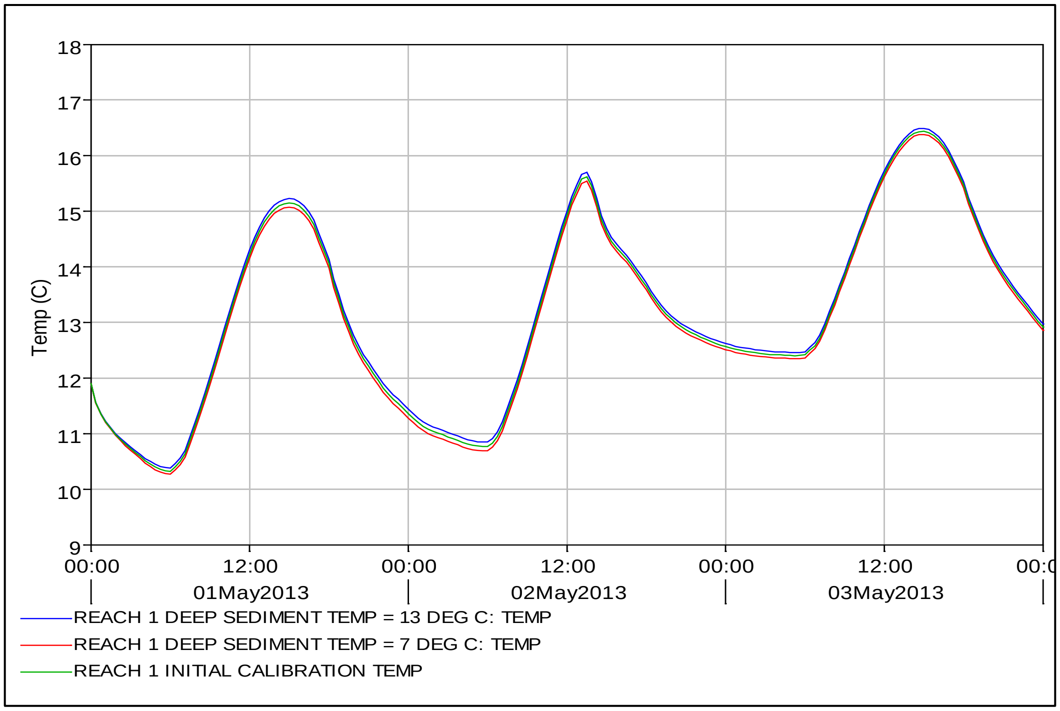


Figure 25. Hyporheic flow fraction sensitivity analysis (0.1 -0.4)



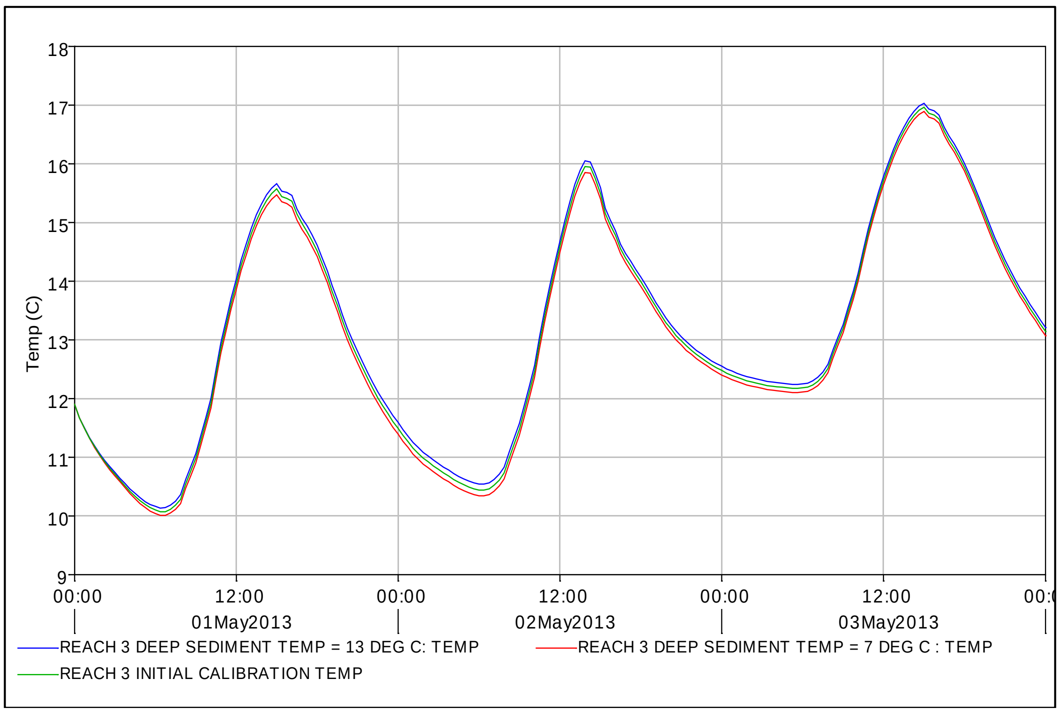
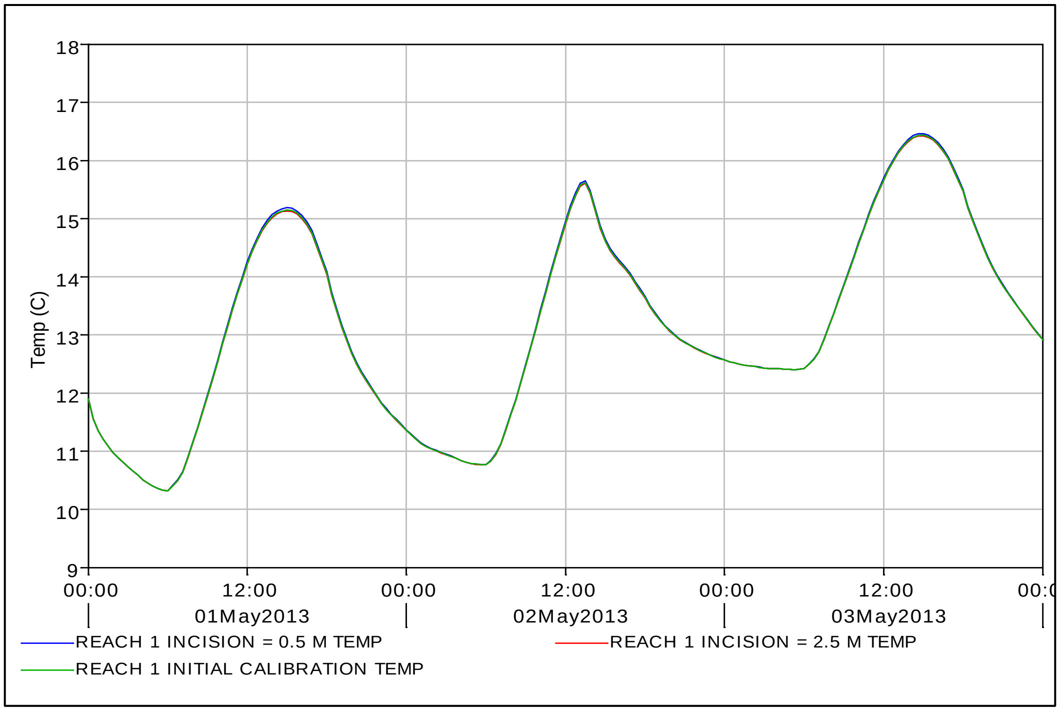


Figure 26. Deep sediment temperature sensitivity analysis (7 – 13 °C)



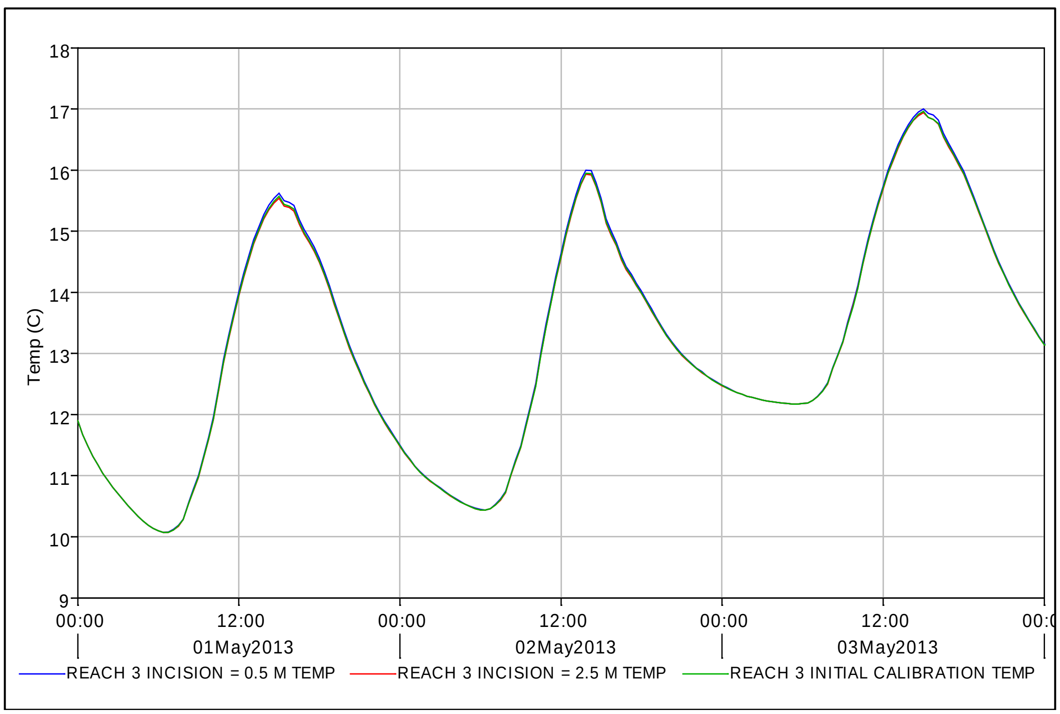
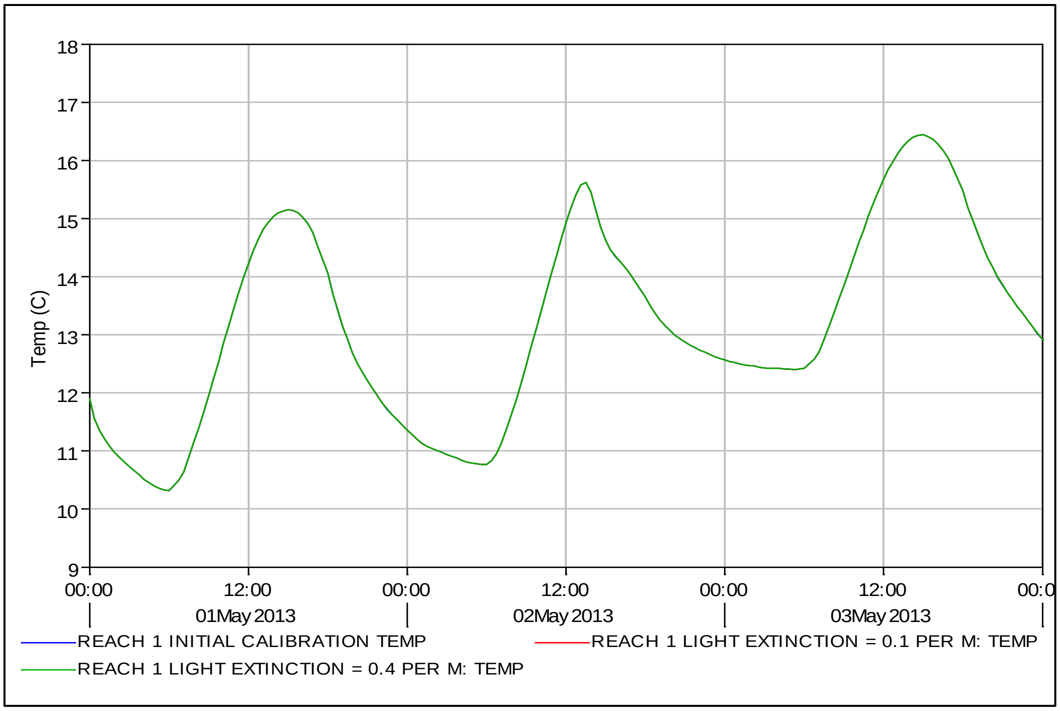


Figure 27. Incision sensitivity analysis (0.5 – 2.5 m)



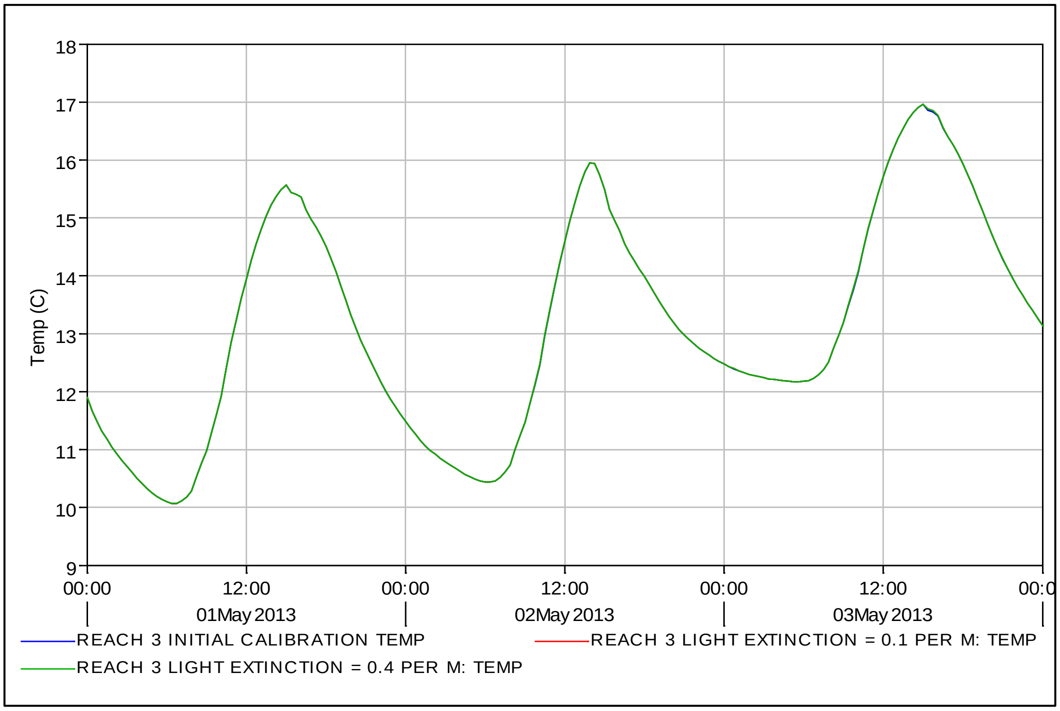
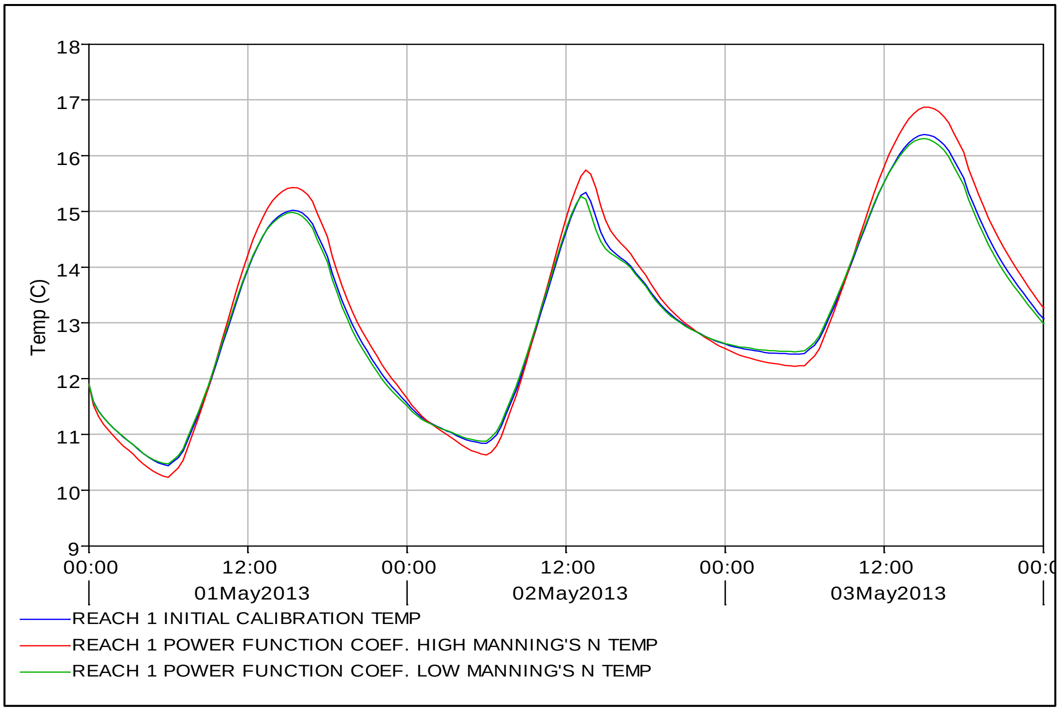


Figure 28. Light Extinction Sensitivity Analysis (0.1 – 0.4 / m)



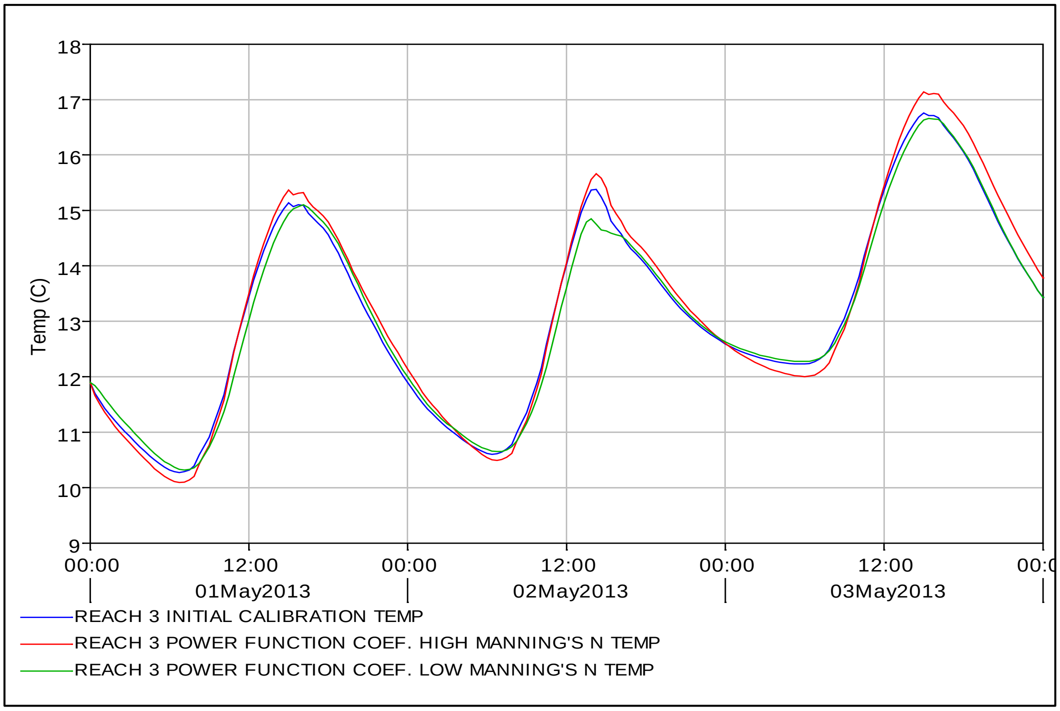


Figure 29. Changing Qual2kw Power Function Coefficients (Velocity and Depth) Corresponding to Reasonable Manning's n Values.

Table 8. Sensitivity analysis statistics, with error as deviation from initial calibration results

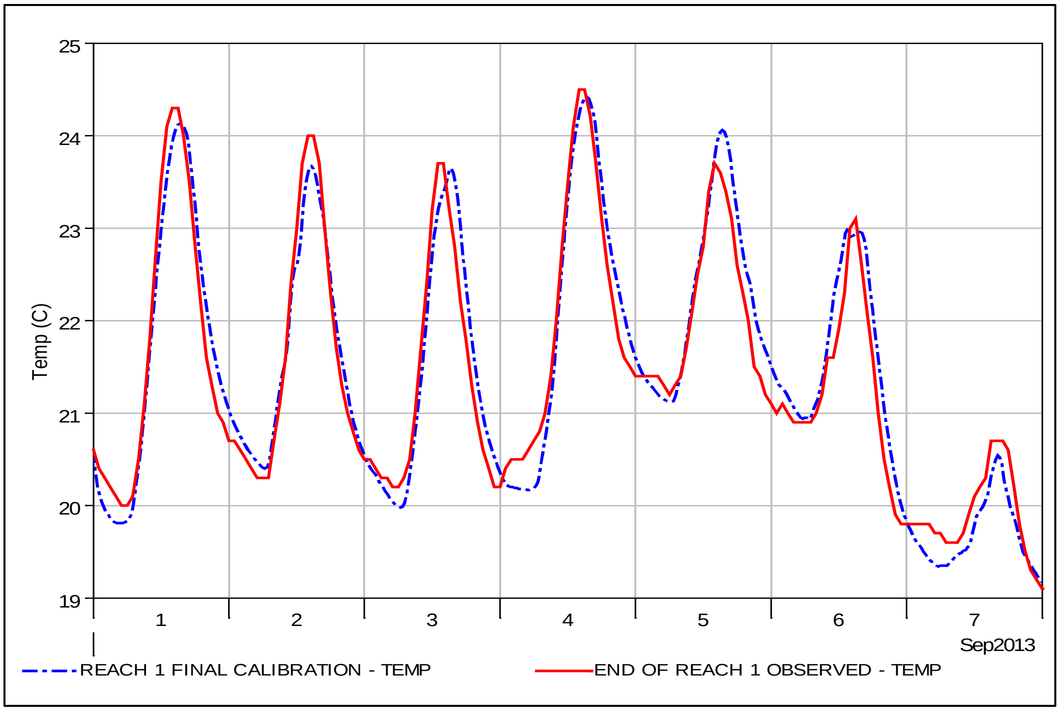
			Reach 1			Reach 3		
Parameter (value)	Initial Parameter Value	Change from Base Value	Mean Error (°C)	Mean Absolute Error	Root Mean Square Error	Mean Error (°C)	Mean Absolute Error	Root Mean Square Error
Sediment Thermal Diffusivity (0.005 cm^2/sec)	.007 cm^2/s	- 29%	-0.047	0.141	0.172	-0.056	0.191	0.233
Sediment Thermal Diffusivity (0.0095 cm^2/sec)		+ 36%	0.031	0.115	0.141	0.038	0.161	0.197
Sediment Thermal Conductivity (1.5 W/m/°C)	2.2 W/m/°C	- 32%	0.063	0.145	0.182	0.077	0.200	0.253
Sediment Thermal Conductivity (3.0 W/m/°C)		+ 36%	-0.070	0.136	0.168	-0.085	0.182	0.227
Hyporheic Zone Thickness (30cm)	60 cm	- 50%	-0.012	0.237	0.274	-0.020	0.336	0.391
Hyporheic Zone Thickness (100cm)		+ 67%	-0.050	0.213	0.255	-0.057	0.287	0.345
Hyporheic Sediment Porosity (0.35)	0.4	- 13%	0.000	0.000	0.000	0.000	0.000	0.000
Hyporheic Sediment Porosity (0.50)		+ 25 %	0.000	0.000	0.000	0.000	0.000	0.000
Hyporheic Flow Fraction (0.1)	0.2	- 50%	0.010	0.113	0.145	0.011	0.138	0.180
Hyporheic Flow Fraction (0.4)		+ 100%	-0.008	0.080	0.105	-0.009	0.098	0.126
Deep Sediment Temperature (7 °C)	10 °C	- 30%	-0.059	0.059	0.059	-0.073	0.073	0.074
Deep Sediment Temperature (13 °C)		+ 30%	0.058	0.058	0.058	0.073	0.073	0.074
Shade.xls Incision (0.5 m)	2.0 m	- 75%	0.013	0.013	0.017	0.021	0.021	0.027
Shade.xls Incision (2.5 m)		+25%	-0.006	0.006	0.009	-0.008	0.008	0.011
Background Light Extinction (0.1/m)	0.2/m	- 50%	0.000	0.000	0.002	0.001	0.001	0.005
Background Light Extinction (0.4/m)		+ 100%	0.002	0.002	0.002	0.001	0.001	0.005
Power Function Coefficients (high Manning's n) (Velocity*0.9 Depth*1.07)	Manning's n increased 20% (reachwide)		0.146	0.217	0.071	0.147	0.218	0.069
Power Function Coefficients (low Manning's n) (Velocity*1.15 Depth*0.92)	Manning's n decreased 20% (reachwide)		-0.021	0.045	0.003	-0.045	0.106	0.023

4.4 Model Calibration

We completed final model calibration using information provided by the sensitivity analysis. This consisted of changing parameters characterizing the hyporheic zone, as these are the most sensitive calibration parameters in the temperature model. Table 9 shows parameter values characterizing the hyporheic zone. The model was calibrated to temperature gauges located at the end of study reach 1 and study reach 2 (see study reach locations in Figure 1). Calibrated temperature model results can be seen in Figure 30, and calibration error statistics can be seen in Table 10.

Table 9. Final QUAL2Kw temperature model hyporheic zone parameters

QUAL2Kw Reach	Sediment Thermal conductivity (W/m/°C)	Sediment Thermal Diffusivity (cm^2/s)	Hyporheic Zone Thickness (cm)	Hyporheic Flow Fraction	Hyporheic Sediment Porosity	Deep Sediment Temperature (°C)
1	2.6	0.007	60	0.3	0.4	12
2	2.6	0.007	60	0.3	0.4	12
3	2.6	0.007	60	0.3	0.4	12
4	2.6	0.007	60	0.3	0.4	12
5	2.6	0.007	60	0.3	0.4	12
6	2.6	0.007	60	0.3	0.4	12
7	2.6	0.007	60	0.3	0.4	12
8	2.6	0.007	60	0.3	0.4	12
9	2.6	0.007	60	0.3	0.4	12
10	2.6	0.007	60	0.3	0.4	12
11	2.6	0.007	60	0.3	0.4	12
12	2.6	0.007	60	0.3	0.4	12
13	2.6	0.007	60	0.3	0.4	12
14	2.6	0.007	60	0.3	0.4	12
15	2.6	0.007	60	0.3	0.4	12
16	2.6	0.007	75	0.3	0.4	12
17	2.6	0.007	75	0.3	0.4	12
18	2.6	0.007	75	0.3	0.4	12
19	2.6	0.007	75	0.3	0.4	12
20	2.6	0.007	75	0.3	0.4	12
21	2.6	0.007	75	0.3	0.4	12
22	2.6	0.007	75	0.3	0.4	12
23	2.6	0.007	75	0.3	0.4	12



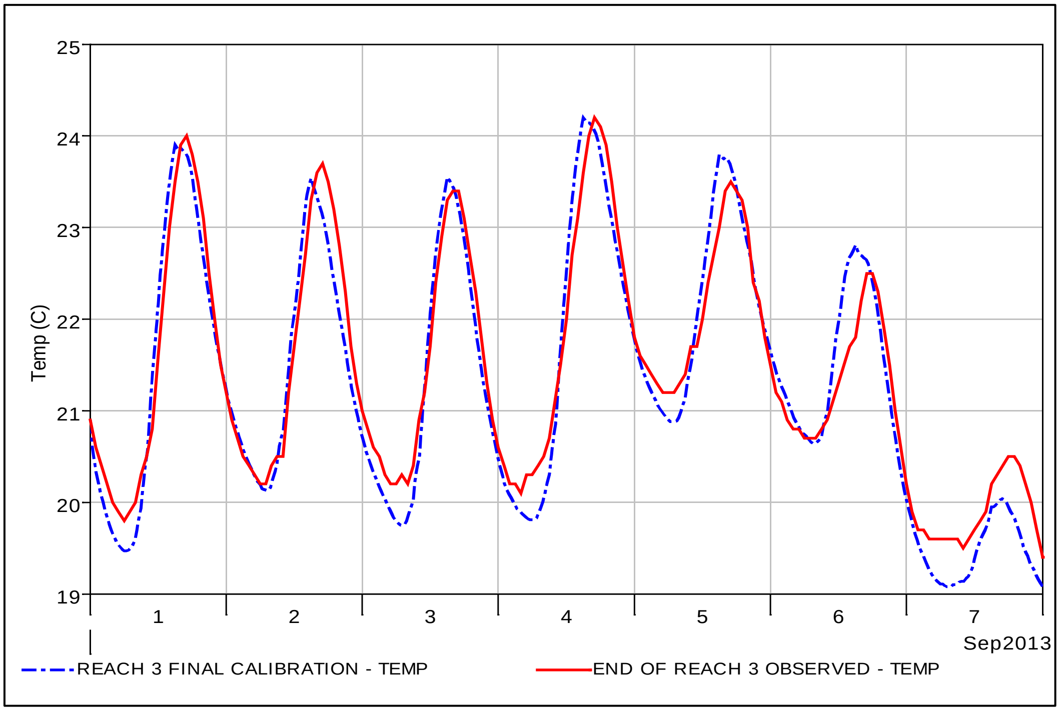


Figure 30. Calibrated temperature model results

Table 10. Final calibration error statistics, with error defined as: $T_{Model} - T_{Observed}$

Observed Temperature Location	Mean Error (°C)	Mean Absolute Error (°C)	Root Mean Square Error (°C)
End of Reach 1	0.05	0.27	0.33
End of Reach 3	-0.10	0.32	0.38

4.5 Model Validation

We validated the temperature model using the April 2010, May 2013, July 2014, and March 2015 events. These events were set up with the same processes and calibration parameters in QUAL2Kw, the only difference between models being input data (including flow, water temperature, and atmospheric forcing). Model results were compared to observed temperatures at three locations: the end of Reach 1, end of Reach 3, and end of Reach 4 gauges. This comparison is shown in Figure 31 through Figure 42 below. Error statistics are shown in Table 11. Observed data were not available in Reach 1 during the July 2014 event, but was available for all three locations for the other events. The root mean square error (RMSE) for validation over the four events (6-8 days) and at different river locations ranged from 0.21 °C – 0.74 °C, which compares with an average validation RMSE of 0.75 °C for QUAL2Kw simulations over 10 day periods (Sanderson and Pickett, 2014).

Table 11. Validation error statistics, with error defined as: $T_{Model} - T_{Observed}$

Simulation	Temperature Sensor Location	Mean Error (°C)	Mean Absolute Error (°C)	Root Mean Square Error (°C)
April 2010	End of Study Reach 1	-0.25	0.56	0.71
April 2010	End of Study Reach 3	-0.37	0.43	0.51
April 2010	End of Study Reach 4	-0.47	0.47	0.51
May 2013	End of Study Reach 1	-0.08	0.36	0.45
May 2013	End of Study Reach 3	-0.22	0.33	0.47
May 2013	End of Study Reach 4	0.25	0.28	0.34
July 2014	End of Study Reach 1	*	*	*
July 2014	End of Study Reach 3	-0.07	0.35	0.42
July 2014	End of Study Reach 4	-0.16	0.27	0.33
March 2015	End of Study Reach 1	-0.45	0.48	0.57
March 2015	End of Study Reach 3	-0.58	0.65	0.74
March 2015	End of Study Reach 4	-0.14	0.15	0.21

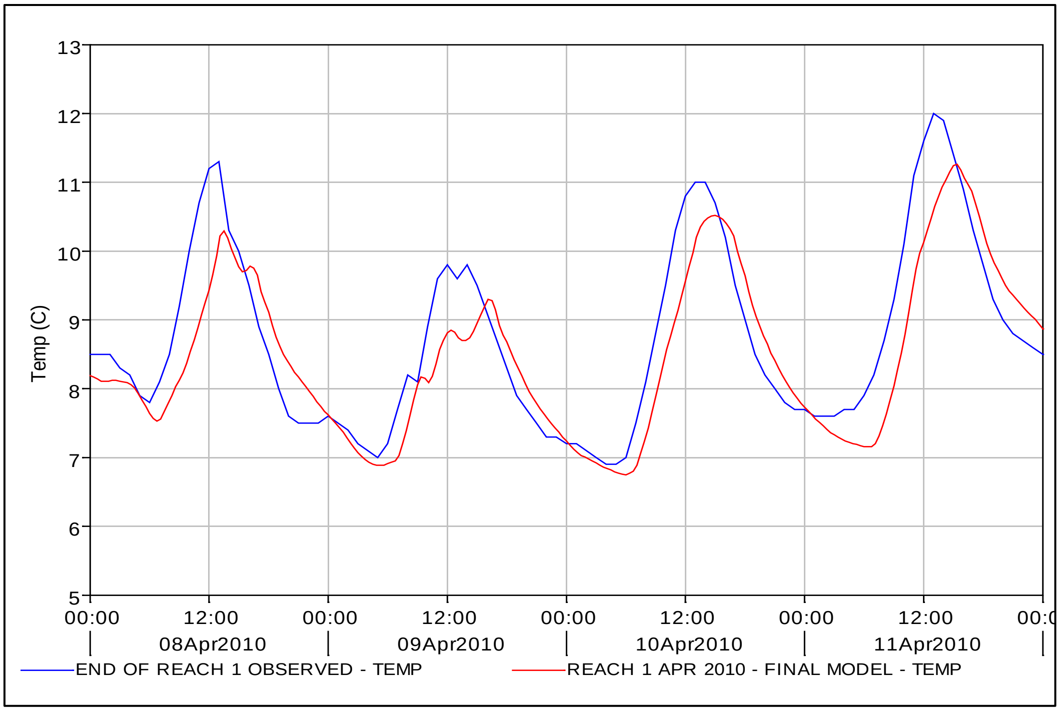


Figure 31. April 2010 end of Reach-1 validation results

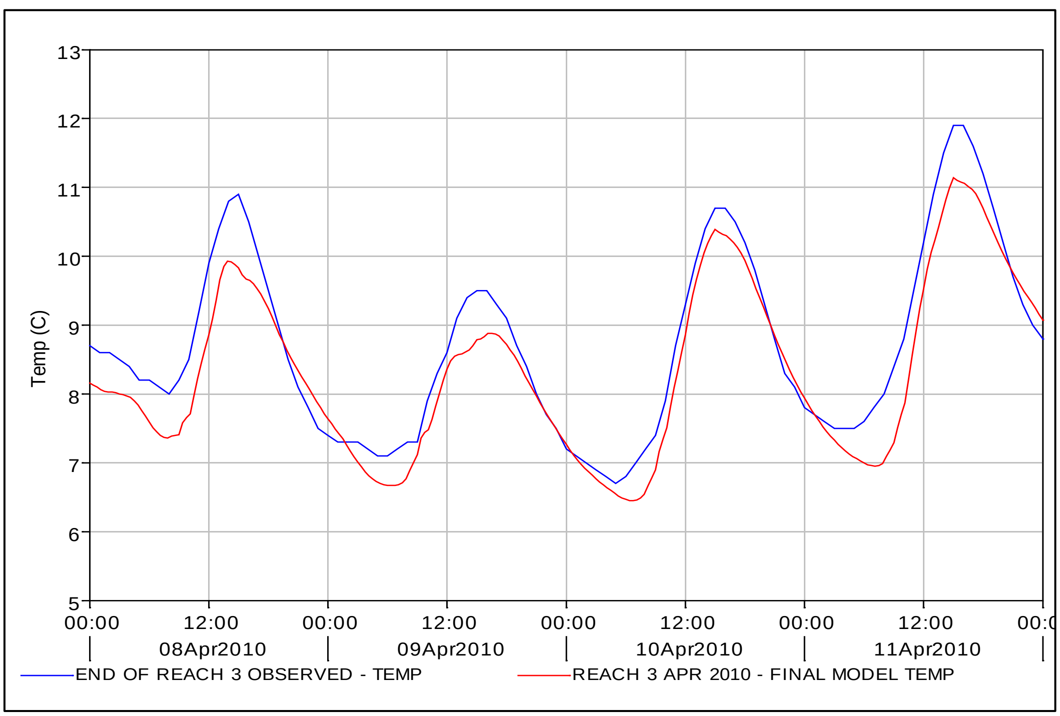


Figure 32. April 2010 end of Reach-3 validation results

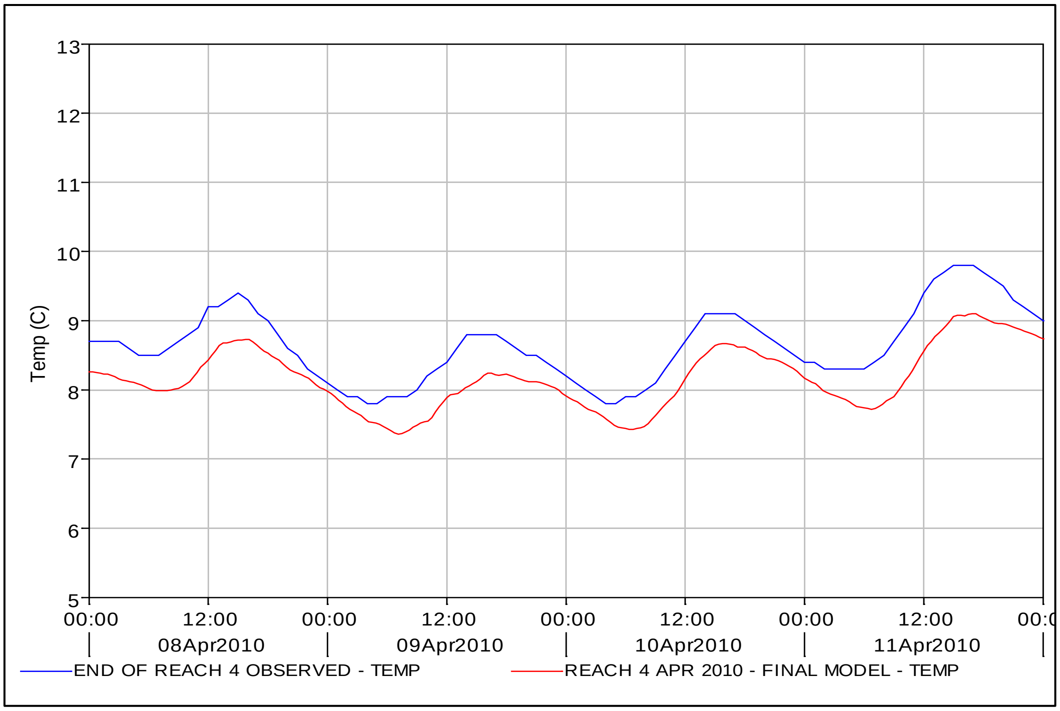


Figure 33. April 2010 end of Reach-4 validation results

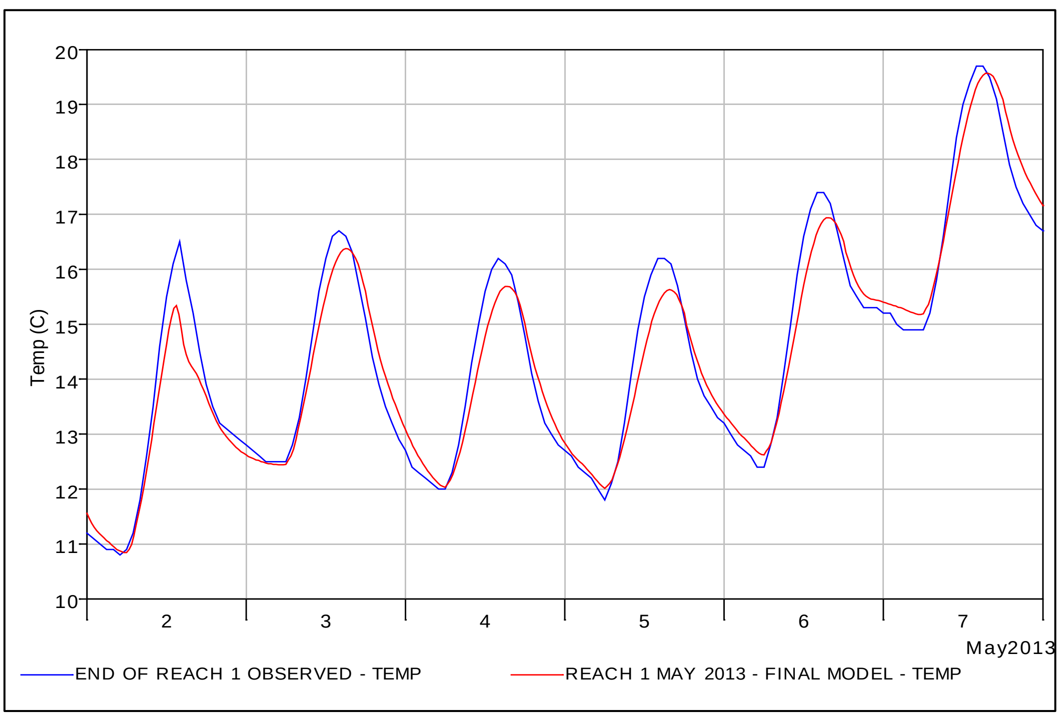


Figure 34. May 2013 end of Reach-1 validation results

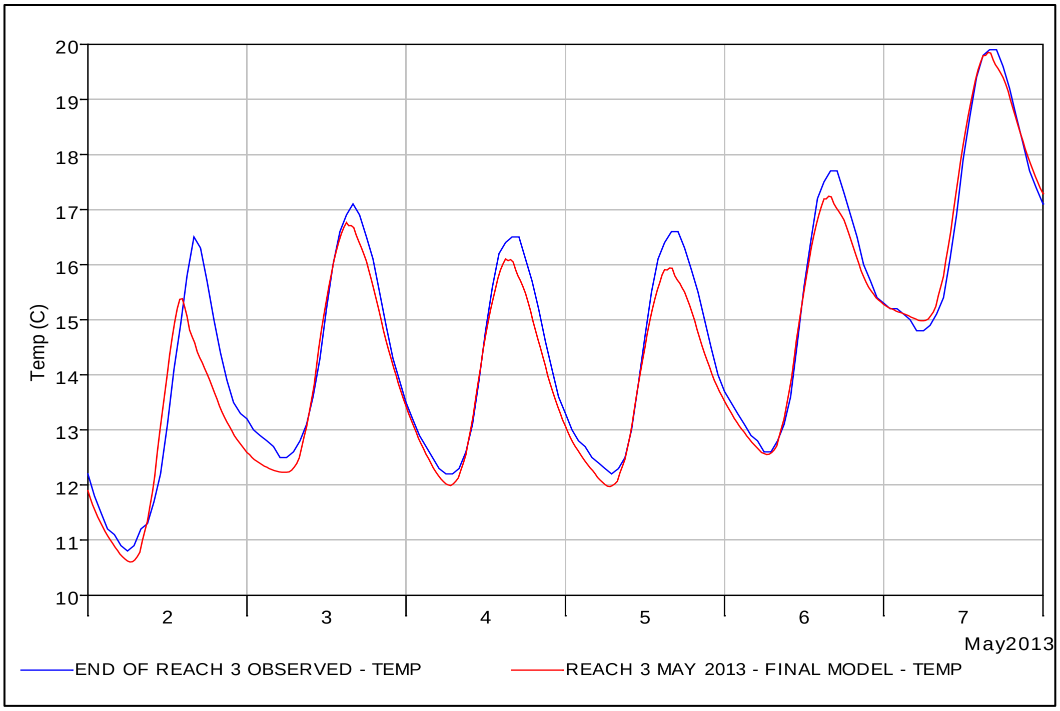


Figure 35. May 2013 end of Reach-3 validation results

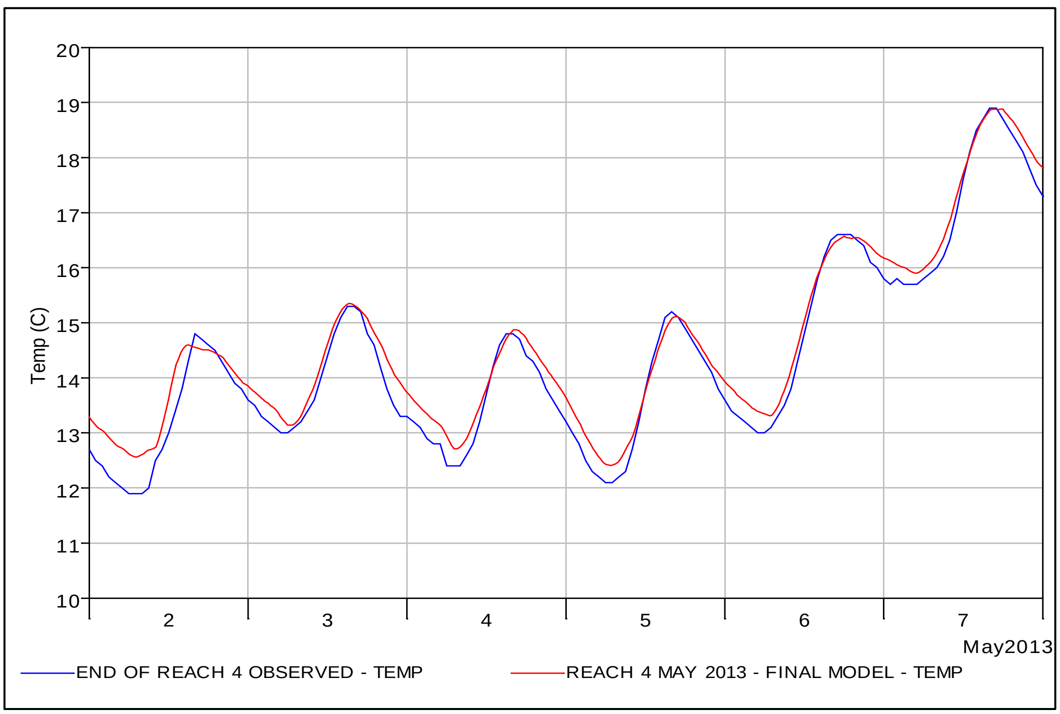


Figure 36. May 2013 end of Reach-4 validation results

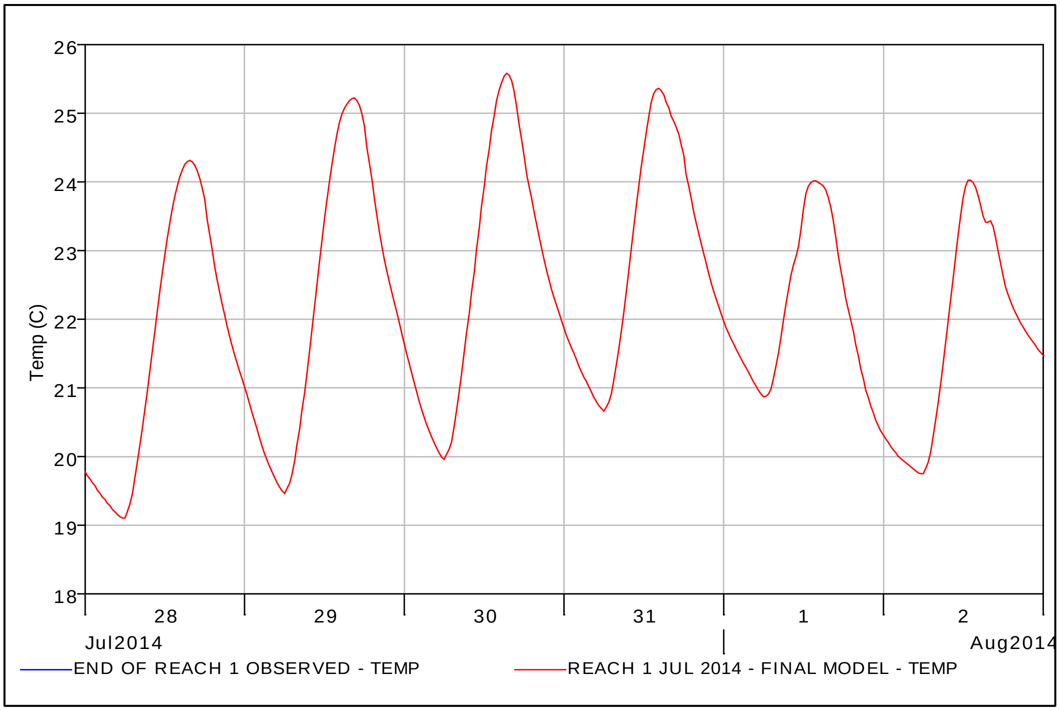


Figure 37. July 2014 end of Reach-1 validation results (observed data unavailable)

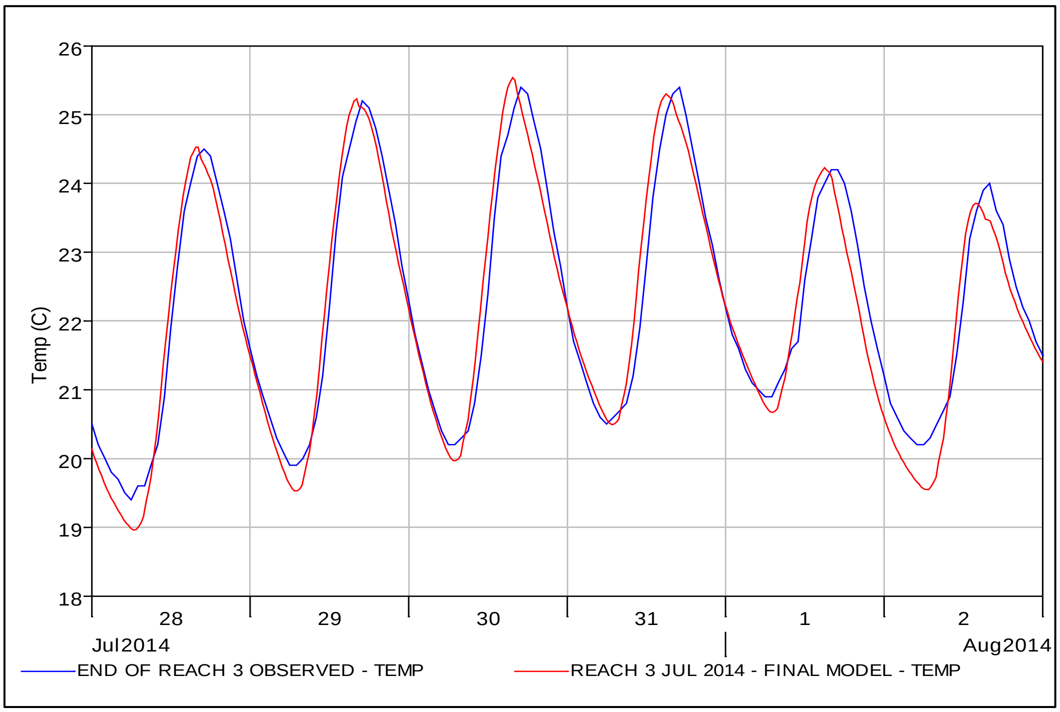


Figure 38. July 2014 end of Reach-3 validation results

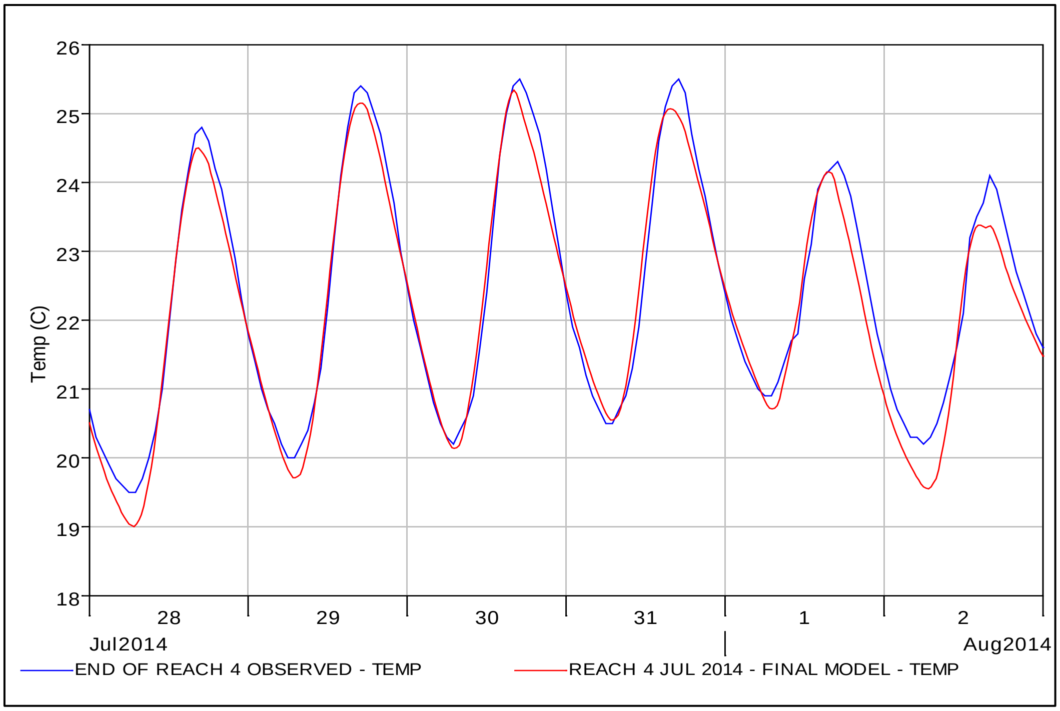


Figure 39. July 2014 end of Reach-4 validation results

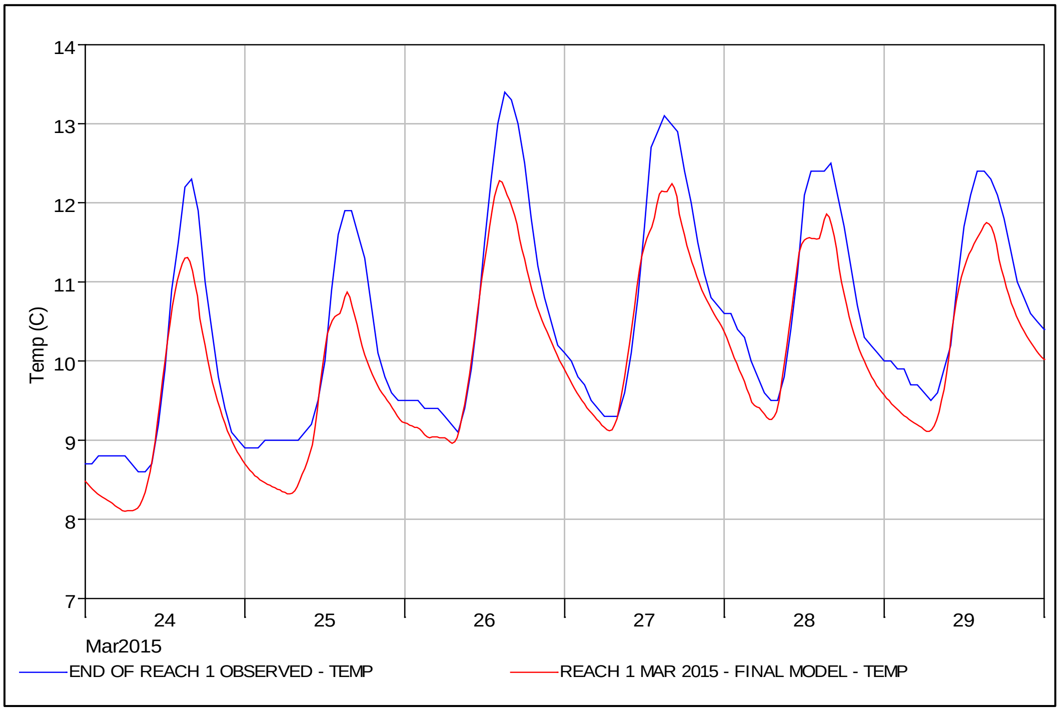


Figure 40. March 2015 end of Reach-1 validation results

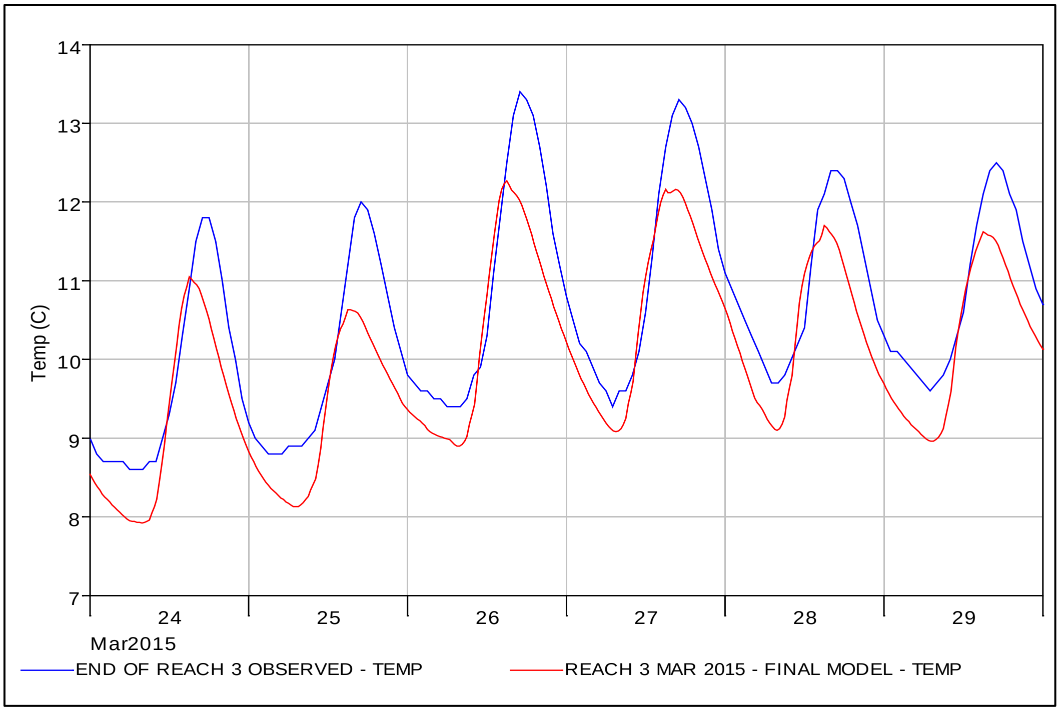


Figure 41. March 2015 end of Reach-3 validation results

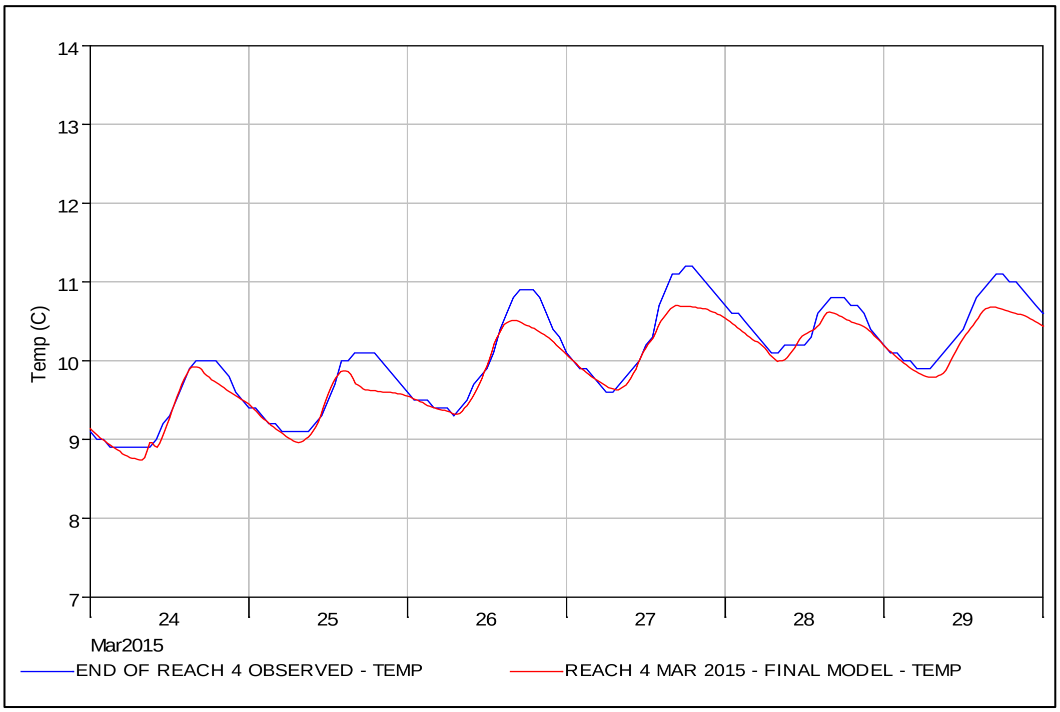


Figure 42. March 2015 end of Reach-4 validation results

4.6 Evaluation of Model Results

Generally, the model validation statistics are similar to the calibration statistics. The statistics (Table 8 and Table 11) do show a small temporal bias. The magnitude of the mean error from March to September becomes consistently smaller. It is possible that this is due to a small increase in groundwater temperatures at the base of the hyporheic zone. Without shallow groundwater data, we specified a fixed groundwater temperature for all model simulations.

5 Initial Results of Shade and Flow Scenarios

5.1 Incorporation of Existing and Potential Future Vegetative Shade

Chelan PUD contracted with Herrera to conduct a riparian limiting factors and revegetation feasibility assessment. Following completion of that assessment and the completion of the calibration and validation of the QUAL2Kw model by WEST, Chelan PUD contracted for additional work by Herrera to develop input files with existing and future potential vegetative shade for incorporation by WEST into the QUAL2Kw model. The details of the methods used in the development of existing and potential future vegetative shade are described in a Technical Memorandum (Appendix 1).

The QUAL2Kw model was used to evaluate the potential difference in water temperatures at the ends of Reach 1 and Reach 3 for a single day's peak temperature profile, as well as for each simulation period (calibration and validation) previously conducted without the inclusion of vegetative shade. Overall the results are very similar within and between time periods. The existing condition with updated vegetative shade reduces the temperature (from WEST's calibration) roughly by 1/10 °C or less during daylight hours. The fully mature vegetation alternative reduces the temperature more than the updated existing condition, but still only a couple tenths of a degree Celsius.

In the following figures, "Final Model" results refer to WEST's final calibration model results, which assumed no vegetative shading on the Chelan River. "Herrera Existing" results were obtained by updating the shade information in the Qual2kw model with Herrera's updated existing condition shade input. Herrera's full maturity vegetative shade input was used to obtain the "Herrera Full Growth" results.

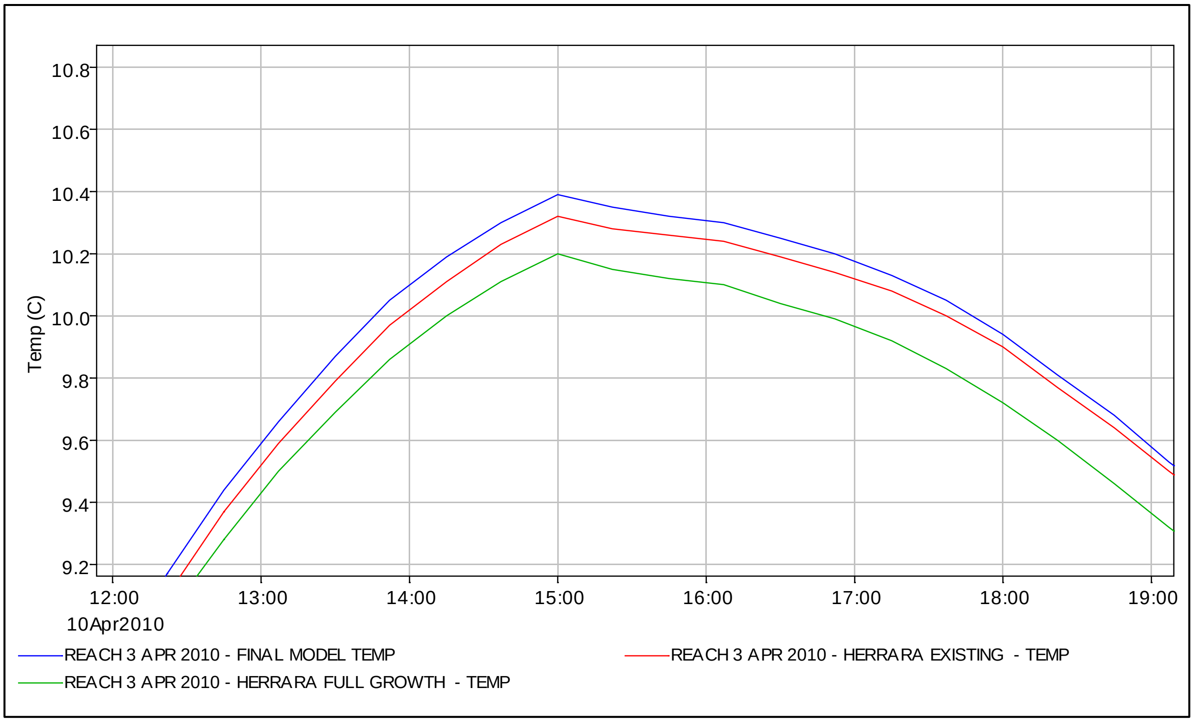


Figure 43. Single day peak temperature profile, 10 April 2010

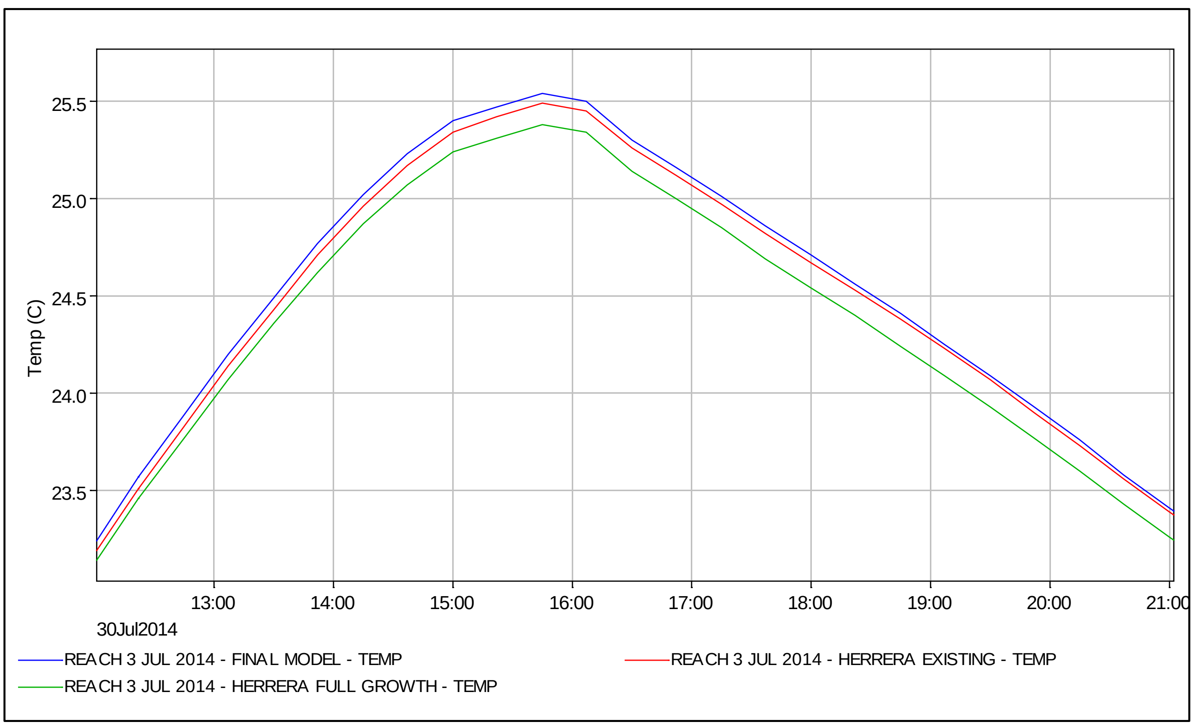


Figure 44. Single day peak temperature profile, 30 July 2014

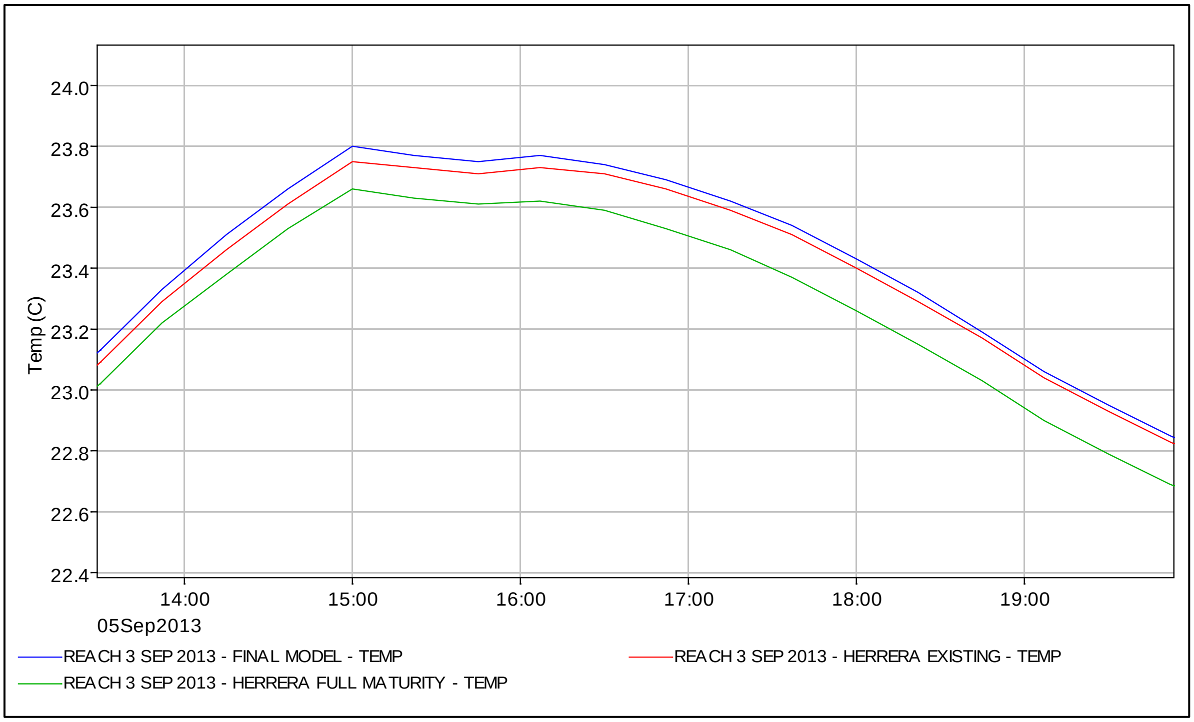


Figure 45. Single day peak temperature profile, 5 September 2013

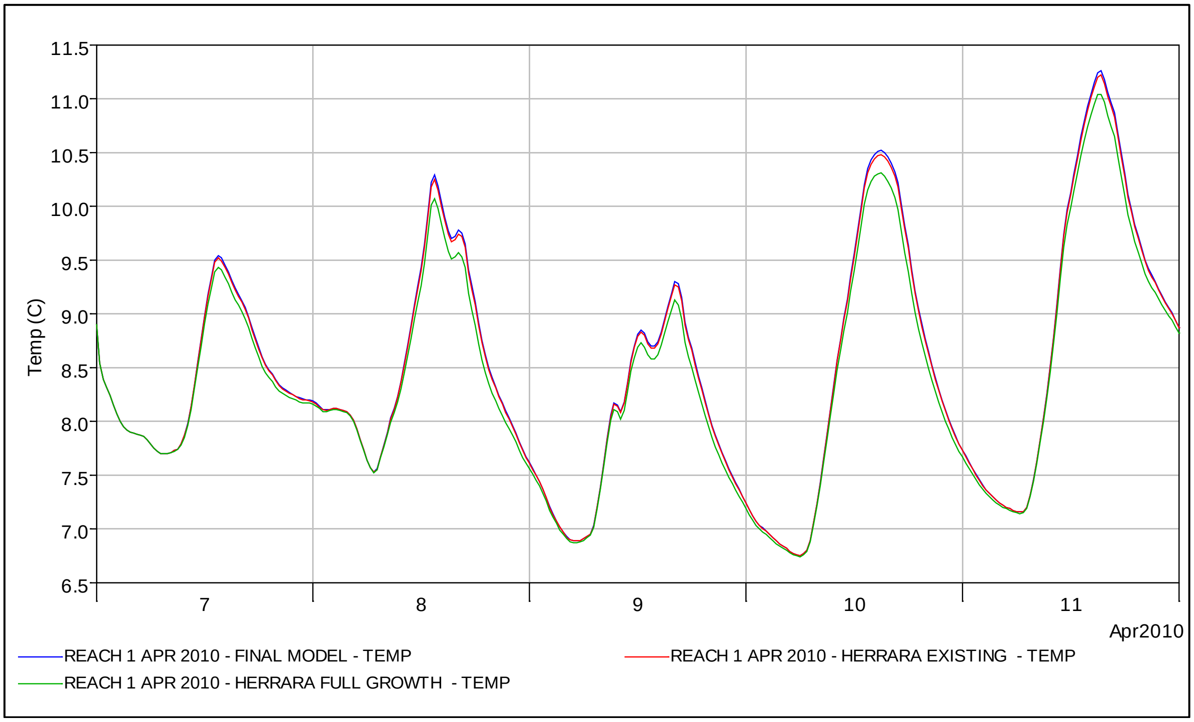


Figure 46. April 2010 end of Reach-1 shade results

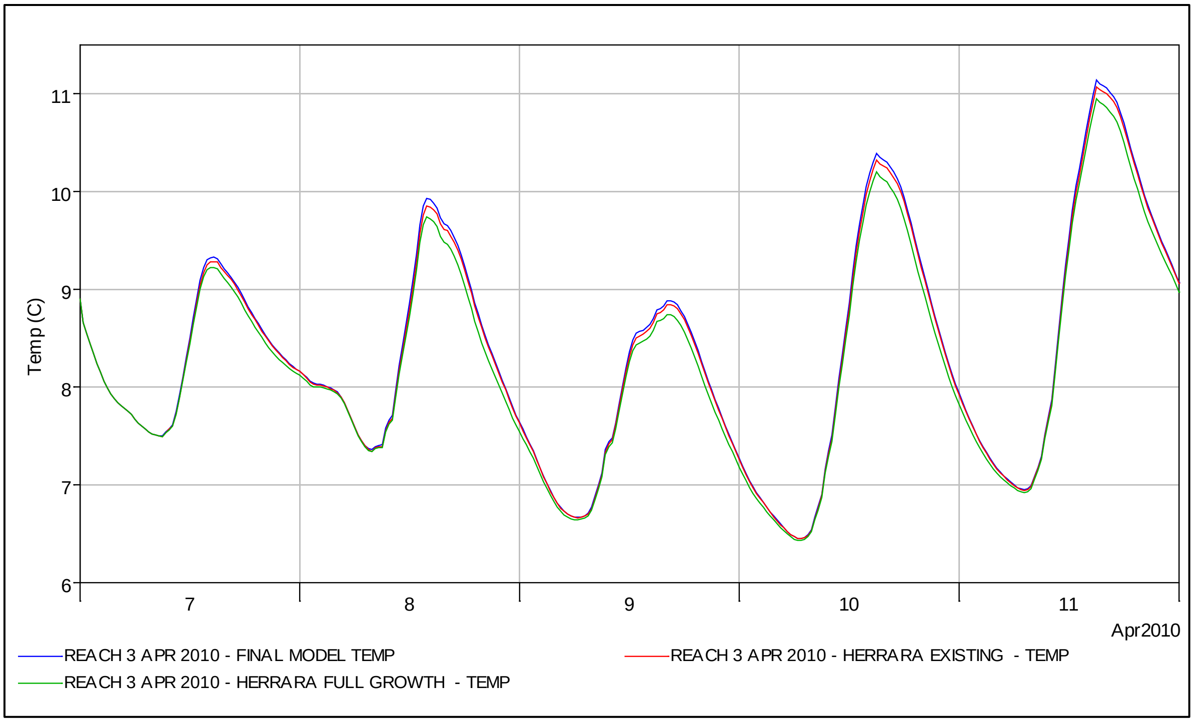


Figure 47. April 2010 end of Reach-3 shade results

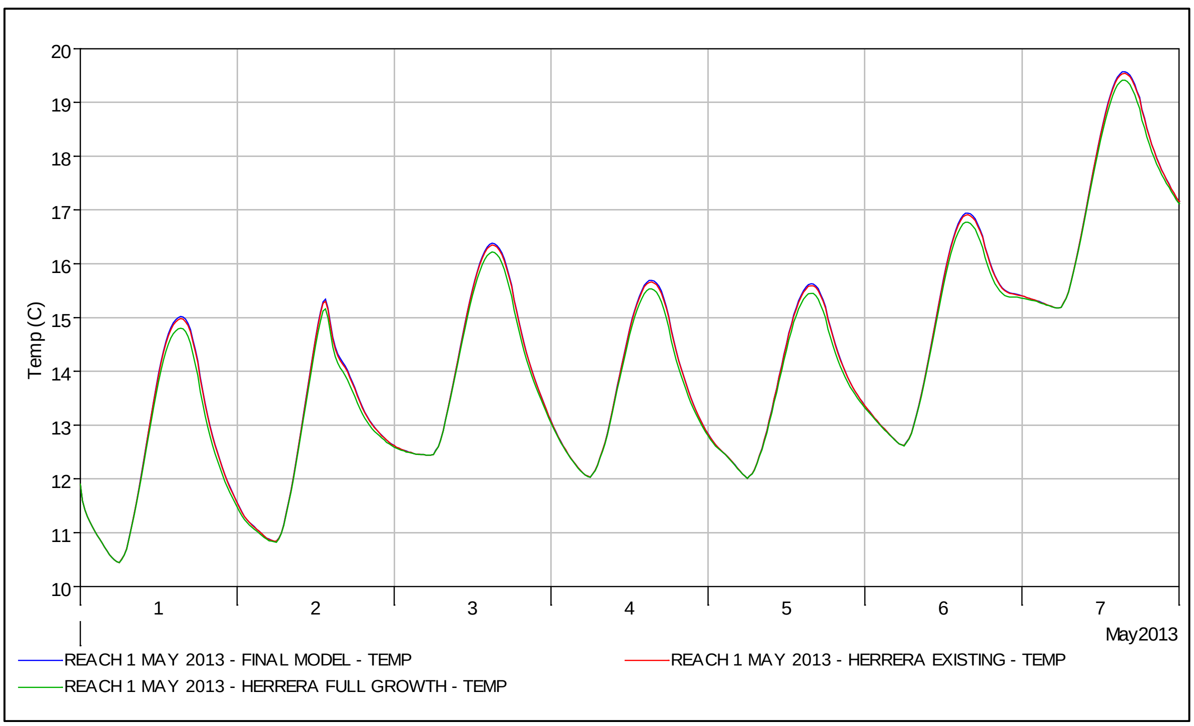


Figure 48. May 2013 end of Reach-1 shade results

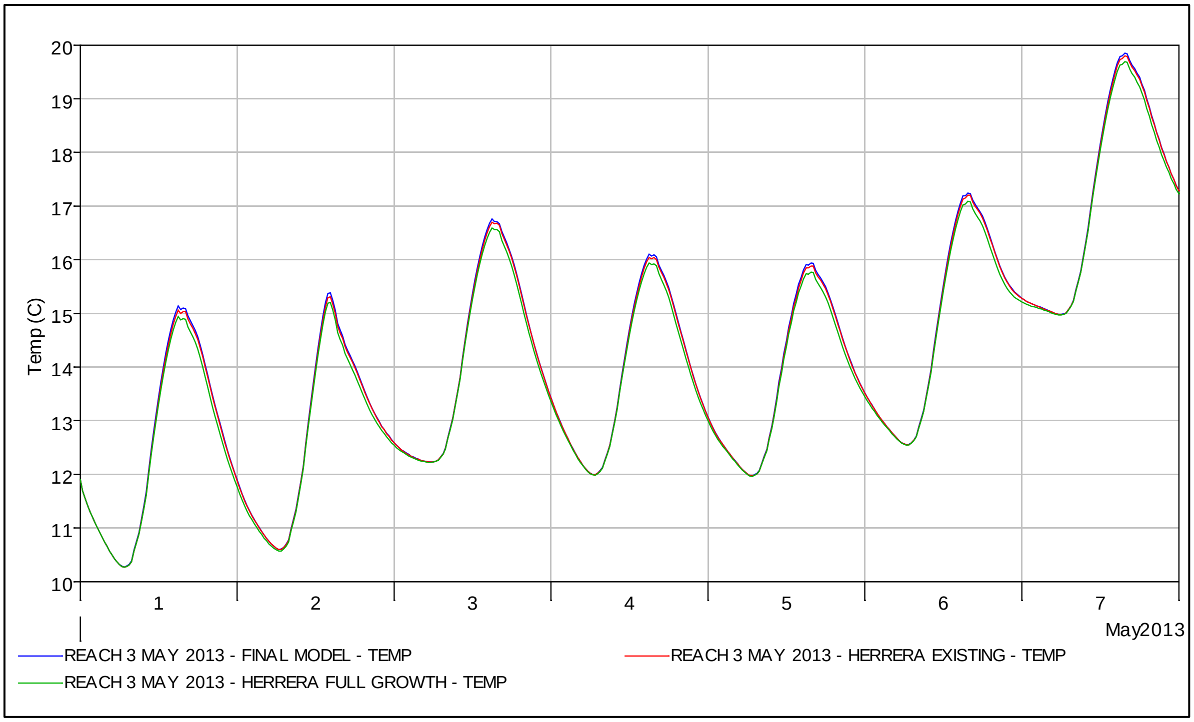


Figure 49. May 2013 end of Reach-3 shade results

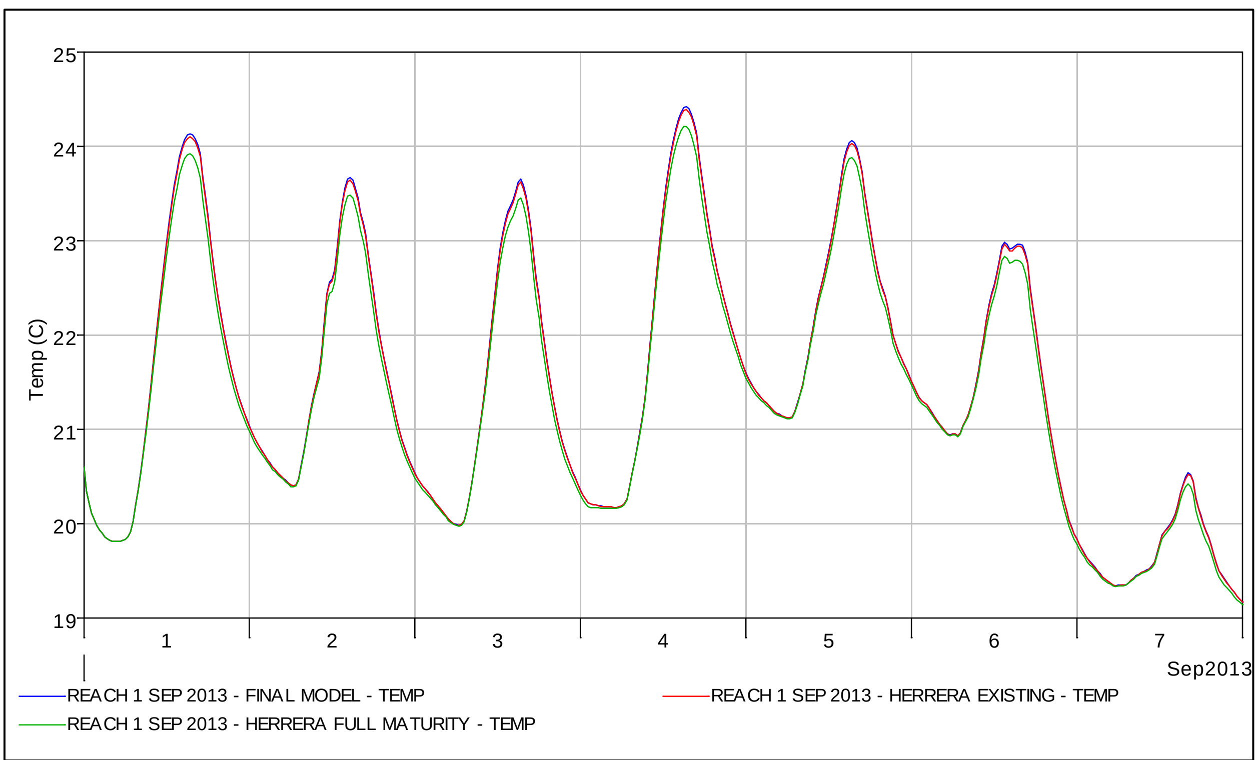


Figure 50. September 2013 end of Reach-1 shade results

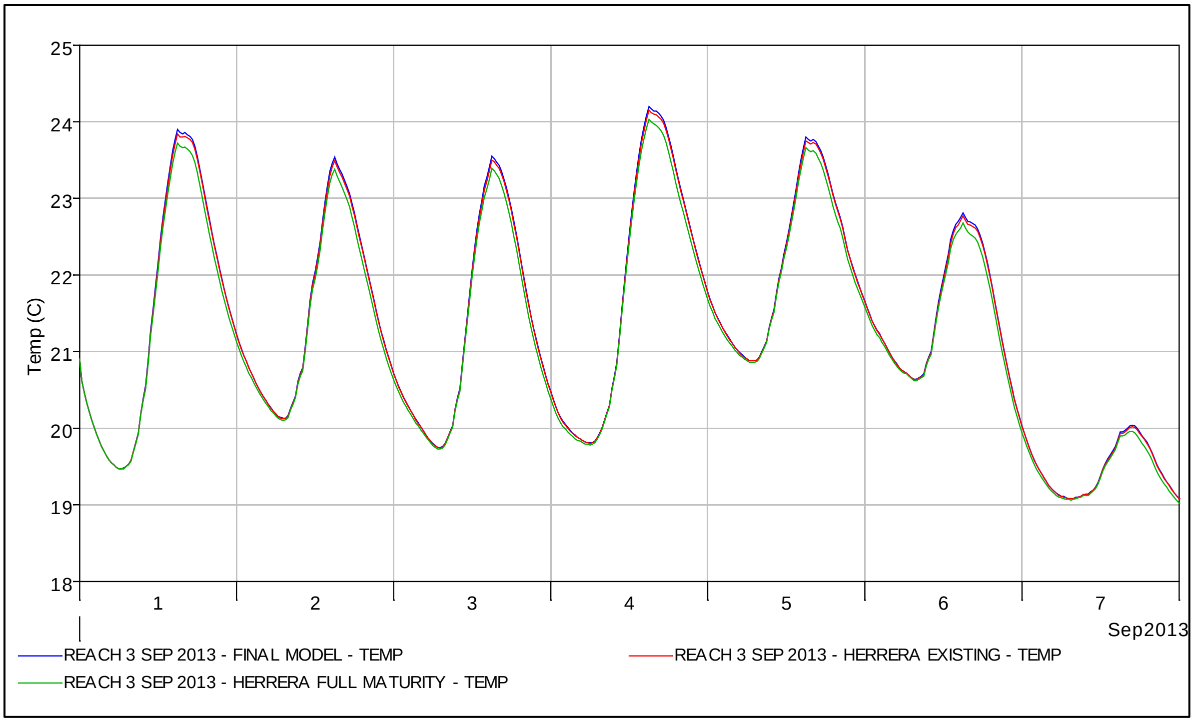


Figure 51. September 2013 end of Reach-3 shade results

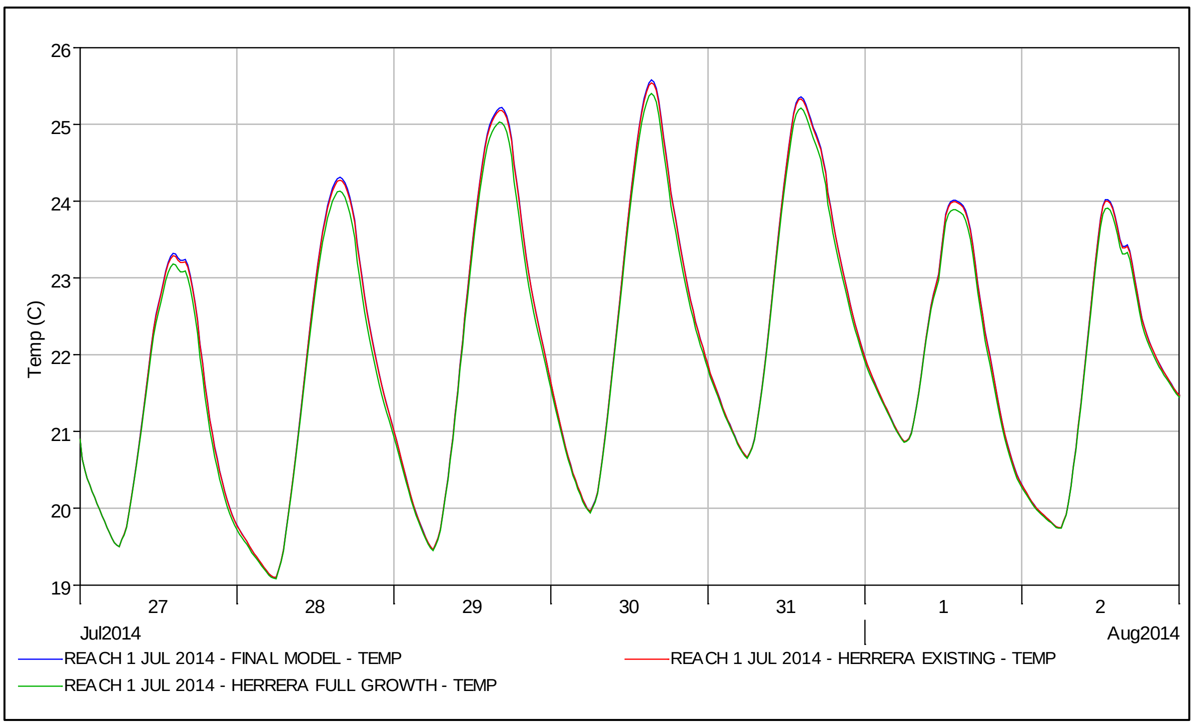


Figure 52. July 2014 end of Reach-1 shade results

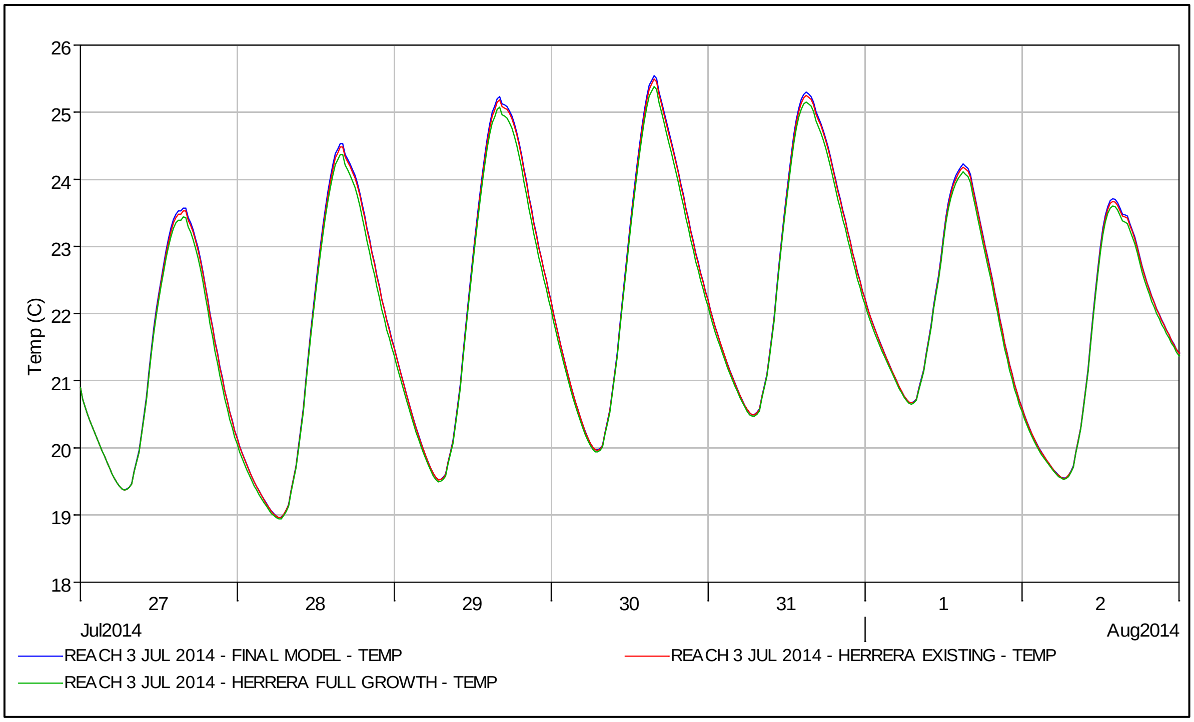


Figure 53. July 2014 end of Reach-3 shade results

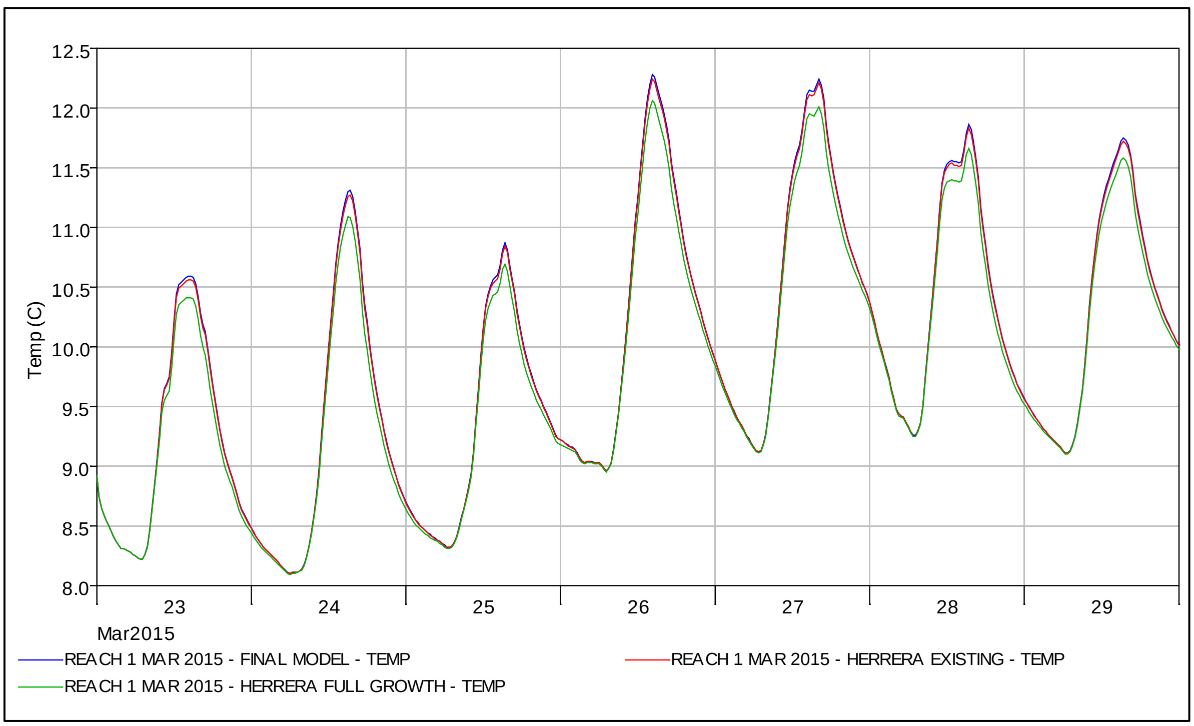


Figure 54. March 2015 end of Reach-1 shade results

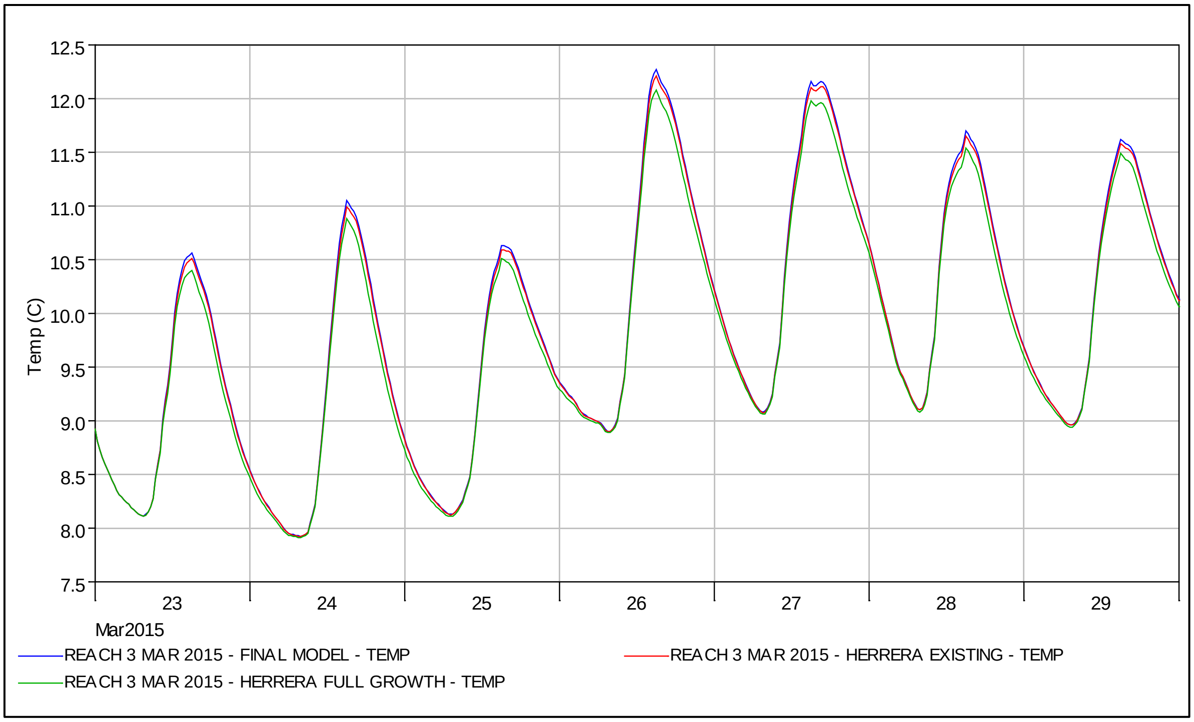


Figure 55. March 2015 end of Reach-3 shade results

5.2 Evaluation of Increased Flows for Temperature Reductions

The effect of increased flows on water temperatures at the ends of Reach 1 Reach 3 was evaluated for flows ranging from the 80 cfs minimum flow up to flows of 500 cfs. The simulation was conducted for the model validation period of July 27 – August 2. This time period had daily maximum water temperatures that exceeded 25 °C, both observed in the field and in model simulations. The model simulations were conducted for constant flow rates throughout the time period, which resulted in both reductions of daily maximum water temperature at higher flows, but with concurrent increases in the nighttime minimum water temperatures at higher flows. The model simulations, shown in figures 56 and 57, estimated that the daytime maximum temperature would be reduced by up to about 1 °C by increasing flow from 80 cfs to 200 cfs, with up to 2 °C temperature reduction at flows of 500 cfs. However, the average reduction in daily maximum water temperature was about 0.5 °C for 200 cfs and 1.5 °C for 500 cfs. Regression analysis of the relationship between flow and daily maximum water temperature showed a consistent trend, but with a somewhat low coefficient of determination (r^2=.1946). However, this is expected since the climatic conditions were not constant from day to day (figure 58). Plotting the simulated reduction in temperature from the minimum 80 cfs flow does not eliminate the effect of variation in climatic influence between days, but the coefficient of determination (r^2=.3541) is better for the regression (figure 59). There was less consistent temperature benefit for increased flows at the end of Reach 3, with the simulation for August 2, 2014, indicating increased daily maximum temperatures at higher flows (figures 60 and 61). This day was cooler with air temperature of 36.7 °C, compared to July 29-31, when air temperatures were 37.8 °C, 39.4 °C and 39.4 °C.

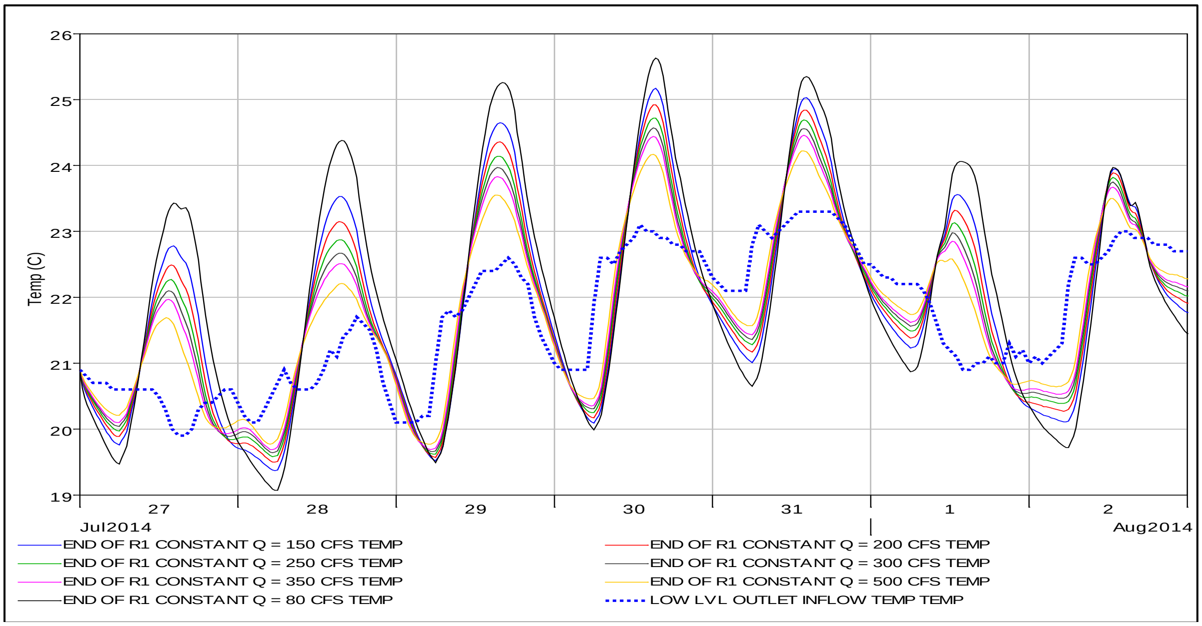


Figure 56. July 2014 end of Reach-1 effect of increased flow

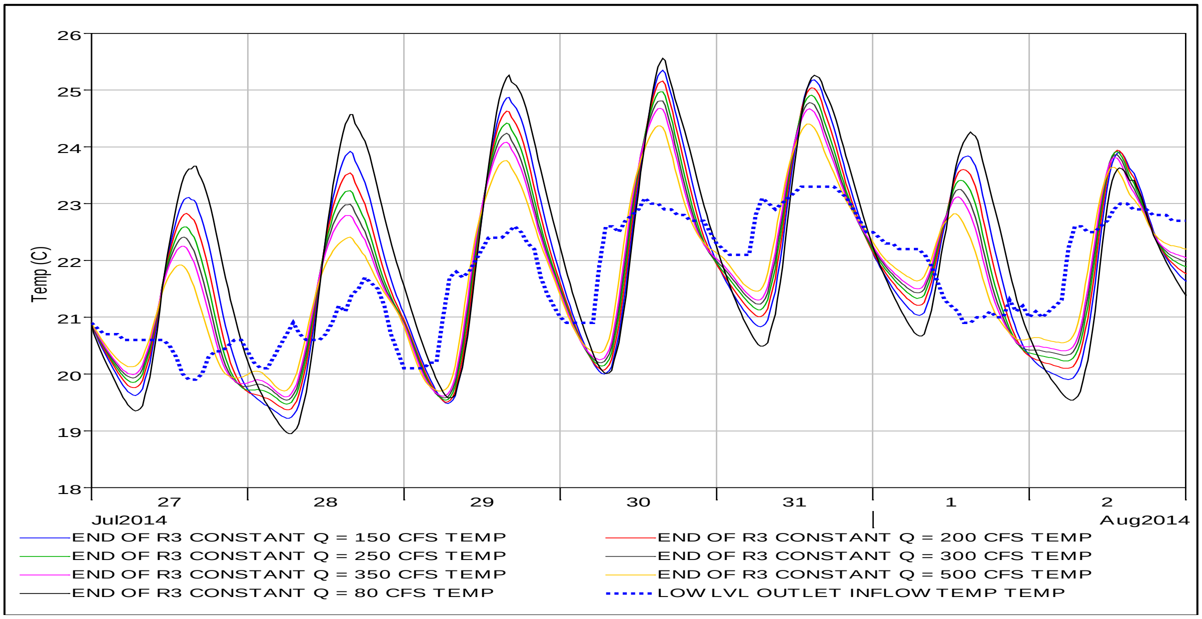


Figure 57. July 2014 end of Reach-3 effect of increased flow

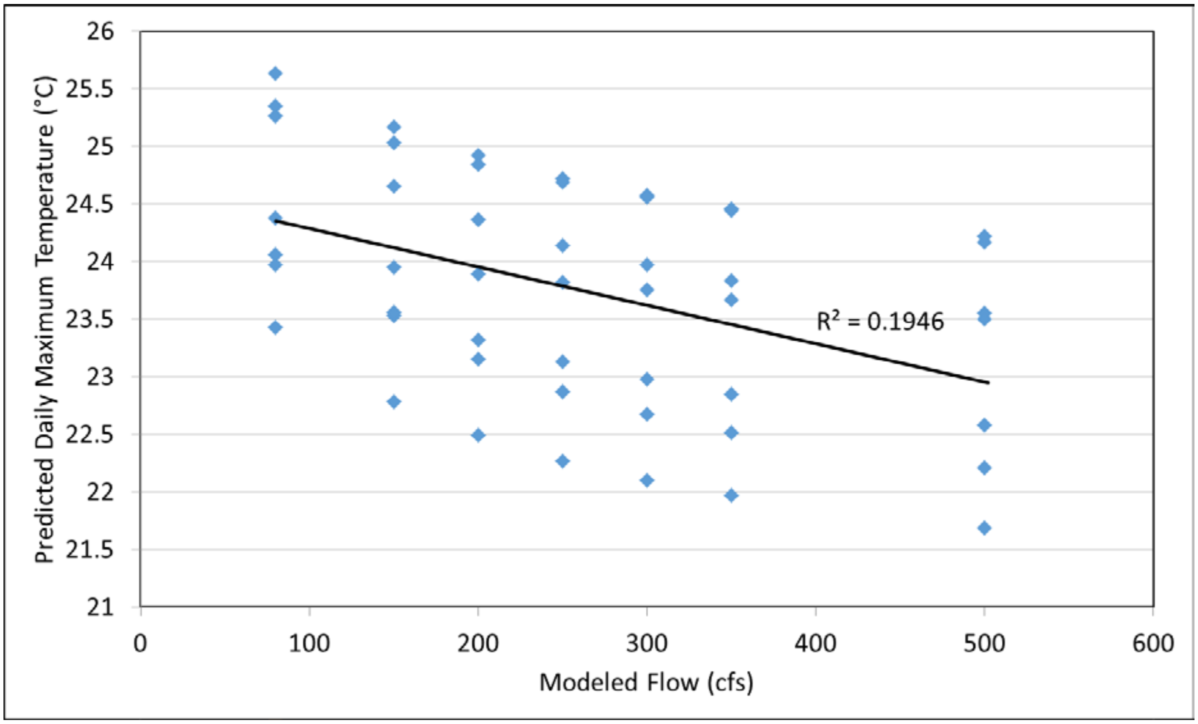


Figure 58. July 2014 end of Reach-1 effect of increased flow on daily maximum

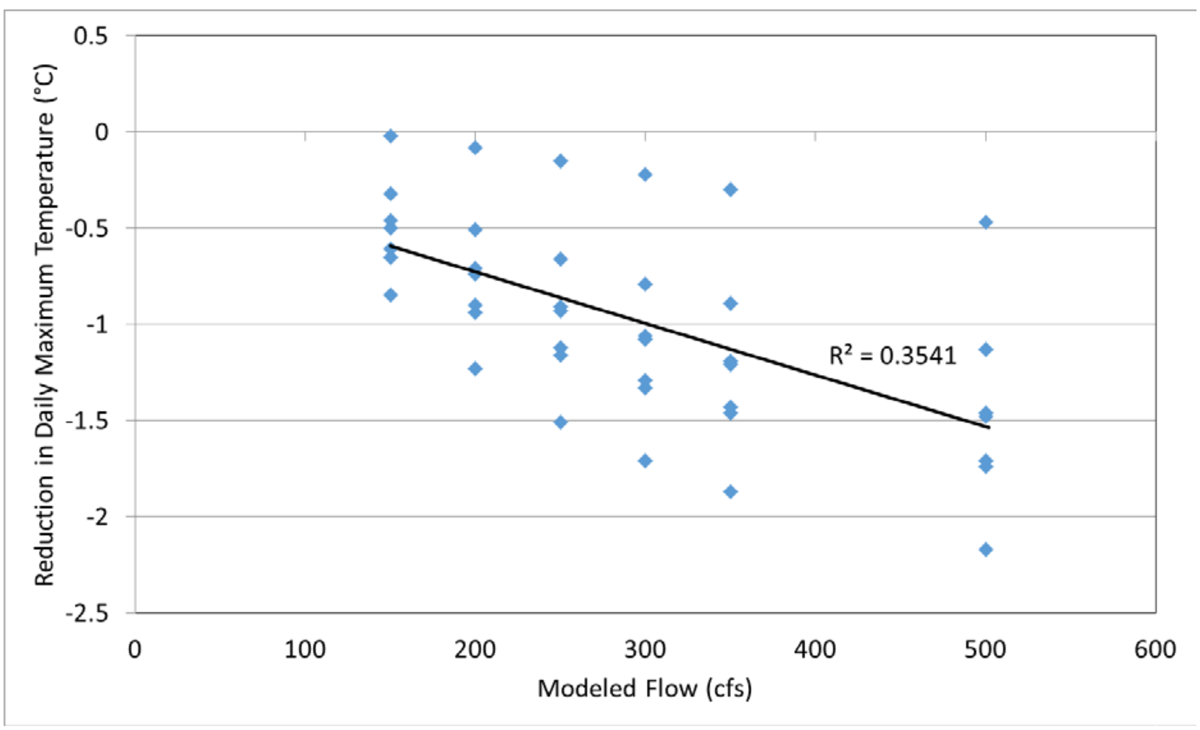


Figure 59. July 2014 end of Reach-1 reduction in daily maximum with increased flow

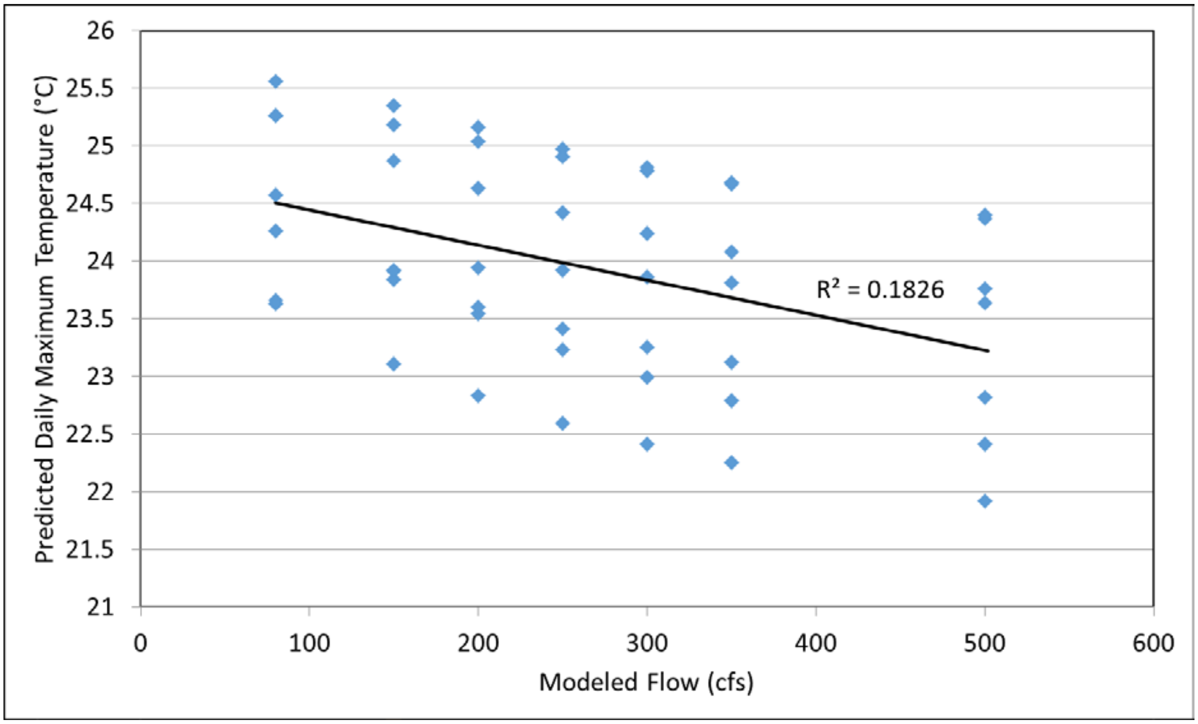


Figure 60. July 2014 end of Reach-3 effect of increased flow on daily maximum

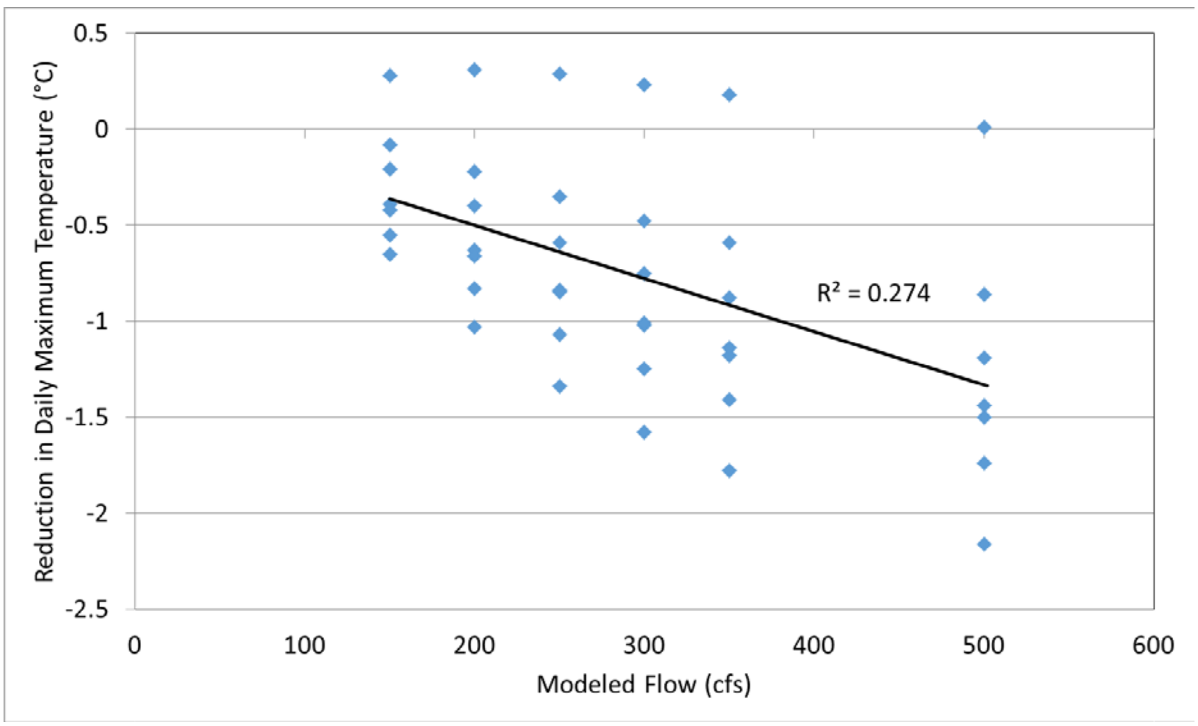


Figure 61. July 2014 end of Reach-3 reduction in daily maximum with increased flow

The faster travel time of water at increased flows, which thus results in shorter periods for thermal loading to raise surface water temperatures, is probably the main factor contributing to reduced daily maximum temperatures. These model runs also assumed that the ratio of hyporheic zone to surface flow was constant, which is unlikely since the depth to which the river substrate is actively in exchange with the surface flow probably remains constant, whereas the depth of the surface flow increases substantially as flow increases. However, reducing the hyporheic flow fraction from 30 percent to 5 percent did not greatly change the simulated reductions in daily maximum water temperatures at higher flows.

6 Discussion and Next Steps

An HEC-RAS hydraulic model was constructed to develop rating curves of depth and mean velocity as a function of relatively low flows in the Chelan River (50-600 cfs). We calibrated the hydraulic model to observed top widths during three low-flow conditions (85, 200, and 350 cfs). In this process, we noted that the calibration was difficult because so many large rocks protrude through the water surface in numerous riffles along the Chelan River. Using reasonable values of Mannings *n* bottom roughness, we tended to underestimate top widths especially in observed riffles. However, the agreement improved at larger flows

Using these hydraulic rating curves, we developed a temperature model of the Chelan River using the Washington State Department of Ecology water temperature model, QUAL2Kw (Pelletier et al., 2006). Initial simulations found that physical processes associated with the hyporheic zone had to be included in the model description to simulate the cooling influence of shallow groundwater on reducing the diurnal variations in surface water temperatures, and a sensitivity analysis confirmed that hyporheic zone parameters were generally the most important model parameters. Using this information, we calibrated and validated the temperature model to five one-week periods in the months of March-September, 2010-2015. The model was calibrated primarily using observed water temperatures at the ends of Reach 1 and Reach 3, and showed good agreement (visually and statistically) between the model and observations.

Even though the sensitivity for the groundwater temperature at the base of the hyporheic zone was “moderate”, it might be useful to try to measure this temperature in the Chelan River. We recommend installing hyporheic temperature probes (at approximately 50 cm depth) near the ends of Reach 1 and Reach 2 for the remaining summer months of 2015 and perhaps again from March-October 2016. These data might shed light on (1) the magnitude of temperatures at the base of the hyporheic zone, and (2) their variations during summer months.

Following model development, calibration and validation, the model was used to assess two alternatives that might improve use attainment in the Chelan River. The temperature model was used to evaluate the effect of vegetative shading. The existing vegetation is sparse and provides little significant shading for the existing river and the model simulation of existing vegetative shade, as expected, demonstrated little effect of shade on water temperatures. This is partially due to the historically dry conditions that supported little tall vegetation elsewhere in the area, but also because the Chelan River is very wide for the depths it supports under low-flow conditions. Model simulations of a potential future condition with mature riparian vegetation estimated that water temperatures would only be reduced by 0.1 °C by vegetative shade.

The release of higher flows from the low level outlet during periods of high daily maximum water temperatures was also simulated in the model. Increasing flows was shown to reduce daily maximum temperature by up to 1 °C for an increase from 80 cfs to 200 cfs, while increasing flow to 500 cfs could reduce daily maximum water temperature by 2 °C. The model simulations were for constant flows, which also resulted in increases in the nighttime minimum temperatures. Under these simulations, the influence of the hyporheic zone was held constant at all flows, including the hyporheic zone fraction of total flow. This assumption may not accurately reflect reality since the thickness of the hyporheic zone does not increase in proportion to the increases in surface flow depth as flow increases. Thus, these model simulations may have overestimated the effects of higher flows on daily maximum water temperatures. Another model assumption related to the hyporheic zone is that hyporheic water temperatures were constant at 12 °C. However, hyporheic zone water temperature probably has seasonal variability that will affect the model's predictions of surface water temperatures.

Another possible scenario for reducing daily maximum water temperatures would be to develop a narrower channel within the bounds of the existing river, sized specifically for low flows. However, it is clear that the bed materials, large gravels and cobbles, are consistent with a large flowing river before the dam was built. Under low-flow conditions, this material serves as a relatively thick hyporheic zone, which already functions to modify water temperatures. If a low-flow channel were considered, it would probably be excavated through the hyporheic zone, resulting in a narrower channel but without the existing bed materials, and possibly without the hyporheic zone's moderating influence unless it was part of the low-flow channel design.

We believe that the water temperature model of the Chelan River is well developed, and will serve as a useful tool to evaluate a range of use attainment alternatives. However, improvement in the predictive capabilities of the model could be achieved through collection of additional empirical information to refine the model. The actual temperature of water in the hyporheic zone of the river bed could be measured with piezometers equipped with temperature loggers. Also, use of the existing array of temperature loggers to measure the actual effect of flow increases by scheduling changes in flows during periods of hot summer weather (July – August) would evaluate whether extremes in daily maximum water temperatures could feasibly be reduced through flow releases.

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8 Appendix 1 – Technical Memorandum, SHADE Model Vegetation Parameterization for the Chelan River Revegetation Feasibility Investigation in Chelan County, Washington

TECHNICAL MEMORANDUM

Date: November 19, 2015

To: Jeff Osborn, Chelan County Public Utility District

Copy to: Joy Michaud and Len Ballek, Herrera Environmental Consultants, Inc.

From: Jeremy Bunn

Subject: SHADE Model Vegetation Parameterization for the Chelan River Riparian Revegetation Feasibility Investigation in Chelan County, Washington

Introduction

Chelan PUD recently completed a riparian limiting factors and revegetation feasibility assessment (Herrera 2015) to fulfill requirements stemming from the relicensing process for the Lake Chelan Hydroelectric Project Dam. Due to the significant physical constraints associated with Reaches 2 and 3 of the Chelan River, the feasibility assessment focused on Reach 1, which begins immediately below the dam in Chelan, Washington, and extends downstream for approximately 2.29 miles. Streamside vegetation is scarce along Reach 1, and is mainly present as patches of cottonwoods and alders and isolated conifer stands. The feasibility assessment concluded that there are select species of various plant types (trees, shrub, sedges, etc.) that can be expected to survive in the harsh conditions of Reach 1 of the Chelan River, even without supplemental water. It also concluded that there are a number of locations in the upper part of Reach 1 where conditions are appropriate for initiating establishment of a diverse riparian community, as well as a few locations amenable to establishing bands of willows. The feasibility assessment recommended a planting strategy expected to result in establishment of extensive patches of riparian vegetation throughout Reach 1 over the long term (50 years and beyond), thus increasing riparian habitat area and shade.

In addition to the revegetation feasibility assessment, temperature modeling is being performed for the entire Chelan River; from just below the dam to its confluence with the Columbia River. WEST Consultants is currently developing a Qual2kW model to predict water temperatures along the Chelan River and, as part of that effort, developed a preliminary SHADE spreadsheet model to quantify the shading effect of topography and existing riparian vegetation. Since the feasibility assessment indicated that revegetation is feasible, it was appropriate to model future conditions with implementation of the planting strategy developed for Reach 1. The purpose of this report is to provide riparian vegetation parameter specifications for input to the Chelan River SHADE spreadsheet model being developed by WEST Consultants, consistent with the results and recommendations of the feasibility assessment.

This addendum to the feasibility assessment (Herrera 2015) describes the methods used by Herrera Environmental Consultants Inc. (Herrera) to specify vegetation parameters for three scenarios:

1. Existing conditions

2. Riparian conditions 20 years after implementation of the planting recommendations described in the feasibility assessment, assuming optimal growth conditions

3. Riparian conditions at full maturity, after implementation of the planting recommendations described in the feasibility assessment and optimal growth conditions

Methods

Model Segmentation and Riparian Zone Delineation

WEST Consultants provided Herrera with a preliminary input file for the SHADE model and an ArcGIS shapefile showing the boundaries of the QUAL2Kw model segments. Because the longitudinal extents of Qual2kW segments did not match up with the proposed planting zones from the feasibility assessment, Herrera defined more closely-spaced segments between cross-sections from a HEC-RAS model also provided by WEST Consultants. Nine riparian vegetation zones on each side of the river were delineated for each model segment (Figure 1). Because the SHADE model allows riparian zone elevation or width, but not both, to vary, and elevations along the Chelan River are widely variable and strongly influence potential shading of the river, fixed zone widths were set to cover the maximum width of the Chelan River floodplain within Reach 1.

Vegetation Type Definition

Based upon observations made during a 2014 site visit and review of recent aerial photography on Google Earth for areas not observed during the site visit, Herrera defined nine potential vegetation types. Two of the vegetation types represent proposed revegetation applications from the feasibility assessment, four vegetation types encompass existing riparian vegetation, and three vegetation types represent existing upland areas. The vegetation types include:

- Proposed willow band planting
- Proposed riparian area planting
- Existing willow bands
- Existing scattered tree areas

- Existing scattered shrub areas
- Existing vegetation on Reach C
- Scrub/shrub upland
- Grass upland
- Barren

Vegetation Parameter Specification

Height, canopy density, and overhang parameters specified by Washington State Department of Ecology (Ecology) are provided within the SHADE spreadsheet for the scrub/shrub upland, grass upland, and barren vegetation types. Current conditions of height, canopy density, and overhang parameters for the four existing vegetation types were estimated from information gathered during the site visit. Potential heights, densities and bank overhangs (at 20 years and at maturity) were estimated using a variety of sources. For the two proposed vegetation planting type's the US Department of Agriculture PLANTS Database (USDA 2015) and the Washington State University NorthWest Plants Database (WSU 2015) were used as references. Professional experience and visits to the project site and to the riparian area on the nearby Methow River also provided a basis for the predicted future condition of the planted types. The fairly well vegetated lower section of Reach 1 provided some information of what could be expected at 20 years and at full maturity for the four vegetation types that represent existing conditions. Professional experience in planting of similar sites over the past 30 years was also valuable for estimating future conditions. Table 1 lists the specified parameters for each vegetation type and scenario.

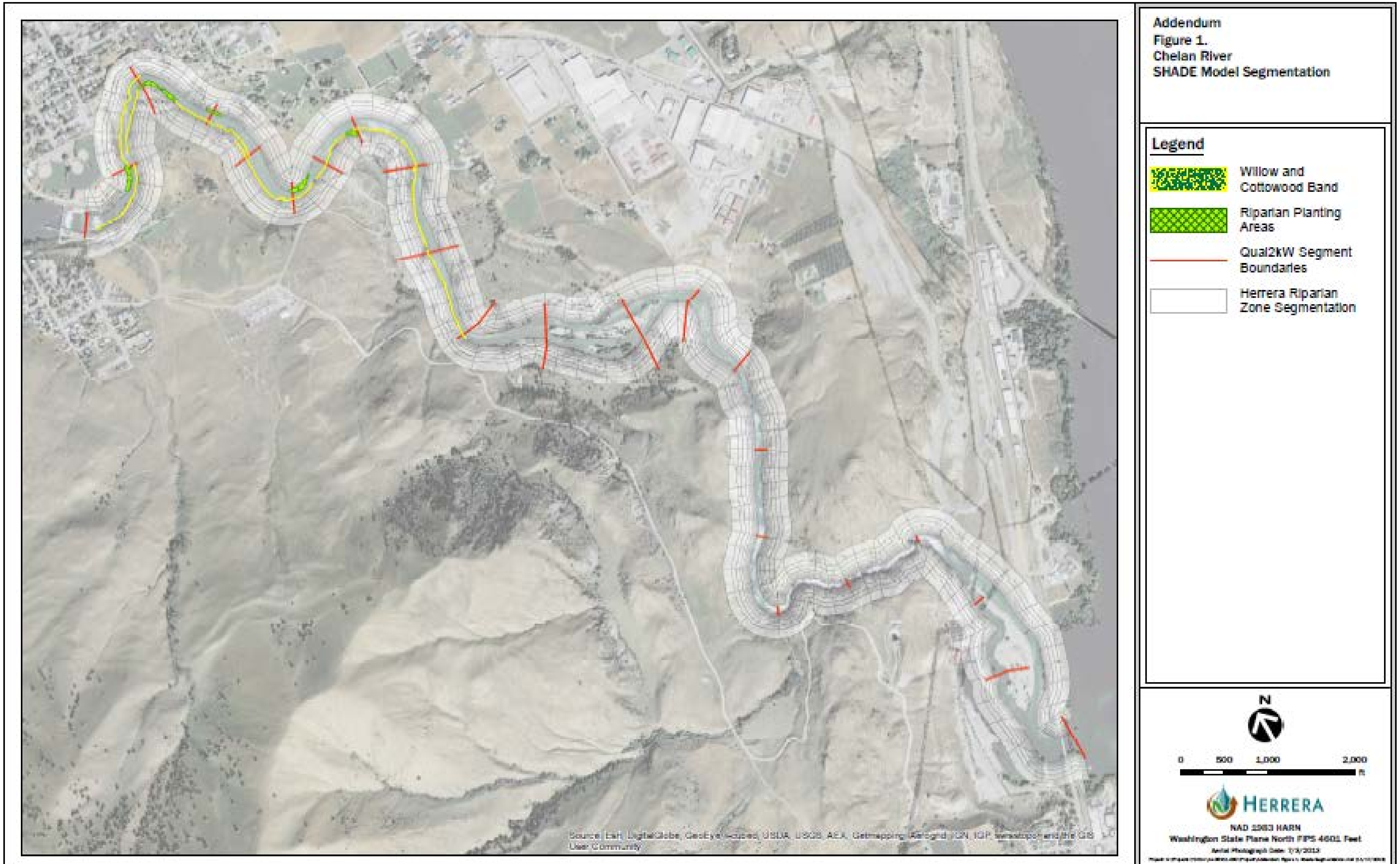
Assignment of Vegetation Types and Elevations to Riparian Zones

The existing conditions vegetation type was assigned to each of nine riparian zones on each bank for each Herrera model segment through the use of current aerial photography on Google Earth. Average elevation for each riparian zone was calculated in ArcGIS from 2009 lidar data. Vegetation type and elevation for each riparian zone were aggregated to Qual2kW segments by taking the average (for elevation) or mode (for vegetation type) of each riparian zone over the Herrera model segments included within each Qual2kW segment.

The preliminary SHADE model input file provided by WEST Consultants was duplicated to create an input file for each scenario. The input files were modified to incorporate Herrera-specified riparian zones, vegetation types and elevations. Because the resolution of the Qual2kW segments may be too coarse to capture the potential shading effect of the plantings recommended in the feasibility assessment (see Appendix A), input files were made using Herrera's segmentation in addition to those based on the Qual2kW segmentation provided by WEST Consultants. The modified SHADE model input files were transmitted to WEST Consultants for testing and further development.

Table 1. Current and Estimated Future Conditions of Chelan River Riparian Vegetation Types.

	Current Conditions			20 Years			Full Maturity		
Vegetation Type	**Height (m)**	**Density (%)**	**Overhang (m)**	**Height (m)**	**Density (%)**	**Overhang (m)**	**Height (m)**	**Density (%)**	**Overhang (m)**
Proposed Willow Band Planting	NA	NA	NA	6.1	70	0.6	9.1	95	0.9
Proposed Riparian Area Planting	NA	NA	NA	9.1	60	0.9	18.3	85	1.8
Existing Willow Bands (within Reach 1)	1.8	60	0.6	6.1	80	0.6	6.1	95	0.6
Existing Willow Bands (planted in confluence area downstream)	3.7	60	1.2	6.1	80	0.6	6.1	95	0.6
Existing Scattered Tree Areas	3.0	30	0.0	4.6	40	0.0	6.1	60	0.0
Existing Scattered Shrub Areas	0.8	20	0.0	0.6	30	0.0	1.2	50	0.0
Reach C	5.0	55	0.5	9.1	70	0.9	18.3	85	1.8
Scrub/Shrub Upland	2.0	25	0.2	2.0	25	0.2	2.0	25	0.2
Grass Upland	0.5	25	0.1	0.5	25	0.1	0.5	25	0.1
Barren	0.0	100	0.0	0.0	100	0.0	0.0	100	0.0


Addendum
Figure 1.
Chelan River
SHADE Model Segmentation
Legend
Willow and Cottowood Band
Riparian Planting Areas
Qual2kW Segment Boundaries
Herrera Riparian Zone Segmentation
N
0
500
1,000
2,000
ft
HERRERA
NAD 1983 HARN
Washington State Plane North FIPS 4601 Feet
Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

References

Herrera. 2015. Feasibility Assessment: Chelan River Riparian Revegetation Feasibility Investigation. Prepared for Chelan County Public Utility District by Herrera Environmental Consultants, Inc., Seattle, Washington.

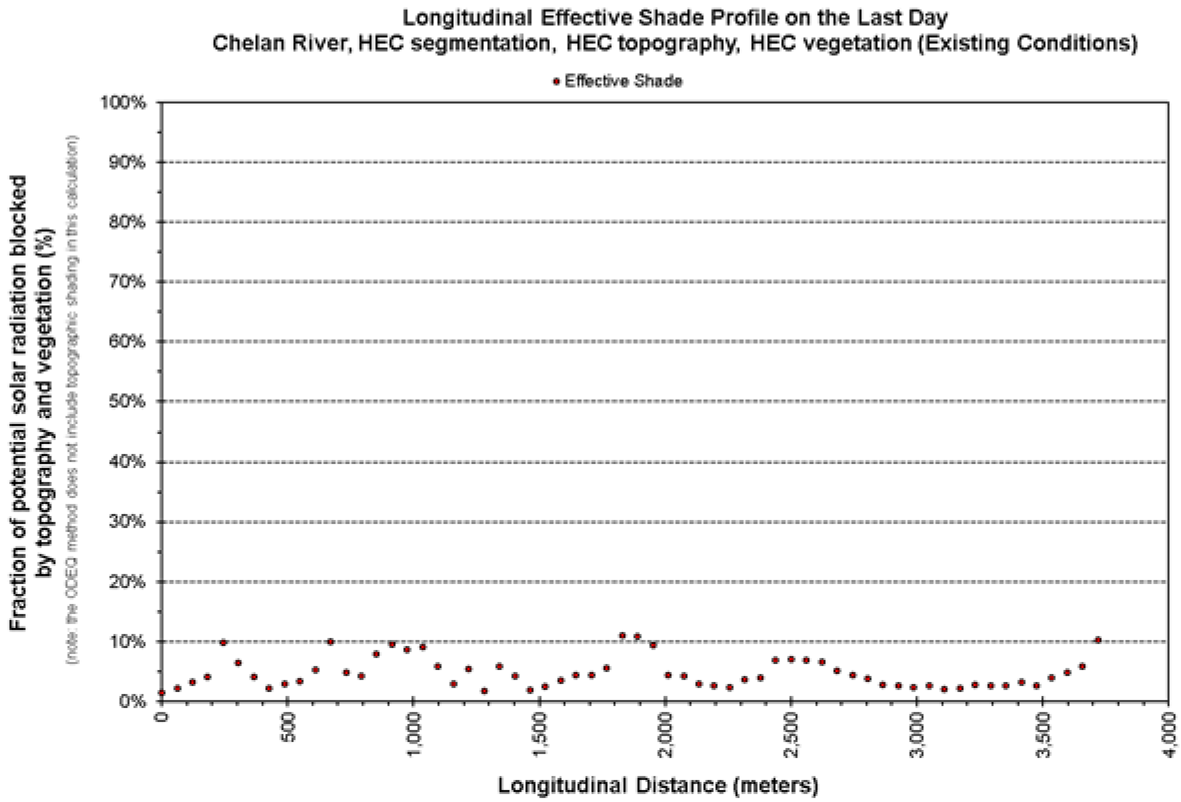
Li, Guoyuan, C.R. Jackson, K.A. Craseski. 2012. Modeled riparian stream shading: Agreement with field measurements and sensitivity to riparian conditions. Journal of Hydrology, 428-429 (2012) 142-151.

USDA. 2015. PLANTS Database. US Department of Agriculture, Natural Resources Conservation
Service. http://plants.usda.gov.

WSU. 2015. WSU Clark County Extension PNW Plants, NorthWest Plants Database system. Washington State University. http://www.pnwplants.wsu.edu/.

APPENDIX A

Preliminary SHADE Model Output


Longitudinal Effective Shade Profile on the Last Day
Chelan River, HEC segmentation, HEC topography, HEC vegetation (Existing Conditions)
Effective Shade
Fraction of potential solar radiation blocked by topography and vegetation (%)
(note: the ODEQ method does not include topographic shading in this calculation)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
500
1,000
1,500
2,000
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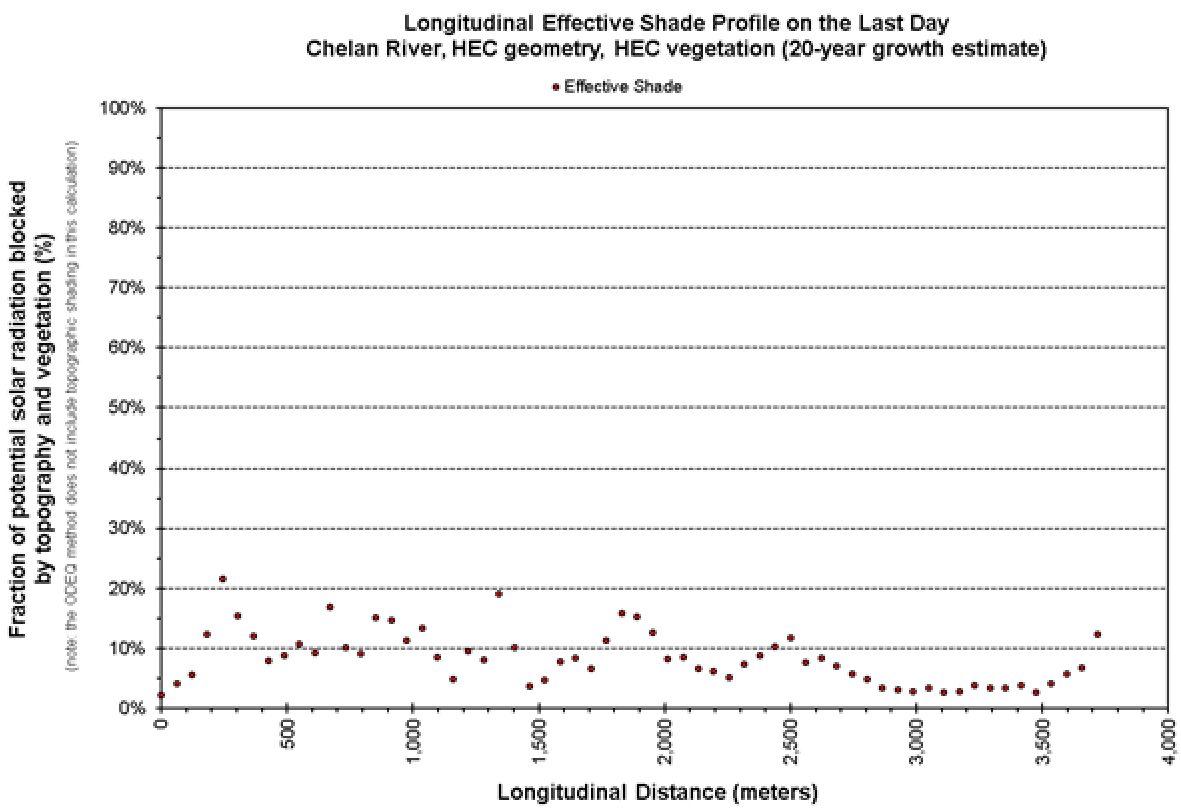
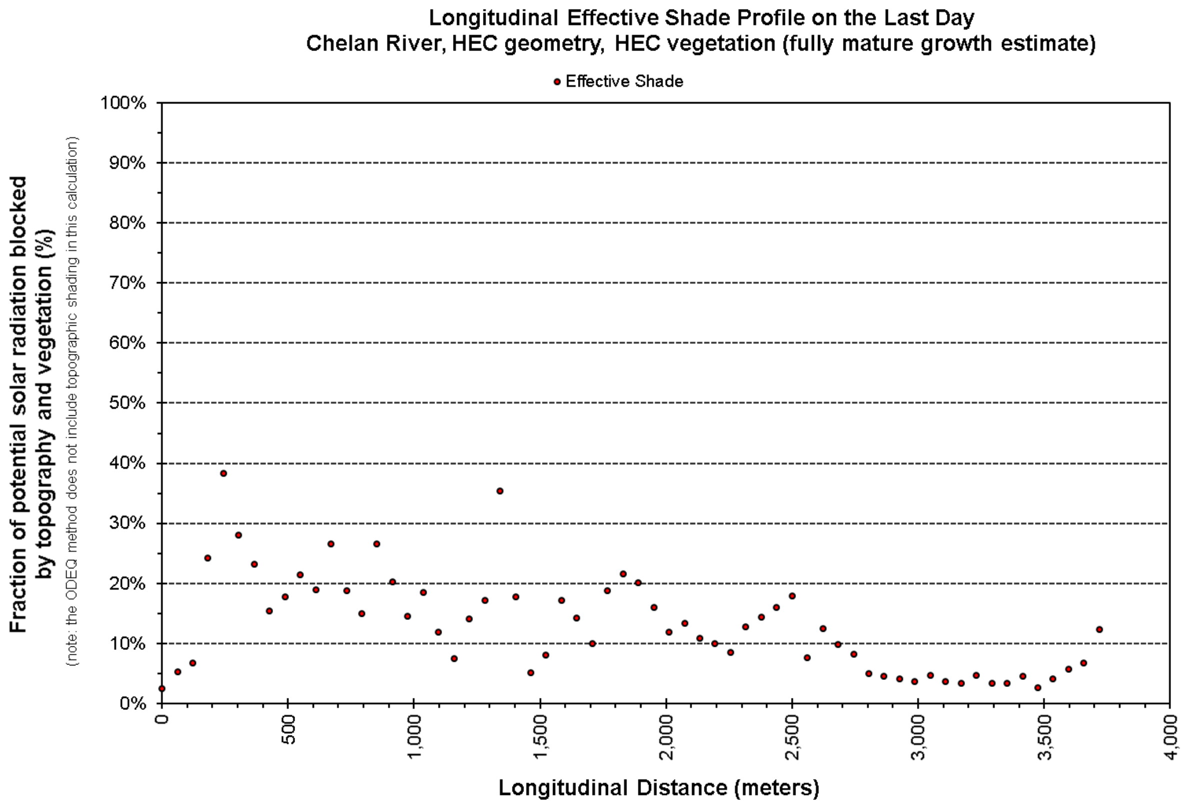
3,000
3,500
4,000
Longitudinal Distance (meters)


Longitudinal Effective Shade Profile on the Last Day
Chelan River, HEC geometry, HEC vegetation (20-year growth estimate)
Effective Shade
Fraction of potential solar radiation blocked by topography and vegetation (%)
(note: the ODEQ method does not include topographic shading in this calculation)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
Longitudinal Distance (meters)



Longitudinal Effective Shade Profile on the Last Day
Chelan River, HEC geometry, HEC vegetation (fully mature growth estimate)
Effective Shade
Fraction of potential solar radiation blocked by topography and vegetation (%)
(note: the ODEQ method does not include topographic shading in this calculation)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
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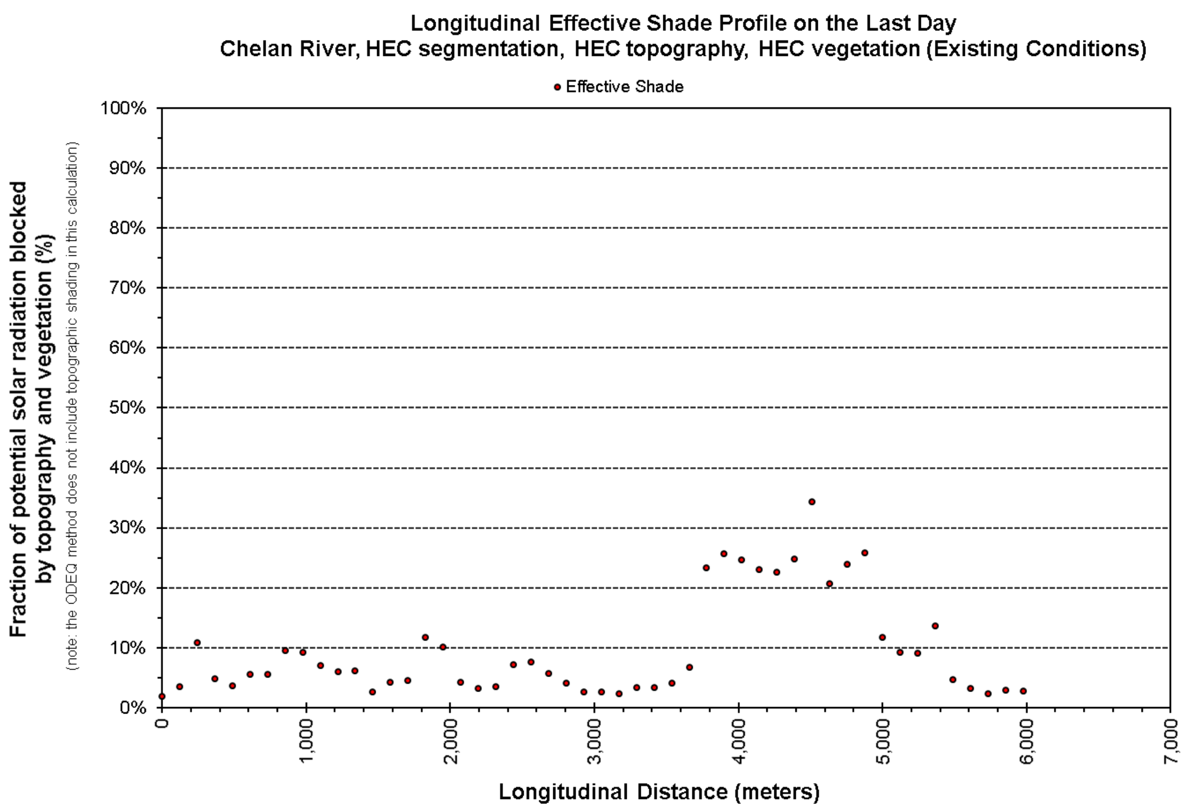
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
Longitudinal Distance (meters)



Longitudinal Effective Shade Profile on the Last Day
Chelan River, HEC segmentation, HEC topography, HEC vegetation (Existing Conditions)
Effective Shade
Fraction of potential solar radiation blocked by topography and vegetation (%)
(note: the ODEQ method does not include topographic shading in this calculation)
100%
90%
80%
70%
60%
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40%
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20%
10%
0%
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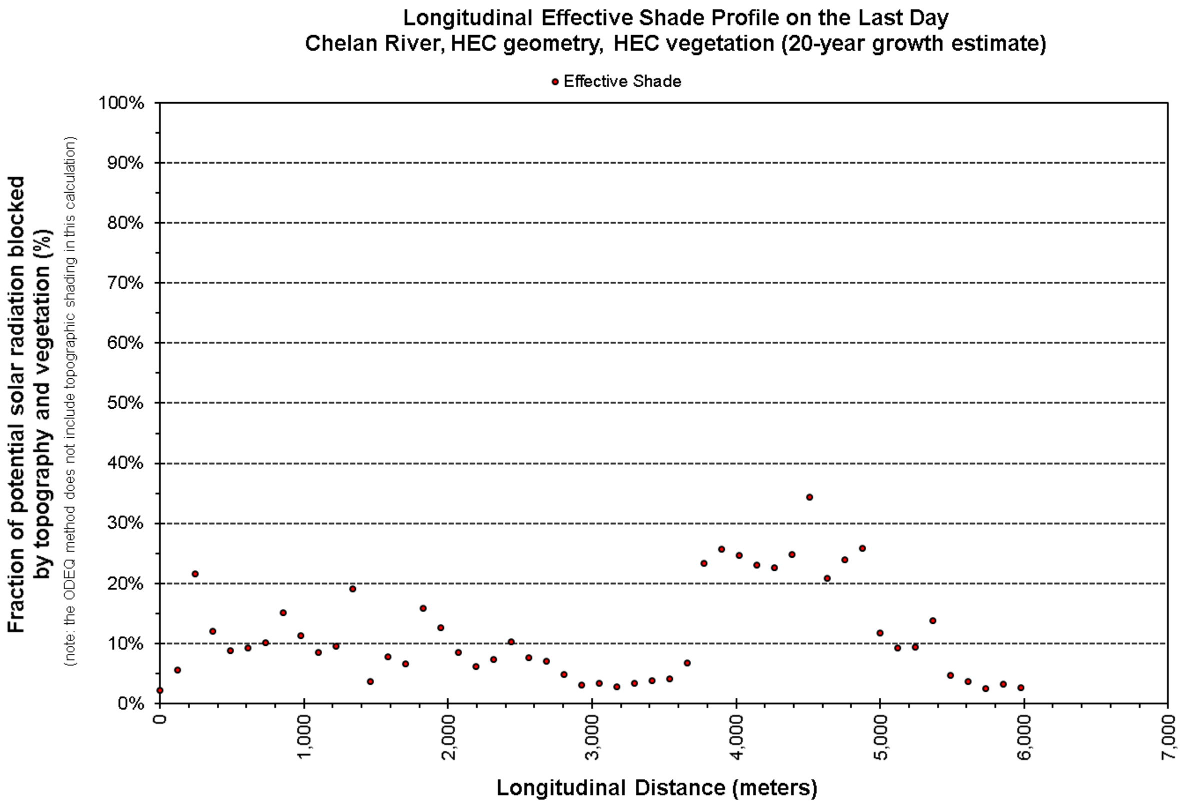
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Longitudinal Distance (meters)



Longitudinal Effective Shade Profile on the Last Day
Chelan River, HEC geometry, HEC vegetation (20-year growth estimate)
Effective Shade
Fraction of potential solar radiation blocked by topography and vegetation (%)
(note: the ODEQ method does not include topographic shading in this calculation)
100%
90%
80%
70%
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10%
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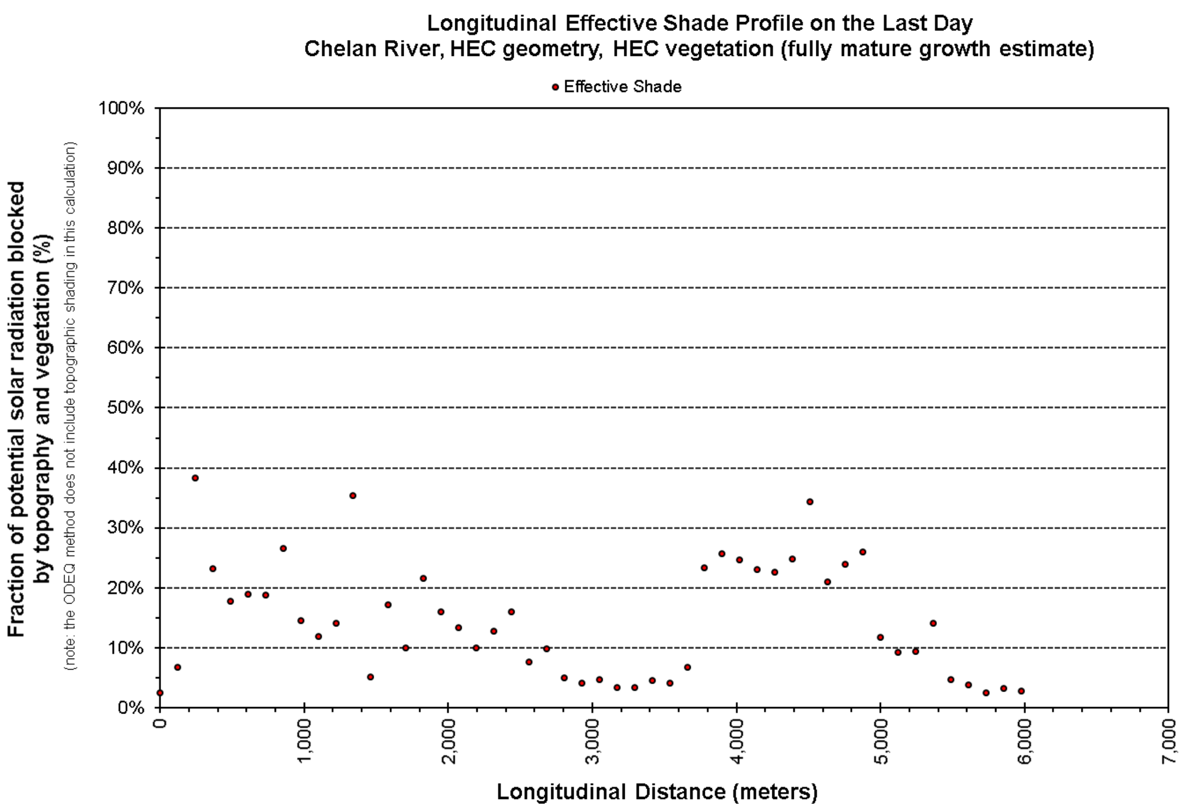
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Longitudinal Distance (meters)



Longitudinal Effective Shade Profile on the Last Day
Chelan River, HEC geometry, HEC vegetation (fully mature growth estimate)
Effective Shade
Fraction of potential solar radiation blocked by topography and vegetation (%)
(note: the ODEQ method does not include topographic shading in this calculation)
100%
90%
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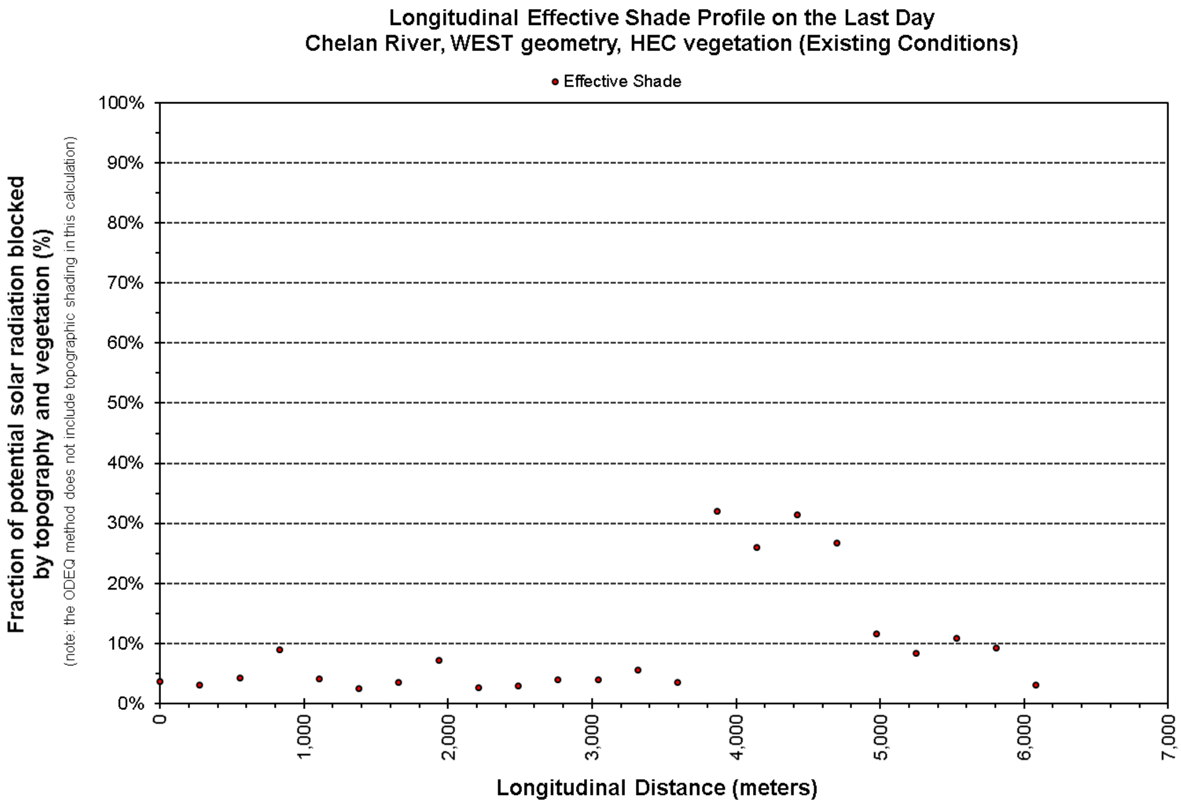
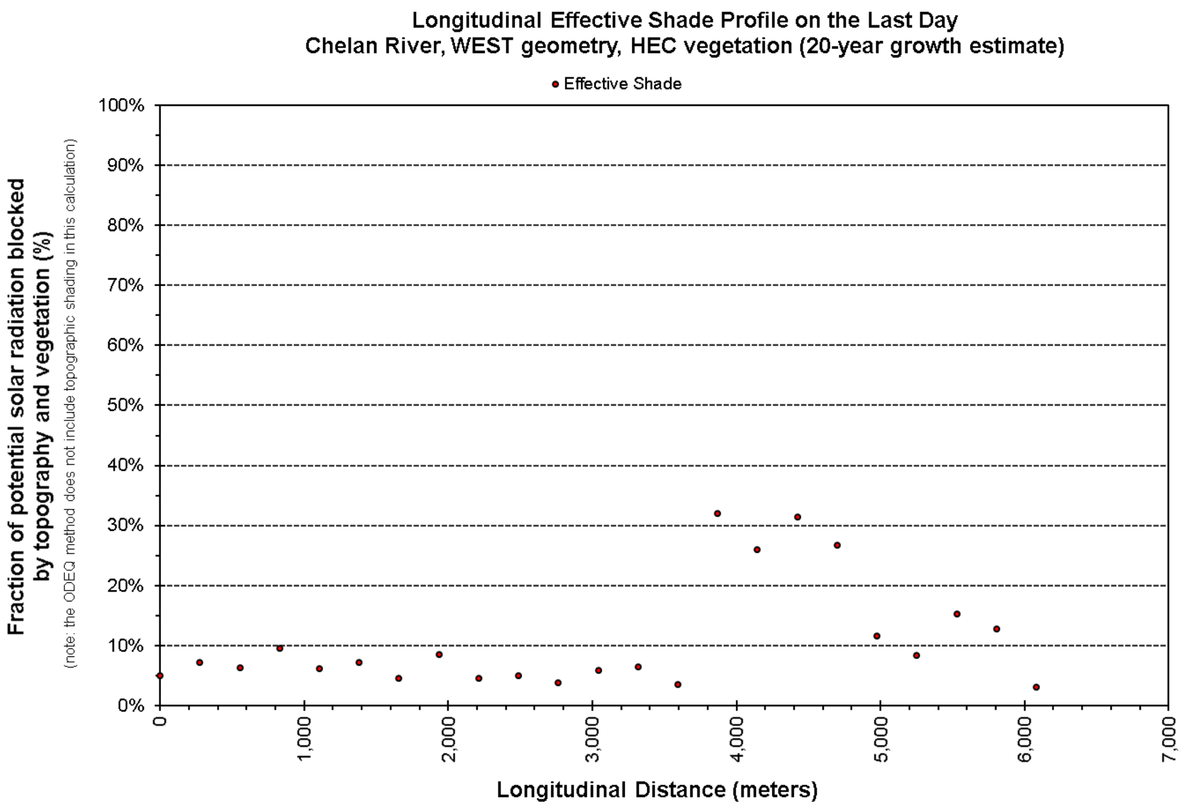
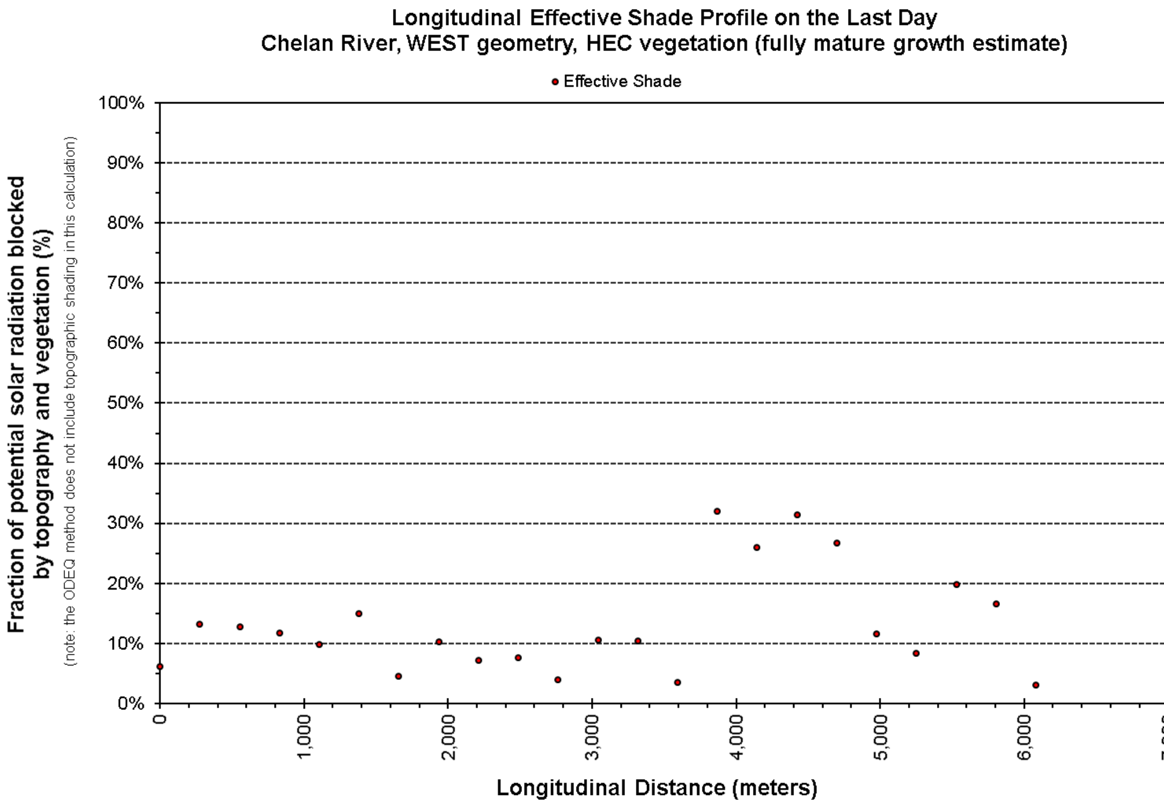
2,000
3,000
4,000
5,000
6,000
7,000
Longitudinal Distance (meters)


Longitudinal Effective Shade Profile on the Last Day
Chelan River, WEST geometry, HEC vegetation (Existing Conditions)
Effective Shade
Fraction of potential solar radiation blocked by topography and vegetation (%)
(note: the ODEQ method does not include topographic shading in this calculation)
Longitudinal Distance (meters)


Longitudinal Effective Shade Profile on the Last Day
Chelan River, WEST geometry, HEC vegetation (20-year growth estimate)
Effective Shade
Fraction of potential solar radiation blocked by topography and vegetation (%)
(note: the ODEQ method does not include topographic shading in this calculation)
Longitudinal Distance (meters)



Longitudinal Effective Shade Profile on the Last Day
Chelan River, WEST geometry, HEC vegetation (fully mature growth estimate)
Effective Shade
Fraction of potential solar radiation blocked by topography and vegetation (%)
(note: the ODEQ method does not include topographic shading in this calculation)
100%
90%
80%
70%
60%
50%
40%
30%
20%
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3,000
4,000
5,000
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7,000
Longitudinal Distance (meters)

9 Appendix 2 – Consultation Record

On April 22, 2016, Chelan PUD provided a draft of a report titled "Chelan River Temperature Model Calibration and Initial Results" to the USGS and members of the CRFF and LCRF for review and comment. This report documents the development and calibration of a functional water temperature model, as required in the FERC Order approving the Chelan River Water Temperature Modeling Study Quality Assurance Project Plan issued on September 4, 2014. Pursuant to ordering paragraph (B) of the approving order, Chelan PUD was required to file the Chelan River Water Temperature Modeling Study QAPP Report (*Report*) with the Commission by August 1, 2015. Subsequently, Chelan PUD filed requests for extensions of time to file the Report, first to extend the time to February 15, 2016, then later to June 1, 2016. The reasons for the time extension requests were related to ongoing work to improve the model and to produce the results produced by the model for hypothetical changes to river flows and riparian vegetation shade. On January 14, 2016, the FERC approved Chelan PUD's request for extension of time to file the report, as follows:

> "Public Utility District No. 1 of Chelan County's (licensee) December 3, 2015 request to extend the deadline for filing its final water temperature modeling study report is approved. The licensee must file the report with the Federal Energy Regulatory Commission, including documentation of consultation with the Washington Department of Ecology, by June 1, 2016. ."

Members of the Chelan River Fishery Forum and additional participants were sent draft copies for a 30 day review period from April 22 – May 24. At the request of Paul Pickett, Washington State Department of Ecology, additional time was granted for his comments, which were provided on May 25. His comments were the only ones received. His comments and how they were addressed are as follows:

1. Section 2.9: You report the MQOs for flow and temperature. You should also report the results of your quality assessment – were MQOs met?

   These sentences were added to Section 2.9: "The temperature loggers were checked prior to and following deployments and all tests met the measurement quality objectives. Flow measurements also met these objectives."

2. Section 4.2, Table 7: Show the percentile of the observed air temperatures for the dates. This would be useful for comparison to "critical condition" warm air temperatures.

   Daily minimum and maximum air temperature data for 1920 – 2015 were downloaded from the NOAA Global Historical Climatology Network for the Chelan location. From these 95 years of data, the daily maximum for the 2014 July 27 – August 3 model validation period were ranked and the percentile of the 95 year data set was calculated for each date. Of the eight days in 2014, the daily maximum air temperature was at or above the 95th percentile on five days, with one day being the highest (100th percentile) for that date. The following sentence was added to Section 4.2: "The July 2014 event represented the critical condition for air temperatures, with daily maximum temperatures at or above the 95 percentile for five of those dates for years from 1920 – 2015."

3. Section 4.4, Table 10: Provide some calibration results from other models for comparison. Ecology published a report on modeling quality results that can be a reference.

The Ecology report "A Synopsis of Model Quality from the Department of Ecology's Total Maximum Daily Load Technical Studies", Publication No. 14-03-042 was reviewed and the following sentence added to Section 4.5: "The root mean square error (RMSE) for validation over the four events (6-8 days) and at different river locations ranged from 0.21 °C – 0.74 °C, which compares with an average validation RMSE of 0.75 °C for QUAL2Kw simulations over 10 day periods (Sanderson and Pickett, 2014)." The citation for Sanderson and Pickett was added to the References section.

4. Section 5.2: Provide some example graphs that show peak daily temperatures (or 7DAvgDMax) as a function of flow for the scenarios with the hottest water temperatures.

The daily maximum temperatures for these simulated flows and temperatures were plotted and a linear regression trend line was shown. Similarly, the reduction in maximum water temperature from the 80 cfs minimum flow was plotted for each of the increased flows and a linear regression trend line was included. These plots, for the end of Reach 1 and the end of Reach 3 were added to the report as figures 58, 59, 60 and 61. A discussion of these plots and interpretation of the regression analysis was added to Section 5.2.

In addition to the response to these comments, some minor edits were made to improve clarity in some other sections of the report. Also, one additional model run of the July 2014 period was conducted to evaluate whether temperature reductions associated with increased flow were potentially biased by assuming too much hyporheic exchange at the higher flows. The model was calibrated for the low flow condition, which had a high hyporheic contribution. The result of this model simulation was briefly discussed in Section 5.2.

The following individuals were sent draft copies for a 30 day review period.

NAME	***AGENCY***	***Comments***
Peterschmidt, Mark	Washington State Department of Ecology	-
Pacheco, Jim	Washington State Department of Ecology	-
Pickett, Paul	Washington State Department of Ecology	
Korth, Jeffrey	Washington State Department of Fish and Wildlife	-
Simon, Graham	Washington State Department of Fish and Wildlife	-
Maitland, Travis	Washington State Department of Fish and Wildlife	-
Grover Wier, Kari	United States Department of Agriculture – Forest Service	-
Martinez, Alex	United States Department of Agriculture – Forest Service	-
Vacirca, Richard	United States Department of Agriculture – Forest Service	-
Rawhouser, Ashley	National Park Service	-
Anthony, Hugh	National Park Service	-
Lewis, Steve	United States Fish and Wildlife Service	-
Yeager, Justin	National Marine Fisheries Services	-
Domingue, Richard	National Marine Fisheries Services	
Towey, Bill	Confederated Tribes of the Colville Reservation	-
Rose, Bob	Yakama Indian Nation	-
Merkle, Carl	Confederated Tribes of the Umatilla Indian Reservation	-
Goedde, Robert	City of Chelan	-
Archibald, Phil	Lake Chelan Sportsman Association	-
Elwell, Nick	United States Geological Survey	-
Ernsberger, Tom	Washington State Parks and Recreation Commission	-
Snell, Nona	Washington State Recreation and Conservation Office	-
Petersen, Wai	Manson Parks and Recreation Department	-
Uhlhorn, Richard	Lake Chelan Recreation Association	-
O'Keefe, Thomas	American Whitewater	-

The model development and refinement has been a collaborative process, with primary development of the model by WEST Consultants, but with frequent collaboration regarding model development with Paul Pickett, Washington State Department of Ecology, and with Chelan PUD. A selection of email correspondence is included in the following pages to document the high degree of collaborative effort that went into development and calibration of the Chelan River Water Temperature Model and into the production of this report.

From: Pickett, Paul (ECY) [mailto:Ppic461@ECY.WA.GOV]
Sent: Wednesday, May 25, 2016 5:36 PM
To: Hays, Steve
Cc: Osborn, Jeff
Subject: RE: Comments for Chelan PUD....RE: Draft Report for Review - Chelan River Temperature Model Calibration and Initial Results

Steve,

Some responses below. I hope they clarify my intent.

Paul

Paul J. Pickett
WA Dept. of Ecology

From: Hays, Steve [mailto:steve.hays@chelanpud.org]
Sent: Wednesday, May 25, 2016 4:49 PM
To: Pickett, Paul (ECY) <Ppic461@ECY.WA.GOV>
Cc: Osborn, Jeff <Jeff.Osborn@chelanpud.org>
Subject: RE: Comments for Chelan PUD....RE: Draft Report for Review - Chelan River Temperature Model Calibration and Initial Results

Thanks Paul,

I am a bit confused about two of the comments and, with a quick search of the Ecology web site, I could not find the report on modeling quality results (could you please tell me where to look).
https://fortress.wa.gov/ecy/publications/SummaryPages/1403042.html

On the comments that I didn't understand:

- Section 4.2, Table 7: Show the percentile of the observed air temperatures for the dates. This would be useful for comparison to "critical condition" warm air temperatures.
  Are you asking for the percentile of the historical data of record for the source of the climatic data? I believe the data source was a fairly new station so there wouldn't be much historical data, but I am not sure this is what you meant by the percentile.
- ➔ There are data sets out there for long-term stations like the Wenatchee airport with report the historical distribution of data. So for example, for any given day there would be a distribution of the daily maximum air temperatures for that date. The same applies for the month. We often use the 95th percentile of the daily maximum air temperature as a "critical condition" for temperature modeling. I don't have a specific way you could address this. The purpose was to put the daily maximum temperatures in some context. Was that a hot day for that time of year? Average? Here's one source of information: http://www.climate.washington.edu/climate.html. One example from http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?wa9082:
- ➔

  Section 5.2: Provide some example graphs that show peak daily temperatures (or 7DAvgDMax) as a function of flow for the scenarios with the hottest water temperatures.

I thought Figures 56 and 57 showed the peak daily temperatures for each flow that was modeled. Were you looking for a regression of flow vs daily max temperature for the 7 days of model runs?

- ➔ Yes, a plot of daily max temperature as a function of the flow. You could get a regression from that graph, which would be interesting.

Thanks for providing the comments

Steve

From: Pickett, Paul (ECY) [mailto:Ppic461@ECY.WA.GOV]
Sent: Wednesday, May 25, 2016 4:34 PM
To: Hays, Steve
Subject: Comments for Chelan PUD....RE: Draft Report for Review - Chelan River Temperature Model Calibration and Initial Results

Steve, My apologies for doing this last minute.

This is a good report, and I have only a few suggestions for improvement:

- Section 2.9: You report the MQOs for flow and temperature. You should also report the results of your quality assessment – were MQOs met?
- Section 4.2, Table 7: Show the percentile of the observed air temperatures for the dates. This would be useful for comparison to "critical condition" warm air temperatures.
- Section 4.4, Table 10: Provide some calibration results from other models for comparison. Ecology published a report on modeling quality results that can be a reference.
- Section 5.2: Provide some example graphs that show peak daily temperatures (or 7DAvgDMax) as a function of flow for the scenarios with the hottest water temperatures.

Paul

Paul J. Pickett
WA Dept. of Ecology

From: Pickett, Paul (ECY) [mailto:Ppic461@ECY.WA.GOV]
Sent: Tuesday, May 24, 2016 1:57 PM
To: Hays, Steve
Cc: Peterschmidt, Mark F. (ECY); Osborn, Jeff
Subject: Re: Draft Report for Review - Chelan River Temperature Model Calibration and Initial Results

Thanks for the feedback. I can get you my major comments by first thing tomorrow. And hopefully all of them - I'm not expecting surprises.

Sent from my iPhone

On May 24, 2016, at 10:40 AM, Hays, Steve <steve.hays@chelanpud.org> wrote:

Paul,

I am sorry to say no, but I have to file this report ready to file with FERC no later than first thing, Tuesday May 31. Monday is a holiday, so that only gives me Wed – Friday of this week to make changes to the report in response to comments.

This is the best I can do:

Please send me any substantive comments (those that will require a lot of work to address) by email by first thing tomorrow. I can handle little things that come in by Thursday mid-day. My access to administrative support staff only lasts until Thursday because all are gone Friday – Monday for the holiday weekend. We need Tuesday to prepare the FERC filing.

Don't forget that we will be continuing to work with you and WEST on the model to further improve the model (hyporheic zone water temperatures, testing model versus empirical water temperatures for last summer's extreme climatic conditions and water temperatures) and to use the model for analysis of flow releases to reduce 7DADMax water temperatures (combined with empirical tests) this summer. Anything you have comment-wise that can be addressed with this additional work, rather than in this report's response to comments, can be incorporated into work going forward.

I understand the juggling – I have a few items in the air myself.

Steve

From: Pickett, Paul (ECY) [mailto:Ppic461@ECY.WA.GOV]
Sent: Monday, May 23, 2016 5:52 PM
To: Hays, Steve
Cc: Peterschmidt, Mark F. (ECY)
Subject: RE: Draft Report for Review - Chelan River Temperature Model Calibration and Initial Results

Chelan County PUD IT Warning:
Please use caution! This is an external email with links or attachments.

Steve, I've been juggling things the last few weeks and still juggling. Could I get comments to you by the end of this week?

Thanks,

Paul

Paul J. Pickett
WA Dept. of Ecology
P.O. Box 47710
Olympia, WA 98504-7710
desk (360) 407-6882
cell (509) 406-2459

From: Hays, Steve [mailto:steve.hays@chelanpud.org]
Sent: Friday, April 22, 2016 1:46 PM

To: Peterschmidt, Mark F. (ECY) <MAPE461@ECY.WA.GOV>; Pickett, Paul (ECY) <Ppic461@ECY.WA.GOV>; Pacheco, James (ECY) <JPAC461@ECY.WA.GOV>; Korth, Jeff W (DFW) <Jeff.Korth@dfw.wa.gov>; Simon, Graham A (DFW) <Graham.Simon@dfw.wa.gov>; Maitland, Travis W (DFW) <Travis.Maitland@dfw.wa.gov>; 'Kari Grover Wier' <kgroverwier@fs.fed.us>; 'Alex Martinez (ramartinez@fs.fed.us)' <ramartinez@fs.fed.us>; 'rvacirca@fs.fed.us' <rvacirca@fs.fed.us>; 'Ashley_Rawhouser@nps.gov' <Ashley_Rawhouser@nps.gov>; 'Hugh_Anthony@nps.gov' <Hugh_Anthony@nps.gov>; 'Steve Lewis (Stephen_Lewis@fws.gov)' <Stephen_Lewis@fws.gov>; 'Rich Domingue (richard.domingue@noaa.gov)' <richard.domingue@noaa.gov>; 'Justin Yeager (Justin.Yeager@noaa.gov)' <Justin.Yeager@noaa.gov>; 'Bill Towey' <bill.towey@colvilletribes.com>; 'Bob Rose (rosb@yakamafish-nsn.gov)' <rosb@yakamafish-nsn.gov>; 'Carl Merkle (carlmerkle@ctuir.com)' <carlmerkle@ctuir.com>; 'Robert Goedde (bgoedde@cityofchelan.us)' <bgoedde@cityofchelan.us>; 'Phil Archibald (ndmarkey@gmail.com)' <ndmarkey@gmail.com>; 'Nick Elwell' <'nelwell@usgs.gov'>; Ernsberger, Tom (PARKS) <Tom.Ernsberger@PARKS.WA.GOV>; Snell, Nona (RCO) <nona.snell@rco.wa.gov>; 'wai@mansonparks.com' <wai@mansonparks.com>; 'Richard Uhlhorn (richard@richarduhlhorn.com)' <richard@richarduhlhorn.com>; 'Thomas O'Keefe (okeefe@amwhitewater.org)' <okeefe@amwhitewater.org>
Cc: Osborn, Jeff <Jeff.Osborn@chelanpud.org>; Smith, Michelle <michelle.smith@chelanpud.org>; Sokolowski, Rosana <Rosana.Sokolowski@chelanpud.org>; Steinmetz, Marcie <Marcie.Steinmetz@chelanpud.org>; Underwood, Alene <Alene.Underwood@chelanpud.org>
Subject: Draft Report for Review - Chelan River Temperature Model Calibration and Initial Results

PUBLIC UTILITY DISTRICT NO. 1 of CHELAN COUNTY
P.O. Box 1231, Wenatchee, WA 98807-1231 • 327 N. Wenatchee Ave., Wenatchee, WA 98801
(509) 663-8121 • Toll free 1-888-663-8121 • www.chelanpud.org

To: Chelan River Fishery Forum:
Washington Department of Ecology
Washington Department of Fish and Wildlife
United States Forest Service
National Park Service
United States Fish and Wildlife Service
National Marine Fisheries Service
CCT (Colville)
YN (Yakama)
CTUIR (Umatilla tribe)
Lake Chelan Sportsman Association
United States Geological Survey
Washington State Parks and Recreation Commission
Washington State Recreation and Conservation Office
City of Chelan
Manson Parks and Recreation Department
Lake Chelan Recreation Association
American Whitewater

From: Steven Hays, Fish & Wildlife Senior Advisor
Public Utility District No. 1 of Chelan County (Chelan PUD)
steve.hays@chelanpud.org
(509)661-4181

Re: Draft Report for Review

Dear Chelan River Fishery Forum and Other Parties:

In accordance with Articles 405 and 408 of the Lake Chelan Hydroelectric Project License, Chelan PUD invites comments on the Draft Report - Chelan River Temperature Model Calibration and Initial Results (attached).

Please submit your comment letters on or before 5:00 p.m., May 24, 2016 to Steve Hays via email at steve.hays@chelanpud.org. I have provided the report in MSWORD format for your convenience. Please feel free to use the review features in MSWORD to make your suggested edits. However, in order to facilitate documentation of your comments and Chelan PUD's responses to comments regarding significant substantive issues, please provide those comments and any supportive rationales or data in a separate document so that it can be incorporated into the record of consultation.

All comments received will be incorporated into a summary table and appended to the Final Chelan River Temperature Model Calibration and Initial Results Report with a notation regarding how each comment or recommendation was incorporated in the report, or, if not incorporated, the reasons why the comment was not incorporated.

If you have any questions, please do not hesitate to contact me at (509-661-4181).

Steven Hays
Fish and Wildlife Senior Advisor
steve.hays@chelanpud.org
(509) 661-4181

From: Pickett, Paul (ECY) [mailto:Ppic461@ECY.WA.GOV]
Sent: Tuesday, July 07, 2015 10:58 AM
To: Ray Walton
Cc: Hays, Steve; Coffin, Chris (ECY); McKinney, Charlie (ECY)
Subject: RE: Chelan River Temperature Model Draft Calibration Report

Ray, your initial responses look pretty reasonable. I look forward to seeing your revisions in the next draft.

We can discuss more if you want, but it’s not needed at my end.

Paul

Paul J. Pickett

WA Dept. of Ecology

From: Ray Walton [mailto:rwalton@westconsultants.com]
Sent: Thursday, July 02, 2015 1:01 PM
To: Pickett, Paul (ECY)
Cc: Hays, Steve (steve.hays@chelanpud.org)
Subject: RE: Chelan River Temperature Model Draft Calibration Report

Paul:

Thanks for providing the comments below. I quickly reviewed them, imported them into a review document, and provided some initial responses. Perhaps we might talk early next week to go over them and map the path forward? Thanks, and have a great July 4th….

Ray

Raymond Walton, **PhD, PE, D.WRE**
WEST Consultants, Inc.

From: Pickett, Paul (ECY) [mailto:Ppic461@ECY.WA.GOV]
Sent: Wednesday, June 24, 2015 2:44 PM
To: Hays, Steve; Ray Walton; Osborn, Jeff
Cc: Mackie, Thomas L. (ECY); Coffin, Chris (ECY); McKinney, Charlie (ECY); Pelletier, Greg (ECY)
Subject: FW: Chelan River Temperature Model Draft Calibration Report

Steve, Ray, and Jeff,

Here are some preliminary comments on the calibration report that I'd like to get to you before tomorrow's meeting. I expect there will be further discussion over the next few weeks to address these comments and explore the report more deeply.

1. Section 2, "Model Data": provide a quantitative and qualitative analysis of the quality of the data used for input data. For example, what quality planning documents are used for flows and temperature monitoring, what are the results of any quality assessment, and are there confidence band estimates for the data?
2. Section 2.8: what existing information is available on current riparian conditions? Can you verify the assumption of no shade from aerial photo analysis? For example, it appears that the Reach 4 Habitat Channel has some riparian vegetation, and I recall from the site visit there was some limited riparian vegetation emerging in Reach 1.
3. Section 3.2: As we discussed, your analysis of modeled widths versus observed makes sense. However, that doesn't leave us with confidence about the hydraulic model calibration. Do you have any information regarding modeled versus observed time of travel, velocities, or depths?
4. Section 3.3, your power equations depend on the quality of calibration mentioned in the previous comment. Could the error in width you described also have implications for depth or velocity, and therefore for the accuracy of the power equations?
5. I would expect that the temperature model would be sensitive to stream width. How could this be tested? Discuss how the model results were translated to widths for the thermal exchange in

the temperature model, and the implications of the hydraulic model's under-predicted stream width on the temperature model.

6. Section 4.3.1 refers to "July 2014". This is inconsistent with Table 6 and Figure 20. Please correct or explain.
7. Section 4.3.7: It is difficult to interpret the sensitivity analysis with only the input values shown. Generally, a sensitivity analysis varies inputs by a small set percentage. It would be helpful in Table 7 to show the initial calibrated values and the percentage that they were varied for the analysis. This would help to support the conclusions about the relative sensitivity of the different parameters.
8. Section 4.4: It surprises me that you calibrated to one data set and validated to 4 others. The model was calibrated was calibrated during a period of relatively warm water (20-24 degC). Validation runs tended to perform equivalently for higher temperatures but somewhat less well for lower temperatures. It would be a more robust calibration process to calibrate to all the data sets, or at least to calibrate to 3 data sets in a wide range of temperatures and validate with two sets.
9. Since the criterion from the standards is 17.5, it would be informative to develop calibration and validation statistics for temperature above 17.5. Also, since the WQ standards is based on the 7DADMax, it would be helpful to see the calibration and validation statistics for that metric.
10. Why were only five 7-day data sets used? It would seem that longer time periods would result in a stronger calibration and allow the 7DADMax to be calculated from multiple moving averaging periods.
11. Section 4.6: Your statement "the model validation statistics are similar to the calibration statistic" overlooks the tendency to perform better for higher temperature than for lower. As such, this seems like an over-simplistic statement that misses some key patterns. Some sensitivity analysis with one of the cooler calibration periods could help to understand the performance of the model in those conditions.
12. Section 5, "This is partially due to the dry conditions that support little tall vegetation elsewhere in the area, but also because the Chelan River is very wide for the depths it supports under low-flow conditions." My understanding is that this is also due to the history of the river being dry, so that riparian vegetation has only recently had enough water to survive the summer.

Paul

Paul J. Pickett
WA Dept. of Ecology

From: Pickett, Paul (ECY) [mailto:Ppic461@ECY.WA.GOV]
Sent: Friday, May 29, 2015 10:53 AM
To: Hays, Steve; 'Ray Walton'
Cc: Osborn, Jeff; Steinmetz, Marcie; Coffin, Chris (ECY); Mackie, Thomas L. (ECY)
Subject: RE: Riparian Shade Analysis - Herrera Draft Report

Steve,

From the feedback I've gotten so far, the Chen method using Shade.xls is our standard approach. It should work well for the Chelan River.

One question: What vegetation assemblages are being evaluated for riparian planting? One comment I got was that willows were relatively short and would only create near-bank microclimate. This is a good thing for fish, but won't do much for the river as a whole. The model will be evaluating average temperature and not thermal refugia.

Which leads to two thoughts:

- Tall eastern Washington trees should be considered, such as Cottonwood or Ponderosa Pine.
- Some evaluations of thermal refugia might be useful, since it could provide more information about fish suitability than can be provided by only the model.

Paul

From: Pickett, Paul (ECY)
Sent: Thursday, May 21, 2015 11:35 AM
To: 'Hays, Steve'; 'Ray Walton'
Cc: Osborn, Jeff; Steinmetz, Marcie; Pelletier, Greg (ECY); Coffin, Chris (ECY); Mackie, Thomas L. (ECY)
Subject: RE: Riparian Shade Analysis - Herrera Draft Report

Steve,

Here's some thoughts about the shade analysis.

The work below is a good first step. However, it appears that they are only looking at the shade "footprint". An assumption that shade is 100% effective would be incorrect.

The Qual2kw model requires input of percent effective shade for each model segment for each time period of the day. This would require a calculation that takes into account the "footprint", the canopy density, and perhaps also the height and width of the riparian area. There are different approaches to developing that calculation:

- The more complex and physically complete method would be to use the method developed by Chen (see attachment). In my opinion, this approach would be more robust and defensible.
- A simple approach is to estimate canopy density and assume that would equal shade density. However, this ignores the factors of riparian vegetation height and width. But it would take less time to develop and might be good for a "first cut".

The Shade.xls model is a commonly used tool, and it allows options for both the Chen and simple methods. It has the advantage of directly linking the shade analysis to the model segmentation and time steps. However, it's possible to generate percent effective shade estimates directly from GIS using either method.

A couple other thoughts about this analysis:

- If local knowledge is needed to estimate the riparian zone width, height, and canopy density, the Chelan River Fish Forum might be a resource for finding that information.
- Since the expected future shade is uncertain, it might be useful to do a sensitivity analysis on the shade inputs to see the effect of assumptions. For example, you might model high, medium, and low estimates of canopy density, tree height, and buffer width. This would provide better

understanding of the effects of different implementation strategies or of their ultimate outcome.

A few more thoughts on this might come my way, so if I have more to add I'll send it along.

Also, of course, if you have questions about this, let me know.

Thanks,

Paul

Paul J. Pickett
WA Dept. of Ecology

From: Hays, Steve [mailto:steve.hays@chelanpud.org]
Sent: Tuesday, May 12, 2015 2:24 PM
To: 'Ray Walton'; Pickett, Paul (ECY)
Cc: Osborn, Jeff; Steinmetz, Marcie
Subject: Riparian Shade Analysis - Herrera Draft Report

Ray and Paul,

We are currently reviewing a draft Riparian Feasibility Report from Herrera and one of the deliverables in our contract was to provide an assessment of potential riparian shade that would be useful for the temperature model gaming. Below is the discussion regarding shade modeling that is in their draft report. My question to you is whether this method of analysis could be used by QUAL2Kw for gaming a future condition of mature (or partially mature) riparian shade. If this type of analysis is not useful, please let me know what other method could be used that would provide input needed for gaming with QUAL2Kw.

Thanks for your help on this,

Steve

Shadow modeling in GIS was used to assess the degree to which riparian revegetation could be used to increase shading of the Chelan River during the period when water temperatures are high. A date representative of the period of highest water temperatures was chosen by consulting a Chelan PUD annual temperature report for the upper Chelan River. The middle of the period of highest temperatures recorded in 2011 was approximately August 21.
Hourly solar elevation and azimuth were calculated for August 21, 2015, using the Washington Department of Ecology's SolRAd solar radiation model. These were entered into the ArcGIS Hillshade tool, along with 2009 top surface lidar elevation data from Puget Sound Lidar Consortium, to calculate shadows at two hour increments between 6:00 am and 6:00 pm. Figure 4 depicts the resulting existing conditions shade map for 2:00 pm.
The shading effect of riparian revegetation at 20 years growth was estimated for both willow bands, and mixed riparian plantings. The height of expected growth was added to the lidar bare-earth elevation in the areas where each treatment is feasible, and those expected-growth top-surfaces were merged with the existing conditions top-surface to create proposed conditions top surfaces. These were entered into the ArcGIS Hillshade tool using the same solar azimuth and elevation data used for the existing conditions shade calculations. The difference between existing and proposed conditions shading was calculated (Figures 5), and the shaded water surface area at typical late August low-flow conditions was estimated by intersecting the shaded area with the HEC-RAS modeled inundation

surface at 80 cfs

(Table 2).

Table 2. Area of Additional Shade on 80cfs Water Surface, August 21 (ft^2)			
Time	**Willow Bands**	**Riparian Planting**	**Willow Bands + Riparian Planting**
12:00 noon	43 668	26 820	70 200
2:00 pm	67 932	39 744	106 776

From: Pickett, Paul (ECY) [mailto:Ppic461@ECY.WA.GOV]
Sent: Friday, May 01, 2015 4:47 PM
To: Hays, Steve
Cc: Osborn, Jeff; Steinmetz, Marcie; 'Ray Walton'; Coffin, Chris (ECY)
Subject: RE: Data from additional Chelan River temperature loggers

Steve,

Very interesting.

It being Friday, I couldn't resist fiddling with the graphs (attached).

It still doesn't quite capture the response – lots of interesting patterns to explore.

Paul

Paul J. Pickett
WA Dept. of Ecology

From: Hays, Steve [mailto:steve.hays@chelanpud.org]
Sent: Friday, May 01, 2015 11:39 AM
To: 'Ray Walton'; Pickett, Paul (ECY)
Cc: Osborn, Jeff; Steinmetz, Marcie
Subject: Data from additional Chelan River temperature loggers

Hello Ray and Paul,

Attached is a spreadsheet with the first data pulled from the additional sensors that I installed in Reach 1 of the Chelan River. There are now 4 sensors located in Reach 1 downstream from the dam, at approximately 200 feet below the Low Level Outlet, 0.55 miles, 1.56 miles and 2.23 miles. The chart shows two lines, one for the sensor at the top of Reach 1 just downstream from the spillway and Low Level Outlet and the other for the sensor at the end of Reach 3. These represent initial temperature and the temperature after water has passed through the falls and pools in the gorge. The little bars in the chart are for the downstream sensors. These sensors in Reach 1 are the two new ones, downstream at 0.55 miles and 1.56 miles, and the one at the end of Reach 1 at 2.23 miles that has again been repositioned out in the flow away from the hyporheic influence that has affected some of the past data at this site.

The data shows that significant heat exchange happens within that first 0.55 miles, account by eyeball estimation for about 1/3 of the warming that occurred by the time water came to the end of Reach 1. In the next mile, at 1.56 miles, the daily maximum temperature generally seems to be about 0.5 degrees C cooler than the daily maximum seen at the end of Reach 1. The braided, multiple channel section lies between Miles 1.56 and 2.23, but the river goes around a large bend with absolutely no shade between the end of the braided section and the sensor at Mile 2.23.

The sensors are located as shown below.

I hope this data is useful in calibrating the model.

Steve

From: Pickett, Paul (ECY) [mailto:Ppic461@ECY.WA.GOV]
Sent: Thursday, March 26, 2015 5:07 PM
To: Coffin, Chris (ECY)
Cc: Hays, Steve; Mackie, Thomas L. (ECY); Ray Walton
Subject: Chelan River modeling chat

Chris,

FYI, Ray Walton called with some technical questions about the Chelan River modeling. I brought in Greg Pelletier, and I think we've answered his questions. If you want the gory details, let me now and I'll send my notes.

Several unanticipated glitches are slowing the modeling. However, Ray is supportive of the concept of issuing the calibration "chapters" first, so folks can review them and get questions answered (and hopefully agree to the approach). Then the full report with scenarios would be issued later. He is working with Steve Hays on how that would work, schedule-wise.

That's the update…

Paul

Paul J. Pickett
WA Dept. of Ecology
P.O. Box 47710

From: Pickett, Paul (ECY) [mailto:Ppic461@ECY.WA.GOV]
Sent: Thursday, February 05, 2015 1:34 PM
To: Ray Walton
Cc: Pelletier, Greg (ECY); Alec Robertson; Hays, Steve
Subject: RE: Qual2kw on Chelan River

Sounds ok to me with concurrence from Greg and with one caveat:

- Model reach 4 with the habitat channel as the "river", with the pumped inflows as a tributary, and ignore the overflow channel. But I'd like to confirm with Steve that that's a reasonable assumption, given that flows you would be modeling.
  Steve, at what flows does the overflow channel come into use, and what are the highest flows we're likely to be modeling?

Paul

Paul J. Pickett
WA Dept. of Ecology

From: Ray Walton [mailto:rwalton@westconsultants.com]
Sent: Thursday, February 05, 2015 12:56 PM
To: Pickett, Paul (ECY)
Cc: Pelletier, Greg (ECY); Alec Robertson; Hays, Steve (steve.hays@chelanpud.org)
Subject: RE: Qual2kw on Chelan River

Paul and Greg:

Thanks for your quick responses. I would like to propose the following:

1. As the travel time (based on water speed) is about 4 hours for Q=85 cfs, and Greg suggests QUAL2Kw cells with travel times of 45 minutes or less, that we consolidate HEC-RAS geometry into QUAL2Kw cells of nominally 1000 feet. This would give us about 22 cells in QUAL2Kw, or travels times averaging 11 minutes per segment.
2. We will use continuous simulations of about 10 days (travel times are 4 hours or less) for all model runs (calibration, validation, and scenarios). The scenarios would be based on (1) difference model geometries and (2) different combinations of upstream flows, water temperatures and meteorological conditions.
3. We will model just the main flow path in Reach 4 (the main flow path from Reach 3, the canyon, to the Columbia River) and treat the other branches as inflow points.

Does this work for y'all?

Ray

From: Pickett, Paul (ECY) [mailto:Ppic461@ECY.WA.GOV]
Sent: Thursday, February 05, 2015 12:17 PM
To: Ray Walton
Cc: Pelletier, Greg (ECY)
Subject: RE: Qual2kw on Chelan River

Ray,

My thoughts on your questions and Greg's responses are below.

If this gives you information to move forward, could you provide a summary of your preferred approach (short versions of answers to your own questions)?

Or we set up a time for a conversation to work out the details. Possible times (assuming Greg's calendar is up to date):

- Monday Feb 9 at 11:00, 1:30 or 4:00
- Tuesday Feb 10 at 1:00 or 3:30
- Wednesday Feb 11 between 10:00 and noon, or at 1:30

- Thursday Feb 12 anytime except the noon hour between 10 and 4

1. The Chelan River is 4.1 miles long, and we are developing an HEC-RAS model using nominal increments of about 200 feet. However, I think that over 100 cells in QUAL2Kw might be too many. Do you have any thoughts on temperature modeling cell sizes for QUAL2Kw?
   Greg:
   - Each Q2K reach could be the composite of 2 HEC-RAS reaches to reduce the total number to around 50. We usually use fewer than 100 reaches in an application.
   - The number of HEC-RAS reaches to composite for each Q2K reach could be more than 2. Probably ok to aim for travel times of Q2K reaches up to about 45 minutes for each reach.

   Paul:
   - This appears to be straight-forward. Match QUAL2kw reaches to multiples of HEC-RAS reaches. If the river has about a 4 hour travel time, Greg's approach would result in 6 reaches, which seems too little. So while 50 seems like too much, something in between is probably the sweet spot.

2. I think that a very long simulation (order of months to a year) using QUAL2Kw might be unwieldy. Given the short residence time in the river (matter of hours), would model calibration/validation and scenario simulations on the order of 1-2 weeks be more appropriate than longer simulations?
   Greg:
   - This depends on whether you need to simulate day-to-day variations through a season or only a critical period within the season. Q2K has the option of either continuous simulation or repeating diel simulation. I recommend continuous simulation if the model needs to represent day-to-day variations for an entire season or within a critical week. The length of a continuous simulation probably would not need to be more than 60-90 days to include the critical summer period, but could be as short as 3-5 times the travel time if only the worst day needs to be simulated. In some cases the hottest period may not be the most critical period for consideration of anthropogenic influences so a longer continuous simulation would be needed. If the model only needs to simulate a critical day or week, then this could be done with repeating diel simulation, but it may be better to use continuous simulation to include the temporal variations leading up to the critical day. If the conditions on any given day are influenced by varying conditions on previous days then continuous simulation would be best. For a one-day travel time it would be good to include at least the previous 3-5 days in the simulation.
   - Jim and Tighe are typically including the 3-6 month tidbit monitoring in continuous simulation periods for temperature TMDLs on the east side. If there are point sources then these could have the biggest impact during the fall and not during the hottest period.

   Paul:
   - Given the way I understand the system is operated, the short travel time, and Greg's comments, 1-2 weeks sounds about right, with the focus on the final few days. We had discussed modeling

a variety of scenarios addressing combinations of flow rates and seasonal conditions (summer, fall, median, extreme). Steve Hays monitoring data sheds some light on conditions that appear to produce the greatest temperature increases in the river.

3. Reach 4 (the most downstream portion of the Chelan River) has a number of branches. In looking at the QUAL2Kw spreadsheet, it seems that it might be developed for a single reach (not tributaries or branches)? If so, is it appropriate to model the main channel of the Chelan River (including through Reach 4), and include the other downstream channels as tributary inflows?

   Greg:
   - It is unclear whether Ray is describing a braided channel, or whether there are some tributaries entering the main channel and Ray wants to simulate conditions in those tributaries. If it is a braided channel then the model will need to simulate it as if it is not braided. If there is a need to simulate conditions in tributaries entering the main channel then there are a couple of options. XQUAL2KW is a special version of Q2K that is capable of simulating a branching system with a main channel and up to three tributaries. Another option is to use separate Q2K applications for each tributary.
   - If there is a braided channel at the end this could be simulated with XQUAL2KW. XQ2K can simulate a main channel that splits into up to 3 braids.

   Paul:
   - If I recall correctly, as the river leaves the canyon, the main channel goes through the habitat enhancement area. There is an overflow channel for higher flows. And there is a diversion from the powerhouse outflow to augment flows in the habitat channel. So it's a combination of a tributary (powerhouse flow augmentation) and a split channel (overflow channel). I'm not sure the overflow channel is an issue for this modeling exercise, since it would only be used in high flows, so it might be as simple as a single tributary inflow. Maybe we should have Steve Hays in on the call to clarify some of the operating issues.
   - Three channels join at the confluence with the Columbia – the tailrace, habitat channel, and overflow channel. I'm assuming you can get some elevation information to determine the downstream boundary, which would be a elevation control (from Columbia River backwater elevations). Or the model can end at the last structural control and assume free flow into the Columbia backwater.

Paul

Paul J. Pickett
WA Dept. of Ecology

From: Pelletier, Greg (ECY)
Sent: Thursday, February 05, 2015 9:41 AM
To: Pickett, Paul (ECY)
Subject: RE: Qual2kw on Chelan River

… yet another idea:

3) If there is a braided channel at the end this could be simulated with XQUAL2KW. XQ2K can simulate a main channel that splits into up to 3 braids.

From: Pelletier, Greg (ECY)
Sent: Thursday, February 05, 2015 9:35 AM
To: Pickett, Paul (ECY)
Subject: RE: Qual2kw on Chelan River

… some more ideas

1) The number of HEC-RAS reaches to composite for each Q2K reach could be more than 2. Probably ok to aim for travel times of Q2K reaches up to about 45 minutes for each reach.
2) Jim and Tighe are typically including the 3-6 month tidbit monitoring in continuous simulation periods for temperature TMDLs on the east side. If there are point sources then these could have the biggest impact during the fall and not during the hottest period.

From: Pelletier, Greg (ECY)
Sent: Thursday, February 05, 2015 9:09 AM
To: Pickett, Paul (ECY)
Subject: FW: Qual2kw on Chelan River

Paul,

Here are some initial thoughts on Ray's questions:

- Each Q2K reach could be the composite of 2 HEC-RAS reaches to reduce the total number to around 50. We usually use fewer than 100 reaches in an application
- This depends on whether you need to simulate day-to-day variations through a season or only a critical period within the season. Q2K has the option of either continuous simulation or repeating diel simulation. I recommend continuous simulation if the model needs to represent day-to-day variations for an entire season or within a critical week. The length of a continuous simulation probably would not need to be more than 60-90 days to include the critical summer period, but could be as short as 3-5 times the travel time if only the worst day needs to be simulated. In some cases the hottest period may not be the most critical period for consideration of anthropogenic influences so a longer continuous simulation would be needed. If the model only needs to simulate a critical day or week, then this could be done with repeating diel simulation, but it may be better to use continuous simulation to include the temporal variations leading up to the critical day. If the conditions on any given day are influenced by varying conditions on previous days then continuous simulation would be best. For a one-day travel time it would be good to include at least the previous 3-5 days in the simulation.
- It is unclear whether Ray is describing a braided channel, or whether there are some tributaries entering the main channel and Ray wants to simulate conditions in those tributaries. If it is a braided channel then the model will need to simulate it as if it is not braided. If there is a need to simulate conditions in tributaries entering the main channel then there are a couple of options. XQUAL2KW is a special version of Q2K that is capable of simulating a branching system with a main channel and up to three tributaries. Another option is to use separate Q2K applications for each tributary.

Greg

Greg Pelletier
Department of Ecology

From: Ray Walton [mailto:rwalton@westconsultants.com]
Sent: Thursday, February 05, 2015 8:13 AM
To: Pickett, Paul (ECY)
Cc: Pelletier, Greg (ECY); Alec Robertson
Subject: RE: Qual2kw on Chelan River

Paul:

Good to hear from you. I wanted to make such that we are all on the same page regarding the Chelan River modeling, and have the following three general questions:

4. The Chelan River is 4.1 miles long, and we are developing an HEC-RAS model using nominal increments of about 200 feet. However, I think that over 100 cells in QUAL2Kw might be too many. Do you have any thoughts on temperature modeling cell sizes for QUAL2Kw?
5. I think that a very long simulation (order of months to a year) using QUAL2Kw might be unwieldy. Given the short residence time in the river (matter of hours), would model calibration/validation and scenario simulations on the order of 1-2 weeks be more appropriate than longer simulations?
6. Reach 4 (the most downstream portion of the Chelan River) has a number of branches. In looking at the QUAL2Kw spreadsheet, it seems that it might be developed for a single reach (not tributaries or branches)? If so, is it appropriate to model the main channel of the Chelan River (including through Reach 4), and include the other downstream channels as tributary inflows?

Thanks

Ray