Public Utility District No. 1 of Chelan County

Wenatchee, Washington

DRAFT CHELAN RIVER TEMPERATURE MODEL CALIBRATION

June 2015

Prepared by WEST Consultants, Inc. under contract SA No. 12 - 159

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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°F (near 30°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.

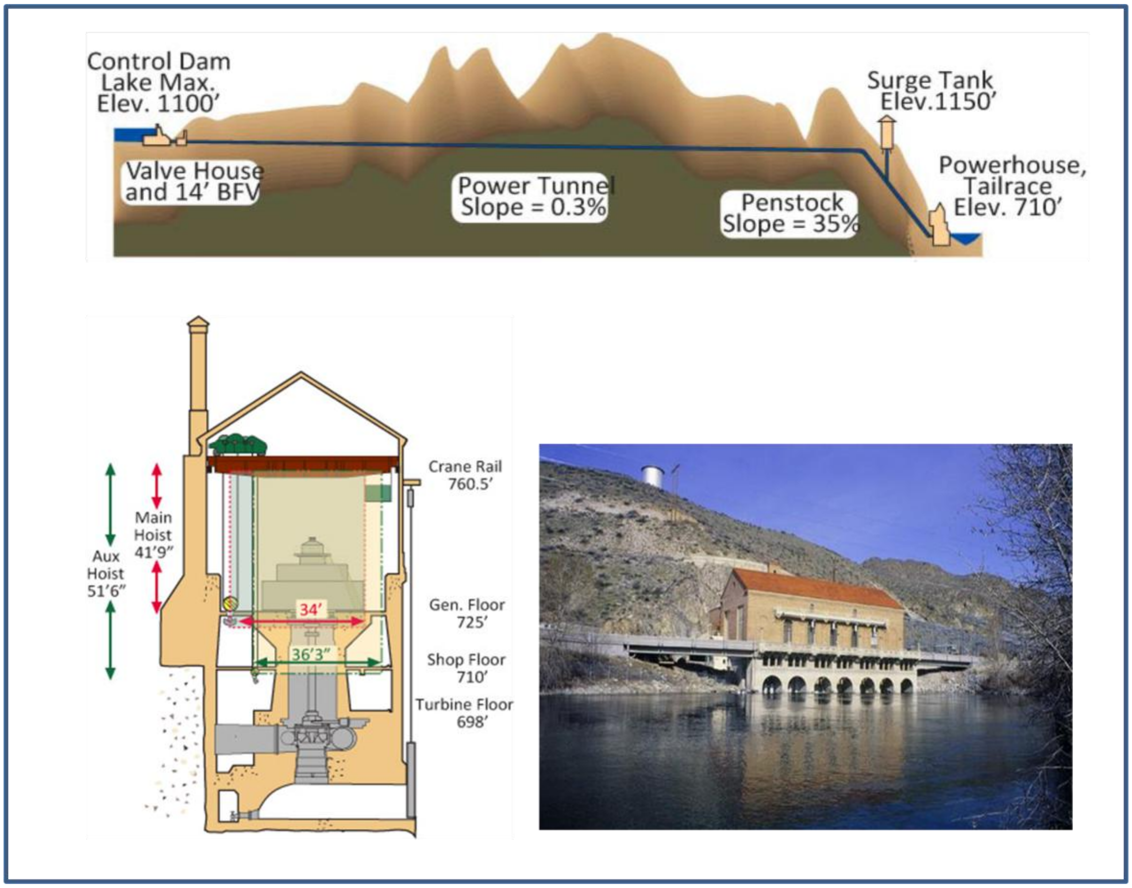


Figure 3. Lake Chelan Hydroelectric Project general views.

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. 12-159 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).

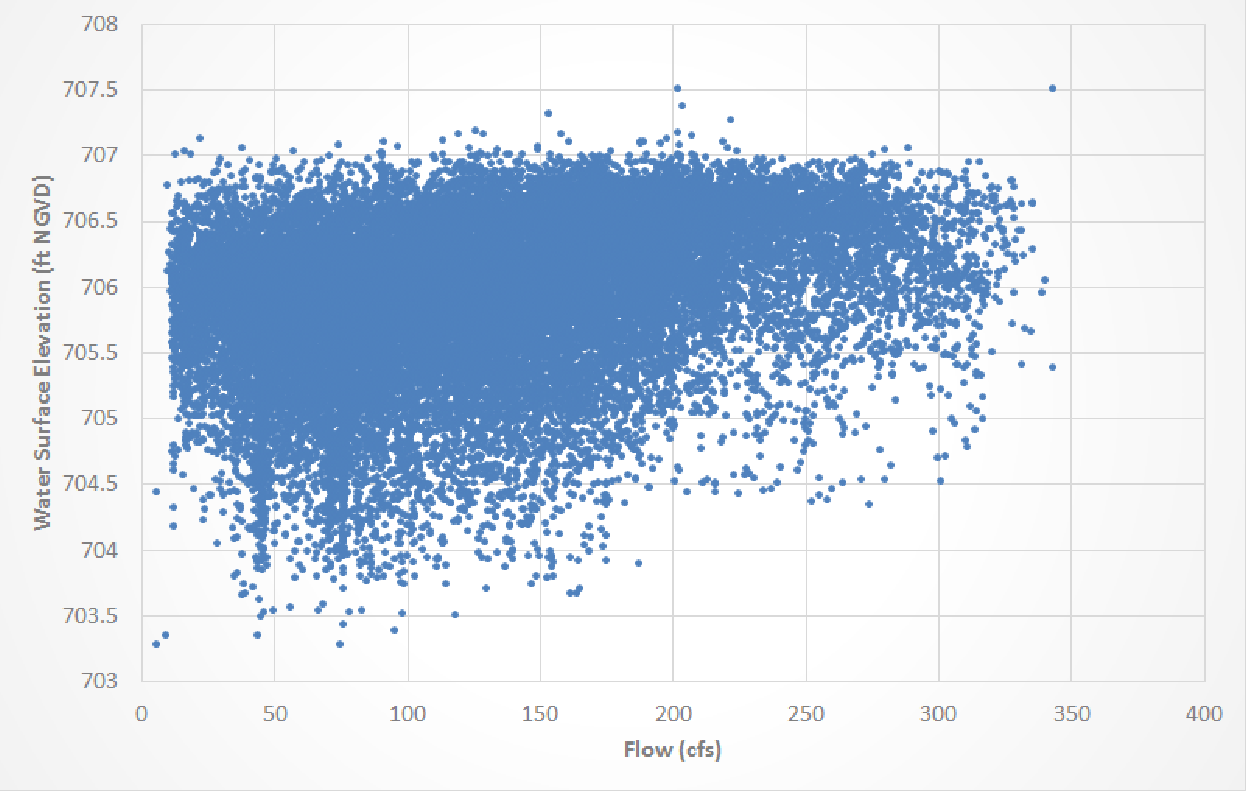


Figure 4. Forebay Water Surface Elevations and Flows at Rocky Reach Dam

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.

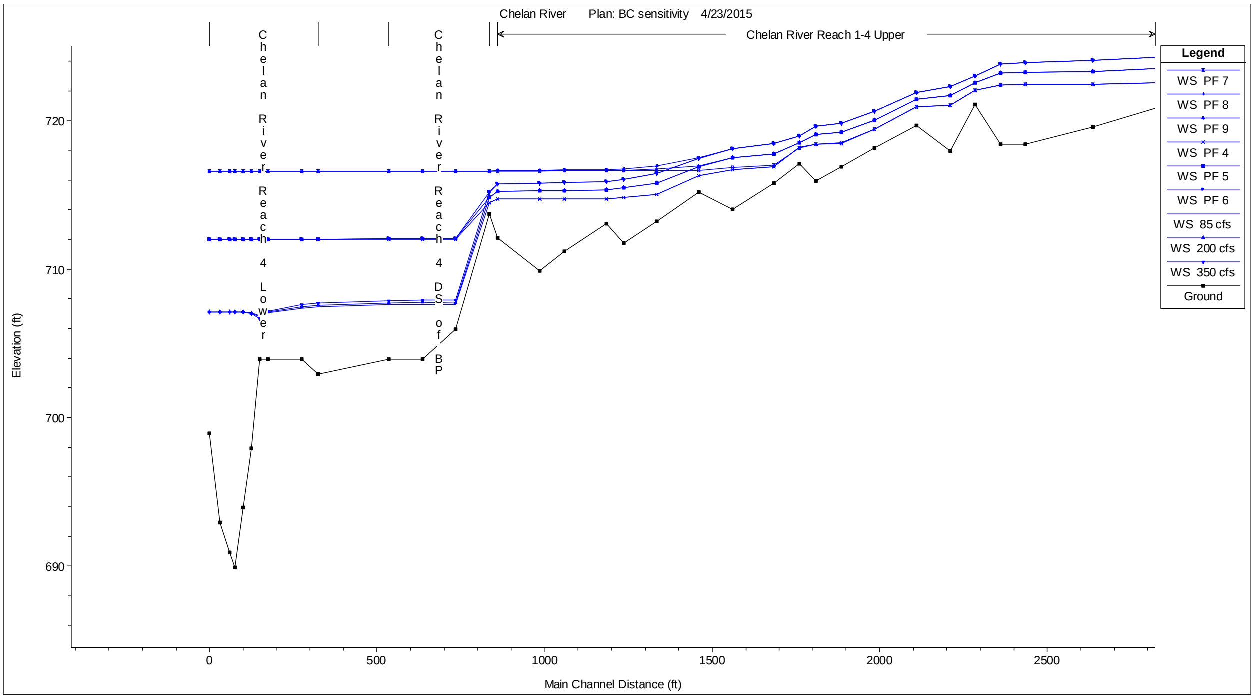


Figure 5. Sensitivity of Columbia River Stage

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	

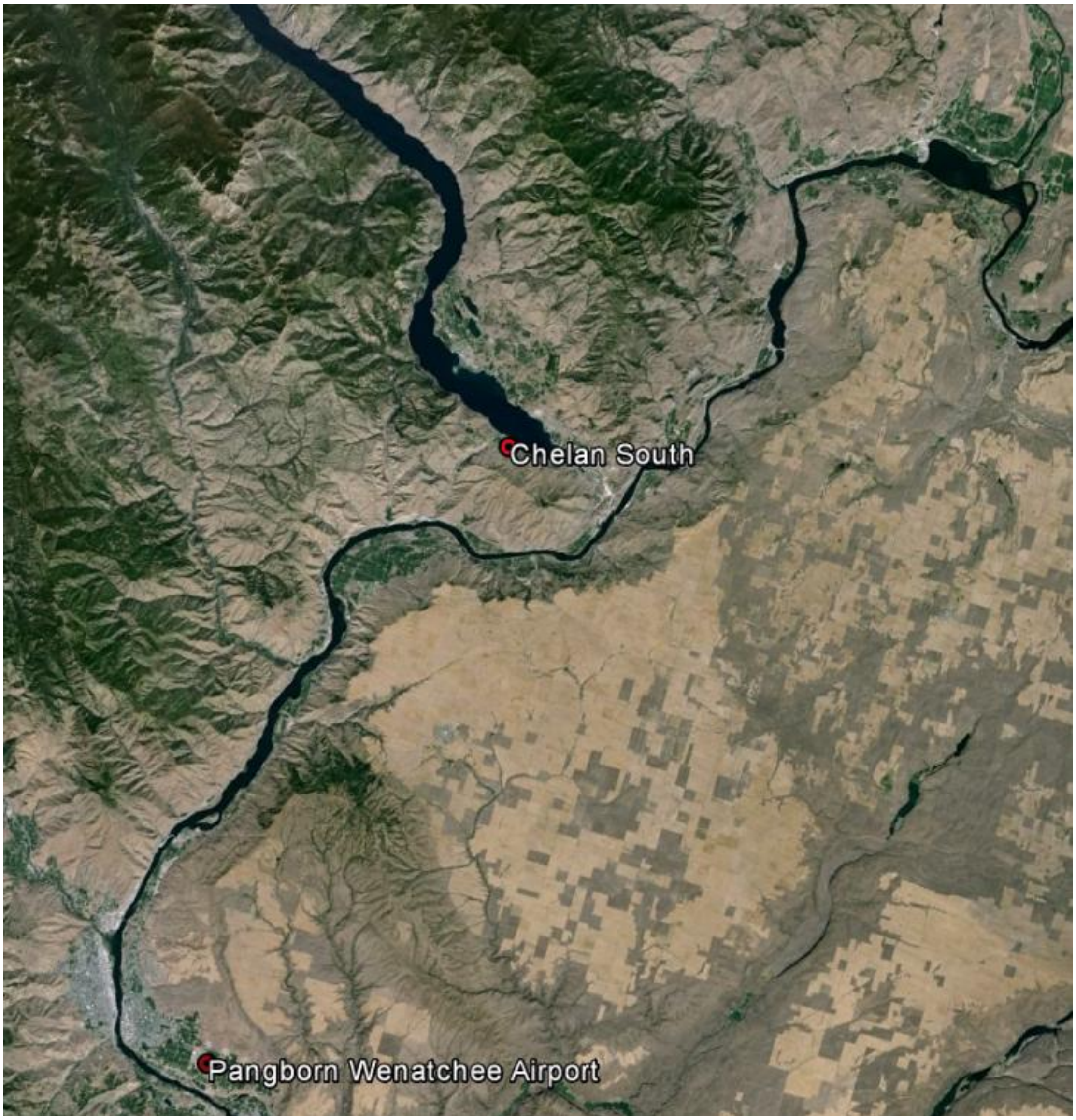


Figure 6. Meteorological Stations near Chelan

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.

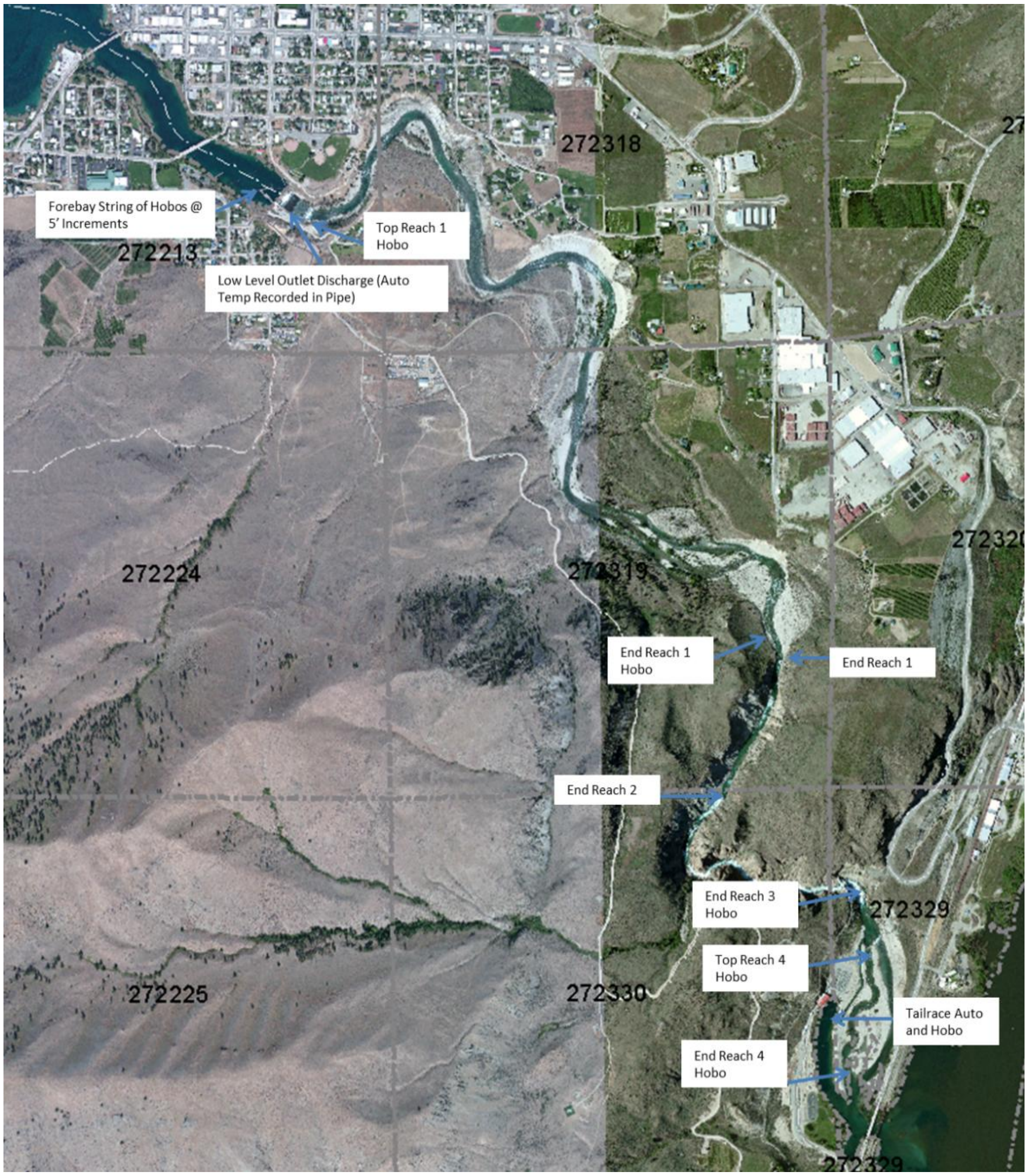


Figure 7. Chelan River in-stream temperature monitoring stations

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 assumed to be almost negligible under existing conditions. 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.

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.

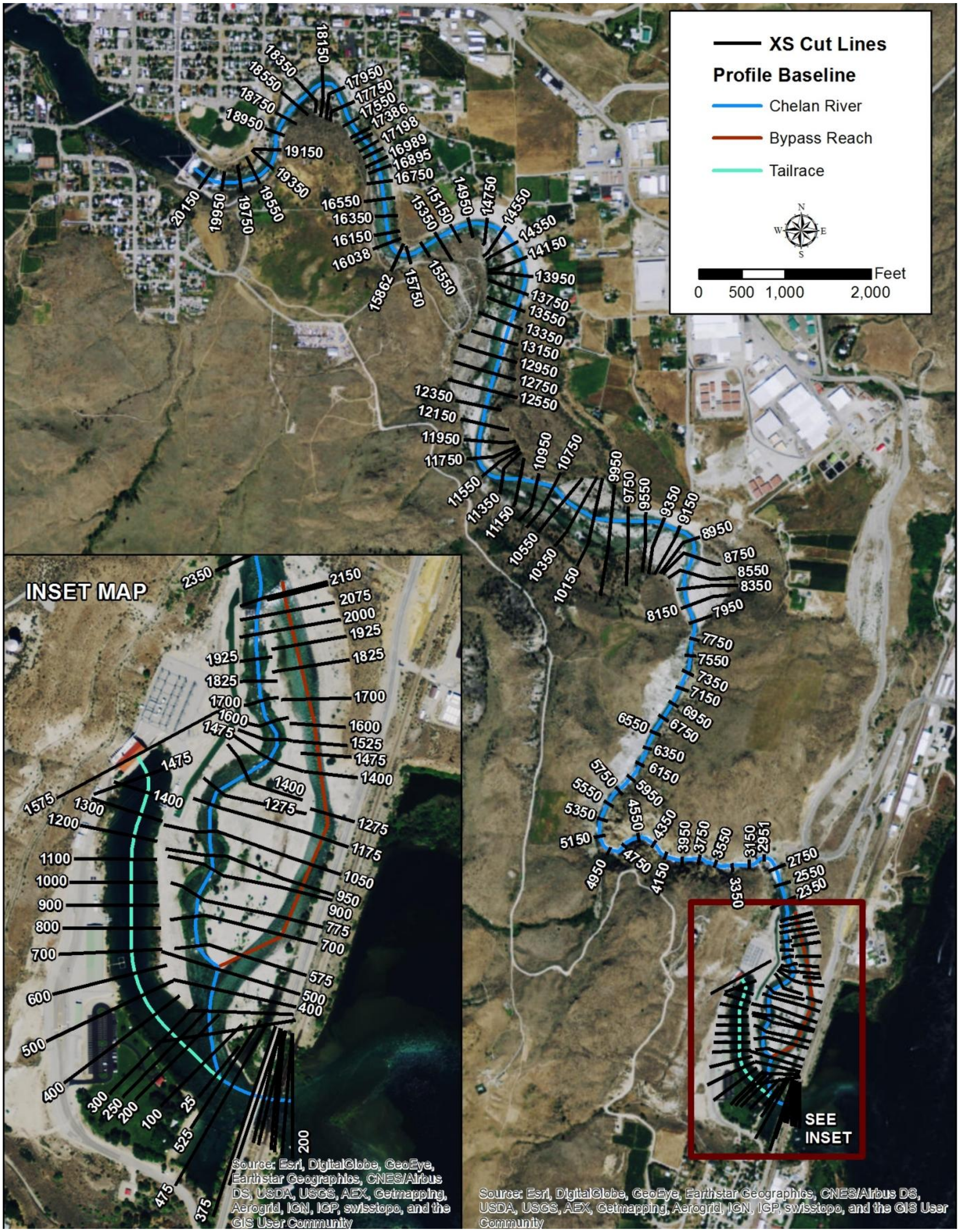


Figure 8. Layout of Chelan River Hydraulic Model

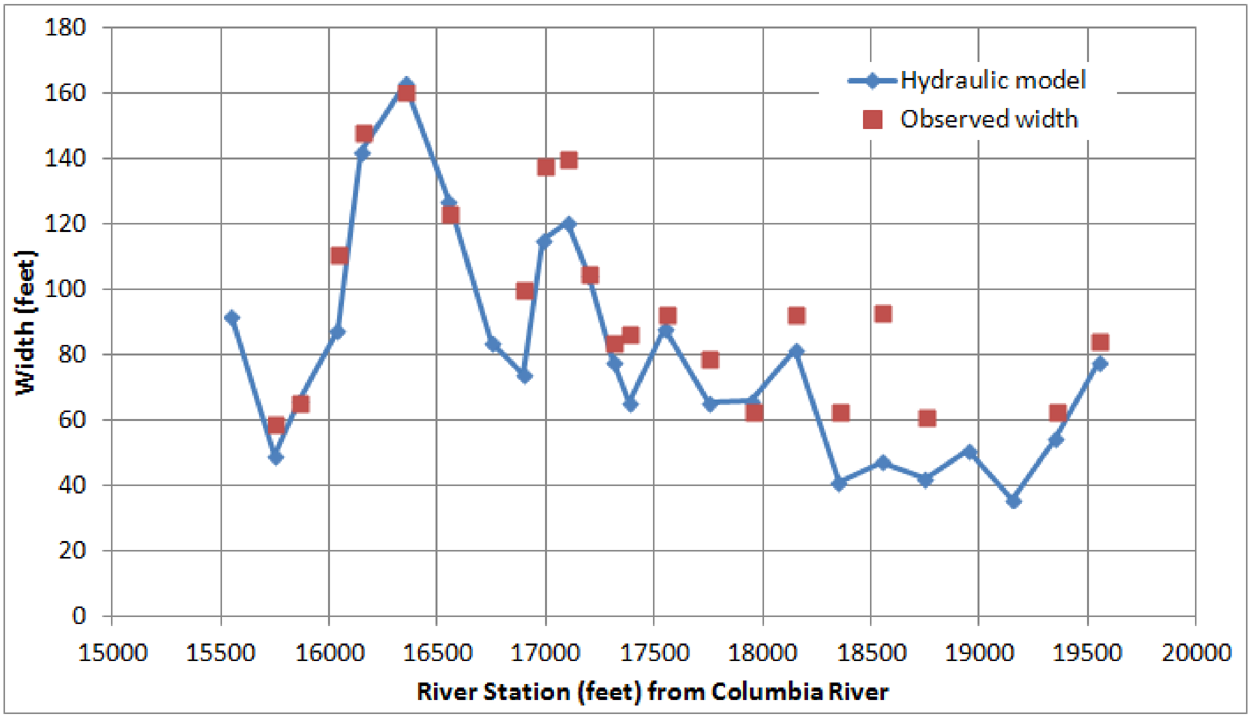


Figure 9. Comparison of Observed and modeled top widths for 85 cfs

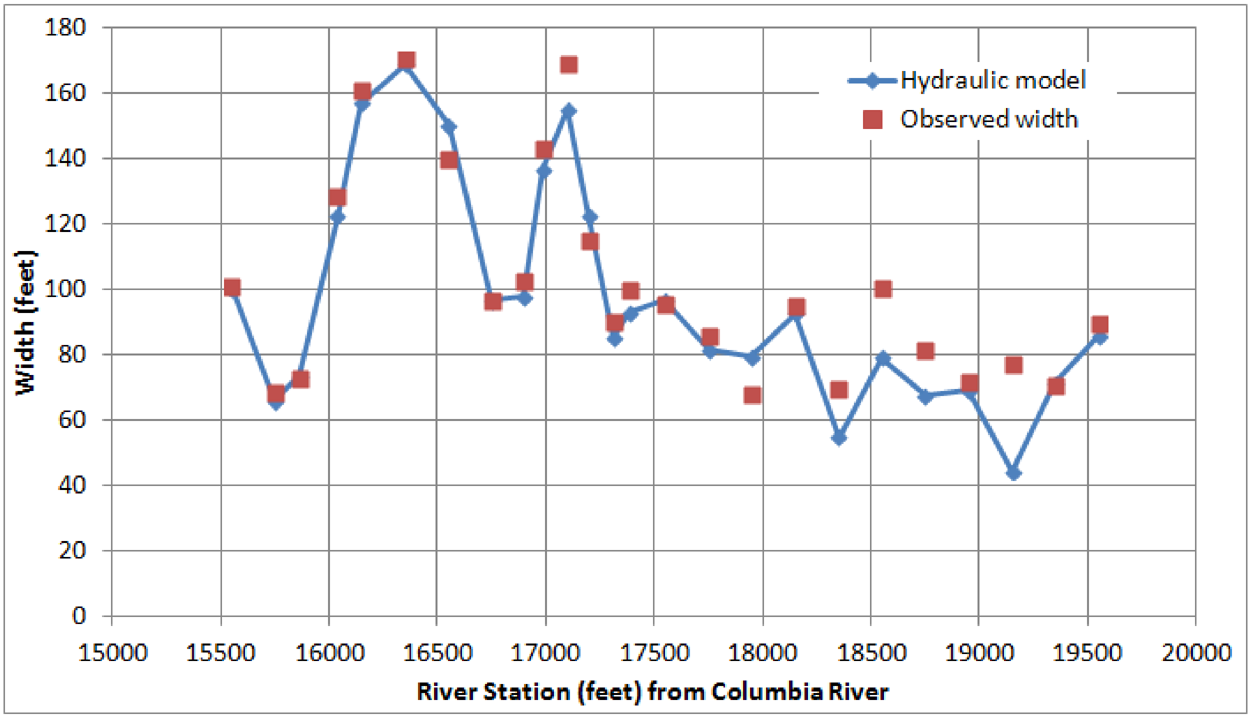


Figure 10. Comparison of Observed and modeled top widths for 200 cfs

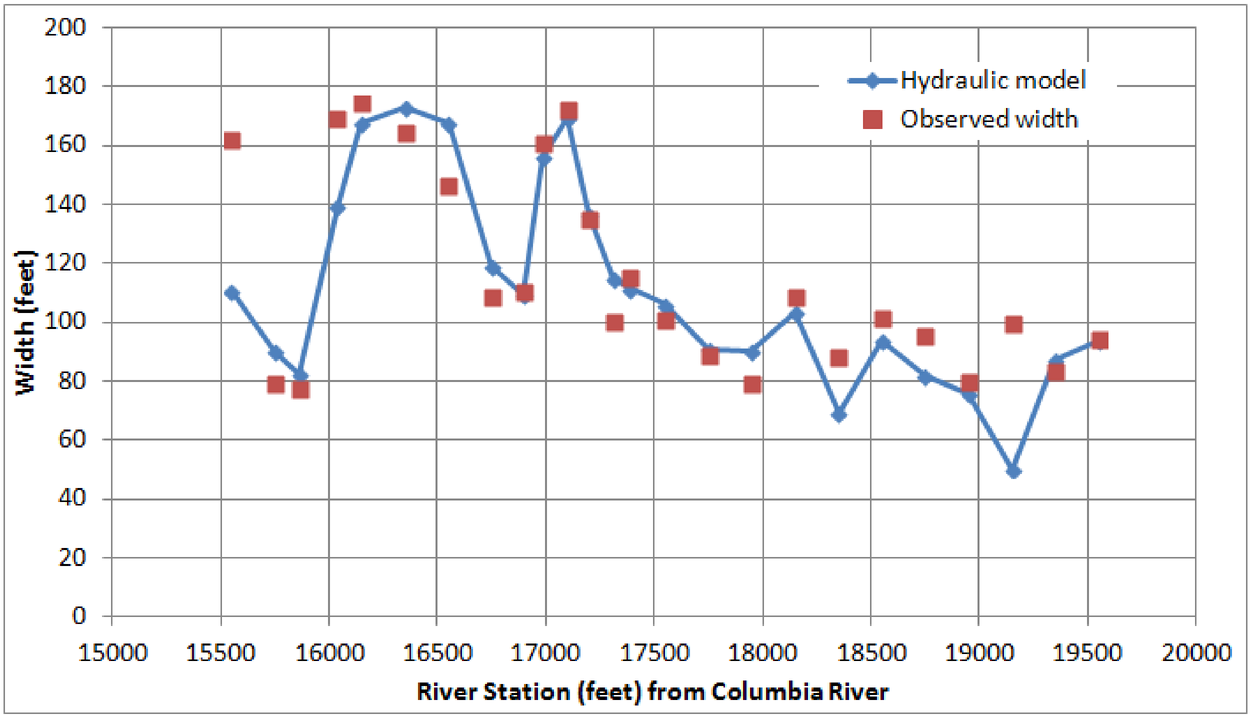


Figure 11. Comparison of Observed and modeled top widths for 350 cfs

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

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:

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

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.

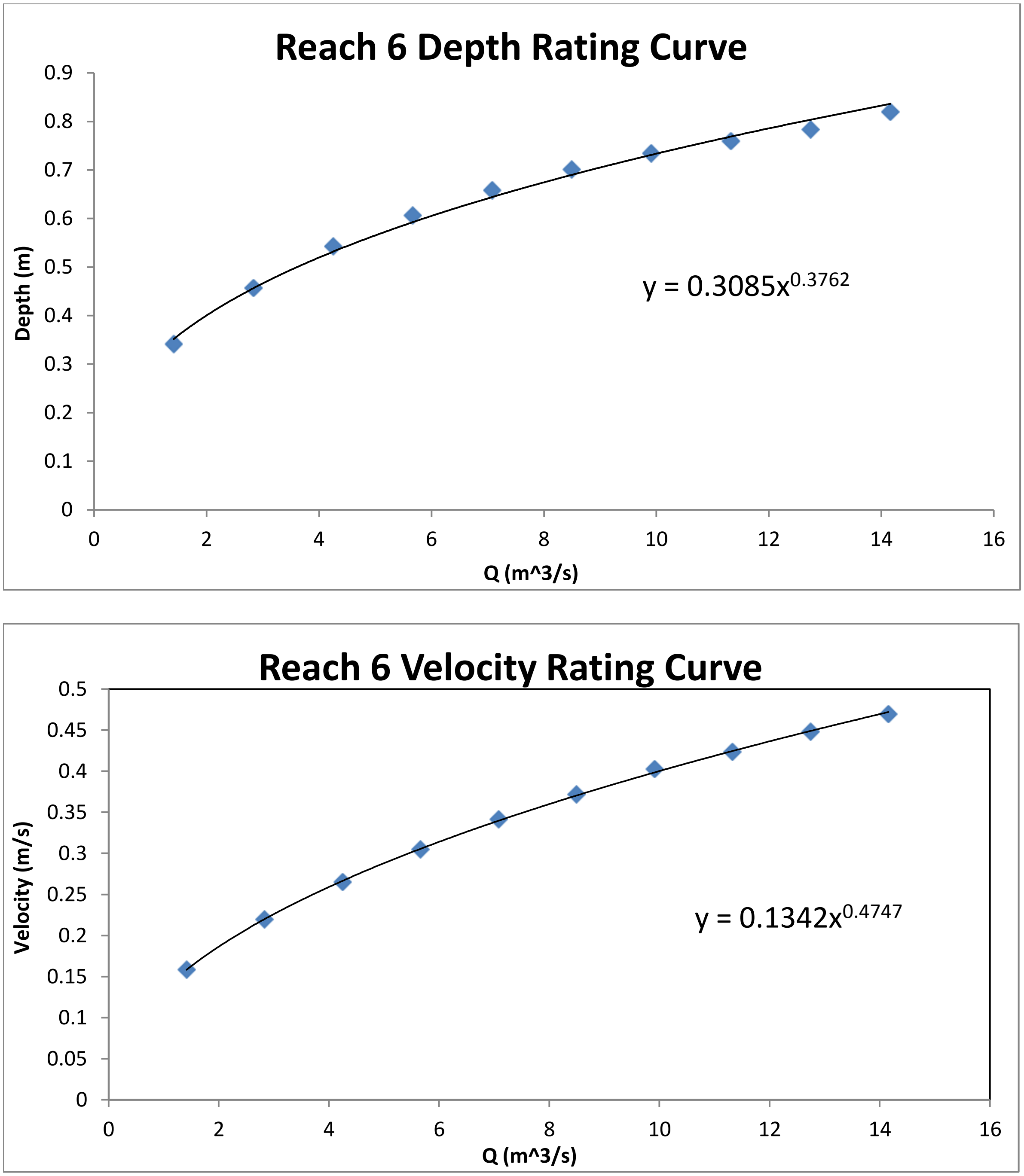


Figure 13. Example rating curve power functions for QUAL2Kw Reach 6

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.

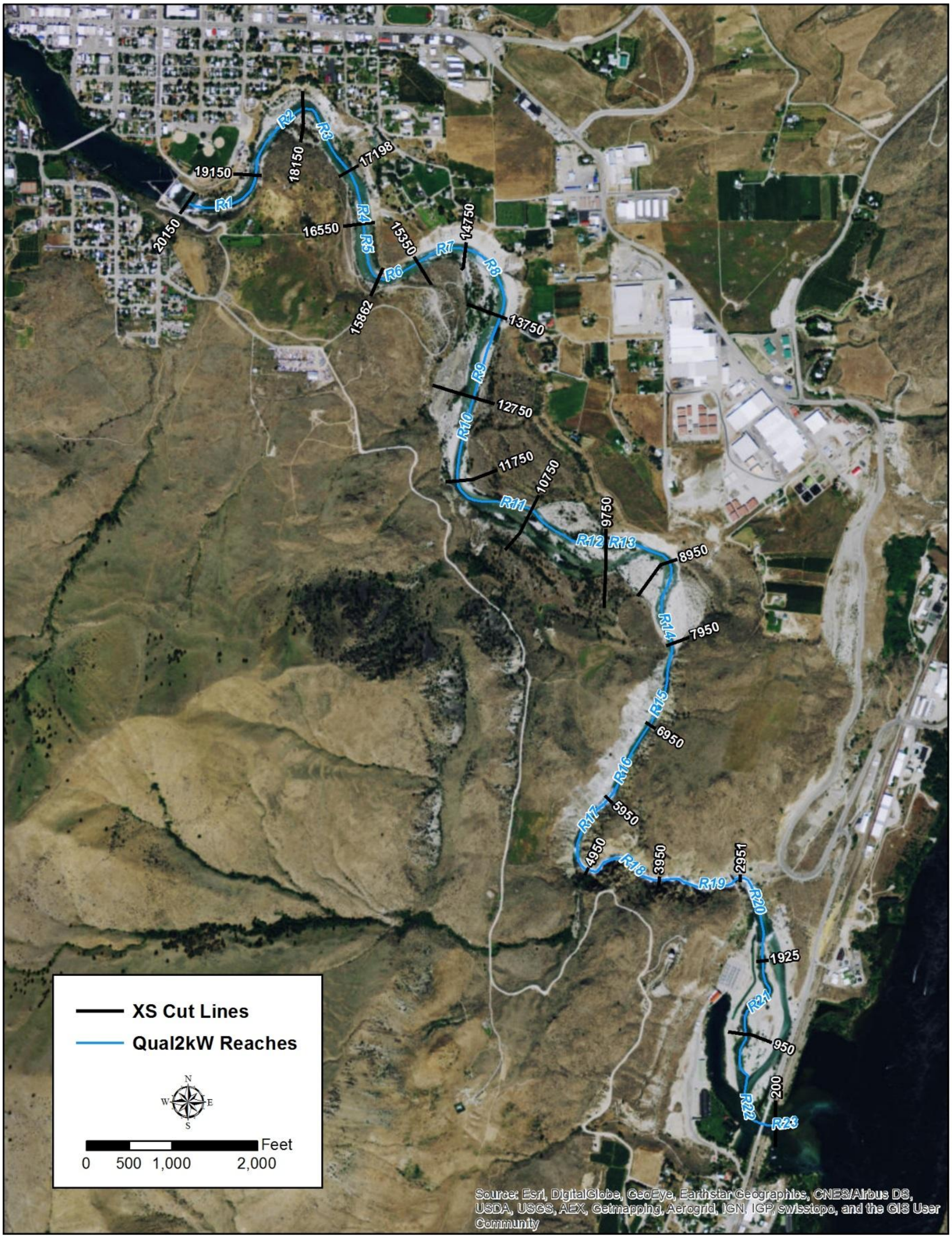
We modeled the tailrace reach as a local inflow to the main stem Chelan River temperature model, and did not perform temperature calculations on this reach. The tailrace pump flows were also modeled as inflows to the main stem Chelan River. We divided the main stem of the Chelan River into 23 QUAL2Kw 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 6). 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 6 and Figure 15 through Figure 19. These periods cover a relatively wide range of air temperatures and solar radiation. The March 2015 calibration period was chosen specifically to analyze the capability of the temperature model to simulate an unusually warm spring condition. The September 2013 Event was chosen as the calibration event, while the May 2013 event was used for the sensitivity analysis. We chose the March 2015 calibration period specifically to analyze the capability of the temperature model to simulate an abnormally warm spring condition. The September 2013 event was chosen as the calibration event, while sensitivity analysis was performed on the May 2013 event.

Table 6. 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



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 14. QUAL2Kw temperature model segmentation

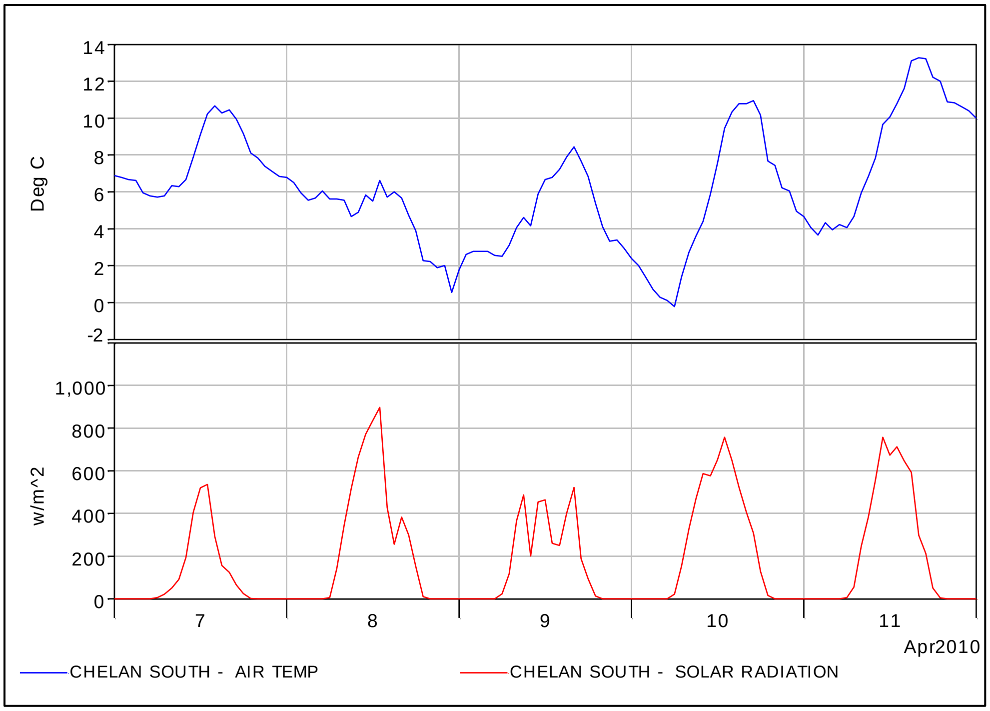


Figure 15. Meteorological variation during the April 2010 event

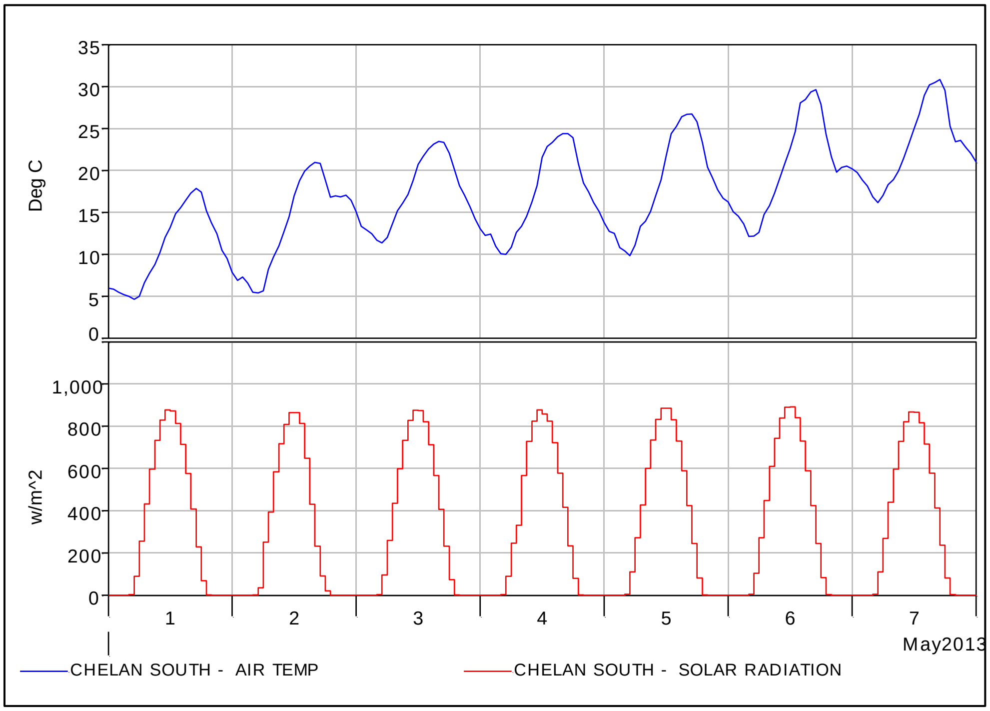


Figure 16. Meteorological variation during the May 2013 event

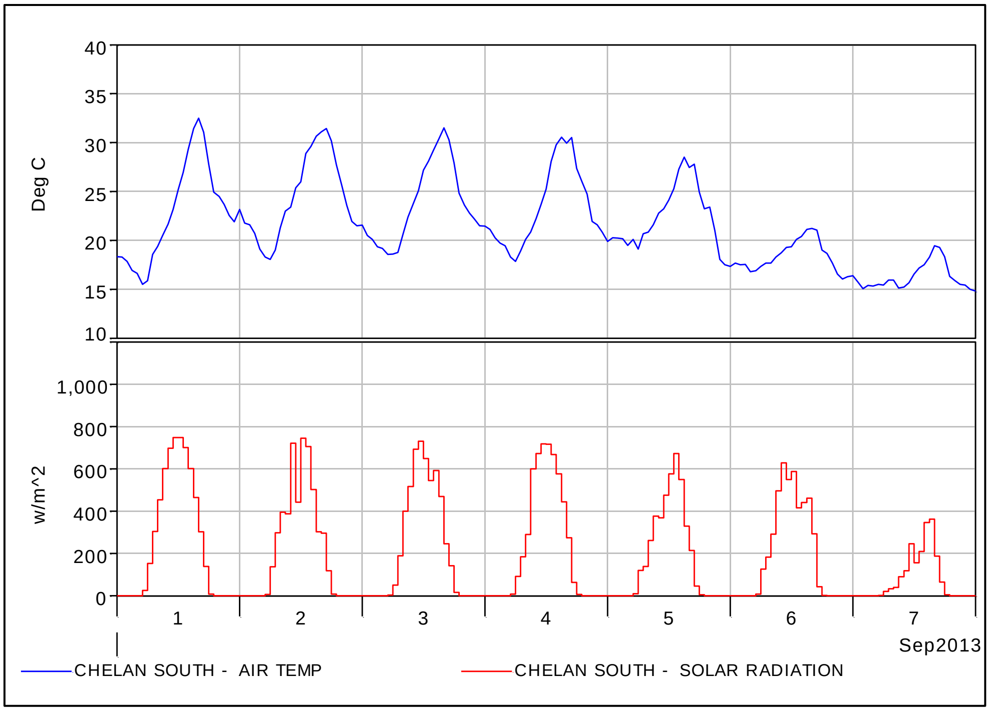


Figure 17. Meteorological variation during the September 2013 event

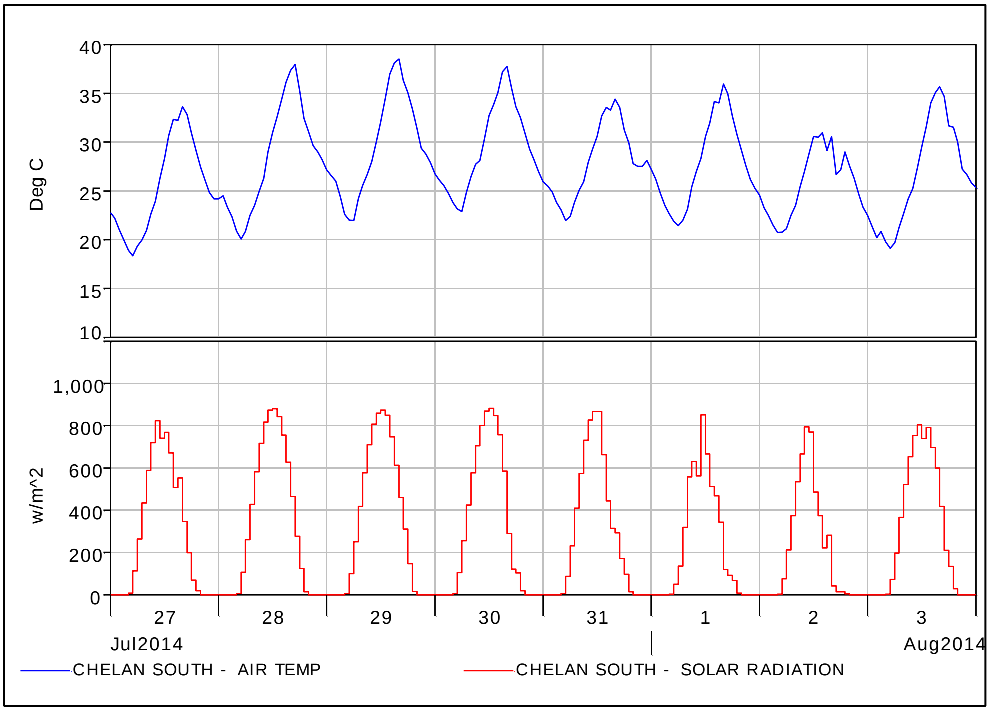


Figure 18. Meteorological variation during the August 2014 event

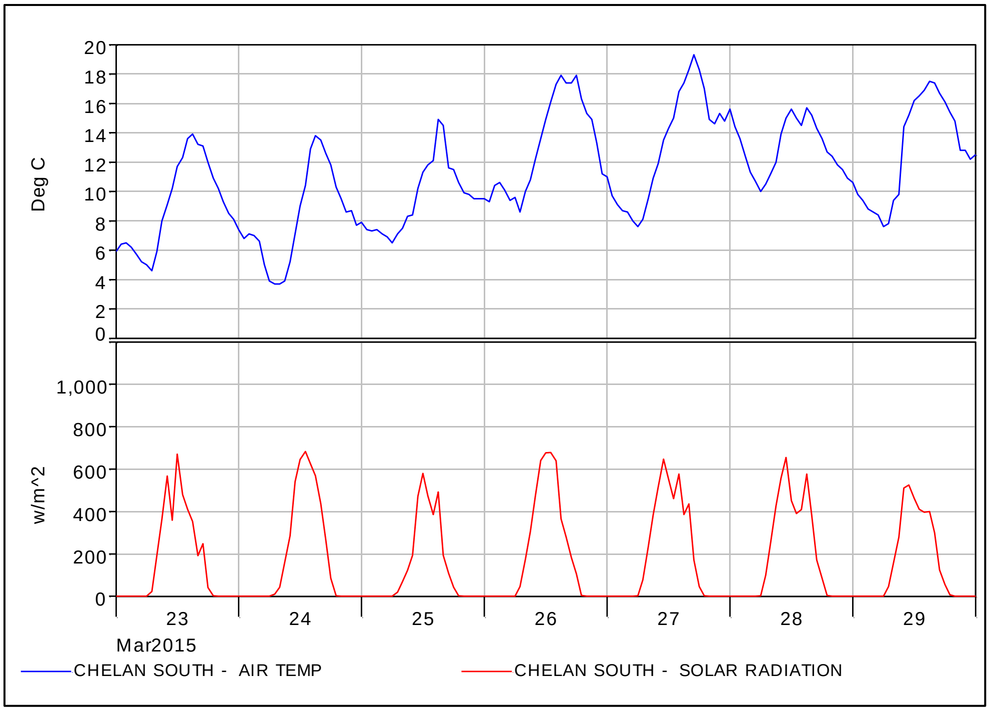


Figure 19. Meteorological variation during the March 2015 event

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 July 2014. 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).

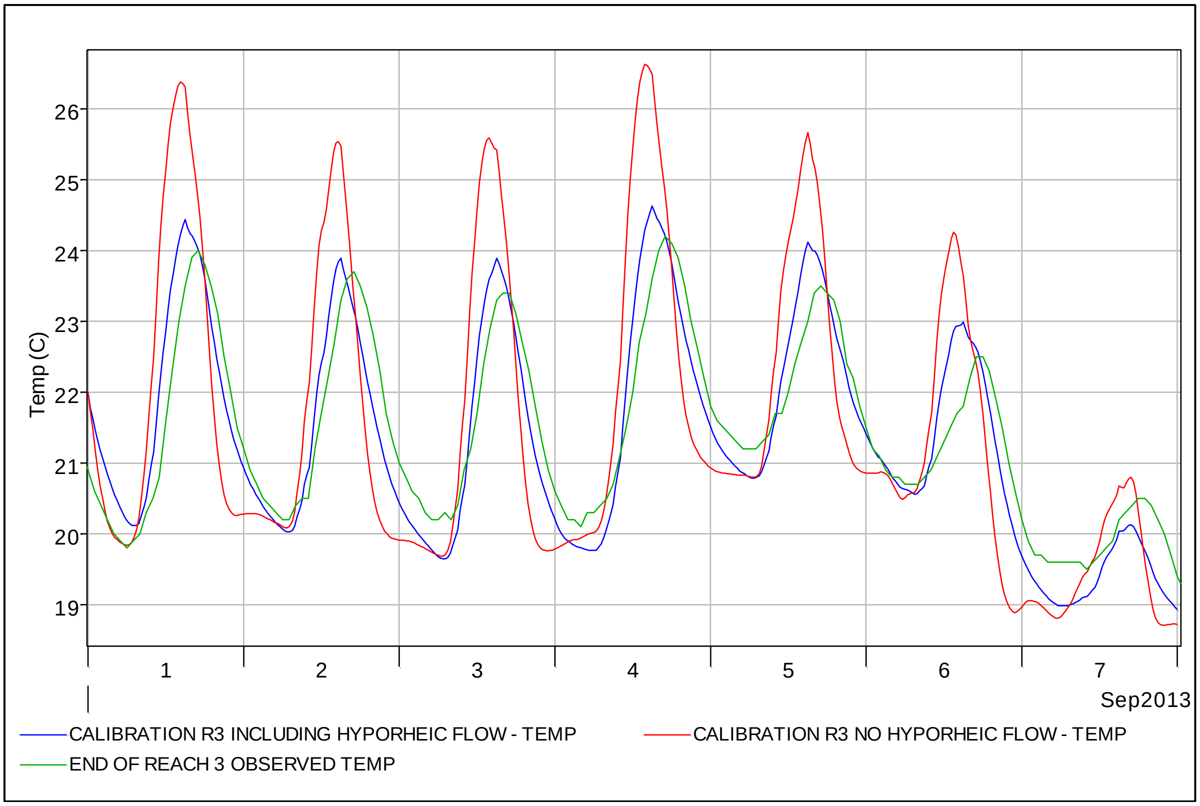


Figure 20. The moderating effects of hyporheic flow on the temperature model

4.3.2 Parameter Sensitivity

We performed a linear parameter sensitivity analysis after initial calibration of the temperature model (Figure 21 through Figure 28). 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 7 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.

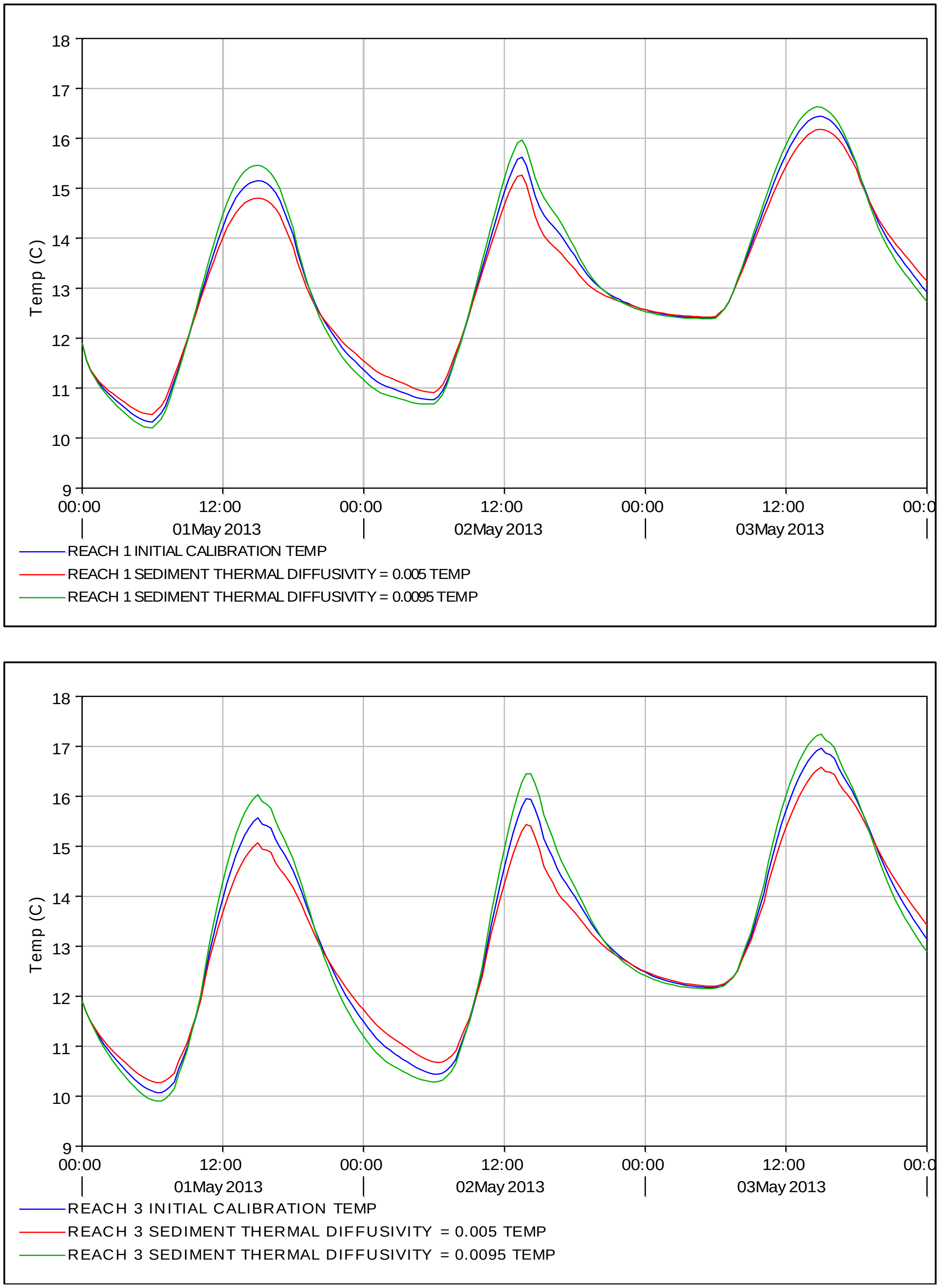
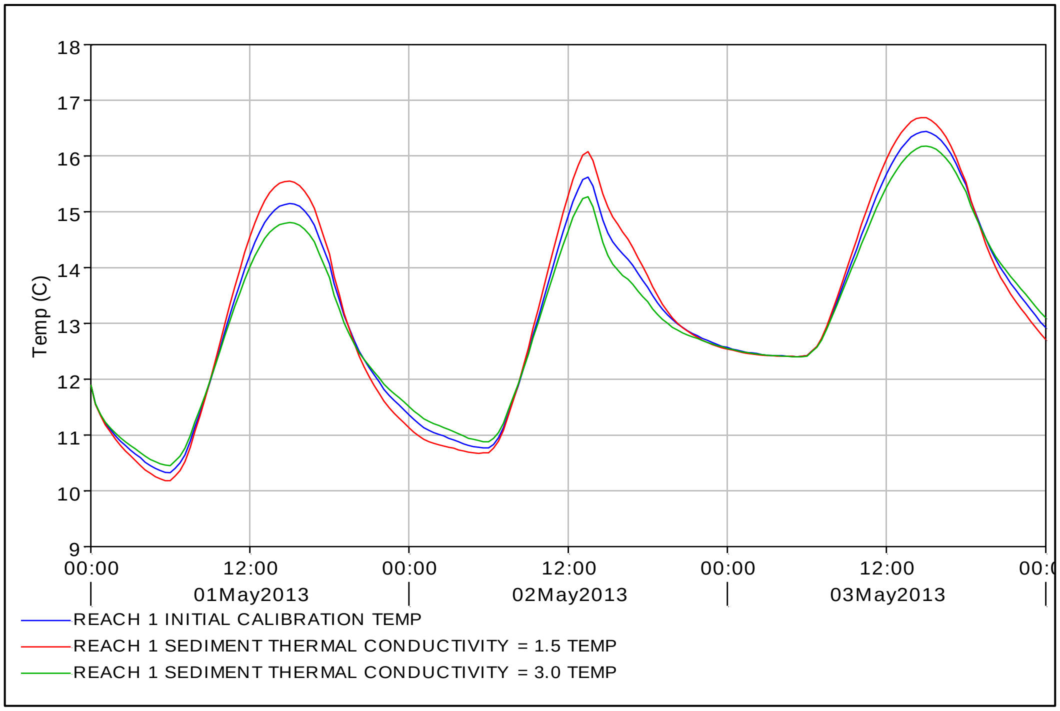


Figure 21. Sediment thermal diffusivity sensitivity analysis (0.005 - 0.0095 cm^2/sec)



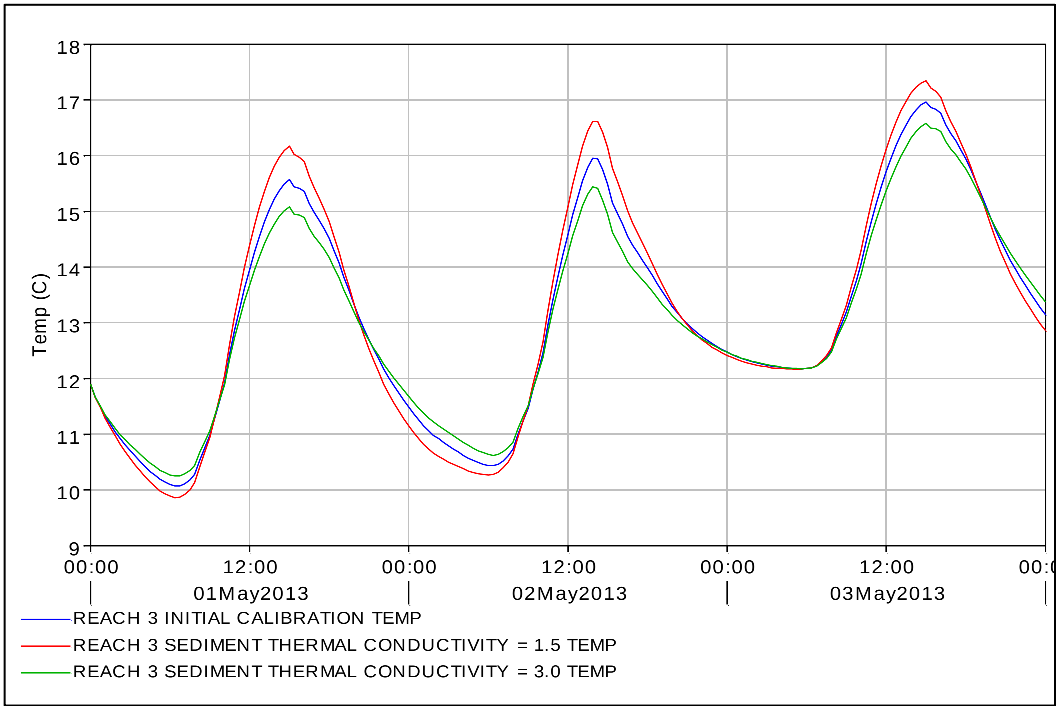


Figure 22. Sediment thermal conductivity sensitivity analysis (1.5 – 3.0 W/m/°C)

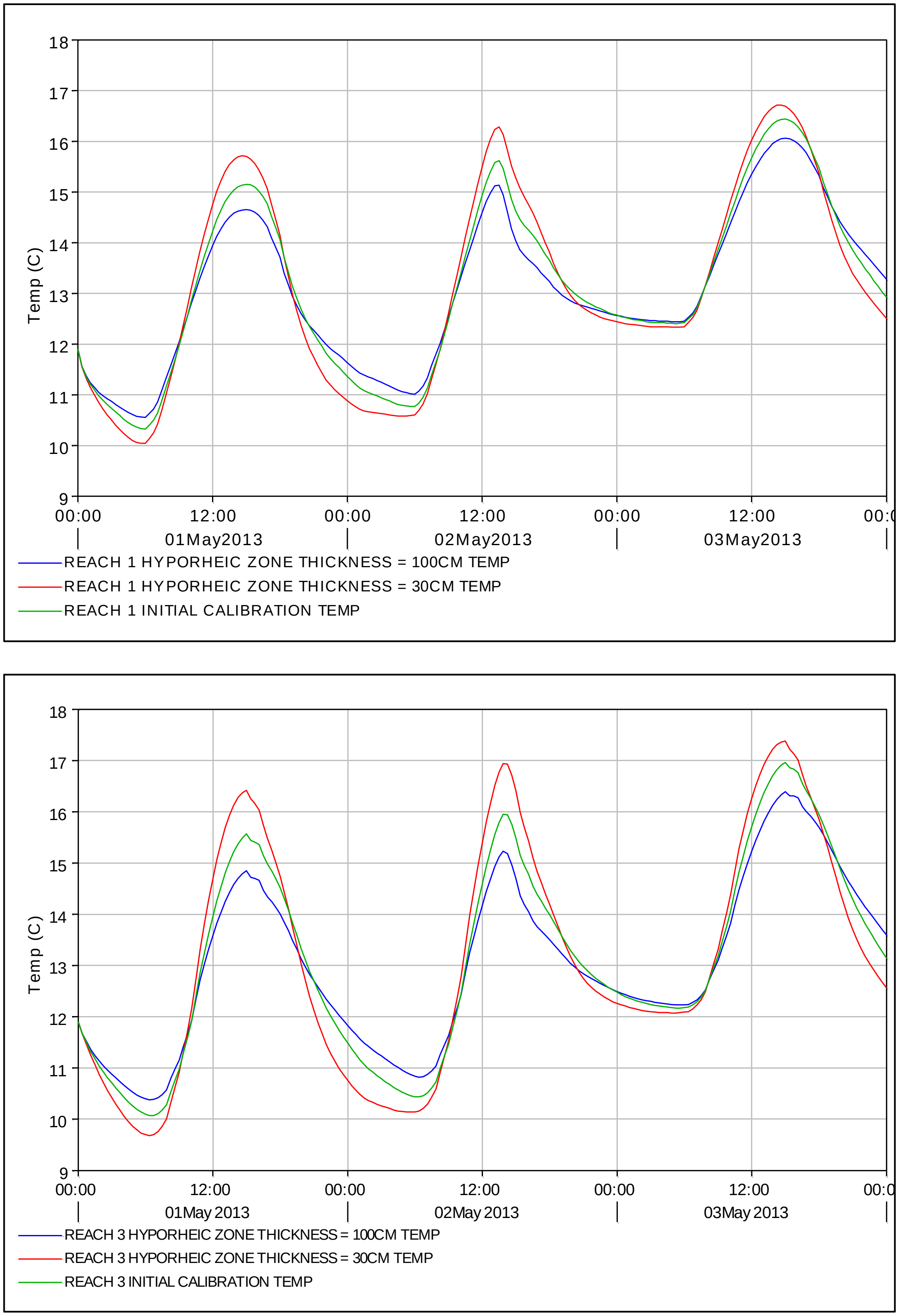


Figure 23. Hyporheic zone thickness sensitivity analysis (30 – 100 cm)

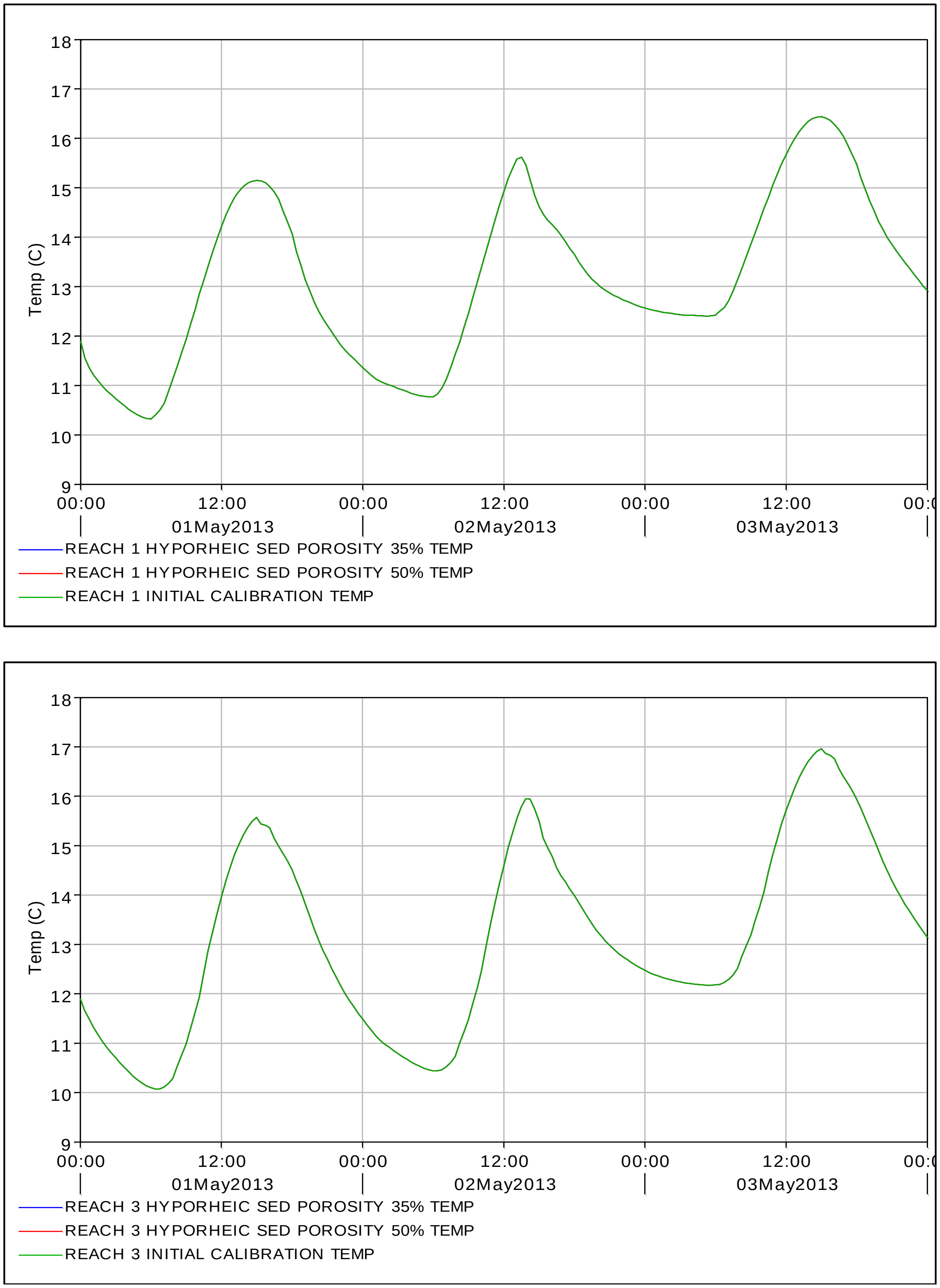


Figure 24. Hyporheic sediment porosity sensitivity analysis (35 – 50%)

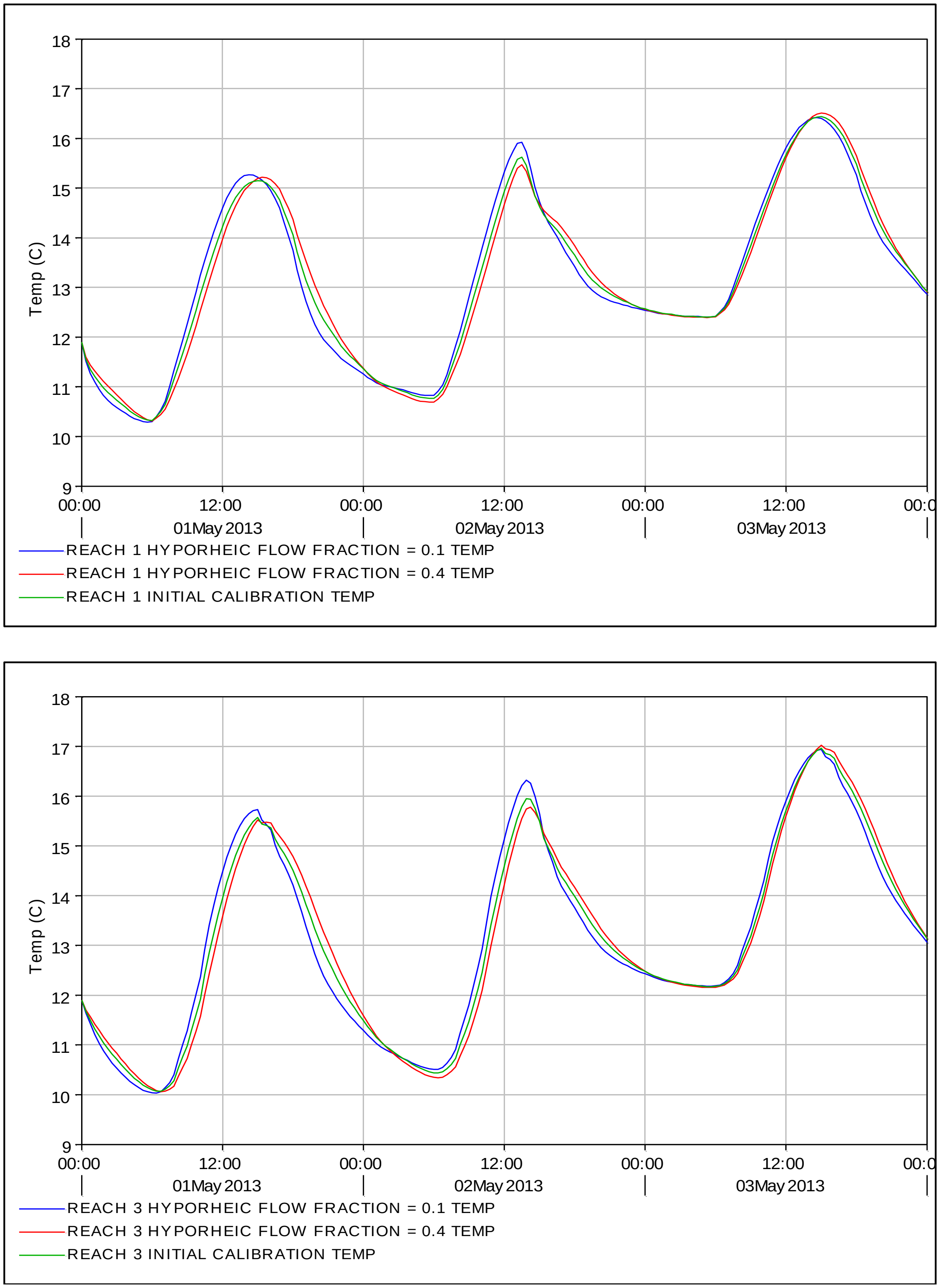


Figure 25. Hyporheic flow fraction sensitivity analysis (0.1 -0.4)

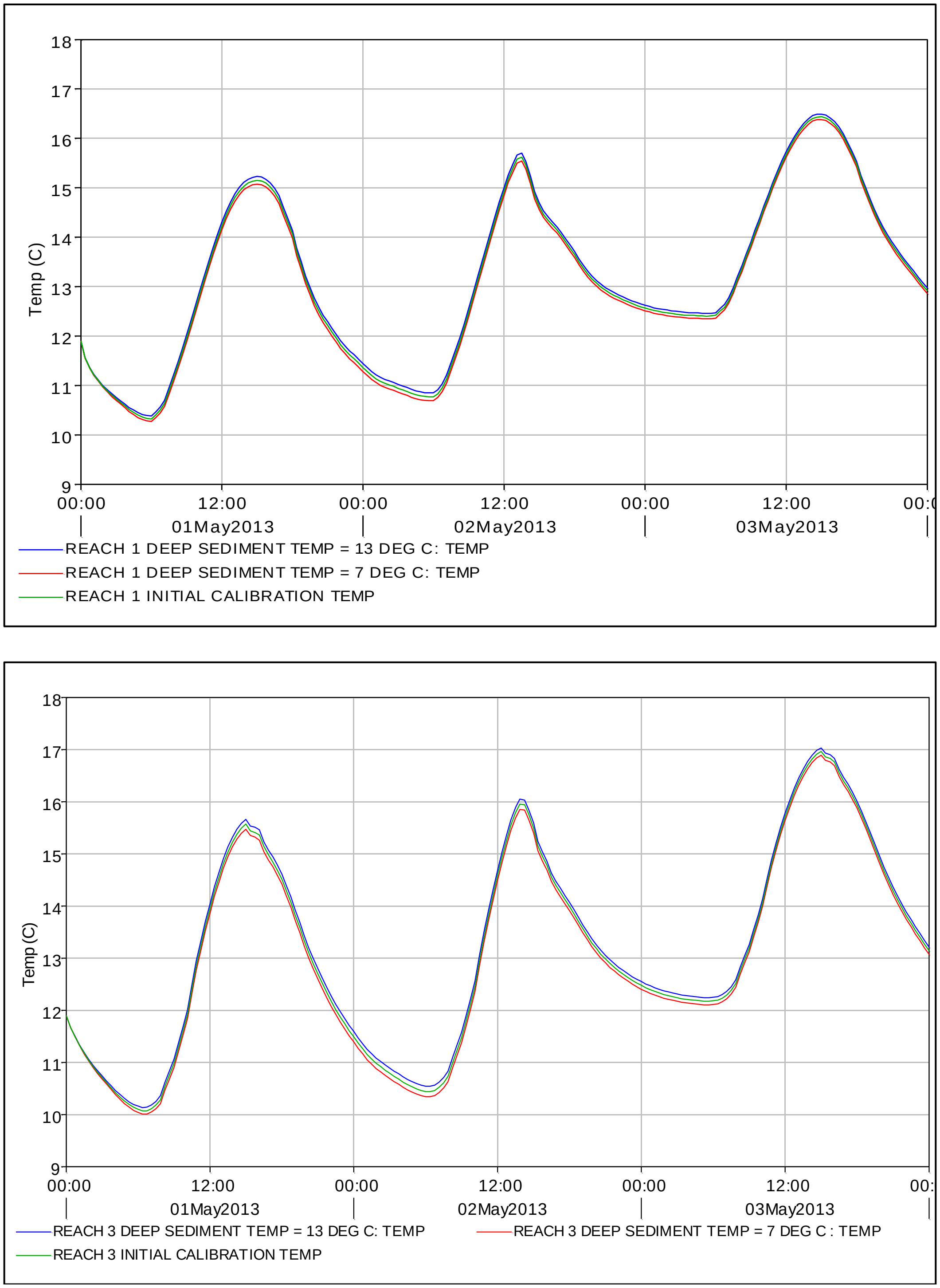
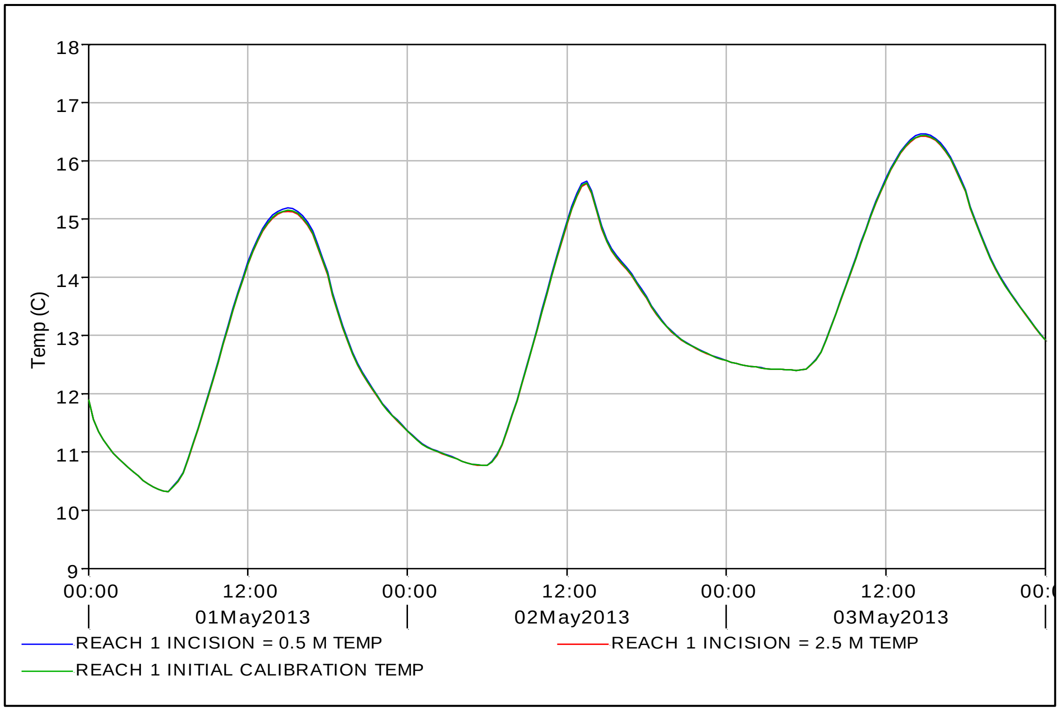


Figure 26. Deep sediment temperature sensitivity analysis (7 – 13 °C)



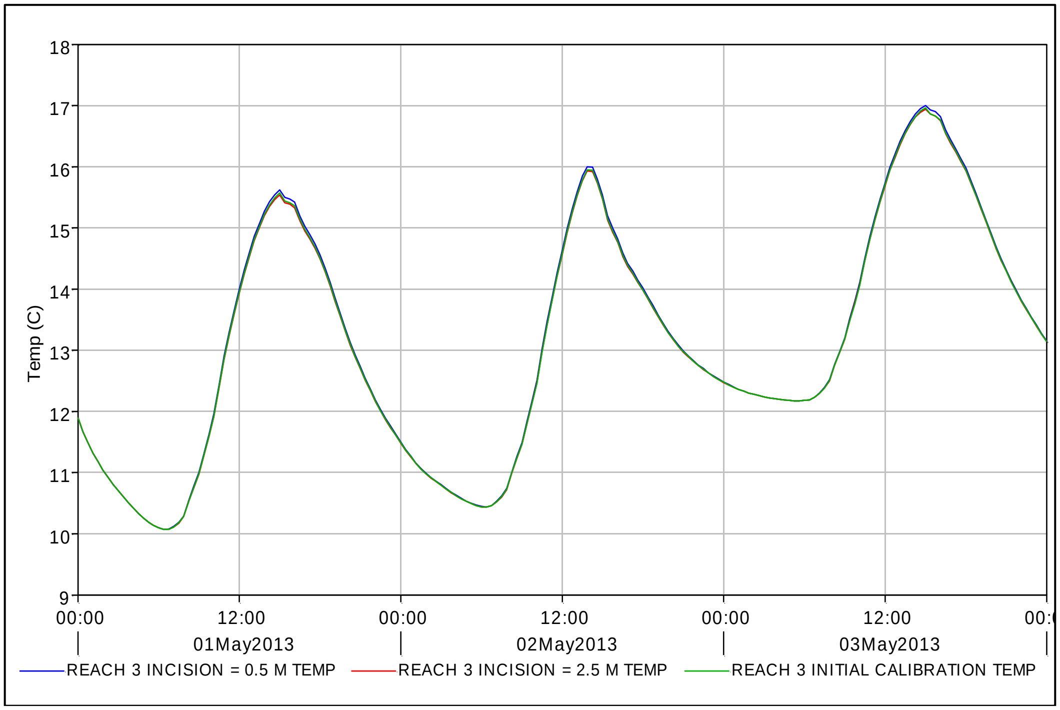
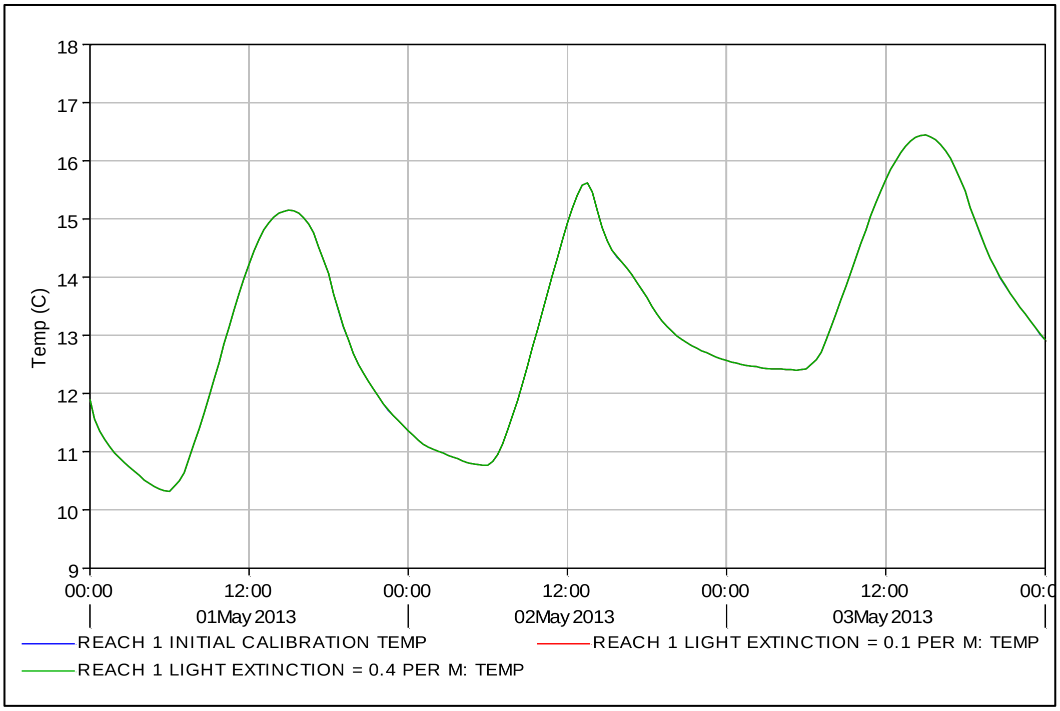


Figure 27. Incision sensitivity analysis (0.5 – 2.5 m)



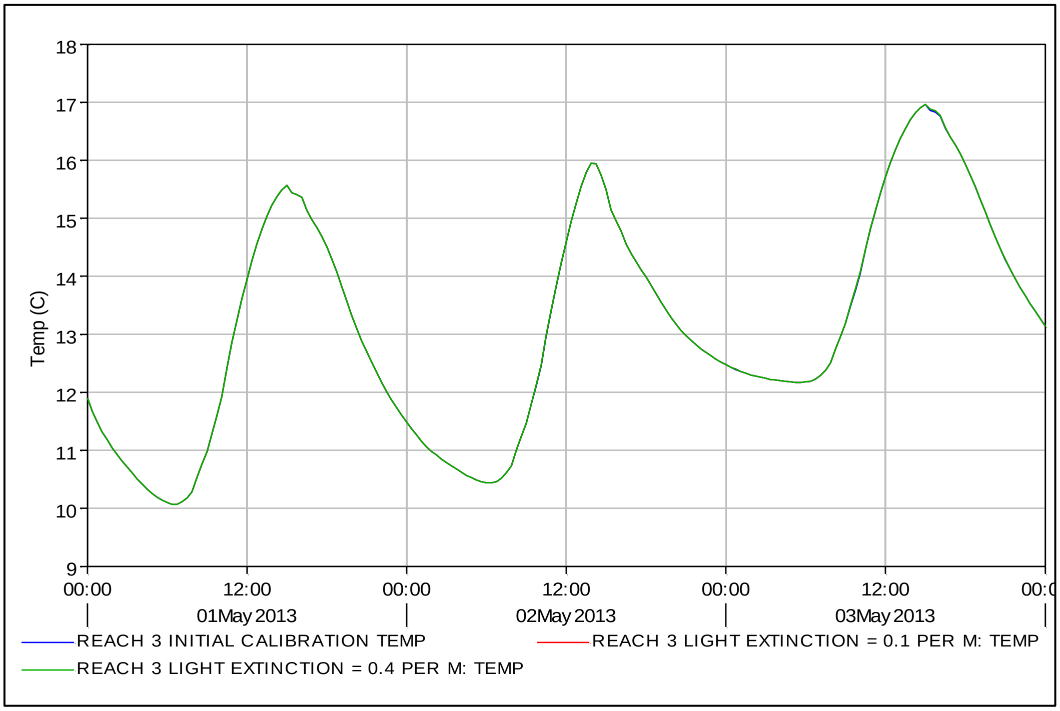


Figure 28. Light Extinction Sensitivity Analysis (0.1 – 0.4 / m)

Table 7. Sensitivity analysis statistics, with error as deviation from initial calibration results

	Reach 1			Reach 3		
Parameter (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)	-0.047	0.141	0.172	-0.056	0.191	0.233
Sediment Thermal Diffusivity (0.0095 cm^2/sec)	0.031	0.115	0.141	0.038	0.161	0.197
Sediment Thermal Conductivity (1.5 W/m/°C)	0.063	0.145	0.182	0.077	0.200	0.253
Sediment Thermal Conductivity (3.0 W/m/°C)	-0.070	0.136	0.168	-0.085	0.182	0.227
Hyporheic Zone Thickness (30cm)	-0.012	0.237	0.274	-0.020	0.336	0.391
Hyporheic Zone Thickness (100cm)	-0.050	0.213	0.255	-0.057	0.287	0.345
Hyporheic Sediment Porosity (35%)	0.000	0.000	0.000	0.000	0.000	0.000
Hyporheic Sediment Porosity (50%)	0.000	0.000	0.000	0.000	0.000	0.000
Hyporheic Flow Fraction (0.1)	0.010	0.113	0.145	0.011	0.138	0.180
Hyporheic Flow Fraction (0.4)	-0.008	0.080	0.105	-0.009	0.098	0.126
Deep Sediment Temperature (7 °C)	-0.059	0.059	0.059	-0.073	0.073	0.074
Deep Sediment Temperature (13 °C)	0.058	0.058	0.058	0.073	0.073	0.074
Shade.xls Incision (0.5 m)	0.013	0.013	0.017	0.021	0.021	0.027
Shade.xls Incision (2.5 m)	-0.006	0.006	0.009	-0.008	0.008	0.011
Background Light Extinction (0.1/m)	0.000	0.000	0.002	0.001	0.001	0.005
Background Light Extinction (0.4/m)	0.002	0.002	0.002	0.001	0.001	0.005

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 8 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 29, and calibration error statistics can be seen in Table 9.

Table 8. 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

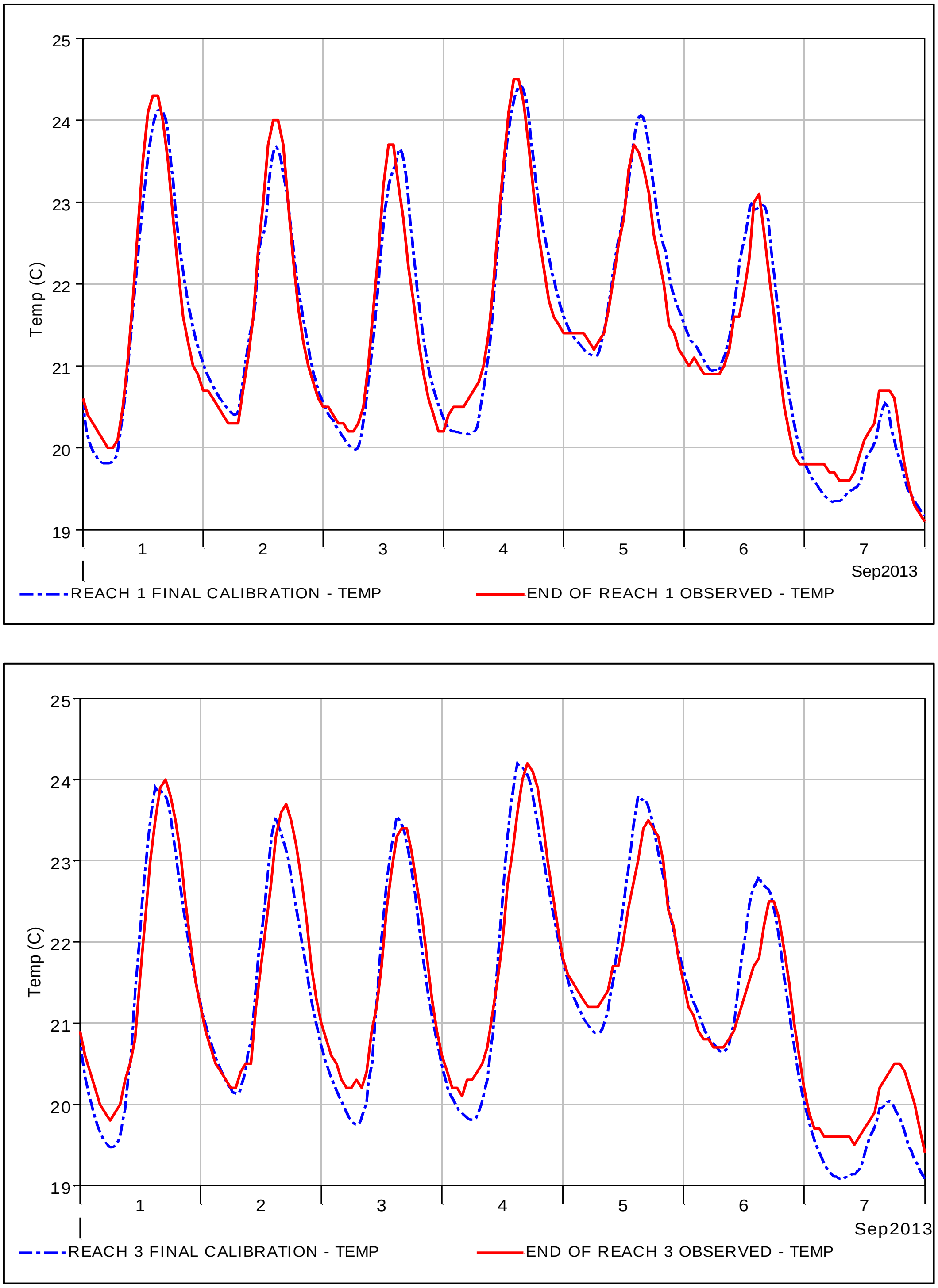


Figure 29. Calibrated temperature model results

Table 9. 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 30 through Figure 41 below. Error statistics are shown in Table 10. Observed data were not available in Reach 1 during the July 2014 event, but was available for all three locations for the other events.

Table 10. 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

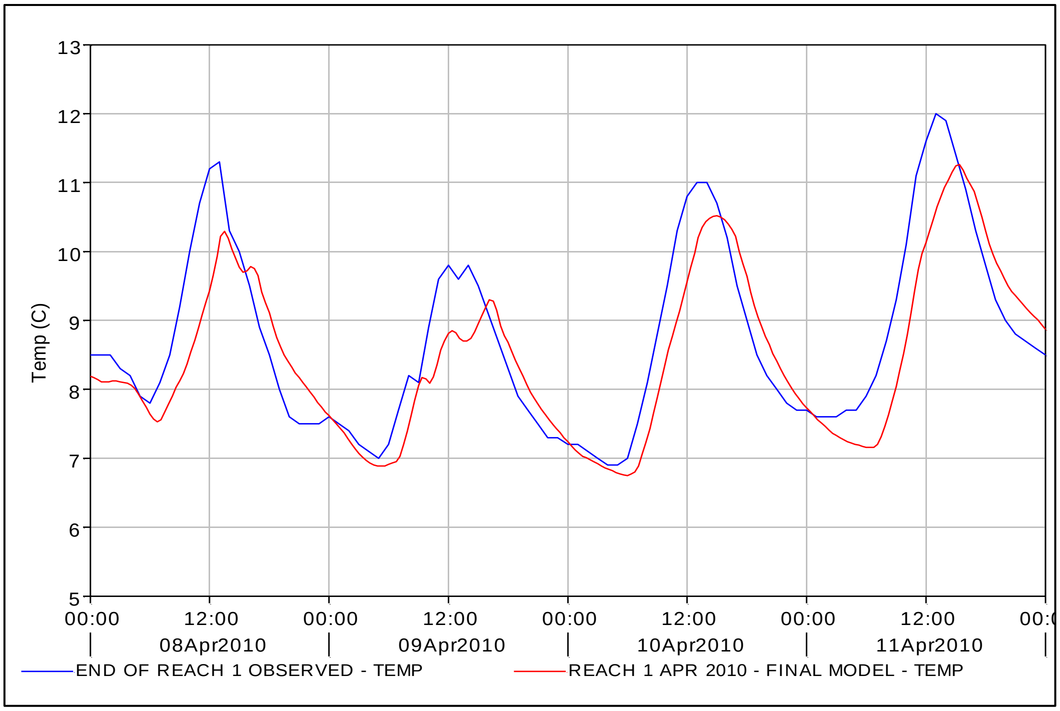


Figure 30. April 2010 end of Reach-1 validation results

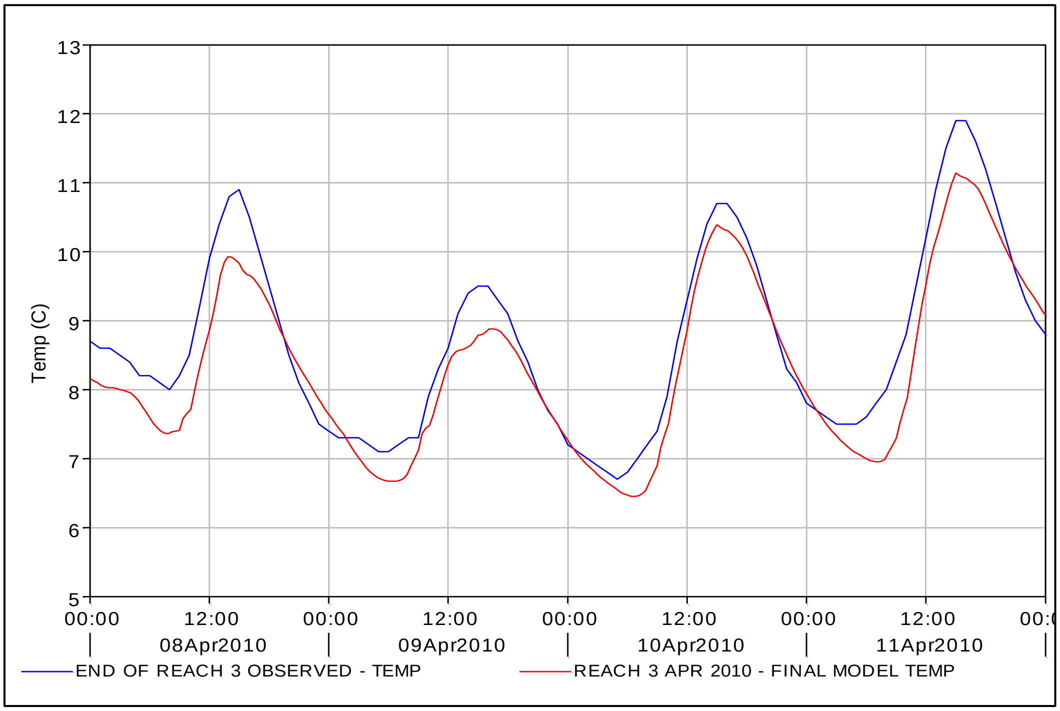


Figure 31. April 2010 end of reach-3 validation results

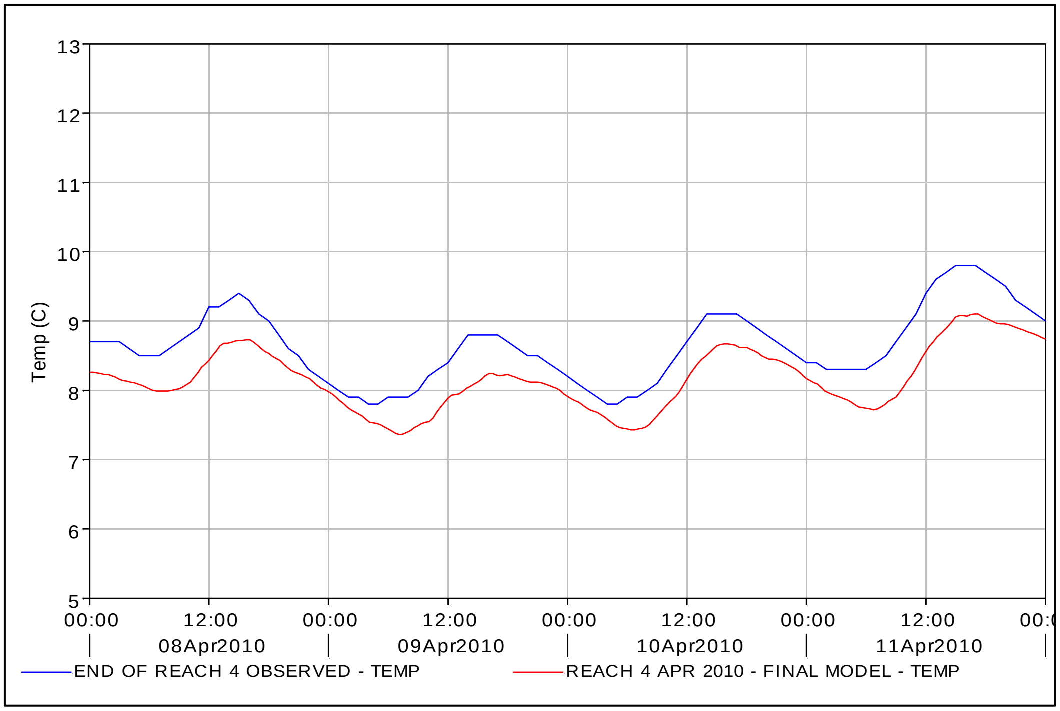


Figure 32. April 2010 end of Reach-4 validation results

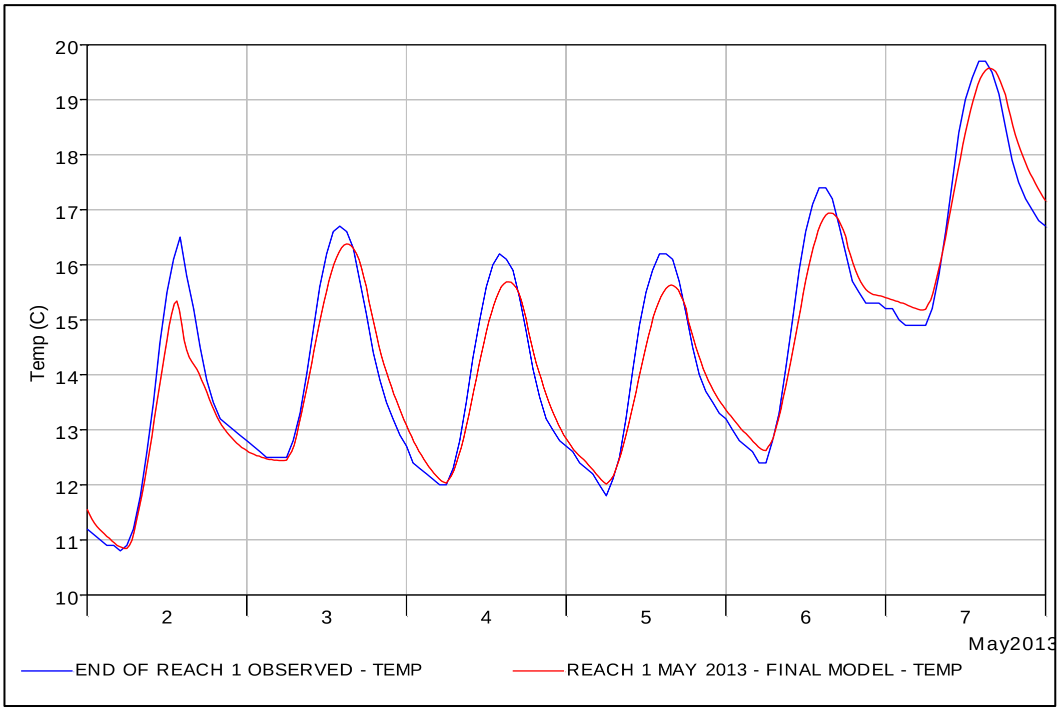


Figure 33. May 2013 end of Reach-1 validation results

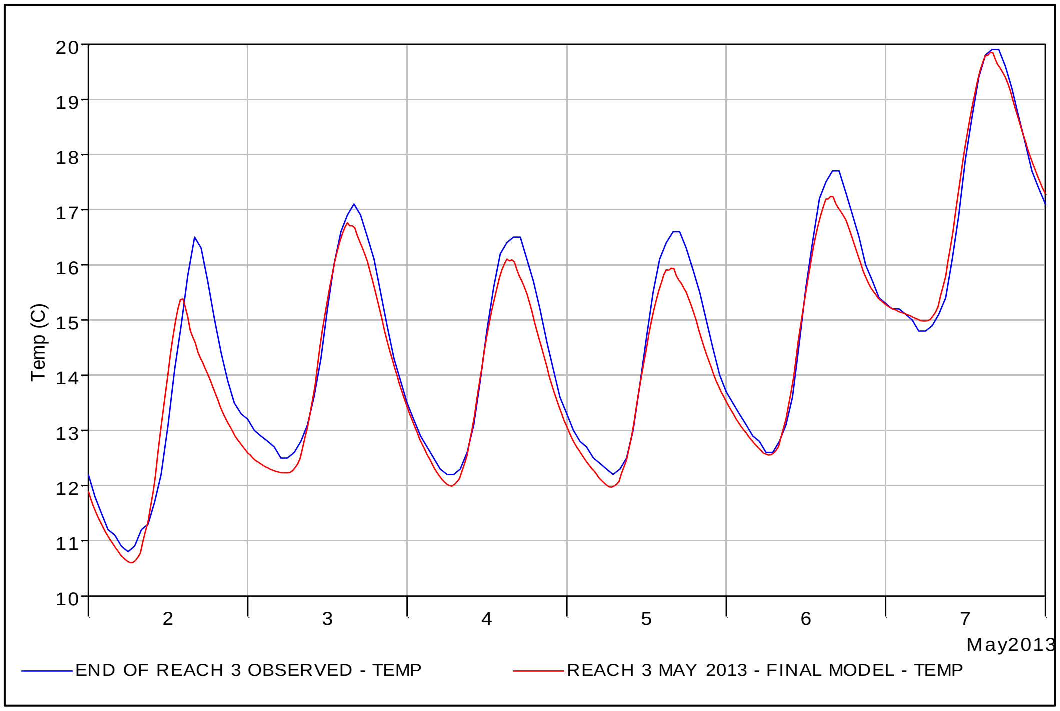


Figure 34. May 2013 end of Reach-3 validation results

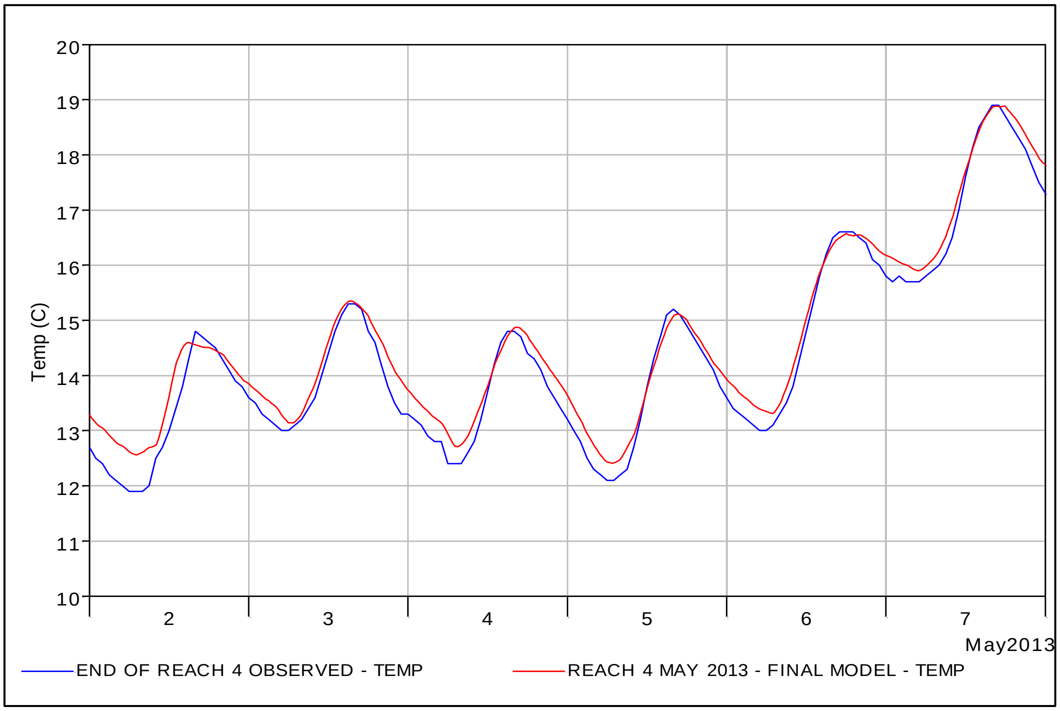


Figure 35. May 2013 end of Reach-4 validation results

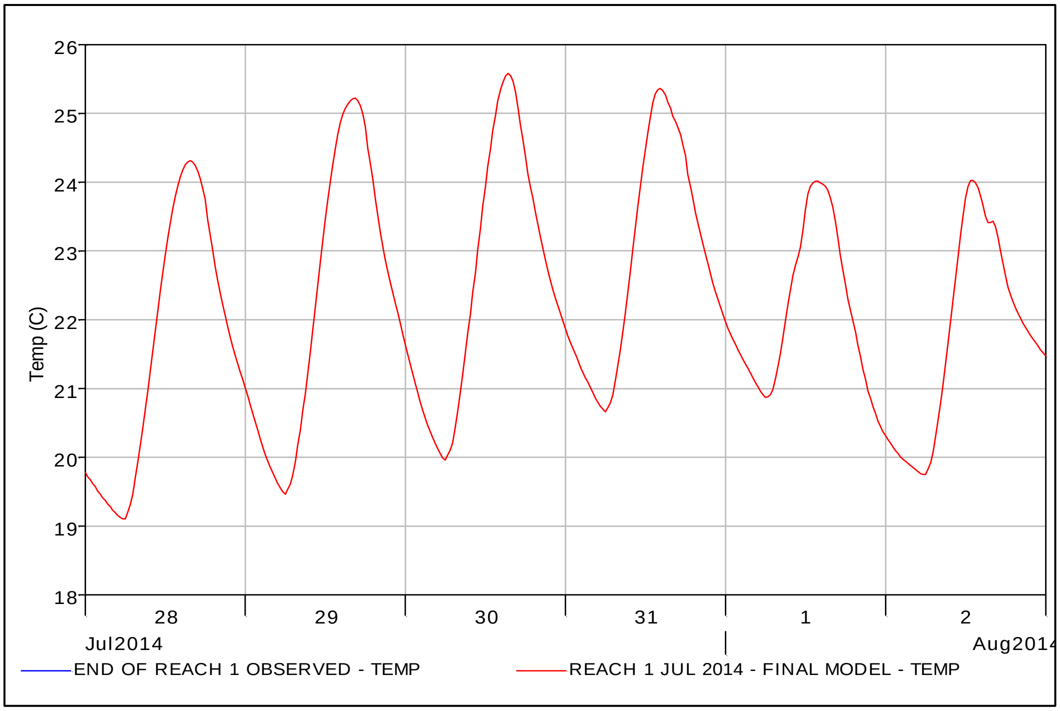


Figure 36. July 2014 end of Reach-1 validation results (observed data unavailable)

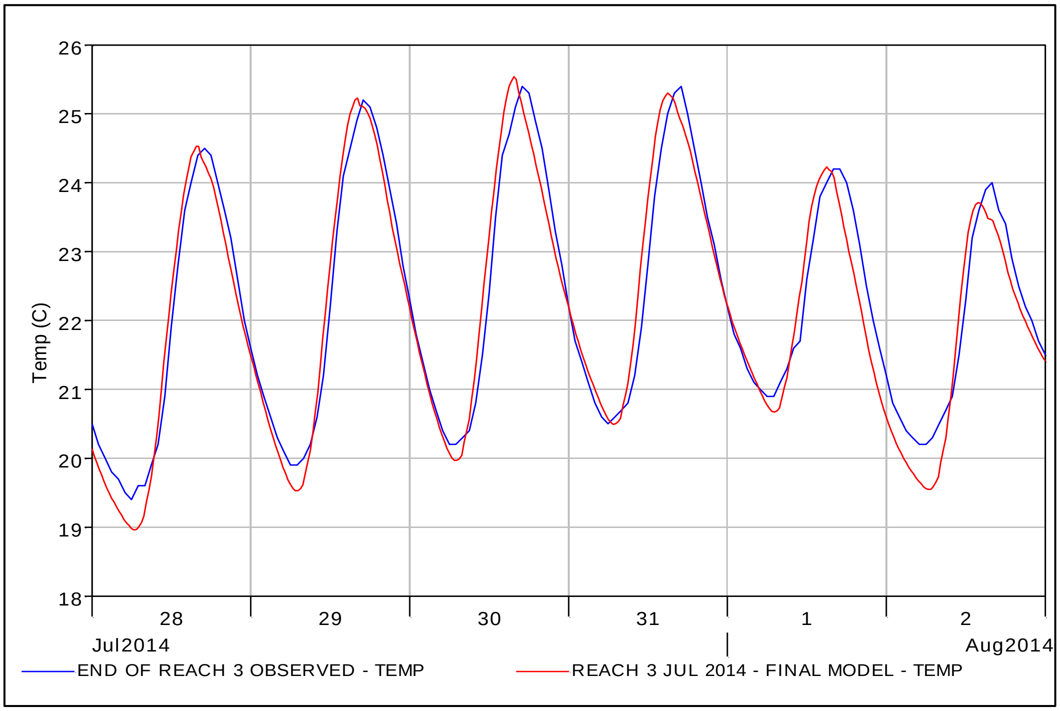


Figure 37. July 2014 end of Reach-3 validation results

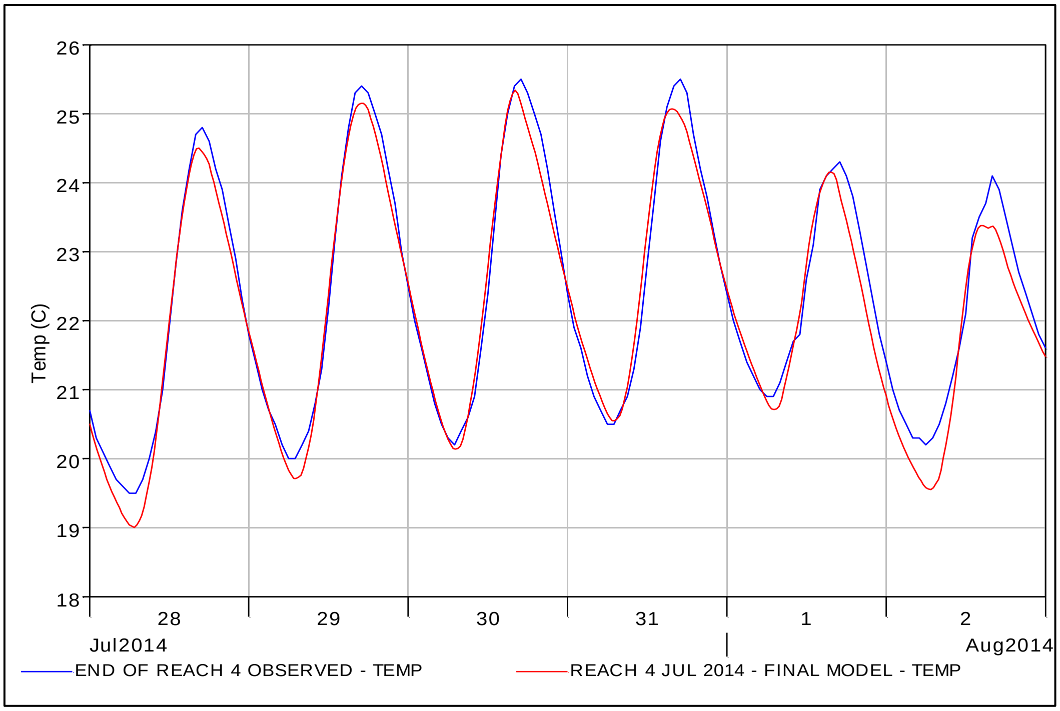


Figure 38. July 2014 end of Reach-4 validation results

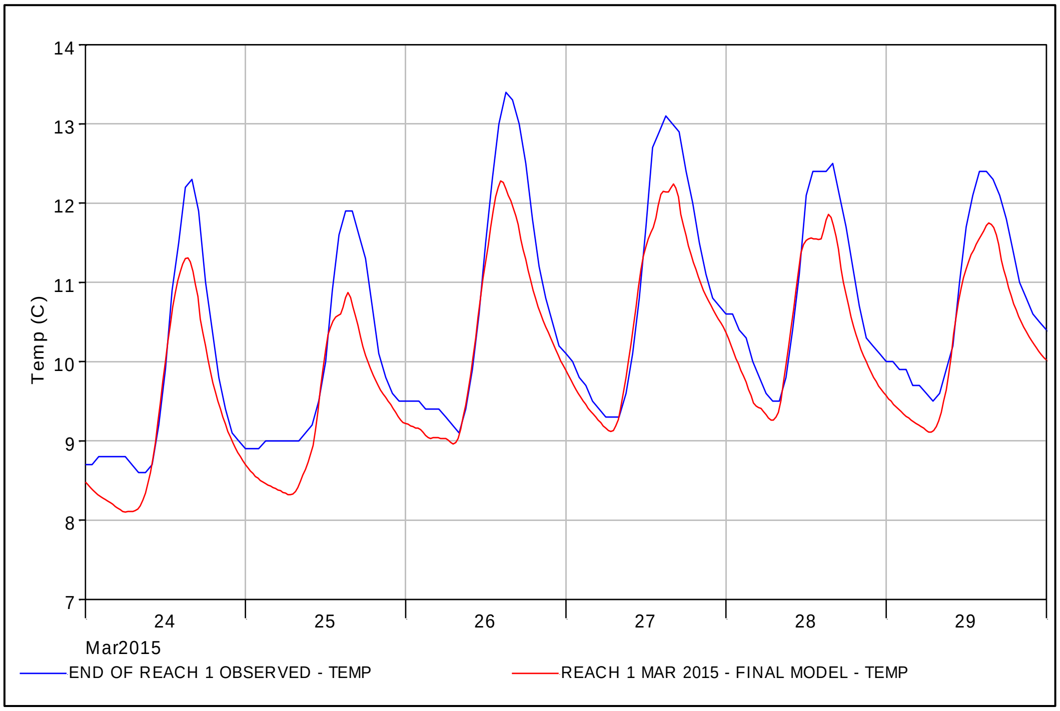


Figure 39. March 2015 end of Reach-1 validation results

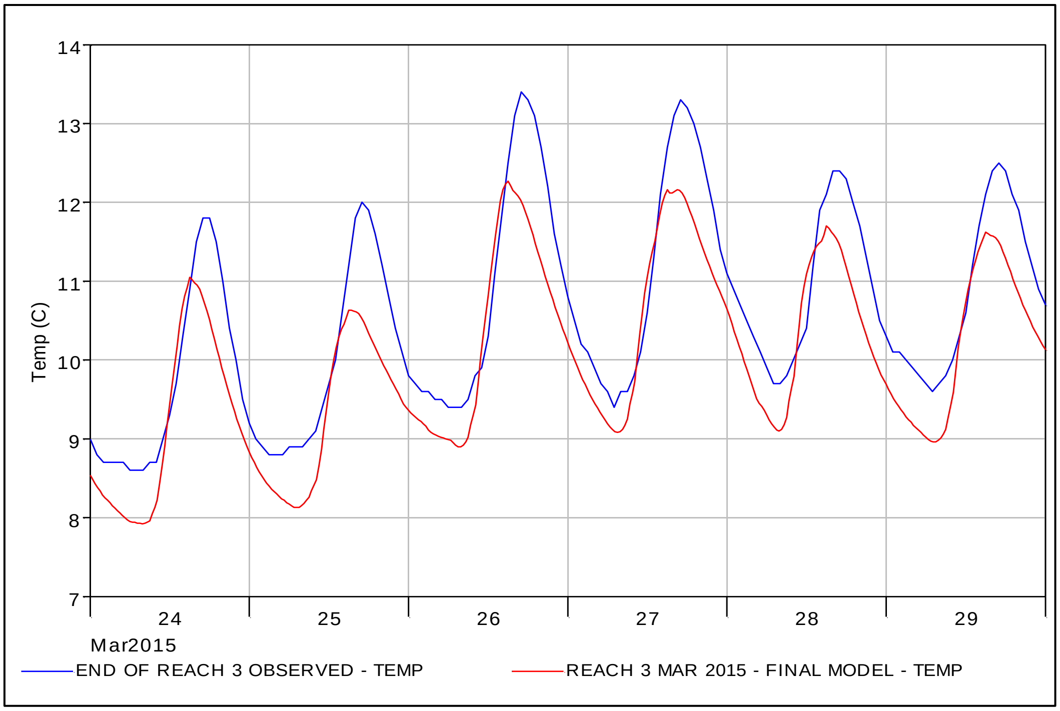


Figure 40. March 2015 end of Reach-3 validation results

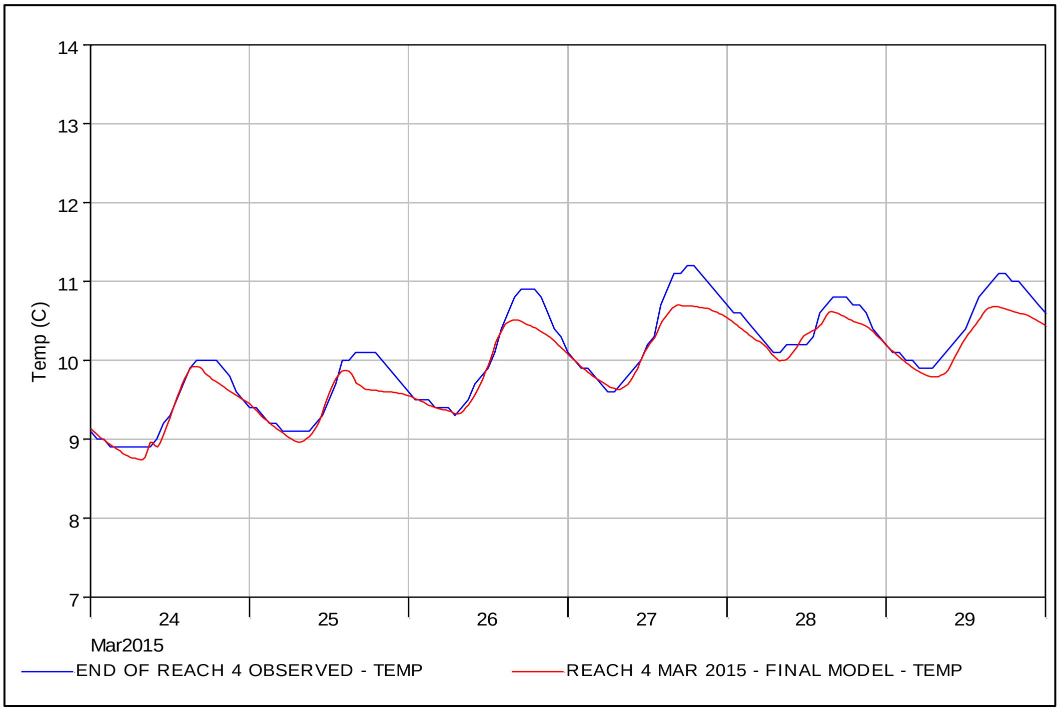


Figure 41. March 2015 end of Reach-4 validation results

4.6 Evaluation of Model Results

Generally, the model validation statistics are similar to the calibration statistics. The statistics (Table 7 and Table 10) 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 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.

Following model development, calibration and validation, we now expect that the model will be used to assess a number of alternatives that might improve use attainment in the Chelan River. The temperature model included topographic shading, but not vegetative shading, as existing vegetation is sparse and provides little significant shading for the existing river. 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. In theory, tall vegetation, such as large canopy trees might provide enough shading to be considered as an alternative.

Another possibility, is to develop a small 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 serves 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.

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