US Army Corps of Engineers
Seattle District

BUILDING STRONG®

DEVELOPMENT OF A CE-QUAL-W2 MODEL FOR HOWARD A. HANSON RESERVOIR

November 2011

WEST CONSULTANTS, INC.

Prepared by WEST Consultants, Inc. under contract W9128F-09-D-0002

Task Order EC01

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1 Introduction

1.1 General

WEST Consultants, Inc. (WEST) was contracted by the Seattle District, U.S. Army Corps of Engineers (the District) to develop a temperature model of the Howard A. Hanson Reservoir, extending approximately 0.8 miles downstream of the dam to a USGS streamflow and temperature gauge located in the Green River. Howard A. Hanson Dam is currently considering modifying its outlet structures to also discharge near-surface water from the to the Green River to meet temperature targets for fish passage and habitat.

1.2 Study Area

The Howard A. Hanson Dam project is located in King County, in western Washington on the Green River approximately 72 kilometers (km) (45 miles) southeast of Seattle, Washington. The locations of the project and the Green River are shown in Figure 1-1. The dam is located at river kilometer (RK) 103.7 (river mile (RM) 64.5) in Section 28, Township 21N, Range 8E, Willamette Meridian.

Howard A. Hanson Dam is an earth-and-rockfill embankment, with the outlet works and a gated spillway in the left abutment. The embankment has an inclined core of sand and gravel material and riprap protection. The total length of the dam, including spillway and abutment structures, is 205.74 m (675 feet). The spillway is a gate controlled, concrete ogee overflow section with a downstream chute. The spillway is anchored in rock on the left abutment and a concrete monolith on the right adjacent to the dam. Two tainter gates 13.72 m by 9.14 m (45 feet wide by 30 feet high) permit storage to 367.59 m (1,206 feet) without spillway discharge. The outlet tunnel was used for diversion during project construction and now serves to pass normal flows for project regulation. It is a 274.32 m (900-foot) long horseshoe-shaped tunnel 5.79 m by 5.79 m (19 feet wide and 19 feet high) with a flat bottom. A 1.22 m (48-inch) bypass pipe is provided for low flow releases from the conservation pool and for passing minimum releases during inspection and repair of the main outlet works.

The reservoir extends approximately 7.25 km (4.5 miles) eastward along the main river channel and 3.22 km (2 miles) northerly up the main tributary, the North Fork, at pool elevation 349.61 m (1147 feet) and would impound 3129 ha-m (25,375 acre-feet). The reservoir was cleared below elevation 347.78 m (1141 feet) when the project was built to protect the quality of water stored over the summer and fall period. Lands above that elevation were not cleared since they would be subjected to flooding so infrequently and for such short durations that vegetation would not be damaged appreciably and water quality not adversely affected to the extent it would not be acceptable. The drainage area at the dam site is 572.39 km^2 (221 sq. mi.).

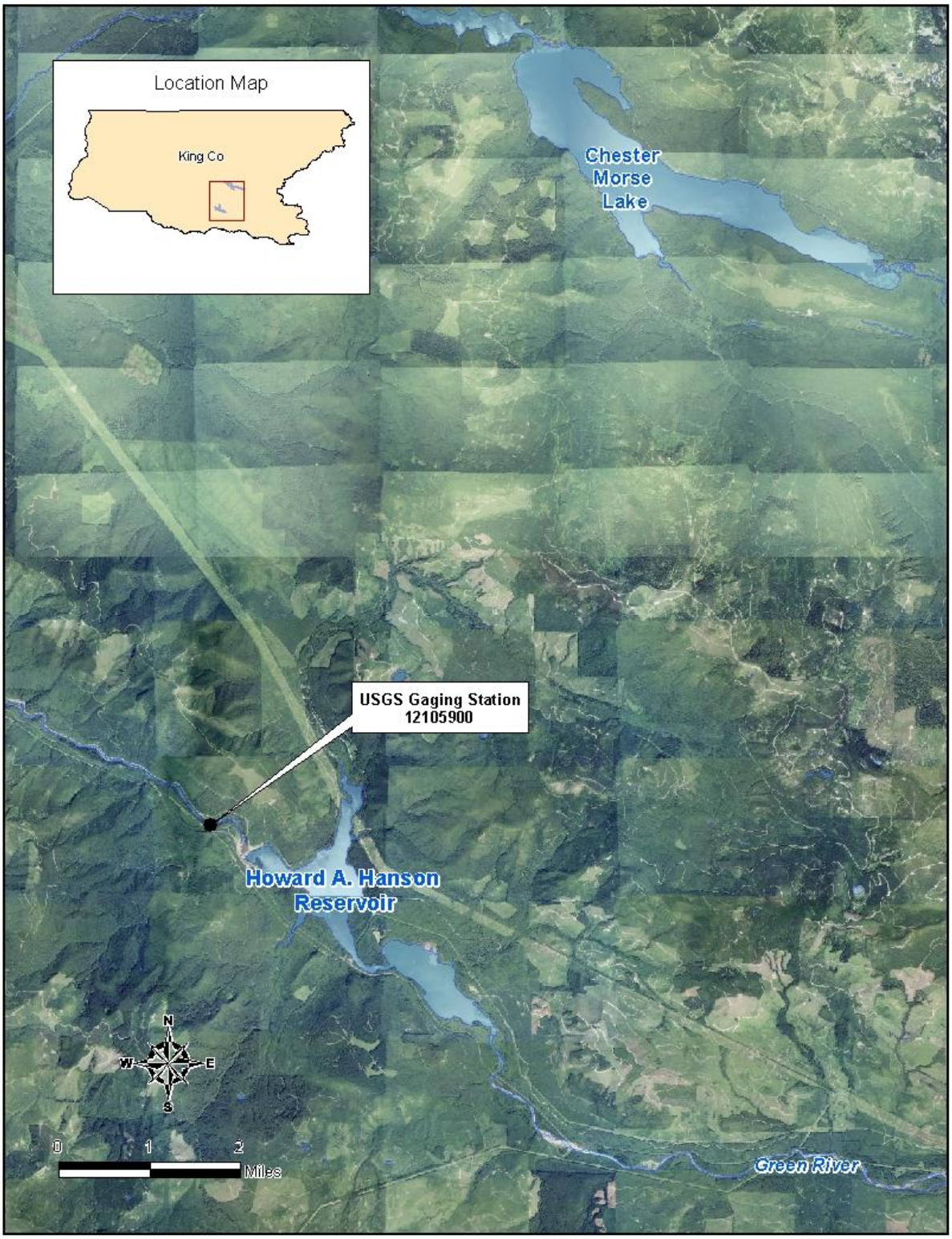

Figure 1-1. Location map for Howard A. Hanson Reservoir and gage location.

1.3 Authorization

WEST Consultants, Inc. (WEST) was contracted to conduct this study under Contract No. W9128F-09-D-0002, Task Order No. EC02, for the Seattle District, Corps of Engineers. The contact at the Seattle District for this project is Mr. Ken Brettmann.

1.4 Scope of Work

Specific tasks performed for the contract included the following:

- Develop a two-dimensional longitudinal/vertical hydrodynamic and temperature model of the Howard A. Hanson Reservoir
- Calibrate and validate the model to observed temperatures
- Evaluate operational alternatives for downstream temperature management
- Simulate average, high and low temperature and flow years

1.5 Study Team

Dr. Raymond Walton was WEST Consultant's Project Manager and lead modeler. He was assisted by Ms. Sarah Bengtson. Mr. Ken Brettmann and Mr. Kent Easthouse provided assistance in managing the contract and addressing technical questions for the Seattle District.

2 Model Data

Data for the CE-QUAL-W2 model of the Howard A. Hanson (HAH) Reservoir included bathymetry, inflows and outflows, inflow and outflow water temperatures, reservoir stage, meteorology, and in-pool temperature profiles for model calibration and validation. The available data from or near HAH Reservoir are shown in Table 2-1 from 2003. Data before 2003 have significant gaps or are not available. The main data sites are (1) at the HAH project, (2) upstream on the Green River near Lester, (3) about six miles north in the vicinity of Chester Morse Dam on the Cedar River, and (4) from SeaTac Airport. The various data types and sources are discussed in the following sections.

2.1 Bathymetry

The Seattle District provided bathymetry data of the reservoir. King County, Washington, provided LiDAR coverage of overbank areas. These data were blended, processed using GIS tools to create a TIN, and cross sections cut.

2.2 Flows and Water Temperatures

Flows and water temperatures are required at all upstream boundaries of the W2 model as shown in Figure 2-1. In this figure, the blue arrows indicate flow and the orange arrows indicate water temperature inputs. Only flow is required at the downstream boundary.

Flow data were obtained from the U.S. Army Corps dataquery database (Army Corps of Engineers, 2009). We obtained historical inflow water temperature directly from the dataquery data base. All inflow and outflow data were converted to Julian days (assigning Julian Day 1 to 1/1/1900 at 12:00 a.m.) and to metric units, as necessary.

2.2.1 Flow Data

Outflow and forebay stage data for the HAH reservoir were obtained from the dataquery database in six-hour intervals from 1992. As the flows in a CE-QUAL-W2 reservoir model have to balance perfectly to conserve mass, a FORTRAN program was developed to calculate the total reservoir inflows from the observed reservoir stage and the measured outflows, using the model's geometry. The inflows were then assigned a weight based on the proportion of total contributing watershed area and historical inflows.

Flows in the Green River upstream of HAH were discontinued in 1993. In addition, there are some historical flow measurements in the North Fork Green River and in Charley Creek, both tributaries to the HAH reservoir. Table 2-2 lists the historic gauges, their periods of record, and their contributing watershed areas.

Table 2-1. Available Data near Howard A. Hanson Reservoir (red indicates no data, yellow indicates sparse data, and green indicates almost continuous data)

	Site	HAH	Lester	Cedar lake	Lester	Lester	Lester	Lester	Cedar lake	Cedar lake	SeaTac	Lester	Cedar Lake
	Units	Deg F	Deg F	Deg F	Deg F	%	mph	Deg	mph	Deg		w/m2	w/m2
		Av Air	Av Air	Av Air	Fuel	Rel	Wind	Wind	Wind	Wind	Cloud	Solar	Solar
	Parameter	Temp	Temp	Temp	Temp	Humidty	Speed	Direc	Speed	Direc	Cover	Rad.	Rad.
2003	January	x	--	x	--	--	--	--	x	x	x	--	x
	February	x	--	x	--	--	--	--	x	x	x	--	x
	March	x	--	x	--	--	--	--	x	x	x	--	x
	April	x	--	x	--	--	--	--	x	x	x	--	x
	May	x	*	x	*	*	*	*	x	x	x	--	x
	June	x	x	x	x	x	x	x	x	x	x	--	x
	July	x	x	x	x	x	x	x	x	x	x	--	x
	August	x	x	x	x	x	x	x	x	x	x	--	x
	September	x	x	x	x	x	x	x	x	x	x	--	x
	October	x	*	x	*	*	*	*	x	x	x	--	x
	November	x	--	x	--	--	--	--	x	x	x	--	x
	December	x	--	x	--	--	--	--	x	x	x	--	x
2004	January	x	--	x	--	--	--	--	x	x	x	--	x
	February	x	--	x	--	--	--	--	x	x	x	--	x
	March	x	--	x	--	--	--	--	x	x	x	--	x
	April	x	*	x	*	*	*	*	x	x	x	--	x
	May	x	x	x	x	x	x	x	x	x	x	--	x
	June	x	x	x	x	x	x	x	x	x	x	--	x
	July	x	x	x	x	x	x	x	x	x	x	--	x
	August	x	x	x	x	x	x	x	x	x	x	--	x
	September	x	x	x	x	x	x	x	x	x	x	--	x
	October	x	x	x	x	x	x	x	x	x	x	--	x
	November	x	x	x	x	x	x	x	x	x	x	--	x
	December	x	x	x	x	x	x	x	x	x	x	--	x
2005	January	x	x	x	x	x	x	x	x	x	x	--	x
	February	x	x	x	x	x	x	x	x	x	x	--	x
	March	x	x	x	x	x	x	x	x	x	x	--	x
	April	x	x	x	x	x	x	x	x	x	x	--	x
	May	x	x	x	x	x	x	x	x	x	x	--	x
	June	x	x	x	x	x	x	x	x	x	x	*	x
	July	x	x	x	x	x	x	x	x	x	x	x	x
	August	x	x	x	x	x	x	x	x	x	x	x	x
	September	x	x	x	x	x	x	x	x	x	x	x	x
	October	x	x	x	x	x	x	x	x	x	x	x	x
	November	x	x	x	x	x	x	x	x	x	x	x	x
	December	x	*	x	*	*	*	*	x	x	x	*	x
2006	January	x	*	x	*	*	*	*	x	x	x	*	x
	February	x	*	x	*	*	*	*	x	x	x	*	x
	March	x	x	x	x	x	x	x	x	x	x	x	x
	April	x	x	x	x	x	x	x	x	x	x	x	x
	May	x	x	x	x	x	x	x	x	x	x	x	x
	June	x	x	x	x	x	x	x	x	x	x	x	x
	July	x	x	x	x	x	x	x	x	x	x	x	x
	August	x	x	x	x	x	x	x	x	x	x	x	x
	September	x	x	x	x	x	x	x	x	x	x	x	x
	October	x	x	x	x	x	x	x	x	x	x	x	x
	November	x	*	x	*	*	*	*	x	x	x	*	x
	December	x	*	x	*	*	*	*	x	x	x	*	x
2007	January	x	*	x	*	*	*	*	x	x	x	*	x
	February	x	x	x	x	x	x	x	x	x	x	x	x
	March	x	x	x	x	x	x	x	x	x	x	x	x
	April	x	x	x	x	x	x	x	*	*	x	x	*
	May	x	x	x	x	x	x	x	*	*	x	x	*
	June	x	x	x	*	x	x	x	x	x	x	x	x
	July	x	x	x	*	x	x	x	x	x	x	x	x
	August	x	x	x	*	x	x	x	x	x	x	x	x
	September	x	x	x	*	x	x	x	x	x	x	x	x
	October	x	x	x	*	x	x	x	x	x	x	x	x
	November	x	*	x	*	*	*	*	x	x	x	*	x
	December	x	*	x	*	*	*	*	x	x	x	*	x
2008	January	x	*	x	*	*	*	*	x	x	x	*	x
	February	x	*	*	*	*	*	*	x	x	x	*	x
	March	x	*	x	*	*	*	*	x	x	x	*	x
	April	x	*	x	*	*	*	*	x	x	x	*	x
	May	x	*	x	*	*	*	*	x	x	x	*	x
	June	x	*	x	*	*	*	*	x	x	x	*	x
	July	x	*	x	*	*	*	*	x	x	x	*	x
	August	x	*	x	*	*	*	*	x	x	x	*	x
	September	x	x	x	x	x	x	x	x	x	x	x	x
	October	x	x	x	x	x	x	x	x	x	x	x	x
	November	x	x	x	x	x	x	x	x	x	x	x	x
	December	x	x	x	x	x	x	x	x	x	x	x	x
2009	January	x	x	x	x	x	x	x	x	x	x	x	x
	February	x	x	x	x	x	x	x	x	x	x	x	x
	March	x	x	x	x	x	x	x	x	x	x	x	x
	April	x	x	x	x	x	x	x	x	x	x	x	x
	May	x	x	x	x	x	x	x	x	x	x	x	x
	June	x	x	x	x	x	x	x	x	x	x	x	x
	July	x	x	x	x	x	x	x	x	x	x	x	x
	August	x	x	x	x	x	x	x	x	x	x	x	x
	September	x	x	x	x	x	x	x	x	x	x	x	x
	October	x	*	x	*	*	*	*	x	x	x	*	x
	November	--	*	--	*	*	*	*	--	--	x	*	--
	December	--	x	--	x	x	x	x	--	--	x	x	--

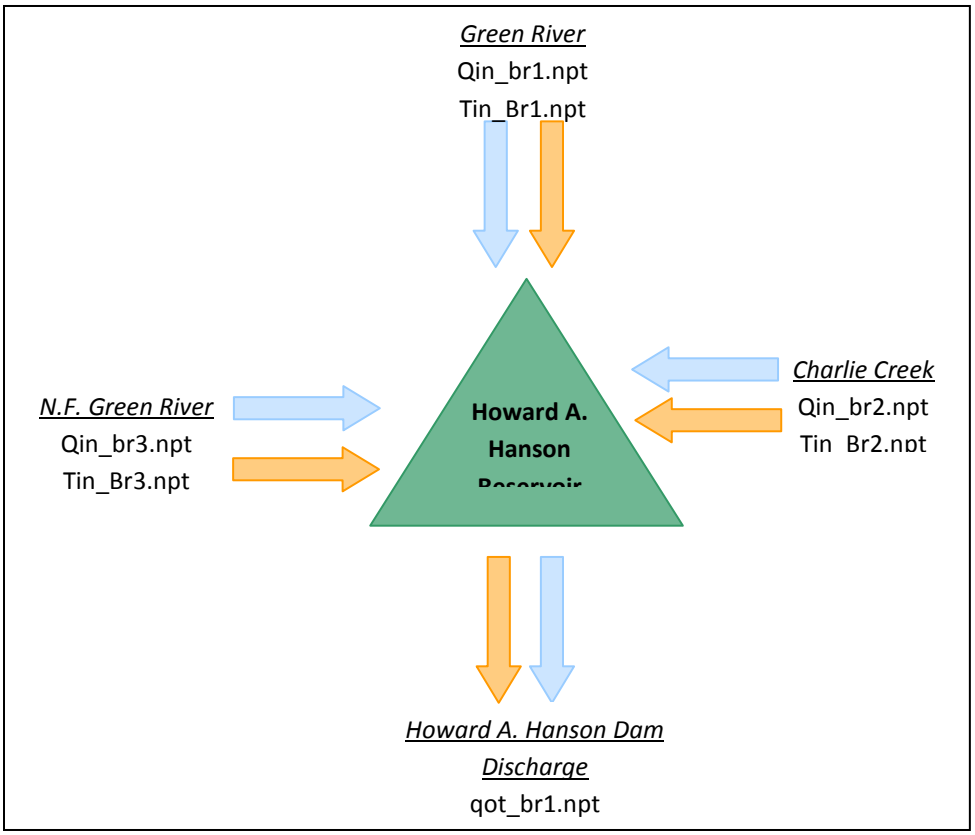

Figure 2-1. Schematic of W2 Boundary Condition Files (blue arrows = flow; orange arrows = temperature).

Table 2-2. Available Streamflow Data near Howard A. Hanson Reservoir

Gauge Number	Gauge Name	Period of Record	Area at Gauge (mi^2)	Area at Reservoir (mi^2)
USGS 12104500	Green River near Lester	1945-1993	96.2	166.18
USGS 12105710	N. F. Green River near Lemolo	1965-1987	16.7	27.96
USGS 12105500	Charley Creek near Eagle Gorge	1947-1956	11.3	12.75
Ungauged inflows				14.06

The daily flows from the three gauges listed in Table 2-2 were analyzed, and ratios of the flows in the North Fork and Charley Creek to flows in the Green River at Lester developed for their periods of overlapping records. These estimates were then extended to the inflow points of the HAH reservoir using drainage basin area ratios. From this analysis, it was estimated that 68.3 percent of inflows came from the Green River, 15.7 percent from the North Fork Green River, and 16 percent from Charley Creek and ungauged inflows. These percentages were used to apportion the total inflows to the reservoir.

2.2.2 Inflow Water Temperatures

Daily inflow temperatures are available from 1994. There are periods with more frequent observations (such as 2008), however, these data either have significant gaps (September-December 2008) or coincide with relatively sparse data on in-pool temperature profiles. As the summers are characterized by relatively low inflows, we felt that the use of daily inflow temperatures was not a significant shortcoming in the modeling. However, some of the readings are "instantaneous" but taken once per day, and therefore do not reflect even a daily average.

2.3 Meteorology

Meteorological data were obtained from:

- A meteorological station at the HAH dam that measured air temperature.
- A meteorological station about fourteen miles upstream on the Green River near Lester that measured air temperature, relative humidity, wind speed and direction, and solar radiation.
- A meteorological station about nine miles to the north in the vicinity of the Chester Morse Dam on the Cedar River that measured air temperature, relative humidity, wind speed and direction, and solar radiation.
- The meteorological station at SeaTac Airport that measured, amongst other things, cloud cover.

2.3.1 Air Temperature

As good quality measurements of air temperature are available at the HAH dam, these data were used directly in the temperature model.

2.3.2 Dew Point Temperature Data

The CE-QUAL-W2 model uses dew point temperatures in its thermal transfer routines. Air temperatures and relative humidity data from the Lester meteorological station were used to calculate dew point temperatures based on the Magnus-Tetens formula (Barenbrug, 1974):

$$DP = \frac{237.7\left(\frac{17.27T}{237.7+T} + \ln(RH)\right)}{17.27 - \left(\frac{17.27T}{237.7+T} + \ln(RH)\right)}$$

where DP = dew point temperature (°C), T = air temperature (°C),and RH = relative humidity fraction

These calculated dew point temperatures were used directly in the temperature model.

2.3.3 Wind

Wind measurement are not available at the HAH dam. However, data are available in the same valley about fourteen miles upstream of the project near Lester, and also about nine miles to the north in the vicinity of the Chester Morse Dam. The Cedar River valley has a similar orientation as the Green River valley at the two dams, and so seemed a useful location to provide wind speed and direction data (Figure 2-2). However, the wind direction data due show some significant differences as the Chester Morse station is located near the dam where the valley begins to broaden and open to a confluence valley. As Lester is in the same valley as HAH reservoir, we decided to use the wind speed and direction from Lester, and later test the sensitivity to wind speed.

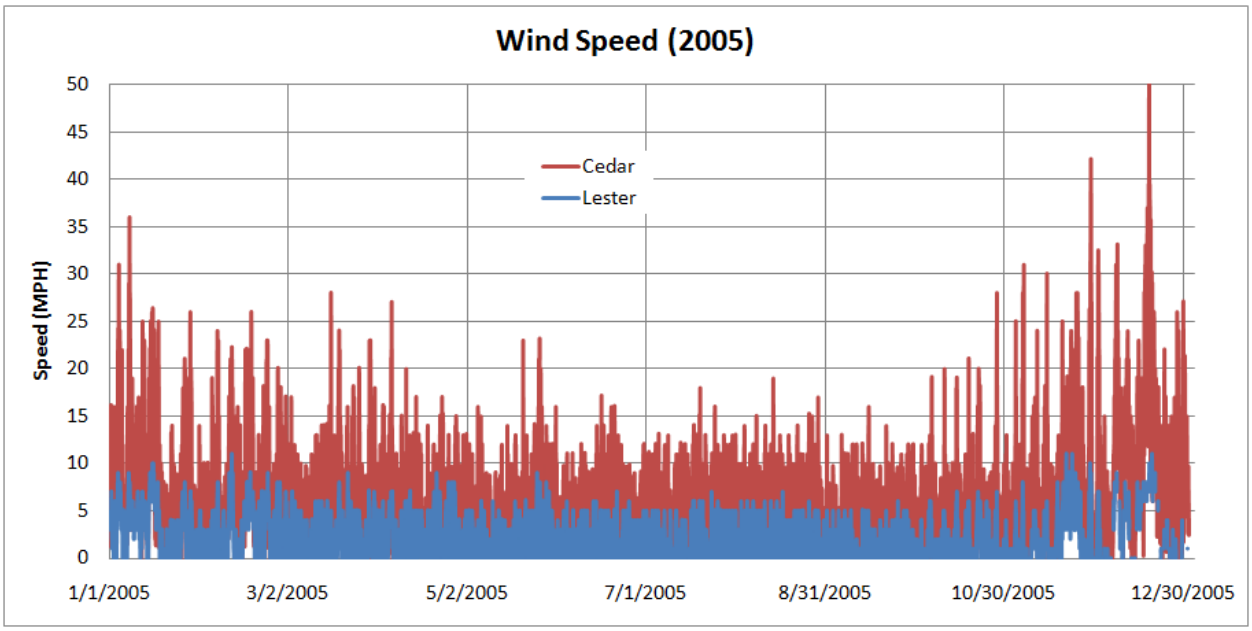

Figure 2-2. Comparison of observed wind speed at the Lester and Chester Morse meteorological stations.

2.3.4 Cloud Cover

CE-QUAL-W2 requires cloud cover for the calculation of long-wave radiation. The closest available data are measured at Stampede Pass, and were used directly in the temperature model, after they were converted to cover in tenths, using the conversions in Table 2-3.

Table 2-3. Cloud cover conversion from SeaTac to CE-QUAL-W2 input.

SeaTac Sky Condition			CE-QUAL-W2 Cloud Cover
3-Letter Code	**Definition**	**Sky Cover**	
CLR	Clear	Clear below 12,000 ft	0
FEW	Few	0/8 - 2/8	1.3
SCT	Scattered	3/8 - 4/8	4.4
BKN	Broken	5/8 - 7/8	7.5
OVC	Overcast	8/8	10

2.3.5 Solar Radiation Data

Solar radiation data are available at the meteorological stations near Lester and near Chester Morse dam. Figure 2-3 shows a comparison of the data for 2009 for these two locations, and their similarity. We used direct observations of solar radiation from the station at Lester in the temperature model, and filled any data gaps using the observations from Chester Morse Dam

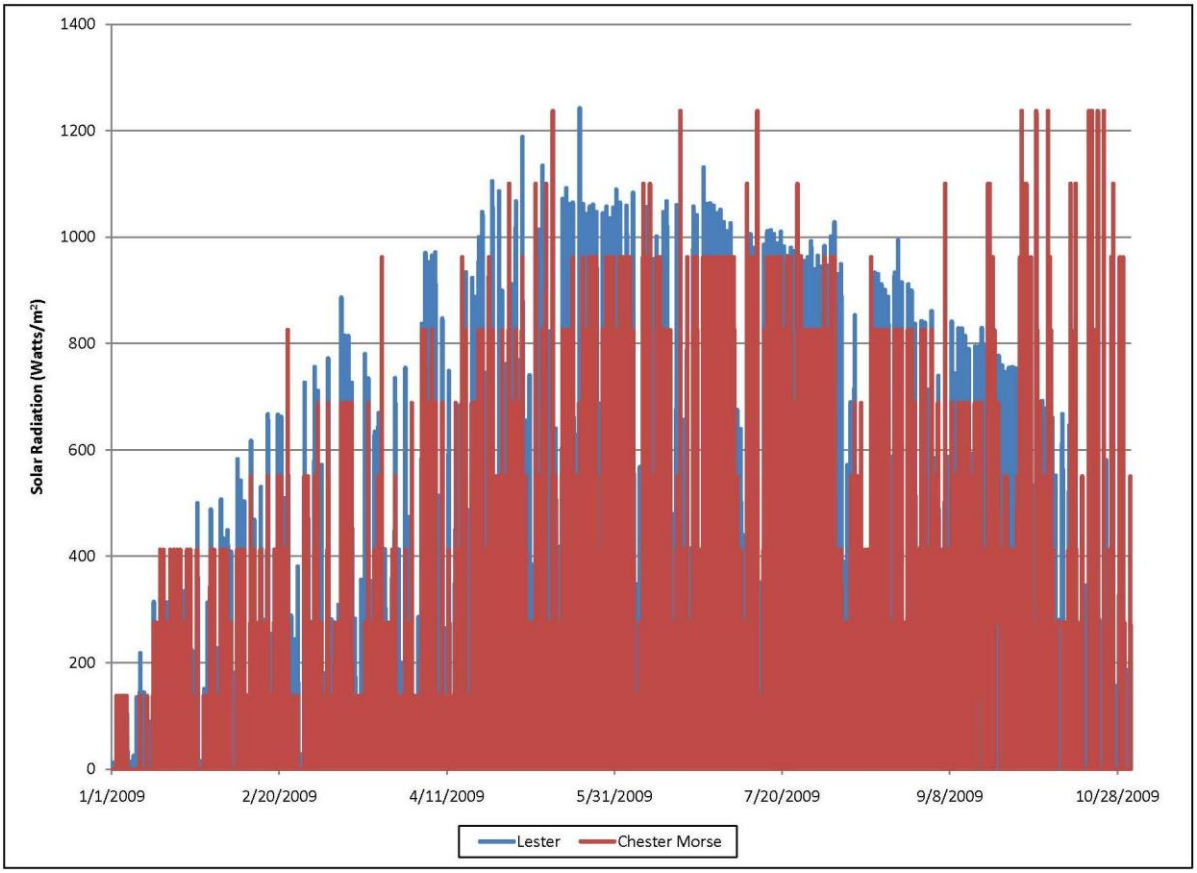

Figure 2-3. Comparison of observed solar radiation at the Lester and Chester Morse meteorological stations.

2.4 In-Reservoir Temperature Profiles

Table 2-4 the number of in-pool vertical temperature profiles measured each year. While there are a number of sampling stations that were occupied since about 2002, only the four stations shown in Figure 2-4 were occupied each year, although their frequency of observations varied significantly from year-to-year. In addition, Tacoma Public Utility (TPU) measured profiles between 2007 and 2009 near the dam (1DAM site). They are also shown in Table 2-4, and overlap with the days data were collected by the Corps. The observations for 2005, 2007, and 2009 are shown in Appendices 1-3, respectively.

Table 2-4. Number of in-pool temperature profiles measured each year in HAH reservoir.

Year	Number of Corps temperature profiles	Number of TPU temperature profiles
2003	9	
2004	10	
2005	8	
2006	4	
2007	5	20
2008	6	24
2009	8	20

2.5 Downstream Hydraulic and Temperature Model

There is a USGS streamflow gauge (#12105900) located in the Green River approximately 0.8 miles downstream of Howard A. Hanson Dam. This gauge has reported flows since 1961 and temperatures since 1985. This gauge was used to calibrate and validate releases from the dam. The model the potential changes in water temperature below the dam, the Seattle District provided an existing hydraulic model of the Green River using HEC-RAS. The model extended from the dam about 20 miles downstream.

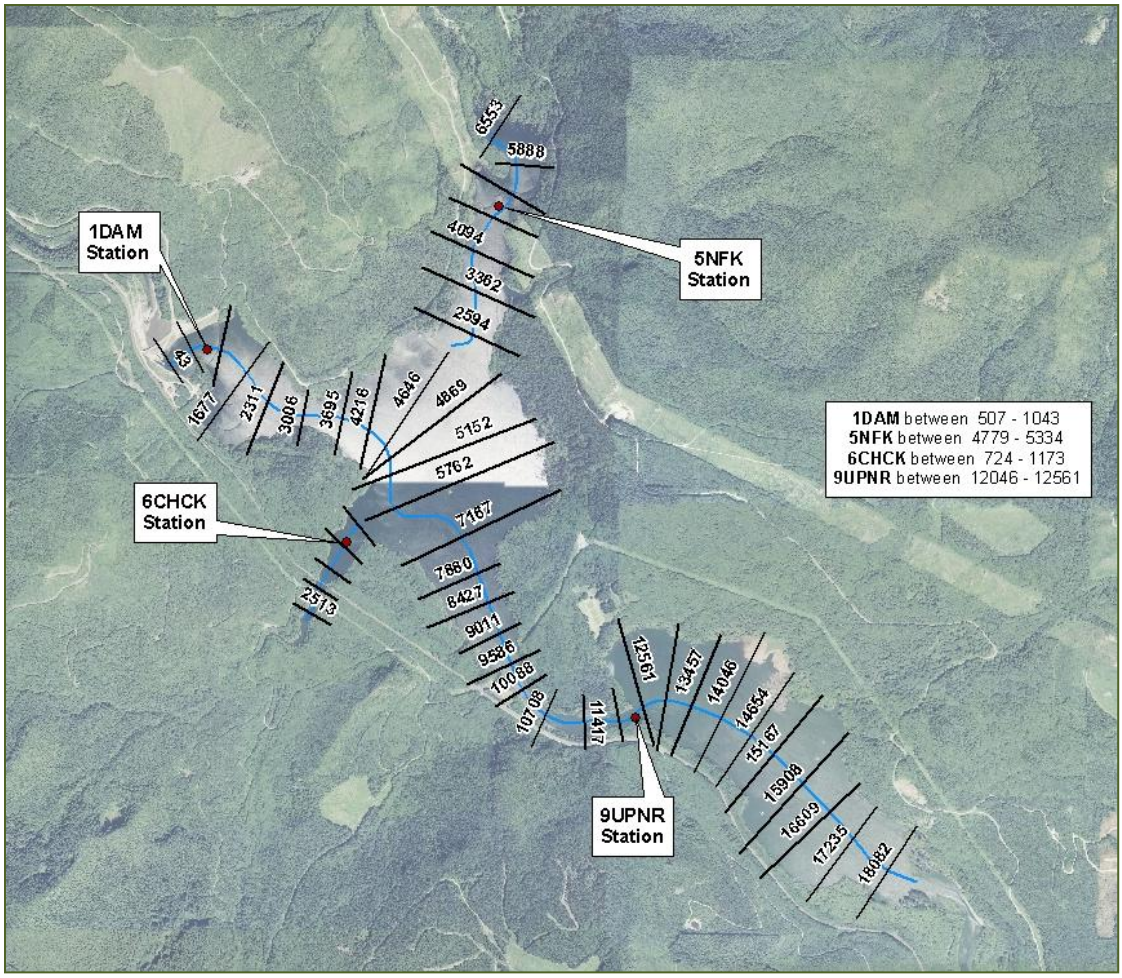

Figure 2-4. Location of in-pool temperature profile stations.

3 Model Development and Calibration

3.1 Model Development Approach

We used the following approach in modeling the Howard A. Hanson (HAH) Reservoir:

1. Develop the geometry for the reservoir,
2. Ensure that the model flows would "balance" water in the reservoir,
3. Perform model sensitivity to determine the most sensitive calibration parameters,
4. Calibrate to observed, in-pool temperature profiles collected during 2009
5. Validated the model to in-pool temperature from 2005 and 2007

3.2 Description of Numerical Model

CE-QUAL-W2 is a two-dimensional, laterally-averaged hydrodynamic and water quality model. Because the model assumes lateral homogeneity, it is best suited for relatively long and narrow waterbodies exhibiting longitudinal and vertical water quality gradients. The model has been applied to numerous rivers, lakes, reservoirs and estuaries, many with length-to-width ratios similar to that of HAH Reservoir.

The hydrodynamic routine of the model predicts water surface elevations, velocities and temperatures. Temperature is included in the hydrodynamic calculations because of its effect on water density. The water quality routines simulate any combination of constituents that can represent a range of simple-to-complex eutrophication kinetics and various trophic levels. The model includes algal dynamics driven by nitrogen, phosphorus and silicon, and carbon cycling. Both water column and interactions with sediment can be modeled as defined by the user. For this study, we used CE-QUAL-W2 Version 3.6 (Cole and Wells, 2008).

3.3 Development of the CE-QUAL-W2 Model

The Seattle District provided bathymetry of the HAH reservoir in digital form. These data were blended with a LiDAR dataset flown over King County, and clipped to the study area. The resulting dataset was formatted as a TIN (Figure 3-1), and HEC-GeoRAS used to cut cross sections for import to HEC-RAS, Version 4.0. The cross sections were placed at the centerlines of the CE-QUAL-W2 segments of the reservoir. The final model grid is shown in Figure 3-2 and Figure 3-3.

The geometry pre-processor for unsteady flow in HEC-RAS was used to develop tables of segment widths at 0.5-meter intervals above the lowest elevation in the reservoir, and the results exported to an excel spreadsheet. These data were then processed using a FORTRAN program to develop an initial bathymetry (BTH) file for the CE-QUAL-W2 model. The resulting model has three branches (representing the Green River mainstem, Charlie Creek, and North Fork

Green River), divided into 49 horizontal segments of about 200 m length, and 101 0.5 m-thick layers.

The model geometry was then compared with elevation-volume curves developed from information in the Water Control Manual (Corps of Engineers, 2001; Figure 3-4), and found to agree within 5 percent. The agreement is even closer if we note that summer full pool is about elevation 356 m (1168 feet). Dimensions of the dam and outlet structures are summarized in Table 3-1. All other model parameters and features were initially assigned default values.

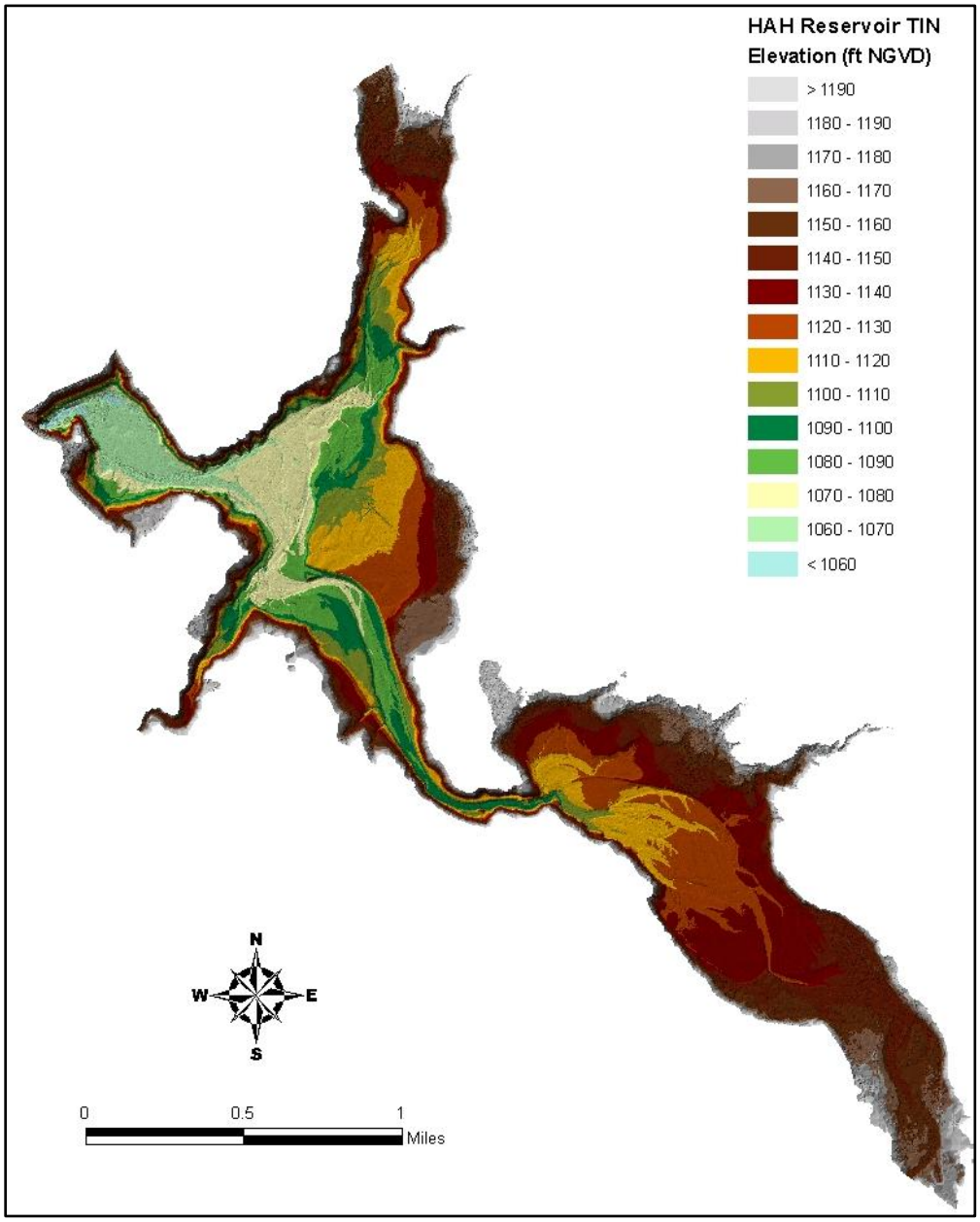

Figure 3-1. Howard A. Hanson Reservoir TIN.

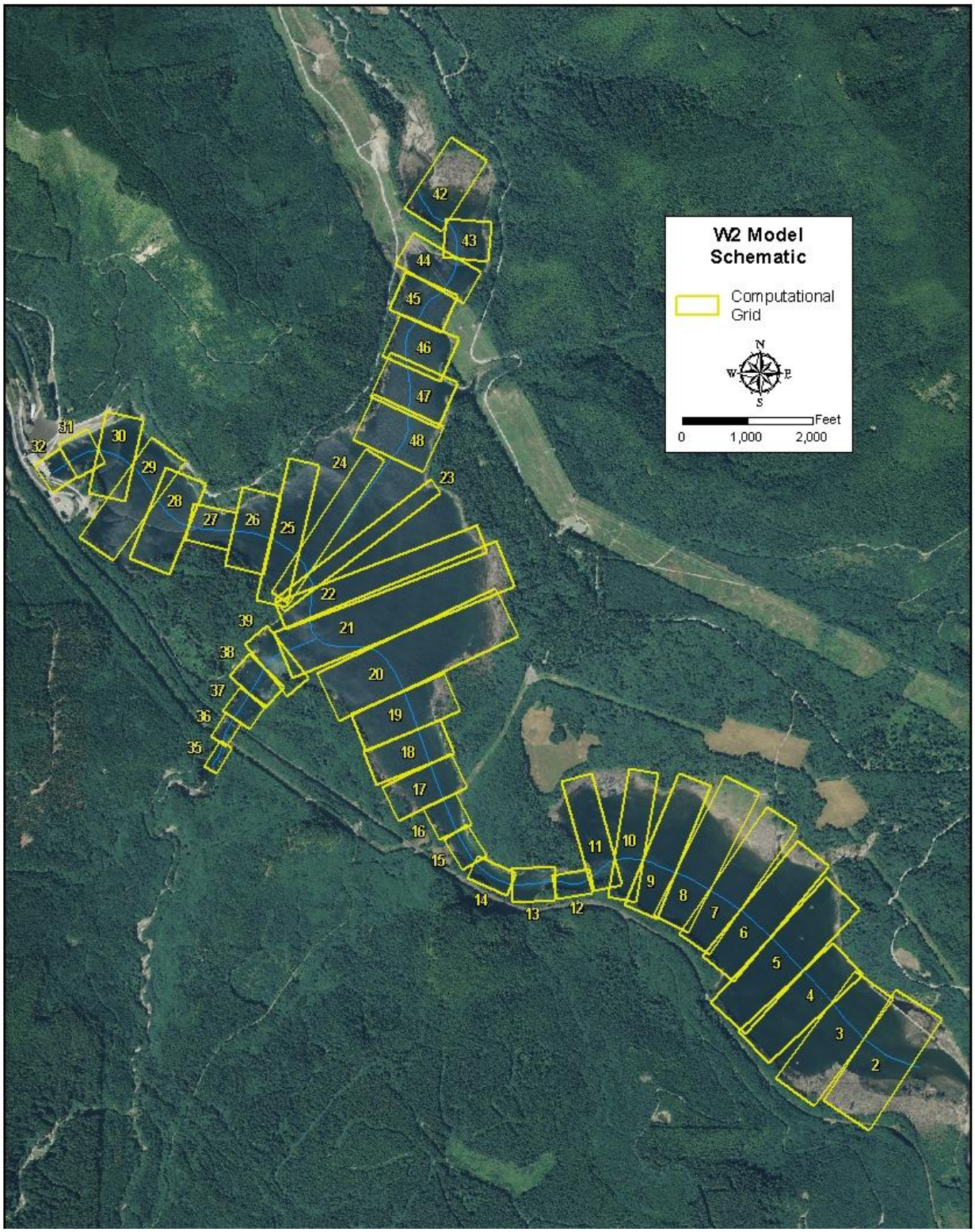

Figure 3-2. Final model grid for HAH reservoir.

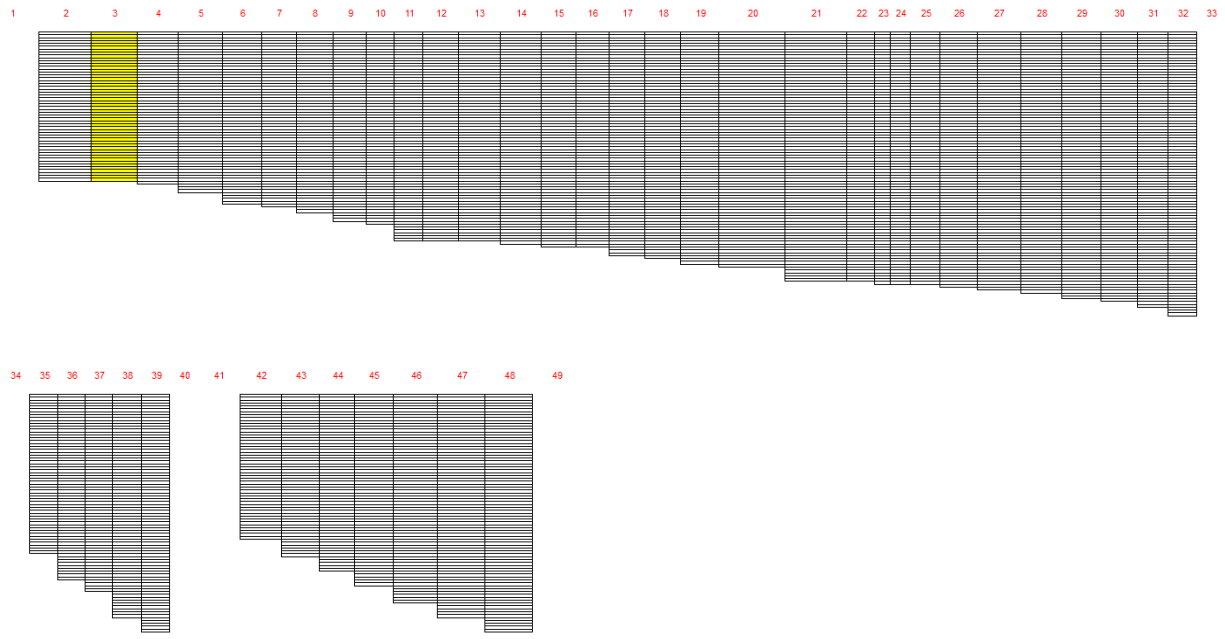

Figure 3-3. Model longitudinal profile (2-32 are main reservoir; 35-39 are Charley Creek; 42-48 are the NF Green River)

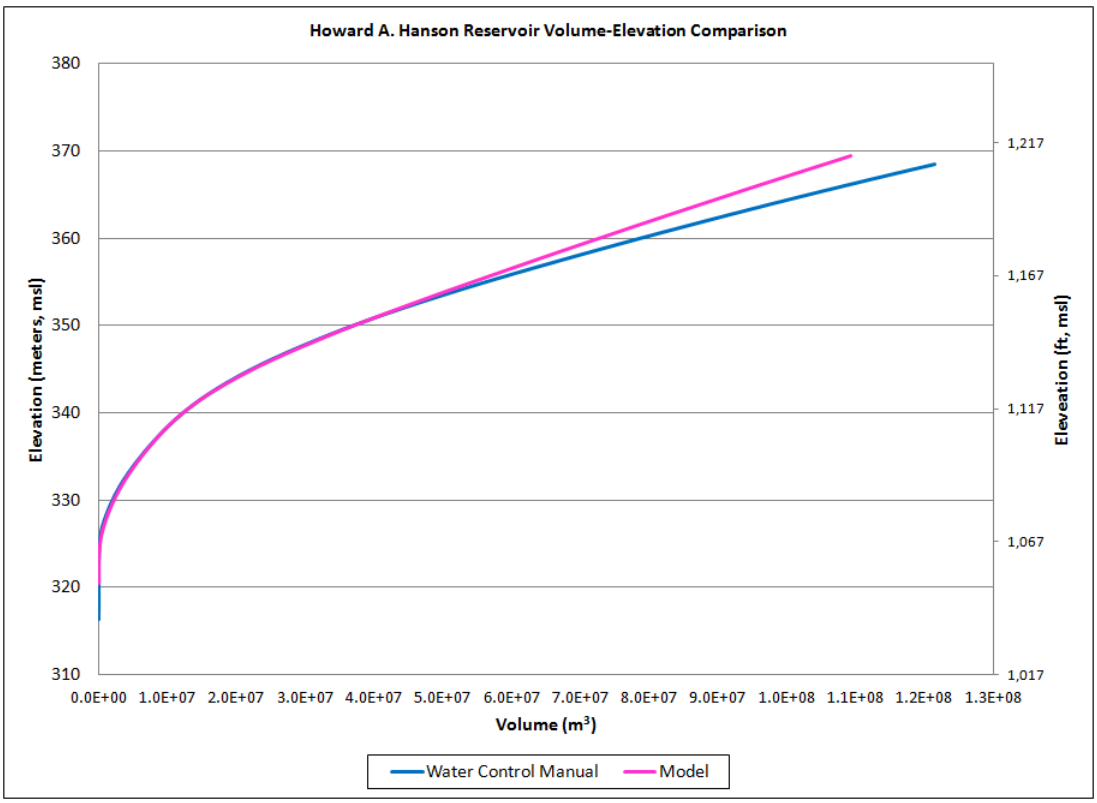

Figure 3-4. Stage-Volume Curve for Howard A. Hanson Reservoir.

Table 3-1. Elevations of Discharge Structure for Howard A. Hanson Reservoir.

	U.S. Customary Units	Metric Units
Top of dam crest elevation	1,228.0 ft NGVD	374.29 m NGVD
Length of dam	675 ft	205.74 m
Spillway crest elevation	1,176.0 ft	358.44 m
Spillway gates (2)	30 ft by 45 ft	9.14 m by 13.72 m
Low-level gated tunnel	19 ft diameter	5.79 m diameter
Tunnel invert	1035 ft NGVD	315.46 m NGVD
Additional bypass diameter	4 ft	1.22 m
Bypass invert elevation	1069.5 ft NGVD	326 m NGVD

3.4 Initial and Boundary Conditions Data

The reservoir model requires initial and boundary conditions. These are:

- Initial reservoir stage
- Initial reservoir temperature
- Inflows to the reservoir
- Water temperatures of the reservoir inflows
- Outflows from the reservoir through the various structures
- Meteorology

The initial reservoir stages were using observed stages from the Corps' dataquery database, and the initial reservoir water temperature was set based on observed inflow temperatures and the assumption that the reservoir would be essentially isothermal at that time. Reservoir inflows, inflow temperature, and outflows were developed (as described in Section 2) from historic flow measurements adjusted to maintain an annual mass balance.

CE-QUAL-W2 automatically calculates each time step internally to satisfy certain stability criteria. These values are limited to a range defined by the user. For this study, the minimum time step was set to one second, and the maximum to 3600 seconds.

3.5 Hydrodynamic Validation

As there are no observations of velocities in the reservoir, hydrodynamic validation was achieved by ensuring accurate model geometries and good agreement with observed reservoir stages. Once the inflows and the outflows had been balanced to ensure compatibility for the model calibration period, March-October 2009, the resulting stages from the model were compared with observed stages in the reservoir. Figure 3-5 show that the HAH Reservoir W2 model accurately simulates the observed variability of stages in the reservoir.

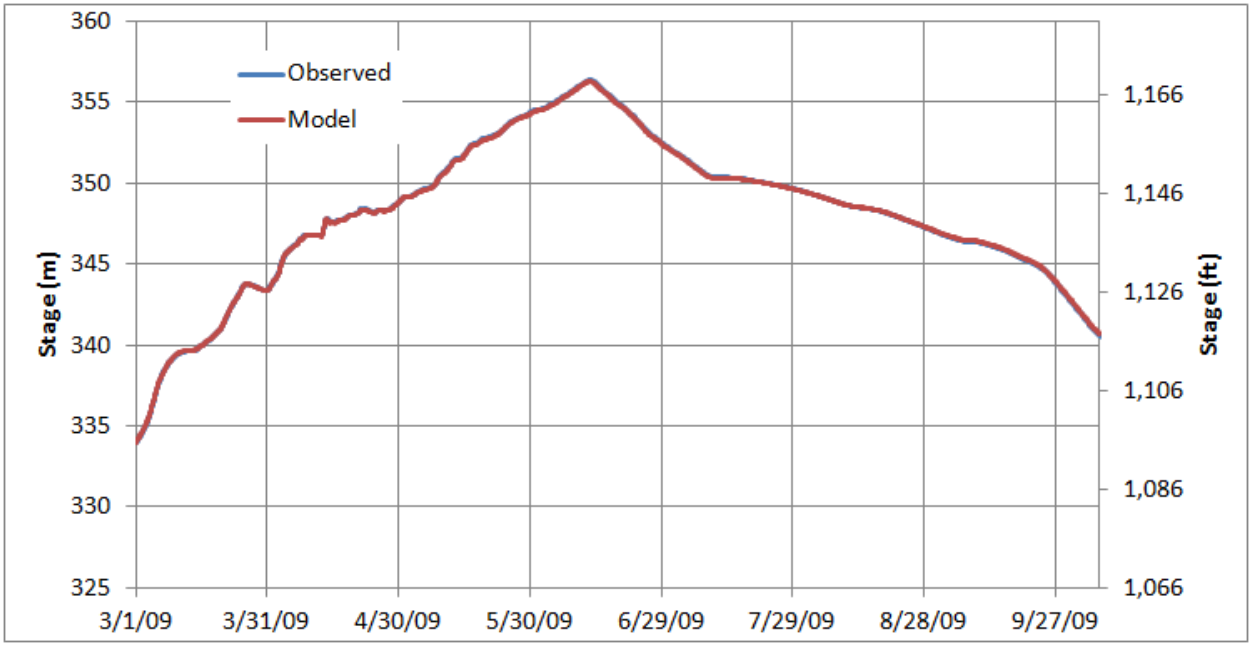

Figure 3-5. Comparison of observed and simulated stage at HAH Reservoir for 2009.

3.6 Development of the HEC-RAS Model Below the Dam

The HEC-RAS model of the Green River provided by the Seattle District was set up to run steady-state simulations. We edited the HEC-RAS model geometry to included only the upper three miles of the model, and defined a downstream "normal depth" boundary condition, using the bed slope from the model data. This simple model of the upper Green River is intended to use flows and temperatures released from Howard Hanson reservoir, and using the same meteorological data, to route temperatures downstream to be compared with observations at the USGS streamflow gauge #12109500, located about 0.8 miles downstream of the dam.

3.7 Model Sensitivity Analysis and Initial Calibration

The period March 1-October 10, 2009 was used for model calibration and sensitivity analyses. The initial reservoir stages on March 1, 2009 was observed to be 334.0 m (1095.8 ft), and the initial reservoir water temperature was set to 3°C, based on observed outflow temperatures and

the assumption that the reservoir would be essentially isothermal at that time. Reservoir inflows and outflows (Figure 3-6), and inflow temperatures (Figure 3-7) were developed (as described in Section 2) from historic flow measurements adjusted to maintain an annual mass balance. The model's preprocessor indicated that at the starting elevation of 334.0 m (1095.8 ft) on March 1, 2009, the residence time of the reservoir is approximately two days. This provides ample model warm-up time that the initial conditions will not influence the results during the observation period.

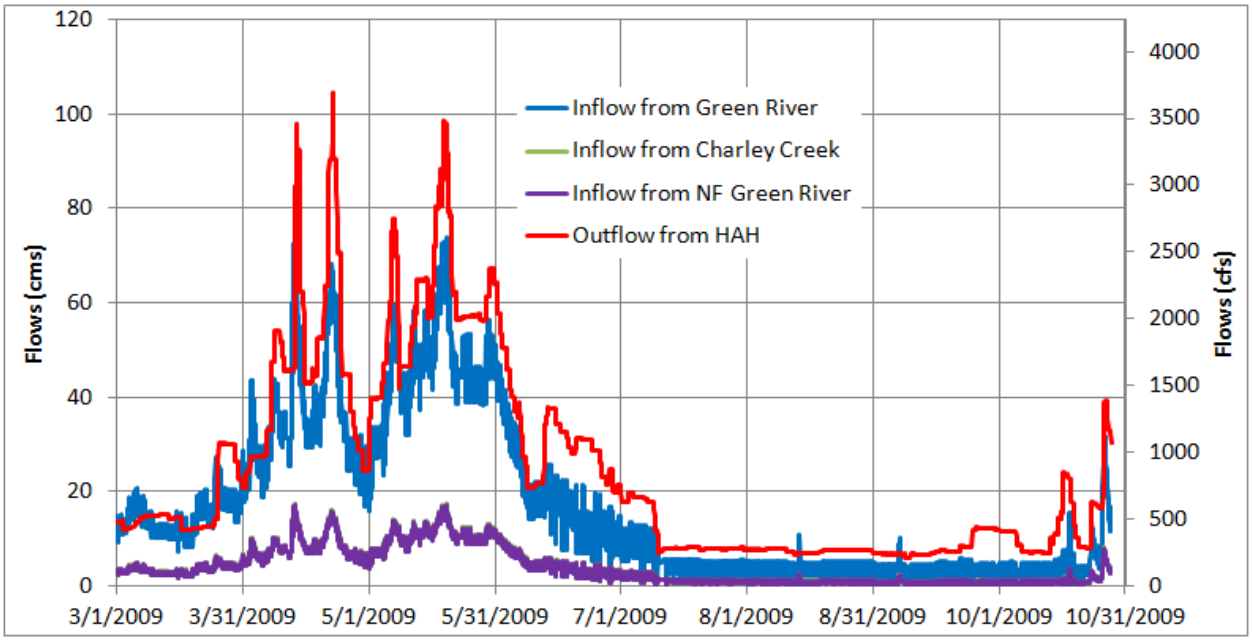

Figure 3-6. Inflows and Outflows for 2009 Calibration Period.

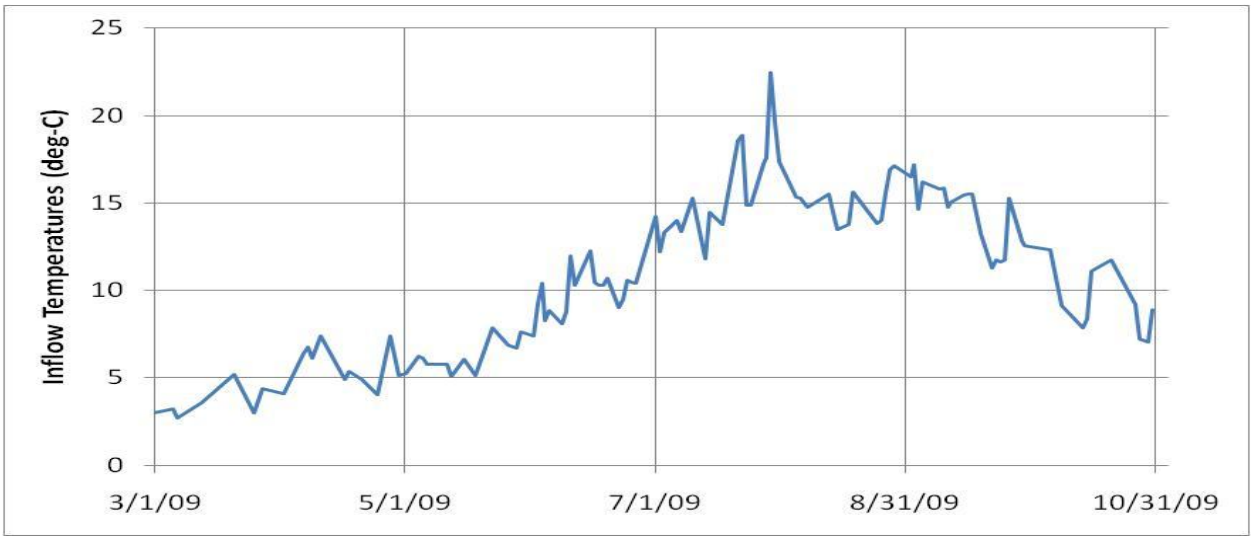

Figure 3-7. Inflows Temperatures for 2009 Calibration Period.

Once the initial CE-QUAL-W2 model of HAH Reservoir had been developed using default parameters, a sensitivity analysis was performed varying model parameters individually. The sensitivity analysis was performed for the calibration period of March-October 2009. Table 3-2 summarizes the simulations performed and the statistics obtained. The first row Table 3-2 shows default or starting values for the parameters evaluated. Statistics were developed for the four profile stations (Figure 2-4), and included the 8 profiles at all stations and the additional 12 (total of 20) profiles near the dam. The statistics were also evaluated over all the observations (all time periods and depths), and included mean error (ME), mean absolute error (MAE), and root mean square error (RMSE). Mean error (ME) was calculated as model results minus observed, and measures how much the model underestimates or overestimates actual temperatures as a whole. Generally, the ME should be close to zero. The mean absolute error (MAE) measured the average difference between model results and observation, regardless of whether the difference is positive or negative. Generally, the MAE should be minimized. The root mean square (RMSE) is another estimator of the difference between model results and observations, and is the square root of the variance. Again, RMSE should be minimized.

Table 3-2. Statistics for Sensitivity Analyses.

Solar Radiation Method	Shade	Wind sheltering	Horizontal Eddy viscosity	Min. vertical eddy viscosity	Vert. eddy viscosity method	Coefficient of bed exchange	Temperature of bed sediments	Fraction of bed heat returned	Extinction coefficient	ME	MAE	RMSE
ET	1	1	1	0.1	W2	0.3	10	0	0.45	0.76	1.06	1.30
TERM	1	1	1	0.1	W2	0.3	10	0	0.45	-0.18	1.17	1.93
ET	1	1	1	0.1	**W2N**	0.3	10	0	0.45	0.9	1.16	1.41
ET	1	1	1	**0.01**	W2	0.3	10	0	0.45	0.76	1.05	1.30
ET	1	1	1	**0.001**	W2	0.3	10	0	0.45	0.75	1.05	1.29
ET	1	1	1	0.1	W2	**7.0E-8**	10	0	0.45	0.81	1.11	1.37
ET	**0.9/0.7**	1	1	0.1	W2	0.3	10	0	0.45	0.03	0.72	0.96
ET	0.9/0.7	**0.6**	1	0.1	W2	0.3	10	0	0.45	-0.05	0.72	0.97
ET	0.9/0.7	**2**	1	0.1	W2	0.3	10	0	0.45	0.22	0.84	1.06
ET	0.9/0.7	**1.5**	1	0.1	W2	0.3	10	0	0.45	0.11	0.75	0.98
ET	0.9/0.7	1	1	0.1	W2	0.3	10	**1**	0.45	0.34	0.86	1.11
ET	0.9/0.7	1	1	0.1	W2	0.3	10	1	**0.6**	0.18	0.75	1.00
ET	0.9/0.7	1	1	0.1	W2	0.3	**8**	1	0.45	0.33	0.85	1.09
ET	0.9/0.7	1	1	0.1	W2	0.3	**12**	1	0.45	0.36	0.87	1.12

Sensitivity simulations looked at various methods to calculate vertical mixing, always using "implicit" methods. The analysis found that the simulations using different turbulence closure schemes became extremely slow without a significant improvement in the summary statistics. We also increased the bed roughness Mannings *n* from 0.025 to 0.035 with little difference in the model results.

The sensitivity analysis and visually comparing the resulting vertical temperature led to the conclusion that the parameters highlighted in green in Table 3-2 resulted in the best model calibration of temperatures. In addition, the shading multiplier was 0.9 in the upper reservoir and 0.7 in the more shaded lower pool, Charley Creek and the North Fork. The analysis concluded that the most sensitive model parameters are the solar shading coefficient, including bed heat exchange, and the light extinction coefficient.

Figure 3-8 compares observed temperatures downstream of HAH with releases from the dam. Also included on this figure are the inflow temperatures to obtain a perspective of how the reservoir modifies temperatures. Generally, the agreement is good, except during the later summer months (August and September) where the model over-predicts the released temperatures by 2-2.5^{o}C. As the water is released from HAH near the bottom of the reservoir, we wondered if this is an overall problem with outflow water balance because there is simply insufficient water stored in the reservoir to supply the observed cool water during the later summer months. In the model, the late-summer temperatures are almost vertically uniform, and all the cooler water near the reservoir bottom has been discharged downstream.

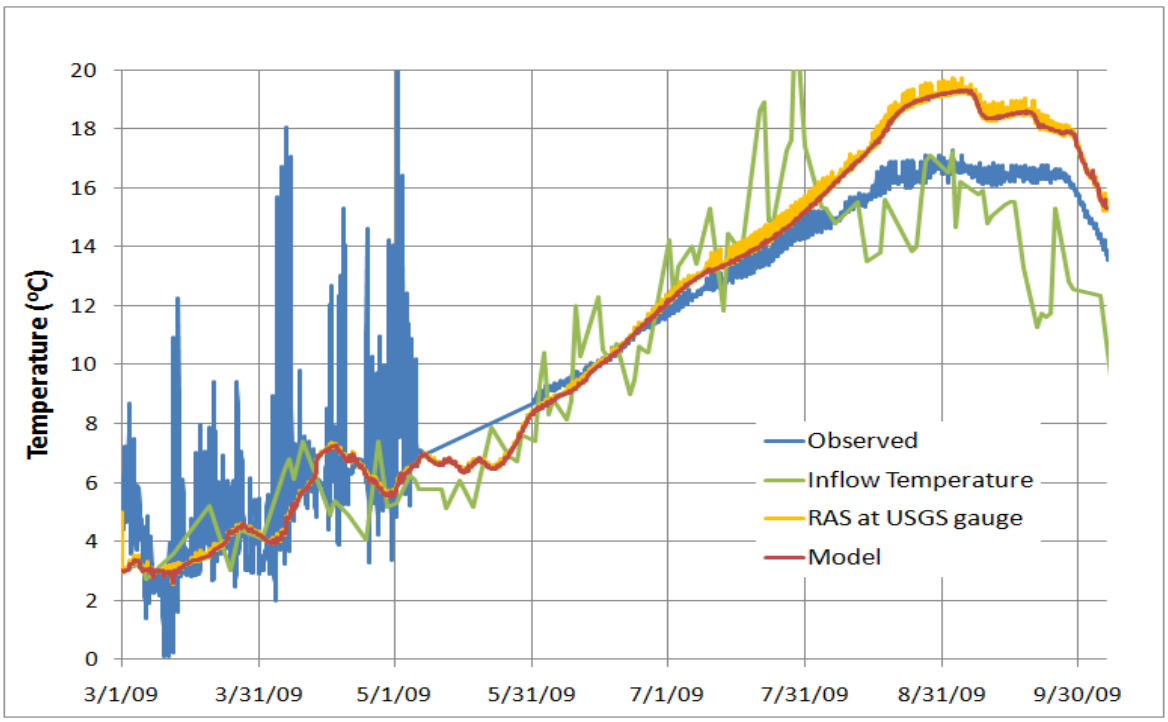

Figure 3-8. Comparison of modeled and observed downstream temperatures during 2009 calibration period.

Temperatures downstream of HAH Reservoir are measured at a USGS gauge located about 0.8 miles downstream. To confirm that there is little influence of thermal exchange in this short reach that might cause the difference in downstream temperatures observed, an HEC-RAS model of the upper Green River was obtained from the Seattle District and used to model flows and temperatures in the upper three miles of the Green River below HAH Dam.

Outflows and outflow temperatures were entered into the HEC-RAS model, and the same meteorological data used to model heat exchange. The orange line in Figure 3-8 shows the change in the modeled releases (red line) at the location of the USGS temperature gauge. The results show little change in the average water temperatures but do show the same diurnal variations seen in the observations.

3.8 Initial Temperature Validation

The year 2005 was identified for model validation because the input data coverage was fair, and there are eight times when vertical profiles of in-pool temperatures were measured at the main four sampling stations (Table 2-1 and Figure 2-4). The period March 17-December 29, 2005 was selected because by March 17 the pool was sufficiently full that the two tributaries (Charlie Creek and NF Green River) were partially connected to the pool. Even though the first in-pool observation was on April 26, 2005, the W2 pre-processor results indicated very short residence times at pool elevations in mid-March. The observed starting pool elevation was 331.97 m (1,089.14 ft) on March 17, and the initial pool temperature was specified as 7°C from observations of outflow temperatures and assuming that the reservoir would by isothermal in March.

Figure 3-9 compares the modeled outflow temperatures with measurements at the USGS temperature gauge located about 0.8 miles downstream of HAH Dam. Also included in the figure are results from the HEC-RAS model of flows and temperature releases from the dam. As for the 2009 calibration period, the results compare fairly well with observations until the late summer (August and September) when the release temperatures increase considerably as all the cooler water has been discharged from the reservoir.

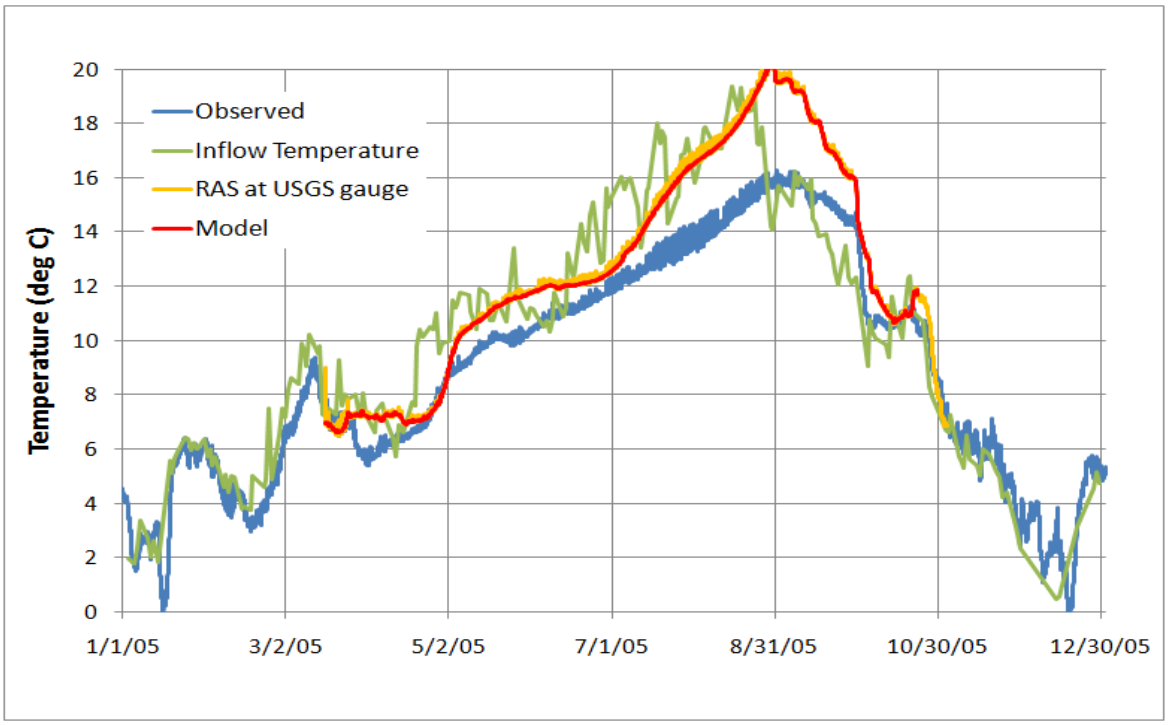

Figure 3-9. Comparison of modeled and observed downstream temperatures during 2005 validation period.

To examine this issue further, the year 2007 was also simulated because it had more frequent inflow temperature measurements in the Green River. However, there were only five times when vertical profiles of in-pool temperatures were measured at the main four sampling stations (Table 2-4 and Figure 2-4). The period March 5-October 31, 2007 was selected because by March 5 the pool was sufficiently full that the two tributaries (Charlie Creek and NF Green River) were partially connected to the pool. The observed starting pool elevation was 332.69 m (1,091.50 ft) on March 5, and the initial pool temperature was specified as 4°C from observations of outflow temperatures and assuming that the reservoir would by isothermal in March.

Figure 3-10 compares the modeled outflow temperatures with measurements at the USGS temperature gauge located about 0.8 miles downstream of HAH Dam. Also included in the figure are results from the HEC-RAS model of flows and temperature releases from the dam. As for the 2009 calibration period and the 2005 validation period, the results compare fairly well with observations until the late summer (August and September) when the release temperatures increase considerably as all the cooler water has been discharged from the reservoir. In-pool temperature profiles (not shown) show a similar pattern as for the 2009 and 2005 observations.

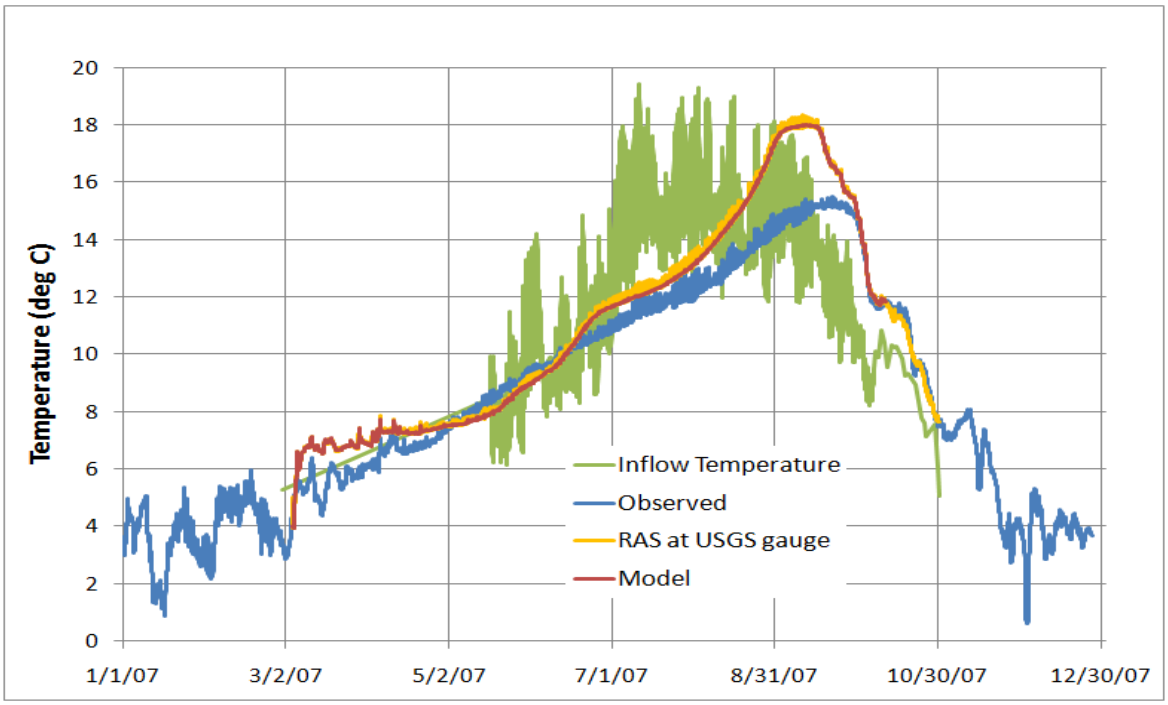

Figure 3-10. Comparison of modeled and observed downstream temperatures during 2007 validation period.

3.9 Revised Calibration and Validation

In the 2005, 2007, and 2009 simulations, it appeared that the model "ran out of" cooler water before the fall atmospheric cooling, and therefore over-predicted late summer water temperatures released from the HAH Reservoir. Early in the reservoir filling period (March-June), release temperatures are generally the same as inflow temperatures, as inflows are large and the residence time relatively short. Later in the summer (July through August), inflows decrease significantly, and have a smaller effect than heat exchange with the atmosphere, as residence times are now relatively large.

One possible mechanism considered was that the light extinction coefficient, λ, used in CE-QUAL-W2, is too small. The sensitivity analysis did confirm that this is a sensitive parameter, as is the solar "shading" coefficient. The final model calibration uses the default value of 0.45 (when only temperature is being modeled). Larger values of the extinction coefficient tend to decrease the summer peak temperatures, but also decrease early summer temperatures as well. Decreasing the solar "shading" coefficient has a similar affect, and we felt we could not justify values smaller than 0.9 in the open pool areas because solar radiation was measured nearby in a similar topographic region.

To explore whether the light extinction coefficient, λ, was of the right order of magnitude, we used the equation:

$$\lambda = 1.11\ Z_s^{-0.73}$$

in the CE-QUAL-W2 user manual (Cole and Wells, 2008), where Z_s is the Secchi disk reading in meters. Data provided by the Seattle District reported Secchi disk depths in the range 6-29 feet (2-5 m), with the majority of the readings exceeding 10 feet (3 m). From Table 3-3, it can be seen that the default value of 0.45 is reasonable for a system with Secchi disk depths exceeding 10 feet (3 m). Further, a discussion with Seattle District staff and the data themselves show no obvious annual "event", such as a late-summer algal bloom, that might tend to significantly decrease water clarity at that time.

Table 3-3. Light extinction coefficients as a function of Secchi disk depths

Secchi disk depth (m [ft])	Light extinction coefficient
2 (6.6)	0.66
3 (9.8)	0.49
4 (13.1)	0.40
5 (16.4)	0.34
Default in CE-QUAL-W2	0.45

As we further investigated the possible cause of the high modeled peak release temperatures, we noted that most of the inflow temperatures were measured a short distance upstream in the Green River from the upper reservoir pool, and that at high pool levels, the reservoir might inundate the measurement location. In addition, it was thought possible that the manual measurements, taken only once per day, but also near the river's bank in an area where the water is shallow, might over-estimate the actual river inflow temperatures.

To test this idea, during August-October 2010, the Seattle District deployed four pairs of in-situ temperature probes in the Green River upstream of the reservoir. Pairs were deployed near each bank of the river in the general vicinity of the usual measurement location, and additional pairs were deployed near each bank but further upstream beyond the backwater of the summer high pool elevation. Figure 3-11 shows that the upstream and downstream temperature observations were very similar except at one location – the more downstream measurements on the north side of the river (red line in Figure 3-11). There is no clear explanation as to why both temperature probes measured the same "different" temperatures at this location.

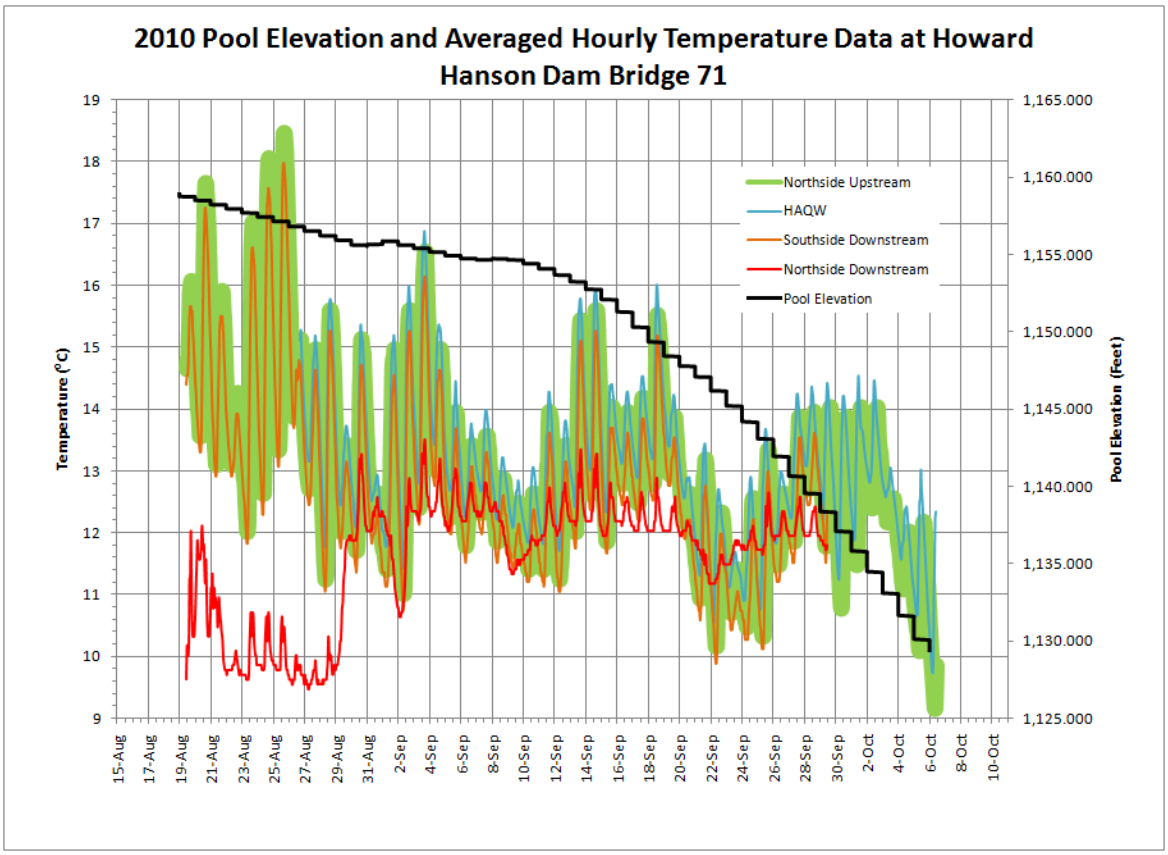

Figure 3-11. Observed temperatures in Green River inflow during August-October 2010.

In addition, we note that there are no temperature measurements in Charley Creek or the North Fork. Discussions with Seattle District personnel led to the hypothesis that water temperatures in local inflows to HAH Reservoir, including Charley Creek and the North Fork, were probably somewhat lower than measured in the Green River as these tributaries are more shaded and that there could be a significant groundwater inflow. This was initially examined by comparing the measured inflow temperatures from the Green River with the deepest observations at in-pool profile locations in the upper pool (9UPNR), North Fork (5NFK), and Charley Creek (5CHCK) for 2005, 2007, and 2009. The comparisons are shown in Figure 3-12, Figure 3-13, and Figure 3-14.

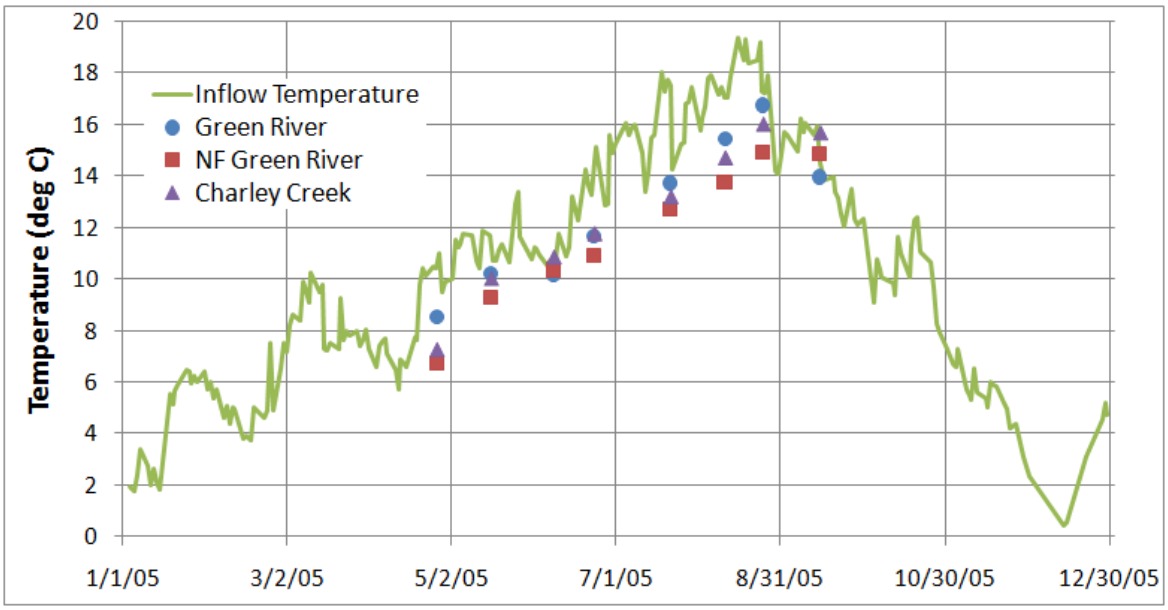

Figure 3-12. Comparison of inflow and deep in-pool temperatures during 2005.

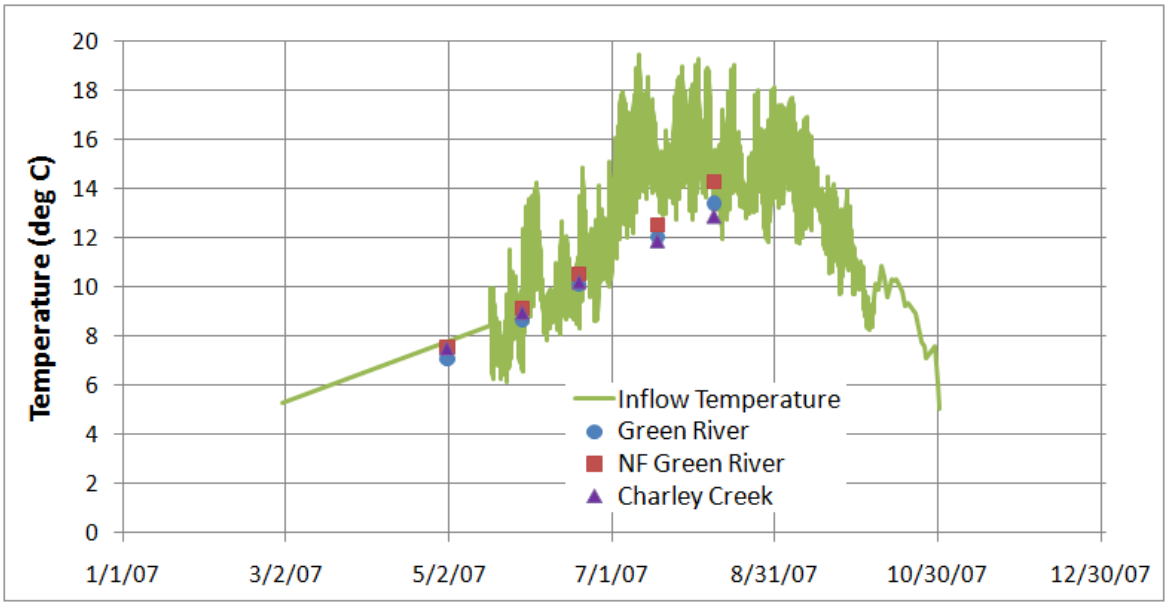

Figure 3-13. Comparison of inflow and deep in-pool temperatures during 2007.

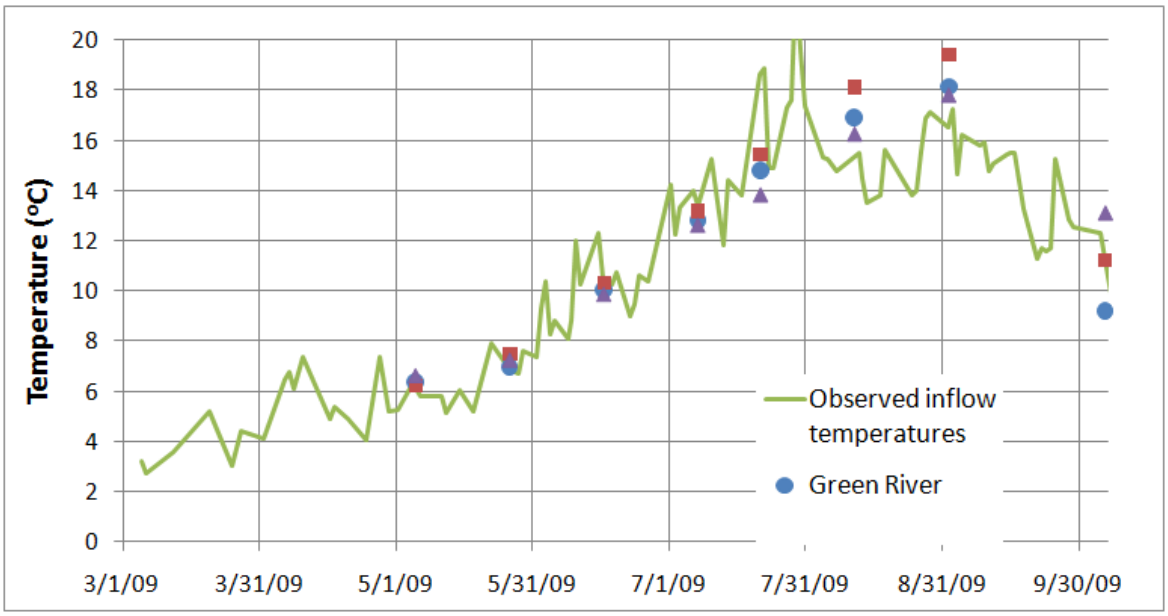

Figure 3-14. Comparison of inflow and deep in-pool temperatures during 2009.

The comparison shows that the deeper in-pool temperatures are generally lower than the inflow temperatures measured in the Green River. This could be remnant water from earlier (colder) months in the reservoir. However, these locations are relatively close to the inflow points to the reservoir. To test this hypothesis, the Seattle District examined available groundwater information, and estimated a range of possible groundwater inflows from the Green River and from the North Fork. The information available suggested that there would be little groundwater inflow from Charley Creek. A memo prepared by the Seattle District is included as Appendix 4.

After some initial testing, we decided to use the maximum groundwater inflow estimate of 2.5 m^3/s (88.3 cfs), and distributed the groundwater inflows as 2 m^3/s (70.6 cfs) from the Green River valley and 0.5 m^3/s (17.7 cfs) from the North Fork. Having no measurements of groundwater temperatures, we adopted the common rule-of-thumb that the groundwater temperature is approximately equal to the average annual air temperature. Analyzing the air temperature data at the dam, the average air temperature is very close to 9°C. To simulate these inflow conditions, we modified the input temperatures from the Green River and the North Fork to include flows of 2 m^3/s and 0.5 m^3/s at 9°C, respectively.

Additional testing found that this did reduce the excess peak release temperatures somewhat, but not enough to match observations. At this point, we uncovered an older study of temperature modeling in Howard Hanson reservoir using a one-dimensional, vertical model (Schneider and Price, 1988). In that study, they reported using a value of the surface absorption coefficient, β, of 0.85. In the CE-QUAL-W2 manual (Cole and Wells, 2008), and in all examples they provide, the "default" value of β is 0.45. To test this, we reran the models with β=0.85, and found that this did significantly decrease the peak release temperatures. Therefore, the final model calibration and validation was achieved using the estimated groundwater inflows and the parameters shown in Table 3-4, which included small adjustments to some other parameters.

Table 3-4. Statistics for Final Model Calibration.

Solar Radiation Method	Shade	Wind sheltering	Horiz. Eddy viscosity	Min. vert. eddy viscosity	Vert. eddy viscosity method	Coefficient of bed exchange	Temperature of bed sediments	Fraction of bed heat returned	Extinction coefficient	Fraction of solar absorbed at surface	ME	MAE	RMSE
ET	1/0.8	1	1	0.1	W2	0.3	9	1	0.45	0.85	-0.48	0.98	1.32

Figure 3-15 shows the revised and final calibration for 2009. While the statistics in Table 3-4 are not a good as in Table 3-2, the summer peak temperatures are significantly improved. Figure 3-16 shows the revised validation for 2005, and Figure 3-17 shows the revised validation for 2007. In both cases, the model peak summer temperature releases are significantly reduced and much closer to those observed. Table 3-5 compares observed and computed vertical temperature profiles at stations in the reservoir. The table shows that the statistics between stations are similar, and that they are similar between the years modeled. Table 3-6 compares observed and computed temperature time series at the location of the USGS streamflow gauge located about 0.8 miles downstream of the dam. The statistics for the 2009 calibration period and the 2007 validation period are similar, are confirm that the model is accurate within about 1°C. The statistics for the 2005 simulation, however, are influenced by the model's over-prediction of the summer peak release temperatures, and the general over-prediction of late-spring release temperatures as well.

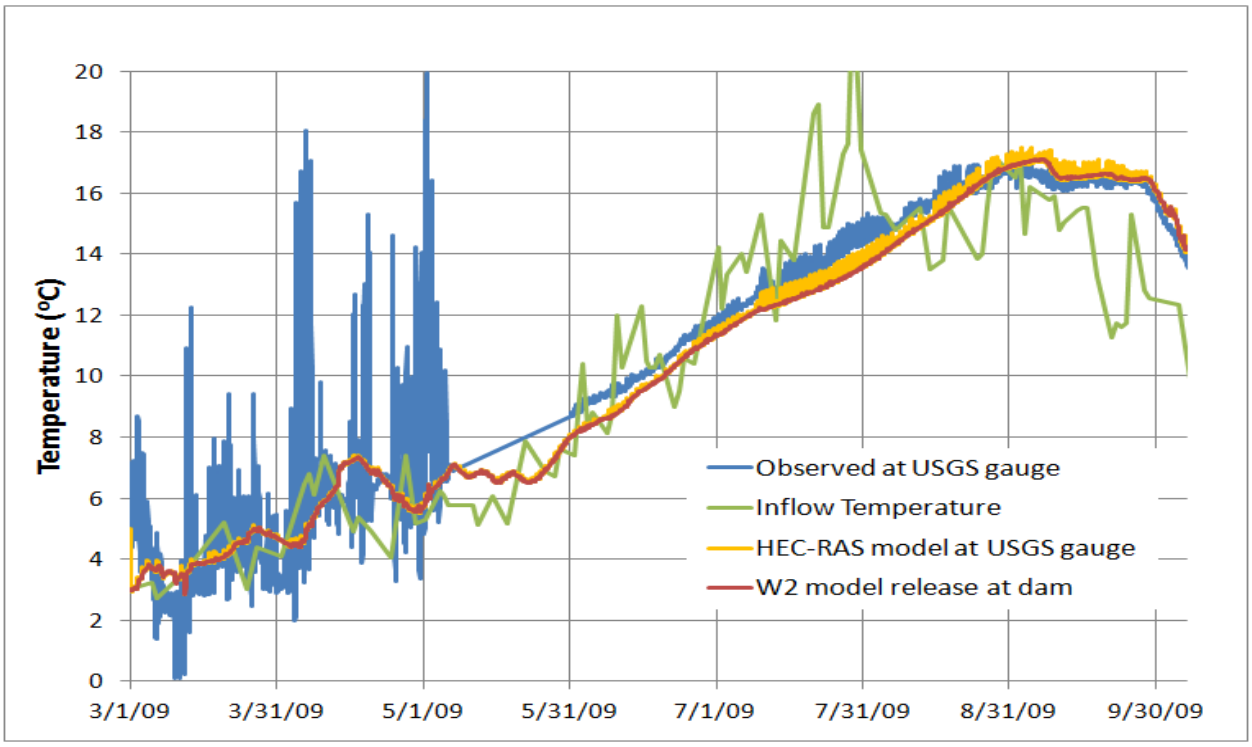

Figure 3-15. Final Calibration for 2009 using groundwater inflows and revised parameters.

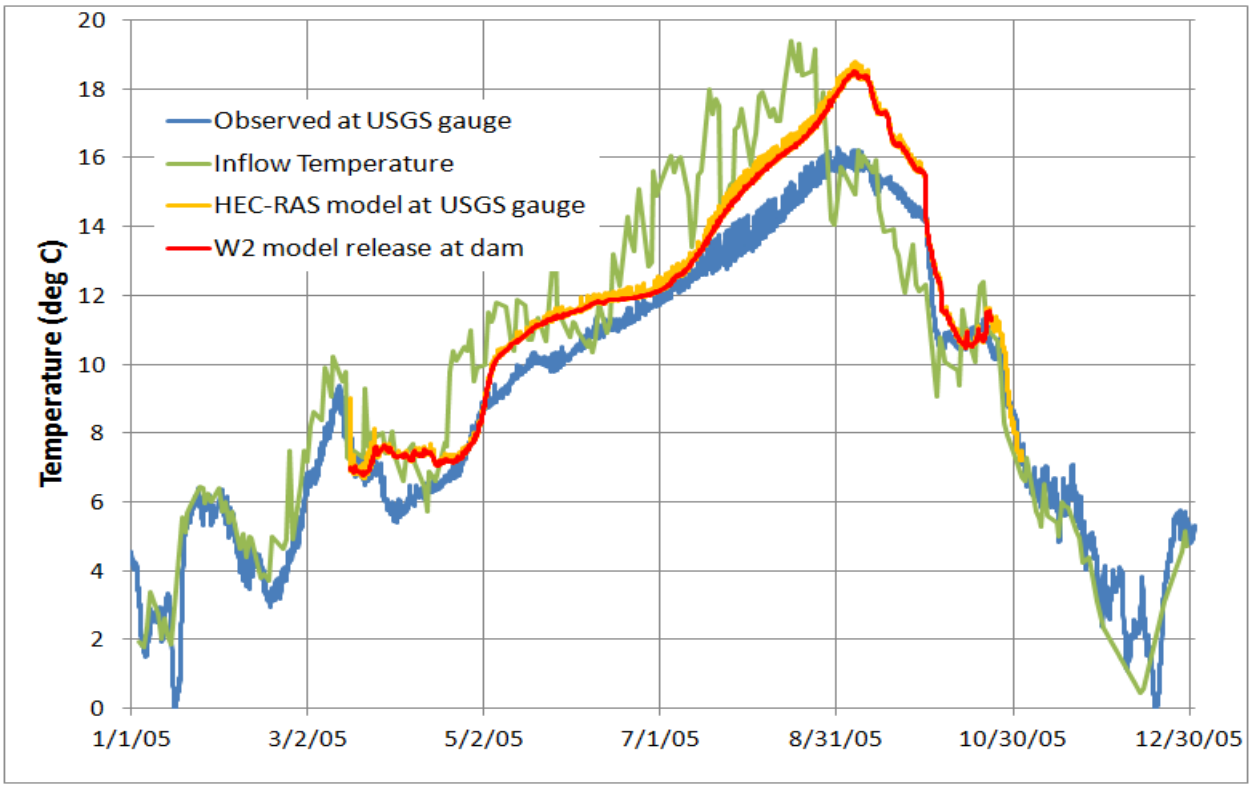

Figure 3-16. Final Validation for 2005 using groundwater inflows and revised parameters.

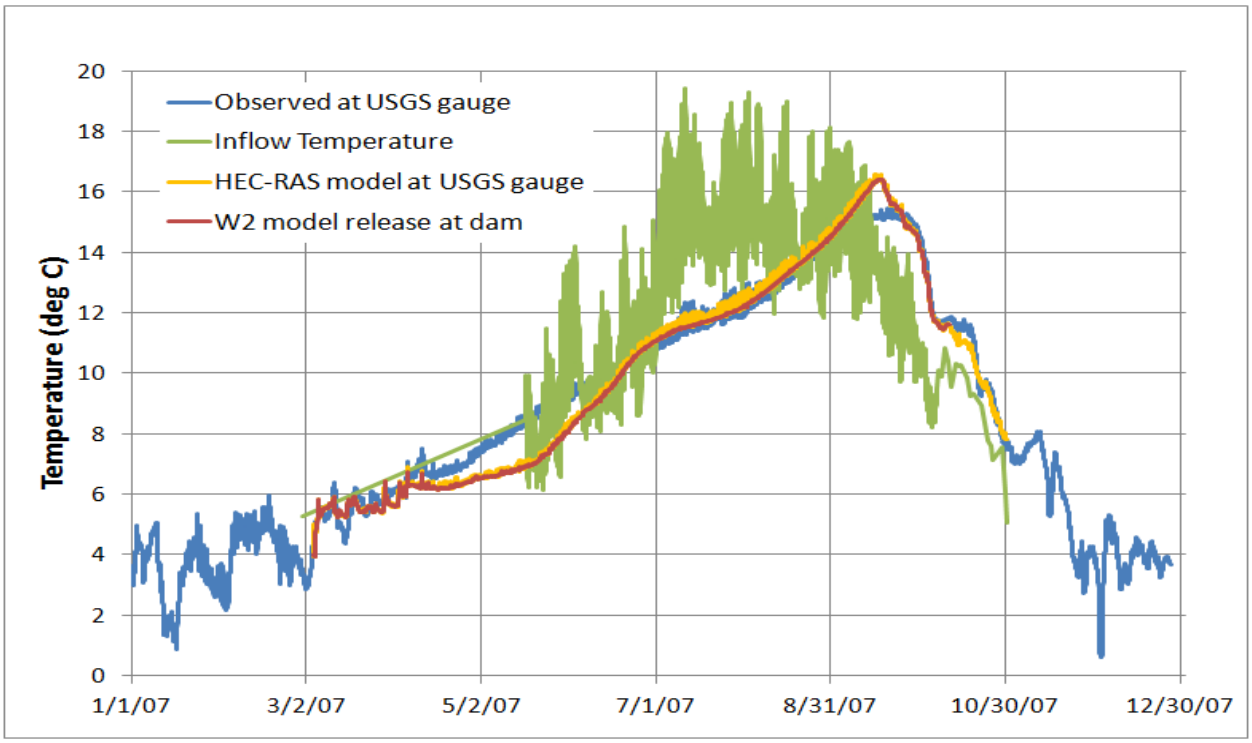

Figure 3-17. Final Validation for 2007 using groundwater inflows and revised parameters

Table 3-5. Statistics for Vertical Temperature Profile Comparison

Year	Site	Model Segment #	Mean Error (ME)	Mean Absolute Error (MAE)	Root Mean Square Error (RMSE)
2009	1DAM	30	-0.64	0.95	1.28
	9UPNR	11	-0.47	1.17	1.57
	SCHCK	38	-0.81	1.16	1.49
	5NFK	45	-0.96	1.28	1.56
	All stations		-0.72	1.09	1.42
2005	1DAM	30	0.45	0.91	1.09
	9UPNR	11	0.22	1.04	1.28
	SCHCK	38	0.05	0.95	1.19
	5NFK	45	0.43	1.00	1.21
	All stations		0.31	0.97	1.18
2007	1DAM	30	-0.42	0.71	0.92
	9UPNR	11	-0.99	1.08	1.40
	SCHCK	38	-1.03	1.08	1.35
	5NFK	45	-1.17	1.19	1.46
	All stations		-0.68	0.87	1.14

Table 3-6. Statistics for Time Series Comparison at Downstream USGS Temperature Gauge

Year	No. of Comparisons	Mean Error (ME)	Mean Absolute Error (MAE)	Root Mean Square Error (RMSE)
2009	667	-0.29	0.53	0.37
2005	504	1.10	1.25	2.24
2007	581	-0.16	0.56	0.70

4 Temperature Blending

When the modeling project started, the District was considering the constructing of a fish passage facility with a multiple outlet structure ("tower") that could discharge water from the reservoir to the Green River. The purpose of the multi-port tower was to provide the ability to blend water between the two existing low-level outlets and near-surface outlets from the multi-port tower. Currently, the District is considering the possibility of adding a "floating" outlet that could blend the at-surface warmer water with near-bottom cooler water through the existing outlets.

4.1 Modifications to CE-QUAL-W2

Recently, CE-QUAL-W2 version 3.7 (beta) was developed to include the capability of discharging water through a structure's outlets to meet user-specified temperature targets. The "blending" algorithm was designed to handle a number of configurations and control options. There are three main configurations. Figure 4-1 shows the blending between two fixed outlets. This is a common feature of many of the existing Corps projects in the Oregon Cascades. In this option, if the upper outlet elevation is above the water surface, it is automatically lowered to the water surface, thus simulating a "floating" outlet. Figure 4-2 shows the single release from a multi-port tower that allows water to be withdrawn from a number of reservoir pool elevations. Figure 4-3 shows the combinations of withdrawals from a single fixed outlet and a multi-port tower.

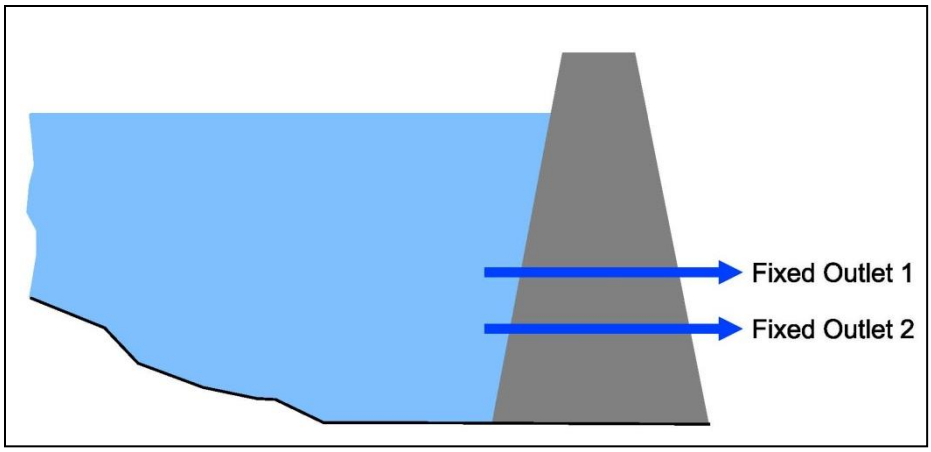

Figure 4-1. Schematic blending between two fixed outlets.

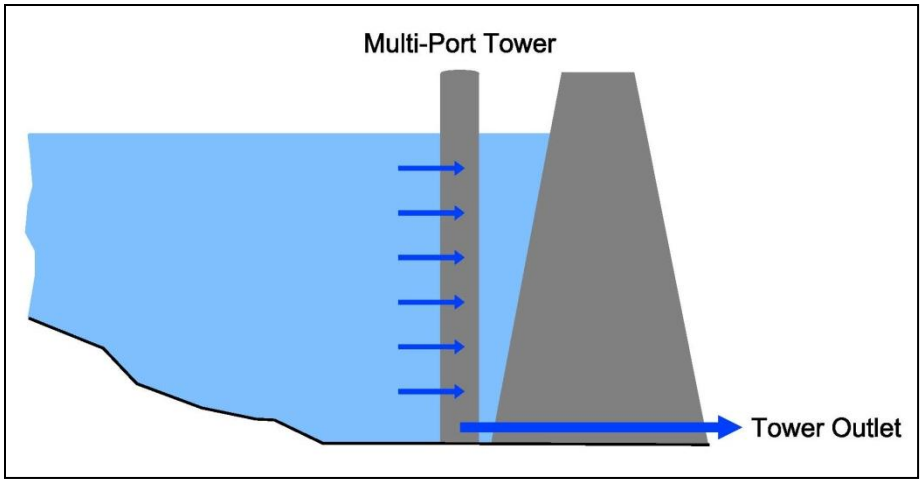

Figure 4-2. Schematic outflow from multiport tower.

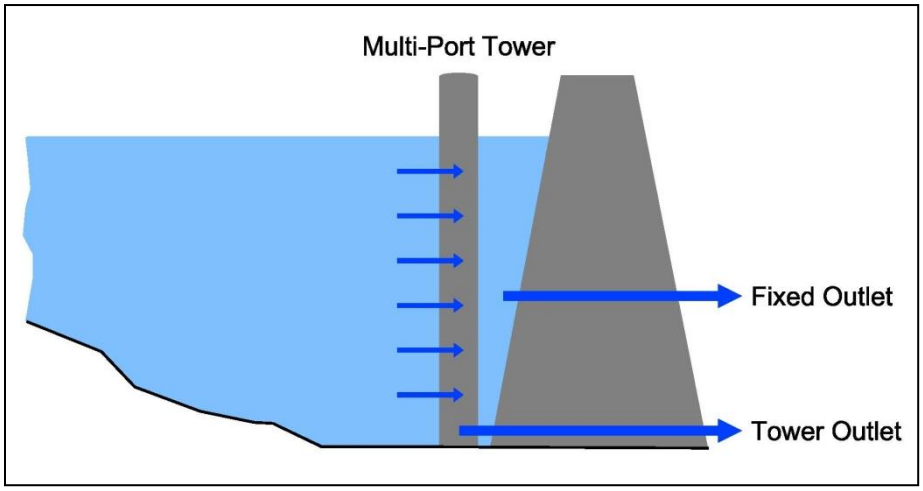

Figure 4-3. Schematic blending between a fixed outlet and a multi-port tower.

4.2 Selection of Years to Simulate and Temperature Targets

The District asked the study team to model three years with specified combinations of summer maximum air temperatures and average annual inflows. Air temperature and reservoir inflow data for 1962-2009 were analyzed and average annual daily maximum temperatures calculated for the period May-September of each year. Table 4-1 lists the average of the daily maximum summer high temperatures, its variance from the long-term mean, the average annual inflow, its variance from the long-term mean, and a "score" computed as the sum of the normalized variance in air temperatures and inflows. In each category, we evaluated several candidate years for (1) years with average air temperatures and average inflows (highlighted in yellow in Table 4-1), (2) years with low air temperatures and average inflows (highlighted in blue in Table 4-1), and (3) years with high air temperatures and low inflows (highlighted in red in Table 4-1).

Recognizing that no inflows water temperature measurements were available before 1994 and no solar radiation data were available before 2002, we selected the following years for each category:

- 2007 as the year with average air temperatures and average annual inflows
- 2001 as the year with low air temperatures and average annual inflows
- 2003 as the year with high air temperatures and low average annual inflows

Table 4-1. Summary of air temperatures and inflows to Howard Hanson Reservoir

Year	Average Max air temperature (°F)	Variance in air temperatures (°F)	Annual average inflows (cfs)	Variance in inflows (cfs)	Weighted normalized average
1962	64.1	-3.1	527	-99	0.44
1963	65.4	-1.8	434	-192	0.39
1964	63.6	-3.6	1284	658	1.06
1965	66.3	-1.0	507	-119	0.22
1966	66.1	-1.2	619	-7	0.13
1967	71.8	4.5	638	12	0.50
1968	66.3	-0.9	647	21	0.12
1969	67.6	0.4	820	194	0.23
1970	67.3	0.1	573	-53	0.06
1971	66.9	-0.3	1032	406	0.45
1972	66.6	-0.7	1129	503	0.58
1973	67.1	-0.1	408	-218	0.23
1974	67.7	0.4	1228	602	0.65
1975	66.0	-1.2	964	338	0.47
1976	64.6	-2.6	751	125	0.41
1977	66.9	-0.3	463	-163	0.20
1978	65.9	-1.3	476	-150	0.29
1979	68.8	1.5	476	-150	0.32
1980	64.4	-2.8	439	-187	0.49
1981	66.3	-0.9	601	-25	0.12
1982	67.0	-0.2	628	2	0.03
1983	65.2	-2.0	496	-130	0.35
1984	66.0	-1.3	719	93	0.23
1985	71.1	3.8	608	-18	0.43
1986	70.0	2.8	482	-143	0.45
1987	71.2	3.9	375	-251	0.68
1988	67.4	0.1	545	-81	0.10
1989	69.2	1.9	446	-180	0.39
1990	71.2	4.0	654	28	0.46
1991	68.3	1.1	519	-107	0.22

1992	70.5	3.3	296	-330	0.69
1993	66.2	-1.0	668	42	0.16
1994	69.1	1.9	359	-267	0.47
1995	66.6	-0.6	350	-276	0.35
1996	65.1	-2.2	413	-212	0.45
1997	67.2	0.0	920	295	0.30
1998	66.4	-0.9	443	-183	0.28
1999	62.5	-4.7	741	115	0.63
2000	64.7	-2.5	613	-13	0.28
2001	63.5	-3.8	583	-43	0.45
2002	66.3	-0.9	806	180	0.28
2003	71.6	4.3	335	-291	0.76
2004	68.9	1.7	572	-54	0.24
2005	68.4	1.1	393	-232	0.36
2006	70.5	3.3	558	-68	0.42
2007	67.9	0.7	460	-166	0.24
2008	64.9	-2.3	1258	632	0.89
2009	70.8	3.5	787	161	0.54

The District provided the following set of temperature targets for the model simulations:

- 13°C between January 1 and July 1
- 16°C between July 2 and September 14
- 13°C between September 15 and December 31

4.3 Setup of Blending Alternatives

CE-QUAL-W2 version 3.7 (beta) can model a multi-port tower with up to 10 ports at user-specified fixed elevations. Examining the observed reservoir stages for the years to be simulated (2001, 2003, and 2007), we determined this range to be approximately 340-355 m. Therefore, we defined a multi-port tower with 8 port elevations at 2 m (6.6 ft) intervals between elevation 340 m (1115.5 ft) and 354 m (1161.4 ft) , and added the existing two lower elevations of 320.5 m (1051.5 ft) and 326.0 m (1069.6 m). To simulate the three proposed years using this "multi-port tower", we modified the model's "control" file to include the "selective withdrawal" option.

In the second alternative, we simulated the combination of a "floating" outlet and a single low-level outlet at 320.5 m (1-51.5 ft) , the elevation of the dam's current major outlet. We specified the elevation of the second outlet at 360 m (1181 ft), so that it would always be above the water surface, and therefore automatically lowered by the model to the water surface, simulating a "floating" outlet. The existing outflows were defined to be "split" between these two outlets in the "selective withdrawal" file.

4.4 Simulation of Average Air Temperatures and Average Inflows

2007 was selected as the year in the period of record that most closely approximated conditions with average annual air temperatures and average annual inflows. Figure 4-4 compares the release temperatures with existing conditions, inflow temperatures, and the temperature targets, Figure 4-5 shows the "tower" elevations selected by the model to meet the release temperature targets, and Figure 4-6 shows the flow distribution between the "floating" and low-level outlets for the "split" option. The results demonstrate that either structure type would be able to meet temperature targets throughout the year for this "average" condition. In addition, Figure 4-6 shows that the strategy would be to discharge water from near the reservoir's surface for as long as possible, until the surface layer exceeds the temperature target, and then to blend the near-surface water with some deeper, cooler, water during the peak of the summer, mid-July to late September.

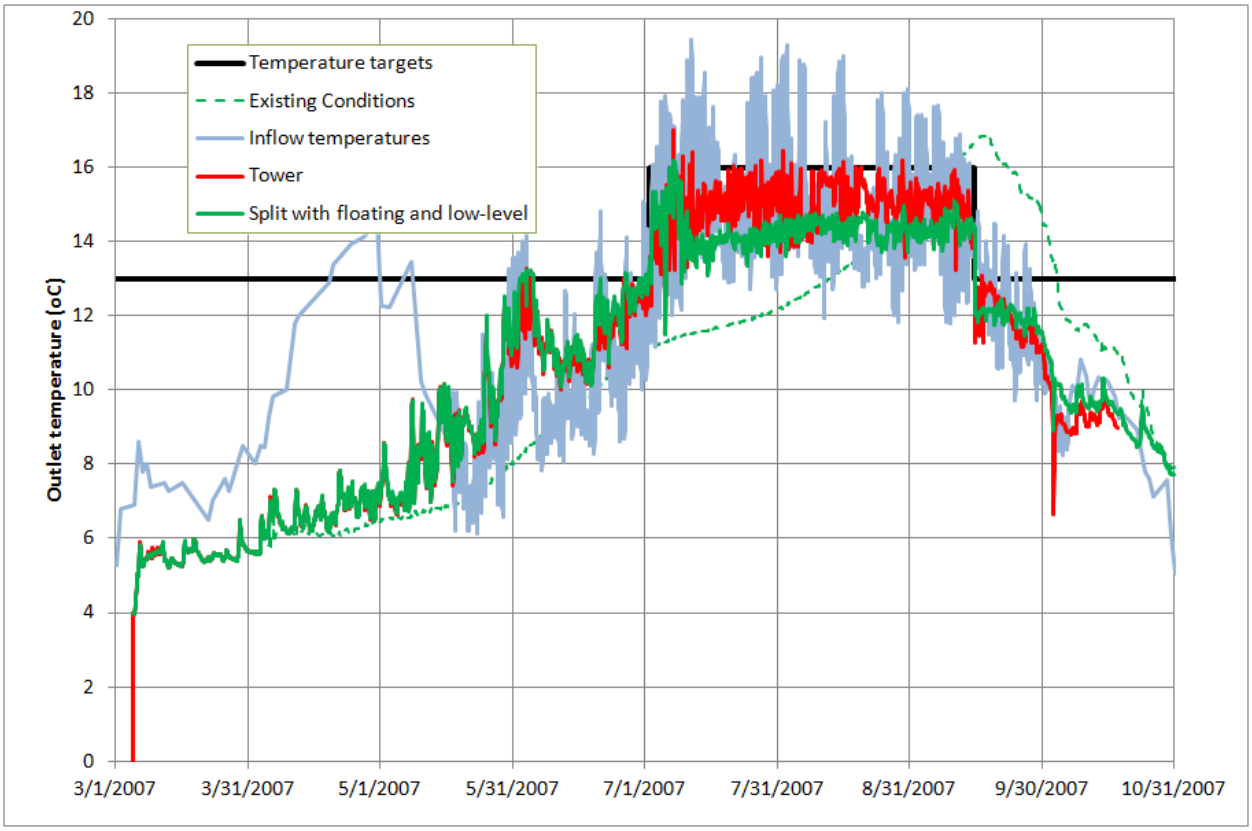

Figure 4-4. Release Temperatures for 2007 (Average Air Temperatures and Average Inflows)

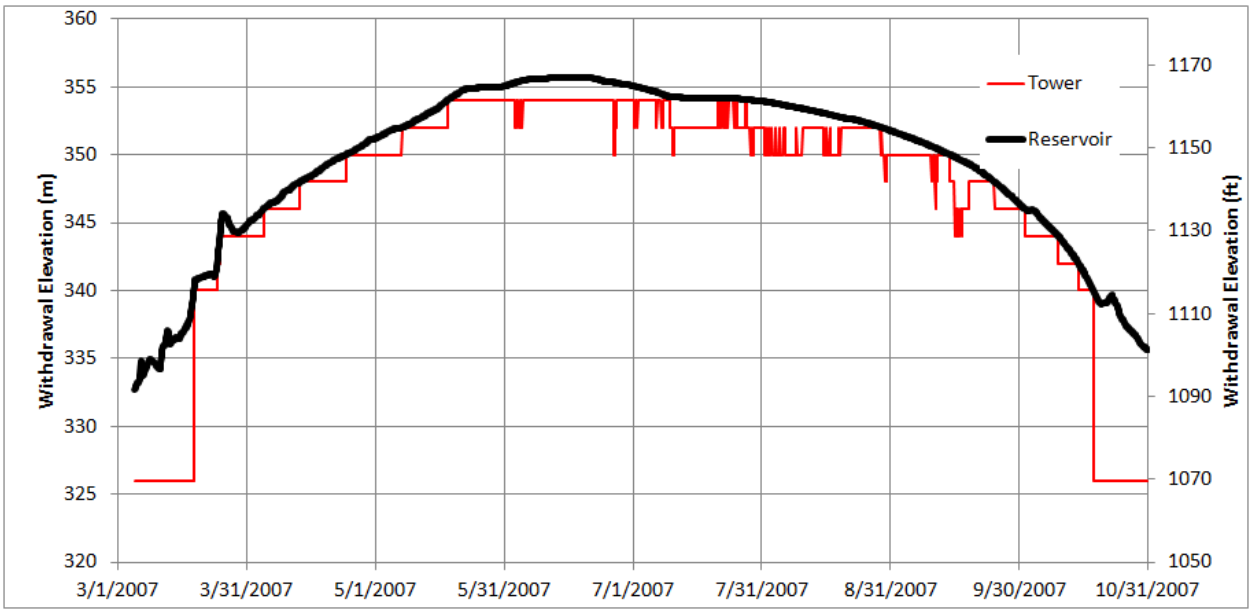

Figure 4-5. Release "Tower" Elevations for 2007 (Average Air Temperatures and Average Inflows)

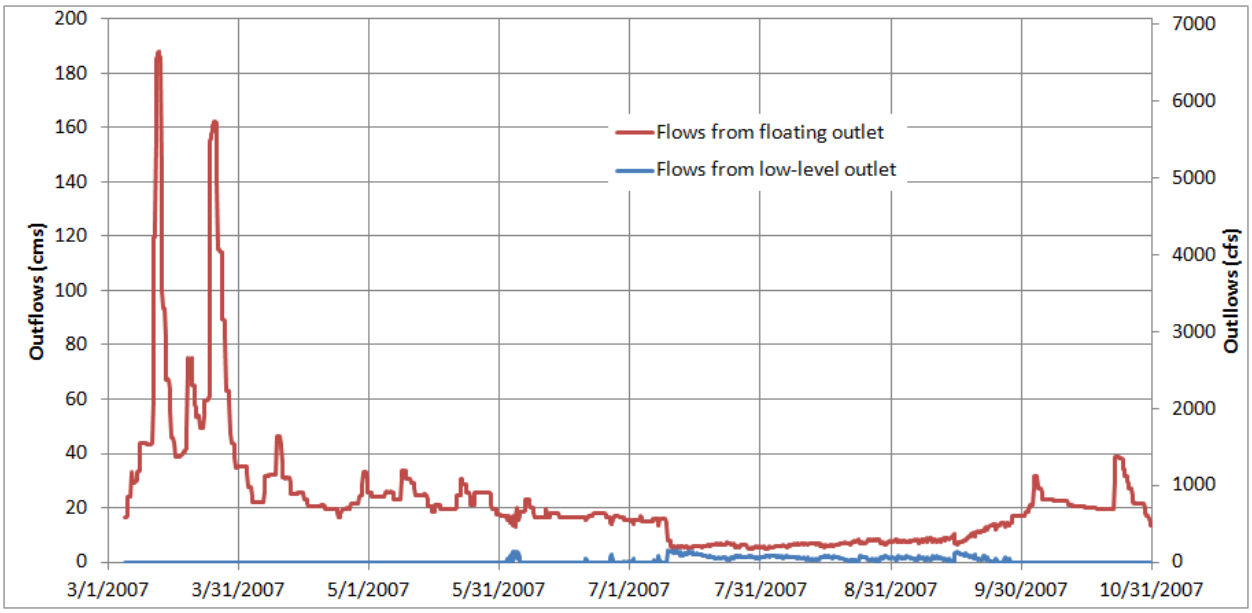

Figure 4-6. "Split" Outflows for 2007 (Average Air Temperatures and Average Inflows)

4.5 Simulation of Low Air Temperatures and Average Inflows

2001 was selected as the year in the period of record that most closely approximated conditions with low annual air temperatures and average annual inflows. Solar radiation data were not available for 2001, and so cloud cover was used in the model to simulate all forms of incident radiation. Figure 4-7 compares the release temperatures with existing conditions, inflow temperatures, and the temperature targets, Figure 4-8 shows the "tower" elevations selected by

the model to meet the release temperature targets, and Figure 4-9 shows the flow distribution between the "floating" and low-level outlets for the "split" option. The results demonstrate that either structure type would be able to meet temperature targets throughout the year for this "low temperature" condition, with very little need to blend the near-surface water with near-bottom water. In addition, Figure 4-9 again shows that the strategy would be to discharge water from near the reservoir's surface for as long as possible, until the surface layer exceeds the temperature target, and then to blend the near-surface water with some deeper, cooler, water during the summer.

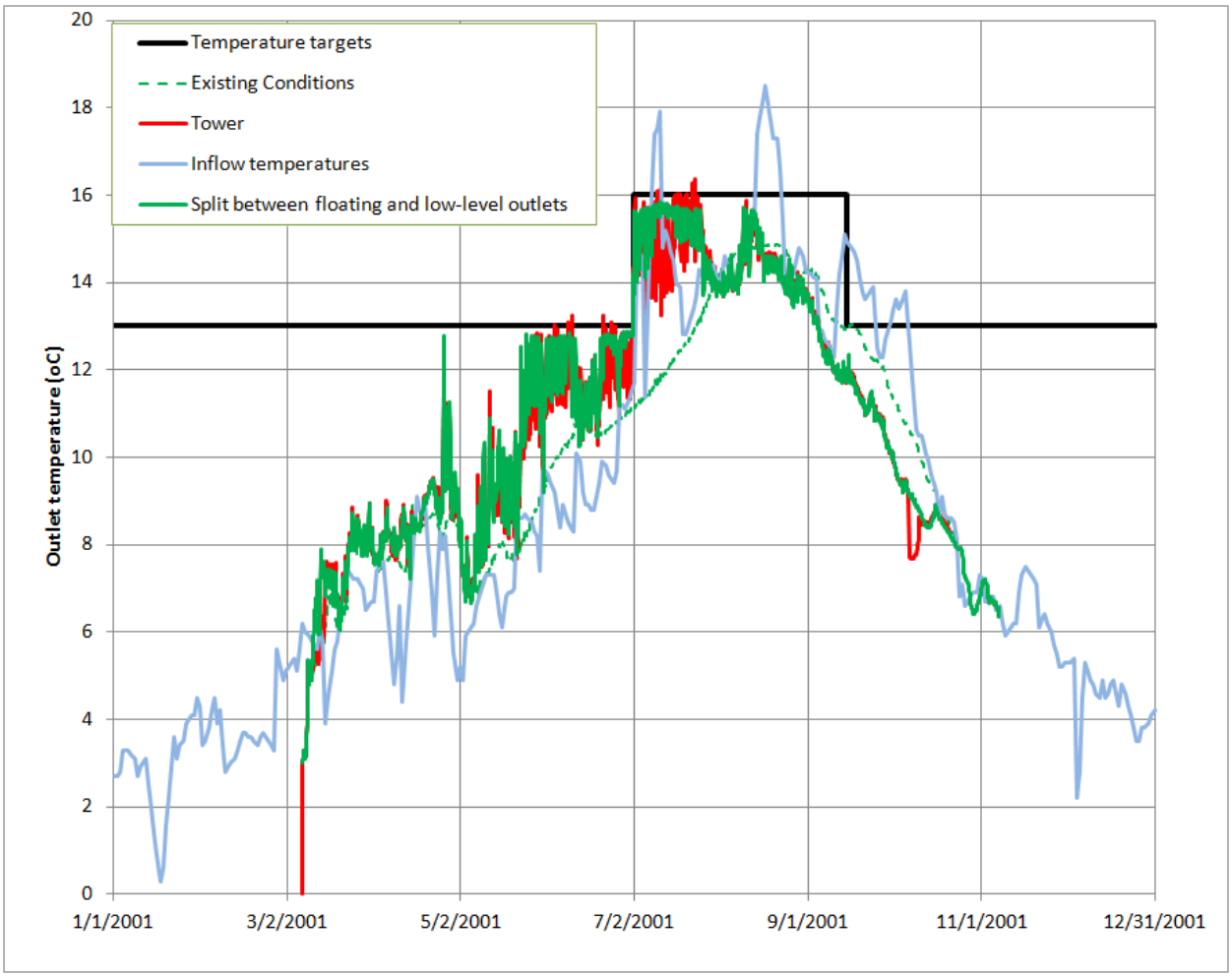

Figure 4-7. Release Temperatures for 2001 (Low Air Temperatures and Average Inflows)

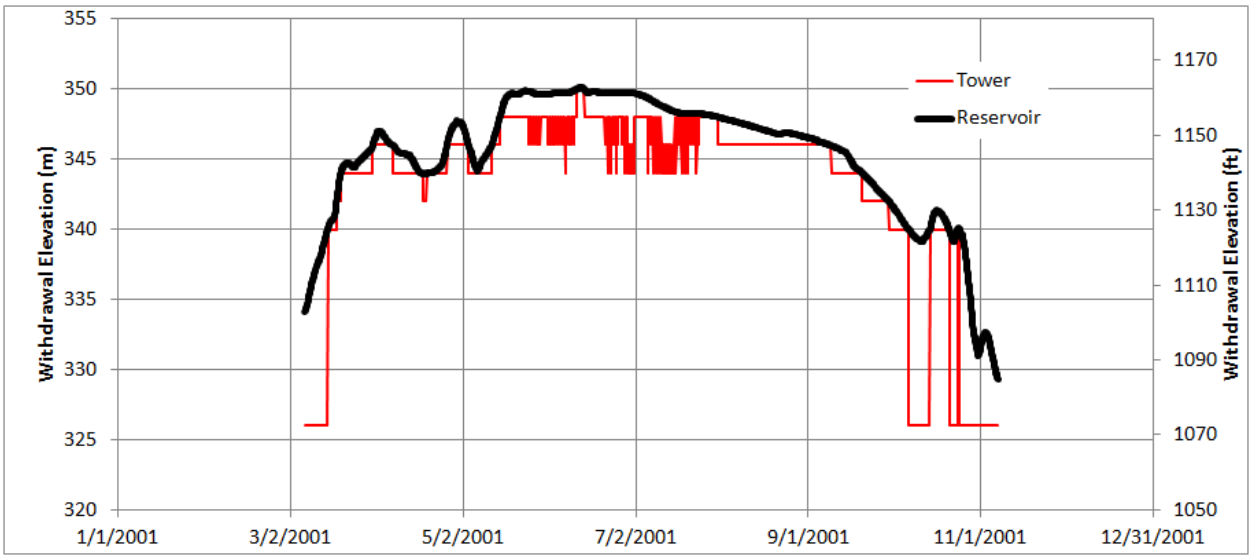

Figure 4-8. Release "Tower" Elevations for 2001 (Low Air Temperatures and Average Inflows)

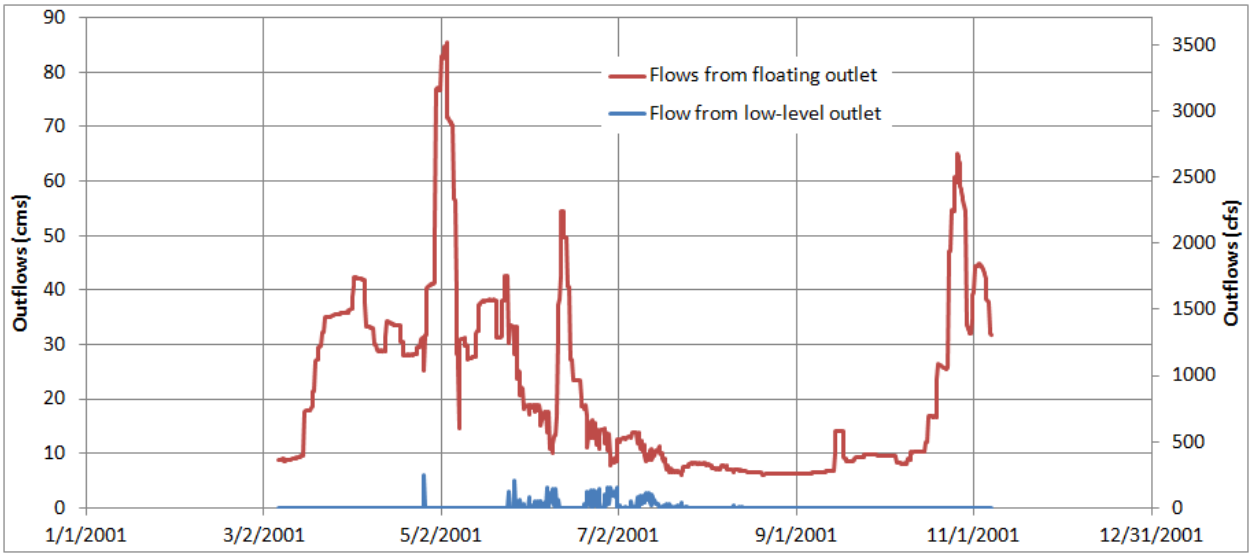

Figure 4-9. "Split" Outflows for 2001 (Low Air Temperatures and Average Inflows)

4.6 Simulation of High Air Temperatures and Low Inflows

2003 was selected as the year in the period of record that most closely approximated conditions with high annual air temperatures and low annual inflows. Figure 4-10 compares the release temperatures with existing conditions, inflow temperatures, and the temperature targets, Figure 4-11 shows the "tower" elevations selected by the model to meet the release temperature targets and Figure 4-12 shows the flow distribution between the "floating" and low-level outlets for the "split" option. The results show that the "tower", as modeled, would not be able to meet temperature targets in the late summer/early fall. This is because the model is selecting a single outlet that best meets the temperature targets with no blending, and occasionally selects a lower

port that discharges water significantly cooler than needed. By contrast, Figure 4-12 demonstrates that the combination of a "floating" outlet and a low-level outlet would be able to meet temperature targets throughout the year for this "warm" condition, as near-bottom water is used sparingly to blend with the near-surface water. The figure again shows that the strategy would be to discharge water from near the reservoir's surface for as long as possible, until the surface layer exceeds the temperature target, and then to blend the near-surface water with some deeper, cooler, water during the peak of the summer, mid-July to late September.

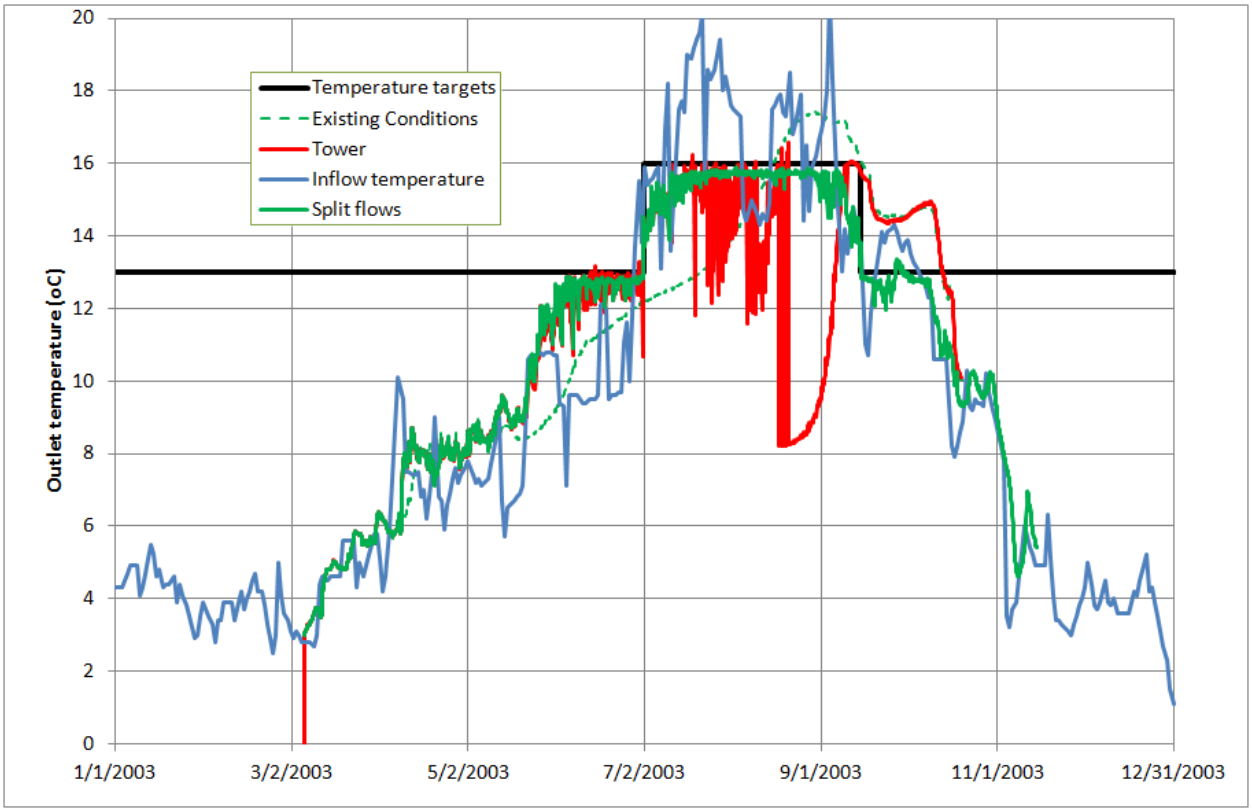

Figure 4-10. Release Temperatures for 2003 (High Air Temperatures and Low Inflows)

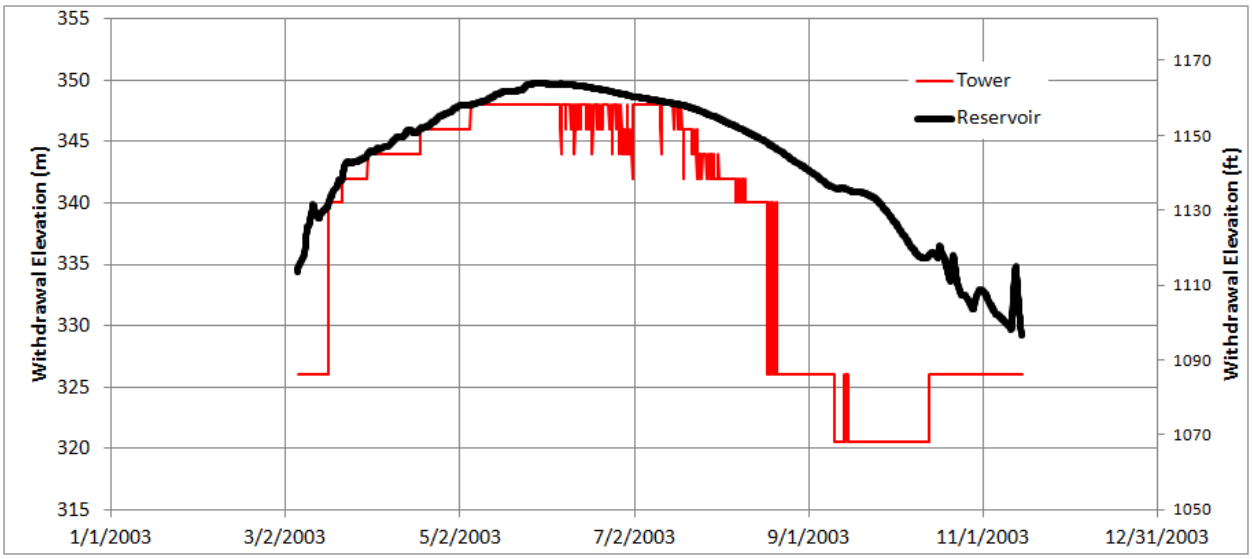

Figure 4-11. Release "Tower" Elevations for 2003 (High Air Temperatures and Low Inflows)

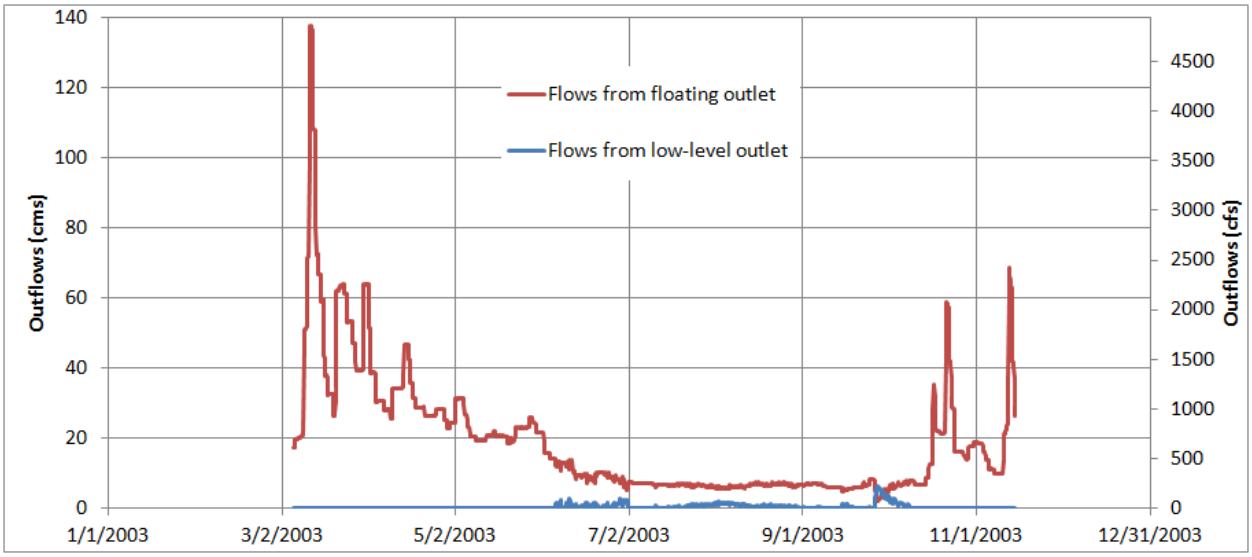

Figure 4-12. "Split" Outflows for 2003 (Low Air Temperatures and Average Inflows)

4.7 Discussion of Results

The results show that the addition of a "floating" outlet would be able to manage release temperatures during all modeled conditions of air temperatures and inflows. For this range of conditions, the model was generally taking water from near the surface (Figure 4-6, Figure 4-9, and Figure 4-12) before the surface heated beyond the temperature targets. During the warmer summer months, cooler near-bottom water was reserved to provide some temperature blending, as needed, to allow the outflow meet temperature targets.

The multi-port tower was generally successful in meeting temperature targets, except during the warmest year modeled. Under these more-extreme conditions, the selection of a suitable outlet elevation to discharge water that meets the temperature targets was more difficult to attain, and the model was forced to withdraw near-bottom water to meet the temperature targets, thus not making optimal use of the reservoir's thermal distribution.

5 Discussion

In this report, we present the development, calibration, and validation of a CE-QUAL-W2 model of Howard A. Hanson (HAH) Reservoir. The Corps of Engineers, Seattle District is currently considering modifying its outlet structures to also discharge near-surface water from the reservoir to the Green River to meet downstream temperature targets for fish passage and habitat. The purpose of the study is to model the blending of water released from different outlets to meet downstream temperature targets.

Geometry for the CE-QUAL-W2 model of HAH was developed from a detailed bathymetric survey of the pool and LiDAR coverage of the overbank areas. Inflow temperatures and near-site meteorology were used to simulate in-pool and releases temperatures for 2009 (model calibration), and 2005 and 2007 (model validation). However, in each of these seasons (generally March-October), the initial model tended to over-predict the peak late-summer reservoir temperatures by 2-4°C. Further investigation into the model results showed that all the cooler water in the lower elevations of the reservoir had been discharged to the Green River below the dam by late summer, and that the pool was being modeled as largely isothermal.

To investigate this further, we noted that the only inflow temperature measurements to the reservoir were in the Green River upstream of the reservoir, and many of these were manually taken once a day. As we compared inflow temperatures to in-pool profiles near the inflow points, we noted that near-bed temperatures were often several degrees cooler than measured inflow temperatures. To test the hypothesis, the District analyzed available groundwater data and concluded that there could be significant groundwater inflows from the Green River and especially from the North Fork. We re-estimated inflow temperatures using these groundwater inflow estimates and assuming that the groundwater temperature was close to the annual average air temperature, 9°C. We re-calibrated the model with these revised inflows and succeeded in significantly reducing the modeled peak-summer release temperatures.

Recently, CE-QUAL-W2 version 3.7 (beta) was developed to include the capability of discharging water through a structure's outlets to meet specified temperature targets. The "blending" algorithm was designed to handle a number of configurations and control options: (1) blending between two fixed outlets ("split" option), including the ability to simulate a "floating" outlet, (2) release from a multi-port tower that allows water to be withdrawn from a number of reservoir pool elevations, and (3) the combination of withdrawals from a single fixed outlet and a multi-port tower. The multi-port tower and the "split" option were successfully used to model:

- 2007, a year with average air temperatures and average annual inflows
- 2001, a year with low air temperatures and average annual inflows
- 2003, a year with high air temperatures and low average annual inflows

The results indicated that the combination of a floating outlet and a low-level outlet, perhaps the existing main discharge outlet for the dam, was successful in meeting temperature targets for all

the years simulated, including the warmest year. By contrast, the multi-port tower, as modeled with 8 of the 10 ports defined to discharge from the near-surface waters, was able to meet temperature targets for the low, and average years, but not for the warmest year. Under these conditions, the constraint of discharging from a single outlet eliminated the models ability to add cooler, near-bottom water to the too-warm near surface water.

In conducting the modeling, we had to extrapolate available data to improve model calibration. In the future, it would be useful to test these hypotheses in the field through monitoring. We would recommend that the District develop a field program for one-two years (April through November) to measure all inflows, the groundwater flux and temperature, in-pool temperatures, and release temperature, and that the model calibration be revisited with this new information.

6 References

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U. S. Army Corps of Engineers. October 2009. "Database query" webpage, http://www.nwd-wc.usace.army.mil/index.html.

Appendix 1. Observed Temperature Profiles for 2005

Table A1-1. Observed Temperature Profiles near Dam (1DAM)

Date (MMDDYY)	Time (HHMMSS)	JULIAN	Temp (C°)	Depth (meters)
4/26/2005	110515	38468	10.87	0.1
4/26/2005	110452	38468	10.65	1
4/26/2005	110428	38468	10.26	2
4/26/2005	110407	38468	10.07	3
4/26/2005	110340	38468	10	4
4/26/2005	110318	38468	9.87	5
4/26/2005	110230	38468	9.78	6
4/26/2005	110206	38468	9.45	7
4/26/2005	110143	38468	9.25	8
4/26/2005	110119	38468	9.06	9
4/26/2005	110057	38468	8.83	10
4/26/2005	110032	38468	8.54	12
4/26/2005	105957	38468	8	14
4/26/2005	105915	38468	7.46	16
4/26/2005	105853	38468	7.3	18
4/26/2005	105824	38468	6.98	20
4/26/2005	105745	38468	6.71	25
5/16/2005	104514	38488	13.76	0.1
5/16/2005	104456	38488	13.66	1
5/16/2005	104437	38488	13.41	2
5/16/2005	104411	38488	12.81	3
5/16/2005	104353	38488	12.15	4
5/16/2005	104337	38488	11.56	5
5/16/2005	104321	38488	11.12	6
5/16/2005	104300	38488	10.9	7
5/16/2005	104245	38488	10.69	8
5/16/2005	104230	38488	10.54	9
5/16/2005	104215	38488	10.44	10
5/16/2005	104148	38488	10.24	12
5/16/2005	104132	38488	10.06	14
5/16/2005	104115	38488	9.96	16
5/16/2005	104056	38488	9.88	18
5/16/2005	104041	38488	9.7	20
5/16/2005	104027	38488	9.61	22

5/16/2005	104011	38488	9.48	24
5/16/2005	103939	38488	9.33	25
5/16/2005	103916	38488	9.29	25.5
6/8/2005	104951	38511	14.86	0.1
6/8/2005	104938	38511	14.58	1
6/8/2005	104927	38511	14.52	2
6/8/2005	104912	38511	14.46	3
6/8/2005	104836	38511	13.84	4
6/8/2005	104813	38511	13.06	5
6/8/2005	104749	38511	12.58	6
6/8/2005	104719	38511	12.24	7
6/8/2005	104701	38511	11.98	8
6/8/2005	104638	38511	11.75	9
6/8/2005	104617	38511	11.61	10
6/8/2005	104600	38511	11.4	12
6/8/2005	104541	38511	11.27	14
6/8/2005	104522	38511	11.13	16
6/8/2005	104446	38511	11.01	18
6/8/2005	104414	38511	10.9	20
6/8/2005	104345	38511	10.78	22
6/8/2005	104302	38511	10.64	24
6/8/2005	104119	38511	10.35	25.7
6/23/2005	95930	38526	17.43	0.1
6/23/2005	95912	38526	17.21	1
6/23/2005	95853	38526	17.11	2
6/23/2005	95835	38526	17	3
6/23/2005	95824	38526	14.73	4
6/23/2005	95758	38526	13.64	5
6/23/2005	95732	38526	13.09	6
6/23/2005	95712	38526	13.01	7
6/23/2005	95702	38526	12.53	8
6/23/2005	95646	38526	12.33	9
6/23/2005	95621	38526	12.21	10
6/23/2005	95537	38526	11.95	12
6/23/2005	95507	38526	11.8	14
6/23/2005	95350	38526	11.67	16
6/23/2005	95325	38526	11.52	18
6/23/2005	95311	38526	11.41	20
6/23/2005	95211	38526	11.26	22

6/23/2005	95127	38526	11.08	24
6/23/2005	95029	38526	10.9	25.6
7/21/2005	110408	38554	20.51	0.1
7/21/2005	110347	38554	20.48	1
7/21/2005	110335	38554	20.23	2
7/21/2005	110320	38554	20.14	3
7/21/2005	110303	38554	18.35	4
7/21/2005	110237	38554	16.62	5
7/21/2005	110223	38554	15.7	6
7/21/2005	110157	38554	14.65	8
7/21/2005	110136	38554	14.14	10
7/21/2005	110106	38554	13.86	12
7/21/2005	110049	38554	13.68	14
7/21/2005	110031	38554	13.5	16
7/21/2005	110002	38554	13.24	18
7/21/2005	105918	38554	13.1	20
7/21/2005	105854	38554	12.95	22
7/21/2005	105824	38554	12.85	24
7/21/2005	105759	38554	12.72	25.6
8/10/2005	111029	38574	21.6	0.1
8/10/2005	111006	38574	21.64	1
8/10/2005	110945	38574	21.64	2
8/10/2005	110917	38574	21.3	3
8/10/2005	110849	38574	19.54	4
8/10/2005	110825	38574	18.22	5
8/10/2005	110731	38574	17.39	6
8/10/2005	110704	38574	16.83	7
8/10/2005	110639	38574	16.37	8
8/10/2005	110619	38574	16.09	9
8/10/2005	110558	38574	15.76	10
8/10/2005	110537	38574	15.42	12
8/10/2005	110505	38574	15.13	14
8/10/2005	110442	38574	14.85	16
8/10/2005	110408	38574	14.51	18
8/10/2005	110345	38574	14.33	20
8/10/2005	110301	38574	14.13	22
8/10/2005	110208	38574	13.74	24.5
8/24/2005	103113	38588	20.57	0.1

8/24/2005	103029	38588	20.5	1
8/24/2005	102954	38588	20.44	2
8/24/2005	102917	38588	20.41	3
8/24/2005	102855	38588	20.38	4
8/24/2005	102823	38588	20.35	5
8/24/2005	102751	38588	18.94	6
8/24/2005	102718	38588	17.99	7
8/24/2005	102646	38588	17.63	8
8/24/2005	102615	38588	17.24	9
8/24/2005	102553	38588	16.98	10
8/24/2005	102504	38588	16.61	12
8/24/2005	102431	38588	16.3	14
8/24/2005	102324	38588	15.98	16
8/24/2005	102243	38588	15.75	18
8/24/2005	102209	38588	15.54	20
8/24/2005	102144	38588	15.22	22
8/24/2005	102112	38588	15.01	24
8/24/2005	102048	38588	14.93	24.6
9/14/2005	93840	38609	17.66	0.1
9/14/2005	93805	38609	17.62	1
9/14/2005	93736	38609	17.61	2
9/14/2005	93711	38609	17.6	3
9/14/2005	93653	38609	17.6	4
9/14/2005	93634	38609	17.59	5
9/14/2005	93616	38609	17.48	6
9/14/2005	93541	38609	17.36	7
9/14/2005	93459	38609	16.97	8
9/14/2005	92954	38609	16.74	9
9/14/2005	92932	38609	16.52	10
9/14/2005	92855	38609	16.2	12
9/14/2005	92828	38609	15.85	14
9/14/2005	92801	38609	15.53	16
9/14/2005	92735	38609	15.23	18
9/14/2005	92712	38609	15	20
9/14/2005	92525	38609	14.87	22

Table A1-2. Observed Temperature Profiles at Upper Reservoir (9UPNR)

Date (MMDDYY)	Time (HHMMSS)	JULIAN	Temp (C°)	Depth (meters)
4/26/2005	115047	38468	10.86	0.1
4/26/2005	115030	38468	10.57	1
4/26/2005	115008	38468	10.28	2
4/26/2005	114943	38468	10.27	3
4/26/2005	114914	38468	10.2	4
4/26/2005	114847	38468	10.17	5
4/26/2005	114827	38468	9.97	6
4/26/2005	114802	38468	9.6	7
4/26/2005	114731	38468	9.46	8
4/26/2005	114703	38468	8.91	9
4/26/2005	114641	38468	8.82	10
4/26/2005	114618	38468	8.6	12
4/26/2005	114543	38468	8.47	14
4/26/2005	114505	38468	8.5	15
4/26/2005	114431	38468	8.51	15.3
5/16/2005	112657	38488	13.93	0.1
5/16/2005	112642	38488	13.84	1
5/16/2005	112630	38488	13.7	2
5/16/2005	112615	38488	12.85	3
5/16/2005	112559	38488	11.8	4
5/16/2005	112544	38488	11.19	5
5/16/2005	112528	38488	11	6
5/16/2005	112503	38488	10.77	8
5/16/2005	112446	38488	10.55	9
5/16/2005	112429	38488	10.52	10
5/16/2005	112414	38488	10.39	12
5/16/2005	112356	38488	10.18	14
5/16/2005	112341	38488	10.19	15
5/16/2005	112309	38488	10.2	15.3
6/8/2005	113421	38511	14.95	0.1
6/8/2005	113405	38511	14.7	1
6/8/2005	113352	38511	14.65	2
6/8/2005	113338	38511	14.62	3
6/8/2005	113324	38511	14.01	4
6/8/2005	113308	38511	13.33	5

6/8/2005	113254	38511	12.45	6
6/8/2005	113230	38511	12.15	7
6/8/2005	113159	38511	11.75	8
6/8/2005	113137	38511	10.83	9
6/8/2005	113119	38511	10.58	10
6/8/2005	113054	38511	10.44	12
6/8/2005	113017	38511	10.17	14.6
6/23/2005	105141	38526	17.86	0.1
6/23/2005	105122	38526	17.54	1
6/23/2005	105103	38526	17.47	2
6/23/2005	105047	38526	16.83	3
6/23/2005	105031	38526	14.49	4
6/23/2005	105016	38526	13.58	5
6/23/2005	104958	38526	13.07	6
6/23/2005	104933	38526	12.62	8
6/23/2005	104904	38526	12.1	10
6/23/2005	104828	38526	11.74	12
6/23/2005	104807	38526	11.61	14
6/23/2005	104738	38526	11.65	14.7
7/21/2005	114735	38554	21.56	0.1
7/21/2005	114718	38554	21.3	1
7/21/2005	114651	38554	20.77	2
7/21/2005	114614	38554	20.63	3
7/21/2005	114602	38554	17.42	4
7/21/2005	114540	38554	16.11	5
7/21/2005	114522	38554	15.13	6
7/21/2005	114458	38554	14.52	8
7/21/2005	114442	38554	14.1	10
7/21/2005	114422	38554	13.81	12
7/21/2005	114405	38554	13.73	14
7/21/2005	114236	38554	13.72	16
7/21/2005	114220	38554	13.72	16.4
8/10/2005	115312	38574	22.25	0.1
8/10/2005	115256	38574	22.26	1
8/10/2005	115239	38574	22.23	2
8/10/2005	115221	38574	22.18	3
8/10/2005	115201	38574	21.07	4
8/10/2005	115142	38574	19.51	5

8/10/2005	115117	38574	18.36	6
8/10/2005	115054	38574	17.61	7
8/10/2005	115032	38574	16.91	8
8/10/2005	115015	38574	16.4	9
8/10/2005	114953	38574	16.09	10
8/10/2005	114925	38574	15.73	12
8/10/2005	114850	38574	15.45	13.2
8/24/2005	113107	38588	20.85	0.1
8/24/2005	113030	38588	20.83	1
8/24/2005	113004	38588	20.73	2
8/24/2005	112934	38588	20.63	3
8/24/2005	112907	38588	20.23	4
8/24/2005	112844	38588	19.54	5
8/24/2005	112819	38588	17.69	6
8/24/2005	112758	38588	17.41	7
8/24/2005	112734	38588	17.1	8
8/24/2005	112716	38588	17.07	9
8/24/2005	112657	38588	16.86	10
8/24/2005	112606	38588	16.79	11
8/24/2005	112515	38588	16.75	11.8
9/14/2005	102854	38609	17.87	0.1
9/14/2005	102832	38609	17.71	1
9/14/2005	102818	38609	17.67	2
9/14/2005	102805	38609	17.64	3
9/14/2005	102749	38609	17.6	4
9/14/2005	102731	38609	16.96	5
9/14/2005	102717	38609	16.23	6
9/14/2005	102642	38609	15.86	7
9/14/2005	102622	38609	14.42	8
9/14/2005	102605	38609	14.28	9
9/14/2005	102548	38609	13.97	10

Table A1-3. Observed Temperature Profiles In Charley Creek (SCHCK)

Date (MMDDYY)	Time (HHMMSS)	JULIAN	Temp (C°)	Depth (meters)
4/26/2005	123134	38468	11.06	0
4/26/2005	123116	38468	10.76	1
4/26/2005	123057	38468	10.58	2
4/26/2005	123043	38468	10.27	3
4/26/2005	123029	38468	10.07	4
4/26/2005	123009	38468	9.91	5
4/26/2005	122954	38468	9.43	6
4/26/2005	122932	38468	9.22	8
4/26/2005	122913	38468	8.8	10
4/26/2005	122856	38468	8.43	12
4/26/2005	122836	38468	7.74	14
4/26/2005	122818	38468	7.56	16
4/26/2005	122703	38468	7.28	17.4
5/16/2005	115822	38488	13.97	0.1
5/16/2005	115804	38488	13.86	1
5/16/2005	115746	38488	13.38	2
5/16/2005	115728	38488	12.84	3
5/16/2005	115708	38488	12.02	4
5/16/2005	115649	38488	11.64	5
5/16/2005	115628	38488	11.18	6
5/16/2005	115610	38488	10.75	8
5/16/2005	115550	38488	10.38	10
5/16/2005	115537	38488	10.21	12
5/16/2005	115524	38488	10.08	14
5/16/2005	115456	38488	10.04	15.8
6/8/2005	121345	38511	15.35	0.1
6/8/2005	121334	38511	15.12	1
6/8/2005	121316	38511	14.65	2
6/8/2005	121259	38511	14.58	3
6/8/2005	121228	38511	13.78	4
6/8/2005	121152	38511	13.07	5
6/8/2005	121126	38511	12.57	6
6/8/2005	121059	38511	12.33	7
6/8/2005	121031	38511	12.14	8
6/8/2005	121004	38511	11.91	9

6/8/2005	120940	38511	11.73	10
6/8/2005	120911	38511	11.44	12
6/8/2005	120845	38511	11.13	14
6/8/2005	120758	38511	10.91	16
6/8/2005	120727	38511	10.87	17.4
6/23/2005	113042	38526	18.06	0.1
6/23/2005	113021	38526	17.9	1
6/23/2005	113008	38526	17.6	2
6/23/2005	112954	38526	16.85	3
6/23/2005	112942	38526	15.13	4
6/23/2005	112931	38526	14.16	5
6/23/2005	112914	38526	13.33	6
6/23/2005	112855	38526	12.66	8
6/23/2005	112841	38526	12.2	10
6/23/2005	112824	38526	12.01	12
6/23/2005	112807	38526	11.83	14
6/23/2005	112746	38526	11.78	15.2
7/21/2005	123207	38554	21.21	0.1
7/21/2005	123147	38554	20.95	1
7/21/2005	123127	38554	20.83	2
7/21/2005	123106	38554	20.33	3
7/21/2005	123036	38554	19.77	4
7/21/2005	123008	38554	17.6	5
7/21/2005	122935	38554	16.34	6
7/21/2005	122912	38554	14.64	8
7/21/2005	122836	38554	14.28	10
7/21/2005	122817	38554	13.97	12
7/21/2005	122752	38554	13.72	14
7/21/2005	122727	38554	13.44	16
7/21/2005	122655	38554	13.26	18
7/21/2005	122632	38554	13.21	18.4
8/10/2005	123035	38574	22.08	0.1
8/10/2005	123016	38574	22.01	1
8/10/2005	122954	38574	22.06	2
8/10/2005	122931	38574	22.01	3
8/10/2005	122907	38574	21.27	4
8/10/2005	122847	38574	18.79	5
8/10/2005	122830	38574	17.78	6

8/10/2005	122810	38574	17.12	7
8/10/2005	122749	38574	16.65	8
8/10/2005	122725	38574	16.41	9
8/10/2005	122710	38574	16.18	10
8/10/2005	122626	38574	15.71	12
8/10/2005	122600	38574	15.16	14
8/10/2005	122534	38574	14.8	16
8/10/2005	122453	38574	14.72	16.9
8/24/2005	121038	38588	21.68	0.1
8/24/2005	121019	38588	21.42	1
8/24/2005	120952	38588	20.69	2
8/24/2005	120915	38588	20.6	3
8/24/2005	120843	38588	20.54	4
8/24/2005	120806	38588	19.67	5
8/24/2005	120748	38588	18.62	6
8/24/2005	120728	38588	17.82	7
8/24/2005	120704	38588	17.59	8
8/24/2005	120612	38588	17.32	9
8/24/2005	120516	38588	17.06	10
8/24/2005	120423	38588	16.66	12
8/24/2005	120359	38588	16.25	14
8/24/2005	120255	38588	16.03	16
9/14/2005	111137	38609	17.95	0.1
9/14/2005	111121	38609	17.85	1
9/14/2005	111043	38609	17.69	2
9/14/2005	111012	38609	17.69	3
9/14/2005	110916	38609	17.61	4
9/14/2005	110837	38609	17.47	5
9/14/2005	110803	38609	17.25	6
9/14/2005	110742	38609	17.16	7
9/14/2005	110702	38609	16.98	8
9/14/2005	110640	38609	16.8	9
9/14/2005	110609	38609	16.56	10
9/14/2005	110511	38609	16.19	12
9/14/2005	110430	38609	15.69	13.3

Table A1-4. Observed Temperature Profiles in NF Green River (5NFK)

Date (MMDDYY)	Time (HHMMSS)	JULIAN	Temp (C°)	Depth (meters)
4/26/2005	110515	38468	10.87	0.1
4/26/2005	110452	38468	10.65	1
4/26/2005	110428	38468	10.26	2
4/26/2005	110407	38468	10.07	3
4/26/2005	110340	38468	10	4
4/26/2005	110318	38468	9.87	5
4/26/2005	110230	38468	9.78	6
4/26/2005	110206	38468	9.45	7
4/26/2005	110143	38468	9.25	8
4/26/2005	110119	38468	9.06	9
4/26/2005	110057	38468	8.83	10
4/26/2005	110032	38468	8.54	12
4/26/2005	105957	38468	8	14
4/26/2005	105915	38468	7.46	16
4/26/2005	105853	38468	7.3	18
4/26/2005	105824	38468	6.98	20
4/26/2005	105745	38468	6.71	25
5/16/2005	104514	38488	13.76	0.1
5/16/2005	104456	38488	13.66	1
5/16/2005	104437	38488	13.41	2
5/16/2005	104411	38488	12.81	3
5/16/2005	104353	38488	12.15	4
5/16/2005	104337	38488	11.56	5
5/16/2005	104321	38488	11.12	6
5/16/2005	104300	38488	10.9	7
5/16/2005	104245	38488	10.69	8
5/16/2005	104230	38488	10.54	9
5/16/2005	104215	38488	10.44	10
5/16/2005	104148	38488	10.24	12
5/16/2005	104132	38488	10.06	14
5/16/2005	104115	38488	9.96	16
5/16/2005	104056	38488	9.88	18
5/16/2005	104041	38488	9.7	20
5/16/2005	104027	38488	9.61	22
5/16/2005	104011	38488	9.48	24
5/16/2005	103939	38488	9.33	25

5/16/2005	103916	38488	9.29	25.5
6/8/2005	104951	38511	14.86	0.1
6/8/2005	104938	38511	14.58	1
6/8/2005	104927	38511	14.52	2
6/8/2005	104912	38511	14.46	3
6/8/2005	104836	38511	13.84	4
6/8/2005	104813	38511	13.06	5
6/8/2005	104749	38511	12.58	6
6/8/2005	104719	38511	12.24	7
6/8/2005	104701	38511	11.98	8
6/8/2005	104638	38511	11.75	9
6/8/2005	104617	38511	11.61	10
6/8/2005	104600	38511	11.4	12
6/8/2005	104541	38511	11.27	14
6/8/2005	104522	38511	11.13	16
6/8/2005	104446	38511	11.01	18
6/8/2005	104414	38511	10.9	20
6/8/2005	104345	38511	10.78	22
6/8/2005	104302	38511	10.64	24
6/8/2005	104119	38511	10.35	25.7
6/23/2005	95930	38526	17.43	0.1
6/23/2005	95912	38526	17.21	1
6/23/2005	95853	38526	17.11	2
6/23/2005	95835	38526	17	3
6/23/2005	95824	38526	14.73	4
6/23/2005	95758	38526	13.64	5
6/23/2005	95732	38526	13.09	6
6/23/2005	95712	38526	13.01	7
6/23/2005	95702	38526	12.53	8
6/23/2005	95646	38526	12.33	9
6/23/2005	95621	38526	12.21	10
6/23/2005	95537	38526	11.95	12
6/23/2005	95507	38526	11.8	14
6/23/2005	95350	38526	11.67	16
6/23/2005	95325	38526	11.52	18
6/23/2005	95311	38526	11.41	20
6/23/2005	95211	38526	11.26	22
6/23/2005	95127	38526	11.08	24
6/23/2005	95029	38526	10.9	25.6

7/21/2005	110408	38554	20.51	0.1
7/21/2005	110347	38554	20.48	1
7/21/2005	110335	38554	20.23	2
7/21/2005	110320	38554	20.14	3
7/21/2005	110303	38554	18.35	4
7/21/2005	110237	38554	16.62	5
7/21/2005	110223	38554	15.7	6
7/21/2005	110157	38554	14.65	8
7/21/2005	110136	38554	14.14	10
7/21/2005	110106	38554	13.86	12
7/21/2005	110049	38554	13.68	14
7/21/2005	110031	38554	13.5	16
7/21/2005	110002	38554	13.24	18
7/21/2005	105918	38554	13.1	20
7/21/2005	105854	38554	12.95	22
7/21/2005	105824	38554	12.85	24
7/21/2005	105759	38554	12.72	25.6
8/10/2005	111029	38574	21.6	0.1
8/10/2005	111006	38574	21.64	1
8/10/2005	110945	38574	21.64	2
8/10/2005	110917	38574	21.3	3
8/10/2005	110849	38574	19.54	4
8/10/2005	110825	38574	18.22	5
8/10/2005	110731	38574	17.39	6
8/10/2005	110704	38574	16.83	7
8/10/2005	110639	38574	16.37	8
8/10/2005	110619	38574	16.09	9
8/10/2005	110558	38574	15.76	10
8/10/2005	110537	38574	15.42	12
8/10/2005	110505	38574	15.13	14
8/10/2005	110442	38574	14.85	16
8/10/2005	110408	38574	14.51	18
8/10/2005	110345	38574	14.33	20
8/10/2005	110301	38574	14.13	22
8/10/2005	110208	38574	13.74	24.5
8/24/2005	103113	38588	20.57	0.1
8/24/2005	103029	38588	20.5	1
8/24/2005	102954	38588	20.44	2

8/24/2005	102917	38588	20.41	3
8/24/2005	102855	38588	20.38	4
8/24/2005	102823	38588	20.35	5
8/24/2005	102751	38588	18.94	6
8/24/2005	102718	38588	17.99	7
8/24/2005	102646	38588	17.63	8
8/24/2005	102615	38588	17.24	9
8/24/2005	102553	38588	16.98	10
8/24/2005	102504	38588	16.61	12
8/24/2005	102431	38588	16.3	14
8/24/2005	102324	38588	15.98	16
8/24/2005	102243	38588	15.75	18
8/24/2005	102209	38588	15.54	20
8/24/2005	102144	38588	15.22	22
8/24/2005	102112	38588	15.01	24
8/24/2005	102048	38588	14.93	24.6
9/14/2005	93840	38609	17.66	0.1
9/14/2005	93805	38609	17.62	1
9/14/2005	93736	38609	17.61	2
9/14/2005	93711	38609	17.6	3
9/14/2005	93653	38609	17.6	4
9/14/2005	93634	38609	17.59	5
9/14/2005	93616	38609	17.48	6
9/14/2005	93541	38609	17.36	7
9/14/2005	93459	38609	16.97	8
9/14/2005	92954	38609	16.74	9
9/14/2005	92932	38609	16.52	10
9/14/2005	92855	38609	16.2	12
9/14/2005	92828	38609	15.85	14
9/14/2005	92801	38609	15.53	16
9/14/2005	92735	38609	15.23	18
9/14/2005	92712	38609	15	20
9/14/2005	92525	38609	14.87	22

Appendix 2. Observed Temperature Profiles for 2007

Table A2-1. Observed Temperature Profiles near Dam (1DAM)

Date (MMDDYY)	Time (HHMMSS)	JULIAN	Temp (C°)	Depth (meters)
5/1/2007	91743	39203	9.92	0.1
5/1/2007	91722	39203	9.88	1
5/1/2007	91630	39203	9.78	2
5/1/2007	91656	39203	9.78	2
5/1/2007	91600	39203	9.63	3
5/1/2007	91530	39203	9.31	4
5/1/2007	91445	39203	9.12	5
5/1/2007	91403	39203	8.96	6
5/1/2007	91239	39203	8.79	7
5/1/2007	91152	39203	8.58	8
5/1/2007	91107	39203	8.5	9
5/1/2007	91043	39203	8.18	10
5/1/2007	91016	39203	7.93	12
5/1/2007	90945	39203	7.69	14
5/1/2007	90910	39203	7.58	16
5/1/2007	90838	39203	7.32	18
5/1/2007	90809	39203	7.28	20
5/1/2007	90744	39203	7.21	21
5/1/2007	90719	39203	7.07	23
5/1/2007	90631	39203	6.98	25
5/1/2007	90609	39203	6.88	27.3
5/29/2007	84309	39231	13.7	0.1
5/29/2007	84327	39231	13.63	1
5/29/2007	84344	39231	13.4	2
5/29/2007	84434	39231	13.33	3
5/29/2007	84458	39231	13.3	4
5/29/2007	84514	39231	13.27	5
5/29/2007	84535	39231	12.09	6
5/29/2007	84554	39231	10.83	7
5/29/2007	84607	39231	10.54	8
5/29/2007	84631	39231	10.28	9
5/29/2007	84705	39231	10.14	10
5/29/2007	84738	39231	9.86	12
5/29/2007	84804	39231	9.68	14

5/29/2007	84832	39231	9.6	16
5/29/2007	84849	39231	9.5	18
5/29/2007	84904	39231	9.36	20
5/29/2007	84928	39231	9.05	25
5/29/2007	84952	39231	8.59	30
5/29/2007	85026	39231	8.53	31.5
6/19/2007	84414	39252	14.79	0.1
6/19/2007	84437	39252	14.72	1
6/19/2007	84521	39252	14.76	2
6/19/2007	84546	39252	14.69	3
6/19/2007	84613	39252	14.57	4
6/19/2007	84638	39252	14.43	5
6/19/2007	84725	39252	13.33	6
6/19/2007	84757	39252	12.75	7
6/19/2007	84823	39252	12.19	8
6/19/2007	84848	39252	11.77	9
6/19/2007	84911	39252	11.64	10
6/19/2007	84941	39252	11.32	11
6/19/2007	85004	39252	11.15	12
6/19/2007	85029	39252	10.87	14
6/19/2007	85054	39252	10.79	16
6/19/2007	85128	39252	10.75	18
6/19/2007	85159	39252	10.54	20
6/19/2007	85233	39252	10.37	25
6/19/2007	85305	39252	10.14	30
6/19/2007	85337	39252	10.03	32
7/3/2007		39266	18.7	0.3048
7/3/2007		39266	18.5	1.524
7/3/2007		39266	18.2	3.048
7/3/2007		39266	15.4	4.572
7/3/2007		39266	13.7	6.096
7/3/2007		39266	12.7	7.62
7/3/2007		39266	12.3	9.144
7/3/2007		39266	11.6	12.192
7/3/2007		39266	11.4	15.24
7/3/2007		39266	11.2	18.288
7/3/2007		39266	11.1	21.336
7/3/2007		39266	10.8	24.384
7/3/2007		39266	10.7	27.432

7/3/2007		39266	10.4	30.48
7/18/2007	91956	39281	21.61	0.1
7/18/2007	91940	39281	21.55	1
7/18/2007	91912	39281	21.59	2
7/18/2007	91841	39281	21.59	3
7/18/2007	91800	39281	19.61	4
7/18/2007	91734	39281	17.6	5
7/18/2007	91711	39281	16.31	6
7/18/2007	91652	39281	15.31	7
7/18/2007	91630	39281	14.44	8
7/18/2007	91613	39281	13.92	9
7/18/2007	91550	39281	13.43	10
7/18/2007	91523	39281	12.69	12
7/18/2007	91501	39281	12.36	14
7/18/2007	91434	39281	12.08	16
7/18/2007	91416	39281	11.92	18
7/18/2007	91352	39281	11.78	20
7/18/2007	91322	39281	11.46	25
7/18/2007	91259	39281	11.36	28.1
7/31/2007		39294	20.49	0.3048
7/31/2007		39294	20.38	1.524
7/31/2007		39294	20.36	3.048
7/31/2007		39294	20.23	4.572
7/31/2007		39294	17.57	6.096
7/31/2007		39294	16.16	7.62
7/31/2007		39294	15.34	9.144
7/31/2007		39294	14.51	10.668
7/31/2007		39294	14.21	12.192
7/31/2007		39294	13.68	13.716
7/31/2007		39294	13.34	15.24
7/31/2007		39294	13.1	16.764
7/31/2007		39294	12.8	18.288
7/31/2007		39294	12.53	19.812
7/31/2007		39294	12.28	21.336
7/31/2007		39294	12.16	22.86
7/31/2007		39294	12.07	24.384
7/31/2007		39294	11.94	25.908
7/31/2007		39294	11.82	27.432
7/31/2007		39294	11.7	28.956

8/7/2007		39301	20.51	0.3048
8/7/2007		39301	20.51	1.524
8/7/2007		39301	20.46	3.048
8/7/2007		39301	19.62	4.572
8/7/2007		39301	18.06	6.096
8/7/2007		39301	16.66	7.62
8/7/2007		39301	15.69	9.144
8/7/2007		39301	15.09	10.668
8/7/2007		39301	14.53	12.192
8/7/2007		39301	14.08	13.716
8/7/2007		39301	13.66	15.24
8/7/2007		39301	13.46	16.764
8/7/2007		39301	13.2	18.288
8/7/2007		39301	12.94	19.812
8/7/2007		39301	12.71	21.336
8/7/2007		39301	12.56	22.86
8/7/2007		39301	12.4	24.384
8/7/2007		39301	12.22	25.908
8/7/2007		39301	12.15	27.432
8/7/2007		39301	12.02	28.956
8/8/2007	84324	39302	19.97	0.1
8/8/2007	84407	39302	19.97	1
8/8/2007	84432	39302	19.97	2
8/8/2007	84500	39302	19.97	3
8/8/2007	84539	39302	19.83	4
8/8/2007	84628	39302	19.03	5
8/8/2007	84656	39302	17.83	6
8/8/2007	84742	39302	16.72	7
8/8/2007	84812	39302	16.07	8
8/8/2007	84843	39302	15.64	9
8/8/2007	84917	39302	15.15	10
8/8/2007	85023	39302	14.42	12
8/8/2007	85104	39302	13.92	14
8/8/2007	85150	39302	13.52	16
8/8/2007	85241	39302	13.14	18
8/8/2007	85320	39302	12.86	20
8/8/2007	85408	39302	12.68	22
8/8/2007	85451	39302	12.49	24
8/8/2007	85529	39302	12.33	26

8/8/2007	85600	39302	12.28	27.5
8/14/2007		39308	19.94	0.3048
8/14/2007		39308	19.76	1.524
8/14/2007		39308	19.69	3.048
8/14/2007		39308	19.66	4.572
8/14/2007		39308	18.62	6.096
8/14/2007		39308	16.56	7.62
8/14/2007		39308	15.87	9.144
8/14/2007		39308	15.44	10.668
8/14/2007		39308	14.98	12.192
8/14/2007		39308	14.59	13.716
8/14/2007		39308	14.41	15.24
8/14/2007		39308	14.22	16.764
8/14/2007		39308	13.99	18.288
8/14/2007		39308	13.65	19.812
8/14/2007		39308	13.37	21.336
8/14/2007		39308	13.17	22.86
8/14/2007		39308	12.98	24.384
8/14/2007		39308	12.89	25.908
8/14/2007		39308	12.72	27.432
8/14/2007		39308	12.51	28.956
8/21/2007		39315	19.5	0.3048
8/21/2007		39315	19.28	1.524
8/21/2007		39315	19.24	3.048
8/21/2007		39315	19.2	4.572
8/21/2007		39315	17.72	6.096
8/21/2007		39315	16.48	7.62
8/21/2007		39315	16.02	9.144
8/21/2007		39315	15.61	10.668
8/21/2007		39315	15.26	12.192
8/21/2007		39315	14.95	13.716
8/21/2007		39315	14.72	15.24
8/21/2007		39315	14.54	16.764
8/21/2007		39315	14.3	18.288
8/21/2007		39315	14.1	19.812
8/21/2007		39315	13.93	21.336
8/21/2007		39315	13.76	22.86
8/21/2007		39315	13.61	24.384
8/21/2007		39315	13.41	25.908

8/21/2007	39315	13.26	27.432
8/21/2007	39315	12.91	28.956
8/28/2007	39322	18.91	0.3048
8/28/2007	39322	18.87	1.524
8/28/2007	39322	18.88	3.048
8/28/2007	39322	18.84	4.572
8/28/2007	39322	17.57	6.096
8/28/2007	39322	16.64	7.62
8/28/2007	39322	16.09	9.144
8/28/2007	39322	15.71	10.668
8/28/2007	39322	15.43	12.192
8/28/2007	39322	15.19	13.716
8/28/2007	39322	14.94	15.24
8/28/2007	39322	14.84	16.764
8/28/2007	39322	14.75	18.288
8/28/2007	39322	14.61	19.812
8/28/2007	39322	14.52	21.336
8/28/2007	39322	14.29	22.86
8/28/2007	39322	13.97	24.384
8/28/2007	39322	13.96	25.908
8/28/2007	39322	13.82	27.432
8/28/2007	39322	13.67	28.956
9/4/2007	39329	19.81	0.3048
9/4/2007	39329	19.82	1.524
9/4/2007	39329	19.82	3.048
9/4/2007	39329	19.32	4.572
9/4/2007	39329	17.56	6.096
9/4/2007	39329	16.71	7.62
9/4/2007	39329	16.17	9.144
9/4/2007	39329	15.87	10.668
9/4/2007	39329	15.67	12.192
9/4/2007	39329	15.51	13.716
9/4/2007	39329	15.29	15.24
9/4/2007	39329	15.04	16.764
9/4/2007	39329	15.03	18.288
9/4/2007	39329	14.86	19.812
9/4/2007	39329	14.76	21.336
9/4/2007	39329	14.6	22.86
9/4/2007	39329	14.54	24.384

9/4/2007	39329	14.41	25.908
9/4/2007	39329	14.02	27.432
9/11/2007	39336	19.16	0.3048
9/11/2007	39336	19.11	1.524
9/11/2007	39336	19.06	3.048
9/11/2007	39336	19.05	4.572
9/11/2007	39336	19.02	6.096
9/11/2007	39336	17.08	7.62
9/11/2007	39336	16.48	9.144
9/11/2007	39336	16.31	10.668
9/11/2007	39336	15.95	12.192
9/11/2007	39336	15.82	13.716
9/11/2007	39336	15.7	15.24
9/11/2007	39336	15.51	16.764
9/11/2007	39336	15.35	18.288
9/11/2007	39336	15.31	19.812
9/11/2007	39336	15.19	21.336
9/11/2007	39336	15	22.86
9/11/2007	39336	14.92	24.384
9/11/2007	39336	14.83	25.908
9/11/2007	39336	14.69	26.8224
9/19/2007	39344	17.45	0.3048
9/19/2007	39344	17.44	1.524
9/19/2007	39344	17.43	3.048
9/19/2007	39344	17.41	4.572
9/19/2007	39344	17.41	6.096
9/19/2007	39344	17.34	7.62
9/19/2007	39344	16.52	9.144
9/19/2007	39344	16.29	10.668
9/19/2007	39344	16.1	12.192
9/19/2007	39344	15.95	13.716
9/19/2007	39344	15.83	15.24
9/19/2007	39344	15.74	16.764
9/19/2007	39344	15.6	18.288
9/19/2007	39344	15.46	19.812
9/19/2007	39344	15.34	21.336
9/19/2007	39344	15.31	22.86
9/19/2007	39344	15.18	24.384
9/19/2007	39344	14.92	25.908

9/27/2007	39352	15.65	0.3048
9/27/2007	39352	16.01	1.524
9/27/2007	39352	16.02	3.048
9/27/2007	39352	16.02	4.572
9/27/2007	39352	16.01	6.096
9/27/2007	39352	16.01	7.62
9/27/2007	39352	16.01	9.144
9/27/2007	39352	16.01	10.668
9/27/2007	39352	15.7	12.192
9/27/2007	39352	15.54	13.716
9/27/2007	39352	15.43	15.24
9/27/2007	39352	15.2	16.764
9/27/2007	39352	15.12	18.288
9/27/2007	39352	14.94	19.812
9/27/2007	39352	14.8	21.336
9/27/2007	39352	14.67	22.86
9/27/2007	39352	14.59	23.7744
10/2/2007	39357	15.1	0.3048
10/2/2007	39357	15.13	1.524
10/2/2007	39357	15.14	3.048
10/2/2007	39357	15.13	4.572
10/2/2007	39357	15.13	6.096
10/2/2007	39357	15.12	7.62
10/2/2007	39357	15.03	9.144
10/2/2007	39357	14.95	10.668
10/2/2007	39357	14.71	12.192
10/2/2007	39357	14.52	13.716
10/2/2007	39357	14.13	15.24
10/2/2007	39357	13.95	16.764
10/2/2007	39357	13.61	18.288
10/2/2007	39357	13.49	19.812
10/2/2007	39357	13.41	21.336
10/2/2007	39357	13.44	22.86
10/9/2007	39364	13.59	0.3048
10/9/2007	39364	13.59	1.524
10/9/2007	39364	13.59	3.048
10/9/2007	39364	13.56	4.572
10/9/2007	39364	13.5	6.096
10/9/2007	39364	13.07	7.62

10/9/2007	39364	12.69	9.144
10/9/2007	39364	12.14	10.668
10/9/2007	39364	12.03	12.192
10/9/2007	39364	11.9	13.716
10/9/2007	39364	11.57	15.24
10/9/2007	39364	11.49	16.764
10/9/2007	39364	11.25	18.288
10/9/2007	39364	11.13	19.812
10/16/2007	39371	12.69	0.3048
10/16/2007	39371	12.69	1.524
10/16/2007	39371	12.66	3.048
10/16/2007	39371	12.64	4.572
10/16/2007	39371	12.30	6.096
10/16/2007	39371	11.91	7.62
10/16/2007	39371	11.36	9.144
10/16/2007	39371	11.33	10.668
10/16/2007	39371	11.12	12.192
10/16/2007	39371	11.00	13.716
10/16/2007	39371	10.99	15.24
10/16/2007	39371	11.00	17.0688
10/24/2007	39379	11.07	0.3048
10/24/2007	39379	11.04	1.524
10/24/2007	39379	11.02	3.048
10/24/2007	39379	10.00	4.572
10/24/2007	39379	9.27	6.096
10/24/2007	39379	9.23	7.62
10/24/2007	39379	8.82	9.144
10/24/2007	39379	8.72	10.668
10/24/2007	39379	8.65	12.192
10/24/2007	39379	8.56	14.0208
10/30/2007	39385	7.94	0.3048
10/30/2007	39385	7.94	1.524
10/30/2007	39385	7.94	3.048
10/30/2007	39385	7.14	4.572
10/30/2007	39385	7.46	6.096
10/30/2007	39385	7.17	7.62
10/30/2007	39385	7.09	9.144
10/30/2007	39385	7.05	10.668
10/30/2007	39385	7.06	11.5824

Table A2-2. Observed Temperature Profiles at Upper Reservoir (9UPNR)

Date (MMDDYY)	Time (HHMMSS)	JULIAN	Temp (C°)	Depth (meters)
5/1/2007	105749	39203	10.96	0.1
5/1/2007	105728	39203	10.62	1
5/1/2007	105700	39203	9.59	2
5/1/2007	105553	39203	9.35	3
5/1/2007	105528	39203	9.28	4
5/1/2007	105508	39203	9.23	5
5/1/2007	105443	39203	9.07	6
5/1/2007	105423	39203	8.66	7
5/1/2007	105401	39203	8.25	8
5/1/2007	105339	39203	8.06	9
5/1/2007	105316	39203	7.75	10
5/1/2007	105254	39203	7.59	12
5/1/2007	105232	39203	7.05	14
5/1/2007	105201	39203	7.07	16
5/29/2007	94849	39231	13.8	0.1
5/29/2007	94907	39231	13.77	1
5/29/2007	94932	39231	13.82	2
5/29/2007	95019	39231	13.65	3
5/29/2007	95047	39231	13.42	4
5/29/2007	95110	39231	13.25	5
5/29/2007	95135	39231	11.24	6
5/29/2007	95156	39231	10.77	7
5/29/2007	95227	39231	10.45	8
5/29/2007	95247	39231	10.26	9
5/29/2007	95307	39231	10.15	10
5/29/2007	95346	39231	9.39	12
5/29/2007	95411	39231	9.32	14
5/29/2007	95444	39231	9.17	16
5/29/2007	95514	39231	8.83	18
5/29/2007	95540	39231	8.65	20
5/29/2007	95554	39231	8.62	20.4
6/19/2007	100848	39252	15.86	0.1
6/19/2007	100907	39252	15.36	1
6/19/2007	100949	39252	15.14	2
6/19/2007	101008	39252	15.09	3

6/19/2007	101041	39252	15.05	4
6/19/2007	101123	39252	14.63	5
6/19/2007	101151	39252	12.58	6
6/19/2007	101228	39252	12.14	7
6/19/2007	101248	39252	11.8	8
6/19/2007	101307	39252	11.57	9
6/19/2007	101354	39252	11.29	10
6/19/2007	101431	39252	10.9	12
6/19/2007	101459	39252	10.63	14
6/19/2007	101521	39252	10.24	16
6/19/2007	101544	39252	10.12	18
6/19/2007	101611	39252	10.15	20
6/19/2007	101632	39252	10.09	22.1
7/18/2007	104631	39281	21.98	0.1
7/18/2007	104617	39281	21.98	1
7/18/2007	104549	39281	21.9	2
7/18/2007	104518	39281	21.93	3
7/18/2007	104441	39281	20.34	4
7/18/2007	104356	39281	17.41	5
7/18/2007	104324	39281	16.23	6
7/18/2007	104245	39281	15.65	7
7/18/2007	104210	39281	15.05	8
7/18/2007	104141	39281	14.24	9
7/18/2007	104114	39281	13.51	10
7/18/2007	104045	39281	12.93	12
7/18/2007	104014	39281	12.34	14
7/18/2007	103945	39281	12.12	16
7/18/2007	103918	39281	12.04	18
7/18/2007	103853	39281	12	20
7/18/2007	103837	39281	12.02	20.5
8/8/2007	93736	39302	20.65	0.1
8/8/2007	93800	39302	20.61	1
8/8/2007	93823	39302	20.57	2
8/8/2007	93846	39302	20.56	3
8/8/2007	93909	39302	20.55	4
8/8/2007	93945	39302	19.66	5
8/8/2007	94012	39302	17.42	6
8/8/2007	94044	39302	16.68	7
8/8/2007	94110	39302	15.98	8

8/8/2007	94133	39302	15.72	9
8/8/2007	94207	39302	15.27	10
8/8/2007	94239	39302	14.39	12
8/8/2007	94324	39302	13.96	14
8/8/2007	94412	39302	13.74	16
8/8/2007	94704	39302	13.44	18
8/8/2007	94736	39302	13.39	18.6

Table A2-3. Observed Temperature Profiles In Charley Creek (SCHCK)

Date (MMDDYY)	Time (HHMMSS)	JULIAN	Temp (C°)	Depth (meters)
5/1/2007	113033	39203	11.01	0.1
5/1/2007	113014	39203	10.44	1
5/1/2007	112944	39203	10.13	2
5/1/2007	112917	39203	9.84	3
5/1/2007	112842	39203	9.31	4
5/1/2007	112817	39203	8.63	5
5/1/2007	112746	39203	8.44	6
5/1/2007	112725	39203	8.32	7
5/1/2007	112708	39203	8.25	8
5/1/2007	112647	39203	8.07	9
5/1/2007	112629	39203	7.91	10
5/1/2007	112604	39203	7.87	12
5/1/2007	112529	39203	7.77	14
5/1/2007	112501	39203	7.66	16
5/1/2007	112433	39203	7.61	18
5/1/2007	112408	39203	7.52	20
5/1/2007	112344	39203	7.47	21
5/29/2007	103428	39231	14.62	0.1
5/29/2007	103502	39231	14.54	1
5/29/2007	103522	39231	14.37	2
5/29/2007	103543	39231	13.91	3
5/29/2007	103637	39231	13.76	4
5/29/2007	103659	39231	12.81	5
5/29/2007	103714	39231	11.94	6
5/29/2007	103744	39231	11.15	7
5/29/2007	103812	39231	10.67	8
5/29/2007	103838	39231	10.39	9
5/29/2007	103908	39231	10.15	10
5/29/2007	103935	39231	9.84	12
5/29/2007	104011	39231	9.56	14
5/29/2007	104035	39231	9.49	16
5/29/2007	104056	39231	9.21	18
5/29/2007	104111	39231	9.11	20
5/29/2007	104128	39231	8.92	22.4
6/19/2007	104920	39252	15.79	0.1

6/19/2007	104952	39252	15.27	1
6/19/2007	105043	39252	15.09	2
6/19/2007	105116	39252	14.91	3
6/19/2007	105133	39252	14.75	4
6/19/2007	105153	39252	13.57	5
6/19/2007	105219	39252	12.76	6
6/19/2007	105243	39252	12.39	7
6/19/2007	105303	39252	11.9	8
6/19/2007	105321	39252	11.67	9
6/19/2007	105339	39252	11.36	10
6/19/2007	105412	39252	11.01	12
6/19/2007	105436	39252	10.83	14
6/19/2007	105502	39252	10.71	16
6/19/2007	105546	39252	10.54	18
6/19/2007	105605	39252	10.41	20
6/19/2007	105627	39252	10.33	25
6/19/2007	105641	39252	10.17	26.3
7/18/2007	113133	39281	21.73	0.1
7/18/2007	113119	39281	21.73	1
7/18/2007	113100	39281	21.71	2
7/18/2007	113039	39281	21.69	3
7/18/2007	113002	39281	20.28	4
7/18/2007	112929	39281	18.25	5
7/18/2007	112853	39281	16.67	6
7/18/2007	112827	39281	15.73	7
7/18/2007	112754	39281	14.9	8
7/18/2007	112733	39281	14.08	9
7/18/2007	112709	39281	13.7	10
7/18/2007	112640	39281	12.8	12
7/18/2007	112612	39281	12.4	14
7/18/2007	112546	39281	12.17	16
7/18/2007	112517	39281	11.94	18
7/18/2007	112453	39281	11.82	20
7/18/2007	112410	39281	11.85	21
8/8/2007	102406	39302	20.37	0.1
8/8/2007	102426	39302	20.33	1
8/8/2007	102453	39302	20.27	2
8/8/2007	102517	39302	20.24	3
8/8/2007	102544	39302	20.22	4

8/8/2007	102610	39302	19.56	5
8/8/2007	102645	39302	17.99	6
8/8/2007	102723	39302	17.24	7
8/8/2007	102757	39302	16.45	8
8/8/2007	102826	39302	15.87	9
8/8/2007	102850	39302	15.4	10
8/8/2007	102927	39302	14.72	12
8/8/2007	102957	39302	14.22	14
8/8/2007	103024	39302	13.66	16
8/8/2007	103054	39302	13.37	18
8/8/2007	103119	39302	13	20
8/8/2007	103134	39302	12.85	20.6

Table A2-4. Observed Temperature Profiles in NF Green River (5NFK)

Date (MMDDYY)	Time (HHMMSS)	JULIAN	Temp (C°)	Depth (meters)
5/1/2007	114128	39203	10.66	0.1
5/1/2007	114115	39203	10.54	1
5/1/2007	114053	39203	10.32	2
5/1/2007	114024	39203	9.65	3
5/1/2007	113954	39203	9.27	4
5/1/2007	113935	39203	9.04	5
5/1/2007	113914	39203	8.92	6
5/1/2007	113831	39203	8.76	7
5/1/2007	113845	39203	8.75	7
5/1/2007	113758	39203	8.38	8
5/1/2007	113731	39203	8.16	9
5/1/2007	113708	39203	8.06	10
5/1/2007	113631	39203	7.4	12
5/1/2007	113600	39203	7.53	14
5/29/2007	101755	39231	14.04	0.1
5/29/2007	104755	39231	14	1
5/29/2007	104812	39231	13.85	2
5/29/2007	104831	39231	13.7	3
5/29/2007	104853	39231	13.53	4
5/29/2007	104908	39231	13.02	5
5/29/2007	104924	39231	11.73	6
5/29/2007	104939	39231	10.94	7
5/29/2007	105003	39231	10.44	8
5/29/2007	105016	39231	10.21	9
5/29/2007	105026	39231	10.2	10
5/29/2007	105039	39231	9.52	12
5/29/2007	105108	39231	9.44	14
5/29/2007	105121	39231	9.14	15.7
6/19/2007	110144	39252	15.26	1
6/19/2007	110202	39252	14.98	2
6/19/2007	110215	39252	14.8	3
6/19/2007	110233	39252	14.71	4
6/19/2007	110253	39252	14.4	5
6/19/2007	110311	39252	13.31	6
6/19/2007	110330	39252	12.44	7

6/19/2007	110344	39252	11.95	8
6/19/2007	110403	39252	11.6	9
6/19/2007	110417	39252	11.42	10
6/19/2007	110438	39252	11.09	12
6/19/2007	110457	39252	10.78	14
6/19/2007	110518	39252	10.56	16
6/19/2007	110533	39252	10.52	17.2
7/18/2007	114140	39281	21.73	0.1
7/18/2007	114122	39281	21.74	1
7/18/2007	114058	39281	21.72	2
7/18/2007	114044	39281	21.67	3
7/18/2007	114022	39281	20.74	4
7/18/2007	114002	39281	17.92	5
7/18/2007	113926	39281	16.38	6
7/18/2007	113849	39281	15.36	7
7/18/2007	113831	39281	14.88	8
7/18/2007	113754	39281	14.28	9
7/18/2007	113732	39281	13.77	10
7/18/2007	113708	39281	13.11	12
7/18/2007	113641	39281	12.53	13.6
8/8/2007	103610	39302	20.3	0.1
8/8/2007	103634	39302	20.32	1
8/8/2007	103655	39302	20.27	2
8/8/2007	103715	39302	20.23	3
8/8/2007	103737	39302	20.2	4
8/8/2007	103806	39302	19.49	5
8/8/2007	103840	39302	17.59	6
8/8/2007	103911	39302	16.79	7
8/8/2007	103934	39302	16.12	8
8/8/2007	104002	39302	15.68	9
8/8/2007	104035	39302	15.26	10
8/8/2007	104120	39302	14.63	12
8/8/2007	104145	39302	14.28	13.3

Appendix 3. Observed Temperature Profiles for 2009

Table A3-1. Observed Temperature Profiles near Dam (1DAM)

Date (MMDDYY)	Time (HHMMSS)	JULIAN	Temp (C°)	Depth (meters)
4/21/2009		39924	8.69	0.3048
4/21/2009		39924	8.54	1.524
4/21/2009		39924	8.2	3.048
4/21/2009		39924	8.01	4.572
4/21/2009		39924	7.84	6.096
4/21/2009		39924	6.96	7.62
4/21/2009		39924	6.61	9.144
4/21/2009		39924	6.48	10.668
4/21/2009		39924	6.34	12.192
4/21/2009		39924	6.06	13.716
4/21/2009		39924	5.98	15.24
4/21/2009		39924	5.89	16.764
4/21/2009		39924	5.29	18.288
4/21/2009		39924	5.3	19.812
4/21/2009		39924	5.34	21.336
4/21/2009		39924	5.1	22.86
4/21/2009		39924	5.05	24.384
4/21/2009		39924	5.05	25.146
5/5/2009	95037	39938	8.64	0.1
5/5/2009	95055	39938	8.63	1
5/5/2009	95114	39938	8.6	2
5/5/2009	95131	39938	8.56	3
5/5/2009	95148	39938	8.35	4
5/5/2009	95209	39938	8.31	5
5/5/2009	95227	39938	8.23	6
5/5/2009	95245	39938	8.11	7
5/5/2009	95302	39938	8.06	8
5/5/2009	95316	39938	7.86	9
5/5/2009	95337	39938	7.57	10
5/5/2009	95403	39938	7.42	12
5/5/2009	95443	39938	7.08	14
5/5/2009	95521	39938	6.81	16
5/5/2009	95549	39938	6.59	18
5/5/2009	95609	39938	6.54	20

5/5/2009	95804	39938	6.43	24.7
5/26/2009	95137	39959	13.02	0.1
5/26/2009	95155	39959	12.91	0.9
5/26/2009	95218	39959	12.88	2
5/26/2009	95239	39959	12.45	3
5/26/2009	95300	39959	11.01	4
5/26/2009	95323	39959	10.37	5
5/26/2009	95344	39959	9.9	6
5/26/2009	95408	39959	9.29	7
5/26/2009	95425	39959	9	8
5/26/2009	95443	39959	8.82	9
5/26/2009	95459	39959	8.47	10
5/26/2009	95528	39959	8.36	12
5/26/2009	95552	39959	8.07	14
5/26/2009	95623	39959	7.83	16
5/26/2009	95652	39959	7.47	18
5/26/2009	95730	39959	7.24	19.9
5/26/2009	95933	39959	7.14	24.7
5/26/2009	95959	39959	6.99	30
6/16/2009	95050	39980	16.37	0.1
6/16/2009	95137	39980	16.32	1
6/16/2009	95155	39980	16.28	2
6/16/2009	95218	39980	16.27	3
6/16/2009	95239	39980	16.25	4
6/16/2009	95300	39980	14.86	5
6/16/2009	95323	39980	13.49	6
6/16/2009	95344	39980	12.85	7
6/16/2009	95408	39980	12.1	8
6/16/2009	95425	39980	11.57	9
6/16/2009	95443	39980	11.44	10
6/16/2009	95459	39980	11.03	12
6/16/2009	95528	39980	10.79	14
6/16/2009	95552	39980	10.57	16
6/16/2009	95623	39980	10.4	18
6/16/2009	95652	39980	10.22	20
6/16/2009	95730	39980	9.83	25
6/16/2009	95933	39980	9.28	30
6/16/2009	95959	39980	9.28	31.1

6/30/2009		39994	17.2	0.3048
6/30/2009		39994	17.13	1.524
6/30/2009		39994	17.07	3.048
6/30/2009		39994	16.99	4.572
6/30/2009		39994	14.97	6.096
6/30/2009		39994	13.87	7.62
6/30/2009		39994	12.96	9.144
6/30/2009		39994	12.45	10.668
6/30/2009		39994	12.41	12.192
6/30/2009		39994	12.39	13.716
6/30/2009		39994	12.11	15.24
6/30/2009		39994	11.99	16.764
6/30/2009		39994	11.93	18.288
6/30/2009		39994	11.85	19.812
6/30/2009		39994	11.72	21.336
6/30/2009		39994	11.47	22.86
6/30/2009		39994	11.37	24.384
6/30/2009		39994	11.22	25.908
6/30/2009		39994	11.07	27.432
6/30/2009		39994	11.06	28.956
6/30/2009		39994	10.98	30.48
7/7/2009	93813	40001	18.28	0.1
7/7/2009	94000	40001	18.33	1
7/7/2009	94042	40001	18.33	2
7/7/2009	94104	40001	18.33	3
7/7/2009	94124	40001	18.32	4
7/7/2009	94144	40001	17.71	5
7/7/2009	94206	40001	16.48	6
7/7/2009	94228	40001	15.64	7
7/7/2009	94255	40001	15.07	8
7/7/2009	94321	40001	14.53	9
7/7/2009	94346	40001	14.02	10
7/7/2009	94422	40001	13.53	12
7/7/2009	94456	40001	13.33	14
7/7/2009	94530	40001	13.08	16
7/7/2009	94558	40001	12.69	18
7/7/2009	94624	40001	12.41	20
7/7/2009	94654	40001	12.31	22
7/7/2009	94714	40001	12.16	24
7/7/2009	94734	40001	11.99	25

7/7/2009	94754	40001	11.8	26.1
7/14/2009		40008	18.36	0.3048
7/14/2009		40008	18.34	1.524
7/14/2009		40008	18.24	3.048
7/14/2009		40008	17.84	4.572
7/14/2009		40008	16.52	6.096
7/14/2009		40008	15.87	7.62
7/14/2009		40008	15.22	9.144
7/14/2009		40008	14.8	10.668
7/14/2009		40008	14.43	12.192
7/14/2009		40008	14.17	13.716
7/14/2009		40008	13.91	15.24
7/14/2009		40008	13.59	16.764
7/14/2009		40008	13.29	18.288
7/14/2009		40008	13.14	19.812
7/14/2009		40008	13.03	21.336
7/14/2009		40008	12.84	22.86
7/14/2009		40008	12.71	24.384
7/14/2009		40008	12.31	25.908
7/21/2009	93352	40015	20.91	0.1
7/21/2009	93519	40015	20.83	1
7/21/2009	93543	40015	20.72	2
7/21/2009	93609	40015	20.66	3
7/21/2009	93631	40015	20.62	4
7/21/2009	93703	40015	20.63	4
7/21/2009	93727	40015	19.05	5
7/21/2009	93818	40015	17.66	6
7/21/2009	93922	40015	16.69	7
7/21/2009	94024	40015	16.4	8
7/21/2009	94200	40015	15.94	9
7/21/2009	94410	40015	15.24	10
7/21/2009	94510	40015	15.07	12
7/21/2009	94556	40015	14.65	14
7/21/2009	94658	40015	14.27	16
7/21/2009	94729	40015	14.04	18
7/21/2009	94810	40015	13.76	20
7/21/2009	94841	40015	13.54	22
7/21/2009	94919	40015	13.38	24
7/21/2009	94948	40015	13.11	25

7/21/2009	95011	40015	12.82	26
7/21/2009	95058	40015	12.83	26.2
7/28/2009		40022	23.16	0.3048
7/28/2009		40022	23.04	1.524
7/28/2009		40022	22.98	3.048
7/28/2009		40022	20.99	4.572
7/28/2009		40022	18.55	6.096
7/28/2009		40022	17.42	7.62
7/28/2009		40022	16.73	9.144
7/28/2009		40022	16.16	10.668
7/28/2009		40022	15.7	12.192
7/28/2009		40022	15.38	13.716
7/28/2009		40022	15.1	15.24
7/28/2009		40022	14.91	16.764
7/28/2009		40022	14.74	18.288
7/28/2009		40022	14.46	19.812
7/28/2009		40022	14.32	21.336
7/28/2009		40022	14.1	22.86
7/28/2009		40022	13.87	24.384
7/28/2009		40022	13.53	25.908
7/28/2009		40022	13.46	27.432
8/4/2009		40029	23.67	0.3048
8/4/2009		40029	23.68	1.524
8/4/2009		40029	23.68	3.048
8/4/2009		40029	21.72	4.572
8/4/2009		40029	20.16	6.096
8/4/2009		40029	18.55	7.62
8/4/2009		40029	17.75	9.144
8/4/2009		40029	17.12	10.668
8/4/2009		40029	16.69	12.192
8/4/2009		40029	16.28	13.716
8/4/2009		40029	15.88	15.24
8/4/2009		40029	15.57	16.764
8/4/2009		40029	15.36	18.288
8/4/2009		40029	15.07	19.812
8/4/2009		40029	14.92	21.336
8/4/2009		40029	14.67	22.86
8/4/2009		40029	14.31	24.384

8/11/2009	95358	40036	20.31	0.1
8/11/2009	95457	40036	20.35	1
8/11/2009	95614	40036	20.34	2
8/11/2009	95703	40036	20.34	3
8/11/2009	95729	40036	20.33	4
8/11/2009	95819	40036	20.27	5
8/11/2009	95849	40036	19.85	6
8/11/2009	95924	40036	19.29	7
8/11/2009	95953	40036	18.81	8
8/11/2009	100022	40036	18.4	9
8/11/2009	100111	40036	18.39	9
8/11/2009	100150	40036	17.97	10
8/11/2009	100225	40036	17.45	12
8/11/2009	100307	40036	16.89	14
8/11/2009	100349	40036	16.56	16
8/11/2009	100427	40036	16.06	18
8/11/2009	100517	40036	15.69	20
8/11/2009	100554	40036	15.45	22
8/11/2009	100627	40036	15.16	23.6
8/18/2009		40043	19.74	0.3048
8/18/2009		40043	19.74	1.524
8/18/2009		40043	19.67	3.048
8/18/2009		40043	19.6	4.572
8/18/2009		40043	19.25	6.096
8/18/2009		40043	18.75	7.62
8/18/2009		40043	18.08	9.144
8/18/2009		40043	17.67	10.668
8/18/2009		40043	17.44	12.192
8/18/2009		40043	17.32	13.716
8/18/2009		40043	17.11	15.24
8/18/2009		40043	16.79	16.764
8/18/2009		40043	16.52	18.288
8/18/2009		40043	16.38	19.812
8/18/2009		40043	16.24	21.336
8/18/2009		40043	16.09	22.86
8/18/2009		40043	15.84	24.384
8/18/2009		40043	15.66	25.908
8/25/2009		40050	19.73	0.3048
8/25/2009		40050	19.76	1.524

8/25/2009		40050	19.76	3.048
8/25/2009		40050	19.76	4.572
8/25/2009		40050	19.75	6.096
8/25/2009		40050	18.88	7.62
8/25/2009		40050	18.39	9.144
8/25/2009		40050	17.97	10.668
8/25/2009		40050	17.67	12.192
8/25/2009		40050	17.53	13.716
8/25/2009		40050	17.27	15.24
8/25/2009		40050	17.04	16.764
8/25/2009		40050	16.87	18.288
8/25/2009		40050	16.74	19.812
8/25/2009		40050	16.69	21.336
8/25/2009		40050	16.5	22.86
9/1/2009	101943	40057	19.8	0.1
9/1/2009	102007	40057	19.8	1
9/1/2009	102041	40057	19.8	2
9/1/2009	102109	40057	19.8	3
9/1/2009	102138	40057	19.8	4
9/1/2009	102208	40057	19.66	5
9/1/2009	102249	40057	19.16	6
9/1/2009	102312	40057	18.85	7
9/1/2009	102335	40057	18.63	8
9/1/2009	102357	40057	18.42	9
9/1/2009	102423	40057	18.15	10
9/1/2009	102507	40057	17.91	12
9/1/2009	102611	40057	17.61	14
9/1/2009	102656	40057	17.34	16
9/1/2009	102738	40057	17.2	18
9/1/2009	102805	40057	16.99	20
9/1/2009	102844	40057	16.71	21.4
9/8/2009		40064	18.25	0.3048
9/8/2009		40064	18.29	1.524
9/8/2009		40064	18.28	3.048
9/8/2009		40064	18.27	4.572
9/8/2009		40064	18.26	6.096
9/8/2009		40064	18.24	7.62
9/8/2009		40064	17.87	9.144
9/8/2009		40064	17.66	10.668

9/8/2009	40064	17.46	12.192
9/8/2009	40064	17.29	13.716
9/8/2009	40064	17.16	15.24
9/8/2009	40064	16.98	16.764
9/8/2009	40064	16.94	18.288
9/8/2009	40064	16.55	19.812
9/8/2009	40064	16.5	20.4216
9/15/2009	40071	18.84	0.3048
9/15/2009	40071	18.82	1.524
9/15/2009	40071	18.82	3.048
9/15/2009	40071	18.81	4.572
9/15/2009	40071	18.79	6.096
9/15/2009	40071	18.17	7.62
9/15/2009	40071	17.69	9.144
9/15/2009	40071	17.49	10.668
9/15/2009	40071	17.31	12.192
9/15/2009	40071	17.14	13.716
9/15/2009	40071	16.98	15.24
9/15/2009	40071	16.73	16.764
9/15/2009	40071	16.63	18.288
9/15/2009	40071	16.51	18.8976
9/22/2009	40078	18.2	0.3048
92209	92209	18.17	1.524
9/22/2009	40078	18.15	3.048
9/22/2009	40078	18.12	4.572
9/22/2009	40078	18.13	6.096
9/22/2009	40078	18.1	7.62
9/22/2009	40078	18.09	9.144
9/22/2009	40078	17.61	10.668
9/22/2009	40078	17.22	12.192
9/22/2009	40078	17.09	13.716
9/22/2009	40078	16.92	15.24
9/22/2009	40078	16.82	16.764
9/22/2009	40078	16.71	18.288
9/22/2009	40078	16.41	19.812
9/22/2009	40078	16.21	21.336
9/22/2009	40078	16.18	21.9456
9/29/2009	40085	16.98	0.3048

9/29/2009		40085	17	1.524
9/29/2009		40085	17.02	3.048
9/29/2009		40085	17.01	4.572
9/29/2009		40085	17.01	6.096
9/29/2009		40085	17.01	7.62
9/29/2009		40085	17.01	9.144
9/29/2009		40085	16.95	10.668
9/29/2009		40085	16.7	12.192
9/29/2009		40085	16.25	13.716
9/29/2009		40085	16.18	15.24
9/29/2009		40085	15.89	16.764
9/29/2009		40085	15.76	19.812
10/6/2009	93955	40092	15.13	0.1
10/6/2009	94019	40092	15.12	1
10/6/2009	94056	40092	15.13	2
10/6/2009	94113	40092	15.13	3
10/6/2009	94135	40092	15.13	4
10/6/2009	94154	40092	15.13	5
10/6/2009	94216	40092	15.13	6
10/6/2009	94237	40092	15.14	7
10/6/2009	94307	40092	15.13	8
10/6/2009	94330	40092	15.13	9
10/6/2009	94346	40092	15.11	10
10/6/2009	94412	40092	14.42	12
10/6/2009	94437	40092	13.93	14
10/6/2009	94509	40092	13.74	16
10/6/2009	94528	40092	13.69	17.8
10/13/2009		40099	12.54	0.3048
10/13/2009		40099	12.54	1.524
10/13/2009		40099	12.52	3.048
10/13/2009		40099	12.5	4.572
10/13/2009		40099	12.51	6.096
10/13/2009		40099	12.52	7.62
10/13/2009		40099	12.53	9.144
10/13/2009		40099	12.52	10.668
10/13/2009		40099	12.52	12.192
10/13/2009		40099	12.52	13.716
10/13/2009		40099	12.5	15.24

Table A3-2. Observed Temperature Profiles at Upper Reservoir (9UPNR)

Date (MMDDYY)	Time (HHMMSS)	JULIAN	Temp (C°)	Depth (meters)
5/5/2009	110422	39938	7.13	0.2
5/5/2009	110443	39938	7.1	1
5/5/2009	110505	39938	7.02	2
5/5/2009	110534	39938	7.01	3
5/5/2009	110605	39938	7	4
5/5/2009	110627	39938	7	5
5/5/2009	110652	39938	6.98	6
5/5/2009	110713	39938	6.98	7
5/5/2009	110737	39938	6.98	8
5/5/2009	110753	39938	6.95	9
5/5/2009	110814	39938	6.83	10
5/5/2009	110836	39938	6.51	12
5/5/2009	110857	39938	6.42	14
5/5/2009	110911	39938	6.38	14.7
5/26/2009	112513	39959	12.89	0.1
5/26/2009	112531	39959	12.77	1
5/26/2009	112552	39959	11.07	2
5/26/2009	112615	39959	10.87	3
5/26/2009	112640	39959	10.54	4
5/26/2009	112707	39959	9.97	5
5/26/2009	112726	39959	9.4	6
5/26/2009	112745	39959	9.06	7
5/26/2009	112803	39959	8.74	8
5/26/2009	112824	39959	8.13	9
5/26/2009	112846	39959	7.61	10
5/26/2009	112909	39959	7.54	12
5/26/2009	112928	39959	7.62	14
5/26/2009	112948	39959	7.5	16
5/26/2009	113009	39959	7.08	18
5/26/2009	113029	39959	6.98	18.6
6/16/2009	112513	39980	16.86	0.1
6/16/2009	112531	39980	16.65	1
6/16/2009	112552	39980	16.59	2
6/16/2009	112615	39980	16.45	3
6/16/2009	112640	39980	16.06	4

6/16/2009	112707	39980	13.22	5
6/16/2009	112726	39980	12.44	6
6/16/2009	112745	39980	12.17	7
6/16/2009	112803	39980	12.23	8
6/16/2009	112824	39980	11.89	9
6/16/2009	112846	39980	11.54	10
6/16/2009	112909	39980	11.07	12
6/16/2009	112928	39980	10.95	14
6/16/2009	112948	39980	10.39	16
6/16/2009	113009	39980	10.06	18
6/16/2009	113029	39980	10.14	20
6/16/2009	113119	39980	10.04	21.3
7/7/2009	103050	40001	18.89	0.1
7/7/2009	103110	40001	18.93	1
7/7/2009	103136	40001	18.92	2
7/7/2009	103201	40001	18.93	3
7/7/2009	103220	40001	18.26	4
7/7/2009	103244	40001	17.79	5
7/7/2009	103305	40001	16.6	6
7/7/2009	103326	40001	16.22	7
7/7/2009	103357	40001	15.39	8
7/7/2009	103432	40001	14.97	9
7/7/2009	103457	40001	14.43	10
7/7/2009	103532	40001	13.5	12
7/7/2009	103550	40001	13.24	14
7/7/2009	103617	40001	13.07	16
7/7/2009	103639	40001	12.83	16.9
7/21/2009	105553	40015	21.29	0.1
7/21/2009	105641	40015	21.21	1
7/21/2009	105707	40015	21.1	2
7/21/2009	105742	40015	21.02	3
7/21/2009	105821	40015	19.79	4
7/21/2009	105853	40015	18.79	5
7/21/2009	105923	40015	17.53	6
7/21/2009	105952	40015	16.83	7
7/21/2009	110013	40015	16.36	8
7/21/2009	110052	40015	15.46	9
7/21/2009	110116	40015	15.05	10
7/21/2009	110150	40015	15.15	12

7/21/2009	110231	40015	14.87	14
7/21/2009	110304	40015	14.81	15.6
8/11/2009	105639	40036	20.43	0.1
8/11/2009	105719	40036	20.43	1
8/11/2009	105744	40036	20.42	2
8/11/2009	105812	40036	20.42	3
8/11/2009	105836	40036	20.42	3
8/11/2009	105854	40036	20.41	4
8/11/2009	105919	40036	20.13	5
8/11/2009	105954	40036	19.9	6
8/11/2009	110005	40036	19.87	6
8/11/2009	110044	40036	19.11	7
8/11/2009	110129	40036	18.46	8
8/11/2009	110206	40036	18.2	9
8/11/2009	110725	40036	17.82	10
8/11/2009	110759	40036	17.73	11
8/11/2009	110828	40036	17.22	12
8/11/2009	110853	40036	17.12	13
8/11/2009	110921	40036	16.93	13.7
9/1/2009	111625	40057	20.31	0.1
9/1/2009	111654	40057	20.33	1
9/1/2009	111721	40057	20.3	2
9/1/2009	111737	40057	20.25	3
9/1/2009	111801	40057	20.18	4
9/1/2009	111814	40057	19.85	5
9/1/2009	111839	40057	19.23	6
9/1/2009	111857	40057	18.8	7
9/1/2009	111917	40057	18.35	8
9/1/2009	111935	40057	18.21	9
9/1/2009	111948	40057	18.14	9.5
10/6/2009	105850	40092	14.91	0.1
10/6/2009	105906	40092	14.86	1
10/6/2009	105928	40092	14.14	2
10/6/2009	105949	40092	12.26	3
10/6/2009	110011	40092	9.83	4
10/6/2009	110037	40092	9.23	5
10/6/2009	110209	40092	9.21	5.4

Table A3-3. Observed Temperature Profiles In Charley Creek (SCHCK)

Date (MMDDYY)	Time (HHMMSS)	JULIAN	Temp (C°)	Depth (meters)
5/5/2009	113530	39938	8.79	0.1
5/5/2009	113610	39938	8.5	1
5/5/2009	113632	39938	8.32	2
5/5/2009	113700	39938	8.25	3
5/5/2009	113731	39938	8.15	4
5/5/2009	113752	39938	7.94	5
5/5/2009	113808	39938	7.82	6
5/5/2009	113831	39938	7.58	7
5/5/2009	113854	39938	7.53	8
5/5/2009	113920	39938	7.42	9
5/5/2009	113941	39938	7.28	10
5/5/2009	114006	39938	7.04	12
5/5/2009	114029	39938	6.78	14
5/5/2009	114050	39938	6.71	16
5/5/2009	114107	39938	6.6	17.6
5/26/2009	120257	39959	12.78	0.1
5/26/2009	120313	39959	12.57	1
5/26/2009	120334	39959	12.18	2
5/26/2009	120401	39959	11.59	3
5/26/2009	120424	39959	10.94	4
5/26/2009	120446	39959	10.71	5
5/26/2009	120506	39959	10.34	6
5/26/2009	120524	39959	9.71	7
5/26/2009	120539	39959	8.72	8
5/26/2009	120555	39959	8.52	9
5/26/2009	120614	39959	8.47	10
5/26/2009	120636	39959	7.99	12
5/26/2009	120657	39959	7.76	14
5/26/2009	120720	39959	7.58	16
5/26/2009	120741	39959	7.49	18
5/26/2009	120801	39959	7.22	19.8
6/16/2009	120257	39980	17.44	0.1
6/16/2009	120313	39980	16.69	1
6/16/2009	120334	39980	16.54	2
6/16/2009	120401	39980	16.49	3

6/16/2009	120424	39980	15.7	4
6/16/2009	120446	39980	14.52	5
6/16/2009	120506	39980	13.64	6
6/16/2009	120524	39980	12.54	7
6/16/2009	120539	39980	11.63	8
6/16/2009	120555	39980	11.46	9
6/16/2009	120614	39980	11.4	10
6/16/2009	120636	39980	11.01	12
6/16/2009	120657	39980	10.63	14
6/16/2009	120720	39980	10.44	16
6/16/2009	120741	39980	10.26	18
6/16/2009	120801	39980	10.14	20
6/16/2009	120821	39980	9.95	22
6/16/2009	120855	39980	9.84	23.3
7/7/2009	110824	40001	18.72	0.1
7/7/2009	110847	40001	18.79	1
7/7/2009	110907	40001	18.79	2
7/7/2009	110928	40001	18.78	3
7/7/2009	110955	40001	18.73	4
7/7/2009	111024	40001	17.74	5
7/7/2009	111055	40001	16.3	6
7/7/2009	111126	40001	15.64	7
7/7/2009	111401	40001	14.89	8
7/7/2009	111421	40001	14.56	9
7/7/2009	111440	40001	14.4	10
7/7/2009	111509	40001	13.88	12
7/7/2009	111534	40001	13.26	14
7/7/2009	111600	40001	13.02	16
7/7/2009	111626	40001	12.81	18
7/7/2009	111644	40001	12.6	18.6
7/21/2009	113639	40015	21.56	0.1
7/21/2009	113709	40015	21.45	1
7/21/2009	113729	40015	20.92	2
7/21/2009	113802	40015	20.74	3
7/21/2009	113830	40015	20.59	4
7/21/2009	113909	40015	18.7	5
7/21/2009	113944	40015	17.8	6
7/21/2009	114013	40015	16.78	7
7/21/2009	114035	40015	16.14	8

7/21/2009	114110	40015	15.76	9
7/21/2009	114131	40015	15.36	10
7/21/2009	114158	40015	14.99	12
7/21/2009	114444	40015	14.55	14
7/21/2009	114505	40015	14.22	16
7/21/2009	114525	40015	13.81	17.3
8/11/2009	113955	40036	20.52	0.1
8/11/2009	114027	40036	20.54	1
8/11/2009	114056	40036	20.52	2
8/11/2009	114122	40036	20.52	3
8/11/2009	114200	40036	20.49	4
8/11/2009	114234	40036	20.42	5
8/11/2009	114258	40036	19.67	6
8/11/2009	114332	40036	19.2	7
8/11/2009	114359	40036	18.94	8
8/11/2009	114420	40036	18.4	9
8/11/2009	114450	40036	17.86	10
8/11/2009	114520	40036	17.39	12
8/11/2009	114550	40036	16.98	14
8/11/2009	114623	40036	16.42	16
8/11/2009	114643	40036	16.24	16.2
9/1/2009	114924	40057	19.98	0.1
9/1/2009	114940	40057	19.9	1
9/1/2009	115011	40057	19.87	2
9/1/2009	115033	40057	19.86	3
9/1/2009	115105	40057	19.84	4
9/1/2009	115130	40057	19.81	5
9/1/2009	115152	40057	19.59	6
9/1/2009	115217	40057	19.12	7
9/1/2009	115255	40057	18.76	8
9/1/2009	115506	40057	18.35	9
9/1/2009	115545	40057	18.12	10
9/1/2009	115634	40057	17.93	12
9/1/2009	115704	40057	17.79	13.3
10/6/2009	113537	40092	15.44	0.1
10/6/2009	113553	40092	15.27	1
10/6/2009	113624	40092	15.24	2
10/6/2009	113644	40092	15.21	3

10/6/2009	113710	40092	15.18	4
10/6/2009	113738	40092	15.14	5
10/6/2009	113759	40092	15.1	6
10/6/2009	113819	40092	14.73	7
10/6/2009	113841	40092	13.06	8
10/6/2009	114016	40092	13.09	8.3

Table A3-4. Observed Temperature Profiles in NF Green River (5NFK)

Date (MMDDYY)	Time (HHMMSS)	JULIAN	Temp (C°)	Depth (meters)
5/5/2009	114739	39938	8.95	0.1
5/5/2009	114809	39938	8.9	1
5/5/2009	114834	39938	8.84	2
5/5/2009	114855	39938	8.73	3
5/5/2009	114915	39938	8.71	4
5/5/2009	114939	39938	8.68	5
5/5/2009	115007	39938	8.47	6
5/5/2009	115026	39938	8.33	7
5/5/2009	115054	39938	7.48	8
5/5/2009	115131	39938	7.2	9
5/5/2009	115203	39938	6.26	10
5/5/2009	115214	39938	6.21	10.2
5/26/2009	115331	39959	13.22	0.1
5/26/2009	115343	39959	12.86	1
5/26/2009	115359	39959	12.59	2
5/26/2009	115419	39959	11.9	3
5/26/2009	115433	39959	11.47	4
5/26/2009	115449	39959	11	5
5/26/2009	115502	39959	9.87	6
5/26/2009	115519	39959	9.16	7
5/26/2009	115536	39959	8.63	8
5/26/2009	115553	39959	8.41	9
5/26/2009	115611	39959	8.2	10
5/26/2009	115628	39959	8.06	11
5/26/2009	115641	39959	7.82	12
5/26/2009	115657	39959	7.7	13
5/26/2009	115713	39959	7.6	14
5/26/2009	115724	39959	7.48	14.2
6/16/2009	115331	39980	16.72	0.1
6/16/2009	115343	39980	16.56	1
6/16/2009	115359	39980	16.35	2
6/16/2009	115419	39980	16.19	3
6/16/2009	115433	39980	16.03	4
6/16/2009	115449	39980	14.79	5
6/16/2009	115502	39980	13.02	6

6/16/2009	115519	39980	12.23	7
6/16/2009	115536	39980	11.88	8
6/16/2009	115553	39980	11.65	9
6/16/2009	115611	39980	11.4	10
6/16/2009	115628	39980	10.97	12
6/16/2009	115641	39980	10.66	14
6/16/2009	115657	39980	10.3	16
6/16/2009	115713	39980	10.31	16.6
7/7/2009	112314	40001	18.9	0.1
7/7/2009	112332	40001	18.9	1
7/7/2009	112349	40001	18.89	2
7/7/2009	112410	40001	18.9	3
7/7/2009	112432	40001	18.3	4
7/7/2009	112452	40001	17.35	5
7/7/2009	112509	40001	16.47	6
7/7/2009	112623	40001	16.44	6
7/7/2009	112644	40001	15.78	7
7/7/2009	112705	40001	15.2	8
7/7/2009	112731	40001	14.74	9
7/7/2009	112751	40001	14.31	10
7/7/2009	112807	40001	13.39	11
7/7/2009	112825	40001	13.18	11.9
7/21/2009	112633	40015	21.57	0.1
7/21/2009	112659	40015	21	1
7/21/2009	112722	40015	20.83	2
7/21/2009	112740	40015	20.78	3
7/21/2009	112812	40015	20.65	4
7/21/2009	112838	40015	18.61	5
7/21/2009	112905	40015	17.14	6
7/21/2009	112941	40015	16.52	7
7/21/2009	113004	40015	16.21	8
7/21/2009	113033	40015	15.7	9
7/21/2009	113054	40015	15.55	10
7/21/2009	113112	40015	15.44	10.6
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8/11/2009	113138	40036	20.44	1
8/11/2009	113209	40036	20.44	2
8/11/2009	113228	40036	20.43	3

8/11/2009	113312	40036	20.4	4
8/11/2009	113341	40036	20.38	5
8/11/2009	113407	40036	20.04	6
8/11/2009	113433	40036	19.02	7
8/11/2009	113506	40036	18.65	8
8/11/2009	113531	40036	18.25	9
8/11/2009	113547	40036	18.11	9.6
9/1/2009	120218	40057	19.96	0.1
9/1/2009	120240	40057	19.94	1
9/1/2009	120308	40057	19.88	2
9/1/2009	120338	40057	19.83	3
9/1/2009	120411	40057	19.78	4
9/1/2009	120441	40057	19.69	5
9/1/2009	120517	40057	19.5	6
9/1/2009	120546	40057	19.42	6.7
10/6/2009	114812	40092	15.49	0.1
10/6/2009	114826	40092	15.27	1
10/6/2009	114845	40092	15.15	2
10/6/2009	114901	40092	14.99	3
10/6/2009	114918	40092	14.64	4
10/6/2009	114937	40092	12.63	5
10/6/2009	115012	40092	11.23	5.7

Appendix 4. Groundwater Inflow Memo from Seattle District

CENWS-EN-HH-WM **11 July 2011**

MEMORANDUM FOR THE RECORD

SUBJECT: Estimated Groundwater Discharges into Howard Hanson Reservoir

1. Background: An outside consulting firm (WEST Consultants) has been tasked with developing a water quality model of Eagle Gorge Reservoir (Hanson Reservoir) specifically focused on water temperature. During the development of the model groundwater discharges into Eagle Gorge Reservoir (EGR), located upstream of HHD, were deemed negligible, most likely to simplify model inputs, and were not integrated into the model. The purpose of this memorandum is to provide an estimate of groundwater discharge to the reservoir, focusing on the groundwater flow within the unconsolidated sediments underlying the mainstem and North Fork of the Green River.

a. Groundwater discharges into EGR may have a role in regulating late season pool temperatures, and including these discharges in the water quality model will likely improve the predictive capability of the model. No extensive data exists on groundwater discharges or the hydrogeologic properties of basins draining into EGR. Past fieldwork in the North Fork Green River includes well pumping tests conducted by Tacoma Water (2002 and 2004), and a geohydrologic reconnaissance by WA Department of Ecology (1971-72).

b. The current analysis estimated groundwater discharges into EGR by:

- Importing elevation data (DEM) for the Upper Green River Basin (UGRB) into ArcGIS
- Gathering relevant geologic information for the UGRB
- Conducting a literature review to obtain pertinent hydrogeologic characteristics for identifiable lithologic units within the UGRB
- Creating topographic cross sections for both North Fork and mainstem Green River before entering EGR at full pool level (1167')
- Calculating subsurface cross sectional area based on geologic data and topographic profiles
- Determining channel surface slope from DEM
- Calculating groundwater discharges using Darcy's Law: $Q = -(-KA(dh/dl))$

2. Geology: The UGRB is predominantly underlain by Tertiary bedrock (undifferentiated). The mainstem Green River contained alpine glaciers in its upper reaches during the Vashon Stade of the Fraser Glaciation (~18-15 ka). The valleys that contain either the North Fork Green River or

mainstem Green River are underlain by recessional outwash deposits (Q_{vr}) that overlie the Tertiary bedrock.

3. Hydrogeologic Units and Characteristics: The main hydrogeologic unit in the study area is the recessional outwash deposits of the Vashon Stade (Q_{vr}). This unit contains stratified sand and gravel that is well sorted; and well-bedded silty sand to silty clay. The thickness of this unit is highly variable, anywhere from 15' to 200' in localized settings. There have been reported values of the hydraulic conductivity that range from 0.08 ft/d to 5,065 ft/d, though it should be noted that none of the studies that determined these values from well pumping tests were conducted in the UGRB.

4. Assumptions in Calculations:

- Thickness of Q_{vr} ranges from ~16' to 60' (5 m to 18 m)
- Hydraulic conductivity (K) ranges from 62 ft/d(K_{min}) to 5,065 ft/d(K_{max}) with a median value of 933 ft/d(K_{median}) (from USGS S.I. Report 2010-5055)
- Hydraulic gradient (dh/dl) is the same as channel slope determined from DEM, with North Fork = 0.014 and mainstem = 0.0057

5. Results:

Table 1: Q_{gw} into EGR from UGRB

	Main Stem		North Fork	
Q_{vr} Thickness (ft)	16	60	16	60
$\bar{Q}_{min}\ (ft^3/s)$	0.07	0.26	0.30	1.07
$\bar{Q}_{median}\ (ft^3/s)$	1.10	3.95	4.48	16.11
$\bar{Q}_{max}\ (ft^3/s)$	5.96	21.44	24.29	87.46
$\bar{Q}_{min}\ (ft^3/s)*$	0.17		0.68	
$\bar{Q}_{median}\ (ft^3/s)*$	2.52		10.29	
$\bar{Q}_{max}\ (ft^3/s)*$	13.70		55.88	

* Mean values of *Q* at 16' and 60'

6. Conclusion: The results for the North Fork are consistent with past estimates by WA DOE (OFTR 71-04, p. 3). The mainstem contributes less groundwater discharge since its gradient is the lesser of the two. The lowest inflows occur in August and/or September; for WY 2006-2009 have a monthly mean of 176 cfs and 144 cfs respectively. Groundwater discharges may

contribute from 0.5% to ~40% of inflows during August and from 0.6% to ~48% of inflows during September, assuming baseflow is completely from groundwater recession.

Christopher M. Maffucci

CENWS-EN-HH-WM

Appendix A

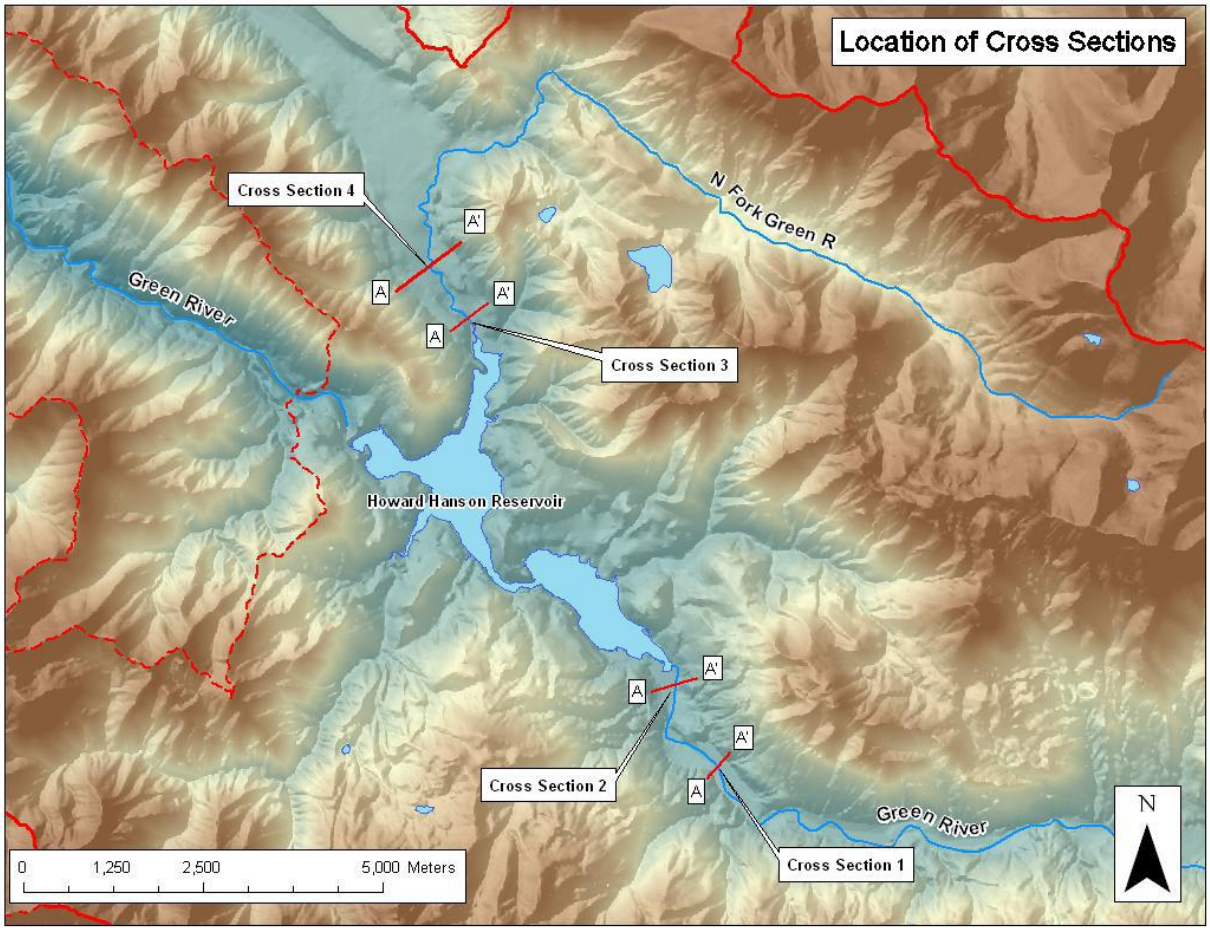


Figure 1: Locations of cross sections in relation to EGR

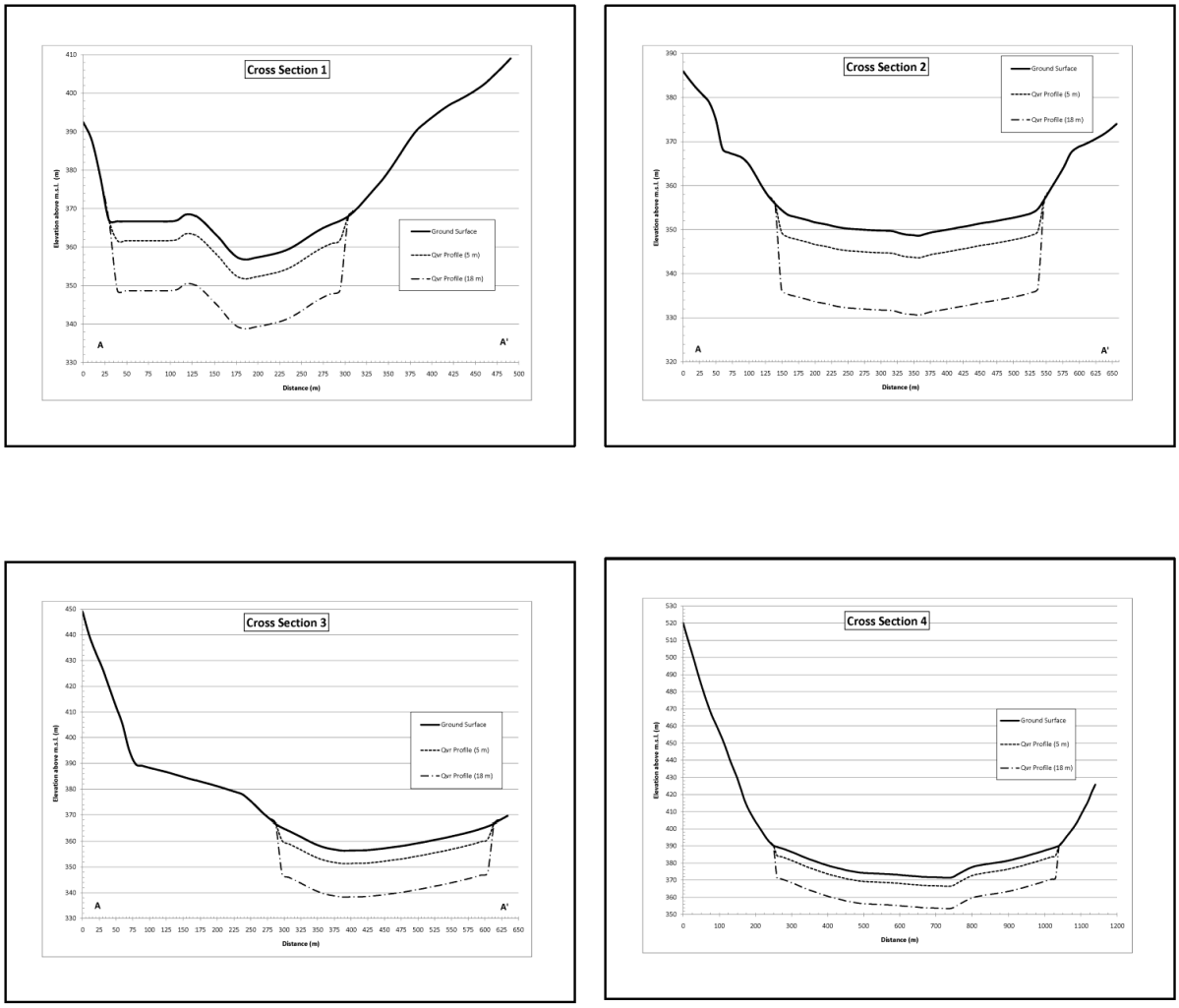
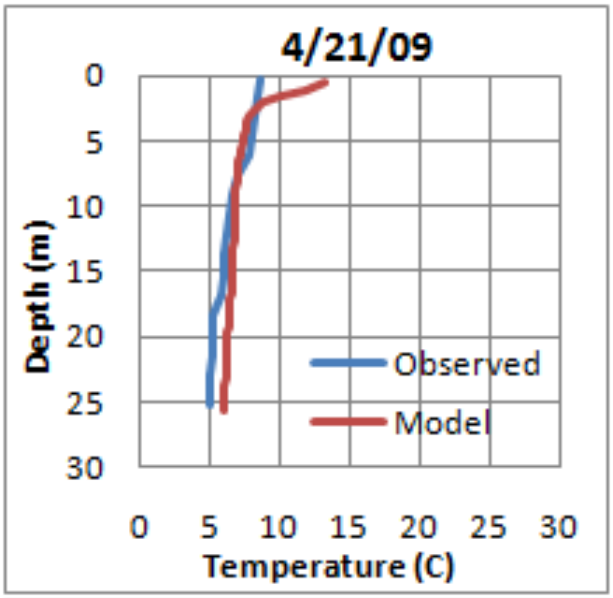
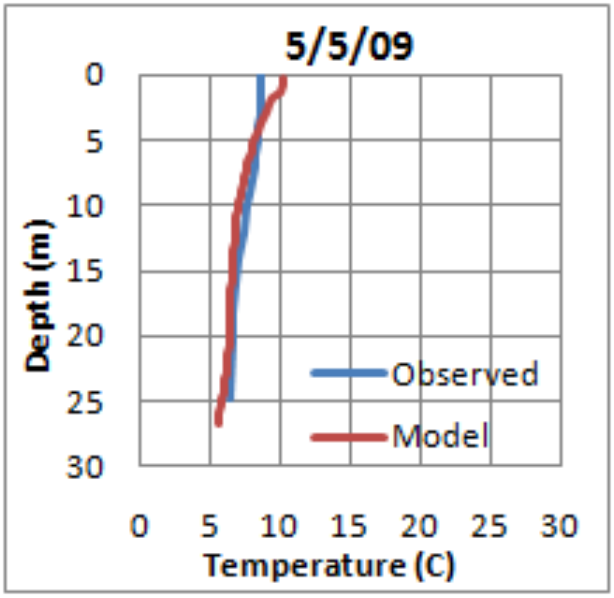
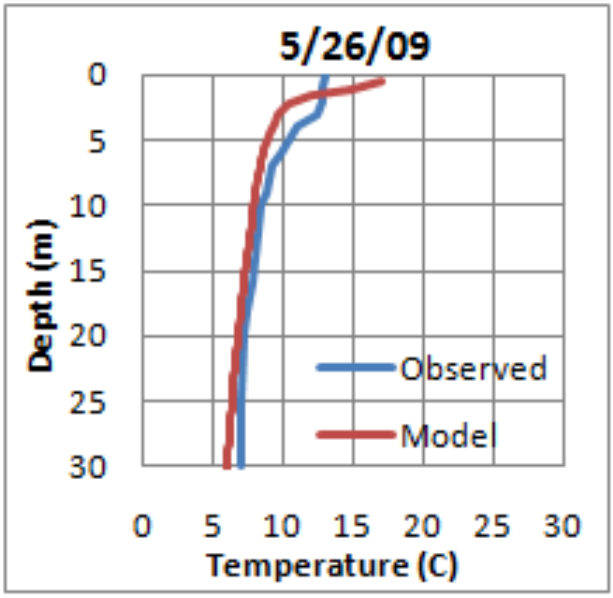


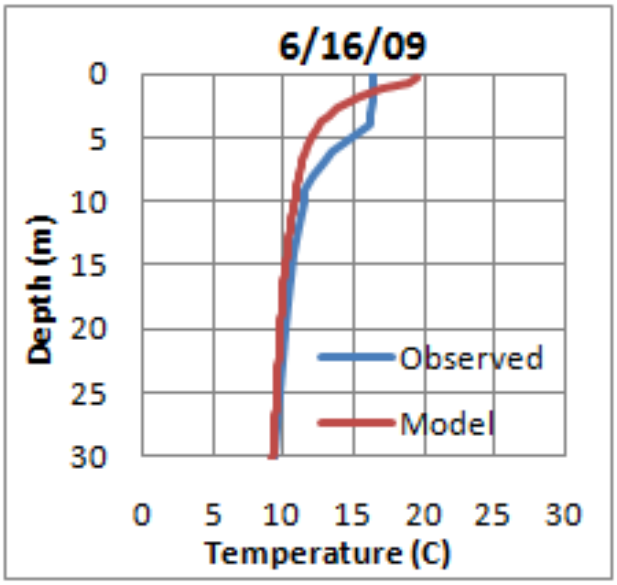
Figure 2: Topographic profiles of cross section 1 - 4

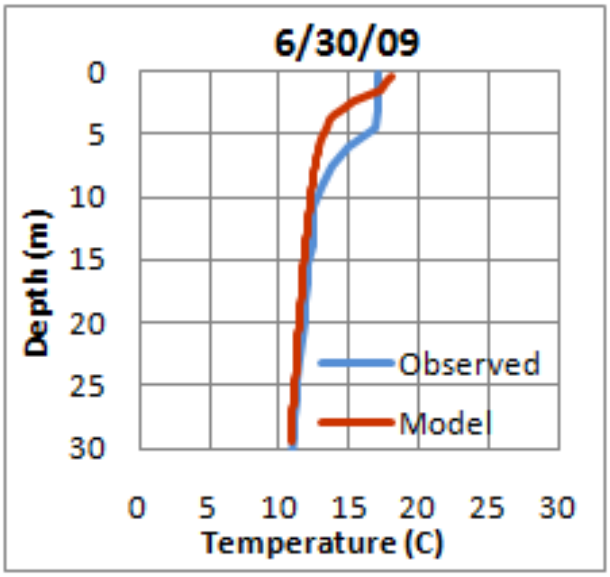
Appendix 5. Temperature Profiles for 2009 Calibration







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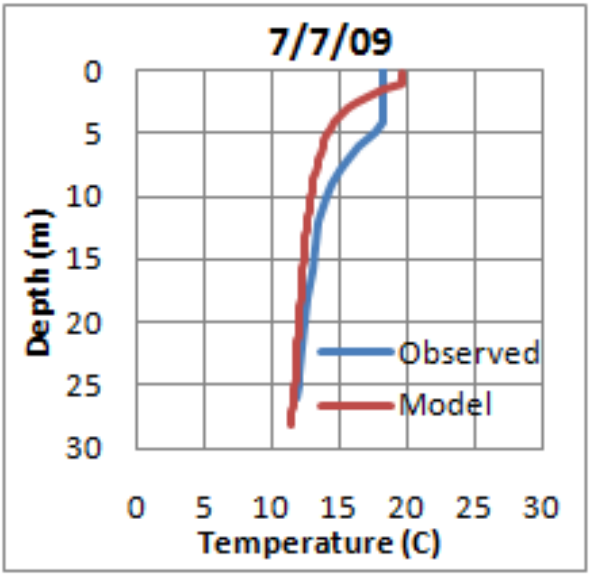
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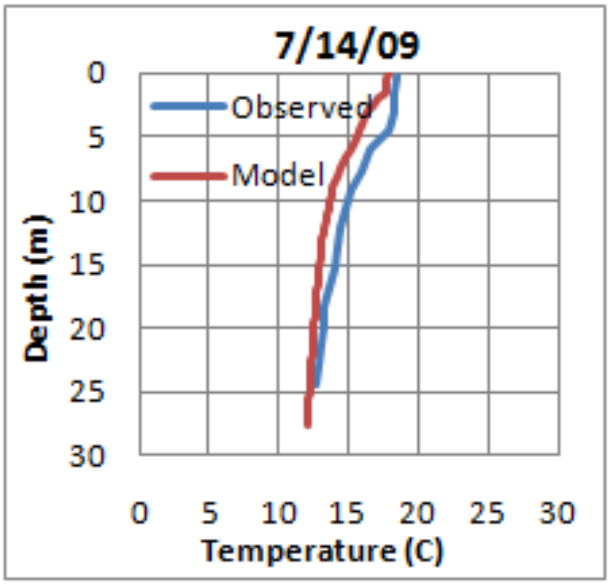
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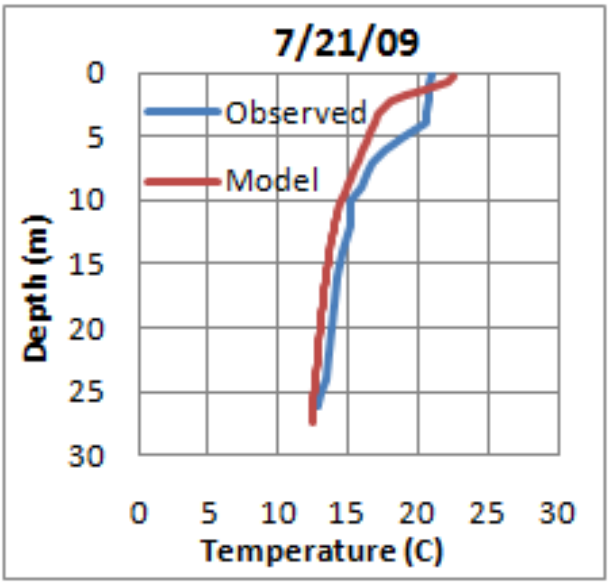
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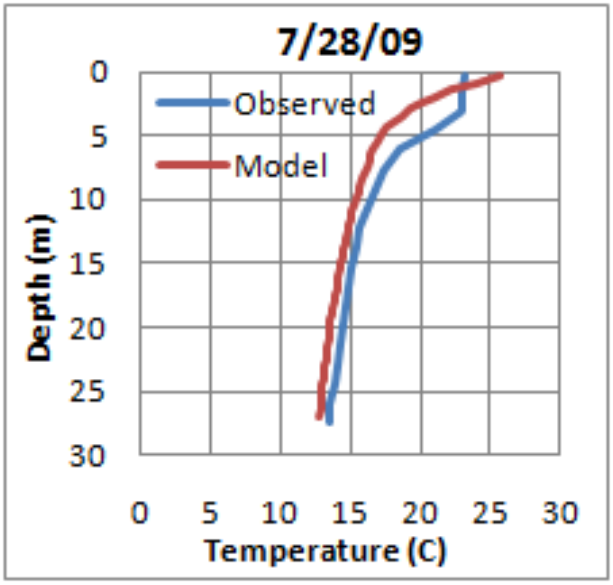
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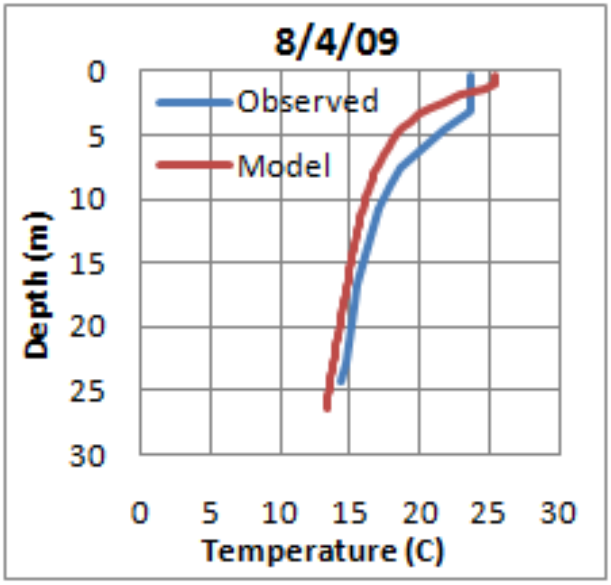
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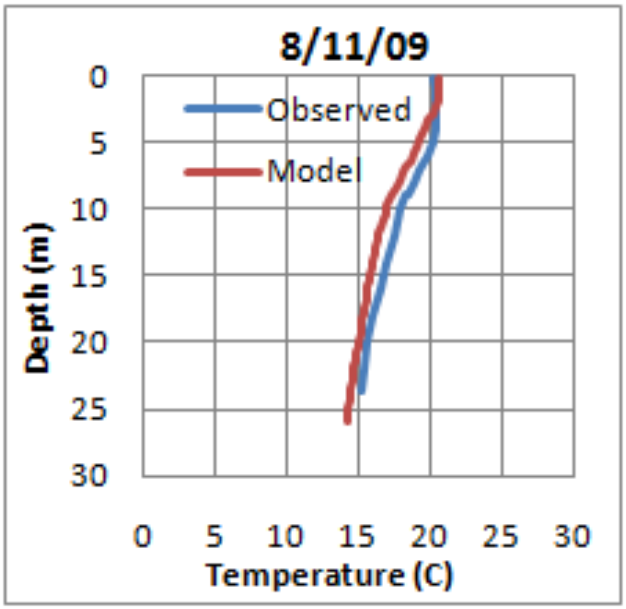
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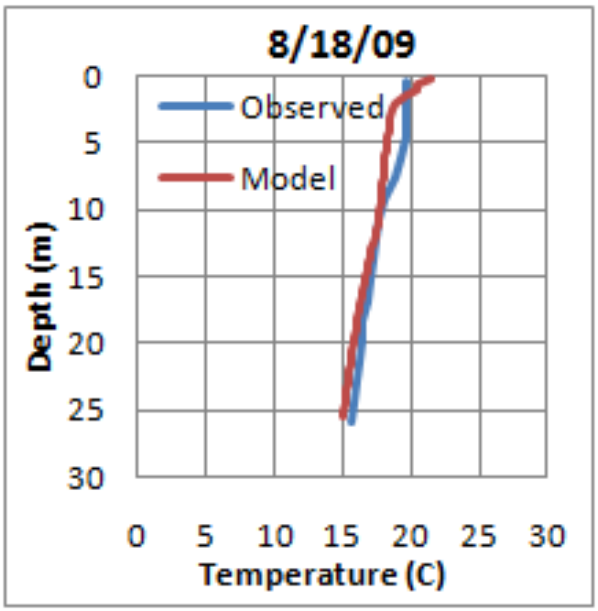
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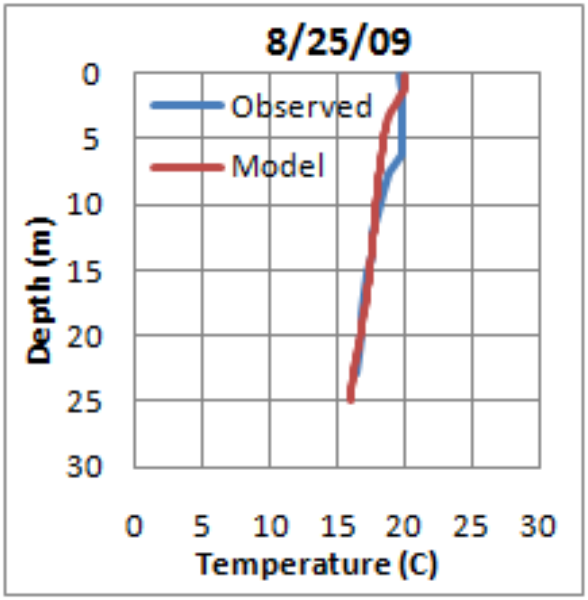
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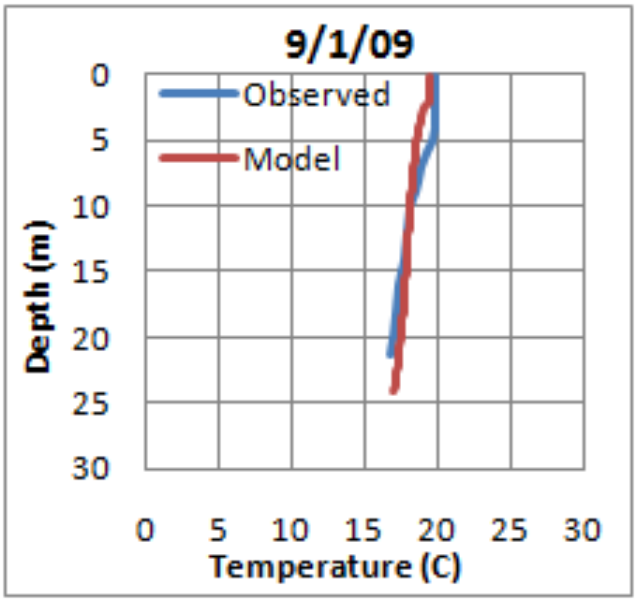
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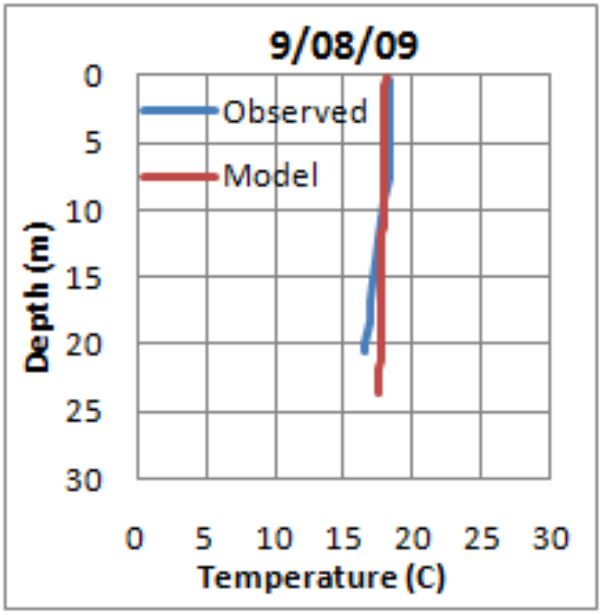
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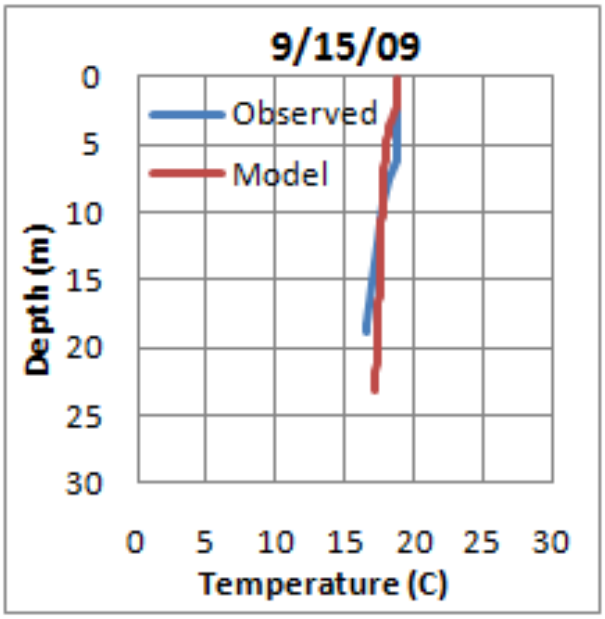
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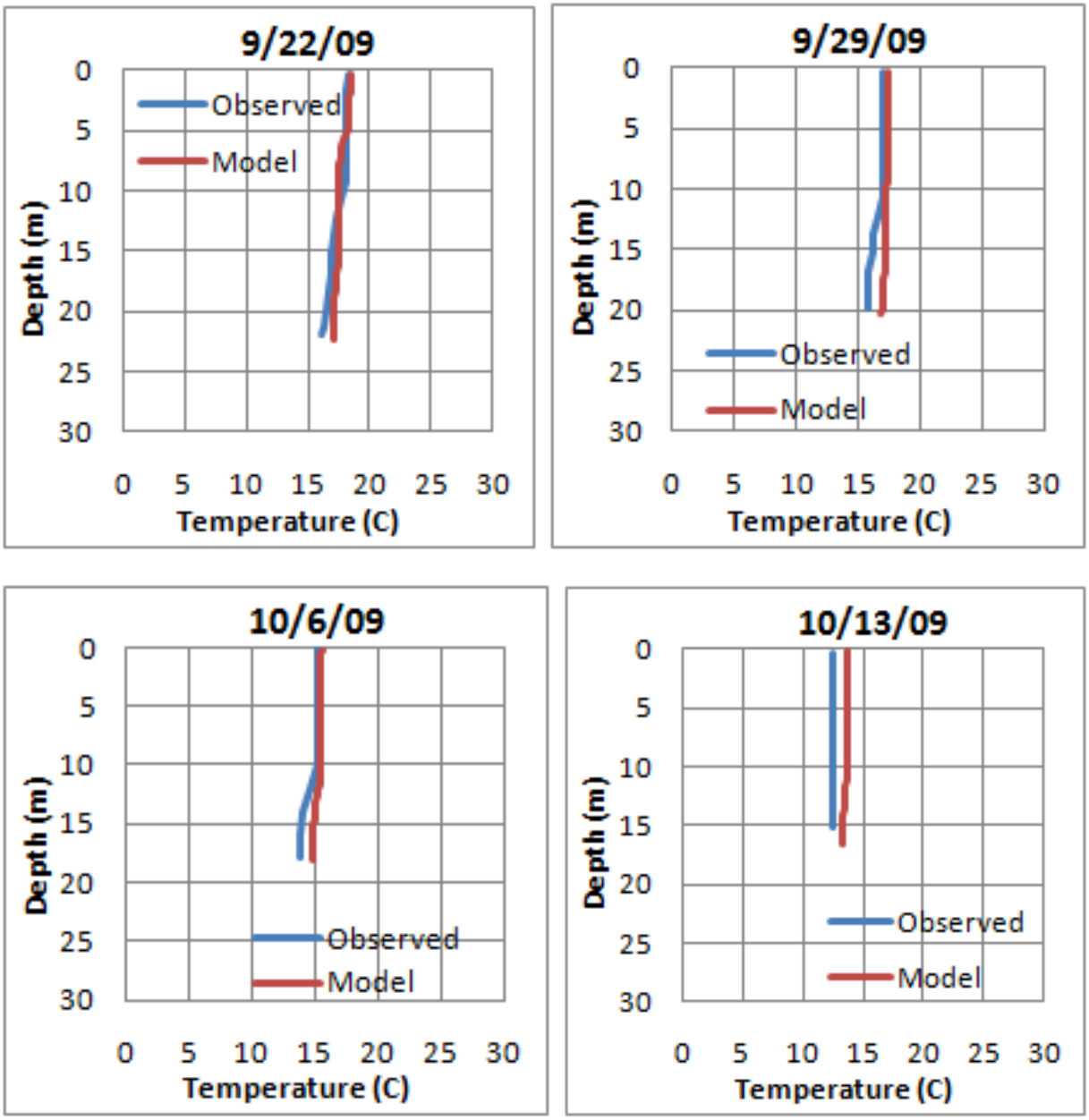
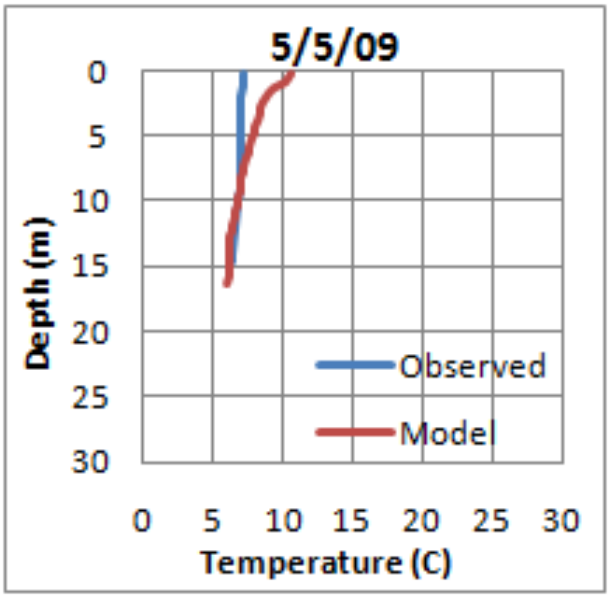


Figure A5-1. Model Calibration at dam (1DAM) location for 2009.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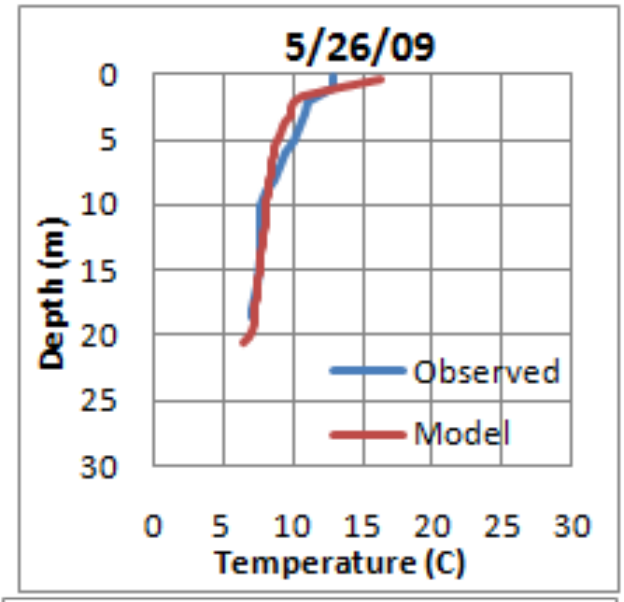
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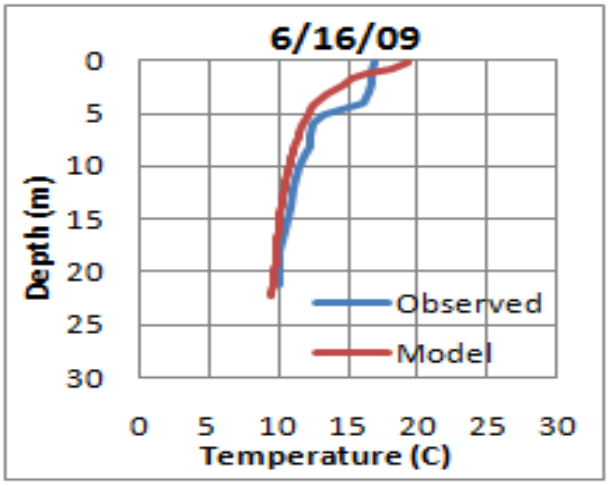
Temperature (C)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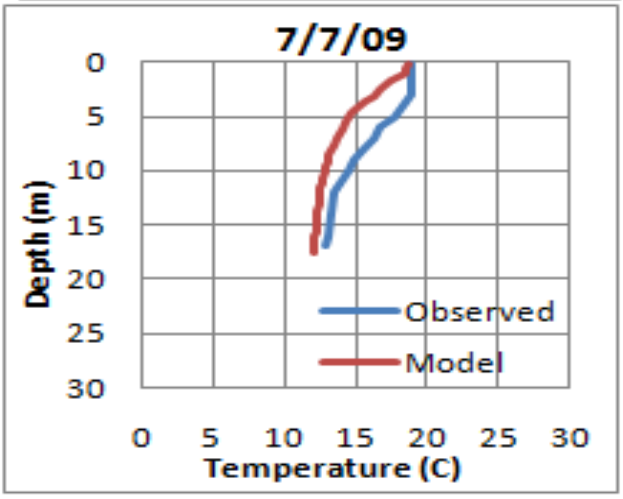
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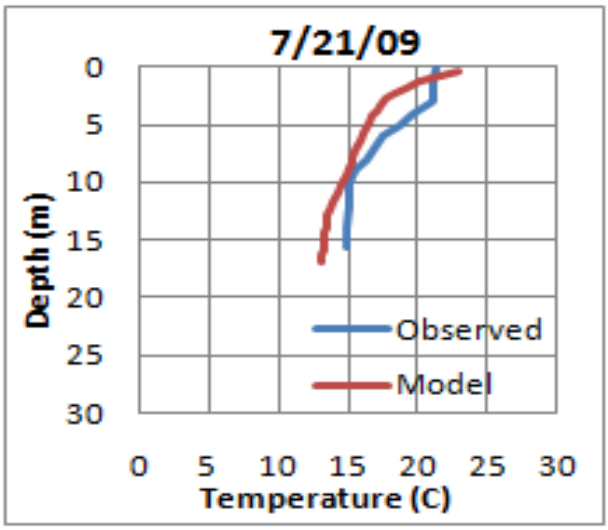
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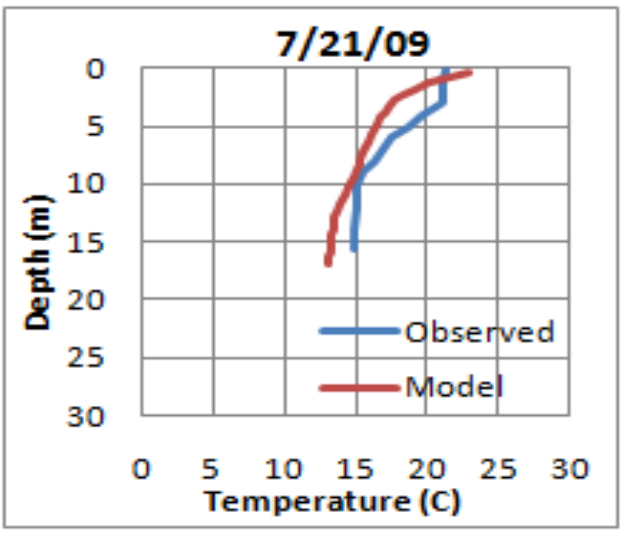
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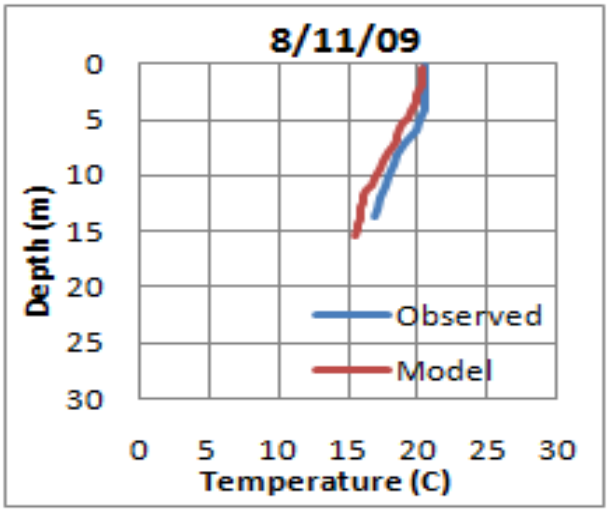
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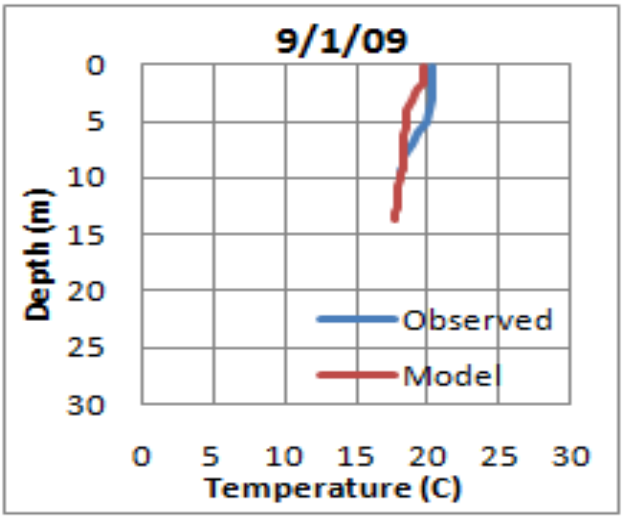
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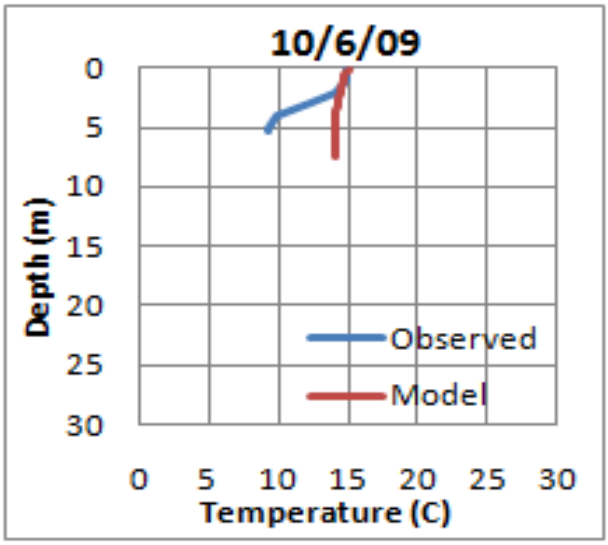
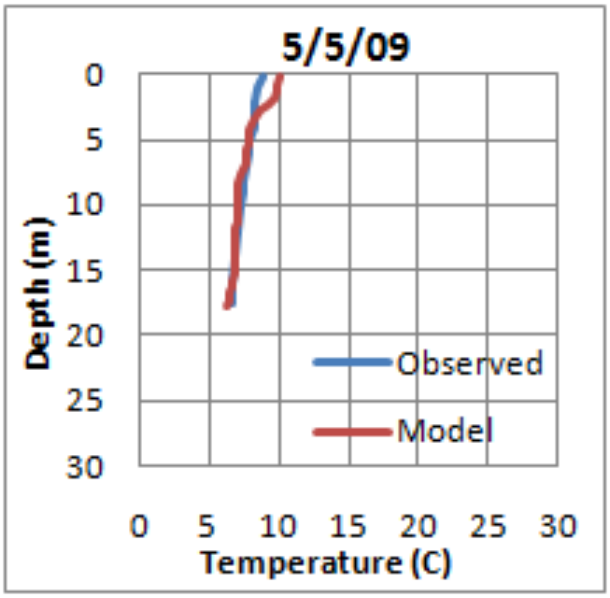


Figure A5-2. Model Calibration at upper pool (9UPNR) location for 2009.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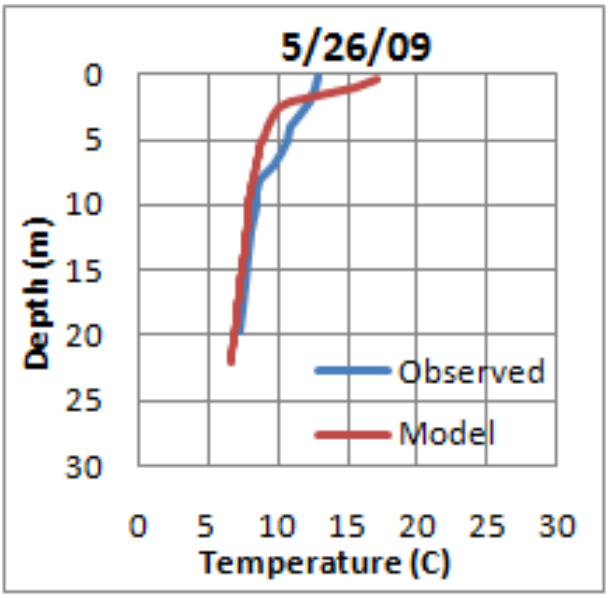
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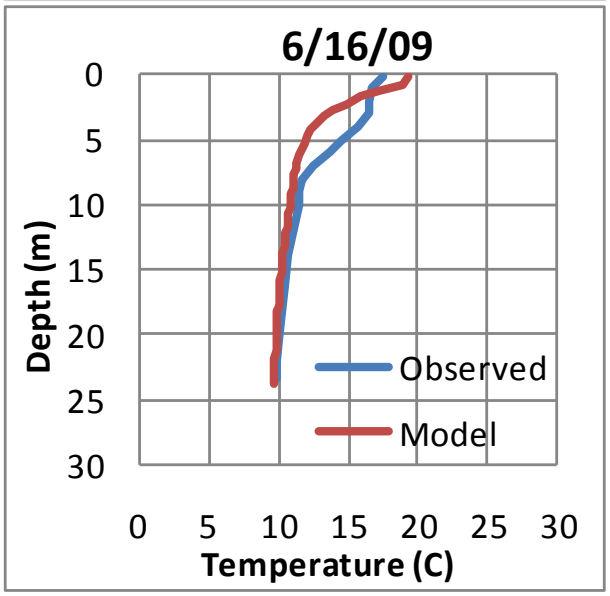
Temperature (C)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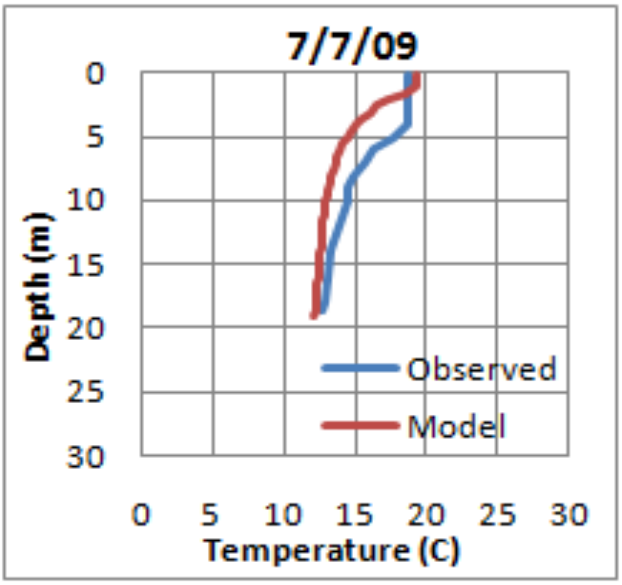
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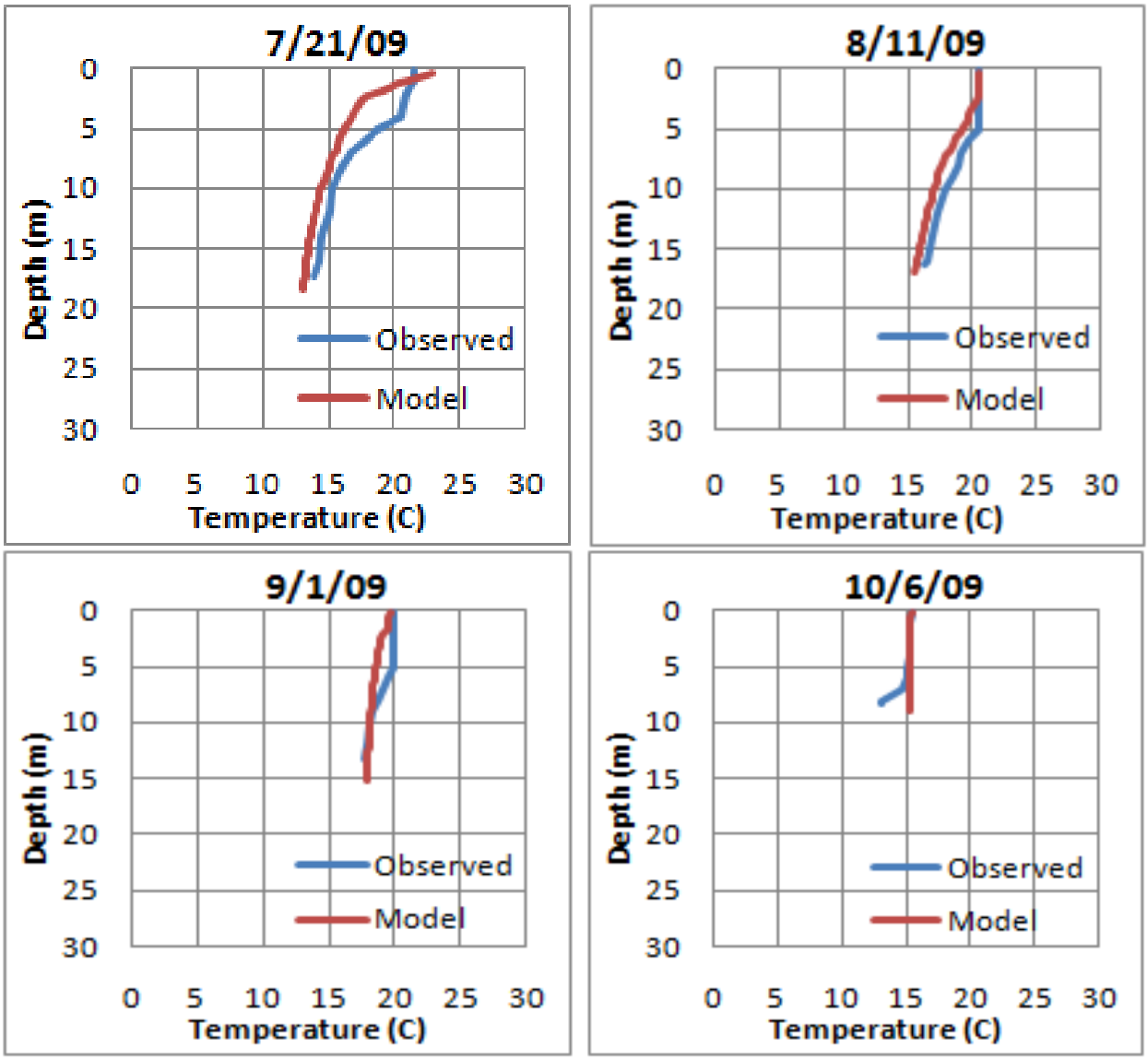
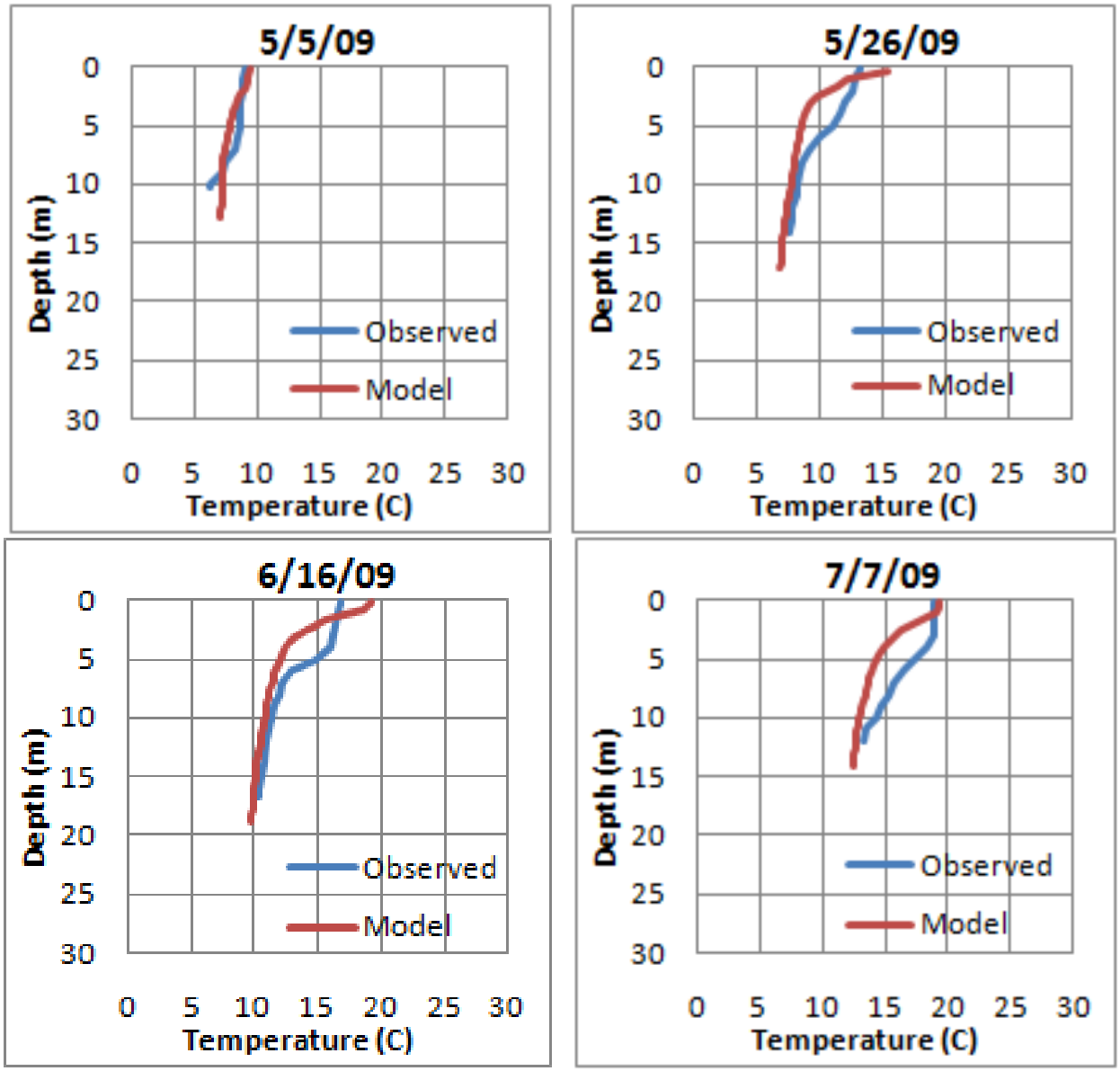


Figure A5-3. Model Calibration for Charlie Creek (SCHCK) location for 2009.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Temperature (C)
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25
30

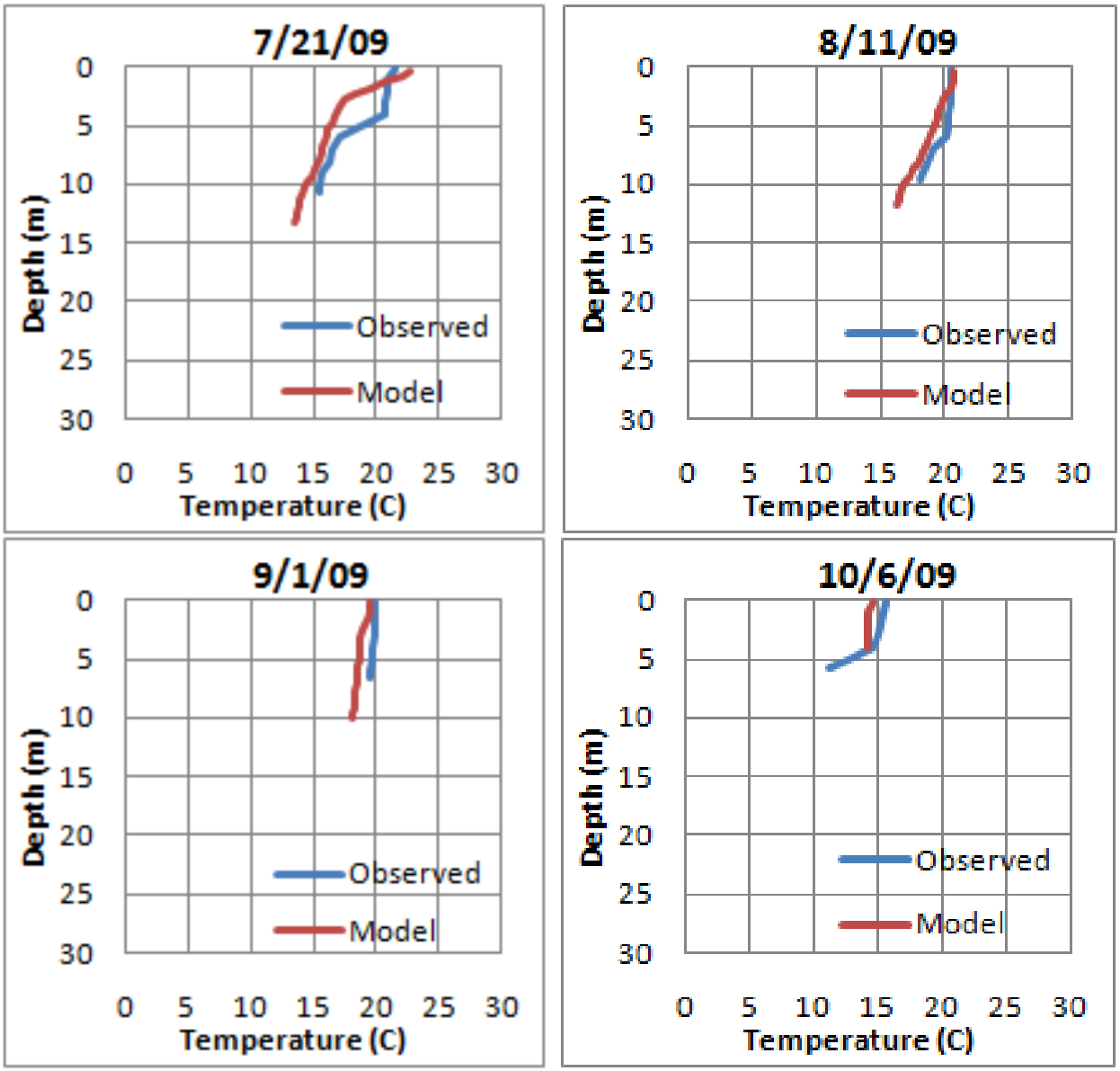
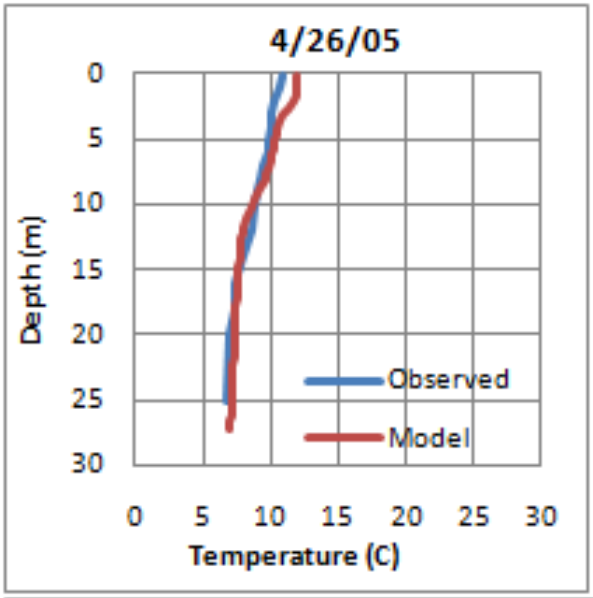
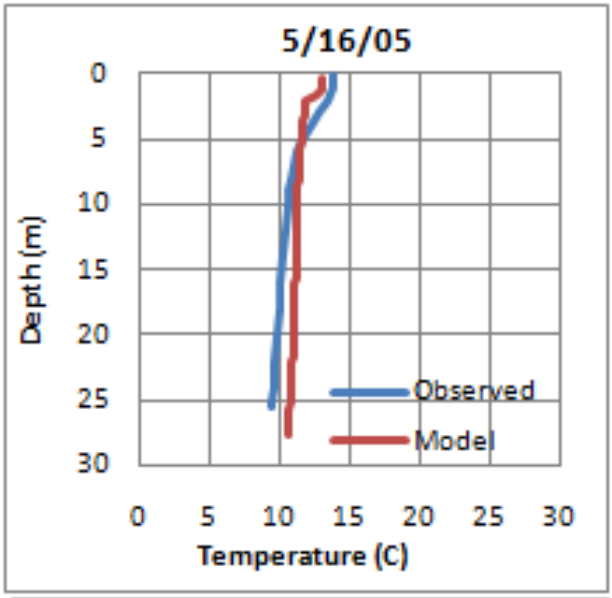
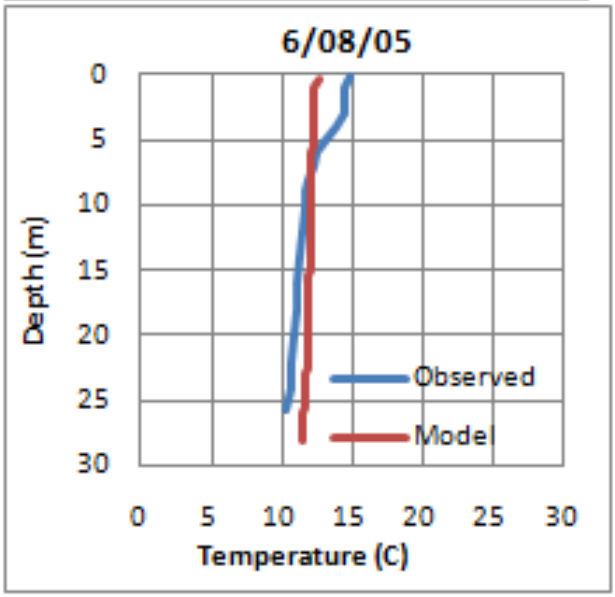


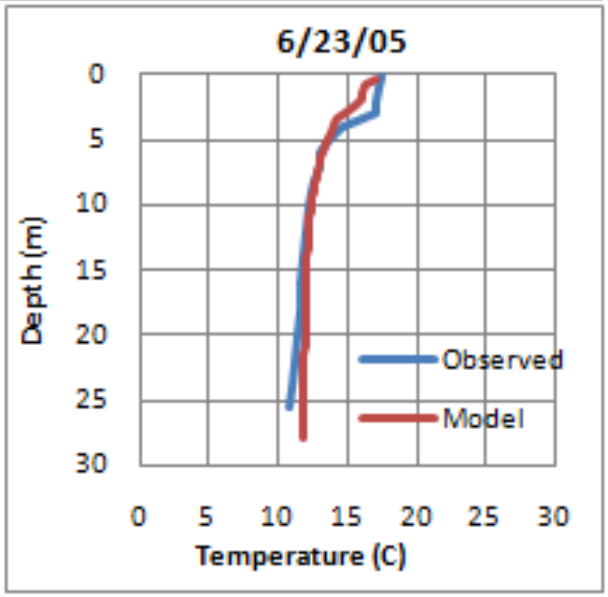
Figure A5-4. Model Calibration for North Fork (5NFK) location for 2009.

Appendix 6. Temperature Profiles for 2005 Validation









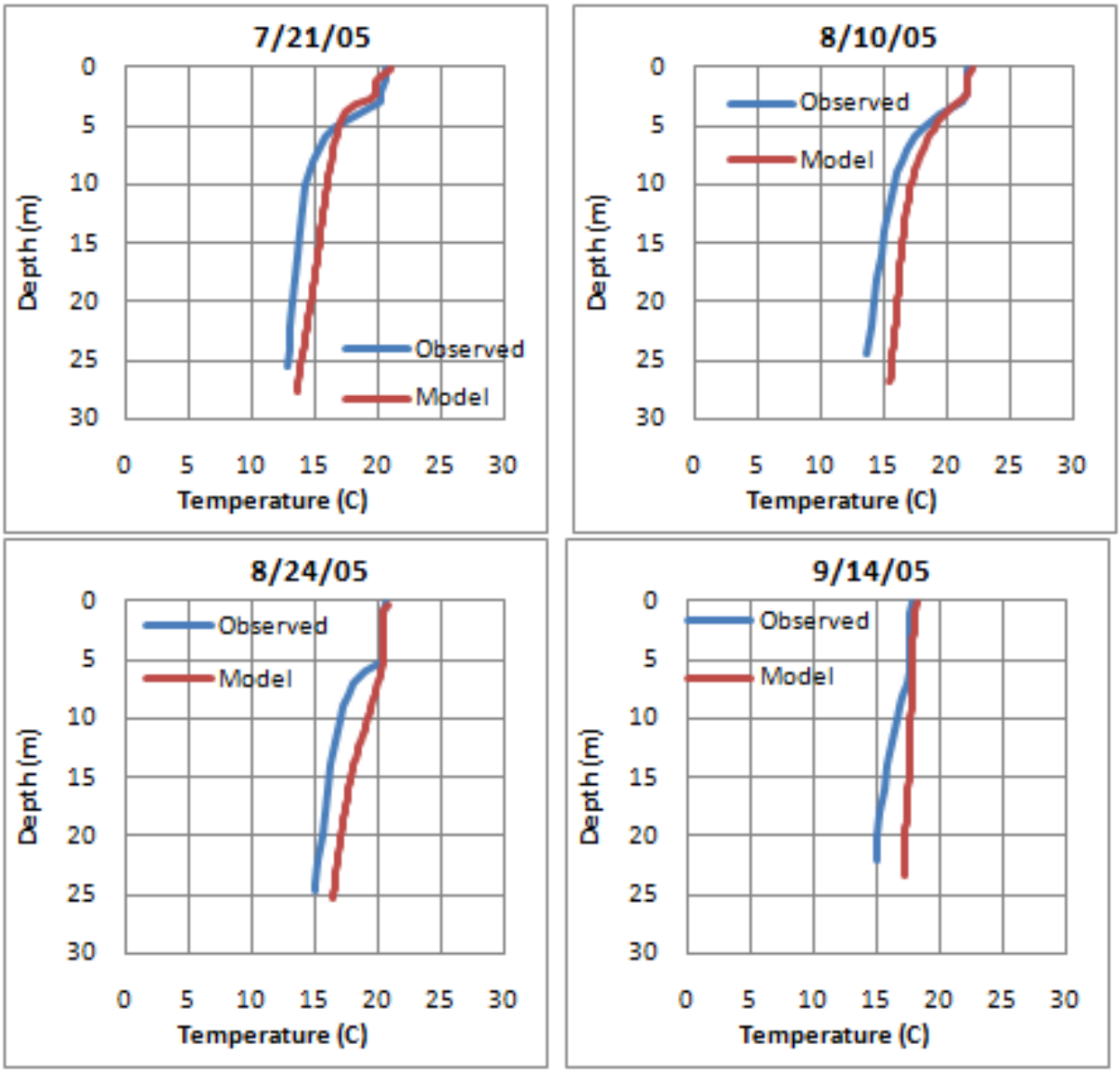
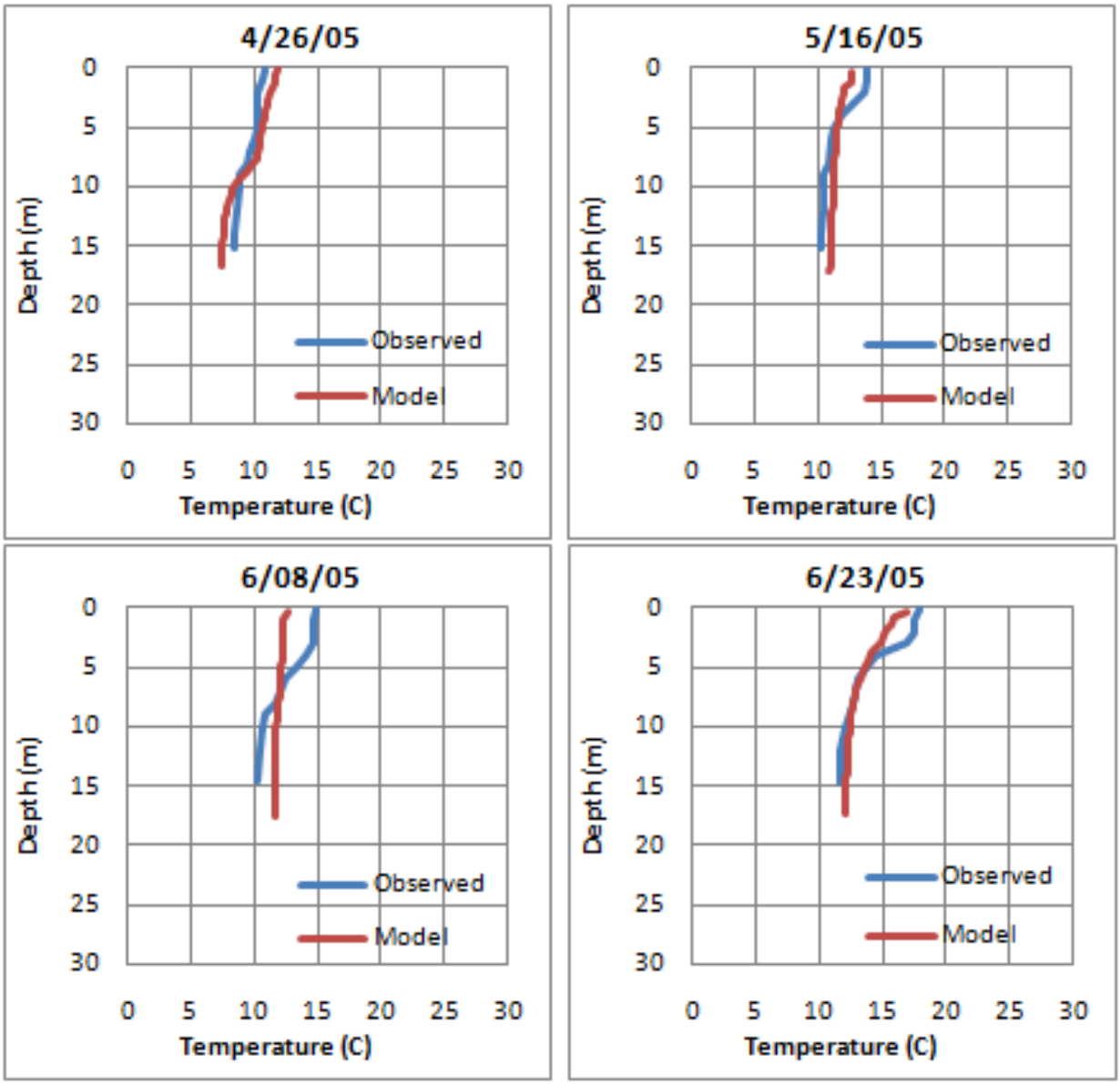


Figure A6-1. Model Calibration at dam (1DAM) location for 2005.


4/26/05
5/16/05
6/08/05
6/23/05
Depth (m)
Temperature (C)
Observed
Model
0
5
10
15
20
25
30

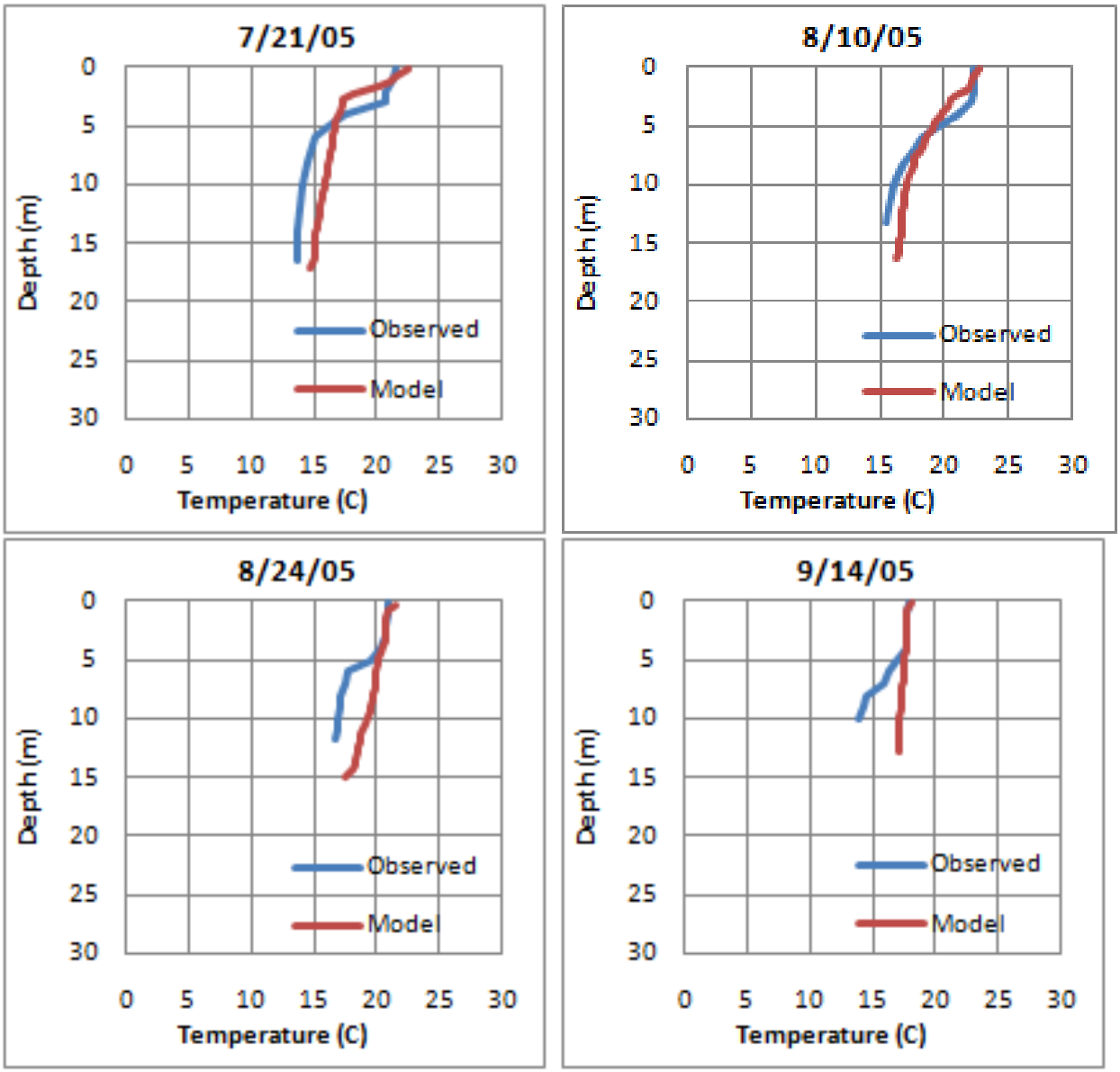
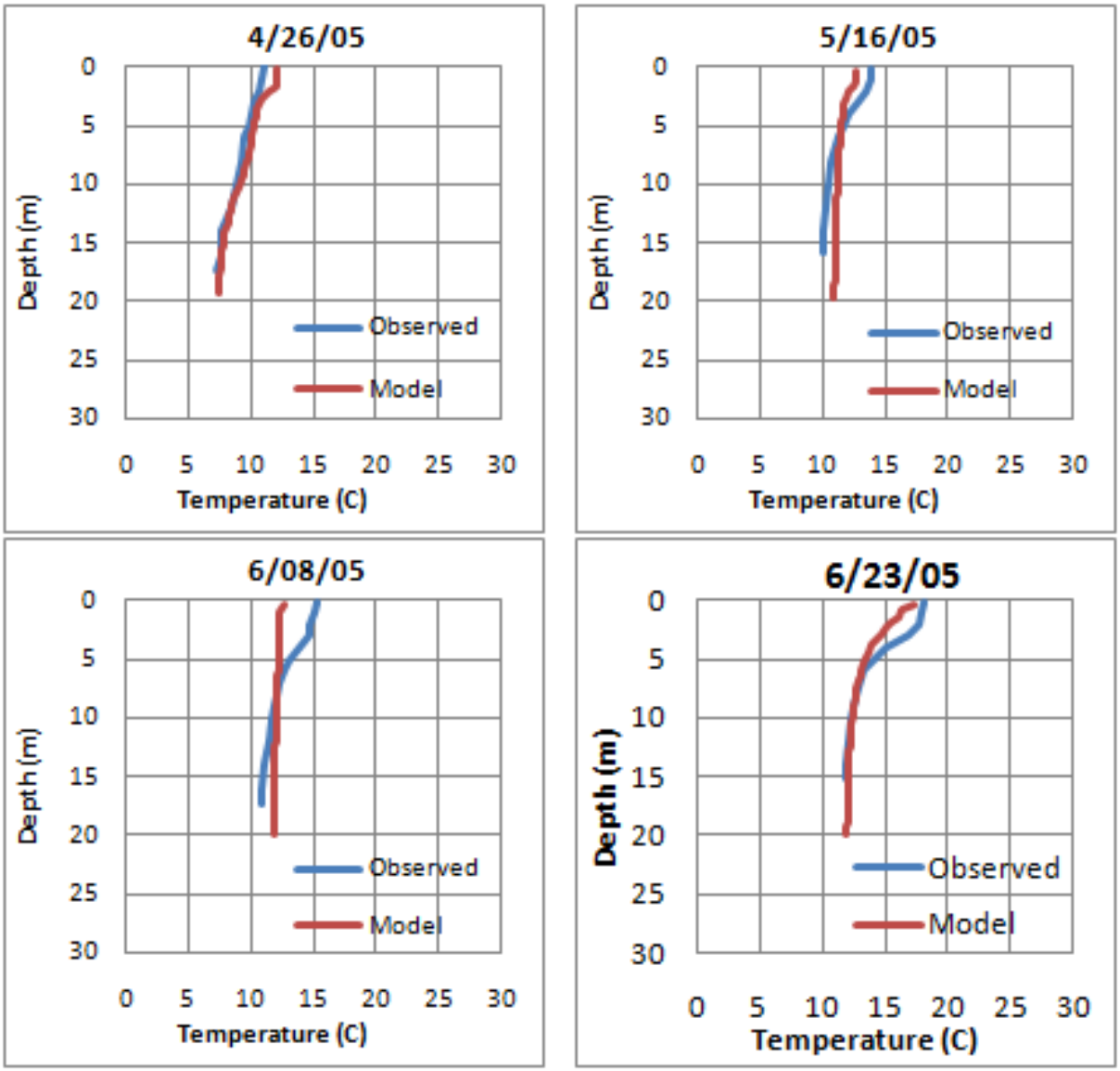


Figure A6-2. Model Calibration at upper pool (9UPNR) location for 2005.


4/26/05
5/16/05
6/08/05
6/23/05
Depth (m)
Temperature (C)
Observed
Model
0
5
10
15
20
25
30

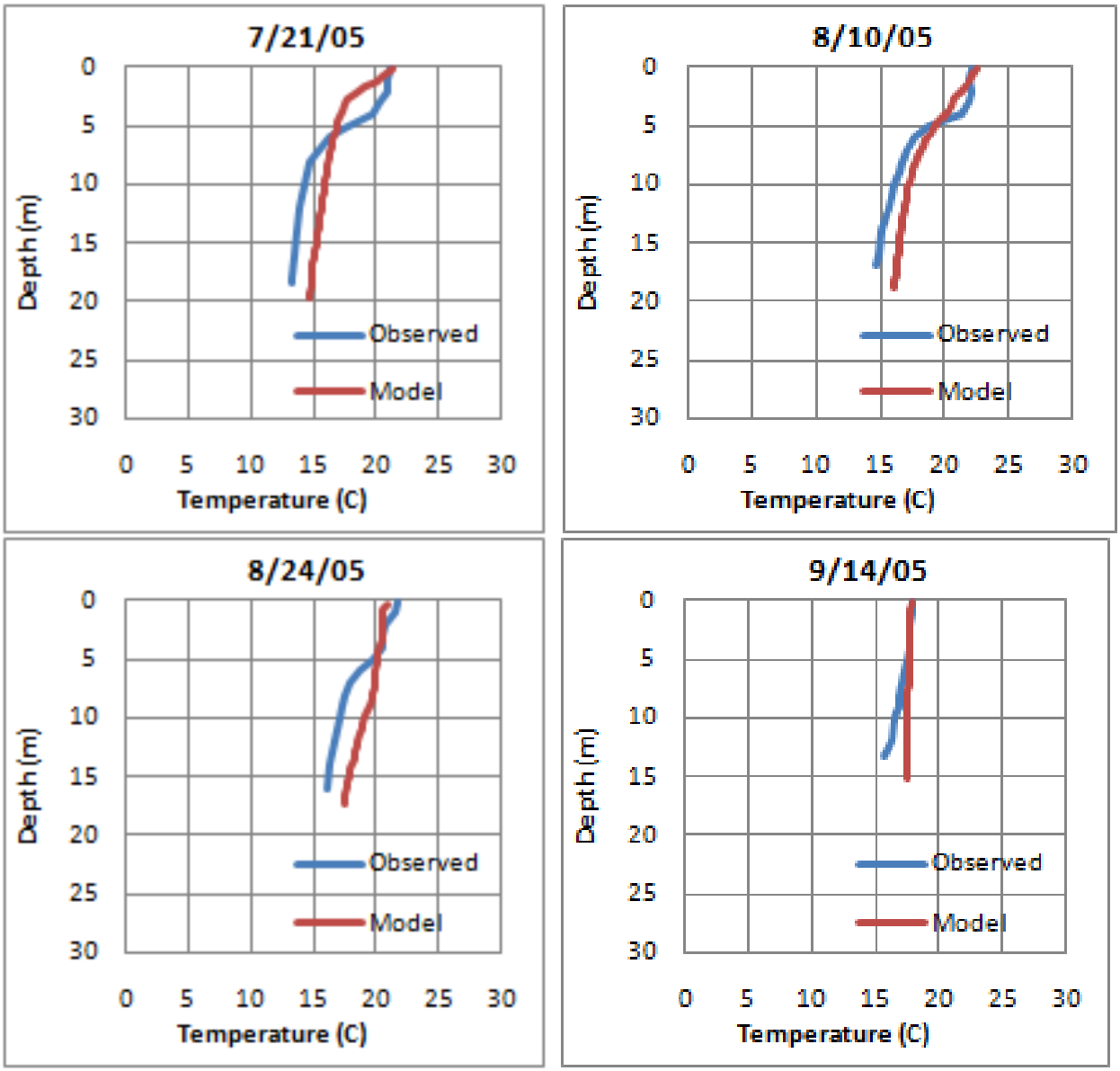
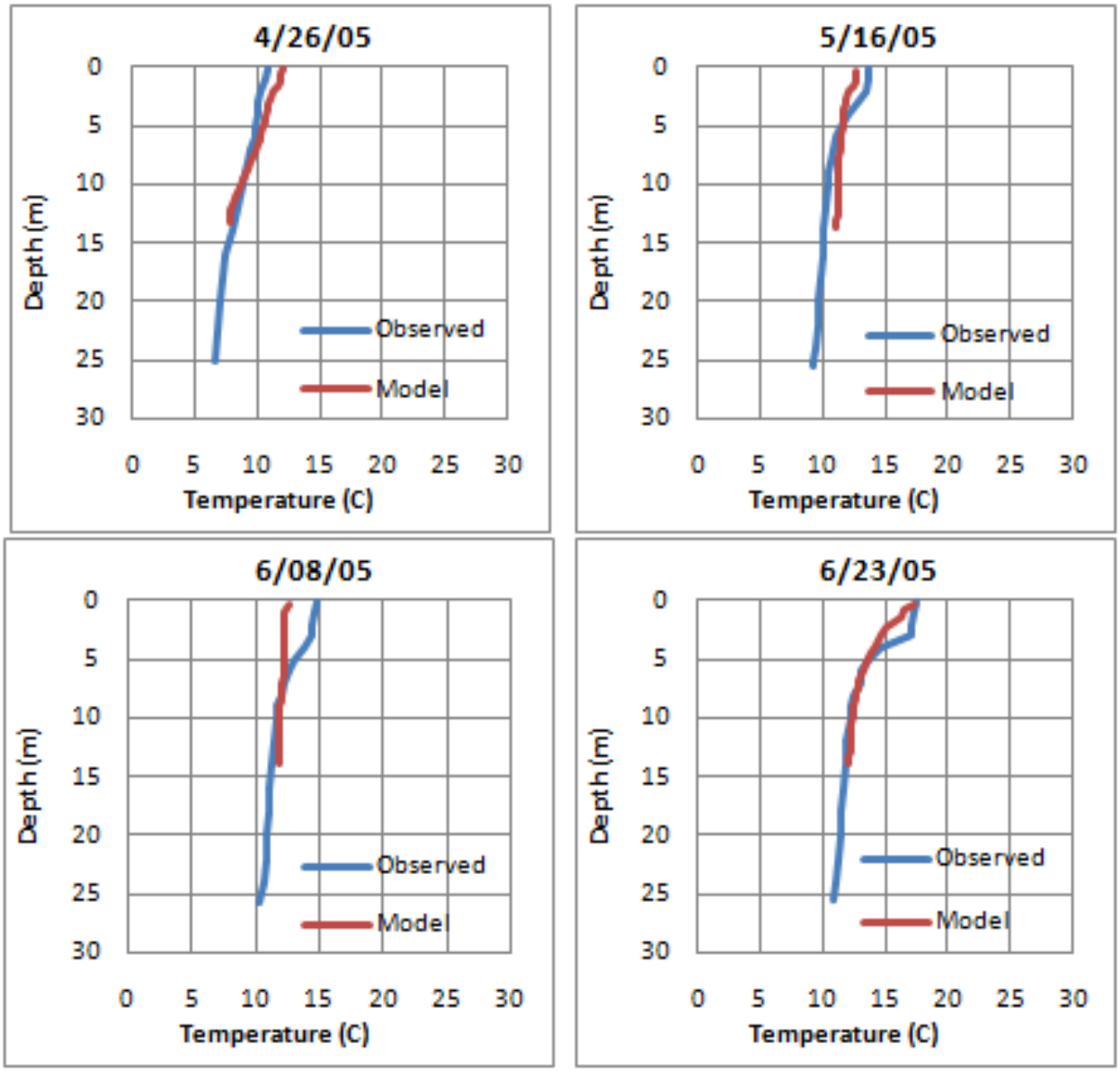


Figure A6-3. Model Calibration for Charlie Creek (SCHCK) location for 2005.


4/26/05
5/16/05
6/08/05
6/23/05
Depth (m)
Temperature (C)
Observed
Model
0
5
10
15
20
25
30

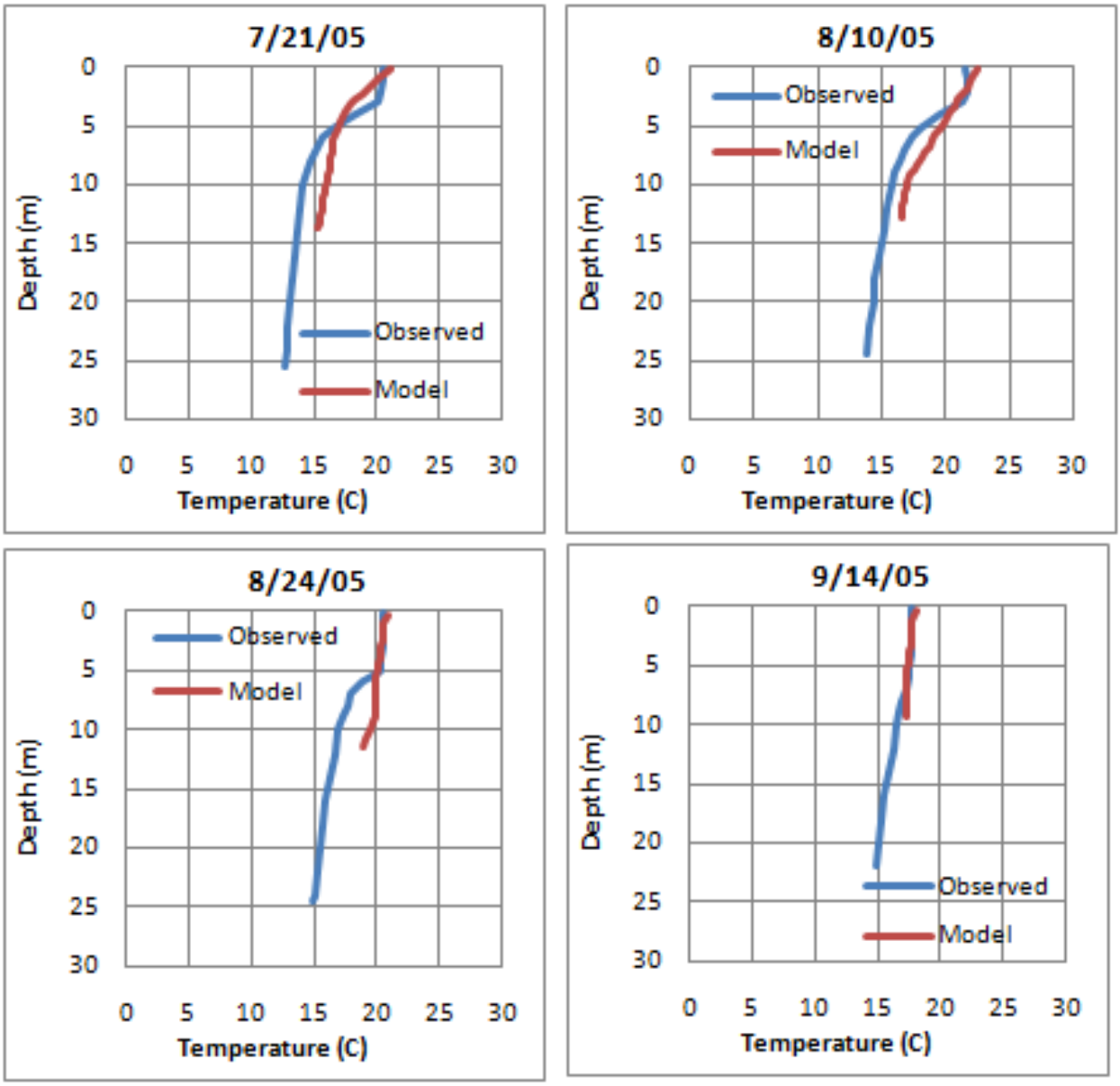
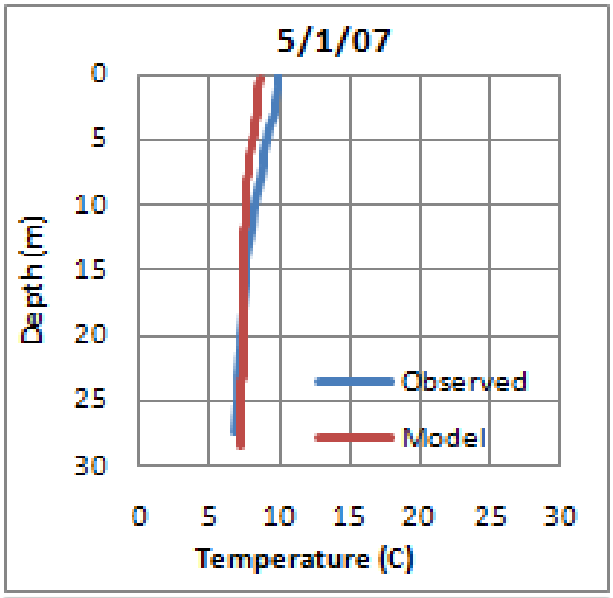
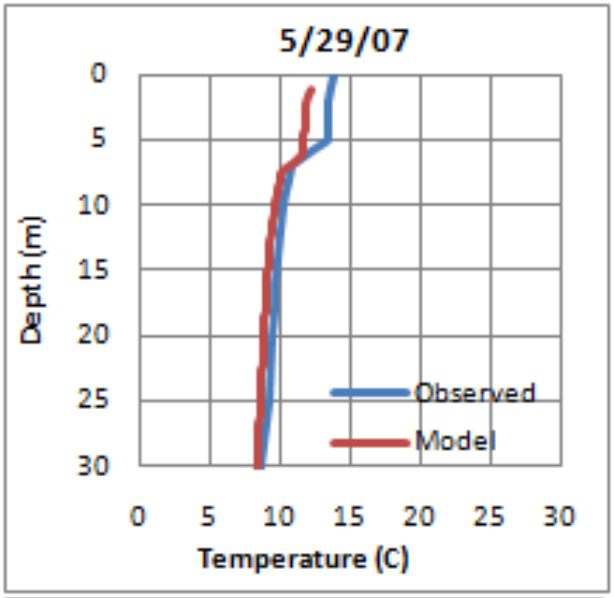
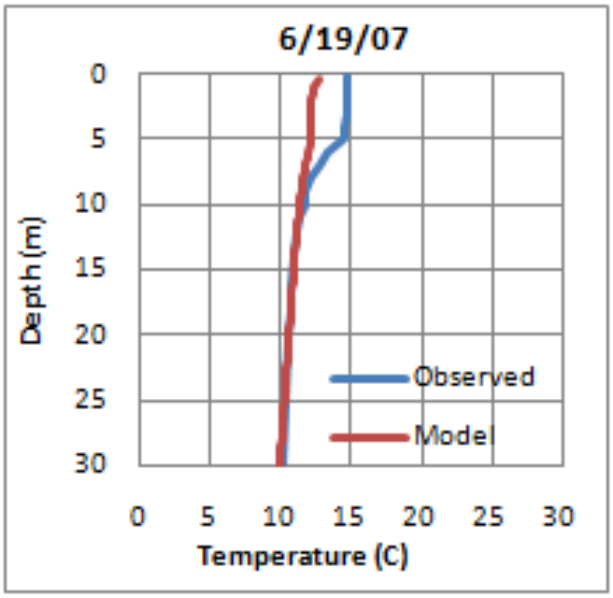


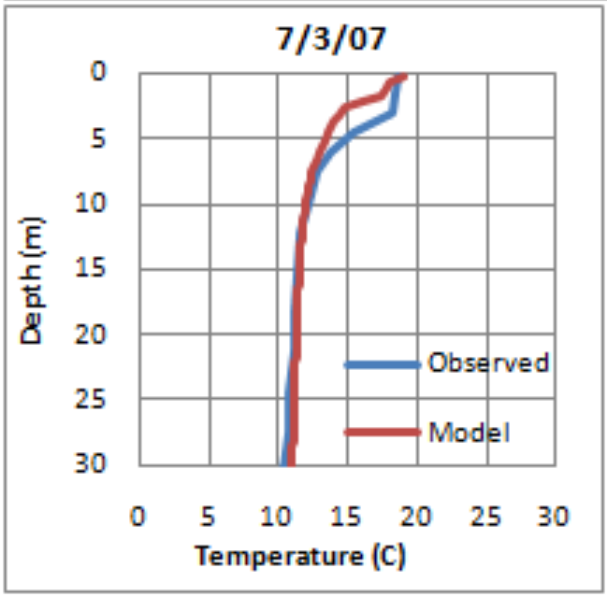
Figure A6-4. Model Calibration for North Fork (5NFK) location for 2005.

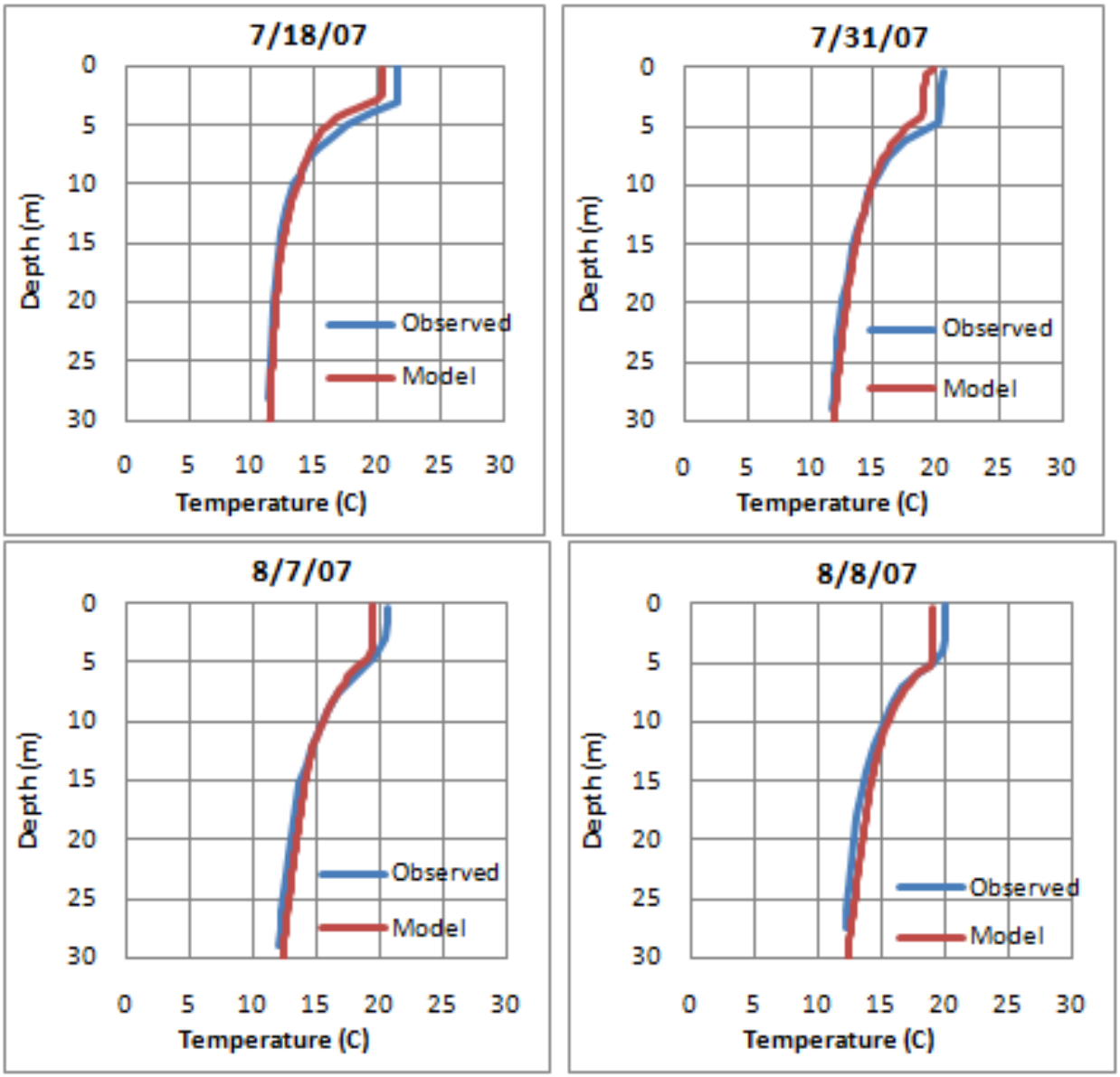
Appendix 7. Temperature Profiles for 2007 Validation

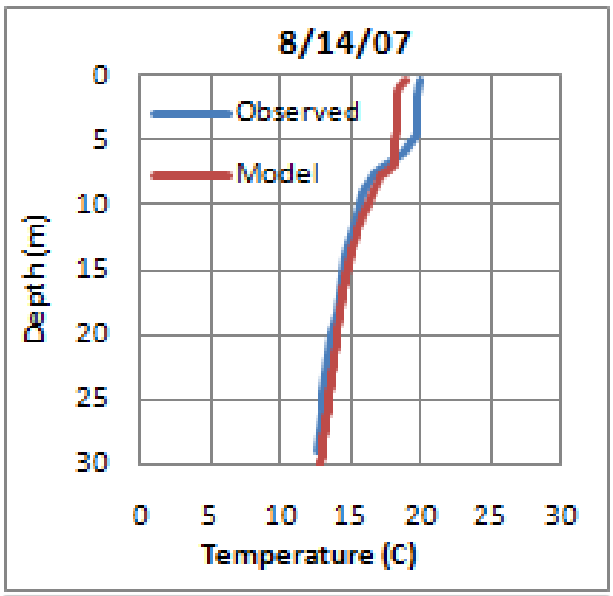


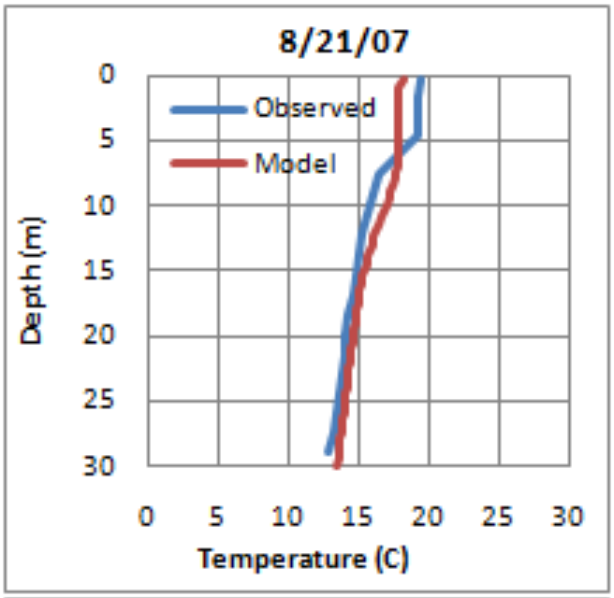


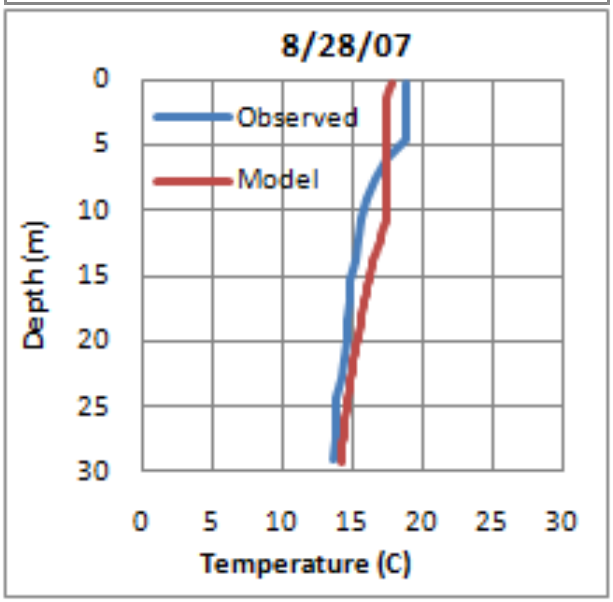


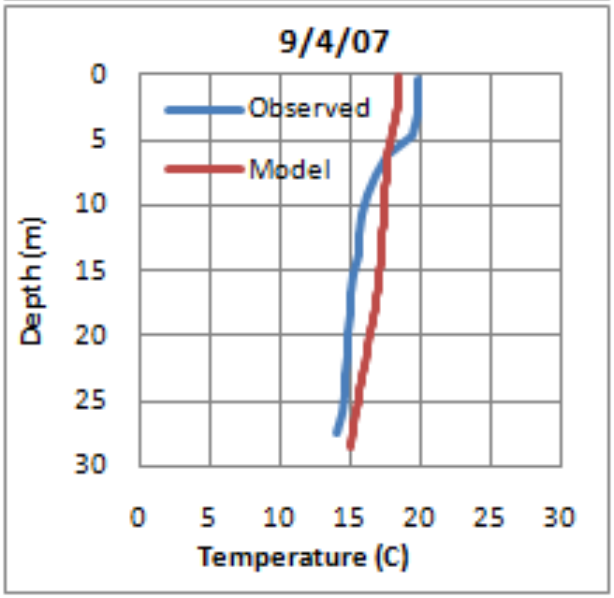


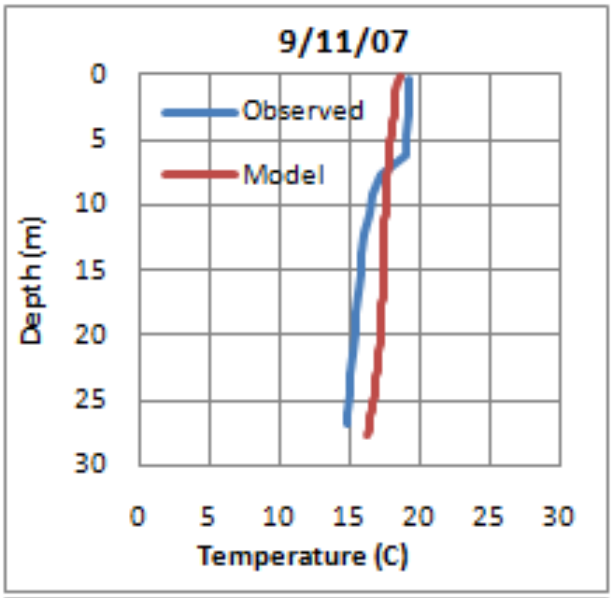

7/18/07
7/31/07
8/7/07
8/8/07
Depth (m)
Temperature (C)
Observed
Model
0
5
10
15
20
25
30

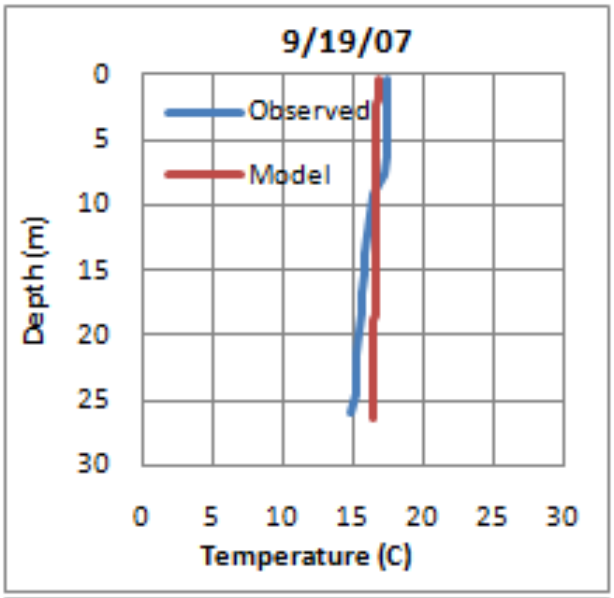

8/14/07
Observed
Model
Depth (m)
0
5
10
15
20
25
30
0 5 10 15 20 25 30
Temperature (C)

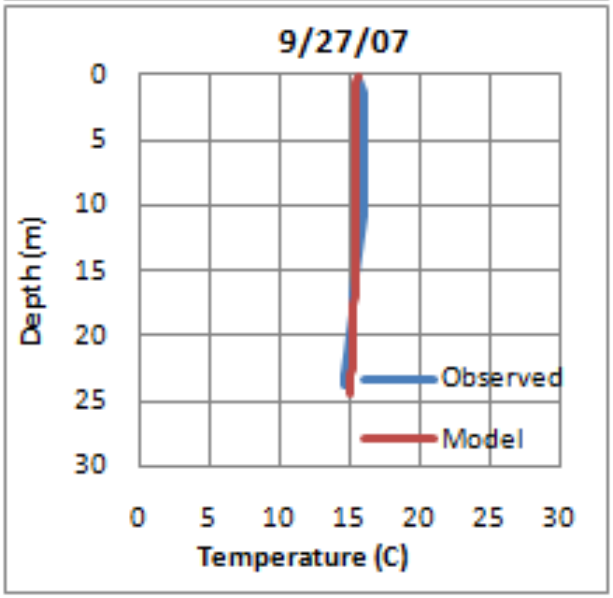

8/21/07
Observed
Model
Depth (m)
0
5
10
15
20
25
30
0 5 10 15 20 25 30
Temperature (C)

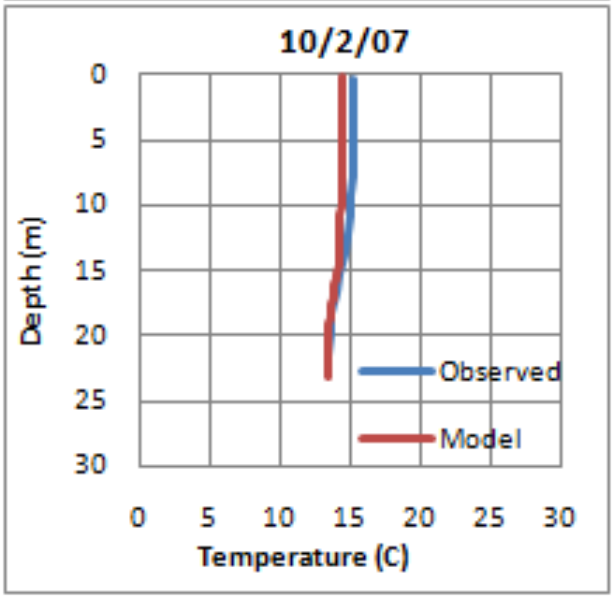

8/28/07
Observed
Model
Depth (m)
0
5
10
15
20
25
30
0 5 10 15 20 25 30
Temperature (C)


9/4/07
Observed
Model
Depth (m)
0
5
10
15
20
25
30
0 5 10 15 20 25 30
Temperature (C)


9/11/07
Observed
Model
Depth (m)
0
5
10
15
20
25
30
0
5
10
15
20
25
30
Temperature (C)


9/19/07
Observed
Model
Depth (m)
0
5
10
15
20
25
30
0
5
10
15
20
25
30
Temperature (C)


9/27/07
Observed
Model
Depth (m)
0
5
10
15
20
25
30
0
5
10
15
20
25
30
Temperature (C)


10/2/07
Observed
Model
Depth (m)
0
5
10
15
20
25
30
0
5
10
15
20
25
30
Temperature (C)

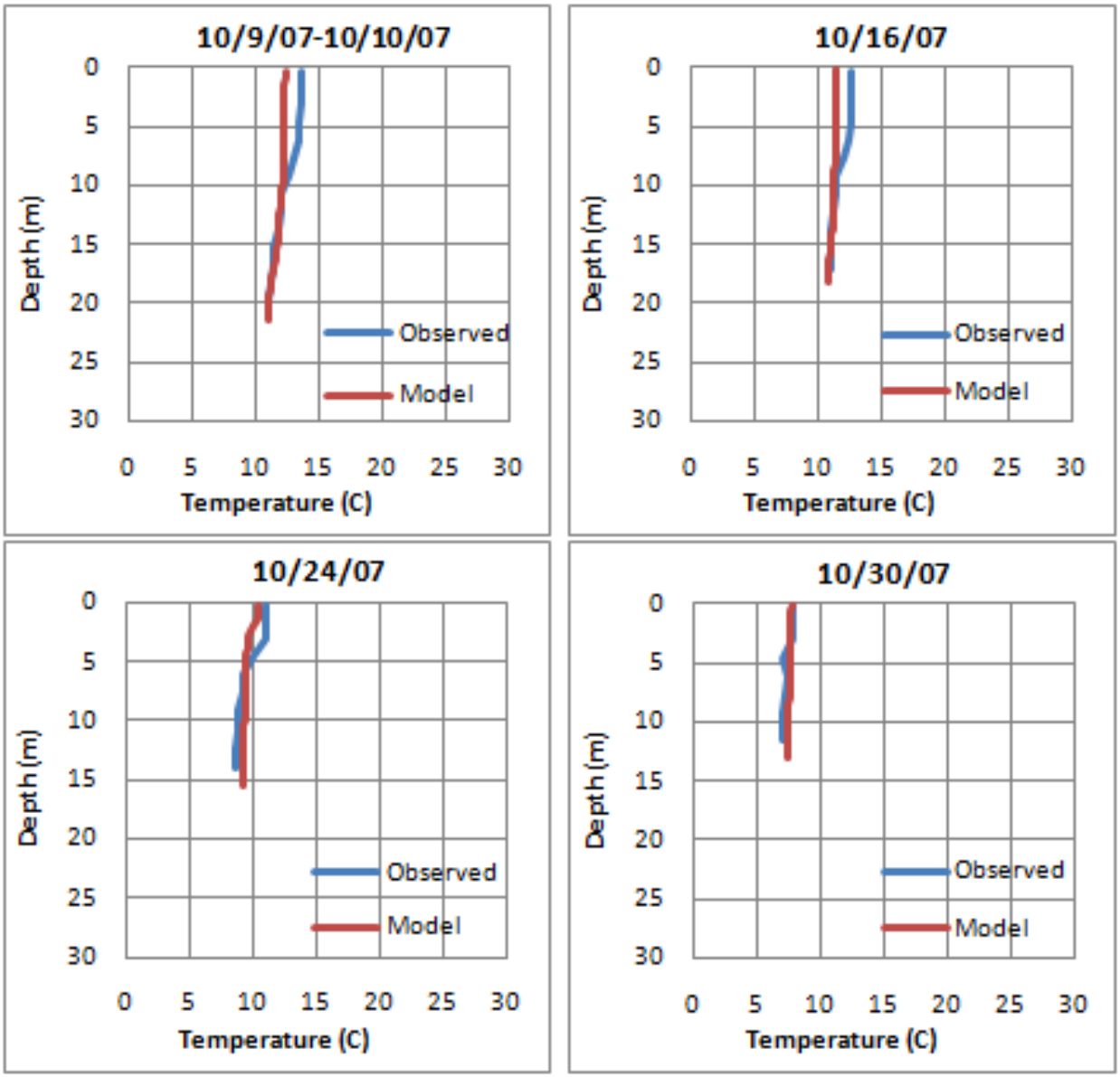
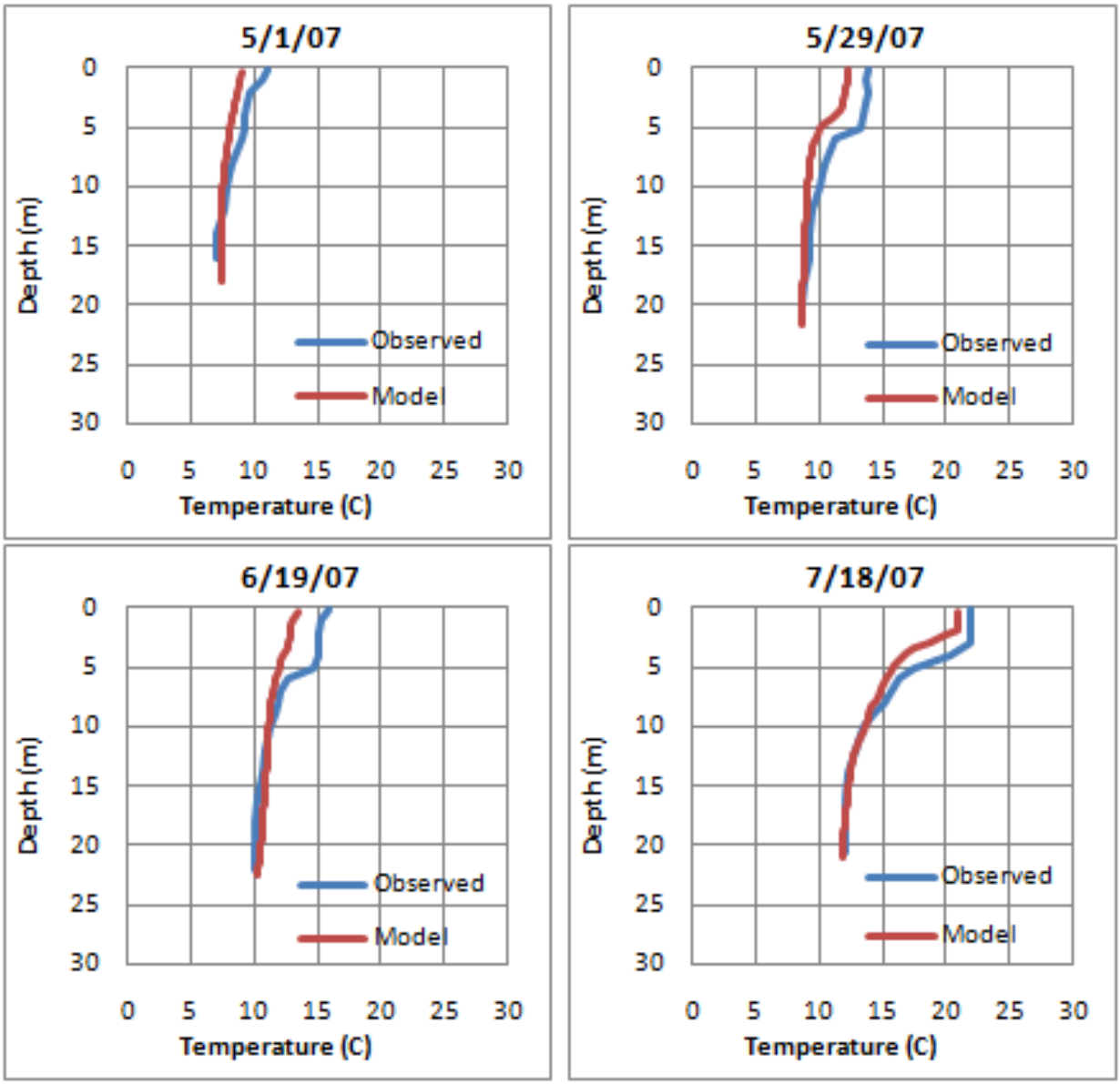


Figure A7-1. Model Calibration at dam (1DAM) location for 2007.


5/1/07
5/29/07
6/19/07
7/18/07
Depth (m)
Temperature (C)
Observed
Model
0
5
10
15
20
25
30

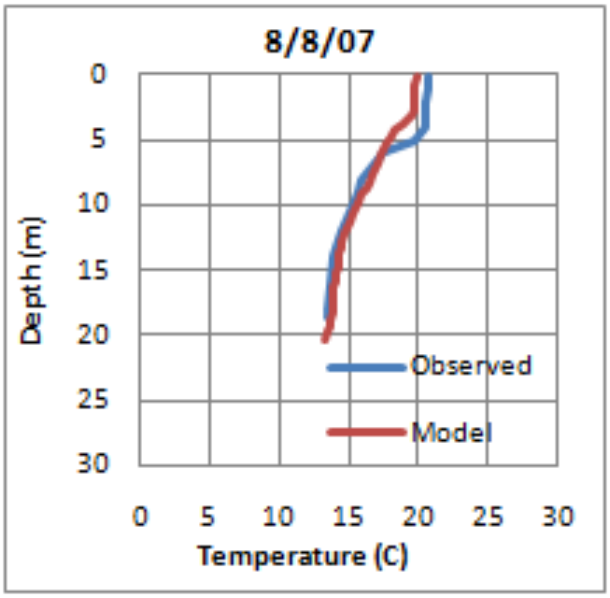
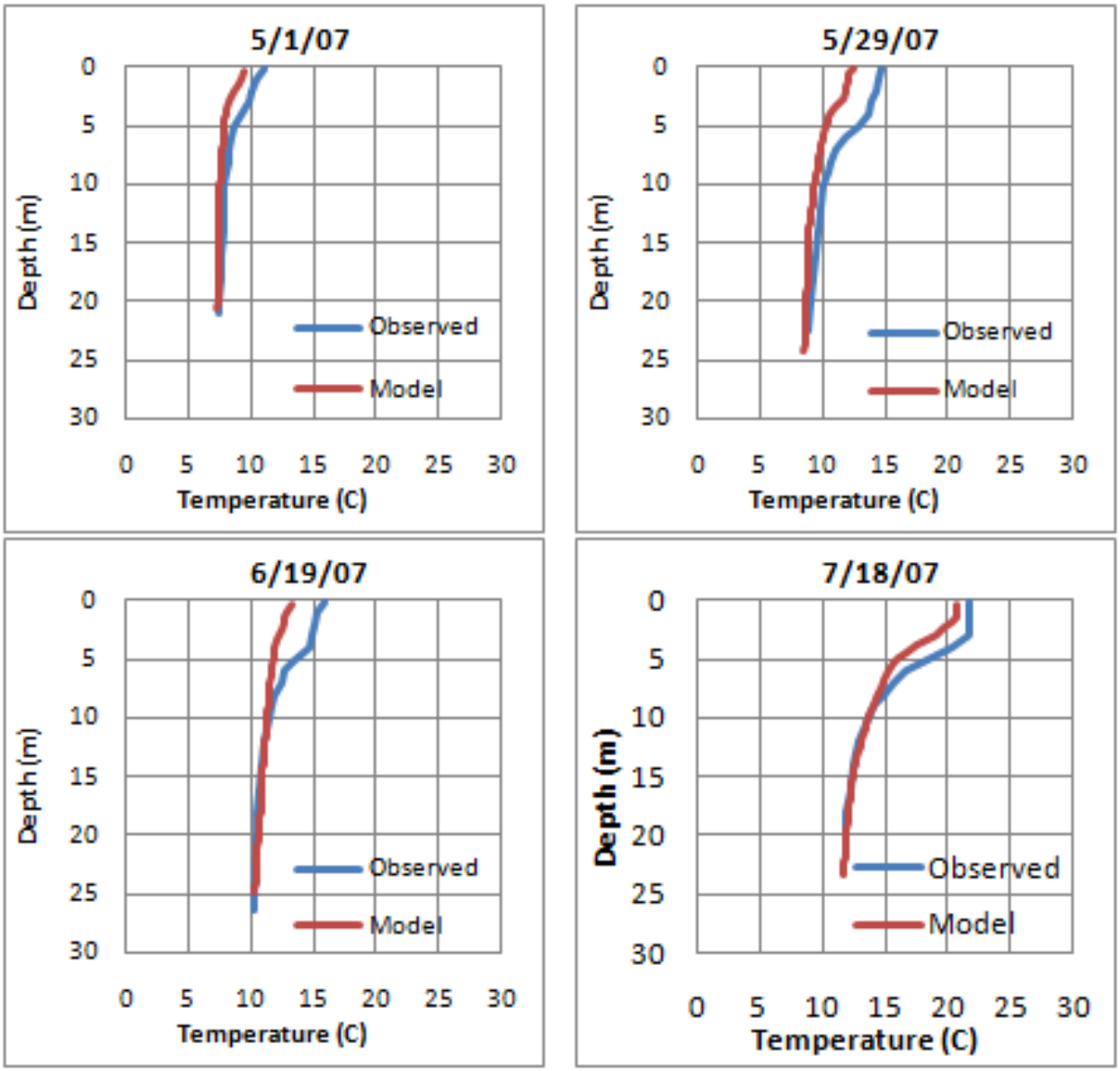


Figure A7-2. Model Calibration at upper pool (9UPNR) location for 2007.


5/1/07
5/29/07
6/19/07
7/18/07
Depth (m)
Temperature (C)
Observed
Model
0
5
10
15
20
25
30

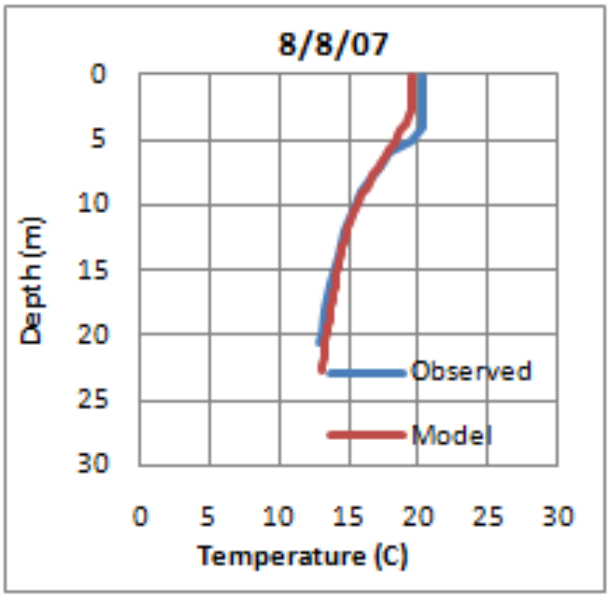
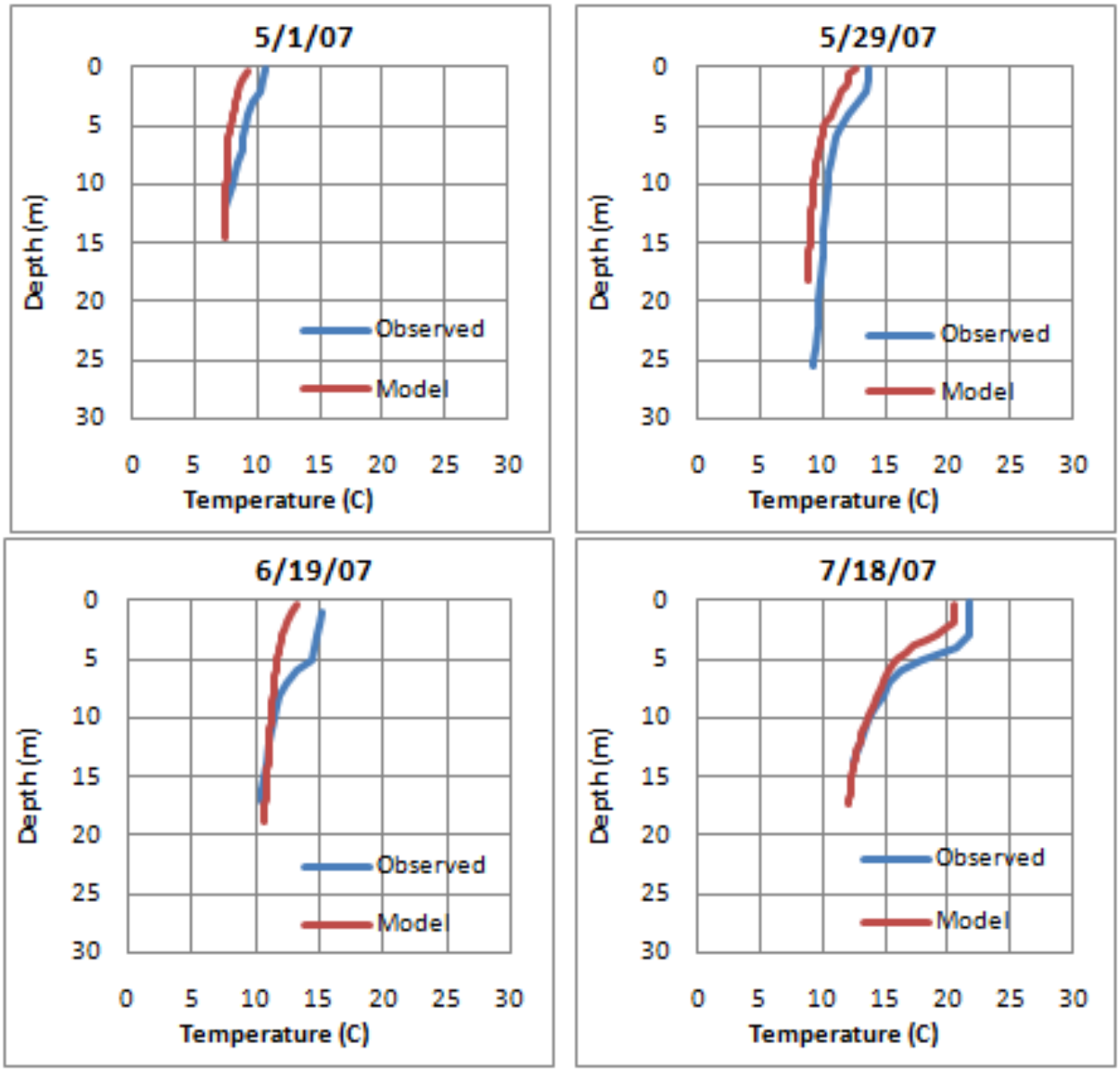


Figure A7-3. Model Calibration for Charlie Creek (SCHCK) location for 2007.


5/1/07
5/29/07
6/19/07
7/18/07
Depth (m)
Temperature (C)
Observed
Model
0
5
10
15
20
25
30

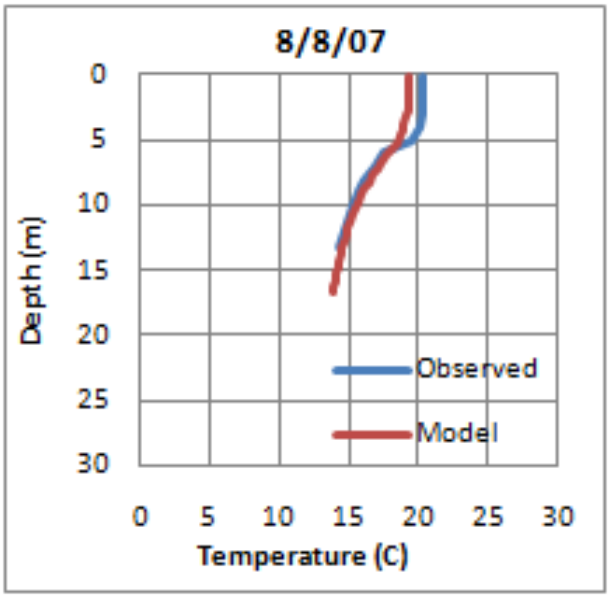


Figure A7-4. Model Calibration for North Fork (5NFK) location for 2007.