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Temperature Model of the Pelton Round Butte Hydroelectric Project Reservoirs

December 2015

W Xu
T Khangaonkar

U.S. DEPARTMENT OF
ENERGY

Prepared for Portland General Electric
through CWFO Agreement No. 64271 under
U.S. Department of Energy Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Seattle, Washington 98109

Executive Summary

Pacific Northwest National Laboratory (PNNL) under a contract with Portland General Electric (PGE) developed temperature models of the Pelton Round Butte Hydroelectric Project reservoirs. The models are capable of simulating temperature variations in the system as a function of hourly variations in power generation flows, hydrological inputs, and meteorological loads. The Pelton Round Butte Hydroelectric Project on the Deschutes River consists of three hydropower generating dams that impound three reservoirs: 1) Lake Billy Chinook (LBC; Round Butte Dam), 2) Lake Simtustus (Pelton Dam), and 3) Reregulating Reservoir (Reregulating Dam). PGE and the Confederated Tribes of the Warm Springs Reservation of Oregon jointly own the Pelton Round Butte Hydroelectric Project. PGE has implemented an adaptive management plan to reestablish anadromous fish runs above Round Butte Dam and is addressing issues associated with potential in-lake and downstream water quality. As part of these efforts, PGE conducted numerous studies from 1997 to 2005 that evaluated the feasibility of making improvements through structural and operational modifications at Round Butte Dam. A key water-quality parameter of concern was temperature, and PGE selected the installation of a Surface Water Withdrawal (SWW) structure at LBC that would allow the Round Butte Dam powerhouse to discharge a blend of surface warm water and cool bottom water to achieve compliance with temperature standards. The surface withdrawal was also designed to provide surface attraction velocities to enhance the collection and downstream transport of juvenile migrating fish.

After SWW became operational in 2010, PGE noted that the resulting downstream temperatures were higher than anticipated in certain months of 2012 and 2013. The SWW structure was initially operated using a water withdrawal blending sequence that was developed as part of the design prior to construction. The blending sequence defines the fraction of surface water discharged through the SWW structure as a function of time in a calendar year. PGE contracted PNNL to review the monitoring data and evaluate the performance of the SWW structure to determine if it was functioning as designed and, if required, to develop revised guidance for SWW operation and the blending sequence. PGE was also concerned that the operation of the Pelton Round Butte Hydroelectric Project had changed from the regular 12 hr peaking-mode cycle of powerhouse discharge that was used in the design of the SWW structure to one with rapid variations governed by power demand and load requirements, which could be affecting system performance. After a review of PGE's monitoring data, PNNL recommended an upgrade of the predictive temperature models of the Pelton Round Butte Hydroelectric Project reservoirs using the state-of-the-art CE-QUAL-W2 model with calibration to the post-SWW construction period to ensure reproduction of the observed performance of the system.

The overall objective is to assist PGE in improving temperature control of discharge through the operation of the SWW structure at LBC. As part of this effort, the existing model of LBC was upgraded to CE-QUAL-W2 software, grid resolution was refined, and SWW was incorporated reflecting the as-built dimensions. The LBC model and Lake Simtustus models were calibrated using data from 2013. The Lake Simtustus model had been previously developed using CE-QUAL-W2. The Reregulation Reservoir model was a new development as part of this effort. Also presented in this report is the development of a Pelton Round Butte river model that is representative of pre-project conditions. Pre-project conditions are defined as simulated conditions without the dams subjected to existing flows and meteorological loads. This model was developed using the CE-QUAL-W2 Stream Temperature Model and it extends from upstream of LBC to Madras, Oregon.

The model calibration results generally showed good agreement with the observed data. The simulated vertical temperature profiles of the Round Butte forebay have a root mean square error (RMSE) of less than 0.95°C when compared to observed values. The simulated vertical profiles of the Pelton forebay have an RMSE less than 0.90°C. In the absence of measurement sites inside the Reregulating Reservoir, the model results were compared with Madras Gauge Station data, which corresponds to the discharge to the Lower Deschutes River. The results show that the predicted temperature time series at the Madras station is in good agreement with observations, exhibiting an RMSE of 0.39°C.

A key accomplishment of this effort was the upgrade of the temperature model of LBC from a prior tool that used 12 hr time steps to the CE-QUAL-W2 software that allows higher frequency variations in flows and generates hourly simulation results. Another major improvement was the development of the Reregulating Reservoir model. Prior to this effort, Reregulation Reach was simplified using regression relationships between the Pelton Dam and Madras Gauge locations.

The results show that the LBC model, Lake Simtustus model, and Reregulating Reservoir model reflect as-built SWW conditions well. The model results and monitoring data confirm that the SWW structure was performing as expected. The operation of the SWW structure by PGE provided the desired change in the annual temperature regime: the timing of peak temperatures in September (prior to SWW) to peak temperatures in July mimicked the temperature regimes of free-flowing rivers without dams. This is reflected in the in-reservoir stations as well as at the Madras Gauge location just below Reregulating Dam based on monitoring data. The results also confirmed that the as-built SWW structure performance with respect to surface water withdrawal was different from the default assumption in the prior version of the model used in design and blending sequence calculations. The results indicate that the SWW structure withdraws from the surface layers that are restricted by a sharp “top-hat” distribution above the pycnocline, as opposed to withdrawal in the form of a “parabolic fan” that was the default assumption in the prior version of the model. The resulting discharge temperatures are therefore warmer than those previously computed for the design of blending operations.

Also included in this report is an analysis of the pre-project temperatures conducted using the Pelton Round Butte Reach river model. Pre-project temperatures are required by PGE as part of its temperature compliance assessment and temperature management plan. The river model for 2013 was set up using 2013 data synthesized based on the correlation developed from limited pre-project data from 1954−1956. This effort provided a strong indication of the possibility of groundwater heat influencing the Pelton Round Butte Project Reach between LBC and Reregulation Dam tailrace at Madras.

Acknowledgments

The authors acknowledge PGE staff member Don Ratliff who initiated this investigation and encouraged the researchers to examine data, PGE's operations, and modeling assumptions to evaluate the performance of the SWW structure at Round Butte Dam. We also thank PGE staff members Scot Lawrence and Lori Campbell for their guidance and direction. Lori Campbell was also responsible for organizing the temperature and flow monitoring data sets for PNNL use. PNNL staff supported PGE during the development of the design of the SWW structure and its operation using mathematical models almost a decade ago. We appreciate the opportunity to re-engage with the PGE project team to examine the post-construction performance of the system.

Acronyms

°C	degrees Celsius
AME	absolute mean error
BETTER	Box Exchange Transport Temperature Ecology Reservoir
cfs	cubic foot(feet) per second (f^3/s)
EFDC	Environmental Fluid Dynamics Code
fps	foot (feet) per second
ft	foot (feet)
hr	hour(s)
LBC	Lake Billy Chinook
MAE	Mean Absolute Error
m	meter(s)
ME	Mean Error
MRSO	Madras AgriMet Weather Station
m/s	meter(s) per second
m^3/s	cubic meter(s) per second (m^3/s)
POBO	Powell Butte AgriMet Weather Station
PGE	Portland General Electric
RM	river mile
RMSE	Root Mean Square Error
SLHTC	Heat Exchange Scheme
SWW	Surface Water Withdrawal
SWB	Selective Withdrawal Bottom
SWT	Selective Withdrawal Top
USGS	United States Geological Survey
WSC	Wind Sheltering Coefficient

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1.0 Introduction

A Surface Water Withdrawal (SWW) structure installed at Round Butte Dam—part of the Pelton Round Butte Hydroelectric Project on the Deschutes River in Oregon—allows the powerhouse to discharge a blend of warm surface water and cool bottom water. It was designed to enable the dam to meet temperature standards and provide surface attraction velocities that enhance the collection and downstream transport of juvenile migrating fish. When resulting conditions did not meet targeted expectations during certain months of 2012 and 2013, Pacific Northwest National Laboratory (PNNL) under contract to Portland General Electric was asked to conduct a study to determine whether the SWW structure is functioning as designed and to develop revised guidance for SWW operation and the blending sequence, as needed. This report documents the study results.

1.1 Background

The Pelton Round Butte Hydroelectric Project, jointly owned by Portland General Electric (PGE) and the Confederated Tribes of the Warm Springs Reservation of Oregon, is located on the Deschutes River, near the town of Madras, Oregon. The project consists of three hydropower generating dams that impound three reservoirs: 1) Lake Billy Chinook (LBC; Round Butte Dam), 2) Lake Simtustus (Pelton Dam), and 3) Reregulating Reservoir (Reregulating Dam). Lake Billy Chinook, which is the first (upstream) and largest of the three reservoirs, receives inflow from three tributaries: the Crooked, Deschutes, and Metolius Rivers (see Figure 1.1). These inflows have distinct temperature characteristics. The Crooked River is the warmest, and its water tends to stay at or near the reservoir surface. The Metolius River typically supplies the coldest inflow, and its water tends to plunge deep into the reservoir. Historically, the penstock of Round Butte Dam at LBC was always a deep outlet located approximately 70 m below the water surface. The Deschutes River enters the lake at median temperatures warmer than Metolius River but cooler than the Crooked River waters. Superimposed on this pattern is the effect of summer heating that further warms the surface of the reservoir. These complex thermal and hydrodynamic conditions resulted in currents that were oriented away from the collection facilities in the LBC forebay. These conditions were likely responsible for the overall failure of the fish passage system constructed as part of original project facilities.

The Pelton Round Butte Hydroelectric Project's fish passage program recognized that suitable currents must exist to provide consistent movement of water toward the forebay where a collection structure could be designed and operated. This would be achieved through structural and operational modifications at the Round Butte Dam. As part of its Federal Energy Regulatory Commission relicensing process, PGE developed adaptive management plans committed to reestablishing upstream and downstream fish migration at the project and operating in compliance with water-quality requirements. Between 1997 and 2004, PGE conducted a series of studies that examined the feasibility of improving fish passage and water quality by making structural and operational modifications at Round Butte Dam. A key water-quality parameter of concern was temperature. PGE selected the installation of a SWW structure at LBC that would allow the Round Butte Dam powerhouse to discharge a blend of warm surface water and cool bottom water to achieve compliance with temperature standards. The surface withdrawal was also designed to provide surface attraction velocities to enhance the collection and downstream transport of juvenile migrating fish.

After the SWW structure became operational in 2010, PGE noted that the resulting downstream temperatures were higher than anticipated in certain months of 2012 and 2013. The SWW structure was initially operated using a water withdrawal blending sequence that was developed as part of the design prior to construction. Blending sequence defines the fraction surface water discharged through the SWW structure as a function of time in a calendar year. PGE contracted PNNL to review the monitoring data and evaluate the performance of the SWW structure to determine if it was functioning as designed and if revised guidance was needed for the as-built SWW operation. PGE was also concerned that the operation of the Pelton Round Butte Hydroelectric Project had changed from the regular 12 hr peaking-mode cycle powerhouse discharge that was used in the design of the SWW structure to one with rapid variations governed by power demand and load requirements, which could be affecting system performance. After a review of PGE's monitoring data, PNNL recommended that the predictive temperature models of the Pelton Round Butte Hydroelectric Project reservoirs be upgraded using the state-of-the-art CE-QUAL-W2 model with an updated calibration to the post-SWW construction period to ensure reproduction of the observed performance of the system.

This report summarizes the development and calibration of hydrodynamic and temperature models for the three project reservoirs calibrated to Year 2013 data representative of conditions with a SWW structure in operation. This includes upgrade of the existing LBC model to the state-of-the-art CE-QUAL-W2 software with higher resolution and the development of a new Reregulation Reservoir model. The Lake Simtustus model was previously developed using the CE-QUAL-W2 software and was also validated for 2013 conditions. Also included herein is an analysis of the pre-project temperatures using the Pelton Round Butte Reach river model developed during this effort.

1.2 General Study Area and the Dams

The Pelton Round Butte Hydroelectric Project on the Deschutes River is surrounded by a gently sloping, high plateau at about 2,500 ft above mean sea level with deep, river-cut canyons. The project area is primarily semi-arid and within the rain shadow cast by the Cascade Range. Most precipitation falls during the winter and spring months and very little additional moisture is received in the summer. The project includes three dams and reservoirs. The three dams, from upstream to downstream, are Round Butte Dam at river mile (RM) 110.4, Pelton Dam at RM 103.4, and Reregulating Dam at RM 100.1. The dams impound LBC, Lake Simtustus, and Reregulating Reservoir as shown in Figure 1.1—the study area.

1.2.1 Round Butte Dam and Selective Water Withdrawal Tower

Round Butte Dam is a 134 m (440 ft) high, rock-filled, earthen dam that was completed in 1964. It is the uppermost development of the Pelton Round Butte Hydroelectric Project. Round Butte Dam impounds LBC. With a gross storage capacity of 535,000 acre-ft, LBC is the largest storage reservoir of the three reservoirs. The dam is operated by PGE with a normal minimum operating water-surface level of 586.7 m (1,925 ft).

Round Butte Dam features a 273 ft tall SWW tower that is about 213.4 m (700 ft) upstream of the dam. Construction of the structure was completed in 2009, and it began operating in 2010. It facilitates withdrawal of water as a blend of the surface and bottom water to be discharged through the penstock of Round Butte Dam. The surface water intake elevation is 585.2 m (1,920 ft) and the bottom water intake elevation is 523.5 m (1,718 ft). Figure 1.2 shows a perspective view of the SWW structure in the forebay of Round Butte Dam. The selective withdrawal top intake is indicated by SWT and selective withdrawal bottom intake is indicated by SWB.

1.2.2 Pelton Dam

Pelton Dam construction was completed in 1958. The 62 m (204 ft) high, concrete dam impounds approximately 31,000 acre-ft of water. The dam crest elevation is at 1,585 ft and the spillway crest is at

474.9 m (1,558 ft). The powerhouse withdrawal from the forebay occurs through a concrete intake structure connected to three 16 ft diameter penstocks. Each inlet gate and penstock is protected by a trash rack. The intake centerline elevation is at 435.8 m (1,430 ft).

1.2.3 Reregulating Dam

Reregulating Dam is a 328 m (1,067 ft) long, 26.8 m (88 foot) high, concrete and rock-filled dam with a crest elevation of 427 m (1,402 ft) above mean sea level. The dam construction was completed in 1957. The Reregulating Dam powerhouse contains a single, 18.9 MW bulb-type turbine generator and its water intake centerline is at 418.7 m (1373.75 ft).

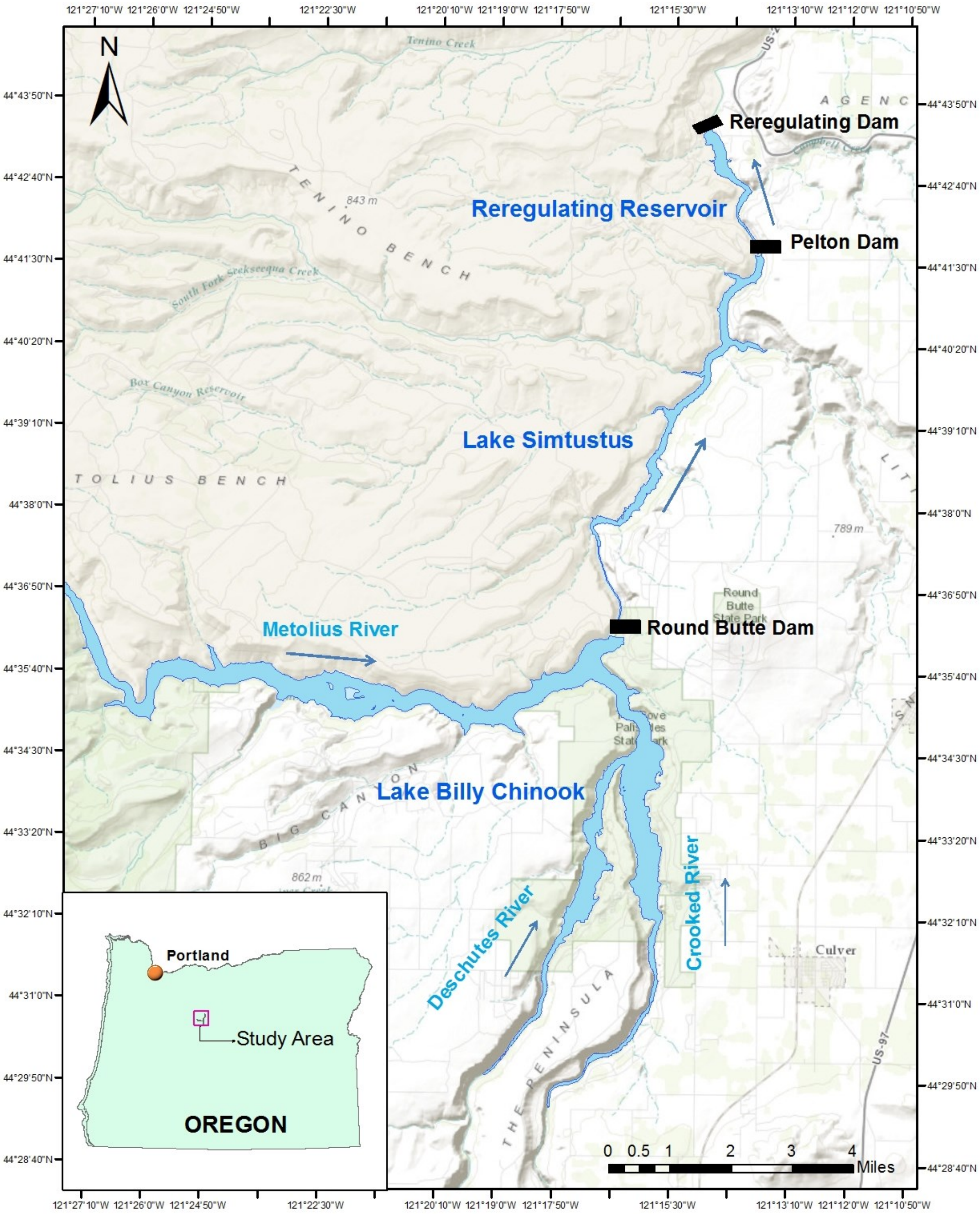
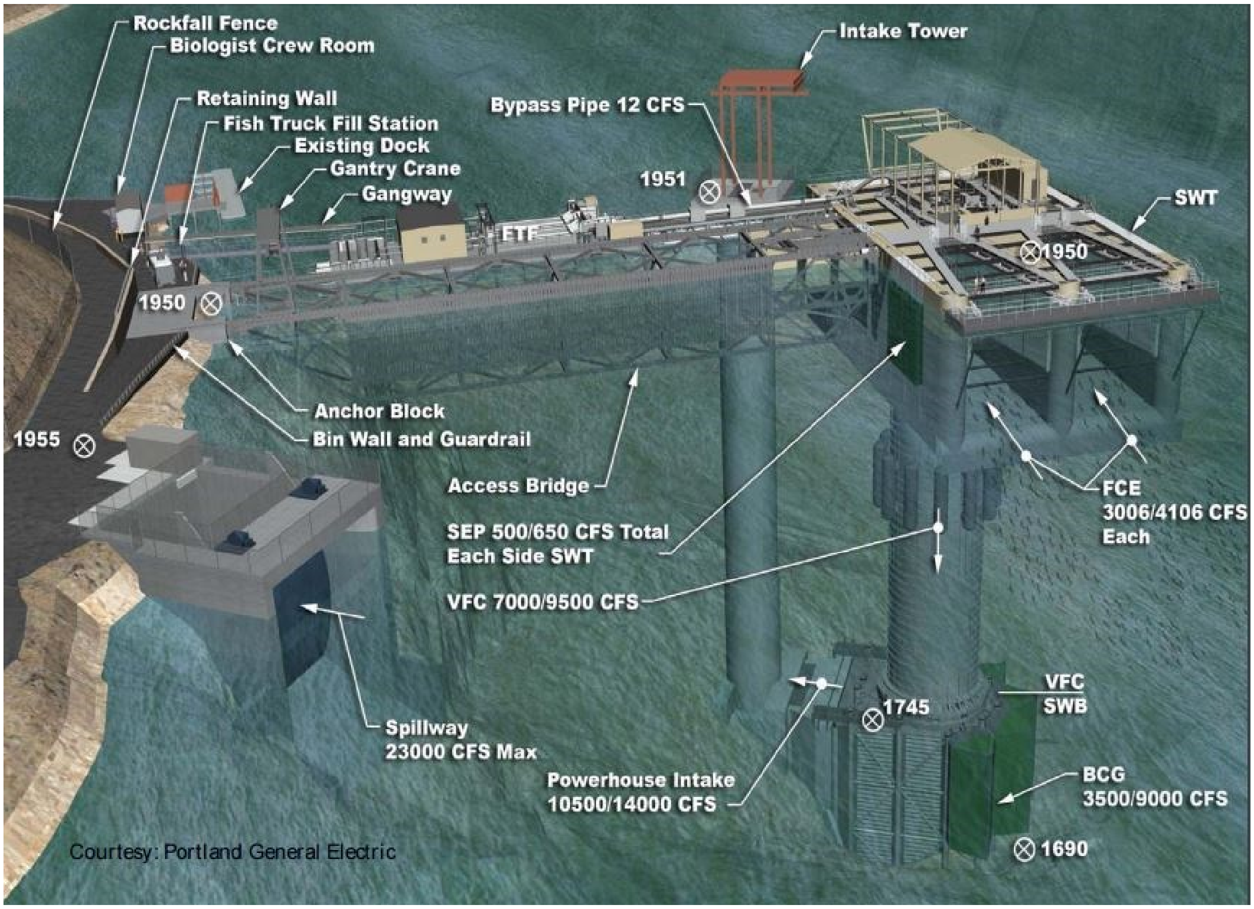


Figure 1.1. Study Area.



Courtesy: Portland General Electric

Figure 1.2. Perspective view of the SWW structure in the forebay of Round Butte Dam.

1.3 Report Content and Organization

The ensuing chapters of this report first describe the review of available data conducted as part of the study (Chapter 2.0). Then the hydrodynamic and temperature models of LBC, Lake Simtustus, and Regulating Reservoir are described (Chapters 3.0 through 5.0). The river temperature model of pre-project conditions is described in Chapter 6.0, followed by the presentation of conclusions and recommendations in Chapter 7.0.

2.0 Review of Available Data

This chapter reviews and summarizes the existing data on bathymetry, tributary, discharge flow rate, water quality, and meteorology of Pelton Round Butte Hydroelectric Project reservoirs. The purpose of the data review is to examine the validity of the available data and their sufficiency for purposes of hydrodynamic temperature model development and calibration. In consultation with PGE, the Year 2013 was selected for this effort because it represented the most complete data set for a full year of operation of the SWW structure. The locations of monitoring stations are indicated in Figure 1.1.

2.1 Geometry Data

Bathymetry data define the physical features of the reservoirs. These data are used to construct the model grid. The CE-QUAL-W2 model uses a laterally averaged vertical-two dimensional (2D) grid that was developed independently for each reservoir.

The LBC bathymetry was derived from E&S Environmental Chemistry's 1994 complete bathymetric survey. The resulting lake raster is shown in Figure 2.1. The average depth of the lake is 60.6 m (199 ft) and the maximum water depth is 120.1 m (394 ft). The same bathymetry was used in the previous modeling efforts (ENSR 1999; Khangaonkar et al 2005; Khangaonkar et al. 2008).

The bathymetry of Lake Simtustus is based on a product developed by Charles Rose and Associates using image processing of pre-project aerial photographs and survey data from PGE and the U.S. Geological Survey (USGS). This bathymetry was used in the development of the Lake Simtustus model as described by Foster Wheeler (2001) and is shown in Figure 2.2. The average depth of the lake is 16.7 m (55 ft) and the maximum water depth is 50.3 m (165 ft).

The bathymetry map of the Reregulating Reservoir was developed by PGE by digitizing a historical survey drawing. It was provided to PNNL under the file name of "rr_bth_3.shp" (shown in Figure 2.3). The date of the bathymetry survey is not known, but the contour map delineates the topography before the construction of Reregulating Dam in 1957. Because the map was the only data source that could be obtained, its bathymetry data were used to construct the model grid.

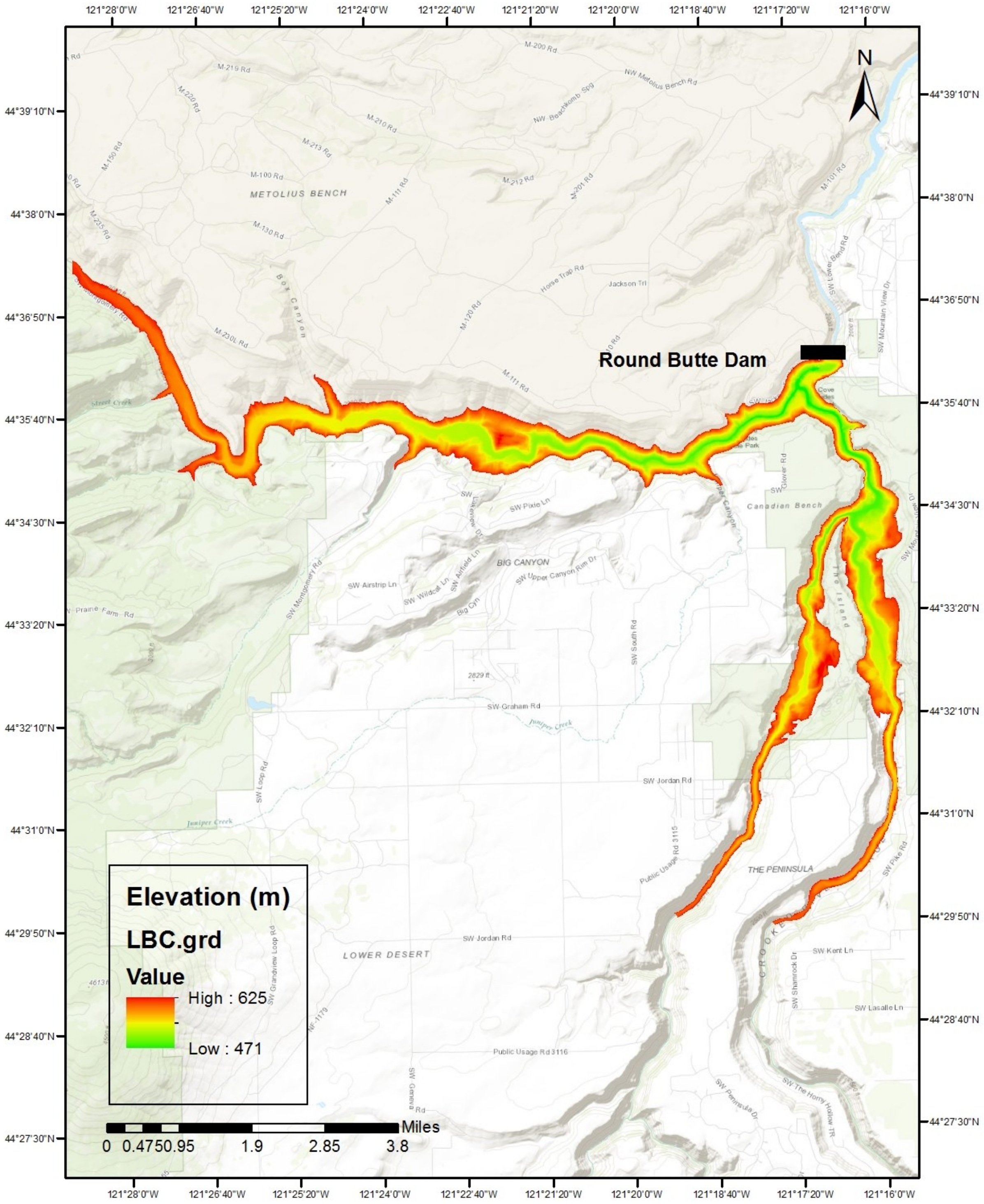


Figure 2.1. Lake Billy Chinook bathymetry and monitoring stations.

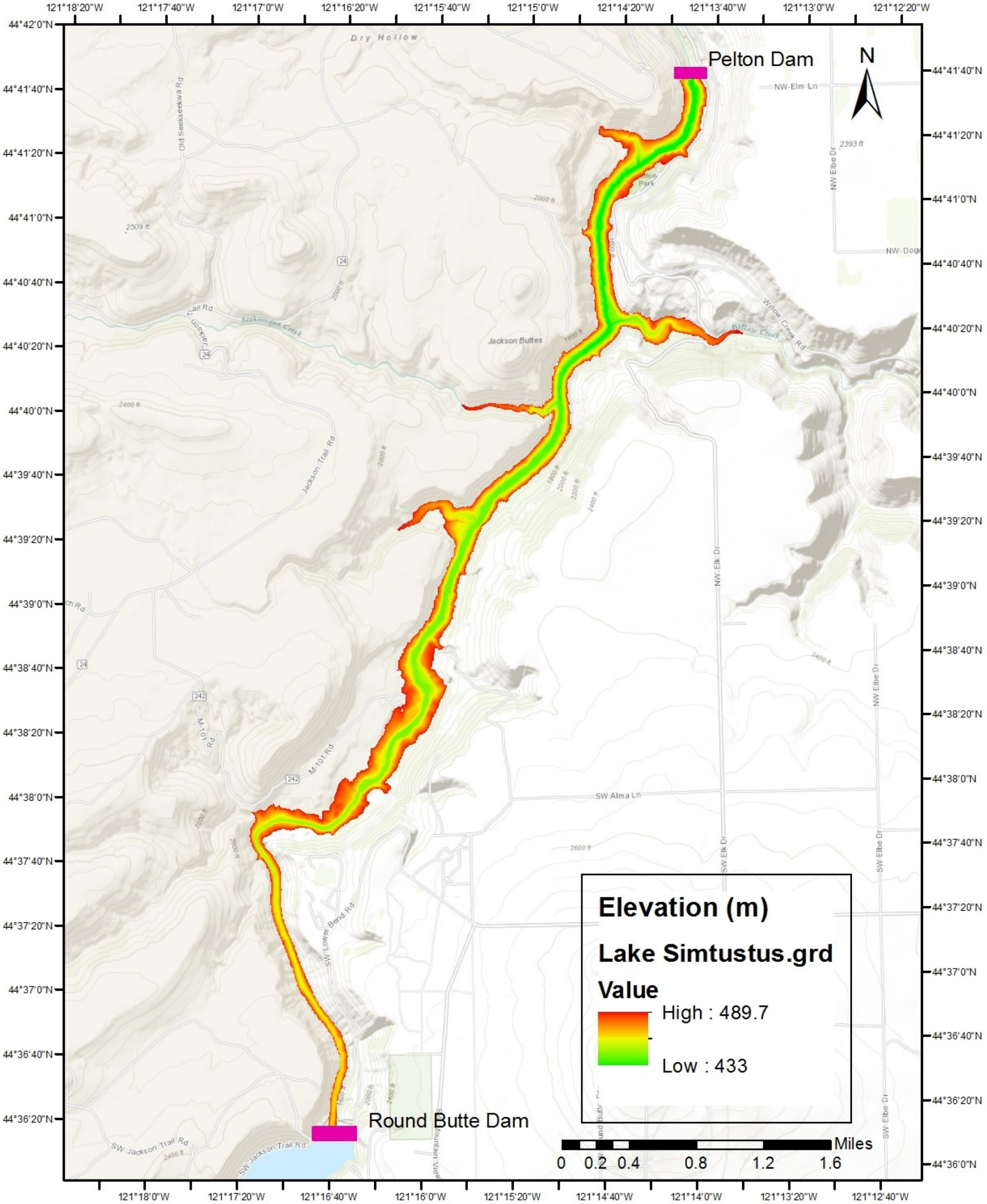


Figure 2.2. Lake Simtustus bathymetry and monitoring stations.

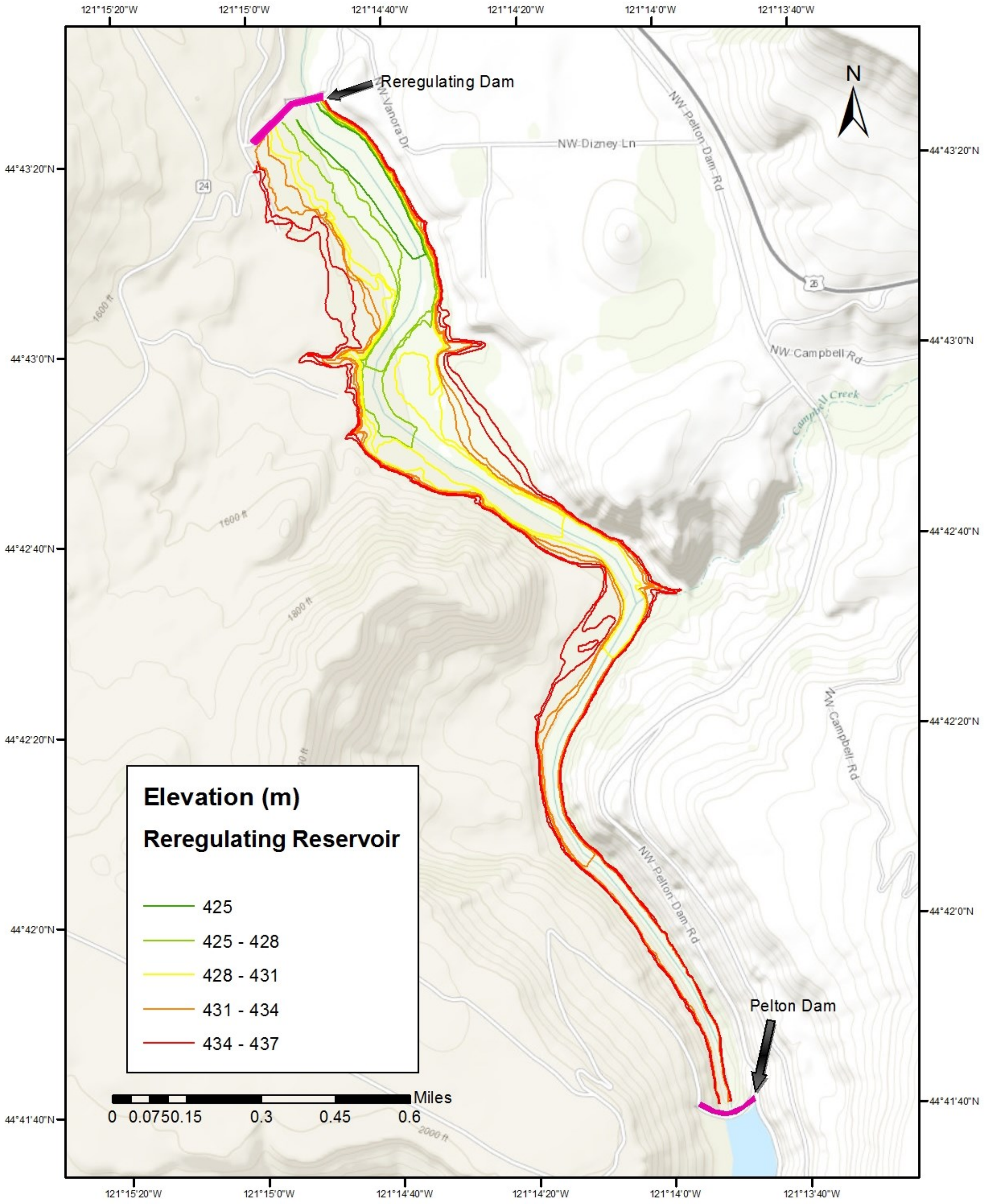


Figure 2.3. Reregulating Reservoir bathymetry.

2.2 Hydrological Data

2.2.1 Discharge from Dams

At Round Butte Dam the total power generation flow from the penstock released to Lake Simtustus includes a combination of surface and bottom flows from the SWW structure in the LBC forebay. The total flow magnitude was estimated from power generation records, and the split between surface and bottom flow fractions was estimated from gate-setting information recorded from SWW operations. The flow data through the SWW structure were generated at 1 min intervals for 2013 by PGE and are shown in Figure 2.4. Hourly discharge data from Pelton Dam were provided by PGE and are also plotted in Figure 2.4. Hourly discharge data at Reregulating Dam in 2013 were not available. However, USGS maintains a hydrologic gauge (USGS 14092500) that is 274 m (900 ft) below the dam. Fifteen-minute interval flow data in 2013, shown in Figure 2.4, were downloaded from the USGS website and represent the Reregulating Dam outflow. Unlike the Round Butte and Pelton Dams, which operate in peaking mode, the Reregulating Dam maintains a steady flow into the Lower Deschutes River; discharge ranges from 107.3 to 164.0 m^3/s (3,790 to 5,790 cfs) and averages 127.4 m^3/s (4,500 cfs) based on Year 2013 records.

2.2.2 Stage or Water Surface Elevation Data

Hourly stage (water depth) data are required while simulating the flows in riverine reaches for hydraulic calculations, which often rely on stage-discharge relationships to compute flows and velocities. In reservoirs, water-surface elevations are used in combination with three-dimensional (3D) geometry defined in a model grid to ensure continuity between inflow, outflow, and storage within the reservoir. Water surface elevations at the three reservoirs based on monitoring conducted by PGE in 2013 are plotted in Figure 2.5. The water surface in LBC shows daily fluctuations of LBC $\approx$ 0.2 m (0.6 ft) corresponding to Round Butte Dam peaking-mode operation and an annual range of approximately 2 m based on Year 2013 data. Lake Simtustus also shows a daily peaking-mode variation of $\approx$ 0.4 m (1.3 ft). The Reregulating Reservoir fluctuates up to 5 m daily. The average water surface elevations at the Round Butte, Pelton, and Reregulating forebays are 592.2 m (1943 ft), 480.7 m (1577 ft), 434.9 m (1426.7 ft), respectively, based on Year 2013 data.

2.3 Tributary Inflow Data

Lake Billy Chinook receives inflows from the Deschutes, Crooked, and Metolius Rivers. USGS maintains hydrologic gauges on the three rivers just upstream of LBC. The gauges and available flow summaries for Year 2013 are described in Table 2.1. The 2013 flow is plotted shown in Figure 2.6.

Table 2.1. USGS Hydrologic Gauging Stations

Station	Gauge Number	River Mile	2013 Average Discharge (m^3/s)	Time Interval
Deschutes River Near Culver, Oregon	14076500	120.6	24.2 (854.6 cfs)	Hourly
Crooked River Below Opal Springs	14087400	6.7	37.9 (1,338.4 cfs)	Hourly
Metolius River Near Grandview, Oregon	14091500	13.6	43.5 (1,536.2 cfs)	Hourly

In addition to receiving inflow from the major rivers, the three reservoirs receive inflows from a number of small streams. The two most prominent year-round streams are Willow Creek and Seekseequa Creek that flow into Lake Simtustus. Willow Creek drains an area of approximately 170 square miles including the town of Madras on the east side of Lake Simtustus. Seekseequa Creek drains an area of approximately 47 square miles on the west side of the lake. The discharges of Willow Creek and Seekseequa Creek were not measured in 2013, but the monthly flows were measured in the two streams from May to December in 2000. Additional historical flow data for Seekseequa Creek are also available from May 22, 1987 to September 30, 1993. Based on available information, the average discharge in Willow Creek is ≈ 1 m^3/s (32.7 cfs) and the average discharge in Willow Creek is ≈ 0.07 m^3/s (2.4 cfs).

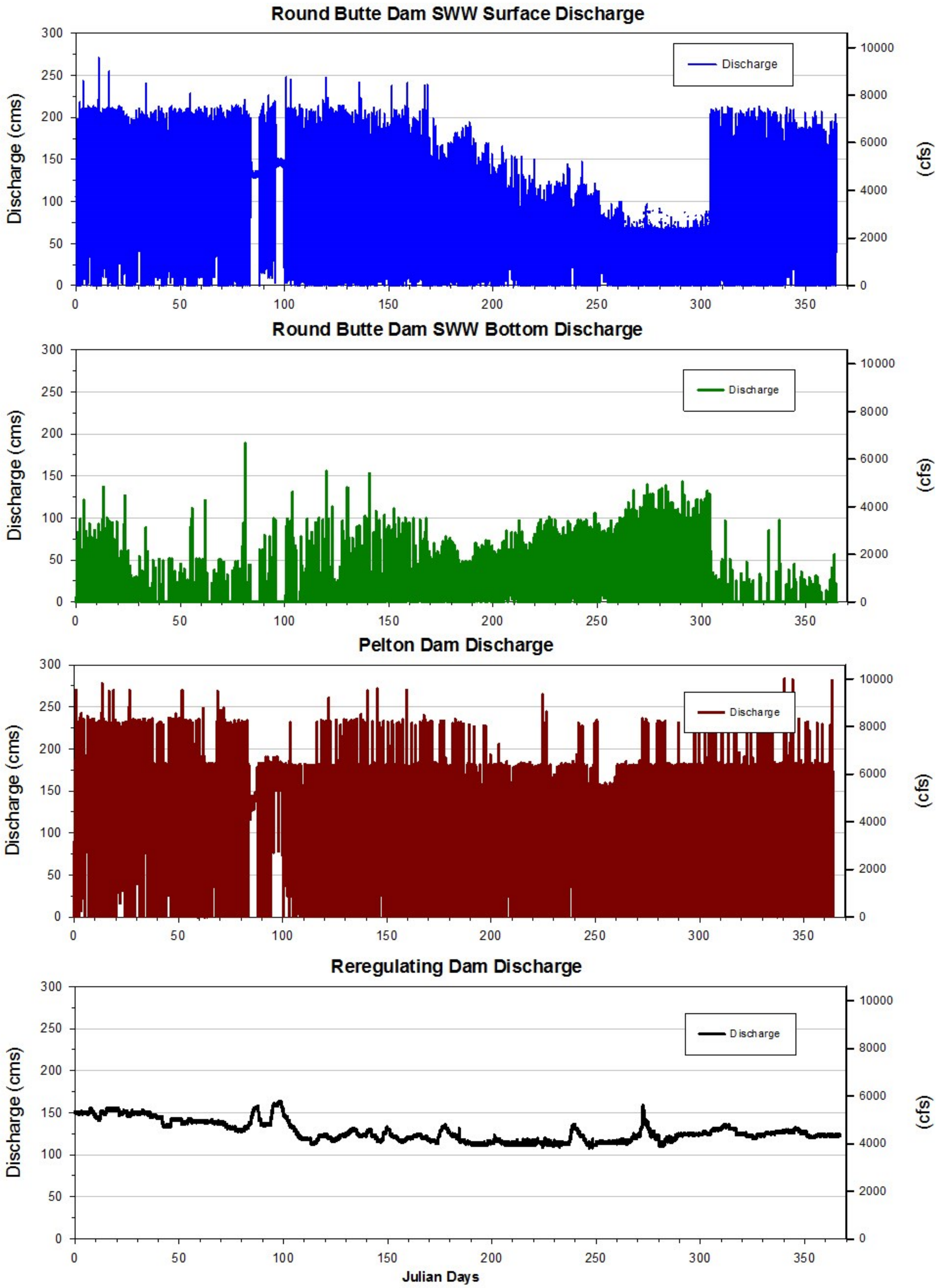
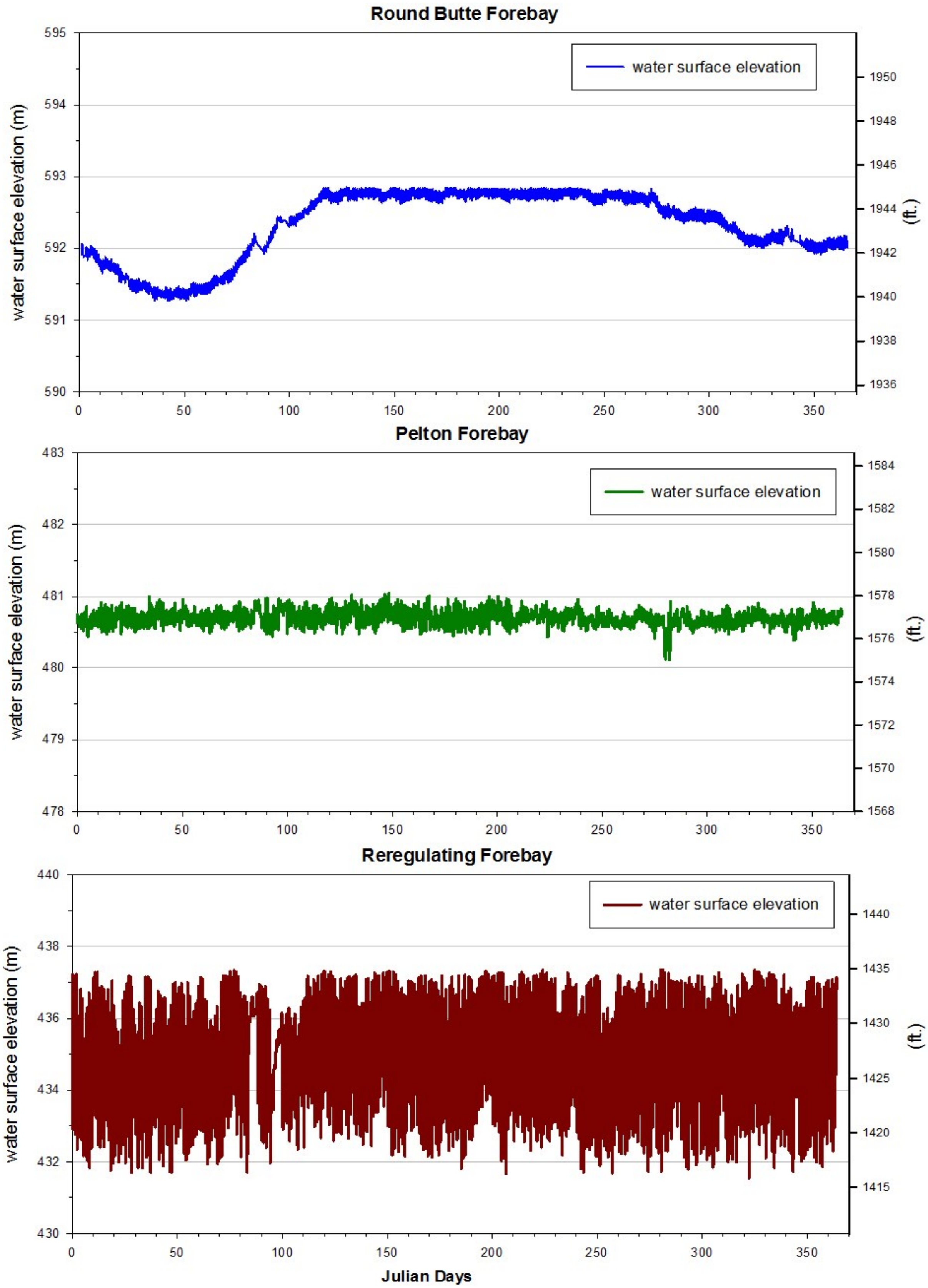


Figure 2.4. Pelton Round Butte Hydroelectric Project discharges from the dams.


Round Butte Forebay

Pelton Forebay

Reregulating Forebay

Figure 2.5. Pelton Round Butte Project water-suface elevations in 2013 (relative to mean sea level).

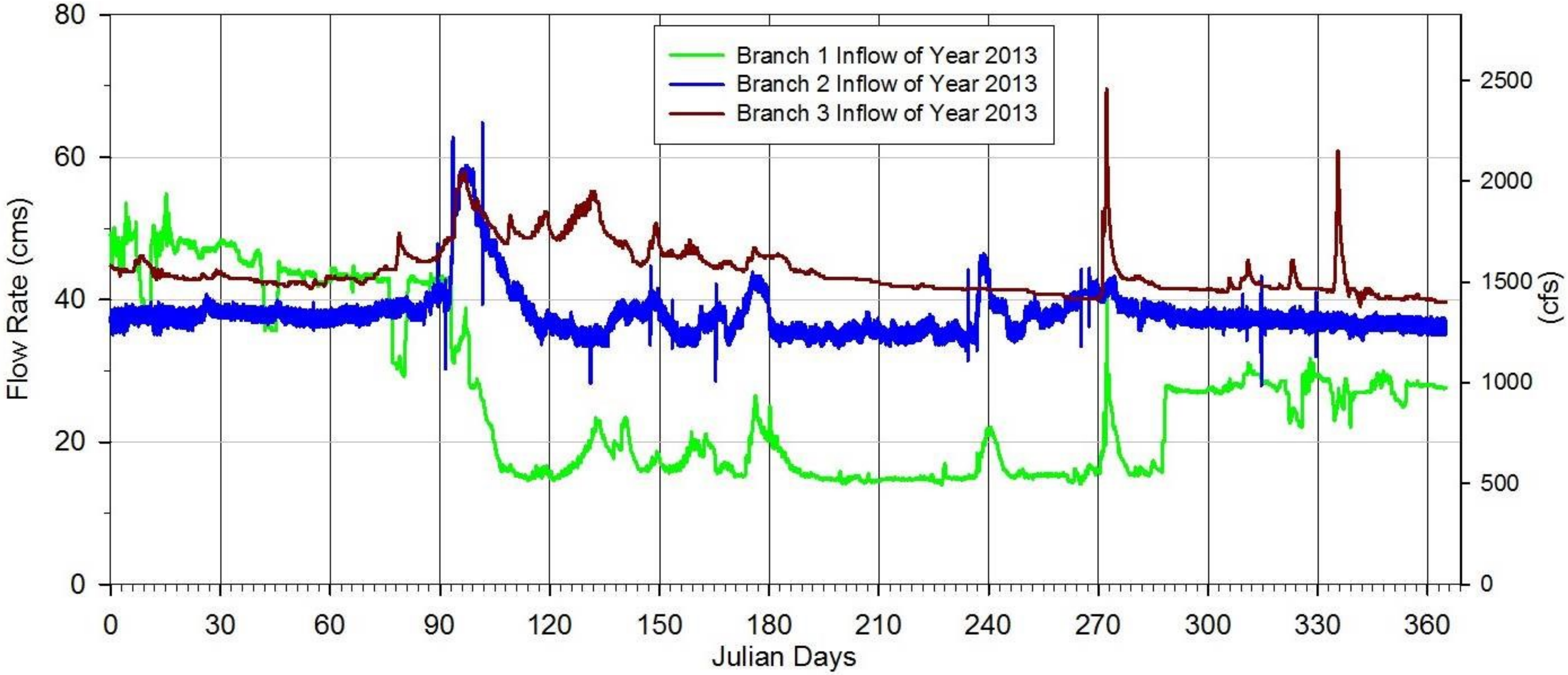


Figure 2.6. Lake Billy Chinook tributary inflows. **Branch 1: Deschutes River; Branch 2: Crooked River; Branch 3: Metolius River**

2.4 Water Temperature Data

2.4.1 Temperature of Tributary Inflow

Hourly temperature data from the three tributaries of LBC—Deschutes River, Crooked River, and Metolius River—were obtained from the USGS gauging stations and are plotted in Figure 2.7. Deschutes River was the coldest river in the beginning of 2013, but also the warmest river in the summer months, to enter LBC. Crooked River temperatures do not show as much seasonal variation in 2013; the river maintains a consistently higher temperature throughout the year, and temperatures as high as 11°C in the winter indicate the influence of warm springs in its drainage basin. Metolius River is relatively cool throughout the year.

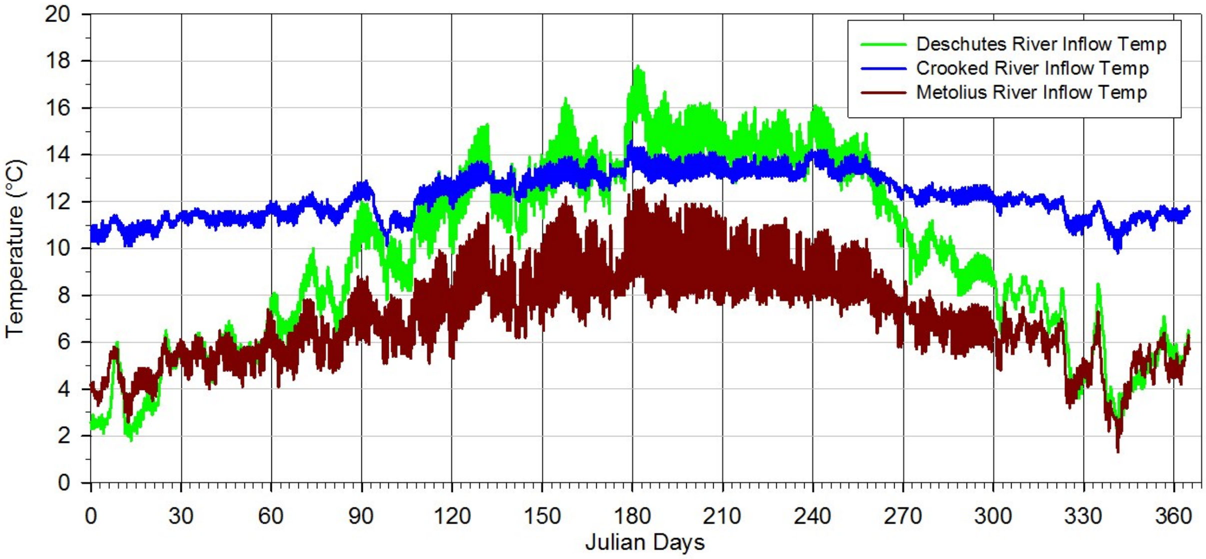


Figure 2.7. Lake Billy Chinook tributary inflow temperatures.

2.4.2 Temperature of Water Discharged by the Dams

The temperature of the LBC tailrace was measured at hourly intervals in 2013, and is shown in Figure 2.8. The tailrace temperature ranges from 6°C to 17°C. Daily fluctuations in temperature of up to 5°C were noted in the temperature records. It is not clear whether these temperatures truly reflect the variation in discharged water or are due to the surface heating of shallow regions of Lake Simtutus's upstream pool. Lake Simtustus tailrace temperatures were also measured at hourly intervals and are plotted in Figure 2.9. Lake Simtustus tailrace temperature ranges from 6°C to 14.5°C. Reregulation Dam tailrace temperatures were obtained from the USGS gauging station at Madras and are discussed in the following chapters as part of model calibration.

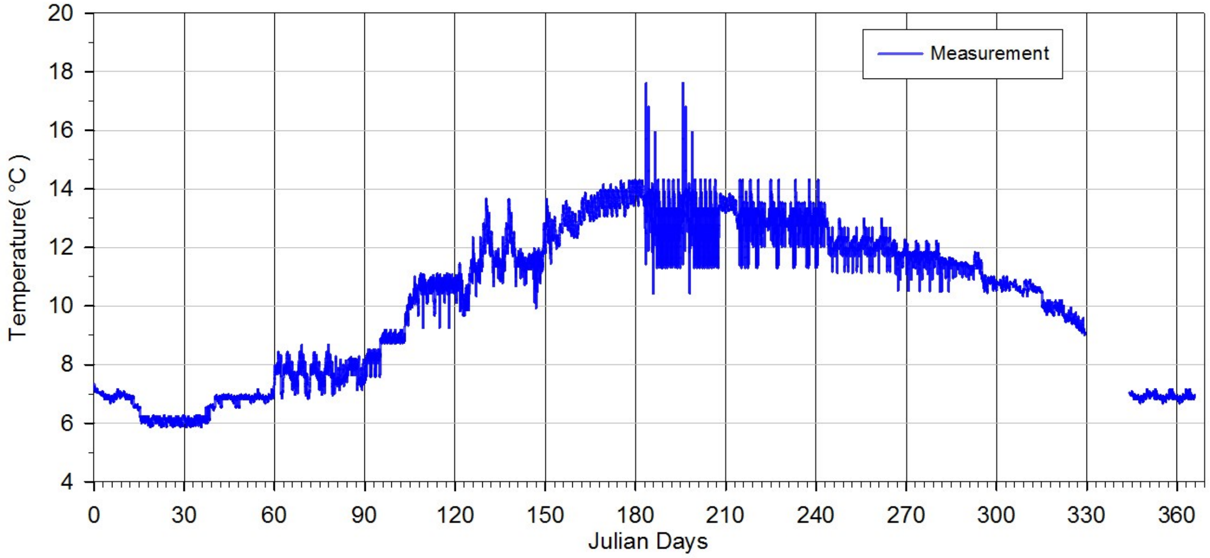


Figure 2.8. Observed LBC tailrace temperature in 2013.

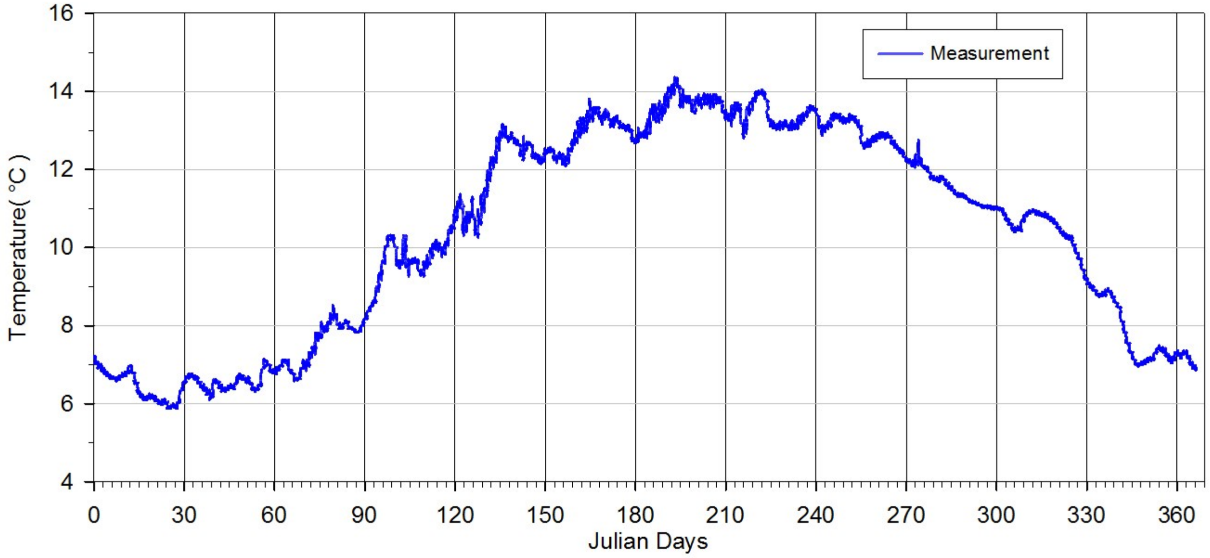


Figure 2.9. Observed Lake Simtustus tailrace temperature in 2013.

2.4.3 In-Reservoir Water Temperature Profile Time Series Data

Water temperature profiles were recorded at hourly intervals at the Round Butte forebay at PGE Station 7 (Figure 2.10) and in the Pelton forebay at PGE Station 4 (Figure 2.11) in 2013. Both LBC and Lake Simtustus are thermally stratified in the summer and well mixed in the winter. In summer the Round Butte surface water temperature reaches a high temperature of 25°C. The Pelton forebay peak temperature in surface water is 22°C.

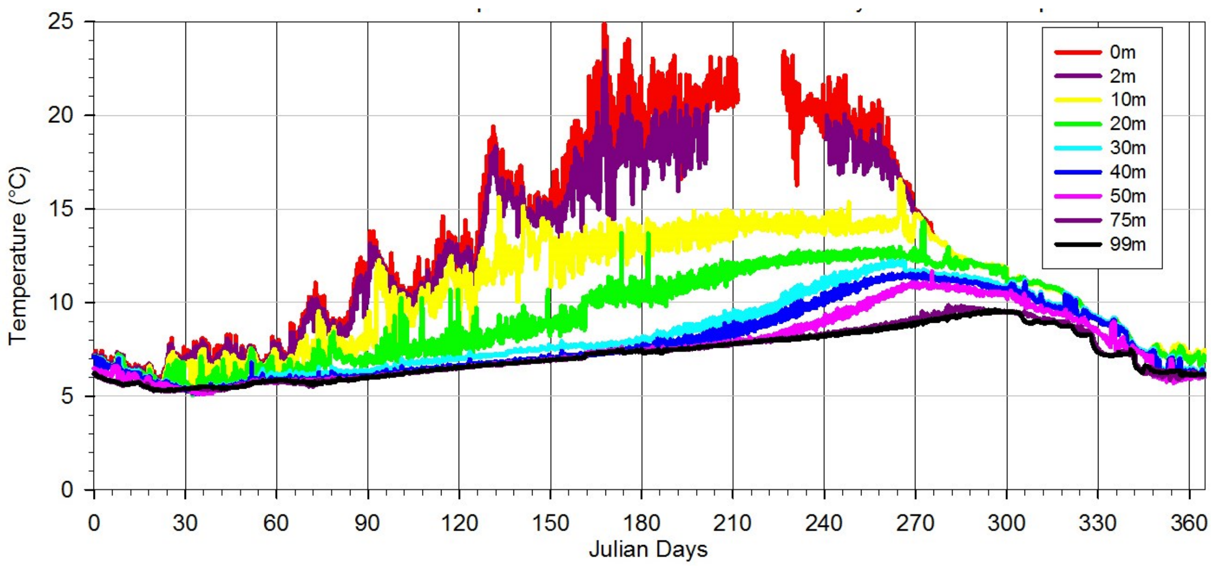


Figure 2.10. Measured water temperature in the Round Butte Dam forebay at various depths in 2013.

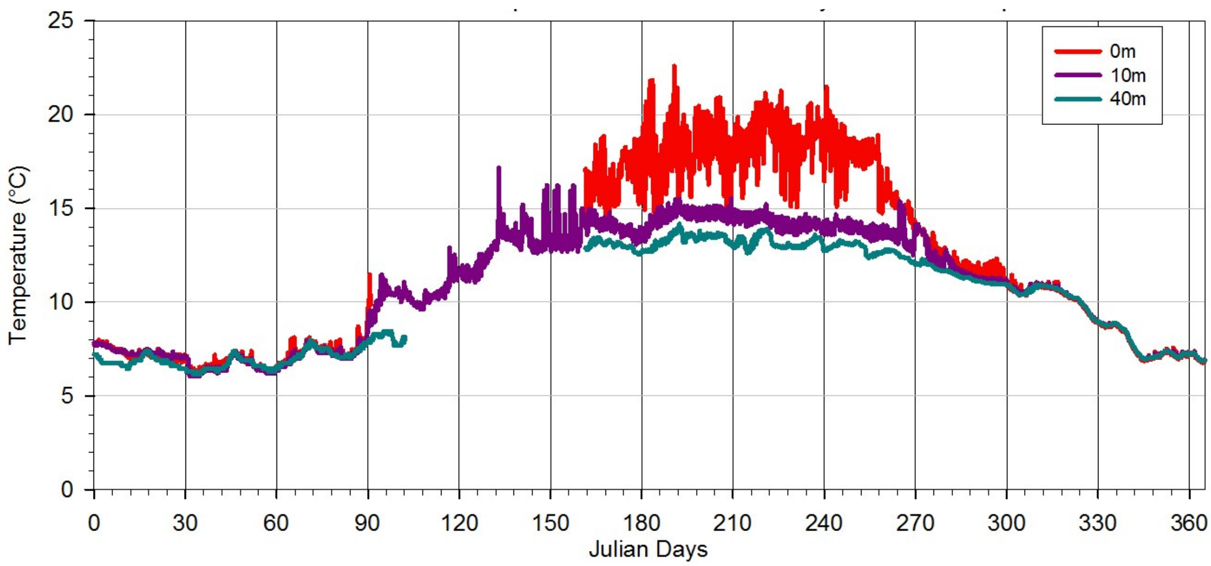


Figure 2.11. Measured water temperature in the Pelton Dam forebay at various depths in 2013.

2.5 Meteorological Data

Meteorological data have been compiled from three data sources and locations in the vicinity of the project (see Figure 2.12). The closest station is the Madras AgriMet Weather Station (MRSO), which is 4 miles east of Lake Simtustus. Meteorological data from MRSO and Powell Butte AgriMet Weather Station (POBO) were obtained from the U.S. Bureau of Reclamation. Meteorological data from Redmond Airport were obtained from the National Centers for Environmental Information. Meteorological station information in Table 2.2 includes the available data types, station elevation, and distances to study area and frequency.

Table 2.2. Meteorological station information.

Station	Available Data Type	Elevation	Distance	Frequency
Madras AgriMet Weather Station, MRSO	Air Temperature, Dew Point Temperature, Solar Radiation, Wind Speed, Wind Direction	743.7 m (2,440 ft)	4 miles	Hourly
Redmond Airport	Air Temperature, Dew Temperature, Wind Speed, Wind Direction, Cloud Cover	927.5 m (3,043 ft)	15 miles	Hourly
Powell Butte AgriMet Weather Station, POBO	Air Temperature, Dew Temperature, Solar Radiation, Wind Speed, Wind Direction	975.4 m (3,200 ft)	23 miles	Hourly

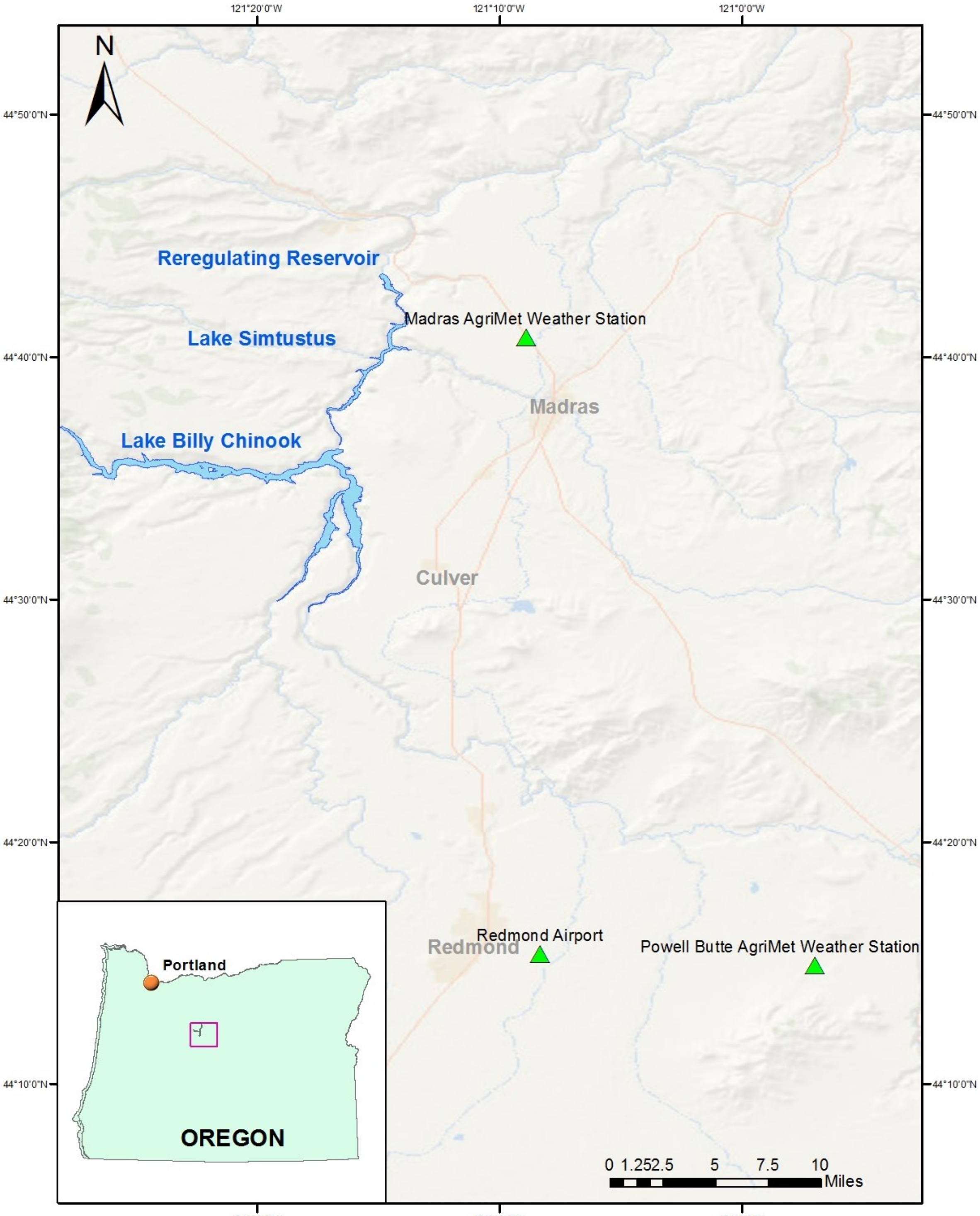


Figure 2.12. Meteorological station locations.

2.5.1 Ambient Air Temperature

Hourly air temperature data from MRSO were compared with Redmond Airport data in Figure 2.13.[1] From the figure, air temperature at the two stations looks similar. The mean value of the 2013 air temperature at MRSO (9.05°) is 0.9°C higher than that at Redmond Airport. The mean of daily maximum 2013 air temperature at MRSO (16.2°C) is 0.5°C lower than that at Redmond Airport (16.7°C). The mean of the daily minimum air temperature at MRSO (2.3°C) is 2°C higher than that at Redmond Airport (0.3°C).

2.5.2 Dew Point Temperature

Dew point temperature is defined as the temperature below which water will leave the air and condense into liquid water. The MRSO data from 2013 contained 64 anomalous (extreme low) values. Further examination showed that dew point temperature data at MRSO were derived from relative humidity, which contained false values. Extreme values in MRSO dew point temperature were deleted, and the data gaps were filled using linear interpolation. Hourly dew point temperature data from MRSO are compared with those obtained at Redmond Airport in **Error! Reference source not found.**. The mean value of dew point temperature in 2013 at MRSO (1.18°C) was 2.1°C higher than that at Redmond Airport (-0.87°C).

2.5.3 Wind Speed and Direction

Wind speed and direction are highly affected by site-specific boundary effects. The closest station, MRSO, was examined for wind data. Hourly wind speed and hourly wind direction from MRSO are plotted in Figure 2.15. The wind rose plot (Figure 2.16) of the wind speed and direction at MRSO was generated to obtain a better understanding of the predominant wind orientation and magnitudes. The average value of wind speed is 2.42 m/s (7.94 fps). The dominant wind in 2013 was from north and southeast.

2.5.4 Shortwave Solar Radiation

Hourly shortwave solar radiation data from MRSO are plotted in the upper portion of Figure 2.17. The solar radiation plot generally follows a bell-shape curve, with peak radiation occurring in the summer and low radiation in the winter. However, solar radiation data from MRSO displayed an unusual low radiation period from Julian Day 174 to 217. To validate and compare the data, hourly solar radiation data from POBO were plotted in Figure 2.17. The data from POBO followed a trend similar to the MRSO data for the entire year except Julian Day 174 to 217. Considering that the two stations are only 30 miles apart, and that a similar pattern of continuous low radiation was not observed for the same period at POBO, solar radiation data from MRSO during Julian Day 174-217 were considered to be in error.

Shortwave solar radiation can also be estimated from sun angle relationships, based on geographic location and cloud cover, and is incorporated in the CE-QUAL-W2 model (Annear and Wells 2007). The shortwave solar radiation computed by the CE-QUAL-W2 model is plotted in Figure 2.17. The daily peak of the shortwave solar radiation computed using the W2 model is smaller than that of MRSO observation during most parts of the year, and especially in winter.

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[1] Figures 2.13 through 2.18 are provided at the end of this section.

2.5.5 Cloud Cover

Cloud cover data are only available at Redmond Airport. Hourly cloud cover data from Redmond Airport are plotted in Figure 2.18. These data denote the fraction of the total celestial dome covered by clouds or other obscuring phenomena—in units of 0 (no cloud cover) to 10 (dark overcast). Of the approximately 9,000 data points collected in 2013, 7,000 had value of 0, indicating there was very little cloud cover through most of the year. The data also show that the cloud formations were minimal during the summer and fall months relative to early parts of the year in 2013.

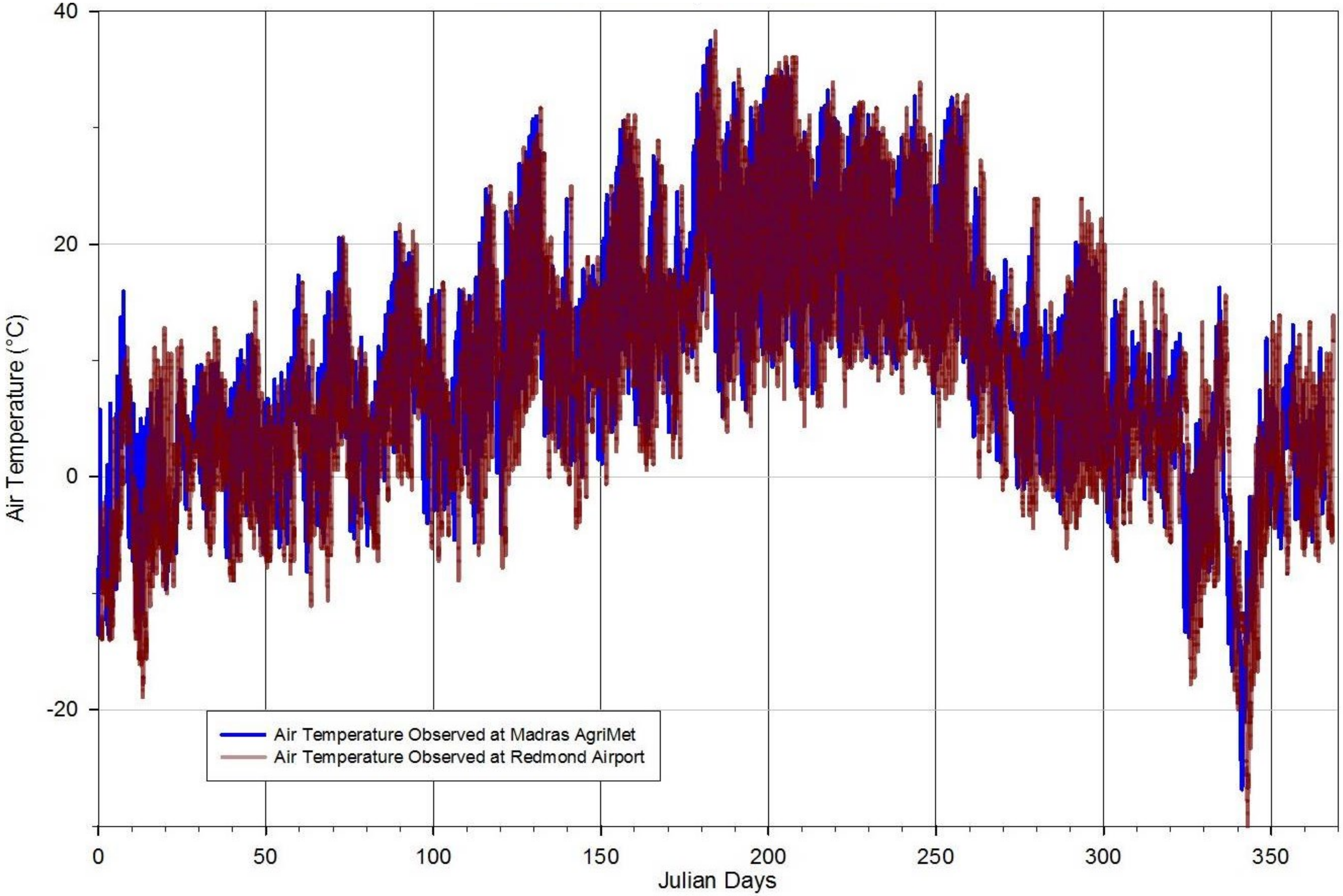


Figure 2.13. Air temperature comparison between the Madras AgriMet Weather Station and Redmond Airport Station in 2013.

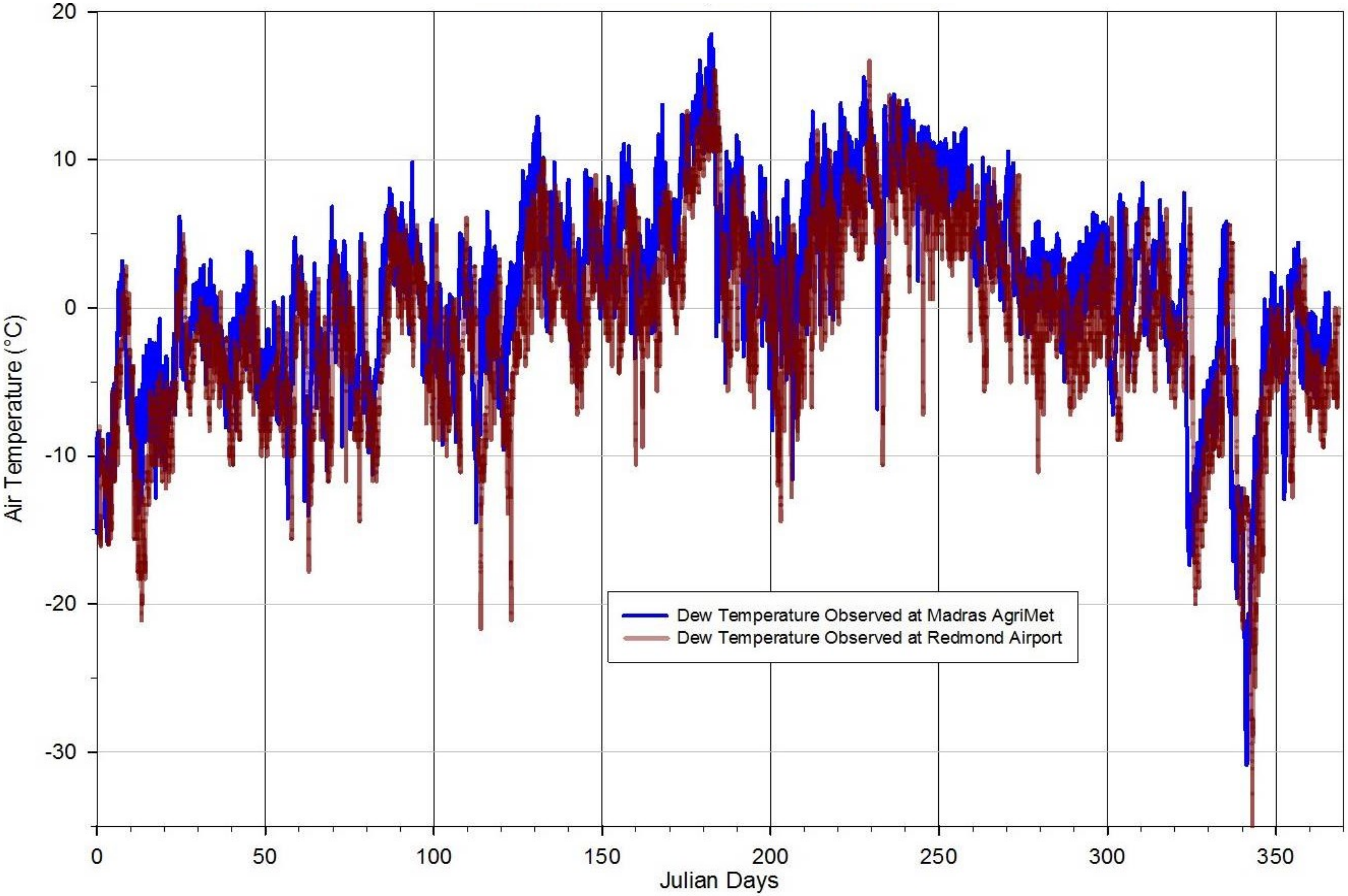


Figure 2.14. Dew point temperature comparison between the Madras AgriMet Weather Station and Redmond Airport Station in 2013.

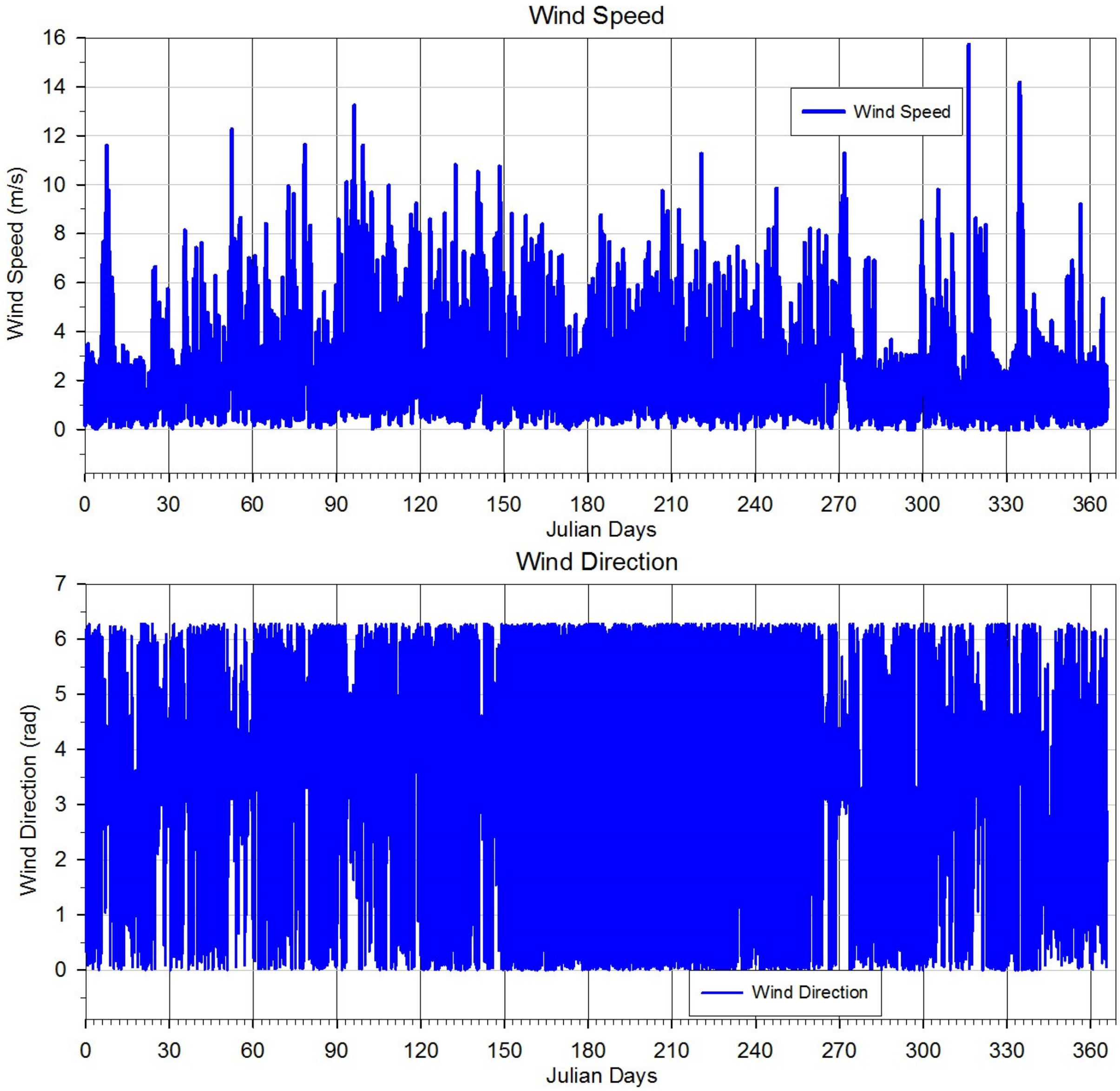


Figure 2.15. Wind speed and direction at the Madras AgriMet Weather Station in 2013.

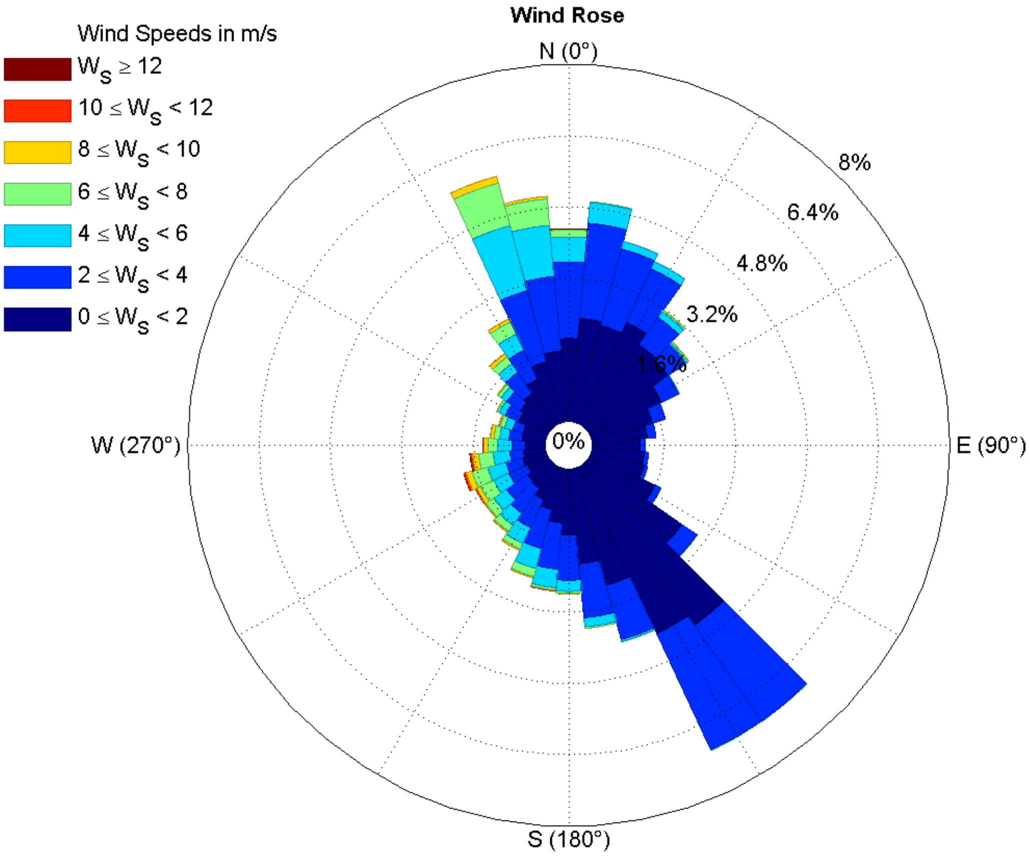


Figure 2.16. Wind rose plot of wind direction data at the Madras AgriMet Weather Station in 2013.

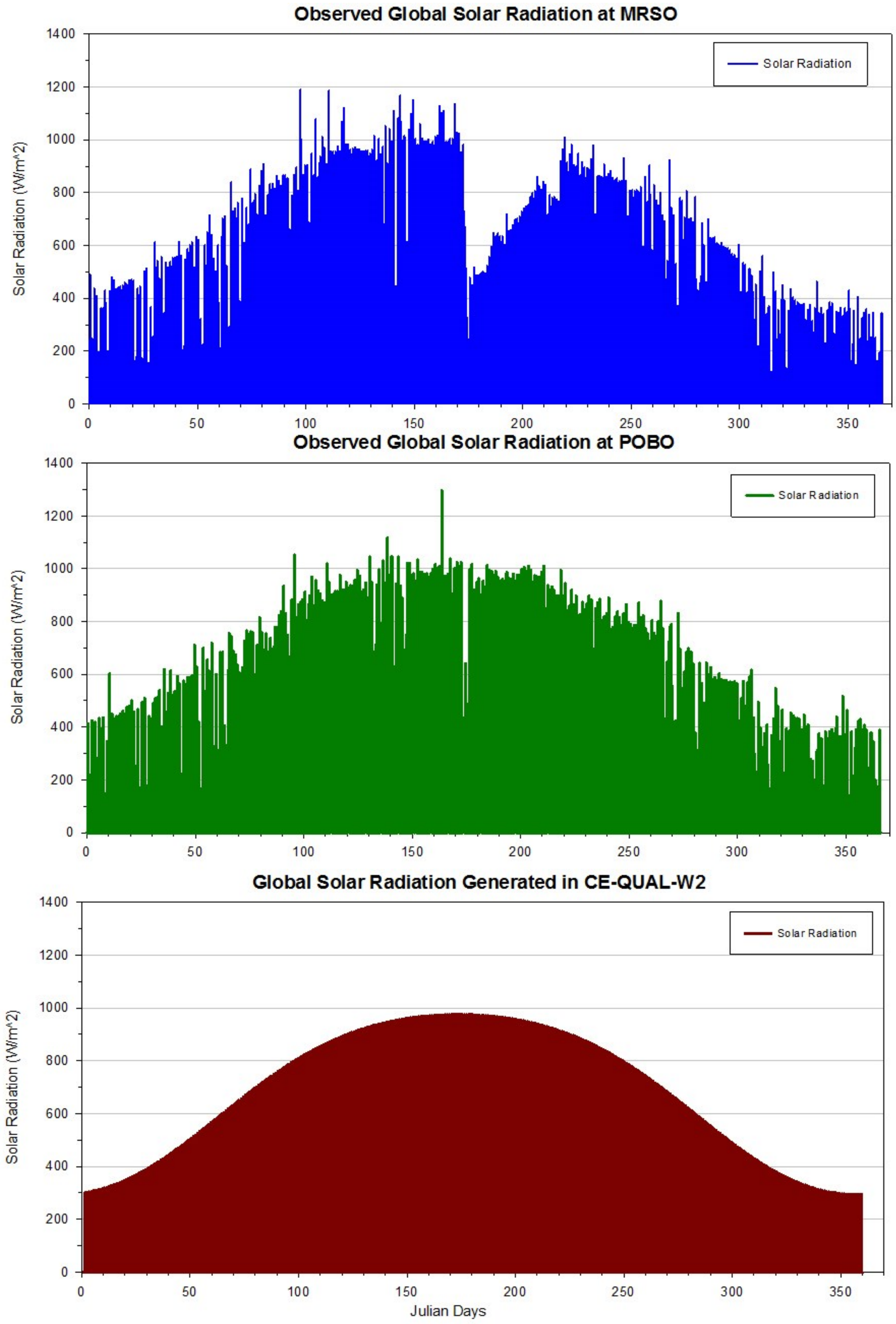


Figure 2.17. Shortwave solar radiation data in 2013.

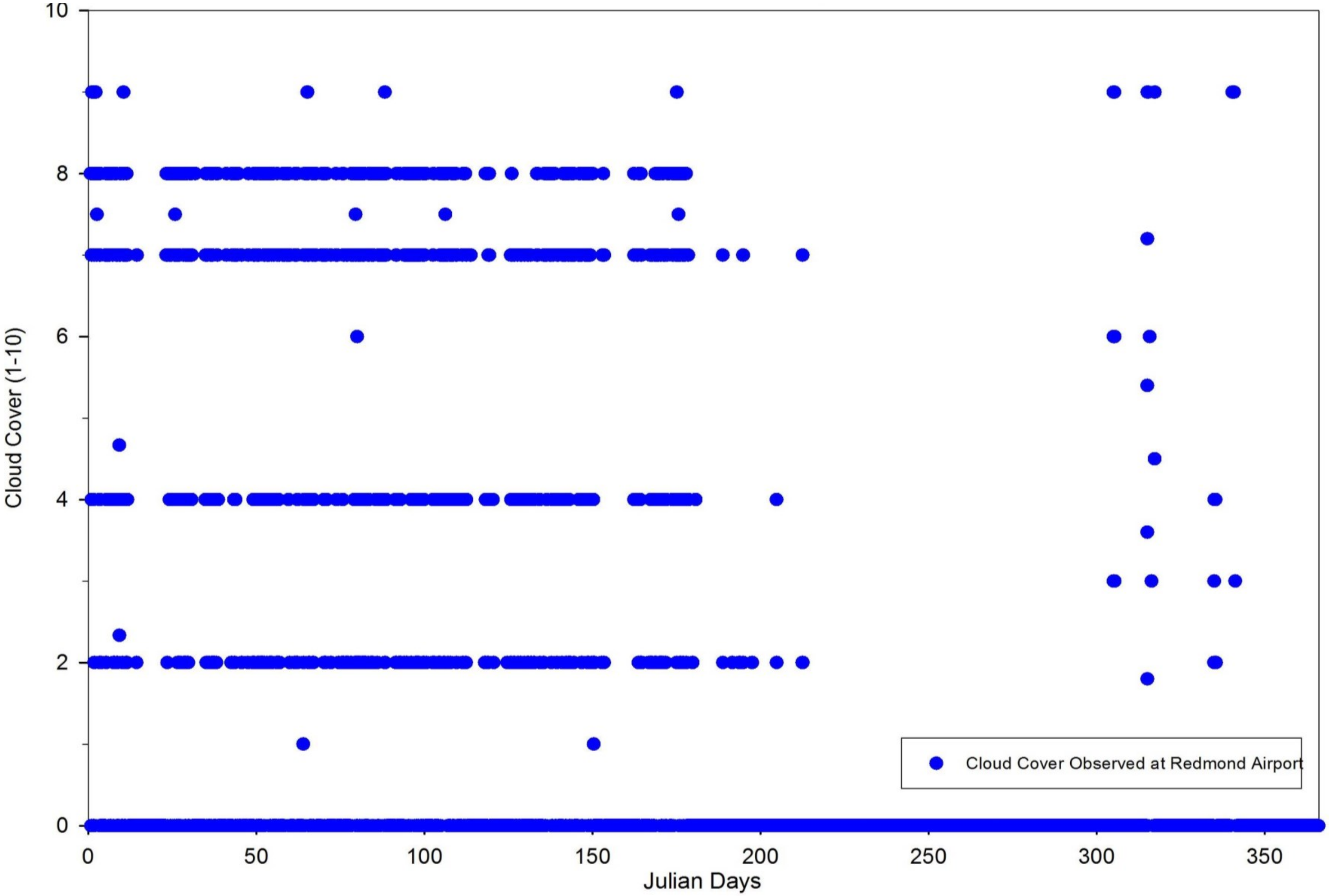


Figure 2.18. Cloud cover data at Redmond Airport in 2013.

3.0 Hydrodynamic and Temperature Model of Lake Billy Chinook

Hydrodynamic and temperature models of LBC were developed previously by PGE using the BETTER model and Environmental Fluid Dynamics Code (EFDC) (Khangaonkar 2005; Foster Wheeler 2000; and ENSR 1999). These models were developed prior to the construction of the SWW structure using data from years 1995 and 1997. The BETTER model of LBC was used for generating year-long temperature response and the EFDC was used to simulate hydrodynamics over a short duration. The primary limitation of the BETTER model was that it operated using a 12 hr time step. For the analysis of temperature response for present conditions with the SWW structure in place it was deemed inadequate. Modification was desired to improve the model's computational capability to account for momentum and mixing at the SWW structure's surface intake and to allow the simulation to be conducted at hourly variations of flow. To this end, the temperature modeling software at LBC was upgraded from the BETTER model to the state-of-the-art CE-QUAL-W2 model (Khangaonkar and Long 2014) using 1995 data. In this chapter we present the CE-QUAL-W2 model setup and calibration for the present conditions incorporating the as-built SWW structure using observed data from 2013.

3.1 Model Setup

Model setup involves the development of the model grid and establishment of initial and boundary conditions. Boundary conditions include upstream inflow and tributary flow rate and temperature, meteorological data, and reservoir discharge data. The setup of the LBC 2013 W2 model is described in detail below.

3.1.1 Model Grid

LBC was divided into three branches. Previous studies defined the Deschutes River as the main stem, but in this study Crooked River was incorporated as the main stem because it has a wider water surface area relative to the Deschutes River and it appears to be the dominant branch because it has a more direct path to the point of confluence near the LBC forebay. Crooked River is labeled as Branch 2 in the model. The Deschutes River and Metolius River arms are specified as secondary branches and are labeled as Branch 1 and Branch 3, respectively. A constant longitudinal resolution of 200 m and a constant vertical resolution of 1 m were used in this version. The final model grid has 152 horizontal segments and 129 vertical layers. Figure 3.1 shows the model plan view and Figure 3.2 shows the model profile views of the three branches. The new model of LBC has a resolution that is 5 times finer than the previous version using the BETTER model presented by ENSR (1999).

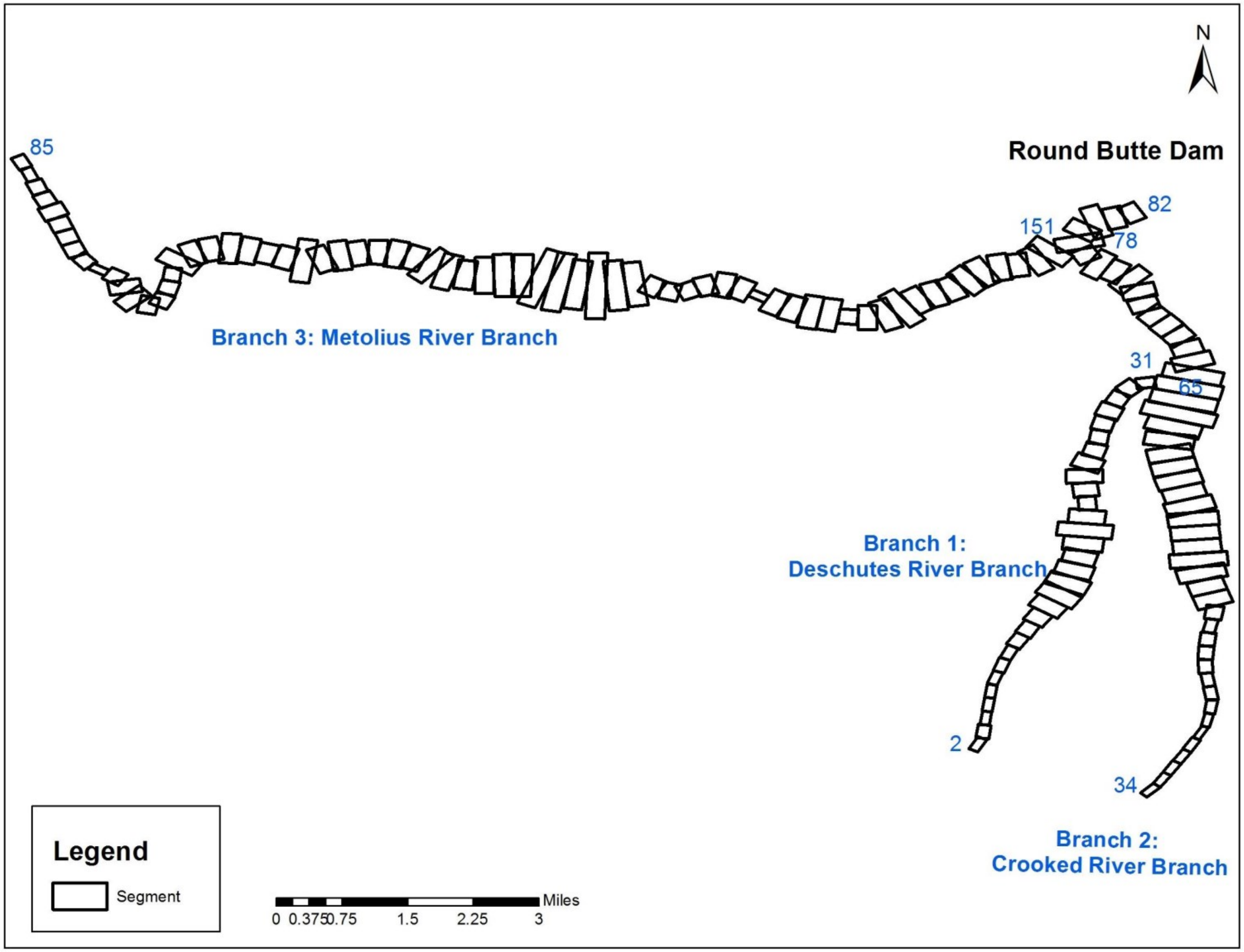


Figure 3.1. Lake Billy Chinook grid plan view.

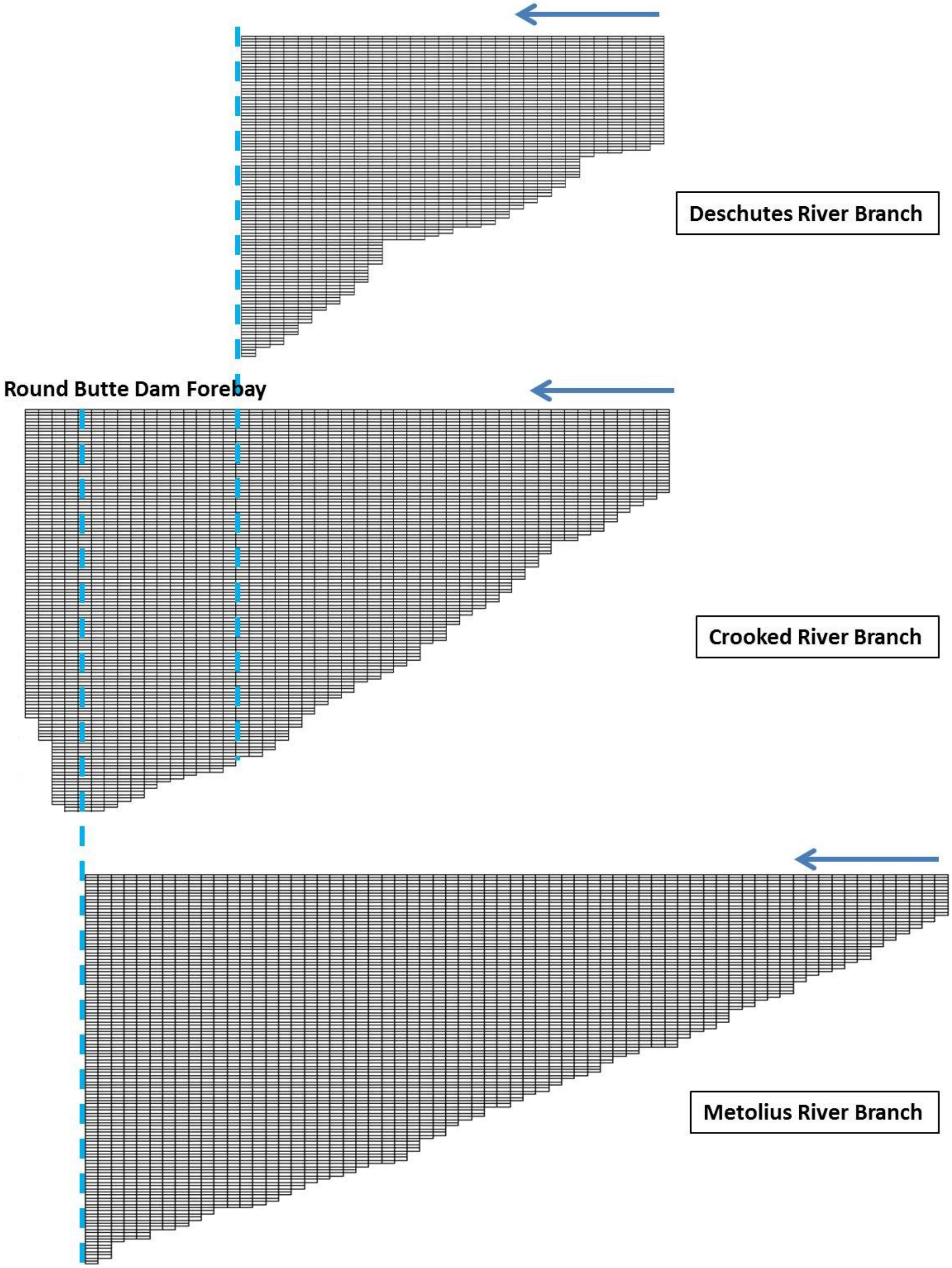


Figure 3.2. Lake Billy Chinook grid profile view.

3.1.2 Initial Conditions

Initial conditions consist of the reservoir water-surface elevation and temperature at the start of the model simulation period. The initial reservoir water-surface elevation was set to 591.9 m (1,942 ft) based on measurements from January 1, 2013 in the LBC forebay. The water temperature measurements in the LBC forebay indicate that although LBC in January is not stratified, the temperature difference between the surface warmer water and bottom cold-water layer is more than 1°C. The initial reservoir temperature was therefore specified based on measurement conducted on January 1 2013; the top layer temperature was 7.21°C, the bottom layer temperature was 6.0°C, and linearly interpolated values were specified at all other depths.

3.1.3 Meteorological Inputs

Meteorological data from MRSO and Redmond Airport in 2013 were used in model calibration. MRSO provides hourly air temperature, dew temperature, wind speed, wind direction, and solar radiation as described in Figure 2.13 through Figure 2.17 in Chapter 2. Cloud cover data from Redmond Airport, as shown in Figure 2.18, were used in the model and linearly interpolated to prepare the CE-QUAL-W2 meteorological input file. Figure 2.17 shows solar radiation levels from MRSO from Julian Day 174 to 217 are lower than those during the period before and after. This unusual phenomenon is not observed at nearby POBO and cannot be explained. Theoretical radiation values were calculated using internal an algorithm in the CE-QUAL-W2 model for Julian Day 174 to 217, and were scaled to match the general trend of solar radiation at MRSO. The final solar radiation input used in this simulation is shown in Figure 3.3.

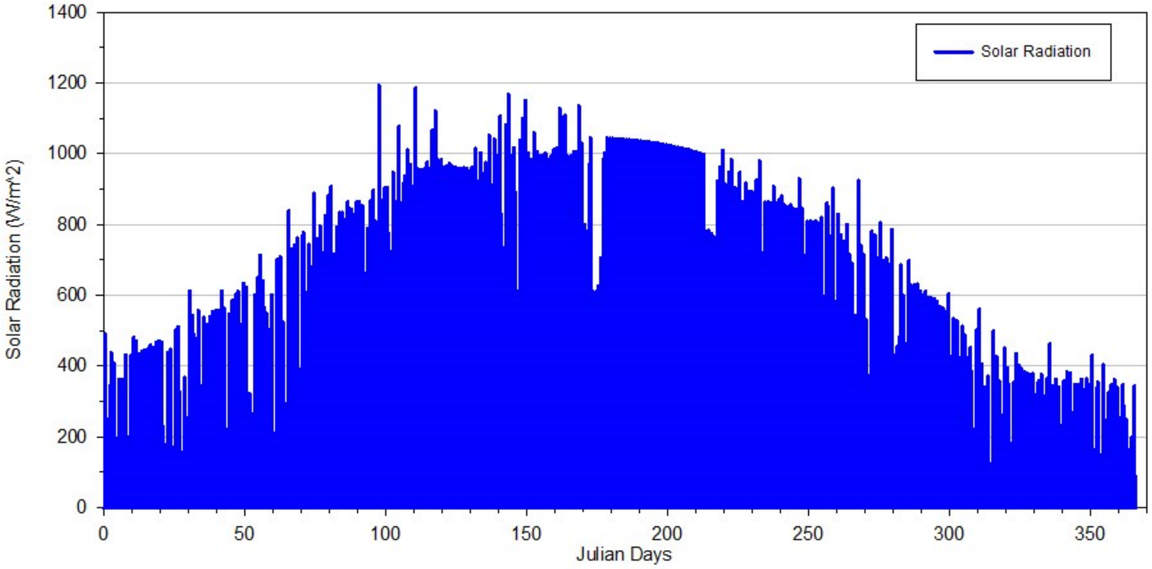


Figure 3.3. Solar radiation input for 2013 simulation.

3.1.4 Hydrological Inputs and Pelton Round Butte Discharge

Hydrological inputs to the model include inflows from Deschutes River, Crooked River, and Metolius River. Hourly inflows from the three rivers are shown in Figure 2.6, and are used as input to the model.

Round Butte Dam SWW structure release data (Figure 2.4) were specified in the model. The SWW structure is incorporated in the model as two hydraulic point sink type modules. The SWW structure has a centerline at 585.20 m (1,920 ft) elevation, and the bottom withdrawal structure has a centerline at 523.50 m (1,717.5 ft) elevation. Each withdrawal is allowed to pull water from a depth bounded by the Structure Top and Structure Top elevations (STR TOP and STR BOT) that are specified. Through numerous sensitivity tests, limiting the surface structure to withdraw water from the water surface to layer 18 (a height of 12 m, 39 ft), and limiting the bottom structure to withdraw water from layer 69 to layer 85 (a height of 16 m, 52.5 ft) were found to best represent the performance of the SWW structure in the model.

3.1.5 Inflow Water Temperature Data

Hourly river inflow temperature from Deschutes River, Crooked River, and Metolius River specified in the model were based on measured data from the USGS gauges and were presented previously in Figure 2.7.

3.2 Model Calibration

3.2.1 Hydrodynamic Calibration/Flow Balance

In the calibration of a reservoir numerical model, the first step is to ensure that the model correctly conserves mass. This was done by comparing the simulated water-surface level variations with measured forebay levels at LBC. The initial setup of the model inflow and outflow resulted in a steady drop in the water-surface level in LBC. This was expected because the initial model setup did not account for the inflow of ungauged water into LBC. To correctly reproduce observed water surface variation, a water balance calculation using a tool called “Water Balance Utility” (Portland State University and Corps of Engineers) was used. A time series of ungauged flow was calculated iteratively until the predicted water-surface elevation matched the measured data. This flow time series was time averaged over 24 hr intervals. The daily averaged ungauged flow is shown in Figure 3.4, and it had a mean value of 2.25 m^3/s (79.5 cfs) in 2013. This daily flow value (+tive or –tive) was added the three river inflows in proportion to the respective yearly averaged flow rate. The final flow calibration results are shown in Figure 3.5, and show that simulated water-surface levels match the measured data within an RMSE of 0.02 m (0.06 ft).

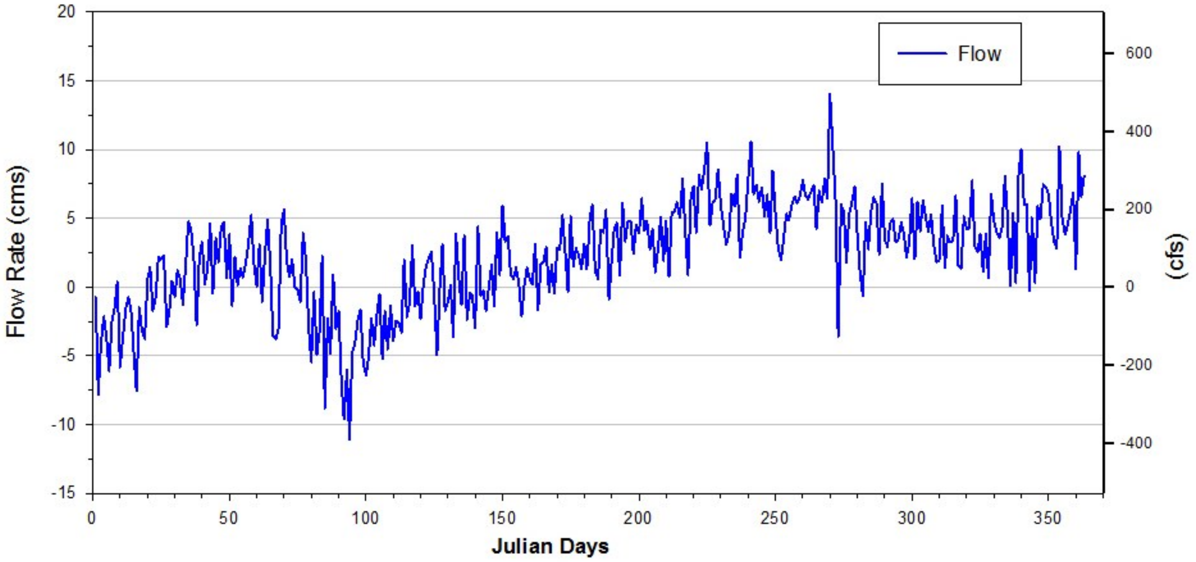


Figure 3.4. Daily averaged ungauged flow of LBC in 2013.

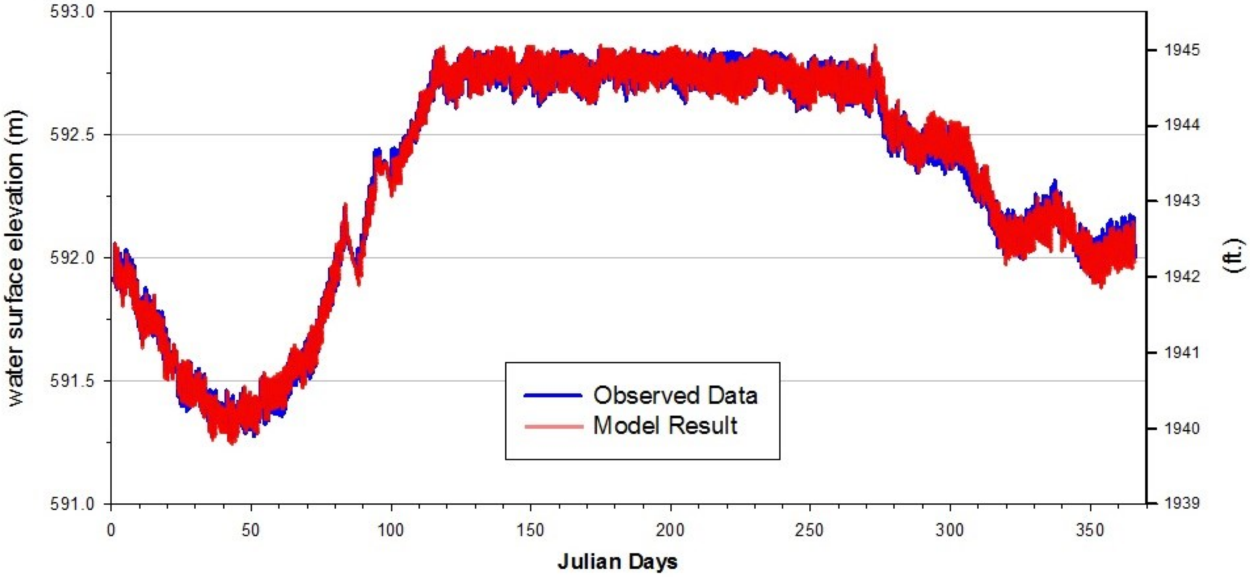


Figure 3.5. Comparisons of the predicted and observed Round Butte forebay water-surface elevation in 2013.

3.2.2 Temperature Calibration

The temperature calibration for LBC focused on matching the observed data consisting of vertical temperature profiles for the Round Butte forebay and the temperature time series for the Round Butte Dam tailrace. During the temperature calibration process, the approach was to use typical/default values of model parameter coefficients to the extent possible and only change parameters as dictated by site-specific conditions and results of numerous sensitivity tests. The model was found to be sensitive to the Wind Sheltering Coefficient (WSC). To reproduce the observed mixing inside the reservoir and the available wind data, the WSC was 1, implying full wind stress was necessary. The Heat Exchange Scheme (SLHTC) was set to ET, implying that the surface heat exchange was computed using the “equilibrium temperature” method option in CE-QUAL-W2. This setting was selected after testing the term-by-term approach, which underestimated the surface temperatures in the system. CE-QUAL-W2 provides the option of specifying the dynamic or static input of topographical and vegetative shading for a model segment. For this effort a static value of 1 was used for shading in LBC, implying no vegetative shading. During the calibration effort it became clear that the sensible heat flux derived from air temperature values from nearby meteorological stations was barely adequate to generate the temperature response observed in the surface layers of LBC. It is possible that air temperatures at LBC would be higher due to the adiabatic heating of air at lower elevation (the LBC water-surface elevation is approximately 149 m [489 ft] lower than the MRSO gauge). In this application, we elected not to use the adiabatic heating adjustment of air temperatures, because PGE plans to collect site-specific air temperature data in years 2016, 2017, and 2018. However, this required that model calibration be conducted with zero shading to achieve a match with surface temperatures.

The major CE-QUAL-W2 model coefficients determined as part of the calibration process for the LBC Temperature Model are listed in Table 3.1 below.

Table 3.1. CE-QUAL-W2 model coefficients for the LBC Temperature Model.

Model Parameter	Calibrated Value	Typical Value
Wind Sheltering Coefficient (WSC)	1	0-1
Heat Exchange Scheme (SLHTC)	ET	TERM or ET
Shading	1	0-1 or dynamic
The Light Extinction Coefficient (EXH2O)	0.45	0.45
Horizontal Eddy Viscosity (AX)	1	1
Horizontal Eddy Diffusivity (DX)	1	1
Transport Scheme (SLTRC)	Ultimate	Quickest or Ultimate
Time Weighting for Advection (THETA)	0.55	0.55

Figure 3.6 shows a comparison of predicted and observed vertical temperature profiles for the Round Butte forebay plotted at monthly (30-day) intervals. The model captures the full annual temperature cycle in LBC starting with the cold well-mixed conditions in the winter to initiation of stratification in March to the highly stratified conditions in summer months followed by destratification in October. For most of the year, the model predicts a cooler hypolimnion notable for the water column below 75 m (246 ft).

The simulated Round Butte Dam release temperature is compared to observed temperature data in the LBC tailrace in Figure 3.7. Note that the tailrace temperature is influenced by several factors besides dam release temperature. The station is within the Lake Simtustus pool and is affected by surface heating and mixing as the pool water elevation fluctuates. The temperature comparison between tailrace and dam release must therefore be interpreted with caution. Table 3.2 shows a summary of the error statistics based on comparison of model results versus observed data. The daily averaged Round Butte tailrace temperature is compared with the dam release temperature.

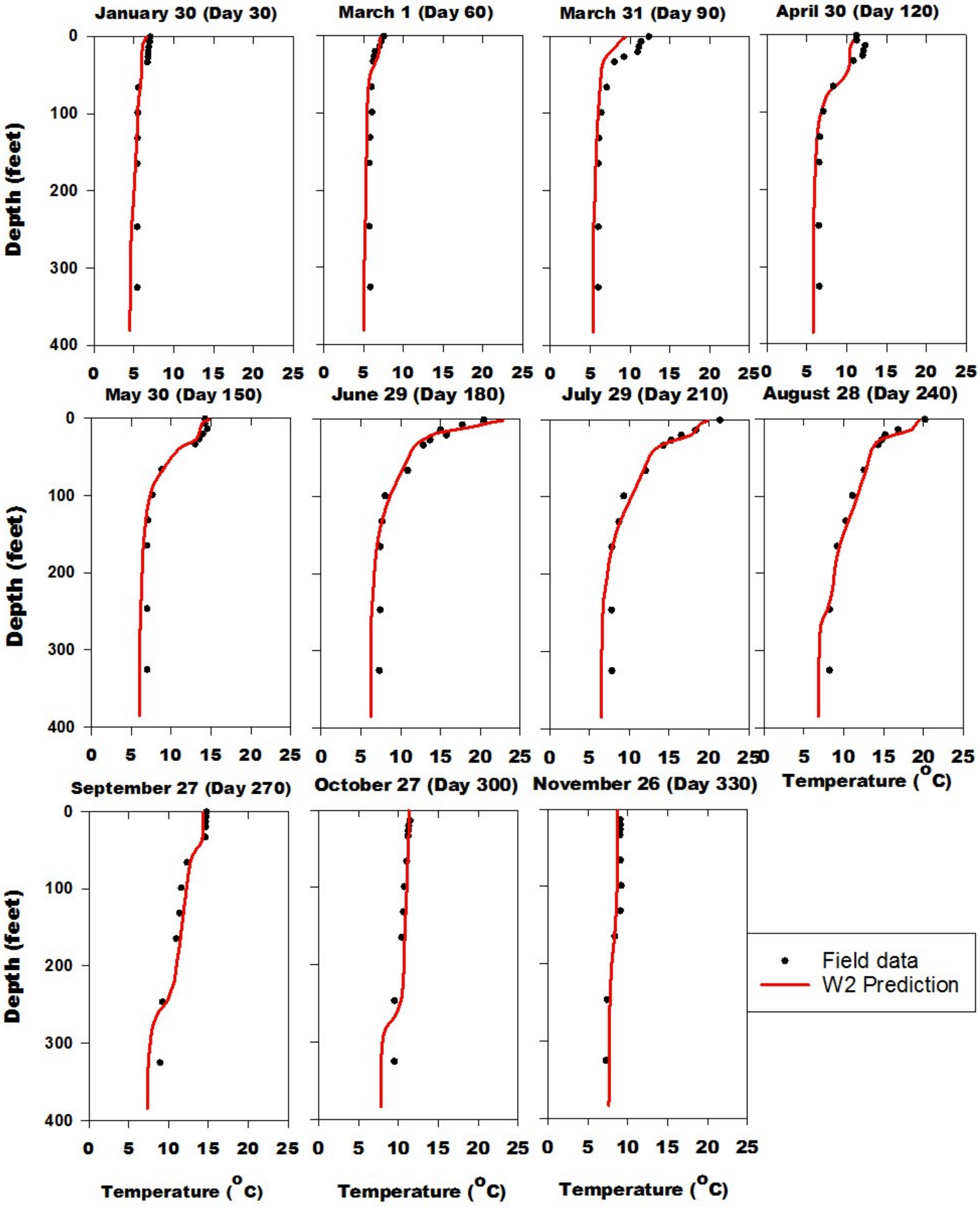


Figure 3.6. Comparisons of predicted and observed water temperature profiles at LBC in 2013.

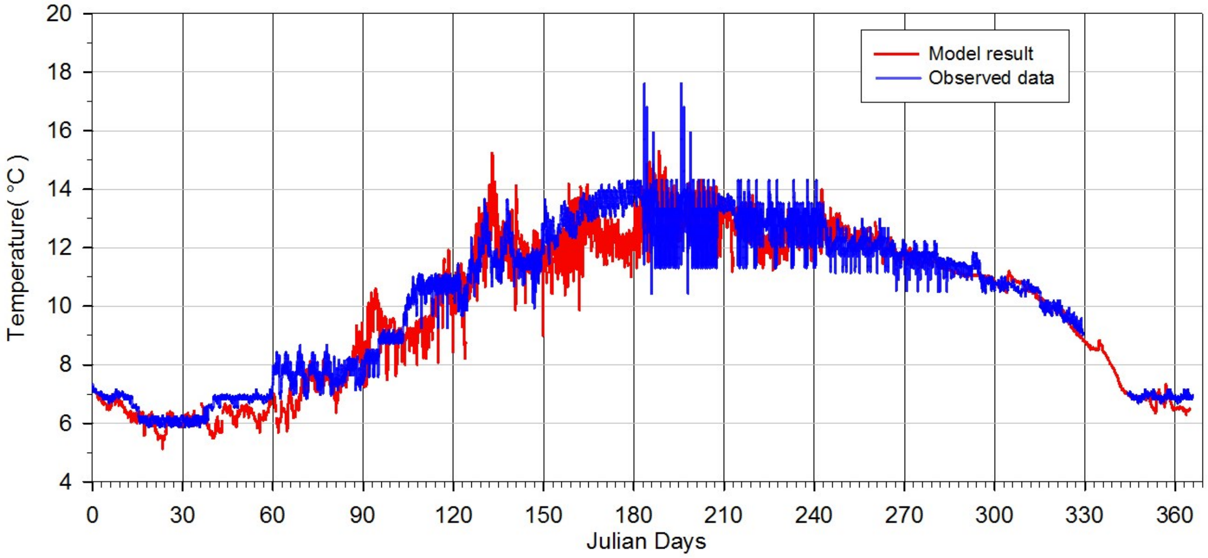


Figure 3.7. Simulated Round Butte Dam release temperature compared with the observed LBC tailrace temperature in 2013.

Table 3.2. Model error statistics for 2013.

Station	ME(˚C)	AME(˚C)	RMSE(˚C)	Number of Comparisons
Round Butte Forebay	-0.52	0.73	0.95	98900
Round Butte Tailrace (daily averaged)	0.17	0.48	0.66	349

ME = mean error
AME = absolute mean error
RMSE = root mean square error

4.0 Hydrodynamic and Temperature Model of Lake Simtustus

A model of Lake Simtustus capable of simulating hydrodynamics, temperature, and water quality was previously developed by PGE and used for this effort. The Lake Simtustus model was developed using CE-QUAL-W2 and was previously calibrated using 1995 data. For this study the model was upgraded to the latest version for consistency with the LBC model and validated for 2013 conditions, including the SWW discharge from LBC.

4.1 Model Setup

4.1.1 Model Grid

This study used the same model grid that was developed for the 1995 and 1996 model (Foster Wheeler 2001). The main stem of Lake Simtustus was divided into 26 segments each having an average length of 478 m. Willow Creek and Seekseequa Creek and two small embayments were included as Branch 2, 3, 4, and 5 in order to fully describe the water exchange between the main stem, tributaries, and embayments. The system has 35 active horizontal segments and 53 vertical layers. Figure 4.1 shows the model plan view and Figure 4.2 shows the model profile view of the main stem.

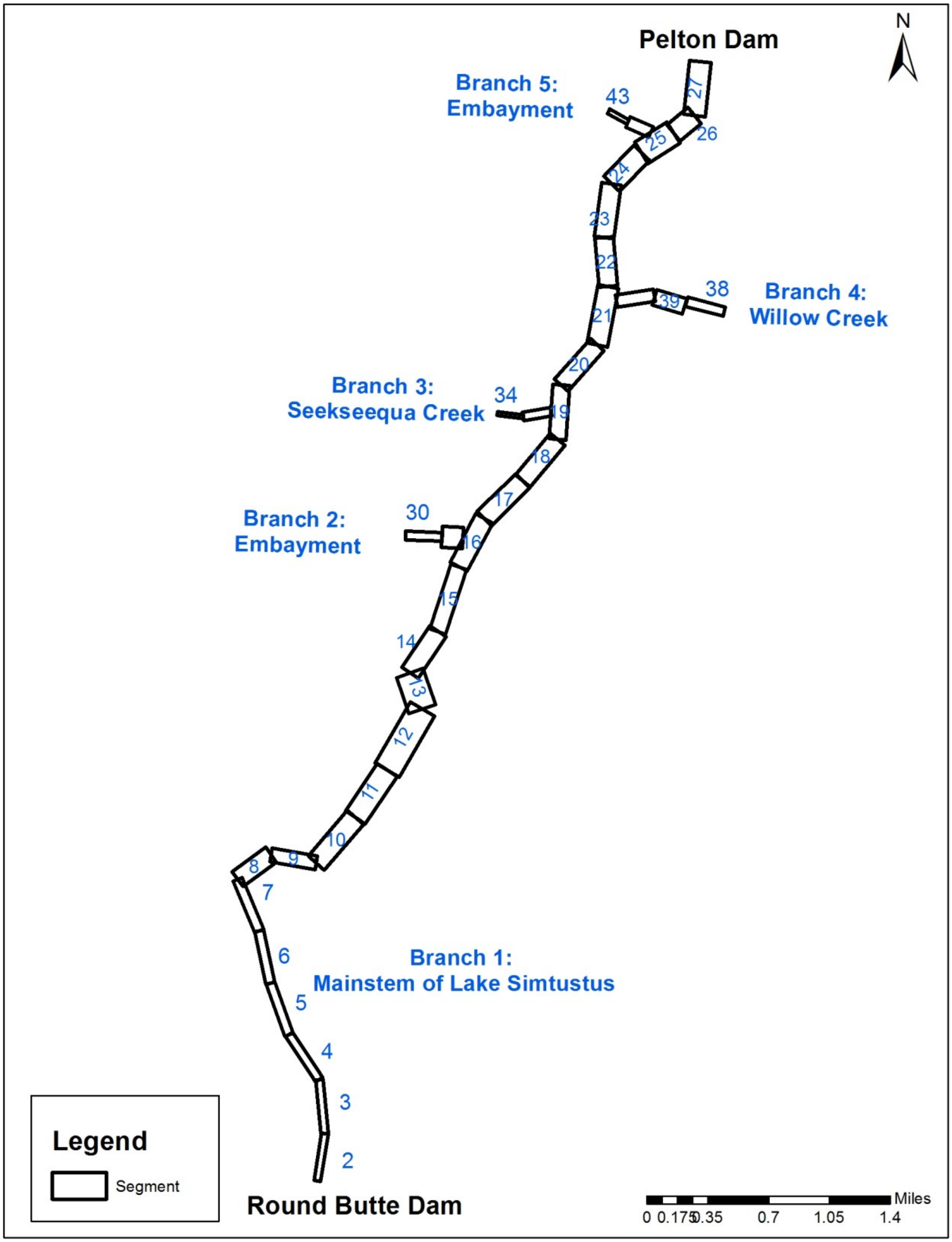


Figure 4.1. Lake Simtustus grid plan view.

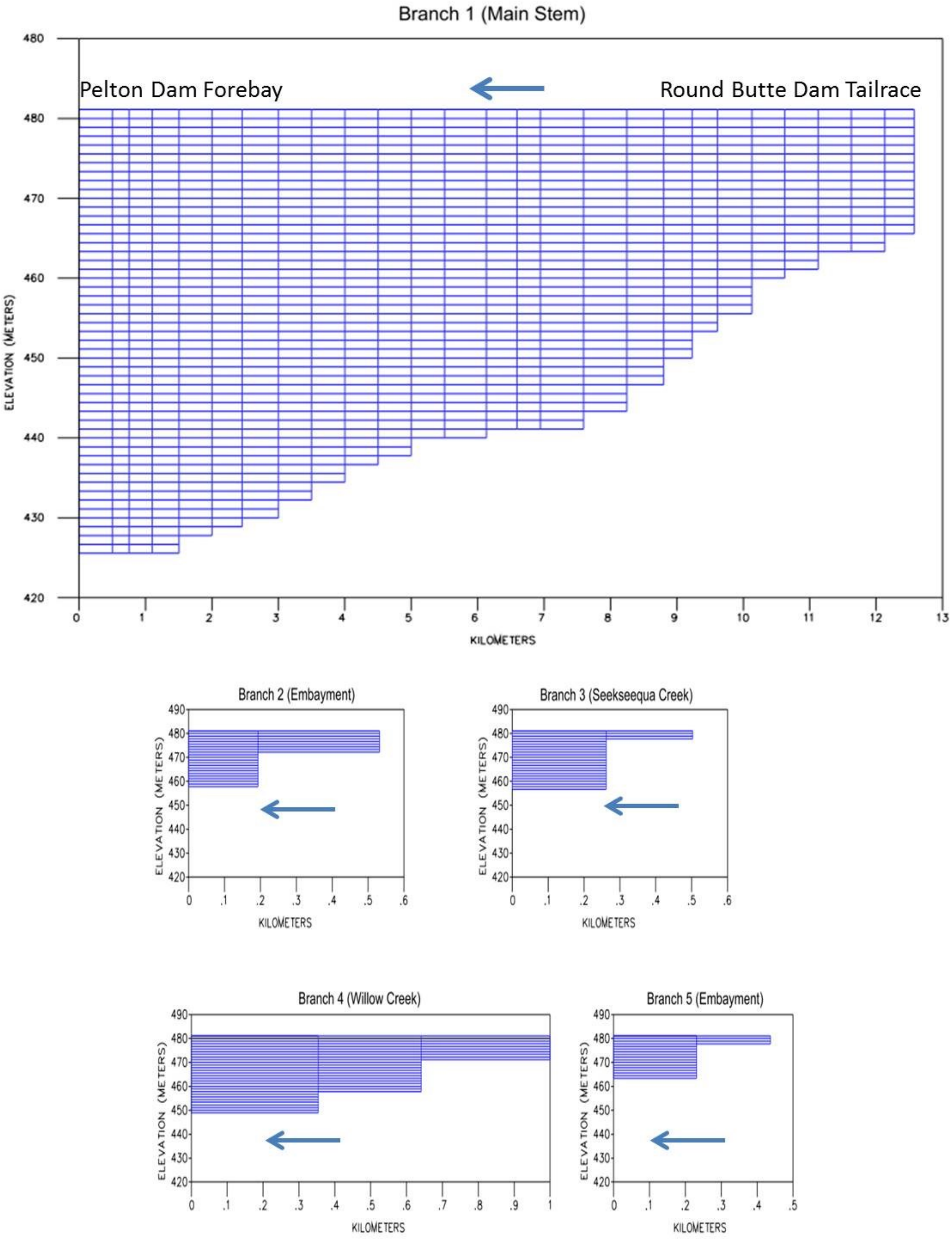


Figure 4.2. Lake Simtustus grid profile view.

4.1.2 Initial Conditions

The initial water-surface elevation in Lake Simtustus was set to 480.7 m (1,577 ft) based on the measured elevations corresponding to January 1, 2013, in the Pelton Dam forebay. The initial reservoir temperature was set to a uniform 7.75°C.

4.1.3 Meteorological Inputs

Meteorological inputs specified for Lake Simtustus model validation for 2013 were the same as those used in LBC model calibration described in Chapter 3.0 (see Sections 3.2 and 2.5 for details).

4.1.4 Hydrographic Inputs and Reservoir Discharge

The hourly discharge from LBC released through the SWW structure is used as inflow to the Lake Simtustus model. The flow rate from SWW structure top and SWW structure bottom were combined to produce a single input file for the main stem of Lake Simtustus (Branch 1). Figure 4.3 provides a time series of the peaking-mode discharge from LBC

Hourly Pelton Dam release data (see Figure 4.4) were specified as the outflow boundary in the model. The Pelton Dam intake was specified in the model as a structure module, and its centerline was set at 433.6 m (1,422.5 ft). The sink type of withdrawal was selected. Unlike at LBC, the water withdrawal was not restricted to selected layers.

4.1.5 Inflow Water Temperature Data

The temperature of the inflow to Lake Simtustus was the water temperature released by Round Butte Dam. This temperature time series was from the LBC model results. The simulated SWW release water temperature was prepared for inputs into the Lake Simtustus model. The temperature of the SWW structure top and SWW structure bottom flows were combined to produce a flow-weighted temperature time series. The temperature of inflow to Lake Simtustus is shown in Figure 4.4.

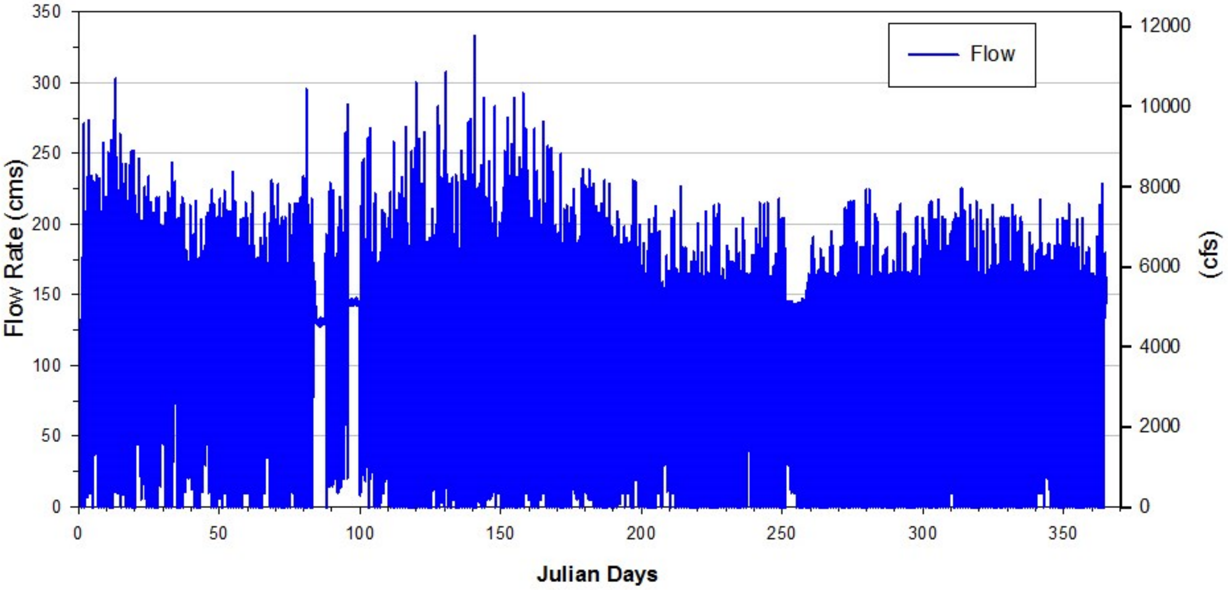


Figure 4.3. Peaking-mode inflow to Lake Simtustus (combined SWW structure top and SWW structure bottom flows from LBC).

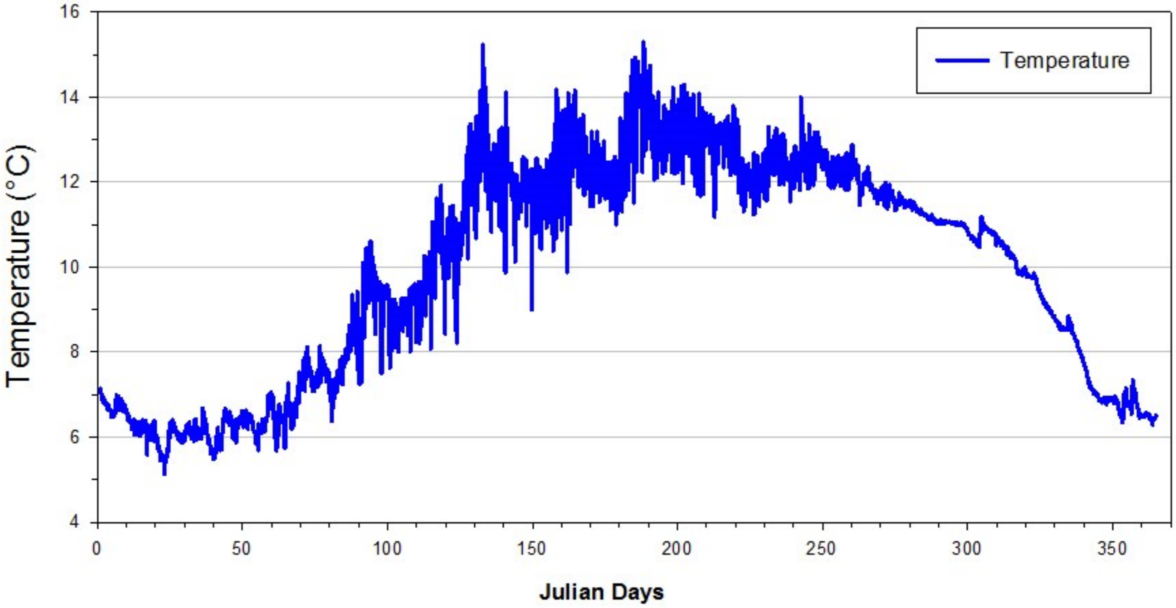


Figure 4.4. Temperature time series of the inflow to Lake Simtustus based on the SWW structure release water temperatures.

4.2 Model Calibration

4.2.1 Hydrodynamic Calibration/Flow Balance

As in the LBC model, the hydrodynamic calibration focused on achieving flow and storage volume balance. The initial setup of the model using measured inflows from LBC and outflows from Pelton Dam alone resulted in a steady drop in the water-surface elevations of Lake Simtustus. As in the case of LBC, this was attributed to ungauged flow entering Lake Simtustus via seepage, runoff, and groundwater flows. The calibration involved iterative application of the CE-QUAL-W2 mass balance tool to estimate the ungauged flow rate. A time series of ungauged flow was calculated that allowed a best match with observed water-surface elevations in Lake Simtustus. This flow was averaged over 24 hr intervals to smooth out large fluctuations. The estimate of daily averaged ungauged flow to Lake Simtustus is plotted in Figure 4.5, and had a mean value of 8.74 m^3/s (308.6 cfs) in 2013. The final flow calibration results are shown in Figure 4.6. The simulated water-surface elevations were within 0.1 m (0.3 ft) of RMSE relative to observed data.

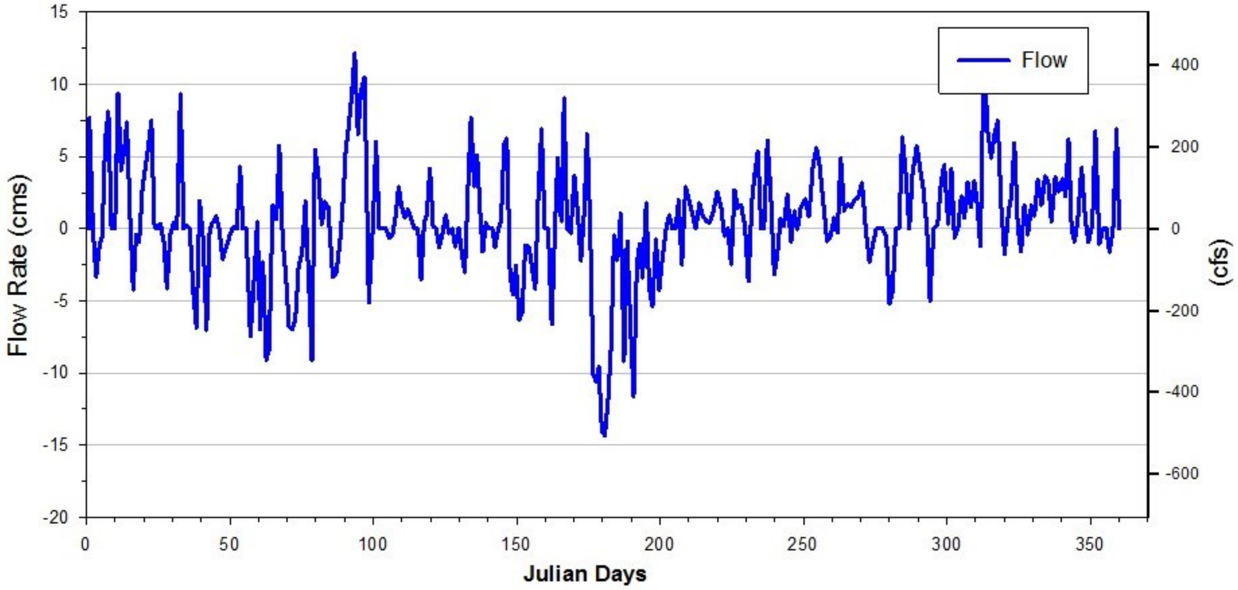


Figure 4.5. Estimated ungauged flows into Lake Simtustus in 2013. Plotted flows are daily averaged values.

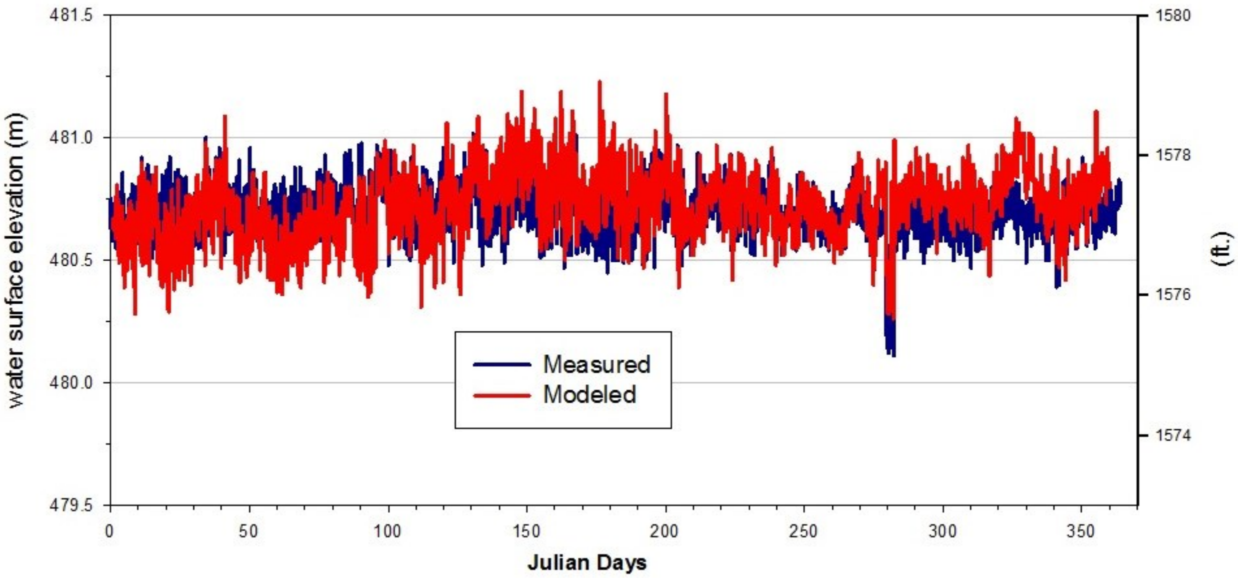


Figure 4.6. Comparisons of simulated and observed water-surface elevations in the Pelton Dam forebay in 2013.

4.2.2 Temperature Calibration

The temperature calibration for Lake Simtustus using CE-QUAL-W2 was similar to that for LBC. The available temperature data were derived from PGE Station 4 where temperature is monitored continuously at multiple depths. The calibration involved iterative application of the model to provide a best match with observed data. In many ways this was a validation exercise because most of the model settings based on the 1995 calibration were retained. The wind shelter coefficient (WSC) was set to be time dependent; less wind sheltering occurs in the earlier part of the year and more wind sheltering occurs in the later part. The Heat Exchange Scheme (SLHTC) was set to TERM, implying that the surface heat exchange was computed using a “term-by-term” approach. A static value of 1 is used for shading, which is equivalent to zero vegetation or topographic shade. The major calibration parameters for the Lake Simtustus model are listed in Table 4.1.

Table 4.1. Major Lake Simtustus model calibration coefficients.

Model Parameter	Calibrated Value	Typical Value
Wind Sheltering Coefficient (WSC)	0.2-1	0-1
Heat Exchange Scheme (SLHTC)	TERM	TERM or ET
Shading	1	0-1 or dynamic
The Light Extinction Coefficient (EXH2O)	0.3	0.45
Horizontal Eddy Viscosity (AX)	1	1
Horizontal Eddy Diffusivity (DX)	1	1
Transport Scheme (SLTRC)	Quickest	Quickest or Ultimate
Time Weighting for Advection (THETA)	0.55	0.55

Figure 4.7 (at the end of this section) shows comparisons of predicted and observed water temperature time series at 0 m and 40 m (0 ft. and 131 ft) of Lake Simtustus Forebay in 2013. Table 4.2 shows a summary of the model versus data error statistics.

Table 4.2. Lake Simtustus model error statistics for 2013.

Station	ME(˚C)	AME(˚C)	RMSE(˚C)	Number of Comparisons
Lake Simtustus Forebay	0.03	0.67	0.89	23013

ME = mean error
AME = absolute mean error
RMSE = root mean square error

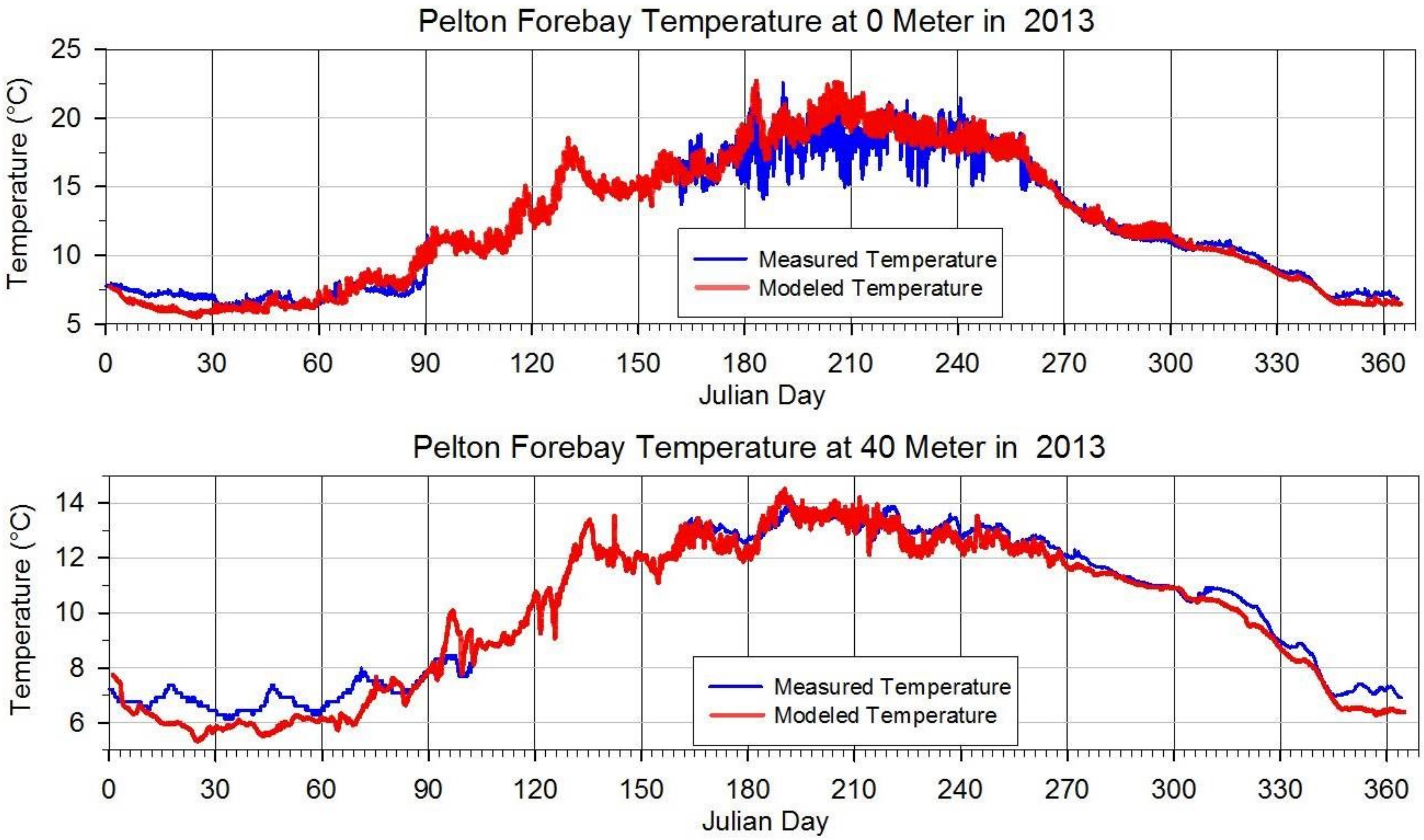


Figure 4.7. Comparisons of predicted and observed water temperature time series at 0 m and 40 m depth of Lake Simtustus forebay in 2013.

5.0 Hydrodynamic and Temperature Model of Reregulating Reservoir

This chapter presents the development of a hydrodynamic and temperature model of Reregulation Reservoir. Unlike for LBC or Lake Simtutus, a model of Reregulation Reservoir had not been developed previously by PGE. In prior studies, temperature and water quality at Madras were estimated using the correlation between Pelton forebay discharge and Reregulating Dam tailrace (discharge) (Foster Wheeler 2000; Foster Wheeler 2001). Commuting the flow from Pelton Dam through Reregulating Reservoir via a CE-QUAL-W2 model was recommended as part of building a consistent set of models for all Pelton Round Butte Hydroelectric Project reservoirs. The expectation is that the model-based results at Madras would improve upon regression-based estimates. The availability of model-based coverage for all reaches would also facilitate the simulation of the project reach for hypothetical pre-project conditions without dams, as described in the following section.

5.1 Model Setup

5.1.1 Model Grid

Reregulating Reservoir was defined as single branch in the model. A constant longitudinal segment length of 250 m (820 ft) and a constant vertical layer thickness of 1 m were used. The final model grid has 18 horizontal segments and 25 vertical layers. Figure 5.1 shows the model plan view and Figure 5.2 shows the model profile view of the main stem.

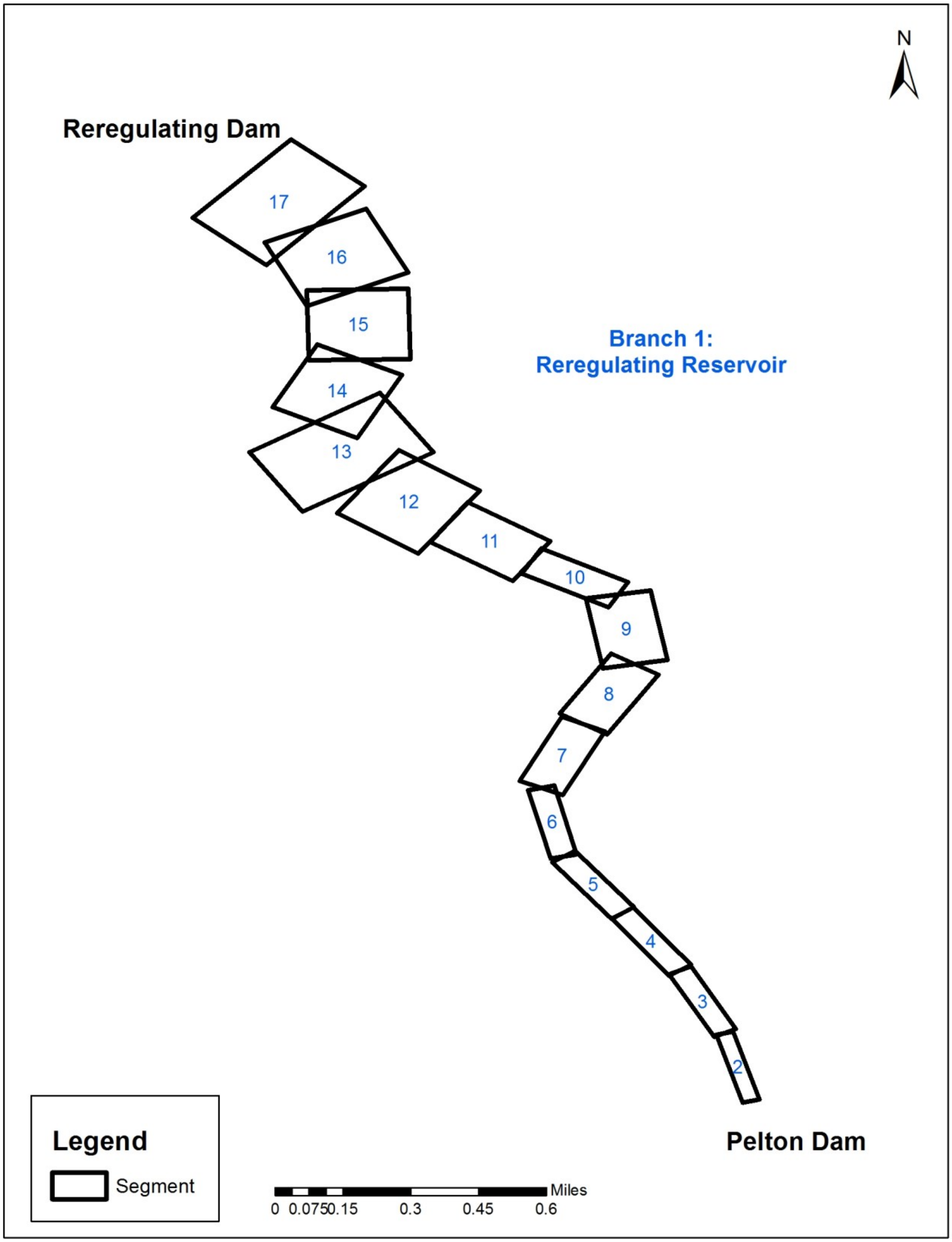


Figure 5.1. Reregulating reservoir grid plan view.

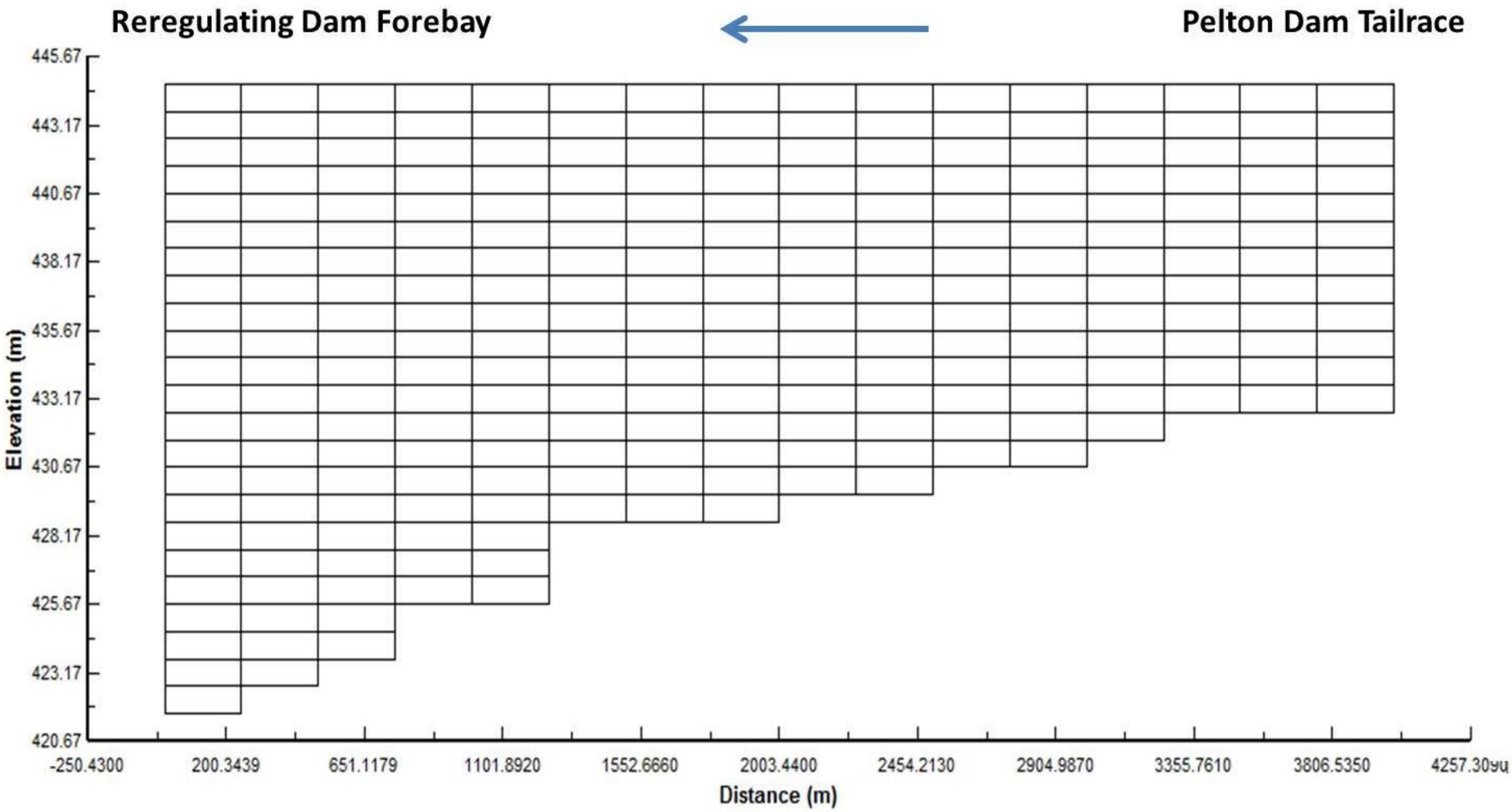


Figure 5.2. Reregulating Reservoir grid profile view.

5.1.2 Model Initial Conditions

Initial conditions at the start of the simulation were set based on measured water-surface levels in Reregulation Reservoir corresponding to January 1, 2013. The initial reservoir temperature was set to 7.7°C.

5.1.3 Meteorological Inputs

Meteorological inputs for the Reregulation Reservoir model were the same as those used for the LBC and Lake Simtustus models described in Chapter 3.0 (see Sections 3.2 and 2.5 for details). The same meteorological inputs used in the LBC 2013 model were specified for the Reregulating Reservoir 2013 model.

5.1.4 Hydrological Inputs and Reservoir Discharge

Inflow to Reregulation Reservoir is the discharge from Lake Simtustus and is shown in Figure 5.3. The outflow from the model is specified as hourly discharge from Reregulating Dam (Figure 5.4). The Reregulating Dam intake to the powerhouse is specified in the model as a structure module. From drawings of Reregulating Dam, the water intake centerline is approximately at 417.6 m (1,370 ft). However, the bathymetry data are coarse and do not adequately resolve the deeper forebay region below 421.17 m (1,382 ft). As a simplification, the structure centerline was set to be at 421.17 m (1,382 ft). A sink type of outlet was selected. The water withdrawal was not restricted to selected layers.

5.1.5 Inflow Temperature Data

The temperature of inflow to Reregulation Reservoir was based on results from the Lake Simtustus model discharge. The 2013 time series used to define the temperature of inflow to the Reregulation Reservoir is shown in Figure 5.4.

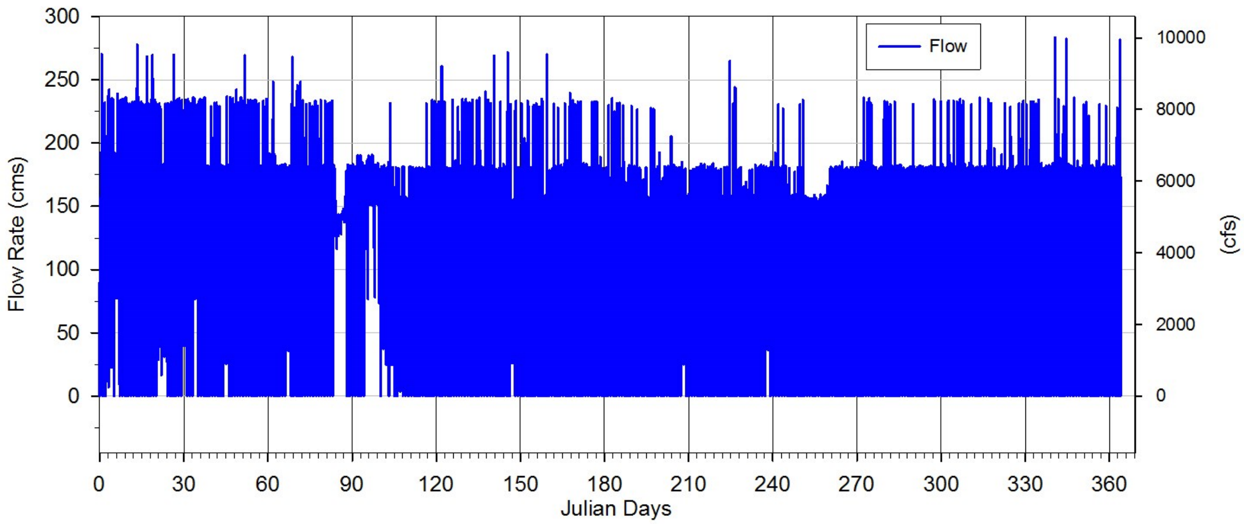


Figure 5.3. Inflow to Reregulation Reservoir (same as Pelton Dam discharge).

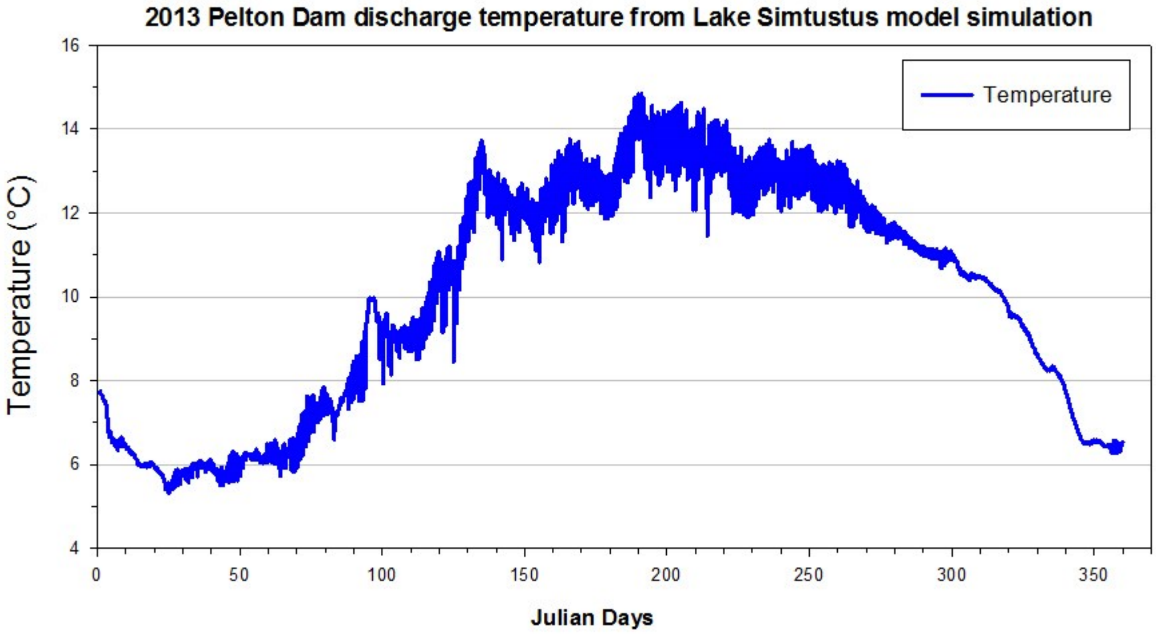


Figure 5.4. Temperature of inflow to Reregulation Reservoir (same as Pelton Dam outflow temperatures).

5.2 Model Calibration

5.2.1 Hydrodynamic Calibration / Flow Balance

As in the LBC and Lake Simtustus models, the hydrodynamic calibration was limited to a flow balance calculation of ungauged flow needed to simulate observed water-surface level variations. A time series of ungauged flow to Reregulation Reservoir was estimated by iteratively running the flow balance tool for CE-QUAL-W2. This ungauged flow time series was averaged over 24 hr intervals to smooth out large fluctuations. The resulting daily averaged ungauged flow is plotted in Figure 5.5; it had a mean value of 6.86 m^3/s (242 cfs) in 2013. This daily-ungauged balance flow was added to the Pelton Dam release. The final flow calibration results are shown in Figure 5.6 with a comparison of simulated and observed water-surface elevations. The simulated water-surface elevations were within 0.34 m (1.1 ft) of RMSE relative to observed data.

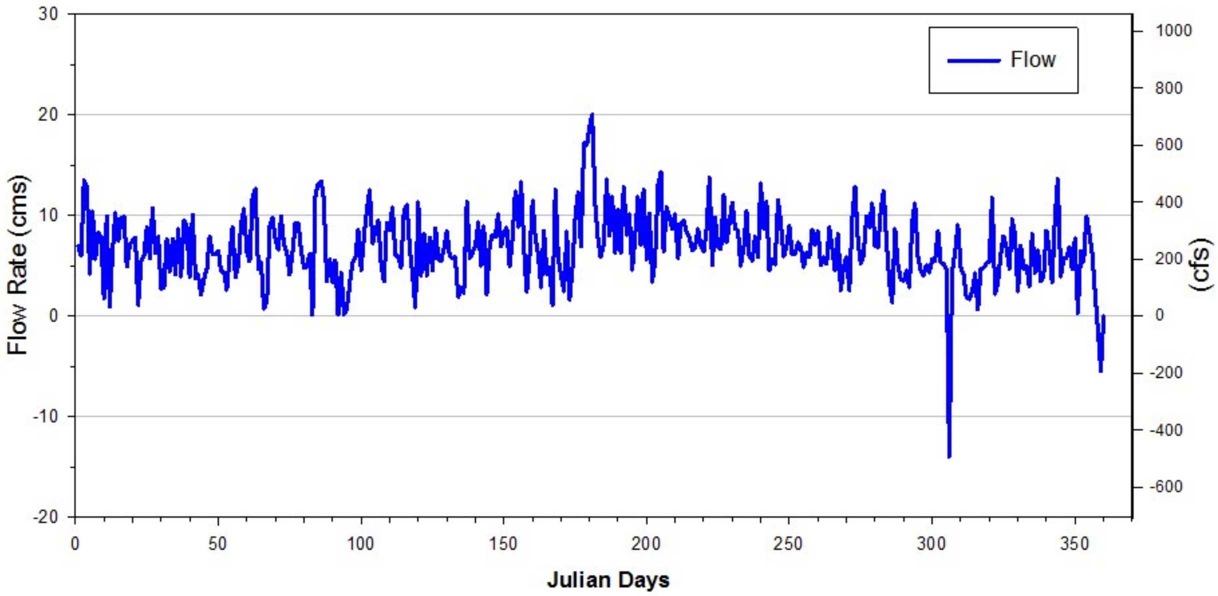


Figure 5.5. Estimated ungauged flow into Reregulating Reservoir in 2013. The plot shows daily averaged flows.

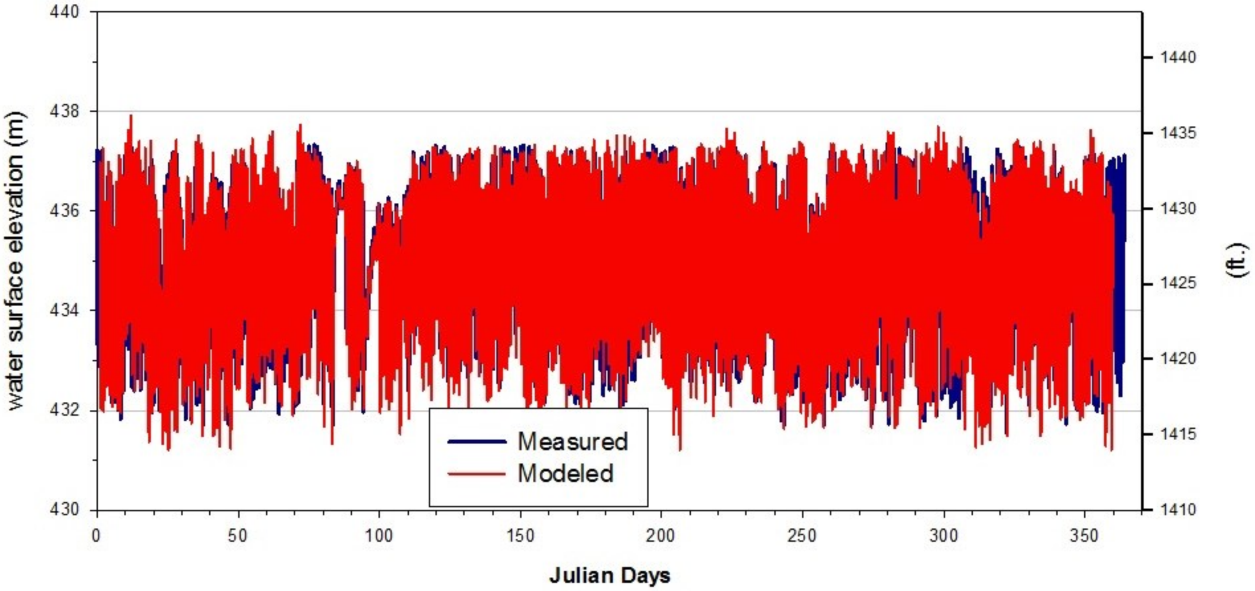


Figure 5.6. Comparisons of predicted and observed water-surface elevations in Reregulating Dam forebay in 2013.

5.2.2 Temperature Calibration

In the absence of temperature profile measurements in the Reregulating forebay, the temperature calibration for the Reregulating Reservoir focused on matching the Reregulation Reservoir discharge temperatures to those observed at Madras Station, which is 182.9 m (600 ft) downstream of the dam. The major model coefficients that were adjusted as part of the calibration for the Reregulating Reservoir are listed in Table 5.1.

Table 5.1. Major calibration coefficients for the Reregulating Reservoir model.

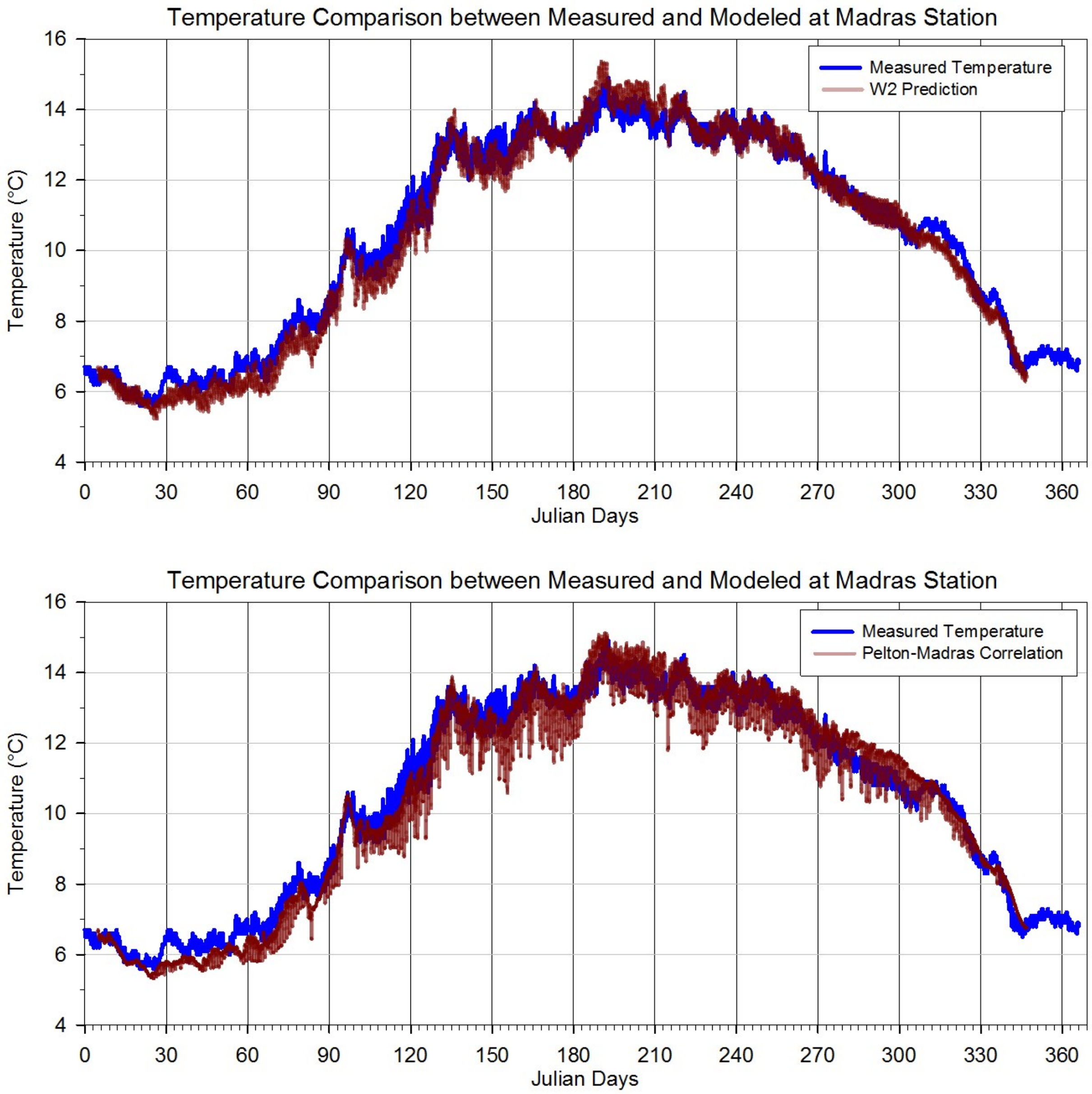
Model Parameter	Calibrated Value	Typical Value
Wind Sheltering Coefficient (WSC)	1	0-1
Heat Exchange Scheme (SLHTC)	TERM	TERM or ET
Shading	1	0-1 or dynamic
The Light Extinction Coefficient (EXH2O)	0.3	0.45
Horizontal Eddy Viscosity (AX, m^2/s)	1	1
Horizontal Eddy Diffusivity (DX, m^2/s)	1	1
Transport Scheme (SLTRC)	Ultimate	Quickest or Ultimate
Time Weighting for Advection (THETA)	0.55	0.55

Figure 5.7 (at the end of this section) shows the observed Madras Station temperatures compared with the Reregulating Reservoir model prediction (top panel). Also plotted in Figure 5.7 (bottom panel) are predicted temperatures using the Foster Wheeler (2000) correlation between Pelton Dam and Madras Station. The Reregulating Reservoir model simulation match to the observed data is an improvement over the Pelton-Madras correlation throughout the year, reducing the RMSE from 0.49°C to 0.39°C. Table 5.2 shows a summary of the model versus data error statistics.

Table 5.2. Reregulating Reservoir Model error statistics for 2013.

Station	ME(˚C)	AME(˚C)	RMSE(˚C)	Number of Comparisons
Madras Station	-0.13	0.39	0.49	23013

ME = mean error
AME = absolute mean error
RMSE = root mean square error


Temperature Comparison between Measured and Modeled at Madras Station

Temperature Comparison between Measured and Modeled at Madras Station

Figure 5.7. Comparison of model results and observed temperatures at Madras Station. The top panel results are from the CE-QUAL-W2 model and the lower panel results are based on the Pelton-Madras correlation.

6.0 Pre-Project Conditions River Temperature Model

The impetus for computing pre-project condition temperatures is the temperature compliance criteria for PGE, as established in PGE's Temperature Management Plan, that are associated with the CWA Section 401 water quality certificate. PGE is required to demonstrate that the 7-day average of the daily maximum temperature (7DADM) of the discharge from Reregulating Dam at Madras Station is below the applicable spawning criterion of 13°C or below "pre-project" condition temperatures.[1] Pre-project condition temperatures are defined as temperatures for existing hydrological and meteorological conditions without the presence of project dams. PGE has relied on computation of pre-project conditions temperature using a regression equation that was based on historical data collected prior to the construction of the Pelton Round Butte Hydroelectric Project (Huntington et al. 1999). However, there was concern that the regression approach was inadequate in representing the river temperature response to rapid changes in meteorological conditions, phase effects associated with mixing of incoming streams, and the travel time between LBC and Madras Station below Reregulating Dam. The availability of a computational model of the entire system allows explicit calculation of hourly pre-project conditions as opposed to simplification using the regression approach. The effort involves re-running the models using 2013 inputs, but without the dams and with one continuous river section from LBC inflows to the Madras station

6.1 Review of Historical (Pre-Project) Data

Historical data were acquired for use in developing the computational model of the pre-project riverine system. These data include available river shoreline, historical river temperature data, and flow data.

The historical river outline, as shown in Figure 6.1, was available for the entire study area except the Crooked River Branch. This river outline was digitized from a historical map (scale 1:24,000) obtained from the Oregon Water Resources Department. The data show that the river width ranges from 10 m (32.8 ft) to 100 m (328 ft). The historical river outline was used as a reference in the development of riverine model grid.

Weekly averaged river temperature data 1954−1956 were provided by PGE based on Huntington et al. (1999) and are shown in Figure 6.2. The figure shows that there was an average increase in temperature of 1.4°C from the confluence of the Deschutes, Crooked, and Metolius Rivers (flow-weighted temperature) to the temperatures at the Madras Station. This phenomenon is observed consistently over the 2-year period of data collection from 1954 through 1956. The increase in temperatures is observed in the winter as well as in summer months.

The fact that this increase in temperature was observed in winter points to a strong possibility that this reach received groundwater inflow at temperatures significantly warmer than typical winter stream temperatures. The flow balance analysis of 2013 data also showed a significant volume of ungauged flow entering the system. However, such a flow balance could not be conducted for the 1954−1956 data as part of this study. To ascertain the presence of ungauged flow (or groundwater flows), a 10-year record of inflow and outflow from the Pelton Round Butte Hydroelectric Project gauges was analyzed. The 10-year flow balance analysis also helped eliminate the possibility that the ungauged flow estimate from 2013 is not due to dam operation's effect on river flow. The 10-year period from 2005 through 2014 was selected for the analysis. The annual average of the combined flow from the three river inflows (Deschutes River,

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[1] The original language was written using the terminology "NTP" which stands for Natural Thermal Potential. NTP for PGE's Temperature Management Plan was defined as temperatures for existing hydrological and meteorological conditions without the presence of project dams.

Crooked River, and Metolius River) and the outflow of the Pelton Round Butte Hydroelectric Project system during the 10 years are plotted in Figure 6.3. The results show that outflow at Madras just below Reregulating Dam always exceeds inflows to LBC each year. The 10-year average of this ungauged inflow is 19.23 m^3/s (679 cfs). The figure shows that although there are interannual variations, the balance flow magnitude of ≈ 680 cfs remains relatively unchanged. This indicates that there are other sources of water entering the system—perhaps seepage flow, ungauged streams, or groundwater.

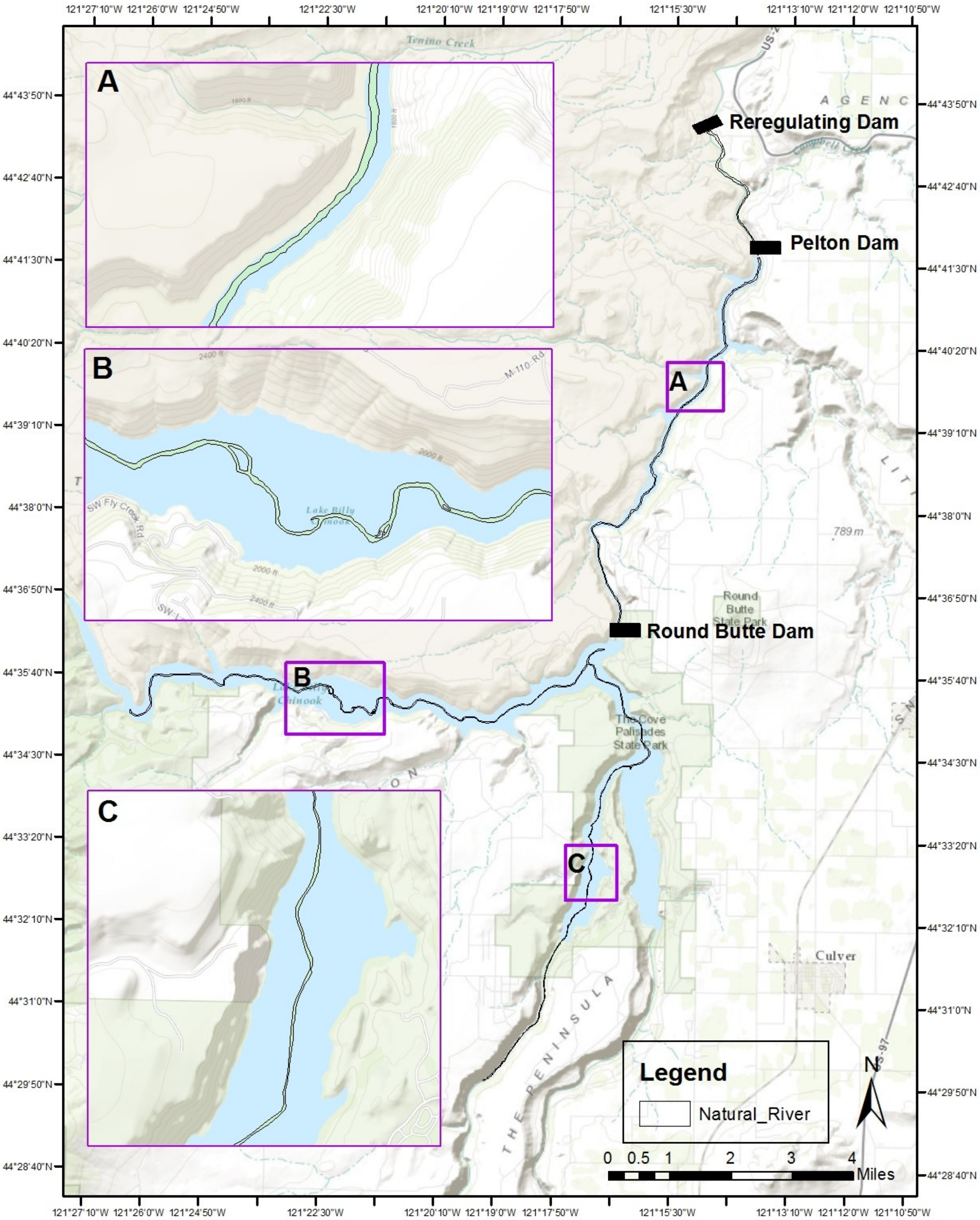

Figure 6.1. Historical river shoreline (source: Oregon Water Resources Department).

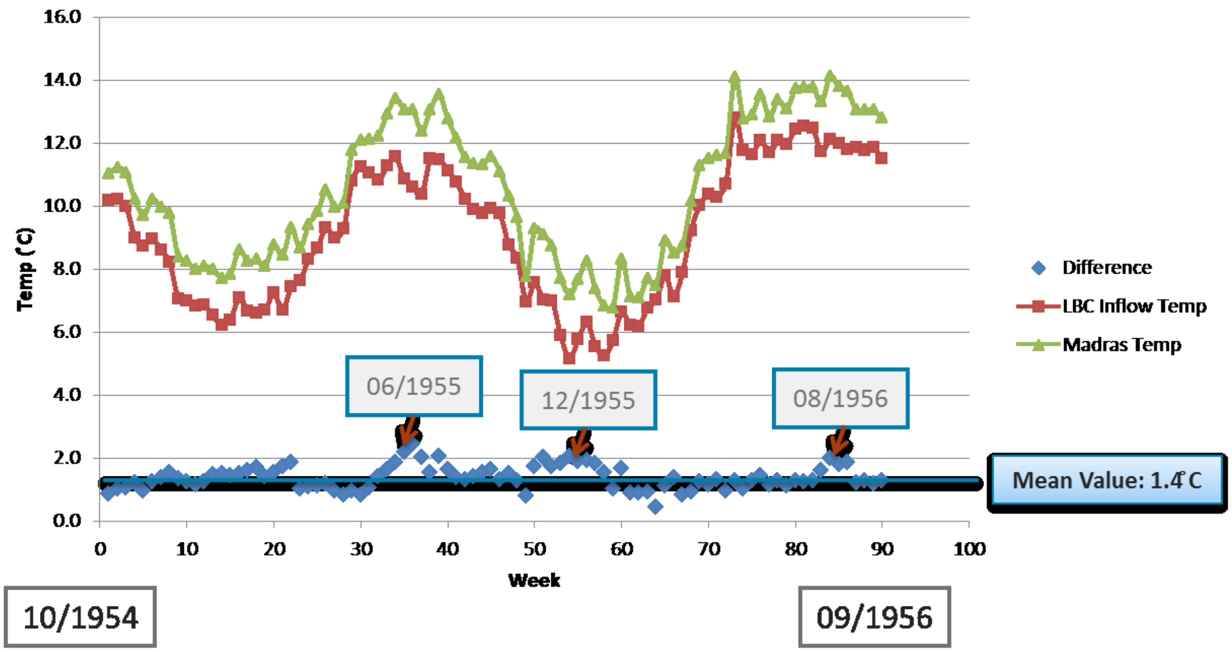

Figure 6.2. Weekly averaged 1954−1956 temperature data of flow-weighted upstream inflow and Madras Station.

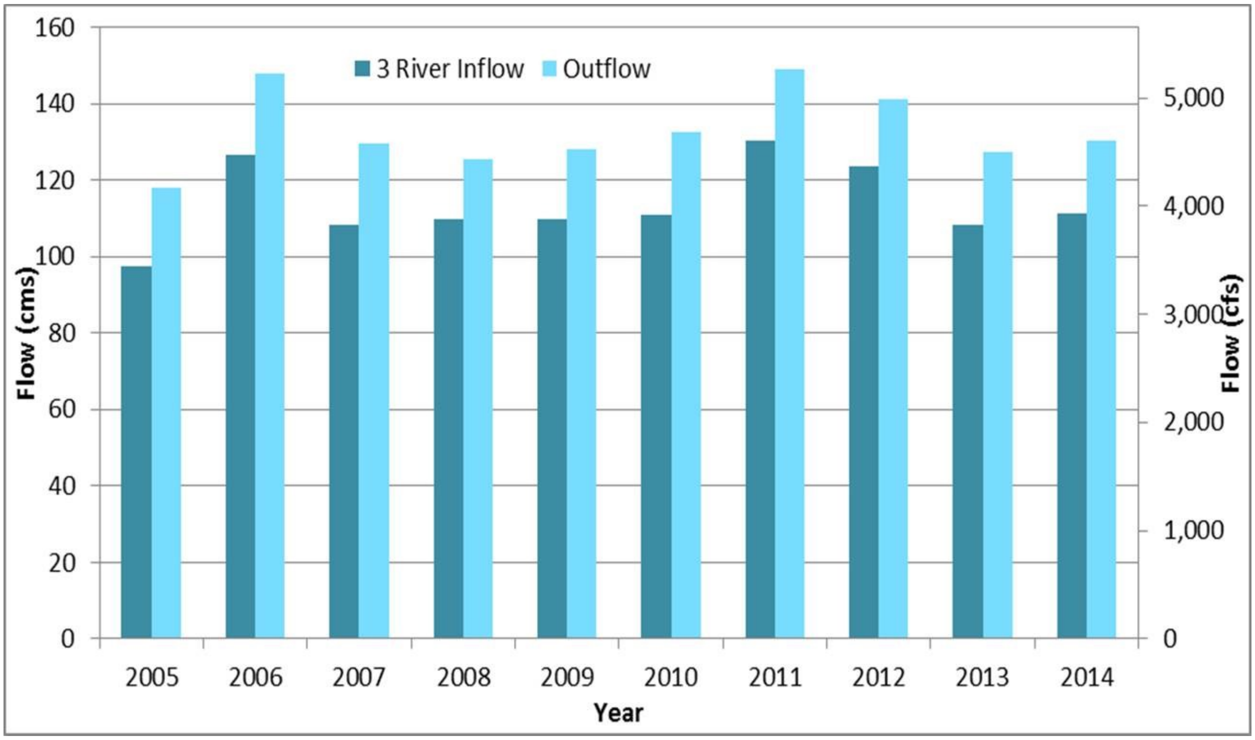

Figure 6.3. 2005−2014 annual average combined three river inflows (Deschutes River, Crooked River, and Metolius River) and outflow of the Pelton Round Butte Hydroelectric Project.

6.2 Model Setup – Pre-Project Conditions

The CE-QUAL-W2 Stream Model (Xu et al. 2014) was selected for the riverine modeling effort. The CE-QUAL-W2 Stream Model is a version of CE-QUAL-W2, which simplifies the computation of hydrodynamics for riverine applications. It uses Manning's equation to calculate water-surface elevation and longitudinal velocity resulting in stable and faster simulations.

6.2.1 Model Grid

The model grid for pre-project conditions was developed using the previously developed grids of the three reservoir models. The difference between river models and reservoir models is that river models use grid slope in the computation to control the vertical fluid acceleration. The grid slope is generally applied to a collection of river segments that have a similar hydraulic gradient. Because water-surface data are not available for pre-project conditions, the bottom of the reservoir model grid was used to specify grid slope. The riverine model was divided into 24 branches and 236 segments, as described in Table 6.1 below. The model grid plan view is shown in Figure 6.4. Each branch has one leading segment and one trailing segment in model configuration used for incorporating upstream and downstream conditions in the computational scheme, e.g. Branch 1 has segment 1 and 8 for boundary conditions and they are not listed in Table 6.1

Table 6.1. Riverine model grid.

BRANCH	Upstream Segment	Downstream Segment	SLOPE	SLOPEC	Corresponding to reservoir models
BR 1	2	7	0.008	0.008	LBC Deschutes Branch
BR 2	10	15	0.016	0.016	LBC Deschutes Branch
BR 3	18	24	0.008	0.008	LBC Deschutes Branch
BR 4	27	31	0.01466	0.01466	LBC Deschutes Branch
BR 5	34	39	0.0072	0.0072	LBC Deschutes Branch
BR 6	42	62	0.015	0.015	LBC Metolius Branch
BR 7	65	83	0.0032	0.0032	LBC Metolius Branch
BR 8	86	88	0.0136	0.0136	LBC Metolius Branch
BR 9	91	111	0.00333	0.00333	LBC Metolius Branch
BR 10	114	116	0.018	0.018	LBC Metolius Branch
BR 11	119	127	0.0112	0.0112	LBC Crooked Branch
BR 12	130	133	0.0076	0.0076	LBC Crooked Branch
BR 13	136	138	0.00622	0.00622	LBC Crooked Branch
BR 14	141	144	0.012	0.012	LBC Crooked Branch
BR 15	147	152	0.0052	0.0052	LBC Crooked Branch
BR 16	155	159	0.012	0.012	LBC Crooked Branch
BR 17	162	179	0.00554	0.00554	LBC Crooked Branch
BR 18	182	185	0.0025	0.0025	Lake Simtustus
BR 19	188	193	0.0056	0.0056	Lake Simtustus
BR 20	196	201	0.0014	0.0014	Lake Simtustus
BR 21	204	209	0.0031	0.0031	Lake Simtustus
BR 22	212	215	0.0009	0.0009	Lake Simtustus

BR	23	218	229	0.0029	0.0029	Reregulating Reservoir
BR	24	232	235	0.0053	0.0053	Reregulating Reservoir

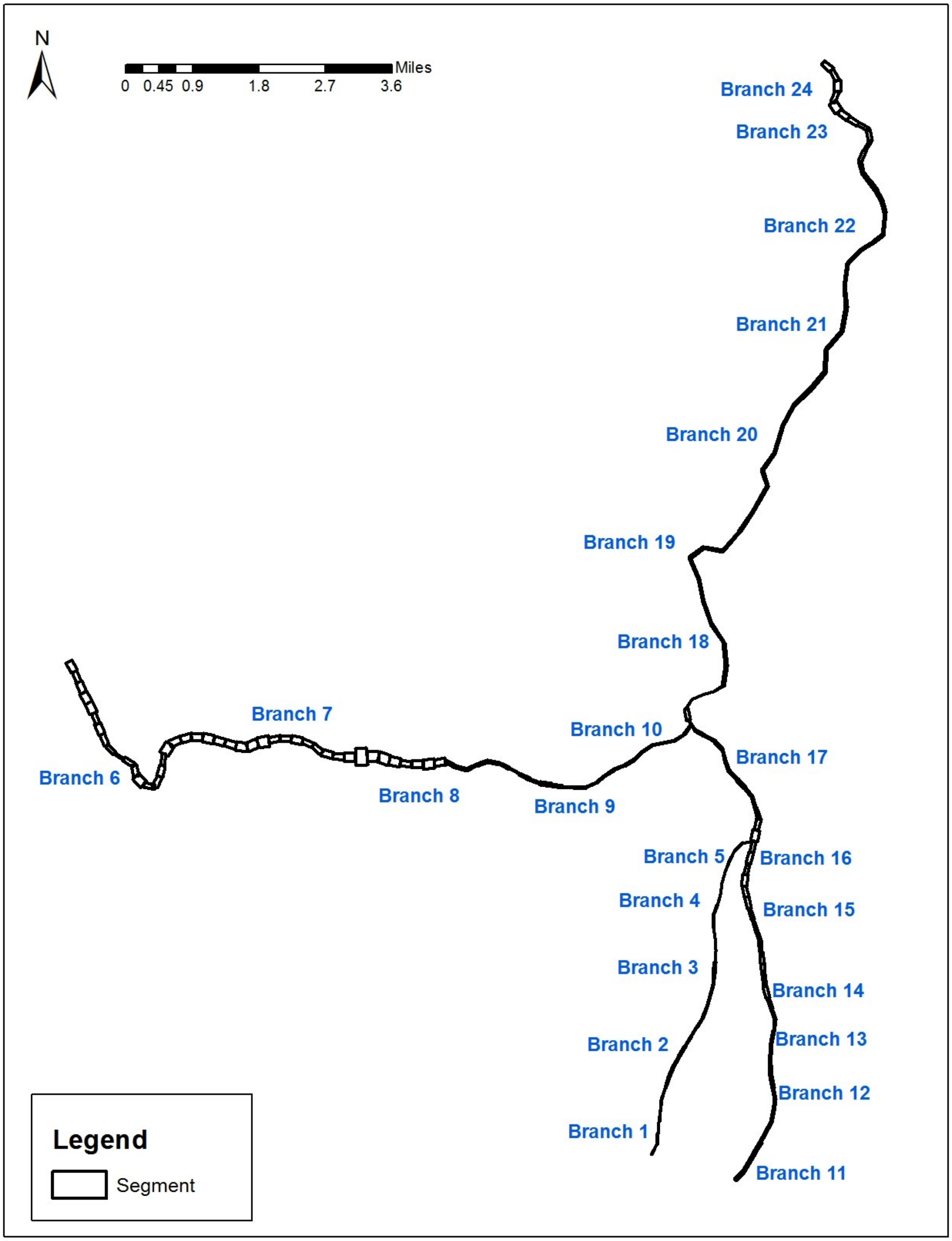

Figure 6.4. Pre-project conditions riverine model grid plan view.

6.2.2 Meteorological Inputs

In accordance with the definition of pre-project conditions, Year 2013 meteorological inputs used in the LBC, Lake Simtustus, and Reregulating Reservoir models were used in the river model.

6.2.3 Hydrological Inputs

Hydrological inputs to the model include inflow from Deschutes River, Crooked River, and Metolius River for Year 2013. Hourly inflows from the three rivers are the same as those discussed previously and are plotted in Figure 2.6.

6.2.4 Inflow Water Temperature Data

The hourly river inflow temperatures from Deschutes River, Crooked River, and Metolius River were the same as those used in the LBC model (see Figure 2.7).

6.3 Model Calibration

Available pre-project condition temperature data for model calibration are from the period 1954 to 1956. Ideally, the calibration would be conducted with the model set up to simulate that historical period during which data were collected. However, that effort is beyond the scope of this study. Instead, the regression equation developed by Huntington et al. (1999) was used to synthesize pre-project condition equivalent temperature data corresponding to Year 2013.

According to Huntington et al. (1999), pre-project conditions water temperature at the Madras Station is computed as a function of flow-weighted inflow to LBC and air temperature from the Redmond Airport.

$$\begin{aligned}\text{Water Temperature}_{Madras\ Station} &= 2.8 + (0.79)(Water\ Temperature_{into\ LBC}) \\ &+ (0.071)(Air\ Temperature_{Redmond})\end{aligned}$$

The water temperature, streamflow, and air temperature parameters in the above equation represent weekly average values. The regression was applied using Year 2013 inputs to generate equivalent pre-project temperature target temperatures for model calibration.

6.3.1 Baseline Model Iteration

In the baseline model iteration, most of the parameters previously developed during reservoir model calibration were retained with the exception of selected parameters. Major parameters used for the river model are listed in Table 6.2. A static shading value of 0.9 is used in the river model compared to 1 used in the reservoir models. This adjustment was based on the assumption that during the pre-project conditions, it is likely that the riverine reaches were affected by topographical and vegetative shading in a manner similar to that in the Lower Deschutes River.

Table 6.2. Major pre-dam river model coefficients.

Model Parameter	Calibrated Value	Typical Value
Wind Sheltering Coefficient (WSC)	1	0-1
Heat Exchange Scheme (SLHTC)	TERM	TERM or ET
Shading	0.9	0-1 or dynamic
The Light Extinction Coefficient (EXH2O)	0.45	0.45
Horizontal Eddy Viscosity (AX)	1	1
Horizontal Eddy Diffusivity (DX)	1	1
Transport Scheme (SLTRC)	Ultimate	Quickest or Ultimate
Time Weighting for Advection (THETA)	0.55	0.55

First, the weekly average of inflow temperatures was computed for 2013 and is plotted as green line in Figure 6.5. The weekly averaged inflow temperature was then transformed using the Huntington et al. (1999) equation to generate the 7-day average of the daily average temperature (7DADA) at the Madras Station temperature; it was plotted as the dark blue line and represents the target for river model calibration. The river model was then applied to simulate temperatures in the system. The results in the form of 7DADA temperatures at the Madras Station are plotted as the brown line.

The results show that the Madras Station temperatures predicted using the river model are close to the LBC location inflow temperature in the winter months, while in summer months predicted temperatures at the Madras Station are ≈ 1.5°C higher than the inflows. This indicates that, according to the river model setup, there is practically no heat gain between inflow to LBC and the Madras Station during the winter. The river gains heat during the summer resulting in a temperature gain of about 1.5°C. However, even during summer months, the predicted temperatures were ≈ 0.5°C lower than the regression-based pre-project data.

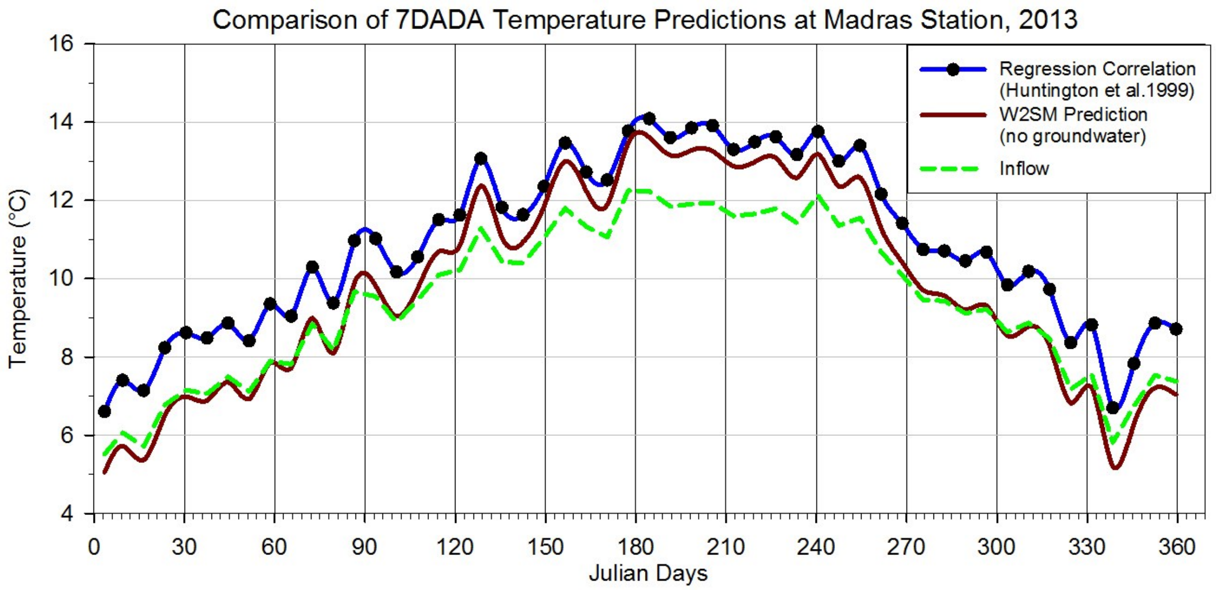

Figure 6.5. Comparison of 7DADA temperature at the Madras Station between regression-based synthesized pre-project data and baseline river model prediction.

6.3.2 Model Sensitivity Tests and Discussion

The fact that pre-project regression-based data indicated an increase in temperature between LBC and the Madras Station during winter indicates a strong external heat source such as groundwater. The baseline model run did not consider groundwater. As discussed in Section 6.1, the 10-year flow balance analysis indicates that the groundwater flow into the system is as high as 19.23 m^3/s (679 cfs). This represents a flow that is nearly 14% of the average Deschutes River flow at Madras Station and could have a significant influence on water temperature. Gannett et al. (2001) conducted a groundwater hydrology study in the upper Deschutes Basin, and estimated that 21.3 m^3/s (750 cfs) of groundwater enters the Deschutes River in the study area. This estimate of groundwater value is comparable to the magnitude of ungauged flow derived from 10-year flow balance calculations. We therefore conclude that flow imbalance may be attributed to groundwater. A preliminary review of the literature on the groundwater temperature revealed that springs at different locations in the system have different temperatures; measured values range from 12°C to 21°C (Ashwell 1982; Watershed Sciences 2002, 2006).

To evaluate the influence of this inflow on river temperatures we also require associated temperatures. In the absence of data on the temperature of the groundwater entering the system, this analysis was conducted in the form of sensitivity tests. First, a constant flow rate of 19.23 m^3/s (679 cfs) was added as groundwater discharge in the river model. This flow was divided into the 24 branches in proportion to branch lengths. Sensitivity tests were then conducted with the river model using various static values of groundwater temperatures, ranging from 10°C to 21°C. With the groundwater temperature at 17°C, the river model results at the Madras Station match the synthesized pre-project temperatures for 2013 (see Figure 6.6).

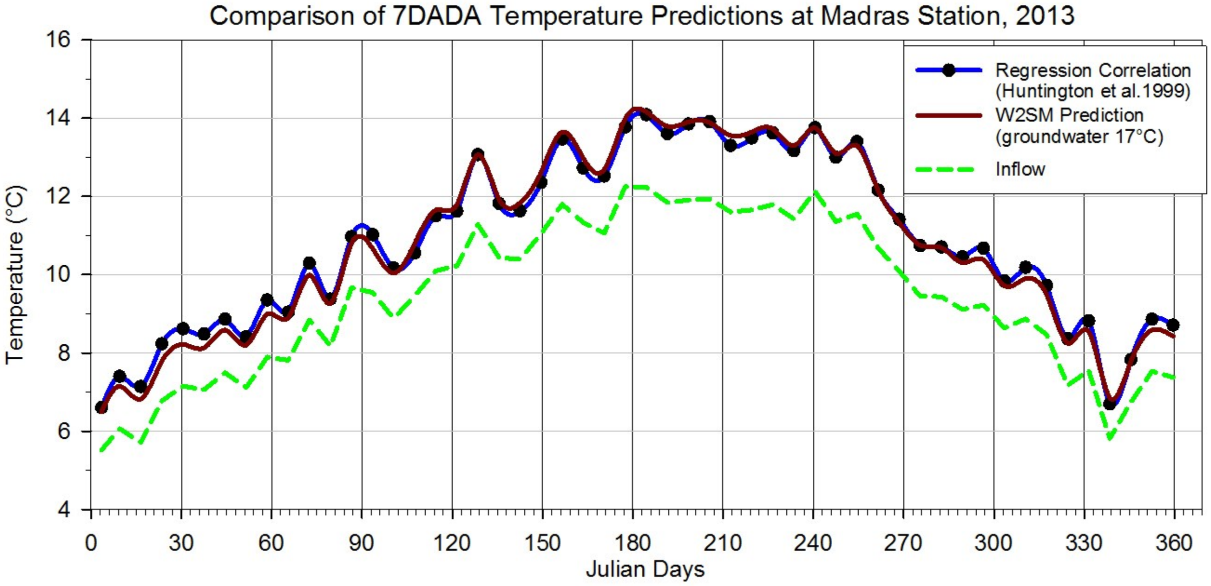

Figure 6.6. Comparison of pre-project 7DADA temperature at the Madras Station using the river model prediction and synthesized data using pre-project data regression.

Note that in addition to groundwater, the riverine model is also sensitive to wind shelter coefficient and shading. However, the influence of these parameters during the winter months is minimal. A more thorough literature review of groundwater temperature in the study area is recommended.

7.0 Conclusions and Recommendations

Predictive models capable of simulating temperature response in the Pelton Round Butte Hydroelectric Project reservoirs to hourly variations in power generation flows and daily and seasonal variations in meteorological conditions were developed during this study. The models use the CE-QUAL-W2 software in a laterally averaged vertical 2D plane and are set up sequentially from the LBC Reservoir at the upstream end, through Lake Simtustus, and to the Reregulating Reservoir at the downstream end of the Pelton Round Butte Hydroelectric Project. The discharge from the Reregulating Reservoir at Madras Station serves as the inflow to the Lower Deschutes River. The models represent current conditions in the reservoirs and include the recent modification with the SWW structure in operation. This effort was initiated by PGE to implement a set of compatible and state-of-the-art set of tools capable of simulating temperature, hydrodynamics, and water quality response in the system to rapid variations in power generation flow load, and meteorological conditions. Also completed during this study was the development of a river model that is representative of conditions prior to the construction of Pelton Round Butte Hydroelectric Project and its application in the form of sensitivity tests to assess temperatures under pre-project conditions.

Specifically the following models were developed,

- The *LBC Temperature Model* developed using CE-QUAL-W2 was calibrated for 2013 conditions reflecting as-built SWW structure operations at Round Butte Dam. The model uses inflows from the Deschutes, Crooked, and Metolius Rivers to simulate hydrodynamics and temperatures in LBC in response to hourly variations of power generation flows and meteorological conditions.
- The *Lake Simtustus Model* previously developed using CE-QUAL-W2 was validated during this study for 2013 conditions. This model is operated using inflows from LBC and power generation flows from Pelton Dam. Temperature and hydrodynamic response in this model is computed using the same meteorological conditions as those used in the LBC model.
- The *Reregulating Reservoir Model* developed using CE-QUAL-W2 model was calibrated for 2013 conditions. This model is operated using inflows from Lake Simtustus and power generation/reregulation flows from Reregulating Dam. Temperature and hydrodynamic response is computed using the same meteorological conditions as those used in the LBC and Lake Simtustus models.
- The *Pelton Round Butte Reach River Model* was developed to represent river conditions prior to the construction of Pelton Round Butte Hydroelectric Project dams using the CE-QUAL-W2 Stream Temperature Model. The model domain includes the entire Pelton Round Butte Hydroelectric Project reaches including the upstream Deschutes, Metolius, and Crooked arms prior to confluence at the Round Butte Dam forebay location, through Deschutes River to the Madras Station, just downstream of Reregulating Dam. The model simulates temperatures in the free-flowing stream using inflows and the same meteorological conditions as those used in reservoir models.

The performance skill of the models was verified through comparison with temperature monitoring data. In general, the simulated results showed good agreement with the observed data. The simulated vertical temperature profiles at the Round Butte forebay were shown to have an RMSE less than 0.95°C when compared to observed values. The simulated vertical profiles at the Pelton forebay have an RMSE less than 0.90°C. In the absence of measurement sites inside Reregulating Reservoir, the Reregulating Reservoir model release was compared with a Madras Station temperature time series where an RMSE of 0.39°C was achieved.

An added outcome of this study was the confirmation that the SWW structure was highly effective in modifying the temperature regime of the Pelton Round Butte Hydroelectric Project's system of reservoirs. Prior to the construction of the SWW structure, data analysis and modeling results from 1995 showed that the peak temperatures in surface waters of reservoirs and the water discharged from Reregulating Dam occurred in September (Khangaonkar 2005; Foster Wheeler 2000; and ENSR 1999). Data and model results presented in this study from 2013 representing present conditions with full use of the SWW structure show clearly that peak temperatures now occur in July; this matches the shape and behavior of temperatures in equivalent streams without dams. This temperature regime modification to one that mimics the natural annual variation peaking in July as opposed to September was one of the original design objectives of SWW structure.

Another notable finding of this study was that the project reservoirs were gaining a significant volume of water through ungauged flow. Ungauged flows typically represent a combination overland nonpoint source runoff and flows from streams that are not routinely monitored. However, only a few streams in the project reaches carry flowing water throughout the year with low flows (≈ 1 m^3/s) and the overland runoff is expected to be relatively small as well. The results of sensitivity tests presented in this study strongly point to the possibility that this ungauged flow is likely groundwater flow and it is as high as 19.23 m^3/s (679 cfs) representing nearly 14% of the average Deschutes River flow. The results also indicate that groundwater could be a previously uncharacterized heat source to the system. These results are based on a combination of pre-project monitoring data and model sensitivity tests, which showed an increase in temperatures of as nearly 1.5°C from the point of tributary confluence above Round Butte Dam to the Madras Station, even during the cold winter months.

Although model performance and calibration results were acceptable, there is opportunity to further improve model accuracy. A review of literature on the groundwater hydrology of the system is therefore recommended. Model calibration and accuracy may also be further improved by incorporating groundwater influence in the model. Additional improvement of the models can be accomplished by 1) refining the model grid with accurate bathymetry of the Reregulating Reservoir and definition of the river channel for the pre-project conditions; 2) incorporating dynamic topographical shading to reflect the canyon shading pattern; and 3) using onsite meteorological measurements (wind and air temperatures).

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