Technical Memorandum

Water Temperature Modeling Platform: Model Development, Calibration, Validation, and Sensitivity Analysis (INTERIM DRAFT)

Central Valley Project Water Temperature Modeling Platform

California-Great Basin Region

U.S. Department of the Interior **June 2022**

Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated Island Communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Water Temperature Modeling Platform: Model Development, Calibration, Validation, and Sensitivity Analysis (INTERIM DRAFT)

Central Valley Project Water Temperature Modeling Platform

California-Great Basin Region

prepared by

United States Department of the Interior, Bureau of Reclamation

California-Great Basin Region

With Technical Support by:

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Resource Management Associates

Cover Photo: Keswick Dam on the Sacramento River by John Hannon

Contents

Figures

Tables

Contents

Abbreviations and Acronyms

API	Application Programming Interface
CVP	Central Valley Project
GUI	Graphical User Interface
I/O	Input/Output
IT	Information Technology
QA	Quality Assurance
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
TCD	Temperature Control Device
TMDL	Total Maximum Daily Load
TMP	Temperature Management Plan
WTMP	Water Temperature Modeling Platform

Chapter 1 Introduction

Flow and water temperature simulation models are useful and necessary tools to support resource managers in their understanding of the temperature dynamics in U.S. Bureau of Reclamation (Reclamation) Central Valley Project (CVP) reservoirs and downstream river reaches. Such tools support evaluation of how operational decisions and various influencing factors can affect water temperature in reservoirs and rivers, as well as the resulting potential impacts to fishery species sensitive to water temperature. The improvement of models, modeling approach, and associated tools to support operational decision making is considered a necessary adaptation strategy that takes advantage of ongoing technological advancement, additional information, and data. Reclamation's objective for the development of the Water Temperature Modeling Platform (WTMP) is the effective and efficient management of resources for downstream regulatory and environmental requirements within the context of an uncertain environment. A primary development goal of the WTMP is to provide realistic predictions of downstream water temperatures with sufficient confidence to carry out the necessary planning for seasonal, real-time, and long-term study applications while also describing situational risk and uncertainty.

Models of large complex reservoir-river systems have been developed for a wide range of applications (DeGeorge et al. 2018, USACE 2016, Goode at al. 2010, Modini 2010). Reservoir and river reaches can be modeled as discrete components, with individual models for each reservoir or river reach, or with a modeling system as an interconnected network of rivers and reservoirs. A modeling system is a single software package (e.g., HEC5Q (HEC 1999, HEC 2000) or HEC ResSim (HEC 2021)) that incorporates all system components (e.g., discrete reservoirs and river reaches) and their inter-connections. However, a single model may not represent all potential characterizations desired by resource managers (Buahin and Horsburgh 2018). For the CVP, there is a need for both high resolution, discrete reservoir and/or river element models that can represent more detailed representations, as well as a modeling system that can accommodate system wide operations in a computationally efficient manner.

The WTMP model selection process is described in *Technical Memorandum: Model Selection (DRAFT)* (Reclamation 2021b). CE-QUAL-W2 was selected to model CVP reservoirs as discrete components. U.S. Army Corp of Engineers Hydrologic Engineering Center Reservoir System Simulation (ResSim) is a system model that was selected to model CVP reservoirs as well as river reaches. Implementation of ResSim models is presented herein as a system model but the discrete components can be run individually or as part of the modeling framework (Reclamation 2021a) with discrete CE-QUAL-W2 reservoir models. As noted in the model selection memorandum, the ResSim model was selected for use in the WTMP to provide the ability to make long-term simulations and/or many short-term simulations relatively quickly. These simulations could support planning analyses or annual temperature management planning. For the latter case, ResSim would be used to assess a range of options as a screening tool. Subsequently, CE-QUAL-W2 (with notably longer simulation times) could then be used for selected simulations where more detail may be desired.

Model implementation is the process of developing the necessary geometric system representations, model boundary conditions, default model parameters and coefficients, and producing a functioning, but uncalibrated model. Model calibration is the process of adjusting selected model parameters and minimizing the difference between simulated results and field observations over the model period. Once calibrated, a model is validated by assessing model performance for a separate period not included in the original calibration. Ultimately, the entire available time series may be used in final model calibration. The calibrate model can then undergo sensitivity testing boundary conditions, individual model parameters, specific operations, or other model assumptions. Data development is described in *Technical Memorandum: Data Development (DRAFT)* (Reclamation 2022a).

The WTMP project includes CVP facilities in the Shasta and Trinity, American, and Stanislaus systems (Figure 1-1). Model development of these individual systems is being completed in stages with the Shasta-Trinity system first, then the American, and finally the Stanislaus. This technical memorandum focuses on the WTMP model development for Shasta Lake, Keswick Reservoir, and the Sacramento River from Keswick Dam to Red Bluff to illustrate the approach to be implemented throughout the remainder of the Sacramento-Trinity, American, and Stanislaus basins.

Figure 1-1. CVP facilities included in the WTMP: (a) Shasta-Trinity, (b) American, (c) Stanislaus systems.

Specifically, this report describes model development, calibration, validation, and sensitivity analysis for CEQUAL-W2 and ResSim models for the upper Sacramento River system. The WTMP for the Shasta-Trinity system will ultimately incorporate Whiskeytown Lake and Clear Creek, as well as Trinity Reservoir, Lewiston Lake, the Trinity River (downstream to the North Fork Trinity River) and tunnel conveyances. Included herein is a background to the upper Sacramento River system and associated models and water temperature management approaches; CE-QUAL-W2 and ResSim model development; model calibration, validation, and sensitivity analysis; and a summary and references. Appendices include model calibration and validation results.

This is a draft calibration report and represents a work in progress. Nonetheless, the report provides a clear example of the model development, model performance metrics, and preliminary calibration/validation results.

Chapter 2 Background

The upper Sacramento River system model domain, models are part of a larger modeling effort that includes portions of the upper Trinity River system. The following sections provide an overview of the upper Sacramento River system, model domain, water temperature management considerations, and a description of the Shasta Lake temperature control device (TCD).

Upper Sacramento River System Overview

The Sacramento River is the largest river in California, with headwaters in northern California. Shasta Lake receives most of its inflow from the Sacramento, McCloud, and Pit Rivers. Shasta Lake experiences seasonal stratification from April through November or December. Isothermal conditions typically occur in January or February, but the lake does not always achieve isothermal conditions in every winter. Annual temperature management strategies are developed each year during the March through May period to assess total storage, cold water pool volume, system demands, and identify strategies to most efficiently utilize stored winter water to meet downstream environmental objectives (e.g., fishery life stage needs) from late spring into fall (Reclamation 2013).

Releases from Shasta Dam (River mile (RM) 312) are typically made through the Shasta Dam Temperature Control Device (TCD). The TCD allows waters to be selectively withdrawn from Shasta Lake at different elevations, and thus different temperatures, through the spring, summer and fall period. The TCD provides important flexibility to manage the cold water pool in Shasta Lake, and dam release temperatures to meet desired downstream water temperatures objectives. Specific details of the TCD and model representations are discussed in Chapter 3.

Keswick Reservoir is located immediately downstream of Shasta Dam and regulates releases from Shasta Dam and Spring Creek Powerhouse diversions from the Trinity Basin prior to releasing waters from Keswick Dam (Rm 302) to the Sacramento River. The reservoir is approximately 10 miles long (16.1 km) and 0.1 miles (0.16 km) wide. Releases and spill from Shasta Dam and Spring Creek Powerhouse releases (from Whiskeytown Lake) provide the majority of inflow into Keswick Reservoir (Reclamation 2018). Despite differing flow, flow timing, and water temperatures, both Shasta Dam and Spring Creek Powerhouse contributions impact the water quality and temperature of Keswick Reservoir.

Spring Creek Powerhouse release temperatures reflect conditions in the Trinity-Lewiston-Whiskeytown system. Releases from Trinity Dam (RM 118.5) are conveyed through Lewiston Lake. Outflows form Lewiston Lake include releases to the Trinity River below Lewiston Dam (RM 111.5), as well as diversions to Whiskeytown Lake via the Clear Creek Tunnel. An important temperature consideration in the Trinity system is that to convey appropriate water temperature through Lewiston Lake to meet downstream water temperature objectives in the Trinity River (NCRWQCB 2018), flow must be sufficient to minimize heating through Lewiston Lake. Waters conveyed through the Clear Creek Tunnel are released to Whiskeytown Lake at the Judge Francis Carr Powerhouse. Whiskeytown Lake, located on Clear Creek, has two principal outflows: releases to Clear Creek at Whiskeytown Dam (RM 18.1), and diversions to Keswick Reservoir through the

Spring Creek Tunnel. Temperature control curtains in Whiskeytown Lake at Oak Bottom (upstream) and Spring Creek Tunnel (downstream) are intended to convey cold waters from the Trinity Basin through the deeper portions of the lake and convey them to the Spring Creek tunnel and ultimately to Keswick Reservoir at the Spring Creek Powerhouse. Flow and temperature from the Spring Creek Powerhouse generally has a modest impact on Keswick Reservoir temperatures; nonetheless, water temperature management decisions at Shasta Dam (e.g., selective withdrawal strategies) need to consider flow and temperature conditions of inputs at the Spring Creek Powerhouse (Reclamation 2015).

The Sacramento River below Keswick Dam is subject to Order 90-5 (SWRCB 1990), which establishes water right requirements on Reclamation operations related to temperature control in the Upper Sacramento River to protect fishery resources. This activity extends to Red Bluff (RM 243), but temperature control is generally limited to the upper reaches of the river (e.g., above Bend Bridge, RM 258). 90-5 requires monitoring and reporting to evaluate temperature management and compliance and simulation modeling has become an important tool to support these activities. Principal features of the study reach include the Anderson Cottonwood Irrigation District Diversion Dam, located in Redding, and the principal tributaries of Clear Creek, Cow Creek, Cottonwood Creek, and Battle Creek (entering the Sacramento River at RM 289.5, RM 280, RM 273.5, and RM 271.5, respectively). Other diversions and tributaries do not significantly impact the temperature regime of the river during the critical spring through summer temperature management period.

Model Domain

The Sacramento-Trinity model configuration will ultimately include five reservoirs, river reaches, and tunnels (Figure 2-1(a)); however, this technical memorandum addresses the upper Sacramento River system (Figure 2-1(b)). Discrete model components for the Sacramento models include Shasta Lake, Keswick Reservoir, and the Sacramento River from Keswick Dam to Red Bluff.

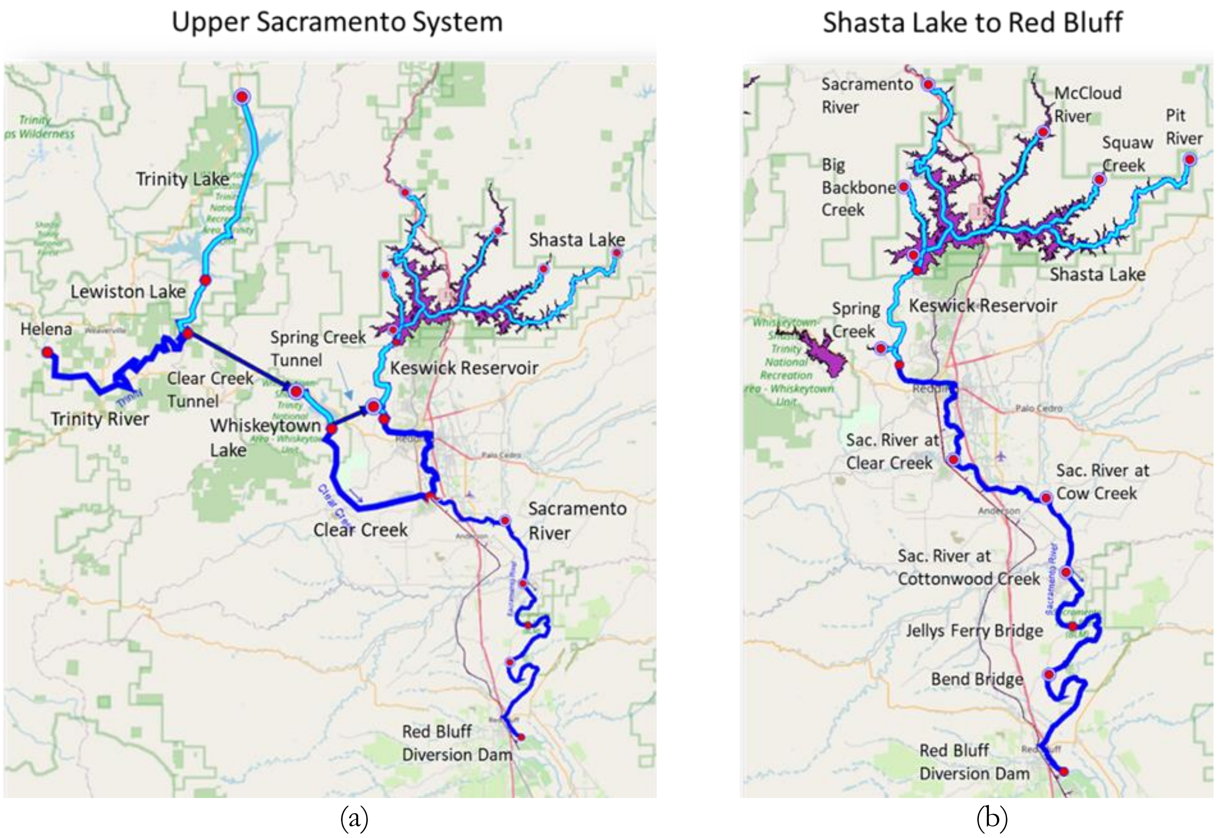


Figure 2-1. Model domains for the entire upper Sacramento River system, (a) including the upper Trinity River system and (b) for the Shasta Lake to Red Bluff model presented in this technical memorandum.

For the current model configuration, the flow and inflow temperatures from the Spring Creek Tunnel to Keswick Reservoir, and from Clear Creek to the Sacramento River, are represented by boundary conditions. In the complete Sacramento-Trinity River system model configuration, Spring Creek tunnel and Clear Creek from Whiskeytown Lake to Sacramento River are each modeled as part of the modeled system.

Water Temperature Management Considerations

Cold-water storage in Shasta Lake directly influences operations to manage downstream water temperature objectives throughout the water temperature management season (Reclamation 2015; Reclamation et al. 2015). Through selective withdrawal, resource managers can accomplish dual purposes of conservation and temperature management. Conservation occurs by using near surface waters earlier in the season (e.g., March through May) and conserving the deeper, colder water for later in the season (e.g., September through November). Temperature management occurs by selectively withdrawing and blending water from various elevations to meet downstream environmental objectives. Selective withdrawal allows resource managers to avoid engaging other, less effective means for temperature management purposes that may adversely affect other purposes and needs in the reservoir-river system. For given storage and flow conditions, different selective withdrawal strategies yield distinct outcomes for progressions of cold-water storage utilization, tailbay temperatures, and downstream river temperatures during the temperature management season (Rheinheimer et al. 2015; Thompson et al. 2012).

Facilities that enable selective withdrawal capabilities – blending water from different depths and temperatures to achieve targeted downstream temperatures – are requisite to manage water temperature in the Sacramento River system (Reclamation et al. 2015). The TCD is the vital infrastructure that supports selective withdrawal strategies at Shasta Dam, and the associated timing and progression of TCD gates and levels throughout the temperature management season are developed considering a range of factors. These factors include downstream environmental objectives, total reservoir storage, cold water storage, TCD performance (including leakage), tailbay water temperature management (immediately below Shasta Dam), meteorological conditions, tributary inflows, project water operations and downstream water demands, imported Trinity Basin water, Keswick Reservoir re-regulation, and downstream river heat gain relationships.

Developing models for Shasta Lake and Keswick Reservoir requires consideration of the overall temperature management activities in the Sacramento River. Not only does the model need to represent Shasta Lake hydrologic and thermal conditions, but the model also requires an appropriate representation of the TCD structure, constraints, and operations. Simulated releases (flow and temperature) from Shasta Dam form the input to the Keswick Reservoir model. Subsequently, the Keswick Reservoir model simulates fate and transport of heat energy from Shasta Dam to Keswick Dam, while accommodating heat exchange as waters are conveyed downstream and inputs from the Trinity Basin via Spring Creek Tunnel. Hydropower peaking at both Shasta Dam and Spring Creek Powerhouses creates complex conditions in Keswick Reservoir that the model must effectively represent on a sub-daily basis. Finally, simulated flow and temperature outputs are produced at an hourly (or similar) time step for use in downstream river models. River models represent fate and transport of heat energy, account for diversions, and accommodate tributary inflows and temperatures. All models require spatial and temporal resolution sufficient to capture critical system elements, operations, and provide biologically relevant information. For this project all models will operate at a sub-daily time step (e.g., hourly) and at a spatial resolution to effectively represent thermal profiles in the seasonally stratified reservoir (e.g., 1 meter), and longitudinal river temperature gradients (e.g., 1 km).

Shasta Dam Temperature Control Device

The TCD is located on the upstream face of Shasta Dam and extends from the water surface to well below the powerhouse intakes. While the spillway and river outlets are located in the central portion of the dam, approximately in line with the original river channel, the TCD is located on river right (looking downstream), covering the powerhouse intakes (Figure 2-2). The TCD is composed of three levels: upper, middle, and lower. Lower level gates are also referred to as pressure relief gates (PRG). In addition, there is a low-level intake (also termed side gate), which accesses deeper waters within the reservoir. Each of the three levels (upper, middle, and lower) are composed of five (5) gates, as shown in Figure 2-2. Herein, TCD levels are either referred to explicitly or by using the following abbreviations:

- Upper Level (TCDU)

- Middle Level (TCDM)
- Lower Level (a.k.a., PRG) (TCDL)
- Low Level Intake: LLI, also referred to as "side gates" (TCDS)

The TCD is designed to take advantage of seasonal thermal stratification in Shasta Lake: the unequal distribution of water temperature, and associated unequal distribution in water density, which leads to a layered thermal structure consisting of an epilimnion (the upper, warmest layer), metalimnion or thermocline (the middle layer that represents the transition between the warmer surface layer and the colder bottom layer, and hypolimnion (the bottom, coldest, and most dense layer) (Figure 2-2). In large, deep lakes and reservoirs, like Shasta Lake, stratified conditions typically persist from spring into fall.

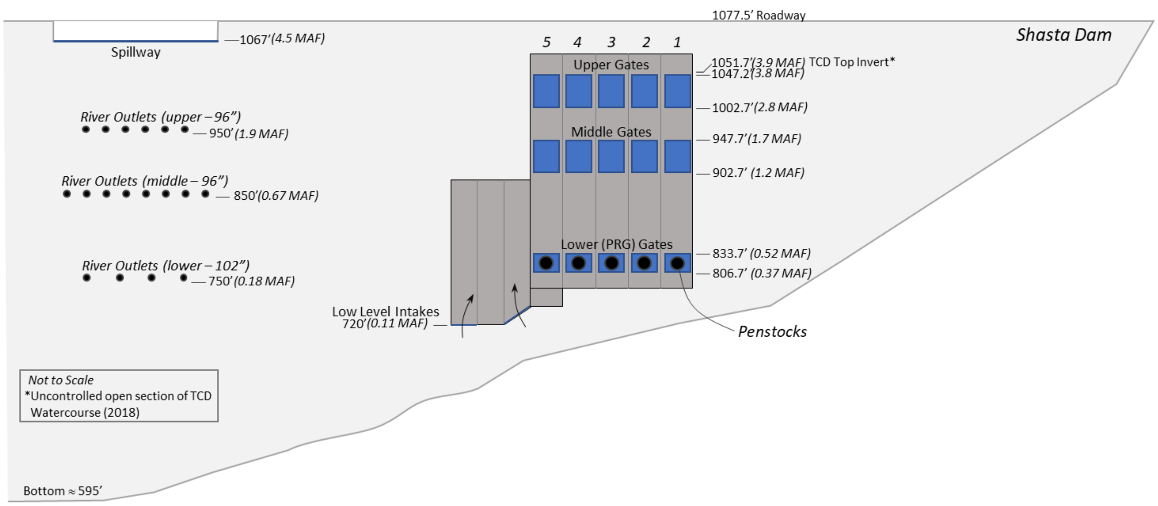


Figure 2-2. Shasta Dam outlet works (left) and Temperature Control Device (right) looking downstream. Powerhouse units 1 through 5 are shown for reference.

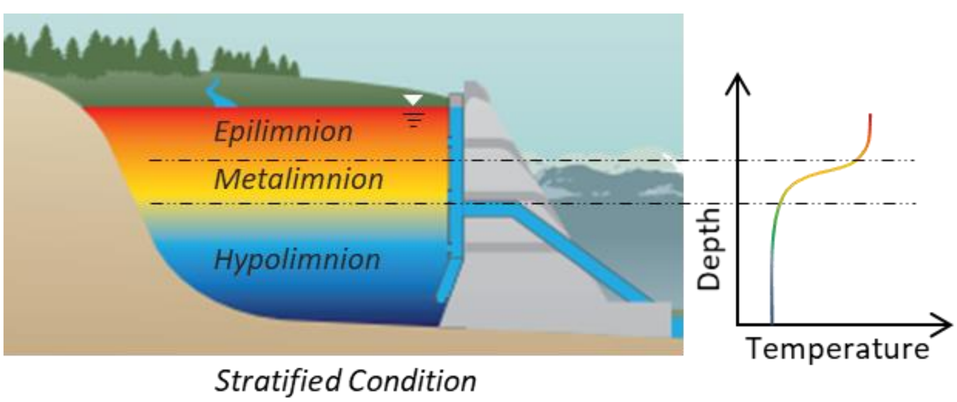


Figure 2-3. Representative seasonal stratification for a large reservoir, showing the epilimnion, metalimnion, and hypolimnion and associated thermal profile.

The multiple intake levels available in the TCD allow operators to selectively withdraw waters from different reservoir depths at different temperatures to manage downstream water temperatures. Temperature management may include discharging water through a single level or multiple levels (i.e., blending). Typical water temperature management operations from spring through summer and into fall follow a progression of releasing water from higher levels to lower levels. Blending is usually limited to two levels at a time, and there are restrictions on the number of gates that must be open on one or more levels and freeboard (water surface elevation above a gate level invert).

There are five gates per level for the upper, middle, and lower levels, and the LLI has two gates on the side of the TCD that, when open, draw water vertically up through openings located on the bottom of the LLI structure (Figure 2-1). Up to five gates may be open on any one level at a time, and gates on more than one level can be open simultaneously, with the constraint that when the TCD is in operation, a minimum of five gates must be open to meet hydrodynamic design considerations of the structure. Waters entering the TCD from any open gate on any level can contribute flow to any active powerhouse penstocks intake. TCD gate operations are further constrained by the amount of water above the gate opening to maintain structural integrity and avoid hydraulic conditions which might collapse the TCD structure. For the upper gate to operate without the middle or lower gate levels open, there must be 35 feet of water above the bottom of the upper gate. When the reservoir surface elevations fall below this criterion, the upper gates can still be operated, but at least one gate at the middle level must be opened. This constraint similarly applies for middle and lower levels.

When blending waters from two TCD levels, the number of gates used on each level provide Reclamation with additional flexibility to meet tailbay temperature targets below Shasta Dam (Reclamation 1999). For example, early in a blending period (e.g., June) there may be more gates open on the upper level than the middle level. As time progresses, upper level gates may be closed and additional middle level gates opened.

Variations in gate settings, leakage (into the TCD structure itself), powerhouse unit operations and units in operation, reservoir storage, and thermal structure of the reservoir contribute to a complex hydrodynamic and temperature regime within the TCD. Leakage into the TCD occurs at several locations because the structure is not watertight due to the design and construction material. Certain areas on the TCD are more prone to leakage (construction joints, gates, and similar areas). Further, the timing of TCD level progression (e.g., upper to middle to lower level utilization), and low-level intake operations are critical decision points in seasonal temperature management. The representation of TCD levels, TCD individual gate operations, leakage, blending from multiple levels, and other TCD elements were important considerations when developing the current CE-QUAL-W2 and ResSim models for Shasta Lake.

Chapter 3 Model Development

Model development includes obtaining the model version that meets the project needs, defining the spatial and temporal resolution that is consistent with desired output and available data, developing a model grid, representing inflow and outflow operations (e.g., allocation to appropriate flow structures), and creation of necessary input files to run the model. Input files needed for running the models include boundary conditions, initial conditions, model values and parameters (coefficients and constants), and model control values. Boundary conditions, often called "forcing functions," describe the changing state of flow, water quality, and meteorology along the boundaries of a modeling system. These conditions are applied at each time step. Most boundary conditions are discrete field observations or values derived directly from discrete observations. Initial conditions consist of the data used to start the model simulation. Initial conditions can be derived from measured data, from other model simulations or can be estimated. The result is a functional, but uncalibrated model.

The ResSim and CE-QUAL-W2 models developed for this effort were designed to utilize the same reservoir bathymetry data, boundary condition data sets, and initial conditions (Reclamation 2022b). Differences in ResSim and CE-QUAL-W2 model characteristics required different approaches to reservoir geometry and TCD representations. In the following section, a description of model geometric representation for CE-QUAL-W2 models for Shasta Lake (including TCD representation) and Keswick Reservoir is provided. The subsequent section in this chapter presents a description of model geometric representation for ResSim models for Shasta Lake (including TCD representation), Keswick Reservoir, and Sacramento River from Keswick Dam to Red Bluff. Development of boundary conditions and initial conditions are described in the last section.

CE-QUAL-W2 Model Development

CE-QUAL-W2 is a laterally averaged, two-dimensional model, representing longitudinal and vertical temperature gradients. The current modeling effort uses Version 3.6 (Cole and Wells 2008). CE-QUAL-W2 model grids were developed for Shasta Lake and Keswick Reservoir using the digital X, Y, Z data from their respective bathymetries (Deas and Sogutlugil 2017a, 2017b, 2017c). Development of the Shasta Lake model grid is presented in the next section, followed by a description of CE-QUAL-W2 model TCD representation. Last, development of the Keswick Reservoir model grid is presented

Shasta Lake Model Geometric Representation

Development of the Shasta Lake CE-QUAL-W2 model geometric representation is described in the following sections. A description of model grid development is provided first. Next, a description of TCD representation in the model is presented, including flow representation for Shasta Dam and TCD, a description of selective withdrawal modeling, and a list of TCD modeling assumptions and considerations.

Model Grid

The Shasta Lake model grid consists of five branches (four branches are connected to a main branch). The main branch (Branch 1) represents the Pit River arm between Pit 7 Afterbay Dam, which is owned by Pacific Gas and Electric Company (PG&E), and Shasta Dam. Branch 2 through Branch 5 are Squaw Creek arm, McCloud River arm, Sacramento River arm and Big Backbone Creek arm, respectively. The CE-QUAL-W2 model grid utilized the Shasta Lake bathymetry to define the segment and layer geometry.

The branches consist of segments linked together in the direction of flow. The number of segments, total branch lengths, average segment lengths, and minimum and maximum segment lengths for each branch are listed in Table 3-1.

Table 3-1. Model grid branches and segments for Shasta Lake.

Branch name (number)	Number of Segments	Total Length, ft (m)	Average Segment Length, ft (m)	Minimum Segment Length, ft (m)	Maximum Segment Length, ft (m)
Pit River arm (1)	76	156,988 (47,850.0)	2,066 (629.6)	820 (250.0)	4,429 (1,350.0)
Squaw Creek arm (2)	33	46,014 (14,025.2)	1,394 (425.0)	656 (200.0)	2,461 (750.2)
McCloud River arm (3)	34	74,020 (22,561.2)	2,177 (663.6)	1,066 (325.0)	4,429 (1,350.0)
Sacramento River arm (4)	70	96,441 (29,395.1)	1,378 (419.9)	492 (150.0)	2,937 (895.1)
Big Backbone Creek arm (5)	12	19,324 (5,890.1)	1,610 (490.8)	689 (210.0)	2,740 (835.1)

Each segment consists of multiple layers to represent depths. Layer thicknesses for the entire model grid are 1.0 m (3.28 ft). The downstream-most segment of the main branch, i.e., the segment just upstream of Shasta Dam, consists of 149 layers, which is also the maximum number of layers for any segment in the Shasta Lake model. Plan views of the Shasta Lake model domain are included in Figure 3-1. Side views of each branch and more detailed information on the model grid are included in Deas and Sogutlugil (2017c). The final model grid was also assessed by reducing the resolution of the grid to a finer level of detail (e.g., 0.5 m layer thickness) to determine if further refinement would improve model results. Little improvement was made under these refined conditions. To balance simulation time and model output resolution, a layer thickness of 1.0 m was used along with the grid representations described in Table 3-1.

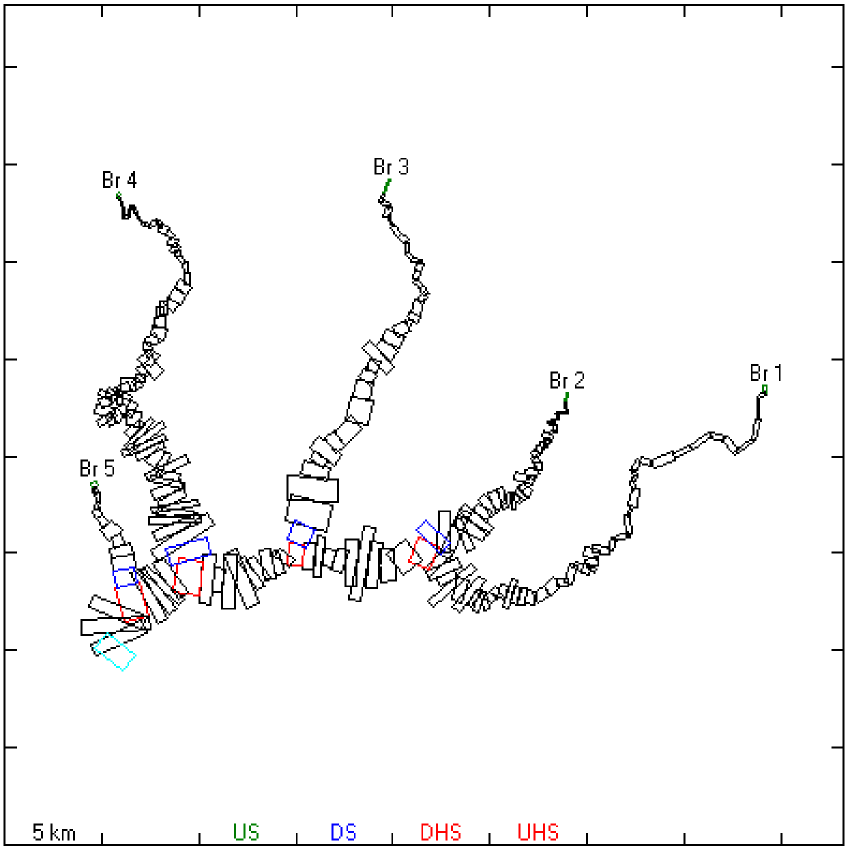


Figure 3-1. Shasta Lake model grid (plan view). The furthest upstream segments of each branch are shown in green (nearest the branch label); terminal downstream segments of Branches 2 through 5 are blue; “connection” segments for the tributaries to the main branch are red; and furthest downstream segment of the entire model grid, just above Shasta Dam, is cyan (bottom left).

TCD Representation in CE-QUAL-W2

The main body of the TCD is approximately 250 ft (76.2 m) wide (the low-level intake structure is approximately 150 ft (45.7 m) wide). While this is considerably wider than an individual penstock, the width is small (< 10 percent) compared to the width of Shasta Dam: 2,750 ft (838.2 m). As a result, outlet structures can be represented in two ways in the model: as a line sink or as a point sink. Representing the Shasta Lake TCD within a model required consideration of several factors unique to the facility, as well as consideration of other outlets in Shasta Dam. The TCD gates are located at different elevations to selectively withdraw water from different depths (and of different temperatures) within the reservoir to both conserve cold water volumes and efficiently manage downstream water temperatures. Several aspects of the TCD required unique consideration when developing the CE-QUAL-W2 model of Shasta Lake, including:

- leakage into the TCD,
- large gate openings,

- low-level intake operations, and
- blending operations.

Certain aspects of TCD representation could be accommodated within the existing CE-QUAL-W2 model logic. In certain cases, such as blending operations, new logic was incorporated into the model to accommodate TCD operations. Each of the topics listed above is addressed in detail in Deas et al. (2020). Flow representation for the Shasta Dam and TCD operations and a discussion of modeling selective withdrawal are presented in the following sections. Assumptions and considerations for the CE-QUAL-W2 model TCD representation are listed in the last section.

Flow Representation for the Shasta Dam and TCD Operations Representing historic Shasta Dam releases and TCD operations in the model was a necessary element of model calibration. Measured flow data were available for reservoir spill and river release outlet levels. However, there were no measured flow data available for releases through the individual TCD gates. Rather, only penstock flow data were available. Monitoring devices installed during the construction of the TCD failed shortly thereafter and have not been replaced. Reclamation operations logs were used to assign flows through the TCD, depending on the active TCD levels, for historical blending and non-blending periods. Blending periods are defined times when two or more TCD levels are active, and non-blending periods are times when there is a single level active. Any TCD level was considered active if at least one gate on a level was open. Throughout the modeling period (2000-2021), there were occasional instances, over short periods of time, when (a) two non-adjacent levels were active (e.g., upper and lower), (b) three levels were active simultaneously (e.g., upper, middle, and lower), or (c) short duration operations occurred, e.g., a gate setting for less than one day. Outlined below are the processes and assumptions used in representing outflows through the TCD.

- Total TCD outflow was based on the measured penstock flows at the Shasta Powerhouse.
- Total TCD leakage was assumed to be equal to up to 20 percent of the total TCD outflow. Leakage was distributed among the six leakage outlets (zones) as described in Deas et al. (2020). These leakage zones are represented by point sinks.
- The remaining total TCD outflow was available to enter the TCD through any active gate(s). This non-leakage portion of total TCD outflow is termed "TCD gate flow" and represents the flow through all active gates on all active levels (upper, middle, lower, side gates).
- Due to the large vertical openings for the upper, middle, and lower gate levels, TCD gate levels could not be effectively represented by a single point sink in the existing CE-QUAL-W2 model. The issue is where to place a single point sink to represent the gate. If located in the middle, the point sink would not be accessible if the reservoir level fell below the mid-gate elevation. If located at the bottom, the point sink would not represent the proper gate opening. Several potential formulations were tested. Ultimately, each TCD level was represented by three individual point sinks, one at the top elevation, one in the middle (centerline) elevation, and one at the bottom (invert elevation) of to represent the large gate opening.
- If the period in question was non-blending (a single active outlet level), TCD gate flow is assigned to this single level. Recall, that each TCD level is represented by three individual point sinks, one at the top elevation, one in the middle (centerline) elevation, and one at the

bottom (invert elevation) to represent the large gate opening. During these non-blending periods the model selective withdrawal logic determines flows into any one of the three individual point sinks, based on TCD flow, minimum flow fractions (MFF1), and water temperatures in Shasta Lake at the elevation of the point sinks. MFFs represent the minimum amount of water that must pass through any point sink (MFFs can be set to zero). For non-blending periods (one active level), MFFs for the top, middle, and bottom point sinks are 2 percent (0.02), 2 percent (0.02), and 10 percent (0.10), respectively, of the TCD gate flow (Figure 3-1(a)). Minimum flow fractions are used because multiple model simulations, as well as review of Reclamation (1999), indicated that a simple uniform flow distribution did not reproduce Shasta Dam release temperatures. For example, an equal distribution of 33.3% per point sink, or other fixed fractions (e.g., upper, middle, and lower point sinks distributions of 25%, 50%, 25%, respectively), did not effectively reproduce Shasta Lake profiles or Shasta Dam release temperatures. Subsequently, logic was developed to allow the model to select the distribution of water from the three point sinks representing any gate level to attain release temperature targets while also effectively simulating reservoir temperature profiles. Details of this logic, including blending of two gate levels, are addressed in Deas et al. (2021).

- If the period in question included blending (two active outlet levels), TCD gate flow is assigned to the two active levels. Because each TCD level is represented by three individual point sinks, during blending periods there will be six individual point sinks – three for each active level. The model selective withdrawal logic will determine flows into any one of the six individual point sinks, based on TCD gate flow, minimum flow fractions (MFF) and water temperatures in Shasta Lake at the elevation of the point sinks. For blending periods, MFFs for the top, middle, and bottom point sinks are 1 percent (0.01) for the three individual point sinks representing the uppermost blending level, and 5 percent (0.05) for the three individual point sinks representing the lowermost blending level (Figure 3-1(b)). Extensive model testing comparing measured data to model simulated temperatures was carried out during blending periods to arrive at the distribution shown in Figure 3-1(b).
- When the low-level outlet (invert 720 ft (219.5 m)) is active, there are three point sinks to represent the low level intake -- one at the invert of the low level intake at 720 ft (219.5 m) and two additional outlets at the higher elevations 760 ft (231.7 m) and 800 ft (243.8 m). These elevations were identified based on Shasta dam release temperatures and reservoir profiles during periods when only the low level intake was active. Field data clearly identify that water was withdrawn from well above the invert elevation (720 ft (219.5m)). However, this representation alone did not consistently result in simulated temperatures matching both observed Shasta Lake profiles and dam release temperatures. A specific outlet configuration was developed to accommodate the unique attributes of this structure, including the vertical withdrawal through the bottom of the structure, proximity of the reservoir bed, and other

[1] MFFs were determined during model calibration.

factors; a deeper outlet was added to the model, termed TCD_d. This TCD_d[2] outlet is included in the selective withdrawal logic and only applies when (a) the lower level and low-level intake are active or (b) only the low-level intake is active. When TCD_d is used, a fixed amount (35 percent) of the TCD total flow (minus leakage) is assigned to this single point sink at elevation 695.5 ft (212 m)[3]. The representation of the low level intake point sinks for CE-QUAL-W2 is shown in Figure 3-2. If only the low-level intake is active, the MFFs for the top, middle, and bottom individual point sinks are 2 percent (0.02), 2 percent (0.02), and 10 percent (0.10), respectively, of the TCD gate flow. If both the lower level and low-level intake are used, the blending MFFs are applied to the six individual point sinks are 1 percent (0.01) lower level, and 5 percent (0.05) for the low-level intake.

[2] Reviewing the available Shasta Lake bathymetry in the vicinity of the dam, the location of the low-level intake structure with respect to the reservoir bed, and recognizing that reservoir storage below 720 ft (219.5 m) is approximately 0.11 MAF (1.357×10^8 m^3), multiple simulations were used to explore the potential elevation of an additional point sink below the 720 ft (219.5 m), termed TCD_d. The TCD_d outlet was assigned a fraction of total low-level outlet flow, but only when the LLI was active. This assumption qualitatively considered the vertical flow direction into the low-level intake structure; the constrained contributing area at this low elevation in the reservoir; proximity of the bed and banks, and the dam; and potential density implication of thermal stratification. Through multiple model runs over multiple years representing a range of thermal stratification conditions, TCD_d was assigned an elevation of 695.5 ft (212.0 m) and allocated 35 percent of the total TCD inflow (not including leakage) when active (**Error! Reference source not found.**). Slightly different combinations of elevations and flow fractions produced similar results. This addition more effectively captured the vertical temperature distribution of the reservoir late in the season when the low-level intake was active

[3] TCD_d elevation 695.5 ft (212 m) and flow fraction (35 percent) were determined during calibration (see Section 6).

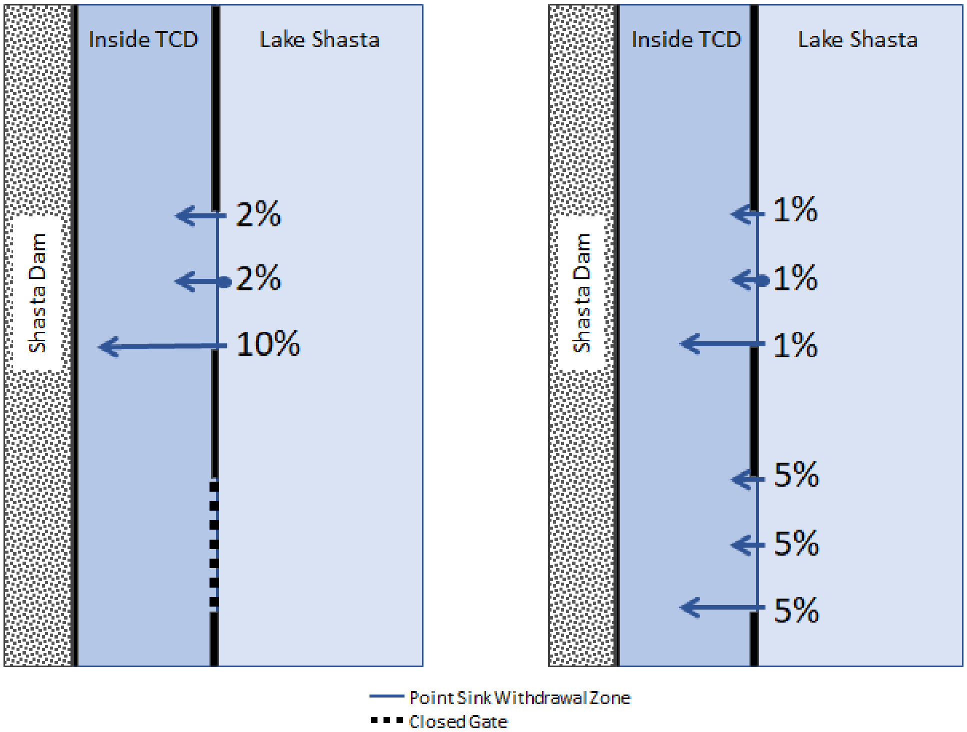


Figure 3-1. Minimum flow fractions (MFF) using upper and middle levels as an example for single active level (left), and two active levels (right).

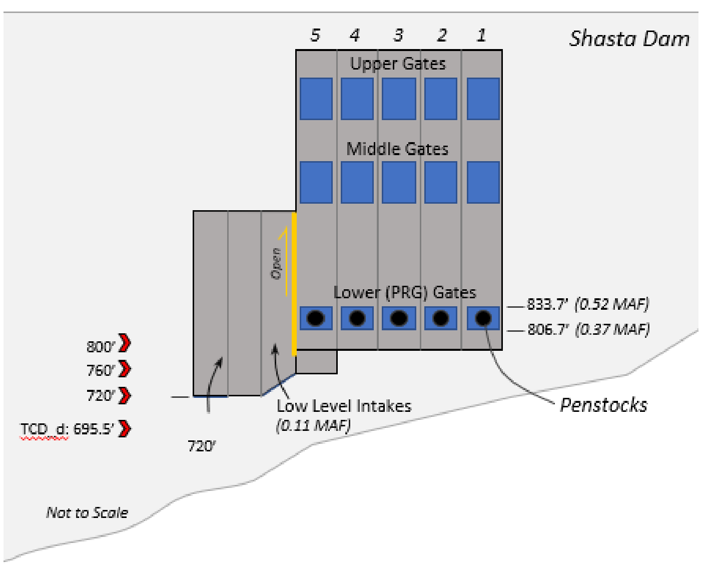


Figure 3-2. Shasta Dam TCD showing low-level intake structure (looking downstream) represented with three individual point sinks at 800 ft (243.8 m), 760 ft (231.7 m), and 720 ft (219.5 m) and the addition of the TCD_d point sink at 695.5 ft (212.0 m).

For calibration, selective withdrawal through the TCD was based on a downstream (tailbay) water temperature set equal to historic conditions. There are two measurements that can be used to define water temperature conditions below Shasta Dam: tailbay temperatures (Keswick Reservoir headwater) and powerhouse penstock temperatures. Each data set has pros and cons. The tailbay temperatures represent conditions in the tailbay, but may not always represent fully mixed releases from Shasta Dam. The penstock temperatures are direct temperature measurements of releases through the TCD, but the final downstream temperature required calculation by mass balance using flow and temperature form each individual penstock, and river outlet temperatures are not directly measured. For the historic calibration period, the averages of the two temperature records were used[4]. Differences between these records were mostly in their diurnal variations (sub-daily) and were more apparent at certain times of the year (e.g., fall and early winter).

Modeling Selective Withdrawal The Shasta Dam TCD allows operators to withdraw water from different levels of the reservoir throughout the year to meet release temperature targets. In releasing water, operators must estimate the long-term effect of their releases on the temperature structure of the reservoir and on the cold-water pool. Typically, cold water is managed to maintain instream target temperatures throughout in the summer and fall season. Operators make daily decisions about gate operations. Unpredictability in hydrology and weather result in temperature structures within the reservoir that respond and evolve in ways that are difficult to foresee. At the same time, resource managers must be kept informed about the future likelihood of meeting instream target temperatures so that management plans can be maintained or adjusted accordingly.

The logic applied in Reclamation's HEC5Q model for Shasta Lake was adapted for use in the CE-QUAL-W2 model for simulating selective withdrawal using the Shasta TCD (Rounds and Buccola 2015). The logic implemented in CE-QUAL-W2 by Rounds and Buccola (2015) was expanded and enhanced to address the specific attributes of the Shasta Dam TCD and improve forecasting in CE-QUAL-W2 selective withdrawal simulations to support in-reservoir and downstream temperature management (Deas et al. 2020). Although the modified model subroutine (referred to here as "W2_TCD") is implemented within the framework of CE-QUAL-W2 selective withdrawal logic introduced by Rounds and Buccola (2015), several features of this approach were disabled in this version of W2_TCD) simply for ease of organization and readability). Logic to implement these features remains in the code, and these features could be incorporated in the future if a need is identified.

In W2_TCD, Shasta TCD operations are defined in terms of levels, flow distribution across those levels, and periods of operation. All sources of release water, both blended and unblended, are specified in a model input file. These sources may include unblended openings, like leakage or spills, and blended openings associated with each of the four TCD gates. Each opening is assigned a "priority" number that determines whether it is blended or not and, if blended, to which level it is assigned. As noted, to maintain reasonable flow distribution across the full depth of release, each

[4] Shasta powerplant release temperatures were calculated by mass balance using individual penstock temperatures and flows. Shasta powerplant release temperatures represent TCD outflows, but do not include river outlets (or spill). Tailbay temperatures (Keswick Reservoir headwater) includes all releases from Shasta Dam, but can reflect local heating in Keswick Reservoir.

level is assigned MFFs. To provide realistic bounds on TCD operations, periods of operation may be specified by a start and end day for each opening. In addition, a period may be defined during which specific restrictions are placed on the selection of levels for blending. These restrictions encourage the model to select progressively lower levels for blending and prevent the model from jumping back-and-forth between levels in response to short-term changes as the model seeks to meet downstream temperature targets.

At the end of the W2_TCD subroutine process, one or two levels are selected to release water to meet required flow and desired temperature. All release structures representing these gates are assigned minimum flows, and one or two adjacent structures in the selected gates are assigned the remainder of the required flow. These release flows, and the elevations of the structures through which they are made, are passed to the main body of the CEQUAL-W2 model for use in its calculation of hydrodynamics and water quality in the subsequent time step.

Assumptions and Considerations Representation of the TCD attributes in CE-QUAL-W2 for TCD leakage, large gate openings, low-level intake operations, and blending required a range of assumptions and considerations. Extensive efforts were undertaken to assess a range of conditions and "test" assumptions. The process has identified information gaps, some of which can be addressed with further data collection. Several points are listed below that address several of the more pertinent issues regarding the current TCD representation in the Lake Shasta model.

- There are no in-reservoir or TCD related data available to identify specific leakage locations or to quantify leakage under the range of typical TCD operations. Although the TCD was originally equipped with monitoring devices, exposure to harsh environmental conditions resulted in damage and the devices failed shortly after installation. Because leakage is incompletely unquantified, the current representation is an estimate that reproduces downstream temperatures over a range of conditions.

- There are no in-reservoir or TCD related data available to quantify inflow to the TCD under the range of typical TCD operations, either by level or individual gates that are open at a particular level.

- Conditions within the reservoir upstream of the TCD as well as complex hydrodynamics around and <u>within</u> the TCD (including impacts of different powerhouse operations) can affect which waters are drawn into the TCD.

- Leakage is assumed to occur as a horizontal line-sink at a single elevation in the CE-QUAL-W2 model; however, as noted above, leakage occurs along all faces of the TCD, and possibly along vertical components of the TCD (e.g., seams, edges).

- There may be areas on the TCD that were not explicitly identified by Reclamation in their TCD assessment (Reclamation 1999) or were not completely defined, and there could be additional failed panels in the lower or middle level gates that need repair. Improvements in technology since 1997 has allowed Reclamation to upgrade its monitoring capabilities, and now Remotely Operated Vehicle (ROV) inspections routinely check for physical damage.

- Basic point sink theory assumes small openings in an otherwise large vertical and lateral domain (vertical for the case of line sinks). Application of the existing point and line sink representations available in CE-QUAL-W2 may face theoretical limitations for large gate openings.

- There are no available field data to provide guidance on the distribution of minimum flow fractions for the three individual point sinks for a single TCD level or for two blending TCD levels. Model results represent an empirical approach – matching downstream water temperatures and in-reservoir temperature vertical profiles.
- While three individual point sinks are used to represent the open bottom of the low-level intake, different numbers of point sinks and different vertical locations in the reservoir could be defined and yield similar results.
- The low-level intake representation included withdrawal points above and below the invert of the low-level intake. While this representation was the culmination of extensive testing and assessment of both simulated dam outflow temperatures and in-lake vertical profiles, little data were available to confirm flow patterns in this region of the lake. This empirical approach addresses complex conditions in the vicinity of the low-level intake but is nonetheless an assumption that requires further testing.
- The TCD is not located in the middle of the dam but is centered over 400 ft (122 m) to the west of the centerline. CE-QUAL-W2, being a laterally averaged model, assumes all outflow features are aligned about the centerline of the dam. There are several attributes of this assumption that present challenges to the TCD representation:
    - The bed and boundaries of the reservoir are adjacent to the TCD; however, the model does not represent this explicitly because all modeled outlets are centered on the dam.
    - The asymmetry of the reservoir morphology in the vicinity of the dam are represented as symmetric cross section in CE-QUAL-W2 as part of the laterally averaged assumption
    - The laterally averaged assumption of CE-QUAL-W2 does not accommodate lateral motion in the reservoir, i.e., horizontal circulation in the vicinity of the dam is not captured in the CE-QUAL-W2 model representation.

All of these conditions can impact local hydrodynamics immediately upstream of the dam and thus influence flows into the TCD. These topics address a range of issues from model limitations (e.g., laterally averaged representation of the reservoir), to data limitations (e.g., lack of specific leakage information), to theory limitations (e.g., point/line sink theory). Such limitations and associated assumptions are common among model applications. As additional information is identified, field data collected, and theory updated, the model can be updated accordingly. U.C. Davis has received Delta Stewardship Council (DSC) funding to pursue detailed acoustic Doppler current profiler measurements immediately upstream of the TCD to quantify flow through individual gates, identify the impact of reservoir density gradients on TCD inflow, determine the effects of reservoir boundaries on withdrawal dynamics, and assess overall TCD gate operations (including blending of two gate levels). This work is slated to start in 2022, and builds on proof of concept field efforts completed in Shasta Lake in 2019 and 2021. These studies are intended to improve the understanding of hydrodynamic conditions upstream of the TCD, quantify gate inflows, possibly identify leakage zones, and better represent the TCD in model applications such as those included in the WTMP. In the interim, the model remains widely applicable for planning and management actions at Shasta Lake as confirmed by model performance comparing simulated and historical vertical temperature profiles and dam release temperatures.

Keswick Reservoir Model Geometric Representation

The Keswick Reservoir model grid consists of two branches. Branch 1 is the main branch, which represents the reservoir, located along the Sacramento River. Branch 2 represents the Spring Creek arm from the Spring Creek Powerhouse to the main branch. The CE-QUAL-W2 model grid utilized the Keswick Reservoir bathymetry (Deas and Sogutlugil 2017b) to define the segment and layer geometry. The branches consist of segments linked together in the direction of flow (Figure 3-3). The number of segments, total branch lengths, average segment lengths, and minimum and maximum segment lengths for each branch are listed in Table 3-2.

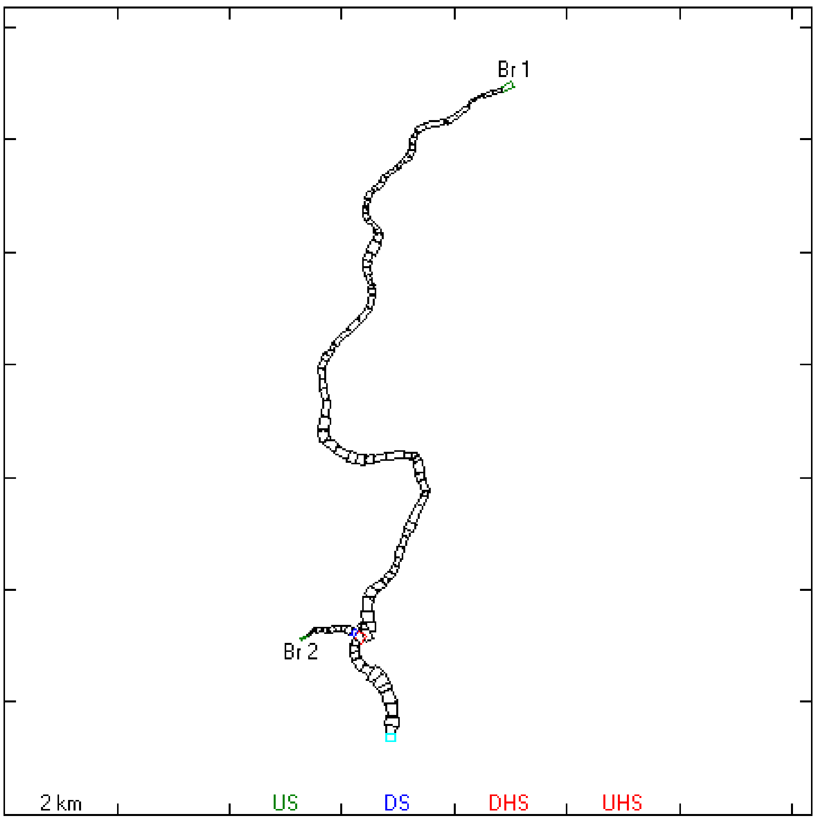


Figure 3-3. Keswick Reservoir model grid (plan view). Upstream-most segments are located near the branch labels on the figure. The downstream-most active segment in the model grid (above Keswick Dam) is located near the bottom of the figure.

Table 3-2. Model grid branches and segments for Keswick Reservoir.

Branch Name (no.)	Number of Segments	Total Length, ft (m)	Average Segment Length, ft (m)	Minimum Segment Length, ft (m)	Maximum Segment Length, ft (m)
Keswick Reservoir (1)	101	51,283 (15,796)	513 (156)	163 (50)	1,132 (345)
Spring Creek arm (2)	12	3,512 (1,071)	293 (89)	137 (42)	492 (150)

Each segment consists of multiple 1.0 m (3.28 ft) layers representing depths. Segment No. 79, located upstream of the confluence/connection point of the Spring Creek branch and the reservoir, consists of 31 layers, which is the maximum number of layers for any segment in the Keswick Reservoir model. Side views of each branch and more detailed information on the model grid are outlined in Sogutlugil (2017b). The final model grid was also assessed by reducing the resolution of the grid to a finer level of detail (e.g., 0.5 m layer thickness) to determine if further refinement would improve model results. Little improvement was made under these refined conditions. To balance simulation time and model output resolution, a layer thickness of 1.0 m was used along with the grid representations described in Table 3-2.

ResSim Model Development

The HEC-ResSim model of the Upper Sacramento River System was created using version 3.6 (beta) (HEC 2022a, 2022b). A general description of ResSim model development is presented below. The next section provides a description of Shasta Lake ResSim model geometric representation, including description of TCD representation, followed by a section describing Keswick Reservoir ResSim model geometric representation. Last, development of a ResSim model for Sacramento River from Keswick Dam to Res Bluff is outlined.

The physical information required to configure reservoirs in the ResSim model includes elevation-storage-area curves, outlet configuration, and temperature control device specifications. Hydraulic characteristics of river reaches are represented using look up tables relating river flow to depth, velocity, and top width derived from steady flow simulations performed with HEC-RAS. HEC-RAS models for river segments included in the ResSim network have been derived using the best available data from existing cross-section, LIDAR, and bathymetric surveys.

ResSim may be run for any time period, provided appropriate initial conditions, boundary conditions, and operational controls are specified. Initial conditions include the starting elevation and vertical thermal profile in reservoirs, and initial flow and temperature for river reaches. Flow and temperature must be defined for all inflow points, throughout the simulation period. Meteorology data must also be provided for the simulation period. Reservoir operations may be rule based or fully specified, depending on the purpose of the simulation. For model calibration and validation simulations, reservoir releases and TCD operations are specified throughout the simulation period.

The ResSim flow model computational time step is specified as a regular interval varying from five minutes to one day. For this application, the model has been configured for temperature simulation with a computational time step of 1 hour. The simulation time window is divided into a "lookback" period and "forecast" period. This approach was initially developed to support the use of ResSim as a forecasting model where the lookback period was used to initialize (or "spin-up") the model using recently observed data. For reservoir simulations this period may be a few weeks or longer, depending on time of year, and for rivers a few days. During the lookback period special logic is employed to set reservoir elevation/storage and reservoir releases based on observations. During the forecast period, reservoir releases are based on operations logic and change in reservoir storage is computed based on the balance of reservoir inflow, outflow, and losses. Flow in river reaches is initialized during the lookback period with measured tributary inflows and reservoir releases. The simulation time window is identified by a "Lookback Date/Time," "Start Date/Time," and "End Date/Time." The lookback period ranges from the "Lookback Date/Time" to the "Start Date/Time," and the forecast period ranges from the "Start Date/Time" to the "End Date/Time." Water quality computations are only computed during the forecast period.

Whenever possible, the ResSim model has been made comparable to the corresponding CE-QUAL-W2 configurations to facilitate driving both models with the same set of boundary conditions.

Geometric Representation

Shasta Lake Model Geometric Representation

Shasta Lake is represented as a one-dimensional (1D) vertically stratified reservoir with boundary inflow points from the Pit River, Squaw Creek, McCloud River, and Sacramento River. The model includes physical outlet representations for the spillway, power penstocks and river outlet gates, as well as the Shasta TCD. Elevation-storage and elevation-area curves are shown in Figure 3-3. At full pool, Shasta Lake has an elevation of 1,067 ft. (325.2 m), storage of 4,552,000 AF (~5,615x109 m3), and a surface area of 30,000 acres (12,150 hectares). For water-quality computations, Shasta Lake is discretized into 151 horizontal layers in ResSim, each with a thickness of 3.0 ft (0.91 m).

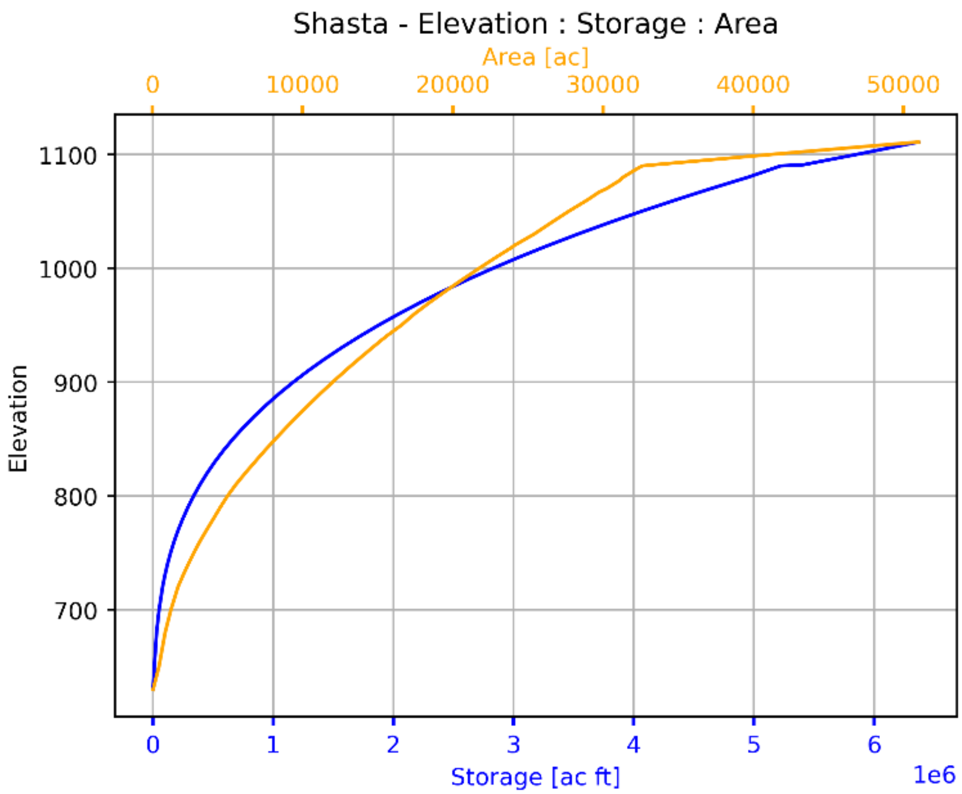


Figure 3-3. Shasta Lake Elevation-Storage and Elevation-Area Curves.

Shasta Dam and TCD Representation in ResSim

ResSim supports detailed definition of complex outlet structures. Outlets may be represented individually, or as sets of comparable outlets. Shasta Dam outlet configuration is shown in Table 3-3. The ResSim representation of these outlets is summarized in Table 3-3.

Table 3-3. ResSim Shasta Dam outlet configuration summary.

ResSim Combined Outlet	Invert Elevation (ft)	Individual Outlet Dimension (ft)	Number of Outlets	Total Maximum Capacity (cfs)
Power Penstocks	807.5	15 (diameter)	5	17,600
Spillway	1037	110 (width) 28 (height)	3	186,000
River Outlets – Upper	938	8 (diameter)	6	39,204
River Outlets – Middle	838	8 (diameter)	8	24,800
River Outlets – Lower	737.75	8.5 (diameter)	4	17,800

In ResSim, the withdrawal level associated with a physical reservoir outlet may be managed by associating a “Water Quality Control Device” (WQCD) with a single outlet or a group of outlets.

As with physical outlets, ports on a WQCD may be defined individually or in sets that draw from the same reservoir elevation. For the Shasta Lake configuration, a WQCD representing the Shasta TCD is associated with the combined power penstocks outlet. The TCD port configuration is summarized in Table 3-4. Note that the upper, middle, and lower ports in the TCD are parallel to the face of the dam. The low-level intake is a downward-facing port at the bottom of a 130 ft. wide structure on the side of the main TCD structure, as shown in Figure 2-2.

Table 3-4. ResSim Shasta TCD configuration summary.

ResSim Shasta TCD Combined Port	Invert Elevation (ft)	Individual Port Dimension (ft)	Number of Ports
Upper Gates	1,002.7	50 (width) 44.5 (height)	5
Middle Gates	902.7	50 (width) 45 (height)	5
Lower Gates	806.7	50 (width) 27 (height)	5
Low Level Intakes	720	130 (width) 50 (depth)	2

The TCD gates are very large and have been further subdivided in a manner similar to the CE-QUAL-W2 implementation to better represent the distribution of withdrawal over the water column. Port withdrawal elevations were defined to represent each of the shutter levels as well as representative leakage elevations (Table 3-5). Three port elevations are defined for each of the upper, middle, and lower shutter sets and four port elevations are defined for the lower side gates. Leakage zones are represented by six ports. The shutter and side gate ports are operable (they may be set as open or closed). The leakage ports are always active if the reservoir elevation is above the leakage port elevation. The leakage port flows are informed by the 1999 computational fluid dynamics (CFD) study (Reclamation 1999), with additional accommodation for the period (2000-2009) when several panels on the middle gate level were missing.

Table 3-5. ResSim TCD withdrawal ports.

Port Level	Elevation (ft)	Name	Operable
1	695.5	TCD Deep	Y
2	720	TCD Side A	Y
3	749.5	Leakage Zone 6	N
4	760	TCD Side B	Y
5	780	Leakage Zone 5	N
6	800	TCD Side C	Y
7	802	TCD Lower Bot	Y
8	805.6	Leakage Zone 4	N
9	816	TCD Lower Mid	Y
10	830	TCD Lower Top	Y
11	833.6	Leakage Zone 3	N

Port Level	Elevation (ft)	Name	Operable
12	896.7	Leakage Zone 2	N
13	900	TCD Middle Bot	Y
14	921	TCD Middle Mid	Y
15	942	TCD Middle Top	Y
16	946.7	Leakage Zone 1	N
17	1,000	TCD Upper Bot	Y
18	1,021	TCD Upper Mid	Y
19	1,042	TCD Upper Top	Y

Shasta Dam and TCD Flow Representation in ResSim

ResSim accommodates the use of Jython/Python based scripts for defining operation rules. This feature is commonly used to represent complex reservoir operations that are not accommodated through the standard ResSim rule set. The Shasta TCD rule controls activation of withdrawal ports, thereby setting the flow distribution over the active ports, at each computational time step, prior to the water quality transport calculations. A summary of the rule logic for calibration simulation is as follows

- Get data at current time step
  - Outflow temperature target
  - Reservoir water surface elevation
  - Total penstock flow requirement
  - Shutter opening state
- Identify TCD port levels associated with the open gates, with consideration of potential limitation caused by low water levels
- Find the optimal flow distribution across active ports and the resulting average water temperature of the total penstock flow
- Set the port flow distribution in the water quality engine for this time step

The leakage calculation involves determining the leakage fraction of the total penstock flow and the distribution of that leakage across the leakage "ports" identified in Deas et al. (2020) and summarized in Table 3-6 through Table 3-8.

Table 3-6. Total TCD leakage fraction of total penstock flow percentage (Deas et al. 2020).

Level	Leakage Fraction (%): 2000-09	Leakage Fraction (%): 2009-present
Upper Fraction	13.09	16.3
Middle Fraction	19.7	0.
Lower Fraction	12.65	15.75

Table 3-7. Total TCD leakage fraction representation (Deas et al. 2020).

Reservoir Elevation	resElevFac	Total Leakage Fraction (%)
elev >= 1000 ft		0.2
1000 ft > elev >= 945 ft	1-(elev-945)/(1000-945)	0.2*(1-upperFrac*resElevFac)
945 ft > elev >= 900 ft	1-(elev-900)/(945-900)	0.2*(1-upperFrac – middleFrac*resElevFac)
900 ft > elev >= 831 ft	1-(elev-831)/(900-831)	0.2*(1-upperFrac – middleFrac - lowFrac*resElevFac)
831 ft > elev	N/A	0.

Table 3-8. TCD Zone distribution coefficients.

Leakage Zone	2000-2009: Val1	2000-2009: Val2	2010-present: Val1	2010-present: Val2
1	13.09	N/A	16.3	N/A
2	8.05	11.65	0.0	0.0
3	9.34	3.31	11.63	4.12
4	1.03	10.01	1.28	12.47
5	3.84	31.12	4.78	38.76
6	1.79	6.77	2.23	8.44

Leakage flow is computed per zone as follows:

Leakage flow[zone i] – distTable[zone i, val1]/100. * totalLeakageFraction*totalPenstockFlow

The distribution of the remaining fraction of the total penstock flow is distributed across the currently open TCD gates based on an optimization to meet the target outflow temperature. If the reservoir water surface elevation is approaching the invert elevation of a set of open gates, the flow though that shutter level is limited by a maximum value computed using a sharp crested weir equation.

$$Q_{\max} = n_{\text{open}} * (C_w B \sqrt{g} H^{3/2})$$

where n_{open} is the number of gates open on this shutter layer, C_w is the weir coefficient (0.564), B is the width of each shutter (approximately 50 ft), g is gravitational acceleration (32.1 ft/s^2), and H is the height of the water surface elevation above the gate level invert.

The flow distribution optimization utilizes a simplex method with linear constraints on the minimum and maximum flows at each level and the sum of the total flow through all levels. The objective function to be minimized is the deviation between the flow-weighted, average TCD temperature and the specified target temperature. Outlet temperatures at all the port levels are initially determined as the modeled reservoir temperatures at the port centerlines. The optimization then determines the distribution of flows through the port levels to best meet the target temperature. Once the flow distribution is determined, it is used to obtain a better estimate of outlet temperatures for all the ports. This is necessary because port level temperatures are influenced by the magnitude of the port outflow, which determines the vertical limits of the outflow withdrawal zone. The solution scheme iteratively solves the optimization and updates the outlet temperatures until convergence is reached.

Modeling Selective Withdrawal In ResSim, the WQCD essentially modifies the reservoir layers from which water is withdrawn to provide flow for the Shasta Dam penstocks. Representation of the Shasta TCD in the ResSim Shasta Lake model includes characterization of the upper, middle, and lower gates, the low-level side gates, and leakage.

For historical simulations, ResSim schedules releases from Shasta Dam as specified by flow time series representing each of the reservoir outlet components: the spillway; the upper, middle and lower river outlets; and the total penstock flow through the powerhouse. Reclamation's operations logs are used to set gate openings in the TCD. Mixing within the TCD is modeled to match an "observed" target temperature calculated as the average of the flow-weighted average of the temperatures in the 5 penstocks and the measured tailbay temperature.

In Shasta Lake, the vertical flow distribution into the TCD is a complex function of the penstock flows, TCD shutter openings, TCD leakage, local bathymetry, and the current reservoir water surface elevation and state of stratification. Explicit simulation of flow into the TCD requires a detailed 3-dimensional computational fluid dynamics (CFD) model that considers horizontal and vertical momentum conservation, density variation due to temperature stratification and a detailed description of the TCD geometry and neighboring reservoir bathymetry. CFD modeling performed in the 1990's has provided a basic understanding of the flow through the TCD (Reclamation 1999). It is not feasible to include a detailed CFD model as part of the ResSim computational engine. The current ResSim modeling effort follows an approach that has been successfully utilized for CE-QUAL-W2 and HEC-5Q simulations: a target temperature is established for the total penstock outflow, and an optimization approach is used to establish the withdrawal envelope, given the constraints of the current shutter openings. For historical simulations, the observed flow-weighted average penstock temperatures are used as the temperature target. For seasonal temperature management planning, and typical forecasting simulations, the temperature target is part of the input data for scenarios under analysis.

The ResSim Water Quality Engine allows definition of port withdrawals at specific elevations in a 1D vertical reservoir. Standard functions are used to compute the withdrawal envelope associated with each point withdrawal as a function of flow and local stratification, such that

$$\frac{Q}{Z^3 N} = \frac{\theta}{\pi} \qquad N = \sqrt{\frac{\Delta\rho}{\rho}\frac{g}{Z}}$$

where Q is the outflow, Z is the distance from the withdrawal centerline to the upper or lower withdrawal limit, θ is the withdrawal angle (in radians, assumed = π), and N is the buoyancy frequency. Because the density difference term ($\Delta\rho$) in N (buoyancy frequency) depends on the distance from the withdrawal centerline (Z), the equation needs to be solved iteratively. If Z is located above the water surface or below the bed, interference is said to exist and a version of this equation is solved:

$$\frac{Q}{D'^3 N} = \frac{0.125\,\delta\,\theta}{X^3}\frac{}{\pi} \qquad \delta = \frac{1}{2}\left[1 + \frac{1}{\pi}\sin\left(\frac{b/_{D'}}{1 - b/_{D'}}\pi\right) + \frac{b/_{D'}}{1 - b/_{D'}}\right]$$

$$X = \frac{1}{2}\left[1 + \frac{b/_{D'}}{1 - b/_{D'}}\right] \qquad N = \sqrt{\frac{\Delta\rho}{\rho}\frac{g}{D'}}$$

where b is the distance between the centerline and the interference boundary and D' is the distance between the free withdrawal limit and the interference boundary.

Once the withdrawal limits are found, the location of the maximum velocity is found using

$$\Upsilon_L = H_e\left[\sin\left(1.57\frac{Z_L}{H_e}\right)\right]$$

where Υ_L is the distance between the lower withdrawal limit and the elevation of maximum velocity, H_e is the height of the withdrawal envelope, and Z_L is distance between the port centerline and the lower withdrawal limit. The final velocity distribution is parabolic around the elevation of maximum velocity.

$$\boldsymbol{V_i = 1 - \left(\frac{y_i}{\Upsilon_L}\frac{\Delta\rho_i}{\Delta\rho_{\max}}\right)^2}$$

where the subscript $\boldsymbol{i}$ denotes the layer values. Additional details are included in HEC (2022b).

Shasta Lake Inflow Entrainment When negatively buoyant inflows enter a reservoir, they flow along the submerged river valley until they reach the reservoir level having matching density. As these flows pass through the upper layers of the reservoir, they mix with the warmer water and pull a small fraction of it into the plunging inflow. This increases the magnitude of flow of the intrusion and decreases its density. Since the intrusion ultimately inserts itself into the lower layers of the reservoir, the process of entrainment acts to transport heat from shallower layers to deeper layers.

Entrainment has been studied in a number of field and lab experiments, and the process has been parameterized for use with 1D, vertically stratified reservoir models. Reviews of these experiments and equations are given in Fischer et al. (1979), Martin and McCutcheon (2005), and Fleenor (2001). In 2D reservoir models where the longitudinal and vertical directions are explicitly modeled using conservation of mass and momentum equations, the process of entrainment may be adequately represented without any additional parameterization.

A schematic of a plunging inflow with entrainment is shown in Figure 3-4. As the river first enters the reservoir, there is a zone of initial mixing, where entrainment from the surface water is typically higher because of the momentum dissipation of the inflowing tributary.

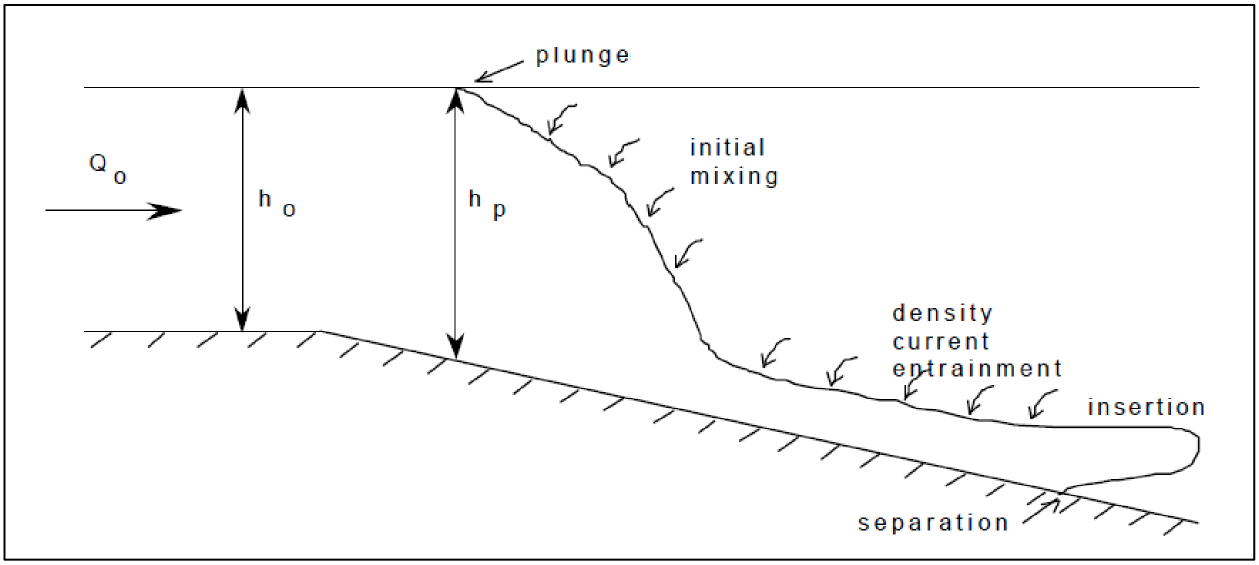


Figure 3-4 Schematic of entrainment for an interflow (from Fleenor (2001)

The location where the momentum of the inflow is dissipated and buoyancy begins to drive the movement of the inflow down the submerged river slope is called the "plunge point". Initial mixing is typically parameterized using a constant ratio, so that the flow after the initial mixing (Q_p) is calculated as

$$Q_p = Q_0\,(1 + \xi)$$

where Q_0 is the original river inflow and ξ is the initial mixing ratio. For mild slopes (S < 0.007), ξ has been estimated at 0.15 (Akiyama and Stefan, 1987), although other studies have shown considerable variability in this parameter.

After initial mixing, the inflow entrains water as a function of the entrainment coefficient (E). This entrainment coefficient is pre-calculated and is constant for a given tributary inflow. It is a function of the stream cross-section half angle (ϕ), the bed drag coefficient (C_D) and the tributary slope (S)

$$E = \frac{1}{2} C_k C_D^{3/2} F_p^2$$

$$F_p^2 = \frac{\sin\phi\ \tan S}{C_D}(1 - 0.85\, C_D^{0.5} \sin\phi)$$

where C_k = 3.2 (Imberger and Patterson 1981).

Since the entrainment of warmer waters decreases the density of the plunging inflow, the depth, flow rate, and density of the inflow must be updated as it passes through each reservoir layer to find the depth of neutral density.

In ResSim, the inflow is updated to account for entrainment in the following manner. From the top layer until either the point of neutral density or the bottom of the reservoir is reached:

- Update the depth of the inflow, $h_i = 1.2\,E\,x + h_{i-1}$, where x is the distance along the river channel ($x = d/S$, where d is the depth) and h_{i-1} is the inflow depth estimate from the previous layer

- Update the inflow flow rate, $Q_i = Q_{i-1}(\left(\frac{h_i}{h_{i-1}}\right)^{5/3} - 1)$

- Update the inflow density using a flow weighted average of the current inflow density and the density of the entrained water

For Lake Shasta and the other reservoirs on the Upper Sacramento, the initial mixing ratio ξ was assumed to be 0.15, the stream half angle ϕ was 0.85, the drag coefficient C_D was 0.04, and the tributary slopes were calculated based on the distance from their inflow point to the face of the reservoir dam. These slopes are shown in Table 3-9.

Table 3-9. Approximate river channel slope used for inflow entrainment calculations.

Shasta Tributary Inflow	Approximate River Channel Slope
Pit River	0.00274
Squaw Creek	0.00425
McCloud River	0.00490
Sacramento River	0.00417

Keswick Reservoir Model Geometric Representation

Keswick Reservoir is represented as a one-dimensional (1D) vertically stratified reservoir with inflows from Shasta Dam and Spring Creek. The ResSim model represents flow controls at Keswick Dam as a single composite outlet, which combines the capacities of the dam's powerhouse, spillway, and fish ladder.

Elevation-storage and elevation-area curves are shown in Figure 3-5. At full pool, Keswick Reservoir has an elevation of 587 ft. (178.92 m) storage of 23,800 AF (~2.936x107 m3) and surface area of 640 acres (259 hectares). For water-quality computations, Keswick Reservoir is discretized into 6 horizontal layers in ResSim with a thickness of 15.0 ft (4.57 m).

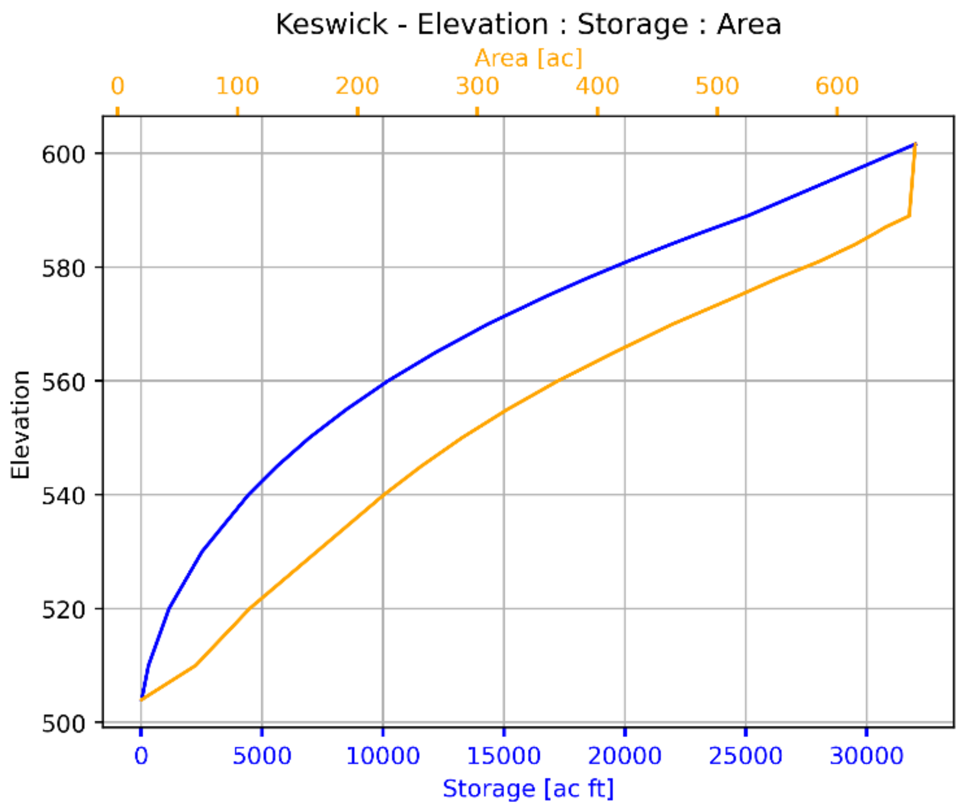


Figure 3-5. Keswick Reservoir elevation-storage and elevation-area curves.

Sacramento River from Keswick Reservoir to Red Bluff

The following sections present the geometric representation of the Sacramento River ResSim model reach from Keswick Dam to Red Bluff. The first section addresses the longitudinal geometric representation of reach. The following section provides a description of channel cross section development. Other modeling considerations are presented in the last section.

Model Reaches ResSim represents river segments as 1-dimensional, horizontally segmented reaches. The portions of the ResSim model that represent channel geometry from Keswick Dam to Red Bluff follow the structure of the existing HEC-5Q model. Dams, tributary confluences and other inflow sources, outflows, and gage locations are represented in ResSim as junction elements. Flows originating upstream of the model extent, and incremental additions to stream flow at confluences, are referred to as "Local Flows" at junctions. The location of outflow at Anderson-Cottonwood Irrigation District diversion canal (ACID) was not explicitly represented in the HEC-5Q or ResSim model but the diverted flow at the canal is removed from the volume in the river downstream of Keswick dam. The ResSim model represents this section of the river system as 8 junctions with 6 reaches connecting them. The locations of junctions and reaches in this portion of the model, as they appear in the ResSim interface, are shown in Figure 3-6 and listed in Table 3-10. The reach segments in the model are 3,000 feet long, with a longer segment at the downstream end to complete the length of the reach. The number of segments in each reach in the model are listed in Table 3-11.

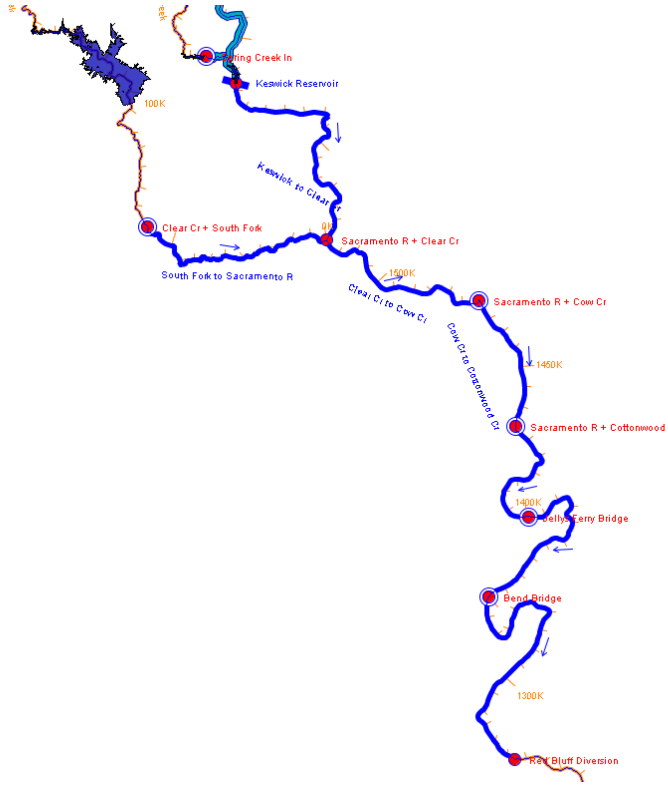


Figure 3-6. ResSim configuration of the Sacramento River from Keswick Reservoir to Red Bluff.

Table 3-10. Sacramento River ResSim model junctions.

Junction Name	**Functions in ResSim**	**Local Flow**
Keswick Dam	Upstream Boundary/model element	No
Sacramento R + Clear Cr	Confluence	No
Sacramento R + Cow Cr	Confluence/Gauge (water temperature at Balls Ferry Bridge)	Yes
Sacramento R + Cottonwood Cr	Confluence	Yes
Jellys Ferry Bridge	Confluence/Gauge (water temperature)	Yes
Bend Bridge	Gauge (flow and water temperature)	Yes
Red Bluff Diversion	Gauge (water temperature)	No

Table 3-11. Water-Quality Modeling Reaches from Keswick Dam to Red Bluff Diversion.

Reach Name	**Reach Length (miles)**	**Number of Segments**
Keswick to Clear Cr	12.8	22
Clear Cr to Cow Cr	9.3	16
Cow Cr to Cottonwood Cr	6.7	12
Cottonwood Cr to Jellys Ferry Bridge	6.7	12
Jellys Ferry Bridge to Bend Bridge	9.3	16

Reach Name	Reach Length (miles)	Number of Segments
Bend Bridge to Red Bluff Diversion	14.6	25
Clear Creek to Sacramento River	11.1	19

The Clear Creek to Sacramento River represents Clear Creek from the stream gauge at Igo (approximately RM 10.9) to the confluence with the Sacramento River. All other reaches are segments of the Sacramento River between Keswick Dam and the Red Bluff diversion dam.

Channel Cross Section Development Reach segments in the ResSim water quality model require tables of flow cross section area, water velocity, and channel top width as a function of river discharge. However, ResSim does not calculate these quantities. Instead, these values are calculated in HEC-RAS and imported to ResSim as part of developing the river system model. This process requires that a geometry model using the same sections of river that are present in ResSim must be developed in HEC-RAS. In addition, a sequence of steady-flow profiles must be run in HEC-RAS to generate values for the aforementioned parameters, over the range of flows that will be represented in the ResSim model.

For ResSim reaches on the Sacramento River, cross section geometry and roughness coefficients were extracted from hydraulically-representative cross sections in the existing HEC-5Q model and imported to a new HEC-RAS geometry. These cross sections – spaced roughly 1 mile apart in the HEC-5Q model – were placed along HEC-RAS reaches developed from the centerline geometry of the ResSim stream alignment, with stationing set to match that given in the HEC-5Q data set.

A typical cross section from the HEC-5Q model of the Sacramento River, as presented in the HEC-RAS interface after being imported is shown in Figure 3-7.

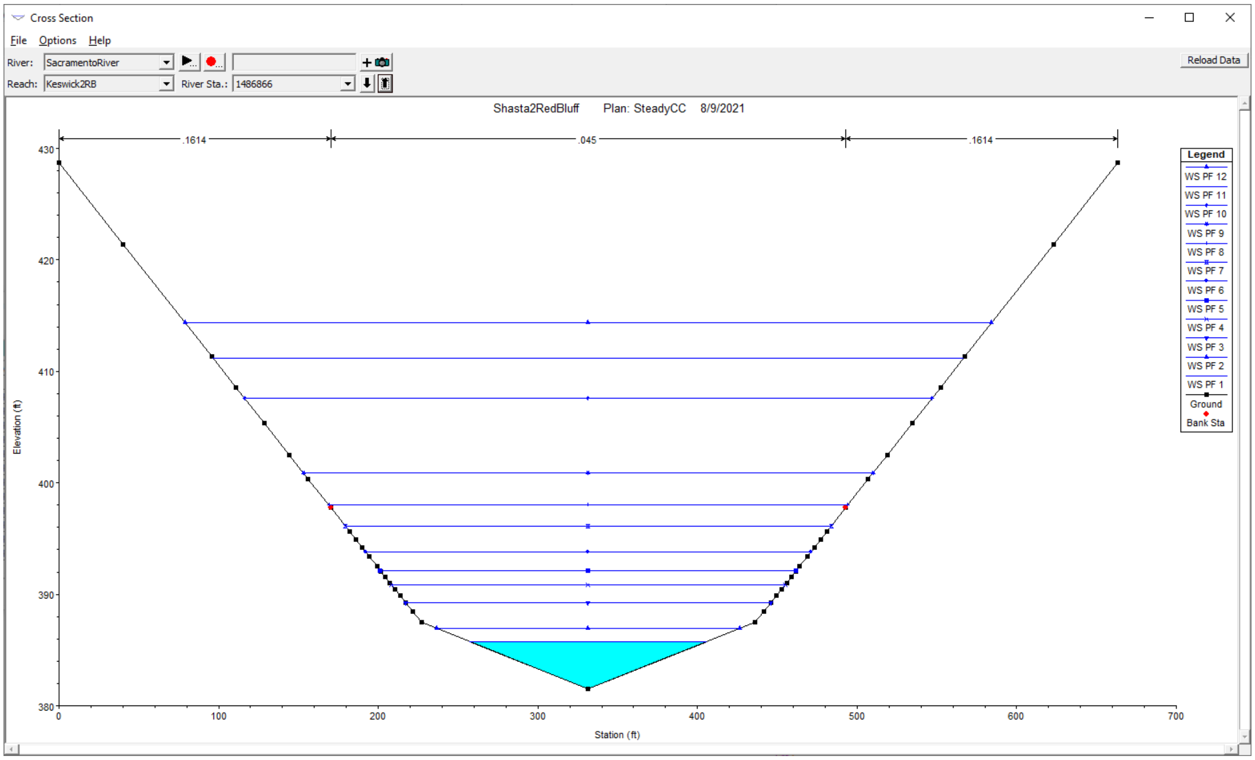
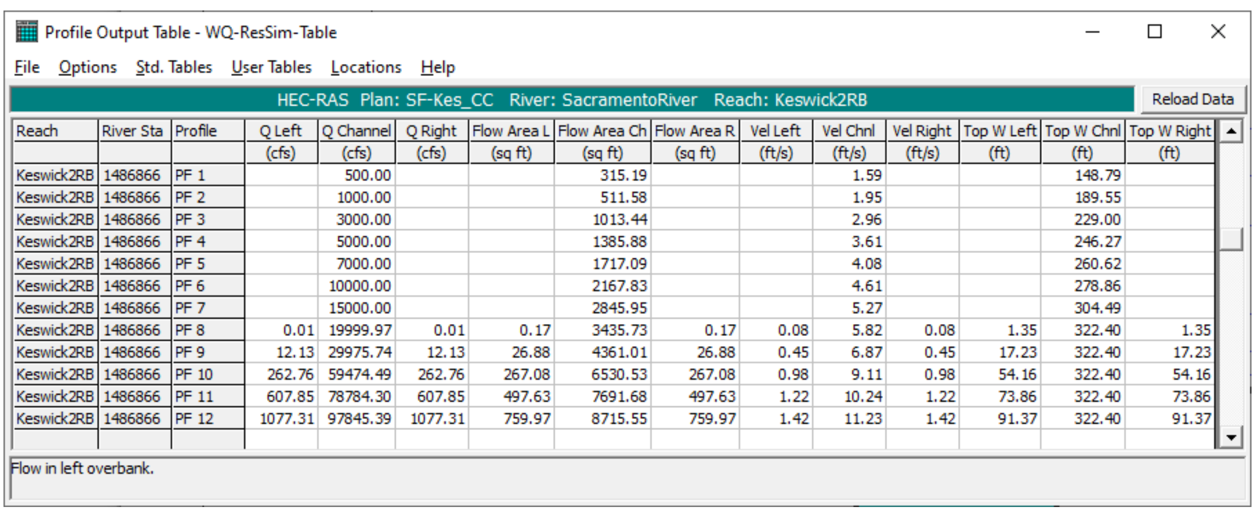


Figure 3-7. HEC-RAS display of an exported HEC-5Q cross section, representing a section of the Sacramento River below Clear Creek.

In HEC-RAS, steady flows ranging from 500 cfs to 100,000 cfs were used to generate flow profiles. The results were collected into a set of tables like the one shown in Figure 3-8. Finally, the contents of the tables were exported to a file that was imported to the ResSim model as a component of the Water Quality geometry.



Reach	River Sta	Profile	Q Left (cfs)	Q Channel (cfs)	Q Right (cfs)	Flow Area L (sq ft)	Flow Area Ch (sq ft)	Flow Area R (sq ft)	Vel Left (ft/s)	Vel Chnl (ft/s)	Vel Right (ft/s)	Top W Left (ft)	Top W Chnl (ft)	Top W Right (ft)
Keswick2RB	1486866	PF 1		500.00			315.19			1.59			148.79	
Keswick2RB	1486866	PF 2		1000.00			511.58			1.95			189.55	
Keswick2RB	1486866	PF 3		3000.00			1013.44			2.96			229.00	
Keswick2RB	1486866	PF 4		5000.00			1385.88			3.61			246.27	
Keswick2RB	1486866	PF 5		7000.00			1717.09			4.08			260.62	
Keswick2RB	1486866	PF 6		10000.00			2167.83			4.61			278.86	
Keswick2RB	1486866	PF 7		15000.00			2845.95			5.27			304.49	
Keswick2RB	1486866	PF 8	0.01	19999.97	0.01	0.17	3435.73	0.17	0.08	5.82	0.08	1.35	322.40	1.35
Keswick2RB	1486866	PF 9	12.13	29975.74	12.13	26.88	4361.01	26.88	0.45	6.87	0.45	17.23	322.40	17.23
Keswick2RB	1486866	PF 10	262.76	59474.49	262.76	267.08	6530.53	267.08	0.98	9.11	0.98	54.16	322.40	54.16
Keswick2RB	1486866	PF 11	607.85	78784.30	607.85	497.63	7691.68	497.63	1.22	10.24	1.22	73.86	322.40	73.86
Keswick2RB	1486866	PF 12	1077.31	97845.39	1077.31	759.97	8715.55	759.97	1.42	11.23	1.42	91.37	322.40	91.37

Flow in left overbank.

Figure 3-8. HEC-RAS result table, showing parameters required by the ResSim Water Quality model for a reach segment.

Assumptions and Considerations At present, the ResSim water quality model does not account for the lag or attenuation effects of routing flow through stream reaches. Water temperature is computed in a sequence of river segments, each of which is internally represented by flow-dependent tables of water velocity, water surface top width, and flow area (see "Other Modeling Values" below).

Development of Boundary Conditions

The WTMP models were designed to utilize common input files whenever possible. A description of common boundary conditions and initial conditions for Shasta Lake models is presented first, followed by descriptions for Keswick Reservoir models. The last section describes boundary conditions developed for the ResSim model for Sacramento River from Keswick Dam to Red Bluff.

Shasta Lake

Boundary conditions applied in the Shasta Lake CE-QUAL-W2 and ResSim models are presented in the next section, followed by a description of initial conditions utilized in the models.

Boundary Conditions The CE-QUAL-W2 and ResSim models require time series meteorology data for the modeled periods. Inflow boundary condition time series are required for each model branch, tributary inflow, and outflow location. Time series water temperature data are needed for all inflows.

Meteorology Boundary Conditions Meteorology boundary conditions include hourly air temperature, wet bulb (or dew point) temperature, wind speed, solar radiation, and cloud cover. Proximity of Shasta Lake, Keswick Reservoir, and Sacramento River from Keswick Dam to Red Bluff allows for use of a common set of meteorology data for all models.

Flow Boundary Conditions Flow boundary conditions for Shasta Lake models include inflow boundary conditions, ungaged flow into and out of Shasta Lake (also known as distributed tributary inflow and outflow), and the outflows measured at Shasta Dam.

Inflow boundary conditions Historic hourly flow data acquired from USGS, CDEC and Reclamation sources were used to develop time series input files for Shasta Lake models for 2000 through 2021. A detailed description of data development is provided in Reclamation (2022b). Flow data were not available for Squaw Creek during the modeled period. Instead, daily flow data for Sacramento River and Squaw Creek from 1945 to 1966 were used to develop regression equations for dry, normal, and wet years, which were then used to construct flow data files for Squaw Creek from 2000 to 2021. Flow data were also not available for Big Backbone Creek, but its flow was assumed to be negligible for the purposes of this model. Boundary condition files were constructed for inflow from each of the five branches in the Shasta Lake model for each year from 2000 through 2021.

Distributed tributary inflow/outflow Distributed inflow and outflow account for ungaged inflows to Shasta Lake from small tributaries, ungaged surface runoff, rainfall, losses due to evaporation, gains and losses due to groundwater exchange. Precipitation to and evaporation from the lake surface are not explicitly modeled in this application. Net ungaged accretions and depletions were calculated from a water balance based on measured inflows and outflows and the change in storage recorded at Shasta Dam. Thus, the distributed tributary also includes gage error of these measured inflows and outflows. The distributed accretion/depletion flow was applied to a junction labeled "Distributed in" on a tributary arm of the lake, labeled "Squaw Creek W," near the dam.

Outflow Hourly outflow data from Shasta Dam were available from Reclamation and CDEC. The outflow files for the Shasta Lake models include hourly spill, individual and total penstock flows, and river outlets (upper, middle, and lower) release data.

Water Temperature Boundary Conditions Water temperature boundary conditions in Shasta Lake models include upstream boundary inflow temperatures and the temperatures of the distributed tributary inflows.

Upstream boundary inflow Historical hourly water temperature data were acquired from USGS, CDEC, and Reclamation sources for the Pit, McCloud, and Sacramento rivers from 2000 through 2021. Water temperature data were not available for Squaw Creek during the modeled period, so data from the Sacramento River site at Delta, CA was used to represent water temperatures in Squaw Creek. Water temperature data were also not available for Big Backbone Creek, but because its flow was assumed to be negligible for the purposes of this model, its impact on water temperature in Shasta Lake is also assumed to be negligible. Boundary condition files were developed for each of the five branches in the Shasta Lake model for each year from 2000 through 2021 for this phase of the study.

Distributed tributary inflow The distributed tributary water temperature is applied to the Pit River arm (Branch 1 of the CE-QUAL-W2 model grid). For the purposes of this model, the water temperature of the distributed inflow is assumed to be the same as the Pit River inflow water temperature.

Initial Conditions For Shasta Lake, there were both measured profile temperatures (measured at monthly or sub-monthly intervals) and temperature string data (a string of thermistors collecting hourly or sub-hourly temperature data at depth intervals over an extended period of time). As measured profiles were not always recorded on January 1st, the temperature string data from January 1st 00:00 for each model year were applied as the initial condition. Initial reservoir stages were set to January 1st 00:00 measured values for the year of interest.

Keswick Reservoir

Boundary conditions applied in the Keswick Reservoir CE-QUAL-W2 and ResSim models are presented in the next section, followed by a description of initial conditions utilized in the models.

Boundary Conditions The CE-QUAL-W2 and ResSim models require time series meteorology data for the modeled periods. Inflow boundary condition time series are required for each model branch, tributary inflow, and outflow location. Time series water temperature data are needed for all inflows.

Meteorology Boundary Conditions Meteorology boundary conditions include hourly air temperature, wet bulb (or dew point) temperature, wind speed, solar radiation, and cloud cover. Proximity of Shasta Lake, Keswick Reservoir, and Sacramento River from Keswick Dam to Red Bluff allows for use of a common set of meteorology data for all models.

Flow Boundary Conditions Flow boundary conditions for Keswick Reservoir models include inflow boundary conditions, ungaged flow into and out of Keswick Reservoir (also known as distributed tributary inflow and outflow), and the outflows measured at Shasta Dam.

Inflow Boundary Conditions The hourly outflow data from Shasta Dam was used as the inflow boundary condition for the Keswick Reservoir model. The sum of hourly outflow data from Spring Creek Dam and Spring Creek powerhouse provided the inflow boundary condition information for the Spring Creek branch.

Distributed Tributary Inflow Net ungaged accretions and depletions were calculated from a water balance based on measured inflows and outflows and the change in storage recorded at Keswick Dam. Distributed inflow and outflow account for ungaged inflows to Keswick Reservoir from small tributaries, surface runoff, rainfall, and losses due to evaporation. The distributed accretion/depletion flow was applied to the Spring Creek branch at the same junction, labeled "Spring Creek In," where flows from the Spring Creek diversion dam and the Spring Creek powerhouse enter the pool.

Outflow Hourly outflow data from Keswick Dam, which includes the dam spill and powerhouse outflow were available from Reclamation and CDEC. For historical simulations, ResSim schedules releases from the composite Keswick Dam outlet as specified by the sum of three flow time series representing flow from the powerhouse, spillway and fish ladder. For use in the model, these were summed to a single time series.

Water Temperature Boundary Condition Water temperature boundary conditions for Keswick Reservoir include the temperatures of the outflow from Shasta Dam, the temperatures of the Spring Creek tributary, and temperatures of the distributed tributary inflows.

Upstream Boundary Inflow Hourly measured data from Reclamation gage SHD (below Shasta Dam) were used to construct input files for the model years.

Tributary Inflow Hourly measured data from Reclamation gage SPP (Spring Creek powerhouse) were used to construct input files of Spring Creek branch inflow temperatures for the model years.

Distributed Tributary Inflow The distributed tributary inflow temperature is applied to the Spring Creek branch of the stream alignment within the Keswick pool. For the purposes of this model, the water temperature of the distributed inflow is assumed to be the same as the ambient temperature of Keswick Reservoir.

Measured temperature data for Reclamation stations SHD and SPP exhibited variations that suggested the temperature loggers were exposed to the atmosphere in several years, recording invalid water temperature data during multiple periods. For those years, these invalid water temperatures were removed to develop representative inflow temperature at SHD and SPP.

Initial Conditions Reservoir profiles for January 1st were unavailable for Keswick Reservoir. An initial reservoir water temperature was set to 11.0oC (51.8oF) and isothermal conditions were assumed. These conditions represent an estimated winter condition based on Keswick Reservoir profile data from January 1 in 2018 and 2019. These initial conditions are "washed out" of the reservoir due to the short residence time. Initial reservoir stages were set to January 1st, 00:00 measured values for the year of interest.

Sacramento River from Keswick Dam to Red Bluff

Boundary conditions applied in the Sacramento River ResSim model are presented in the next section, followed by a description of initial conditions utilized in the models.

Boundary Conditions ResSim models require time series meteorology data for the modeled periods. Inflow boundary condition time series are required for each model branch, tributary inflow, and outflow location. Time series water temperature data are needed for all inflows.

Meteorology Boundary Conditions Meteorology boundary conditions include hourly air temperature, wet bulb (or dew point) temperature, wind speed, solar radiation, and cloud cover. Proximity of Shasta Lake, Keswick Reservoir, and Sacramento River from Keswick Dam to Red Bluff allows for use of a common set of meteorology data for all models.

Flow Boundary Conditions Flow boundary conditions for the Sacramento River model includes inflow boundary conditions and outflows measured at ACID diversion dam.

Upstream Boundary Inflow Upstream inflow boundary conditions are set by the reservoir model results at Keswick Dam.

Tributary Inflow Inflow data for Clear Creek is available from USGS gauge 11372000 (Clear Creek near Igo). Flows and temperatures on other Sacramento tributaries are available from CDEC and USGS sources. Additional inflow boundary condition flows were estimated by calculating the difference between the gaged flow at Bend Bridge ("Sacramento River above Bend Bridge" (SBB)(CDEC-USBR)) and the sum of flows at Keswick Dam, Clear Creek and the other Sacramento tributaries. This accretion/depletion flow was inserted at ambient river temperature above Bend Bridge. Locations of inflows, data sources, and flow fractions applied are listed in Table 3-12.

Table 3-12. Boundary condition parameters, units, and source.

Location	Parameter	Units	Source
Keswick Dam	Flow	cfs	Keswick Reservoir model element
Keswick Dam	Temperature	deg C	Keswick Reservoir model element
Sacramento R + Cow Cr	Flow	cfs	Cow Creek at Millville CA (CDEC-USGS)
Sacramento R + Cow Cr	Temperature	deg C	Cow Creek at Millville CA (CDEC-USGS)
Sacramento R + Cottonwood Cr	Flow	cfs	Cottonwood CR near Cottonwood CA (CDEC-USGS)
Sacramento R + Cottonwood Cr	Temperature	deg C	Cottonwood CR near Cottonwood CA (CDEC-USGS)

Location	Parameter	Units	Source
Jellys Ferry Bridge	Flow	cfs	Battle Creek below Coleman Fish Hatchery near Cottonwood CA (CDEC-USGS)
Jellys Ferry Bridge	Temperature	deg C	Battle Creek below Coleman Fish Hatchery near Cottonwood CA (CDEC-USGS)
Bend Bridge	Flow	cfs	Accretion/Depletion Flow
Bend Bridge	Temperature	deg C	Ambient river conditions
Clear Cr + South Fork	Flow	cfs	Clear Creek near Igo (IGO) (CDEC-USGS)
Clear Cr + South Fork	Temperature	deg C	Clear Creek near Igo (IGO) (CDEC-USGS)

*Outflow Boundary Conditions*_ Historic hourly flow data in ACID canal in Reading was acquired from USGS.

Water Temperature Boundary Conditions Water temperature boundary conditions for Sacramento River include the temperatures of the outflow from Keswick Dam and, the temperatures of the tributary inflows.

Upstream Boundary Inflow Upstream inflow boundary conditions are set by the reservoir model results at Shasta Dam.

Tributary Inflow Tributary inflow temperatures are set from reported temperature at Spring Creek Powerhouse for the tunnel flow, and to pool ambient temperature for the accretion/depletion contribution.

Initial Conditions The Sacramento River ResSim water-quality model requires an initial temperature for all junctions in the stream network. Initial water temperature was set to 9℃ on January 1st at 00:00 at all junctions.

Chapter 4 Model Calibration, Validation, and Sensitivity

Model calibration is the process of adjusting selected model parameters and minimizing the difference between simulated results to field observations. Calibration utilized both graphical and statistical assessments to evaluate model performance. Graphing simulated and field observation provides subjective evaluation, providing a qualitative assessment of magnitude, phase, rate of change and other information that may not be readily apparent in statistical analysis. Below is a description of the ResSim calibration, validation, and sensitivity analysis followed by calibration, validation, and sensitivity analysis for the CE-QUAL-W2 model.

Statistical assessment provides a quantitative measure of model performance. Statistics were completed for hourly time series for flow, temperature, and stage at the above listed locations, as well as for the monthly temperature profiles in Shasta Lake and Keswick Reservoir. The selection and use of a specific performance criterion should be sufficiently broad to provide an effective interpretation of results because rarely is one error measure sufficient (Zhong and Dutta 2015, Hwang et al. 2012, Jain and Sudheer 2008, Legates and McCabe 1999). Quantitative assessment of model performance included mean bias (ε), mean absolute error (MAE), root-mean squared error (RMSE) and Nash-Sutcliffe (NSE) efficiency coefficient.

Mean Bias, $\varepsilon = \frac{1}{n}\sum_{i=1}^{n}(Xsim_i - Xmeas_i)$

$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}|Xsim_i - Xmeas_i|$

$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(Xsim_i - Xmeas_i)^2}{n}}$

$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}(Xsim_i - Xmeas_i)^2}{\sum_{i=1}^{n}(Xmeas_i - \overline{Xmeas_i})^2}$

where *Xsim* is simulated data, *Xmeas* is measured data, $\overline{Xmeas}$ is the mean of measured data, and *n* is sample size. These metrics represent bias (mean bias), absolute error (MAE and RMSE), one goodness-of-fit (NSE) measures, providing a robust means to assess and quantify model performance.

Mean bias, ε, provides information relating to systematic model over- or under-prediction. Equal model over- or under-prediction results in a ε value of zero. MAE is the average of the absolute value of the bias of paired observations and simulated values, thus negative and positive errors do not cancel out. MAE provides an estimate of overall model error. RMSE is a function of the square of the difference between the paired observations and simulated values, and large values indicate that there are periods where differences are appreciable (e.g., outliers).

The Nash-Sutcliffe efficiency (NSE) is a relative index of agreement between observed and computed values between periods or basins (Mathevet et al. 2006). Nash and Sutcliffe (1970) define the NSE as a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance and is an indication of how well the plot of observed versus simulated data fits the 1:1 line. Thus, NSE is a useful goodness-of-fit parameter for model evaluation because it is sensitive to differences in the observed and modeled means as well as variances (Legates and McCabe 1999; Krausel et al. 2005; McCuen 2006). NSE ranges from $-\infty$ to 1. If NSE is equal to 1, it indicates perfect model performance, a value of zero indicates that the model predictions are as accurate as the mean of the observed data, and for values less than zero the observed mean is a better predictor than the model. While the NSE is typically used to assess the performance of rainfall-runoff models (Mathevet et al. 2006), the statistic has also been used to assess other water quality parameters (Moriasi et al. 2007).

These error statistics are used together to provide insight into model performance. For this project the calibration targets for water temperature, flow and stage are included in Table 6-3. Metrics were based on past experience in applying CE-QUAL-W2 models and considered measurement accuracy of typical instrumentation used to collect stage, flow, and water temperature data; bathymetric representation used to develop model grid; selected model spatial resolution (e.g., 3.28 ft (1 m) layer thickness); representative meteorological data; and overall model structure and process representations (e.g., governing equations, numerical solutions, withdrawal logic representations, wind forcing approximations, etc.).

Table 4-1. Model performance metrics for water temperature, flow and reservoir stage in the Shasta Lake and Keswick Reservoir. MAE – mean absolute error. RMSE – root mean squared error. NSE – Nash Sutcliffe efficiency.

Parameter	**Mean Bias**	**MAE**	**RMSE**	**NSE**
Stage	±0.5 ft (0.15 m)	≤1.0 ft (0.3 m)	≤1.5 ft (0.45 m)	≥0.65
Flow	±50 cfs (1.4 cms)	≤150 cfs (4.2 cms)	≤500 cfs (14.2 cms)	≥0.65
Water Temperature	±0.75°C	≤1.0°C	≤1.5°C	≥0.65

Generally, if the absolute value of mean bias is equal to MAE, the model systematically over- or under-predicted measured data. The RMSE will always be larger or equal to the MAE, and the greater difference between them, the greater the variance in the individual errors in the sample. If RMSE is approximately equal to MAE, then all the errors are of the same magnitude (low variance). Guidance on model performance values for NSE were derived from Moriasi et al. (2007). As noted, NSE can be sensitive to outliers; however, RMSE can be used in tandem with NSE to evaluate such conditions. Similarly, NSE can be sensitive when the measured data have little variability (e.g., isothermal conditions on reservoir vertical temperature profiles), thus relying on other summary statistics can provide insight into model performance.

Calibration considered information from an 18-year record (2000-2017). This period includes:

- Hydrology that ranges from critically dry years to extremely wet years.

- Shasta Lake storage that ranges from historic lows (since TCD inception) to spill conditions.
- A wide range of inter- and intra-annual variations in:
    - TCD operations in response to variable storage, outflows, temperature conditions within the lake,
    - Keswick Reservoir and Spring Creek Tunnel operations, and
    - Local meteorological conditions.

Overall, this historical period provided a wide range of conditions that proved valuable to test and calibrate the models. The objective was to fit all years with a common set of assumptions and calibration parameters (i.e., not changing assumptions and calibration parameters year to year) for each system. Model validation was completed for years 2018 through 2021. Model simulations for these four years were completed without modifying the calibration parameters from the 2000-2017 period. Results and summary statistics were computed and compared with calibration period values.

Model calibration parameters and associated information for CE-QUAL-W2 models are provided in the following section, followed by a discussion of model calibration, validation, and sensitivity analysis for Shasta Lake and Keswick Reservoir CE-QUAL-W2 models. Subsequent sections present model calibration parameters and associated information for ResSim models, followed by a discussion of model calibration, validation, and sensitivity analysis for Shasta Lake, Keswick Reservoir, and Sacramento River ResSim models.

CEQUAL-W2 Calibration Parameters

Final CE-QUAL-W2 model parameters and settings considered in calibration of the Shasta Lake and Keswick Reservoir models are presented herein, and the calibration results for the two reservoirs are presented in the subsequent sections of this chapter. Generally, calibration and model parameters, presented with default values in Table 4-2, are the same for the two reservoirs, but differences occur. Notable differences include:

- DLTMIN, DLTMAX, DLTF: minimum and maximum time step, and maximum time step fraction. Minimum time step was 1.0 second for all years except 2016, when 0.40 seconds was required for model stability. Maximum time step varied from 360 seconds to 3,600 seconds and was used in concert with DLTF to maintain model stability on a year-to-year basis.
- T2I: initial temperature profile for the reservoirs. For Shasta Lake, measured profiles were used as the initial condition for vertical temperature distribution. Each year of the simulation had a distinct initial profile that typically occurred within 1 week of January 1. Because measured profiles were unavailable for Keswick Reservoir, an isothermal condition was assumed with an assigned temperature of 11ºC. This assumption was representative because Keswick Reservoir typically experiences weak stratification and is isothermal on January 1. Historic Keswick Reservoir measured outflow temperatures were typically in the 10ºC to 11ºC range, and the short residence time "washes" this initial condition signal out of the reservoir in a short time (e.g., a few days).

- AFW, BFW, CFW: *a*, *b*, and *c* coefficients for wind speed formulation related to evaporation. Shasta Lake the *a* (9.45 Wm-2 mm Hg-1) and *c* (2.05) values were slightly modified during calibration. CE-QUAL-W2 default values were used for Keswick Reservoir.
- CBHE and TSED: coefficient of bottom heat exchange and sediment temperature. For Shasta Lake CBHE was increased to 0.6 Wm-2 ºC-1 and sediment temperature set to 6ºC. The Keswick Reservoir CBHE default value was used, and bed temperature set to 1ºC. The bed temperature was insensitive in Keswick Reservoir.
- BETA: Fraction of incident solar radiation absorbed at the water surface. Beta was set to 0.40 for Shasta Lake, while the default value of 0.45 was employed for Keswick Reservoir.

Table 4-2. CE-QUAL-W2 default model parameters, and final calibrated values for Shasta Lake and Keswick Reservoir.

Parameter	Default	Shasta Lake	Keswick Reservoir	Description
DLTMIN	NA	0.40-1.00	1.00	Minimum time step, sec
DLTMAX	NA	360-3,600	Variable	Maximum time step, sec
DLTF	NA	0.4-0.9	Variable	Fraction of calculated maximum time step necessary for numerical stability
SLOPE	NA	0.00	0.00	Branch bed slope
AX	1.00	1.00	1.00	Longitudinal eddy viscosity, m^2sec^{-1}
AZC	TKE	TKE	TKE	Form of vertical turbulence closure algorithm
AZSLC	IMP	IMP	IMP	IMP specifies implicit treatment of the vertical eddy viscosity in the longitudinal momentum equation.
AZMAX	1.00	1.00	1.00	Maximum value for vertical eddy viscosity, m^2sec^{-1}
FRICC	CHEZY	CHEZY	CHEZY	Bed friction type
T2I	NA	-1.00[1]	11.00	Initial Temperature, ºC
PQC	OFF	ON	ON	Density placed inflows
EVC	ON	ON	ON	Evaporation included in water budget
PRC	OFF	OFF	OFF	Precipitation included
SLHTC	TERM	TERM	TERM	Specify either term-by-term (TERM) or equilibrium temperature computations (ET) for surface heat exchange
SROC	OFF	ON	ON	Read in observed short wave solar radiation
RHEVC	OFF	OFF	OFF	Ryan-Harleman evaporation formula
METIC	ON	ON	ON	Meteorological data interpolation
FETCHC	OFF	OFF	OFF	Fang and Stefan fetch calculation
AFW	9.2	9.45	9.20	"a" coeff. in wind speed formulation, Wm^{-2} mm Hg^{-1}
BFW	0.46	0.46	0.46	"b" coeff. in wind speed formulation, Wm^{-2} mm Hg^{-1} $(m/s)^{-1}$
CFW	2.0	2.05	2.00	"c" coefficient in wind speed formulation, [-]
WINDH	-	2.00	2.00	Wind speed measurement height, m
ICEC	OFF	OFF	OFF	Ice calculations
SLTRC	ULTIMATE	ULTIMATE	ULTIMATE	Transport solution scheme

THETA	0.55	0.55	0.55	Time-weighting for vertical advection scheme
CBHE	0.3	0.60	0.30	Coefficient of bottom heat exchange, $Wm^{-2}\,^{o}C^{-1}$
TSED	-	6.00	10.00	Sediment temperature, ^{o}C
FI	0.01	0.01	0.01	Interfacial friction factor
TSEDF	1.0	1.0	1.0	Heat lost to sediments added back to water column
EXH2O	0.45	0.45	0.45	Extinction for pure water, m^{-1}
BETA	0.45	0.40	0.45	Fraction of incident solar radiation absorbed at the water surface
DX	1.00	1.00	1.00	Longitudinal eddy diffusivity, m^2sec^{-1}
Wind Sheltering	1.00	1.00	1.00	Wind sheltering coefficient (1.00 – no sheltering values. <1.00 – sheltering)

[1] "-1.0" is the model parameter value that is used to specify a measured vertical profile is used to initialize every segment in the model domain.

CEQUAL-W2 Calibration

CE-QUAL-W2 calibration utilized both graphical and statistical assessments to evaluate model performance. Graphing simulated and field observation provides subjective evaluation, providing a qualitative assessment of magnitude, phase, rate of change and other information that may not be readily apparent in statistical analysis. Graphical assessment was completed for the entire simulation period for:

- Hourly time series comparison of flow and water temperature data below Shasta Dam and below Keswick Dam, as well as time series of Shasta Lake and Keswick Reservoir elevations.
- Temperature profiles, with measured data available at approximately monthly intervals, for Shasta Lake above Shasta Dam and Keswick Reservoir upstream of Keswick Dam (only a partial year is available for Keswick Reservoir).

Important in this assessment was the objective of effectively simulating thermal profiles in Shasta Lake, which are used by resource managers to track available cold water, and tailbay temperatures, which determine downstream temperatures.

Shasta Lake

Shasta Lake CE-QUAL-W2 calibration included assessing model performance for reservoir elevation, reservoir outflow, in-reservoir vertical temperature profiles, and tailbay temperature. Graphical results are presented for selected years, and the complete suite of graphs containing simulated versus observed values included in the Appendices. Where feasible summary statistics are presented in this discussion for the entire simulation period. The comprehensive tables of all simulation years are reproduced in the Appendices. All calibration metrics identified herein refer to Table 4-1.

Reservoir Stage

Graphically, simulated Shasta Lake stage tracked measured values closely in all years. The calendar year 2015 is shown as an example in Figure 4-1. Mean bias was within the calibration metric of ±0.5 ft (0.15 m) for all years except 2007 (-0.55 ft (0.17 m)), 2010 (-0.52 ft (0.16 m)), and 2015 (-0.81 ft (0.25 m)). MAE and RMSE were less than the identified, with maximum values of 0.81 ft (0.25 m) and 0.86 ft (0.26 m), respectively, both of which occurred in 2015. NSE was equal to 1.0 in all years, indicating the model reproduced lake stage through seasons with a high degree of confidence. Summary statistics are included in Table 4-3. Graphical and tabular information for all years is provided in Appendix A.

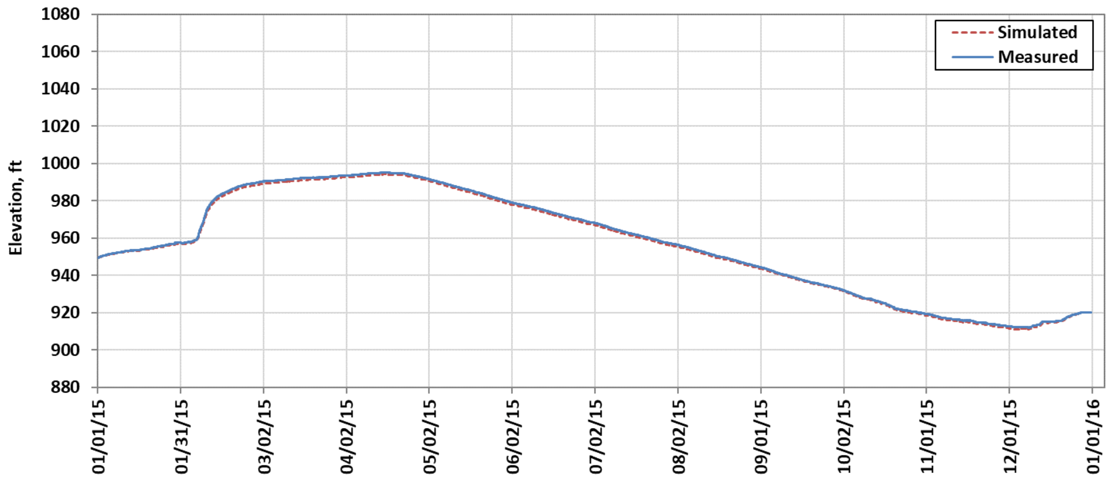


Figure 4-1. Simulated versus measured Shasta Lake stage: 2015.

Table 4-3. Summary statistics of Shasta Lake stage: 2000-2017. Information was split into two tables: the upper table lists summary statistics for 2000-2008; the lower table lists summary statistics for 2009-2017. An asterisk (also highlighted gray) indicates value was outside the calibration criteria.

Statistic	2000	2001	2002	2003	2004	2005	2006	2007	2008
Mean Bias (ft)	-0.14	0.02	-0.19	-0.03	0.02	-0.17	-0.06	0.07	-0.22
MAE (ft)	0.22	0.44	0.26	0.23	0.34	0.39	0.29	0.42	0.53
RMSE (ft)	0.28	0.53	0.31	0.30	0.42	0.48	0.32	0.50	0.61
Nash-Sutcliffe (NSE)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
COUNT	8,472	8,760	8,760	8,760	8,784	8,760	8,760	8,760	8,784

Statistic	2009	2010	2011	2012	2013	2014	2015	2016	2017
Mean Bias (ft)	0.09	-0.61*	0.03	-0.42	-0.39	-0.15	-0.45	-0.02	-0.10
MAE (ft)	0.37	0.62	0.21	0.67	0.53	0.66	0.49	0.50	0.41
RMSE (ft)	0.49	0.68	0.24	0.82	0.66	0.77	0.55	0.66	0.50
Nash-Sutcliffe (NSE)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
COUNT	8,760	8,760	8,760	8,784	8,760	8,760	8,760	8,784	8,760

Outflow

Simulated versus measured Shasta Lake outflow tracked measured values exactly in all years. Calendar year 2015 is shown in as an example in Figure 4-2. Mean bias, MAE, and RMSE were zero, and NSE was 1.0. Because outflow is a specified boundary condition to the CE-QUAL-W2 model, simulated values, will match the measured outflow used to define the boundary condition. Summary statistics are included in Table 4-4. Graphical and tabular information for all years is provided in Appendix A.

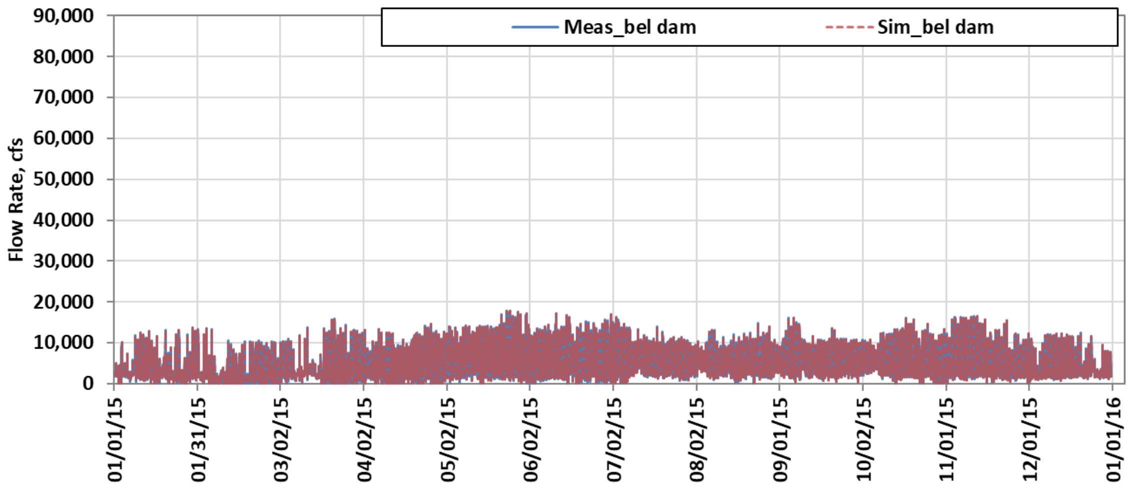


Figure 4-2. Simulated versus measured Shasta Dam outflow: 2015.

Table 4-4. Summary statistics for Shasta Dam outflow: 2000-2017. Table has been split into two sections to ease reading: upper section presents statistics for 2000-2008; lower section presents statistics for 2009-2017.

Statistic	2000	2001	2002	2003	2004	2005	2006	2007	2008
Mean Bias (ft)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MAE (ft)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RMSE (ft)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nash-Sutcliffe (NSE)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
COUNT	8,472	8,760	8,760	8,760	8,784	8,760	8,760	8,760	8,784

Statistic	2009	2010	2011	2012	2013	2014	2015	2016	2017
Mean Bias (ft)	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
MAE (ft)	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
RMSE (ft)	0.2	0.1	0.0	0.0	0.3	0.2	0.5	0.1	0.0
Nash-Sutcliffe (NSE)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
COUNT	8,760	8,760	8,760	8,784	8,760	8,760	8,760	8,784	8,760

Reservoir Temperature Profiles

Simulated versus measured Shasta Lake temperature profiles tracked measured values closely in all years, except for short periods. Calendar year 2015 is shown as an example (Figure 4-3), and tabular results monthly mean bias, MSE, RMSE and NSE are included in Table 4-5 through Table 4-8. Mean bias ranged from -0.74ºC (December 2004) to 1.26ºC (October 2001). Mean bias did not meet the calibration metric of ±0.75ºC in in 15 months over six years (2001, 2002, 2013, 2014, 2015) or 7.2 percent of the time. Seven of those occurrences were in 2014, where the model predicted warmer temperatures than observed (Table 4-5).

MAE ranged from 0.14ºC (January 2000) to 1.32ºC (August 2014). MAE did not meet the calibration metric of ≤1.0ºC in 11 months over five years (2001, 2008, 2009, 2013, 2014) or 5.3 percent of the time. Six of those occurrences were in 2014 (Table 4-6). RMSE ranged from 0.20ºC (January 11) to 1.75ºC (August 2014). RMSE did not meet the calibration metric of ≤1.5ºC in in one month over five years (October 2008), or 0.5 percent of the time (Table 4-7). NSE ranged from -0.92 (January 2015)) to 1.0 (multiple occurrences). NSE did not meet the calibration metric of ≥0.65 in at least one month in 16 of the 18 years. However, NSE met the calibration metric in all years for the months from April through November with one exception (April 2014) (Table 4-8). NSE tended to have very low values under isothermal or near isothermal conditions during winter (December through March), which had little variability in water temperature with depth.

While NSE did not meet the criteria in December through March on 26 occurrences (32.5 percent), the total number of times that mean bias, MAE, and RMSE criteria were not met in the December through March period was three, two, and five (3.75, 2.5, and zero percent), respectively. The model performed well with low bias, MAE, and RMSE during the winter months, even though NSE was poor. Review of graphical results comparing simulated and observed vertical profiles illustrate this issue for January, February, and March of 2015 (Figure 4-3) This approach is an example of using qualitative graphical analysis and quantitative statistics that include bias, absolute error, and goodness-of-fit, allow a broad approach to assess model performance. Graphical and tabular information for all years is provided in Appendix A.

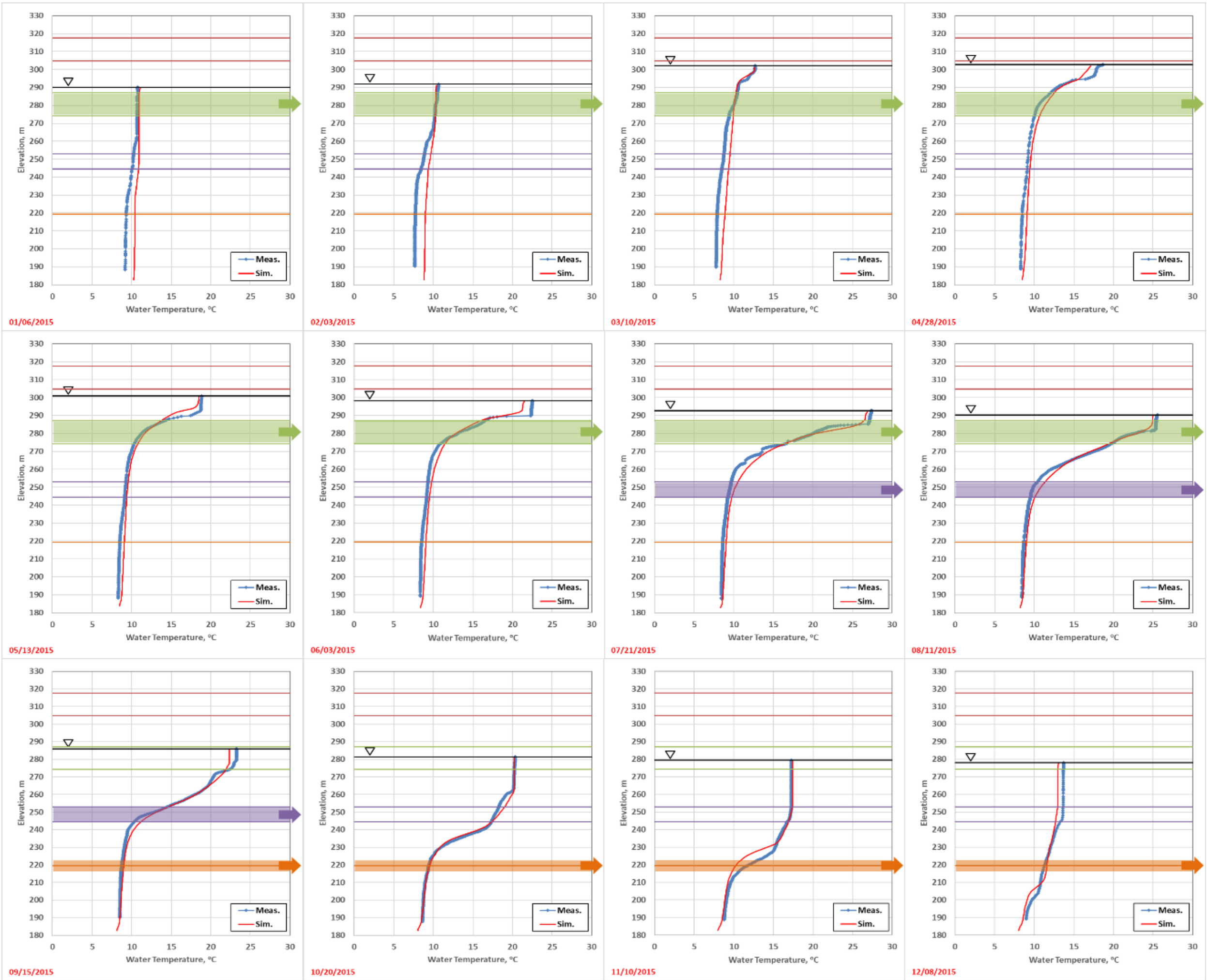


Figure 4-3. Simulated versus measured temperature profiles upstream of Shasta Dam: 2015.

Table 4-5. Mean bias for monthly temperature profiles (°C) for Shasta Lake above Shasta Dam: 2000-2017. (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of ±0.75°C.) A "—" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.11	0.21	-0.29	-0.23	-0.07	-0.13	-0.07	-0.08	-0.13	0.23	0.02	-0.38
2001	0.03	0.01	-0.01	0.21	0.48	0.40	0.52	0.74	1.19*	1.57*	1.30*	-0.16
2002	-0.15	0.08	0.24	0.38	0.36	0.45	0.39	0.56	0.56	0.84*	0.80*	--
2003	0.33	-0.04	0.02	0.27	0.43	0.25	0.11	0.16	0.12	0.07	-0.03	0.07
2004	0.32	0.13	0.19	0.09	0.09	0.01	-0.09	-0.16	-0.31	-0.44	-0.59	-0.74
2005	0.04	0.13	0.09	0.39	0.36	0.52	0.33	0.51	0.64	0.69	0.52	0.42
2006	-0.15	-0.17	-0.28	0.03	0.00	0.19	0.10	0.00	0.06	-0.19	-0.06	-0.22

2007	0.37	0.12	0.38	0.19	0.13	0.12	0.08	-0.08	0.00	-0.78	-0.68	-0.50
2008	0.20	-0.02	0.32	0.45	0.29	0.08	0.27	0.14	0.13	-0.70	-0.31	-0.10
2009	0.56	0.90*	0.26	0.57	0.71	0.82*	0.71	0.75	0.72	0.41	0.47	0.54
2010	0.25	-0.45	-0.45	--	0.08	0.43	0.35	0.20	0.26	0.07	0.04	-0.11
2011	0.13	0.34	0.21	0.12	0.06	0.18	0.19	0.26	0.43	0.48	0.34	0.08
2012	0.18	0.28	0.40	--	0.55	0.43	0.37	0.22	0.27	0.08	0.26	--
2013	0.35	0.35	0.54	0.58	0.87*	--	--	0.30	0.72	0.27	-0.05	-0.38
2014	0.39	0.56	1.09*	1.21*	1.26*	1.10*	1.24*	1.37*	0.94*	0.71	0.54	0.53
2015	0.75	0.82*	0.62	0.39	0.22	0.23	0.49	0.25	0.17	0.06	-0.29	-0.38
2016	0.36	-0.12	0.56	0.48	0.56	0.68	0.59	0.71	0.69	0.57	0.36	--
2017	0.41	0.25	-	0.20	0.46	0.54	0.63	0.54	0.60	0.57	0.50	0.37

Table 4-6. Mean absolute error (MAE) for monthly temperature profiles (°C) for Shasta Lake above Shasta Dam: 2000-2017. (Values marked with an asterisk (also highlighted gray) indicate values greater than the calibration criteria of 1.0°C.) A "—" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.28	0.41	0.30	0.26	0.15	0.37	0.29	0.37	0.43	0.52	0.38	0.41
2001	0.24	0.44	0.41	0.61	0.62	0.54	0.55	0.79	1.19*	1.57*	1.30*	0.60
2002	0.17	0.29	0.44	0.51	0.66	0.73	0.63	0.66	0.67	0.84	1.00	--
2003	0.36	0.23	0.23	0.50	0.62	0.40	0.37	0.31	0.39	0.32	0.30	0.28
2004	0.42	0.44	0.52	0.33	0.25	0.29	0.22	0.33	0.56	0.48	0.63	0.74
2005	0.43	0.46	0.35	0.66	0.59	0.66	0.54	0.64	0.68	0.80	0.67	0.58
2006	0.27	0.80	0.28	0.29	0.36	0.42	0.24	0.22	0.26	0.25	0.37	0.28
2007	0.37	0.40	0.66	0.50	0.41	0.34	0.42	0.31	0.32	0.80	0.74	0.55
2008	0.22	0.50	0.66	0.58	0.68	0.54	0.47	0.45	0.40	0.91	0.59	0.55
2009	0.62	1.02*	0.49	0.72	0.74	0.85	0.82	0.76	0.76	0.47	0.47	0.54
2010	0.26	0.45	0.45	--	0.37	0.54	0.42	0.40	0.43	0.34	0.48	0.47
2011	0.14	0.39	0.39	0.20	0.16	0.36	0.32	0.44	0.57	0.64	0.50	0.26
2012	0.19	0.30	0.59	--	0.93	0.68	0.58	0.54	0.47	0.52	0.37	--
2013	0.35	0.44	0.67	0.64	1.08*	--	--	0.50	0.75	0.59	0.43	0.76
2014	0.39	0.61	1.31*	1.32*	1.32*	1.24*	1.34*	1.37*	0.95	0.88	0.73	0.60
2015	0.75	0.86	0.68	0.56	0.51	0.58	0.59	0.42	0.38	0.23	0.47	0.49
2016	0.75	0.27	0.81	0.58	0.71	0.83	0.78	0.88	0.88	0.87	0.77	--
2017	0.61	0.54	-	0.42	0.48	0.71	0.70	0.61	0.66	0.75	0.74	0.44

Table 4-7. Root mean squared error (RMSE) for monthly temperature profiles (°C) for Shasta Lake above Shasta Dam: 2000-2017. (Values marked with an asterisk (also highlighted gray) indicate values greater than the calibration criteria of 1.5ºC.) A "—" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.31	0.43	0.39	0.52	0.20	0.61	0.37	0.44	0.48	0.64	0.46	0.50
2001	0.26	0.47	0.56	0.75	0.69	0.59	0.62	0.95	1.48	1.86*	1.70*	0.67
2002	0.20	0.32	0.49	0.60	0.81	0.84	0.74	0.84	0.85	1.20	1.36	--
2003	0.48	0.30	0.28	0.53	0.66	0.59	0.50	0.40	0.48	0.40	0.35	0.33
2004	0.52	0.46	0.56	0.47	0.41	0.57	0.35	0.39	0.73	0.58	0.76	0.95
2005	0.48	0.52	0.39	0.68	0.66	0.81	0.70	0.73	0.78	0.91	0.81	0.83
2006	0.29	0.41	0.40	0.33	0.61	0.69	0.38	0.32	0.36	0.30	0.45	0.36
2007	0.46	0.42	0.76	0.68	0.69	0.54	0.50	0.43	0.45	1.29	1.14	0.68
2008	0.26	0.52	0.69	0.63	1.01	0.64	0.50	0.62	0.60	1.54*	1.03	0.73
2009	0.82	1.16	0.52	0.76	0.96	0.98	0.91	0.82	0.84	0.68	0.66	0.80
2010	0.34	0.51	0.47	--	0.60	0.76	0.54	0.62	0.52	0.41	0.61	0.54
2011	0.21	0.45	0.41	0.22	0.20	0.68	0.52	0.66	0.80	0.84	0.71	0.42
2012	0.21	0.34	0.65	--	1.12	0.76	0.70	0.60	0.53	0.59	0.43	--
2013	0.42	0.50	0.73	0.71	1.16	--	--	0.56	0.94	0.65	0.48	0.86
2014	0.49	0.73	1.41	1.43	1.37	1.35	1.39	1.43	1.08	0.94	0.85	0.74
2015	0.83	0.99	0.75	0.60	0.64	0.70	0.73	0.50	0.47	0.35	0.79	0.56
2016	0.82	0.35	0.89	0.67	0.93	1.00	1.00	1.10	1.15	1.11	0.93	--
2017	0.69	0.58	-	0.47	0.58	0.96	0.90	0.75	0.83	0.99	0.94	0.71

Table 4-8. Nash Sutcliffe Efficiency for monthly temperature profiles (°C) for Shasta Lake above Shasta Dam: 2000-2017. (Values marked with an asterisk (also highlighted gray) indicate values less than the calibration criteria of 0.65.) A "—" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.93	0.74	0.48*	0.91	0.99	0.98	0.99	0.99	0.99	0.97	0.97	0.90
2001	0.90	0.26*	0.83	0.88	0.96	0.98	0.99	0.98	0.94	0.85	0.71	0.74
2002	0.88	0.87	0.71	0.94	0.92	0.96	0.98	0.98	0.98	0.93	0.83	--
2003	0.79	0.82	0.91	0.83	0.90	0.98	0.99	0.99	0.99	0.99	0.99	0.97
2004	0.56*	0.68	0.41*	0.95	0.98	0.99	1.00	1.00	0.98	0.98	0.92	0.50*
2005	0.74	0.70	0.91	0.75	0.91	0.95	0.98	0.98	0.97	0.94	0.90	0.75
2006	0.91	0.80	0.60*	0.84	0.93	0.97	0.99	1.00	1.00	1.00	0.98	0.98
2007	0.81	0.82	0.35*	0.87	0.96	0.99	0.99	0.99	0.99	0.88	0.81	0.90
2008	0.92	0.21*	0.55*	0.78	0.90	0.98	0.99	0.99	0.99	0.88	0.86	0.88

2009	0.60*	-0.44*	0.01*	0.77	0.90	0.95	0.97	0.98	0.98	0.97	0.95	0.85
2010	0.88	0.36*	0.50*	--	0.91	0.94	0.99	0.99	0.99	0.99	0.97	0.90
2011	0.94	0.81	0.43*	0.93	0.99	0.96	0.99	0.98	0.98	0.96	0.95	0.97
2012	0.97	0.81	0.48*	--	0.79	0.95	0.98	0.99	0.99	0.99	0.99	--
2013	0.84	0.77	0.64*	0.82	0.84	-	-	0.99	0.97	0.98	0.97	0.63*
2014	0.84	0.37*	-0.14*	0.37*	0.83	0.91	0.95	0.95	0.96	0.95	0.93	0.76
2015	-0.93*	0.17*	0.64*	0.94	0.96	0.97	0.98	0.99	0.99	0.99	0.95	0.87
2016	0.03*	0.84	-0.18*	0.90	0.85	0.93	0.96	0.96	0.95	0.95	0.88	--
2017	0.43*	0.53*	--	0.90	0.96	0.96	0.97	0.98	0.98	0.95	0.89	0.91

Outflow Temperature

Simulated versus measured Shasta Lake outflow temperature tracked measured values closely in all years, except for a few short periods. Calendar year 2015 is shown as an example in Figure 4-4. This graphic contains several elements:

- Vertical dashed lines represent TCD level changes (when a level was first or last accessed).
- Upper Graphic:
    - Simulated versus measured outflow Shasta Dam outflow temperatures time series are shown (left axis). There are two measured outflow temperature time series that are used to represent conditions below Shasta Dam: (a) measured temperatures in the headwater of Keswick Reservoir (listed as "Meas." in graph legends) and (b) simulated temperatures leaving the powerhouse penstocks that are calculated based on a mass balance using individual penstock flow and associated temperatures (listed as "Twtrgt" in graph legends).
    - Outflows from the dam via the TCD, river outlets, and/ spill are shown (on right axis). Flows from each TCD level (e.g., TCDU, TCDM, TCDL, TCDS) are represented by their respective point sink flows (e.g., TCDU1, TCDU2, TCDU3, representing upper, middle, and lower point sinks, respectively). The low-level intake or side gate structure (TCDS) also includes the deeper outlet representation (TCD_d or TCD_dwn in graph legends).
    - The upper, middle, and lower river outlets levels are included (RRU, RRM, RRL, respectively) as is spill (SPILL)
- Middle Graphic:
    - Active TCD gates indicate which of the five gates (TCDU, TCDM, TCDL) are active through the year (e.g., for the five gates located on the upper level are labelled U1, U2, U3, U4, U5). Similarly, the graphic indicates which of the two gates for the low-level intake (TCDS) are active.
    - Also shown are the relative percentages of flow for each of the penstocks (P1 through P5). TCD gate numbers on the upper, middle, and lower levels correspond to the penstock numbers.

- Lower Graphic:
    - Simulated water surface elevation through the year.
    - The upper and lower elevations of TCDU, TCDM, TCDL, TCDS levels (physical elevation of the gate top ("upp") and bottom ("low")).

Results are presented for all simulation years in Appendix A.

The information contained in these figures was particularly useful to the analyst during model calibration. Basic information such as flow, stage, and temperature are common conditions to consider in calibration. Specifically, information regarding TCD operations, active levels, number of gates open on any one level, and powerhouses in operation assist the analyst in interpreting model simulation results and adjusting model parameters during calibration[5].

Mean bias ranged from -0.41ºC (2004) to 0.20ºC (2016), meeting the calibration metric of ±0.75ºC all years. MAE ranged from 0.16ºC (2005) to 0.61ºC (2000) and met the calibration metric of ≤1.0ºC all years. RMSE ranged from 0.26ºC (2005) to 0.75ºC (2000) and met the calibration metric of ≤1.5ºC in all months. NSE ranged from 0.37 (2016) to 0.96 (2005). Two years did not meet the calibration metric of ≥0.65 (2016: 0.37 and 2000: 0.53). Summary statistics for mean bias, MAE, RMSE, and NSE are included in Table 4-9.

[5] TEST

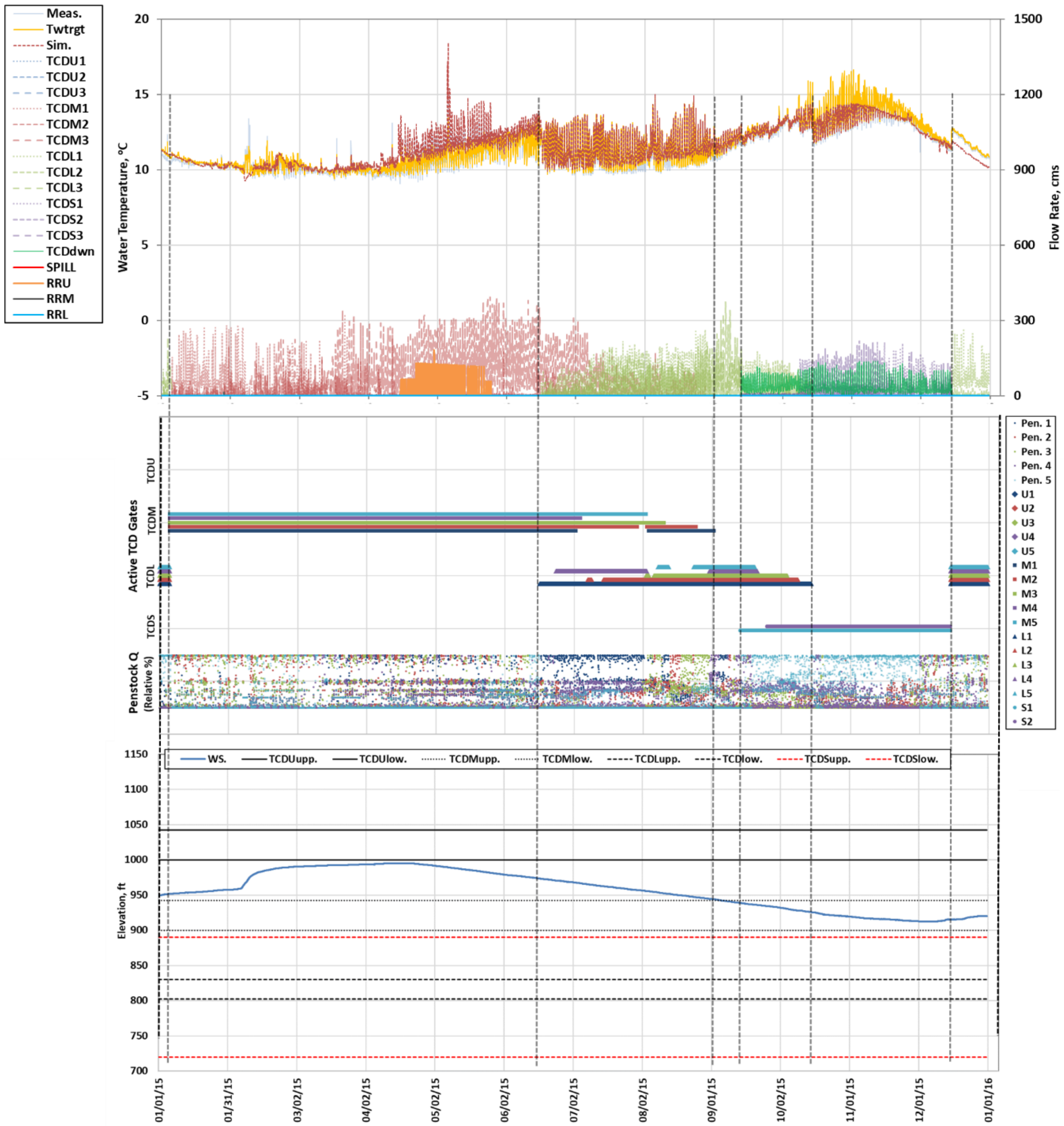


Figure 4-4. Shasta Lake simulated temperature vs. target temperature & measured temperature, and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2015.

Table 4-9. Summary statistics of Shasta Dam outflow temperature: 2000-2017. (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistic	2000	2001	2002	2003	2004	2005	2006	2007	2008
Mean Bias (ºC)	-0.08	0.09	-0.01	-0.11	-0.42	-0.06	-0.31	-0.29	-0.24
MAE (ºC)	0.60	0.36	0.31	0.20	0.47	0.15	0.33	0.38	0.38
RMSE (ºC)	0.74	0.59	0.45	0.31	0.73	0.25	0.47	0.64	0.69
Nash-Sutcliffe (NSE)	0.54*	0.85	0.88	0.88	0.85	0.97	0.78	0.82	0.92
COUNT	8,472	8,760	8,760	8,760	8,784	8,760	8,760	8,760	8,784

Statistic	2009	2010	2011	2012	2013	2014	2015	2016	2017
Mean Bias (ºC)	0.23	-0.19	-0.12	-0.04	-0.06	-0.03	0.07	0.20	0.07
MAE (ºC)	0.41	0.30	0.19	0.24	0.45	0.43	0.39	0.38	0.30
RMSE (ºC)	0.60	0.49	0.32	0.36	0.66	0.66	0.58	0.59	0.39
Nash-Sutcliffe (NSE)	0.90	0.64*	0.82	0.88	0.80	0.93	0.83	0.52*	0.84
COUNT	8,760	8,760	8,760	8,784	8,760	8,760	8,760	8,784	8,760

Keswick Reservoir

Keswick Reservoir CE-QUAL-W2 calibration included assessing model performance for reservoir elevation, reservoir outflow, limited in-reservoir vertical temperature profiles, and outflow temperature. Graphical results are presented for selected years, and the complete suite of graphs containing simulated versus observed values included in the Appendices. Where feasible, summary statistics are presented in this discussion for the entire simulation period. The comprehensive tables of all simulation years are reproduced in the Appendices. Year 2010 was selected as a representative year because several temperature profiles were available. Model results graphics and the related statistics for all model years (2000-17) are included in Appendix B.

Reservoir Stage

Simulated versus measured Keswick Reservoir (elevation) graph is reported relative to mean sea level. Graphically, simulated Keswick Reservoir stage tracked measured values closely in all years. Calendar year 2010 is shown as an example in Figure 4-5. Summary statistics are included in Table 4-10. Mean bias was within the calibration metric of ±0.5 ft (0.15 m) for all years except 2003 (-0.61 ft (-0.19 m)). MAE was less than the identified calibration metric for all years except 2003 (1.09 ft (0.33 m)) and 2011 (1.10 ft (0.34 m)). RMSE were less than the identified calibration metric, with maximum value of 1.32 ft (0.40 m) in 2003 and 2011. NSE ranged from 0.54 to 0.93, with two years below the 0.65 criteria (2003 and 2006, with NSE values of 0.54 and 0.57, respectively).

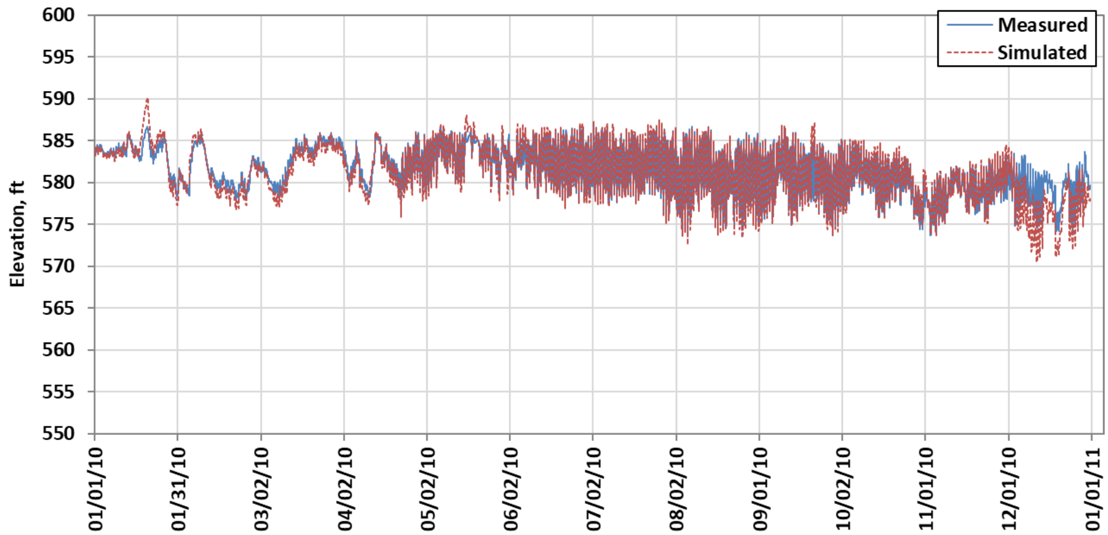


Figure 4-5. Simulated versus measured Keswick Reservoir stage (msl). Year 2010.

Table 4-10. Summary statistics of Keswick Reservoir stage: 2000-2017 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistic	2000	2001	2002	2003	2004	2005	2006	2007	2008
Mean Bias (ft)	-	0.19	0.25	-0.61*	-0.06	0.20	-0.34	0.01	0.49
MAE (ft)	-	0.65	0.79	1.09*	0.50	0.66	0.81	0.43	0.72
RMSE (ft)	-	0.95	1.10	1.32	0.60	0.97	1.13	0.71	0.92
Nash-Sutcliffe (NSE)	-	0.78	0.71	0.54*	0.91	0.72	0.57*	0.81	0.78
COUNT	-	8,760	8,760	8,760	8,784	8,760	8,760	8,760	8,784

Statistic	2009	2010	2011	2012	2013	2014	2015	2016	2017
Mean Bias (ft)	0.37	-0.23	-0.30	0.38	0.23	-0.31	0.36	-0.24	0.20
MAE (ft)	0.68	0.64	1.10*	0.79	0.77	0.67	0.61	0.58	0.70
RMSE (ft)	0.90	0.99	1.32	1.05	1.02	0.87	0.73	0.72	0.89
Nash-Sutcliffe (NSE)	0.75	0.87	0.77	0.85	0.87	0.91	0.92	0.93	0.86
COUNT	8,760	8,760	8,760	8,784	8,760	8,760	8,760	8,784	8,760

Outflow

Simulated versus measured Keswick Reservoir outflow tracked measured values exactly in all years. Calendar year 2010 is shown as an example in Figure 4-6. Mean bias, MAE, and RMSE were in the range between 0.0 cfs and 0.2 cfs, and NSE was 1.0. Because outflow is a specified boundary condition to the CE-QUAL-W2 model, simulated values, will match the measured outflow used to define the boundary condition. Summary statistics are included in Table 4-11. Graphical and tabular information for all years is provided in Appendix B.

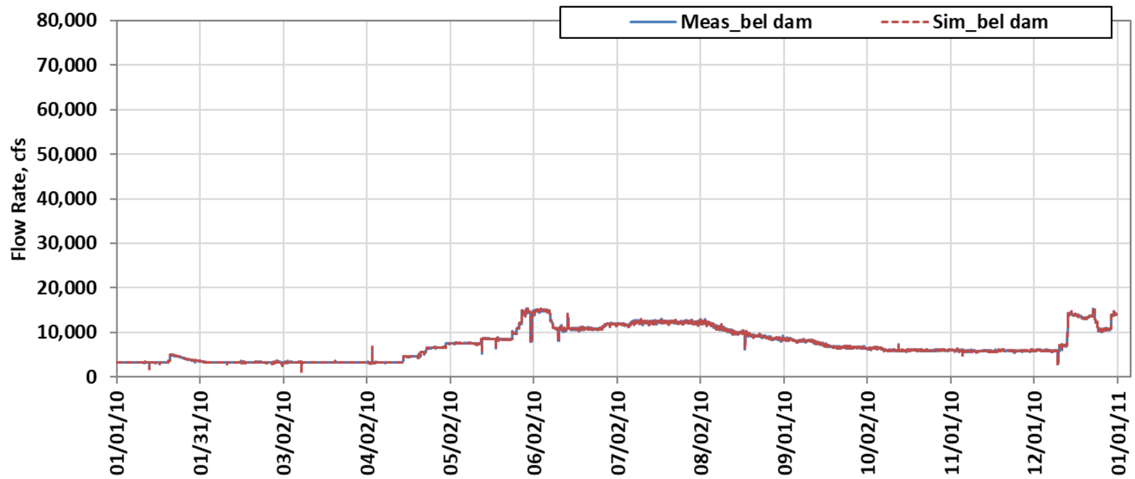


Figure 4-6. Simulated versus measured outflow below Keswick Dam. Year 2010.

Table 4-11. Summary statistics for Keswick Dam outflow: 2000-2017.

Statistic	2000	2001	2002	2003	2004	2005	2006	2007	2008
Mean Bias (cfs)	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0
MAE (cfs)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
RMSE (cfs)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Nash-Sutcliffe (NSE)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
COUNT	8,520	8,662	8,620	8,725	8,601	8,674	8,745	8,753	8,778

Statistic	2009	2010	2011	2012	2013	2014	2015	2016	2017
Mean Bias (cfs)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
MAE (cfs)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
RMSE (cfs)	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.2	0.1
Nash-Sutcliffe (NSE)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
COUNT	8,740	8,755	8,757	8,778	8,754	8,759	8,758	8,783	8,759

Reservoir Temperature Profiles

There are total of eight temperature profiles for Keswick Reservoir, measured in two different locations, in year 2010 (Figure 4-8).[6] The two locations are above and below the Spring Creek

[6] Temperature profiles for Keswick Reservoir were only available for year 2010. No other years had data collected. See Section **Error! Reference source not found.**.

Branch, 2.34 miles and 1.52 miles upstream of the Keswick Dam, respectively. From upstream to downstream, those locations correspond to Segment 87 and Segment 93 in the model grid.

Mean bias ranged from -0.47ºC (January 21, above Spring Creek) to 0.57ºC (March 30, above Spring Creek). Mean bias met the calibration metric for all profiles (Table 4-5). MAE ranged from 0.06ºC (April 14, below Spring Creek) to 0.57ºC (March 30, above Spring Creek). MAE met the calibration metric in all months. RMSE ranged from 0.07ºC (April 14, below Spring Creek) to 0.58ºC (March 30, above Spring Creek). RMSE met the calibration metric in all months.

NSE ranged from -23.14 (May 18, above Spring Creek) to 0.88 (April 14, below Spring Creek). NSE was below the calibration metric of ≥0.65 for all the profiles except April 14, below Spring Creek (0.88). NSE tended to have lower values under isothermal or near isothermal conditions typical of Keswick Reservoir, when one or both data sets showed low variability. Review of graphical results illustrate this issue. In short, when isothermal or near isothermal conditions occur, mean bias, MAE, and RMSE are low, indicating good model performance, i.e., small error. Under isothermal or near isothermal conditions, there is little variability in temperature values, which can lead to low NSE values, even though mean bias, MAE, and RMSE are indicating good performance (i.e., small error); however, review of graphical results confirms the model is representing field data well. This is another example of using qualitative graphical analysis and quantitative statistics that include bias, absolute error, and goodness-of-fit, to assess model performance. In general, the isothermal nature of Keswick Reservoir suggests that NSE may not be a useful metric for assessing model performance.

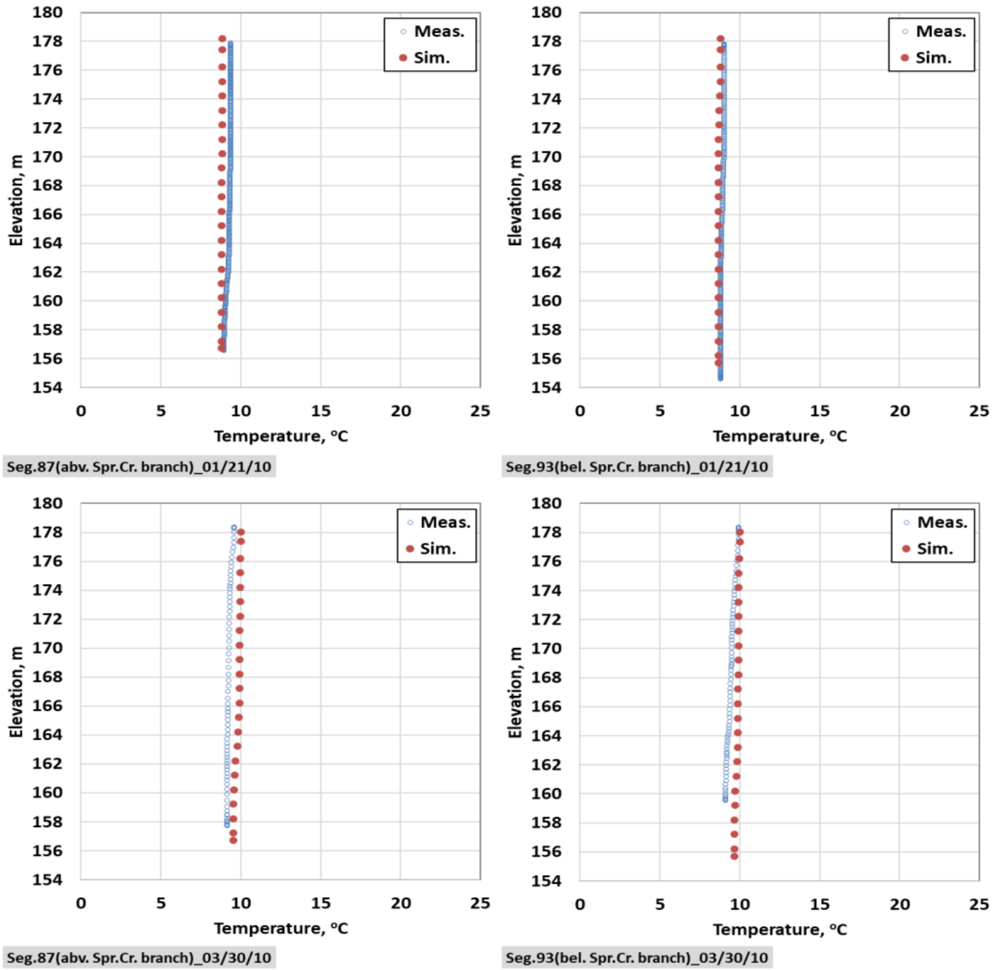


Figure 4-7. Simulated versus measured temperature profiles. 01/21 (top) and 03/30 (bottom), Year 2010.

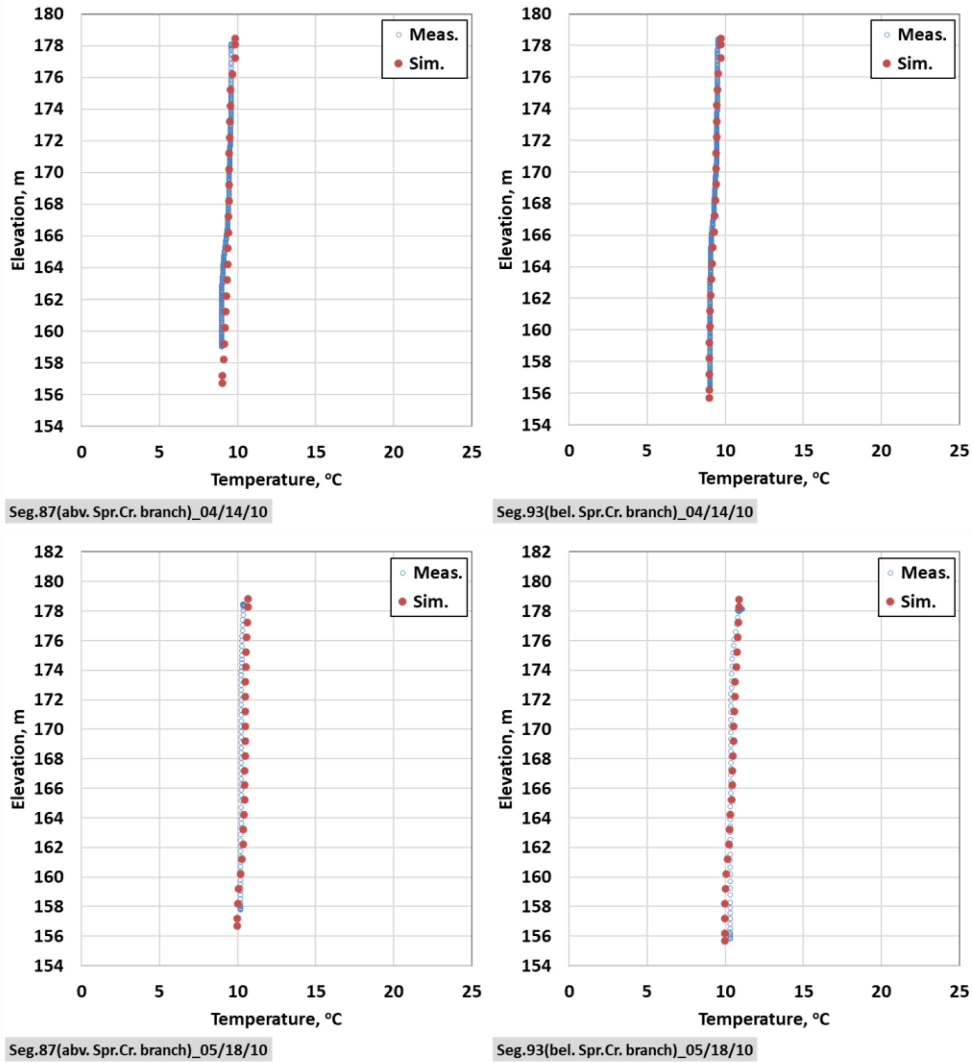


Figure 4-8. Simulated versus measured temperature profiles. 01/21 & 03/30 (top), 04/14 & 05/18 (bottom). Year 2010.

Table 4-12. Mean bias for monthly temperature profiles for Keswick Reservoir: 2010 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistic	Above Spring Ck	Below Spring Ck	Above Spring Ck	Below Spring Ck	Above Spring Ck	Below Spring Ck	Above Spring Ck	Below Spring Ck
Date	1/21/10	1/21/10	3/30/10	3/30/10	4/14/10	4/14/10	5/18/10	5/18/10
Mean Bias (ºC)	-0.47	-0.24	0.57	0.37	0.09	0.02	0.16	-0.01
MAE (ºC)	0.47	0.24	0.57	0.37	0.13	0.06	0.20	0.18
RMSE (ºC)	0.48	0.25	0.58	0.42	0.16	0.07	0.21	0.21
Nash-Sutcliffe (NSE)	-14.02*	-6.64*	-14.88*	-1.73*	0.53*	0.88	-23.14*	-1.35*
COUNT	20	23	21	20	19	22	21	23

Outflow Temperature

Simulated versus measured Keswick Reservoir outflow temperature tracked measured values closely in all years, except for short periods. Calendar year 2010 is shown in as an example in Figure 4-9. Mean bias ranged from -0.03ºC (2005, 2016) to 0.08ºC (2011). Mean bias met the calibration metric for all years (Table 4-13). MAE ranged from 0.14ºC (2006) to 0.26ºC (2015). MAE met the calibration metric in all months. RMSE ranged from 0.19ºC (2000, 2003) to 0.34ºC (2015). RMSE met the calibration metric in all months. NSE ranged from 0.82 (2010, 2011) to 0.98 (2004, 2008 and 2014), and met the calibration metric in all months. Calibration results for additional years are available in **Error! Reference source not found.**.

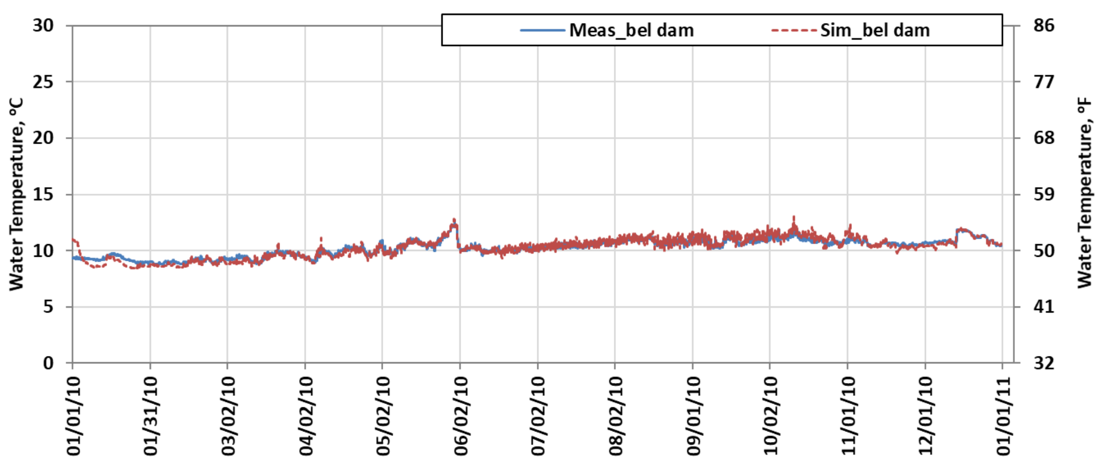


Figure 4-9. Simulated versus measured temperature below Keswick Dam. Year 2010.

Table 4-13. Summary statistics of Keswick Dam outflow temperature: 2000-2017.

Statistic	2000	2001	2002	2003	2004	2005	2006	2007	2008
Mean Bias (ºC)	0.01	0.01	0.07	0.00	-0.01	-0.03	0.01	0.00	0.00
MAE (ºC)	0.15	0.18	0.21	0.15	0.16	0.19	0.14	0.19	0.21
RMSE (ºC)	0.19	0.24	0.28	0.19	0.21	0.24	0.20	0.26	0.29
Nash-Sutcliffe (NSE)	0.96	0.97	0.94	0.94	0.98	0.96	0.96	0.96	0.98
COUNT	8,268	8,568	8,239	8,365	8,018	8,665	8,717	8,619	8,465

Statistic	2009	2010	2011	2012	2013	2014	2015	2016	2017
Mean Bias (ºC)	0.01	-0.01	0.08	-0.01	0.04	0.03	0.03	-0.03	0.00
MAE (ºC)	0.21	0.24	0.24	0.17	0.22	0.22	0.26	0.18	0.15
RMSE (ºC)	0.29	0.32	0.32	0.23	0.33	0.29	0.34	0.23	0.21
Nash-Sutcliffe (NSE)	0.97	0.82	0.82	0.94	0.93	0.98	0.92	0.93	0.96
COUNT	8,739	8,668	8,735	8,739	8,639	8,731	8,642	8,762	8,745

CEQUAL-W2 Validation

Calendar years 2018 through 2021 were used as model validation for the Shasta Lake and Keswick Reservoir models. Model simulations were completed without modifying any calibration parameters from the 2000-2017 period, and summary statistics were computed. Model performance is presented for Shasta Lake and Keswick Reservoir herein.

Shasta Lake

Mean bias, MAE, RMSE, and NSE were calculated for Shasta Lake stage, outflow, temperature profiles, and outflow temperatures for 2018-2021 and are presented with 2000-2017 period calibration summary statistics for comparison. Model performance metrics for Shasta Lake stage and outflow for the validation years are consistent with the calibration period (Table 4-14 and Table 4-15). Shasta Lake model simulated temperature profile results (Table 4-16 through Table 4-19) indicate that validation period metrics are within the range of the calibration results. Mean bias and MAE for 2019 were outside the range of selected model performance criteria for June through November, simulating warmer than observed conditions. Inflow temperature data for the Pit River was unavailable for 2019 and water temperatures were estimated. This data gap may have contributed to reduced model performance. For 2018-2021, simulated outflow temperatures were consistent with the 2000-2017 period (Table 4-20). The model was not recalibrated following validation. Validation results for 2018-2021 are included with calibration results in Appendix B.

Table 4-14. Summary statistics of Shasta Lake stage comparing validation years 2018 and 2019 versus calibration period 2000-2017 (light grey text) (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistic	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009

Mean Bias (ft)	-0.14	0.02	-0.19	-0.03	0.02	-0.17	-0.06	0.07	-0.22	0.09
MAE (ft)	0.22	0.44	0.26	0.23	0.34	0.39	0.29	0.42	0.53	0.37
RMSE (ft)	0.28	0.53	0.31	0.30	0.42	0.48	0.32	0.50	0.61	0.49
Nash-Sutcliffe (NSE)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
COUNT	8,472	8,760	8,760	8,760	8,784	8,760	8,760	8,760	8,784	8,760

Statistic	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Mean Bias (ft)	-0.61*	0.03	-0.42	-0.39	-0.15	-0.45	-0.02	-0.10	-0.06	-0.22
MAE (ft)	0.62	0.21	0.67	0.53	0.66	0.49	0.50	0.41	0.28	0.34
RMSE (ft)	0.68	0.24	0.82	0.66	0.77	0.55	0.66	0.50	0.33	0.41
Nash-Sutcliffe (NSE)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
COUNT	8,760	8,760	8,784	8,760	8,760	8,760	8,784	8,760	8760	8760

Table 4-15. Summary statistics for Shasta Dam outflow comparing validation years 2018 and 2019 versus calibration period 2000-2017 (light grey text) (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistic	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Mean Bias (cfs)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MAE (cfs)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RMSE (cfs)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Nash-Sutcliffe (NSE)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
COUNT	8,472	8,760	8,760	8,760	8,784	8,760	8,760	8,760	8,784	8,760

Statistic	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Mean Bias (cfs)	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
MAE (cfs)	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2
RMSE (cfs)	0.1	0.0	0.0	0.3	0.2	0.5	0.1	0.0	0.0	0.3
Nash-Sutcliffe (NSE)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
COUNT	8,760	8,760	8,784	8,760	8,760	8,760	8,784	8,760	8760	8760

Table 4-16. Mean bias for monthly temperature profiles (°C) for Shasta Lake above Shasta Dam comparing validation years 2018 and 2019 versus calibration period 2000-2017 (light grey text). (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of ±0.75°C.). A "—" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

2000	0.11	0.21	-0.29	-0.23	-0.07	-0.13	-0.07	-0.08	-0.13	0.23	0.02	-0.38
2001	0.03	0.01	-0.01	0.21	0.48	0.40	0.52	0.74	1.19*	1.57*	1.30*	-0.16
2002	-0.15	0.08	0.24	0.38	0.36	0.45	0.39	0.56	0.56	0.84*	0.80*	--
2003	0.33	-0.04	0.02	0.27	0.43	0.25	0.11	0.16	0.12	0.07	-0.03	0.07
2004	0.32	0.13	0.19	0.09	0.09	0.01	-0.09	-0.16	-0.31	-0.44	-0.59	-0.74
2005	0.04	0.13	0.09	0.39	0.36	0.52	0.33	0.51	0.64	0.69	0.52	0.42
2006	-0.15	-0.17	-0.28	0.03	0.00	0.19	0.10	0.00	0.06	-0.19	-0.06	-0.22
2007	0.37	0.12	0.38	0.19	0.13	0.12	0.08	-0.08	0.00	-0.78	-0.68	-0.50
2008	0.20	-0.02	0.32	0.45	0.29	0.08	0.27	0.14	0.13	-0.70	-0.31	-0.10
2009	0.56	0.90*	0.26	0.57	0.71	0.82*	0.71	0.75	0.72	0.41	0.47	0.54
2010	0.25	-0.45	-0.45	--	0.08	0.43	0.35	0.20	0.26	0.07	0.04	-0.11
2011	0.13	0.34	0.21	0.12	0.06	0.18	0.19	0.26	0.43	0.48	0.34	0.08
2012	0.18	0.28	0.40	--	0.55	0.43	0.37	0.22	0.27	0.08	0.26	--
2013	0.35	0.35	0.54	0.58	0.87*	--	--	0.30	0.72	0.27	-0.05	-0.38
2014	0.39	0.56	1.09*	1.21*	1.26*	1.10*	1.24*	1.37*	0.94*	0.71	0.54	0.53
2015	0.75	0.82*	0.62	0.39	0.22	0.23	0.49	0.25	0.17	0.06	-0.29	-0.38
2016	0.36	-0.12	0.56	0.48	0.56	0.68	0.59	0.71	0.69	0.57	0.36	--
2017	0.41	0.25	--	0.20	0.46	0.54	0.63	0.54	0.60	0.57	0.50	0.37
2018	-0.09	0.03	0.10	0.40	0.32	0.18	0.13	0.07	-0.03	-0.21	-0.40	-0.50
2019	-0.07	-0.16	0.13	0.28	0.30	1.12*	1.11*	1.04*	1.01*	1.08*	0.82*	0.27

Table 4-17. Mean absolute error (MAE) for monthly temperature profiles (°C) for Shasta Lake above Shasta Dam comparing validation years 2018 and 2019 versus calibration period 2000-2017 (light grey text). (Values marked with an asterisk (also highlighted gray) indicate values were greater than the calibration criteria of 1.0ºC.). A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.28	0.41	0.30	0.26	0.15	0.37	0.29	0.37	0.43	0.52	0.38	0.41
2001	0.24	0.44	0.41	0.61	0.62	0.54	0.55	0.79	1.19*	1.57*	1.30*	0.60
2002	0.17	0.29	0.44	0.51	0.66	0.73	0.63	0.66	0.67	0.84	1.00	--
2003	0.36	0.23	0.23	0.50	0.62	0.40	0.37	0.31	0.39	0.32	0.30	0.28
2004	0.42	0.44	0.52	0.33	0.25	0.29	0.22	0.33	0.56	0.48	0.63	0.74
2005	0.43	0.46	0.35	0.66	0.59	0.66	0.54	0.64	0.68	0.80	0.67	0.58
2006	0.27	0.80	0.28	0.29	0.36	0.42	0.24	0.22	0.26	0.25	0.37	0.28
2007	0.37	0.40	0.66	0.50	0.41	0.34	0.42	0.31	0.32	0.80	0.74	0.55
2008	0.22	0.50	0.66	0.58	0.68	0.54	0.47	0.45	0.40	0.91	0.59	0.55
2009	0.62	1.02*	0.49	0.72	0.74	0.85	0.82	0.76	0.76	0.47	0.47	0.54
2010	0.26	0.45	0.45	--	0.37	0.54	0.42	0.40	0.43	0.34	0.48	0.47
2011	0.14	0.39	0.39	0.20	0.16	0.36	0.32	0.44	0.57	0.64	0.50	0.26
2012	0.19	0.30	0.59	--	0.93	0.68	0.58	0.54	0.47	0.52	0.37	--

2013	0.35	0.44	0.67	0.64	1.08*	--	--	0.50	0.75	0.59	0.43	0.76
2014	0.39	0.61	1.31*	1.32*	1.32*	1.24*	1.34*	1.37*	0.95	0.88	0.73	0.60
2015	0.75	0.86	0.68	0.56	0.51	0.58	0.59	0.42	0.38	0.23	0.47	0.49
2016	0.75	0.27	0.81	0.58	0.71	0.83	0.78	0.88	0.88	0.87	0.77	--
2017	0.61	0.54	--	0.42	0.48	0.71	0.70	0.61	0.66	0.75	0.74	0.44
2018	0.14	0.13	0.35	0.60	0.62	0.39	0.35	0.32	0.28	0.26	0.42	0.59
2019	0.15	0.23	0.56	0.50	0.40	1.21*	1.17*	1.05*	1.10*	1.33*	1.28*	0.65

Table 4-18. Root mean squared error (RMSE) for monthly temperature profiles (°C) for Shasta Lake above Shasta Dam comparing validation years 2018 and 2019 versus calibration period 2000-2017 (light grey text). (Values marked with an asterisk (also highlighted gray) indicate values were greater than the calibration criteria of 1.5ºC.). A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.31	0.43	0.39	0.52	0.20	0.61	0.37	0.44	0.48	0.64	0.46	0.50
2001	0.26	0.47	0.56	0.75	0.69	0.59	0.62	0.95	1.48	1.86*	1.70*	0.67
2002	0.20	0.32	0.49	0.60	0.81	0.84	0.74	0.84	0.85	1.20	1.36	--
2003	0.48	0.30	0.28	0.53	0.66	0.59	0.50	0.40	0.48	0.40	0.35	0.33
2004	0.52	0.46	0.56	0.47	0.41	0.57	0.35	0.39	0.73	0.58	0.76	0.95
2005	0.48	0.52	0.39	0.68	0.66	0.81	0.70	0.73	0.78	0.91	0.81	0.83
2006	0.29	0.41	0.40	0.33	0.61	0.69	0.38	0.32	0.36	0.30	0.45	0.36
2007	0.46	0.42	0.76	0.68	0.69	0.54	0.50	0.43	0.45	1.29	1.14	0.68
2008	0.26	0.52	0.69	0.63	1.01	0.64	0.50	0.62	0.60	1.54*	1.03	0.73
2009	0.82	1.16	0.52	0.76	0.96	0.98	0.91	0.82	0.84	0.68	0.66	0.80
2010	0.34	0.51	0.47	--	0.60	0.76	0.54	0.62	0.52	0.41	0.61	0.54
2011	0.21	0.45	0.41	0.22	0.20	0.68	0.52	0.66	0.80	0.84	0.71	0.42
2012	0.21	0.34	0.65	--	1.12	0.76	0.70	0.60	0.53	0.59	0.43	--
2013	0.42	0.50	0.73	0.71	1.16	--	--	0.56	0.94	0.65	0.48	0.86
2014	0.49	0.73	1.41	1.43	1.37	1.35	1.39	1.43	1.08	0.94	0.85	0.74
2015	0.83	0.99	0.75	0.60	0.64	0.70	0.73	0.50	0.47	0.35	0.79	0.56
2016	0.82	0.35	0.89	0.67	0.93	1.00	1.00	1.10	1.15	1.11	0.93	--
2017	0.69	0.58	--	0.47	0.58	0.96	0.90	0.75	0.83	0.99	0.94	0.71
2018	0.19	0.17	0.39	0.64	0.87	0.67	0.47	0.46	0.43	0.41	0.51	0.64
2019	0.19	0.31	0.60	0.56	0.58	1.59	1.31	1.22	1.39	1.68*	1.54*	0.77

Table 4-19. Nash Sutcliffe Efficiency for monthly temperature profiles (°C) for Shasta Lake above Shasta Dam comparing validation years 2018 and 2019 versus calibration period 2000-2017 (light grey text) (Values marked with an asterisk (also highlighted

gray) indicate values outside the calibration criteria). . A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.93	0.74	0.48*	0.91	0.99	0.98	0.99	0.99	0.99	0.97	0.97	0.90
2001	0.90	0.26*	0.83	0.88	0.96	0.98	0.99	0.98	0.94	0.85	0.71	0.74
2002	0.88	0.87	0.71	0.94	0.92	0.96	0.98	0.98	0.98	0.93	0.83	--
2003	0.79	0.82	0.91	0.83	0.90	0.98	0.99	0.99	0.99	0.99	0.99	0.97
2004	0.56*	0.68	0.41*	0.95	0.98	0.99	1.00	1.00	0.98	0.98	0.92	0.50*
2005	0.74	0.70	0.91	0.75	0.91	0.95	0.98	0.98	0.97	0.94	0.90	0.75
2006	0.91	0.80	0.60*	0.84	0.93	0.97	0.99	1.00	1.00	1.00	0.98	0.98
2007	0.81	0.82	0.35*	0.87	0.96	0.99	0.99	0.99	0.99	0.88	0.81	0.90
2008	0.92	0.21*	0.55*	0.78	0.90	0.98	0.99	0.99	0.99	0.88	0.86	0.88
2009	0.60*	-0.44*	0.01*	0.77	0.90	0.95	0.97	0.98	0.98	0.97	0.95	0.85
2010	0.88	0.36*	0.50*	--	0.91	0.94	0.99	0.99	0.99	0.99	0.97	0.90
2011	0.94	0.81	0.43*	0.93	0.99	0.96	0.99	0.98	0.98	0.96	0.95	0.97
2012	0.97	0.81	0.48*	--	0.79	0.95	0.98	0.99	0.99	0.99	0.99	--
2013	0.84	0.77	0.64*	0.82	0.84	--	--	0.99	0.97	0.98	0.97	0.63*
2014	0.84	0.37*	-0.14*	0.37*	0.83	0.91	0.95	0.95	0.96	0.95	0.93	0.76
2015	-0.93*	0.17*	0.64*	0.94	0.96	0.97	0.98	0.99	0.99	0.99	0.95	0.87
2016	0.03*	0.84	-0.18*	0.90	0.85	0.93	0.96	0.96	0.95	0.95	0.88	--
2017	0.43*	0.53*	--	0.90	0.96	0.96	0.97	0.98	0.98	0.95	0.89	0.91
2018	0.99	0.98	0.79	0.75	0.89	0.97	0.99	0.99	0.99	0.99	0.97	0.85
2019	0.96	0.85	0.59*	0.73	0.96	0.87	0.93	0.95	0.93	0.85	0.78	0.86

Table 4-20. Summary statistics of Shasta Dam outflow temperature comparing validation years 2018 and 2019 versus calibration period 2000-2017 (light grey text). (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria)

Statistic	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Mean Bias (oC)	-0.08	0.09	-0.01	-0.11	-0.42	-0.06	-0.31	-0.29	-0.24	0.23
MAE (oC)	0.60	0.36	0.31	0.20	0.47	0.15	0.33	0.38	0.38	0.41
RMSE (oC)	0.74	0.59	0.45	0.31	0.73	0.25	0.47	0.64	0.69	0.60
Nash-Sutcliffe (NSE)	0.54*	0.85	0.88	0.88	0.85	0.97	0.78	0.82	70.92	0.90
COUNT	8,472	8,760	8,760	8,760	8,784	8,760	8,760	8,760	8,784	8,760

Statistic	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Mean Bias (oC)	-0.19	-0.12	-0.04	-0.06	-0.03	0.07	0.20	0.07	-0.19	0.28
MAE (oC)	0.30	0.19	0.24	0.45	0.43	0.39	0.38	0.30	0.35	0.65

RMSE (oC)	0.49	0.32	0.36	0.66	0.66	0.58	0.59	0.39	0.51	0.87
Nash-Sutcliffe (NSE)	0.64*	0.82	0.88	0.80	0.93	0.83	0.52*	0.84	0.76	-0.52*
COUNT	8,760	8,760	8,784	8,760	8,760	8,760	8,784	8,760	8,760	8,760

Keswick Reservoir

Mean bias, MAE, RMSE, and NSE were calculated for Keswick Reservoir stage, outflow, temperature profiles, and outflow temperatures for 2018-2021 and are presented with 2000-2017 period calibration summary statistics for comparison. Model performance metrics for Keswick Reservoir stage and outflow for the validation years are consistent with the calibration period (Table 4-21 and Table 4-22). While few temperature profiles were available for the calibration period, measured profiles were available for Keswick Reservoir from April through December and May through December for 2018 and 2019, respectively (Deas 2019, Semmens and Deas 2020). Simulated outflow temperatures for 2018-2021 were consistent with the 2000-2017 period (Table 4-23). Keswick Reservoir model simulated temperature profile results for the 15th of each month where data were available (Table 4-24 and Table 4-25) indicate model performance for the validation period was consistent with metrics. The model was not recalibrated following validation. Validation results for 2018-2021 are included with calibration results in Appendix B.

Table 4-21. Summary statistics of Keswick Reservoir stage comparing validation years of 2018 and 2019 versus calibration period 2000-2017 (light grey text). (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria)

Statistic	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Mean Bias (ft)	-	0.19	0.25	-0.61	-0.06	0.20	-0.34	0.01	0.49	0.37
MAE (ft)	-	0.65	0.79	1.09	0.50	0.66	0.81	0.43	0.72	0.68
RMSE (ft)	-	0.95	1.10	1.32	0.60	0.97	1.13	0.71	0.92	0.90
Nash-Sutcliffe (NSE)	-	0.78	0.71	0.54	0.91	0.72	0.57	0.81	0.78	0.75
COUNT	-	8,760	8,760	8,760	8,784	8,760	8,760	8,760	8,784	8,760

Statistic	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Mean Bias (ft)	-0.23	-0.30	0.38	0.23	-0.31	0.36	-0.24	0.20	0.25	-0.54
MAE (ft)	0.64	1.10	0.79	0.77	0.67	0.61	0.58	0.70	0.60	0.79
RMSE (ft)	0.99	1.32	1.05	1.02	0.87	0.73	0.72	0.89	0.78	0.95
Nash-Sutcliffe (NSE)	0.87	0.77	0.85	0.87	0.91	0.92	0.93	0.86	0.89	0.83
COUNT	8,760	8,760	8,784	8,760	8,760	8,760	8,784	8,760	8,760	8,760

Table 4-22. Summary statistics of Keswick Reservoir outflow comparing validation years of 2018 and 2019 versus calibration period 2000-2017 (light grey text). (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistic	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Mean Bias (cfs)	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.1
MAE (cfs)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
RMSE (cfs)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Nash-Sutcliffe (NSE)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
COUNT	8,520	8,662	8,620	8,725	8,601	8,674	8,745	8,753	8,778	8,740

Statistic	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Mean Bias (cfs)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
MAE (cfs)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
RMSE (cfs)	0.1	0.1	0.2	0.1	0.1	0.1	0.2	0.1	0.1	0.1
Nash-Sutcliffe (NSE)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
COUNT	8,755	8,757	8,778	8,754	8,759	8,758	8,783	8,759	8,752	8,760

Table 4-23. Summary statistics of Keswick Reservoir outflow temperature comparing validation years of 2018 and 2019 versus calibration period 2000-2017 (light grey text). (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistic	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Mean Bias (ºC)	0.01	0.01	0.07	0.00	-0.01	-0.03	0.01	0.00	0.00	0.01
MAE (ºC)	0.15	0.18	0.21	0.15	0.16	0.19	0.14	0.19	0.21	0.21
RMSE (ºC)	0.19	0.24	0.28	0.19	0.21	0.24	0.20	0.26	0.29	0.29
Nash-Sutcliffe (NSE)	0.96	0.97	0.94	0.94	0.98	0.96	0.96	0.96	0.98	0.97
COUNT	8,268	8,568	8,239	8,365	8,018	8,665	8,717	8,619	8,465	8,739

Statistic	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Mean Bias (ºC)	-0.01	0.08	-0.01	0.04	0.03	0.03	-0.03	0.00	0.00	0.00
MAE (ºC)	0.24	0.24	0.17	0.22	0.22	0.26	0.18	0.15	0.16	0.18
RMSE (ºC)	0.32	0.32	0.23	0.33	0.29	0.34	0.23	0.21	0.20	0.23
Nash-Sutcliffe (NSE)	0.82	0.82	0.94	0.93	0.98	0.92	0.93	0.96	0.93	0.92
COUNT	8,668	8,735	8,739	8,639	8,731	8,642	8,762	8,745	8,730	8,696

Table 4-24. Mean bias, mean absolute error (MAE), root mean squared error (RMSE) and Nash-Sutcliffe efficiency (NSE) for temperature profiles measured at noon for Keswick Reservoir above Keswick Dam:2018. (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistic	04/15	05/15	06/15	07/15	09/15	10/15	11/15	12/10[1]
Mean Bias (oC)	-0.55	-0.07	-0.34	-0.05	-0.29	-0.09	-0.28	-0.29
MAE (oC)	0.55	0.14	0.34	0.14	0.34	0.12	0.29	0.29
RMSE (oC)	0.59	0.17	0.46	0.17	0.38	0.16	0.31	0.29
NSE	0.37*	0.45*	0.53*	0.70	-1.78*	-0.84*	-2.79*	-69.68*
COUNT	23	23	23	23	23	23	23	23

[1] Profile measured at 11:00 AM is listed. No data is available at noon.

Table 4-25. Mean bias, mean absolute error (MAE), root mean squared error (RMSE) and Nash-Sutcliffe efficiency (NSE) for temperature profiles measured at noon for Keswick Reservoir above Keswick Dam:2019. (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistic	05/15	06/15	07/15	08/15	09/15	10/15	11/15	12/15
Mean Bias (ºC)	-0.23	-0.03	0.19	-0.34	-0.12	-0.13	-0.43	-0.35
MAE (ºC)	0.24	0.09	0.25	0.37	0.29	0.18	0.43	0.35
RMSE (ºC)	0.25	0.15	0.44	0.63	0.35	0.23	0.44	0.35
NSE	-0.51	0.89	-0.24	0.50	-1.36	0.63	-0.56	-13.96
COUNT	23	23	23	23	23	23	23	23

CEQUAL-W2 Sensitivity Analysis

One form of sensitivity analysis tests the implication of changing a single model variable, parameter, or assumption and assessing the impact on model results. Such analyses can be used to identify important characteristics of a system. Sensitivity analysis can be used to:

- Confirm that model response is consistent with theory,
- Quantify the effect of error on state variables,
- Identify sensitive parameters or variables that must be reliably estimated,
- Indicate the relationship between control variables and decision (or state) variables to help ensure that a change in control variable can have a desirable effect on the decision variables, and
- Identify regions of "design invariance" where target levels of decision variables are insensitive to errors of estimation in control variables and parameters.

Extensive sensitivity analysis occurred when developing the CE-QUAL-W2 models for the Shasta Lake and Keswick Reservoir through the implementation, calibration, refinements, and extension of the model to the 21-year period. In this multifaceted, complex system a formal sensitivity analysis would be a large effort. For this study, selected model parameters for both models were varied to determine the model's relative sensitivity. Neither flow, water quality, nor meteorological boundary conditions were altered; however, during implementation these parameters were varied over a large range and model testing was extensive. Generally, parameters used in calibration were also tested for sensitivity.

This qualitative assessment gives an estimate of the sensitivity of important state variables to specific parameters, and provides insight on model performance (e.g., was model consistent with theory?). All parameter values were changed over representative ranges. Although presented herein as qualitative results, the actual model simulations were quantitative and indicate there is little reduction in model performance accuracy for the coupled model versus the individual models considered independently. Comprehensive parameter descriptions are included in Wells (2021a, 2021b, 2021c, 2021d, 2021e). When the full functionality of HEC-WAT within the WTMP is complete, a more detailed, quantitative assessment of sensitivity of key parameters will be assessed through an automated reporting feature (See Reclamation 2021a, 2022a).

Shasta Lake

Generally, temperature at the system level was sensitive to evaporative heat flux parameters (AFW, BFW, CFW). The modification of AFW, BFW, and CFW had an impact on thermal profiles over the course of the annual simulations. Bed heat flux parameters (CBHE and TSED) were moderately sensitive, but only had an impact on the very bottom temperatures. Wind sheltering was insensitive, as was the initial vertical profile used to start the model in January of each year. Relative sensitivity for these parameters and comments with respect to each are included in Table 4-26. Parameter definitions can be found in Cole and Wells (2008).

Table 4-26. Parameters and their relative sensitivity for the Shasta Lake CE-QUAL-W2 model (H-High, M-Moderate, L-Low, I-Insensitive).

Parameter[1]	Sensitivity	Notes
AFW	M	AFW was moderately sensitive and a range of values were explored. The default value of 9.2 mb^{-1} m s^{-1} was modified slightly to a value of 9.45 mb^{-1} m s^{-1} during model calibration.
BFW	M	BFW was moderately sensitive and a range of values were explored. The default value of 0.46 mb^{-1} was ultimately selected.
CFW	M	CFW was moderately sensitive and a range of values were explored. The default value of 2.0 was modified slightly to 2.05 during model calibration.
CBHE	M	CBHE only had an effect for the bottommost waters in the reservoir (i.e., approximately 30 ft (9.1m)), and was used to calibrate the lower most section of the vertical profile. From a reservoir storage perspective, this represents a small volume of water, and calibration of this parameter did not impact outflow temperatures in any meaningful manner.
TSED	M	TSED only had an effect for the bottommost waters in the reservoir (i.e., approximately 30 ft (9.1m)), and was used to calibrate the lower most section of the vertical profile. From a reservoir storage perspective, this represents a small volume of water, and calibration of this parameter did not impact outflow temperatures in any meaningful manner.

EXH2O	I	EXH2O was relatively insensitive to overall water temperature profiles and did not impact release temperatures. Under certain values the near-surface temperatures changed slightly.
BETA	I/L	BETA was relatively insensitive to overall water temperature profiles and did not impact release temperatures. Under certain values the near-surface temperatures changed slightly.
Wind Sheltering	I/L	Wind sheltering had a low impact on TCD_d water temperatures. Reasons for the lack of sensitivity might be due to the single meteorology station from used (Redding Airport, approximately 15 miles south of the reservoir), using this single meteorological station to represent the large dendritic lake, and topography conditions that may not sufficiently modify wind speeds.
Initial Profile	I/L	Generally, the model was largely insensitive to changes in the initial water temperature profile assumed for the January 1 model start date. Assumed isothermal conditions instead of employing measured profiles resulted in similar model results.

[1]Model parameters associated with model stability (e.g., DLTMIN, DLTMAX, DLTF) were not considered in sensitivity analysis because these parameters were associated primarily with numerical solution of the model governing equations and model stability, and not with simulation performance related to reproducing field observations.

Keswick Reservoir

Generally, simulated temperature was insensitive to parameters listed in Table 4-26 for Keswick Reservoir. During calibration these parameters were assessed for a representative range, but ultimately default model parameters were used in the Keswick Reservoir model. The model was insensitive to the initial thermal profile. The insensitivity of model parameters and assumptions in Keswick Reservoir is due to the short travel time and large flow rates through Keswick Reservoir (both from Shasta Dam and Spring Creek powerhouse inflows), and relatively small reservoir volume. Model performance statistics indicate that the model performs well over a range of flows, thermal conditions, operations, and meteorological conditions.

ResSim Calibration Parameters

ResSim calibration parameters can be divided into those that effect the physical flow and timing, and those that are specific to the water quality module. The physical flow and timing parameters are set as a part of the ResSim alternative (in the Simulation Module in ResSim, or by editing the model from HEC-WAT). During calibration, the physical flow and timing parameters were invariant for all modeled reaches, and both flow and water quality time stepping was set at 1 hour to fully utilize the input data sources, which had a minimum time resolution of 1 hour. The physical flow and timing parameters relevant to simulations are listed in Table 4-27.

Table 4-27. ResSim physical flow and timing parameters, set as a part of the calibration ResSim alternative.

Parameter	Setting	Description

Time Step	1 Hour	Minimum time step, sec
Flow Computation Method	Period Average	Considered the time-averaged flow in computations
Alternative Type	Standard	Normal single-simulation mode
WQ Time Step	1 Hour	Independent water quality minimum time step
Control Coupling of Flow and Water Quality Simulation	Coupled Simulation	Running coupled is required for dynamic water quality-based operations, such as an optimizing TCD
Resolution of Hydrodynamic Continuity Error	Preserve Concentration	Mass balance
Solution Scheme	First Order	An efficient Upwind solver is used for rapid computation

Water Quality Module parameters are specific to reaches specified in the ResSim water quality geometry. In the Shasta-Keswick-Sacramento ResSim watershed, calibrated parameter values are specific to Shasta Lake, Keswick Reservoir, or the Keswick to Red Bluff river reaches (three total parameter sets), and are listed in Table 4-28, and parameters relating to vertical dispersion in Shasta Lake and Keswick reservoir in Table 4-29. All three reaches used the same parameter values for this application.

Table 4-28. ResSim water quality parameters, set in the water quality mode of the ResSim application.

Parameter	Sacramento River	Shasta Lake	Keswick Reservoir	Description
Coefficient a in Wind Function	1.0	1.0	1.0	Minimum wind function parameter [10^{-9} mb^{-1}]
Coefficient b in Wind Function	2.5	4.0	2.5	Scalar wind function parameter [10^{-9} mb^{-1}]
Coefficient c in Wind Function	1.0	0.5	1.0	Exponential wind function parameter [10^{-9} mb^{-1}]
Turbulent Diffusivity Ratio	1.0	1.0	1.0	Factor that splits…. Steve help. [0-1]
Sediment Layer Thickness	0.25	0.25	0.25	Thickness of the sediment temperature layer [m]
Sediment Bulk Density	1,600.0	1,600.0	1,600.0	Density [kg m^{-3}]
Sediment Specific Heat Capacity	1,674.72	1,674.72	1,674.72	Heat Capacity [J kg^{-1} m^{-3}]
Sediment Thermal Diffusivity	0.0432	0.0432	0.0432	Diffusivity [m^2 day^{-1}]
Shortwave Radiation Bed Reflectivity	0.2	0.2	0.2	Fraction of radiation reflected by sediment/bed [0-1]
Background Light Attenuation	0.45	0.45	0.45	Base shortwave absorption by water [m^{-1}]
Suspended Sediment Light Attenuation	0.052	0.052	0.052	Absorption by scripted suspended sediment [L mg^{-1} m^{-1}]
Stream Slope	-1.0	-1.0	-1.0	Override for slope used by entrainment [-1 for default; otherwise 0-0.1]
Stream Cross-Sect Half Angle	85.0	85.0	85.0	Fractional angle of widening at site of inflow, where 0=0 and 1=180 degrees, used by entrainment [0-1]
Initial Mixing Ratio	0.15	0.15	0.15	Entrainment fraction before plunge [0-1]
Entrainment Rate	-1.0	-1.0	-1.0	Override for angle and slope-based entrainment rate, used by entrainment [-1 for default; otherwise 0-0.1]
Mixed Layer Tolerance	0.03	0.03	0.03	Density gradient at which entrainment is effectively blocked [kg m^{-3}]
Richardson Number Function Option	Use Bowen	Use Bowen	Use Bowen	Switch meteorological heat transfer method
Entrainment Option	OFF	ON	ON	Switch for inflow entrainment calculation

Table 4-29. Calibration parameters used in the wind method for vertical dispersion calculation in ResSim.

Vertical Dispersion Coefficient	Shasta Lake	Keswick Reservoir	Description
Dz_{min}	2.0e-5	1.08e-5	Minimum vertical dispersion [ft^2 s^{-1}]
A_1	1.0e-4	3.28e-5	Linear dispersion scalar [ft]
A_z	1.5	2.0	Exponential dispersion scalar [dimensionless]
Dz_{max}	<not used>	<not used>	Maximum vertical dispersion [ft^2 s^{-1}]

ResSim Calibration

The ResSim models were initially calibrated for flow and storage, followed by calibration for water temperature. Water temperature calibration consisted of iteratively varying select model parameters from the default values in ResSim. Evaluation of model performance was first performed graphically comparing temperatures to observed data to identify key parameters (i.e., sensitive model coefficients, constants). Once these key parameter values were identified, values were further refined to minimizing statistical error metrics.

Calibration occurred in stages, generally starting with upstream features and surface waters. Reservoir surface temperatures were calibrated initially using observed profiles, followed by sub-surface reservoir dynamics including dispersion and entrainment, and related reservoir outflow characteristics. Calibration of Shasta Lake included focusing on replicating both temperature profile and outflow temperature. Keswick Reservoir calibration focused on outflow temperature due to the short residence time and the lack of measured temperature profiles. Sacramento River reaches were calibrated to hourly temperature data at several stations between Keswick Dam and Red Bluff.

Calibration was evaluated using observation data from the calendar years 2000-2017.

Shasta Lake

Shasta Lake calibration included flow, stage, and water temperature. Measured Shasta Lake inflow, outflow, and water surface elevation (or storage) were used to calculate an accretion/depletion term via a water balance. The accretion/depletion terms ensured the correct reservoir elevation was maintained and that the historical TCD gate openings were properly prescribed. Simulated dam lake reservoir elevation and dam release match observed historical observations (Figure 4-10 and Figure 4-11, respectively). Subsequently the calibration focused on system inflows and outflows, meteorological forcing, subsurface mixing, and TCD withdraw parameterization. Outflow statistics from Shasta Lake shows a match to observed outflow with the following exceptions: balancing accretion and depletion on the first day of simulation (as the hourly balance flows adjust to the daily periodicity of various input datasets), and for one hour at the end of both 2016 and 2017 (where input penstock flows do not exactly match the total observed flow (Table 4-30)).

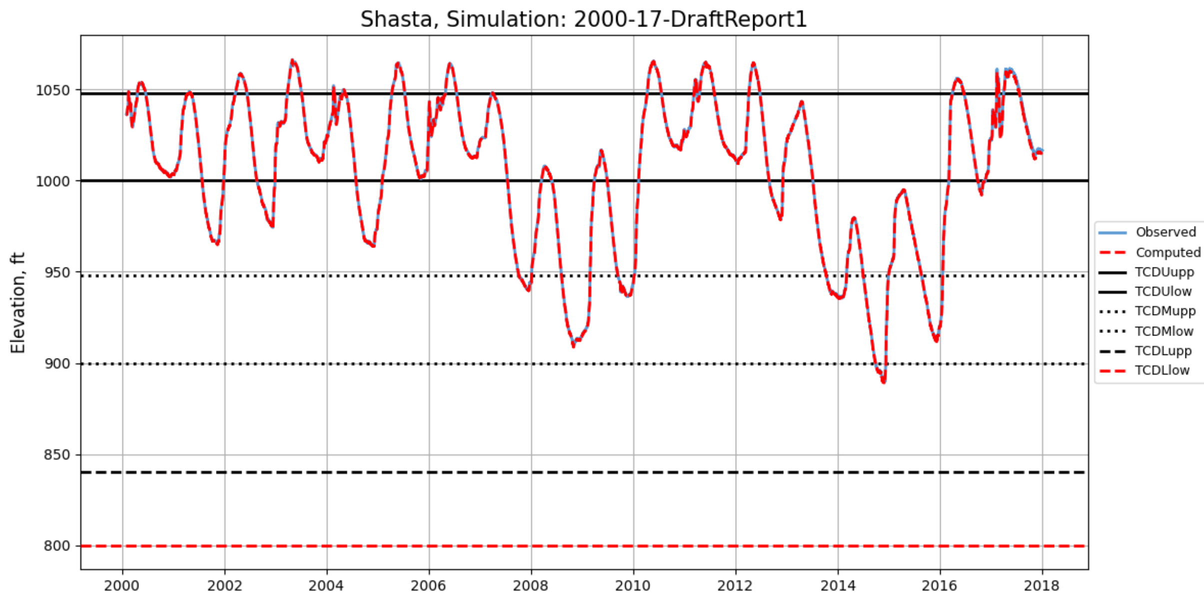


Figure 4-10. Shasta Lake simulated and observed water surface elevation, with TCD gate elevations, 2000-2017.

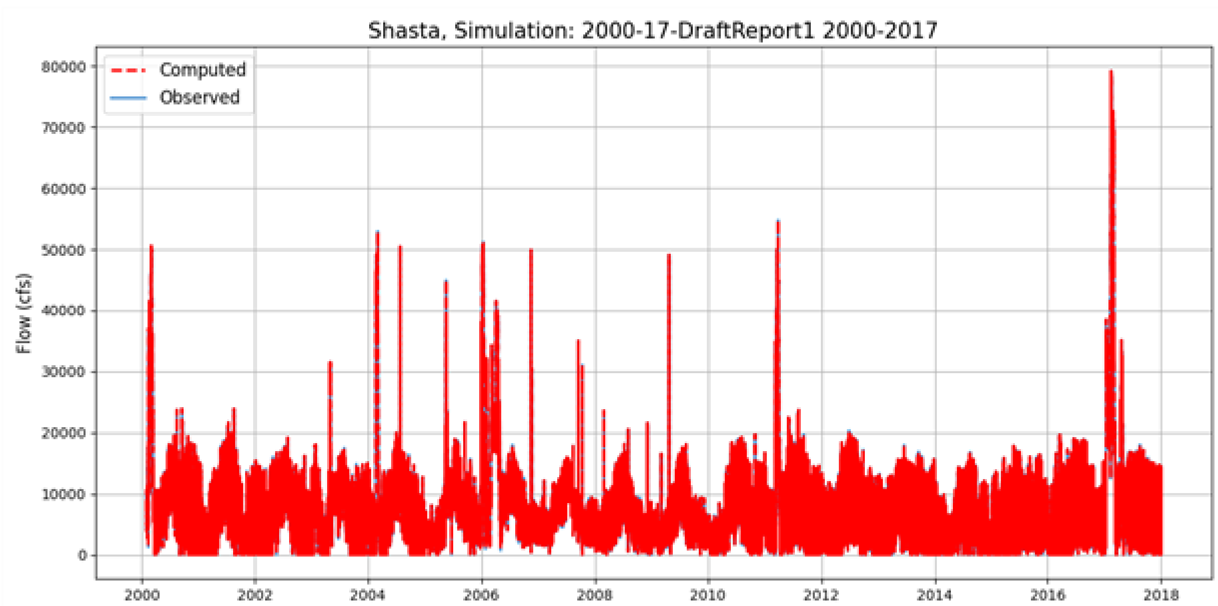


Figure 4-11. Shasta Lake simulated and observed out flow, 2000-2017.

Table 4-30. Shasta Dam outflow error statistics: 2000-2017.

Statistics	2000	2001	2002	2003	2004	2005
Mean Bias (cfs)	-0.31	0.00	0.00	0.00	0.00	0.00
MAE (cfs)	1.08	0.00	0.00	0.00	0.00	0.00
RMSE (cfs)	35.38	0.00	0.00	0.00	0.00	0.00
Nash-Sutcliffe (NSE)	1.00	1.00	1.00	1.00	1.00	1.00
COUNT	8040	8760	8760	8760	8784	8760

Statistics	2006	2007	2008	2009	2010	2011
Mean Bias (cfs)	0.00	0.00	0.00	0.00	0.00	0.00
MAE (cfs)	0.00	0.00	0.00	0.00	0.00	0.00
RMSE (cfs)	0.00	0.00	0.00	0.00	0.00	0.00
Nash-Sutcliffe (NSE)	1.00	1.00	1.00	1.00	1.00	1.00
COUNT	8760	8760	8784	8760	8760	8760

Statistics	2012	2013	2014	2015	2016	2017
Mean Bias (cfs)	2012	2013	2014	2015	2016	2017
MAE (cfs)	0.00	0.00	0.00	0.00	-0.07	0.32
RMSE (cfs)	0.00	0.00	0.00	0.00	0.08	0.32
Nash-Sutcliffe (NSE)	0.00	0.00	0.05	0.00	6.85	30.18
COUNT	1.00	1.00	1.00	1.00	1.00	1.00

Statistics	All Years
Mean Bias (cfs)	-0.00
MAE (cfs)	0.08
RMSE (cfs)	10.84
Nash-Sutcliffe (NSE)	1.00
COUNT	157057

Graphical comparison of ResSim simulated temperature profiles with observed temperatures profiles show good agreement in the epilimnion and hypolimnion, and moderate agreement in the metalimnion (thermocline). Selective withdrawal patterns of operation at Shasta heavily rely on metalimnion waters. The parameterized processes of internal mixing/dispersion, inflow/entrainment, and withdraws is important in this region under stratified conditions (e.g., Figure 4-12 and Figure 4-13). Two distinct areas where parametrizations have difficulty reproducing observed profiles are at the bottom of the epilimnion (transition from the epilimnion of the metalimnion), and in late summer into fall, at the top of the hypolimnion (transition from metalimnion to the hypolimnion). The current 1-dimensional dispersion parametrization options in ResSim apply variations on a power-law decay of dispersion that applies below the epilimnion, which may not always reproduce the extremely sharp thermoclines sometimes encountered in Shasta Lake in the late summer into fall during low storage conditions (Figure 4-13).

Shasta Lake reservoir temperature profiles calibrated within the model performance metrics for bias, MAE, and RMSE (Table 4-31 to Table 4-33) with the exception of mean bias and MAE, with the exception of several months in late summer and fall 2013-2015 (Table 4-31). During those periods, the simulated cold pool volume of the reservoir was depleted to a greater degree compared to observations.

While mean biases, MAE and RMSE metrics are all within the model performance metrics for much of the calibration period, the NSE metric for winter temperature profiles shows many months are below the threshold of 0.65 (Table 4-34), while winter biases were generally quite small (always under 0.75°C, Table 4-31). The NSE metric incorporates a division by the variance, thereby penalizing consistent biases, therefore relatively small errors in temperature have a disproportionate effect on decreasing NSE when the temperature profiles are isothermal or near isothermal, as is typical during winter periods. Small, but consistent deviations between simulated and observed profiles can extend the over much of the reservoir depth, leading to low NSE values. These low values, all occurring between November and April, do not fully represent model performance. This is a case where other model metrics and graphical analysis augment model calibration assessment.

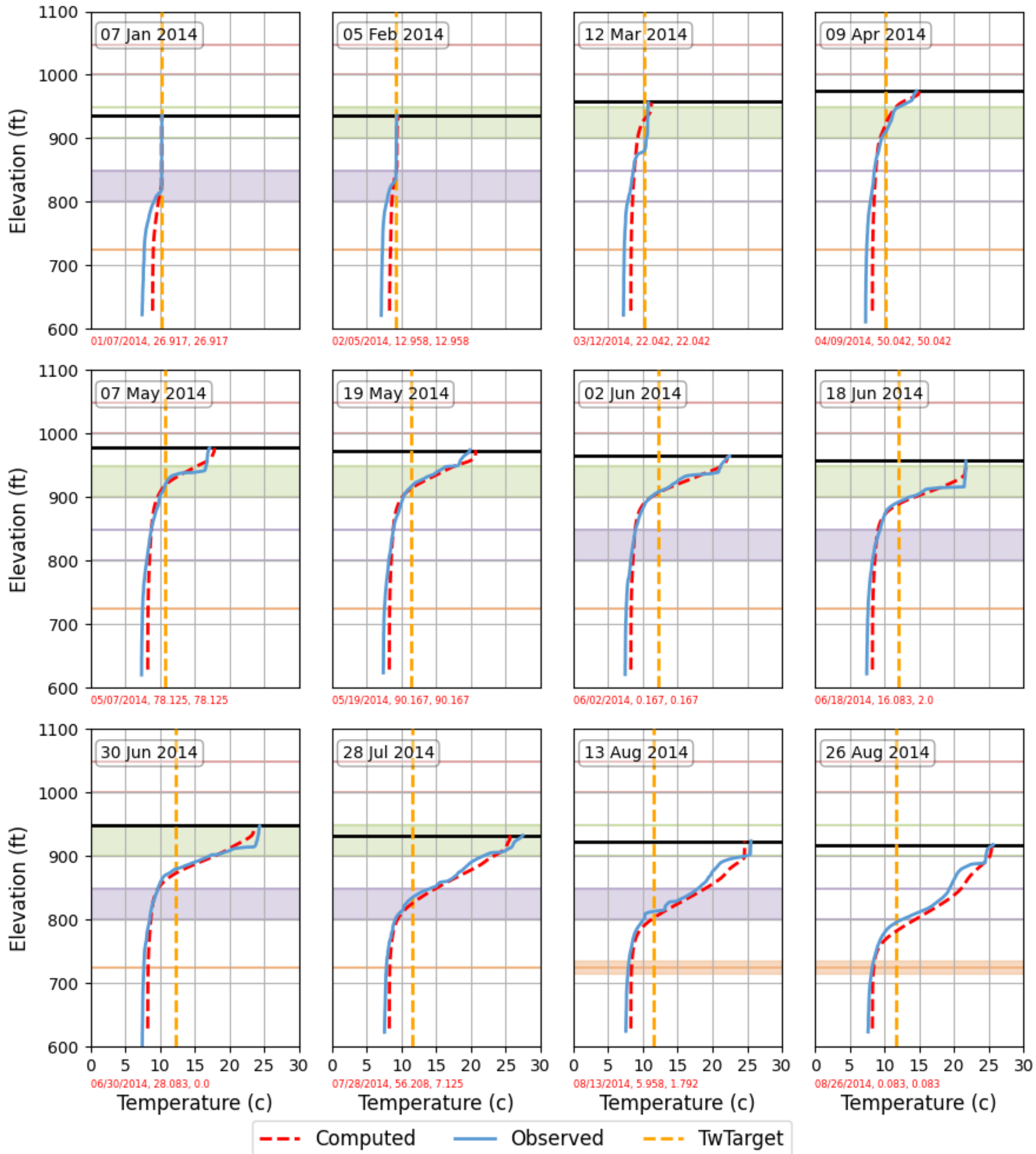


Figure 4-12. Simulated and observed temperature profiles and TCD gate positions during 2014 (1/2).

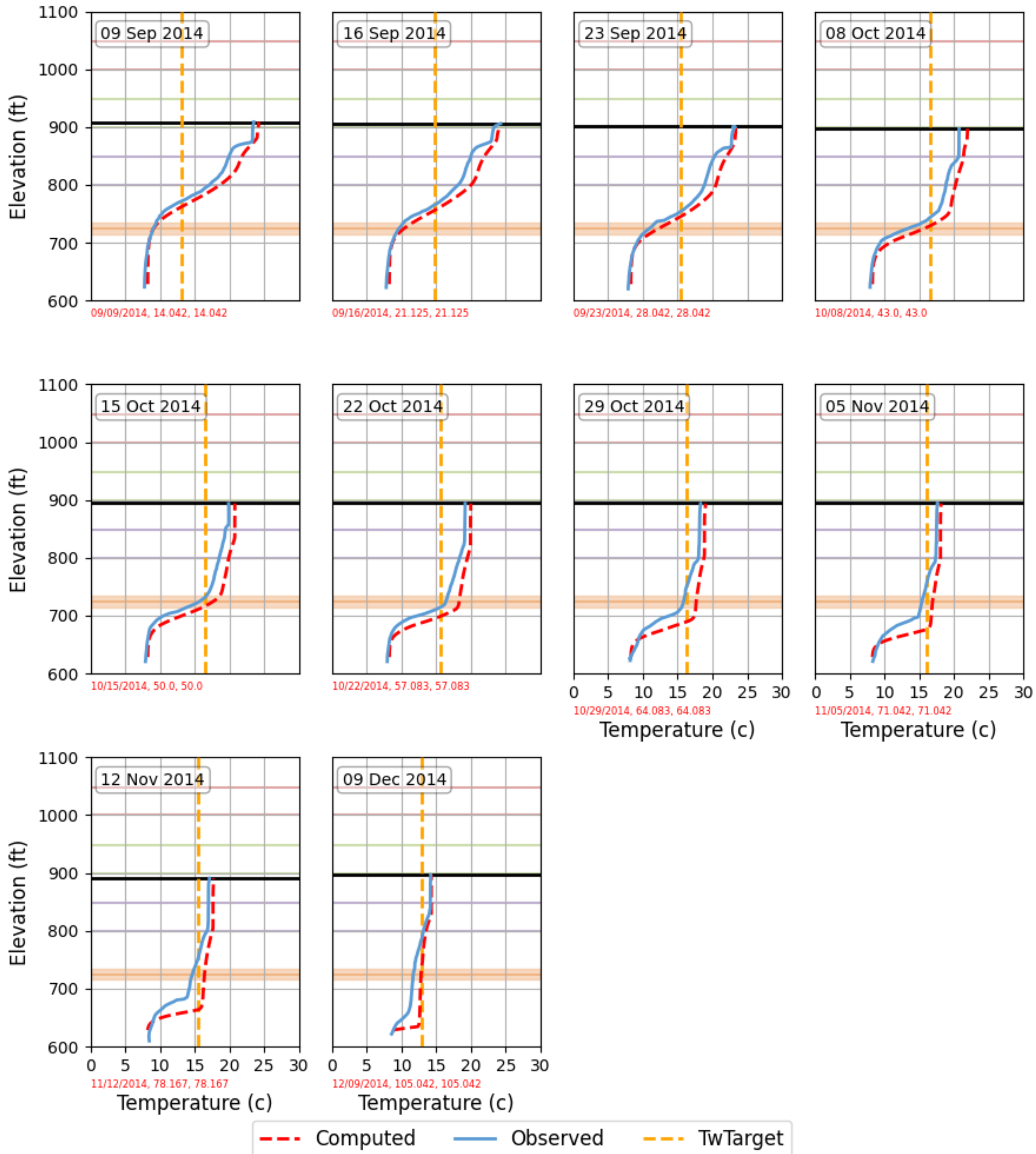


Figure 4-13. Simulated and observed temperature profiles and TCD gate positions during 2014 (2/2).

Table 4-31. Shasta Profile Temperature Mean Bias (ºC) (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of +-0.75ºC). A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	--	0.50	0.25	0.22	-0.09	-0.23	-0.10	0.06	0.09	0.39	0.58	0.48
2001	--	--	--	--	-0.39	-0.28	-0.21	0.02	0.11	0.23	0.20	-0.26
2002	-0.32	0.04	0.04	-0.22	-0.21	-0.29	-0.19	-0.05	-0.07	-0.04	-0.15	--
2003	-0.32	-0.04	0.08	-0.03	-0.09	-0.15	0.06	0.14	0.34	0.23	0.23	0.29
2004	-0.05	0.17	0.04	-0.01	0.02	-0.05	-0.09	0.06	-0.01	-0.06	-0.17	-0.23
2005	-0.12	0.01	0.09	-0.06	-0.12	-0.23	-0.35	-0.23	-0.20	-0.46	-0.74	-0.64
2006	-0.32	0.01	-0.20	-0.15	-0.42	-0.38	-0.08	-0.02	-0.04	-0.34	-0.15	-0.42
2007	-0.37	-0.09	-0.06	-0.07	-0.18	-0.13	-0.19	-0.12	-0.09	-0.38	-0.40	-0.32
2008	-0.16	-0.21	-0.02	-0.05	-0.25	-0.26	-0.26	-0.12	-0.24	-0.60	-0.58	-0.13
2009	0.14	0.49	-0.08	-0.40	-0.41	-0.22	-0.18	0.07	0.26	0.08	0.34	0.52
2010	0.58	0.07	0.23	---	-0.03	-0.12	-0.02	-0.03	0.05	0.06	-0.01	-0.31
2011	-0.29	0.17	0.14	-0.04	-0.02	0.01	0.18	0.28	0.51	0.68	0.60	0.41
2012	0.39	0.53	0.46	--	-0.04	-0.03	-0.03	0.05	0.16	0.24	0.21	--
2013	0.20	0.59	0.63	0.59	0.45	--	--	0.49	0.76*	0.66	0.78*	0.52
2014	0.74	0.70	0.41	0.40	0.40	0.35	0.56	0.79*	0.97*	1.24*	1.29*	0.85*
2015	0.10	0.68	0.61	0.43	0.15	0.20	0.43	0.71	1.01*	1.66*	2.09*	0.94*
2016	0.10	-0.15	0.03	-0.17	-0.19	-0.07	0.01	0.13	0.28	0.36	0.26	--
2017	0.09	0.29	--	-0.01	-0.10	-0.12	0.08	0.09	0.23	0.20	0.32	0.39
All	0.02	0.24	0.16	0.02	-0.08	-0.10	-0.03	0.15	0.29	0.31	0.25	0.14

Table 4-32. Shasta Profile Temperature MAE (°C) (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of >1.0°C). A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	--	0.53	0.42	0.41	0.26	0.39	0.36	0.53	0.62	0.71	0.68	0.79
2001	--	--	--	--	0.50	0.40	0.38	0.50	0.55	0.69	0.84	0.58
2002	0.32	0.44	0.41	0.54	0.40	0.45	0.44	0.37	0.39	0.32	0.37	--
2003	0.44	0.31	0.35	0.35	0.33	0.40	0.52	0.75	0.84	0.89	0.69	0.56
2004	0.21	0.52	0.44	0.30	0.36	0.43	0.52	0.64	0.87	0.77	0.55	0.65
2005	0.53	0.62	0.52	0.46	0.41	0.53	0.69	0.74	0.88	1.04*	0.89	0.65
2006	0.37	0.55	0.24	0.31	0.45	0.52	0.65	0.84	0.90	0.83	0.72	0.58
2007	0.48	0.51	0.59	0.52	0.41	0.42	0.41	0.44	0.52	0.66	0.73	0.41
2008	0.39	0.25	0.48	0.41	0.41	0.36	0.47	0.60	0.68	1.28*	0.99	0.65
2009	0.69	0.65	0.20	0.62	0.56	0.53	0.62	0.73	0.95	1.11*	0.93	0.77
2010	0.63	0.31	0.33	--	0.28	0.32	0.42	0.52	0.65	0.79	0.78	0.54
2011	0.34	0.51	0.24	0.34	0.22	0.28	0.38	0.53	0.70	0.79	0.71	0.51
2012	0.44	0.53	0.55	--	0.40	0.33	0.31	0.31	0.31	0.29	0.30	--
2013	0.29	0.61	0.81	0.65	--	--	--	0.54	0.78	0.66	0.78	0.55
2014	0.77	0.71	0.79	0.59	0.58	0.58	0.66	0.88	0.98	1.26*	1.34*	0.86
2015	0.19	0.77	0.70	0.53	0.37	0.43	0.65	0.80	1.05*	1.66*	2.09*	0.96
2016	0.29	0.40	0.36	0.36	0.33	0.44	0.51	0.57	0.62	0.64	0.53	--
2017	0.18	0.45	--	0.29	0.35	0.43	0.51	0.62	0.72	0.51	0.58	0.62
All	0.41	0.51	0.46	0.45	0.39	0.42	0.50	0.62	0.74	0.82	0.75	0.65

Table 4-33. Shasta Profile Temperature RMSE (°C) (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of >1.5°C). A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	--	0.64	0.53	0.49	0.37	0.59	0.51	0.73	0.75	0.89	0.94	0.95
2001	--	--	--	--	0.94	0.64	0.55	0.71	0.77	0.85	0.97	0.68
2002	0.44	0.50	0.47	0.94	0.55	0.70	0.64	0.51	0.53	0.40	0.48	--
2003	0.51	0.38	0.42	0.43	0.45	0.56	0.82	1.08	1.21	1.10	0.81	0.67
2004	0.28	0.53	0.48	0.35	0.51	0.69	0.78	0.92	1.08	0.93	0.71	0.71
2005	0.59	0.66	0.59	0.57	0.48	0.72	0.96	1.05	1.17	1.36	1.37	1.08
2006	0.43	0.58	0.34	0.44	0.79	0.76	1.00	1.21	1.18	1.00	0.86	0.74
2007	0.54	0.57	0.64	0.65	0.53	0.58	0.57	0.60	0.70	0.97	1.15	0.58
2008	0.42	0.33	0.58	0.65	0.76	0.53	0.70	0.85	0.83	1.59	1.48	0.96
2009	0.78	0.74	0.28	0.81	0.78	0.77	0.85	1.00	1.15	1.20	0.96	0.85
2010	0.76	0.33	0.40	--	0.44	0.50	0.70	0.83	0.90	0.99	0.91	0.73
2011	0.43	0.57	0.26	0.49	0.33	0.47	0.82	0.99	1.23	1.31	1.02	0.68
2012	0.63	0.57	0.63	--	0.56	0.44	0.41	0.47	0.49	0.47	0.39	--
2013	0.40	0.79	0.90	0.76	0.70	--	--	0.64	0.90	0.90	1.10	0.75
2014	0.98	0.86	0.88	0.67	0.70	0.72	0.77	1.07	1.19	1.50	1.78	1.15
2015	0.20	0.92	0.79	0.65	0.48	0.66	0.95	1.12	1.49	2.36	2.96	1.30
2016	0.36	0.49	0.44	0.47	0.40	0.70	0.85	0.86	0.92	0.88	0.74	--
2017	0.19	0.49	--	0.46	0.53	0.78	0.94	1.01	1.11	0.75	0.74	0.75
All	0.54	0.61	0.56	0.61	0.59	0.65	0.79	0.92	1.05	1.18	1.11	0.86

Table 4-34. Shasta Profile Temperature NSE: 2000-2017 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of <0.65). A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	--	0.32*	0.71	0.92	0.97	0.97	0.99	0.98	0.97	0.95	0.85	0.59*
2001	--	--	--	--	0.91	0.98	0.99	0.99	0.98	0.97	0.92	0.66
2002	0.44*	0.70	0.72	0.84	0.96	0.97	0.99	0.99	0.99	0.99	0.98	--
2003	0.76	0.71	0.76	0.87	0.93	0.98	0.97	0.95	0.94	0.93	0.91	0.88
2004	0.87	0.56*	0.55*	0.97	0.97	0.97	0.98	0.97	0.96	0.95	0.95	0.71
2005	0.61*	0.50*	0.75	0.81	0.95	0.95	0.95	0.96	0.94	0.87	0.71	0.58*
2006	0.81	0.60*	0.67	0.70	0.87	0.96	0.95	0.94	0.94	0.94	0.94	0.91
2007	0.74	0.66	0.53*	0.86	0.97	0.98	0.99	0.99	0.99	0.95	0.84	0.90
2008	0.78	0.68	0.67	0.75	0.92	0.98	0.98	0.98	0.98	0.89	0.76	0.78
2009	0.64*	0.43*	0.71	0.77	0.90	0.96	0.97	0.97	0.96	0.92	0.91	0.83
2010	0.40*	0.72	0.60*	--	0.93	0.97	0.97	0.97	0.96	0.95	0.91	0.82
2011	0.74	0.70	0.78	0.64*	0.97	0.97	0.96	0.96	0.94	0.91	0.92	0.91
2012	0.74	0.46*	0.50*	--	0.94	0.98	0.99	0.99	0.99	0.99	0.99	--
2013	0.85	0.42*	0.41*	0.76	0.93	--	--	0.99	0.98	0.96	0.89	0.69
2014	0.33*	0.14*	0.55*	0.84	0.94	0.97	0.98	0.97	0.96	0.88	0.64*	0.41*
2015	0.89	0.26*	0.66	0.89	0.98	0.97	0.97	0.96	0.92	0.75	0.25*	0.28*
2016	0.82	0.67	0.77	0.93	0.97	0.96	0.97	0.97	0.97	0.96	0.95	--
2017	0.96	0.67	--	0.89	0.96	0.96	0.96	0.96	0.96	0.97	0.95	0.89
All	0.75	0.58*	0.69	0.88	0.95	0.97	0.97	0.97	0.96	0.93	0.88*	0.80*

Shasta Lake outflow temperatures are compared graphically to target outflow temperatures in Figure 4-14 through Figure 4-16, annually in Table 4-35, and monthly in

Table 4-36 through Table 4-38. Over the 18-year calibration period, Shasta outflow temperatures match the daily average warm outflow temperatures in summer, and match, or are cooler than, daily average cool temperatures during winter (Figure 4-14). In some years, while the daily means are reproduced, computed hourly maximum temperatures deviate from observations during certain periods of the year (e.g., autumn in 2001, 2008, 2009); however, these observed target temperatures are not necessarily reflective of downstream release temperature at Keswick Dam (see below), where simulated results better match observed temperatures during these periods. Notably, simulated outflow temperatures match maximums observed during low water, and low flow years of 2007-

2008, and 2014 (Figure 4-15). Short term variability in observed Shasta Lake outflow can occur due to penstock heating during non-peaking periods and also at the onset of hydropower peaking when near-surface water may be mixed into penstock water within the TCD. Such transient conditions observed below Shasta Dam in the spring through fall period generally are not manifest at Keswick Dam. Simulated Shasta Lake outflow temperatures are generally slightly lower than observed during winter, resulting in frequent negative mean biases during Jan-Mar in many years, however those biases are still under the threshold of +- 0.75 in all but two months (Table 4-36).

The two most notable periods differences between simulated and observed are August 2005, and Nov 2010, which illustrate difficulties in predicting computed withdraw envelopes from the Shasta Dam TCD (Figure 4-15, Table 4-36 through Table 4-38). In 2005, multiple levels of TCD gates remained open for long periods, and optimized withdraws developed a colder temperature profile that did not reproduce observed outflow temperatures when upper TCD gates were finally closed during summer. Comparatively cold temperature profiles develop this way in several other above-normal-water years as well (2003, 2006, 2010, 2011; See Appendix C for annual plots), but to a lesser extent than 2005, and in most cases monthly outflow statistics remain below model performance metric thresholds (Table 4-35 through Table 4-38). Model refinement will continue on this condition to improve model performance under conditions when TCD gates remain open for long periods. In 2015, meteorology, withdrawals, and entrainment processes resulted in the simulated cold pool to be depleted too quickly, and outflow temperatures are biased positive by 1.25°C during November (Table 4-36). There are no other periods that perform in this manner during simulations. A combination of warm weather, high winds, low reservoir elevation, may have resulted in challenging conditions for ResSim parameterization to capture the thermal structure of Shasta Lake. This parameterization performs well for the majority of other simulated summer-fall periods.

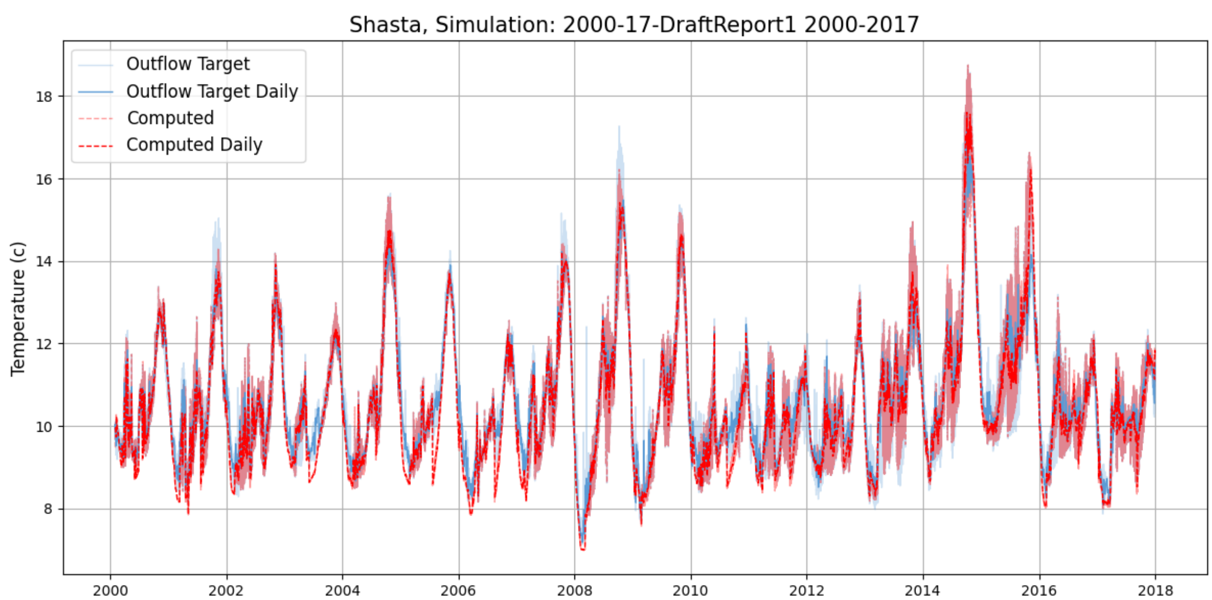


Figure 4-14. Shasta Lake simulated and observed temperatures at Shasta Dam, 2000-2017.

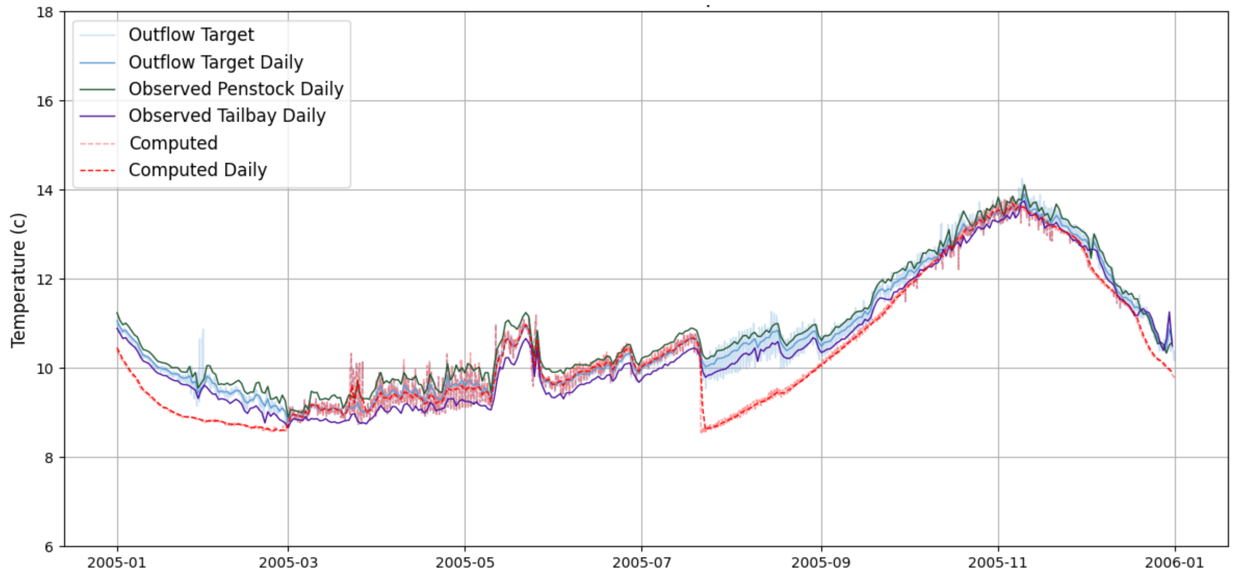


Figure 4-15. Shasta Lake daily simulated and observed temperatures at Shasta Dam, 2005.

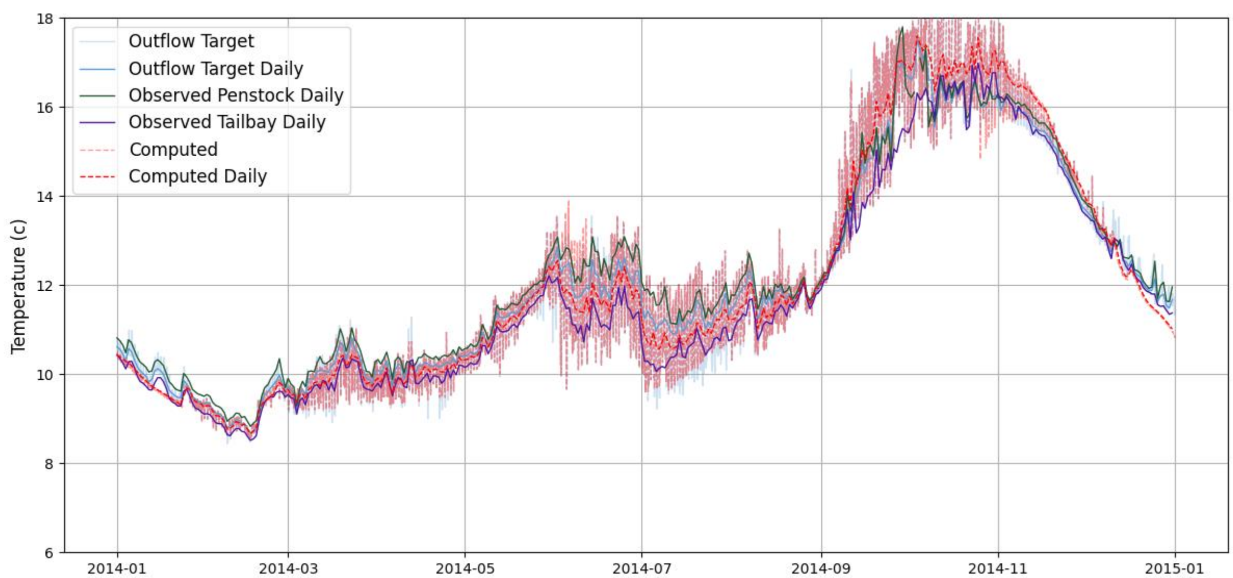


Figure 4-16. Shasta Reservoir hourly simulated and observed temperatures at Shasta Dam, 2014.

Table 4-35. Shasta Lake Outflow Temperature Error Statistics: 2000-2017 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistics	2000	2001	2002	2003	2004	2005
Mean Bias (°C)	-0.02	-0.18	-0.14	-0.20	-0.14	-0.33
MAE (°C)	0.22	0.33	0.34	0.30	0.30	0.40
RMSE (°C)	0.30	0.42	0.43	0.41	0.38	0.56
Nash-Sutcliffe (NSE)	0.92	0.92	0.88	0.80	0.96	0.84
COUNT	8,040	8,760	8,760	8,760	8,784	8,760

Statistics	2006	2007	2008	2009	2010	2011
Mean Bias (°C)	-0.30	-0.16	-0.14	-0.07	-0.22	-0.13
MAE (°C)	0.35	0.34	0.36	0.25	0.35	0.34
RMSE (°C)	0.47	0.45	0.50	0.35	0.46	0.42
Nash-Sutcliffe (NSE)	0.78	0.90	0.96	0.96	0.64*	0.60*
COUNT	8,760	8,760	8,784	8,760	8,760	8,760

Statistics	2012	2013	2014	2015	2016	2017
Mean Bias (c)	-0.01	0.00	0.01	0.12	-0.03	-0.02
MAE (c)	0.27	0.44	0.39	0.52	0.33	0.30
RMSE (c)	0.36	0.57	0.54	0.71	0.43	0.38
Nash-Sutcliffe (NSE)	0.85	0.82	0.95	0.67	0.68	0.83
COUNT	8,784	8,760	8,760	8,760	8,784	8,760

Statistics	All Years
Mean Bias (c)	-0.11
MAE (c)	0.34
RMSE (c)	0.46
Nash-Sutcliffe (NSE)	0.91
COUNT	157,057

Table 4-36. Shasta Lake Outflow Temperature Mean Bias (ºC): 2000-2017 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of +-0.75 ºC). A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	--	0.08	-0.10	0.06	0.01	-0.33	-0.07	-0.07	0.01	0.00	0.01	0.14
2001	-0.10	-0.55	-0.38	-0.23	-0.10	0.01	-0.03	-0.16	0.02	-0.27	-0.16	-0.19
2002	-0.70	-0.51	-0.19	0.01	-0.04	-0.02	0.01	-0.01	-0.02	0.01	-0.00	-0.24
2003	-0.43	-0.37	0.09	0.08	-0.14	-0.61	-0.82*	-0.18	-0.01	-0.00	0.00	-0.01
2004	-0.37	-0.51	-0.12	0.01	-0.04	0.00	-0.02	-0.16	0.00	0.00	-0.05	-0.45
2005	-0.82*	-0.61	0.00	-0.00	0.01	0.07	-0.46	-1.10*	-0.38	-0.11	-0.14	-0.41
2006	-0.67	-0.52	-0.47	-0.26	0.00	-0.08	-0.03	-0.61	-0.58	-0.07	-0.00	-0.31
2007	-0.80*	-0.64	-0.35	-0.02	0.02	0.02	0.01	-0.06	-0.01	-0.04	-0.09	-0.01
2008	-0.24	-0.47	-0.51	-0.01	-0.05	-0.05	0.01	-0.01	-0.12	-0.16	-0.11	0.00
2009	-0.23	-0.15	-0.20	-0.31	-0.00	-0.00	0.01	-0.11	0.01	-0.00	-0.00	0.08
2010	-0.28	-0.34	-0.02	-0.00	0.04	-0.12	-0.05	-0.46	-0.78*	-0.42	-0.06	-0.26
2011	-0.37	-0.32	-0.31	0.02	0.04	-0.14	-0.00	0.01	-0.28	-0.38	-0.00	0.16
2012	0.07	0.00	0.03	-0.06	0.09	0.01	0.03	-0.13	-0.10	0.02	0.00	-0.13
2013	-0.29	-0.16	0.06	0.31	0.02	0.03	0.02	0.11	0.04	0.00	0.01	-0.15
2014	-0.19	-0.04	-0.01	-0.01	0.00	0.02	0.08	0.01	0.00	0.05	0.31	-0.25
2015	-0.38	-0.36	-0.09	-0.01	-0.01	0.13	0.05	0.32	0.29	0.13	1.25*	0.10
2016	-0.44	-0.38	-0.04	0.19	0.08	0.01	0.08	0.13	-0.15	-0.00	0.00	0.21
2017	-0.03	-0.29	-0.21	0.06	0.01	0.00	0.00	0.01	-0.10	-0.03	-0.01	0.30
All	-0.37	-0.34	-0.16	-0.01	-0.00	-0.06	-0.06	-0.14	-0.12	-0.07	0.05	-0.08

Table 4-37. Shasta Lake Outflow Temperature MAE (ºC): 2000-2017 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of >1.0ºC). A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	--	0.15	0.20	0.10	0.01	0.34	0.12	0.09	0.01	0.00	0.01	0.14
2001	0.12	0.55	0.39	0.28	0.14	0.01	0.05	0.17	0.02	0.27	0.16	0.24

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2002	0.72	0.51	0.21	0.05	0.05	0.05	0.01	0.03	0.04	0.01	0.00	0.28
2003	0.43	0.37	0.10	0.09	0.18	0.61	0.82	0.18	0.01	0.00	0.00	0.07
2004	0.37	0.51	0.14	0.01	0.05	0.00	0.05	0.18	0.00	0.00	0.05	0.45
2005	0.82	0.61	0.00	0.01	0.02	0.07	0.49	1.108*	0.38	0.11	0.14	0.41
2006	0.67	0.52	0.47	0.26	0.01	0.11	0.04	0.61	0.58	0.07	0.00	0.31
2007	0.80	0.64	0.36	0.11	0.02	0.02	0.01	0.09	0.04	0.04	0.09	0.01
2008	0.24	0.47	0.52	0.01	0.05	0.05	0.01	0.02	0.12	0.16	0.11	0.00
2009	0.26	0.18	0.20	0.31	0.00	0.00	0.01	0.14	0.01	0.00	0.00	0.08
2010	0.31	0.34	0.02	0.03	0.05	0.14	0.06	0.47	0.78	0.42	0.06	0.27
2011	0.39	0.32	0.31	0.09	0.09	0.15	0.01	0.02	0.28	0.38	0.01	0.19
2012	0.17	0.09	0.08	0.09	0.13	0.02	0.03	0.16	0.12	0.02	0.00	0.27
2013	0.30	0.17	0.11	0.32	0.02	0.03	0.02	0.11	0.04	0.00	0.01	0.18
2014	0.19	0.04	0.03	0.02	0.01	0.06	0.08	0.01	0.00	0.07	0.32	0.31
2015	0.38	0.36	0.10	0.01	0.02	0.13	0.05	0.32	0.29	0.13	1.258*	0.25
2016	0.44	0.38	0.08	0.20	0.12	0.01	0.08	0.13	0.15	0.00	0.00	0.22
2017	0.28	0.31	0.21	0.07	0.08	0.00	0.00	0.01	0.10	0.03	0.01	0.30
All	0.40	0.36	0.20	0.11	0.06	0.10	0.11	0.21	0.17	0.10	0.12	0.22

Table 4-38. Shasta Lake Outflow Temperature RMSE (°C): 2000-2017 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of >1.5°C). A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	-	0.21	0.30	0.27	0.03	0.41	0.23	0.22	0.02	0.00	0.04	0.24
2001	0.17	0.56	0.51	0.38	0.24	0.02	0.18	0.29	0.03	0.52	0.30	0.35
2002	0.75	0.57	0.30	0.10	0.08	0.09	0.03	0.09	0.09	0.02	0.02	0.45
2003	0.45	0.42	0.21	0.18	0.26	0.66	0.85	0.32	0.05	0.01	0.00	0.12
2004	0.42	0.55	0.28	0.02	0.09	0.01	0.17	0.31	0.01	0.00	0.15	0.63
2005	0.84	0.64	0.01	0.04	0.03	0.08	0.82	1.15	0.41	0.18	0.19	0.47
2006	0.70	0.57	0.49	0.35	0.04	0.17	0.10	0.88	0.67	0.12	0.00	0.38

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007	0.86	0.69	0.52	0.21	0.03	0.02	0.03	0.17	0.10	0.13	0.18	0.04
2008	0.30	0.61	0.88	0.06	0.14	0.12	0.02	0.07	0.31	0.31	0.20	0.02
2009	0.39	0.26	0.36	0.57	0.00	0.00	0.03	0.27	0.03	0.02	0.02	0.14
2010	0.44	0.53	0.05	0.06	0.13	0.21	0.12	0.68	0.84	0.53	0.20	0.35
2011	0.41	0.42	0.41	0.18	0.17	0.34	0.06	0.05	0.46	0.49	0.03	0.31
2012	0.29	0.21	0.17	0.18	0.23	0.04	0.07	0.29	0.21	0.03	0.03	0.35
2013	0.37	0.24	0.25	0.59	0.02	0.07	0.06	0.22	0.13	0.02	0.06	0.23
2014	0.27	0.10	0.08	0.06	0.05	0.17	0.16	0.02	0.01	0.20	0.37	0.40
2015	0.40	0.52	0.20	0.08	0.08	0.33	0.10	0.53	0.48	0.35	1.38	0.33
2016	0.51	0.44	0.16	0.32	0.29	0.02	0.14	0.25	0.28	0.02	0.00	0.34
2017	0.37	0.37	0.28	0.19	0.15	0.02	0.01	0.02	0.30	0.10	0.03	0.39
All	0.51	0.47	0.36	0.27	0.14	0.23	0.30	0.44	0.34	0.25	0.36	0.34

Keswick Reservoir

Keswick Reservoir calibration included flow, stage, and water temperature. Keswick Reservoir hourly outflow volumes and water surface elevation are shown in Figure 4-17 and Figure 4-18, respectively. Keswick Reservoir outflow and elevation match observed values, and outflow statistics demonstrate only a slight discrepancy associated with balancing accretion and depletion on the first day of simulation, as the hourly balance flows adjust to the daily periodicity of various input datasets (Table 4-39).

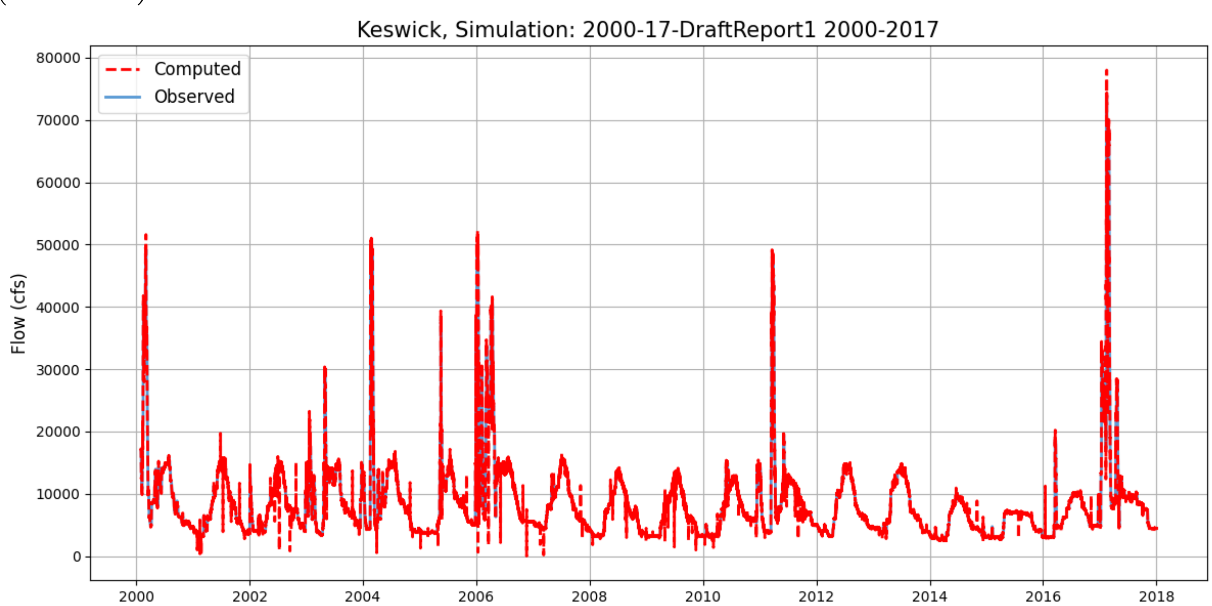


Figure 4-17. Keswick Reservoir simulated and observed flow through Keswick Dam, 2000-2017.

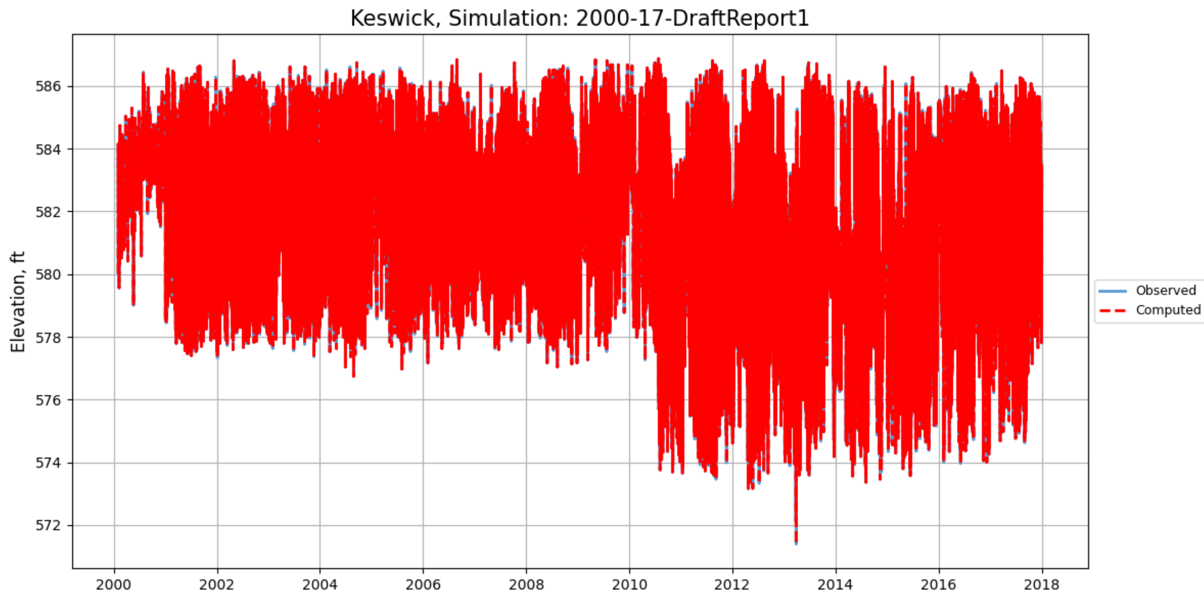


Figure 4-18. Keswick Reservoir simulated and observed water surface elevation, 2000-2017.

Table 4-39. Keswick Reservoir outflow error statistics.

Statistics	2000	2001	2002	2003	2004	2005
Mean Bias (cfs)	0.08	0.00	0.00	0.00	0.00	0.00
MAE (cfs)	0.12	0.00	0.00	0.00	0.00	0.00
RMSE (cfs)	2.61	0.00	0.00	0.00	0.00	0.00
Nash-Sutcliffe (NSE)	1.00	1.00	1.00	1.00	1.00	1.00
COUNT	8040	8760	8760	8760	8784	8760

Statistics	2006	2007	2008	2009	2010	2011
Mean Bias (cfs)	0.00	0.00	0.00	0.00	0.00	0.00
MAE (cfs)	0.00	0.00	0.00	0.00	0.00	0.00
RMSE (cfs)	0.00	0.00	0.00	0.00	0.00	0.00
Nash-Sutcliffe (NSE)	1.00	1.00	1.00	1.00	1.00	1.00

Statistics	2006	2007	2008	2009	2010	2011
COUNT	8760	8760	8784	8760	8760	8760

Statistics	2012	2013	2014	2015	2016	2017
Mean Bias (cfs)	0.00	0.00	0.00	0.00	0.00	0.00
MAE (cfs)	0.00	0.00	0.00	0.00	0.00	0.00
RMSE (cfs)	0.00	0.00	0.00	0.00	0.00	0.00
Nash-Sutcliffe (NSE)	1.00	1.00	1.00	1.00	1.00	1.00
COUNT	8784	8760	8760	8760	8784	8760

Statistics	All Years
Mean Bias (cfs)	0.00
MAE (cfs)	0.01
RMSE (cfs)	0.59
Nash-Sutcliffe (NSE)	1.00
COUNT	157057

Keswick Reservoir profile temperature calibration data consists of profiles from 2010 and 2017, the only periods where observed data exists. Keswick Reservoir is shallow and has a short residence time and experiences only intermittent weak stratification throughout the year. ResSim reproduces these isothermal conditions effectively representing the high levels of vertical mixing and rapid transit time of waters through Keswick reservoir (Figure 4-19 and Figure 4-20). Keswick Reservoir temperature profile statistics for mean bias, MAE, and RMSE are below thresholds except for mean bias in January 2010 (Table 4-40 and Table 4-42). As discussed above for winter profiles in Shasta Lake, the NSE statistic is not always a representative statistic for model performance under isothermal or near isothermal conditions (Table 4-43), and graphical comparisons and other model performance metrics should be relied upon when assessing calibration.

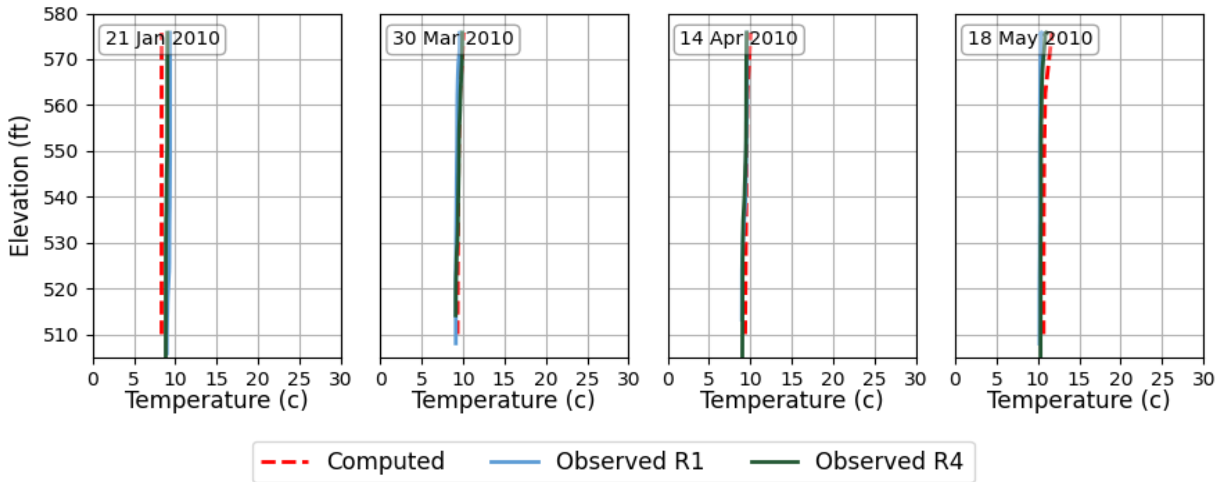


Figure 4-19. Keswick Reservoir simulated and observed temperature profile comparisons, 2010. Station R1 and R4 are 2.3 and 1.5 miles upstream from dam, respectively.

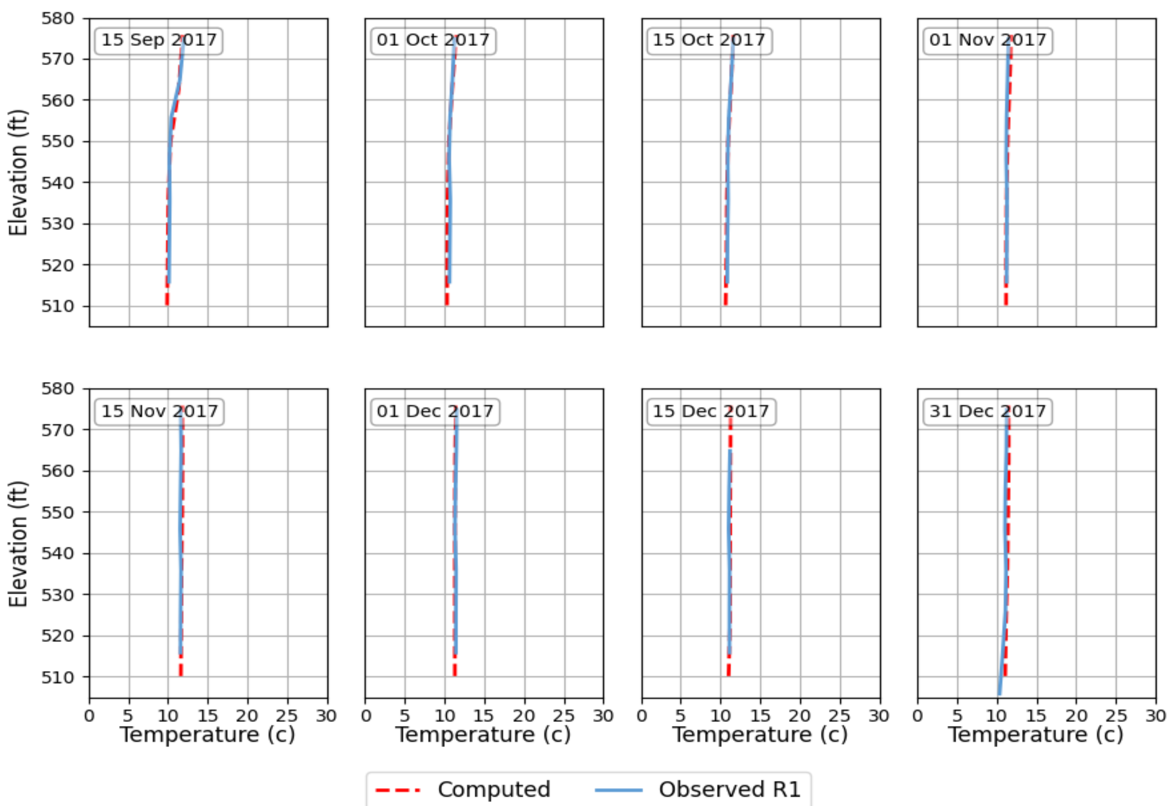


Figure 4-20. Keswick Reservoir simulated and observed temperature profile comparisons, 2017. Profiles data are collected approximately 0.1 miles upstream from dam.

Table 4-40 Keswick Reservoir profile temperature mean bias: 2010, 2017 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of +- 0.75°C). A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2010	-0.94*	--	0.26	0.22	0.58	--	--	--	--	--	--	--
2017	--	--	--	--	--	--	--	--	-0.04	-0.09	0.12	0.10

Table 4-41 Keswick Reservoir profile temperature MAE: 2010, 2017 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of 1.0°C). A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2010	0.94	--	0.26	0.22	0.58	--	--	--	--	--	--	--
2017	--	--	--	--	--	--	--	--	0.15	0.13	0.15	0.17

Table 4-42 Keswick Reservoir profile temperature RMSE: 2010, 2017 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of 1.5°C). A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2010	0.95	--	0.27	0.27	0.61	--	--	--	--	--	--	--
2017	--	--	--	--	--	--	--	--	0.17	0.17	0.17	0.20

Table 4-43. Keswick Profile Temperature NSE: 2010, 2017 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of <0.65). A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2010	-57.41*	--	-3.80*	-0.22*	-252.7*	--	--	--	--	--	--	--
2017	--	--	--	--	--	--	--	--	0.91	0.48*	-0.13*	0.09*

Keswick Reservoir simulated and observed outflow temperature are compared in Figure 4-21 and Figure 4-22. Observed data (USGS 11370500) are measured 0.75 mi downstream of Keswick Dam and have slightly a higher diurnal temperature range than simulated Keswick Dam outflow. Differences may be attributable to warming in the river reach. The fit of simulated to observed Keswick outflow temperatures is generally similar and reflective of the fit of Shasta Lake outflow (i.e., when Shasta outflow is cold, Keswick outflow is cold); however, the statistical fit at Keswick dam is slightly better (compare

Table 4-44 and Table 4-30), likely in part due to the large diurnal fluctuations present in the observed Shasta Lake outflow temperature records. Simulated and observed Keswick Reservoir outflow temperatures for the 2014 are shown in Figure R13. Annually, statistical metrics for Keswick Dam outflow are within thresholds, excepting NSE during 2010, reflecting a more consistent negative temperature bias during that year (

Table 4-44). Complete set of statistical metrics are reported in Appendix D.

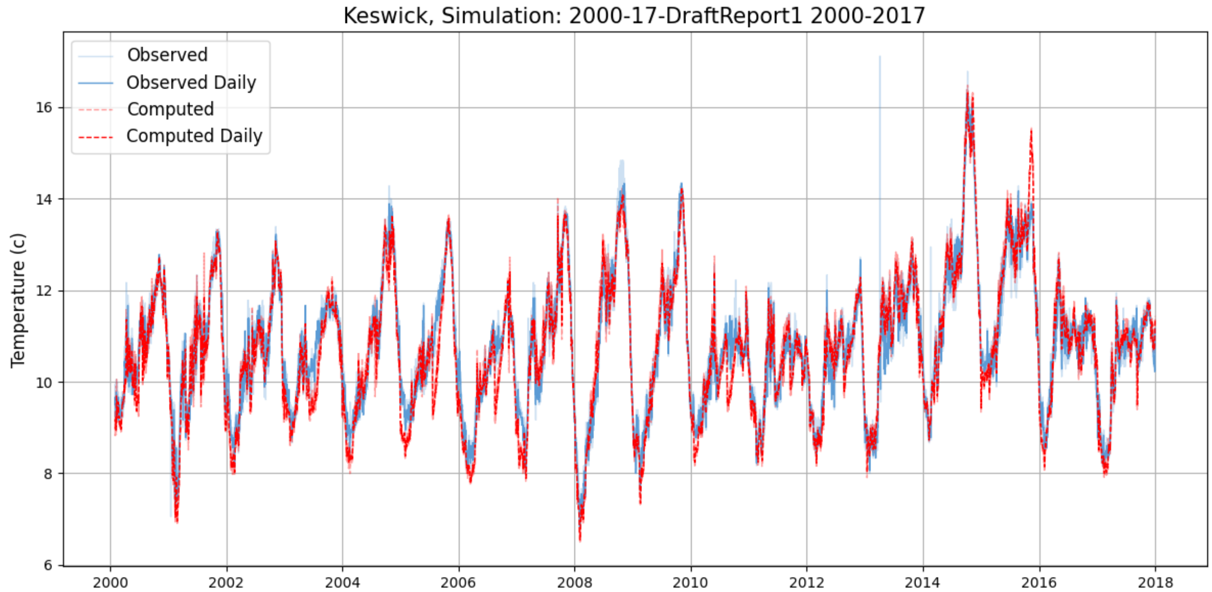


Figure 4-21. Simulated and observed outflow temperatures from Keswick Dam: 2000-2017.

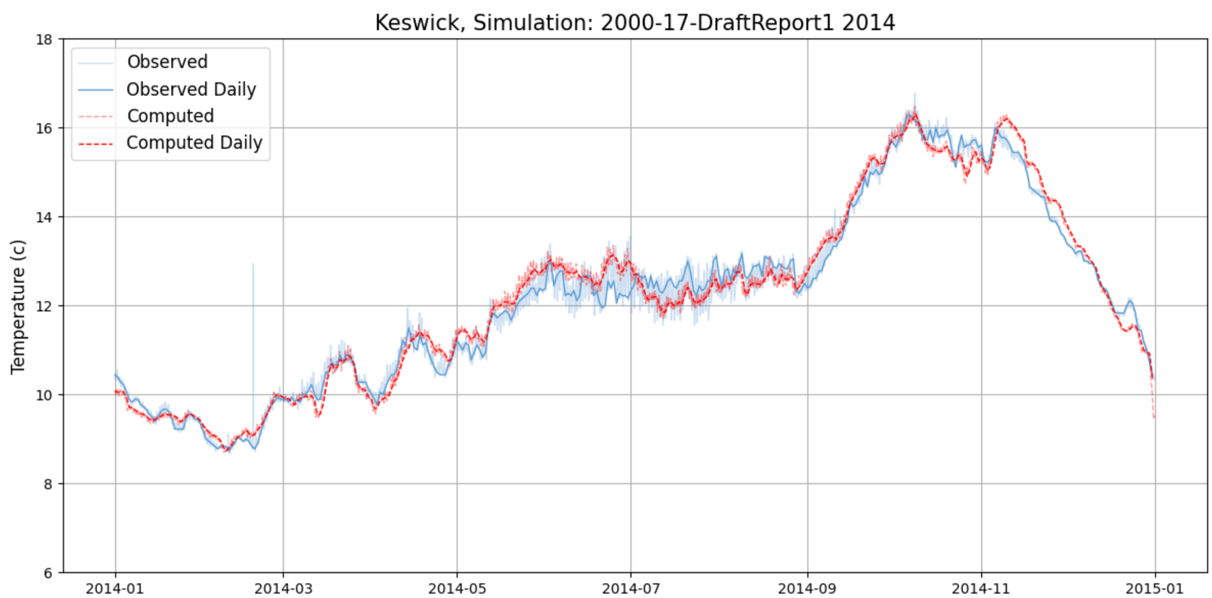


Figure 4-22. Simulated and observed outflow temperatures from Keswick Dam: 2014.

Table 4-44. Keswick Reservoir temperature outflow error statistics (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistics	2000	2001	2002	2003	2004	2005
Mean Bias (ºC)	-0.10	-0.18	-0.09	-0.26	-0.17	-0.33
MAE (ºC)	0.23	0.30	0.30	0.33	0.31	0.44
RMSE (ºC)	0.30	0.39	0.37	0.43	0.38	0.59
Nash-Sutcliffe (NSE)	0.90	0.93	0.89	0.73	0.93	0.76
COUNT	8,040	8,760	8,760	8,760	8,784	8,760

Statistics	2006	2007	2008	2009	2010	2011
Mean Bias (ºC)	-0.22	-0.10	-0.03	-0.06	-0.17	-0.03
MAE (ºC)	0.34	0.29	0.30	0.24	0.33	0.22
RMSE (ºC)	0.46	0.39	0.37	0.30	0.45	0.28
Nash-Sutcliffe (NSE)	0.78	0.92	0.97	0.97	0.64*	0.87
COUNT	8760,	8,760	8,784	8,760	8,760	8,760

Statistics	2012	2013	2014	2015	2016	2017
Mean Bias (ºC)	0.00	0.14	0.03	0.16	0.04	-0.00
MAE (ºC)	0.24	0.27	0.25	0.36	0.26	0.21
RMSE (ºC)	0.30	0.37	0.31	0.50	0.34	0.27
Nash-Sutcliffe (NSE)	0.90	0.92	0.98	0.83	0.85	0.93
COUNT	8,784	8,760	8,760	8,760	8,784	8,760

Statistics	All Years
Mean Bias (oC)	-0.08
MAE (oC)	0.29
RMSE (oC)	0.39
Nash-Sutcliffe (NSE)	0.92
COUNT	157,057

Sacramento River

Sacramento River calibration included flow and water temperature. Simulated and observed flows on the Sacramento River are compared for the Bend Bridge (BND) monitoring station in Figure 4-23 and Figure 4-24 and Table 4-45. To account for local inflows and diversions, gage error, and other unquantified gains and losses in the Sacramento River from Keswick Dam to Bend Bridge, a water balance accounting for flow at Keswick Dam, measured tributary flows (Clear, Cow, Cottonwood, and Battle Creeks), significant diversions (Anderson Cottonwood Irrigation Distriict), and flow Bend Bridge was used to calculate a net accretion/depletion flow to achieve the flow volume at Bend Bridge. A positive accretion/depletion represents a net gain and a negative value a net loss. Because certain flow records are reported daily and because there are appreciable accretions from ungaged watersheds during high flow events, peak hourly flow values are under-represented (Figure 4-23 and Figure 4-24). However, these periods typically do not present water temperature challenges and there is still appreciable accretion/depletion flow. The simulated flow at Bend Bridge conserves mass on a daily average basis.

Statistical errors that reflect variance (MAE, RMSE) are reflective of the differences generated between the hourly accounting and daily inflow records; however, the mean bias is generally less than +- 50 cfs (Table 4-45). The year 2000 shows a high mean bias, reflecting incomplete observed data records and several months of resulting unbalanced flows.

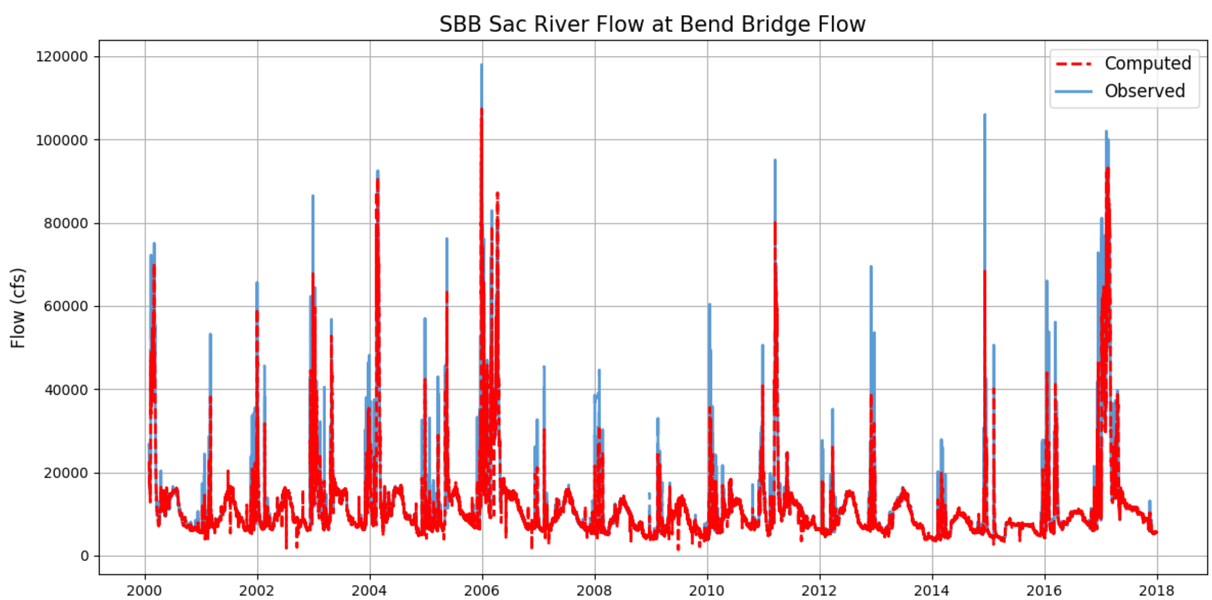


Figure 4-23. Simulated and observed hourly flows at Bend Bridge: 2000-2017.

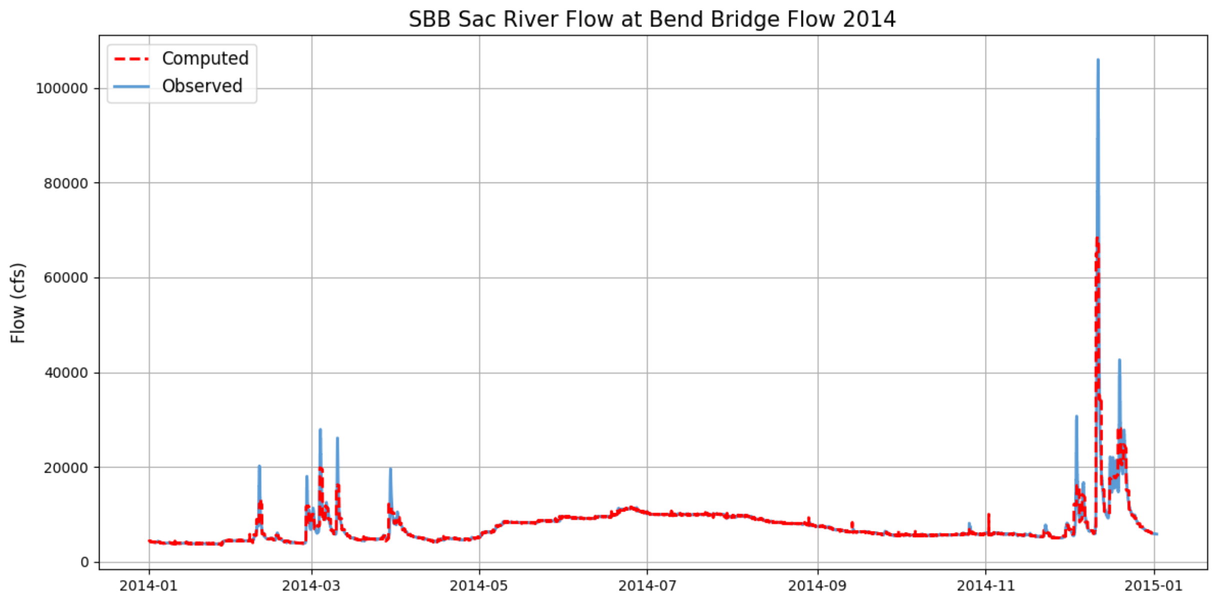


Figure 4-24. Simulated and observed hourly flows at Bend Bridge: 2014.

Table 4-45. Sacramento River flow error statistics at Bend Bridge (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistics	2000	2001	2002	2003	2004	2005
Mean Bias (cfs)	-508.04	-3.94	-5.10	48.13	6.45	-6.32
MAE (cfs)	1,029.12	535.27	442.98	628.12	608.48	745.97
RMSE (cfs)	2,728.77	1,678.87	1,817.45	1,816.15	2,290.53	2,736.61
Nash-Sutcliffe (NSE)	0.95	0.85	0.93	0.95	0.97	0.92
COUNT	8,040	8,760	8,760	8,760	8,784	8,760

Statistics	2006	2007	2008	2009	2010	2011
Mean Bias (cfs)	1.76	-1.93	5.72	2.19	-0.63	0.71
MAE (cfs)	779.97	209.18	333.71	278.82	612.46	466.92
RMSE (cfs)	2,251.00	757.49	1,326.04	774.23	1,701.98	1,396.25
Nash-Sutcliffe (NSE)	0.98	0.94	0.86	0.95	0.89	0.98
COUNT	8,760	8,760	8,784	8,760	8,760	8,760

Statistics	2012	2013	2014	2015	2016	2017
Mean Bias (cfs)	-0.06	0.31	-0.19	0.12	-0.24	0.62
MAE (cfs)	463.20	122.89	400.91	152.00	724.24	871.22
RMSE (cfs)	1,799.83	206.74	2,070.52	783.41	2,587.98	2,674.55
Nash-Sutcliffe (NSE)	0.85	1.00	0.83	0.91	0.83	0.98
COUNT	8,784	8,760	8,760	8,760	8,784	8,760

Statistics	All Years
Mean Bias (cfs)	-23.35
MAE (cfs)	520.21
RMSE (cfs)	1,888.10
Nash-Sutcliffe (NSE)	0.96
COUNT	157,057

Four temperature monitoring stations downstream of Keswick dam were used to calibrate ResSim for the Sacramento River: Sacramento River above Clear Creek (CCR), Balls Ferry Bridge (BSF), Jellys Ferry (JLF), and Bend Bridge (BND).

Simulated and observed hourly temperature time series at CCR are compared in Figure 4-25 through Figure 4-27 for 2000-2017, 2005, and 2014, respectively, and summary statistics for 2000-2017 are included in Table 4-46. Sacramento River temperatures at CCR are generally similar to Keswick Dam outflow temperatures, given the short distance between these two gauges. Observed data from late spring into fall exhibit a diurnal range of 1.0ºC to 2.0ºC (Figure 4-25 through Figure 4-27), while simulated temperatures exhibit a diurnal range of approximately 0.5ºC less. The negative temperature biases in 2005, reflective of biases in Shasta Lake simulations, are carried downstream through Keswick Reservoir and in release to the Sacramento River from Keswick Dam (See Figure 4-15 and Figure 4-26). The bias in 2005 is reflected in the NSE metric, the only annual period beyond statistical thresholds (Table 4-46). In contrast, the low water year of 2014 shows low biases, also reflective of upstream temperature performance by ResSim (Figure 4-27).

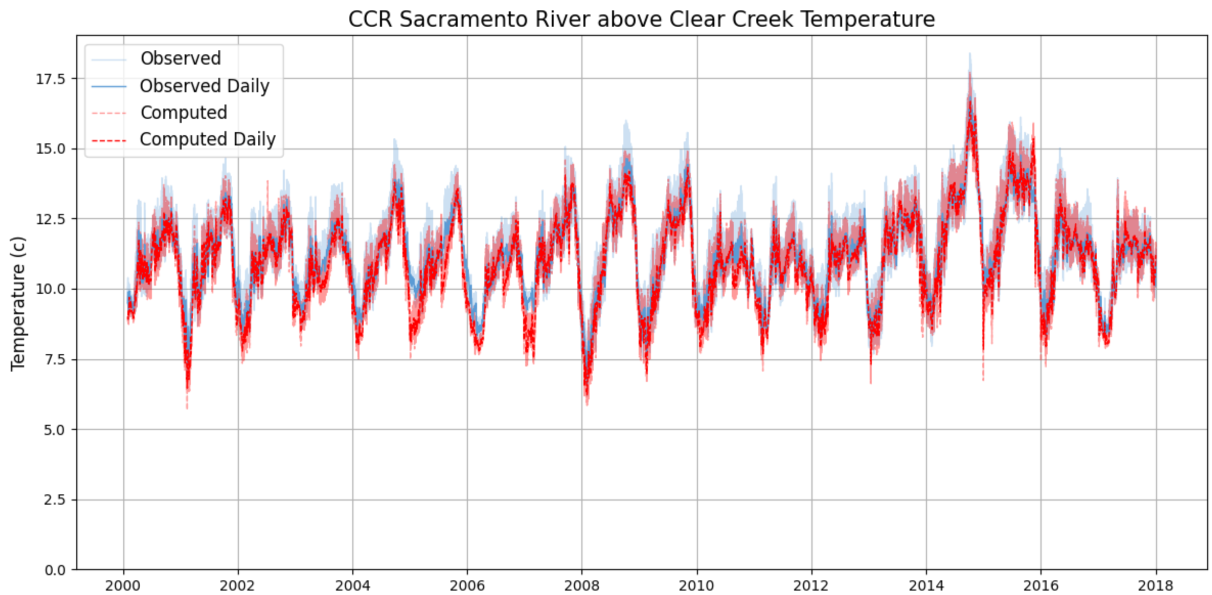


Figure 4-25. Simulated and observed temperatures at CCR: 2000-2017.

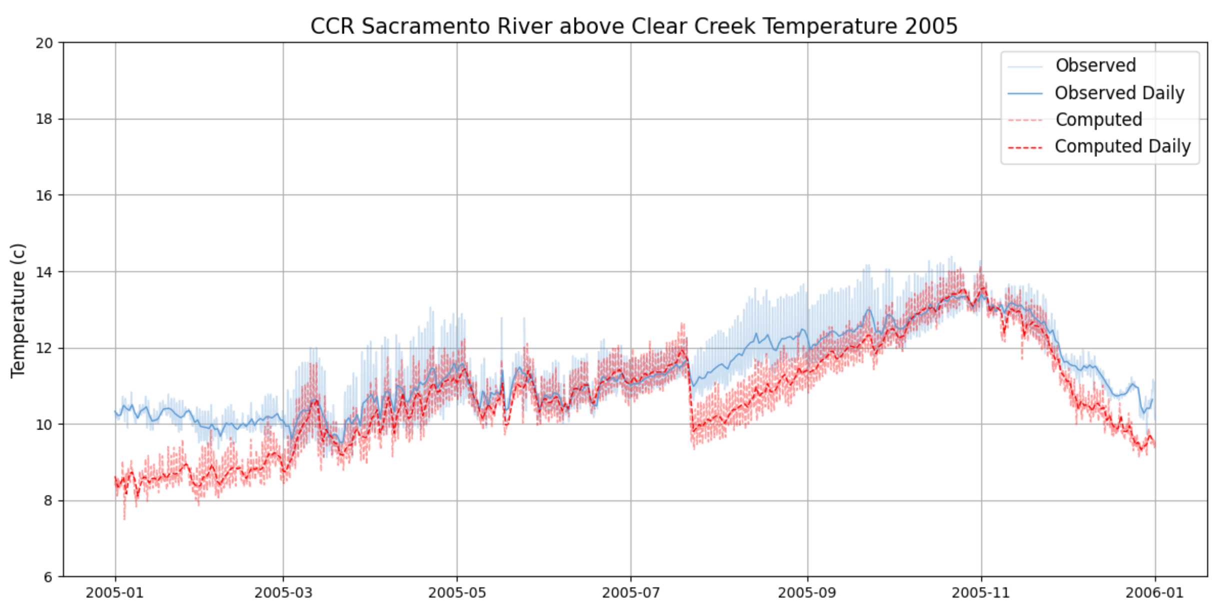


Figure 4-26. Simulated and observed temperatures at CCR: 2005.

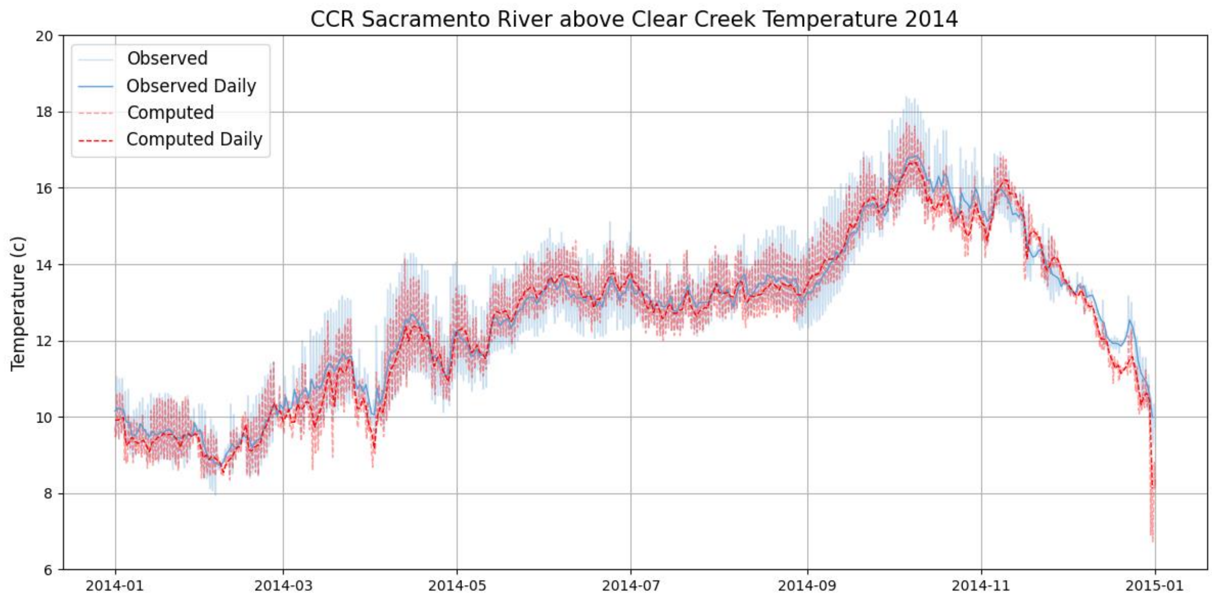


Figure 4-27. Simulated and observed temperatures at CCR: 2014.

Table 4-46. CCR Sacramento River above Clear Creek Temperature Error Statistics (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistics	2000	2001	2002	2003	2004	2005
Mean Bias (°C)	-0.16	-0.28	-0.20	-0.36	-0.33	-0.60
MAE (°C)	0.30	0.45	0.41	0.42	0.48	0.66
RMSE (°C)	0.39	0.57	0.51	0.52	0.60	0.86
Nash-Sutcliffe (NSE)	0.86	0.86	0.82	0.73	0.85	0.42
COUNT	8016	8760	8760	8760	8784	8760

Statistics	2006	2007	2008	2009	2010	2011
Mean Bias (°C)	-0.36	-0.27	-0.19	-0.19	-0.30	-0.18
MAE (°C)	0.47	0.51	0.41	0.37	0.42	0.33
RMSE (°C)	0.60	0.69	0.51	0.47	0.53	0.42
Nash-Sutcliffe (NSE)	0.67	0.73	0.95	0.94	0.71	0.83
COUNT	8760	8760	8784	8760	8760	8760

Statistics	2012	2013	2014	2015	2016	2017
Mean Bias (ºC)	-0.20	-0.03	-0.12	0.01	-0.08	-0.03
MAE (ºC)	0.36	0.34	0.35	0.41	0.35	0.26
RMSE (ºC)	0.47	0.44	0.44	0.56	0.45	0.34
Nash-Sutcliffe (NSE)	0.84	0.92	0.96	0.87	0.85	0.92
COUNT	8,784	8,760	8,760	8,760	8,784	8,760

Statistics	All Years
Mean Bias (oC)	-0.22
MAE (oC)	0.41
RMSE (oC)	0.53
Nash-Sutcliffe (NSE)	0.88
COUNT	157,032

Simulated and observed hourly temperature time series at Balls Ferry Bridge are compared in Figure 4-28 through Figure 4-30 and Table 4-47. At Balls Ferry Bridge, biases developed upstream are still apparent, but reduced as meteorological influences becomes a larger factor as distance from Keswick Dam increases. During late spring through fall, ResSim reproduces the observed diurnal variability of more the 2.0ºC in 2005 (Figure 4-29). Simulated temperatures in 2014 show similar simulated diurnal temperature range; however, observed diurnal range in 2014 at BSF is notably smaller (0.5ºC to 1.5ºC) (Figure 4-30). These observed values appear anomalous considering diurnal temperatures ranges downstream at Jellys Ferry are on the order of 2.0ºC to 2.5ºC (Figure 4-33), and will continue to be explored during final model calibration. Annual statical metrics for hourly temperature comparisons are below thresholds in all years at Ball Ferry Bridge (Table 4-47).

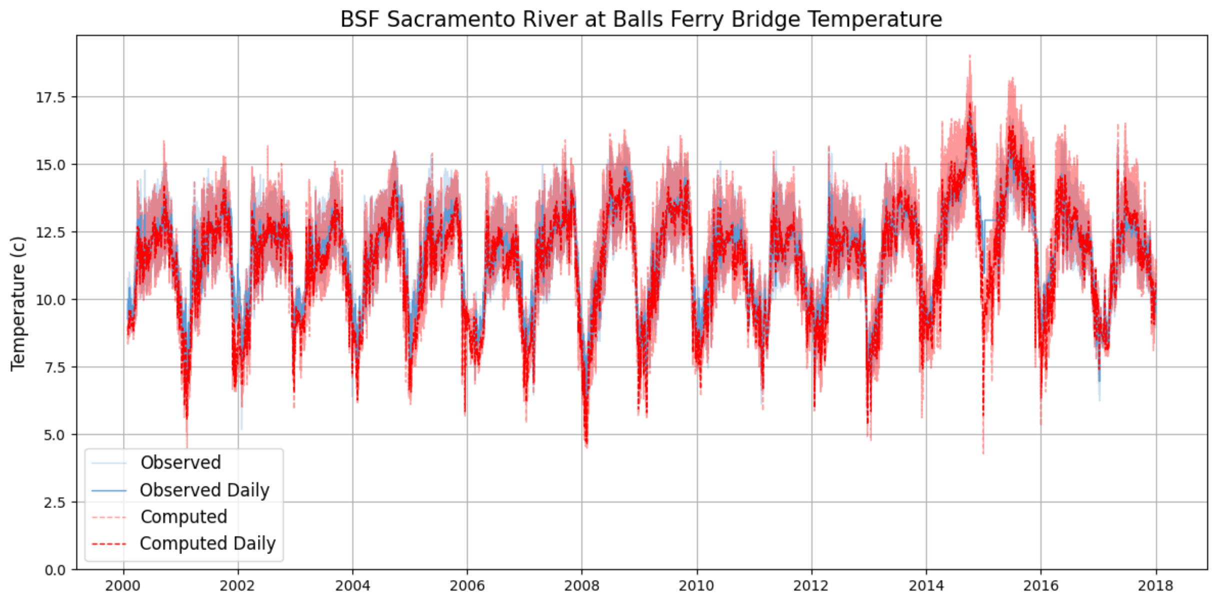


Figure 4-28. Simulated and observed temperatures at BSF: 2000-2017.

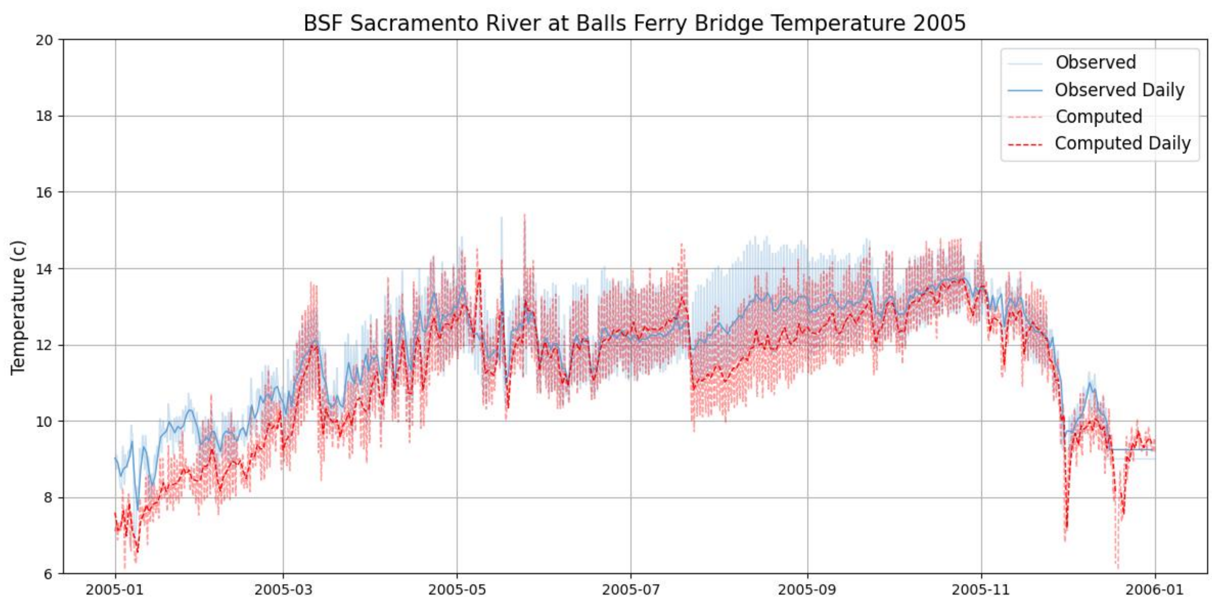


Figure 4-29. Simulated and observed temperatures at BSF: 2005.

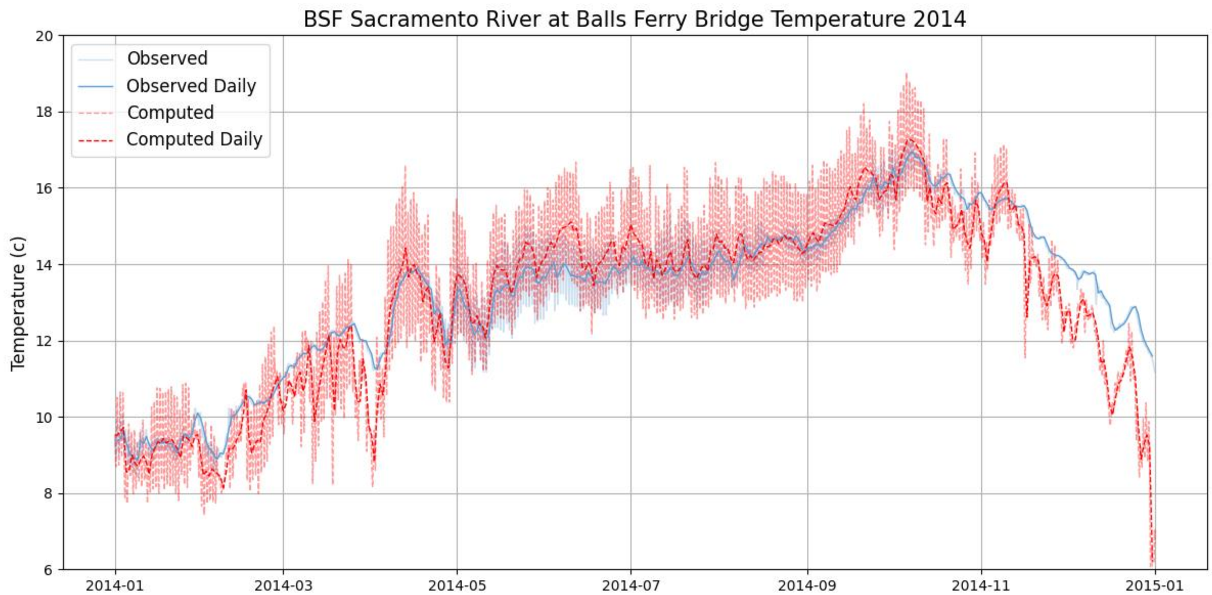


Figure 4-30. Simulated and observed temperatures at BSF: 2014.

Table 4-47. BSF Sacramento River at Balls Ferry temperature error statistics (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistics	2000	2001	2002	2003	2004	2005
Mean Bias (°C)	-0.29	-0.53	-0.31	-0.41	-0.35	-0.53
MAE (°C)	0.51	0.80	0.62	0.59	0.61	0.66
RMSE (°C)	0.62	1.04	0.79	0.71	0.77	0.84
Nash-Sutcliffe (NSE)	0.77	0.67	0.73	0.70	0.81	0.73
COUNT	8,016	8,760	8,760	8,760	8,784	8,760

Statistics	2006	2007	2008	2009	2010	2011
Mean Bias (°C)	-0.25	-0.31	-0.24	-0.19	-0.36	-0.15
MAE (°C)	0.49	0.47	0.52	0.42	0.56	0.39
RMSE (°C)	0.62	0.62	0.68	0.55	0.70	0.49
Nash-Sutcliffe (NSE)	0.83	0.88	0.92	0.93	0.73	0.89
COUNT	8,760	8,760	8,784	8,760	8,760	8,760

Statistics	2012	2013	2014	2015	2016	2017
Mean Bias (ºC)	-0.36	-0.04	-0.26	-0.05	-0.17	0.06
MAE (ºC)	0.57	0.53	0.92	0.78	0.60	0.35
RMSE (ºC)	0.74	0.68	1.19	1.02	0.81	0.46
Nash-Sutcliffe (NSE)	0.79	0.87	0.66	0.66	0.72	0.92
COUNT	8,784	8,760	8,760	8,760	8,784	8,760

Statistics	All Years
Mean Bias (ºC)	-0.26
MAE (ºC)	0.58
RMSE (ºC)	0.76
Nash-Sutcliffe (NSE)	0.82
COUNT	157,032

Simulated and observed hourly temperature time series at Jellys Ferry Bridge are compared in Figure 4-31 through Figure 4-33 through Figure 4-30 and Table 4-47. At JLF, biases developed upstream are still apparent, but reduced as meteorological influences becomes a larger factor as distance from Keswick Dam increases. During late spring through fall, ResSim produces a diurnal variability of approximately 2.5ºC in 2005, consistent with observed conditions (Figure 4-32). Simulated temperatures in 2014 show simulated diurnal temperature range of 2.5ºC to 3.0ºC, slightly larger than the 2.5 ºC range in observed data. (Figure 4-33). Annual statical metrics for hourly temperature comparisons are below thresholds in all years at JLF (Table 4-48).

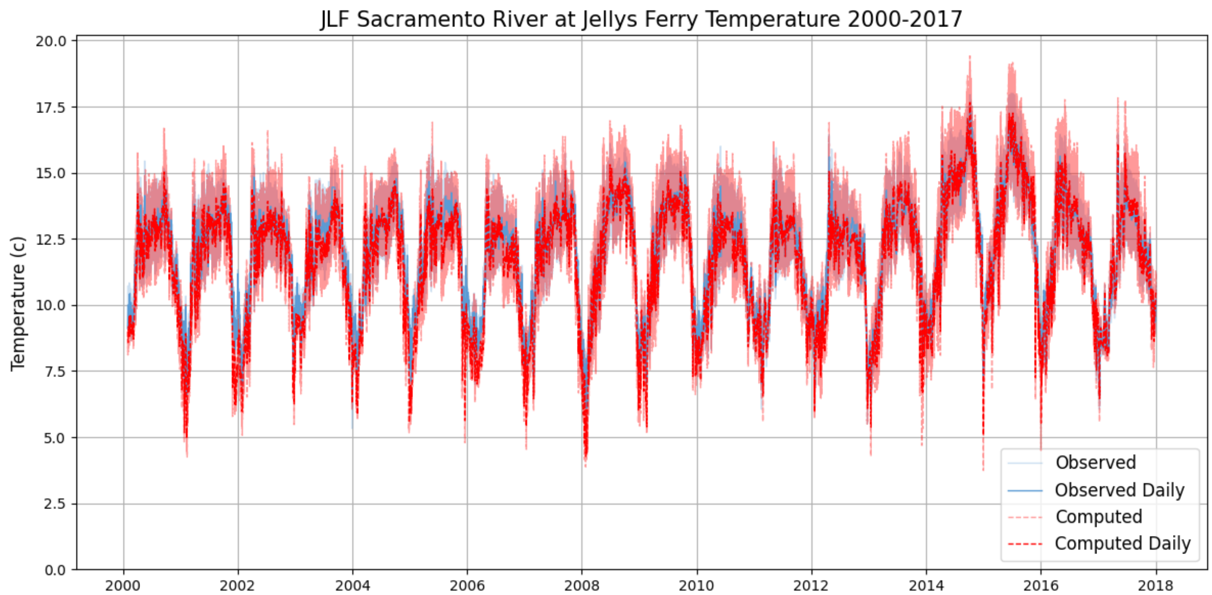


Figure 4-31. Simulated and observed temperatures at JLF: 2000-2017.

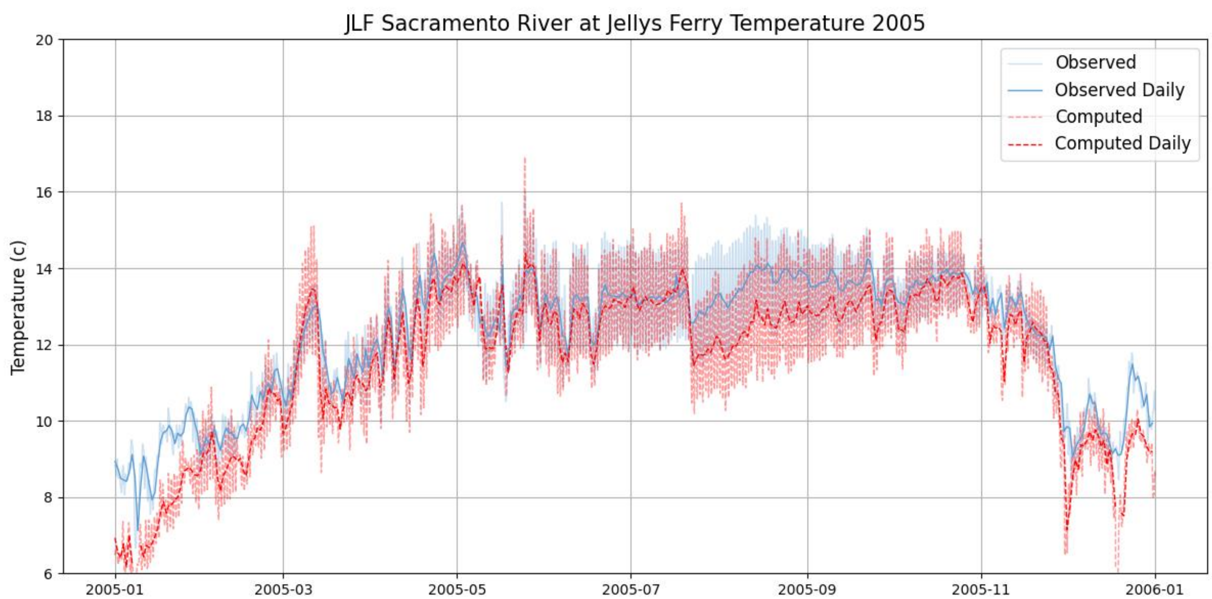


Figure 4-32. Simulated and observed temperatures at JLF: 2005.

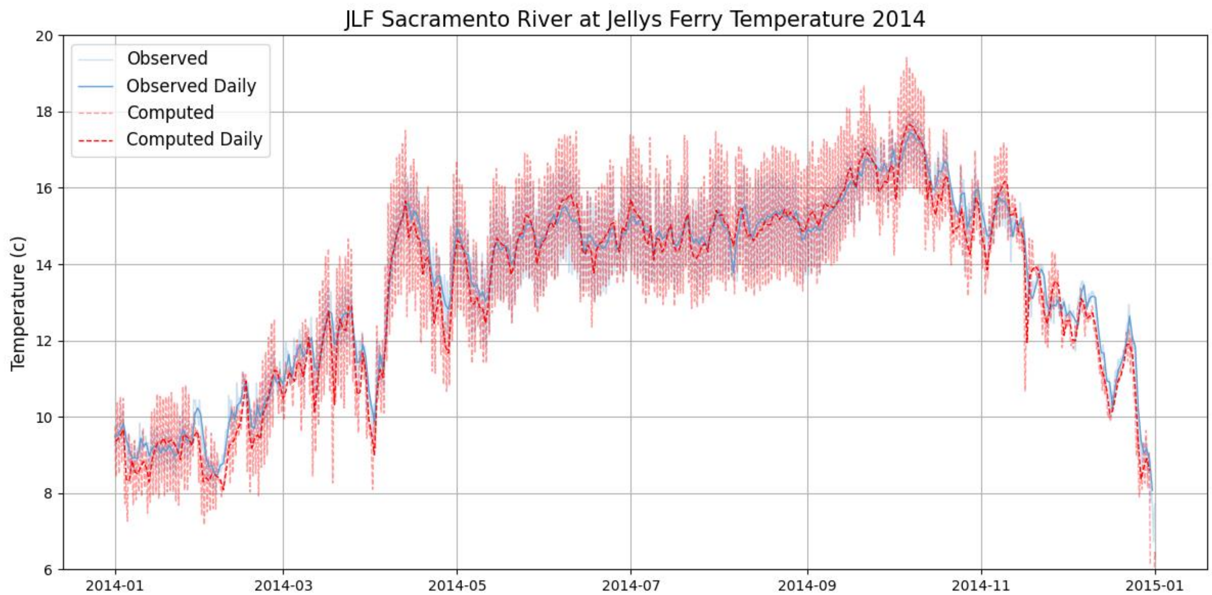


Figure 4-33. Simulated and observed temperatures at JLF: 2014.

Table 4-48. JLF Sacramento River at Jelly Ferry temperature error statistics (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistics	2000	2001	2002	2003	2004	2005
Mean Bias (ºC)	-0.34	-0.65	-0.41	-0.50	-0.43	-0.65
MAE (ºC)	0.57	0.87	0.67	0.66	0.72	0.76
RMSE (ºC)	0.69	1.14	0.84	0.80	0.91	0.97
Nash-Sutcliffe (NSE)	0.78	0.70	0.79	0.76	0.78	0.70
COUNT	8,016	8,760	8,760	8,760	8,784	8,760

Statistics	2006	2007	2008	2009	2010	2011
Mean Bias (ºC)	-0.51	-0.40	-0.27	-0.25	-0.38	-0.17
MAE (ºC)	0.63	0.56	0.60	0.53	0.52	0.42
RMSE (ºC)	0.78	0.72	0.77	0.68	0.65	0.54
Nash-Sutcliffe (NSE)	0.81	0.87	0.91	0.91	0.85	0.91
COUNT	8,760	8,760	8,784	8,760	8,760	8,760

Statistics	2012	2013	2014	2015	2016	2017
Mean Bias (ºC)	-0.42	-0.13	-0.20	-0.11	-0.12	-0.03
MAE (ºC)	0.58	0.47	0.54	0.56	0.44	0.36
RMSE (ºC)	0.74	0.63	0.68	0.73	0.56	0.47
Nash-Sutcliffe (NSE)	0.85	0.92	0.92	0.90	0.92	0.94
COUNT	8,784	8,760	8,760	8,760	8,784	8,760

Statistics	All Years
Mean Bias (ºC)	-0.33
MAE (ºC)	0.58
RMSE (ºC)	0.76
Nash-Sutcliffe (NSE)	0.87
COUNT	157,032

Simulated and observed hourly temperature time series at Bend Bridge are compared in Figure 4-34 through Figure 4-36 and Table 4-47. At BND, biases developed upstream are still apparent, but reduced as meteorological influences become an ever-larger factor with increased distance from Keswick Dam. During late spring through fall, ResSim reproduces the observed diurnal variability of approximately 2.5ºC to 3.0ºC in 2005, approximately 0.5oC to 1.0oC greater than observed conditions (Figure 4-35). Similarly in 2014, simulated diurnal temperature range of 2.5ºC to 3.0ºC, larger than the approximately 2.0ºC range in observed data. (Figure 4-33). Suppressed diurnal range in observed data at BND is consistent with Lowney (2000). Ongoing calibration and refined bathymetry (expected 2023) should improve travel time and represented diurnal range at BND, as well as upstream locations (i.e., BSF and JLF). Annual statical metrics for hourly temperature comparisons are below thresholds in all years at BND (Table 4-49).

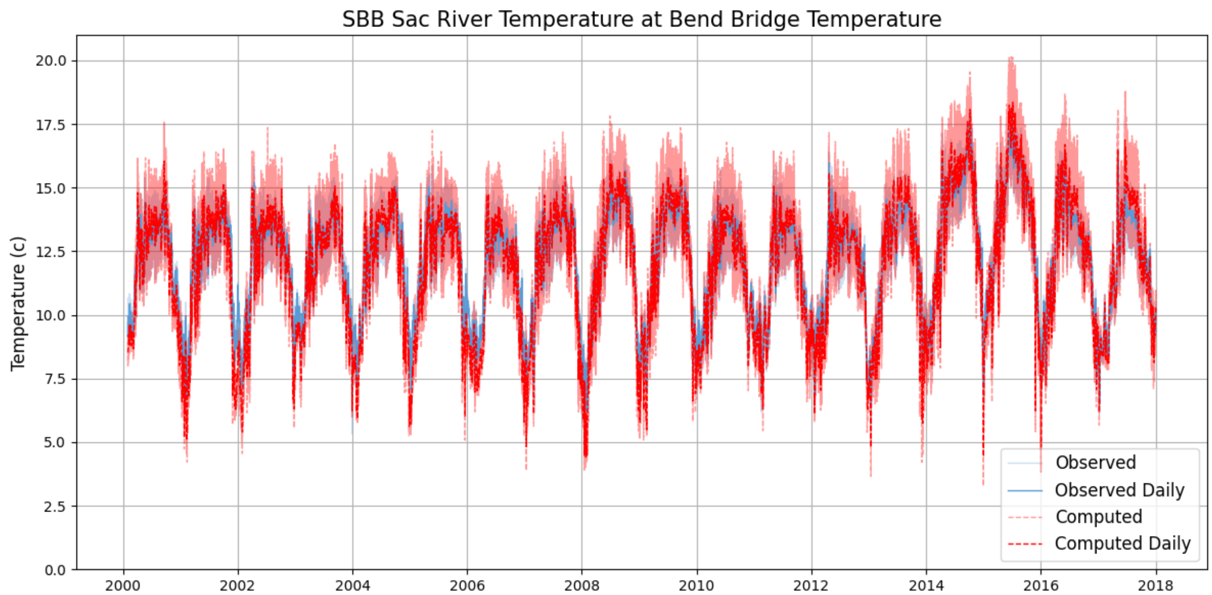


Figure 4-34. Simulated and observed temperatures at BND: 2000-2017.

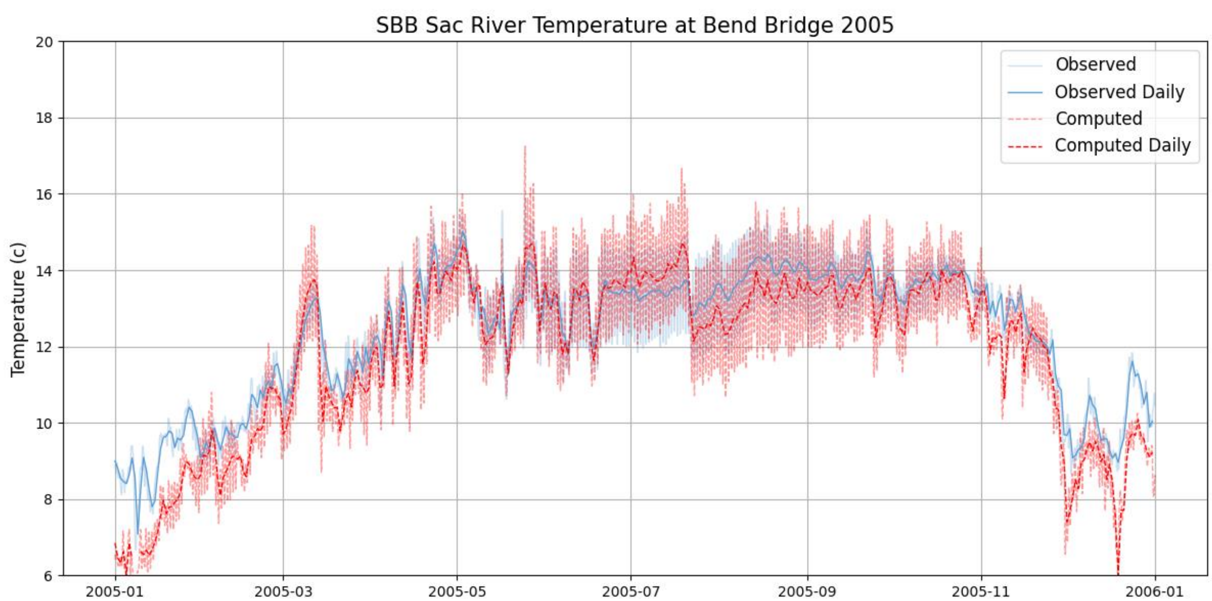


Figure 4-35. Simulated and observed temperatures at BND: 2005.

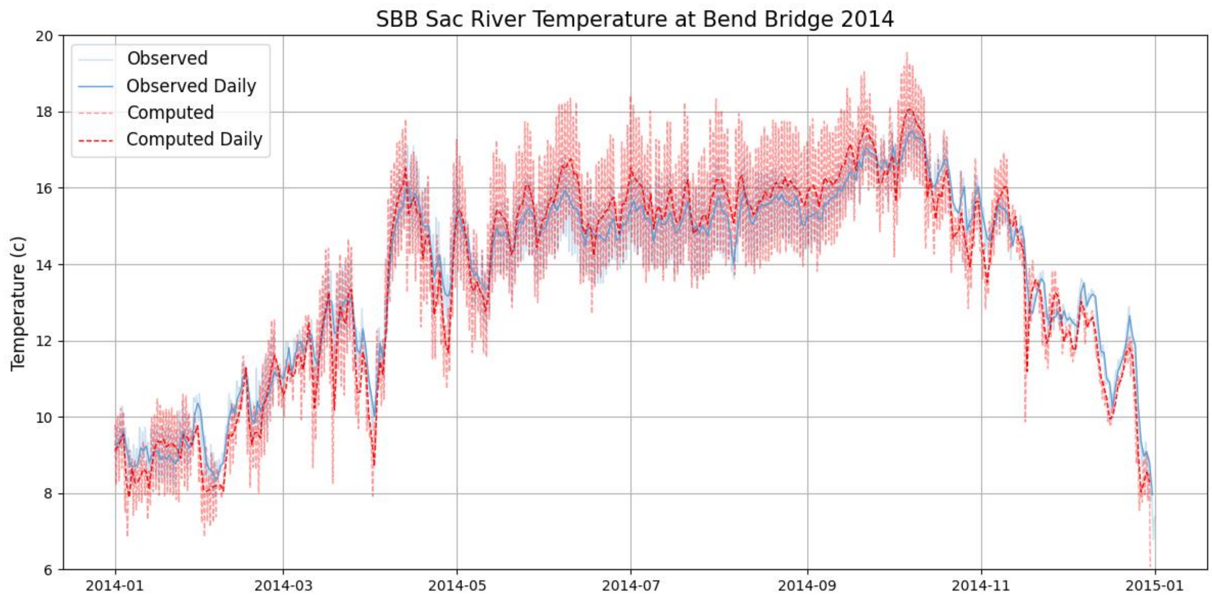


Figure 4-36. Simulated and observed temperatures at BND: 2014.

Table 4-49. BND Sacramento River at Bend Bridge temperature error statistics (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistics	2000	2001	2002	2003	2004	2005
Mean Bias (ºC)	-0.18	-0.48	-0.29	-0.33	-0.32	-0.53
MAE (ºC)	0.62	0.92	0.76	0.61	0.78	0.76
RMSE (ºC)	0.75	1.17	0.95	0.75	0.97	0.96
Nash-Sutcliffe (NSE)	0.77	0.70	0.74	0.81	0.77	0.72
COUNT	8,040	8,760	8,760	8,760	8,784	8,760

Statistics	2006	2007	2008	2009	2010	2011
Mean Bias (ºC)	-0.38	-0.30	-0.18	-0.08	-0.17	-0.09
MAE (ºC)	0.70	0.66	0.73	0.65	0.56	0.49
RMSE (ºC)	0.85	0.84	0.92	0.83	0.69	0.63
Nash-Sutcliffe (NSE)	0.79	0.83	0.87	0.87	0.85	0.89
COUNT	8,760	8,760	8,784	8,760	8,760	8,760

Statistics	2012	2013	2014	2015	2016	2017
Mean Bias (°C)	-0.30	-0.00	-0.05	0.02	0.01	0.12
MAE (°C)	0.63	0.62	0.68	0.69	0.57	0.52
RMSE (°C)	0.78	0.82	0.86	0.89	0.73	0.69
Nash-Sutcliffe (NSE)	0.84	0.87	0.88	0.87	0.88	0.89
COUNT	8,784	8,760	8,760	8,760	8,784	8,760

Statistics	All Years
Mean Bias (°C)	-0.20
MAE (°C)	0.66
RMSE (°C)	0.85
Nash-Sutcliffe (NSE)	0.85
COUNT	157,057

ResSim Validation

ResSim validation was conducted over the period 2018-2019 using the same model parameters and configuration during the calibration period, with the exception of the initial Shasta Lake temperature profile (first available observed temperature profile in 2018) and 2018 and 2019 boundary conditions. Validation results for Shasta Lake, Keswick Reservoir, and the Sacramento River are included herein for the same parameters, locations, and model performance metrics.

Shasta Lake

Shasta Lake elevation, outflow, temperature profiles and dam release temperatures for 2018 to 2019 are presented herein.

Shasta Lake simulated hourly elevation closely track observed hourly elevation (Figure 4-37). Similarly, hourly simulated outflow closely track hourly outflow observations (Figure 4-38), with annual statistics showing a mean bias of +-0.2 cfs or less, which is due to variation between penstock flow input data and observed outflow data of less than 1.0 cfs during 2019-2019 (Table 4-50).

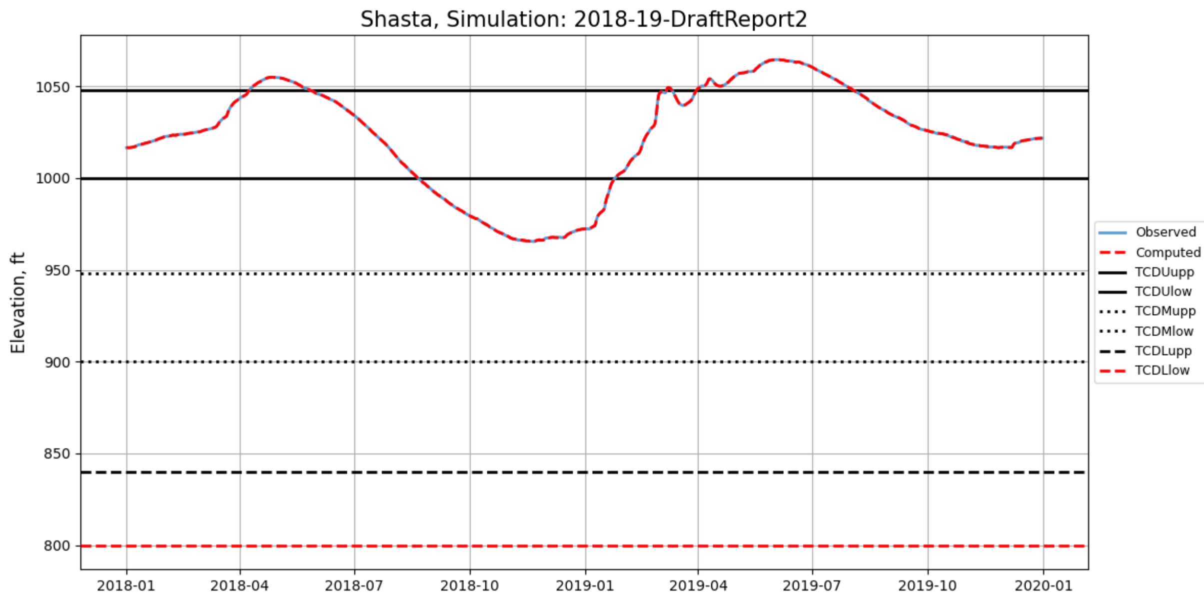


Figure 4-37. Shasta Lake simulated and observed water surface elevation, with TCD gate elevations, 2018-2019.

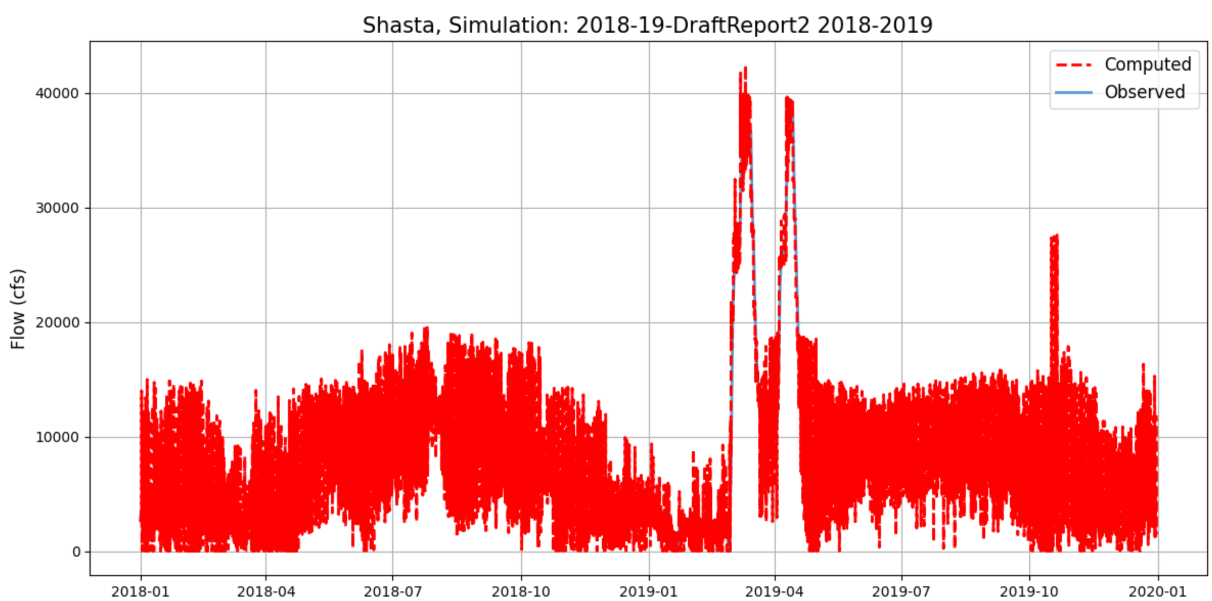


Figure 4-38. Shasta Lake simulated and observed out flow, 2018-2019.

Table 4-50. Shasta Dam outflow error statistics: 2018-2019.

Statistics	2018	2019	All Years
Mean Bias (cfs)	0.16	-0.01	0.08
MAE (cfs)	1.58	0.24	0.91
RMSE (cfs)	68.26	0.28	48.30
Nash-Sutcliffe (NSE)	1.00	1.00	1.00
COUNT	8,760	8,737	17,497

Simulated and observed Shasta Lake temperature profiles for the validation period are compared in Figures R30-32 and Tables T22-25. Simulated temperature profiles generally fit observations better than in most calibration seasons (Figures R30-32), with statistical fits showing metrics outside thresholds only for NSE during winter months in 2018 (Tables T22-26). During winter 2019, entrainment of heat into the cold pool causes deviation from observed, and isothermal nature of the profiles means the NSE is very sensitive.

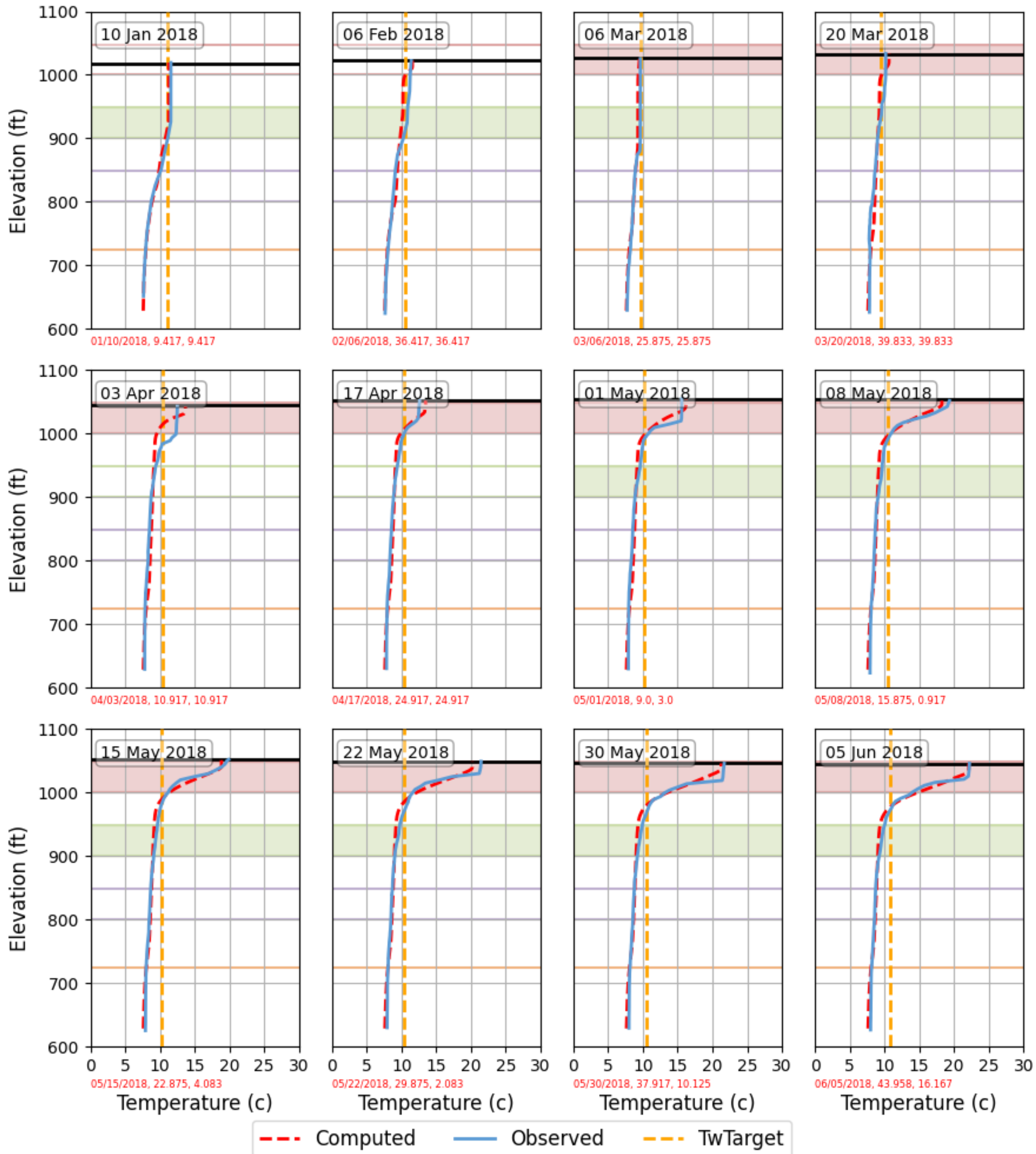


Figure 4-39. Simulated and observed temperature profiles and TCD gate positions during 2018 (1/3).

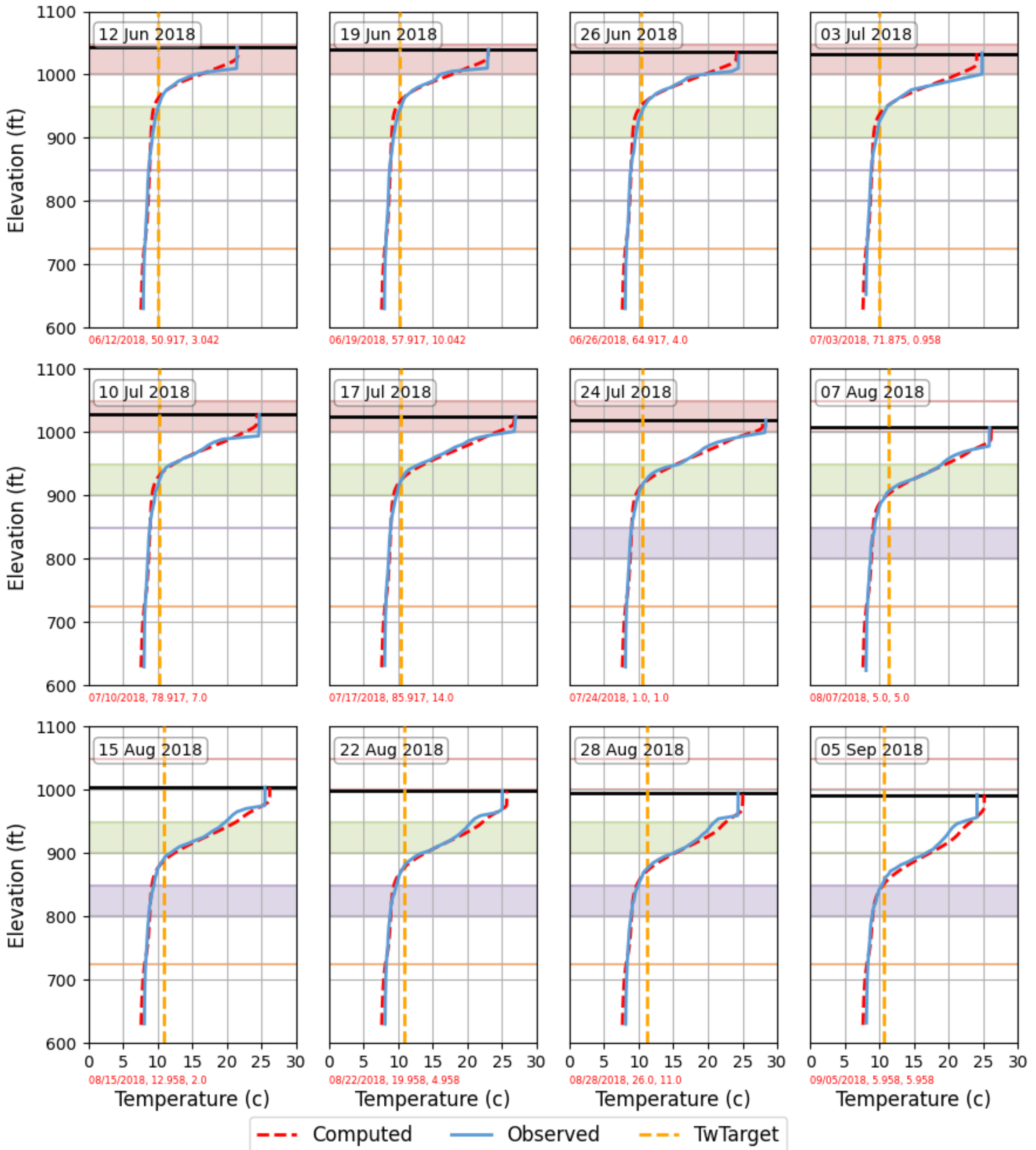


Figure 4-40. Simulated and observed temperature profiles and TCD gate positions during 2018 (2/3).

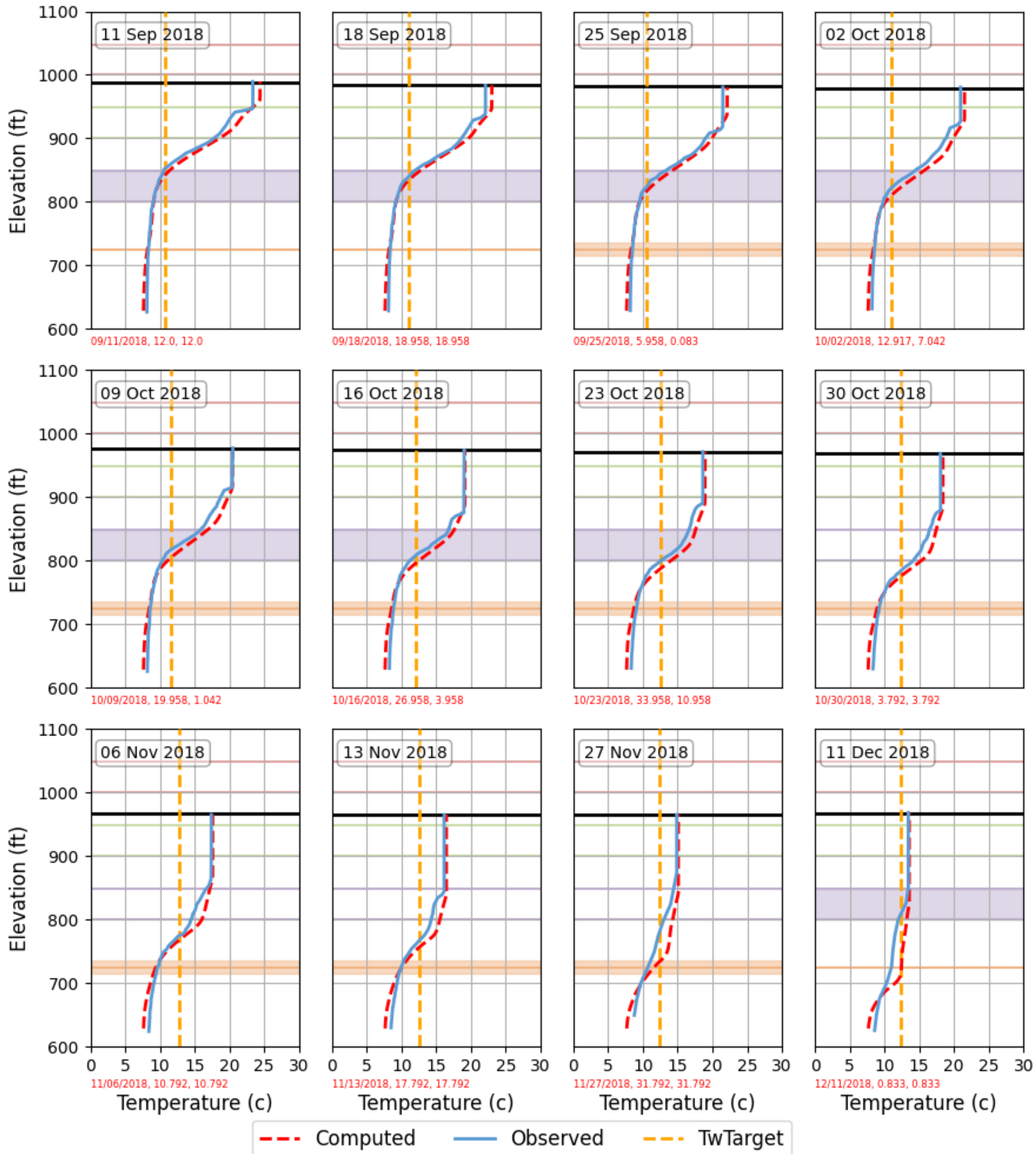


Figure 4-41. Simulated and observed temperature profiles and TCD gate positions during 2018 (3/3).

Table 4-51. Shasta Profile Temperature Mean Bias (°C) (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of +-0.75°C).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2018	-0.12	-0.16	-0.07	-0.07	-0.12	-0.14	-0.11	0.09	0.25	0.25	0.34	0.46
2019	0.41	0.20	0.33	0.30	0.34	0.23	0.39	0.46	0.55	0.59	0.74	0.53
All	0.15	0.02	0.13	0.12	0.09	0.04	0.17	0.27	0.40	0.42	0.54	0.50

Table 4-52. Shasta Profile Temperature MAE (oC) (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of >1.0oC).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2018	0.17	0.30	0.22	0.34	0.30	0.30	0.33	0.36	0.49	0.59	0.65	0.69
2019	0.55	0.42	0.60	0.50	0.60	0.56	0.58	0.62	0.67	0.62	0.75	0.53
All	0.36	0.36	0.41	0.42	0.44	0.43	0.47	0.49	0.58	0.61	0.70	0.61

Table 4-53. Shasta Profile Temperature RMSE (°C) (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of >1.5°C).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2018	0.22	0.42	0.29	0.58	0.47	0.46	0.50	0.50	0.63	0.72	0.80	0.88
2019	0.68	0.47	0.70	0.61	0.80	0.74	0.82	0.95	1.00	0.91	1.03	0.75
All	0.51	0.45	0.54	0.60	0.64	0.62	0.70	0.76	0.84	0.82	0.92	0.82

Table 4-54. Shasta Profile Temperature NSE: 2000-2017 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of <0.65).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2018	0.98	0.89	0.86	0.81	0.97	0.99	0.99	0.99	0.99	0.97	0.93	0.73
2019	0.44	0.63	0.50	0.86	0.88	0.96	0.96	0.97	0.96	0.96	0.90	0.87
All	0.86	0.82	0.71	0.85	0.93	0.97	0.98	0.98	0.98	0.97	0.92	0.84

Simulated and observed Shasta Lake outflow temperatures for the validation period are compared in Figure 4-42 and Table 4-55 through Table 4-58. Simulated Shasta outflow contains computed biases similar to the calibration period, and overall annual and monthly statistical model performance metrics are less than the identified thresholds. There is notable daily variability in observed outflow target temperatures during the validation period that ResSim is able to meet during warmer periods of the year when stratification occurs. During colder periods computed solutions cannot simulate the observed daily variability in outflow temperatures because water of those temperatures does not exist in the reservoir (also illustrated in measured profiles). Penstock heating or non-representative observed water temperatures are undergoing continued investigation.

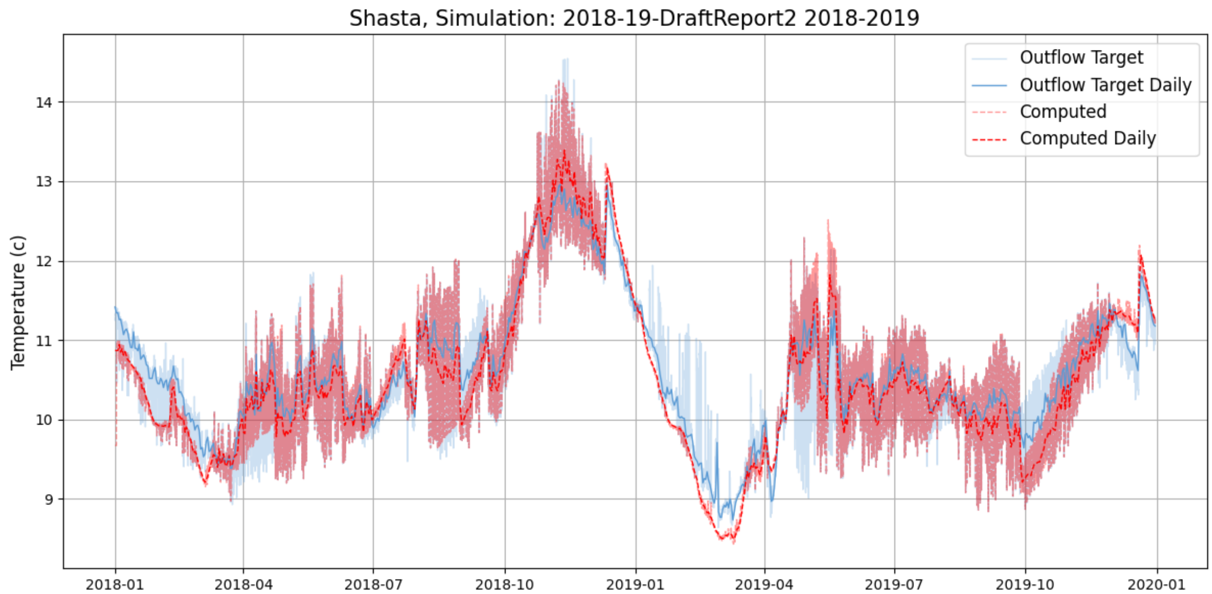


Figure 4-42. Shasta Reservoir simulated and observed temperatures at Shasta Dam, 2018-2019.

Table 4-55. Shasta Lake Outflow Temperature Error Statistics: 2018-2019 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistics	2018	2019	All Years
Mean Bias (cfs)	-0.03	-0.03	-0.03
MAE (cfs)	0.12	0.17	0.15
RMSE (cfs)	0.22	0.34	0.28
Nash-Sutcliffe (NSE)	0.96	0.77	0.91
COUNT	8,760	8,737	17,497

Table 4-56. Shasta Lake Outflow Temperature Mean Bias (ºC): 2018-2019 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of +-0.75 ºC).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2018	-0.35	-0.29	-0.09	0.09	-0.01	0.03	0.18	-0.01	-0.09	0.00	-0.01	0.15
2019	-0.31	-0.47	-0.28	0.17	0.35	0.01	0.01	0.05	-0.04	-0.11	0.01	0.27
All	-0.33	-0.38	-0.18	0.13	0.17	0.02	0.09	0.02	-0.06	-0.05	0.00	0.21

Table 4-57. Shasta Lake Outflow Temperature MAE (ºC): 2018-2019 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of >1.0ºC).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2018	0.36	0.29	0.12	0.10	0.03	0.03	0.18	0.03	0.11	0.01	0.01	0.15
2019	0.31	0.47	0.28	0.19	0.36	0.01	0.01	0.05	0.04	0.11	0.01	0.27
All	0.33	0.38	0.20	0.15	0.20	0.02	0.09	0.04	0.08	0.06	0.01	0.21

Table 4-58. Shasta Lake Outflow Temperature RMSE (ºC): 2018-2019 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of >1.5ºC).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2018	0.47	0.36	0.21	0.19	0.06	0.04	0.23	0.10	0.20	0.04	0.04	0.20
2019	0.42	0.65	0.33	0.34	0.59	0.02	0.04	0.10	0.14	0.20	0.05	0.36
All	0.44	0.53	0.28	0.28	0.42	0.03	0.16	0.10	0.17	0.15	0.05	0.29

Keswick Reservoir

Keswick Reservoir elevation, outflow, temperature profiles and dam release temperatures for 2018 to 2019 are presented herein.

Simulated and observed Keswick Reservoir elevation and outflow for the validation period are compared in Figure 4-43 and Figure 4-44and Table 4-59. Flows are specified, and resulting simulated elevation and outflow are essentially the same.

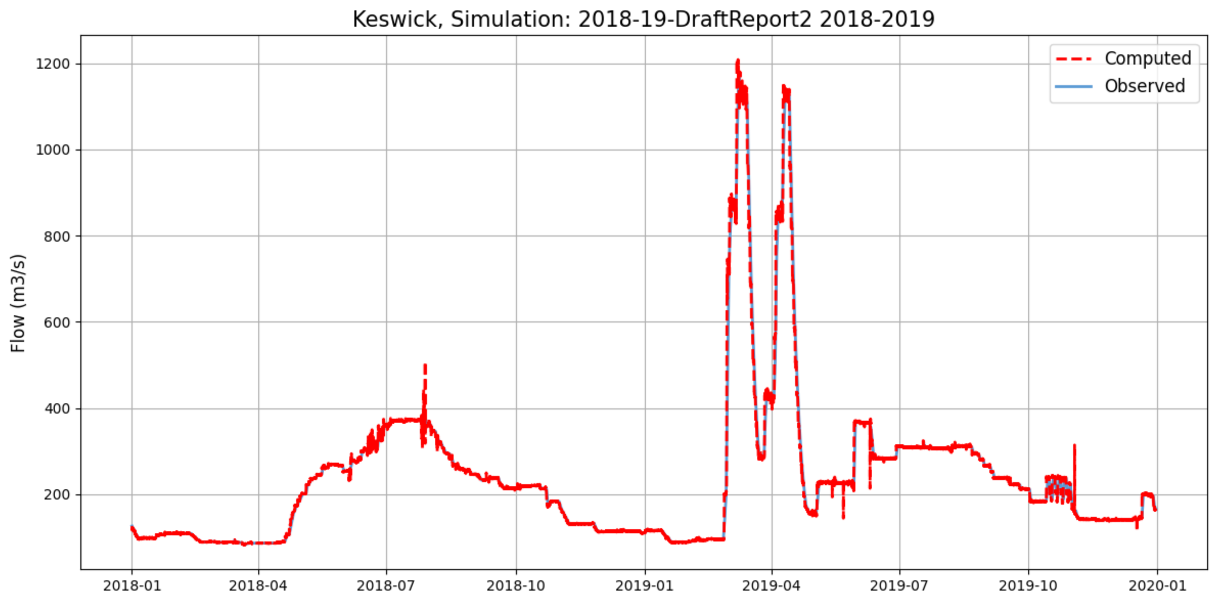


Figure 4-43. Keswick Reservoir simulated and observed flow through Keswick Dam, 2018-2019.

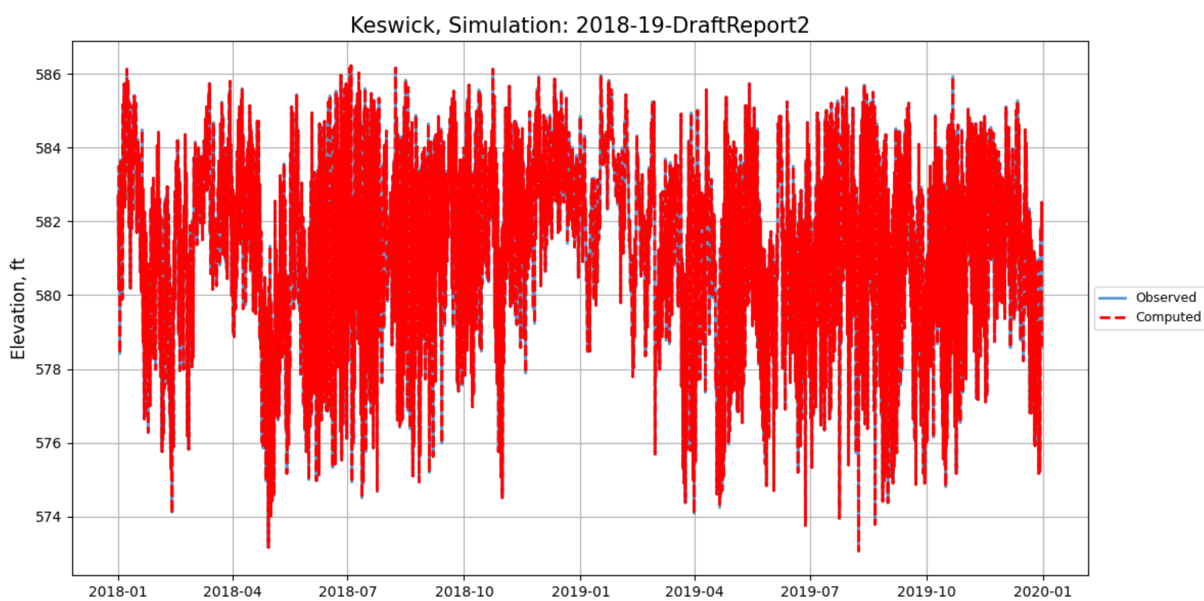


Figure 4-44. Keswick Reservoir simulated and observed water surface elevation, 2018-2019.

Table 4-59. Keswick Reservoir outflow error statistics.

Statistics	2018	2019	All Years
Mean Bias (cfs)	0.01	0.00	0.01
MAE (cfs)	0.06	0.00	0.03
RMSE (cfs)	1.93	0.00	1.37
Nash-Sutcliffe (NSE)	1.00	1.00	1.00
COUNT	8,760	8,737	17,497

Observed temperature profiles from Keswick Reservoir are available for the later parts of 2018 and 2019, and are compared to simulated profiles in Figures Figure 4-45 and Figure 4-46 for 2018) and Table 4-60 through Table 4-63. Performance during the validation period is consistent with the calibration period. As with the calibration period, the NSE performs poorly under the isothermal or near-isothermal conditions typically present in the relatively shallow, short residence time Keswick Reservoir.

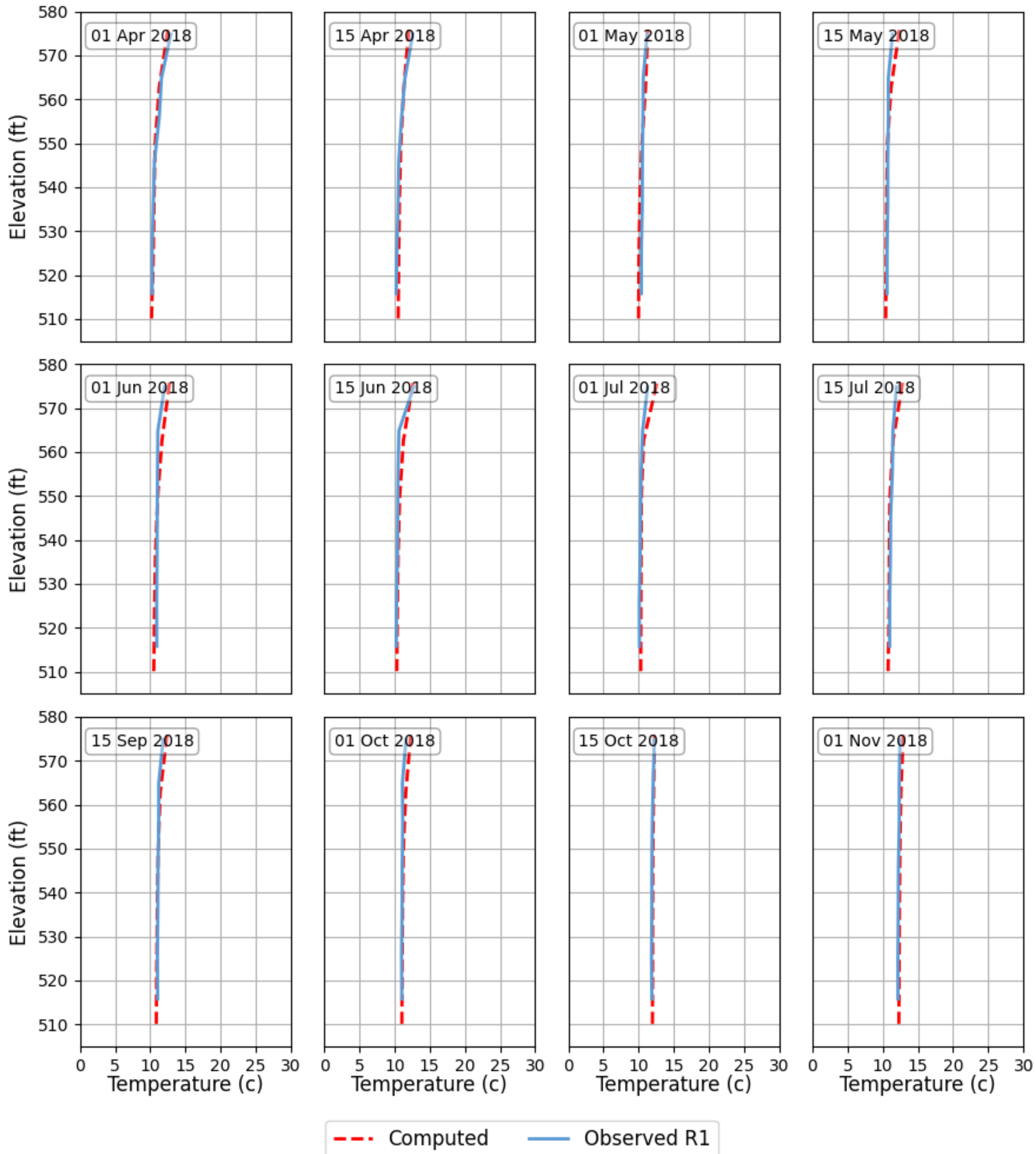


Figure 4-45. Keswick Reservoir simulated and observed temperature profile comparisons, 2018. Profiles data are collected approximately 0.1 miles upstream from dam (1/2).

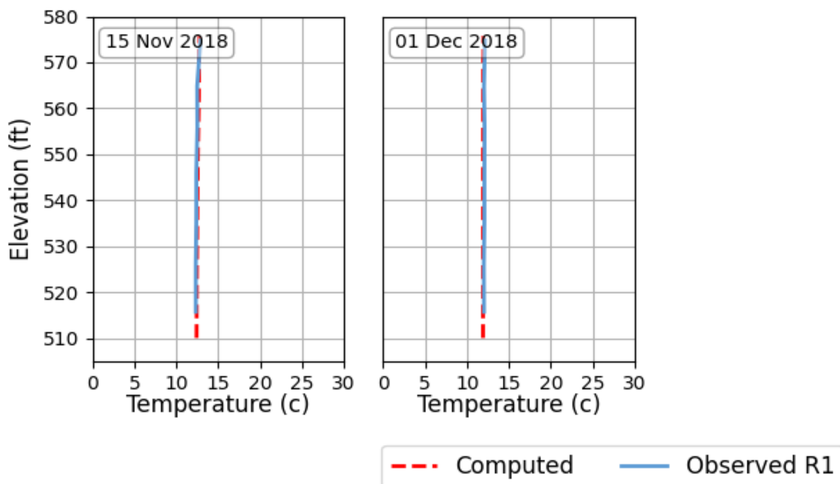


Figure 4-46. Keswick Reservoir simulated and observed temperature profile comparisons, 2018. Profiles data are collected approximately 0.1 miles upstream from dam (2/2).

Table 4-60 Keswick Reservoir profile temperature mean bias: 2010, 2017 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of +- 0.75ºC). A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2018	--	--	--	0.03	-0.01	0.17	0.12	-	0.04	0.17	0.17	-0.13
2019	--	--	--	--	0.21	0.21	-0.13	-0.15	-0.04	-0.16	0.02	-0.01
All	--	--	--	0.03	0.06	0.19	-0.00	-0.15	-0.01	0.01	0.10	-0.05

Table 4-61 Keswick Reservoir profile temperature MAE: 2018-2019 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of 1.0ºC). A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2018	--	--	--	0.19	0.25	0.31	0.23	-	0.14	0.17	0.18	0.13
2019	--	--	--	--	0.21	0.21	0.18	0.22	0.21	0.20	0.08	0.25
All	--	--	--	0.19	0.23	0.26	0.20	0.22	0.19	0.19	0.13	0.21

Table 4-62 Keswick Reservoir profile temperature RMSE: 2018-2019 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of 1.5ºC). A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2018	--	--	--	0.22	0.30	0.38	0.30	-	0.19	0.23	0.19	0.14
2019	--	--	--	--	0.22	0.29	0.21	0.31	0.28	0.23	0.11	0.26
All	--	--	--	0.22	0.28	0.34	0.26	0.31	0.26	0.23	0.15	0.22

Table 4-63 Keswick Reservoir profile temperature mean bias: 2018-2019 (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria of +- 0.75 ºC). A "--" indicates there is no statistical result due to lack of measured data.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2018	--	--	--	0.88	-1.64	0.25	0.64	-	-0.39	0.70	-0.80	-19.36
2019	--	--	--	--	-0.72	0.54	0.64	0.75	0.37	0.72	0.93	-3.23
All	--	--	--	0.88	-1.35	0.40	0.70	0.75	0.49	0.89	0.96	0.87

Simulated and observed hourly outflow temperature time series from Keswick dam and nearby monitoring station KWK are compared over the validation period in Figure 4-47 and Table 4-64. Outflow temperature performance at Keswick dam is similar to the calibration period, and within the statistical metrics thresholds. The impact of initial conditions on Keswick Dam release temperature and the implications of Shasta Dam release temperature on Keswick Reservoir and release temperatures is an ongoing element of model calibration.

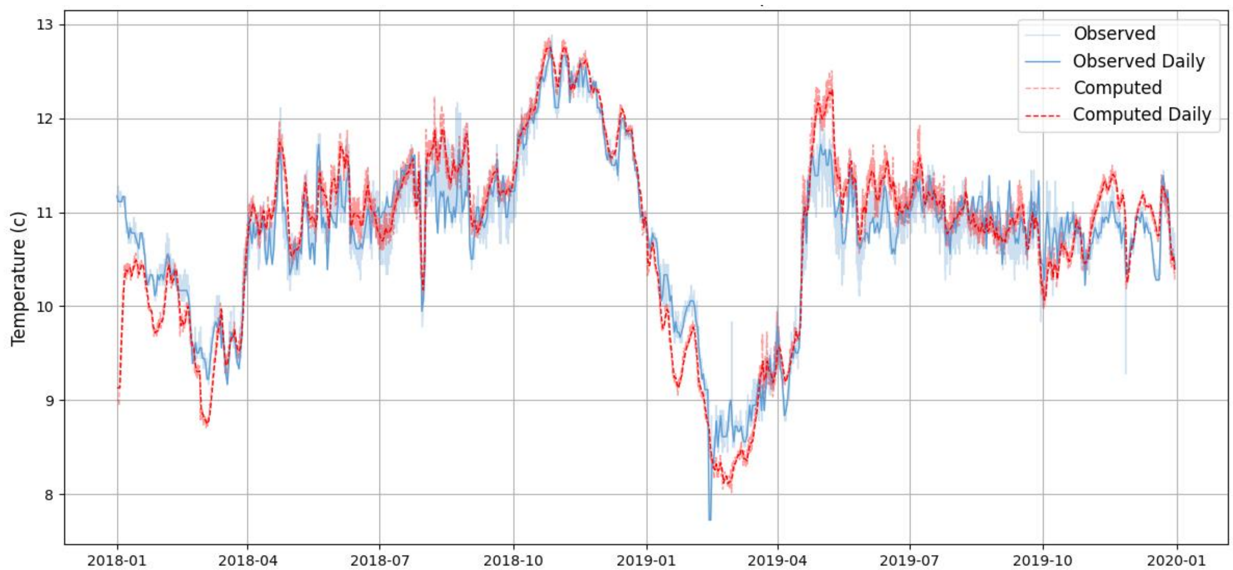


Figure 4-47. Simulated and observed outflow temperatures from Keswick Dam: 2018-2019.

Table 4-64. Keswick Reservoir temperature outflow error statistics (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistics	2018	2019	All Years
Mean Bias (°C)	0.04	0.04	0.04
MAE (°C)	0.25	0.27	0.26
RMSE (°C)	0.35	0.34	0.34
Nash-Sutcliffe (NSE)	0.81	0.82	0.84
COUNT	8,760	8,737	17,497

Sacramento River

Simulated and observed Sacramento River flow at Bend Bridge (USGS 11377100) and temperatures at Clear Creek (CCR), Balls Ferry(BSF), Jellys Ferry (JLF), and Bend Bridge (BND) for 2018 to 2019 are presented herein.

Simulated and observed flows on the Sacramento River over the validation periods are compared for the Bend Bridge (USGS 11377100) in Figure 4-48 and Table 4-65. Balanced flows during the validation period are not meaningfully different than calibration, showing the same differences in peak hourly flows, but matching daily volume as evidenced by the very low mean bias statistics.

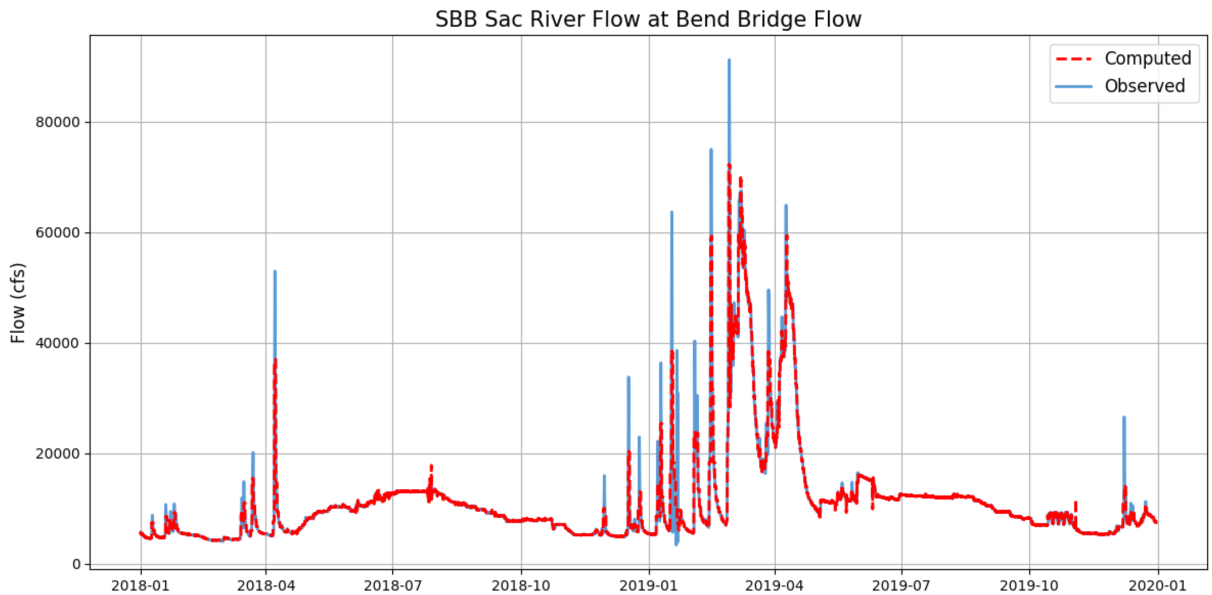


Figure 4-48. Simulated and observed hourly flows at Bend Bridge: 2018-2019.

Table 4-65. Sacramento River flow error statistics at Bend Bridge (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistics	2018	2019	All Years
Mean Bias (cfs)	-0.05	-25.12	-12.57
MAE (cfs)	240.84	707.55	473.89
RMSE (cfs)	965.77	2,306.38	1,767.24
Nash-Sutcliffe (NSE)	0.92	0.96	0.96
COUNT	8,760	8,737	17,497

Simulated and observed temperature time series for Sacramento River at four monitoring stations [Clear Creek (CCR), Balls Ferry Bridge (BSF), Jellys Ferry (JLF), and Ben Bridge (BND)] are compared in Figure 4-49, Figure 4-50, Figure 4-51, and Figure 4-52, respectively, and in Table 4-66, Table 4-67, Table 4-68, and Table 4-69, respectively. Overall statistics show river temperatures during the validation period are below thresholds in all years, and are slightly better fitted than during calibration (Compare with Table 4-45 for flow, and Table 4-46 through Table 4-49 for temperature). As noted in the calibration section, above, channel geometry and continued model refinement and calibration will be continuing in the Sacramento River reach.

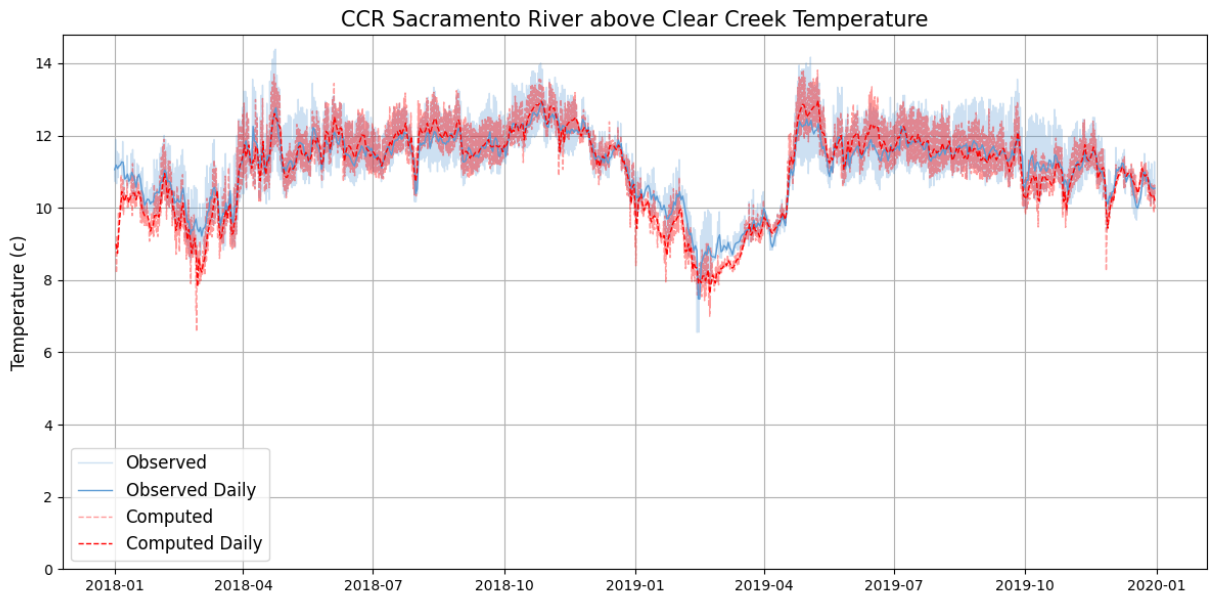


Figure 4-49. Simulated and observed temperatures at CCR: 2018-2019

Table 4-66. CCR Sacramento River at Clear Creek temperature error statistics (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistics	2018	2019	All Years
Mean Bias (ºC)	-0.08	-0.09	-0.09
MAE (ºC)	0.32	0.36	0.34
RMSE (ºC)	0.44	0.45	0.44
Nash-Sutcliffe (NSE)	0.79	0.84	0.83
COUNT	8,736	8,736	17,472

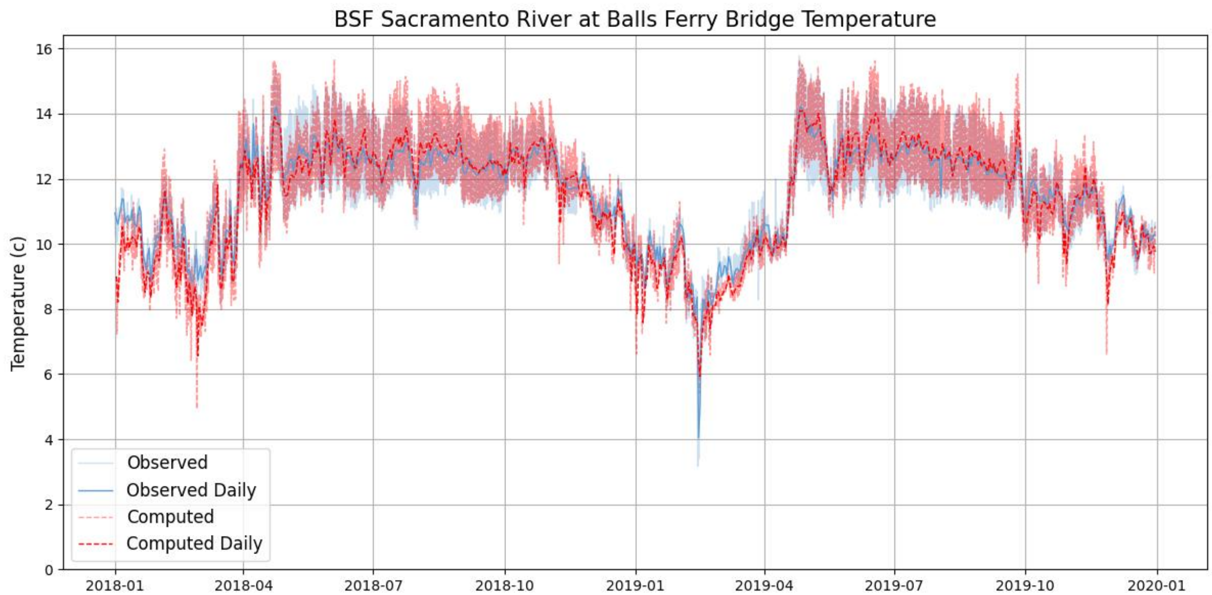


Figure 4-50. Simulated and observed temperatures at BSF: 2018-2019.

Table 4-67. BSF Sacramento River at Balls Ferry temperature error statistics (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistics	2018	2019	All Years
Mean Bias (ºC)	-0.18	-0.08	-0.13
MAE (ºC)	0.45	0.39	0.42
RMSE (ºC)	0.59	0.52	0.55
Nash-Sutcliffe (NSE)	0.81	0.91	0.88
COUNT	8736	8736	17472

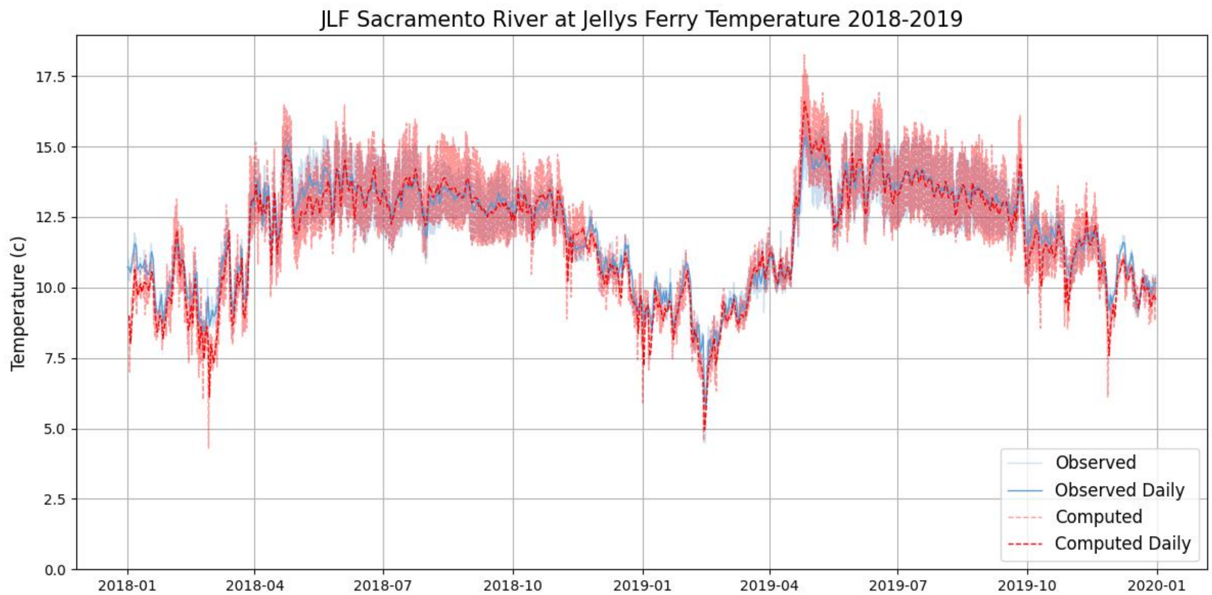


Figure 4-51. Simulated and observed temperatures at JLF: 2018-2019

Table 4-68. JLF Sacramento River at Jelly Ferry temperature error statistics (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistics	2018	2019	All Years
Mean Bias (oC)	-0.26	-0.15	-0.20
MAE (oC)	0.52	0.44	0.48
RMSE (oC)	0.66	0.57	0.62
Nash-Sutcliffe (NSE)	0.83	0.93	0.89
COUNT	8736	8736	17472

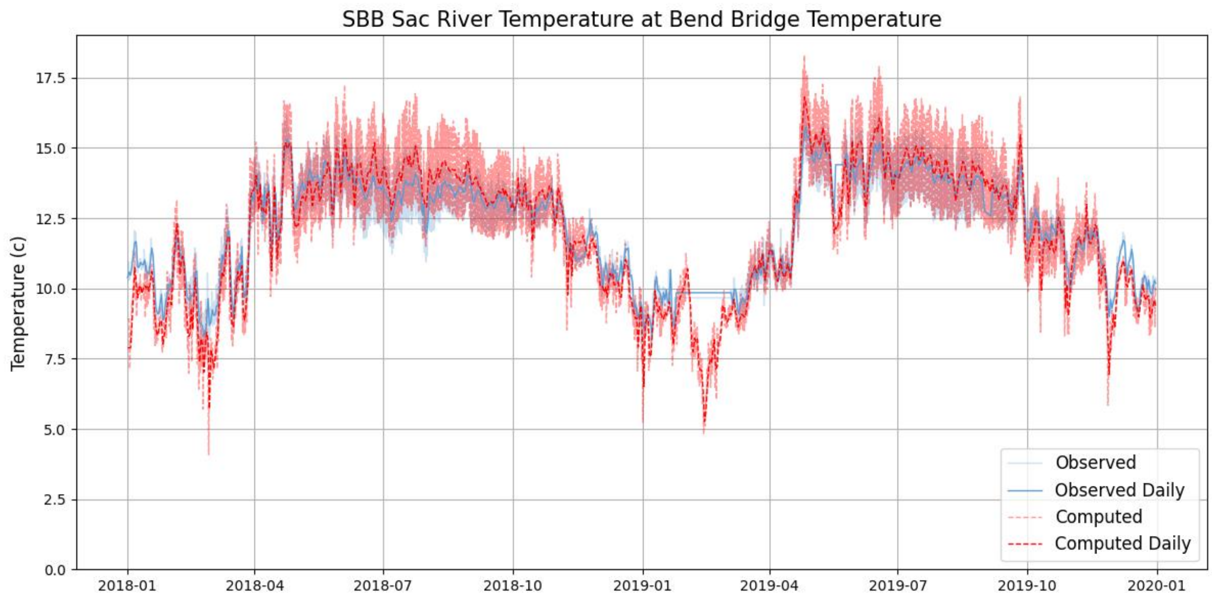


Figure 4-52. Simulated and observed temperatures at BND: 2018-2019.

Table 4-69. BND Sacramento River at Bend Bridge temperature error statistics (Values marked with an asterisk (also highlighted gray) indicate values outside the calibration criteria).

Statistics	2018	2019	All Years
Mean Bias (°C)	-0.10	-0.19	-0.15
MAE (°C)	0.65	0.66	0.66
RMSE (°C)	0.82	0.93	0.88
Nash-Sutcliffe (NSE)	0.77	0.79	0.78
COUNT	8,760	8,737	17,497

ResSim Sensitivity Analysis

General sensitivity analyses were performed for water quality parameters related to temperature modeling on the Shasta Lake-Keswick Reservoir-Sacramento River ResSim model. Sensitivity testing relied on graphical analysis of the effects of perturbations to parameters during calibration, as well as dedicated sensitivity simulations using the calibrated model. While ResSim is divided into geographic regions where distinct water quality parameters may be employed, the large number of parameters and regions creates a large set of possible configurations, and necessitated simplification by testing the parameters as bulk changes across the entire reach (Shasta Lake-Keswick Reservoir-Sacramento River).

In Shasta Lake, several water quality calibration parameters are used to reproduce reservoir thermal profiles and outflow temperatures. Keswick Reservoir has a short residence time, large degree of vertical mixing (as evidenced by largely isothermal temperature profiles), and a temperature regime largely driven by Shasta Dam outflow, leading to a fairly insensitive system. The Sacramento River below Keswick Dam is a notably different environment than the upstream reservoir reaches, and water temperature in the relatively shallow stream reaches are sensitive to atmospheric fluxes due to the large surface area-to-volume ratio, particularly in the high heat-loading summer months.

Principal model parameters considered in calibration and their sensitivities are described in Table 4-70. Parameters were evaluated to produce the calibrated parameter set that best represents the entire calibration period of 2000-2017. Comprehensive parameter descriptions are included in HEC (2022a, 2022b). When the full functionality of HEC-WAT within the WTMP is complete, a more detailed, quantitative assessment of sensitivity of key parameters will be assessed through an automated reporting feature (See Reclamation 2021a, 2022a).

Table 4-70. ResSim Parameters and their relative sensitivity for the Shasta-Keswick-Upper Sacramento model

Parameter	Sensitivity	Notes
Coefficient a in Wind Function	M	The minimum sensible and latent atmospheric heat exchanges are set by this coefficient, which is in effect even when winds are zero. Currently wind coefficients b and c are dominant and changing this parameter has less of an effect than a similar numeric change in coefficients b and c. A positive change generally results in greater equilibration with atmospheric temperatures, but also greater evaporative cooling. Medium sensitivety over [0.0 to 3.0 $mb^{-1}\ m\ s^{-1}$]. The formulation applicable to this parameter is $(a+bw)^c$.
Coefficient b in Wind Function	H	A positive change generally results in greater equilibration with atmospheric temperatures, but also greater evaporative cooling. High sensitivity over [1.0 to 4.0 mb^{-1}]. The formulation applicable to this parameter is $(a+bw)^c$.
Coefficient c in Wind Function	H	A positive change, especially greater than 1.0, generally results in greater equilibration with atmospheric temperatures, but also greater evaporative cooling at high wind speeds. A negative, especially below 1.0, emphasizes the importance of lower wind speeds. High sensitivity over [0.5 to 2.0 unitless]. The formulation applicable to this parameter is $(a+bw)^c$.
Turbulent Diffusivity Ratio	Not Tested	Default parameter used in calibration.
Sediment Layer Thickness	M	Decreasing results in higher diurnal temperatures during summer, as thinner sediment heats up faster and transmits heat to the water faster. Increasing results in smaller diurnal variability, but also delayed nighttime cooling as thick sediment releases heat over a longer period of time. Has little to no effect in reservoirs due to the relatively high shortwave irradiance absorption in the water column (Background Light Absorption). Medium sensitivity over [0.1 to 0.5 m].
Sediment Bulk Density	Not Tested	Default parameter used in calibration.
Sediment Specific Heat Capacity	Not Tested	Default parameter used in calibration.

Parameter	Sensitivity	Notes
Sediment Thermal Diffusivity	Not Tested	Default parameter used in calibration.
Shortwave Radiation Bed Reflectivity	M	May effect diurnal temperature swings and duration in river reaches during high-shortwave irradiance periods. Increasing this parameter can cool river reaches. Low sensitivity over [0.1 to 0.3 unitless].
Background Light Attenuation	H	Raising this parameter causes more heating in shallower reservoir layers. The model is highly sensitive to this parameter, with low values causing excessive heating in lower layers and delaying stratification in reservoirs. Higher settings can hasten stratification and allow excessive nighttime cooling, causing the cool pool to be too large. High sensitivity over [0.2 to 0.5 unitless].
Suspended Sediment Light Attenuation	Not Tested	This parameter would directly add to the Background Light Attenuation, if scripted (variable) suspended light attenuation is used; in this calibration the value is set to zero for pure water/disabled.
Stream Slope	Not Tested	This parameter was (by default entrainment settings) overridden by a dynamic calculation of the slope between inflow location and the reservoir outlet.
Stream Cross-Section Half Angle	L	Dynamic entrainment and dispersion used during in this calibration results in high levels of internal mixing; comparatively, changes in cross-section half angle of the inflow(s) have a smaller effect than related dispersion or entrainment parameters. Low sensitively over [0.5 to 0.89].
Initial Mixing Ratio	Not tested	This parameter is (by using default entrainment settings) overridden by a dynamic calculation of entrainment mixing.
Entrainment Rate	Not tested	This parameter is (by using default entrainment settings) overridden by a dynamic calculation of entrainment mixing.
Mixed Layer Tolerance	M	Decreasing this parameter causes reservoir inflow entrainment to stop at a shallower density gradient, and results in sharper thermoclines at the top of the cold pool; increasing generally causes entrainment to be focuses more shallowly. Medium sensitivity over [0.01 to 0.09].
Richardson Number Function Option	H	Switch for wind-mediated heat transfer method, with "Use Bowen" selected for calibration. Switching to "Use Ri" employs a Richardson number calculation to enhance heat transfer under periods of atmospheric instability, but when used without meteorological data immediately local to a water body (i.e., it requires boundary layer humidity and temperature changes) it causes very excessive cooling. High sensitivity to this method switch.
Entrainment Option	H	Without entrainment of inflows, very little heat reaches lower reservoir layers and resulting calibrations are generally much too cool. High sensitivity to having inflow entrainment enabled or disabled.
DZ_{min}	H	Modifying in minimum internal dispersion changes the shape of most thermal gradients in a reservoir. High sensitivity over [1e-5 to 1.5e-4].
A_1	M	Changes how far surface heating is mixed into deeper layers. Medium sensitivity over [1e-5 to 1.5e-4]
A_z	M	Changes how far surface heating is mixed into deeper layers. Medium sensitivity over [0.9 to 2.5]
D_{zmax}	<not used>	<not used>

Chapter 5 Summary

Model development and preliminary calibration and validation of the CE-QUAL-W2 and ResSim models has been completed for Shasta Lake, Keswick Reservoir, and the Sacramento River from Keswick Dam downstream to Red Bluff. Critical elements of this system include specification of flow, temperature, and meteorologic boundary conditions; representing the Shasta Dam TCD, specification of key inflows from Spring Creek Powerhouse (Whiskeytown Lake and exports from the Trinity River) and defining principal tributaries downstream of Keswick Dam.

The formal development of model performance metrics – both qualitative (graphical) and quantitative (statistical) – not only provides a means of comparing calibration and validation periods, but also assists in identifying conditions where model performance may need to be revisited. Development of data for the 2000-2019 calibration/validation period identified data challenges (Sacramento River bathymetry limitations, tributary temperature data gaps) and model challenges (TCD operations representation). Nonetheless, model performance for much of the period is generally good, capturing the onset, persistence, and breakdown of thermal stratification in Shasta Lake; representing the highly dynamic nature of Keswick Reservoir that receives hydropower peaking flows from both Shasta Dam powerhouse and Spring Creek Powerhouse; and representing the diurnal range of water temperatures in the Sacramento River as waters are conveyed from Keswick Dam downstream and subject to notable thermal loading during spring, summer, and early fall periods. The period of application covers 20 (or more) years and represents an extensive range of hydrology, meteorology, operations, and Shasta Lake storage conditions, including wet years, dry years, multiple dry years, and a range of intermediate hydrologic year types.

Sharing model development steps, data development and model assumptions, and calibration and validation results with the Modeling Technical Committee and others, will assist the model development team in constructing effective, useful tools to assist resource managers in Reclamation's CVP systems.

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