SHASTA LAKE AND KESWICK RESERVOIR FLOW AND TEMPERATURE MODELING
- DEVELOPMENT REPORT -

Prepared by

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December 2020

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Acronyms

CFD – Computational fluid dynamics
CVP – Central Valley Project
ESA – Endangered Species Act
GCID – Glenn-Colusa Irrigation District
KRM – Keswick Reservoir Model (CE-QUAL-W2)
MFF – Minimum Flow Fraction
MTC – Modeling Technical Committee
NMFS – National Marine Fisheries Service
PRG – Pressure release gates
RRL – River release, lower outlets
RRM – River release, middle outlets
RRU – River release, upper outlets
SLM – Shasta Lake Model (CE-QUAL-W2)
TCD – Temperature Control Device
TCD_d – an outlet assigned only when the TCD low-level intake is active (deep level)
TCDL – TCD lower level, consists of TCDL1(lower level, top outlet), TCDL2(lower level, middle/center outlet), TCDL3(lower level, bottom outlet)
TCDM – TCD middle level, consists of TCDM1(middle level, top outlet), TCDM2(middle level, middle/center outlet), TCDM3(middle level, bottom outlet)
TCDS – TCD low-level intake or side gate structure, consists of TCDS1(side level, top outlet), TCDS2(side level, middle/center outlet), TCDS3(side level, bottom outlet)
TCDU – TCD upper level, consists of TCDU1(upper level, top outlet), TCDU2(upper level, middle/center outlet), TCDU3(upper level, bottom outlet)
USBR – U.S. Bureau of Reclamation
USGS – U.S. Geological Survey
CDEC – California Data Exchange Center
WRCC – Western Regional Climate Center

(note, units and model parameters/coefficients are defined in the report and not included in this table)

Executive Summary

Both Shasta Lake and Keswick Reservoir on the Sacramento River are significant water and hydroelectric resources within California. Shasta Lake, California's largest reservoir, and Shasta Dam is located north of Redding, California. Keswick Reservoir is located immediately downstream of Shasta Dam and regulates hydropower peaking releases from Shasta Powerhouse and Spring Creek Powerhouse. Releases at Keswick Dam assist in meeting environmental objectives relevant to fish and aquatic life. Both are located in the Shasta Division of the Central Valley Project (CVP).

Recent drought and associated impacts to fish species have increased attention to water temperature management in the Sacramento River below Keswick Dam. Specifically, winter-run Chinook salmon, a listed species under the Endangered Species Act (ESA), requires cool summer water temperatures in the Sacramento River (NMFS 2014). Water temperature models have been developed to assist resource managers in planning, forecasting, and operating storage and conveyance systems, such as the Shasta and Trinity Divisions of the Central Valley Project (CVP), to meet a wide range of water supply demands. A useful element in ongoing resource management is a periodic assessment of existing temperature modeling tools and opportunities for improvement.

The current HEC-5Q water temperature modeling framework (Reclamation 2008, Willey 1986) for the Shasta and Trinity Divisions remains a valuable and effective tool for operations planning. However, development of more refined spatial and temporal models for Shasta Lake and Keswick Reservoir can support a broader range of analysis and add insight into temperature management in the Sacramento River system. As the U.S. Bureau of Reclamation (Reclamation) proceeds into the future, models that are broadly accepted, frequently updated, well-documented, and actively supported will become increasingly important in the multi-disciplinary based temperature management process (Reclamation 1999, Reclamation 2016a).

With these goals in mind for model development and refinement, this project has resulted in the development of hourly flow and water temperature models for Shasta Lake and Keswick Reservoir that can:

- Identify initial cold-water pool volumes and simulate the evolution of reservoir thermal conditions throughout the year, including the onset and breakdown of thermal stratification;
- Assess the impacts of a range of potential operational strategies on in-reservoir and downstream water temperatures through the temperature control period (late spring into fall), based on the initial reservoir storage and cold-water pool volume, and hydrological and meteorological conditions; and
- Support development of cold-water pool management planning, including the incorporation of uncertainty in model representation and future conditions (e.g., inflow quantity and temperature, meteorology, etc.).

The report documents model development phases of the CE-QUAL-W2 (v4.1) application to the Shasta Lake model (SLM) and Keswick Reservoir model (KRM), including where these models fit in the overall modeling framework of Trinity and Shasta Divisions; model implementation (data development); model development; detailed discussion of the Shasta Dam Temperature Control Device (TCD) model representation; SLM and KRM calibration and validation; field monitoring, and summary and recommendations. Appendices include model representations of TCD leakage distribution, TCD historic operations logs, Shasta TCD specific selective withdrawal logic incorporated into CE-QUAL-W2, Shasta Lake model results and performance metrics, and Keswick Reservoir model results and performance metrics.

Contributions of this project include:

- Updating bathymetry for Shasta Lake and Keswick Reservoir to support modeling.
- Implementing 20 years (2000-2019) of CE-QUAL-W2 model simulations for Shasta Lake and Keswick Reservoir using available flow, water temperature, meteorology, and geometry.
- Development of Shasta TCD representations (including additional model logic), to accommodate leakage, large gate representation, low level intake considerations, blending via selective withdrawal, and operational considerations.
- Comprehensive testing, calibration, validation, and performance metrics for the modeled period.
- Implementing monitoring programs in Shasta Lake and Keswick Reservoir to collect additional data to confirm models (this is an ongoing process and does not significantly affect the simulation period identified in this project)
- Developing recommendations for ongoing model development and application.
- Assembling a Modeling Technical Committee. This diverse group of technical experts provided feedback on everything from basic data questions to complex facility representations in the model. This forum allowed model development to proceed in an open and transparent environment, the opportunity for review of work products, and leveraging a broad range of modeling experience and professions.

Shasta Lake and Keswick Reservoir Flow and Temperature Modeling

1. Introduction

Both Shasta Lake and Keswick Reservoir on the Sacramento River are significant water and hydroelectric resources within California. Shasta Lake, California's largest reservoir, and Shasta Dam are located north of Redding, California. Keswick Reservoir and Dam, nine miles downstream, receive Shasta Lake releases to control upstream power generation peaking and assist in meeting environmental objectives relevant to fish and aquatic life. Both are located in the Shasta Division of the Central Valley Project (CVP).

Recent drought and associated impacts to fish species have increased attention to water temperature management in the Sacramento River below Keswick Dam. Specifically, winter-run Chinook salmon, a listed species under the Endangered Species Act (ESA), requires cool summer and early fall water temperatures in the Sacramento River (NMFS 2014). Water temperature models have been developed to assist resource managers in planning, forecasting, and operating storage and conveyance systems, such as the Shasta and Trinity Divisions of the Central Valley Project (CVP), to meet a wide range of water supply demands. A useful element in ongoing resource management is a periodic assessment of existing temperature modeling tools and opportunities for improvement.

The current HEC-5Q water temperature modeling framework (Reclamation 2008; Willey 1986) for the Shasta and Trinity Divisions remains a valuable and effective tool for operations planning. However, development of more refined spatial and temporal models for Shasta Lake and Keswick Reservoir can support a broader range of analysis and add insight into temperature management in the Sacramento River system. As the U.S. Bureau of Reclamation (Reclamation) proceeds into the future, models that are broadly accepted, frequently updated, well-documented, confident performance, and actively supported will become increasingly important in the multi-disciplinary based temperature management process (Reclamation 1999, 2016a). With these goals in mind for model development and refinement, this project has resulted in:

- Updated bathymetry for Shasta Lake and Keswick Reservoir.
- Updated historical input data for these models for flow, water temperature, meteorology, and geometry (calendar years 2000-2018).
- The development of hourly flow and water temperature models for Shasta Lake and Keswick Reservoir that can:
    - Identify initial cold-water pool volumes and simulate the evolution of reservoir thermal conditions throughout the year, including the onset and breakdown of thermal stratification;
    - Assess the impacts of a range of potential operational strategies on in-reservoir and downstream water temperatures through the temperature

control period (late spring into fall), based on the initial reservoir storage and cold-water pool volume, and hydrological and meteorological conditions; and

  - Support development of cold-water pool management planning, including the incorporation of uncertainty in model representation and future conditions (e.g., inflow quantity and temperature, meteorology, etc.).

This report documents model development phases of the CE-QUAL-W2 (v4.1) application to Shasta Lake and Keswick Reservoir. The project background, scope and objectives are introduced in Section 1. The modeling framework is presented in Section 2, including an overview of the Shasta-Keswick system, a description of the Shasta Dam Temperature Control Device (TCD) operations, and definitions of water temperature management considerations. The data development for Shasta Lake and Keswick Reservoir during model implementation is described in Section 3, including geometry, stage-volume relationship, water temperature, hydrologic and meteorological data. Model development is presented in Section 4 for both Shasta Lake and Keswick Reservoir, including grid development, boundary conditions and initial conditions. Specific details regarding the representation of the TCD in the Shasta Lake model are presented in Section 5. Model calibration for Shasta Lake and Keswick reservoir are presented in Section 6. Section 7 describes field monitoring efforts initiated during the study. Section 8 provides a summary and recommendation for the project. References Ongoing model refinements are addressed in Section 9. There are five appendices that provide supporting information.

Some elements of model development are ongoing, and this document will be updated or augmented (e.g., with technical memoranda) as needed.

1.1. Background

River network models are useful key tools to understand water quality in large, complex basins by providing an ability to quantify past and present trends, as well as to forecast potential future outcomes (Gomez-Velez and Harvey 2014; Yearsly 2009). Currently, Reclamation utilizes the model HEC-5Q to forecast water temperature conditions in the Sacramento River for seasonal operations planning (Reclamation 2008, Willey 1986). The model simulates water temperature in response to specified hydrology on a 6-hour time step. The sub-daily time step of this model provides insight into daily minimum and maximum water temperatures (6:00 a.m. and 6:00 p.m., respectively). The HEC-5Q model domain includes the Trinity and Shasta Divisions of the CVP (Figure 1) and represents:

- Trinity Lake (one-dimensional representation: laterally and longitudinally averaged),
- Lewiston Reservoir (two-dimensional representation:[1] laterally averaged) and diversions to the Whiskeytown Lake via Clear Creek Tunnel,

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[1] Pseudo two-dimensional model presentation, laterally averaged.

- Whiskeytown Lake (one-dimensional representation: laterally and longitudinally averaged) and releases to Clear Creek and diversions to Keswick Reservoir,
- Shasta Lake (one-dimensional representation: laterally and longitudinally averaged),
- Keswick Reservoir (two-dimensional representation:[1] laterally averaged),
- Sacramento River from below Keswick Dam to below the American River, including Clear Creek from Whiskeytown Dam to the Sacramento River (one-dimensional representation: laterally and vertically averaged).

This large-scale network model is a valuable tool to analyze the inter-connected elements of the Trinity and Shasta Divisions for extended periods. The model is computationally efficient, with relatively short simulation times (e.g., minutes) for simulation periods of decades.

Reclamation's internal review of temperature modeling capabilities suggested selecting tools that improve the workflow process and data processing, enhance graphical presentation, and up-grade communication products (Reclamation 2016b). More recently, questions specific to the cold-water pool management in Shasta Lake (Reclamation 2015) have focused around a more detailed model representation of Shasta Lake and Keswick Reservoir and how such a model may improve projecting quantity and management of the cold-water pool. Specifically, the use of the two-dimensional, laterally averaged CE-QUAL-W2 model (Cole and Wells 2008), which represents longitudinal and vertical variations in Shasta Lake, has been implemented by University of Nevada Reno and National Marine Fisheries Service (Hallnan et al. 2017; 2020; Daniels et al. 2018). This modeling platform was adopted for use in this project.

When incorporating a new model into the temperature management modeling process, several elements should be considered (Satkowski et al. 2000), including, but not limited to:

- Contribution of a new model (value added)
- Model objective(s)
- How the model will be used (forecasting, planning)
- Model spatial and temporal scales
- Model data needs
- Model performance
- Interface of new model with other existing models
- Resources required to develop and maintain a model

The proposed approach aims to utilize existing information and models in the development of new models to assist operators managing Shasta Lake, as well as other facilities, for water temperature management in downstream Sacramento River reaches. The project would be phased to accommodate higher priorities sooner, with future phases to be implemented as needed. High priority elements of the system that have been identified include revisiting the temperature tools of Shasta Lake and Keswick Reservoir (Reclamation et al., 2015) for mid- to short-term modeling, particularly under lower storage conditions to:

- Identify cold-water pool volumes early in the calendar year (e.g., March through April period)
- Based on the initial cold-water pool volume, forecast the impacts of potential operational strategies on water temperatures through the temperature control period (late spring into fall)
- Assist in the development of a cold-water management plan that incorporates uncertainty in model representation and future conditions (e.g., inflow quantity and temperature, meteorology, and forecasts of such conditions).

The CE-QUAL-W2 model has been identified as an appropriate tool for Shasta Lake and Keswick Reservoir at this time (Bartholow et al. 2001; Hallnan et al. 2017, 2020; Sapin et al. 2017). This decision was based on the many features that CE-QUAL-W2 possesses, such as:

- Actively supported model
- Access to the principal code author
- Open-source code (allowing review and modification)
- No cost (no initial cost or annual maintenance fee)
- Comprehensive documentation and training available
- Two-dimensional representation allows assessment of longitudinal and vertical gradients
- Supports branching networks (e.g., dendritic nature of Shasta Lake)
- Models large changes in reservoir stage effectively
- Multiple outlets provide flexibility to represent selective withdrawal
- Ability to incorporate temperature control curtains
- User interface for input file quality control
- Post-processors (both public and proprietary) available
- Wide range of applications.

While the CE-QUAL-W2 model is a robust tool with a wide range of capabilities, there are several considerations that are important in the application of this (or any) model to Shasta and Keswick Reservoirs. Such considerations will be discussed throughout this document, as applicable.

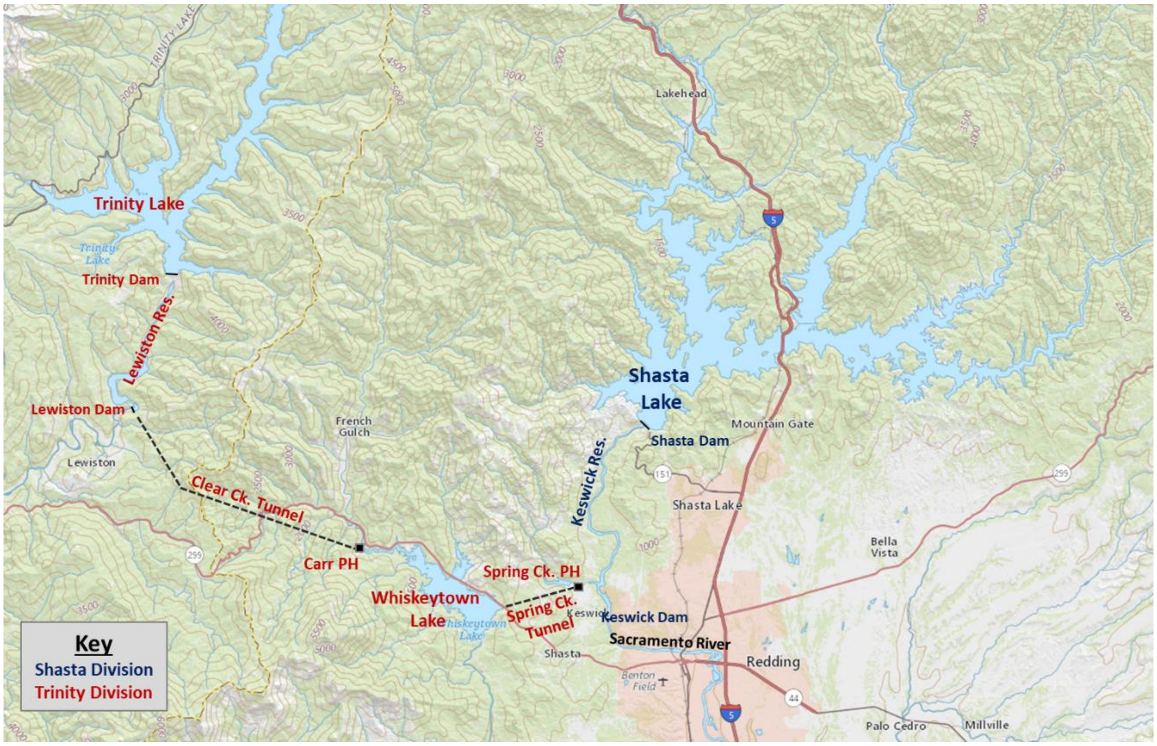

Figure 1. Elements of the Trinity and Shasta Divisions.

1.2. Project Scope

Shasta Dam is located on the Sacramento River, approximately nine miles north of Redding, California (Figure 2). Shasta Lake is California's largest reservoir, with a storage capacity of over 4.5 million acre-feet (AF). Annual temperature management strategies utilize selective withdrawal facilities, systems designed to selectively release a desired quality of water from a density-stratified reservoir (Imberger and Fischer 1970; Rheinheimer et al. 2015). The selective withdrawal facilities at Shasta Dam are used to meet downstream Sacramento River environmental objectives pertaining to fish life stages (i.e., seasonal water temperature targets). In addition to the inflow from the Sacramento River, Shasta Lake receives inflow from the McCloud River, Pit River, and Squaw Creek.

Shasta Dam releases flow into Keswick Reservoir, which acts as an afterbay to control flow releases from Shasta Dam and Powerhouse to the Sacramento River downstream of Keswick Dam. In addition to inflow from Shasta Lake, Keswick Reservoir receives inflow from Spring Creek, which includes flow conveyed from Whiskeytown Lake via Spring Creek Tunnel. Local inflow to the reservoir is typically minimal.

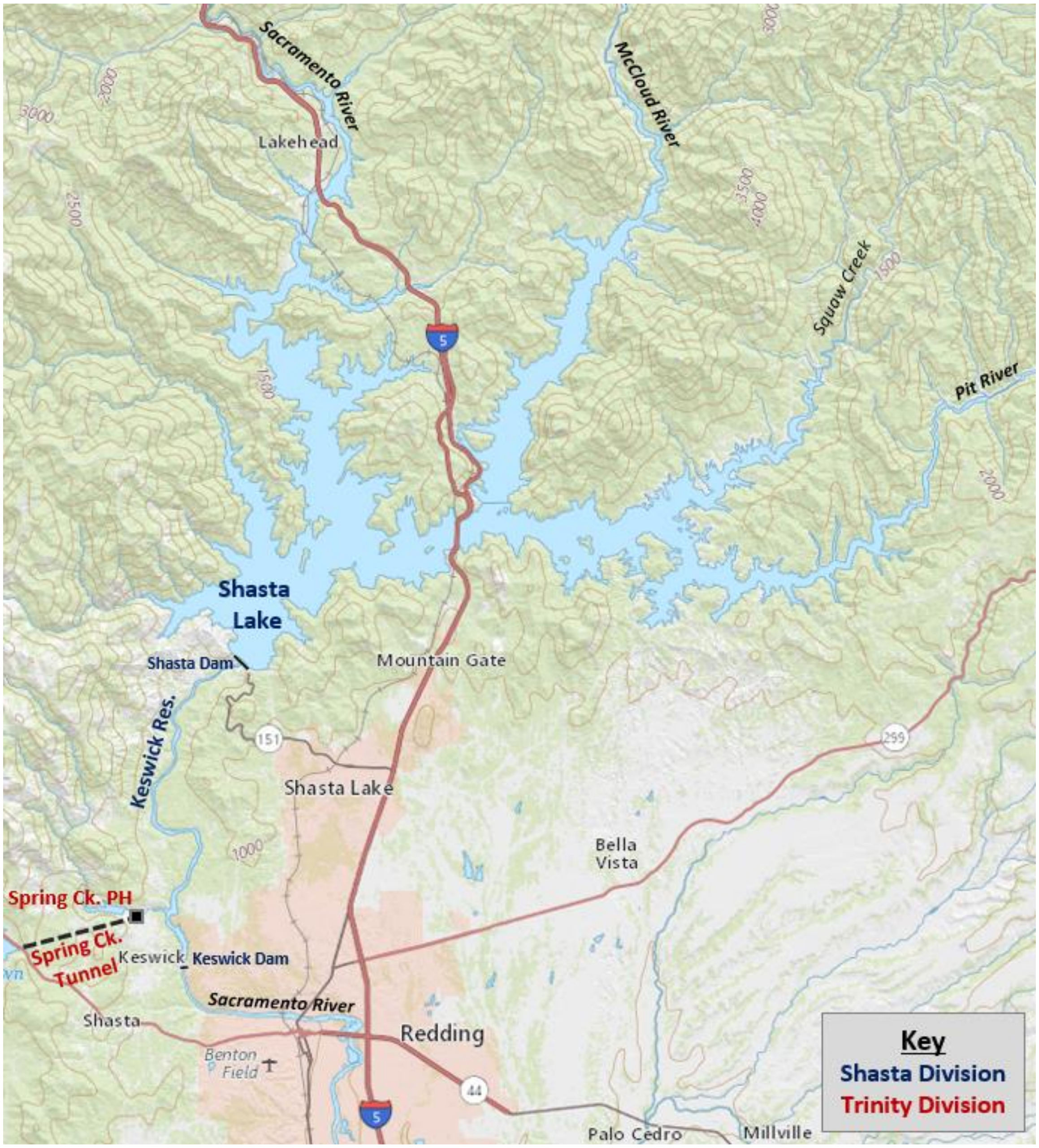

Figure 2. Map with locations of Shasta and Keswick dams and reservoirs.

1.3. Project Objectives

This project is intended to develop a set of tools within a modeling framework to assist resource managers when operating Shasta Lake to meet downstream water temperature targets (Reclamation 2016a). The proposed approach aims to utilize existing information to develop detailed spatial and temporal models of Shasta Lake and Keswick Reservoir. Overall project phases include:

- Modeling Framework Development

The project objectives include:

- Developing calibrated models of Shasta Lake and Keswick Reservoir based on the historic twenty-year period 2000-2017.
- Validate models of Shasta Lake and Keswick Reservoir for years 2018 and 2019.
- Establish a forum (Modeling Technical Committee) to communicate all stages of model development in a transparent fashion.

Subsequent phases of work, not documented herein, include:

- Model Linkage with Downstream River Models
- Developing forecasting logic
- Model Application

These latter three topics will be the subject of future reports.

1.4. Modeling Technical Committee (MTC)

The development of the Shasta Lake and Keswick Models occurred over the period of approximately two years. At the inception of model development, a Modeling Technical Committee (MTC) was formed. Participation was open to any interested party, and distribution list for invitees to the process are listed in Table 1. Some of the indivudals did not attend meetings, but were included on the mailing list. The intent of the MTC was to develop the models in an open and transparent process with a broad range of stakeholders.

Throughout the model development process meetings were held approximately every two months. Presentation of progress to date, assumptions, challenges, data needs, model performance, model limitations, calibration, technical reports, and other information were reviewed with the MTC. All aspects of model development were addressed. Reclamation maintained meeting notes and all presentations and technical memoranda developed as part of this process are available.

1.5. Acknowledgements

The authors are grateful for the assistance and guidance received from several agencies and from the many individuals who generously contributed their time and expertise to the project. In particular, we want to express our gratitude to the Sacramento Settlement Contractors who provided financial support and project management. The roles of collaborating agencies and entities are described briefly as follows:

Glenn Colusa Irrigation District (GCID): Thad Bettner of Glenn Colusa Irrigation District (GCID) managed the project. GCID provided resources to complete a bathymetric survey of Keswick Reservoir in support of the Keswick Reservoir Model.

Reclamation: Provided a venue for all Modeling Technical Committee (MTC) meetings, and Randi Field has managed these meetings and all communications, providing notes and materials to all participants. Further, all data for modeling was reviewed by Reclamation prior to model development.

Table 1. Modeling Technical Committee distribution list.

Craig Anderson	U.S. Fish and Wildlife Service
William Anderson	State Water Resources Control Board
Mohammed Anwar	California Department of Fish and Wildlife
Don Bader	U.S. Bureau of Reclamation
Lewis Bair	Reclamation District 108
Lee Bergfeld	MBK Engineers
Thad Bettner	Glen Colusa Irrigation District
Thomas Boardman	San Luis & Delta-Mendota Water Authority
Benjamin Bray	East Bay Municipal Utility District
Miles Daniels	National Marine Fisheries Service
Ammon Danielson	Western Area Power Administration
Eric Danner	National Marine Fisheries Service
Shelly Dean	East Bay Municipal Utility District
Mike Deas	Watercourse Engineering, Inc.
Vadim Demchuk	State Water Resources Control Board
Bruce DiGennaro	Essex Partnership
Randi Field	U.S. Bureau of Reclamation
Sarah Gallagher	National Marine Fisheries Service
Sheila Greene	Westlands Water District
Elizabeth Hadley	U.S. Bureau of Reclamation
Steven Handy	City of Redding
Chuck Hanson	Hanson Environmental
Michael Harris	California Department of Fish and Wildlife
Robert Hughes	California Department of Fish and Wildlife
Joshua Israel	U.S. Bureau of Reclamation
Matt Johnson	California Department of Fish and Wildlife
Elizabeth Kiteck	U.S. Bureau of Reclamation
Yong Lai	U.S. Bureau of Reclamation
Eric Leitterman	Santa Clara Valley Water District
Todd Manley	Northern California Water Association
Matt Nobriga	U.S. Fish and Wildlife Service
Doug Obegi	Natural Resources Defense Council
Jason Roberts	California Department of Fish and Wildlife
Laurel Saito	The Nature Conservancy
Alessia Siclari Melcho	State Water Resources Control Board
Jim Smith	U.S. Fish and Wildlife Service
I.E. Sogutlugil	Watercourse Engineering, Inc.
Ian Uecker	California Department of Water Resources
Tracy Vermeyen	U.S. Bureau of Reclamation
Thuy Washburn	U.S. Bureau of Reclamation
Craig Williams	State Water Resources Control Board
Paul Work	U.S. Geological Survey
Michael Wright	U.S. Bureau of Reclamation
Tong Wu	Western Area Power Administration
Garwin Yip	National Marine Fisheries Service
Paul Zedonis	U.S. Bureau of Reclamation

Other Reclamation personnel that contributed include Gregory Gotham, Janet Martin, and Tyler Ward in Redding who assisted in field support for placing, maintaining, and retrieving the vertical temperature probe string in Keswick Reservoir, as well as completing vertical profiles in Shasta Lake during the 2019 field summer-fall season. Reclamation staff have shared critical insight into aspects of overall operations. Tracy Vermeyen provided feedback on detailed operations and information regarding the Temperature Control Device (TCD) that was invaluable in representing the TCD in the CE-QUAL-W2 framework.

Laurel Saito, previously a professor at University of Nevada Reno and now with The Nature Conservancy, generously shared her CE-QUAL-W2 models, model data, maps, and other resources at the inception of the project. Her ongoing participation in the MTC has been a valuable contribution to the project.

The MTC members played a vital role in the entire project. This diverse group of technical experts provided feedback on everything from basic data questions to complex facility representations in the model. Their patience, professionalism, and willingness to share openly made this forum a critically important aspect to success of the project.

2. Modeling Framework

Because the project requires modeling multiple systems, a modeling framework approach was adopted to provide a means to simulate conditions throughout the reservoir-river system running models in series. Data are used in the Shasta Lake model to simulate input temperature and flow used in the Keswick Reservoir model to simulate temperature and flow that can be used in downstream Sacramento River models (Figure 3). In addition to running models in series, a modeling framework will be useful during potential future interactions with other models, e.g., downstream river models such as the River Assessment for Forecasting Temperature (RAFT) model (Pike et al. 2013). Outlined below is an overview of the general characteristics of the Shasta Lake and Keswick Reservoir system as it pertains to flow and water temperature, including a brief description of key water temperature modeling considerations, and a short description of the Shasta Dam TCD.

Figure 3. Modeling framework for the Shasta Lake model, Keswick Reservoir model, and a generic downstream Sacramento River model.

2.1. Overview of the Shasta-Keswick System

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 and Squaw Creek as winter runoff and spring snow-melt runoff. Seasonal warming and subsequent stratification occur in Shasta Lake during the hot and relatively dry summer. Annual temperature management strategies are developed each year to most efficiently utilize stored winter and spring cold water to meet downstream environmental objectives (e.g., fishery life stage needs) from late spring to early fall (Reclamation 2013).

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.

Keswick Reservoir is approximately 10 miles long (16.1 km) and 0.1 miles (0.16 km) wide and is used to regulate releases from Shasta Dam and Spring Creek Powerhouse diversions from the Trinity Basin. Releases and spill from Shasta Dam provide the majority of inflow into Keswick Reservoir, with Spring Creek Powerhouse outflows making up the balance of inflows (Reclamation 2018). Despite differing volumes and temperatures, both Shasta Dam and Spring Creek Powerhouse outflows impact the water quality and temperature of the Keswick Reservoir. Spring Creek Powerhouse release temperatures are the result of multiple factors in the Trinity-Lewiston-Whiskeytown reservoirs system, and while water temperature of flow from Spring Creek Powerhouse typically has a modest impact on Keswick Reservoir temperatures, water temperature decisions at Shasta Dam require consideration of selective withdrawal strategies that must accommodate the range of potential flow and temperature conditions of inputs at the Spring Creek Powerhouse (Reclamation 2015).

2.2. Shasta Dam TCD Operations

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 4). The TCD is composed of three levels (upper, middle, lower (or pressure relief gates (PRGs)), plus the low-level intake gates, which accesses the low-level intake structure[2]. Each of the three levels (upper, middle, and lower) are composed of five (5) gates, as shown in Figure 4.

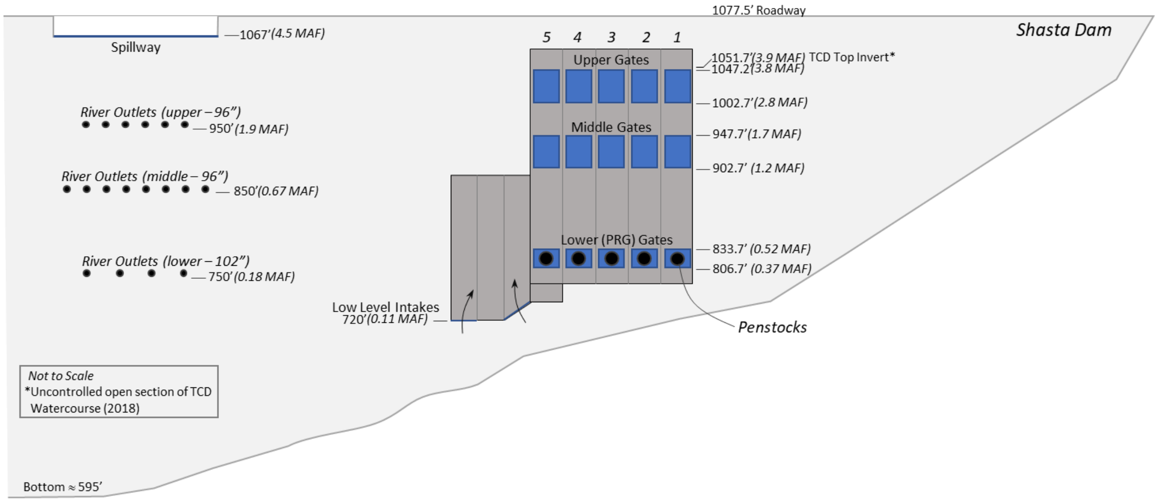

Figure 4. Shasta Dam outlet works (left) and Temperature Control Device (right) looking downstream. Powerhouse units 1 through 5 are shown for reference.

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[2] Herein, TCD levels will be referred to explicitly or using the following abbreviations:
Upper Level: TCDU
Middle Level: TCDM
Lower Level (also termed PRGs): TCDL
Low Level Intake: LLI (also referred to as the side gate or TCDS)
At times, the upper three TCD levels are referred to as "shutters" and the LLI as "side gates." In this document, the above terminology is employed.

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 5). In large, deep lakes and reservoirs, like Shasta Lake, stratified conditions typically persist from spring into fall.

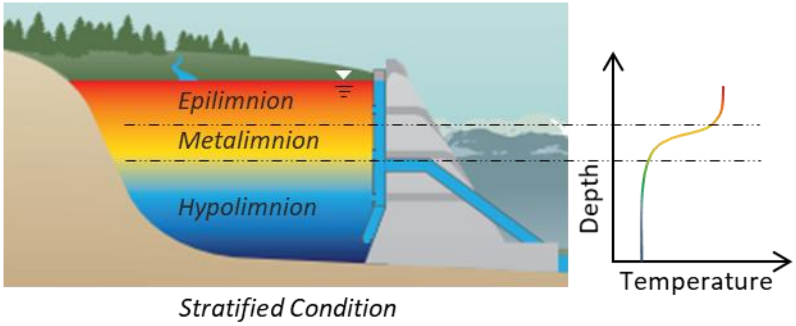

Figure 5. Representative seasonal stratification for a large reservoir, showing the epilimnion, metalimnion, and hypolimnion and associated thermal profile.

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. A TCD progression is shown in Figure 6 for 2012, where a combination of releases through individual levels and multiple level blending was employed to manage tailbay temperatures[3] throughout the temperature management period.

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 three openings located on the bottom of the LLI structure (Figure 4). 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

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[3] Tailbay temperature is the temperature below the dam and includes releases from the dam and powerhouse.

criterion, the upper gates can still be operated, but at least one gate at the middle level must be opened.

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. Because the CE-QUAL-W2 model is a laterally averaged representation of the reservoir, the number of individual gates open at any one level are not explicitly modeled.

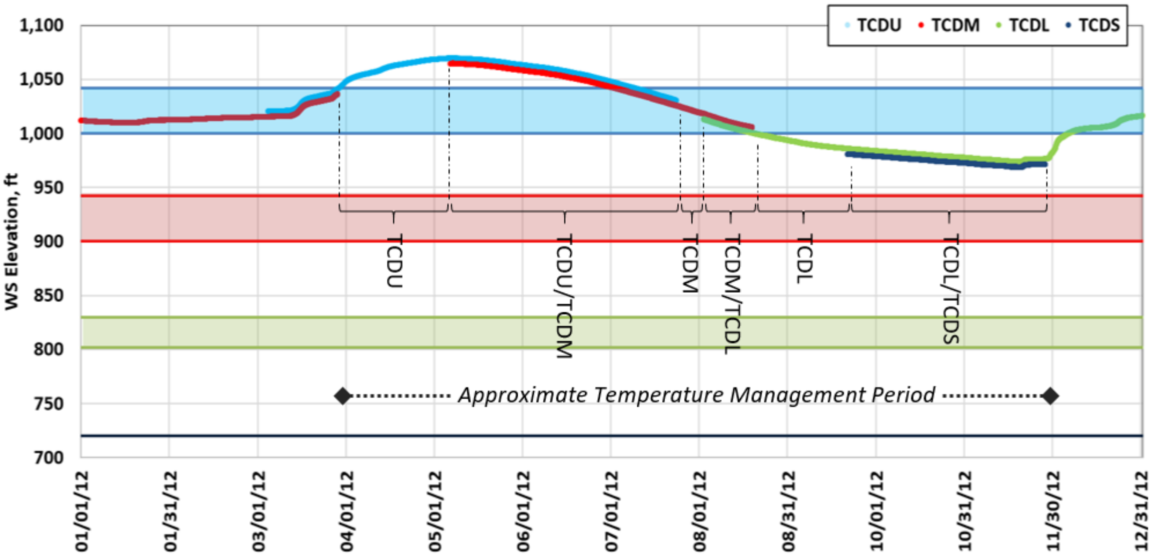

Figure 6. TCD level progression based on field observations: 2012. The blue band denotes the water surface elevation associated with the upper gates (TCDU), the red band denotes the WSE associated with the middle gates (TCDM), the green band denotes the lower (PRG) gates (TCDL), and the black line at 720 ft denotes the invert of the low level intakes (side gates/LLI/TCDS).

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 model for Shasta Lake.

2.3. Water Temperature Management Considerations

The cold-water storage volume in Shasta Lake is an important consideration when managing to meet 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 volumes, tailbay temperatures, and downstream river temperatures during the remaining temperature management season (Rheinheimer et al. 2015; Thompson et al. 2012).

Developing a modeling framework 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 en route and inputs from the Trinity Basin via Spring Creek Tunnel. Hydropower peaking at both the 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 available at an hourly (or similar) time step for use in separate analyses and downstream models.

3. Model Implementation

Model implementation is the process of developing the necessary data for the model and using these data to build the necessary input files to run the model. The outcome of this step is a functioning, but uncalibrated model. Required information for the Shasta Lake and Keswick Reservoir CE-QUAL-W2 model includes geometric information describing the reservoirs and infrastructure; flow, stage, and operational data and information; water temperature data; and meteorology observations. Other model values, coefficients, and constants, such as start date, simulation duration, time step control, calibration parameters, and other model control parameters will be addressed in future documentation. Data development for Shasta Lake and Keswick Reservoir are outlined below.

3.1. Data Development – Shasta Lake

Data development includes the process of aggregating all data necessary to implement a model. Field data describing the Shasta Lake and Keswick Reservoir geometries, hydrology, water temperature, and local meteorology were required to implement and test the model. Geometric data are used to describe the reservoir morphologies (bathymetry), locations of inflow and outflow points, elevations and capacities of outlet works, and provide information regarding topographic shading and the reservoir stage-volume relationship (Table 2).

Table 2. Geometry data types, description, and sources.

Data Type	Data Description	Data Sources
Bathymetry	Contour map of lake or reservoir below water surface and surrounding upland area	Digitized topographic maps/aerial photos Digital Elevation Map (DEM) Bathymetric Survey
Stage-Volume Curve	Mathematical description of the relationship between a reservoir stage and its volume	Bathymetry
Facilities Description	TCD, river outlets, low-level intake and spill elevations Release schedule	Reclamation

Hydrologic data include reservoir stage, inflows, and outflows. Water temperature data include time series at system inflow and outflow locations, as well as vertical profile data. Data are used for boundary conditions, initial conditions and for model calibration. Meteorological data includes solar radiation, air temperature, wet bulb or dew point temperature, wind speed and direction, and cloud cover. Due to the proximity of Shasta Lake and Keswick Reservoir, the same meteorological data set was used for both models.

Data were available from various sources including U.S. Bureau of Reclamation (Reclamation), United States Geological Survey (USGS), the California Data Exchange Center (CDEC), MesoWest and Western Regional Climate Center (WRCC). Additional bathymetry and water temperature profile data were collected in Keswick Reservoir for this study. Details of data-gathering for this study are presented in following sections for Shasta Lake, then for Keswick Reservoir.

3.1.1. Geometry Data

Geometric data collected for application in the water temperature model of Shasta Lake are described in the following sections. Development of a Shasta Lake bathymetric map and the stage-volume relationship are presented, and a brief description of the physical attributes of the Shasta Dam TCD and outlet works is provided.

3.1.1.1. Bathymetry

A geometric representation of Shasta Lake was created by digitizing historic maps of the area currently inundated by Shasta Lake and of the surrounding upland areas. Spatial data used to create Shasta Lake bathymetry came from three principal sources:

- USGS 1:24,000-scale digital elevation models (DEM) (twelve discrete models, 32.8 feet x 32.8 feet (ft) (10 meter x 10 meter (m)) resolution were combined for a total of 17,556,005 XYZ data points used to map the area surrounding Shasta Lake at 1,064.9 ft (324.6 m) elevation.
- Google Earth (GE) images were used to trace reservoir and island shorelines when the Shasta Lake water surface elevation was approximately 1,000 ft (304.8 m) and 940 ft (286.5 m) on 02/21/2014.
- USGS historical topographic map published in 1901, before construction of Shasta Dam (1:125,000-scale quadrangle for Redding, California, with a 20 ft (6.1

m) contour interval) was used to define XYZ data for elevations below 940 ft (286.5 m).

Detailed information regarding the data sources listed above and project methodology is outlined in (Deas and Sogutlugil 2017a). The final bathymetric map is shown in Figure 7**.**

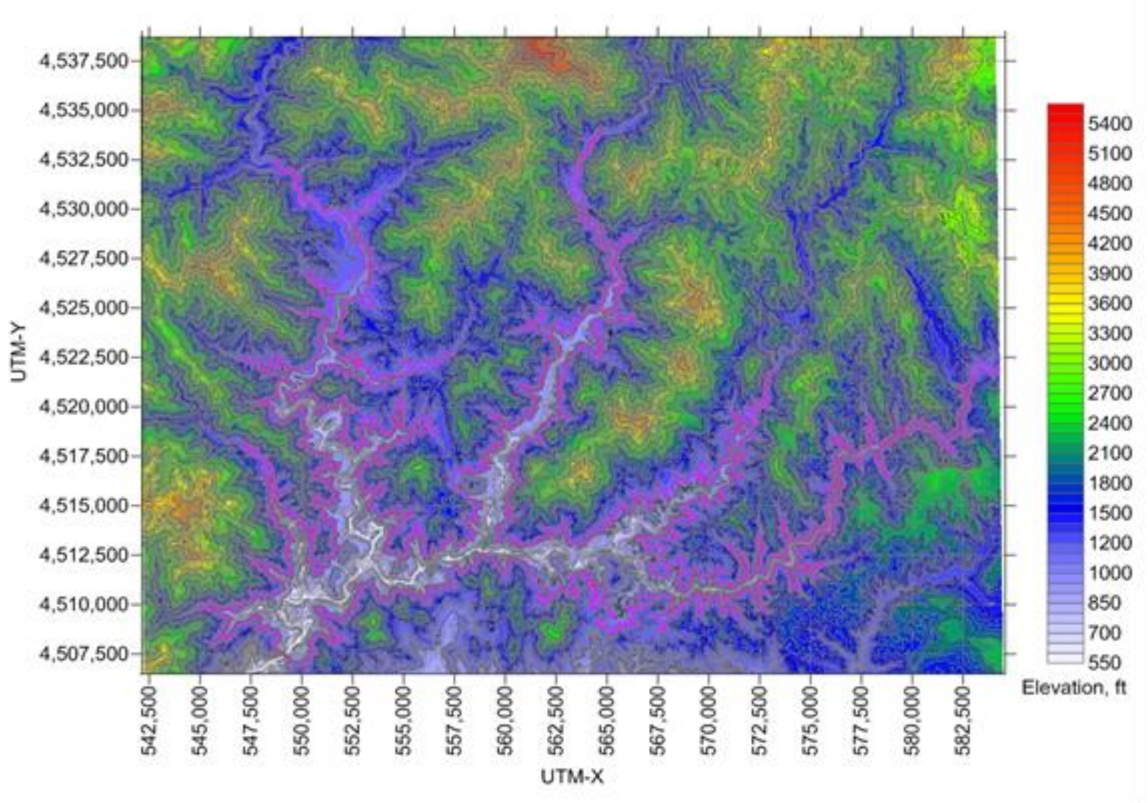

Figure 7. Shasta Lake digital topography and bathymetry map. The 1,100 ft (335.3 m) contour around the lake is shown with magenta line.

3.1.1.2. Stage – Volume Relationship

The stage–volume curve (depicted as a storage versus elevation curve) of the measured hourly data from Shasta Dam (USBR-SHA) station from 2000 through 2017 (Source: California Data Exchange Center web page http://cdec.water.ca.gov) is given in Figure 8. At full pool, Shasta Lake has an elevation of 1,067 ft. (325.2 m), storage of 4,552,000 AF (~5,615x10^9 m^3) and a surface area of 30,000 acres (12,150 hectares). The green dashed lined shows the bathymetric stage-volume relationship produced using Surfer®[4] software based on Figure 7.

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[4] https://www.goldensoftware.com/products/surfer

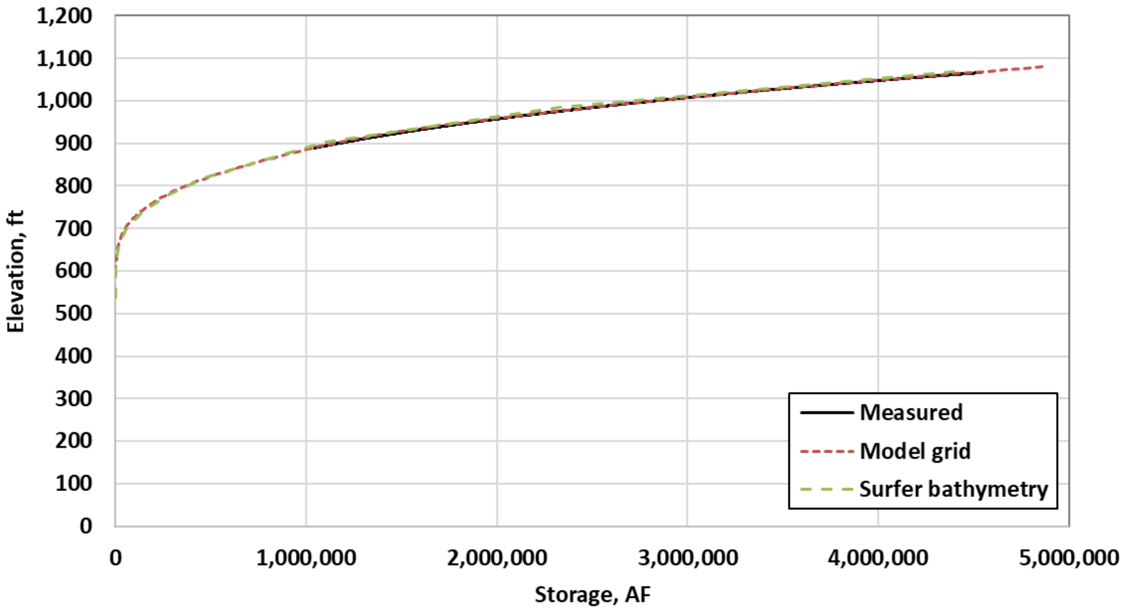

Figure 8. Storage versus elevation curves for Shasta Lake.

3.1.1.3. Shasta Dam TCD and Dam Outlets

The TCD consists of a series of fixed panels with adjustable gates ~~shutters~~ attached to the dam and feeding water to the penstocks that lead to the powerhouse (Figure 4). The 250 ft (76.2 m) wide by 300 ft (91.4 m) high TCD structure has five gate openings, each 50 ft (15.2 m) wide, on three levels (upper, middle, lower). These TCD levels allow water to be drawn into the TCD from different elevations (and temperatures) within Shasta Lake (Figure 4). The TCD extends 50 ft (15.2 m) upstream from the face of the dam. Flow can enter any open gate at any level in the TCD and be conveyed to any operating powerhouse intake, i.e., there are no internal structures to impede flow once waters enter the TCD (Reclamation 1999). In addition to the intake structures mentioned above, a low-level intake structure is attached to the side of the TCD (Figure 4). The 150 ft (45.7 m) wide by 160 ft (48.5 m) tall low-level intake structure is made of three elements that were individually assembled and attached to the dam. The side gate structure has bottom openings at elevation 720 ft (219.5 m). Two slide gates, mounted on the side of the TCD, control the flow from the low-level intake structure to the main TCD structure (Reclamation 1999). Each set of gates on the TCD requires a minimum 35 ft (10.7 m) of freeboard for hydropower production to take place (Personal Communication R. Field, April 12, 2018). For example, if the upper gate level is to be used without any other gate level in use, there must be 35 ft (10.7 m) of water depth above that gate invert. If water levels fall below this level, at a minimum one gate at the middle gate level must be opened. The dam has 18 outlets used for water release directly to the river, known as the upper (six 8 ft (2.4 m) outlets), middle (eight 8 ft (2.4 m) outlets), and lower (four 8.5 ft (2.6 m) outlets) River Release gates. The spillway invert is 1,037 ft (316.1 m) and has a capacity of 186,000 cfs (5,267 cms) at water surface elevation of 1,065 ft (324.6 m), and is controlled by three drum gates, each 28 ft (8.5 m) tall and 110 ft (33.5 m) wide[5]. The

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[5] https://www.usbr.gov/projects/index.php?id=241

TCD structure is not watertight and leakage represents water that enters the TCD through areas other than the operable gates. A detailed discussion on leakage representation in the model is included in Section 5, below.

The centerline elevation assumption in CE-QUAL-W2 does not fully represent the sizes of the upper, middle and lower level gates, which have vertical openings of 45 ft (13.7m), 45 ft (13.7 m), and 27 ft (8.2 m), respectively. Model testing has indicated that these large openings are not completely represented with the simple point or line sink in CE-QUAL-W2, and that locating these outlets at the centerline elevation, as is typically done in similar modeling applications, may not effectively represent outflow through the TCD levels. Outflow from each TCD level – upper, middle, and lower – are represented in the model by three point sinks, located at the top, centerline and bottom of each gate elevations. The low-level intake is also represented by multiple point sinks. A comprehensive discussion of the TCD gate representation, including the low-level intake and leakage into the TCD, is included in Section 5, below. The elevation information for the river release outlets, TCD levels, and other facilities are presented in Table 3.

Table 3. Shasta Dam facilities and elevations.

Outlet Name	Outlet location	CE-QUAL-W2 Outlet Type[1]	Elevation (ft)	Elevation (m)
Spillway	Crest	Line	1,037	316.08
TCD upper level	Top	Point	1,042	317.60
	Centerline	Point	1,021	311.20
	Bottom	Point	1,000	304.80
TCD middle level	Top	Point	942	287.12
	Centerline	Point	921	280.72
	Bottom	Point	900	274.32
TCD lower (Pressure Relief Gates)	Top	Point	830	252.98
	Centerline	Point	816	248.72
	Bottom	Point	802	244.45
TCD low-level intake (side gates)	Intake at Bottom	Point[2]	720	219.46
TCD leakage	Various	Line[3]	Various	Various
River release upper outlets	Center	Point	942	287.12
River release middle outlets	Center	Point	842	256.64
River release lower outlets	Center	Point	742	226.16

[1] CE-QUAL-W2 representation for dam outlets are point or line sinks

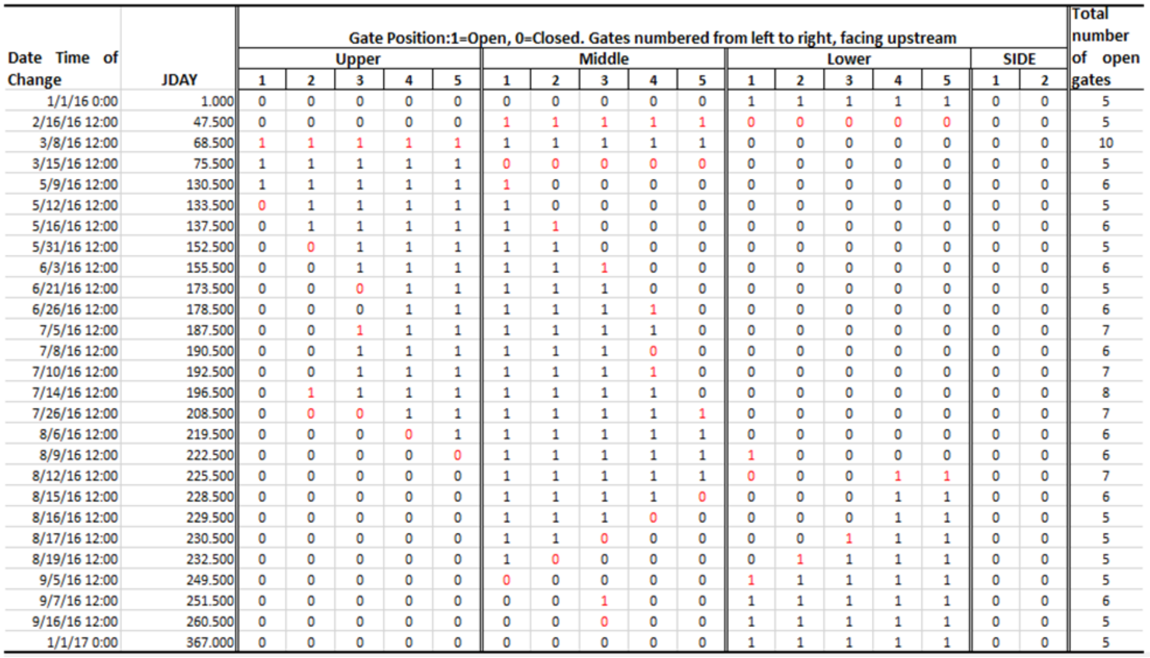
[2] TCD side gates have an invert elevation of 720 ft (219.5 m), but are represented by multiple outlets, as outlined in Section 5.

[3] TCD leakage occurs between elevations 720 ft (219.5 m) and 1,000 ft (304.8 m). Details are outlined in Section 5.

3.1.1.4. Shasta Dam Temperature Control Device Operations

Reclamation provided historic gate schedule information that documented the timing for the opening and closing of each TCD gate from 1997 through 2017. The TCD schedule provides insight to blending and non-blending periods between different levels of the TCD. An example from the TCD schedule record is included in Table 4. In the figure, active gates and closed gates are coded as “1” and “0”, respectively. Operational changes for gates in any one level or between levels are shown in red.

Table 4. Shasta Dam Temperature Control Device Schedule for 2016 (changes for gates in any one level or between levels are shown in red).



Date Time of Change	JDAY	Gate Position:1=Open, 0=Closed. Gates numbered from left to right, facing upstream																	Total number of open gates
		Upper					Middle					Lower					SIDE		
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	
1/1/16 0:00	1.000	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	5
2/16/16 12:00	47.500	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	5
3/8/16 12:00	68.500	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	10
3/15/16 12:00	75.500	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	5
5/9/16 12:00	130.500	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	6
5/12/16 12:00	133.500	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	5
5/16/16 12:00	137.500	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	6
5/31/16 12:00	152.500	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	5
6/3/16 12:00	155.500	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	6
6/21/16 12:00	173.500	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	5
6/26/16 12:00	178.500	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	6
7/5/16 12:00	187.500	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	7
7/8/16 12:00	190.500	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	6
7/10/16 12:00	192.500	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	7
7/14/16 12:00	196.500	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	8
7/26/16 12:00	208.500	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	7
8/6/16 12:00	219.500	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	6
8/9/16 12:00	222.500	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	6
8/12/16 12:00	225.500	0	0	0	0	0	1	1	1	1	1	0	0	0	1	1	0	0	7
8/15/16 12:00	228.500	0	0	0	0	0	1	1	1	1	0	0	0	0	1	1	0	0	6
8/16/16 12:00	229.500	0	0	0	0	0	1	1	1	0	0	0	0	0	1	1	0	0	5
8/17/16 12:00	230.500	0	0	0	0	0	1	1	0	0	0	0	0	1	1	1	0	0	5
8/19/16 12:00	232.500	0	0	0	0	0	1	0	0	0	0	0	1	1	1	1	0	0	5
9/5/16 12:00	249.500	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	5
9/7/16 12:00	251.500	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	0	0	6
9/16/16 12:00	260.500	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	5
1/1/17 0:00	367.000	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	5

3.1.2. Hydrologic Data

Hydrologic data used for model implementation of a reservoir includes inflow, stage (or water surface elevation) and operations (or outflow) data. Inflows to Shasta Lake come primarily from the Sacramento River, McCloud River, Pit River and were recorded by the USGS at various gages. Inflow for Squaw Creek was unavailable for the period of simulation and were estimated using a regression relationship (see section 4.1.2, below). Inflow coming from Big Backbone Creek was assumed to be negligible at this phase of the study. Stage data was recorded as water surface elevation by Reclamation during the operation of the dam. Outflow rates to the powerhouse, river and through the spillway were also recorded by Reclamation during the operation of the dam. A summary of sources for flow data used in the Shasta Lake portion of the model are listed in Table 5.

Table 5. Sources of flow data used for Shasta Lake model, 2000-2017.

Site Number/ Abbreviation	Agency	Site Active	Site Name	Data Types	Data Frequency	Application of Data
11342000	USGS	YES	Sacramento River at Delta CA	Q	15-minute	Branch Inflow
11368000	USGS	YES	McCloud River above Shasta Lake CA	Q	Daily	Branch Inflow
11365500	USGS	NO[5]	Squaw C ab Shasta Lake CA	Q	NA	Branch Inflow
11365000	USGS	YES	Pit River near Montgomery Creek CA	Q	Daily	Branch Inflow
SHA[1]	CDEC-Reclamation	YES	Shasta Dam	Elevation, storage, Q_{ph}[2], spill, $Q_{control}$[3]	Hourly[4]	Boundary Condition and Calibration
DLT	CDEC-Reclamation	YES	Sacramento River at Delta	Q	15-minute	Branch Inflow
MSS	CDEC-PG&E	YES	McCloud River above Shasta Lake	Q	Hourly	Branch Inflow
PMN	CDEC-Reclamation	YES	Pit River near Montgomery Creek	Q	Daily	Branch Inflow

[1] Data from this station are used in the model for calibration and selective withdrawal operations.
[2] Powerhouse flow (Q_{ph}) -- includes flow data for each of five penstocks.
[3] $Q_{control}$ flows consist of releases through the River Release gates.
[4] While elevation and storage data are available in CDEC web page, hourly Q_{ph}, Spill, and $Q_{control}$ data were supplied exclusively by Reclamation to Watercourse Engineering, Inc.
[5] See Section 4.1.2.

3.1.3. Water Temperature Data

Time series and vertical profile water temperature data are required to implement and calibrate the model. Water temperature data describes water temperatures at reservoir inflow locations, which mainly come from upstream sources, as well as from tributaries and surface runoff. Water temperature vertical profiles describe vertical variations (or lack of variation) in water temperature near the TCD and other dam outflow locations.

3.1.3.1. System Inflow Temperatures

Inflows to Shasta Lake are primarily from the Sacramento River, McCloud River, Pit River and Squaw Creek[6]. During the water temperature management season, the temperature of the water released from Shasta Lake into Keswick Reservoir is controlled by the TCD. A summary of sources for water temperature time series data used in the Shasta Lake portion of the model are presented in Table 6.

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[6] See Section 4.1.2 for a discussion of Squaw Creek inflow temperatures.

Table 6. Shasta Lake water temperature data sources, 2000-2017.

Site Number/ Abbreviation	Agency	Site Active	Site Name	Data Types	Data Frequency	Application of Data
DLT	CDEC-Reclamation	YES	Sacramento R at Delta	Tw	Hourly	Branch Inflow
MSS	CDEC-PG&E	YES	McCloud R above Shasta Lk	Tw	Hourly	Branch Inflow
PMN	CDEC-Reclamation	YES	Pit R near Montgomery Cr	Tw	Hourly	Branch Inflow
SHD	CDEC-Reclamation	YES	Shasta Dam Water Quality	Tw	Hourly	Calibration Selective Withdrawal Operations
SP1	CDEC-Reclamation	YES	Shasta Penstock #1	Tw	Hourly	Selective Withdrawal Operations
SP2	CDEC-Reclamation	YES	Shasta Penstock #2	Tw	Hourly	Selective Withdrawal Operations
SP3	CDEC-Reclamation	YES	Shasta Penstock #3	Tw	Hourly	Selective Withdrawal Operations
SP4	CDEC-Reclamation	YES	Shasta Penstock #4	Tw	Hourly	Selective Withdrawal Operations
SP5	CDEC-Reclamation	YES	Shasta Penstock #5	Tw	Hourly	Selective Withdrawal Operations

3.1.3.2. Water Temperature Vertical Profiles

Temperature profiles measured above Shasta Dam in the model years 2000–2019, were supplied by Reclamation. These vertical profiles are collected approximately monthly, with more frequent measurements taken during summer and under certain conditions. The number of profiles available in each month is listed in Table 7. Also, in 2000 through 2019, water temperatures were collected using a temperature logger string suspended in the reservoir that allowed for the collection of data at multiple depths (approximately 20 ft intervals) at 15-minute intervals. The logger string was deployed upstream of the dam in the vicinity of the location where the monthly (or more frequent) thermal profiles are collected.

Table 7. Number of water temperature profiles above Shasta Dam, by month, 2000 through 2017.

	Month												
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
2000	1	1	1	1	2	2	2	2	2	2	2	1	19
2001	1	1	1	1	2	2	2	2	2	2	2	1	19
2002	1	1	1	1	2	2	2	2	2	2	2	0	18
2003	1	1	1	1	2	2	2	2	1	2	2	1	18
2004	1	1	1	1	2	2	2	2	2	2	2	1	19
2005	1	1	1	1	2	2	2	2	2	2	1	1	18
2006	1	1	1	1	1	2	2	2	2	2	1	1	17
2007	1	1	1	1	2	2	2	2	2	2	2	1	18
2008	1	1	1	1	2	2	2	2	2	2	2	1	19
2009	1	1	1	2	2	2	2	2	3	1	2	1	20
2010	1	1	1	0	2	3	2	2	2	2	2	1	19
2011	1	1	1	1	2	3	2	2	2	2	2	1	20
2012	1	1	1	0	3	2	2	2	2	3	2	0	19
2013	1	1	1	1	1	0	0	1	2	1	2	1	12
2014	1	1	1	1	2	3	1	2	3	4	2	1	22
2015	1	1	1	2	3	2	2	4	4	3	1	1	25
2016	1	1	2	2	1	2	4	5	4	4	3	0	29
2017	1	1	0	2	3	4	4	5	4	5	3	1	33

3.1.4. Meteorological Data

Meteorological data were available from multiple sources in the vicinity of Shasta Lake and Keswick Reservoir (Table 8). Meteorological input data, used to calculate heat flux and light intensity in the model, include air temperature (°C), wet bulb temperature (°C), wind speed (m/s), wind direction (degrees), solar radiation (W/m^2) and cloud cover (scale 0.0-1.0). Cloud cover and wet bulb temperature are derived from observed data. Stations KRDD and RRAC1 are in close to each other. Station KRDD supplied air temperature, dew point temperature, and wind speed and direction data. Solar radiation data was collected by station RRAC1 and was used to estimate cloud cover. One meteorology input file was developed for use in both the Shasta Lake and Keswick Reservoir models. Local meteorology at Shasta Lake and Keswick Reservoir at multiple locations throughout the systems were not available. The large spatial extent of Shasta Lake, coupled with the mountainous topography may lead to variable meteorological conditions, particularly local wind field conditions.

Table 8. Available meteorological data and data sources for the Shasta Lake-Keswick Reservoir area.

Site No. / Abbreviation	Agency	Active	Site Name	Data Types	Data Frequency
DLT	CDEC-USGS	YES	Sacramento R at Delta	Tair	Hourly
HRZ	CDEC-Reclamation	YES	HIRZ	Tair, Pr[1]	Hourly
LKS	CDEC-Reclamation	YES	Lakeshore	Tair, Pr[1]	Hourly
SHS	CDEC-Reclamation	YES	Above Shasta Dam	Tair, Pr[1]	Hourly
SHD	CDEC-Reclamation	YES	Below Shasta Dam	Tair, Pr[1]	Hourly
KRDD[2]	MesoWest-WRCC(RAWS)	YES	Redding Municipal (Airport)	Tair, Tdw, Pr, WS, Wdir, RH, SR	Hourly
RRAC1[3]	MesoWest	YES	Redding CA	Tair, Tdw, Twb, WS, Wdir, RH, SR	Hourly
CW5599	MesoWest	YES	C5599 Redding	Tair, Tdw, Pr, WS, Wdir, RH, SR	Hourly
WDLCA	MesoWest	YES	Wonderland (P349) CA	Tair, Tdw, WS, Wdir, RH	Hourly
STDCA	MesoWest	YES	Shasta Dam CA	Tair, Tdw, WS, Wdir, RH	Hourly
SLFC1	MesoWest-WRCC(RAWS)	YES	Sugarloaf (SFC)	Tair, Tdw, Pr, WS, Wdir, RH, SR	Hourly
CTANT	MesoWest	YES	Antlers	Tair, Tdw, Pr, WS, Wdir, RH	Hourly

[1] Precipitation is event (15-min) data.
[2] All meteorological data except SR from this station were used in both models.
[3] SR data from this station were used in both models.
Abbreviations:
Tair: Air temperature, Pr: Precipitation, Tdw: Dewpoint temperature, WS: Wind Speed, Wdir: Wind Direction, RH: Relative Humidity, SR: Solar Radiation

3.2. Data Development – Keswick Reservoir

The following sections describe the data collected for Keswick Reservoir. Geometry data are described first, followed by hydrologic data, meteorological data, and water temperature data. Data sources, as well as other pertinent information, are provided for each type of data.

3.2.1. Geometry Data

Development of geometric data for Keswick Reservoir is discussed in the following sections. Bathymetry data collection is discussed first, followed by the stage-volume relationship for Keswick Reservoir. Lastly, a description of the Keswick Dam outlet facilities is provided.

3.2.1.1. Bathymetry

Information on Keswick Reservoir bathymetry from available literature, previous studies, and other sources is incomplete. Therefore, the Keswick Reservoir temperature modeling effort required the development of a reservoir bathymetry. An in-reservoir bathymetric survey was conducted, and additional bathymetric data were gathered using Google Earth.

From December 17 to December 19, 2016, Glenn-Colusa Irrigation District (GCID), in a collaborative effort with Watercourse Engineering, Inc. (Watercourse) and Reclamation, conducted an in-reservoir bathymetric survey of Keswick Reservoir. The survey involved recording bottom depths (Z) and latitude (x) and longitude (Y) coordinates from a boat. The boat's course followed three longitudinal lines (left bank, right bank, and thalweg) and three transverse lines (alternating from the left and right banks) through the reservoir for bathymetric data collection. Twenty-three individual "paths", i.e., continuous record of bathymetric data, were completed to cover the survey lines mentioned above. Images from Google Earth were used to construct shoreline boundaries and to corroborate water surface elevation. A total of 365,232 X, Y, Z coordinates were collected from the survey of Keswick Reservoir and 6,072 additional X, Y, Z coordinates represent the shoreline and Spring Creek. Details of the methodology used to develop Keswick Reservoir bathymetry are outlined in (Deas and Sogutlugil 2017b). The final bathymetric map is presented in Figure 9.

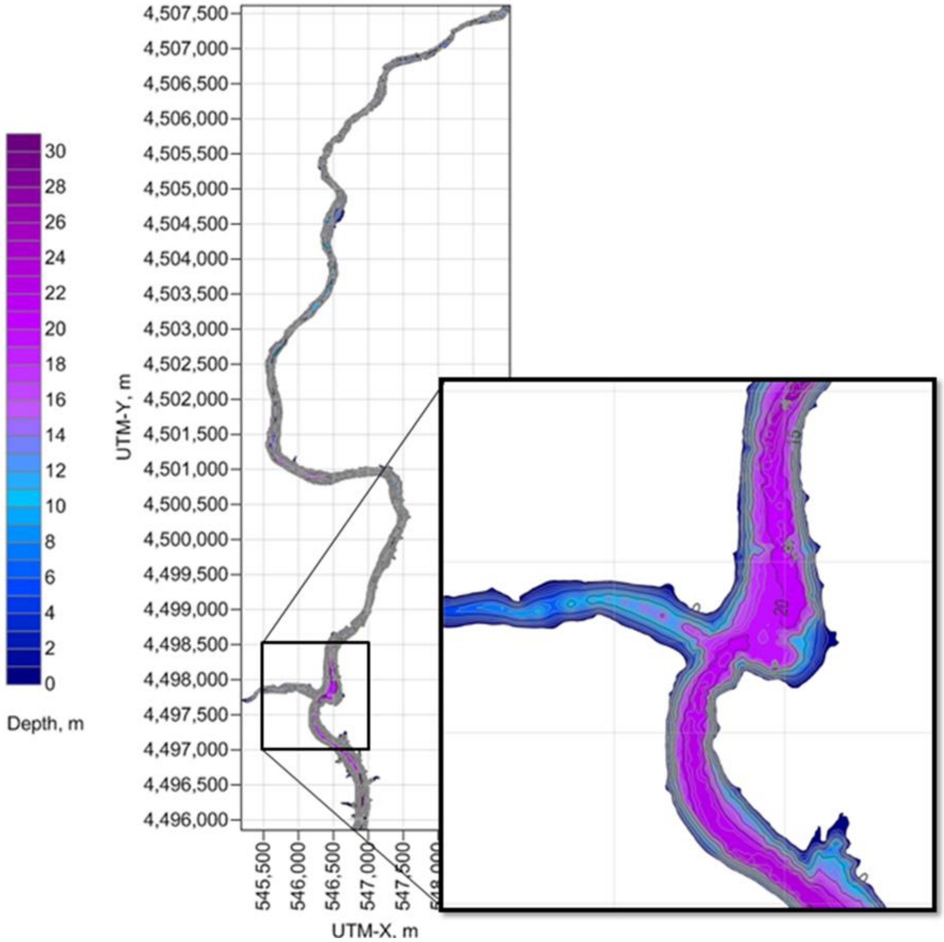

Figure 9. Keswick Reservoir bathymetry. Enlargement provided to show depth contour lines in meters.

3.2.1.2. Stage-Volume Relationship

A stage-volume relationship was developed for Keswick Reservoir from a storage versus elevation data using the measured hourly data from Keswick Reservoir station (KES-Reclamation) in the period from 2000 through 2017 (Source: California Data Exchange Center web page http://cdec.water.ca.gov) (Figure 10).

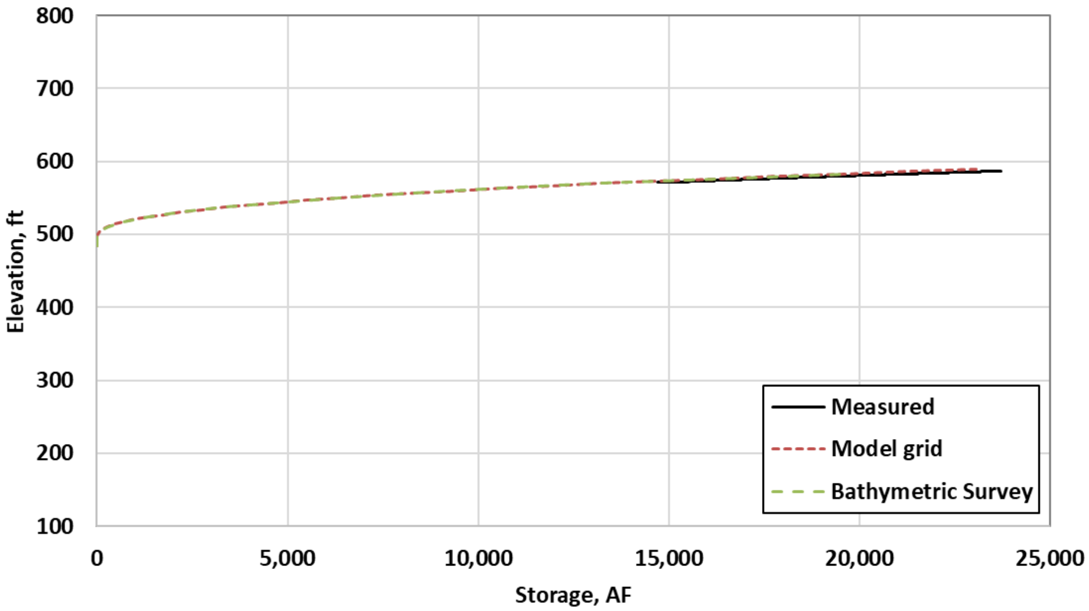

Figure 10. Storage versus elevation curves for Keswick Dam.

3.2.1.3. Keswick Dam Facilities

Keswick Dam is a concrete gravity dam and impounds the Keswick Reservoir, which has a capacity of 23,800 AF (2.936×10^7 m^3) at full pool elevation of 587 ft (178.92 m) (Reclamation 2018). The dam is 157 ft. (47.85 m) high, with crest elevation of 595.5 ft (181.51 m) and has four 50 ft (15.2 m) wide by 50 ft (15.2 m) high spillways (fixed wheel gates) at crest elevation of 537 ft (163.68 m). Keswick power plant has three turbines, with the total capacity of 16,000 cfs (453 cms) at full pool elevation. Top and bottom elevations of powerhouse intakes are listed as 547.25 ft (166.8 m) and 525 ft (160 m), respectively.

3.2.2. Hydrologic Data

Time series flow data are required to implement and test the model. Flow data describes inflows to and outflows from the reservoir. Outflow from Shasta Lake is controlled by Shasta Dam and is the primary source of inflow to Keswick Reservoir. Keswick Reservoir also receives flow from Trinity, Lewiston and Whiskeytown reservoirs via Spring Creek Tunnel. Outflows from Keswick Reservoir are from dam releases and spills. Inflows from precipitation and outflows from evaporation are, however, negligible and omitted, along with any losses or gains to and from the groundwater around the area of interest. In addition, flow data provides information regarding reservoir storage and water surface elevation. Sources for flow data used in the Keswick Reservoir model are listed in Table 9.

Table 9. Sources of flow data used for Keswick Reservoir model, 2010-2016.

Site Number/ Abbreviation	Agency	Site Active	Site Name	Data Types	Data Frequency	Application of Data
SHA	CDEC-Reclamation	YES	Shasta Dam	Q_{out}[1]	Hourly	Headwater Boundary Condition
SPC	CDEC-Reclamation	YES	Spring Creek Debris Dam	Q	Hourly	Tributary Inflow
11371600	USGS	YES	Spring C PH A Keswick CA	Q	Daily – Hourly[2]	Tributary Inflow
KES	CDEC-Reclamation	YES	Keswick Reservoir	Elevation, storage, Q_{out}[1], spill, Q_{ph}[3]	Hourly	Boundary Condition and Calibration

[1] Q_{out} consists of the total flow leaving a structure, as opposed to Q, which represents measured flow at a gage site.

[2] Only daily average Q data are available in the related USGS web page. Hourly Q data were supplied exclusively by Reclamation to Watercourse Engineering, Inc.

[3] Q_{ph} indicates flow from Keswick Reservoir to the powerhouse.

3.2.3. Water Temperature Data

Water temperature data including time series at system inflow and outflow locations, as well as vertical profile data, are required to implement and test the model. Data are used for boundary conditions, initial conditions and for model calibration.

3.2.3.1. System Inflows

During the water temperature management season, the temperature of the water released from Shasta Lake into Keswick Reservoir is controlled by the TCD. Keswick Reservoir also receives flow from Trinity, Lewiston and Whiskeytown reservoirs via Spring Creek Tunnel and Powerhouse. Sources of time series water temperature data for Keswick Reservoir are presented in Table 10.

Table 10. Keswick Reservoir water temperature data sources, 2000-2017.

Site Number/ Abbreviation	Agency	Site Active	Site Name	Data Types	Data Frequency	Application of Data
SHD	CDEC-Reclamation	YES	Shasta Dam Water Quality	Tw	Hourly	Headwater Boundary Condition
SPP	CDEC-Reclamation	YES	Spring Creek Powerhouse	Tw	Hourly	Tributary Inflow
KWK	CDEC-Reclamation	YES	Keswick Water Quality	Tw	Hourly	Calibration

3.2.3.2. Water Temperature Vertical Profiles

In contrast to Shasta Lake, historic measured temperature profiles in Keswick Reservoir for the model years were limited. Only four measurements (one in January, one in March, one in April and one in May) in year 2010 at two different locations in the reservoir were available for calibration purposes. One of the measurement locations mentioned is about 0.3 miles downstream of the Spring Creek confluence point, while the other location is about 0.2 miles upstream of the same confluence point. Additional data for 2017 through 2019 were collected through a collaborative effort by Watercourse and Reclamation, and are described in Section 7, below.

3.2.4. Meteorological Data

Due to the proximity of Shasta Lake and Keswick Reservoir, one meteorological data set was used for both models. Refer to Section 3.1.1 for a description of the types and sources of meteorological data used to construct the meteorological input file.

Project monitoring data for both Shasta Lake and Keswick Reservoir models are shown in Figure 11.

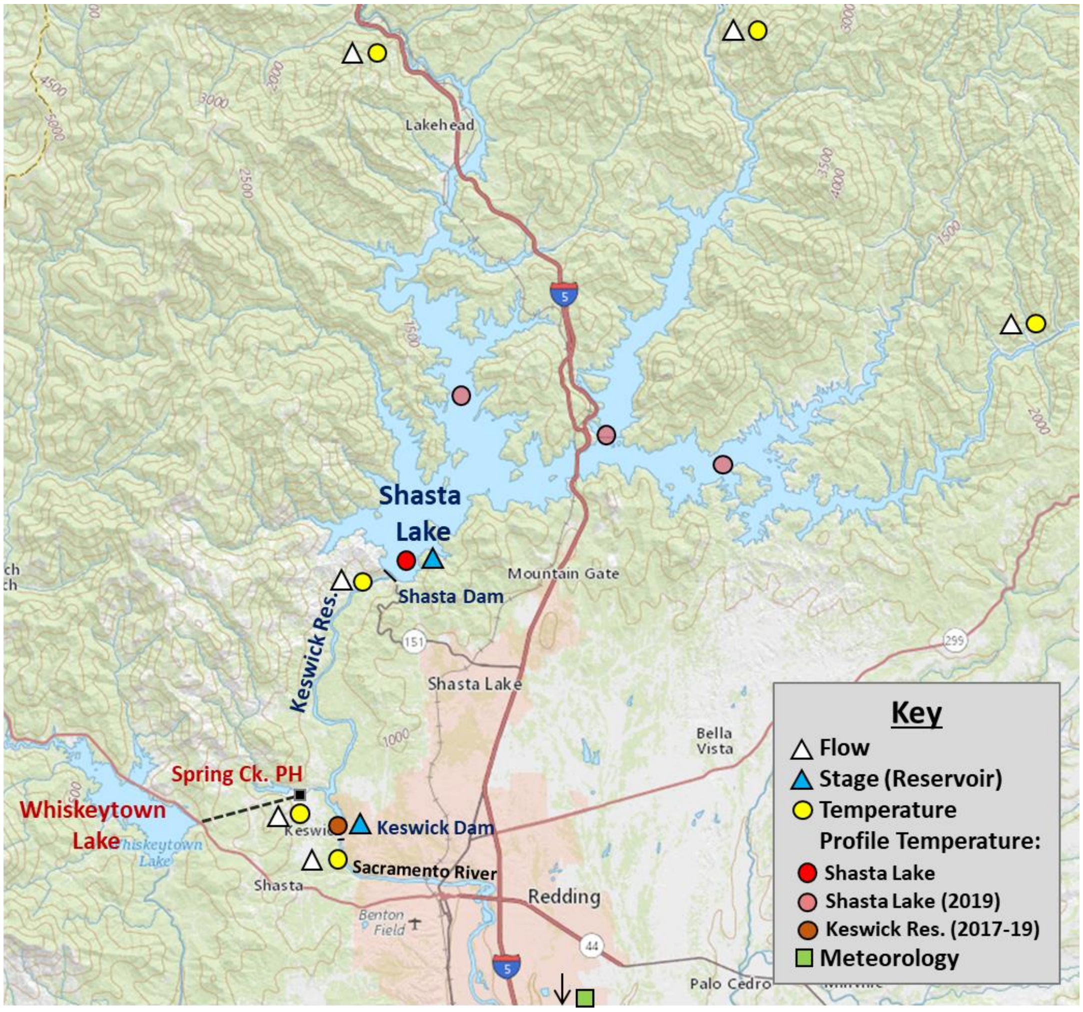

Figure 11. Project monitoring locations for the Shasta Lake and Keswick Reservoir models.

4. Model Development

Model development includes obtaining the model version that meets the project needs/tasks, 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 water temperature boundary conditions for model inflows.

Model grids were developed for Shasta Lake and Keswick Reservoir using the digital X, Y, Z data from the bathymetries. The Shasta Lake model (SLM) grid is composed of five branches representing the Pit River, Squaw Creek, McCloud River, Sacramento River and Big Backbone Creek, respectively. The Keswick Reservoir model (KRM) grid is composed of two branches that include the mainstem Sacramento River and Spring Creek arm.

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. The CE-QUAL-W2 model requires flow and water temperature boundary conditions for each inflow and outflow in the modeled system.

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. Model implementation steps are described below for Shasta Lake, then for Keswick Reservoir.

4.1. Shasta Lake Model (SLM)

Shasta Lake model development is described in the following sections including development of the model grid, a discussion of the flow and water temperature boundary conditions, and a description of initial conditions used in the model.

4.1.1. 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 (Figure 8) 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 11.

Table 11. Model grid branches and segments for Shasta Lake.

Branch name (no.)	Number of Segments	Total Length ft (m)]	Segment Length Average ft (m)	Segment Length Minimum ft (m)	Segment Length Maximum 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)

Layer thickness throughout the model domain was set at 3.28 ft (1 m).

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. The plan views of the Shasta Lake model domain are included in Figure 12 and Figure 13. 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 11.

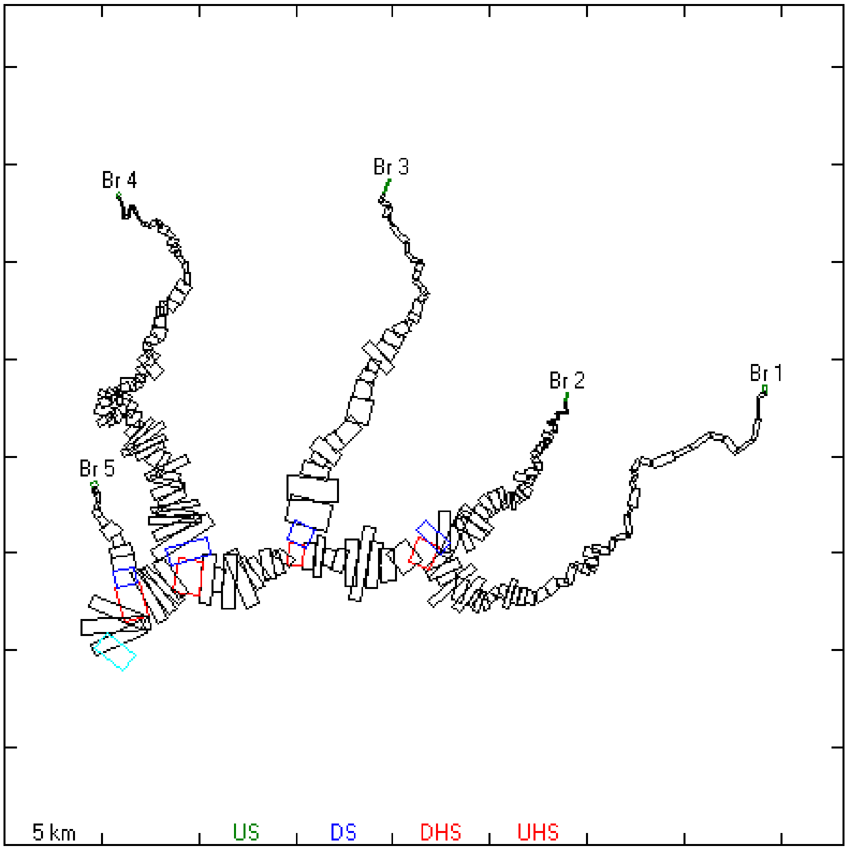

Figure 12. Shasta Lake model grid (plan view). The furthest upstream segments of each branch are shown in green; terminal downstream segments of Branches 2 through 5 are blue; "connection" segments for the tributaries to the main branch are red; and furthest downstream segment of the entire model grid, just above Shasta Dam, is cyan.

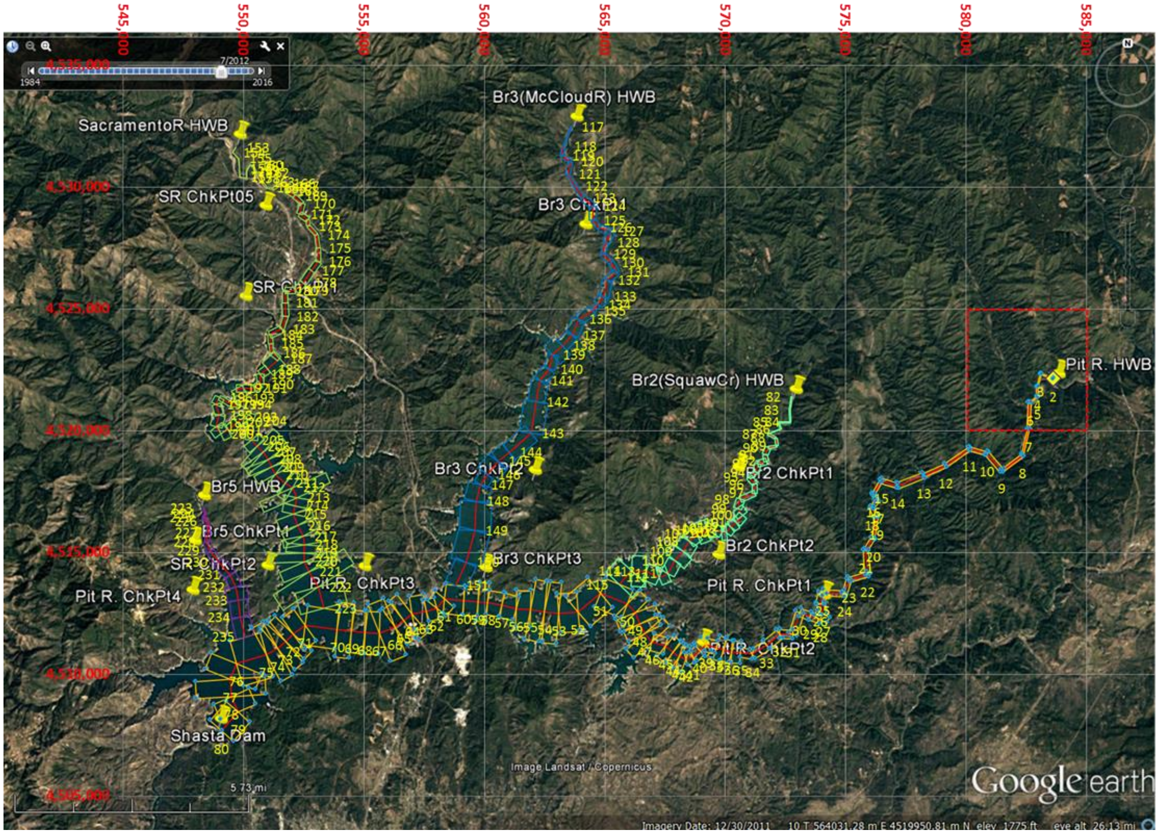

Figure 13. Shasta Lake model grid (plan view) embedded in Google Earth image. Segment numbers are indicated in yellow.

4.1.2. Boundary Conditions

The CE-QUAL-W2 model requires an inflow boundary condition time series for each model branch, tributary inflow, and outflow location.

4.1.2.1. Flow Boundary Conditions

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

Inflow boundary conditions – Historical hourly flow data were acquired from USGS, CDEC and Reclamation sources for the Pit, McCloud, and Sacramento rivers from 2000 through 2017. 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[7] for dry, normal, and wet years, which were then used to construct flow data files for Squaw Creek from 2000 to 2017. Flow data were

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[7] Squaw Creek data (USGS 11365500) were available from 1944 to 1966 and Sacramento River data (USGS 11342000) for the same period were used to develop the following regression equations relating Sacramento River daily flow (Q_{sac}) to Squaw Creek daily flow (Q_{squaw}): $Q_{squaw(dry)} = 0.022912Q_{sac}^{1.266539}$ ($r^2 = 0.879650$), $Q_{squaw(normal)} = 0.018757Q_{sac}^{1.287450}$ ($r^2 = 0.877481$), $Q_{squaw(wet)} = 0.024284Q_{sac}^{1.238937}$ ($r^2 = 0.850436$). Hydrologic year type was based on the Squaw Creek long term mean flow, with the dry, normal, and wet represented by the lower, middle, and upper thirds of the ranked data, respectively.

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 each of the five branches in the Shasta Lake model for each year from 2000 through 2017.

Distributed tributary inflow/outflow – Distributed inflow and outflow account for ungaged inflows to Shasta Lake from small tributaries, ungagged 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 tributary flow was applied to the Pit River arm (Branch 1 of the model grid)[8].

Outflow – Hourly outflow data from Shasta Dam were available from Reclamation and CDEC. The outflow file for the Shasta Lake model includes hourly spill, TCD (upper, middle, lower and side gate) and river outlet (upper, middle, and lower) release data.

4.1.2.2. Water Temperature Boundary Conditions

Water temperature boundary conditions in Shasta Lake 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 2017. 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 2017 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 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.

4.1.3. Initial Conditions

For Shasta Lake, there were both measured profile temperatures and temperature string data. 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

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[8] Sensitivity was carried out on this action, by applying 100 percent of the distributed outflow to the Sacramento River arm and 100 percent of the outflow to the Pit River arm. With little difference in simulated output.

condition. Initial reservoir stages were set to January 1st 00:00 measured values for the year of interest.

4.2. Keswick Reservoir

Keswick Reservoir model development is described in the following sections. Development of the model grid is presented, followed by a discussion of flow and water temperature boundary conditions, and a description of model initial conditions used.

4.2.1. Model Grid

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 (Figure 10) to define the segment and layer geometry. The branches consist of segments linked together in the direction of flow (Figure 14 and Figure 15). The number of segments, total branch lengths, average segment lengths, and minimum and maximum segment lengths for each branch are listed in Table 12.

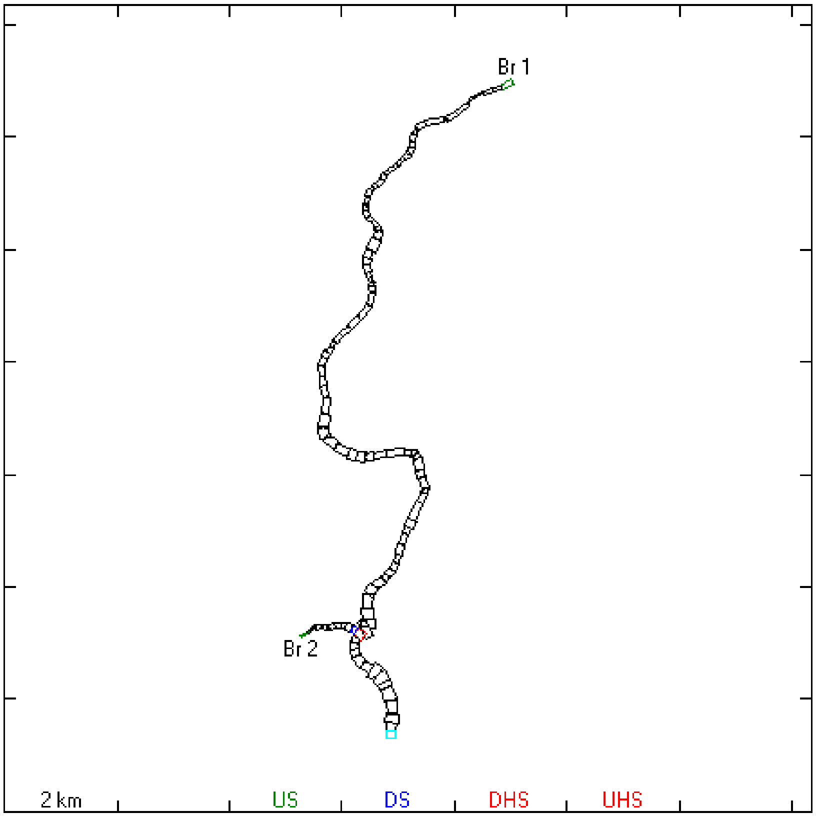
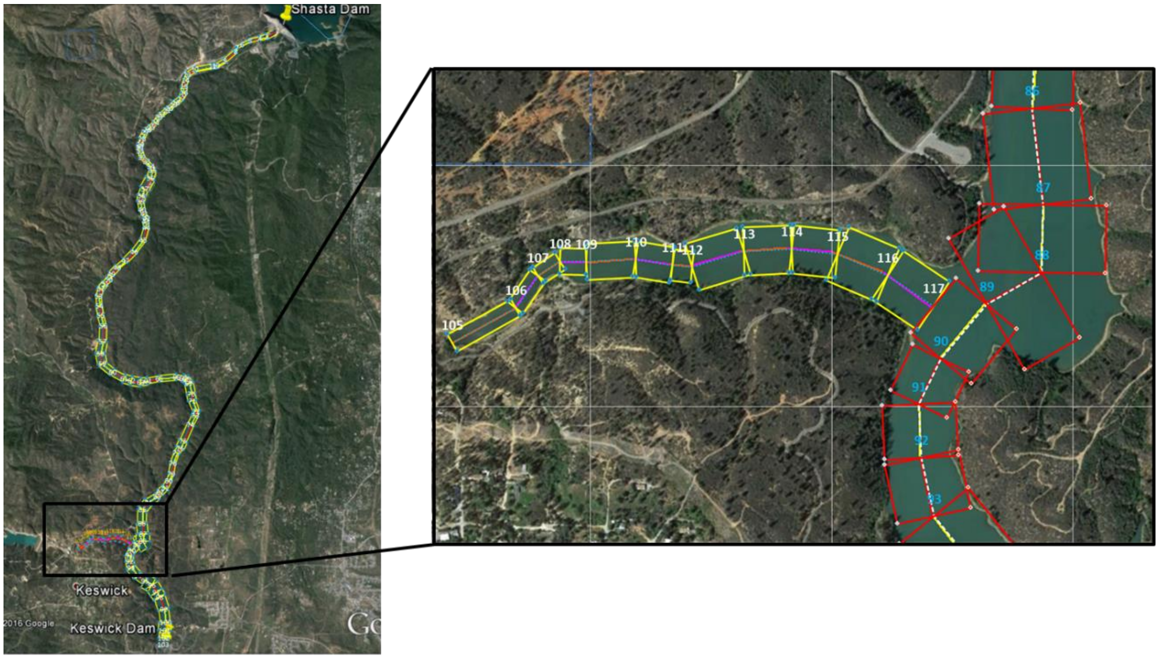


Figure 14. Keswick Reservoir model grid (plan view). Upstream-most segments and downstream-most segments of each branch are green and navy, respectively; "connection" segment for the Spring Creek arm to the main branch is red; and the last active segment in the entire model grid (above Keswick Dam) is cyan.



(a) (b)

Figure 15. Keswick Reservoir model grid (plan view) embedded in GE image for (a) Keswick Reservoir from Shasta Dam to Keswick Dam, and (b) Spring Creek branch (yellow) connection to main branch of Keswick Reservoir (red). Main branch segment numbers are shown blue and Spring Creek branch segment numbers are indicated in white.

Table 12. Model grid branches and segments for Keswick Reservoir.

Branch name (no.)	Number of Segments	Total Length ft (m)	Segment Length		
			Average ft (m)	Minimum ft (m)	Maximum ft (m)
Keswick Reservoir (1)	101	51,823 (15,796)	513 (156)	163 (50)	1,132 (345)
Spring Creek arm (2)	12	3,512 (1,071)	293 (89)	137 (42)	492 (150)
Layer thickness throughout the model domain was set at 3.28 ft (1 m).					

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 (2017). 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 12.

4.2.2. Boundary Conditions

The CE-QUAL-W2 model requires flow and water temperature boundary conditions where there are inflows and outflows in the system. These conditions are applied at each time step. Flow and temperature boundary conditions developed for this model are discussed in the following section.

4.2.2.1. Flow Boundary Conditions

Flow boundary conditions for Keswick Reservoir include inflow from Shasta Dam and Spring Creek, ungaged flow into and out of Keswick Reservoir known as the distributed tributary inflow and outflow, and outflow from Keswick Dam.

Inflow boundary conditions **–**The hourly outflow data from Shasta Dam (see Section 4.1.2.1) 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 tributary flow was applied to the main branch (Branch 1).

Outflow **–** Hourly outflow data from Keswick Dam, which includes the dam spill and powerhouse outflow were available from Reclamation and CDEC.

4.2.2.1. Water Temperature Boundary Conditions

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 main branch (Branch 1) of the model grid. For the purposes of this model, the water temperature of the distributed inflow is assumed to be the same as Keswick Reservoir inflow water temperature.

Measured temperature data for Reclamation stations SHD and SPP exhibited variations suggesting that 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.

4.2.3. Initial Conditions

Reservoir profiles for January 1st were unavailable for Keswick Reservoir. An initial reservoir water temperature was set to 11.0°C (51.8°F) and isothermal conditions were assumed. These conditions represent an estimated winter condition based on Keswick Reservoir profile data from January 1, 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.

5. Shasta Dam Temperature Control Device: Model Representation

Representing the TCD in CE-QUAL-W2 required consideration of several factors unique to the facility as well as considering 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 these four topics is addressed below.

5.1. Temperature Control Device Leakage

Implementing TCD leakage into CE-QUAL-W2 required identifying known leakage "zones" and representing a vertical distribution of leakage in a format amenable to existing model input formats. Available information related to TCD leakage was initially investigated. Subsequently, this information was used to develop a model representation of leakage. Sensitivity analysis using the completed model was used to assess different model representations and the impact on simulated release temperatures from Shasta Dam.

5.1.1. TCD Leakage

Leakage into the TCD structure is due to design features, fabrication challenges, and possibly missing/fallen panels from the gates. The TCD was not intended to be a watertight facility. Having some leakage reduced the risk of damage to the facility under extreme hydraulic conditions. The pressure relief gates (PRG) at the lower gates are intended to open if a certain negative pressure is achieved inside the TCD. Further, leakage at certain locations on the TCD associated with facility construction has been recognized since the early days of the structure operations (Reclamation 1999). Leaking areas have been identified along major fabrication seams, and on the front, sides, and bottom of the TCD. Finally, several missing TCD gate panels were identified in 2009 (Figure 16), leading to a major repair in January of 2010 (Randi Field (Reclamation), personal communication).

For this study, the model representation of the TCD leakage distribution adopts the leakage areas defined/represented in the FLOW-3D[9] computational fluid dynamics (CFD) modeling study of the Shasta TCD (Reclamation 1999) (Table 13) for the model years from 2000 through 2009. For the rest of the model period from 2010 through 2017, the leakages through the middle gates were assumed to no longer occur as a result of the TCD repair mentioned above. The relative total leakage percentages for the rest of the TCD were recalculated accordingly.

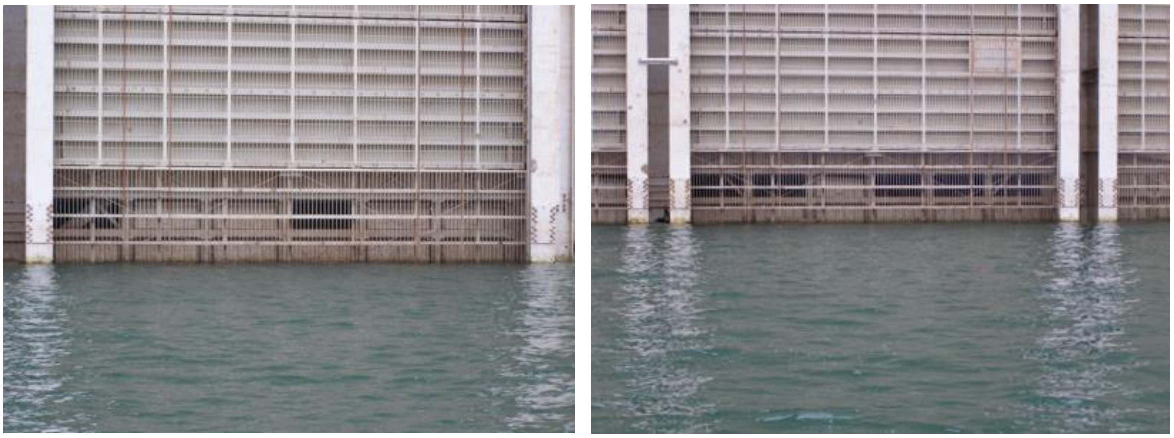


Figure 16. Missing panels on middle gates #1 (left) and #4 (right), photograph date: November 17, 2009. (Source: Field, Randi, U.S. Bureau of Reclamation. "Fwd: TCD MG Missing Panel Areas." Message to Mike Deas. 12 March 2018. Email)

When the powerhouse is operational, leakage enters the TCD and operators have limited ability to control this influx of water. TCD leakage presents considerable challenges to temperature control operations. Early in the temperature control season, leakage from near the bottom of the TCD entrains cold water that ideally would be preserved for later in the season. Conversely, late season temperature control activities must account for warmer than desired surface water entering the TCD via leakage zones in the reservoir epilimnion. Only those zones below the water surface are treated as active inflows to the TCD during model simulation. Leakage zones that daylight (i.e., are above the lake surface) are set to zero in the model until water levels rise sufficiently to inundate them once again. Leakage zones for each side and upstream face of the TCD as defined by Reclamation (1999) were adopted for this project (Table 14).

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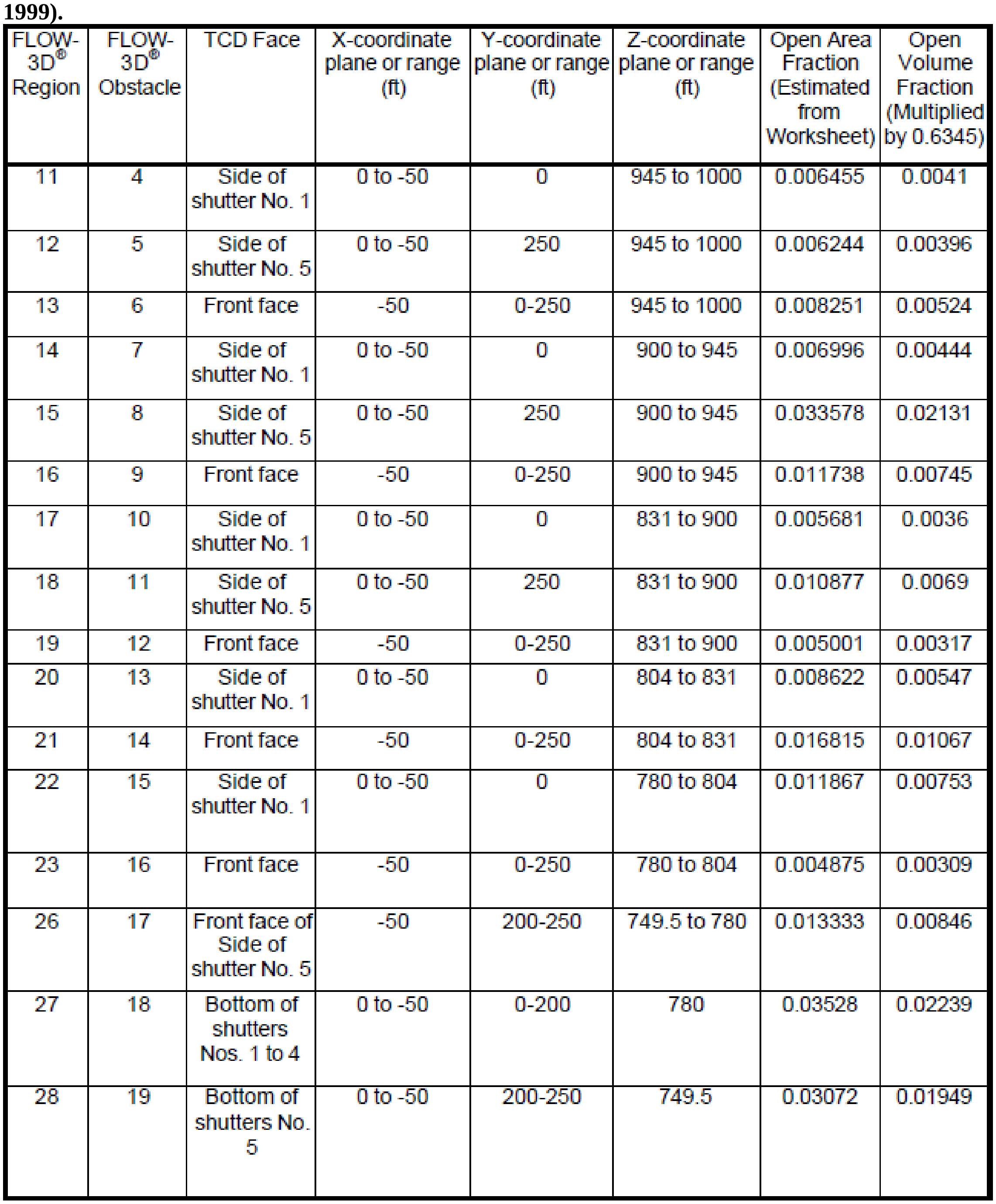
[9] Flow-3D by Flow Science is a finite difference, free surface, transient flow modeling system based on the Navier-Stokes equations using up to three spatial dimensions.

Table 13. Locations and sizes of leakage areas in the TCD structure (Table 4 from Reclamation 1999).



FLOW-3D® Region	FLOW-3D® Obstacle	TCD Face	X-coordinate plane or range (ft)	Y-coordinate plane or range (ft)	Z-coordinate plane or range (ft)	Open Area Fraction (Estimated from Worksheet)	Open Volume Fraction (Multiplied by 0.6345)
11	4	Side of shutter No. 1	0 to -50	0	945 to 1000	0.006455	0.0041
12	5	Side of shutter No. 5	0 to -50	250	945 to 1000	0.006244	0.00396
13	6	Front face	-50	0-250	945 to 1000	0.008251	0.00524
14	7	Side of shutter No. 1	0 to -50	0	900 to 945	0.006996	0.00444
15	8	Side of shutter No. 5	0 to -50	250	900 to 945	0.033578	0.02131
16	9	Front face	-50	0-250	900 to 945	0.011738	0.00745
17	10	Side of shutter No. 1	0 to -50	0	831 to 900	0.005681	0.0036
18	11	Side of shutter No. 5	0 to -50	250	831 to 900	0.010877	0.0069
19	12	Front face	-50	0-250	831 to 900	0.005001	0.00317
20	13	Side of shutter No. 1	0 to -50	0	804 to 831	0.008622	0.00547
21	14	Front face	-50	0-250	804 to 831	0.016815	0.01067
22	15	Side of shutter No. 1	0 to -50	0	780 to 804	0.011867	0.00753
23	16	Front face	-50	0-250	780 to 804	0.004875	0.00309
26	17	Front face of Side of shutter No. 5	-50	200-250	749.5 to 780	0.013333	0.00846
27	18	Bottom of shutters Nos. 1 to 4	0 to -50	0-200	780	0.03528	0.02239
28	19	Bottom of shutters No. 5	0 to -50	200-250	749.5	0.03072	0.01949

Notes:

- FLOW-3D is the computational fluid dynamics model used to assess the TCD in Reclamation (1999). Model results are presented by regions that represent the sides and front face of the TCD for specific elevation, as well as the bottom of the TCD (regions 27 and 28). Shutter 1 (gate opening 1) is the landward edge of the TCD and shutter 5 is closes to the centerline of the dam.
- Individual gate openings at specific gate levels (e.g., upper, middle, lower) used in this report are equivalent to “shutters” in Reclamation (1999).
- For details of the table, the reader is referred to Reclamation (1999).

Table 14. Leakage zone elevation ranges (Reclamation 1999).

Leakage Zone	Elevation Range (Z-coordinate plane/range in Table 13)
Zone 1	945 ft to 1,000 ft (288.0 m to 304.8 m)
Zone 2	900 ft to 945 ft (274.3 m to 288.0 m)
Zone 3	831 ft to 900 ft (253.3 m to 274.3 m)
Zone 4	804 ft to 831 ft (245.1 m to 253.3 m)
Zone 5	780 ft to 804 ft (237.7 m to 245.1 m)
Zone 6	749.5 ft to 780ft (228.5 m to 237.7 m)
Bottom 7[1]	780 ft (237.7 m)
Bottom 8[1]	749.5 ft (228.5 m)

[1] Zone Bottom 7 and Bottom 8 are leakage through the bottom of the TCD and are assigned a single elevation versus a range.

The open area fraction values (Table 13) were multiplied by the corresponding panel areas for the sides and face of the TCD to calculate the percentages of each open/leakage area as a function of total TCD leakage for designated vertical leakage zones (Table 15). Subsequently, the sides and upstream face of the TCD are combined for each leakage zone (Table 14) into a single leakage fraction. As noted previously, repair of the middle gate panels resulted in a different distribution of leakage post 2010 (i.e., 2010 to 2017). The TCD leakage model representation for years 2000 to 2009 is shown in Table 16. Note that the leakage area/percentage is directly proportional to the number of closed/inactive gates on the upstream face of the TCD in certain cases. When an individual TCD gate is open, no leakage is assumed to occur through the open gate.

The TCD leakage distribution shown in Table 15 does not assign leakage above elevation 1,000 ft (304.8 m), consistent with Reclamation (1999). Leakage is assumed to occur between the elevations of 1,000 ft (304.8) and 749.5 ft (228.5) (the bottom of the TCD) and is not affected by TCD upper gate operations. However, leakage through closed middle or lower levels, or low-level intake may be affected by TCD operations (indicated by an asterisk (*) in Table 15). When any gate is open at the middle level, leakage associated with that leakage zone is set to zero because the head loss through the large gate opening is assumed far less than leakage passing through the TCD structure. The same assumption is made for the lower level gates. The low-level intake (side gates) differs from the middle and lower levels in that (a) they are located on the side of the TCD and (b) there are two side gates versus five gates at each of the middle and lower levels. Because the top of the low-level intake structure (and side gate) extends well above the lower level (nearly up to the middle level), leakage associated with the side gates (when closed) are assigned to zone 3.

Total TCD leakage amount at any given time is

$$TL = X*Q_{out} \qquad \text{(Eq. 1)}$$

Where:

TL: total TCD leakage (cfs)

X: fraction of the total outflow through the TCD when the water surface (WS) elevation is equal to or above 1,000 ft and all of the TCD gates below 1,000 ft (304.8 m) are closed.

Q_{out}: total TCD outflow

Total leakage Eq. 1) has not been explicitly measured. However, the current HEC-5Q model of Shasta Lake (RMA, 2003) estimated a leakage fraction of approximately 0.2 (e.g., 20 percent). This fraction translates to 20 percent of all water (at full pool) passing through the TCD is due to leakage, and 80 percent is subject to temperature control management through the various gates. Using hourly measured outflow water temperature for the 2000 and 2017 period and several model simulations assessing various leakage fractions and distributions, leakage assumptions were assigned as per Table 15 using a 20 percent total leakage fraction. The TCD leakage model representation for years 2010-17 is shown in Table 17. A comparison of the leakage distribution for the 2000-2009 period and the 2010-2017 period is shown in Figure 17.

5.1.2. Model Representation

CE-QUAL-W2 is a laterally averaged, two-dimensional model, representing longitudinal and vertical temperature gradients in Shasta Lake. Outlet structures can be representing in two ways in the model: a line sink or a point sink. 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) of the width of Shasta Dam: 2,750 ft (838.2 m). Nonetheless, each leakage zone was represented as line sink type outlet structures with a width of 250 ft (76.2 m) and a vertical placement equal to the assigned elevation in Table 16 and Table 17. Four of the six center elevations listed for the leakage zones were shifted slightly upward or downward considering the vertical layer thickness selected for the Shasta Lake model (3.28 ft) and the center elevations of the other outlet structures, i.e., TCD and river release outlet structures, which are also represented in the model (Table 14). All leakage outlet elevations are located at the bottom of each zone, thus remaining active throughout the entire of the zone. Ultimately, each outlet structure was placed in a discrete layer in the model such that any layer in the model grid had no more than one outlet structure.

Table 15. Information used to develop leakage zones and associated elevations and relative percentages of TCD leakage (Percent Total Leakage).

TCD Face	X-length (ft)	Y-length (ft)	Z-length (ft)	Elevation (ft)	Leakage Zone	Area (ft^2)	Open Area Fraction	Leakage Area (ft^2)	Percent Total Leakage
Side of shutter[1] No.1	50	-	55	945 to 1,000	1	2,750	0.006455	17.75	1.57
Side of shutter[1] No.5	50	-	55	945 to 1,000	1	2,750	0.006244	17.17	1.51
Front face[2]	-	250	55	945 to 1,000	1	13,750	0.008251	113.45	10.01
Side of shutter No.1	50	-	45	900 to 945	2	2,250	0.006996	15.74	1.39
Side of shutter No.5	50	-	45	900 to 945	2	2,250	0.033578	75.55	6.66
Front face[2]	-	250	45	900 to 945	2	11,250	0.011738	132.05	11.65*
Side of shutter No.1	50	-	69	831 to 900	3	3,450	0.005681	19.60	1.73
Side of shutter No.5	50	-	69	831 to 900	3	3,450	0.010877	37.53	3.31*
Front face[2]	-	250	69	831 to 900	3	17,250	0.005001	86.27	7.61
Side of shutter No.1	50	-	27	804 to 831	4	1,350	0.008622	11.64	1.03
Front face[2]	-	250	27	804 to 831	4	6,750	0.016815	113.50	10.01*
Side of shutter No.1	50	-	24	780 to 804	5	1,200	0.011867	14.24	1.26
Front face[2]	-	250	24	780 to 804	5	6,000	0.004875	29.25	2.58
Front face of Side of Shutter No.5	-	50	30.5	749.5 to 780	6	1,525	0.013333	20.33	1.79
Bottom of shutters Nos.1 to 4	50	200	-	780	Bottom1	10,000	0.035280	352.80	31.12
Bottom of shutter No.5	50	50	-	749.5	Bottom2	2,500	0.030720	76.80	6.77
								∑= 1,133.67	∑= 100.00

[1] Individual gate openings at particular gate levels (e.g., upper, middle, lower) are used in this report are equivalent to "shutters" in in Reclamation (1999).

[2] Leakage area/percentage is directly proportional to the number of closed/inactive gates on the TCD front face.

Table 16. TCD leakage model representation: 2000-2009.

2000-2009		**Water Surface Elevation Ranges (WS)[1] (ft)**			
		≥1,000	1,000>WS≥945	945>WS≥900	900>WS≥831
		Total Leakage (TL) Fraction[2,3] (TL/Q_{out})			
		X	X-(X*13.09/100)*(1-(WS-945)/(1,000-945))	X-(X*13.09/100)-(X*19.70/100)*(1-(WS-900)/(945-900))	X-(X*13.09/100)-(X*19.70/100)-(X*12.65/100)*(1-(WS-831)/(900-831))
Zone	**Assigned Elevation (ft)**	**Total Leakage Fraction Relative Percentage (%)**			
Zone 1	945	13.09	13.09*((WS-945)/(1,000-945))	0	0
Zone 2	900	8.05+(# closed TCDM/5)*11.65	8.05+(# closed TCDM/5)*11.65	(8.05+(# closed TCDM/5)*11.65)*((WS-900)/(945-900))	0
Zone 3	831	9.34+(# closed TCDS/2)*3.31	9.34+(# closed TCDS/2)*3.31	9.34+(# closed TCDS/2)*3.31	(9.34+(# closed TCDS/2)*3.31) *((WS-831)/(900-831))
Zone 4	804	1.03+(# closed TCDL/5)*10.01	1.03+(# closed TCDL/5)*10.01	1.03+(# closed TCDL/5)*10.01	1.03+(# closed TCDL/5)*10.01
Zone 5	780	3.84	3.84	3.84	3.84
Zone 6	749.5	1.79	1.79	1.79	1.79
Bottom 7[4]	780	31.12	31.12	31.12	31.12
Bottom 8[4]	749.5	6.77	6.77	6.77	6.77

1 Four WS elevation ranges were considered because the minimum WS elevation recorded during the modeling period is greater than 889.45 ft (11/27/2014, 19:00), notably higher than the lowest end of the selected ranges (831 ft)

2 Theoretical Leakage with all TCD gates closed. During operation with gates open, the values in this column will decrease accordingly.

3 Qout: total outflow from the TCD to the powerhouse.

4 The assigned elevation of Zone 5 and Bottom 7 are equivalent and are added together. Similar for Zone 6 and Bottom 8.

Table 17. TCD leakage model representation: 2010-2017.

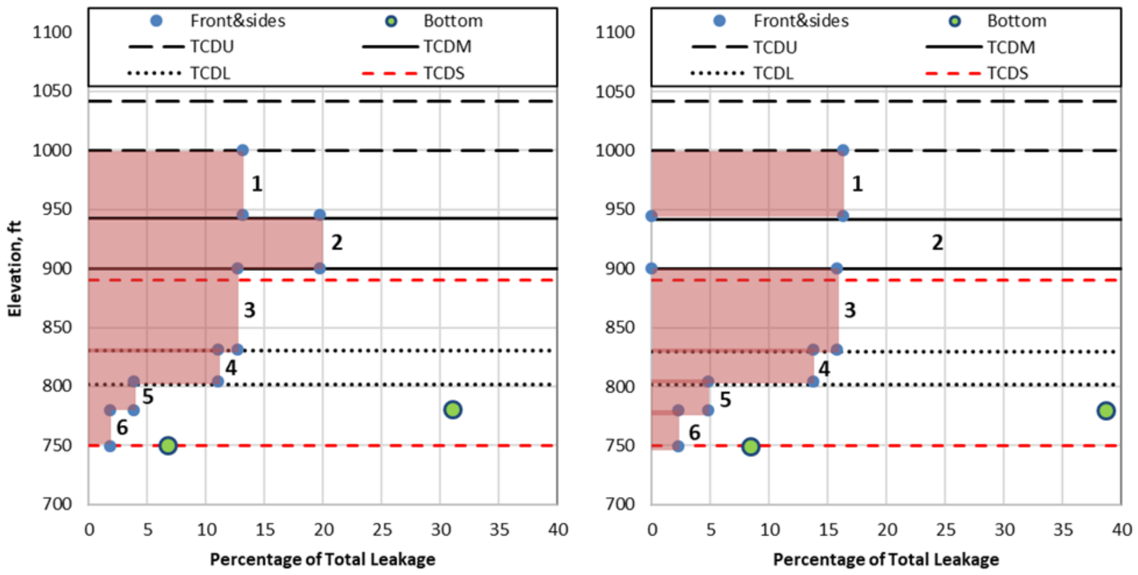
2010-2017		**Water Surface (WS) Elevation Ranges[1] (ft)**			
		≥1,000	1,000>WS≥945	945>WS≥900	900>WS≥831
		Total Leakage (TL) Fraction[2,3] (TL/Q_{out})			
		X	X-(X*16.30/100)*(1-(WS-945)/(1,000-945))	X-(X*16.30/100)-(X*0.00/100)*(1-(WS-900)/(945-900)	X-(X*16.30/100)-(X*0.00/100)-(X*15.75/100)*(1-(WS-831)/(900-831))
Zone	**Assigned Elevation (ft)**	**Total Leakage Fraction Relative Percentage (%)**			
Zone 1	945	16.3	16.30*((WS-945)/(1,000-945))	0	0
Zone 2	900	0	0	0	0
Zone 3	831	11.63+(# closed TCDS/2)*4.12	11.63+(# closed TCDS/2)*4.12	11.63+(# closed TCDS/2)*4.12	11.63+(# closed TCDS/2)*4.12)*((WS-831)/(900-831))
Zone 4	804	1.28+(# closed TCDL/5)*12.47	1.28+(# closed TCDL/5)*12.47	1.28+(# closed TCDL/5)*12.47	1.28+(# closed TCDL/5)*12.47
Zone 5	780	4.78	4.78	4.78	4.78
Zone 6	749.5	2.23	2.23	2.23	2.23
Bottom 7[4]	780	38.76	38.76	38.76	38.76
Bottom 8[4]	749.5	8.44	8.44	8.44	8.44

[1] Four WS elevation ranges were considered because the minimum WS elevation recorded during the modeling period is greater than 889.45 ft (11/27/2014, 19:00), notably higher than the lowest end of the selected ranges (831 ft)

[2] Theoretical Leakage with all TCD gates closed. During operation with gates open, the values in this column will decrease accordingly.

[3] Qout: total outflow from the TCD to the powerhouse.

[4] The assigned elevation of Zone 5 and Bottom 7 are equivalent and are added together. Similar for Zone 6 and Bottom 8.



(a) (b)

Figure 17. TCD percent of total leakage for TCD leakage zones. Bottom and top elevations of TCD gate levels for (a) 2000-2009 and (b) 2010-2017.

An example of the model representation of the Shasta Dam TCD leakage dynamics is shown in Figure 18. The top graph in the figure depicts the various TCD gage levels (upper, middle, lower, low-level intake) and the number of gates[10] operating at each level throughout the year, illustrating blending waters from different levels within the reservoir (e.g., two levels) and changes in number of individual gate openings at a single level throughout time. The middle graph shows the maximum total leakage possible (as a percent of total TCD flow to the Shasta Powerhouse), and the actual leakage calculated based on Table 16. Calculated leakage will always be less than or equal to the maximum possible leakage. Note that the maximum possible leakage changes through time in response to reservoir stage (bottom graph) – as reservoir stage decreases through the summer and fall, leakage is reduced because an ever-increasing portion of the TCD is above the lake water surface.

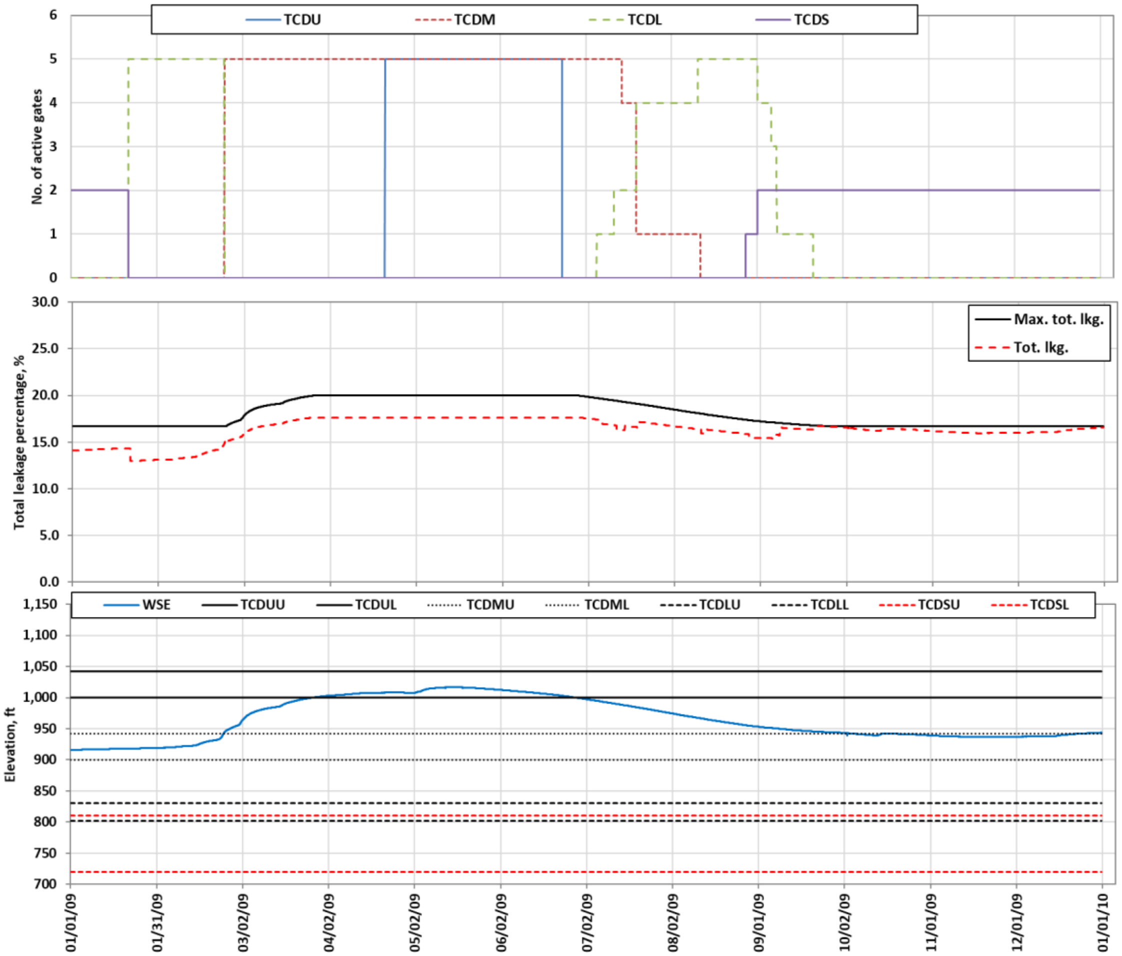


Figure 18. TCD leakage illustration showing active TCD gates (top), maximum total leakage and calculated total leakage (middle), and water surface elevation and TCD gate locations (bottom) for 2009.

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[10] For the upper, middle and lower levels, zero to five gates openings may be used at each level, while for the side gate, zero to two gates may be used.

5.1.3. Leakage Distribution Assessment

Because leakage has not been formally quantified through field measurements, and there were different model formulations (Reclamation 1999, RMA 2003), several model simulations were performed to assess model the implications of assumed TCD total leakage amount (fraction) and vertical distribution throughout selected years.

First, a simulation was completed wherein leakage was removed from the model while maintaining historic TCD operations. The result was slightly warmer simulated temperatures in spring and cooler temperatures in the fall. This outcome illustrated that during spring, when releases were from the upper levels of the TCD, leakage entered the TCD at low levels and contributed cold waters. In the fall, the inverse occurred: releases from the lower levels were impacted by warmer waters entering the TCD closer to the water surface. This result indicated that including leakage in the TCD was an important component in reproducing historic temperatures. Daniels *et al.* (2018) also explored the effect of leakage at different times of year.

Subsequently, to assess the impact of vertical distribution of leakage and total leakage volume, 2013, 2014, and 2015 were simulated under different leakage assumptions. 2013 simulations assessed total leakage amount and vertical distribution, and simulations in 2014 and 2015 assessed for total leakage amount.

Total TCD leakage fraction was set to 0.2 (20 percent of the total TCD outflow to the powerhouse). TCD leakage distribution for the baseline condition (run a) is based on historical conditions, as identified in Figure 17 and Table 17. Three simulations were completed and compared to the baseline (Run_a: historical conditions). Run_b represents a reduced leakage fraction of 0.15 (versus 0.20) for 2013, 2014, and 2015. Run_c and Run_d represent distributions where leakages are increased at shallower depths and at deeper depths, respectively, and were simulated for 2013 (Table 18). All other model assumptions remained unchanged.

Table 18. TCD leakage features modified for scenario assessment.

Scenario	Leakage Distribution	Maximum Total Leakage Fraction	Year(s) Simulated
Run_a (baseline)[1]	Baseline[2]	0.20	2013, 2014, 2015
Run_b[1]	Baseline[2]	0.15	2013, 2014, 2015
Run_c[3]	15 percent was added to the baseline (historic) relative percent (BRP) of Zone 1[4] when water surface elevation was above 945 ft (288.0 m) 15 percent was subtracted from the BRP of Zone 5.	0.15	2013
Run_d[3]	0.25 of the BRP was assigned to Zone 1 0.75 of the BRP of Zone 1 was added to the BRP of Zone 6	0.15	2013

1 Performed for years 2013, 2014 and 2015
2 See Table 17
3 Performed for year 2013
4 See Figure 17 and Table 17

Shasta Dam outflow temperature results of the three runs with different leakage distributions and total leakage fraction than baseline were insensitive to the changes within the tested ranges for 2013 (Figure 19). Findings were similar for different total leakage fractions in 2014 and 2015 (Figure 20, Figure 21, respectively). Overall, TCD leakage is an important component in the Shasta Lake model. While generally insensitive to total fraction and distribution, correct representation should be pursued through additional data collection and subsequent analysis. A more comprehensive description of the analysis and additional results are included in Appendix A.

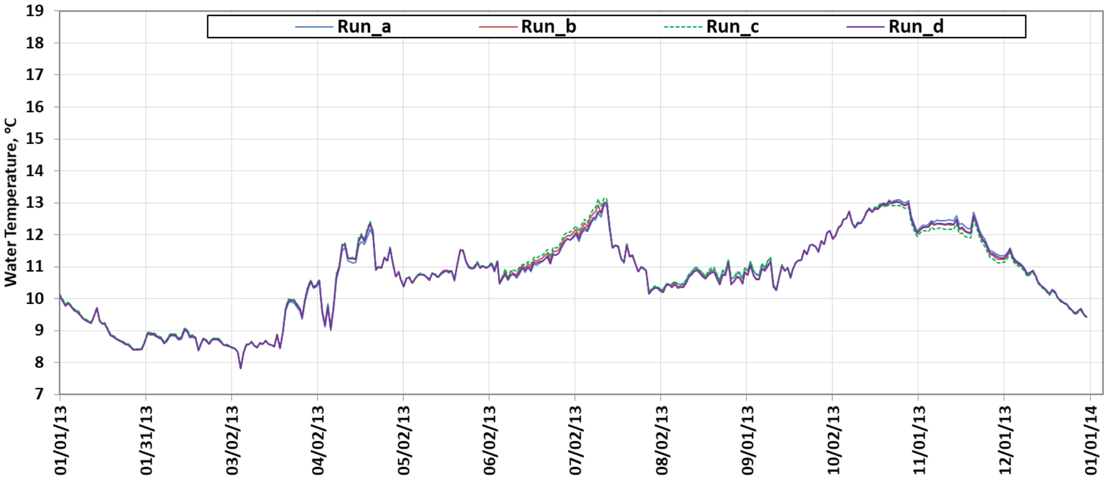


Figure 19. Simulated Shasta Dam release temperatures for baseline conditions (Run_a) and varying leakage distributions (Run_b, Run_c, Run_d): year 2013.

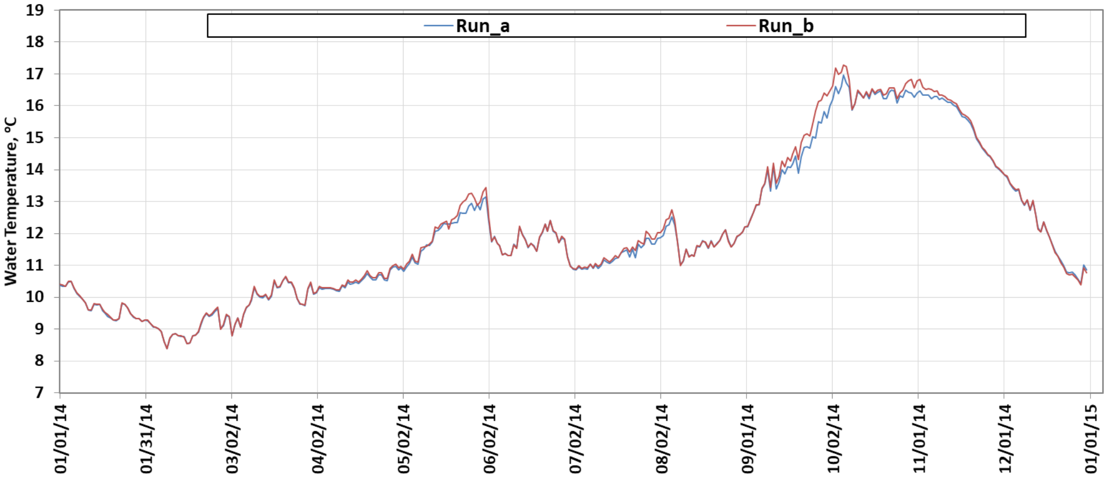


Figure 20. Simulated Shasta Dam release temperatures for baseline conditions (Run_a) and varying leakage distributions (Run_b, Run_c, Run_d): year 2014.

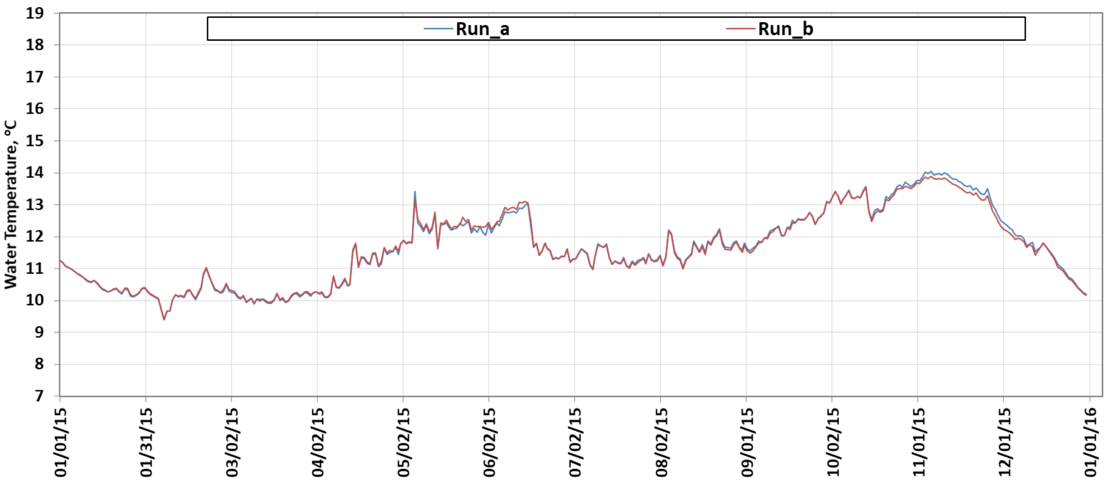


Figure 21. Simulated Shasta Dam release temperatures for baseline conditions (Run_a) and varying leakage distributions (Run_b, Run_c, Run_d): year 2015.

5.2. Temperature Control Device – Large Gate Openings

The Shasta Dam TCD is a large structure that is over 350 ft (106.7 m) in width and height, and 50 ft (15.2 m) from the upstream face of the TCD to the face to the dam. The TCD is located to the west of the centerline of the dam and is large enough to cover the powerhouse penstock intakes and their respective trash racks as shown in Figure 22. Also visible in Figure 22 are the spillway and the trash racks that cover the river outlets. A schematic of the dam features, illustrating the relative position of the various outlets in the dam is provided in Figure 4.

Figure 22. Shasta Dam (looking downstream) showing spillway, river outlet trash racks, and TCD.

Comparing the size of the TCD gate openings and the river outlets (Figure 4) illustrates that both the vertical extent and cross-sectional area of these two outlet types are dramatically different. The upper and middle TCD gates are over 45 ft (13.7 m) in height, while the river outlets range from 8 ft (2.4 m) to 8.5 ft (2.6 m) in height. The cross-sectional area of a single upper or middle level TCD gate is approximately 2,250 ft^2 (209.0 m^2) compared to the largest river outlet (e.g., lower outlets) cross-sectional area of 56.75 ft^2 (5.3 m^2). Submergence criteria require that if there is less than 35 feet of water above the upper and middle levels, at least one gate opening in the next lowest level must be open. Because this report addresses model calibration and relies on historic operations, submergence criteria are assumed to be met.

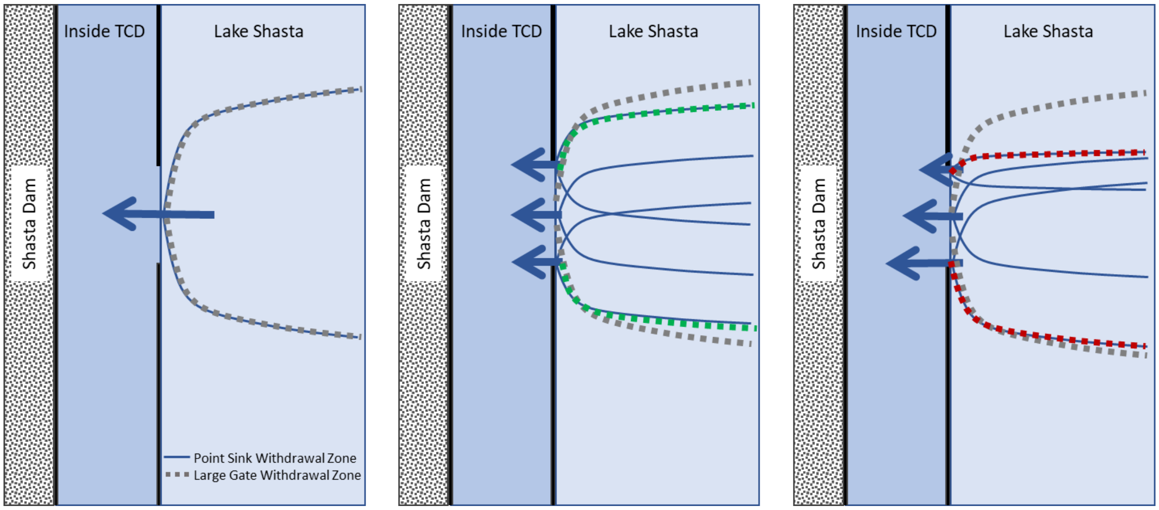
CE-QUAL-W2 has specific logic to address outlet works in the dam, and to accommodate their configuration and the use of multiple outlets (i.e., selective withdrawal). The model uses line and point sink representations for reservoir outlets. Those outlets such as a penstock or pipeline are typically represented with point sink representations (Lawrence and Imberger 1979, Smith et al. 1987, Huntington 1990) and those that have linear configurations can be represented with line sinks (Imberger and Fisher 1970, Pao and Kao 1974). Point sinks assume radial flow approaching the outlet both laterally and vertically, while line sink assumption represents vertical flow (Cole and Wells 2008). These approaches are commonly applied in many reservoir models (Bohan and Grace 1973, USACE 1986, Davis et al. 1987, Cole and Wells 2008).

The point sink and line sink are widely applicable when the outlet works dimensions are sufficiently small compared to the reservoir depth. For example, a river outlet on Shasta Dam could be represented as point sink because the diameter of the outlet (8 ft (2.4 m)) is much less than the depth of the reservoir at the dam (approximately 470 ft (143.3 m)). However, the TCD outlets are considerably larger and represent nearly 10 percent of the reservoir depth at the dam, and a larger fraction of the depth where the TCD is located (Figure 4). These large gate openings were initially modeled with both point and line sinks; however, results indicated that this representation was insufficient to represent outflow dynamics from Shasta Lake.

Beyond the basic point sink representation limitation for the large gate openings, there are other factors that directly impact using these options for modeling the TCD in Shasta Lake. When water levels fall below a point or line sink in CE-QUAL-W2, the outlet no longer is active. Typically, these point and line sinks are placed at the centerline of the outlet. For small outlets, this assumption has minimal impact. However, for a 45 foot (13.7 m) high gate (upper or middle levels), this would mean neglecting the bottom 22.5 ft (6.9 ft) of a potentially open gate. Another approach would mean placing the point or line sink at the bottom of the gate opening. This assumption would shift the contributing area (i.e., withdrawal zone) 22.5 ft (6.9 ft) lower in the reservoir.

To represent the large gate openings and capture the full height of the gates, three individual point sinks were used to represent the TCD gates. A single point sink at the centerline elevation (Figure 23(a)) not only fails to capture the lower 22.5 ft (6.9 ft) should the water level fall below the centerline elevation, as noted above, but may also fail to effectively capture the large gate withdrawal zone. For a single point sink all water is required to pass this single location, while the larger gate opening represented by three point sinks with equal flow located at the top, center, and bottom of the gate would result in lower velocities distributed over 45 ft (13.7 m), resulting in a different withdrawal zone (Figure 23(b)). Finally, assuming unequal flows entering the gates through three individual point sinks located at the top, center, and bottom of the gate (Figure 23(c)) more effectively represents a theoretical withdrawal zone.

The approach utilized the CE-QUAL-W2 point and line sink logic, but different numbers of outlets representing the large gates were examined (e.g., two outlets, three outlets). Lacking in reservoir velocity profiles associated with the TCD and internal TCD hydrodynamics, the approach could not be confirmed with in-reservoir observations. However, the large gate representations, when coupled with additional refinements in the selective withdrawal logic (addressed below) resulted in the simulated outflow temperatures that best reproduced historical conditions when compared with simpler, single point representations.



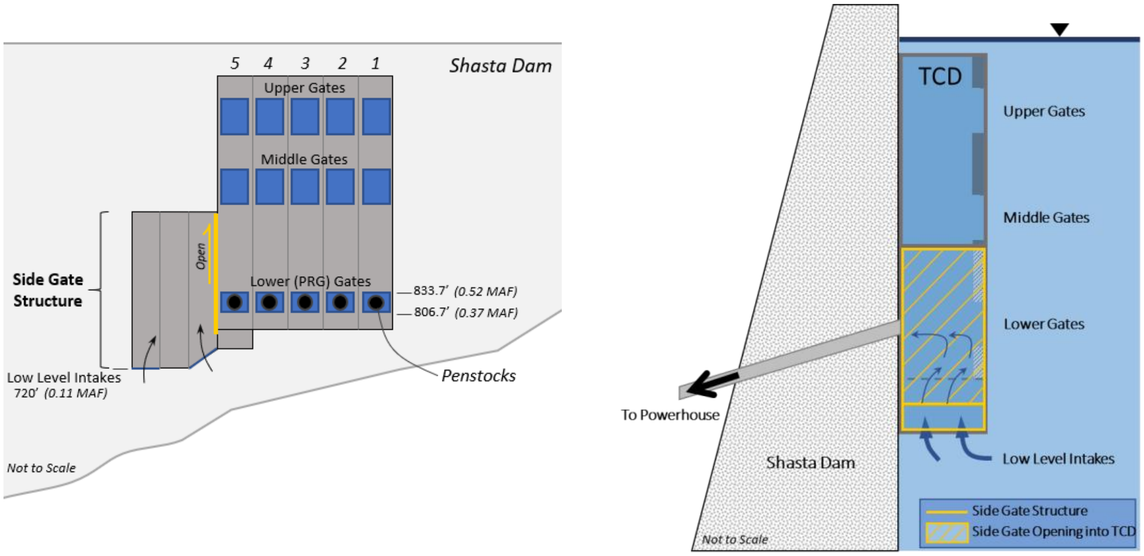
(a) (b) (c)

Figure 23. Conceptual diagram of representation of a large gate for (a) withdrawal zone with a single point sink located at the gate centerline (including large gate withdrawal zone); (b) withdrawal zone represented with three equal point sinks located at the gate top, centerline, and bottom (combined withdrawal zone represented by green line); and (c) asymmetrical withdrawal zone with three unequal point sinks located at the gate top, centerline, and bottom (combined withdrawal zone represented by red line). Conceptualization assumes no surface or bed boundary effects.

The three individual point sink representation of large gates was important to effectively access the full depth of the gate in model simulations. Multiple formulations (e.g., one, two, three individual point sinks) and a wide range of minimum flow fractions for each gate were tested. Some of this testing was completed external to the model to more efficiently test and observe the implication of how multiple point sinks represented conditions in the reservoir, i.e., by placing point sink logic in a spreadsheet and testing dynamics under different flow rates and thermal stratification regimes. Under certain circumstances the minimum flow fraction assignments were quite sensitive. Model results indicate that flow fractions at the lowest point sink had to be larger than the upper two individual point sinks (e.g., Figure 23(c)) at that level to reproduce historic water temperatures over a range of meteorological conditions, temperature profiles, number of active levels, and duration at a particular level. Overall, these simulations indicate that the model is moderately to highly sensitive to gate representation and flow apportionment. Additional discussion is presented in Section 7 under recommendations.

5.3. Low Level Intake Operations

The low-level intake structure is attached to the side of the main TCD structure, is 150 ft (45.7 m) wide and 160 ft (48.8 m) tall, and acts as an extension to access deeper, colder waters (Figure 24). Low-level intake operations within the Shasta Lake model are challenging to represent within the existing CE-QUAL-W2 model framework because the current point/line sink theory does not accommodate vertical inflow into an outlet structure. When the side gates are open, water enters the open bottom of the low-level intake structure, flows vertically upward, then horizontally through the side of the main TCD structure. Regardless of which gates in the TCD are open, waters within the TCD enter the powerhouse penstocks according to which powerhouse units (one to five) are operating (Figure 24). Further, the bottom of the low-level intake is close to the reservoir bed, creating potential boundary effects and unique hydrodynamic conditions that appear to impact where water entering the low-level intake is drawn from the lake.



(a) (b)

Figure 24. Shasta Dam TCD showing low-level intake structure (a) looking downstream and (b) side view (from centerline of dam looking northwest).

There are no available data that provide clear insight into the hydrodynamic conditions in the vicinity of the TCD low-level intake structure; however, there are results from a computational fluid dynamics (CFD) model from Reclamation (1999) that depicts flow into the low-level intake structure (Figure 25). These CFD model simulations illustrate the proximity of the intake to the reservoir bed and that waters flow vertically upward into the low-level intake structure and then into the main TCD.

When initially applying the Shasta Lake model under low-level intake only operations with a single point sink intake at 720 ft (219.5 m), the model neither reproduced outflow temperatures nor in-reservoir vertical temperature profiles. Specifically, simulated dam release temperatures were notably warmer than simulated in-lake temperatures at the elevation of the low-level intake – a condition that also exists in the field data to some extent. Presumably, the proximity of the lake boundary (bed and banks) to the TCD restricts the withdrawal zone of the low-level intake, entraining waters from higher reservoir elevations (Figure 26). Subsequently, the low-level outlet was represented with three individual point sinks (similar but not equivalent to the TCD gates at upper levels) at elevations 800 ft (243.8 m), 760 ft (231.7 m) and 720 ft (219.5 m) to represent the entrainment of warmer waters.

While dam release temperatures were effectively simulated with this configuration, simulated in-lake vertical temperature profiles were too warm in the vicinity of the low-level intake when the low-level intake was the only active TCD outlet late in the season (Figure 27(a)).

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 ($1.357\text{x}10^8$ 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 (Figure 28). 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 (Figure 27(b))

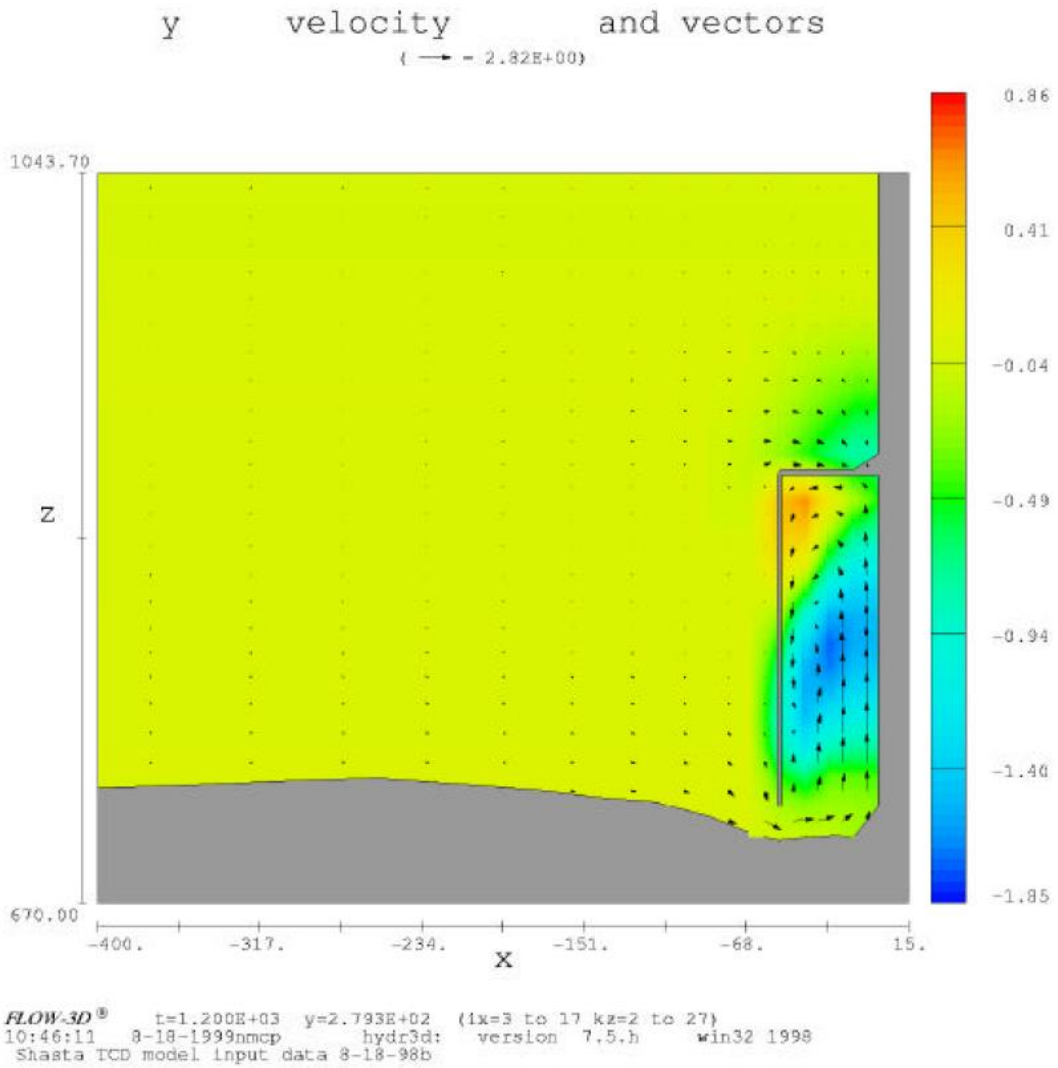


Figure 25. Velocity contours through the low-level intake structure (Figure 3O, Reclamation (1999)).

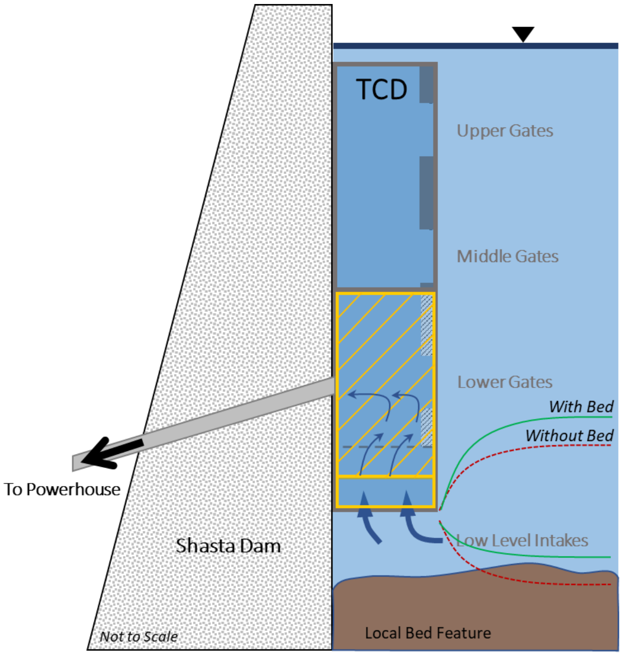
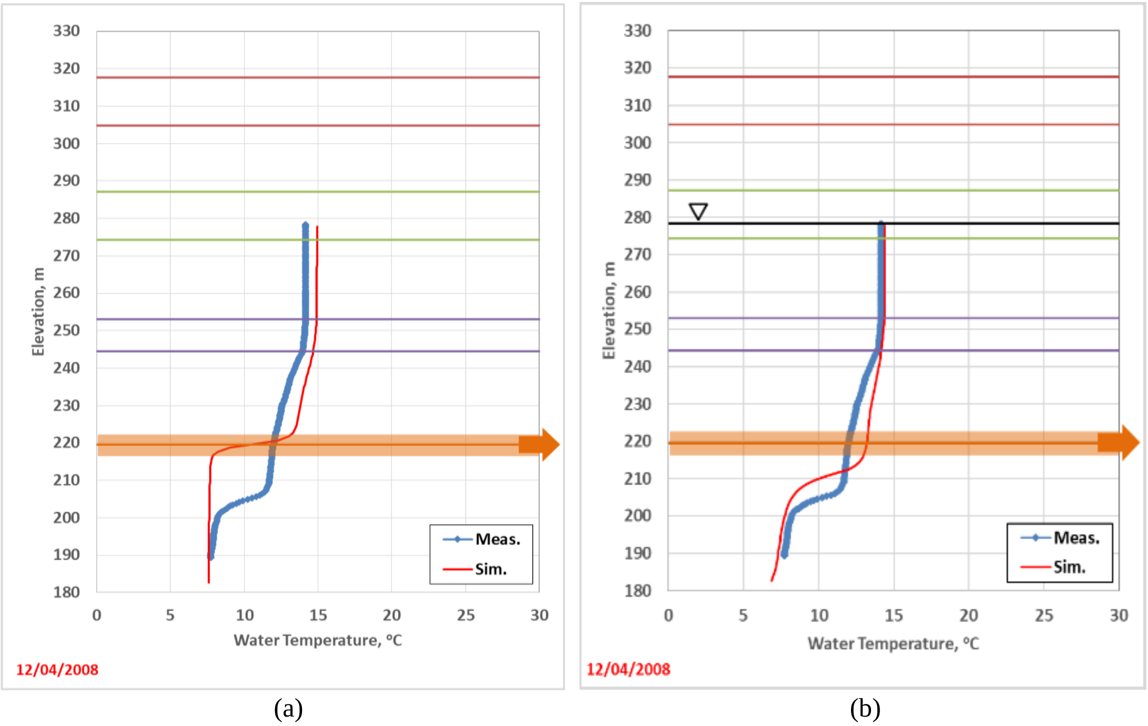


Figure 26. Shasta Dam TCD low-level intake structure and local bed feature impacts on a conceptual withdrawal zone. The red dashed line represents the theoretical withdrawal zone without boundary interference, and the green line represents the withdrawal zone with boundary (bottom) interference.



(a) (b)

Figure 27. Shasta Lake simulated versus measured vertical temperature profiles upstream of the dam for (a) three individual point sink configuration, and (b) three individual point sink configuration and a lower outlet (TCD_d): December 4, 2008.

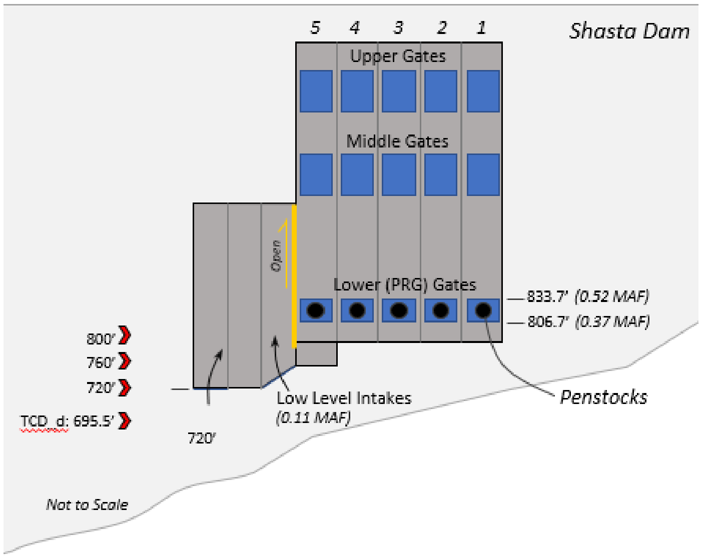


Figure 28. Shasta Dam TCD showing low-level intake structure represented with three individual point sinks (looking downstream) and the addition of the point sink below 720 ft (219.5 m) (TCD_d).

If TCD_d was not employed the model effectively replicated outflow temperatures, but failed to replicate thermal profiles. Numerous simulations were completed to assess both elevation of TCD_d and percentage of total outflow assigned. An example of with and without the TCD_d point sink is shown in Figure 29. Profile water temperatures are sensitive to these assumptions, with the final values determined during calibration. Model outputs were sensitive to TCD_d when the lower level intake was the only TCD level in use, under low storage conditions, and late in the temperature control season (e.g., September-October) such as 2014. Details of this representation are included in Section 5, and additional discussion is presented in Section 8 under recommendations.

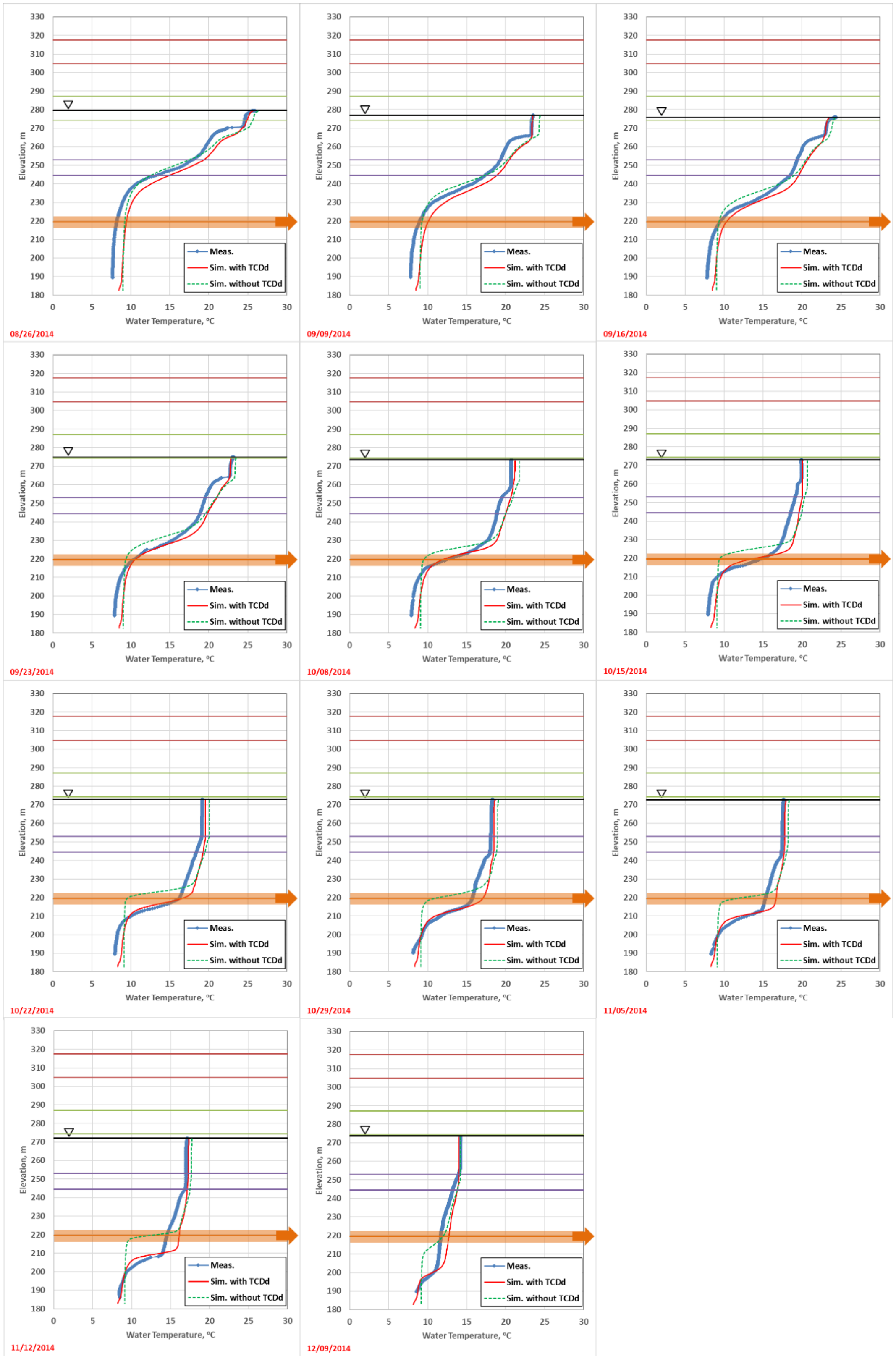


Figure 29. Measured vs. simulated temperature profiles with TCD_d and without TCD_d. 2014 when only the low-level intake is active (8/26/14 – 12/09/14). Orange shaded area indicates the TCDS level.

5.4. Temperature Control Device – Blending

The Shasta Dam TCD is used to manage stored cold water and meet downstream temperatures through selective withdrawal. Operations of the large multiple level gates, including the low-level intake, all while accommodating leakage, is a complex endeavor. In addition to the TCD, there are other outlets in the dam that, at times, must be considered when managing Shasta Dam release temperatures.

5.4.1. Shasta Dam Outlets

In addition to TCD levels and leakage (addressed above), there is a spillway, as well as three levels of river outlets that discharge from the center of the dam below the spillway gates (Figure 4 and Figure 30). Each river outlet (upper, middle, and lower) is represented as a point sink at the centerline elevation in the model. All TCD outlets, TCD leakage zones, spill, and river outlets are presented in Table 19. Included in this table is the TCD_d outlet that represents deeper level withdrawal when the low-level intake is active.

Figure 30. Shasta Dam with river outlets active (Source: Reclamation).

Table 19. Shasta Dam Outlets Included in the Model with designated elevations.

Outlet No.	Outlet	Elevation, ft	Elevation, m
1	Spill	1,037.0	316.08
2	TCDU1 (upper level, top point sink)	1,042.0	317.60
3	TCDU2 (upper level, middle/center point sink)	1,021.0	311.20
4	TCDU3 (upper level, bottom point sink)	1,000.0	304.80
5	TCDM1 (middle level, top point sink)	942.0	287.12
6	TCDM2 (middle level, middle/center point sink)	921.0	280.72
7	TCDM3 (middle level, bottom point sink)	900.0	274.32
8	TCDL1 (lower level, top point sink)	830.0	252.98
9	TCDL2 (lower level, middle/center point sink)	816.0	248.72
10	TCDL3 (lower level, bottom point sink)	802.0	244.45
11	TCDS1 (side level, top point sink)	800.0	243.84
12	TCDS2 (side level, middle/center point sink)	760.0	231.65
13	TCDS3 (side level, bottom point sink)	720.0	219.46
14	RRU (River Release Upper point sink)	942.0	287.12
15	RRM (River Release Middle point sink)	842.0	256.64
16	RRL (River Release Bottom point sink)	742.0	226.16
17	Leakage Zone 1	946.7	288.54
18	Leakage Zone 2	896.7	273.32
19	Leakage Zone 3	833.6	254.09
20	Leakage Zone 4	805.6	245.56
21	Leakage Zone 5	780.0	237.74
22	Leakage Zone 6	749.5	228.45
23	TCD_d (deep level)	695.5	212.00

Spill – spillway

TCDU – TCD upper level
TCDM – TCD middle level
TCDL – TCD lower level
TCDS – TCD low-level intake or side gate structure
Indices on TCD levels are defined as 1: uppermost point sink, 2: middle point sink; 3 lowermost point sink

RRU – River release, upper outlets (point sink)
RRM – River release, middle outlets (point sink)
RRL – River release, lower outlets (point sink)

Leakage Zones – six zones with each outflow defined by a line sink at the bottom of each zone

TCD_d (deep level) – an outlet assigned only when the low-level intake is active

5.4.2. 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 TCD, only penstock flow data were available. Reclamation operations logs were used to assign flows through the TCD depending on the active TCD levels (see Table 4) 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 (2000-2017), there were occasional instances 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. The 2000-2017 Reclamation TCD log is reproduced in Appendix B, and an example year (2013) is shown below in Table 20. 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 Powerplant
- 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 above.
- 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.
- 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) of the large gate opening (see discussion on large gate openings, above). During these non-blending periods the model selective withdrawal logic will determine flows into any one of the three individual point sinks, based on TCD flow, minimum flow fractions (MFF[11]), 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 (MMFs 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 31). These MFFs were developed through multiple model simulations and review of URBR (1999).
- 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

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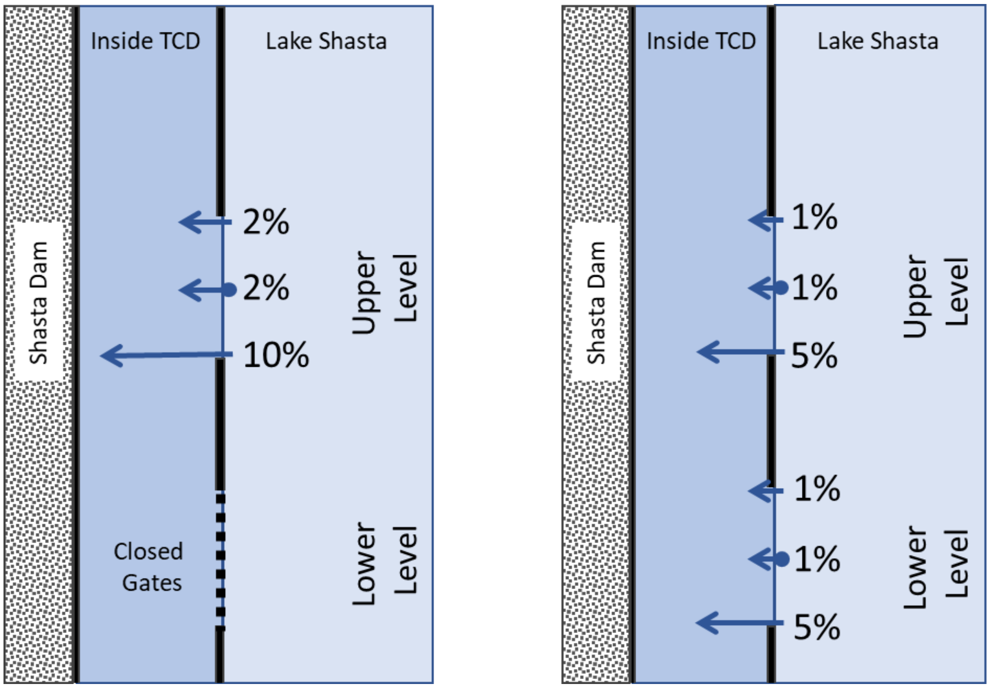
[11] MFFs were determined during model calibration (see Section 6).

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 31). During initial model testing, MFFs during blending periods were simply reduced by 50 percent and assigned to each level. That is, the single level 2%-2%-10% MFF distribution for the three point sinks was applied as 1%-1%-5% MFF to both levels during blending. However, through additional model testing the distribution shown in Figure 31(b) was identified as providing improved model performance (when compared to field observations).

- Further, when the low-level outlet is active, the TCD_d outlet is included in the selective withdrawal logic. This 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)[12]. 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.



(a) (b)

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

Figure 31. Minimum flow fractions (MFF) using upper and middle levels as an example for (a) single active level, and (b) two active levels.

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. Both data sets have 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 average of the two temperature records were used[13]. Differences between these records were mostly in diurnal variations (sub-daily) and were more apparent at certain times of the year (e.g., fall and early winter).

Table 20. Shasta Dam TCD Active Levels: 2013.

Year	Period	JDAY		Date (2013)		Period Type	Notes
2013	1	1.000	31.583	01/01	01/31	TCDL	
	2	31.583	72.458	01/31	03/13	TCDM	
	3	72.458	80.375	03/13	03/21	TCDU&TCDM	
	4	80.375	112.417	03/21	04/22	TCDU	
	5	112.417	184.792	04/22	07/03	TCDU&TCDM	
	6	184.792	196.458	07/03	07/15	TCDM	
	7	196.458	239.458	07/15	08/27	TCDM&TCDL	
	8	239.458	239.667	08/27	08/27	TCDL	Short period
	9	239.667	247.458	08/27	09/04	TCDM&TCDL	
	10	247.458	254.375	09/04	09/11	TCDL	
	11	254.375	276.583	09/11	10/03	TCDL&TCDS	
	12	276.583	276.708	10/03	10/03	TCDS	Short period
	13	276.708	303.417	10/03	10/30	TCDL&TCDS	
	14	303.417	345.500	10/30	12/11	TCDS	
	15	345.500	366.000	12/11	12/31	TCDL	

5.4.3. Modeling Selective Withdrawal

Shasta Dam is outfitted with a temperature control device (TCD) that allows operators to withdraw water from different levels of the reservoir throughout the year to meet release

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[13] 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.

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.

Currently, forecasts of water temperatures on the Sacramento River are made using the USACE hydrodynamic and water quality model, HEC5Q (RMA 2003). The HEC5Q model has been modified and calibrated to simulate releases from the TCD. Given an initial temperature profile, a schedule of total release flow, and a temperature target, HEC5Q simulates TCD operations to meet the temperature target through the temperature management season. Overall, HEC5Q has been effective in anticipating TCD operations and the ability of management to meet downstream temperature criteria (Reclamation 2015).

This section details how the logic currently used in HEC5Q was adapted for use in the CE-QUAL-W2 model for simulating selective withdrawal using the Shasta TCD. This adaption was made to improve forecasting in CE-QUAL-W2 simulations to support temperature management activities in downstream Sacramento River reaches. The existing CE-QUAL-W2 model capability to assess management strategies for downstream temperature control through selective withdrawal was developed by Rounds and Buccola (2015) and included algorithms that simulated blending of reservoir releases from outlets at different elevations in a reservoir. However, modifications to the existing CE-QUAL-W2 model were required because the Rounds and Buccola (2015) logic did not readily forecast reservoir operations desirable for long-term temperature control assessment at Shasta Lake and Shasta Dam. While the existing model allows outlets to be blended according to a user-specified schedule of blending periods, providing flexibility in assessing scheduled gate operations, these algorithms require the user to specify the time periods that outlets are available for selective withdrawal. The logic implemented in CE-QUAL-W2 by Rounds and Buccola (2015) was expanded and enhanced by Watercourse 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.

The modified model (referred to here as “W2_TCD”) is designed to simulate Shasta TCD operations using CE-QUAL-W2 and is implemented within the framework of CE-QUAL-W2 selective withdrawal logic introduced by Rounds and Buccola (2015). Modifications include incorporation of new variables to identify periods of TCD operation and define each of the four TCD levels, logic to associate selective withdrawal openings, or “structures,” with each of the levels, and a new method to select levels for blending. Logic was retained from the original code that allowed TCD leakage and river outlets to be included in the selective withdrawal computation of outflow temperatures as non-blended outflow. Non-blended outflows are those flows that operators cannot control, but have to accommodate when managing other releases to achieve desired tailbay temperatures (e.g., TCD leakage).

Although this new code is placed within the structure of the selective withdrawal logic documented in Rounds and Buccola (2015), several features of this approach were disabled in this version of W2_TCD. These disabled features include specification of floating outlets, constraints on minimum and maximum release rates, and priority ranking of outlets (although priority numbers are still used). Also disabled are any uses of a withdrawal tower or withdrawals (WD) in blending calculations. Only outlets designated as structures (ST) are used in W2_TCD blending. Except for priority ranking, which has no function in the W2_TCD logic, these features were disabled 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.

5.4.3.1. Model Specifications

In W2_TCD, Shasta TCD operations are defined in terms of levels, flow distribution across those levels, and periods of operation. All specifications for selective withdrawal are made, as in previous implementations of selective withdrawal logic, in one file: “w2_selective.npt.” Within this file, all sources of release water, both blended and unblended, are specified. 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 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. These operational restrictions, along with the use of “blending periods” as implemented by Rounds and Buccola (2015) provides flexibility in guiding operations whether for re-creation of historic conditions or forecasting future conditions. Details of W2_TCD model parameters are included in Appendix C.

5.4.3.2. Model Logic

The W2_TCD logic uses these model specifications to simulate operations of the Shasta TCD. Given initial storage and temperature conditions, the logic searches for the one or two highest level(s) to employ to meet a specified release temperature at a specified flow. In this process, the model distributes flow across the open level(s) using the MFFs and iterative testing. To identify levels to open, the model starts at the top of the water column and works down in elevation, following a set of rules to approximate actual TCD operation. Once a level or a pair of levels is selected for blending, the associated point sinks (and MFFs) representing each level or levels are processed to determine flow distribution. First, MFFs are assigned to all point sinks. Then, the remainder of the blended flow is distributed between the selected point sinks to find a distribution that meets temperature targets. Details of level selection logic, along with an example application of modeling selective withdrawal, are provided in Appendix C.

5.4.3.3. Model Results

At the end of the W2_TCD 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 CEQUAL-W2 for use in its calculation of hydrodynamics and water quality in the subsequent time step.

5.5. 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 (Figure 16). 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 or better 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 required 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. In the meantime, the model remains widely applicable for planning and management actions at Shasta Lake as confirmed by model performance comparing simulated and historical parameters in Section 6.

6. Model Calibration and Validation

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. 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.

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.

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

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

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

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

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 (Methevet 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 21. 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 21. Model performance metrics for water temperature, flow, and reservoir stage in the Shasta Lake and Keswick Reservoir CE-QUAL-W2 modeling.

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

MAE – mean absolute error
RMSE – root mean squared error
NSE – Nash-Sutcliffe efficiency

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 the entire 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 calibration parameters and associated information are provided in subsequent sections for Shasta Lake and Keswick Reservoir. All field data, model input, and model simulation results for calibration are available in electronic format.

Model validation was completed for years 2018 and 2019. Model simulations for these two 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.

6.1. Model Calibration Parameters

Final model parameters and settings considered in calibration of the Shasta Lake and Keswick Reservoir model 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 22, are the same for the two reservoirs, but differences occur. Notable differences include[14]:

- 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

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[14] The reader is referred to Cole and Wells (2008) for comprehensive model parameter descriptions.

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 11°C. 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 10°C to 11°C 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 $\mathrm{Wm^{-2}\ mm\ Hg^{-1}}$) 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 $\mathrm{Wm^{-2}\ {}^{o}C^{-1}}$ and sediment temperature set to 6°C. The Keswick Reservoir CBHE default value was used, and bed temperature set to 1°C. 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 22. 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, °C
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} $°C^{-1}$
TSED	-	6.00	10.00	Sediment temperature, °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.

6.2. 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 21.

6.2.1. 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 32. 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 23. Graphical and tabular information for all years is provided in Appendix D.

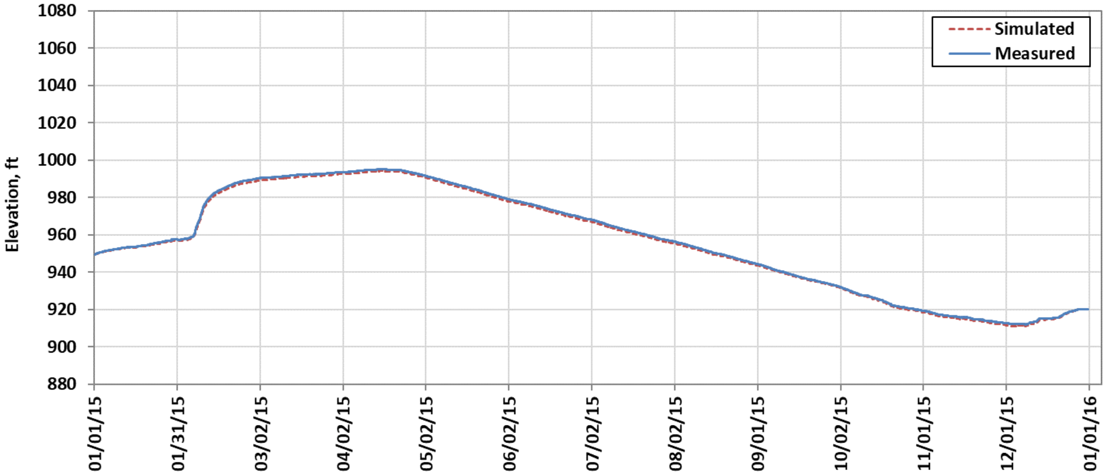

Figure 32. Simulated versus measured Shasta Lake stage: 2015.

Table 23. Summary statistics of Shasta Lake stage: 2000-2017. (Shaded cells indicate values were 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
Mean Bias (ft)	-0.61	0.03	-0.42	-0.39	-0.15	-0.45	-0.02	-0.10
MAE (ft)	0.62	0.21	0.67	0.53	0.66	0.49	0.50	0.41
RMSE (ft)	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
COUNT	8,760	8,760	8,784	8,760	8,760	8,760	8,784	8,760

6.2.1. 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 33. 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 24. Graphical and tabular information for all years is provided in Appendix D.

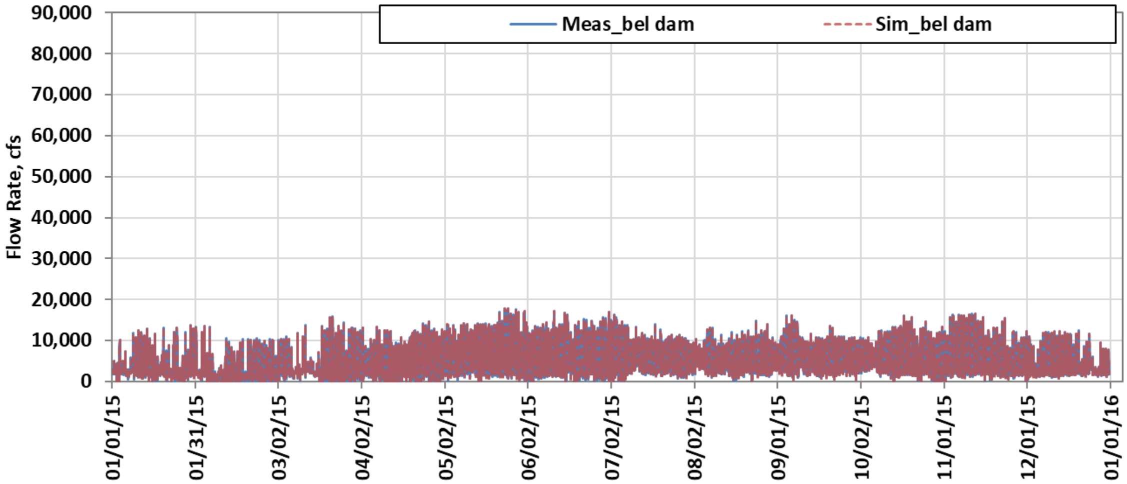

Figure 33. Simulated versus measured Shasta Dam outflow: 2015.

Table 24. Summary statistics for Shasta Dam outflow: 2000-2017.

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**		
Mean Bias (cfs)	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0		
MAE (cfs)	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0		
RMSE (cfs)	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		
COUNT	8,760	8,760	8,784	8,760	8,760	8,760	8,784	8,760		

6.2.2. 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 33), and tabular results monthly mean bias, MSE, RMSE and NSE are included in Table 25 through Table 28. Mean bias ranged from -0.74^{o}C (December 2004) to 1.26^{o}C (October 2001). Mean bias did not meet the calibration metric of ±0.75^{o}C 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 25).

MAE ranged from 0.14^{o}C (January 2000) to 1.32^{o}C (August 2014). MAE did not meet the calibration metric of ≤1.0^{o}C 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 26). RMSE ranged from 0.20^{o}C (January 11) to 1.75^{o}C (August 2014). RMSE did not meet the calibration metric of ≤1.5^{o}C in in one month over five years (October 2008), or 0.5 percent of the time (Table 27). 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 28). 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 34) 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 D.

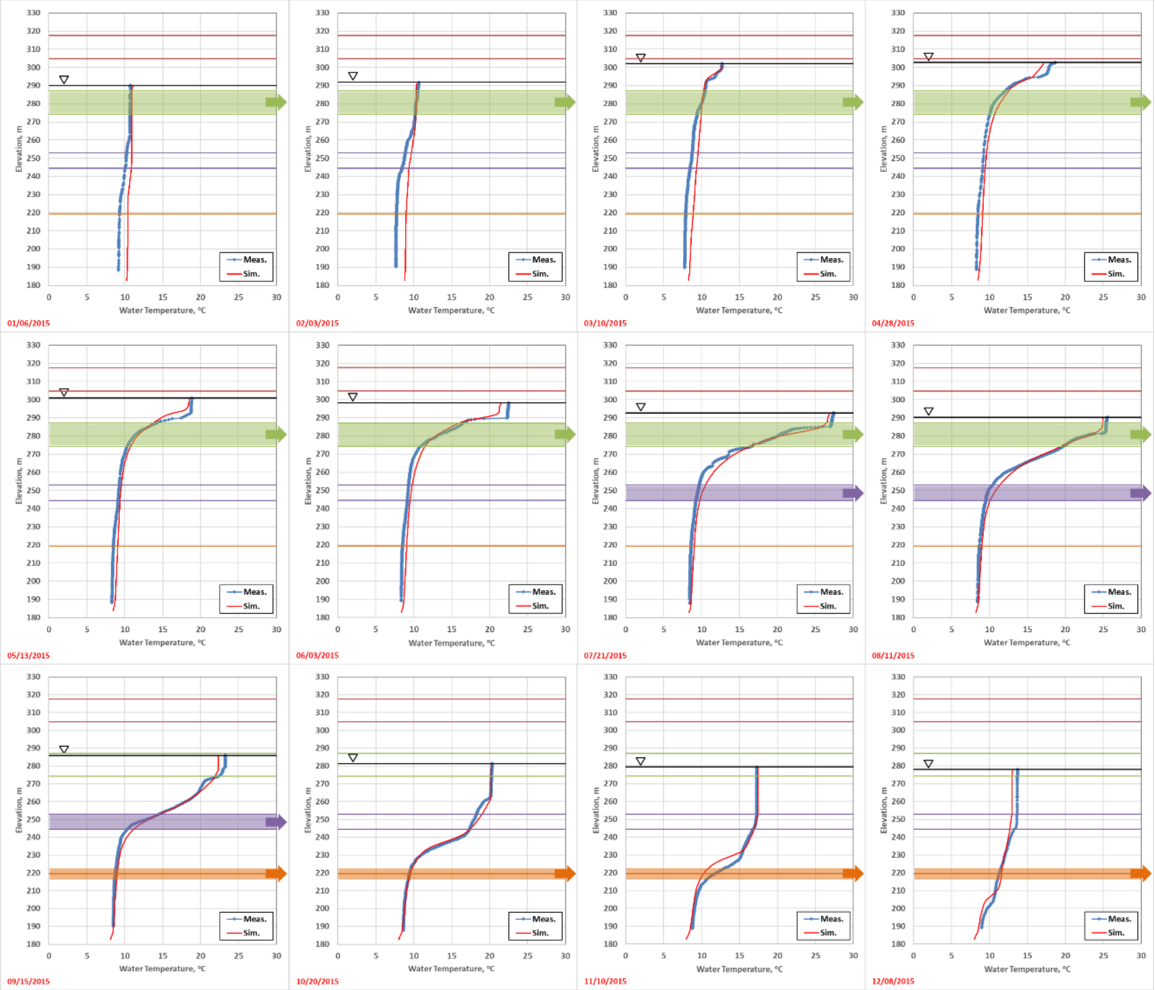

Figure 34. Simulated versus measured temperature profiles upstream of Shasta Dam: 2015.

Table 25. Mean bias for monthly temperature profiles (°C) for Shasta Lake above Shasta Dam: 2000-2017. (Highlighted cells indicate values were outside the calibration criteria of ±0.75ºC.)

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 26. Mean absolute error (MAE) for monthly temperature profiles (°C) for Shasta Lake above Shasta Dam: 2000-2017. (Highlighted cells indicate values were greater than the calibration criteria of 1.0ºC.)

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 27. Root mean squared error (RMSE) for monthly temperature profiles (°C) for Shasta Lake above Shasta Dam: 2000-2017. (Highlighted cells indicate values were greater than the calibration criteria of 1.5ºC.)

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 28. Nash Sutcliffe Efficiency for monthly temperature profiles (°C) for Shasta Lake above Shasta Dam: 2000-2017. (Shaded cells indicate values were less than the calibration criteria of 0.65.)

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

6.2.3. Outflow Temperature

Simulated versus measured Shasta Lake outflow temperature tracked measured values closely in all years, except for short periods. Calendar year 2015 is shown as an example in Figure 35. 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) computed 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 (see Figure 4).

- 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 D.

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[15].

Mean bias ranged from -0.41°C (2004) to 0.20°C (2016), meeting the calibration metric of ±0.75°C all years. MAE ranged from 0.16°C (2005) to 0.61°C (2000) and met the calibration metric of ≤1.0°C all years. RMSE ranged from 0.26°C (2005) to 0.75°C (2000) and met the calibration metric of ≤1.5°C 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 29.

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[15] TEST

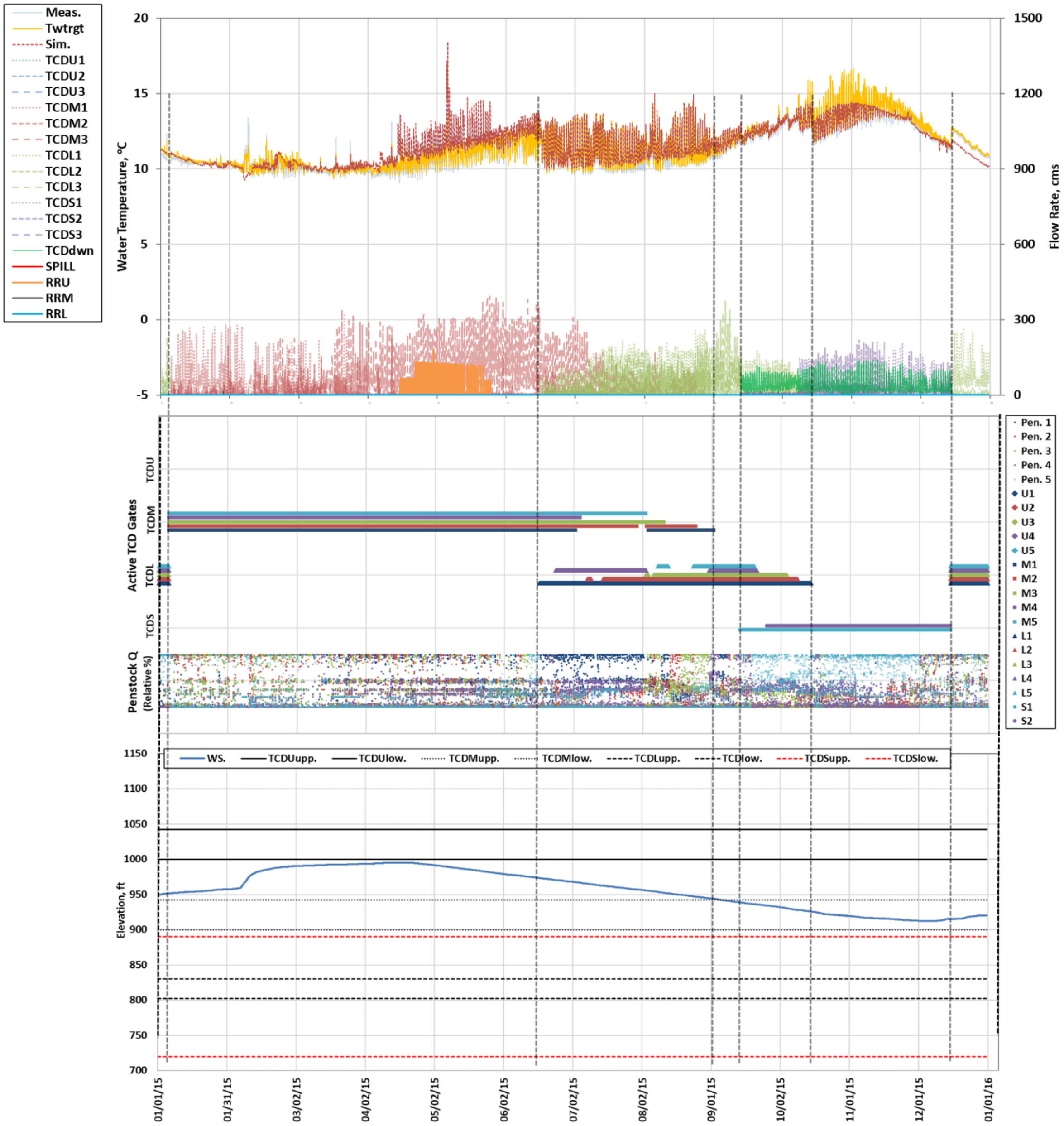

Figure 35. Shasta Lake simulated temperature vs. target temperature & measured temperature, and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2015.

Table 29. Summary statistics of Shasta Dam outflow temperature: 2000-2017. (Shaded cells indicate values were 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	0.92	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
Mean Bias (ºC)	-0.19	-0.12	-0.04	-0.06	-0.03	0.07	0.20	0.07
MAE (ºC)	0.30	0.19	0.24	0.45	0.43	0.39	0.38	0.30
RMSE (ºC)	0.49	0.32	0.36	0.66	0.66	0.58	0.59	0.39
Nash-Sutcliffe (NSE)	0.64	0.82	0.88	0.80	0.93	0.83	0.52	0.84
COUNT	8,760	8,760	8,784	8,760	8,760	8,760	8,784	8,760

6.3. 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. All calibration metrics identified herein refer to Table 21. 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 (2000-19) are included in Appendix C.

6.3.1. 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 36. Summary statistics are included in Table 30. 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).

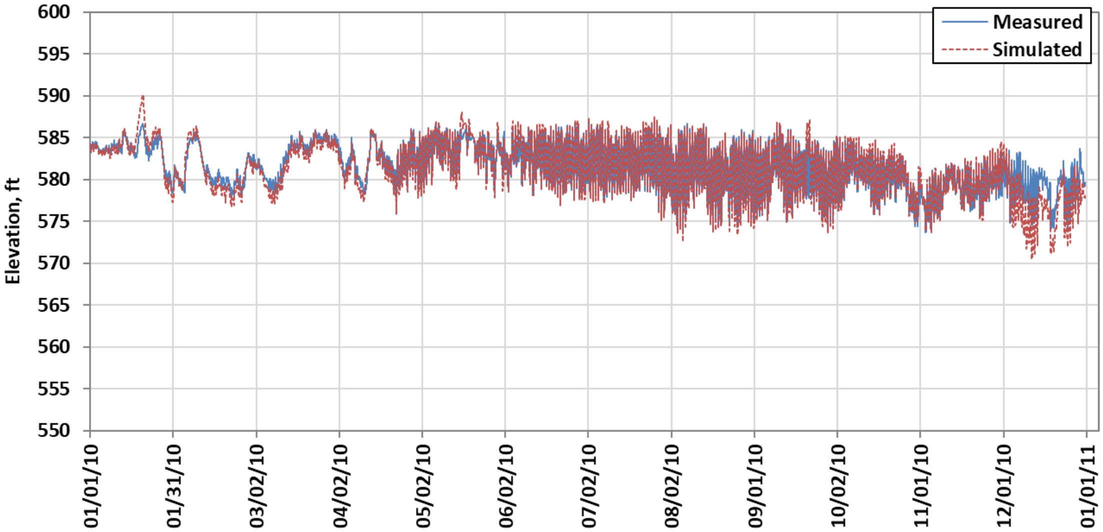

Figure 36. Simulated versus measured Keswick Reservoir stage (msl). Year 2010.

Table 30. Summary statistics of Keswick Reservoir stage: 2000-2017. (Shaded cells indicate values were 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**		
Mean Bias (ft)	-0.23	-0.30	0.38	0.23	-0.31	0.36	-0.24	0.20		
MAE (ft)	0.64	1.10	0.79	0.77	0.67	0.61	0.58	0.70		
RMSE (ft)	0.99	1.32	1.05	1.02	0.87	0.73	0.72	0.89		
Nash-Sutcliffe (NSE)	0.87	0.77	0.85	0.87	0.91	0.92	0.93	0.86		
COUNT	8,760	8,760	8,784	8,760	8,760	8,760	8,784	8,760		

6.3.2. Outflow

Simulated versus measured Keswick Reservoir outflow tracked measured values exactly in all years. Calendar year 2010 is shown as an example in Figure 37. 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 31. Graphical and tabular information for all years is provided in Appendix E.

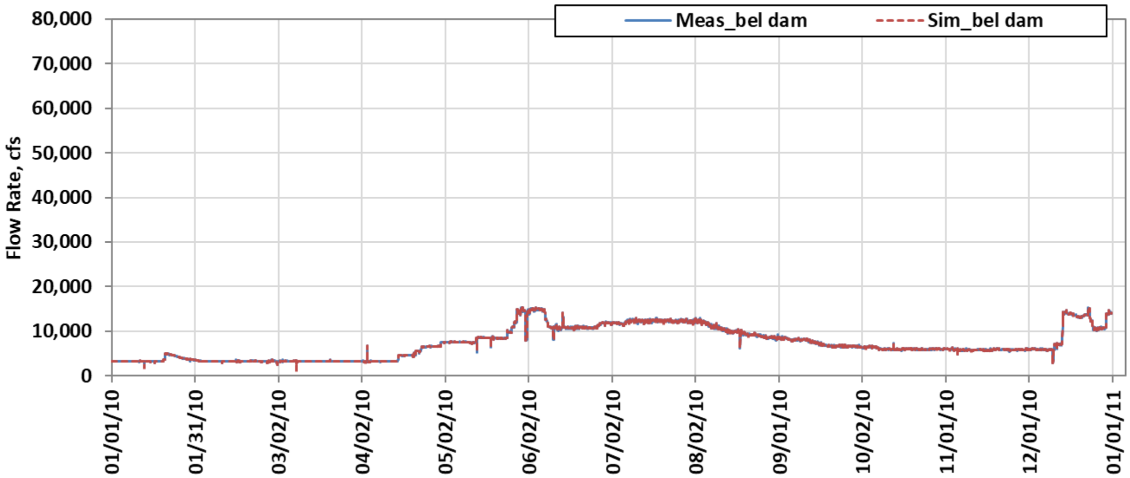

Figure 37. Simulated versus measured outflow below Keswick Dam. Year 2010.

Table 31. Summary statistics for Keswick Dam outflow: 2000-2017.

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**		
Mean Bias (cfs)	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		
RMSE (cfs)	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		
COUNT	8,755	8,757	8,778	8,754	8,759	8,758	8,783	8,759		

6.3.3. Reservoir Temperature Profiles

There are total of eight temperature profiles for Keswick Reservoir, measured in two different locations, in year 2010 (Figure 38).[16] Two locations mentioned are above and below the Spring Creek 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 -0.47°C (January 21, above Spring Creek) to 0.57°C (March 30, above Spring Creek). Mean bias met the calibration metric for all profiles (Table 25). MAE ranged from 0.06°C (April 14, below Spring Creek) to 0.57°C (March 30, above Spring Creek). MAE met the calibration metric in all months. RMSE ranged from

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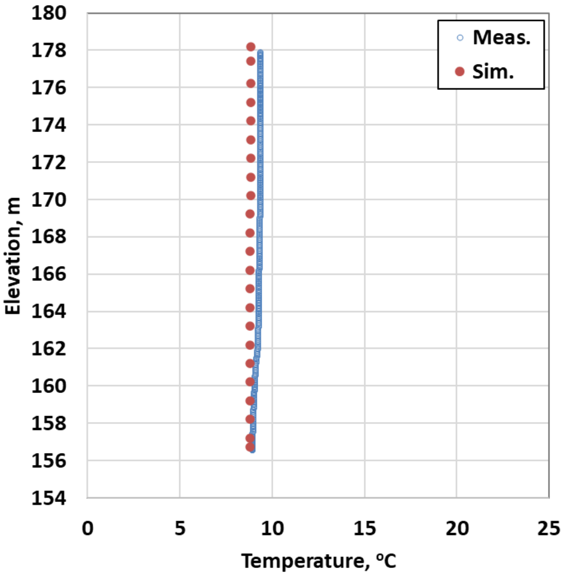
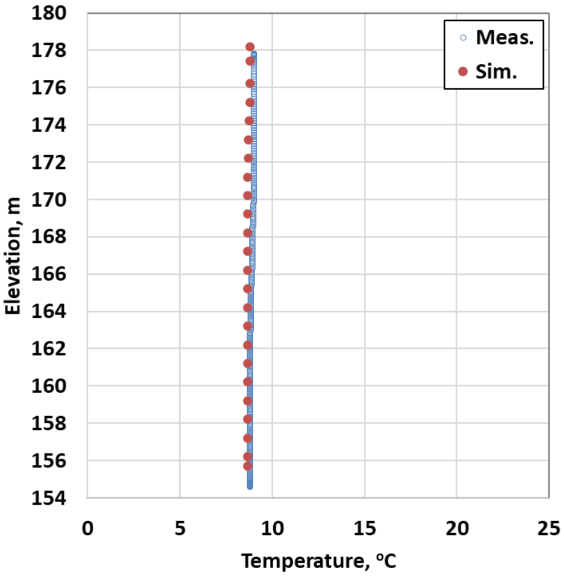
[16] Temperature profiles for Keswick Reservoir were only available for year 2010. No other years had data collected. See Section 3.2.3.2.

0.07°C (April 14, below Spring Creek) to 0.58°C (March 30, above Spring Creek). RMSE met the calibration metric in all months.

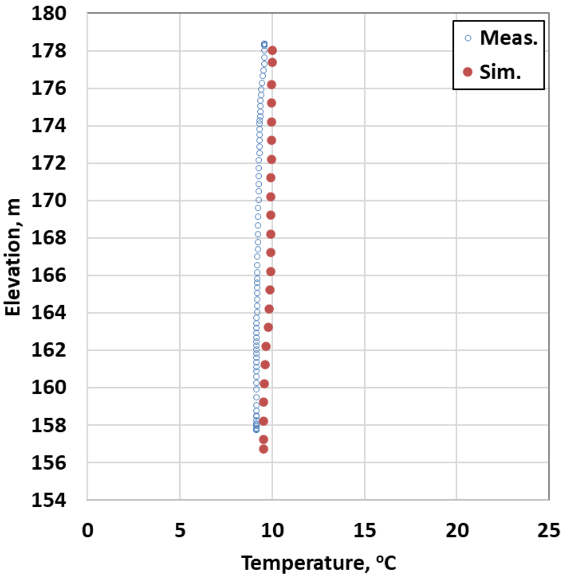
NSE ranged from -23.14 (May 18, above Spring Creek) to 0.88 (April 14, below Spring Creek). NSE was below the calibration metric of ≥0.65 for all the profiles except April 14, below Spring Creek (0.88). NSE tended to have lower values under isothermal or near isothermal conditions typical of Keswick 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.



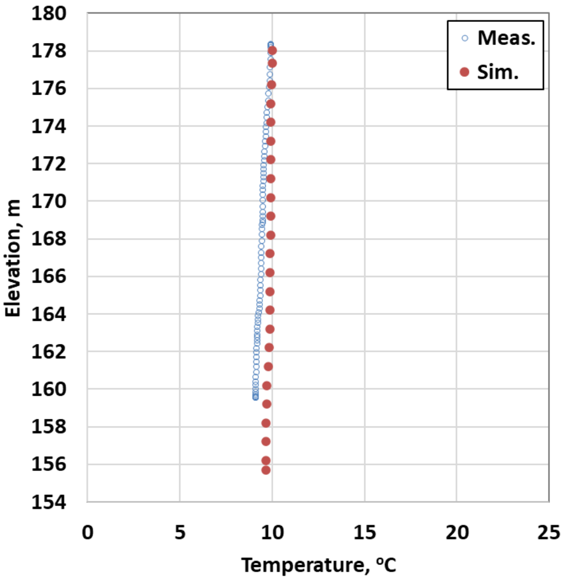
Seg.87(abv. Spr.Cr. branch)_01/21/10



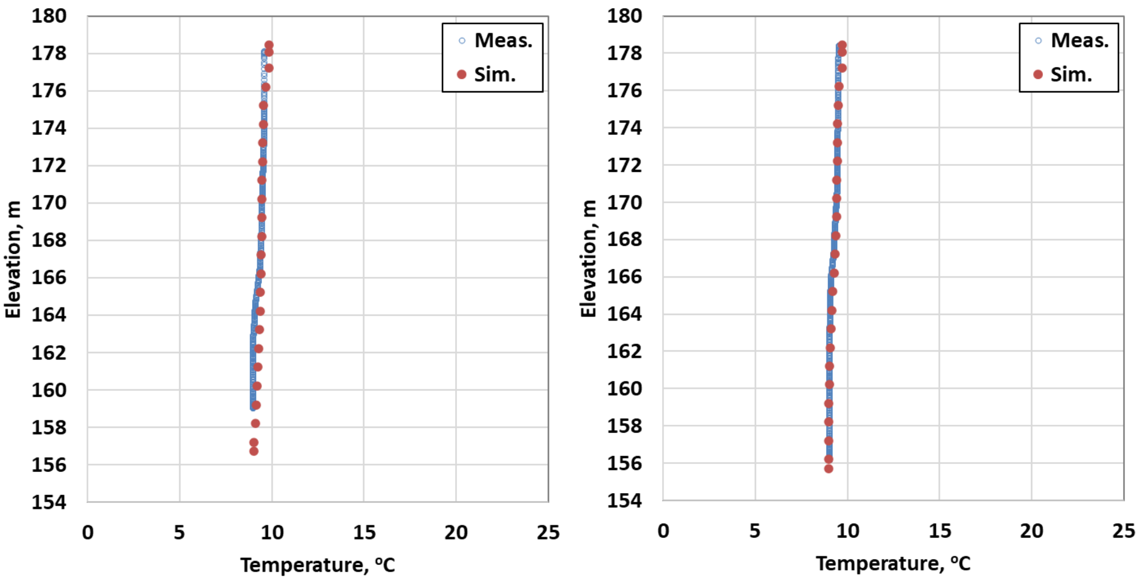
Seg.93(bel. Spr.Cr. branch)_01/21/10



Seg.87(abv. Spr.Cr. branch)_03/30/10

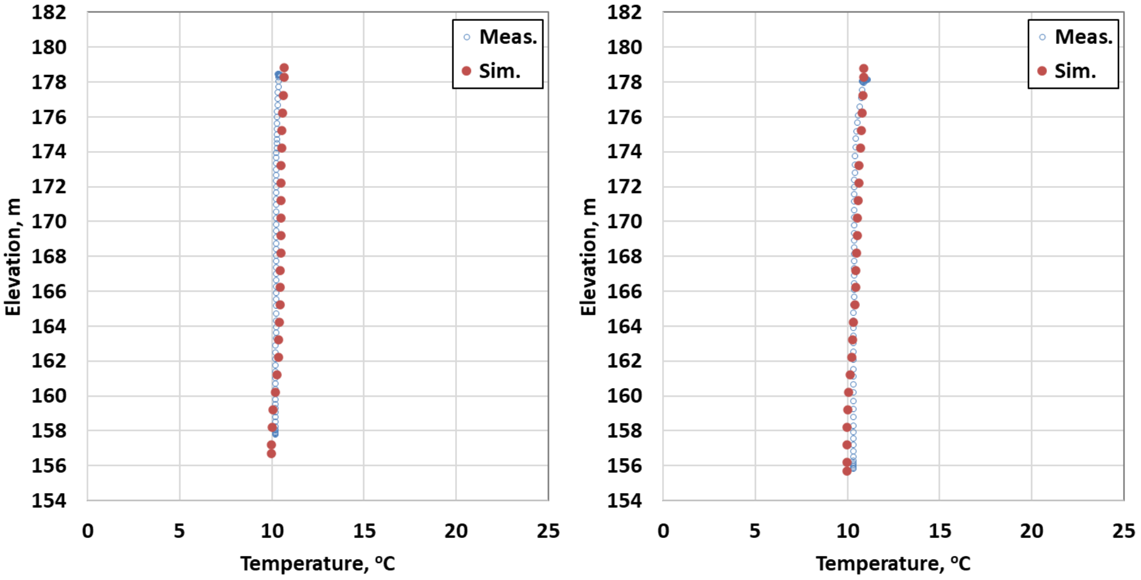


Seg.93(bel. Spr.Cr. branch)_03/30/10



Seg.87(abv. Spr.Cr. branch)_04/14/10

Seg.93(bel. Spr.Cr. branch)_04/14/10



Seg.87(abv. Spr.Cr. branch)_05/18/10

Seg.93(bel. Spr.Cr. branch)_05/18/10

Figure 38. Simulated versus measured temperature profiles. 01/21 & 03/30 (top), 04/14 & 05/18 (bottom). Year 2010.

Table 32. Mean bias for monthly temperature profiles for Keswick Reservoir: 2010. (Highlighted cells indicate values were 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**		**3/30/10**		**4/14/10**		**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

6.3.4. 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 39. Mean bias ranged from -0.03ºC (2005, 2016) to 0.08ºC (2011). Mean bias met the calibration metric for all years (Table 33). 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 Appendix E (Figure E-37 through Figure E-54).

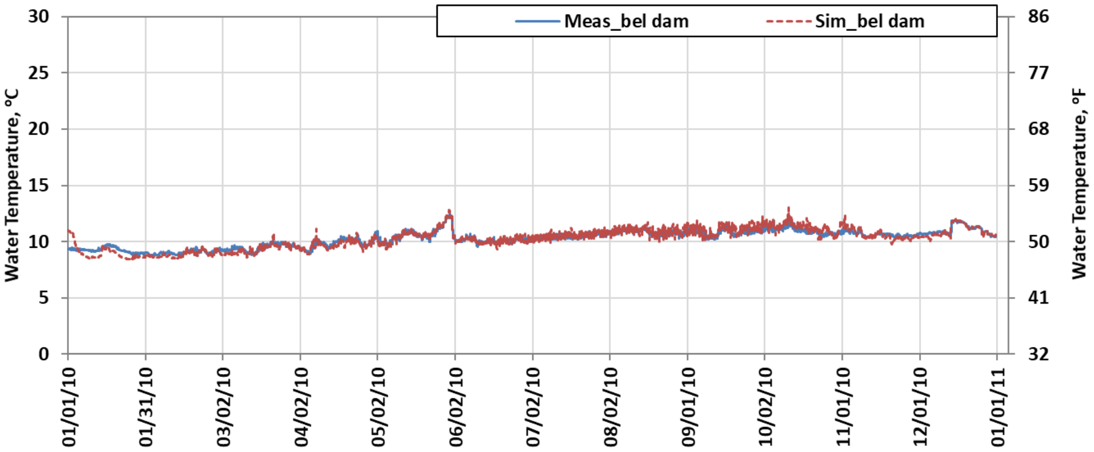


Figure 39. Simulated versus measured temperature below Keswick Dam. Year 2010.

Table 33. Summary statistics of Keswick Dam outflow temperature: 2000-2017.

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**		
Mean Bias (ºC)	-0.01	0.08	-0.01	0.04	0.03	0.03	-0.03	0.00		
MAE (ºC)	0.24	0.24	0.17	0.22	0.22	0.26	0.18	0.15		
RMSE (ºC)	0.32	0.32	0.23	0.33	0.29	0.34	0.23	0.21		
Nash-Sutcliffe (NSE)	0.82	0.82	0.94	0.93	0.98	0.92	0.93	0.96		
COUNT	8,668	8,735	8,739	8,639	8,731	8,642	8,762	8,745		

6.4. Model Validation

Calendar years 2018 and 2019 were used as model validation for the SLM and KRM. 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.

6.4.1. Shasta Lake

Mean bias, MAE, RMSE, and NSE were calculated for Shasta Lake stage, outflow, temperature profiles, and outflow temperatures for 2018 and 2019 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 34 and Table 35). SLM simulated temperature profile results (Table 36 through Table 39) indicate that validation period metrics are within the range of the calibration results. 2019 mean bias and MAE were outside the range of selected model performance criteria for June through November, simulating warmer than observed conditions (Table 21). 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. 2018 and 2019 simulated outflow temperatures were consistent with the 2000-2017 period (Table 40). The model was not recalibrated following validation. Validation results for 2018 and 2019 are included with calibration results in Appendix E.

Table 34. Summary statistics of Shasta Lake stage comparing validation years 2018 and 2019 versus calibration period 2000-2017 (light grey text)

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 35. Summary statistics for Shasta Dam outflow comparing validation years 2018 and 2019 versus calibration period 2000-2017 (light grey text).

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 36. 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). (Highlighted cells indicate values were outside the calibration criteria of ±0.75ºC.)

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 37. 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). (Highlighted cells indicate values were greater than the calibration criteria of 1.0ºC.)

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 38. 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). (Highlighted cells indicate values were greater than the calibration criteria of 1.5ºC.)

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 39. 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). (Shaded cells indicate values were outside the calibration criteria)

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 40. Summary statistics of Shasta Dam outflow temperature comparing validation years 2018 and 2019 versus calibration period 2000-2017 (light grey text). (Shaded cells indicate values were 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

6.4.2. Keswick Reservoir

Mean bias, MAE, RMSE, and NSE were calculated for Keswick Reservoir stage, outflow, temperature profiles, and outflow temperatures for 2018 and 2019 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 41 and Table 42). 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). 2018 and 2019 simulated outflow temperatures were consistent with the 2000-2017 period (Table 43). KRM simulated temperature profile results for the 15th of each month where data were available (Table 44 and Table 45) indicate model performance for the validation period was consistent with metrics. The model was not recalibrated following validation. Validation results for 2018 and 2019 are included with calibration results in Appendix E.

Table 41. Summary statistics of Keswick Reservoir stage comparing validation years of 2018 and 2019 versus calibration period 2000-2017 (light grey text). (Shaded cells indicate values were 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 42. Summary statistics of Keswick Reservoir outflow comparing validation years of 2018 and 2019 versus calibration period 2000-2017 (light grey text). (Shaded cells indicate values were 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 43. Summary statistics of Keswick Reservoir outflow temperature comparing validation years of 2018 and 2019 versus calibration period 2000-2017 (light grey text). (Shaded cells indicate values were 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 44. 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. (Highlighted cells indicate values were outside the calibration criteria).

Statistic	Date (MM/DD)							
	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 45. 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. (Highlighted cells indicate values were outside the calibration criteria).

Statistic	Date (MM/DD)							
	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

6.5. 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 Shasta Lake and Keswick models through the implementation, calibration, refinements, and extension of the model to the 18-year period[17]. In this multifaceted, complex system a formal sensitivity analysis would be a large effort. For this study, selected model parameters for CE-QUAL-W2 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.

6.5.1. 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 46. Parameter definitions can be found in Cole and Wells (2008).

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[17] 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.

Table 46. Parameters and their relative sensitivity for the Shasta Lake CE-QUAL-W2 model.

Parameter	Sensitivity	Notes
AFW	M	AFW was moderately sensitive and a range of values were explored. The default value of 9.2 was modified slightly to a value of 9.45 during model calibration.
BFW	M	BFW was moderately sensitive and a range of values were explored. The default value of 0.46 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.

6.5.2. Keswick Reservoir

Generally, simulated temperature was insensitive to parameters listed in Table 46 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.

6.6. Shasta Lake – Keswick Reservoir: Coupled Model Performance

Once the individual model calibration and validation were completed, the models were run in series to assess overall model performance that included a coupled Shasta Lake – Keswick Reservoir model. To complete this exercise, simulated flow and water temperature conditions from the Shasta Lake Model were used as input into the Keswick

Reservoir model. Because flow is a specified boundary condition for the CE-QUAL-W2 model, the Shasta Dam and Keswick Dam releases were unchanged. Thus, these simulations reflect changes in water temperatures using the coupled models. Summary statistics of Keswick Dam release temperatures for the coupled Shasta Lake-Keswick Reservoir model simulation over the 2000-2019 period are tabulated in Table 47.With the exception of 2019 for the NSE metric, all model performance metrics were met.

Table 47. Summary statistics for Keswick Reservoir outflow temperature for the coupled Shasta Lake-Keswick Reservoir model simulation: 2000-2019.

Statistic	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Mean Bias (ºC)	0.04	0.23	0.20	0.05	-0.15	0.08	-0.08	0.00	0.08	0.41
MAE (ºC)	0.22	0.38	0.34	0.20	0.37	0.26	0.29	0.34	0.33	0.49
RMSE (ºC)	0.31	0.54	0.45	0.26	0.47	0.32	0.36	0.44	0.43	0.67
Nash-Sutcliffe (NSE)	0.89	0.86	0.84	0.90	0.90	0.93	0.87	0.90	0.96	0.85
COUNT	8,220	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)	0.06	0.15	0.09	0.17	0.26	0.21	0.25	0.18	-0.02	0.38
MAE (ºC)	0.36	0.28	0.24	0.39	0.38	0.40	0.37	0.33	0.30	0.57
RMSE (ºC)	0.44	0.36	0.32	0.55	0.49	0.51	0.51	0.40	0.37	0.73
Nash-Sutcliffe (NSE)	0.65	0.78	0.89	0.82	0.94	0.82	0.65	0.84	0.78	0.16
COUNT	8,668	8,735	8,739	8,639	8,731	8,642	8,762	8,745	8,730	8,696

Coupled model results were also examined considering individual model performance. Simulated Shasta Dam outflow temperature (Shasta Lake only model), simulated Keswick Dam (Keswick Reservoir only model), and Keswick Dam for the coupled Shasta Lake – Keswick Reservoir models performance metrics are shown in Figure 40. Mean bias for the coupled model was at times less than and at times greater than mean bias for both Shasta Lake (alone) and Keswick Reservoir (alone) simulated outflow temperatures. The mean bias calculation will result in positive and negative values at certain times canceling and at other being additive. MAE and RMSE for the coupled model were always greater than or equal to the Keswick Reservoir (alone) model; however, the coupled model was both higher and lower than the Shasta Lake (alone) model. NSE for the coupled model and the Shasta Lake (alone) did not meet the calibration criteria while Keswick Reservoir (alone) model did achieve the criteria in 2019. In 2000, 2010 and 2016 the Shasta Lake (alone) model did not meet the NSE criteria, but the coupled model did achieve the criteria. These results illustrate the complex nature of uncertainty propagating through the coupled model (i.e., from the Shasta Lake model through the Keswick Reservoir model), and thus the value of models in quantifying and assessing modeling framework uncertainty.

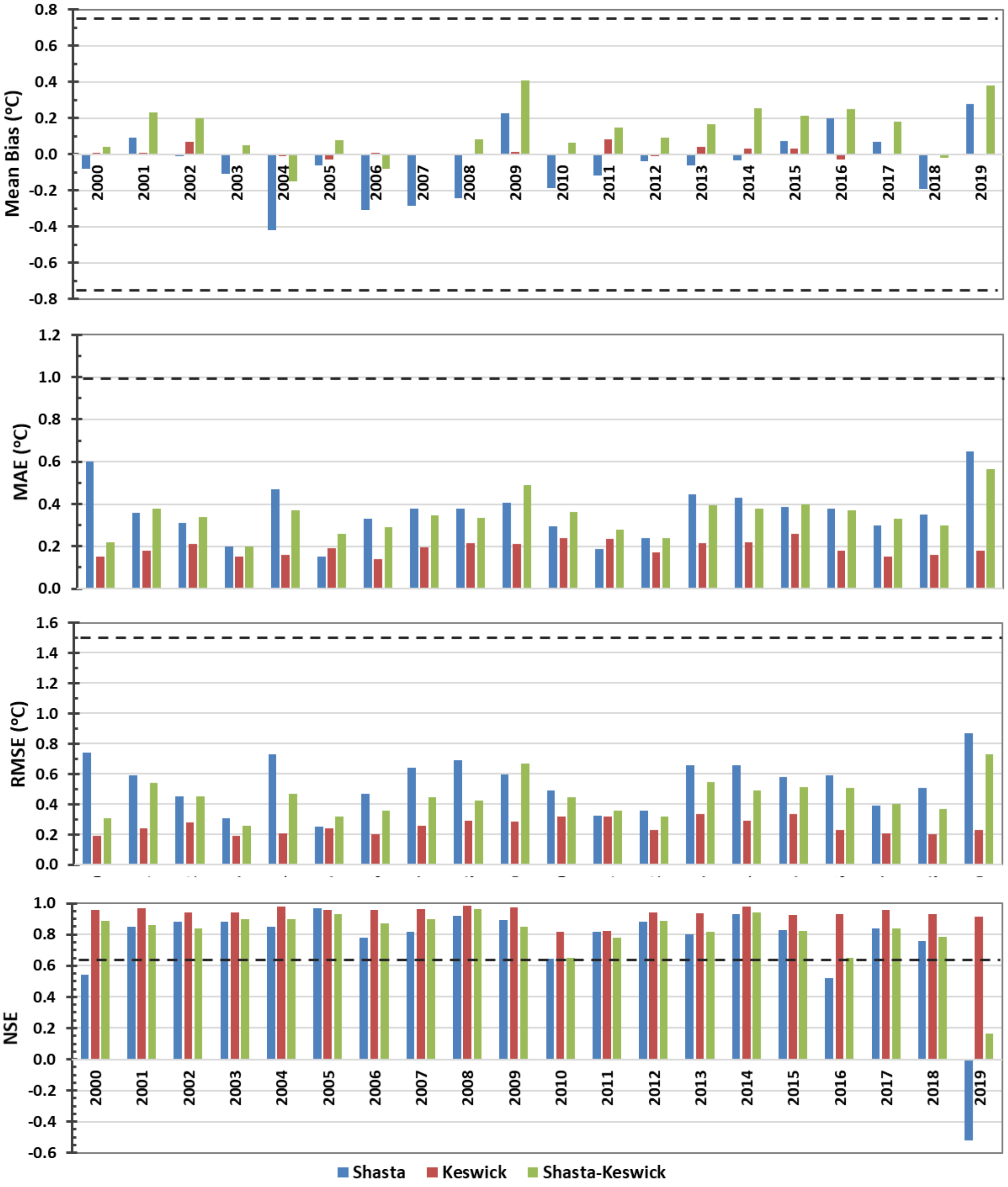

Figure 40. Summary statistics for Mean Bias, MAE, RMSE, and NSE (top to bottom) for Keswick Dam outflow temperature for coupled Shasta Lake-Keswick Reservoir model (Shasta-Keswick) and the Keswick Reservoir model (alone), and outflow temperature for Shasta Lake model (alone) including performance metrics (dashed lines): 2000-2019.

7. Field Monitoring

As part of the Shasta lake temperature model development effort, selective field monitoring efforts have been put into place. In addition to the bathymetry field work completed in Keswick Reservoir (addressed above in section 3.2.1, see also Deas and Sogutlugil (2017b)), water temperature monitoring in Shasta Lake and Keswick Reservoir has been completed.

7.1. Shasta Lake

Through the MTC, three locations - in addition to the current temperature profile immediately upstream of Shasta Dam - were identified locations where additional water temperature profile information in the lake would improve the understanding of in-lake thermal conditions and provide information to assess and test model representation. Additional water temperature profiles were collected in the main tributary arms at Shasta Lake using manual sampling techniques during the months of June, July, August, and September in 2019 (Figure 41). This effort was designed to confirm the extent of longitudinal homogeneity of lake thermal stratification assumed in model development. The effort and preliminary results are included in UBSR (2019), and a sample is included in Figure 42, illustrating general uniform temperature conditions in the lake arms at depth. Near surface variations occur, and may be in response to local, short duration wind mixing coupled with variable diel thermal loading.

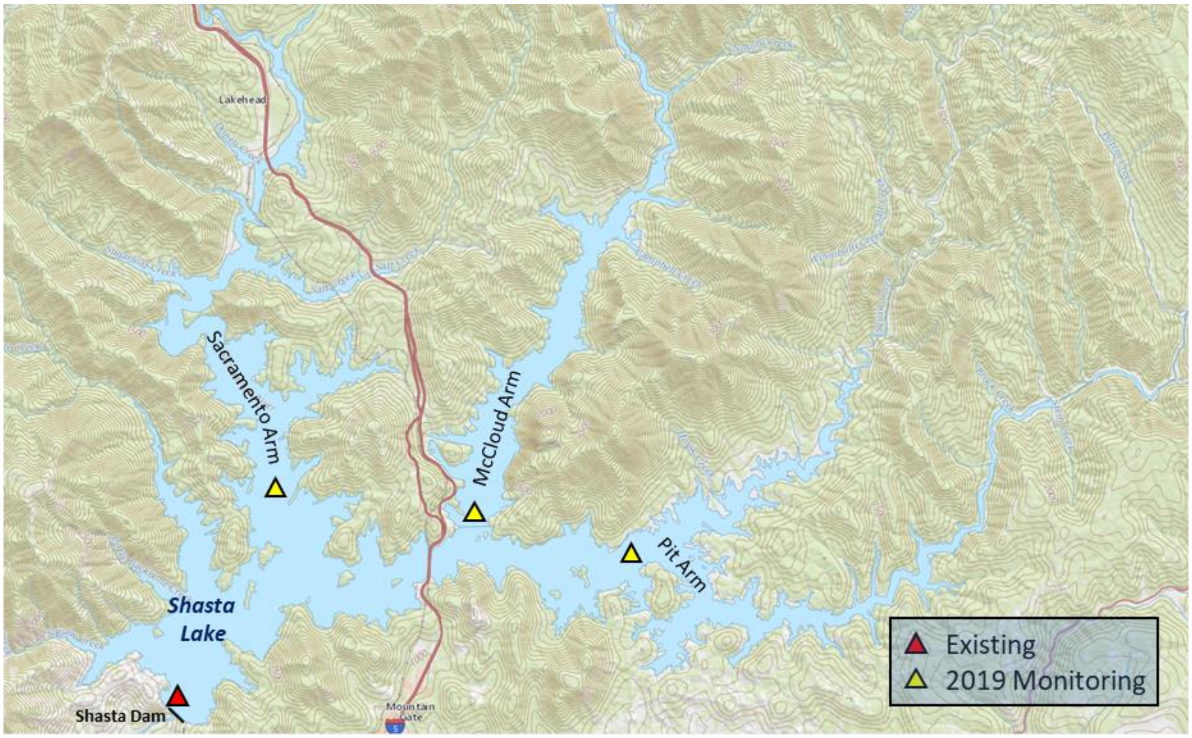

Figure 41. Location of existing thermal profile measurements and 2019 thermal profile measurements.

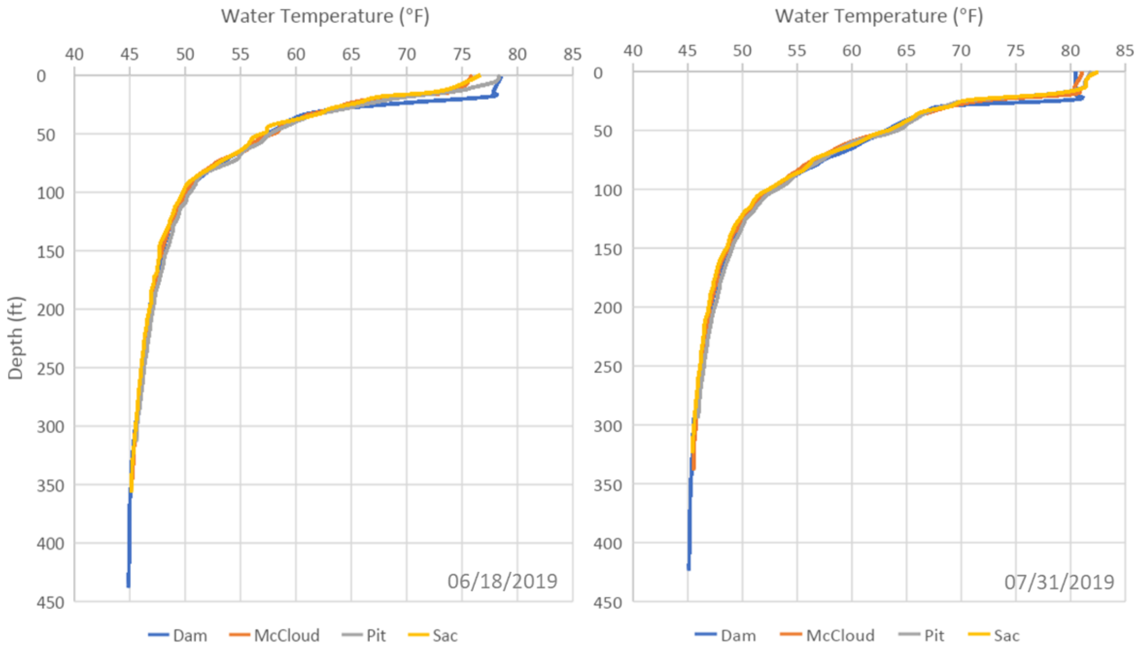

Figure 42. Preliminary results of the 2019 temperature profiles at Shasta Lake at the Dam, Sacramento Arm, McCloud Arm, and Pit Arm locations: 06-18-2019 and 07/31/2019.

7.2. Keswick Reservoir

Temperature profile monitoring was implemented in Keswick Reservoir on September 6. 2017 and has been deployed seasonally[18] through December 31, 2019. Water temperature profile information was collected in the reservoir using remote logging thermistors (temperature loggers) attached to a cable system suspended from the log boom upstream of the dam (Figure 43). Loggers were typically spaced at intervals of 10 feet. The effort is intended to collect vertical profile temperature information in Keswick Reservoir to support current and future modeling efforts. Water temperature data from the surface to a depth of 70 feet are shown in Figure 44, indicating the seasonal deployments and the interruption in 2018 due to the Carr fire.

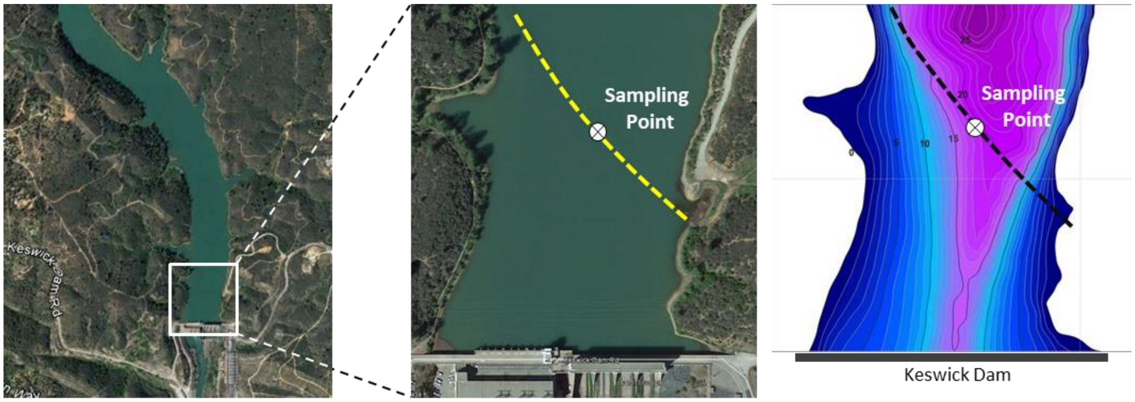

Figure 43. Keswick Reservoir - plan view. Project area (left); sampling point along log boom (middle); sampling point along log boom with bathymetry (right).

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[18] The thermistor cable is removed in winter to avoid potential fouling with debris during high flow events.

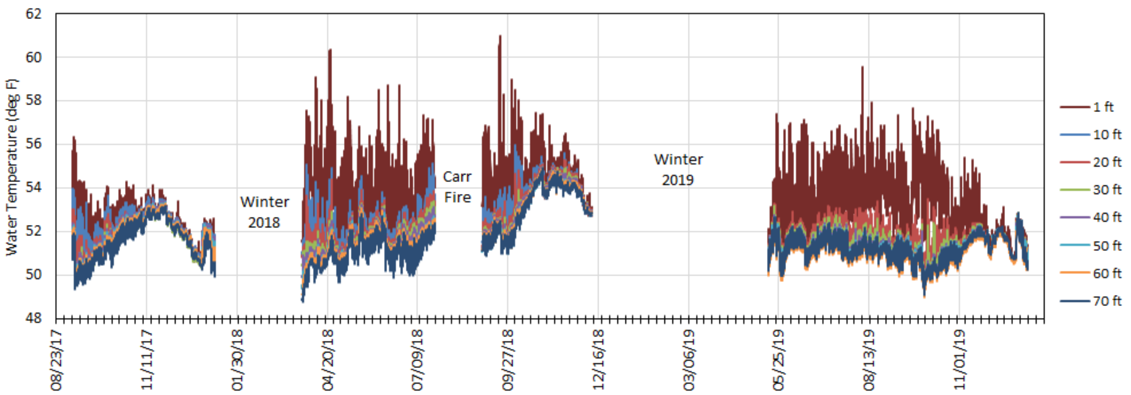

Figure 44. Keswick Reservoir thermistor cable water temperature time series: 9/6/17 to 12/31/2019.

The 2017 data are used in this report to assess model performance for Keswick Reservoir calibration, and 2018 and 2019 for validation. Thermistor cable equipment and methods, thermistor quality assurance, and data summary narratives are included in Deas (2017, 2019) and Semmens and Deas (2020). Field data are available at the Environmental Data Initiative data portal at https://doi.org/10.6073/pasta/0c882e7ef146dc73fe8a64fed9a08ffb and general information about the Environmental Data Initiative can be found at (https://portal.edirepository.org/nis/home.jsp).

8. Summary and Recommendations

The two-dimensional, laterally averaged CE-QUAL-W2 model, representing longitudinal and vertical variations, was successfully developed and calibrated for Shasta Lake and Keswick Reservoir. The project utilized existing information and models in the development of new models to assist operators managing Shasta Lake, as well as other facilities, for water temperature management in downstream Sacramento River reaches. The Shasta Lake Model (SLM) and Keswick Reservoir Model (KRM) were constructed to assist resource managers in assessing for mid- to short-term temperature management, particularly under lower storage conditions to:

- Identify cold-water pool volumes early in the calendar year (e.g., late-March to late-April period)
- Based on the initial cold-water pool volume, forecast the impacts of potential operational strategies on water temperatures through the temperature control period (late spring into fall)
- Assist in the development of a cold-water management plan that incorporates uncertainty in model representation and future conditions (e.g., inflow quantity and temperature, meteorology, and forecasts of such conditions).

Model selection, an overview of the Shasta-Keswick system, a description of the Shasta Dam Temperature Control Device (TCD) operations, and definitions of water temperature management considerations are presented. Necessary model data development for Shasta Lake and Keswick Reservoir during model implementation are presented, including geometry, hydrologic, water temperature, and meteorological data.

The steps of model implementation are detailed, including grid development, boundary conditions and initial conditions. Unique TCD features required extending the CE-QUAL-W2 model approach and logic to represent the large gate opening, the low-level intake operation, and blending between different levels of the TCD. Representation of the low-level intake included a unique use of multiple point sinks, that ultimately provided a means to simulate both in-reservoir profiles and Shasta Dam outflow temperatures during late season, low storage conditions – conditions that occurred in 2014 and 2015.

Model calibration was carried out over the 2000-2017 period and validated for 2018 and 2019 for both the SLM and KRM. Calibration metrics were developed and used to assess model performance for bias, absolute error, and goodness-of-fit. Model results were also assessed graphically to qualitatively assess model performance. Application of calibration metrics with the broad statistical approach provided a means to characterize model uncertainty for a range of hydrology and meteorology (20 years) that included drought periods. Model performance was quantified for the individual applications (SLM alone, and KRM alone) as well as a coupled SLM-KRM application where simulated output from SLM was used as input to KRM.

The assistance of the MTC was instrumental in model development. Some elements of model development are ongoing, and are addressed in the recommendations section, below.

8.1. Recommendations

Throughout the model development and testing process, several areas where additional information or insight would improve model representation were identified. Recommendations focus on data, model representations or assumptions, and model application.

Modeling Data: overall, most data requirements to develop and apply models to Shasta Lake and Keswick Reservoir are met through current monitoring efforts. Recommendations identified herein address continuing these efforts, as well as developing specific efforts to improve model representation of the TCD and operations.

- *Continued collection of key modeling data*: Model boundary condition and calibration data, including inflow, inflow temperature, reservoir outflow, outflow temperature, in-lake temperature profiles, and meteorological conditions were available for much of the entire period of simulations. Additional temperature profile data were collected in both Shasta Lake (discrete profiles at three additional locations 4 times in 2019), and Keswick Reservoir (thermistor string suspended from log boom late 2017 to present, with winter data gaps). Much of this data was collected outside the 2000-2017 calibration period. Recommendations regarding monitoring data for model input and calibration data sets includes:

  - Continued data collection
    - Ensure the continued collection of basic model data needs identified above and included in Section 3. These data are collected by several entities, including but not limited to Reclamation, USGS, PG&E, DWR, NOAA, and others.
    - Continue collection of temperature profile data using a thermistor string at the Keswick Reservoir log boom.
  - New data collection
    - In 2020 collect temperature profile data at the Shasta, McCloud, and Pit River arms of Shasta Lake (approximately 4 times through the temperature season). A second year of data collection would confirm uniform vertical temperature distribution in the lake arms under different storage conditions.
    - Collect meteorological data at Shasta Dam.
    - Consider collecting meteorological data at locations upstream of Shasta Dam to characterize potential spatial variations over the area of the reservoir surface.

- *TCD characterization*: Additional data to confirm or refine assumptions regarding TCD representation in the model could improve simulation performance of this critical infrastructure in water temperature management in the Shasta Lake and the Sacramento River. Specifically, quantifying the amount of water entering open gates at any specific level, as well as the velocity of water in the vicinity of the TCD within Lake Shasta would lend important insight into TCD dynamics. This work should be completed in more than a single phase to ensure that equipment and technical approach will provide information sufficient to address flow into the TCD, as well as capture a range of storage, temperature, and operational conditions. All field work would be coordinated with Reclamation. Recommendations include:
  - <u>TCD performance</u>: While the TCD is a remarkably effective and useful facility, the hydrodynamic challenges, and physical limitations of the structure lead to important operational considerations. Understanding these constraints and limitations of the TCD, as well as the uncertainty they may represent, will improve model representation of the structure and the usefulness of the tool in decision making. Recommend continuing to

    work with Reclamation on TCD specific characterization, maintenance (e.g., ROV inspections), operations, and other TCD related topics.

    - <u>TCD Inflows</u>: Complete an assessment of velocity measurement in the vicinity of the TCD. The work would utilize acoustic Doppler current profiler (ADCP), or similar velocity profiler and/or turbulent measurements to characterize the local velocities and vertical (and lateral) extent of withdrawal zones into open TCD gates. Flow into the low-level outlet may be challenging to capture, but existing and pending technology and equipment suggest that capturing field observations is feasible. Subsequent phases of this work may include assessing different gate and level settings, blending of two levels, and extended assessments to explore the dynamic nature of flow regimes in response Shasta Dam releases and TCD operations. This work will be valuable in assessing the point sink representation for large gates, blending assumptions, and the TCD_d representation for the low-level intake structure.

    - <u>Boundary Effects</u>: Explore available bathymetric surveys in the region of Shasta Dam and TCD to improve the understanding the potential role that reservoir boundaries (bed and banks) have on flows entering the TCD. Focus should be on lower level and low-level intake structure regions, where the TCD is close to the bed of the reservoir, and areas upstream of the TCD. Additional bathymetry of Shasta Lake should be collected as feasible to corroborate the bathymetry developed from existing historical pre-dam topographic maps.

- *Long-term Thermistor String Data*: Reclamation has deployed a thermistor string with loggers collecting data at hourly intervals for the better part of two decades in Lake Shasta. Watercourse used some of these data as a secondary source to the weekly or monthly measured profiles collected by Reclamation staff. This highly temporal data set could be examined in greater detail to provide additional insight into model calibration and developing forecasting protocols. Recommendation:

    - <u>Thermistor string</u>: maintain existing thermistor string data collection.

<u>Model Application</u>: Use the existing model (20 years) to assess a range of conditions including operations as well as forecasting. Recommendations include:

- *Model Refinement*: through model application identify areas of model refinement. The expectation is that when applying the model to any of various conditions or configurations, model and data constraints will emerge. As these topics are revealed, recommend using the MTC for discussion, assessment, and prioritization. Document outcomes.

- *Historical period models*: With the current modeling period spanning nearly two decades and wide range of hydrology and meteorology, the SLM-KRM framework can be used to explore planning level analyses over a range of hydrology, meteorology, and temperature conditions. Explore methods to simulate multiple years with CE-QUAL-W2 to allow efficient long-term simulations.

- *Forecasting*: With the completion of this year's forecasting quickly approaching an end (end of 2019), work cooperatively with Reclamation to develop methods using the 2018 season, to further test the model in a forecasting mode. Document approach with respect to data needs and assumptions, operations, downstream temperature targets, meteorological estimations, and other information.

Data Management: Develop data management protocols for modeling activities. Recommendation:

- *Protocols*: Continue to work closely with Reclamation to develop protocols for managing (i) model input time series, (ii) model calibration data, (iii) model output (simulated time series), (iv) monitoring data, (v) meta data, and other data related tasks.

Modeling Technical Committee (MTC): The MTC is a principal component of model development, model application, and outreach. Recommend:

- *Meetings*: Continue the MTC through the forecasting assessment, model updates, model applications, and other related modeling activities. Training on how to use the SLM-KRM framework (e.g., newly added selective withdrawal logic) should occur through the MTC. Further, consider an annual presentation to a larger group (e.g., science conference) to extend awareness of the MTC and associated activities to a broader group.

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Appendices

- Appendix A – TCD Leakage Sensitivity
- Appendix B – TCD Operations Log
- Appendix C – Selective Withdrawal using W2_TCD
- Appendix D – Shasta Lake Model Results and Model Performance Statistics. Years 2000 - 2017
- Appendix E – Keswick Reservoir Model Results and Model Performance Statistics. Years 2000 - 2017

Appendix A. TCD Leakage Distribution Assessment

To assess the impact of vertical distribution of leakage and total leakage volume, 2013, 2014, and 2015 were simulated under different leakage assumptions. 2013 simulations assessed total leakage amount and vertical distribution, and simulations in 2014 and 2015 assessed for total leakage amount.

Total TCD leakage fraction was set to 0.2 (20 percent of the total TCD outflow to the powerhouse) based on the RMA (2003) estimate. TCD leakage distribution for the baseline condition (run a) is based on historical conditions, as identified in Figure 17 and Table 17. To test model sensitivity to leakage assumptions on model results, three sensitivity simulations were completed and compared to the baseline (historical). Run_b represents a reduced leakage fraction of 0.15 (vs 0.20) for 2013, 2014, and 2015. Run_c and Run_d represent distributions where leakages are increased at shallower depths and at deeper depths, respectively (Table A-1). All other model assumptions remained unchanged.

Table A-1. TCD leakage features in the four identified scenarios.

Run Name	Leakage Distribution	Maximum Total Leakage Fraction
Run_a (baseline)[1]	Baseline[2]	0.20
Run_b[1]	Baseline[2]	0.15
Run_c[3]	15 percent was added to the baseline (historic) relative percent (BRP) of Zone 1[4] when water surface elevation was above 945 ft (288.0 m) 15 percent was subtracted from the BRP of Zone 5.	0.15
Run_d[3]	0.25 of the BRP was assigned to Zone 1 0.75 of the BRP of Zone 1 was added to the BRP of Zone 6	0.15

[1] Performed for years 2013, 2014 and 2015
[2] See Table 17
[3] Performed for year 2013

[4] See Figure 17 and Table 15

Based on the leakage distributions listed above, the relative percentages of six leakage zones for the runs mentioned above are included in Figure A-1. Also, maximum total leakage percentage represents leakage when all the TCD gates are closed, versus simulated total leakage percentage time-series graphs for the same runs are included in Figure A-2.

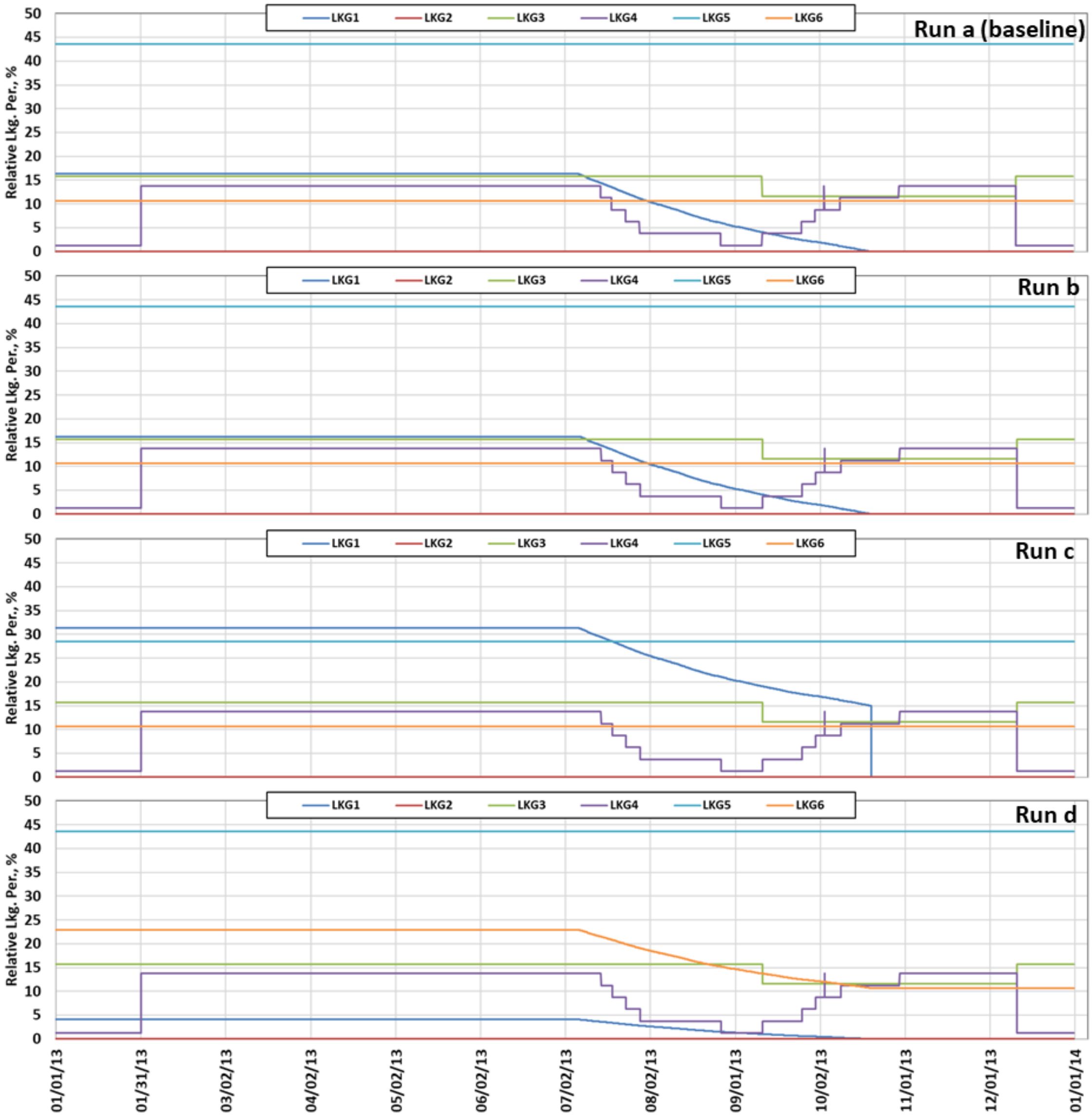


Figure A-1. Relative percentages of the TCD leakage zones LKG1 to LGK6 for (top to bottom) Run_a (baseline), Run_b, Run_c, and Run_d: 2013.

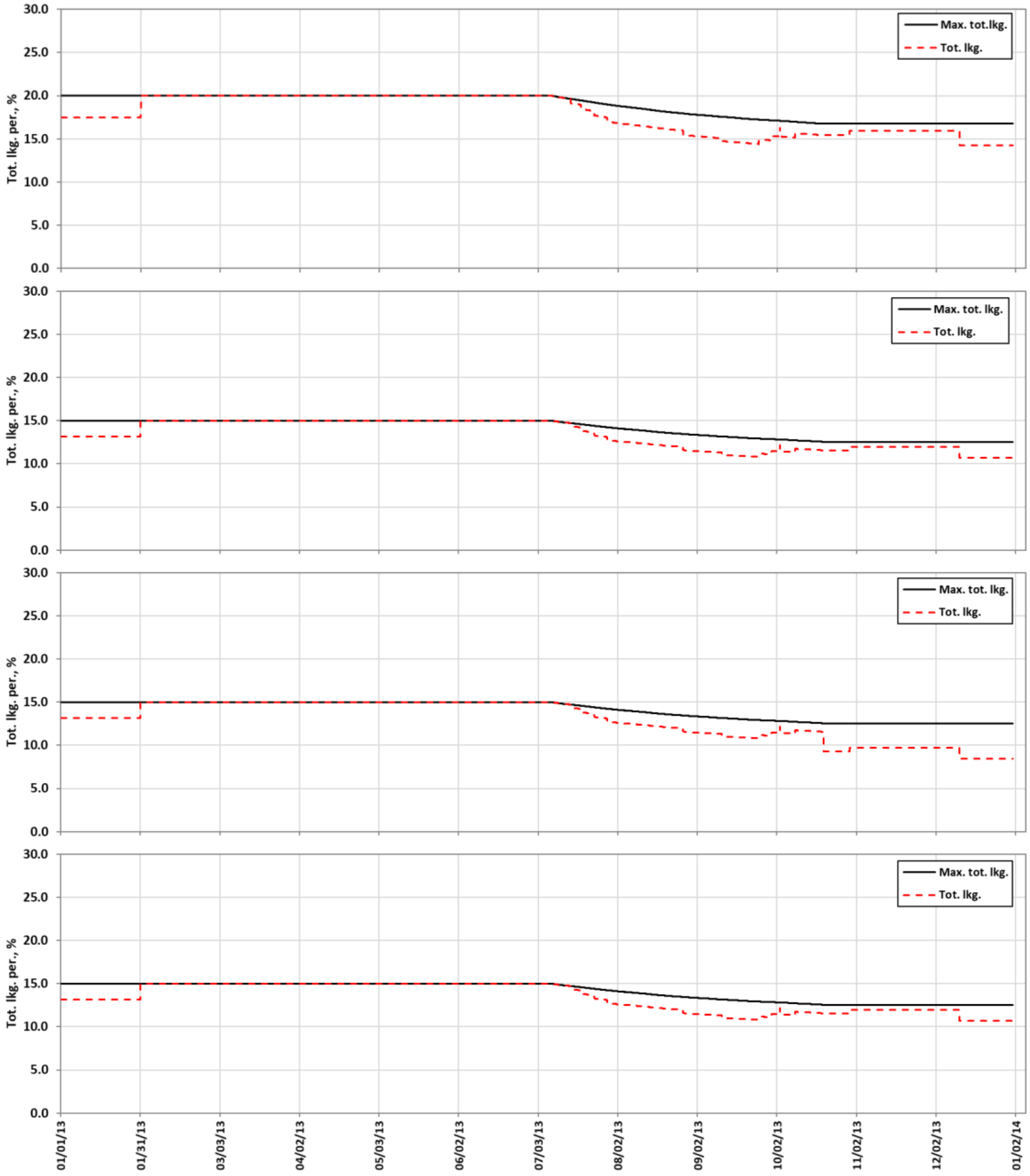


Figure A-2. Maximum total TCD leakage percentage vs. maximum total TCD leakage percentage. From top to bottom, Run_a, Run_b, Run_c, Run_d: 2013.

Shasta Dam outflow temperature results for the three runs with different leakage distributions and total leakage fraction than baseline were insensitive to the changes within the tested ranges for 2013 (Figure A-3). Findings were similar for different total leakage fractions in 2014 and 2015 (Figure A-4 and Figure A-5, respectively). Daily averages of the hourly simulated temperatures are included in the figures. Statistics quantifying the relative difference between baseline and the various runs are included in Table A-2 based on hourly simulated values (for additional information on the statistics used in this analysis, the reader is referred to Section 6). Mean bias, mean absolute error (MAE), root mean squared error (RMSE), and Nash-Sutcliffe efficiency coefficient

(NSE) among the four scenarios for 2013 vary by 0.03°C, 0.05°C, 0.08°C and 0.06, respectively. Among the two runs in years 2014 and 2015, ranges of the same statistics are the same or differ by 0.04 units or less.

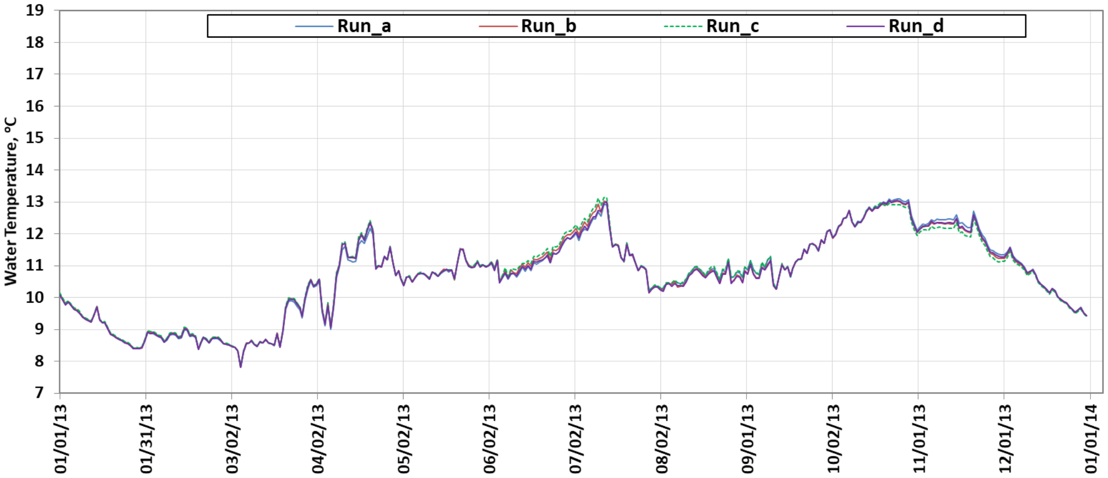


Figure A-3. Daily average simulated temperatures below Shasta Dam for Run_a, Run_b, Run_c, and Run_d for TCD leakage analysis: 2013.

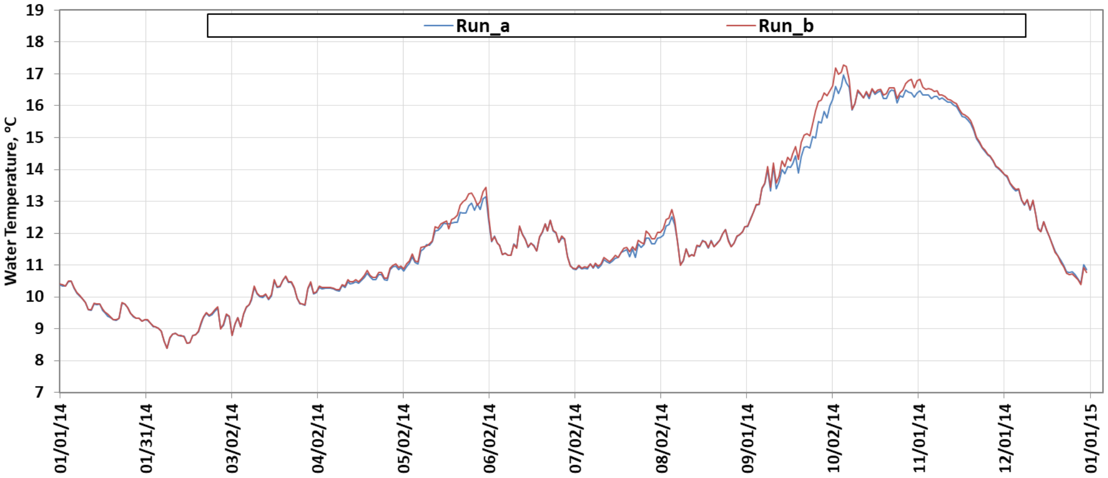


Figure A-4. Daily average simulated temperatures below Shasta Dam for Run_a and Run_b for TCD leakage analysis: 2014.

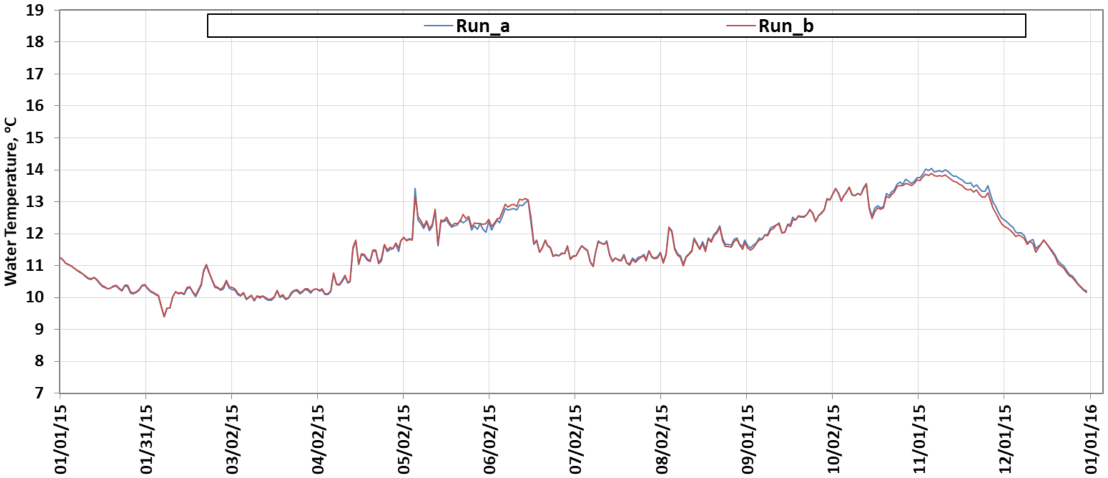


Figure A-5. Daily average simulated temperatures below Shasta Dam for Run_a and Run_b for TCD leakage analysis: 2015.

Table A-2. Temperature statistics for TCD leakage distribution assessment for years 2013, 2014, and 2015.

Year 2013

Statistic	Run_a	Run_b	Run_c	Run_d
Mean bias (°C)	-0.06	-0.06	-0.04	-0.07
Mean absolute error (MAE) (°C)	0.45	0.47	0.50	0.45
Root mean squared error (RMSE) (°C)	0.66	0.70	0.74	0.68
Nash-Sutcliffe (NSE)	0.80	0.77	0.74	0.79
COUNT	8,760	8,760	8,760	8,760

Year 2014

Statistic	Run_a	Run_b	Run_c	Run_d
Mean bias (°C)	-0.03	0.05	-	-
Mean absolute error (MAE) (°C)	0.43	0.43	-	-
Root mean squared error (RMSE) (°C)	0.66	0.62	-	-
Nash-Sutcliffe (NSE)	0.93	0.94	-	-
COUNT	8,760	8,760	-	-

Year 2015

Statistic	Run_a	Run_b	Run_c	Run_d
Mean bias (°C)	0.07	0.06	-	-
Mean absolute error (MAE) (°C)	0.39	0.42	-	-
Root mean squared error (RMSE) (°C)	0.58	0.61	-	-
Nash-Sutcliffe (NSE)	0.83	0.80	-	-
COUNT	8,760	8,760	-	-

Simulated temperature profiles above the dam were also assessed and found to be similar. For years 2013 through 2015, simulated profiles versus available measured temperature profiles (including designations of TCD gate level elevations and active gate levels) are shown in Figure A-6, Figure A-7, and Figure A-8, respectively. Summary statistics for 2013, 2014, and 2015 temperature profiles are included in Table A-3, Table A-4, and Table A-5, respectively. Highlighted cells represent statistical performance metric values outside the project range (see Section 6). Differences between Run_a and Run_b in years 2013-15, for mean bias, MAE, RMSE and NSE varied (maximum value minus minimum value) by 0.23ºC, 0.23ºC, 0.21ºC and 0.03, respectively. Differences between Run_a, Run_b, Run_c, and Run_d in year 2013, for mean bias, MAE, RMSE and NSE varied (maximum value minus minimum value) by 0.22ºC, 0.15ºC, 0.22ºC and 0.02, respectively.

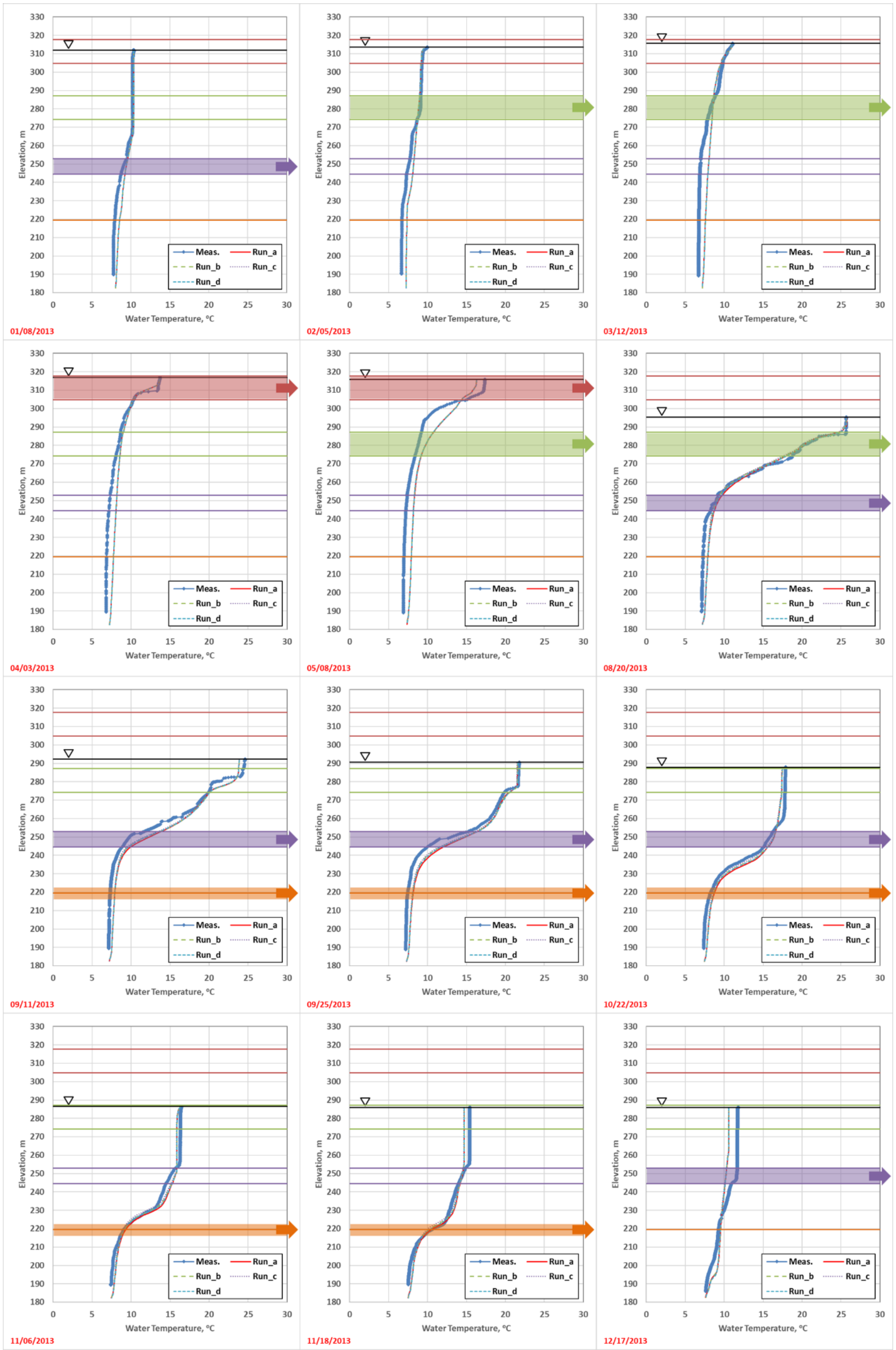


Figure A-6. Simulated vs. measured temperature profiles for TCD leakage analysis: 2013.

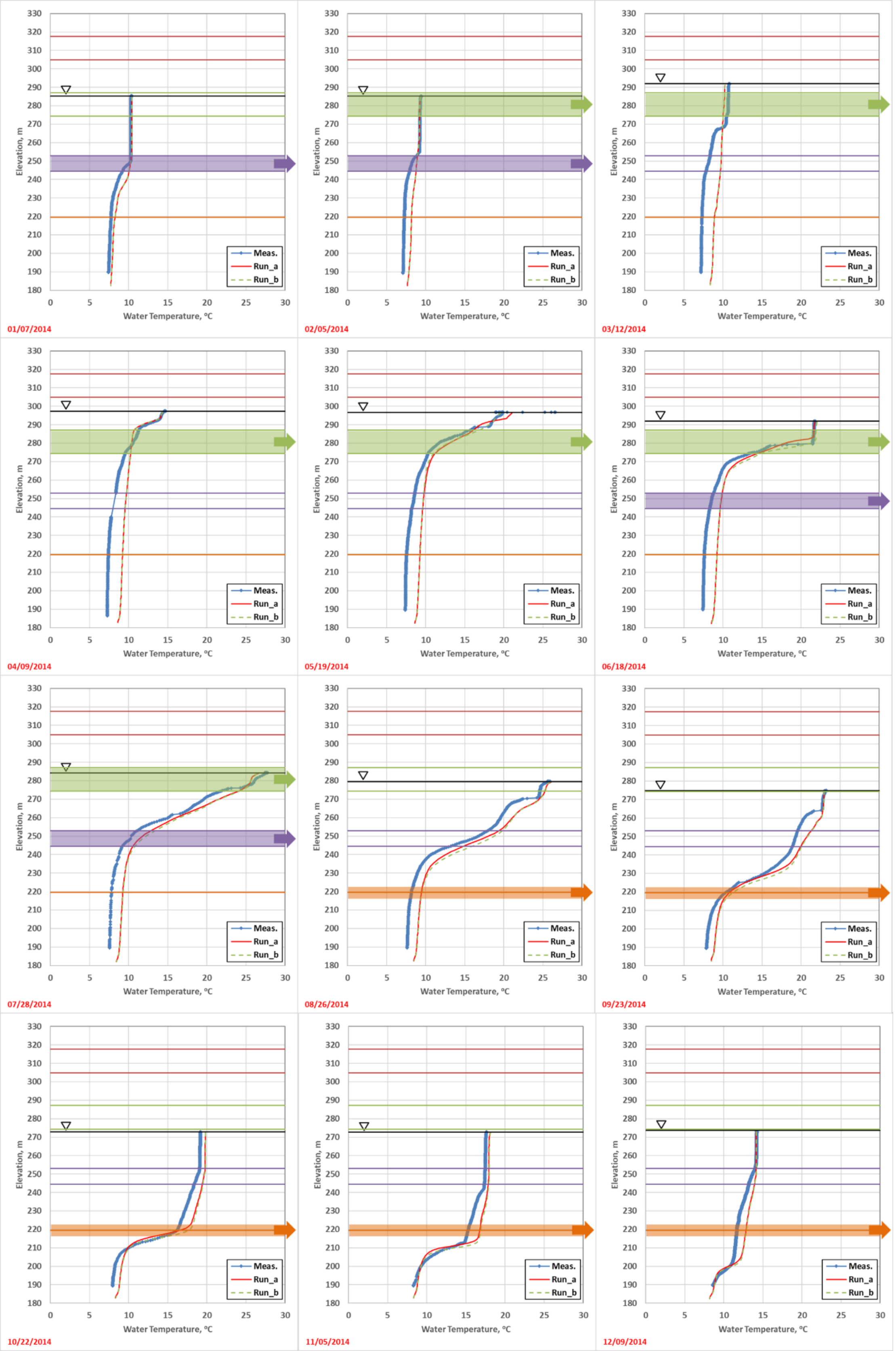


Figure A-7. Simulated vs. measured temperature profiles for TCD leakage analysis: 2014.

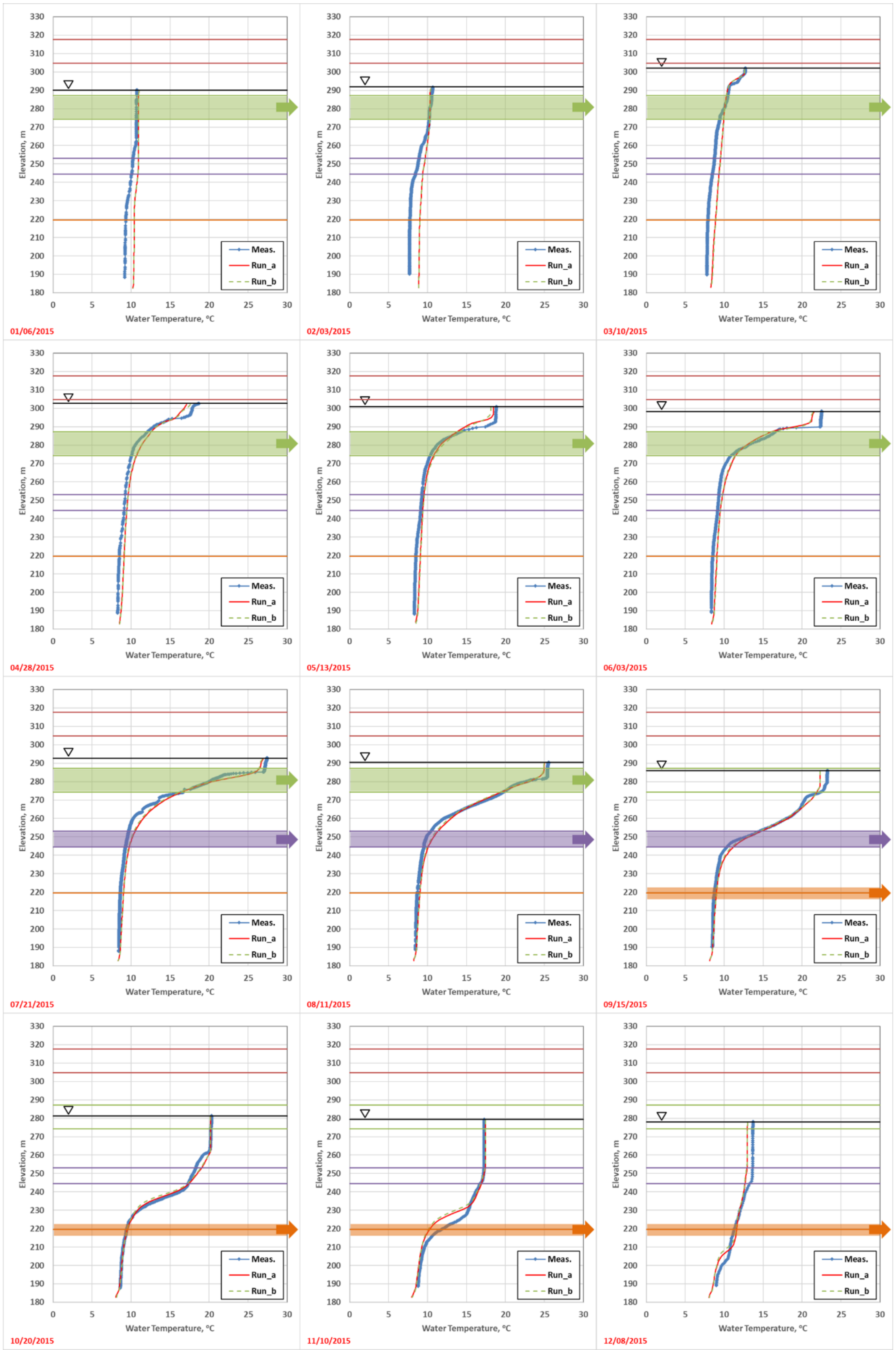


Figure A-8. Simulated vs. measured temperature profiles for TCD leakage analysis: 2015.

Table A-3. Temperature profile statistics for TCD leakage distribution assessment: 2013.

Date	Run Name	Mean Bias, ºC	MAE, ºC	RMSE, ºC	NSE	COUNT
01/08/2013	Run_a	0.35	0.35	0.42	0.84	122
	Run_b	0.35	0.35	0.42	0.84	122
	Run_c	0.35	0.35	0.42	0.84	122
	Run_d	0.35	0.35	0.42	0.84	122
02/05/2013	Run_a	0.35	0.44	0.50	0.77	123
	Run_b	0.35	0.44	0.50	0.77	123
	Run_c	0.35	0.44	0.50	0.77	123
	Run_d	0.35	0.44	0.50	0.77	123
03/12/2013	Run_a	0.54	0.67	0.73	0.64	126
	Run_b	0.54	0.67	0.74	0.64	126
	Run_c	0.54	0.67	0.73	0.65	126
	Run_d	0.55	0.68	0.74	0.64	126
04/03/2013	Run_a	0.58	0.64	0.71	0.82	127
	Run_b	0.58	0.64	0.71	0.82	127
	Run_c	0.58	0.64	0.71	0.82	127
	Run_d	0.58	0.64	0.72	0.82	127
05/08/2013	Run_a	0.87	1.08	1.16	0.84	127
	Run_b	0.85	1.06	1.14	0.85	127
	Run_c	0.85	1.05	1.13	0.85	127
	Run_d	0.87	1.07	1.15	0.84	127
08/20/2013	Run_a	0.30	0.50	0.56	0.99	106
	Run_b	0.17	0.46	0.53	0.99	106
	Run_c	0.08	0.50	0.58	0.99	106
	Run_d	0.28	0.47	0.53	0.99	106
09/11/2013	Run_a	0.74	0.84	1.05	0.97	103
	Run_b	0.69	0.80	0.99	0.97	103
	Run_c	0.59	0.71	0.87	0.98	103
	Run_d	0.69	0.80	0.96	0.98	103
09/25/2013	Run_a	0.72	0.75	0.94	0.97	102
	Run_b	0.65	0.69	0.83	0.98	102
	Run_c	0.54	0.60	0.72	0.98	102
	Run_d	0.69	0.71	0.86	0.98	102
10/22/2013	Run_a	0.27	0.59	0.65	0.98	98
	Run_b	0.20	0.51	0.55	0.98	98
	Run_c	0.09	0.44	0.47	0.99	98
	Run_d	0.23	0.53	0.57	0.98	98
11/06/2013	Run_a	0.17	0.43	0.46	0.98	97
	Run_b	0.08	0.37	0.41	0.99	97

	Run_c	-0.04	0.38	0.41	0.99	97
	Run_d	0.11	0.39	0.43	0.99	97
11/18/2013	Run_a	-0.05	0.43	0.48	0.97	96
	Run_b	-0.12	0.43	0.48	0.97	96
	Run_c	-0.21	0.45	0.52	0.97	96
	Run_d	-0.09	0.43	0.48	0.97	96
12/17/2013	Run_a	-0.38	0.76	0.86	0.63	100
	Run_b	-0.40	0.76	0.87	0.63	100
	Run_c	-0.44	0.78	0.89	0.61	100
	Run_d	-0.39	0.77	0.87	0.63	100

Table A-4. Temperature profile statistics for TCD leakage distribution assessment: 2014.

Date	Run Name	Mean Bias, ºC	MAE, ºC	RMSE, ºC	NSE	COUNT
01/07/2014	Run_a	0.39	0.39	0.49	0.84	95
	Run_b	0.40	0.40	0.49	0.84	95
02/05/2014	Run_a	0.56	0.61	0.73	0.37	96
	Run_b	0.56	0.61	0.73	0.38	96
03/12/2014	Run_a	1.09	1.31	1.41	-0.14	102
	Run_b	1.09	1.32	1.42	-0.14	102
04/09/2014	Run_a	1.21	1.32	1.43	0.37	111
	Run_b	1.21	1.32	1.43	0.37	111
05/19/2014	Run_a	1.26	1.32	1.37	0.83	107
	Run_b	1.20	1.23	1.32	0.84	107
06/18/2014	Run_a	1.10	1.24	1.35	0.91	102
	Run_b	1.28	1.29	1.42	0.90	102
07/28/2014	Run_a	1.24	1.34	1.39	0.95	95
	Run_b	1.34	1.44	1.50	0.94	95
08/26/2014	Run_a	1.37	1.37	1.43	0.95	90
	Run_b	1.55	1.55	1.65	0.93	90
09/23/2014	Run_a	0.94	0.95	1.08	0.96	86
	Run_b	1.17	1.17	1.30	0.95	86
10/22/2014	Run_a	0.71	0.88	0.94	0.95	84
	Run_b	0.92	0.94	1.02	0.94	84
11/05/2014	Run_a	0.54	0.73	0.85	0.93	84
	Run_b	0.72	0.80	0.94	0.91	84
12/09/2014	Run_a	0.53	0.60	0.74	0.76	83
	Run_b	0.60	0.64	0.79	0.73	83

Table A-5. Temperature profile statistics for TCD leakage distribution assessment: 2015.

Date	Run Name	Mean Bias, ºC	MAE, ºC	RMSE, ºC	NSE	COUNT
01/06/2015	Run_a	0.75	0.75	0.83	-0.93	102
	Run_b	0.75	0.75	0.83	-0.93	102
02/03/2015	Run_a	0.82	0.86	0.99	0.17	101
	Run_b	0.81	0.86	0.98	0.18	101
03/10/2015	Run_a	0.62	0.68	0.75	0.64	112
	Run_b	0.65	0.71	0.77	0.61	112
04/28/2015	Run_a	0.39	0.56	0.60	0.94	114
	Run_b	0.40	0.54	0.58	0.95	114
05/13/2015	Run_a	0.22	0.51	0.64	0.96	113
	Run_b	0.28	0.57	0.66	0.95	113
06/16/2015	Run_a	0.23	0.58	0.70	0.97	109
	Run_b	0.24	0.57	0.66	0.97	109
07/21/2015	Run_a	0.49	0.59	0.73	0.98	104
	Run_b	0.42	0.54	0.66	0.99	104
08/11/2015	Run_a	0.25	0.42	0.50	0.99	102
	Run_b	0.16	0.39	0.45	0.99	102
09/15/2015	Run_a	0.17	0.38	0.47	0.99	96
	Run_b	0.10	0.34	0.43	0.99	96
10/20/2015	Run_a	0.06	0.23	0.35	0.99	93
	Run_b	-0.05	0.28	0.46	0.99	93
11/10/2015	Run_a	-0.29	0.47	0.79	0.95	90
	Run_b	-0.40	0.52	0.94	0.93	90
12/08/2015	Run_a	-0.38	0.49	0.56	0.87	89
	Run_b	-0.46	0.53	0.61	0.85	89

Appendix B. TCD Operations Log

The TCD operations log details the timing of level operations: upper (TCDU), middle (TCDM), lower (TCDL), low-level intake or side gate (TCDS). Operations from 2000 through 2017 are provided in the table below, identifying the starting and ending Julian day and date, level(s) in use, and any notes. Data provided by Reclamation.

		JDAY		**Date**		**Period Type**	
Year	**Period**	**Start**	**End**	**Start**	**End**	(Active Gate Level)	**Notes**
2000	1	1.000	39.542	01/01	02/08	TCDM	
	2	39.542	64.500	02/08	03/04	TCDU	
	3	64.500	75.375	03/04	03/15	TCDM	
	4	75.375	87.500	03/15	03/27	TCDU&TCDM	
	5	87.500	94.500	03/27	04/03	TCDU	
	6	94.500	99.375	04/03	04/08	TCDU&TCDM	
	7	99.375	101.625	04/08	04/10	TCDU	
	8	101.625	110.417	04/10	04/19	TCDU&TCDM	
	9	110.417	112.417	04/19	04/21	TCDU	
	10	112.417	139.500	04/21	05/18	TCDU&TCDM	
	11	139.500	152.583	05/18	05/31	TCDM&TCDL	
	12	152.583	153.583	05/31	06/01	TCDM	
	13	153.583	154.667	06/01	06/02	TCDM&TCDL	
	14	154.667	158.625	06/02	06/06	TCDL	
	15	158.625	161.625	06/06	06/09	TCDM&TCDL	
	16	161.625	174.375	06/09	06/22	TCDL	
	17	174.375	174.542	06/22	06/22	TCDM&TCDL	
	18	174.542	180.417	06/22	06/28	TCDL	
	19	180.417	185.458	06/28	07/03	TCDM&TCDL	
	20	185.458	191.375	07/03	07/09	TCDM	
	21	191.375	203.375	07/09	07/21	TCDM&TCDL	
	22	203.375	206.375	07/21	07/24	TCDL	
	23	206.375	209.375	07/24	07/27	TCDM&TCDL	
	24	209.375	212.500	07/27	07/30	TCDL	
	25	212.500	214.375	07/30	08/01	TCDM&TCDL	
	26	214.375	216.417	08/01	08/03	TCDL	
	27	216.417	218.333	08/03	08/05	TCDM&TCDL	
	28	218.333	220.625	08/05	08/07	TCDL	
	29	220.625	221.542	08/07	08/08	TCDM&TCDL	
	30	221.542	223.417	08/08	08/10	TCDL	
	31	223.417	224.417	08/10	08/11	TCDL&TCDS	
	32	224.417	225.500	08/11	08/12	TCDL	
	33	225.500	245.375	08/12	09/01	TCDL&TCDS	
	34	245.375	249.458	09/01	09/05	TCDL	
	35	249.458	336.542	09/05	12/01	TCDL&TCDS	
	36	336.542	367.000	12/01	01/01	TCDM&TCDL	
2001	1	1.000	31.500	01/01	01/31	TCDM&TCDL	

	2	31.500	72.458	01/31	03/13	TCDM	
	3	72.458	89.500	03/13	03/30	TCDU	
	4	89.500	95.542	03/30	04/05	TCDU&TCDM	
	5	95.542	108.625	04/05	04/18	TCDU	
	6	108.625	122.542	04/18	05/02	TCDM	
	7	122.542	124.583	05/02	05/04	TCDU&TCDM	
	8	124.583	125.417	05/04	05/05	TCDM&TCDL	
	9	125.417	127.458	05/05	05/07	TCDL	
	10	127.458	131.417	05/07	05/11	TCDM	
	11	131.417	141.458	05/11	05/21	TCDU&TCDM	
	12	141.458	144.458	05/21	05/24	TCDM	
	13	144.458	186.417	05/24	07/05	TCDU&TCDM	
	14	186.417	190.500	07/05	07/09	TCDM	
	15	190.500	204.500	07/09	07/23	TCDM&TCDL	
	16	204.500	206.417	07/23	07/25	TCDL	
	17	206.417	217.375	07/25	08/05	TCDM&TCDL	
	18	217.375	235.417	08/05	08/23	TCDL	
	19	235.417	243.417	08/23	08/31	TCDL&TCDS	
	20	243.417	243.625	08/31	08/31	TCDS	Short period
	21	243.625	275.417	08/31	10/02	TCDL&TCDS	
	22	275.417	352.625	10/02	12/18	TCDS	
	23	352.625	362.500	12/18	12/28	TCDL	
	24	362.500	366.000	12/28	01/01	TCDM	
2002	1	1.000	52.500	01/01	02/21	TCDM	
	2	52.500	88.708	02/21	03/29	TCDU	
	3	88.708	150.417	03/29	05/30	TCDU&TCDM	
	4	150.417	158.042	05/30	06/07	TCDM	
	5	158.042	200.500	06/07	07/19	TCDU&TCDM	
	6	200.500	203.500	07/19	07/22	TCDM	
	7	203.500	234.542	07/22	08/22	TCDM&TCDL	
	8	234.542	238.458	08/22	08/26	TCDL	
	9	238.458	248.500	08/26	09/05	TCDL&TCDS	
	10	248.500	253.458	09/05	09/10	TCDL	
	11	253.458	339.583	09/10	12/05	TCDL&TCDS	
	12	339.583	361.583	12/05	12/27	TCDL	
	13	361.583	366.000	12/27	01/01	TCDM&TCDL	
2003	1	1.000	8.667	01/01	01/08	TCDM&TCDL	
	2	8.667	50.375	01/08	02/19	TCDM	
	3	50.375	72.542	02/19	03/13	TCDU&TCDM	
	4	72.542	133.292	03/13	05/13	TCDU	
	5	133.292	140.542	05/13	05/20	TCDU&TCDM	
	6	140.542	148.458	05/20	05/28	TCDM	
	7	148.458	156.417	05/28	06/05	TCDM&TCDL	
	8	156.417	188.417	06/05	07/07	TCDL	
	9	188.417	195.000	07/07	07/14	TCDL&TCDS	

	10	195.000	217.417	07/14	08/05	TCDL	
	11	217.417	343.542	08/05	12/09	TCDL&TCDS	
	12	343.542	366.000	12/09	01/01	TCDL	
2004	1	1.000	6.542	01/01	01/06	TCDL	
	2	6.542	37.458	01/06	02/06	TCDU&TCDM	
	3	37.458	63.417	02/06	03/03	TCDU	
	4	63.417	79.458	03/03	03/19	TCDU&TCDM	
	5	79.458	79.708	03/19	03/19	TCDU	Short period
	6	79.708	133.583	03/19	05/12	TCDU&TCDM	
	7	133.583	160.417	05/12	06/08	TCDM	
	8	160.417	180.542	06/08	06/28	TCDU&TCDM	
	9	180.542	182.375	06/28	06/30	TCDU, TCDM&TCDL	3 active levels
	10	182.375	212.417	06/30	07/30	TCDM&TCDL	
	11	212.417	216.417	07/30	08/03	TCDL	
	12	216.417	218.458	08/03	08/05	TCDM&TCDL	
	13	218.458	229.458	08/05	08/16	TCDL	
	14	229.458	357.458	08/16	12/22	TCDL&TCDS	
	15	357.458	366.000	12/22	12/31	TCDM	
2005	1	1.000	59.458	01/01	02/28	TCDM	
	2	59.458	140.333	02/28	05/20	TCDU&TCDM	
	3	140.333	144.625	05/20	05/24	TCDU, TCDM&TCDL	3 active levels
	4	144.625	147.417	05/24	05/27	TCDU&TCDM	
	5	147.417	192.417	05/27	07/11	TCDU, TCDM&TCDL	3 active levels
	6	192.417	202.417	07/11	07/21	TCDM&TCDL	
	7	202.417	229.458	07/21	08/17	TCDL	
	8	229.458	366.000	08/17	01/01	TCDL&TCDS	
2006	1	1.000	5.500	01/01	01/05	TCDL&TCDS	
	2	5.500	88.500	01/05	03/29	TCDM	
	3	88.500	118.458	03/29	04/28	TCDU&TCDM	
	4	118.458	128.583	04/28	05/08	TCDU&TCDL	Upper and Lower
	5	128.583	171.542	05/08	06/20	TCDU&TCDM	
	6	171.542	199.417	06/20	07/18	TCDM	
	7	199.417	228.417	07/18	08/16	TCDM&TCDL	
	8	228.417	251.458	08/16	09/08	TCDL	
	9	251.458	366.000	09/08	01/01	TCDL&TCDS	
2007	1	1.000	8.458	01/01	01/08	TCDL&TCDS	
	2	8.458	57.500	01/08	02/26	TCDU&TCDM	
	3	57.500	115.458	02/26	04/25	TCDU	
	4	115.458	192.500	04/25	07/11	TCDU&TCDM	
	5	192.500	194.625	07/11	07/13	TCDU, TCDM&TCDL	Maximum WS elevation 1004.78 ft. TCDU assumed inactive. Period 5 combined with 6.
	6	194.625	229.458	07/13	08/17	TCDM&TCDL	
	7	229.458	244.542	08/17	09/01	TCDL	
	8	244.542	267.375	09/01	09/24	TCDL&TCDS	

	9	267.375	366.000	09/24	01/01	TCDS	
2008	1	1.000	67.417	01/01	03/07	TCDS	
	2	67.417	93.417	03/07	04/02	TCDM	
	3	93.417	136.625	04/02	05/15	TCDU&TCDM	
	4	136.625	179.458	05/15	06/27	TCDM	
	5	179.458	226.458	06/27	08/13	TCDM&TCDL	
	6	226.458	232.500	08/13	08/19	TCDL	
	7	232.500	246.542	08/19	09/02	TCDL&TCDS	
	8	246.542	367.000	09/02	01/01	TCDS	
2009	1	1.000	21.417	01/01	01/21	TCDS	
	2	21.417	55.417	01/21	02/24	TCDL	
	3	55.417	112.417	02/24	04/22	TCDM	
	4	112.417	175.250	04/22	06/24	TCDU&TCDM	
	5	175.250	187.542	06/24	07/06	TCDM	
	6	187.542	224.500	07/06	08/12	TCDM&TCDL	
	7	224.500	240.500	08/12	08/28	TCDL	
	8	240.500	264.417	08/28	09/21	TCDL&TCDS	
	9	264.417	366.000	09/21	01/01	TCDS	
2010	1	1.000	11.500	01/01	01/11	TCDS	
	2	11.500	19.333	01/11	01/19	TCDM&TCDS	Middle and LLI (Side gate)
	3	19.333	40.000	01/19	02/09	TCDM	
	4	40.000	168.583	02/09	06/17	TCDU&TCDM	
	5	168.583	195.542	06/17	07/14	TCDM	
	6	195.542	228.583	07/14	08/16	TCDM&TCDL	
	7	228.583	260.417	08/16	09/17	TCDL	
	8	260.417	347.417	09/17	12/13	TCDL&TCDS	
	9	347.417	366.000	12/13	01/01	TCDM	
2011	1	1.000	56.625	01/01	02/25	TCDM	
	2	56.625	126.417	02/25	05/06	TCDU	
	3	126.417	138.625	05/06	05/18	TCDU&TCDM	
	4	138.625	140.583	05/18	05/20	TCDU	
	5	140.583	165.458	05/20	06/14	TCDU&TCDM	
	6	165.458	171.417	06/14	06/20	TCDM	
	7	171.417	199.458	06/20	07/18	TCDM&TCDL	
	8	199.458	223.542	07/18	08/11	TCDM	
	9	223.542	260.500	08/11	09/17	TCDM&TCDL	
	10	260.500	353.375	09/17	12/19	TCDL	
	11	353.375	366.000	12/19	01/01	TCDM	
2012	1	1.000	65.417	01/01	03/05	TCDM	
	2	65.417	89.500	03/05	03/29	TCDU&TCDM	
	3	89.500	128.375	03/29	05/07	TCDU	
	4	128.375	206.417	05/07	07/24	TCDU&TCDM	
	5	206.417	215.583	07/24	08/02	TCDM	
	6	215.583	232.500	08/02	08/19	TCDM&TCDL	
	7	232.500	265.375	08/19	09/21	TCDL	

	8	265.375	333.542	09/21	11/28	TCDL&TCDS	
	9	333.542	367.000	11/28	01/01	TCDL	
2013	1	1.000	31.583	01/01	01/31	TCDL	
	2	31.583	72.458	01/31	03/13	TCDM	
	3	72.458	80.375	03/13	03/21	TCDU&TCDM	
	4	80.375	112.417	03/21	04/22	TCDU	
	5	112.417	184.792	04/22	07/03	TCDU&TCDM	
	6	184.792	196.458	07/03	07/15	TCDM	
	7	196.458	239.458	07/15	08/27	TCDM&TCDL	
	8	239.458	239.667	08/27	08/27	TCDL	Short period
	9	239.667	247.458	08/27	09/04	TCDM&TCDL	
	10	247.458	254.375	09/04	09/11	TCDL	
	11	254.375	276.583	09/11	10/03	TCDL&TCDS	
	12	276.583	276.708	10/03	10/03	TCDS	Short period
	13	276.708	303.417	10/03	10/30	TCDL&TCDS	
	14	303.417	345.500	10/30	12/11	TCDS	
	15	345.500	366.000	12/11	01/01	TCDL	
2014	1	1.000	23.542	01/01	01/23	TCDL	
	2	23.542	49.417	01/23	02/18	TCDM&TCDL	
	3	49.417	153.417	02/18	06/02	TCDM	WS elevation too low for TCDM until ~JD60, assume TCDL.
	4	153.417	211.542	06/02	07/30	TCDM&TCDL	
	5	211.542	219.500	07/30	08/07	TCDL	
	6	219.500	238.458	08/07	08/26	TCDL&TCDS	
	7	238.458	349.667	08/26	12/15	TCDS	
	8	349.667	366.000	12/15	01/01	TCDL	
2015	1	1.000	5.583	01/01	01/05	TCDL	
	2	5.583	168.375	01/05	06/17	TCDM	
	3	168.375	243.292	06/17	08/31	TCDM&TCDL	
	4	243.292	243.750	08/31	08/31	TCDL	Short period
	5	243.750	244.292	08/31	09/01	TCDM&TCDL	
	6	244.292	244.708	09/01	09/01	TCDL	Short period
	7	244.708	245.292	09/01	09/02	TCDM&TCDL	
	8	245.292	256.833	09/02	09/13	TCDL	
	9	256.833	288.292	09/13	10/15	TCDL&TCDS	
	10	288.292	349.458	10/15	12/15	TCDS	
	11	349.458	366.000	12/15	01/01	TCDL	
2016	1	1.000	47.417	01/01	02/16	TCDL	
	2	47.417	66.083	02/16	03/06	TCDM	
	3	66.083	75.417	03/06	03/15	TCDU&TCDM	
	4	75.417	130.583	03/15	05/09	TCDU	
	5	130.583	222.458	05/09	08/09	TCDU&TCDM	
	6	222.458	222.667	08/09	08/09	TCDM	Short period
	7	222.667	249.708	08/09	09/05	TCDM&TCDL	
	8	249.708	251.458	09/05	09/07	TCDL	Short period

	9	251.458	260.667	09/07	09/16	TCDM&TCDL	
	10	260.667	297.417	09/16	10/23	TCDL	
	11	297.417	344.458	10/23	12/09	TCDL&TCDS	
	12	344.458	367.000	12/09	01/01	TCDL	
2017	1	1.000	12.500	01/01	01/12	TCDL	
	2	12.500	83.500	01/12	03/24	TCDM	
	3	83.500	88.500	03/24	03/29	TCDU&TCDM	
	4	88.500	122.500	03/29	05/02	TCDU	
	5	122.500	201.667	05/02	07/20	TCDU&TCDM	
	6	201.667	208.625	07/20	07/27	TCDM	
	7	208.625	250.417	07/27	09/07	TCDM&TCDL	
	8	250.417	254.458	09/07	09/11	TCDL	
	9	254.458	296.458	09/11	10/23	TCDM&TCDL	
	10	296.458	362.542	10/23	12/28	TCDL	
	11	362.542	366.000	12/28	01/01	TCDM	

Appendix C. Selective Withdrawal Using W2_TCD

New selective withdrawal logic has been incorporated into CE-QUAL-W2 to simulate Shasta TCD operations. This new logic (referred to here as "W2_TCD") is implemented within the framework of CE-QUAL-W2 selective withdrawal logic introduced by Rounds and Buccola (2015). Routines for selective withdrawal initialization and operation, developed by Rounds and Buccola (2015), are modified to accommodate the new logic. Modifications include incorporation of new variables to identify and accommodate periods of TCD operation and each of the four TCD levels, logic to associate selective withdrawal openings, or "structures," with each of the gates, and a new method to select gates for blending. Additionally, TCD leakage and river outlets can be included in the selective withdrawal computation of outflow temperatures. This new method of selective withdrawal computation is based upon the approach incorporated in the U.S. Bureau of Reclamation (Reclamation) HEC5Q water quality model for use on the Sacramento River.

C.1. Blending overview

W2_TCD augments the Rounds and Buccola (2015) logic with a blending process that is specifically crafted to the Shasta Dam TCD. Some features of the original logic have been retained for use in the TCD logic. For example, the new W2_TCD logic still allows the user to identify blending periods, and each blending period has both temperature targets and outlet structures associated with it. The new logic also supports non-blended releases and both minimum and maximum head requirements, as in the Rounds and Buccola (2015) approach. However, the new W2_TCD code differs from the previous approach in several important ways. These differences include:

- allowing the model to be used in either "Prescribed" or "Forecasting" mode
- allowing outlets to be grouped to represent a single large TCD gate
- using minimum flows or flow fractions to define the minimum of total blended flow required through each opening
- employing a bisection-type iterative calculation to estimate blended flows.

A diagram of the overall model approach is shown in Figure C-1.

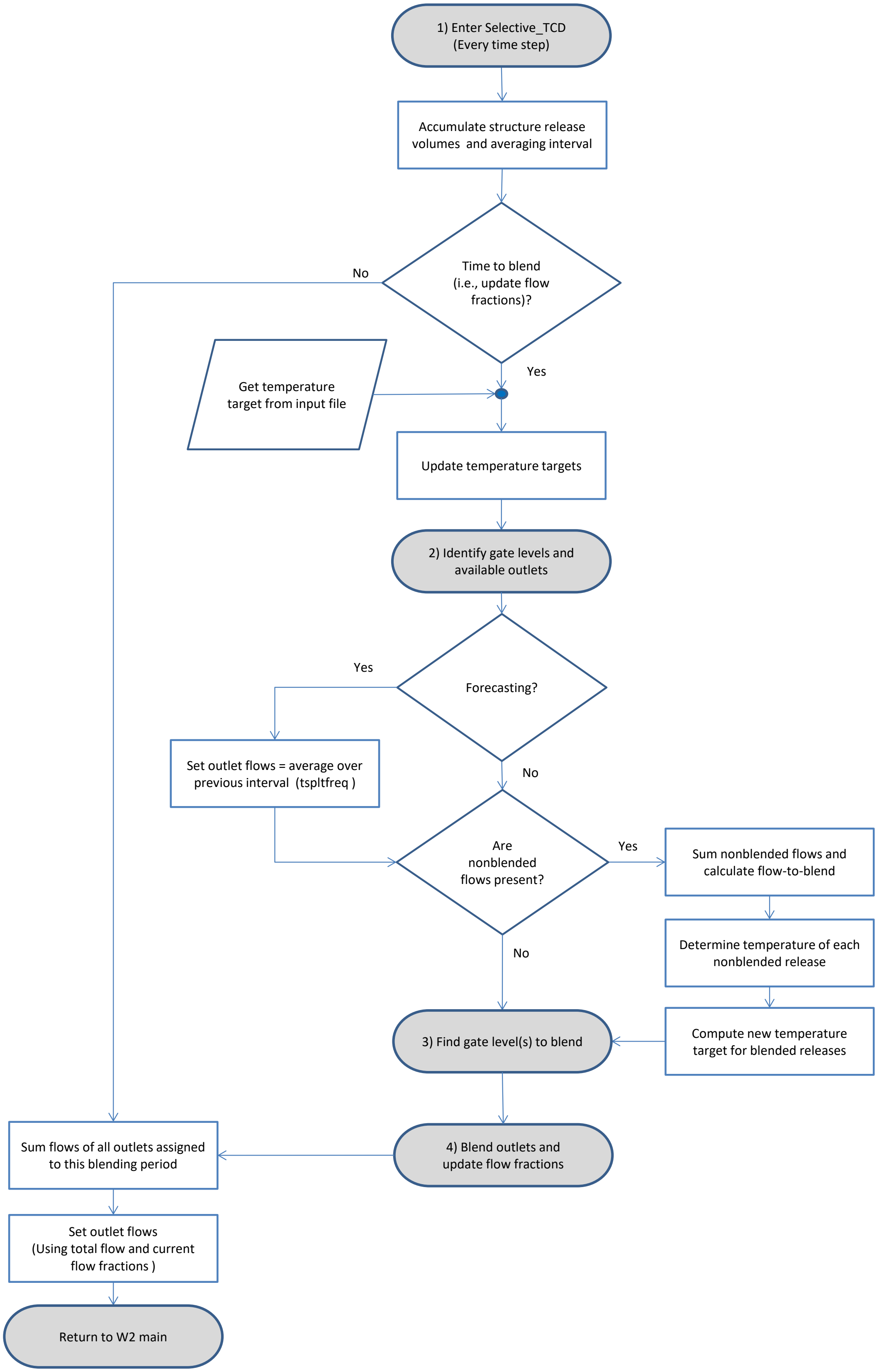


Figure C-1. Blending overview

C.2. Modes of operation: Prescribed vs. Forecasting

W2_TCD has two modes of simulation. The difference between the two modes lies in identifying gate levels to blend. One mode, in which the user specifies blending levels for each blending period, is called “Prescribed.” The second mode of simulation, in which the model searches among all TCD levels for levels to blend, is called “Forecasting.”

The “Prescribed” mode of simulation is designed for historic studies or studies of alternative scenarios in which the one or two gate levels for blending are pre-selected for blending. In this mode, one or two adjacent gate levels are specified for each blending period listed in the “w2_selective.npt” input file. This mode of operation was used in calibrating the Shasta Lake Flow and Temperature Model.

The “Forecasting” mode of simulation is designed to simulate gate operations under forecast hydrologic, inflow temperatures, and meteorologic conditions. In this mode, the model periodically searches among all four TCD gate levels to identify one or two adjacent gate levels for blending. Application of the model in “Forecasting” mode is described in a separate Watercourse technical memorandum.

Once gate level(s) are set to blend, the model determines the set of available outlets at those levels, selects outlets to blend, and apportions total blended flow among all available outlets to meet temperature targets and honor minimum and maximum flow requirements. Using these blended flows and specified non-blending flows, the model calculates new flow fractions for each outlet. These flow fractions are used to distribute release flows at each time step until the next specified flow-fraction update, defined by the user-specified constant, “tspltfreq.”

C.3. Assigning outlets to Gates

The W2_TCD selective withdrawal logic allows outlets to be grouped to represent the large gate openings at each TCD gate level. Gate openings at each level of the Shasta TCD are as much as 45 ft (13.7 m) high, but selective withdrawal outlets in CEQUAL-W2 are represented as point or line sources. So, to better represent TCD gates, W2_TCD allows outlets to be grouped by gate level. Selective withdrawal is modeled first by selecting gate levels for blending (as would TCD operators) and then by selecting outlets to blend within gate levels to attain a target release temperature. In blending calculations, only two outlets are blended and all other outlets at the selected gate level(s) are assigned minimum flows.

One simulated outlet is handled as a special case. This outlet, referred to as “TCDdown” (TCD_d) represents flow that is entrained from below the side gate level whenever the side gates are in use. Associated with the side gate level and never allowed to blend, TCD_d is always assigned its minimum flow fraction whenever the side gate is selected for blending. This flow fraction is unchanged during any given blending period.

When blending with a set of outlets, the W2_TCD model first checks to see if the outlets are under water and if minimum and maximum head criteria are met. The logic then checks each opening to see if restrictions on period-of-operation apply. Any level that meets elevation and head criteria and is not restricted is then processed by priority number. If the outlet priority number is "-1" then the outlet is considered to be a "non-blended" outlet. Flow through these outlets is exactly as given in the flow input file. Target temperature is adjusted in the blending calculations (see following section for equation) to account for the impact of these flows, as is done in Rounds and Buccola (2015) selective withdrawal logic. If the outlet priority number is between one and four then the outlet is assigned to TCD gate levels, with "1" referring to the upper gates, "2" to the middle gates, "3" to the lower gates and "4" to the side gates of the Shasta TCD. The TCD_d outlet is identified by a priority number of "5." This outlet is always associated with the side gate level and is always assigned its minimum flow. All flow specified for blending outlets is summed and re-distributed among outlets of either one or two selected gate levels in the blending calculations. Any outlet with a priority number less than "-1" or greater than "5" is not used in blending calculations; the impact of these outlets is the same as if they had not been included in the list of blended outlets. That is, flow assigned to these outlets is honored in the main W2 logic, but it is not accounted for in blending calculations. A flowchart for determining available outlets and assigning them to gate levels is presented in Figure C-2.

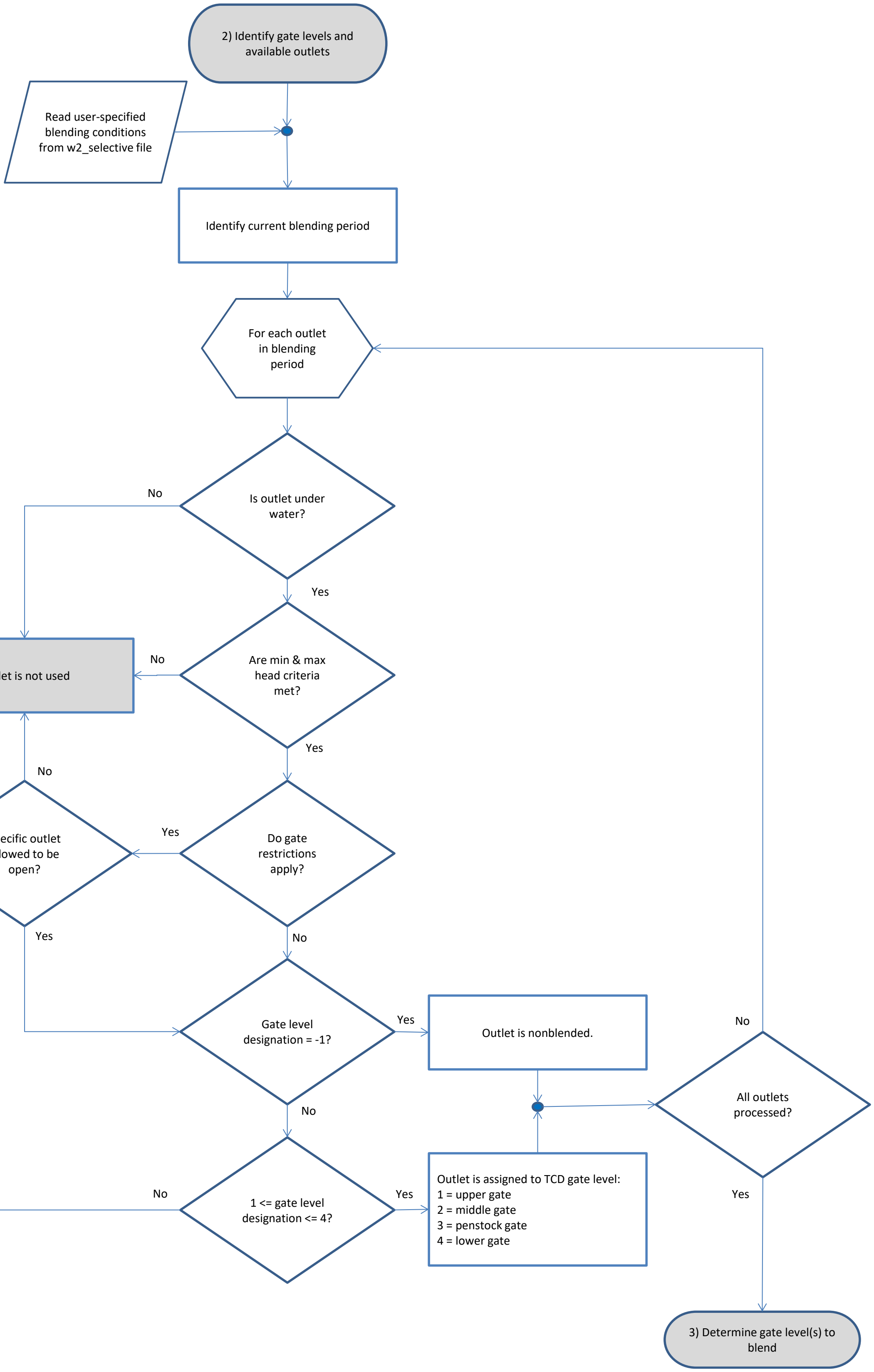


Figure C-2. Flowchart for determining available outlets and assigning TCD gates.

C.4. Defining minimum flows

Minimum flows are set for each outlet in each blending period in the “w2_selective.npt” input file. In W2_TCD, minimum flows are set just as in Rounds and Buccola (2015) logic by either specifying actual minimum flow or minimum flow fractions for each outlet. In Rounds and Buccola (2015) logic, minimum flow fractions define a percentage of total outflow, including flow through both blended and unblended outlets. But in W2_TCD, minimum flow fractions define a percentage of total blended flow only.

As detailed elsewhere in this report, historic releases volumes and temperatures suggest that the withdrawal envelope upstream of any outlet varies in complex ways and is a function of reservoir temperature profile, outflow rate, and whether one or two levels of outlets are open (as well as reservoir boundaries, water surface, wind, and potentially other factors). Because the distribution of flow in the complex hydrodynamic environment of the TCD gates is not well characterized, the model user is provided with minimum flow fractions to partially accommodate this complexity. W2_TCD allows two sets of minimum flows. One set of minimum flows is assigned when only one level is selected for blending, and the other set is applied when two levels are selected for blending.

C.5. TCD Blending Calculations

Whenever flow fractions are updated in W2_TCD, total blended flow is apportioned between outlets of one or two selected gate levels to meet a specified temperature target. Before apportioning begins, the temperature target is adjusted to account for non-blended flows. This adjustment is made by estimating release temperatures from current reservoir temperatures, specified outflow, and the elevation of each non-blending outlet. A new target temperature, T_{blend}, is calculated for blended flows only from the target release temperature specified by the user, $T_{release}$, and flow-weighted temperatures from “non-blending” outlets:

$$T_{blend} = \left(T_{release}Q_{release} - \sum_{i=1}^{n} Q_i T_i\right) / Q_{blend}$$

where Q_{blend} is the total blended outflow, Q_i and T_i are the flow and estimated outflow temperature of each non-blended outlet, i, and n is the number of non-blended outlets.

After non-blended flow is accounted for, gate levels and outlets are selected for blending. In “Prescribed” mode, these gate levels are pre-specified. To mimic TCD operations, only a single gate level or two adjacent gate levels are ever used for blended releases and to represent flow distribution across the selected gate level(s), only two adjacent outlets are ever blended. All other outlets associated with the chosen gate level(s) are assigned minimum flows.

In selecting outlets to blend, the model tries to release the warmest water possible to meet target temperatures, consistent with current TCD water management strategies. Starting at the top of the upper gate level, estimated release temperatures at each outlet are checked successively against the target temperature to identify which outlets to blend.

When an outlet is initially checked the outlet is assigned the bulk of release flow and all other outlets at the associated gate level are assumed to release minimum flows. The process of searching for outlets to blend follows these steps:

- If the target temperature is greater than the temperature of the highest outlet in the gate level being tested, and no gate level above is available for blending, then all releases are made through the level being tested. Minimum flows are assigned to all outlets at that level and the remainder flow is released from the highest outlet.
- If the target temperature is greater than the temperature of the highest outlet at the gate level being tested, and the level above is available, then the gate levels are blended. Minimum flows are assigned to all outlets at both levels. The remainder flow is blended between the lowest outlet in the higher level and the highest outlet in the lower gate level.
- If the target temperature is less than the temperature of the highest outlet in the gate level being tested and greater than the temperature of the lowest outlet in the level being tested, then all releases are made through the gate level being tested. Minimum flows are assigned to all outlets at that level. The remainder flow is blended between the two outlets at that level that bracket the target temperature.
- If the target temperature is less than the temperature of the lowest outlet in the gate level being tested, then the logic moves to the next level down and the process repeats so on, down to the lowest (side) gate level.
- If the target temperature is less than the estimated temperatures at all available gate levels, then all flow is released through the lowest outlet at the lowest available gate level, after honoring minimum flows at other outlets at that level. In this case, the target temperature may not be met.

Once outlets are chosen for blending, the model uses a bisection-type method to find the best blend. Initially, the model creates a search interval representing all possible blending fractions, ranging from 100% flow through the top outlet to 100% flow through the bottom outlet. This interval represents all possible temperatures for the blended flow. The model then bisects this interval by testing the condition in which half the flow is assigned to the higher gate. This test creates two sub-intervals. The top interval represents blends ranging from 100% flow through the top outlet to 50% top and 50% bottom outlet. The bottom interval represents blends ranging from 100% flow through the bottom outlet to 50% top and 50% bottom outlet. The flow-weighted release temperature of this first test condition is calculated and compared to the target temperature. If the test release temperature is within the convergence criteria of the target temperature, the search is complete. If the test release temperature is higher than the target temperature, then the search shifts to the bottom interval. Likewise, if the test release temperature is lower than the target temperature, then the search shifts to the top interval. The method iteratively bisects each search interval, testing within smaller and smaller intervals to match the target temperature. This method converges quickly to a solution and after five iterations (the maximum number of iterations allowed) the search is narrowed to within about 3% of total flow. Currently, the model is set to iterate a maximum of six times. A flowchart for allocating blended flows to TCD gate levels is presented in Figure C-3.

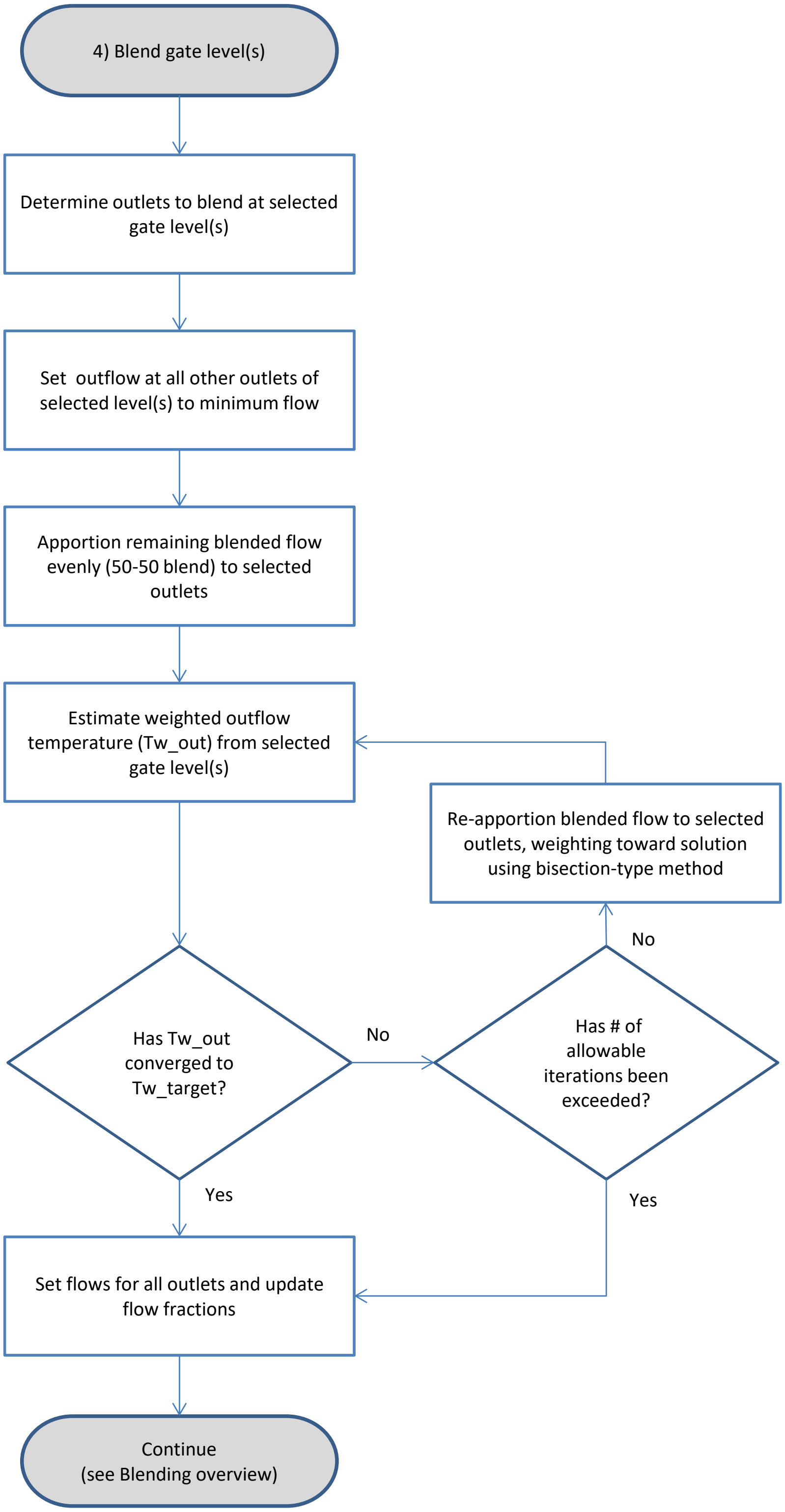


Figure C-3. Flowchart for blending release flows at TCD gate levels.

C.6. User Specified Inputs

All inputs to the W2_TCD selective withdrawal routines are read from the "w2_selective.npt" file, a modified version of the USGS input file. To use the new W2_TCD logic, the parameter "SELECTC" must be set to "   TCD" in the W2 control file (W2_con). With this setting, only W2_TCD logic is used in selective withdrawal calculations and some standard W2 selective withdrawal functions (e.g., a tower of withdrawal structures or floating structures) are disabled.

A few Rounds and Buccola (2015) selective withdrawal features are also disabled in W2_TCD, but several features are incorporated in the new logic. Rounds and Buccola (2015) selective withdrawal logic was the basis upon which W2_TCD was developed, and all original parameters (as of October 2019) are either used as intended by Rounds and Buccola (2015), have been re-purposed for W2_TCD, or have been disabled in W2_TCD calculations. Blending periods are still used, and temperature targets may be either constant or dynamic (i.e., specified by Julian day over a blending period). The new logic also uses minimum and maximum head criteria to determine availability of outlets. All parameters associated with these features are still in use. To leave open the option of implementing disabled features in future versions of W2_TCD, all parameters found in the Rounds and Buccola (2015) selective withdrawal input file are preserved and must be specified in the W2_TCD version.

In addition to Rounds and Buccola (2015) input parameters, W2_TCD uses ten new parameters to specify mode of model operation, define a second minimum flow, control gate level selection in "Forecasting" mode and restrict periods during which gates may be opened. One new parameter, "HR_SET," is not currently used. Unused or modified Rounds and Buccola (2015) parameters and all new input parameters are listed in Table C-1. In this table, six new parameters that are used in "Forecasting" mode are identified. These forecasting parameters are not discussed in this report, but in a separate Watercourse technical memorandum describing the use of W2_TCD in forecasting.

Table C-1. Unused, modified, or new input parameters

Rounds and Buccola (2015) (not used)	Rounds and Buccola (2015) (modified use)	W2_TCD (new)
ELCONT	TSCONV	FCST
TSSHARE	PRIORx	MINFRAC2
DEPTHx	MINFRCx	MINJD
MAXFLOx		MAXJD
		*BEGIN_HI_RESTRICTIONS
		*END_HI_RESTRICTIONS
		*HR_SET (not currently used)
		*N_CONSECUTIVE_ATTEMPTS
		*INIT_GATE
		*MIN_SUBMERGENCE

*used only in "Forecasting" mode

Parameters that are read into W2_TCD but also appear in Rounds and Buccola (2015) selective withdrawal calculations are described in Table C-2. In this table, unused and modified parameters are identified by shading, and modifications to Rounds and Buccola (2015) usage are noted in bold in the parameter descriptions. Parameters that are new in W2_TCD calculations and are applied in the "Prescribed" mode of operation that was used during calibration are described in Table C-3. In both tables, parentheses following a code parameter signify that the parameter is an array in which “j” represents blending group and “n” represents outlet number.

Four Rounds and Buccola (2015) parameters are not currently used in W2_TCD. These parameters were used to specify floating outlets, flow sharing, and maximum release flows. The parameters “ELCONT” and “DEPTHx” are not used because floating outlets are not supported in this version of W2_TCD. The parameter “TSSHARE” is not used because Rounds and Buccola (2015) outlet groups and sharing between them are not used in W2_TCD gate selection logic. The parameter “MAXFLOx” is not used because maximum flow specifications are not currently supported. Disabled parameters should be given values, if only as placeholders for the format-driven READ statements in the code. A value of either “OFF” or “0.0,” depending on the type of parameter, is suggested for all of them.

Three parameters, specifying convergence criterion, priority ranking of outlets and minimum flows are modified from Rounds and Buccola (2015). The parameter “TSCONV” is still used as a convergence criterion, but has been modified to represent the absolute allowable difference between calculated release temperature and temperature target when blending outlets, in units of °C. The parameter “PRIORx” is still used to identify non-blended releases with a value of “-1”, but now, instead of assigning priorities for Rounds and Buccola (2015) blending logic, this parameter associates outlets with TCD gate levels. The parameter “MINFRCx” is now used to specify the minimum blended flow through an outlet when only outlets from one level are blended.

Table C-2. Description of Rounds and Buccola (2015) derived user-specified inputs (w2_selective.npt) for blending in W2_TCD.

Input parameter	Input section	Parameter name in code	Description
CNTR	SPLIT1	tspltc	Turns the blending calculations ON or OFF.
NUM	SPLIT1	numtsplt	Number of blending groups to specify, for different times of year or at different dams, etc.
TSFREQ	SPLIT1	tspltfreq	Frequency at which the blending calculations are updated, specified as a fraction of a day.
TSCONV	SPLIT1	tsconv	Convergence criterion for the iterative blending solution, °C. Constrained to be 0.1 or less, but nonzero. (**Modified for use in TCD logic**)
ST/WD	SPLIT2	tspltcntr(j)	Specification of a group of structures (ST) for blending. (**Note: withdrawals not supported**)
JB	SPLIT2	tspltjb(j)	Branch number for the structures being blended.
YEARLY	SPLIT2	tsyearly(j)	Specifies that starting and ending dates for blending should be repeated (ON) each year, or not (OFF).
TSTR	SPLIT2	tstsrt(j)	Start date (Julian day) for blending calculations for that group (day 1 is the start of January 1).
TEND	SPLIT2	tstend(j)	End date (Julian day) for blending calculations for that group (day 1 is the start of January 1).
TTARGET	SPLIT2	tspltt(j)	Temperature target to try to meet for that period of dates, if not overridden by a time-series input.
TSDYN	SPLIT2	tsdynsel(j)	Specifies that a time-series of temperature targets is set (ON), with targets in the "dynsplit_selectiveX.npt" file where X is the group number designation.
**ELCONT	SPLIT2	elcontspl(j)	Specifies whether an outlet should decrease its elevation to follow the water surface (ON/OFF); **Not currently supported; set value to "OFF"**
NOUTS	SPLIT2	nouts(j)	Number of outlets in this particular blending group, between 2 and 30.
**TSSHARE	SPLIT2	tsshare	(**Not used; set value to "OFF"**)
JSx/NWx	SPLITOUT	jstsplt(j,n)	Structure or outlet number.
**DEPTHx	DEPTH	tsdepth(j,n)	A nonzero value specifies that the outlet is a floating structure (**Not currently supported**; **set all values to zero**)
MINFRCx	MINFRAC	tsminfrac(j,n)	A minimum flow fraction (between 0 and 1) specifying that at least that fraction of the blended release should go through that outlet. When specified as a negative number, this input is interpreted as a minimum flow rate in cubic meters per second. Used when one level is blended. (**Modified for use in TCD logic**)
PRIORx	PRIORITY	tsprior(j,n)	Integer number of the gate to which outlet is assigned: "-1" means the outlet is not blended and its specified flow release rates are unchanged, but the temperature effect is accounted for by blending calculations. Values less than "-1" or greater than "5" are not used in blending logic. (**Modified for use in TCD logic**)
MINHDx	MINHEAD	tsminhead(j,n)	A minimum head designation, in meters. The outlet must be at least this deep to be used. A zero input means that no criterion is specified.
MAXHDx	MAXHEAD	tsmaxhead(j,n)	A maximum head designation, in meters. The outlet must be shallower than this depth to be used. A zero input means that no criterion is specified.
**MAXFLOx	MAXFLOW	tsmaxflow(j,n)	A maximum flow designation, in cubic meters per second. A zero input means that no criterion is specified. (**Not currently supported; set all values to zero**)

Notes: For code parameters, parentheses mean the parameter is an array in which j is blending group and n is outlet number. Grayed parameters are either not used (denoted by "**") or modified from Rounds and Buccola (2015) usage.

In addition to Rounds and Buccola (2015) input parameters, W2_TCD uses four new parameters in the "Prescribed" mode to specify mode of model operation, define a second minimum flow, and restrict periods during which gates may be opened. New parameters used in "Prescribed" mode are described in Table C-3.

Table C-3. Description of new user-specified inputs (w2_selective.npt) for blending in W2_TCD

Input parameter	Input section	Parameter name in code	Description
FCST	SPLIT1	FORECASTING	Determines whether model will search for best gate(s) for blending (ON) or use specified gate(s) (OFF). A maximum of two specified gates is allowed.
MINFRCx	MINFRAC2	tsminfrac2(j,n)	A minimum flow fraction (between 0 and 1) specifying that at least that fraction of the blended release should go through that outlet. When specified as a negative number, this input is interpreted as a minimum flow rate in cubic meters per second. Used when two levels are blended.
MINJDX	MINJD	tsminjday(j,n)	The first Julian day on which the outlet may be open.
MAXJDX	MAXJD	tsmaxjday(j,n)	The last Julian day on which the outlet may be open

Notes: For code parameters, parentheses signify an array in which j is blending group and n is outlet number.

The parameter "FCST" determines whether the model will operate in "Forecasting" mode ("ON") and search for the best gate levels to blend or operate in "Prescribed" mode ("OFF") and use specified gate levels for blending. Parameters listed in the MINFRAC2 section of the input file are used to specify minimum flow in blending period "j" released through any outlet, "n," when outlets from two levels are blended. Parameters MINJDx and MAXJDx are used to set the first and last Julian days on which any specific outlet, "n," may be open during any given blending period, "j."

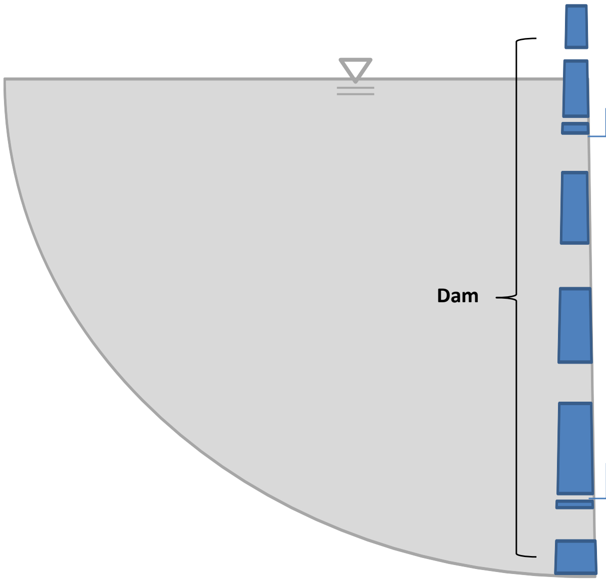
C.7. Example

A relatively simple example of the application of W2_TCD will illustrate the construction of the "w2_selective.npt" input file for use in the "Prescribe" mode. In this example, there are 16 outlets. One outlet represents the Shasta Dam spillway, 13 outlets represent openings associated with the four TCD gate levels, and two outlets represent unblended flows, or leaks (see Section 5 of this report). This example is illustrated in **Error! Reference source not found.**, and the relevant parts of the "w2_selective.npt" input file are presented in Figure C-5. Elevations for all outlet structures are specified in the CEQUAL-W2 input control file ("w2_con.npt").

At the top of the dam is outlet #1, the spillway. This outlet is not included in any blending period and so is not listed in the selective withdrawal input file. Because it is not included in blending calculations, any flows assigned to this outlet in the outflow file are honored, but they are not taken into consideration when trying to match target temperatures.

The four TCD gate levels are represented by three point sinks each. Each of these outlets is assigned a priority that represents the gate level that it is associated with. The upper gates (priority = 1) are represented by outlets #2-4, the middle gates (priority = 2) by outlets #5-7, the lower gates (priority = 3) by outlets #8-10, and the side gates (priority = 4) by outlets #11-13. In addition, a fourth outlet (outlet #16) represents TCD_d, identified with a priority of “5” and assigned to the side gate level.

Two outlets are included in blending calculations but are designated “unblended” by a priority value of “-1”. In this example, these two outlets (numbered 14 and 15) represent leaks. Flows specified for unblended outlets are honored and the effect of these flows on outflow temperatures is accounted for during blending calculations.



Description	Priority	Outlet	Elev. (m)
Spillway	N/A	1	316.1
Upper leak	-1	14	317.8
Upper gates	1	2	317.6
		3	311.2
		4	304.8
Middle gates	2	5	287.1
		6	280.7
		7	274.3
Lower gates	3	8	253.0
		9	248.7
		10	244.5
Lower leak	-1	15	341.2
Side gates	4	11	240.8
		12	230.1
		13	219.5
(TCDdown)	(5)	16	212.0

Figure C-4. Schematic of outlet assignments for W2_TCD example.

```
SPLIT1      CNTR     NUM  TSFREQ  TSCONV    FCST LWRGATE
              ON       3 0.04167     0.1     OFF    0.50

SPLIT2     ST/WD      JB  YEARLY    TSTR    TEND TTARGET   TSDYN  ELCONT   NOUTS TSSHARE
1             ST       1     OFF    1.25  130.25     12.      ON     OFF       5      ON
2             ST       1     OFF  130.25  200.25     12.      ON     OFF       8      ON
3             ST       1     OFF  200.25  366.00     12.      ON     OFF       9      ON

SPLITOUT JS1/NW1 JS2/NW2 JS3/NW3 JS4/NW4 JS5/NW5 JS6/NW6 JS7/NW7 JS8/NW8 JS9/NW9 JS0/NW0
1              2       3       4      14      15
2              5       6       7       8       9      10      14      15
3              8       9      10      11      12      13      14      15      16

DEPTH     DEPTH1  DEPTH2  DEPTH3  DEPTH4  DEPTH5  DEPTH6  DEPTH7  DEPTH8  DEPTH9 DEPTH10
1             0.      0.      0.      0.      0.
2             0.      0.      0.      0.      0.      0.      0.      0.
3             0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
              0.      0.

MINFRAC  MINFRC1 MINFRC2 MINFRC3 MINFRC4 MINFRC5 MINFRC6 MINFRC7 MINFRC8 MINFRC9 MNFRC10
1           0.10    0.10    0.10      0.      0.
2           0.10    0.10    0.10    0.10    0.10    0.10      0.      0.
3           0.10    0.10    0.10    0.10    0.10    0.10    0.10    0.10    0.10      0.
              0.    0.35

PRIORITY  PRIOR1  PRIOR2  PRIOR3  PRIOR4  PRIOR5  PRIOR6  PRIOR7  PRIOR8  PRIOR9 PRIOR10
1              1       1       1      -1      -1
2              2       2       2       3       3       3      -1      -1
3              2       2       2       3       3       3       4       4       4      -1
              -1       5

MINHEAD   MINHD1  MINHD2  MINHD3  MINHD4  MINHD5  MINHD6  MINHD7  MINHD8  MINHD9 MINHD10
1             0.      0.      0.      0.      0.
2             0.      0.      0.      0.      0.      0.      0.      0.
3             0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
              0.      0.

MAXHEAD   MAXHD1  MAXHD2  MAXHD3  MAXHD4  MAXHD5  MAXHD6  MAXHD7  MAXHD8  MAXHD9 MAXHD10
1             0.      0.      0.      0.      0.
2             0.      0.      0.      0.      0.      0.      0.      0.
3             0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
              0.      0.

MAXFLOW  MAXFLO1 MAXFLO2 MAXFLO3 MAXFLO4 MAXFLO5 MAXFLO6 MAXFLO7 MAXFLO8 MAXFLO9 MXFLO10
1             0.      0.      0.      0.      0.
2             0.      0.      0.      0.      0.      0.      0.      0.
3             0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
              0.      0.

MINFRAC2 MINFRC1 MINFRC2 MINFRC3 MINFRC4 MINFRC5 MINFRC6 MINFRC7 MINFRC8 MINFRC9 MNFRC10
1           0.05    0.05    0.05      0.      0.
2           0.05    0.05    0.05    0.05    0.05    0.05      0.      0.
3           0.05    0.05    0.05    0.05    0.05    0.05    0.05    0.05    0.05      0.
              0.    0.35

MINJDX    MINJD1  MINJD2  MINJD3  MINJD4  MINJD5  MINJD6  MINJD7  MINJD8  MINJD9 MINJD10
1              1       1       1       0       0
2            120     120     120     150     150     150       0       0
3            120     120     120     150     150     150     180     180     180       0
               0       0

MAXJDX    MAXJD1  MAXJD2  MAXJD3  MAXJD4  MAXJD5  MAXJD6  MAXJD7  MAXJD8  MAXJD9 MAXJD10
1            150     150     150       0       0       0       0       0       0
2            250     250     250     365     365     365       0       0
3            250     250     250     365     365     365     300     300     300       0
               0       0

GATESET BEGIN_HI  END_HI  HR_SET N_TRIES  INGATE  MINSUB
             100     300     0.0       3       3   10.67
```

Figure C-5. Example input file for W2_TCD showing relevant section of the "w2_selective.npt" file

The input file specifies that the model will operate in "Prescribed" mode, with FCST = OFF. Three blending periods are defined by Julian day (JD), and each blending period starts and ends at 6AM (e.g., JD 1.25). Blending periods begin when blending start time (TSTR) is equaled or exceeded, and blending periods end when blending end time (TEND) is exceeded. If the start time of one blending period equals the end time of the previous blending period, there is no overlap. Blending ratios are updated hourly (TSFREQ = 0.04167 days) and the convergence criterion for matching target temperatures is specified by TSCONV equal to 0.1 °C. Gate levels are not selected in "Prescribed" mode, so the allowable deviation from target temperature, LWRGATE, is not used. The dynamic temperature target option, TSDYN, is turned on for each blending period. This option is implemented just as in USGS selective withdrawal (Rounds and Buccola, 2015). Both high and low leaks (outlets #14 and #15) are present during every blending period. In the first blending period (JD 1.25-130.25), only the top gate level (outlets #2-4) is blended. In the second blending period (JD 130.25-200.25), the middle and lower gate levels (outlets #5-10) are blended. In the third blending period (JD 200.25-365), the lower and side gate levels (outlets #8-13 and outlet #16) are blended.

In the file, minimum flow fractions are set for each outlet used in blending. When blending occurs at one level, each outlet associated with that level shall release at least 10% of the blended flow (MINFRAC = 0.10). When blending occurs at two levels, each outlet associated with those gate levels shall release at least 5% of the blended flow (MINFRAC2 = 0.05). In either case, the minimum flow through TCD_d (outlet #16) will be 35% of blended flow.

Blending of gate levels is restricted to user-specified time intervals. These periods of restriction are illustrated in Figure C-6 which also shows elevations of each gate-related outlet structure and the gate level with which the structures are associated. In this example, gate restrictions are specified so that they are consistent throughout the year regardless of blending period. Top gate outlets may only be opened from JD 1-150 (MINJDX=1; MAXJDX=150), middle gate outlets may only be opened from JD 120-250, lower gate outlets may only be opened from JD 150-365, and side gate outlets may only be opened from JD 180-300.

A final set of parameters are listed in the "GATESET" input section. These parameters are used only in forecasting mode (i.e., FCST = "ON") and do not affect calculations in the "Prescribed" mode. Details for the forecasting mode are available in a separate Watercourse technical memorandum.

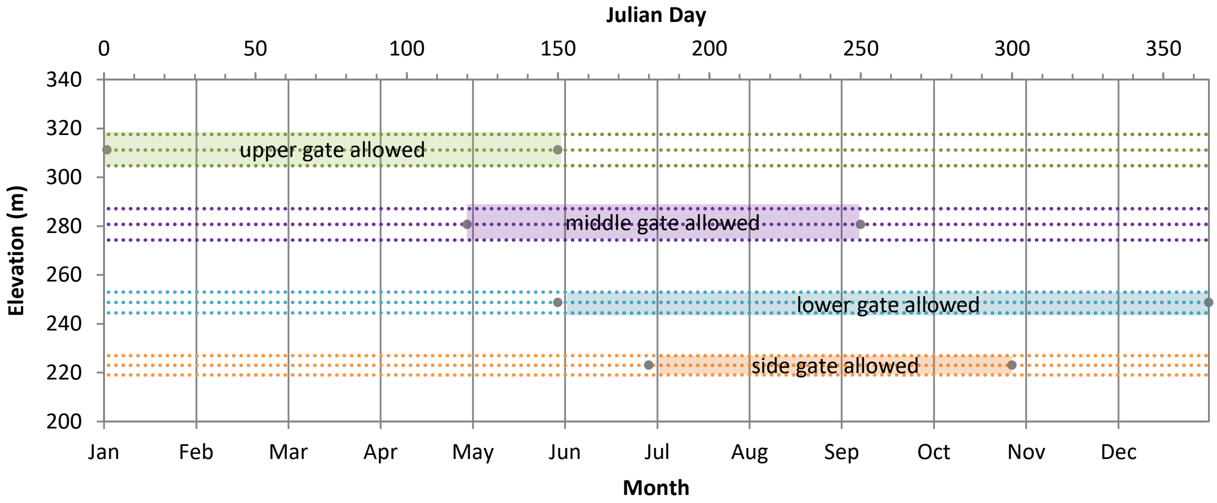


Figure C-6. Example W2_TCD gate restriction.

C.8. Notes on Using W2 with the New W2_TCD Logic

The new W2_TCD logic (version W2_v41_TCD) stands mostly on its own, operating within the CEQUALW2 logic without interfering. Original and USGS-modified versions of selective withdrawal are still supported in this model, along with the new W2_TCD logic. However, a few requirements for running the W2_TCD logic must be observed and the user remain aware of how outflow specifications affect model calculations.

C.8.1. CEQUALW2 Control File (w2_con.npt)

In the w2_con file, note two requirements for running the W2_TCD version of selective withdrawal:

1) The selective withdrawal switch, SELECTC, must be set to “   TCD”

```
MISCELL      NDAY SELECTC HABTATC ENVIRPC AERATEC INITUWL
              100     TCD     OFF     OFF     OFF     OFF
```

2) Gate structures must be listed from high-to-low elevation. This is only important for structures representing gates, but I list all structures from high-to-low just to keep them straight.

```
STR ELEV    ESTR    ESTR    ESTR    ESTR    ESTR    ESTR    ESTR    ESTR    ESTR
BR 1      316.08  317.60  311.20  304.80  287.12  280.72  274.32  252.98  248.72
          244.45  227.00  223.00  219.00  287.12  256.64  226.16  288.54  273.32
          254.09  245.56  237.74  228.45
```

C.8.2. Outflow Specification

Where flows are placed in the file that specifies outflow (QOT FILE) for the simulation is an important consideration. All flows listed in this outflow file are honored, but only flows that are listed (in the “w2_selective.npt file”) for blending are factored into meeting the outflow temperature target. Therefore, flows that are specified in the outflow file, but not listed in a blending period may result in the final simulated outflow temperature deviating from the target temperature, even though the target temperature is met in the blending calculations.

Also, as a result of how specified outflows are processed, unintended things can happen when specified flows are hourly with blending updates specified daily (or, greater than hourly). A problem can occur when flow is given for structures that are not blended and this flow changes to blended gates mid-day, after blending is already set for the day (at, say, 6 AM). It is recommended that blending updates are specified at the same frequency (or a multiple thereof) as outflows.

C.8.3. CEQUALW2 Selective Withdrawal Features Not Currently Supported

Several features that are available in the W2 code are not available in the new TCD selective withdrawal logic. These features are still available to the user of the W2 model; they are only disabled the selective withdrawal switch, SELECTC, is set to "   TCD":

- Standard W2 selective withdrawal options such as using a withdrawal tower or floating withdrawal structures are not supported.
- Withdrawals (signified by "WD") are not supported. Only structures ("ST") are supported in blending calculations.
- Maximum flows ("MAXFLOW") are not supported.

At the current time, there was no identified need to include these features. Original code remains in the W2_TCD logic to implement these features and if a future need is identified, the code should be easily modified.

C.9. Citations

Resource Management Associates (RMA). 2003. Upper Sacramento River Water Quality Modeling with HEC-5Q: Model Calibration and Validation (DRAFT). Prepared for the U.S. Bureau of Reclamation. December.

Rounds, S.A., and Buccola, N.L., 2015, Improved algorithms in the CE–QUAL–W2 water-quality model for blending dam releases to meet downstream water-temperature targets: U.S. Geological Survey Open-File Report 2015-1027, 40 p., http://dx.doi.org/10.3133/ofr20151027

U.S. Bureau of Reclamation. 2015. Initial Hindcast of Temperature Performance Sacramento River 2014. Prepared for the State Water Resources Control Board. March.

Appendix D. Shasta Lake Model Results and Model Performance Statistics (Years 2000-2019)

Appendix D includes graphical and tabular results comparing simulated versus measured data, as well as tabulated model performance statistics for the Shasta Lake model. Specifically, a) Shasta Lake stage, b) Shasta Dam outflow, c) reservoir temperature profiles above Shasta Dam and d) Shasta Dam outflow temperature.

D.1. Reservoir Elevation (Stage) (DRAFT)

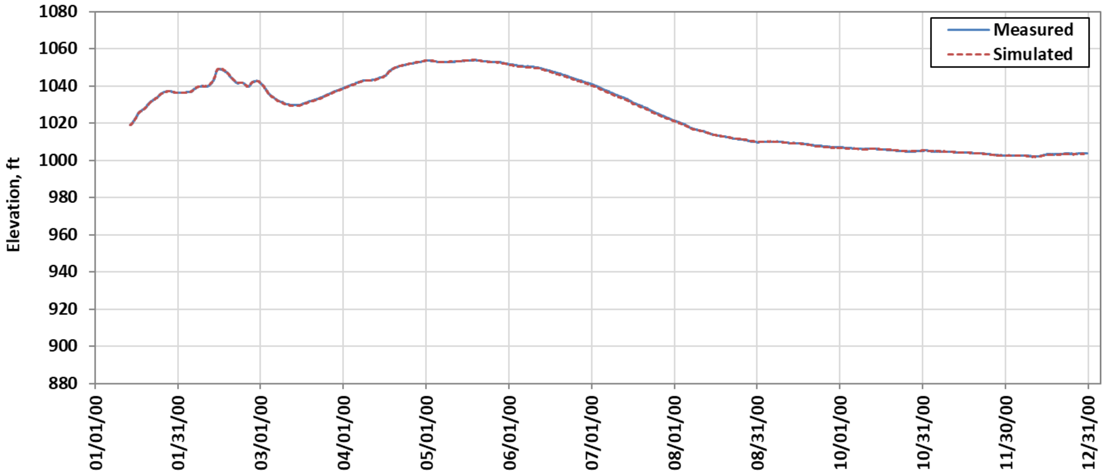


Figure D-1. Simulated versus measured Shasta Lake elevation (stage): 2000.

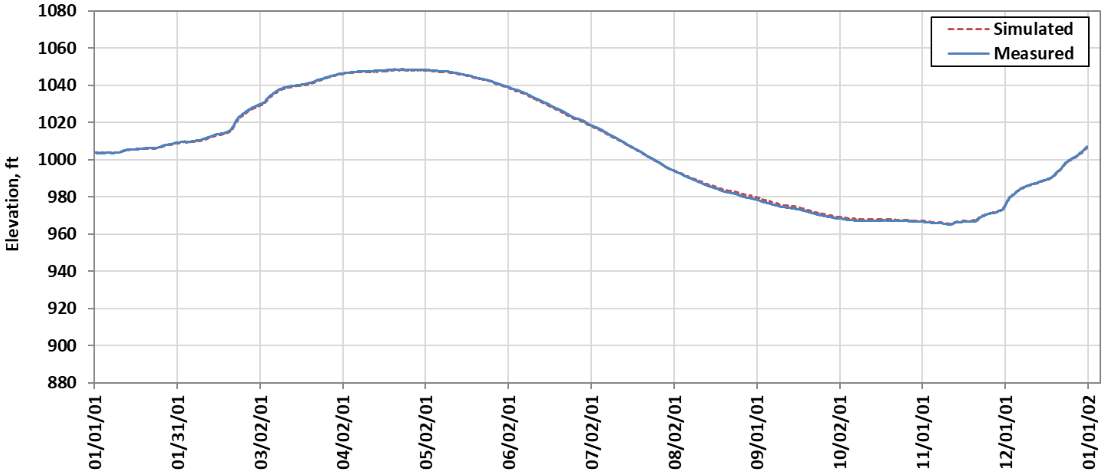


Figure D-2. Simulated versus measured Shasta Lake elevation (stage): 2001

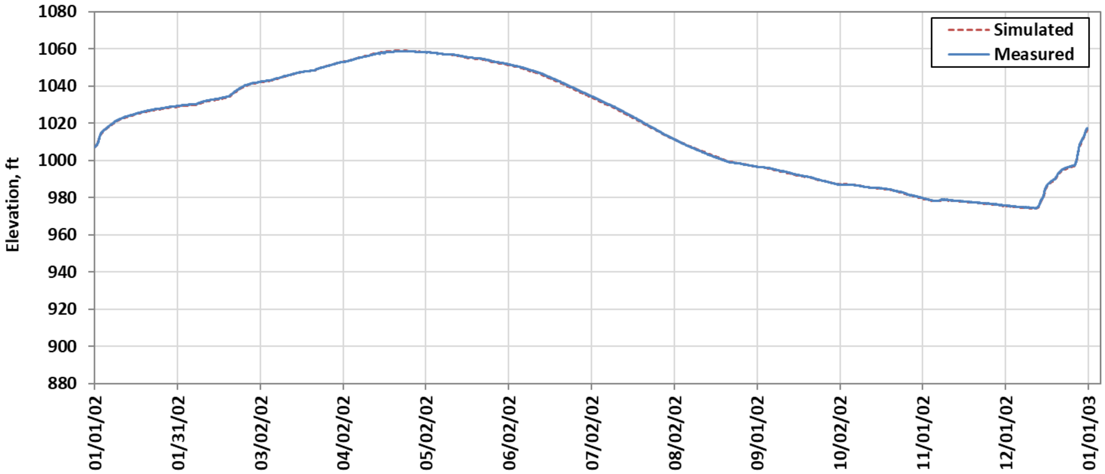


Figure D-3. Simulated versus measured Shasta Lake elevation (stage): 2002.

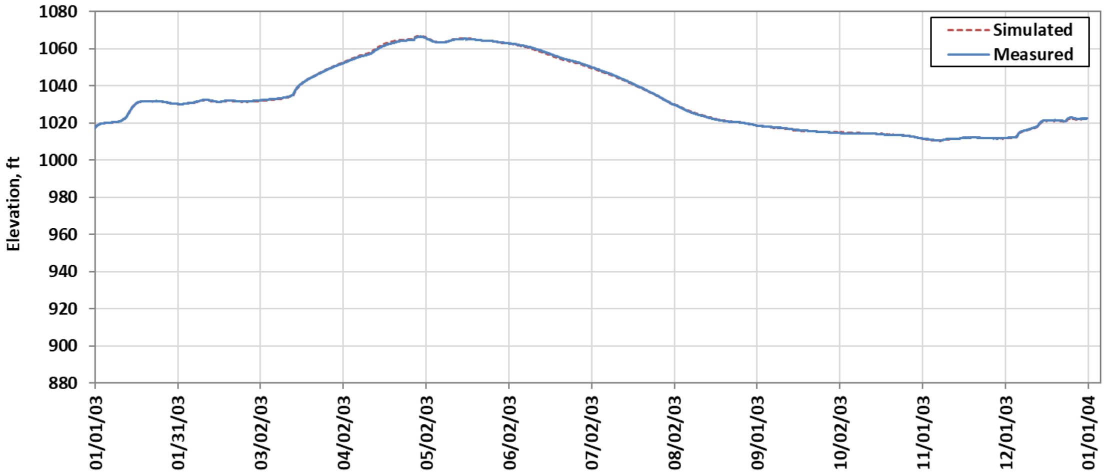


Figure D-4. Simulated versus measured Shasta Lake elevation (stage): 2003.

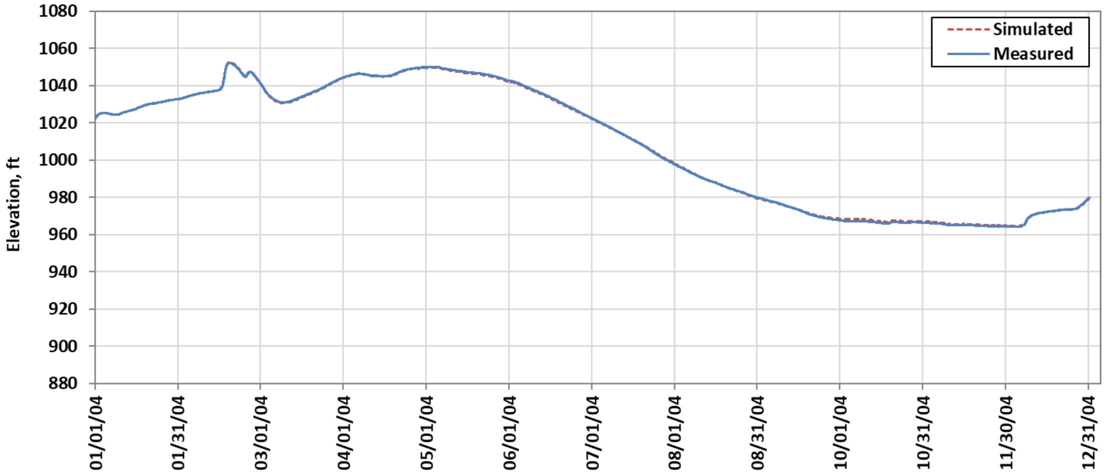


Figure D-5. Simulated versus measured Shasta Lake elevation (stage): 2004.

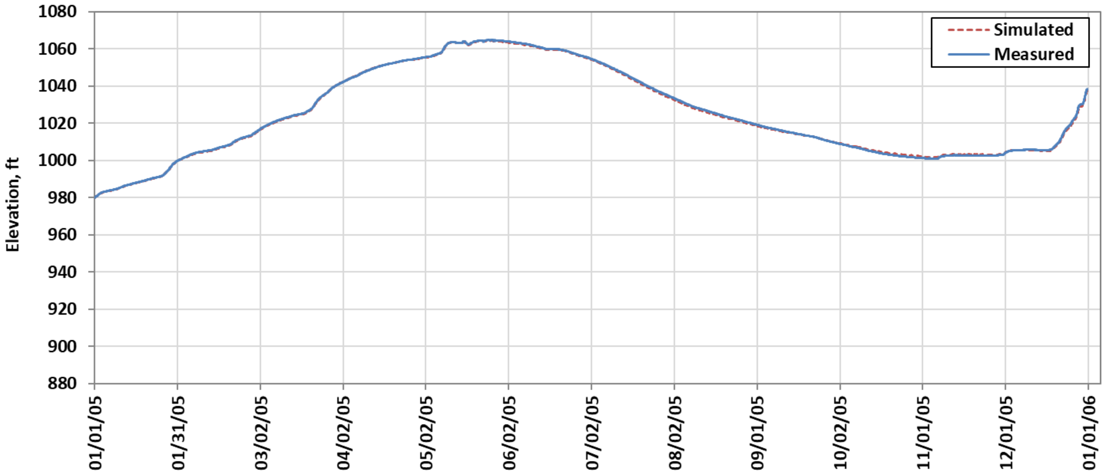


Figure D-6. Simulated versus measured Shasta Lake elevation (stage): 2005.

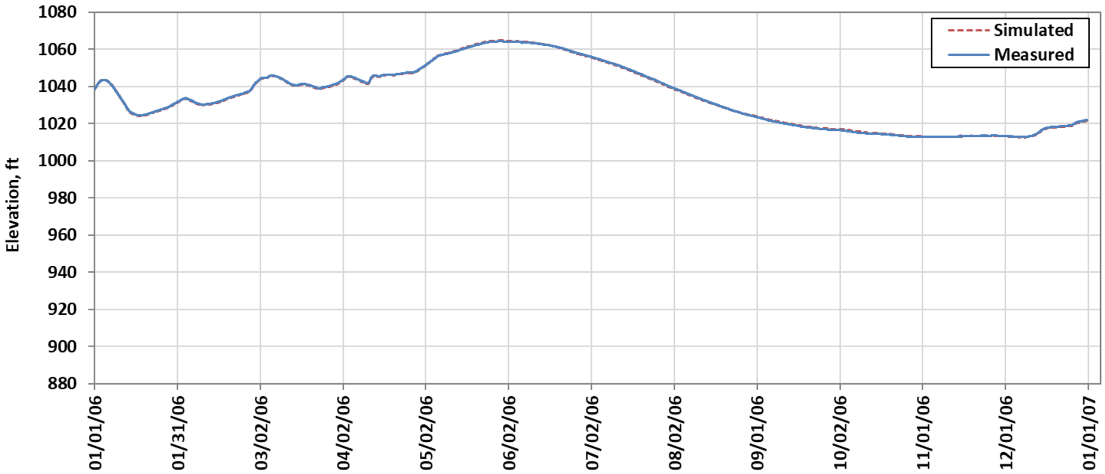


Figure D-7. Simulated versus measured Shasta Lake elevation (stage): 2006.

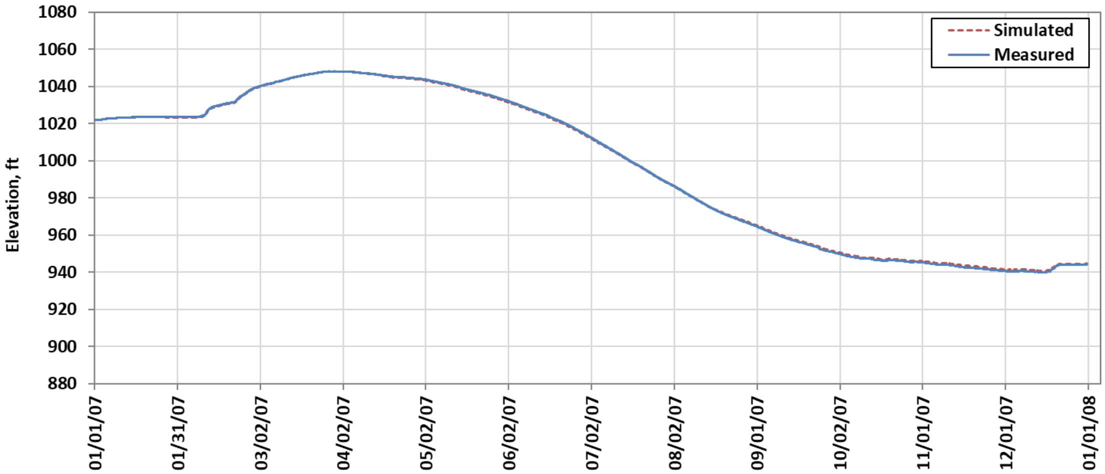


Figure D-8. Simulated versus measured Shasta Lake elevation (stage): 2007.

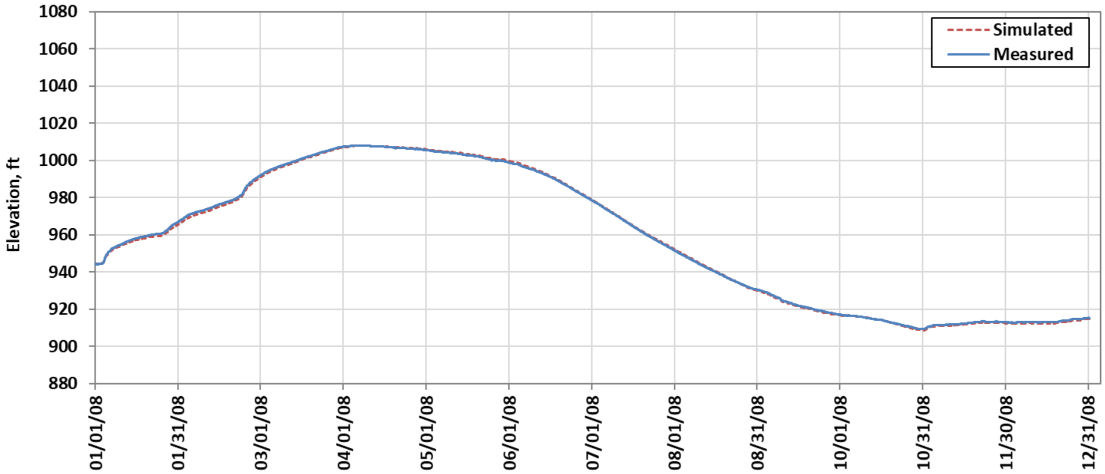


Figure D-9. Simulated versus measured Shasta Lake elevation (stage): 2008.

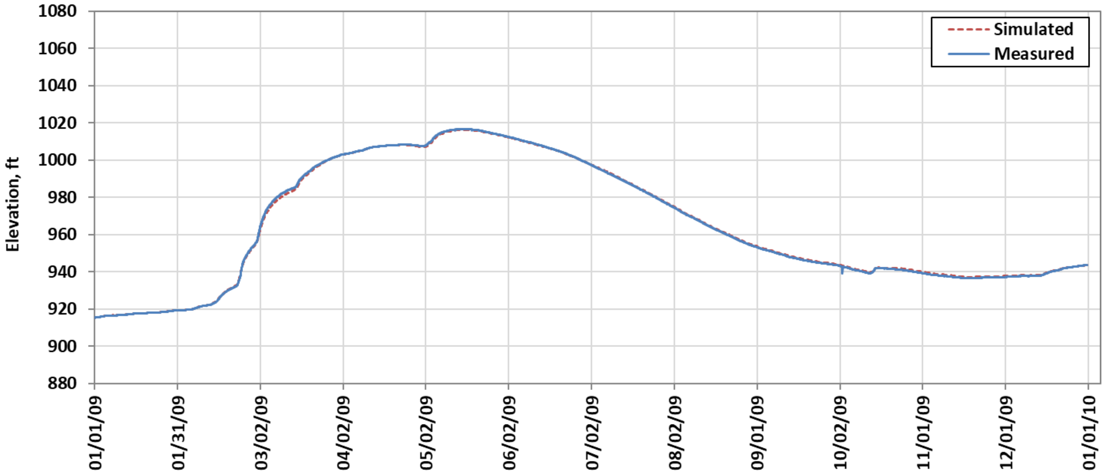


Figure D-10. Simulated versus measured Shasta Lake elevation (stage): 2009.

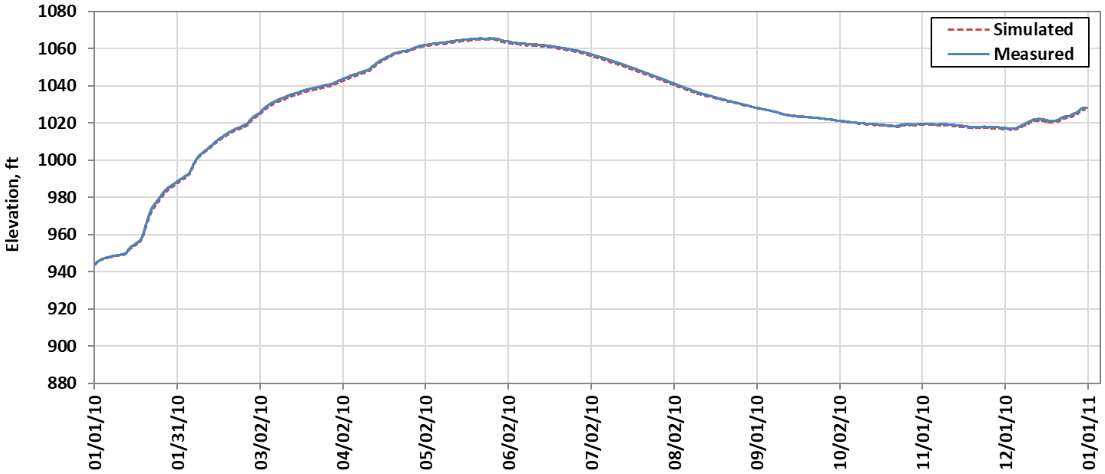


Figure D-11. Simulated versus measured Shasta Lake elevation (stage): 2010.

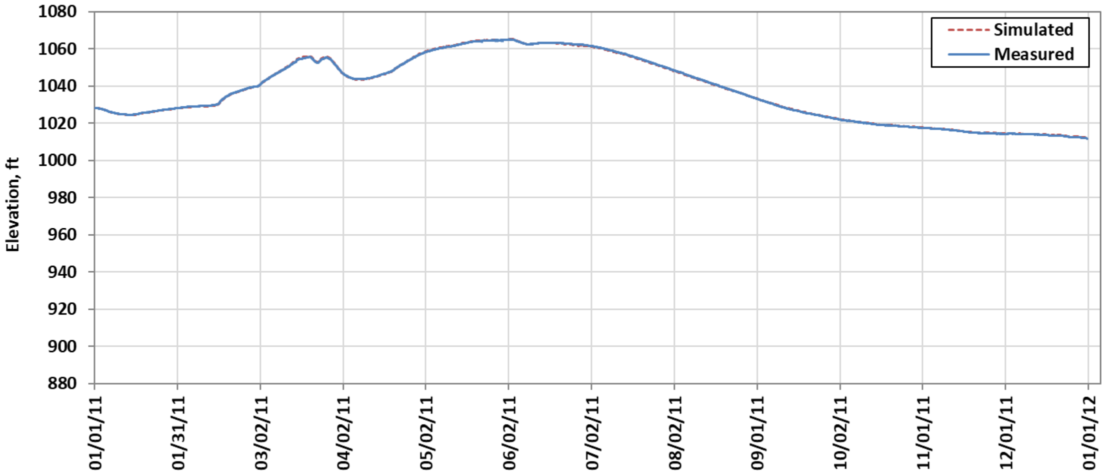


Figure D-12. Simulated versus measured Shasta Lake elevation (stage): 2011.

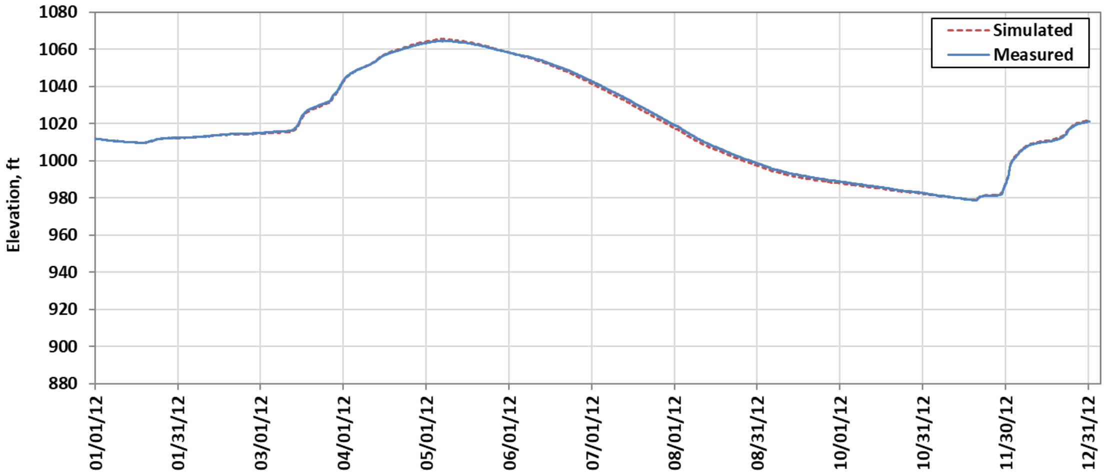


Figure D-13. Simulated versus measured Shasta Lake elevation (stage): 2012.

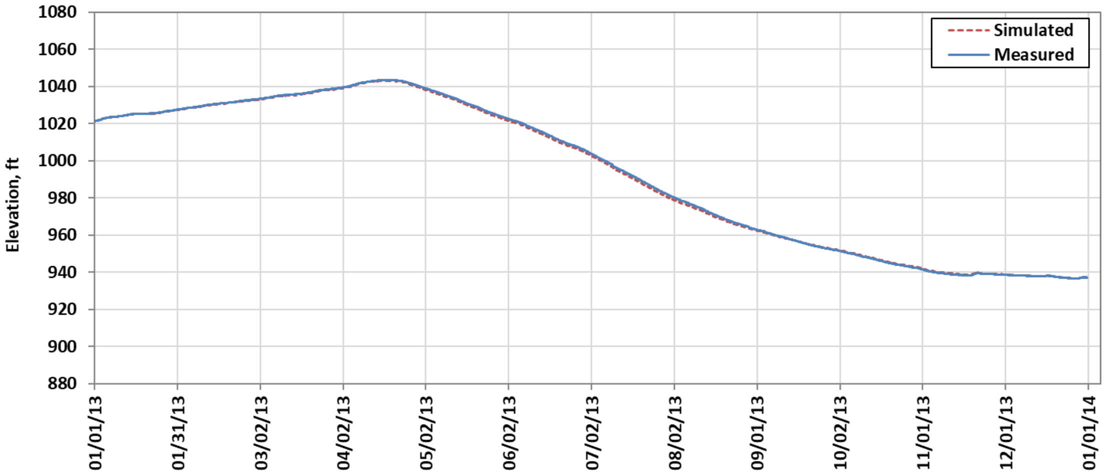


Figure D-14. Simulated versus measured Shasta Lake elevation (stage): 2013.

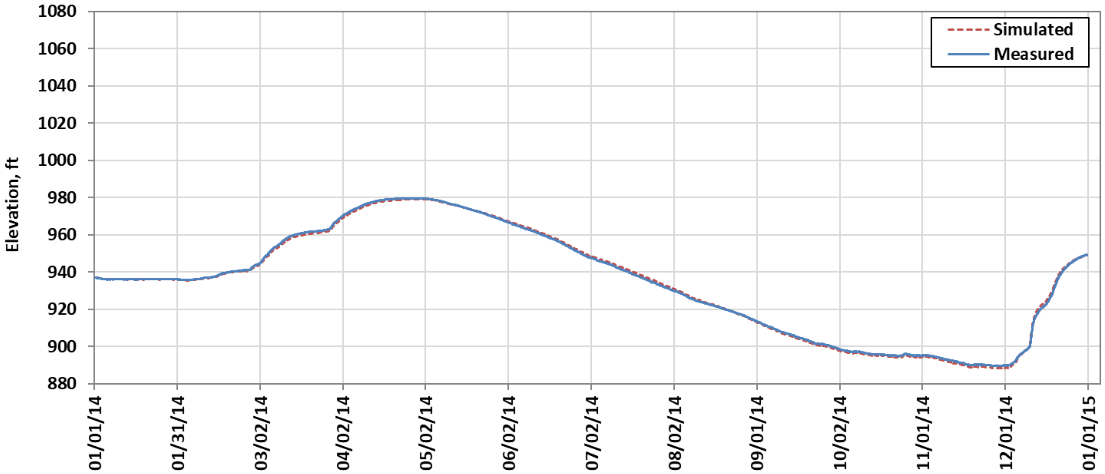


Figure D-15. Simulated versus measured Shasta Lake elevation (stage): 2014.

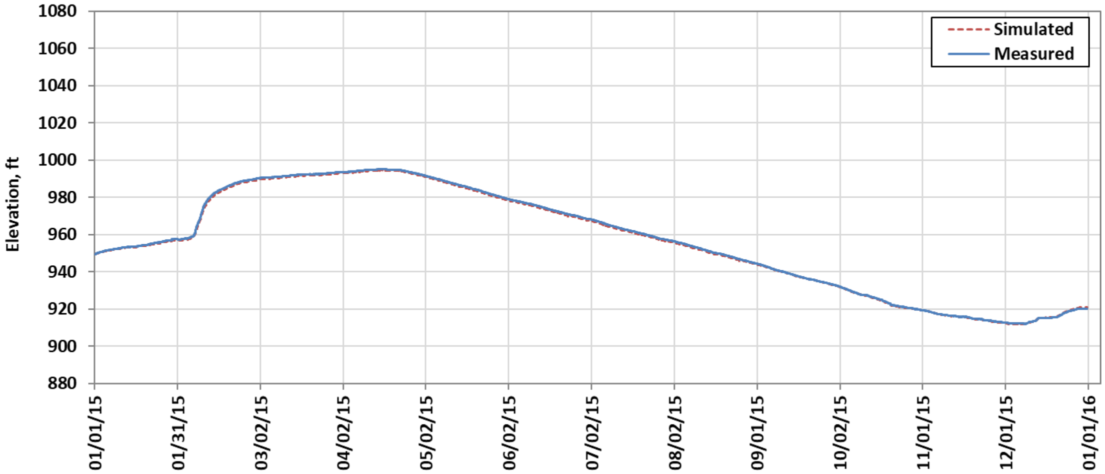


Figure D-16. Simulated versus measured Shasta Lake elevation (stage): 2015.

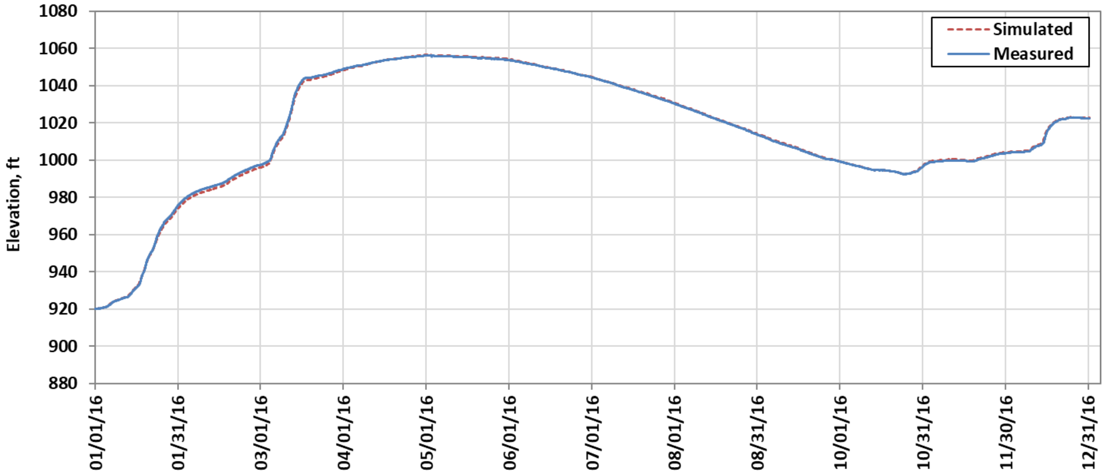


Figure D-17. Simulated versus measured Shasta Lake elevation (stage): 2016.

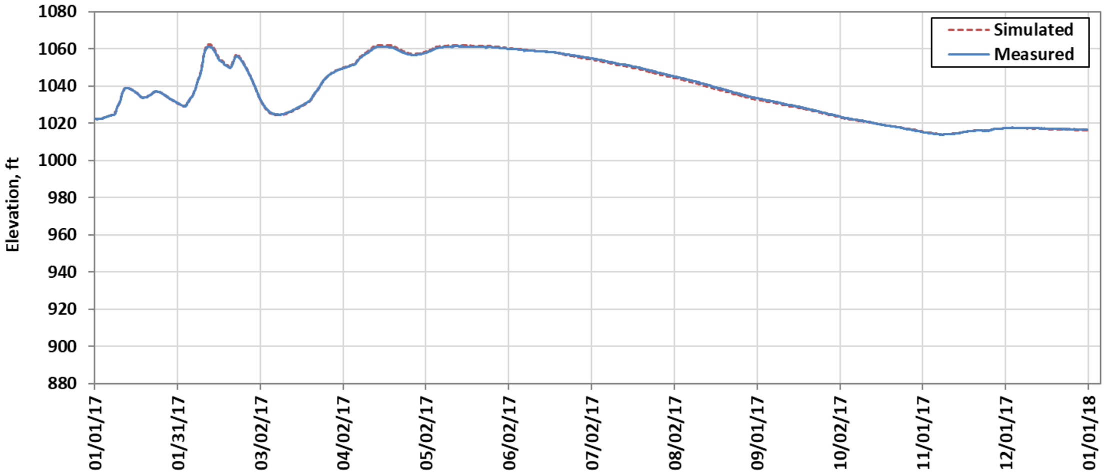


Figure D-18. Simulated versus measured Shasta Lake elevation (stage): 2017.

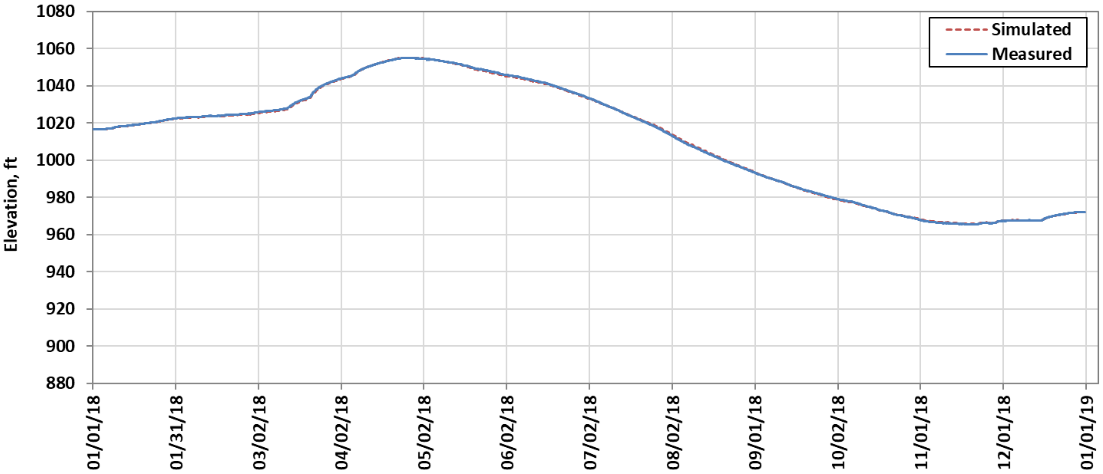


Figure D-19. Simulated versus measured Shasta Lake elevation (stage): 2018.

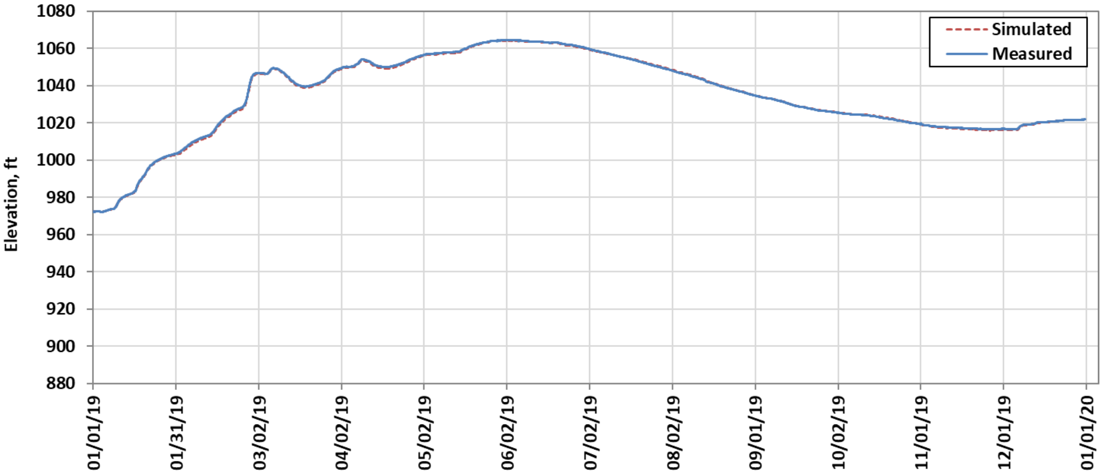


Figure D-20. Simulated versus measured Shasta Lake elevation (stage): 2019.

Table D-1. Summary statistics of Shasta Lake elevation (stage): 2000-2019. DRAFT

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

D.2. Outflow (DRAFT)

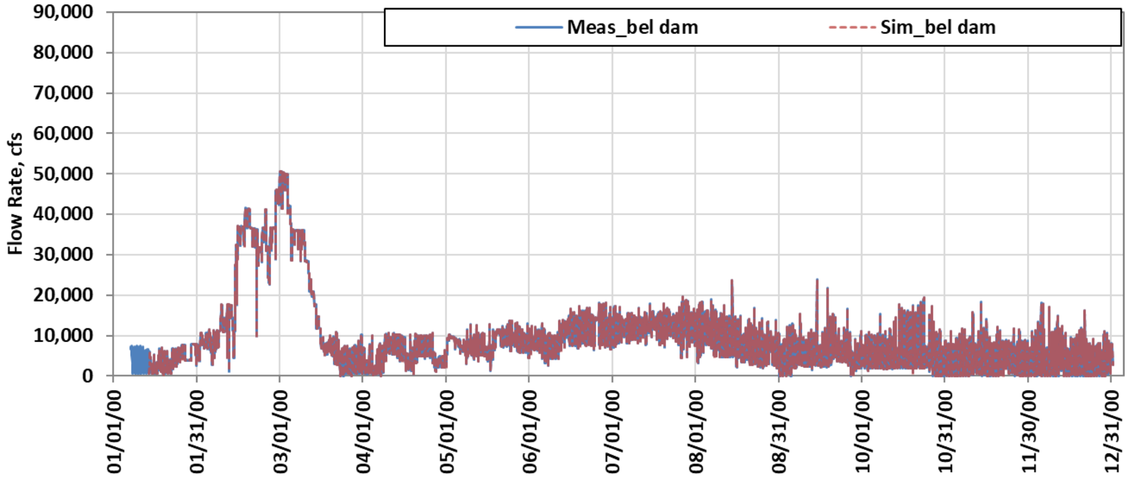


Figure D-21. Simulated versus measured Shasta Dam outflow: 2000.

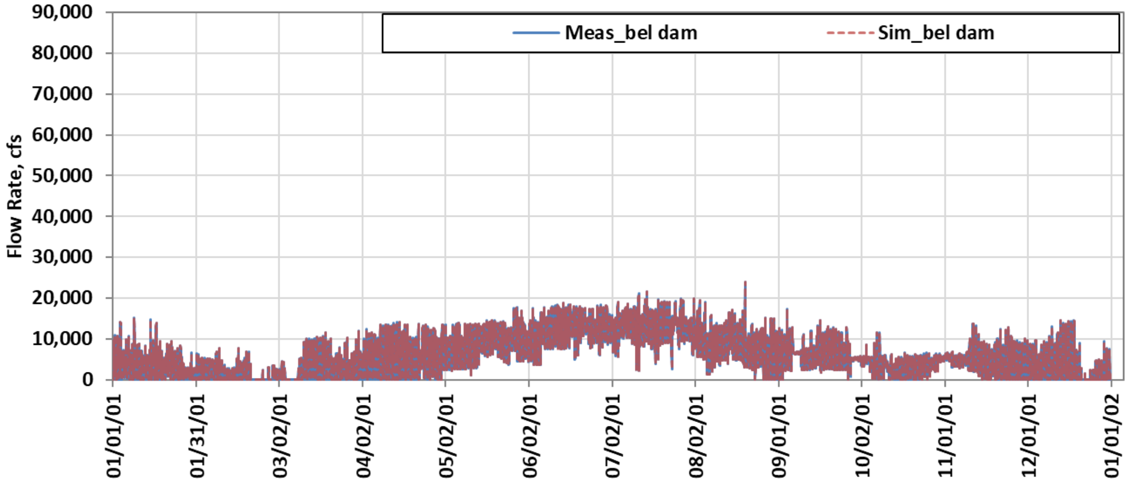


Figure D-19. Simulated versus measured Shasta Dam outflow: 2001.

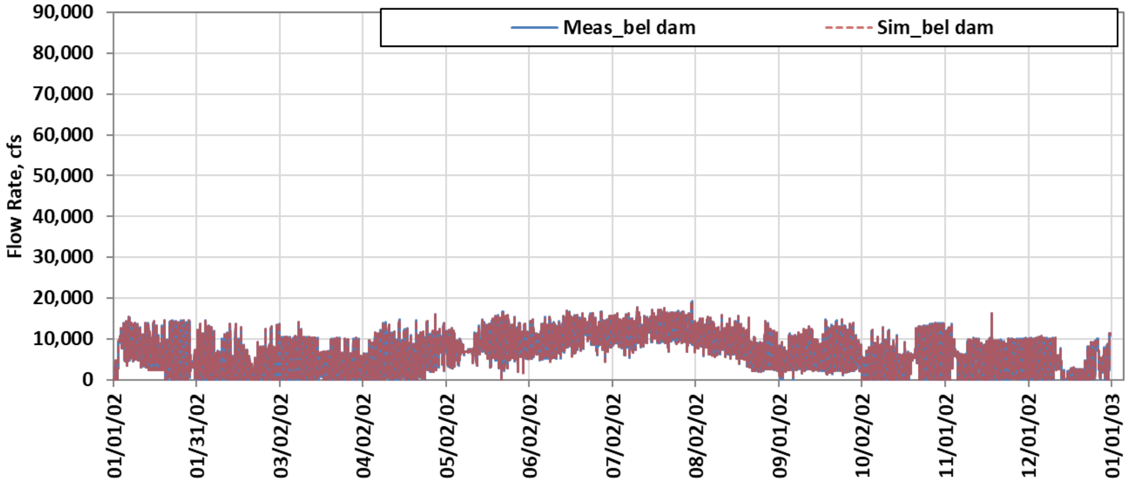


Figure D-20. Simulated versus measured Shasta Dam outflow: 2002.

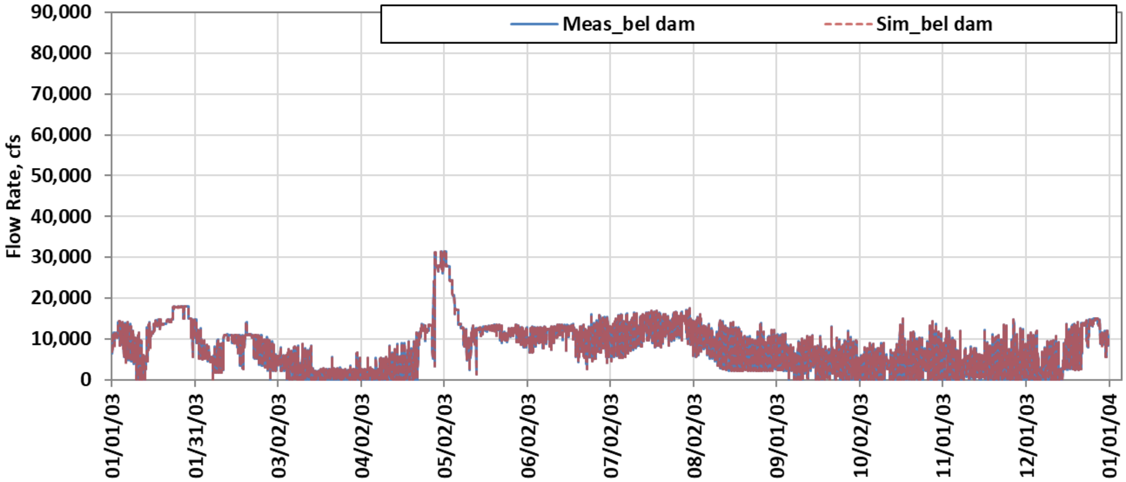


Figure D-21. Simulated versus measured Shasta Dam outflow: 2003.

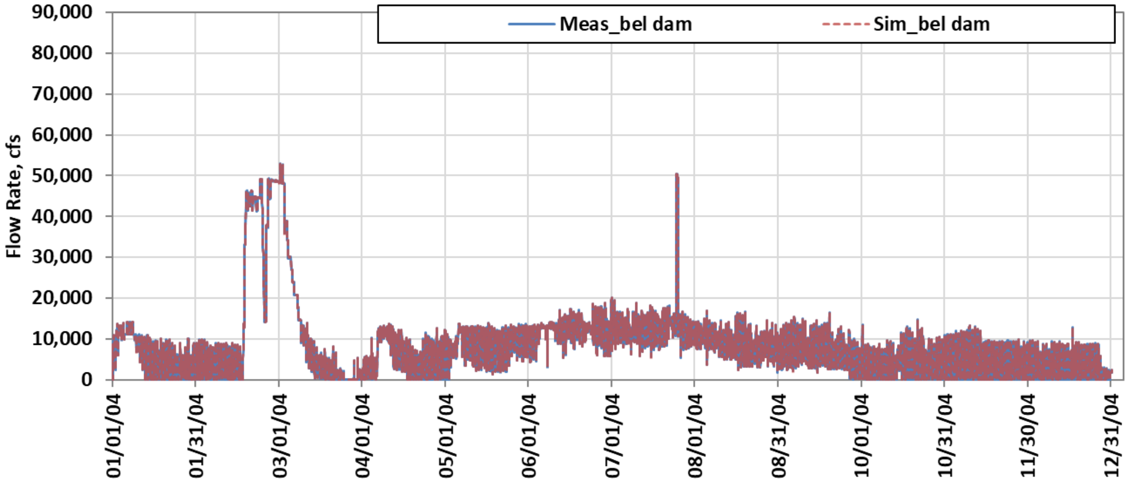


Figure D-22. Simulated versus measured Shasta Dam outflow: 2004.

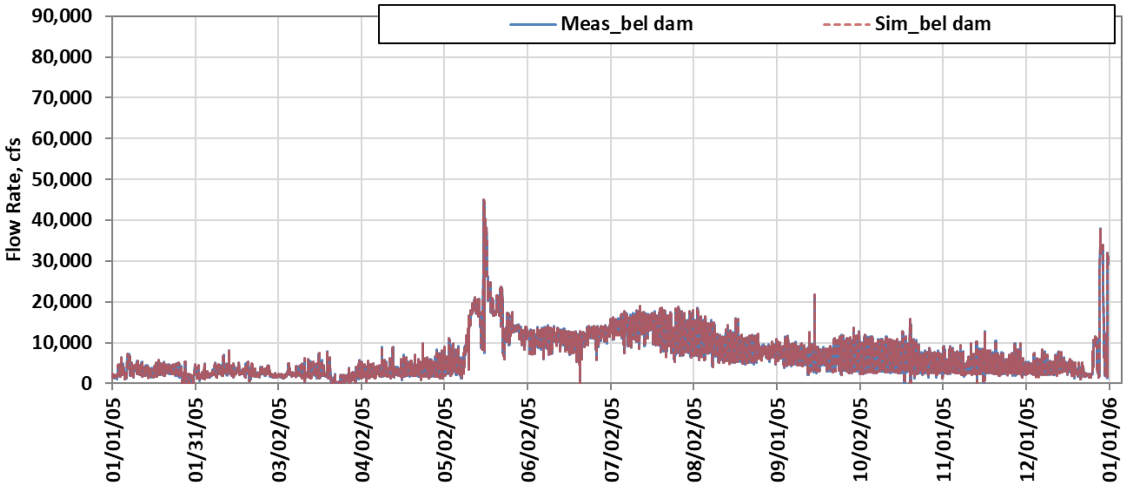


Figure D-23. Simulated versus measured Shasta Dam outflow: 2005.

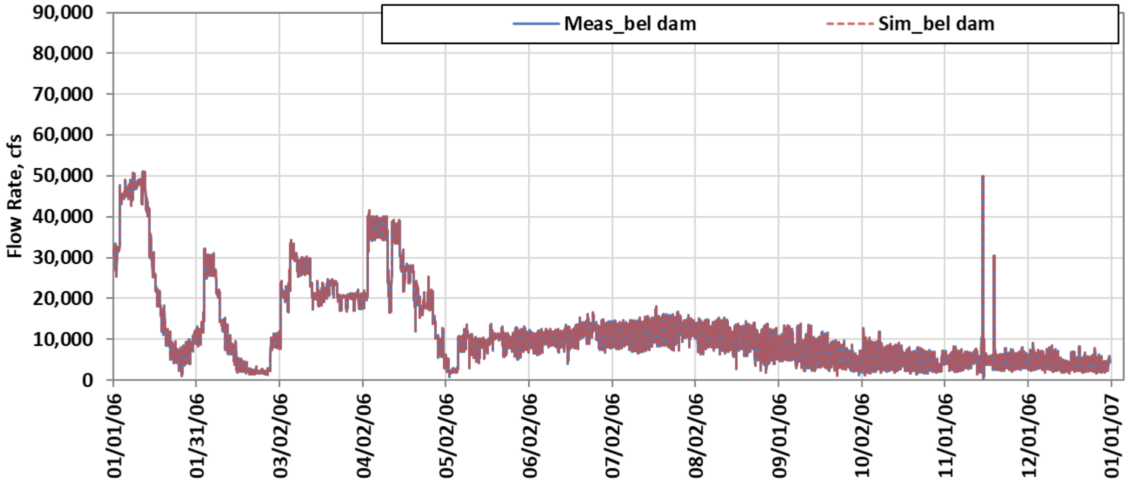


Figure D-24. Simulated versus measured Shasta Dam outflow: 2006.

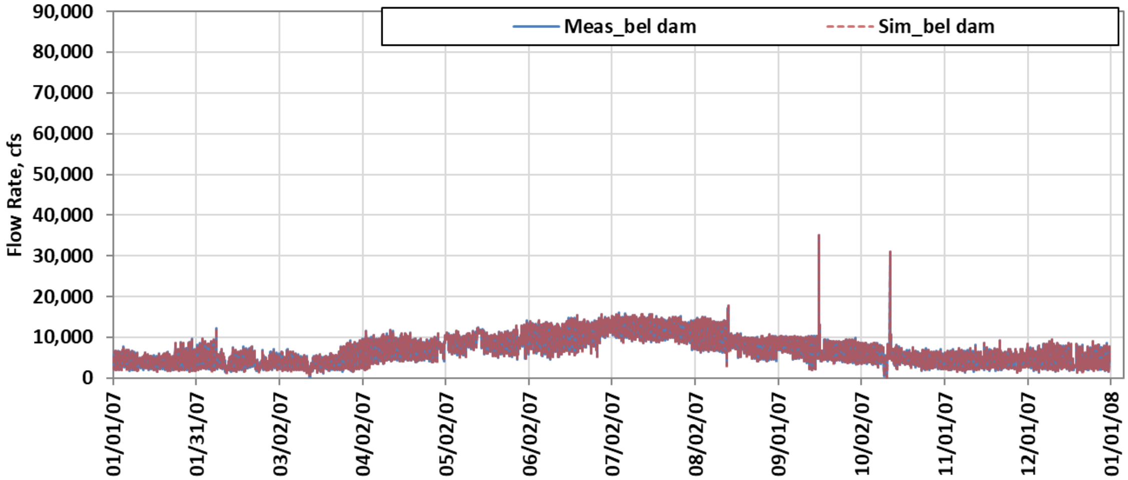


Figure D-25. Simulated versus measured Shasta Dam outflow: 2007.

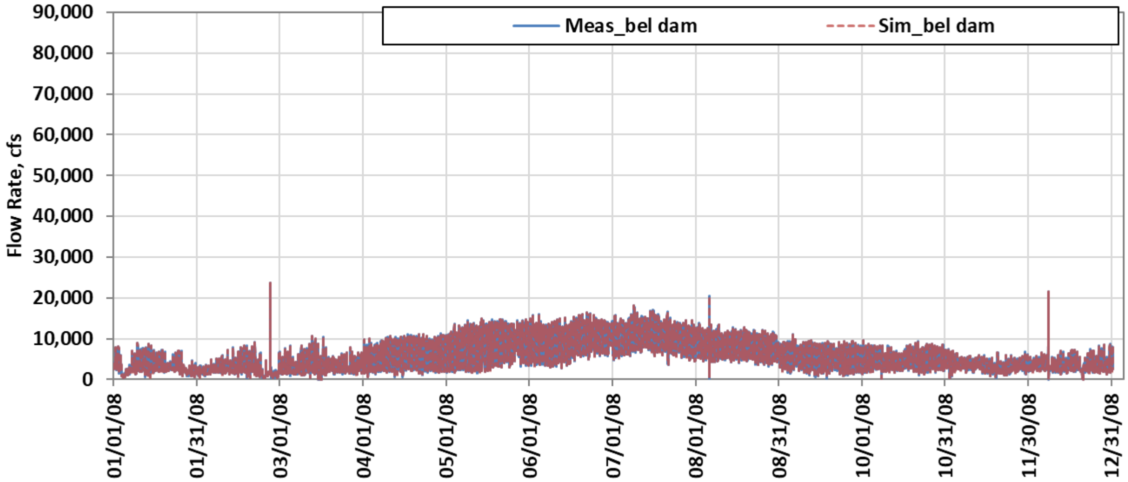


Figure D-26. Simulated versus measured Shasta Dam outflow: 2008.

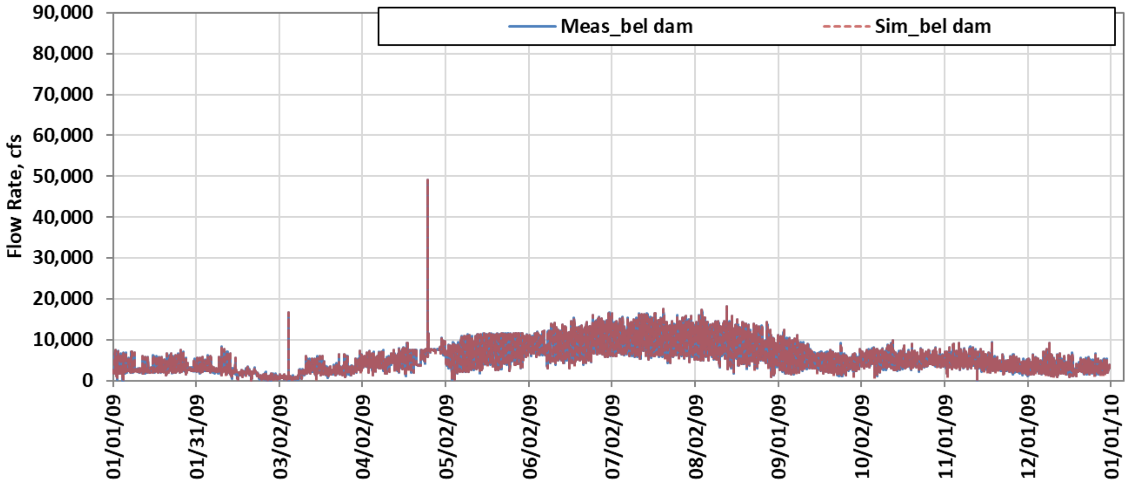


Figure D-27. Simulated versus measured Shasta Dam outflow: 2009.

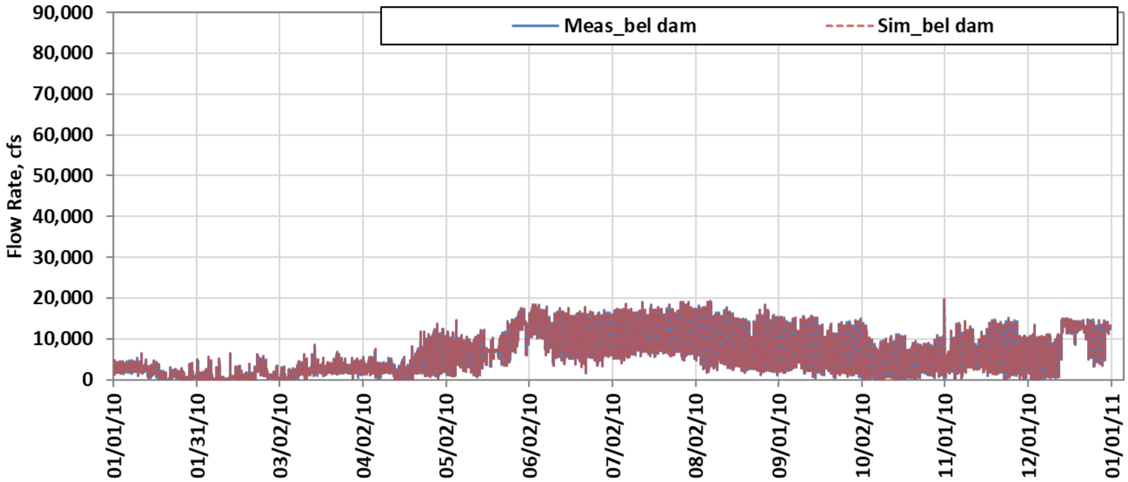


Figure D-28. Simulated versus measured Shasta Dam outflow: 2010.

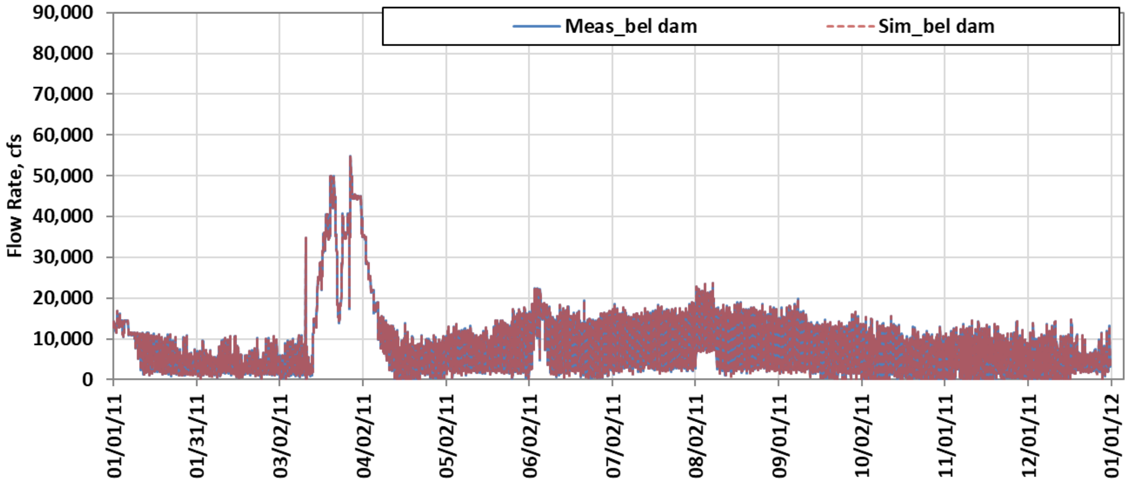


Figure D-29. Simulated versus measured Shasta Dam outflow: 2011.

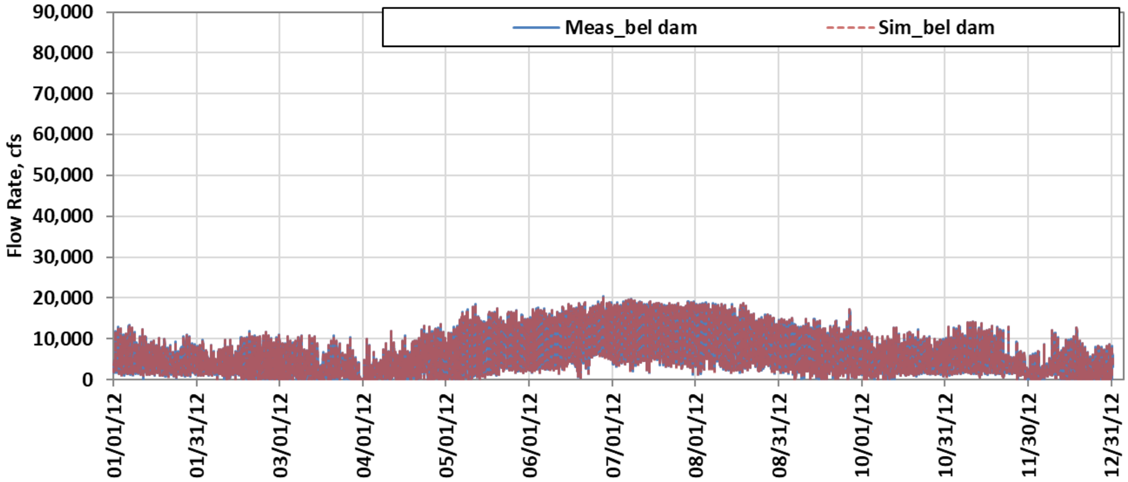


Figure D-30. Simulated versus measured Shasta Dam outflow: 2012.

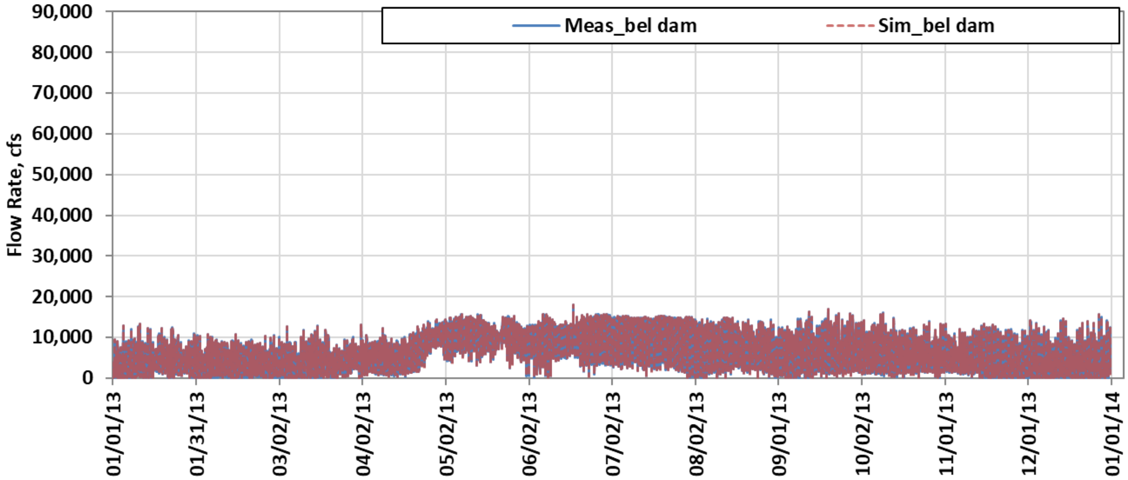


Figure D-31. Simulated versus measured Shasta Dam outflow: 2013.

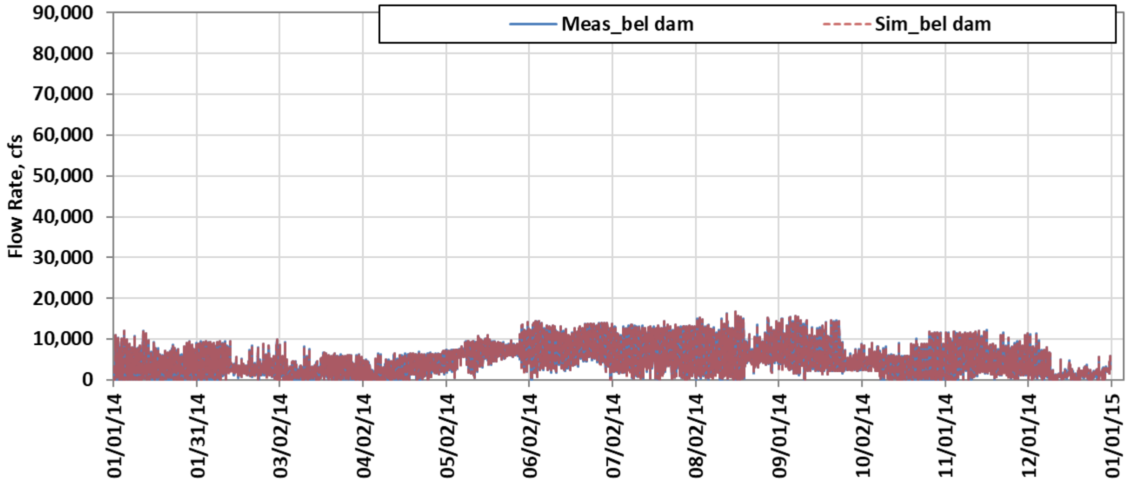


Figure D-32. Simulated versus measured Shasta Dam outflow: 2014.

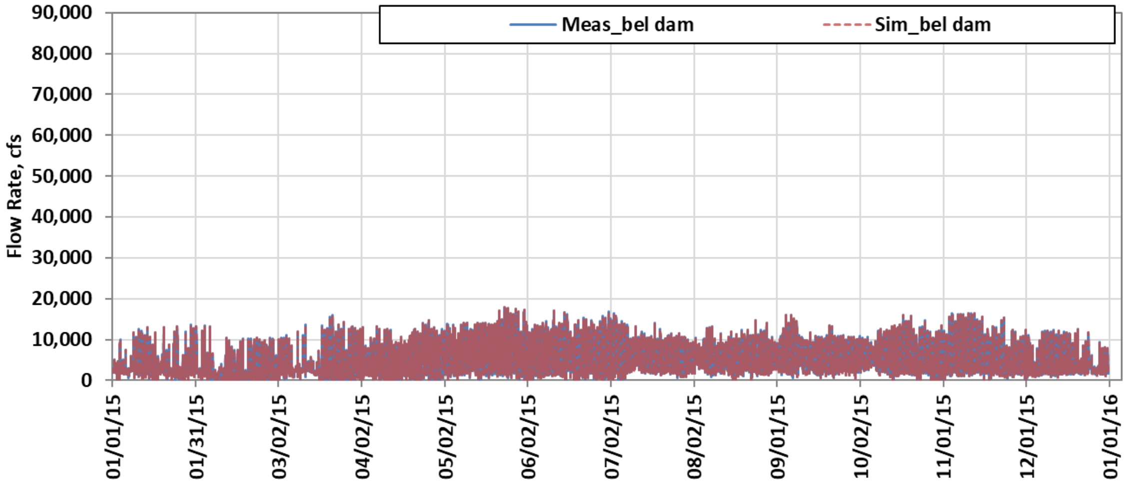


Figure D-33. Simulated versus measured Shasta Dam outflow: 2015.

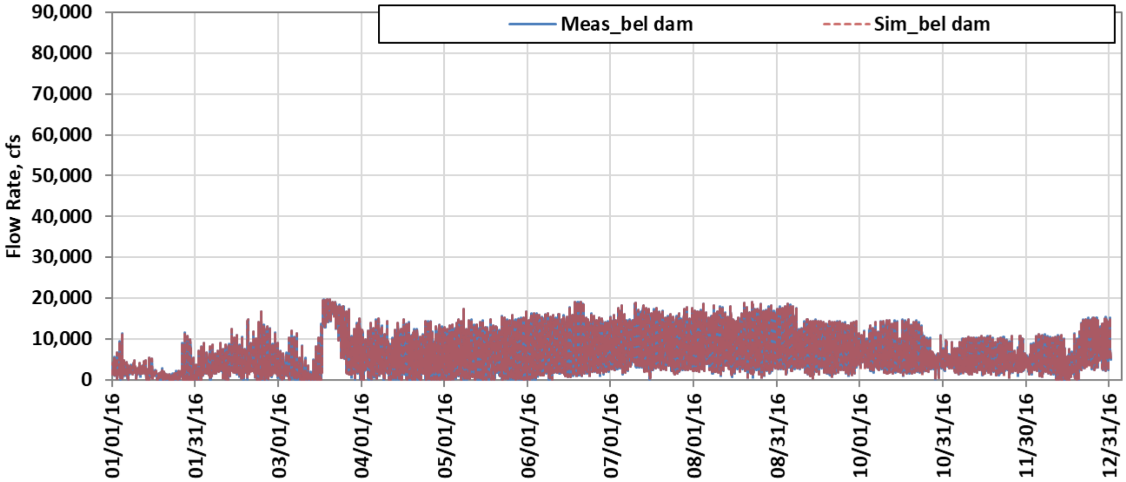


Figure D-34. Simulated versus measured Shasta Dam outflow: 2016.

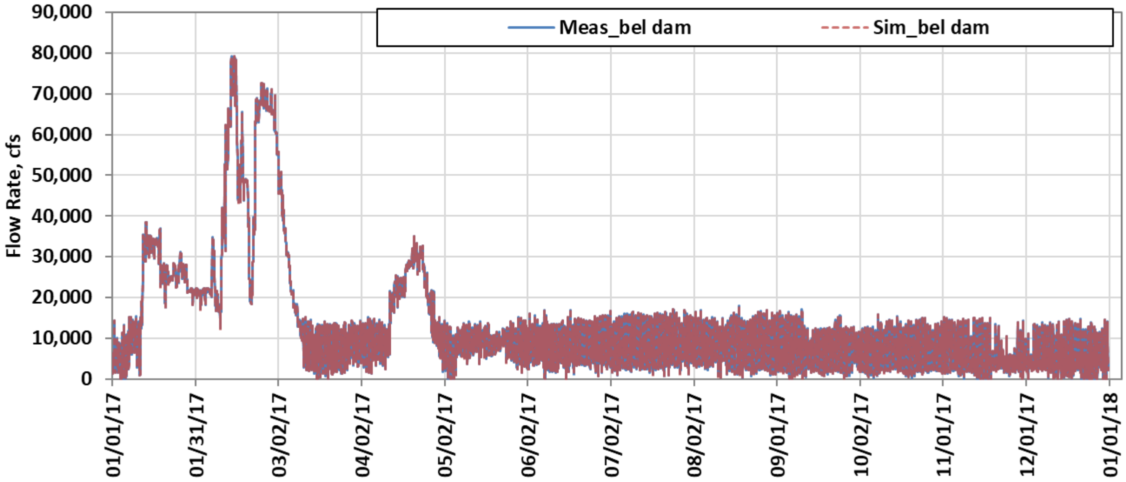


Figure D-35. Simulated versus measured Shasta Dam outflow: 2017.

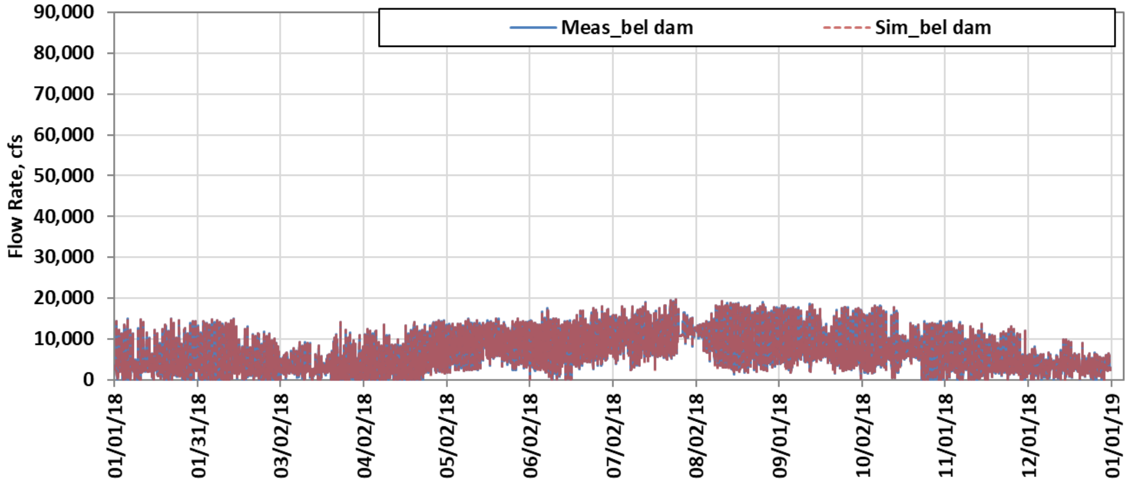


Figure D-39. Simulated versus measured Shasta Dam outflow: 2018.

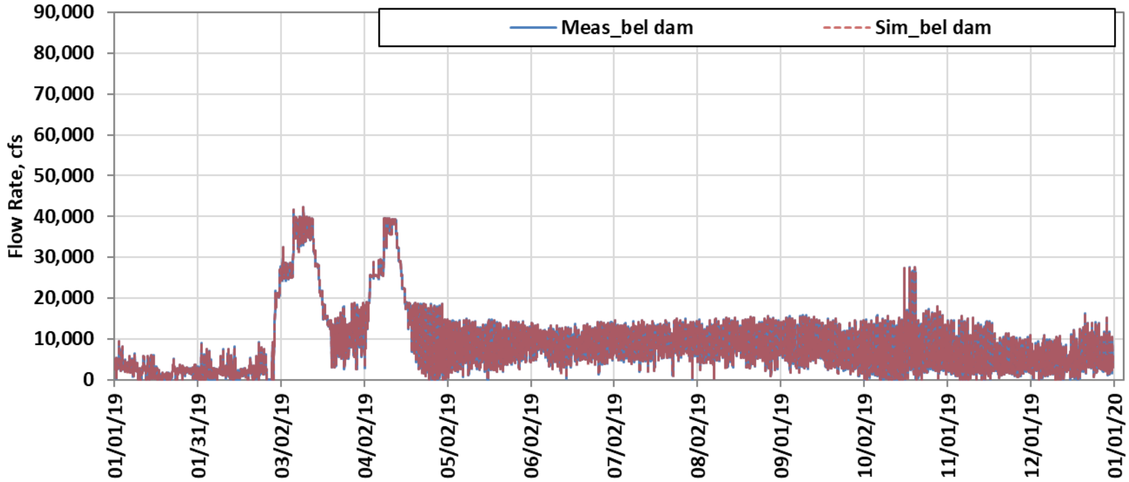


Figure D-40. Simulated versus measured Shasta Dam outflow: 2019.

Table D-2. Summary statistics for Shasta Dam outflow: 2000-2019.

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

D.3. Reservoir Temperature Profiles

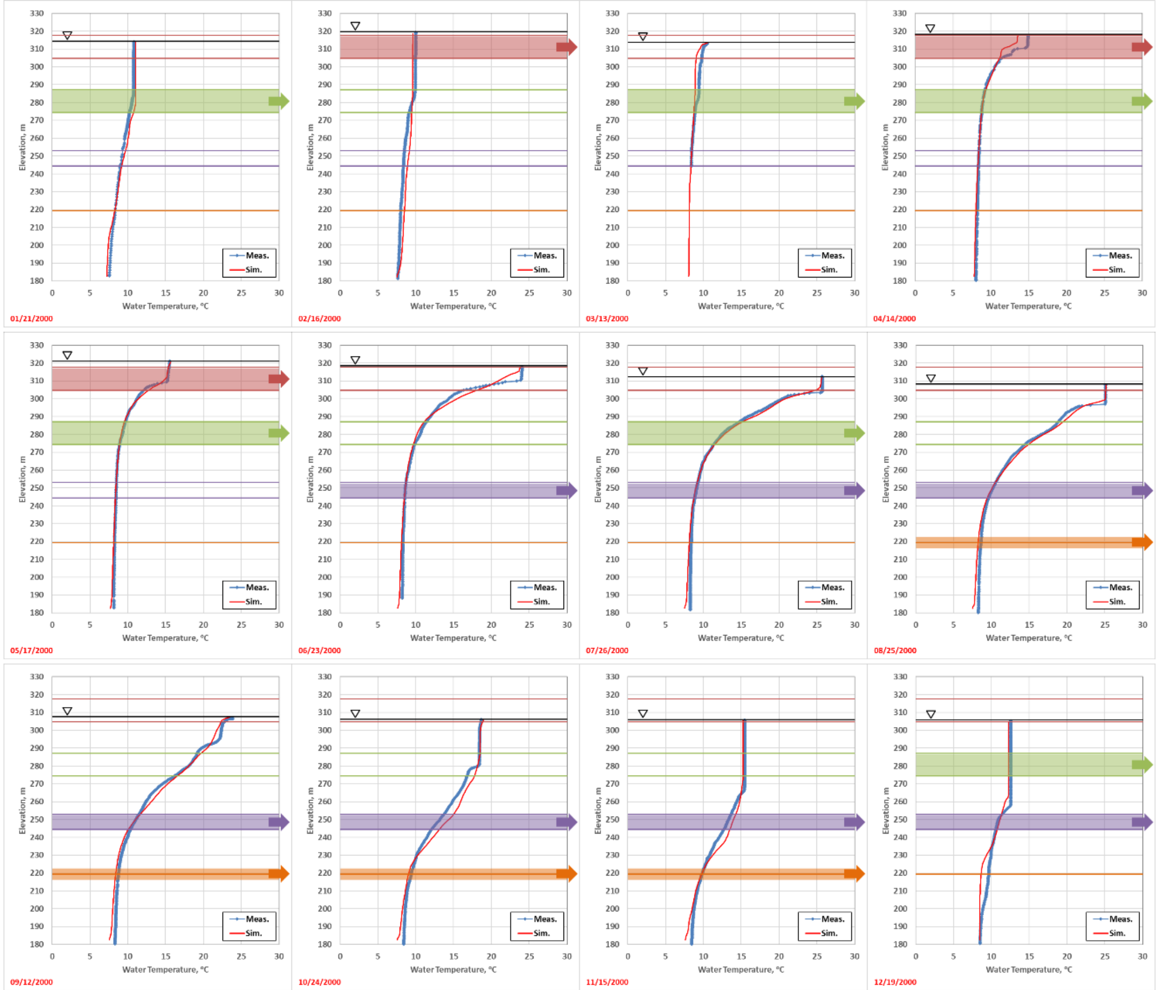


Figure D-36. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2000.

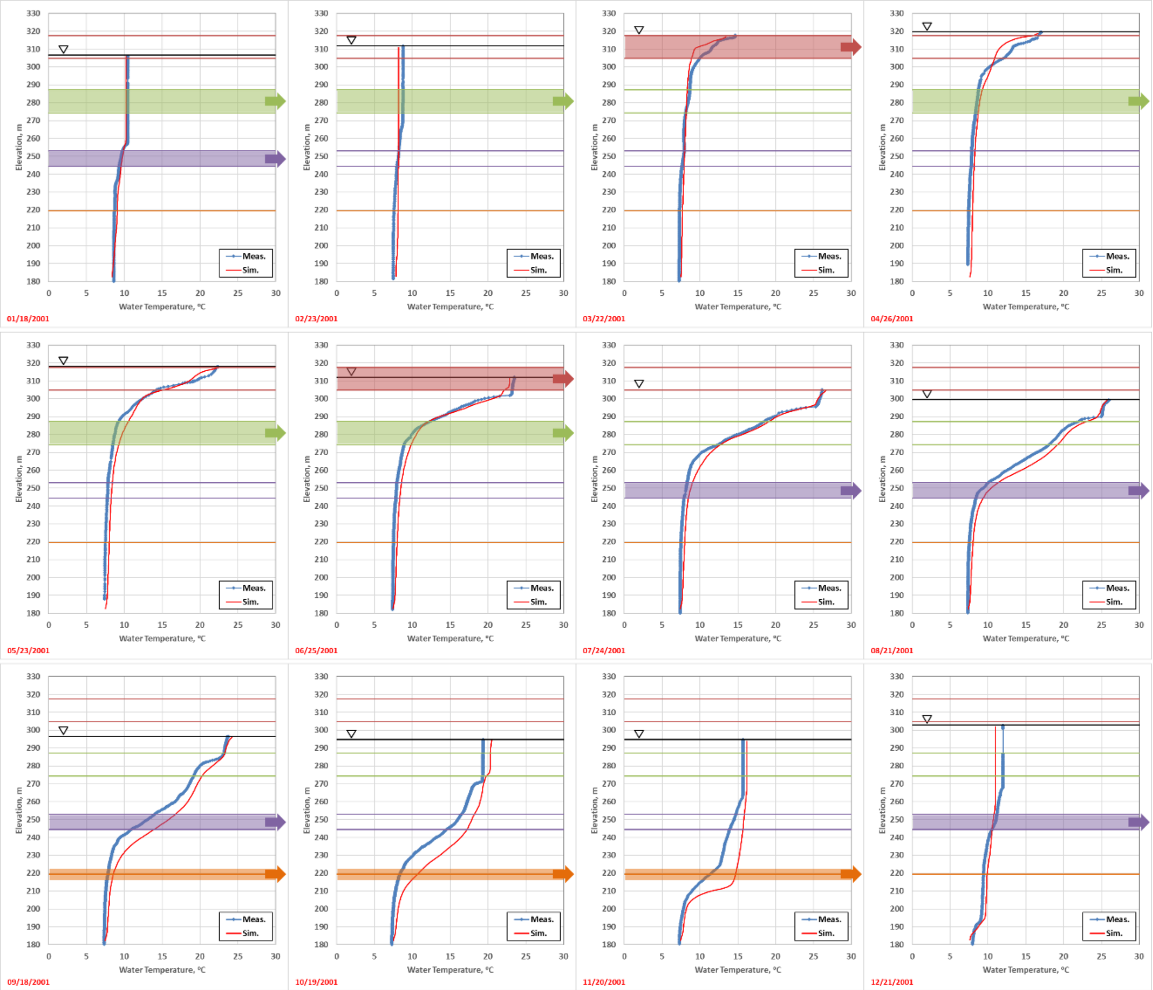
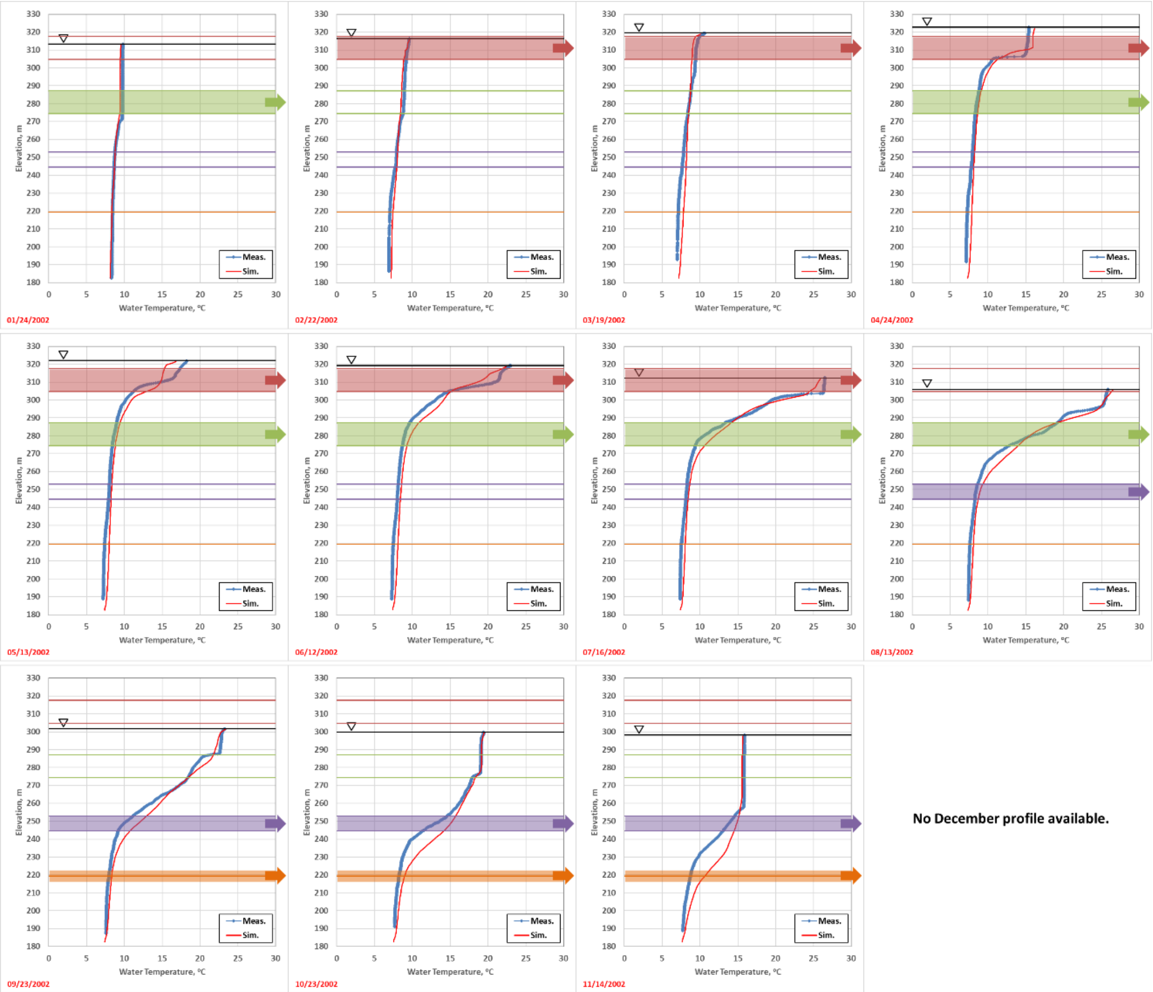


Figure D-37. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2001.



No December profile available.

Figure D-38. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2002.

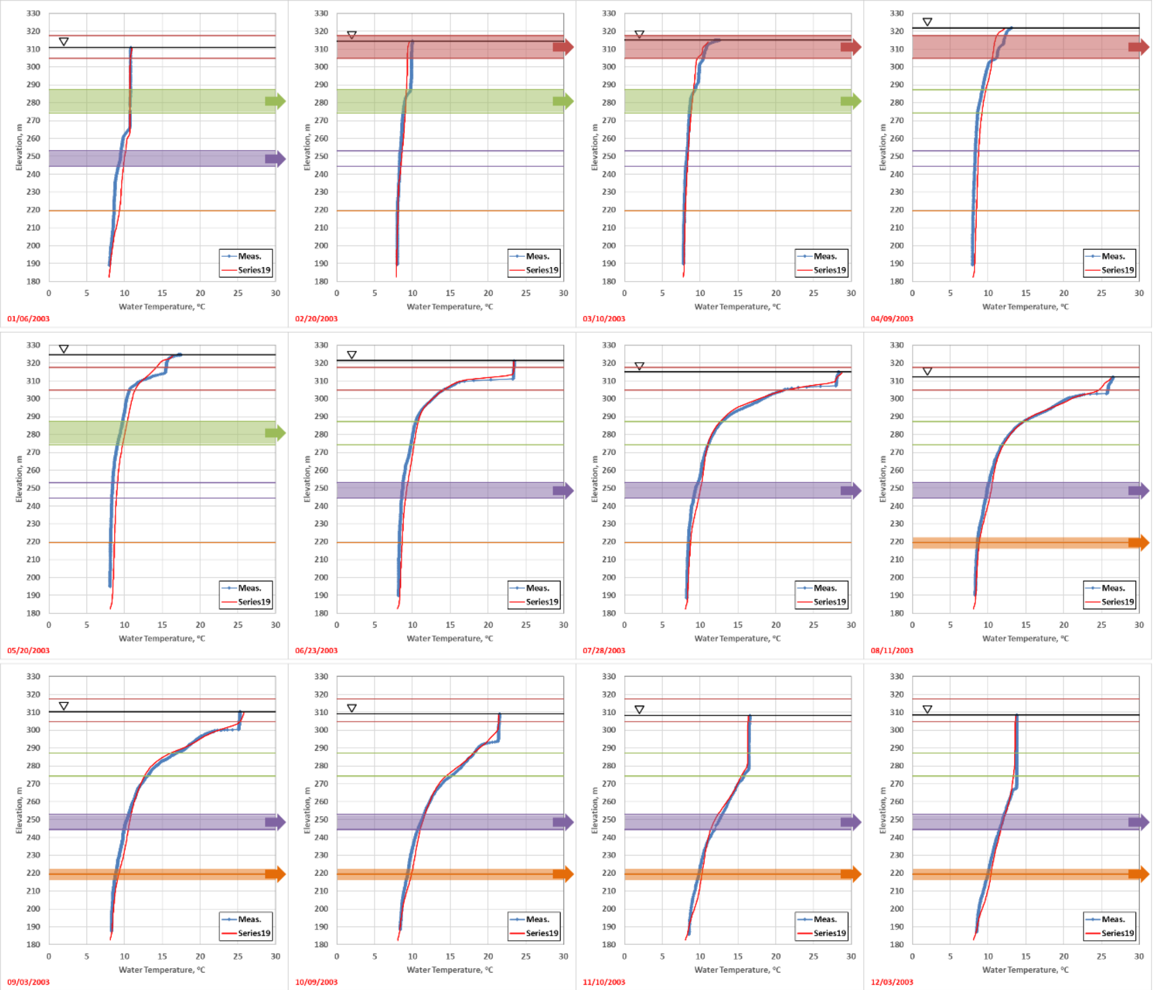


Figure D-39. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2003.

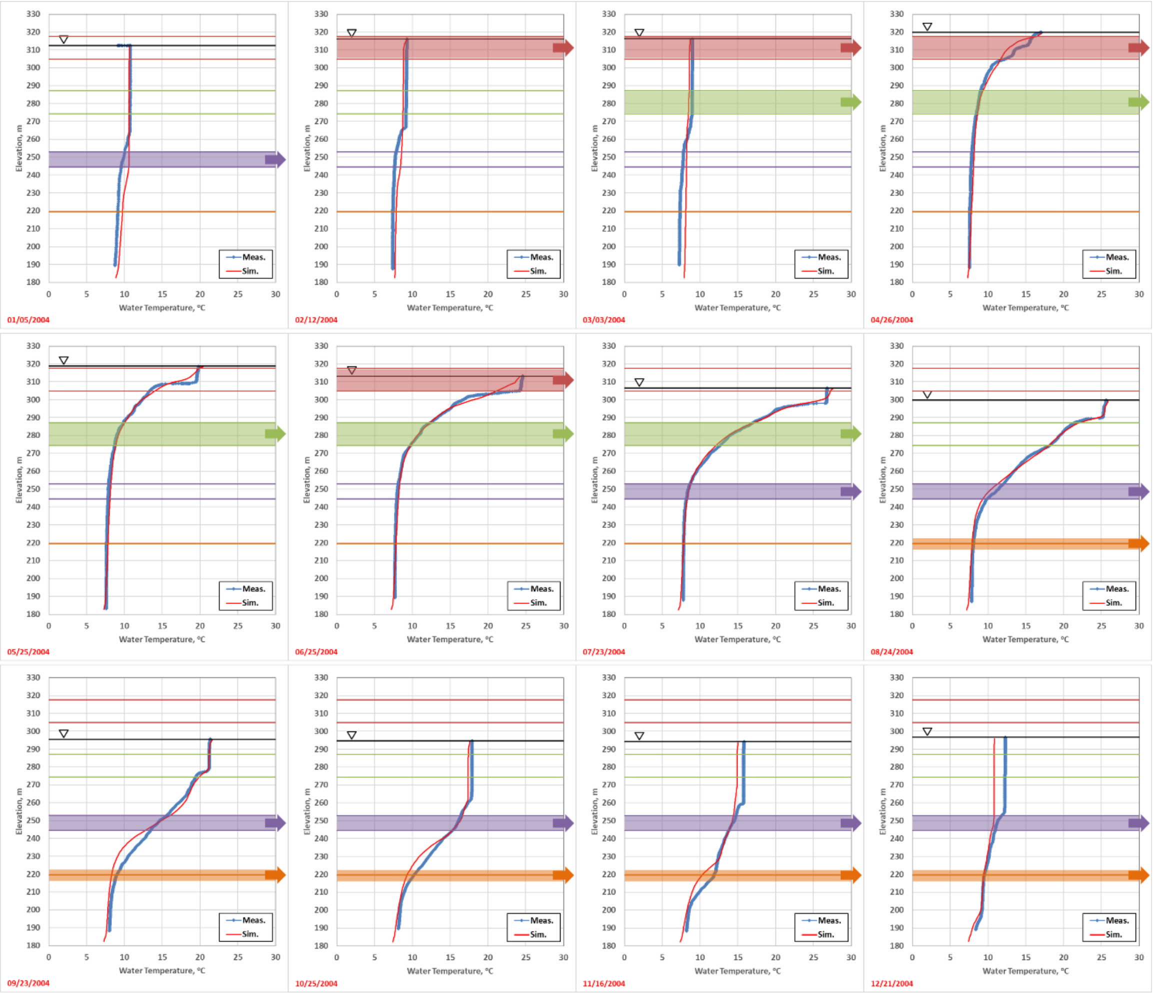


Figure D-40. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2004.

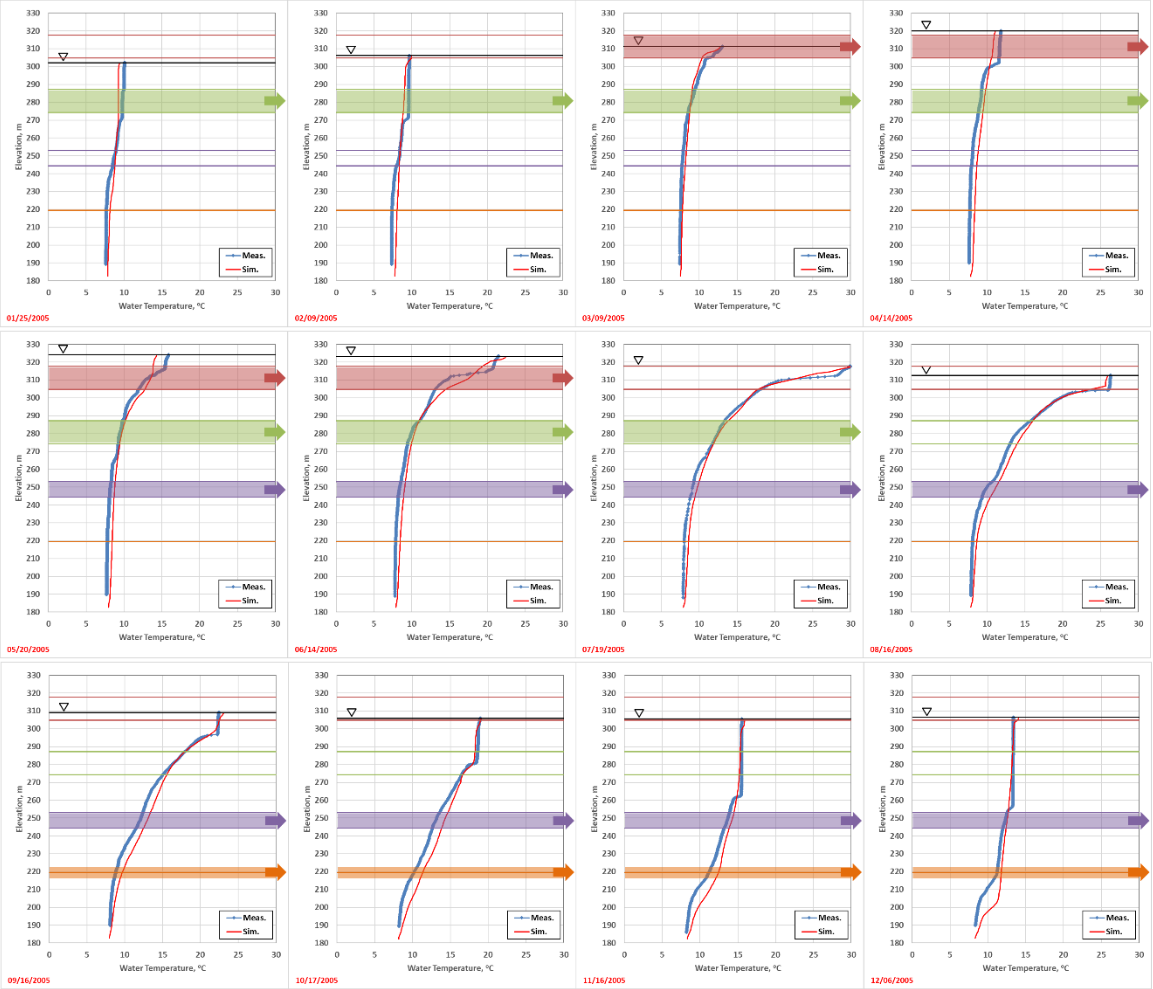


Figure D-41. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2005.

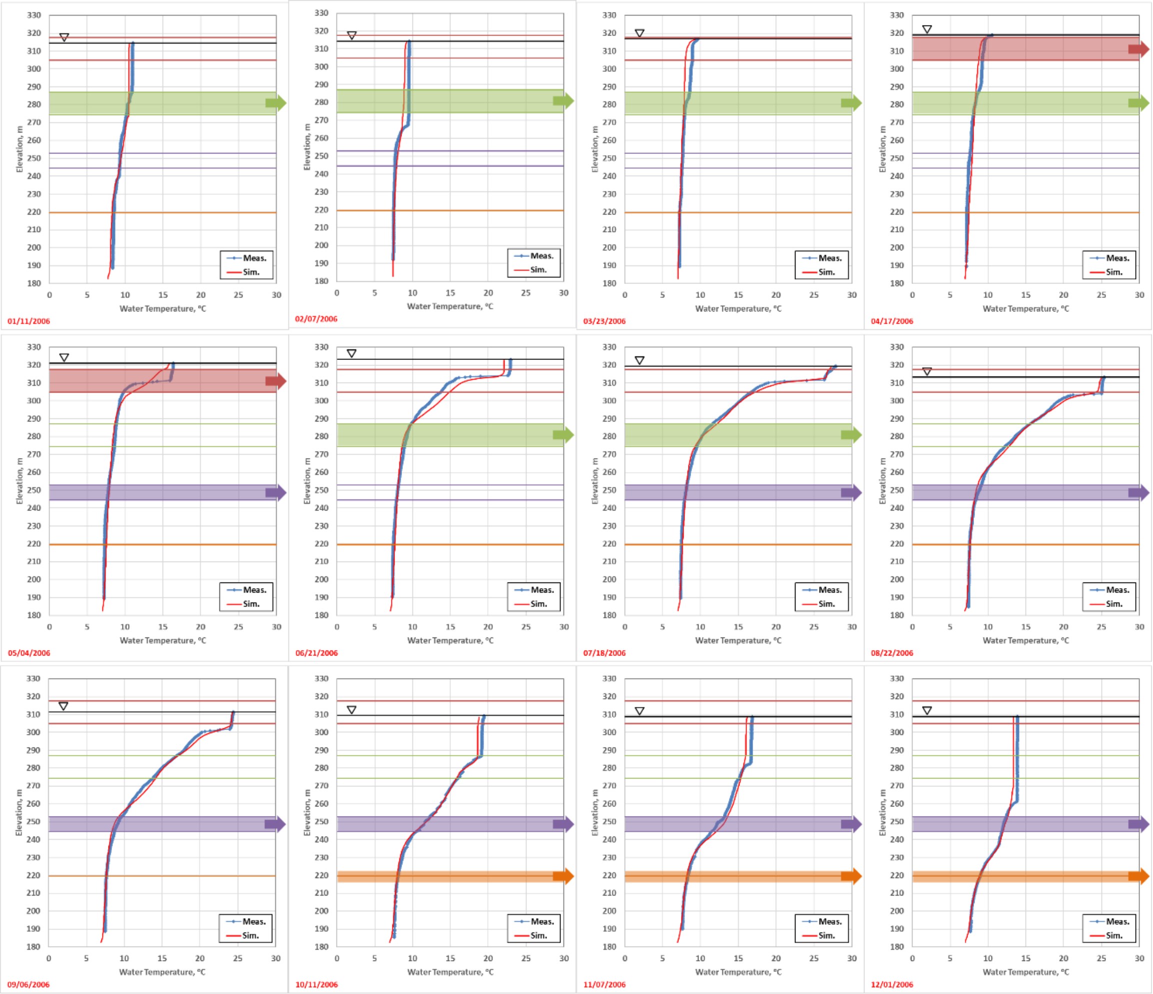


Figure D-42. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2006.

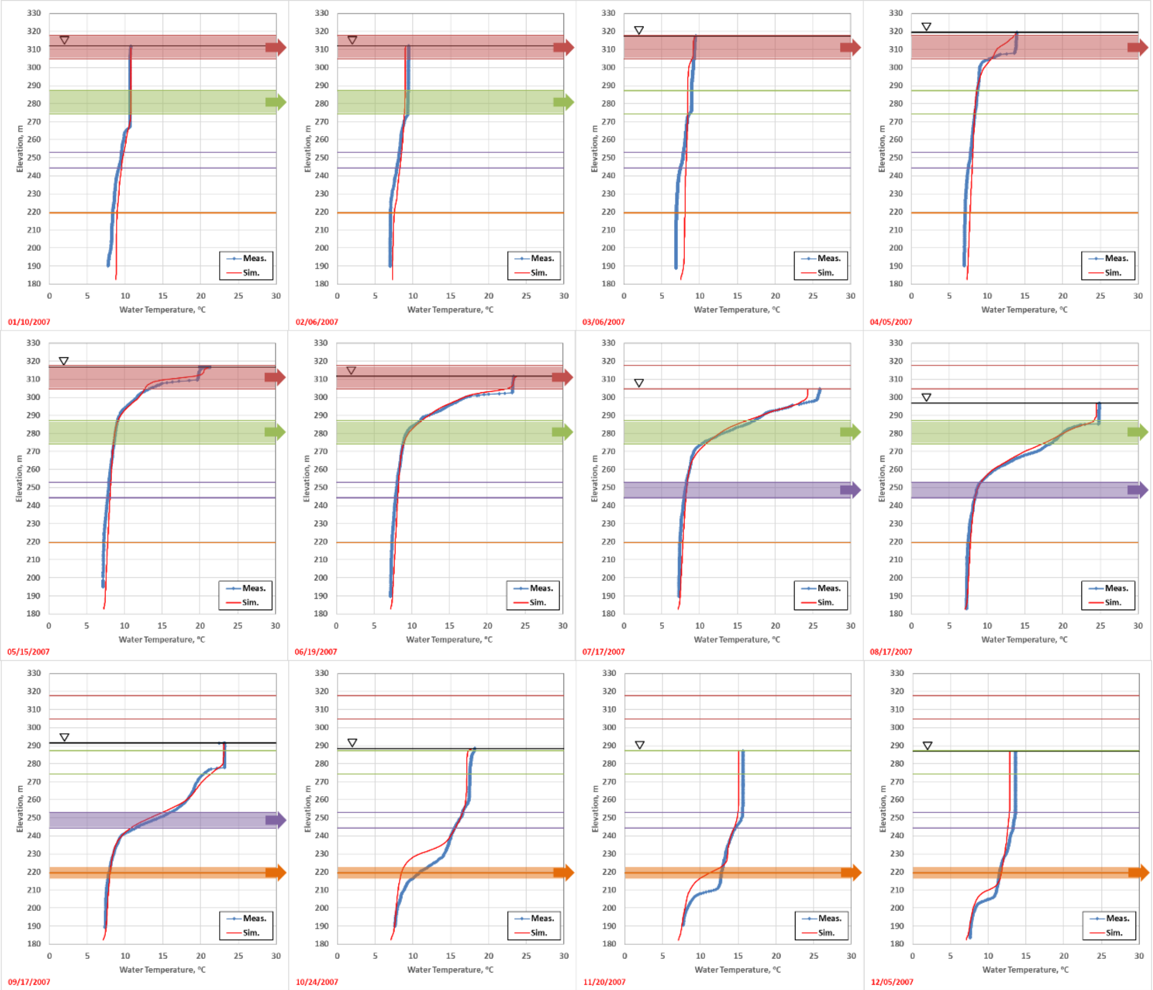


Figure D-43. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2007.

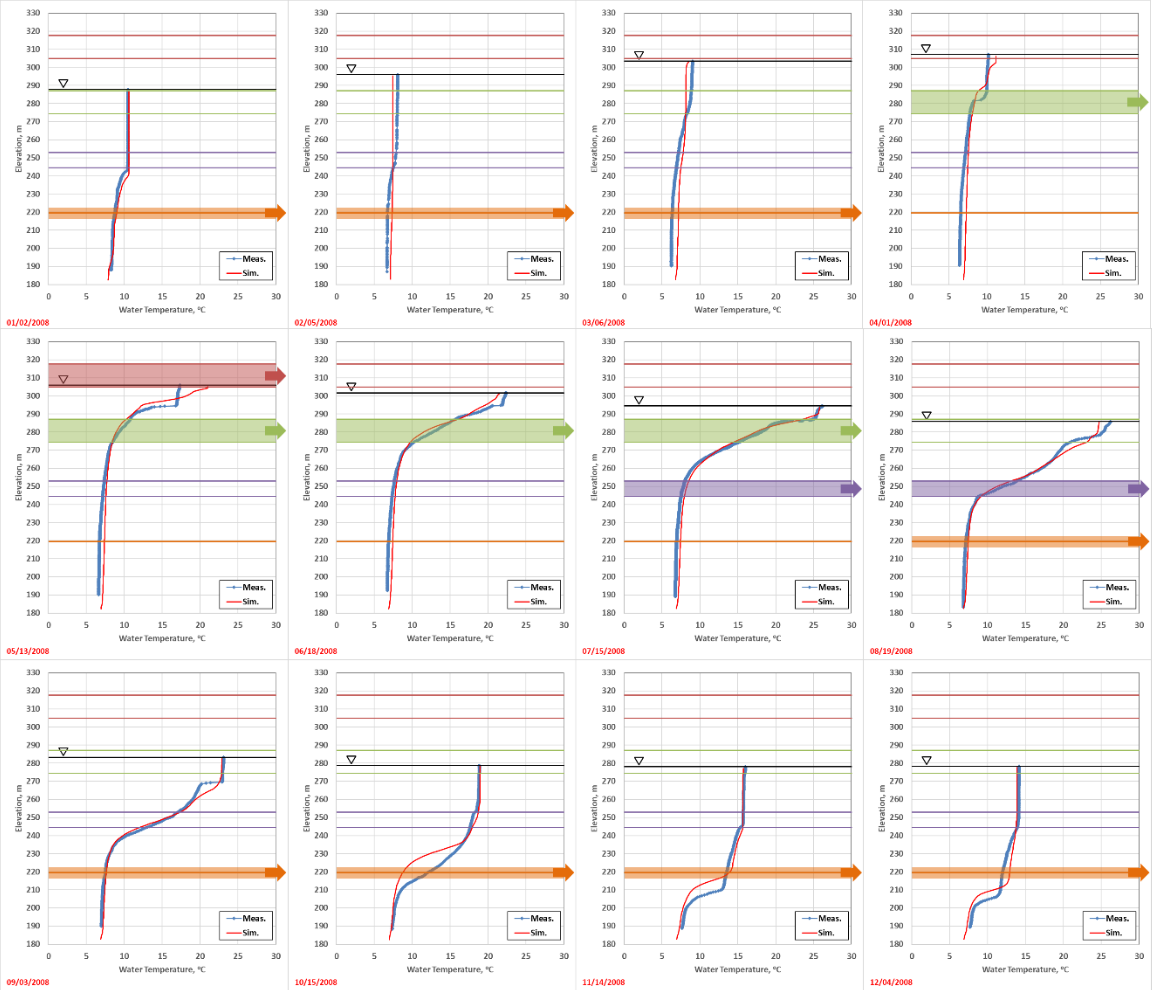


Figure D-44. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2008.

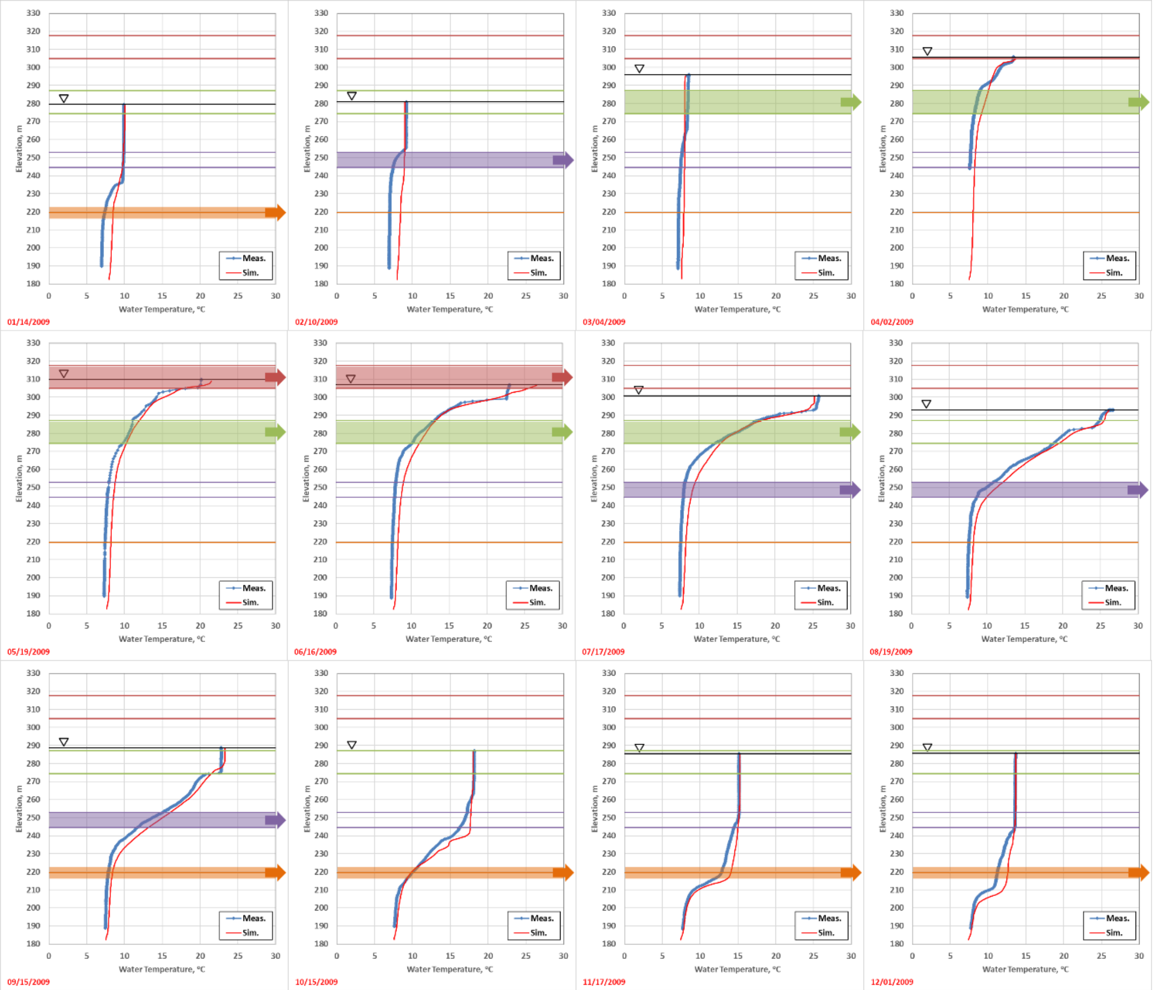
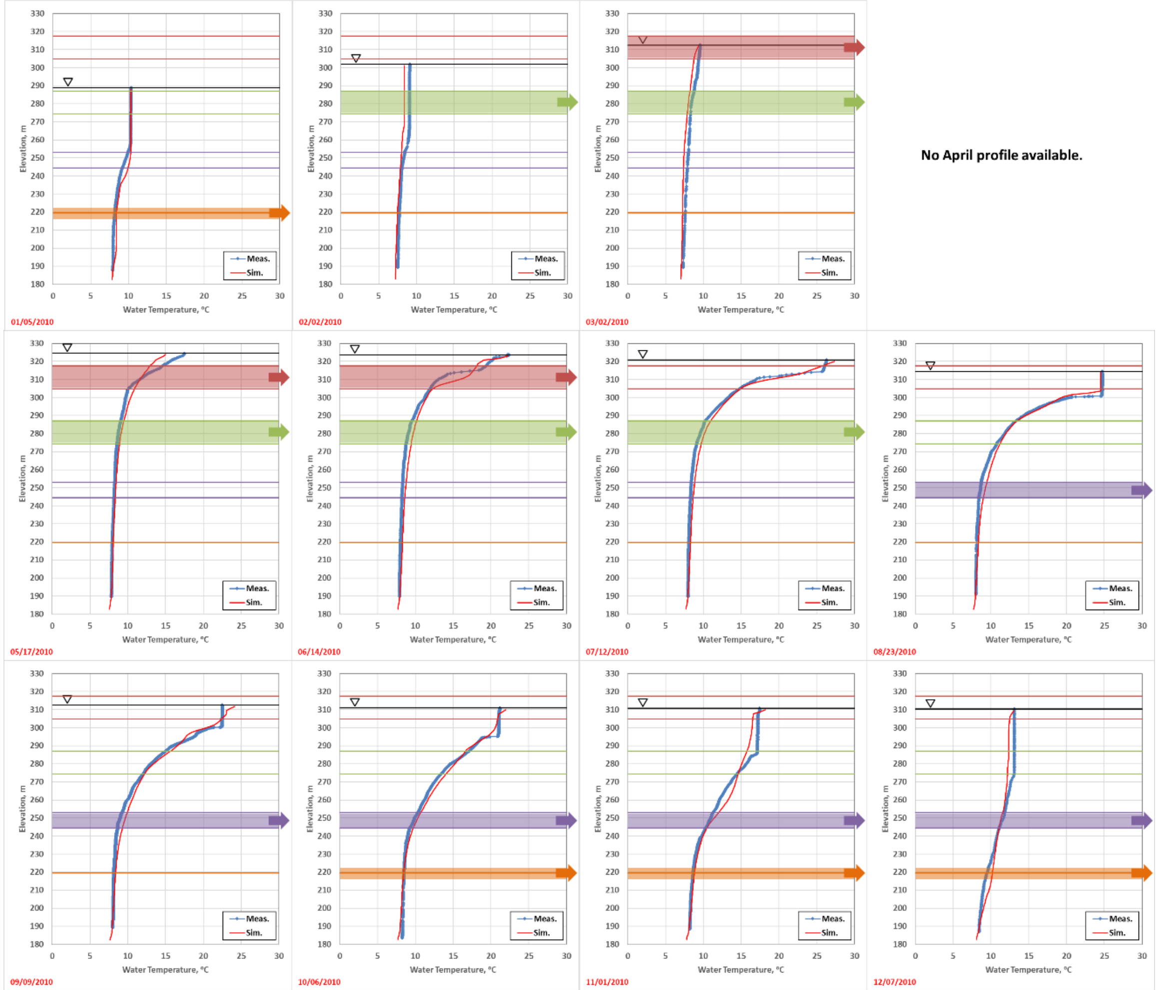


Figure D-45. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2009.



No April profile available.

Figure D-46. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2010.

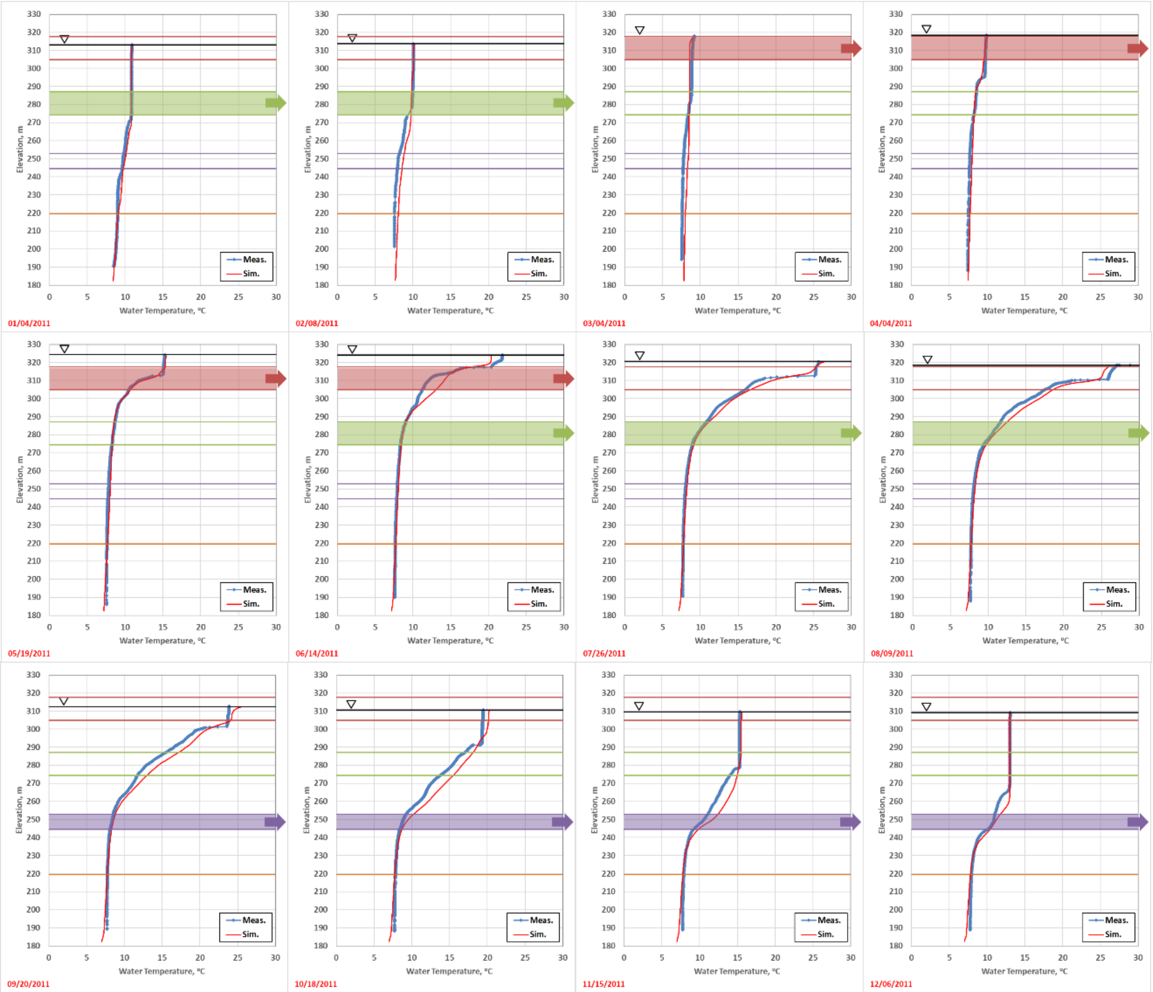
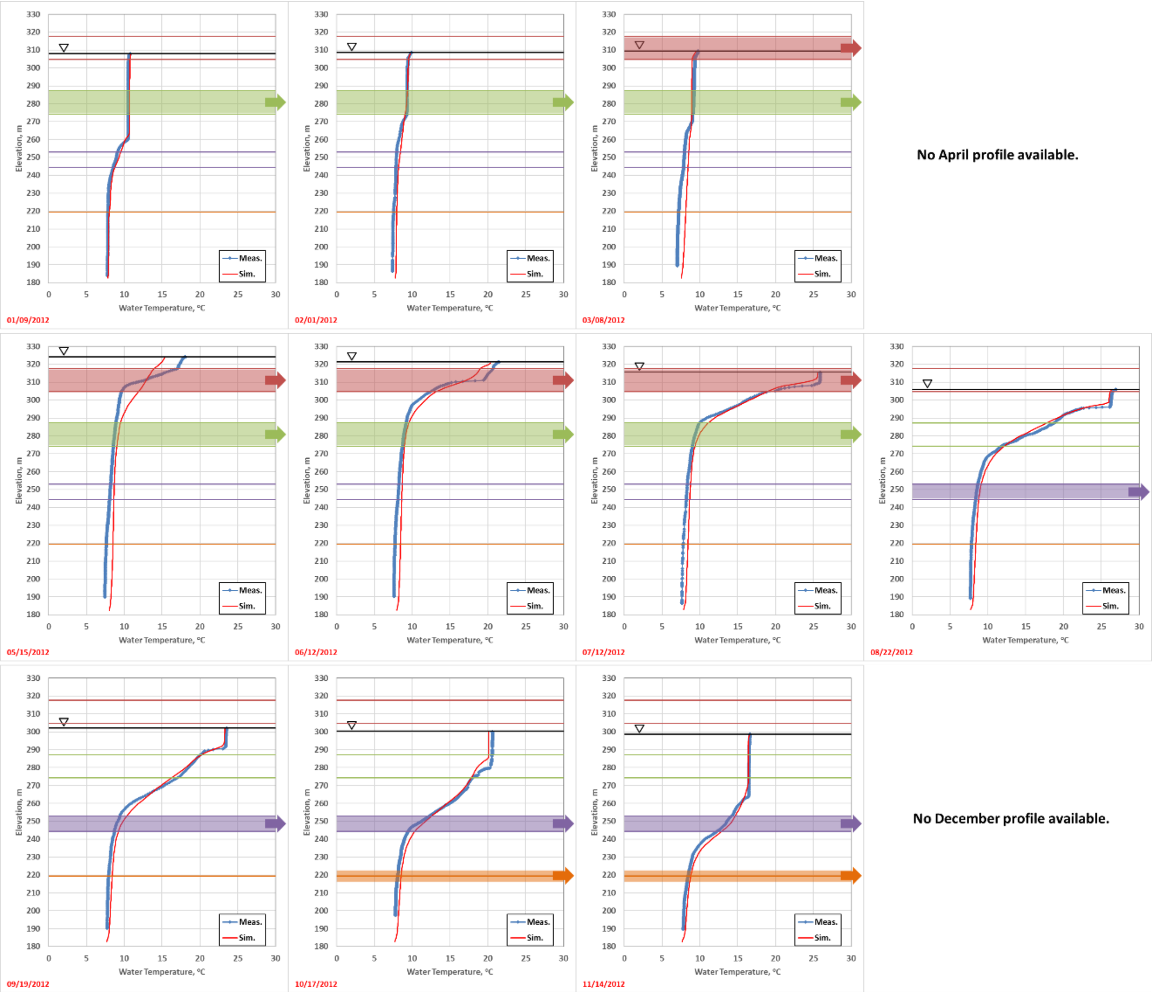


Figure D-47. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2011.



No April profile available.

No December profile available.

Figure D-48. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2012.

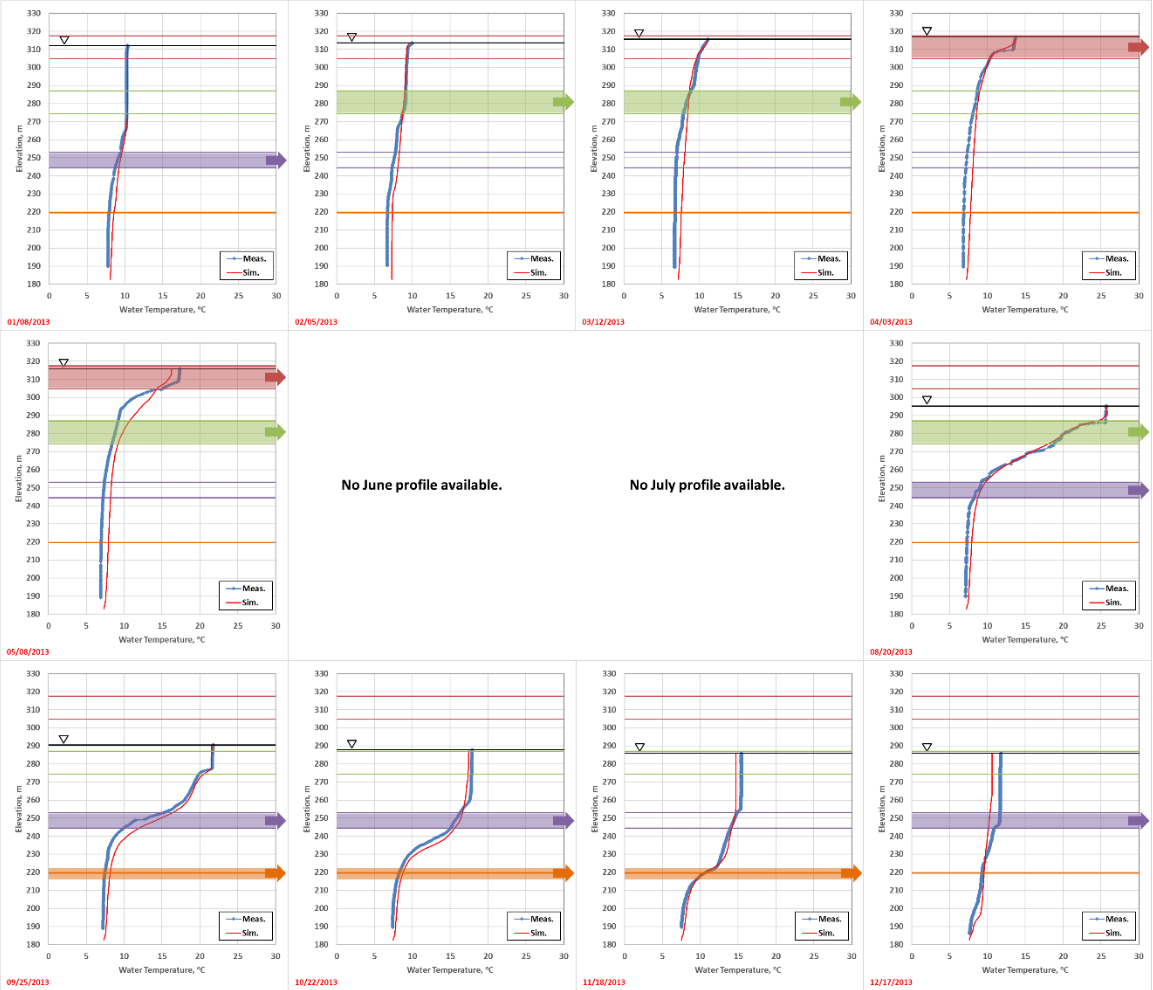


Figure D-49. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2013.

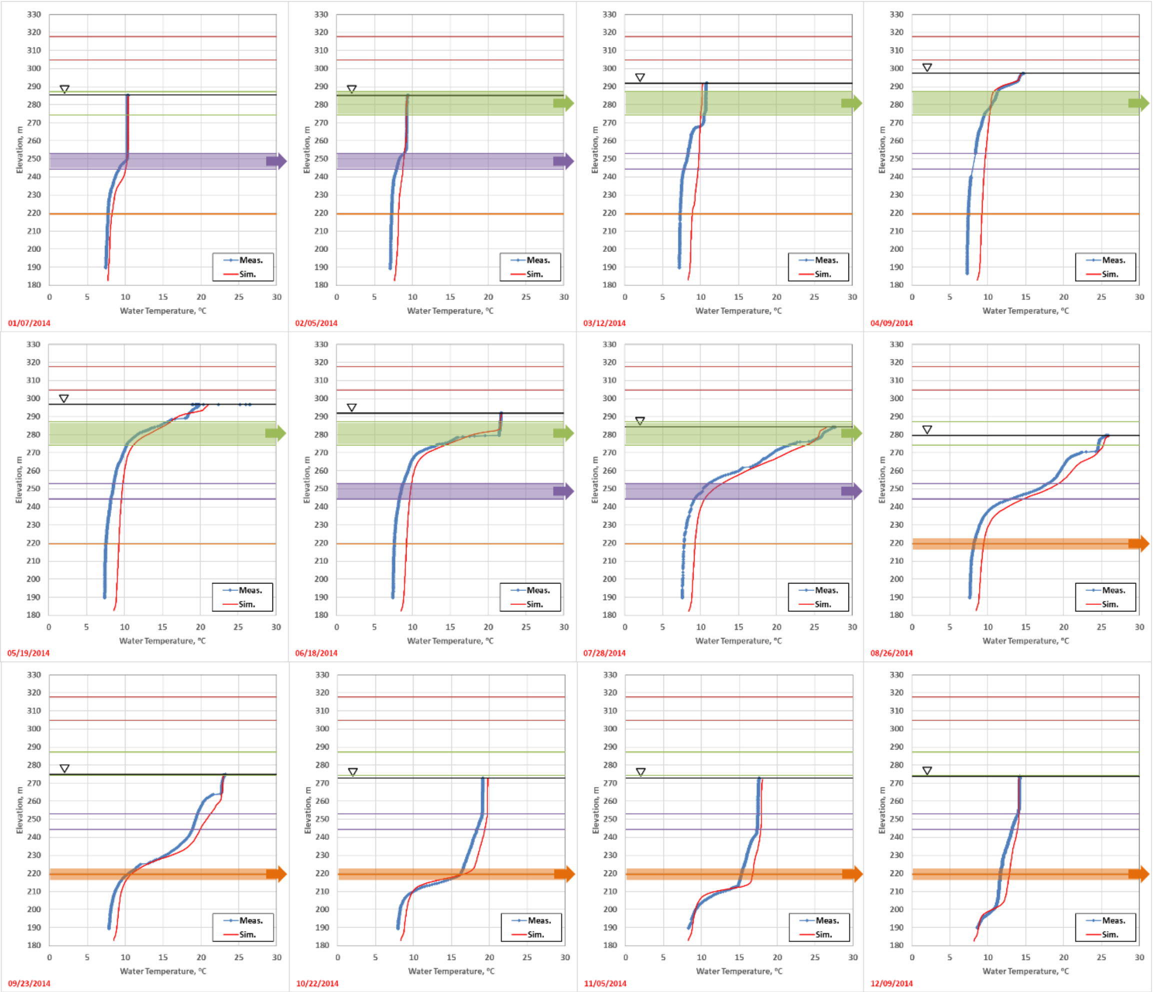


Figure D-50. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2014.

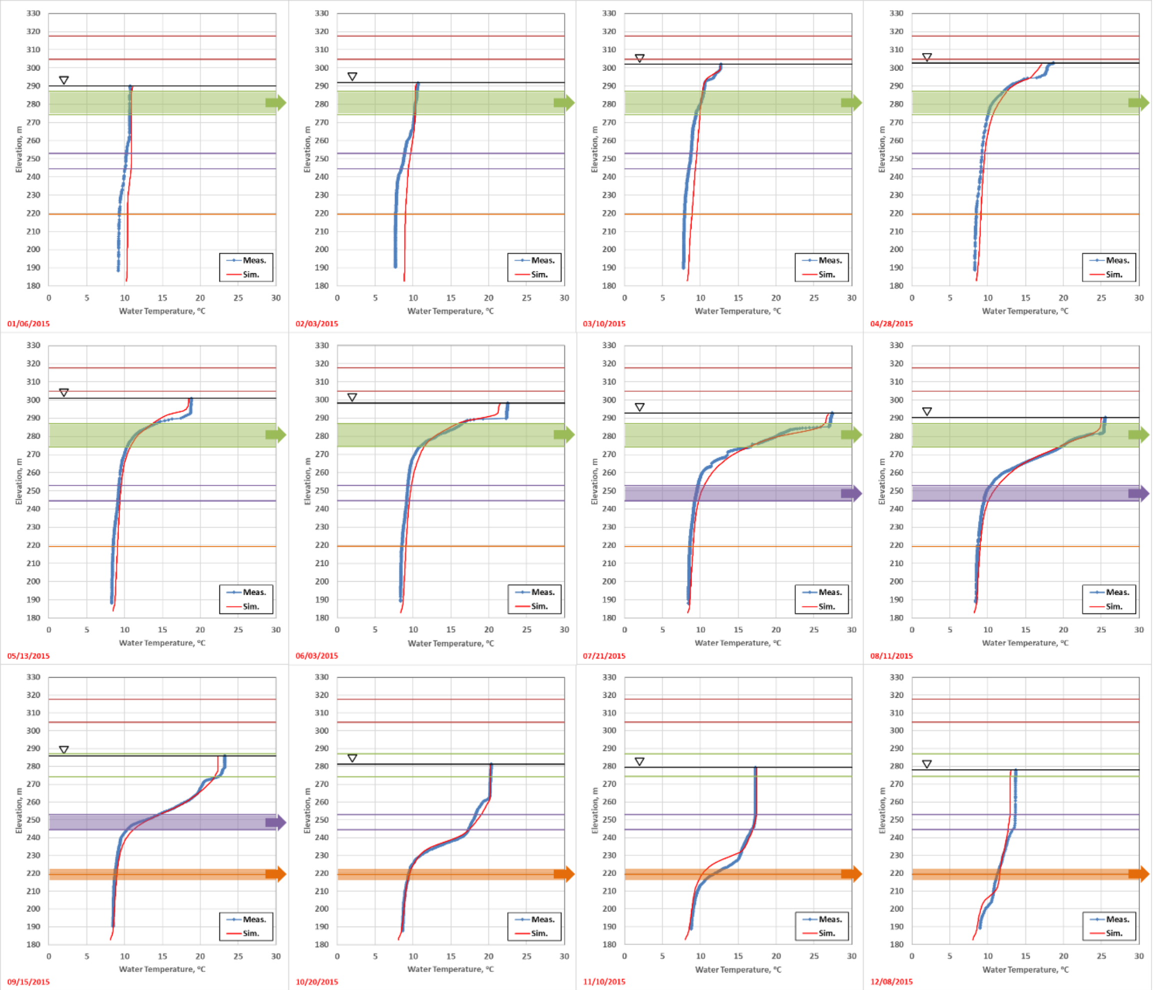


Figure D-51. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2015.

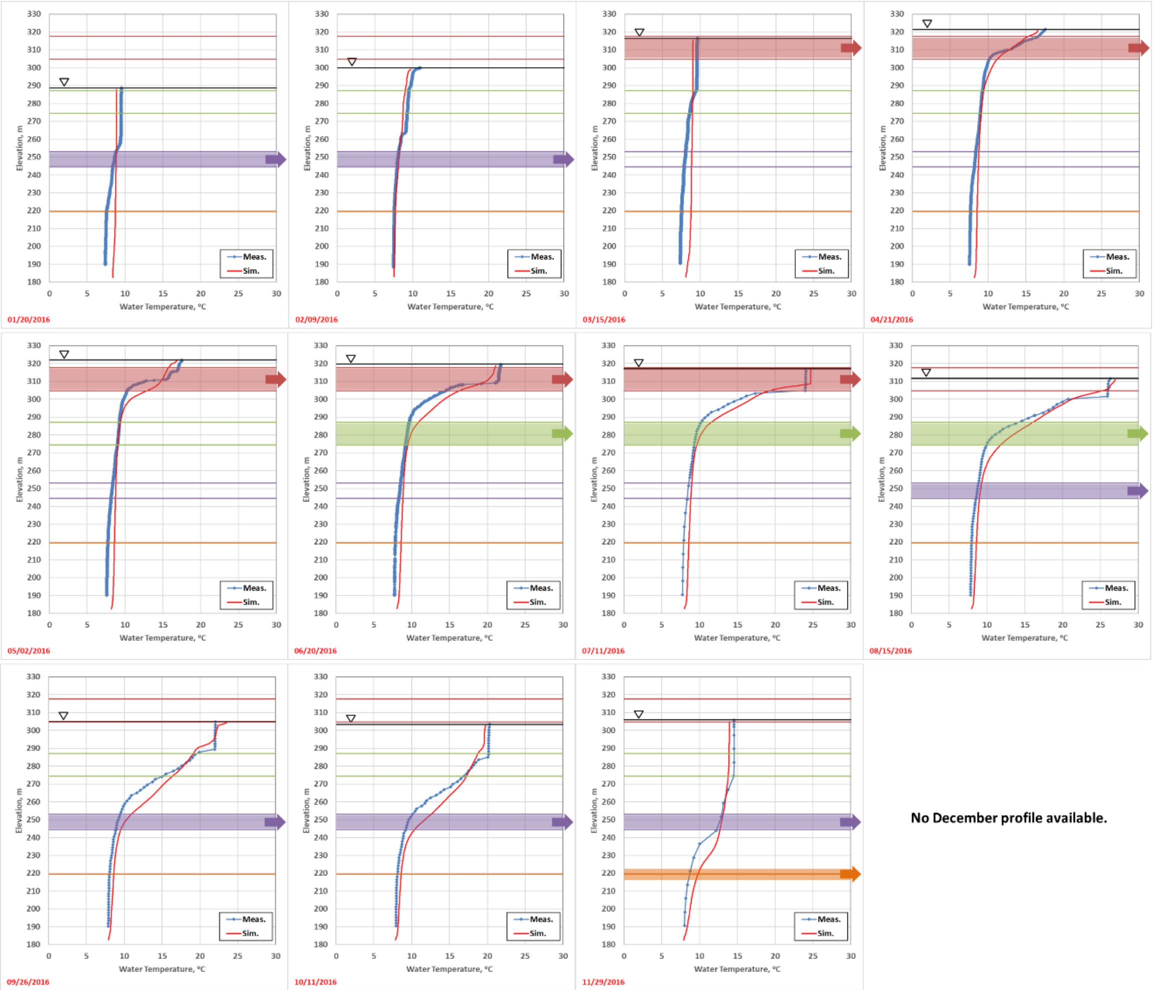


Figure D-52. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2016.

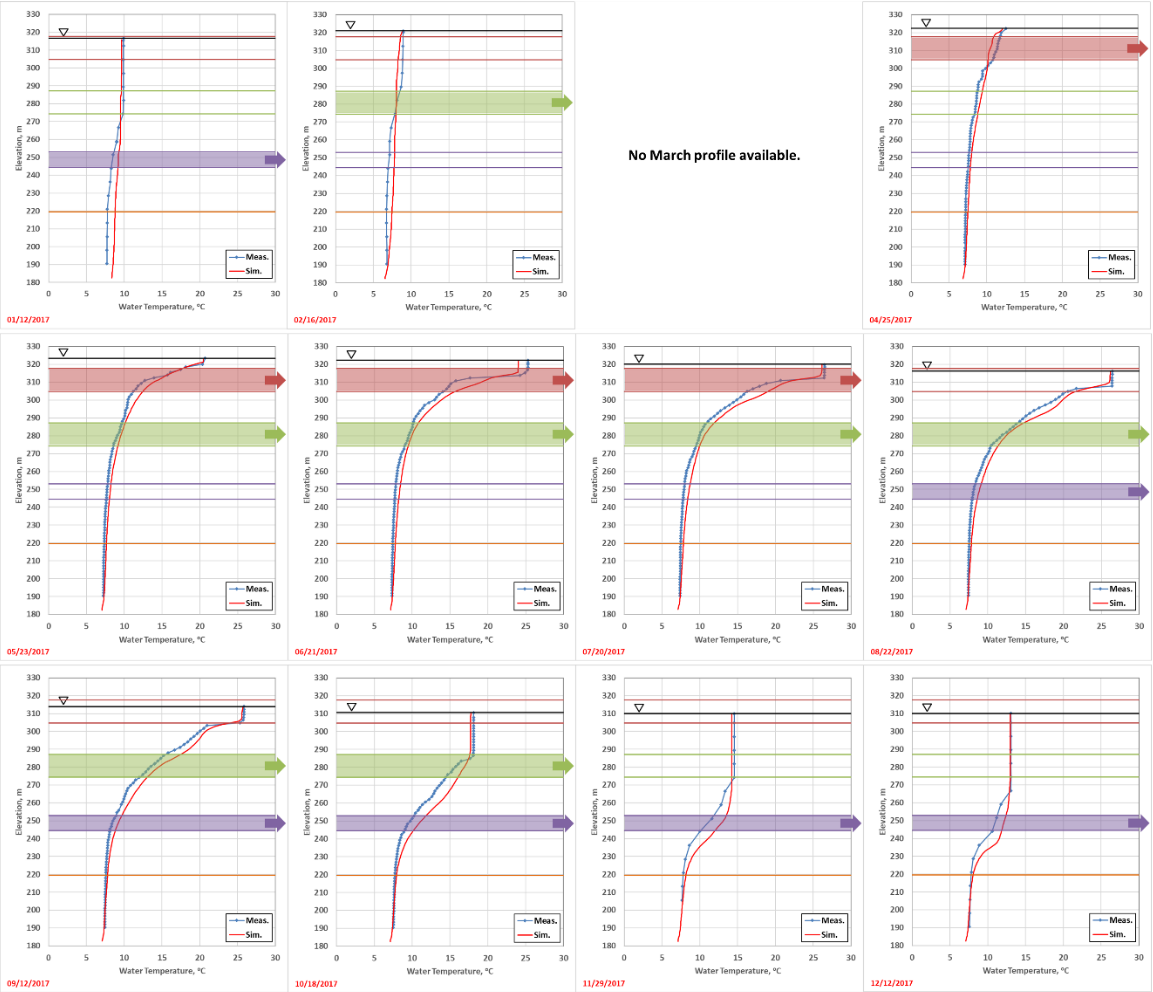


Figure D-53. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2017.

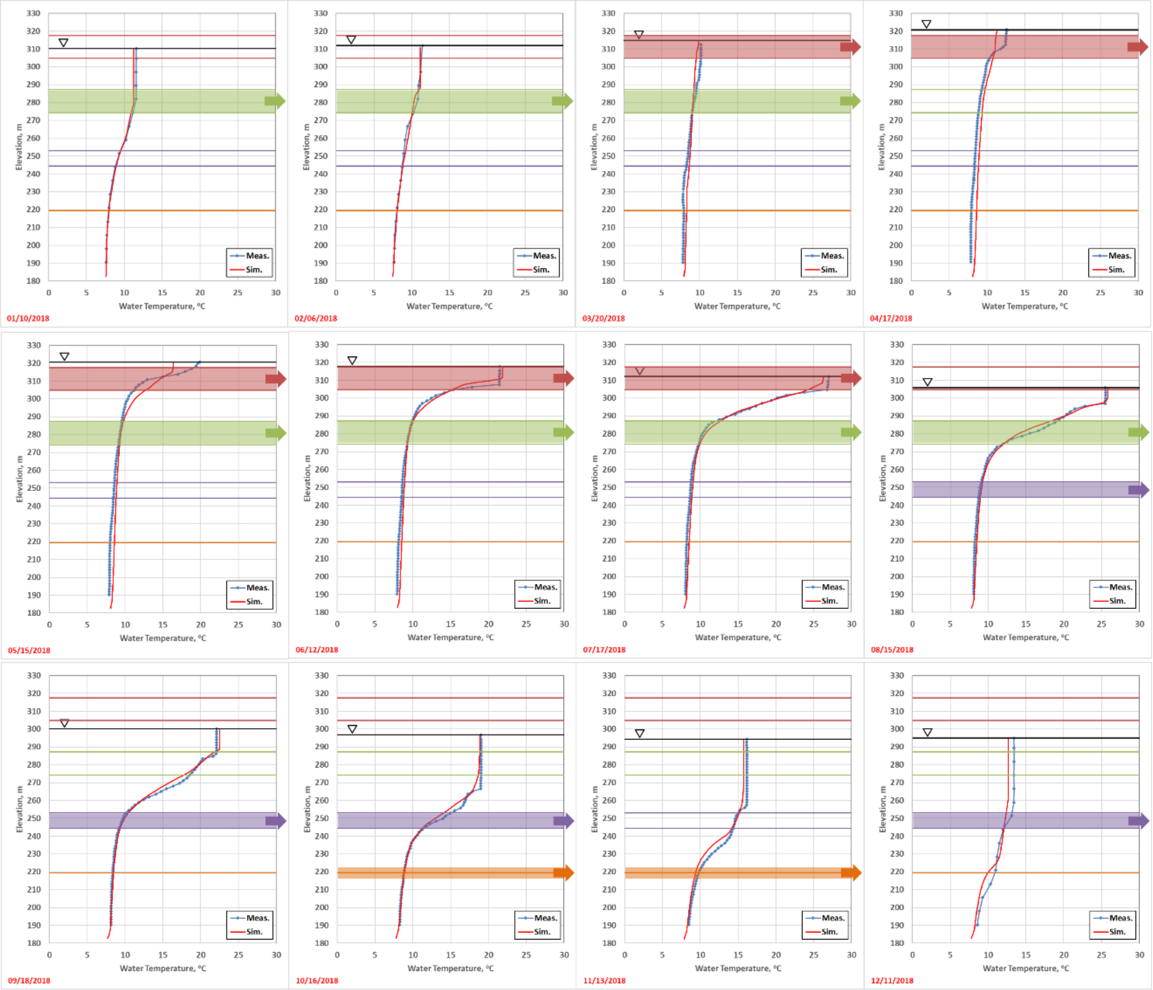


Figure D-59. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2018.

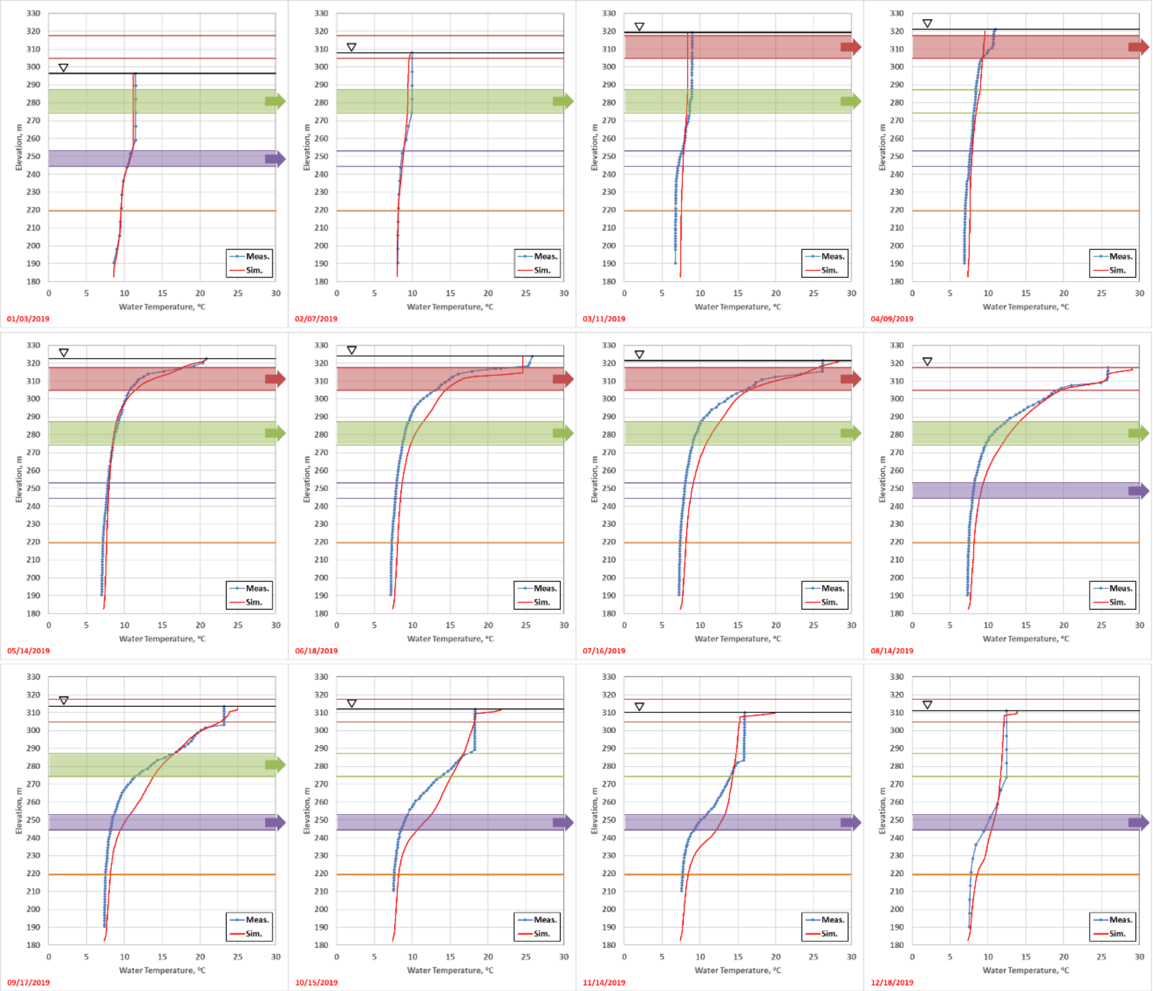


Figure D-60. Simulated versus measured temperature profiles for Shasta Lake above Shasta Dam: 2019.

Table D-3. Summary Statistics of temperature profiles for Shasta Lake above Shasta Dam (Mean Bias, MAE, and RMSE are in ºC): 2000-2005.

2000	**01/21**	**02/16**	**03/13**	**04/14**	**05/17**	**06/23**	**07/26**	**08/25**	**09/12**	**10/24**	**11/15**	**12/19**
Mean Bias	0.11	0.21	-0.29	-0.23	-0.07	-0.13	-0.07	-0.08	-0.13	0.23	0.02	-0.38
MAE	0.28	0.41	0.30	0.26	0.15	0.37	0.29	0.37	0.43	0.52	0.38	0.41
RMSE	0.31	0.43	0.39	0.52	0.20	0.61	0.37	0.44	0.48	0.64	0.46	0.50
NSE	0.93	0.74	0.48	0.91	0.99	0.98	0.99	0.99	0.99	0.97	0.97	0.90
COUNT	131	137	70	136	138	130	130	126	126	124	124	123
2001	**01/18**	**02/23**	**03/22**	**04/26**	**05/23**	**06/25**	**07/24**	**08/21**	**09/18**	**10/19**	**11/20**	**12/21**
Mean Bias	0.03	0.01	-0.01	0.21	0.48	0.40	0.52	0.74	1.19	1.57	1.30	-0.16
MAE	0.24	0.44	0.41	0.61	0.62	0.54	0.55	0.79	1.19	1.57	1.30	0.60
RMSE	0.26	0.47	0.56	0.75	0.69	0.59	0.62	0.95	1.48	1.86	1.70	0.67
NSE	0.90	0.26	0.83	0.88	0.96	0.98	0.99	0.98	0.94	0.85	0.71	0.74
COUNT	124	129	135	130	130	130	123	118	115	113	112	120
2002	**01/24**	**02/22**	**03/19**	**04/24**	**05/13**	**06/12**	**07/16**	**08/13**	**09/23**	**10/23**	**11/14**	**NA**
Mean Bias	-0.15	0.08	0.24	0.38	0.36	0.45	0.39	0.56	0.56	0.84	0.80	
MAE	0.17	0.29	0.44	0.51	0.66	0.73	0.63	0.66	0.67	0.84	1.00	
RMSE	0.20	0.32	0.49	0.60	0.81	0.84	0.74	0.84	0.85	1.20	1.36	
NSE	0.88	0.87	0.71	0.94	0.92	0.96	0.98	0.98	0.98	0.93	0.83	
COUNT	130	130	126	130	133	131	124	118	115	109	109	
2003	**01/06**	**02/20**	**03/10**	**04/09**	**05/20**	**06/23**	**07/28**	**08/11**	**09/03**	**10/09**	**11/10**	**12/03**
Mean Bias	0.33	-0.04	0.02	0.27	0.43	0.25	0.11	0.16	0.12	0.07	-0.03	0.07
MAE	0.36	0.23	0.23	0.50	0.62	0.40	0.37	0.31	0.39	0.32	0.30	0.28
RMSE	0.48	0.30	0.28	0.53	0.66	0.59	0.50	0.40	0.48	0.40	0.35	0.33
NSE	0.79	0.82	0.91	0.83	0.90	0.98	0.99	0.99	0.99	0.99	0.99	0.97
COUNT	122	125	124	133	129	131	127	122	122	121	122	121
2004	**01/05**	**02/12**	**03/03**	**04/26**	**05/25**	**06/25**	**07/23**	**08/24**	**09/23**	**10/25**	**11/16**	**12/21**
Mean Bias	0.32	0.13	0.19	0.09	0.09	0.01	-0.09	-0.16	-0.31	-0.44	-0.59	-0.74
MAE	0.42	0.44	0.52	0.33	0.25	0.29	0.22	0.33	0.56	0.48	0.63	0.74
RMSE	0.52	0.46	0.56	0.47	0.41	0.57	0.35	0.39	0.73	0.58	0.76	0.95
NSE	0.56	0.68	0.41	0.95	0.98	0.99	1.00	1.00	0.98	0.98	0.92	0.50
COUNT	123	129	126	131	136	124	119	113	108	105	105	107
2005	**01/25**	**02/09**	**03/09**	**04/14**	**05/20**	**06/14**	**07/19**	**08/16**	**09/16**	**10/17**	**11/16**	**12/06**
Mean Bias	0.04	0.13	0.09	0.39	0.36	0.52	0.33	0.51	0.64	0.69	0.52	0.42
MAE	0.43	0.46	0.35	0.66	0.59	0.66	0.54	0.64	0.68	0.80	0.67	0.58
RMSE	0.48	0.52	0.39	0.68	0.66	0.81	0.70	0.73	0.78	0.91	0.81	0.83
NSE	0.74	0.70	0.91	0.75	0.91	0.95	0.98	0.98	0.97	0.94	0.90	0.75
COUNT	113	117	122	130	134	134	129	123	119	117	119	116

Table D-4. Summary Statistics of temperature profiles for Shasta Lake above Shasta Dam: 2006-2011.

2006	01/11	02/07	03/23	04/17	05/04	06/21	07/18	08/22	09/06	10/11	11/07	12/01
Mean Bias	-0.15	-0.17	-0.28	0.03	0.00	0.19	0.10	0.00	0.06	-0.19	-0.06	-0.22
MAE	0.27	0.80	0.28	0.29	0.36	0.42	0.24	0.22	0.26	0.25	0.37	0.28
RMSE	0.29	0.41	0.40	0.33	0.61	0.69	0.38	0.32	0.36	0.30	0.45	0.36
NSE	0.91	0.80	0.60	0.84	0.93	0.97	0.99	1.00	1.00	1.00	0.98	0.98
COUNT	126	122	128	129	132	133	130	128	123	124	119	120

2007	01/10	02/06	03/06	04/05	05/15	06/19	07/17	08/17	09/17	10/24	11/20	12/05
Mean Bias	0.37	0.12	0.38	0.19	0.13	0.12	0.08	-0.08	0.00	-0.78	-0.68	-0.50
MAE	0.37	0.40	0.66	0.50	0.41	0.34	0.42	0.31	0.32	0.80	0.74	0.55
RMSE	0.46	0.42	0.76	0.68	0.69	0.54	0.50	0.43	0.45	1.29	1.14	0.68
NSE	0.81	0.82	0.35	0.87	0.96	0.99	0.99	0.99	0.99	0.88	0.81	0.90
COUNT	121	122	128	129	122	122	115	114	102	98	97	103

2008	01/02	02/05	03/06	04/01	05/13	06/18	07/15	08/19	09/03	10/15	11/14	12/04
Mean Bias	0.20	-0.02	0.32	0.45	0.29	0.08	0.27	0.14	0.13	-0.70	-0.31	-0.10
MAE	0.22	0.50	0.66	0.58	0.68	0.54	0.47	0.45	0.40	0.91	0.59	0.55
RMSE	0.26	0.52	0.69	0.63	1.01	0.64	0.50	0.62	0.60	1.54	1.03	0.73
NSE	0.92	0.21	0.55	0.78	0.90	0.98	0.99	0.99	0.99	0.88	0.86	0.88
COUNT	99	108	113	116	116	109	105	103	93	91	89	89

2009	01/14	02/10	03/04	04/02	05/19	06/16	07/17	08/19	09/15	10/15	11/17	12/01
Mean Bias	0.56	0.90	0.26	0.57	0.71	0.82	0.71	0.75	0.72	0.41	0.47	0.54
MAE	0.62	1.02	0.49	0.72	0.74	0.85	0.82	0.76	0.76	0.47	0.47	0.54
RMSE	0.82	1.16	0.52	0.76	0.96	0.98	0.91	0.82	0.84	0.68	0.66	0.80
NSE	0.60	-0.44	0.01	0.77	0.90	0.95	0.97	0.98	0.98	0.97	0.95	0.85
COUNT	89	92	106	61	120	117	111	104	100	97	97	96

2010	01/05	02/02	03/02	NA	05/17	06/14	07/12	08/23	09/09	10/06	11/01	12/07
Mean Bias	0.25	-0.45	-0.45		0.08	0.43	0.35	0.20	0.26	0.07	0.04	-0.11
MAE	0.26	0.45	0.45		0.37	0.54	0.42	0.40	0.43	0.34	0.48	0.47
RMSE	0.34	0.51	0.47		0.60	0.76	0.54	0.62	0.52	0.41	0.61	0.54
NSE	0.88	0.36	0.50		0.91	0.94	0.99	0.99	0.99	0.99	0.97	0.90
COUNT	100	112	123		135	133	131	123	123	127	122	122

2011	01/04	02/08	03/04	04/04	05/19	06/14	07/26	08/09	09/20	10/18	11/15	12/06
Mean Bias	0.13	0.34	0.21	0.12	0.06	0.18	0.19	0.26	0.43	0.48	0.34	0.08
MAE	0.14	0.39	0.39	0.20	0.16	0.36	0.32	0.44	0.57	0.64	0.50	0.26
RMSE	0.21	0.45	0.41	0.22	0.20	0.68	0.52	0.66	0.80	0.84	0.71	0.42
NSE	0.94	0.81	0.43	0.93	0.99	0.96	0.99	0.98	0.98	0.96	0.95	0.97
COUNT	123	112	123	130	138	134	130	130	110	123	121	120

Table D-5. Summary Statistics of temperature profiles for Shasta Lake above Shasta Dam: 2012-2017.

2012	01/09	02/01	03/08	NA	05/15	06/12	07/12	08/22	09/19	10/17	11/14	NA
Mean Bias	0.18	0.28	0.40		0.55	0.43	0.37	0.22	0.27	0.08	0.26	
MAE	0.19	0.30	0.59		0.93	0.68	0.58	0.54	0.47	0.52	0.37	
RMSE	0.21	0.34	0.65		1.12	0.76	0.70	0.60	0.53	0.59	0.43	
NSE	0.97	0.81	0.48		0.79	0.95	0.98	0.99	0.99	0.99	0.99	
COUNT	124	122	120		134	131	129	117	112	103	109	
2013	**01/08**	**02/05**	**03/12**	**04/03**	**05/08**	**NA**	**NA**	**08/20**	**09/25**	**10/22**	**11/18**	**12/17**
Mean Bias	0.35	0.35	0.54	0.58	0.87			0.30	0.72	0.27	-0.05	-0.38
MAE	0.35	0.44	0.67	0.64	1.08			0.50	0.75	0.59	0.43	0.76
RMSE	0.42	0.50	0.73	0.71	1.16			0.56	0.94	0.65	0.48	0.86
NSE	0.84	0.77	0.64	0.82	0.84			0.99	0.97	0.98	0.97	0.63
COUNT	122	123	126	127	127			106	102	99	96	100
2014	**01/07**	**02/05**	**03/12**	**04/09**	**05/19**	**06/18**	**07/28**	**08/26**	**09/23**	**10/22**	**11/05**	**12/09**
Mean Bias	0.39	0.56	1.09	1.21	1.26	1.10	1.24	1.37	0.94	0.71	0.54	0.53
MAE	0.39	0.61	1.31	1.32	1.32	1.24	1.34	1.37	0.95	0.88	0.73	0.60
RMSE	0.49	0.73	1.41	1.43	1.37	1.35	1.39	1.43	1.08	0.94	0.85	0.74
NSE	0.84	0.37	-0.14	0.37	0.83	0.91	0.95	0.95	0.96	0.95	0.93	0.76
COUNT	95	96	102	111	107	102	95	90	86	84	83	83
2015	**01/06**	**02/03**	**03/10**	**04/28**	**05/13**	**06/03**	**07/21**	**08/11**	**09/15**	**10/20**	**11/10**	**12/08**
Mean Bias	0.75	0.82	0.62	0.39	0.22	0.23	0.49	0.25	0.17	0.06	-0.29	-0.38
MAE	0.75	0.86	0.68	0.56	0.51	0.58	0.59	0.42	0.38	0.23	0.47	0.49
RMSE	0.83	0.99	0.75	0.60	0.64	0.70	0.73	0.50	0.47	0.35	0.79	0.56
NSE	-0.93	0.17	0.64	0.94	0.96	0.97	0.98	0.99	0.99	0.99	0.95	0.87
COUNT	102	101	112	114	113	91	104	102	96	93	90	89
2016	**01/20**	**02/09**	**03/15**	**04/21**	**05/02**	**06/20**	**07/11**	**08/15**	**09/26**	**10/11**	**11/29**	**NA**
Mean Bias	0.36	-0.12	0.56	0.48	0.56	0.68	0.59	0.71	0.69	0.57	0.36	
MAE	0.75	0.27	0.81	0.58	0.71	0.83	0.78	0.88	0.88	0.87	0.77	
RMSE	0.82	0.35	0.89	0.67	0.93	1.00	1.00	1.10	1.15	1.11	0.93	
NSE	0.03	0.84	-0.18	0.90	0.85	0.93	0.96	0.96	0.95	0.95	0.88	
COUNT	98	111	125	131	132	129	127	121	115	113	114	
2017	**01/12**	**02/16**	**NA**	**04/25**	**05/23**	**06/21**	**07/20**	**08/22**	**09/12**	**10/18**	**11/29**	**12/12**
Mean Bias	0.41	0.25		0.20	0.46	0.54	0.63	0.54	0.60	0.57	0.50	0.37
MAE	0.61	0.54		0.42	0.48	0.71	0.70	0.61	0.66	0.75	0.74	0.44
RMSE	0.69	0.58		0.47	0.58	0.96	0.90	0.75	0.83	0.99	0.94	0.71
NSE	0.43	0.53		0.90	0.96	0.96	0.97	0.98	0.98	0.95	0.89	0.91
COUNT	126	130		133	132	132	130	126	124	121	104	119

Table D-6. Summary Statistics of temperature profiles for Shasta Lake above Shasta Dam: 2018-2019.

2018	01/10	02/06	03/20	04/17	05/15	06/12	07/17	08/15	09/18	10/16	11/13	12/11
Mean Bias	-0.09	0.03	0.10	0.40	0.32	0.18	0.13	0.07	-0.03	-0.21	-0.40	-0.50
MAE	0.14	0.13	0.35	0.60	0.62	0.39	0.35	0.32	0.28	0.26	0.42	0.59
RMSE	0.19	0.17	0.39	0.64	0.87	0.67	0.47	0.46	0.43	0.41	0.51	0.64
NSE	0.99	0.98	0.79	0.75	0.89	0.97	0.99	0.99	0.99	0.99	0.97	0.85
COUNT	120	121	124	129	131	128	122	116	110	107	104	105

2019	01/03	02/07	03/11	04/09	05/14	06/18	07/16	08/14	09/17	10/15	11/14	12/18
Mean Bias	-0.07	-0.16	0.13	0.28	0.30	1.12	1.11	1.04	1.01	1.08	0.82	0.27
MAE	0.15	0.23	0.56	0.50	0.40	1.21	1.17	1.05	1.10	1.33	1.28	0.65
RMSE	0.19	0.31	0.60	0.56	0.58	1.59	1.31	1.22	1.39	1.68	1.54	0.77
NSE	0.96	0.85	0.59	0.73	0.96	0.87	0.93	0.95	0.93	0.85	0.78	0.86
COUNT	105	117	129	130	132	134	131	128	123	101	100	121

D.4. Outflow Temperature (DRAFT)

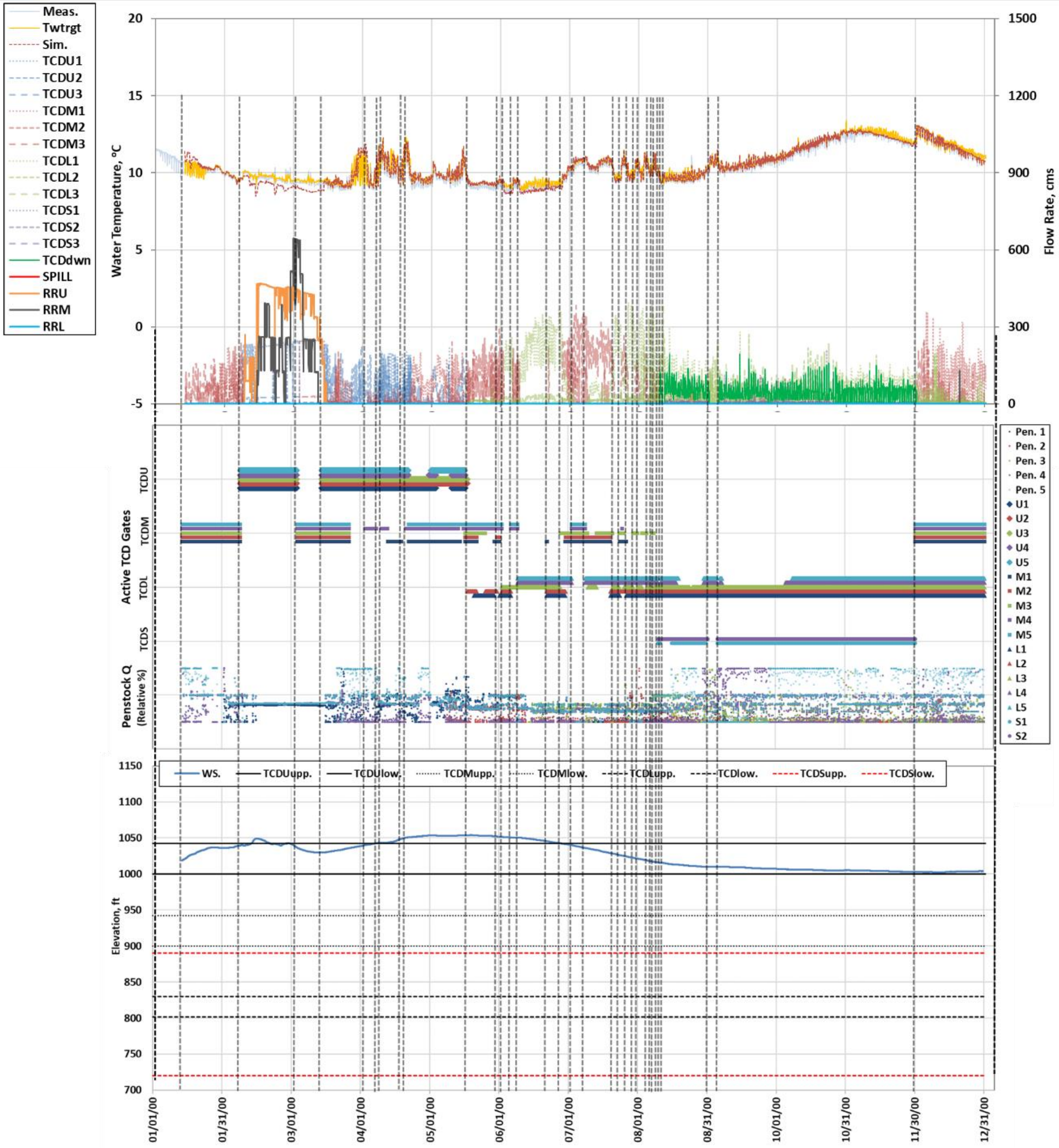


Figure D-54. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2000.

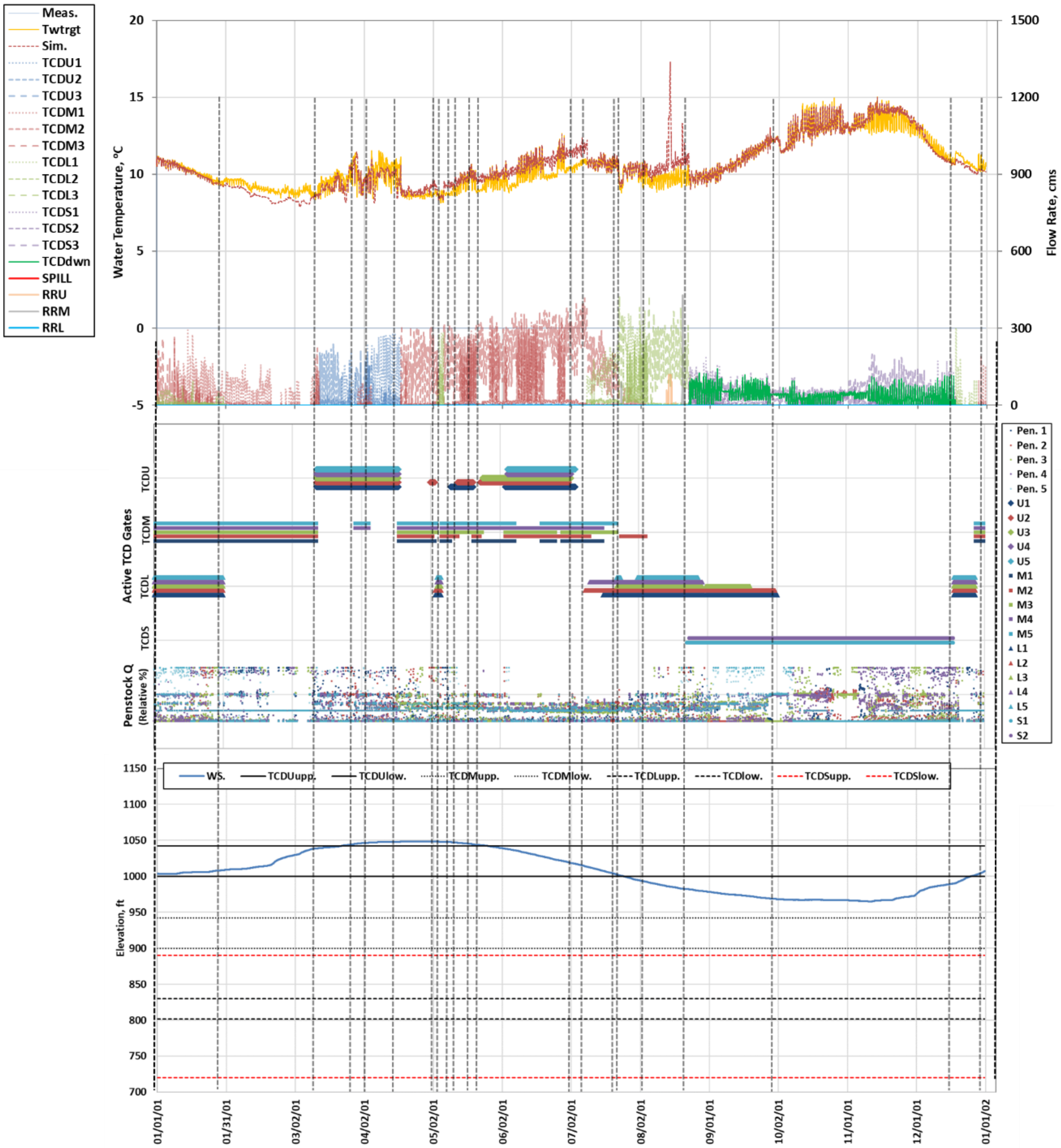


Figure D-55. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2001.

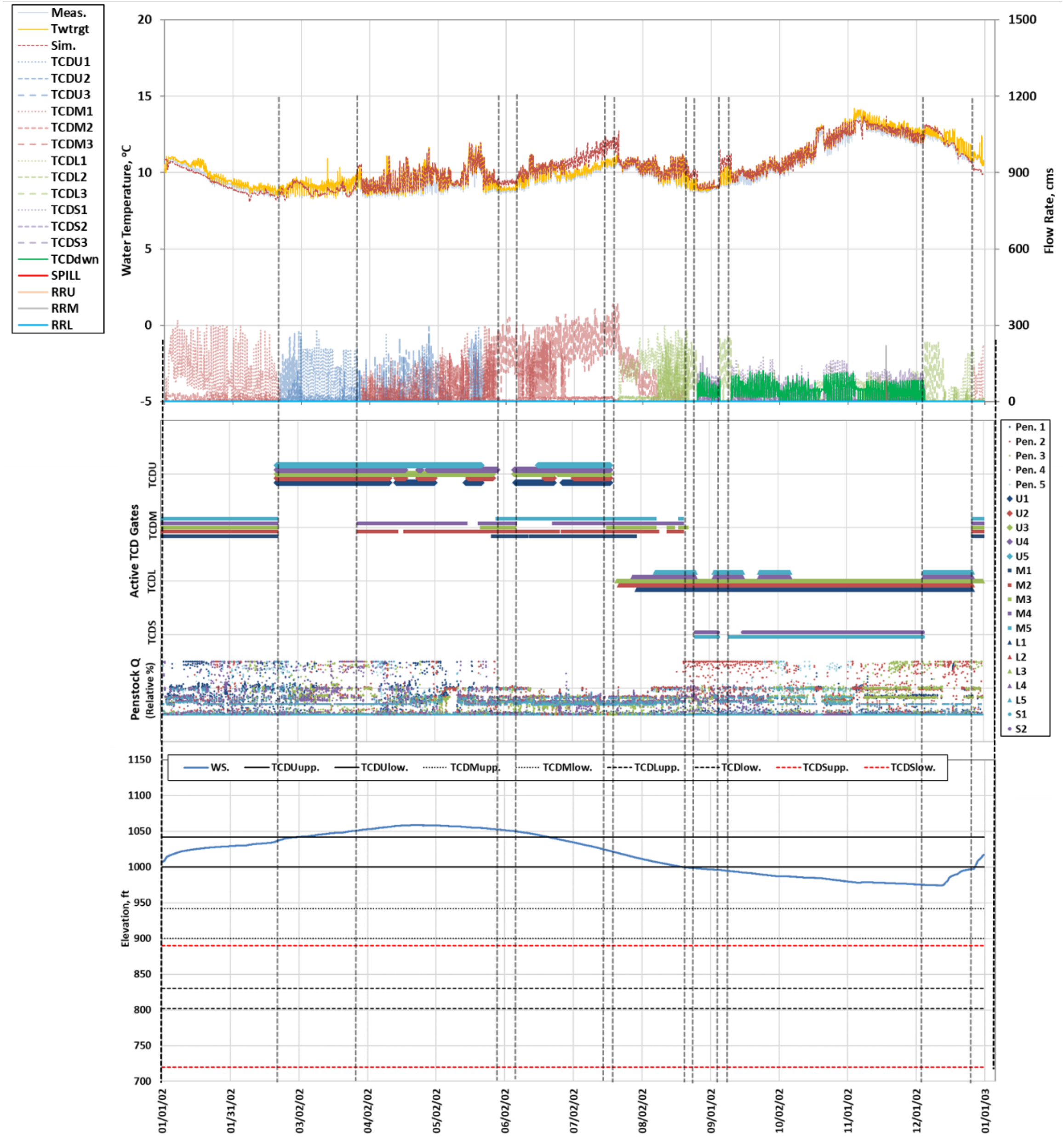


Figure D-56. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2002.

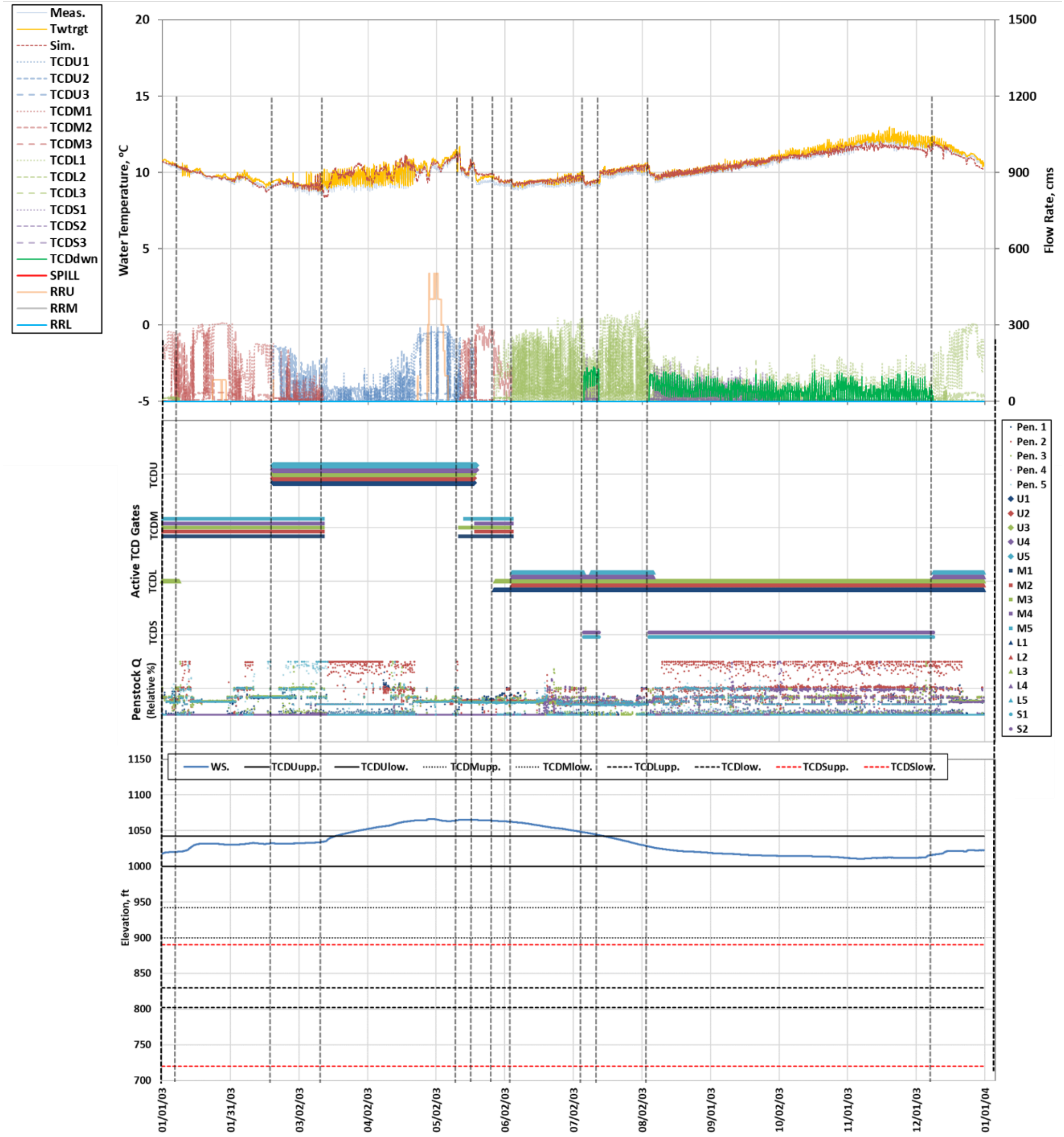


Figure D-57. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2003.

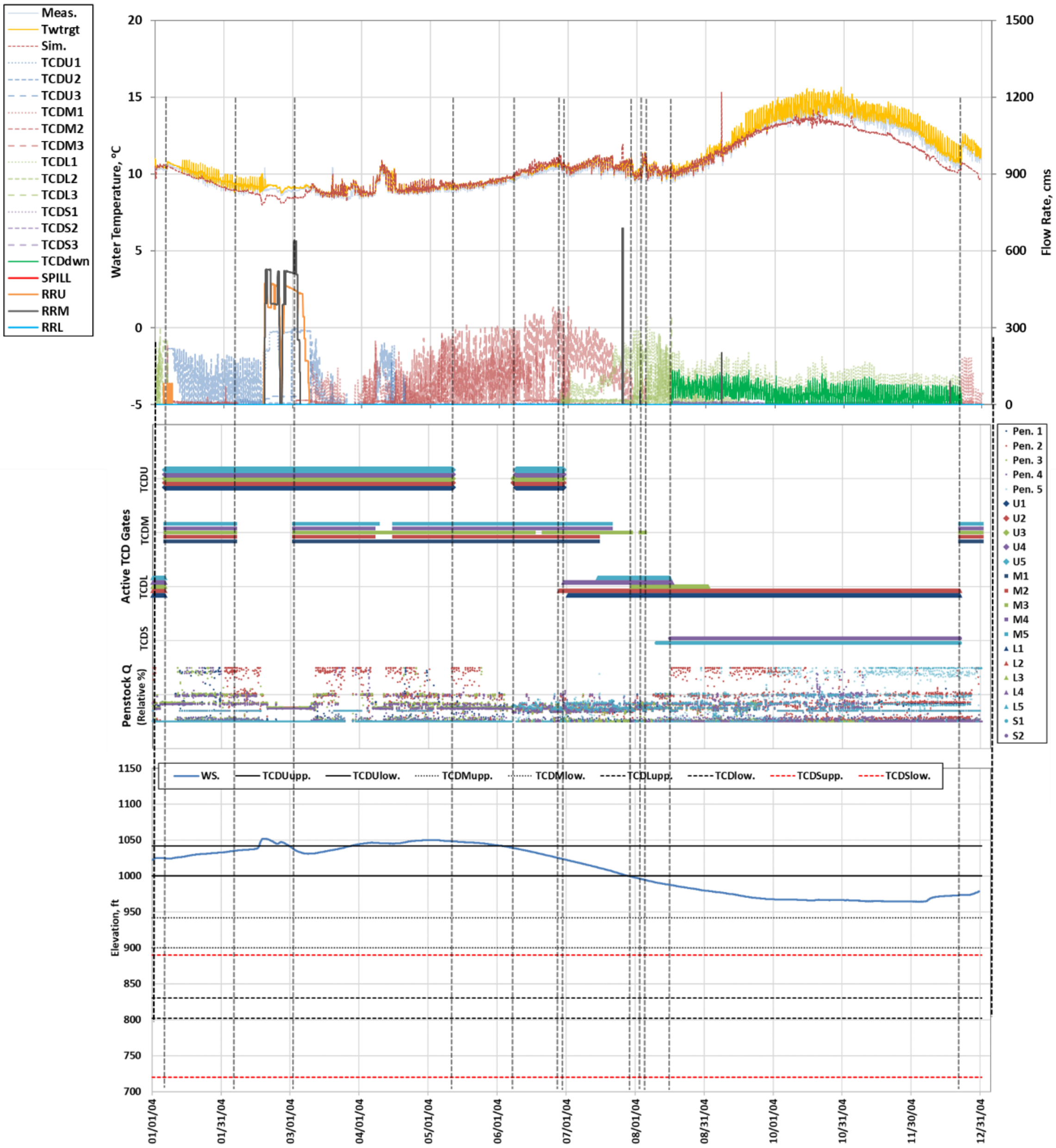


Figure D-58. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2004.

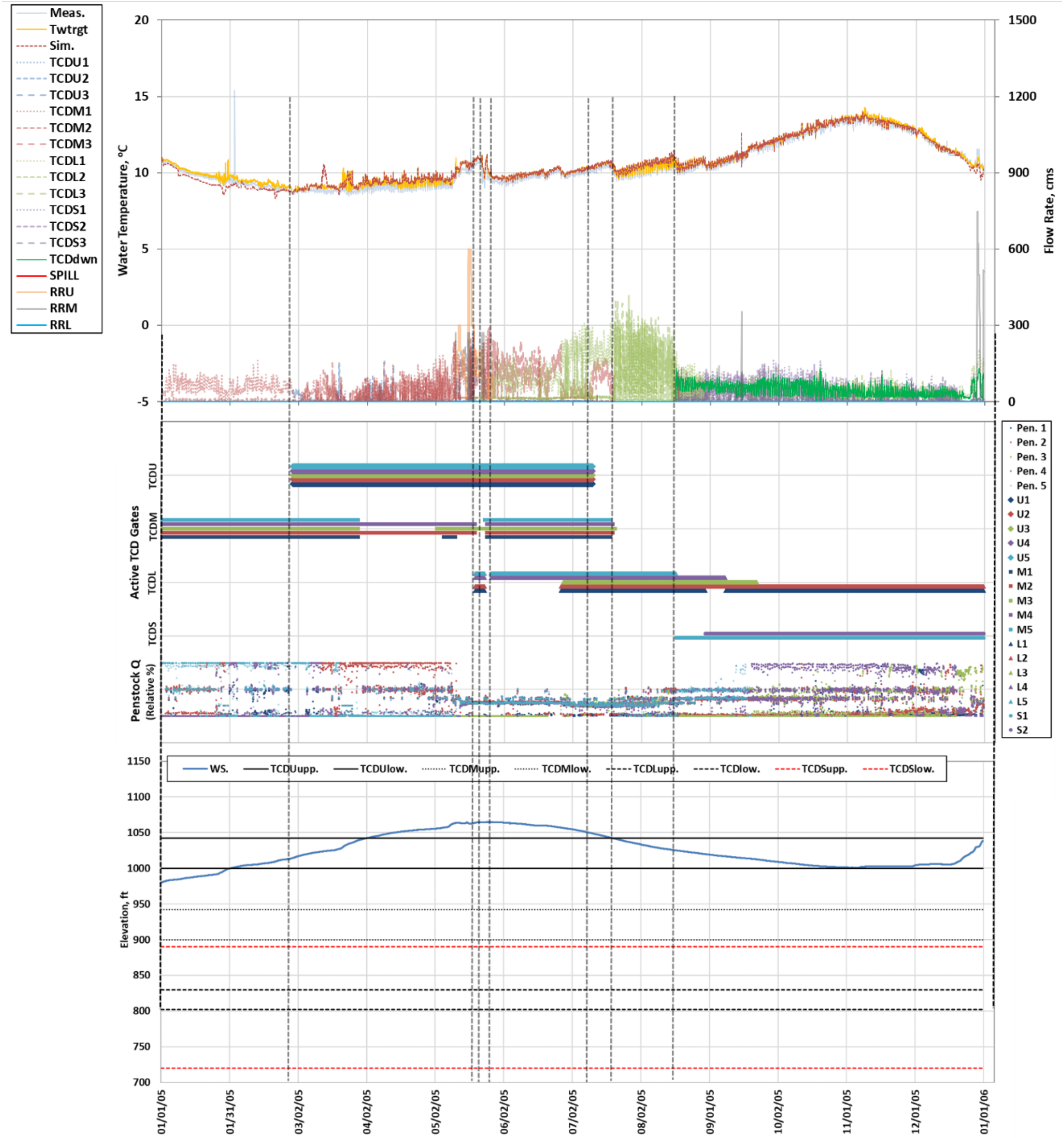


Figure D-59. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2005.

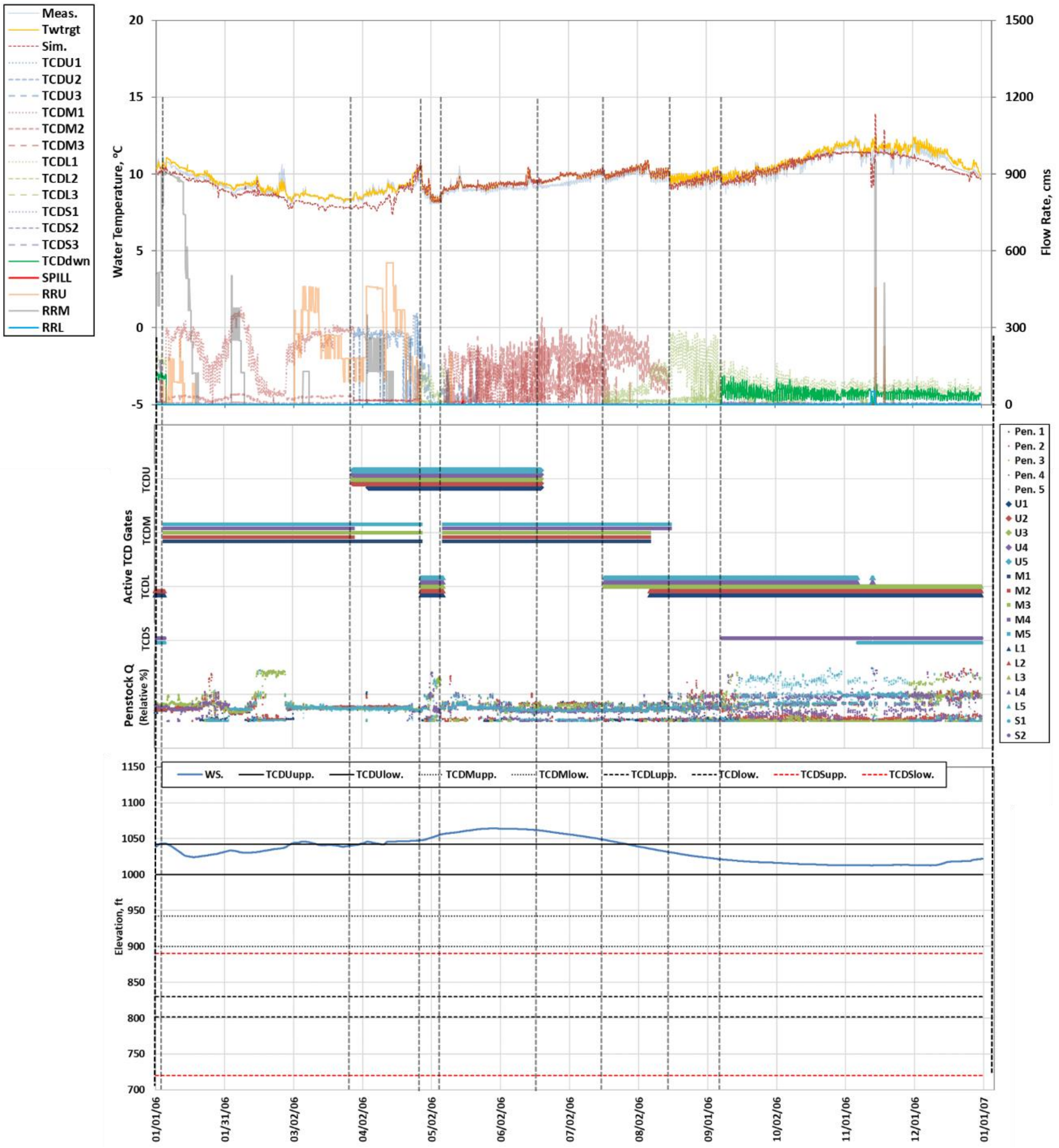


Figure D-60. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2006.

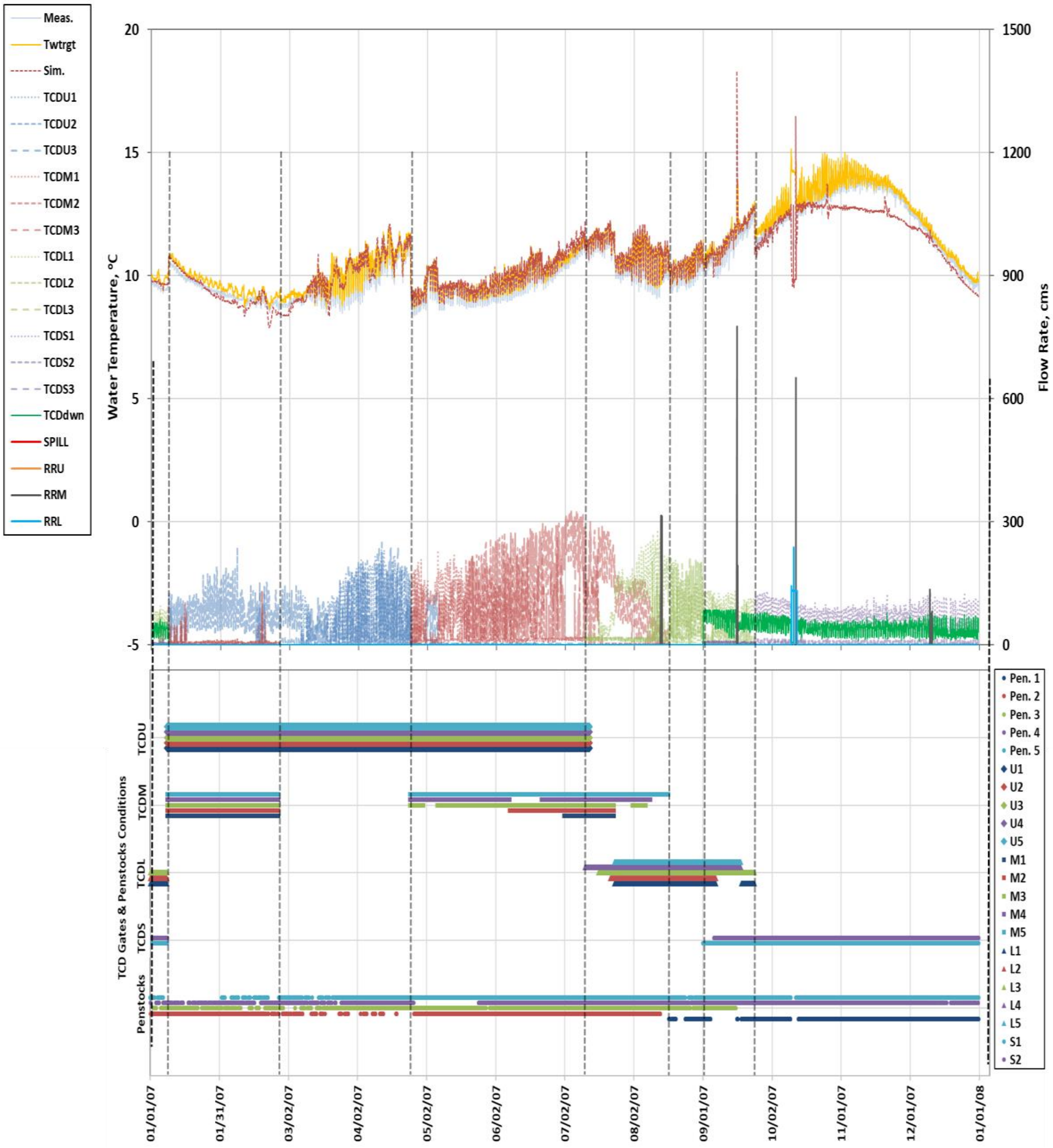


Figure D-61. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2007.

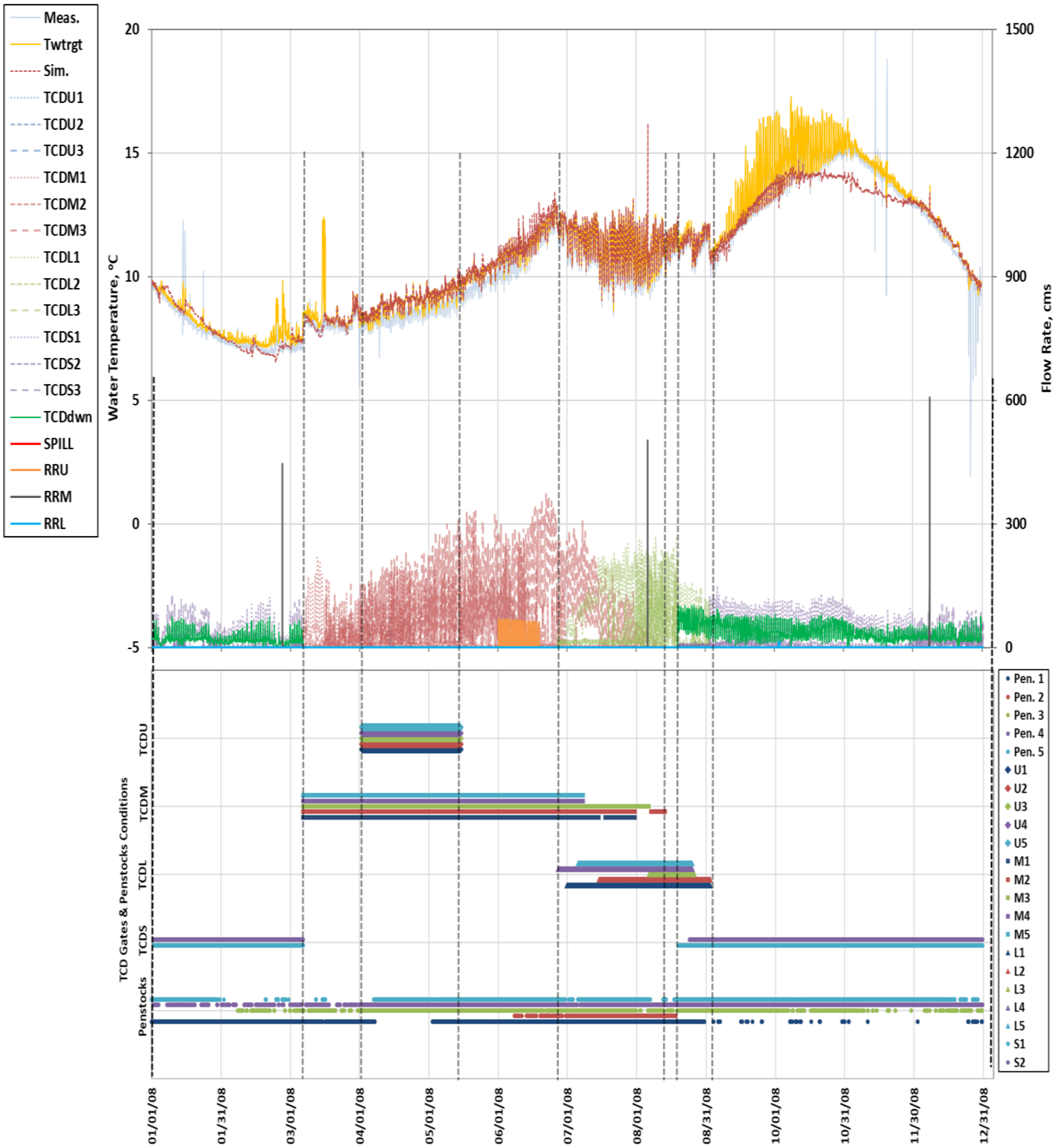


Figure D-62. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2008.

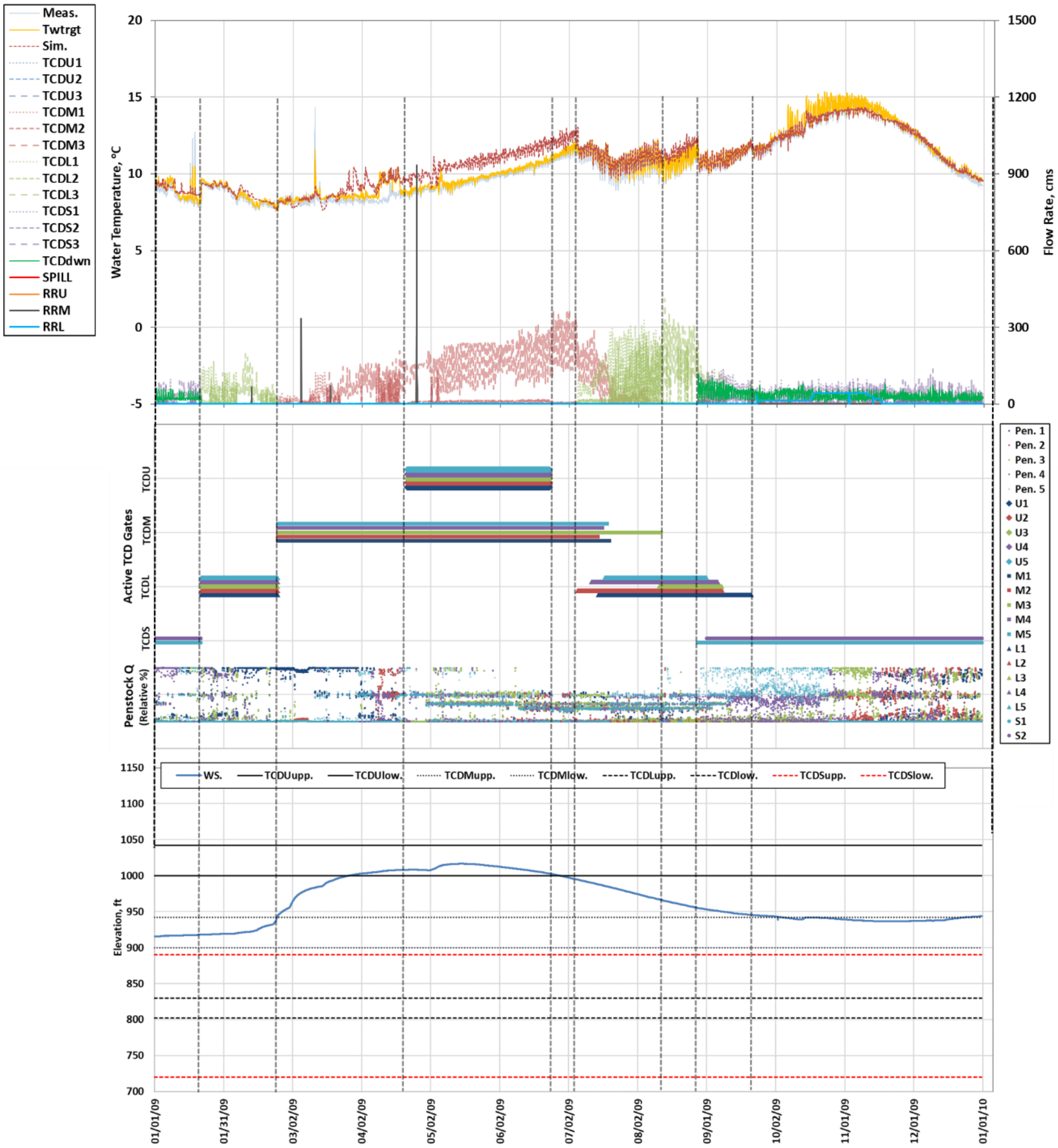


Figure D-63. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2009.

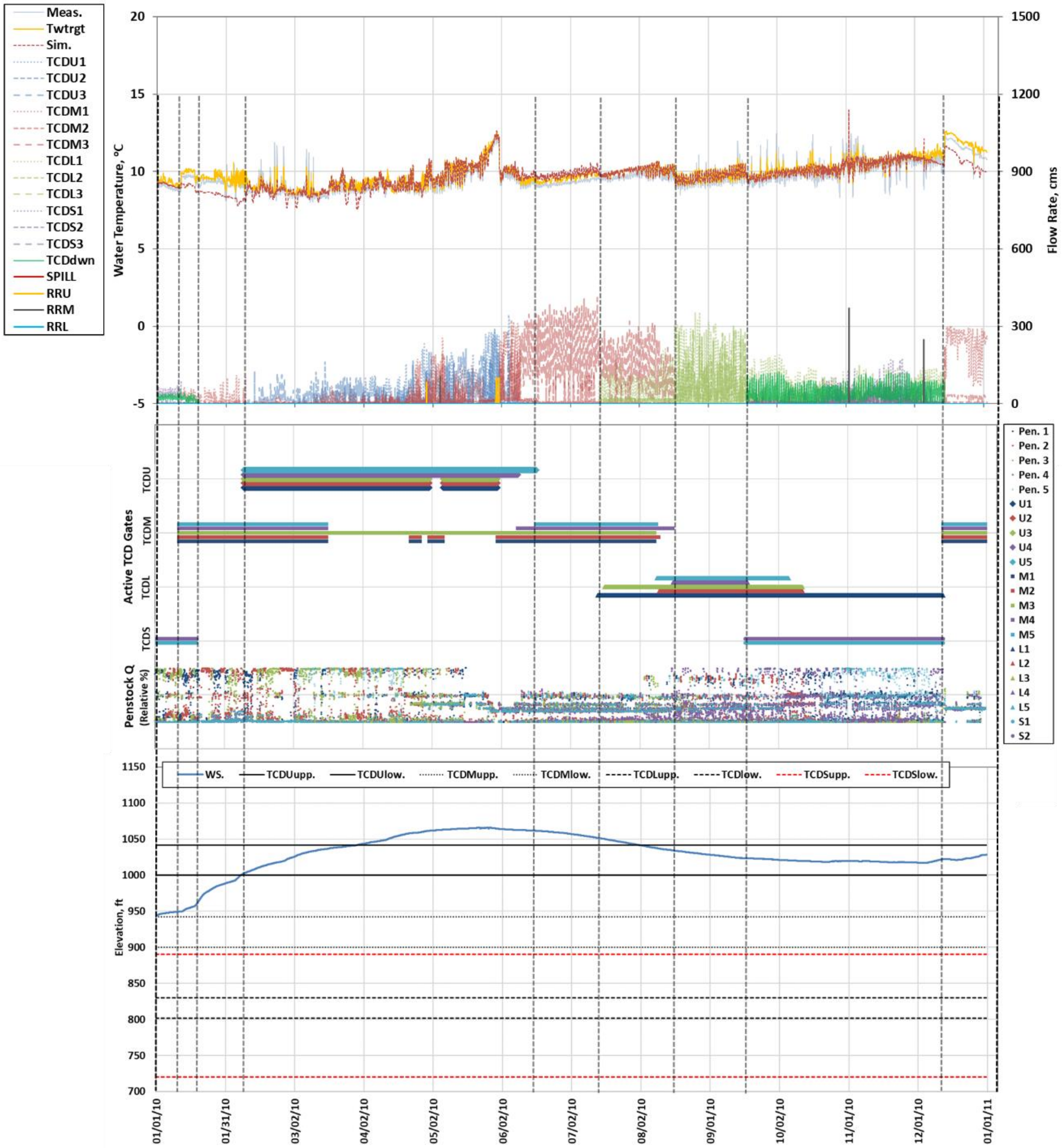


Figure D-64. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2010.

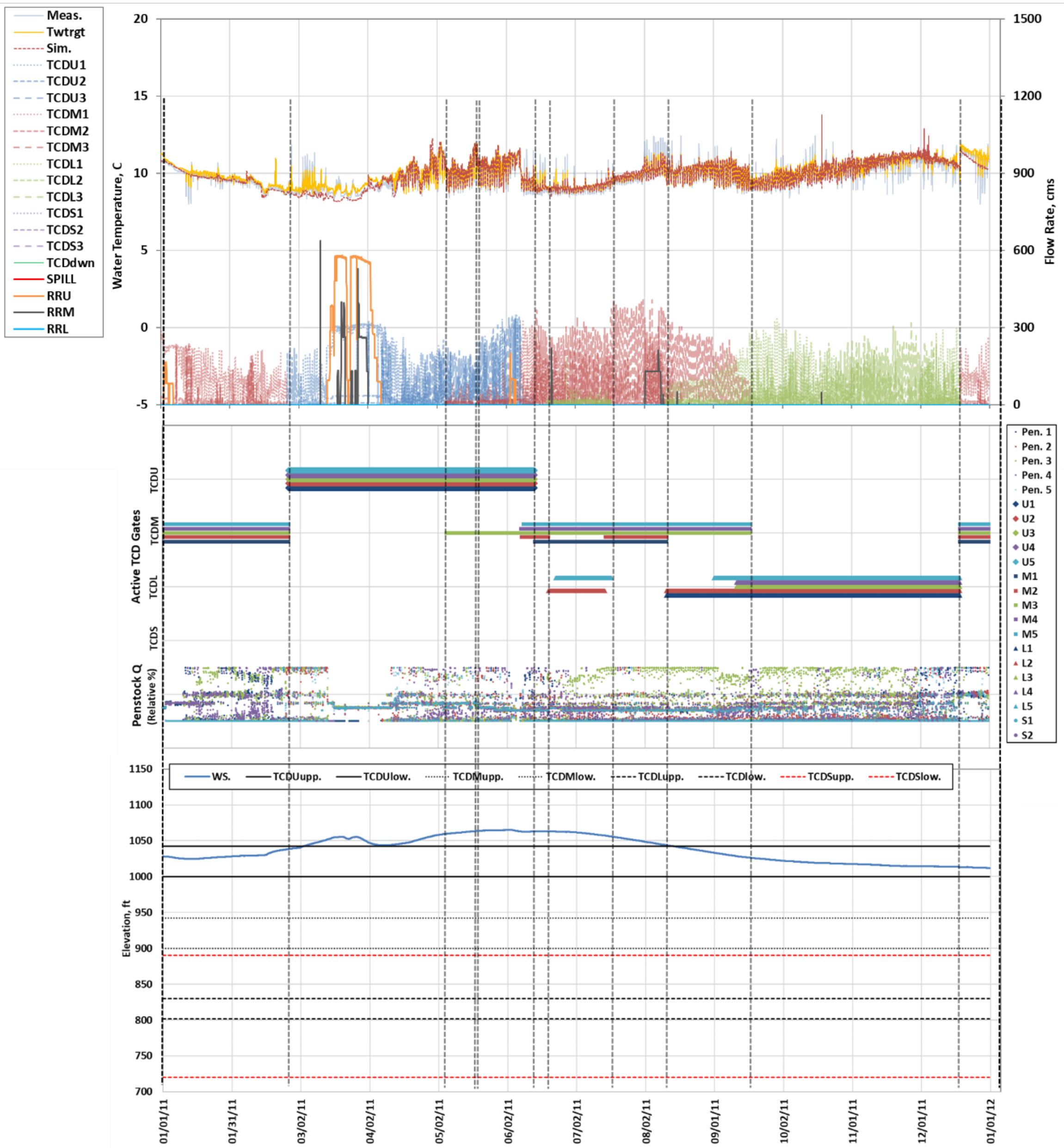


Figure D-65. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2011.

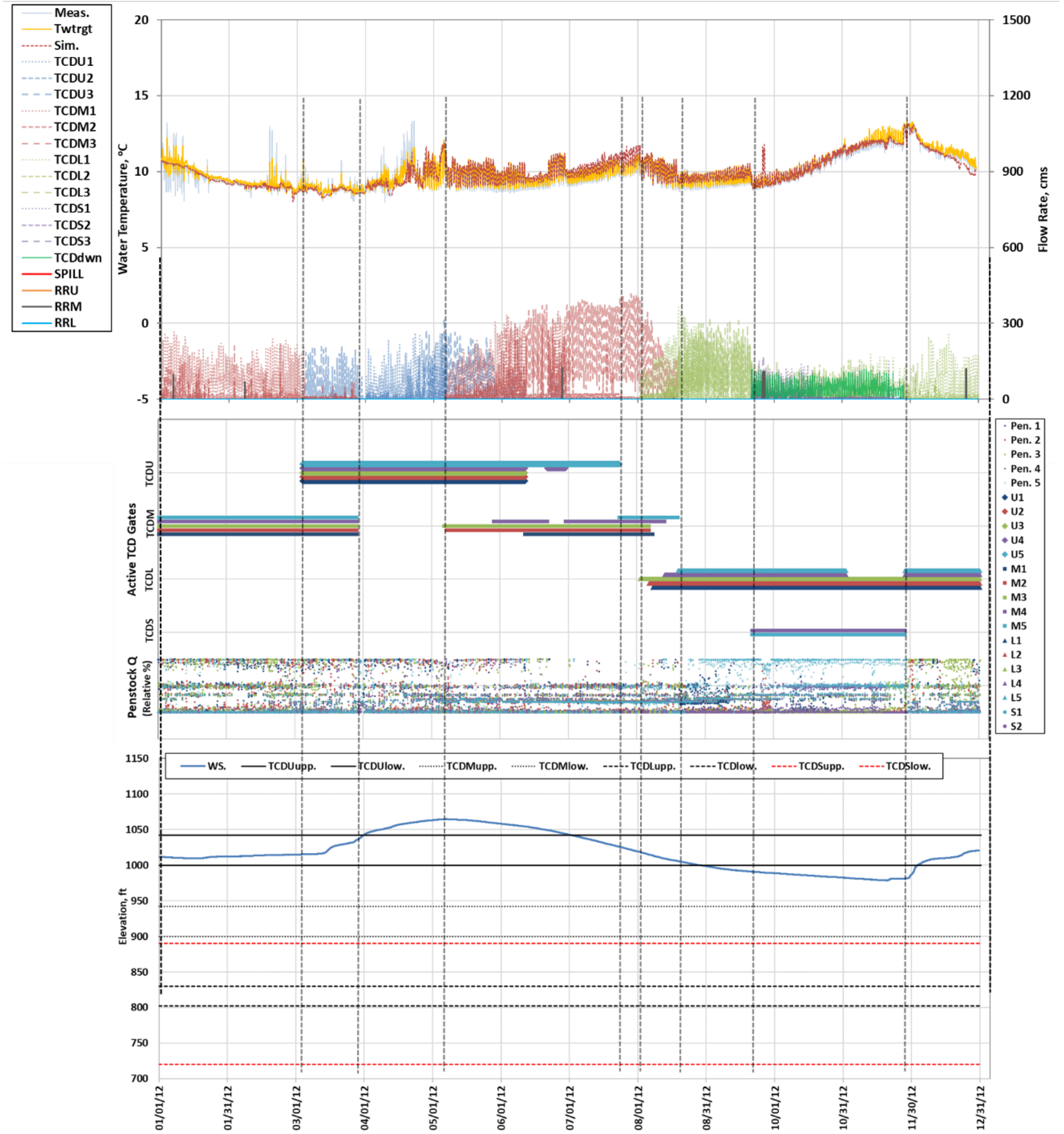


Figure D-66. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2012.

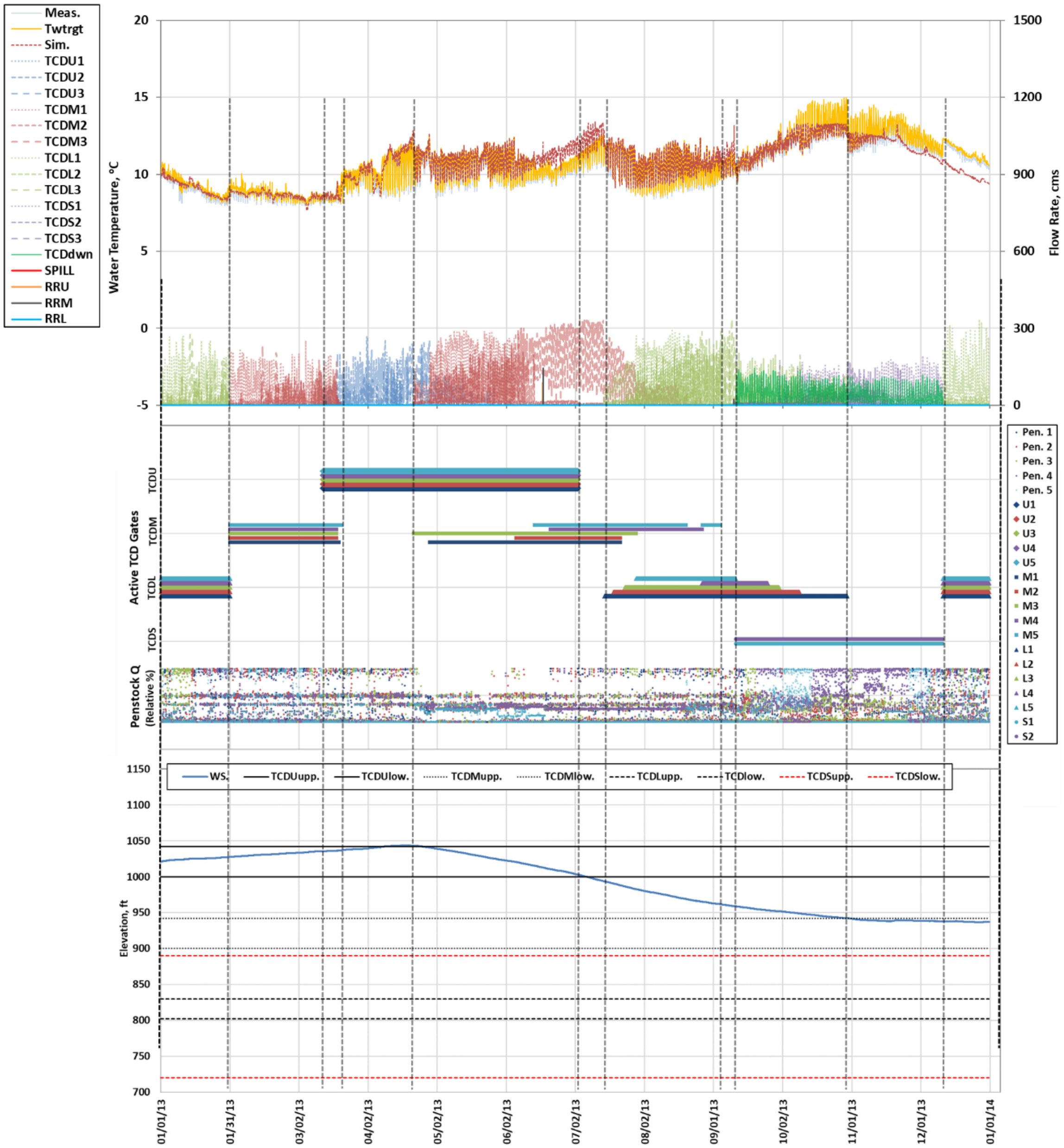


Figure D-67. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2013.

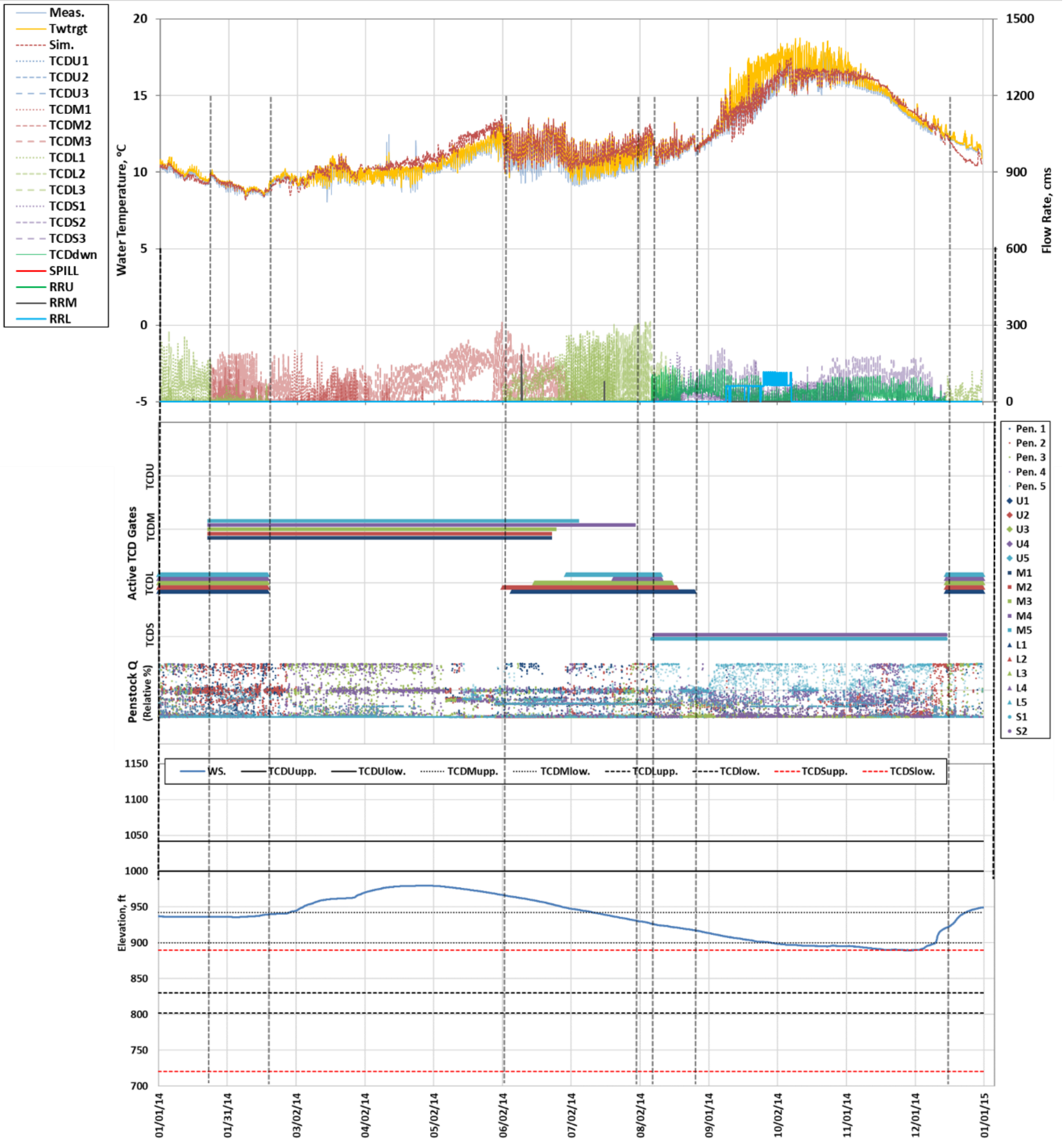


Figure D-68. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2014.

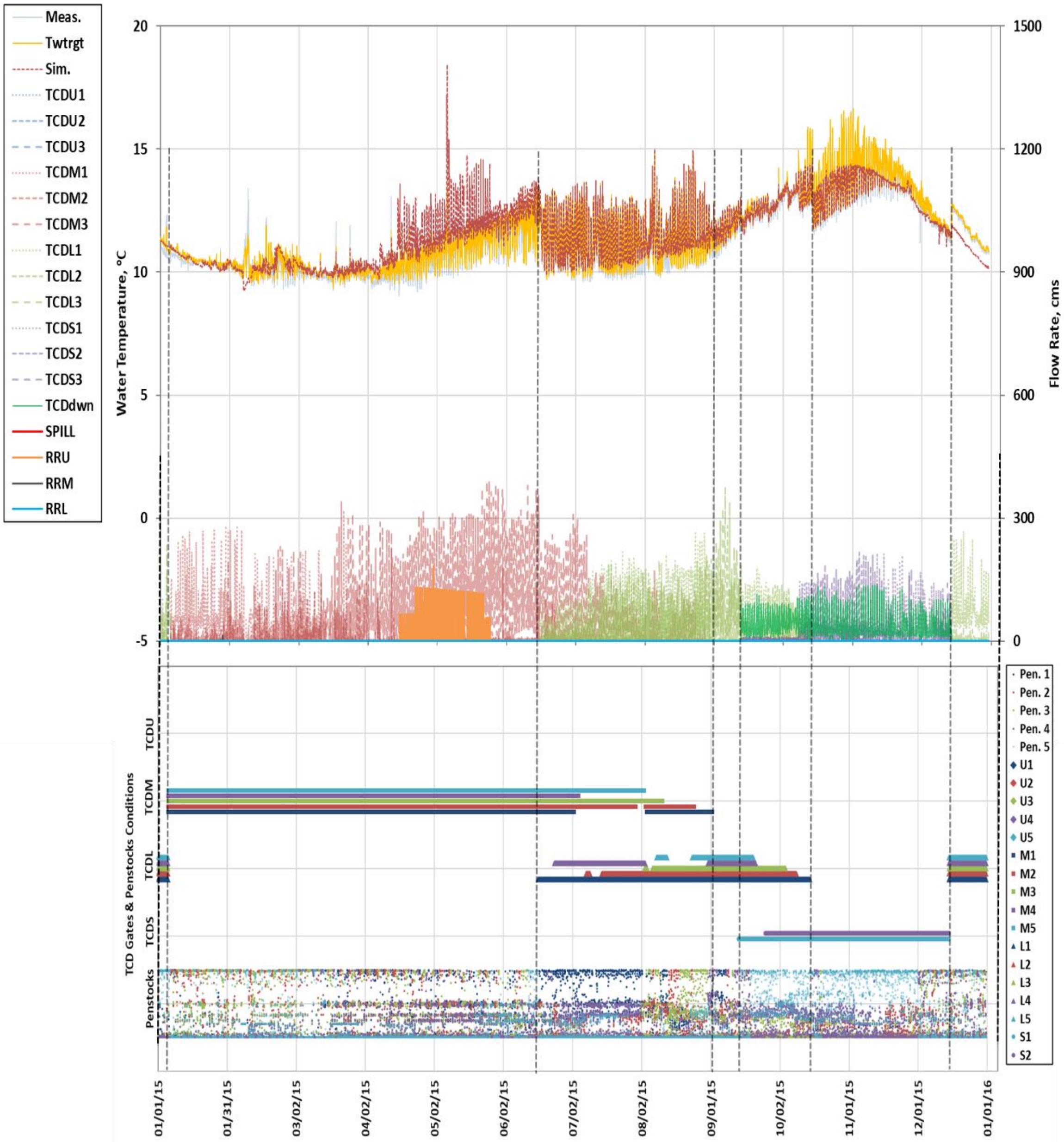


Figure D-69. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2015.

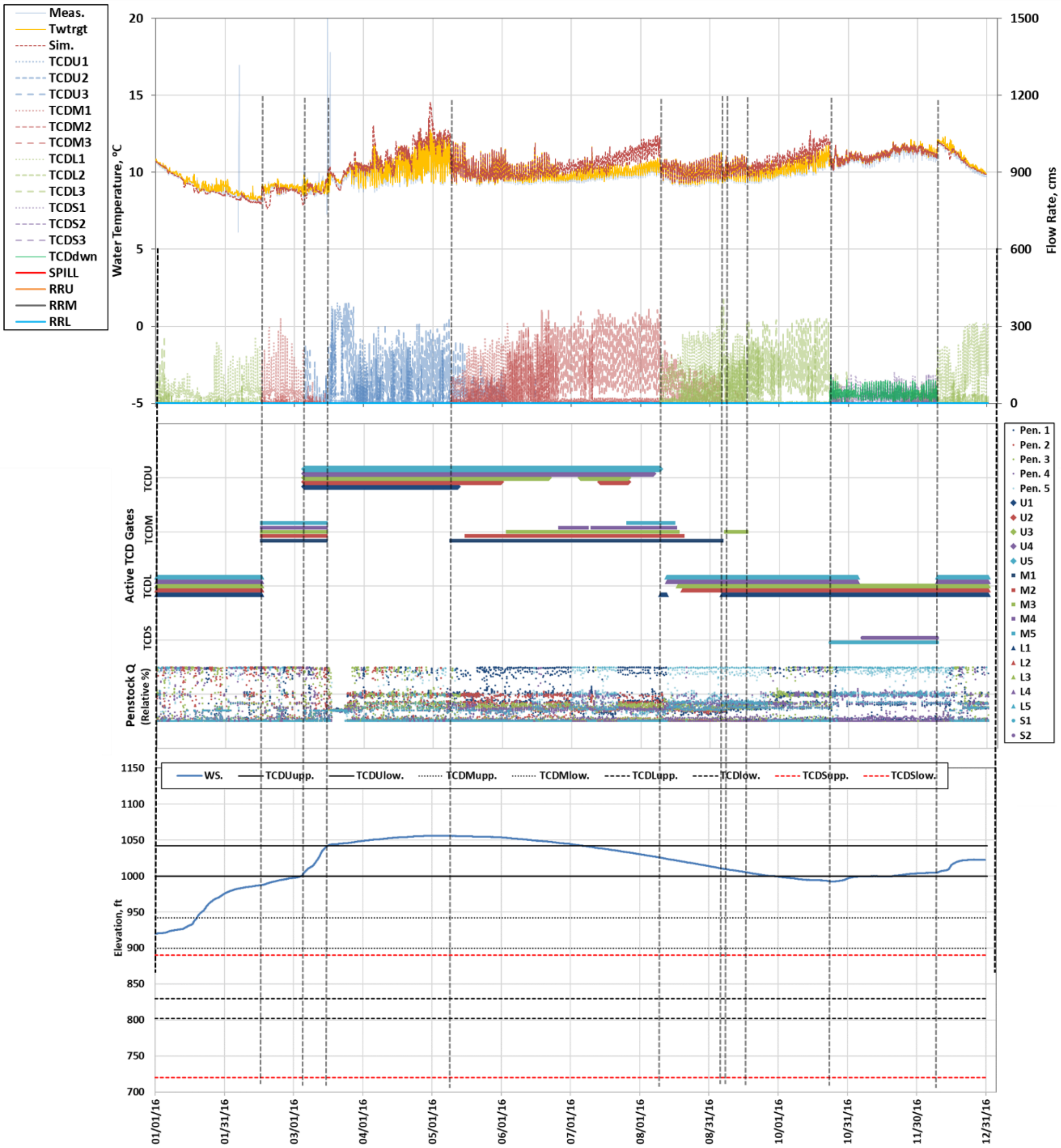


Figure D-70. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2016.

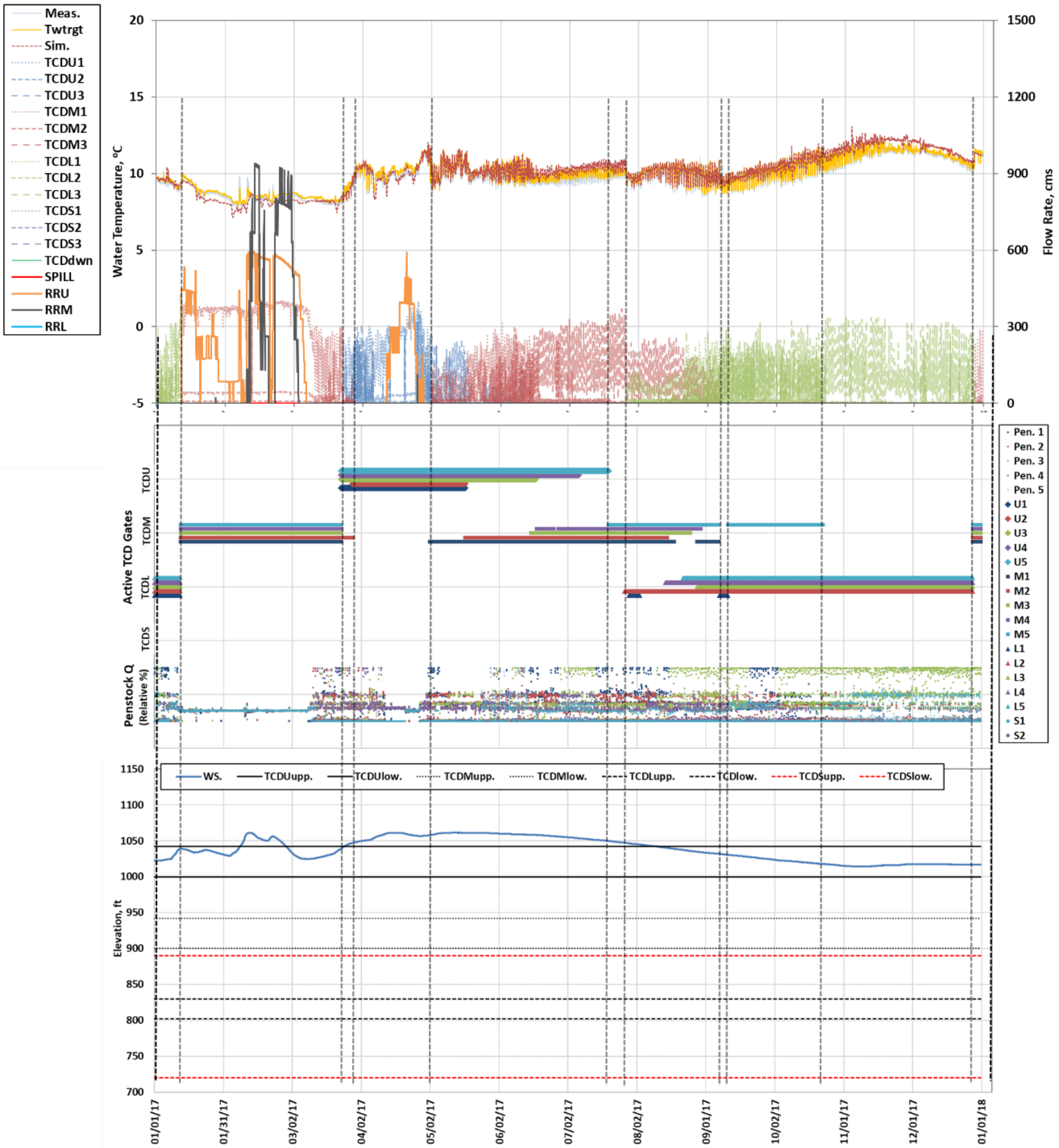


Figure D-71. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2017.

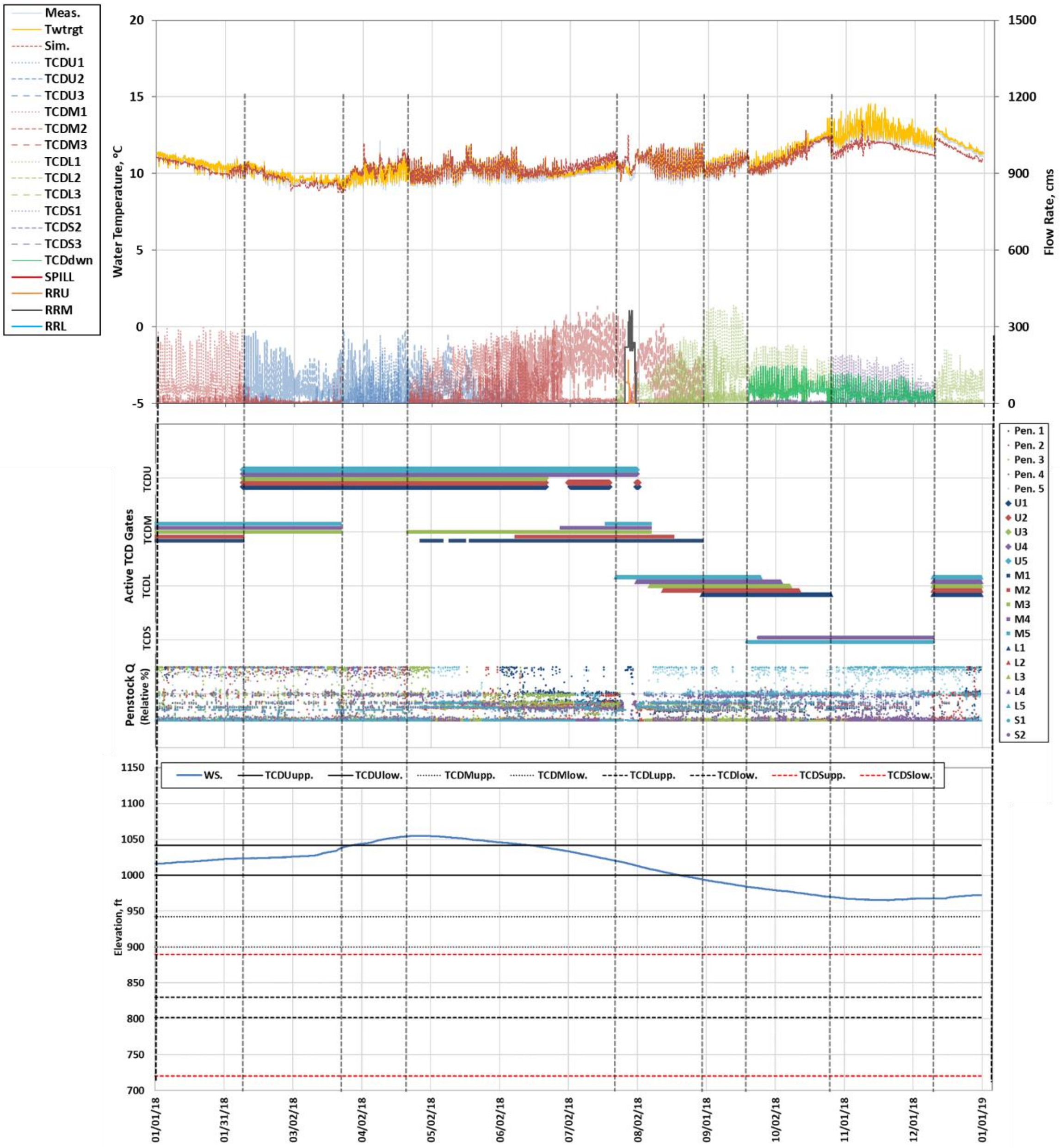


Figure D-79. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2018.

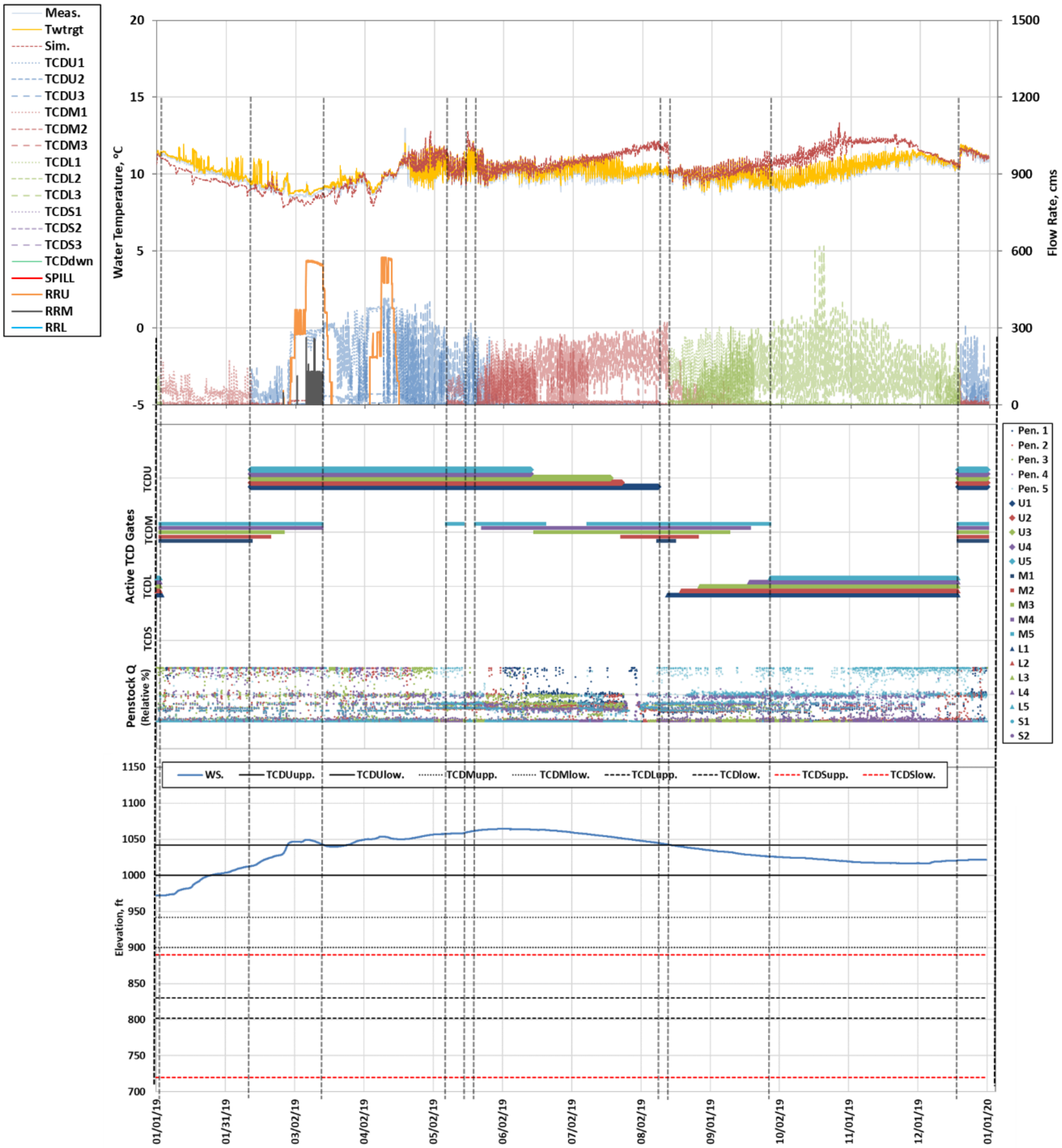


Figure D-80. Shasta Lake simulated temperature vs. target temperature & measured temperature and simulated outflows (top), Shasta Lake the TCD active gates and relative percentage of total outflow through penstocks (middle), Shasta Lake water surface elevation and the TCD gate elevations (bottom): 2019.

Table D-7. Summary statistics of Shasta Dam outflow temperature, ºC: 2000-2019.

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	0.92	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

Appendix E. Keswick Reservoir Model Results and Performance Statistics (Years 2010-2019)

Appendix E includes graphical and tabular results comparing simulated versus measured data, as well as tabulated model performance statistics for the Keswick Reservoir model. Specifically, a) Keswick Reservoir outflow, b) Keswick Reservoir stage and c) Keswick Reservoir outflow temperature.

E.1. Outflow (DRAFT)

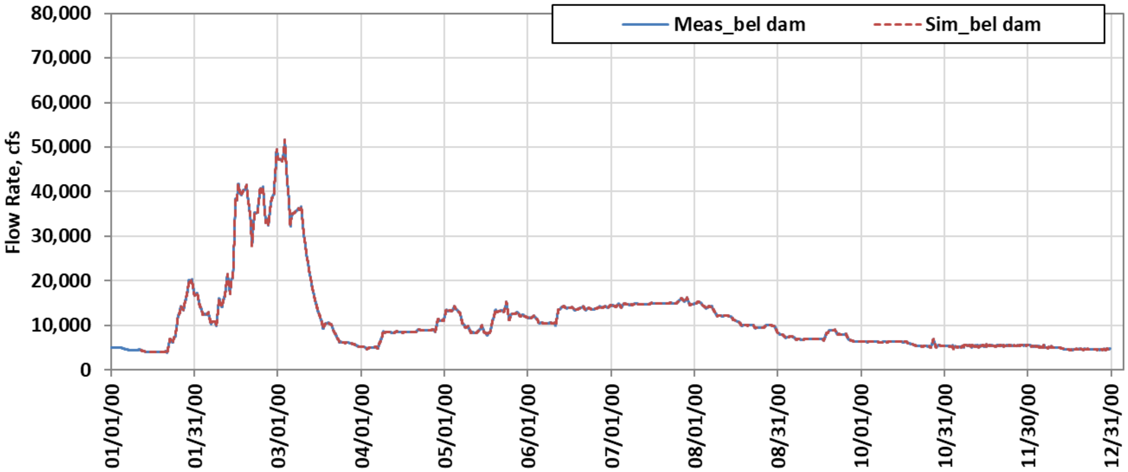


Figure E-1. Simulated versus measured flow below Keswick Dam: 2000.

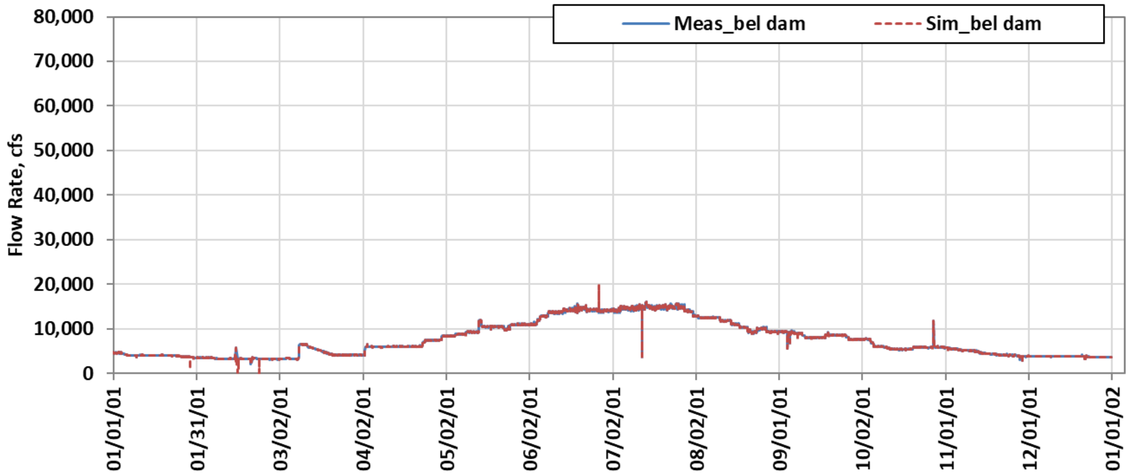


Figure E-2. Simulated versus measured flow below Keswick Dam: 2001.

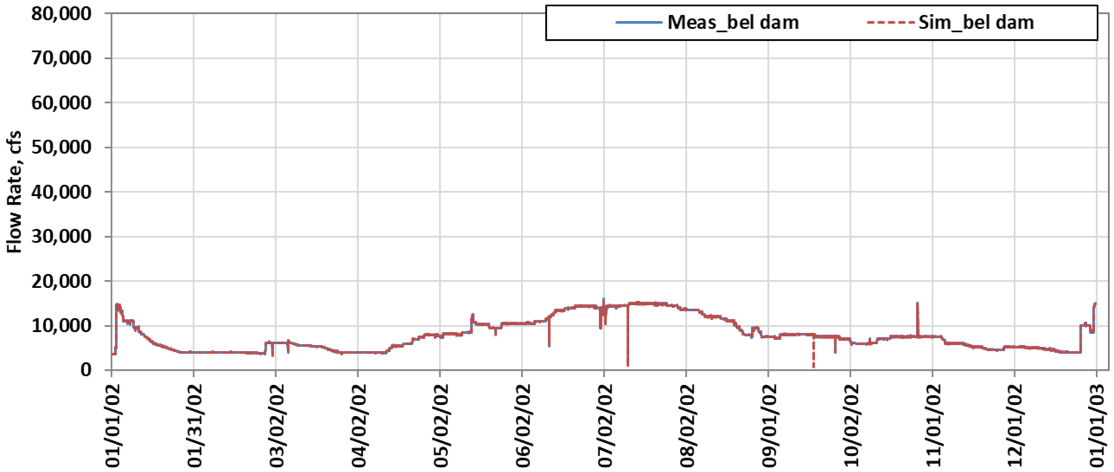


Figure E-3. Simulated versus measured flow below Keswick Dam: 2002.

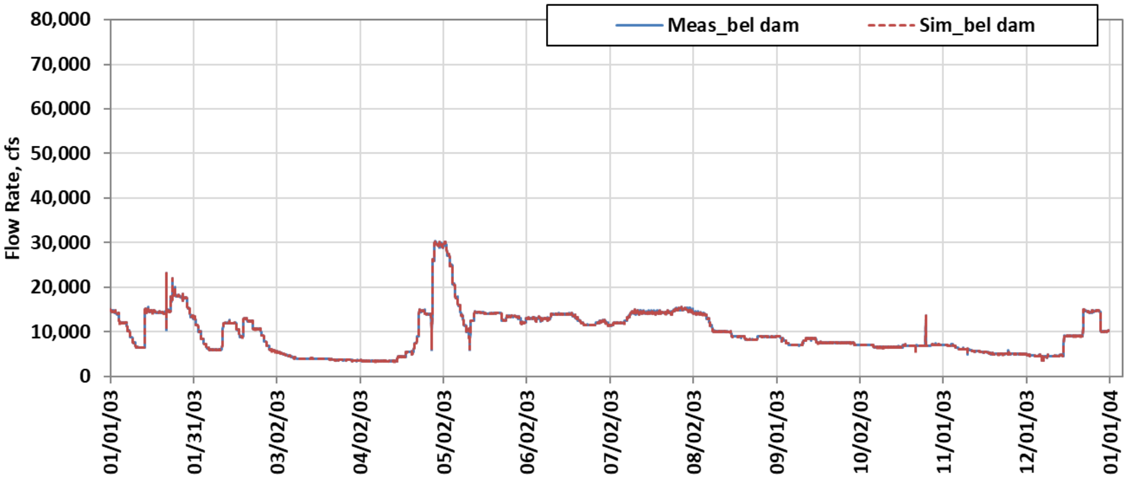


Figure E-4. Simulated versus measured flow below Keswick Dam: 2003.

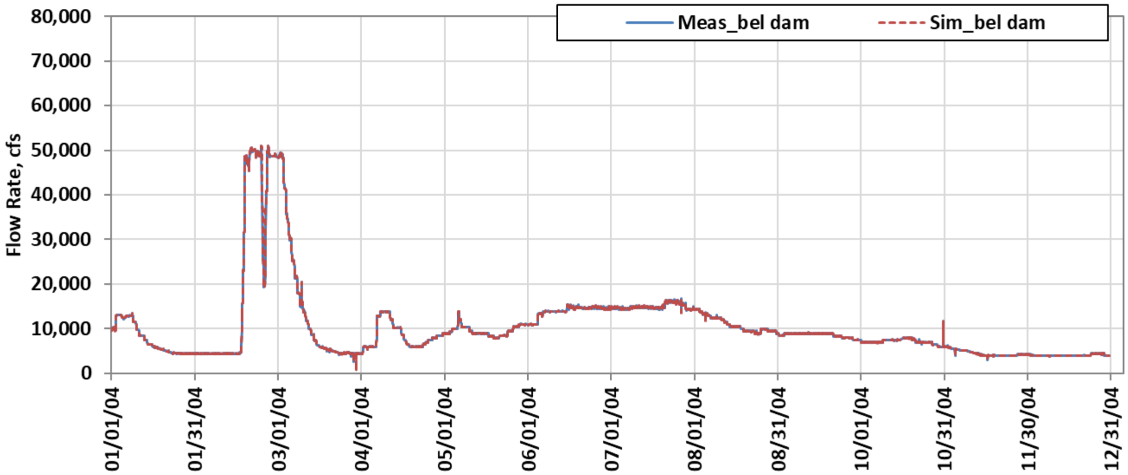


Figure E-5. Simulated versus measured flow below Keswick Dam: 2004.

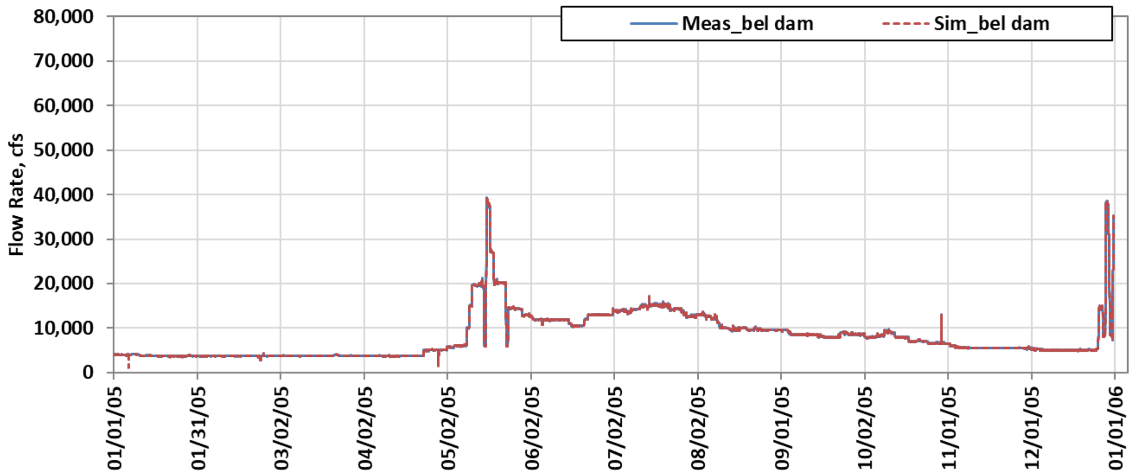


Figure E-6. Simulated versus measured flow below Keswick Dam: 2005.

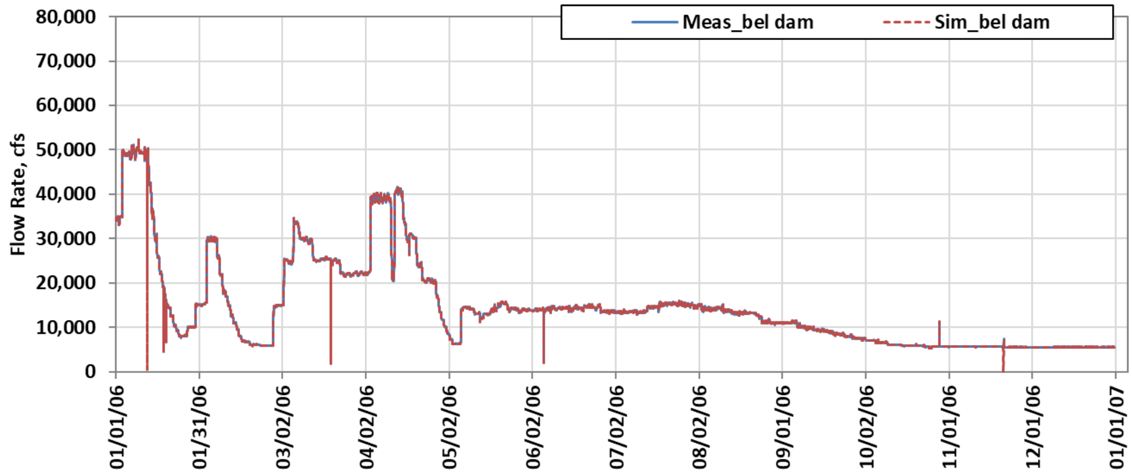


Figure E-7. Simulated versus measured flow below Keswick Dam: 2006.

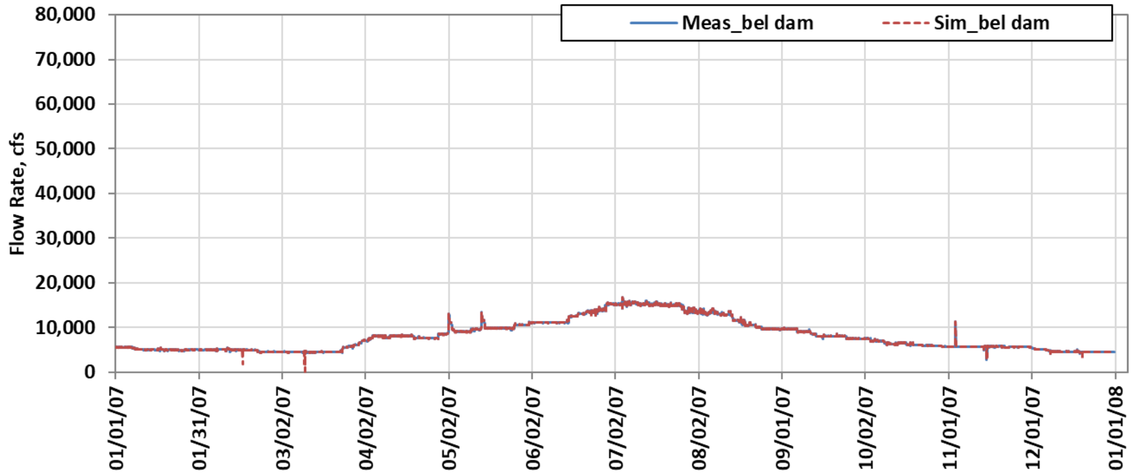


Figure E-8. Simulated versus measured flow below Keswick Dam: 2007.

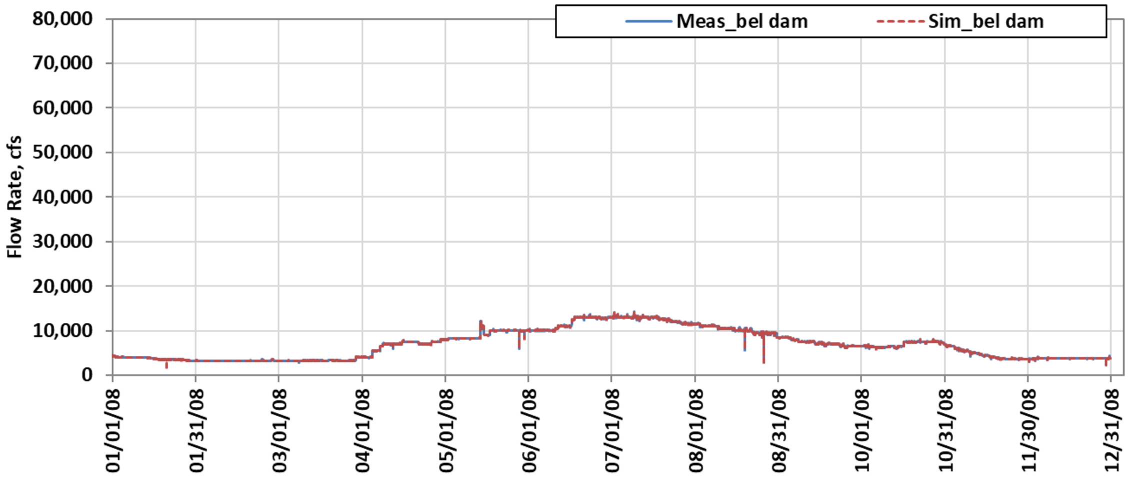


Figure E-9. Simulated versus measured flow below Keswick Dam: 2008.

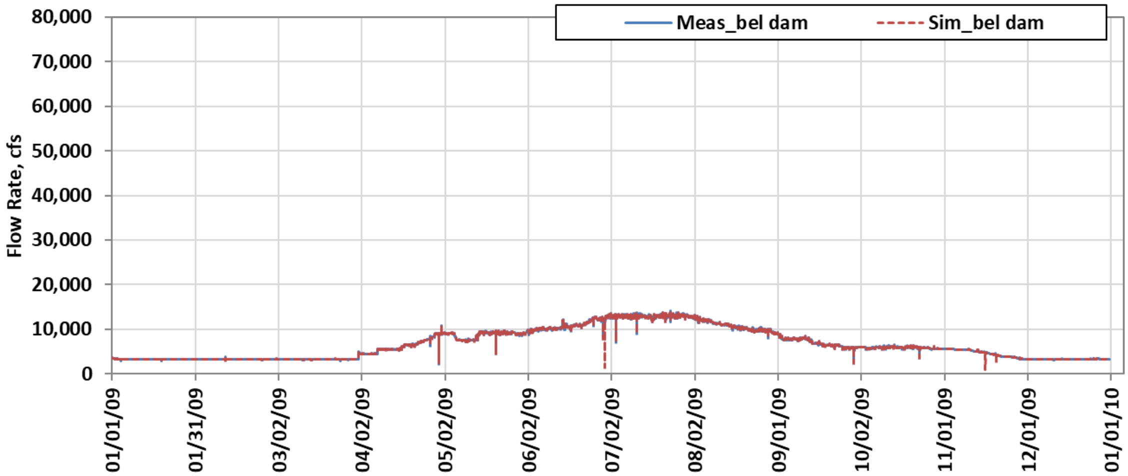


Figure E-10. Simulated versus measured flow below Keswick Dam: 2009.

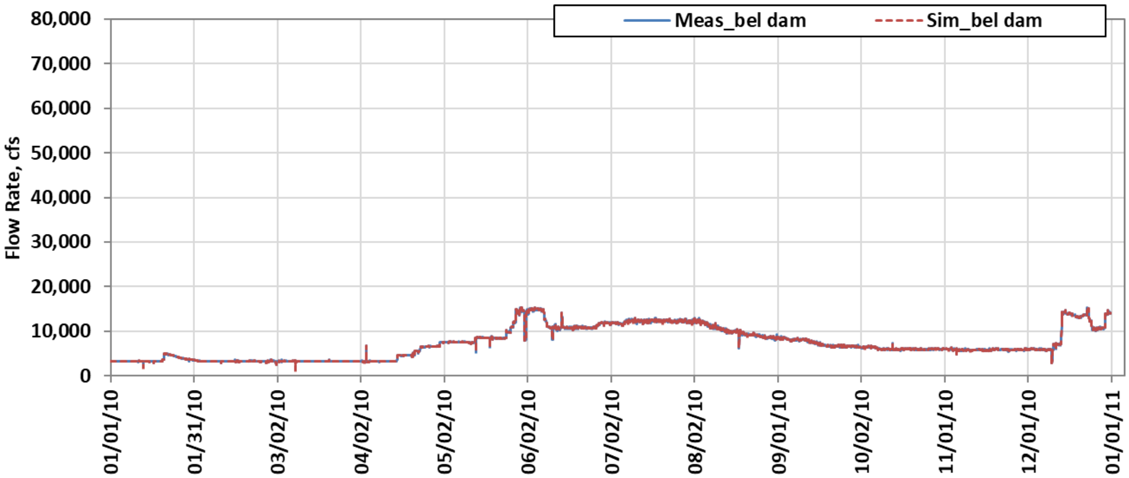


Figure E-11. Simulated versus measured flow below Keswick Dam: 2010.

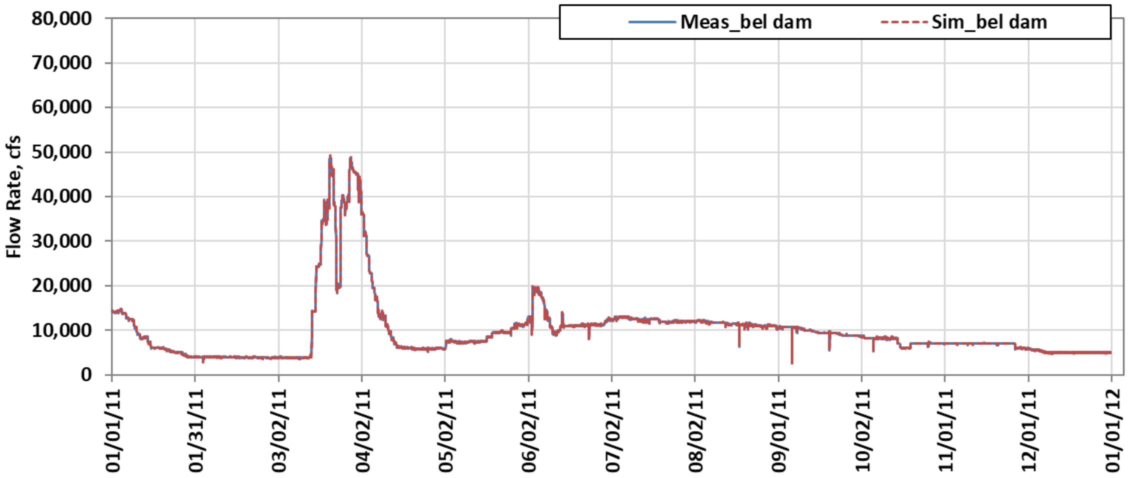


Figure E-12. Simulated versus measured flow below Keswick Dam: 2011.

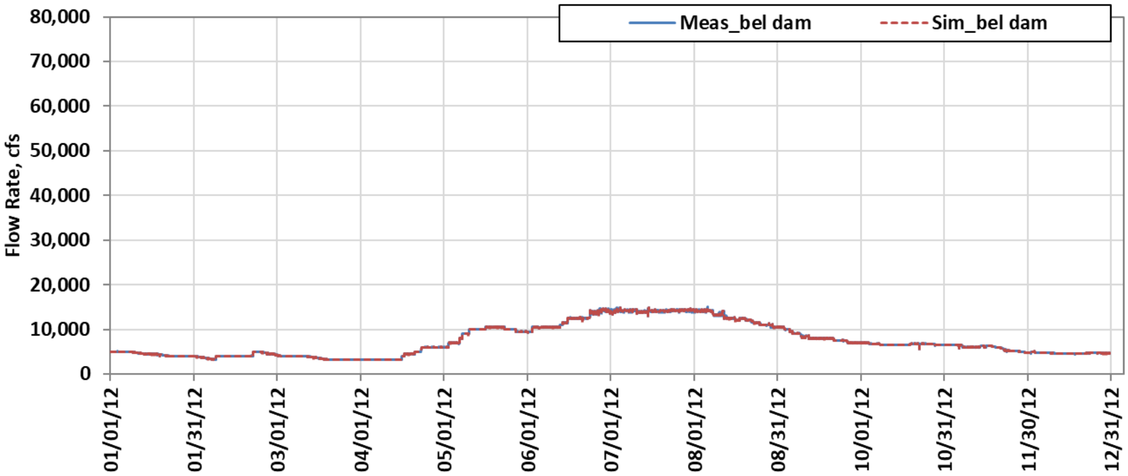


Figure E-13. Simulated versus measured flow below Keswick Dam: 2012.

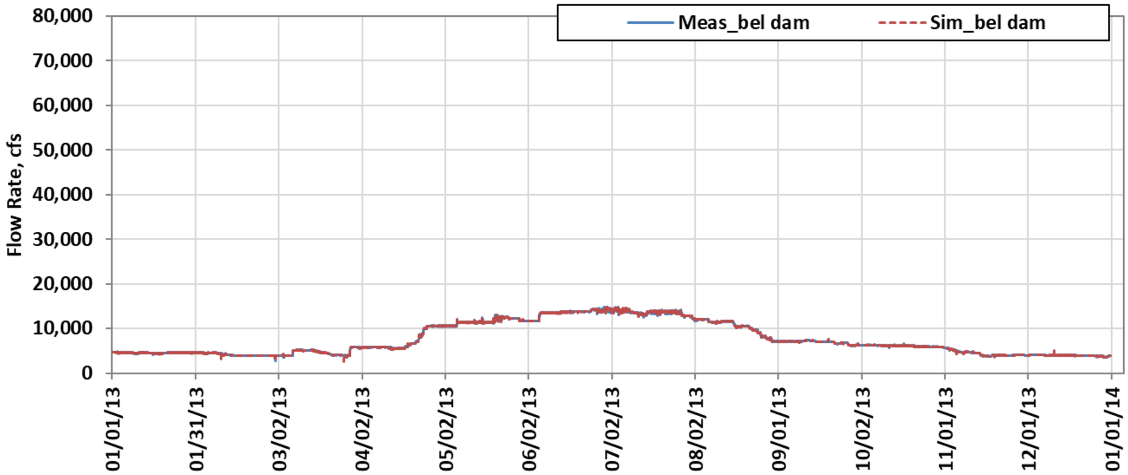


Figure E-14. Simulated versus measured flow below Keswick Dam: 2013.

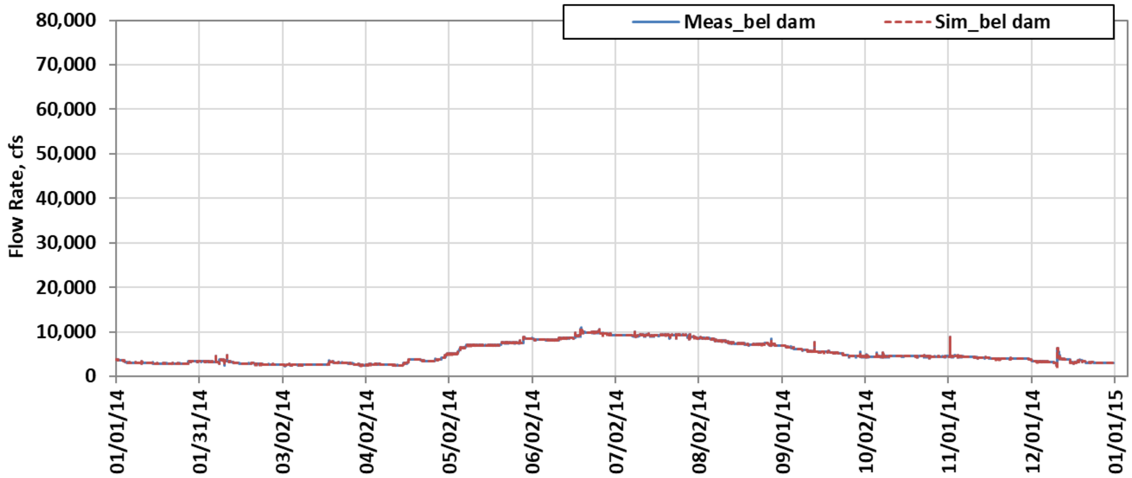


Figure E-15. Simulated versus measured flow below Keswick Dam: 2014.

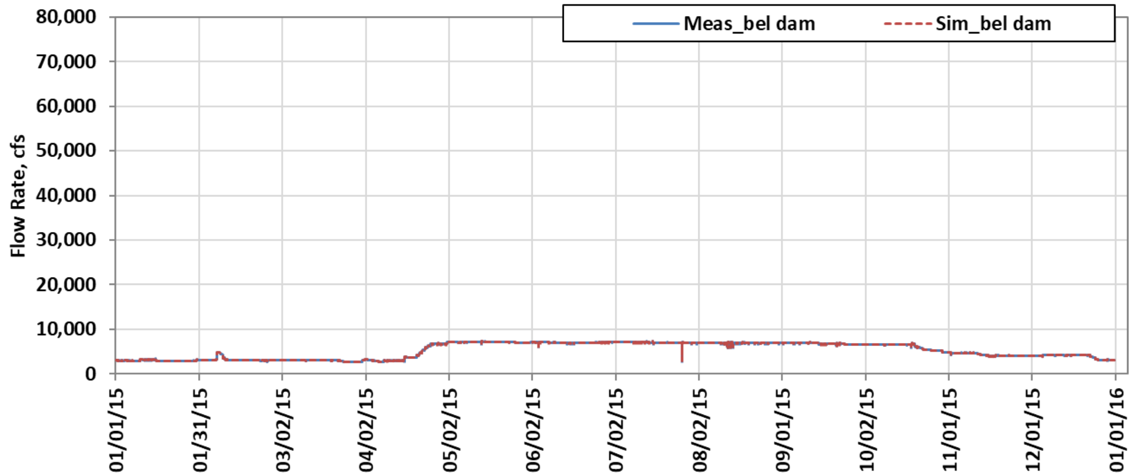


Figure E-16. Simulated versus measured flow below Keswick Dam: 2015.

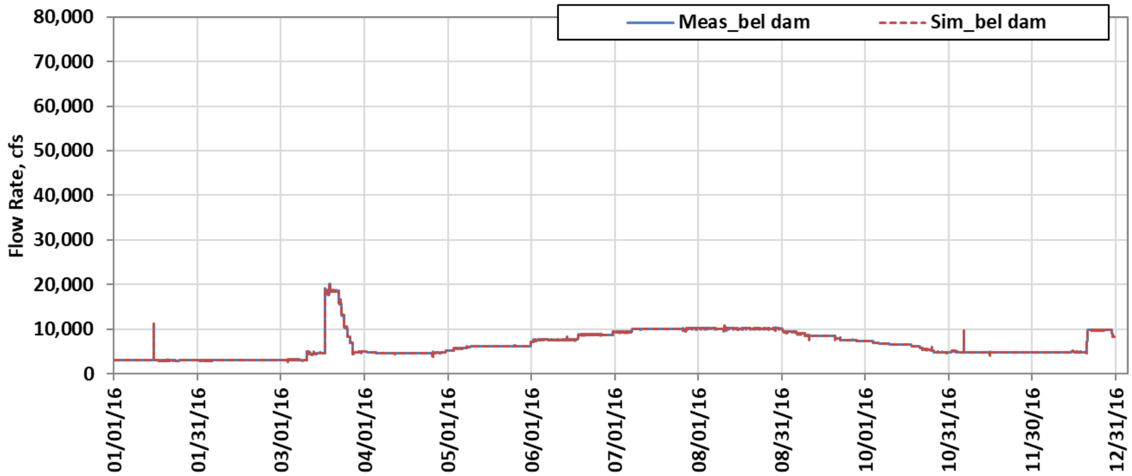


Figure E-17. Simulated versus measured flow below Keswick Dam: 2016.

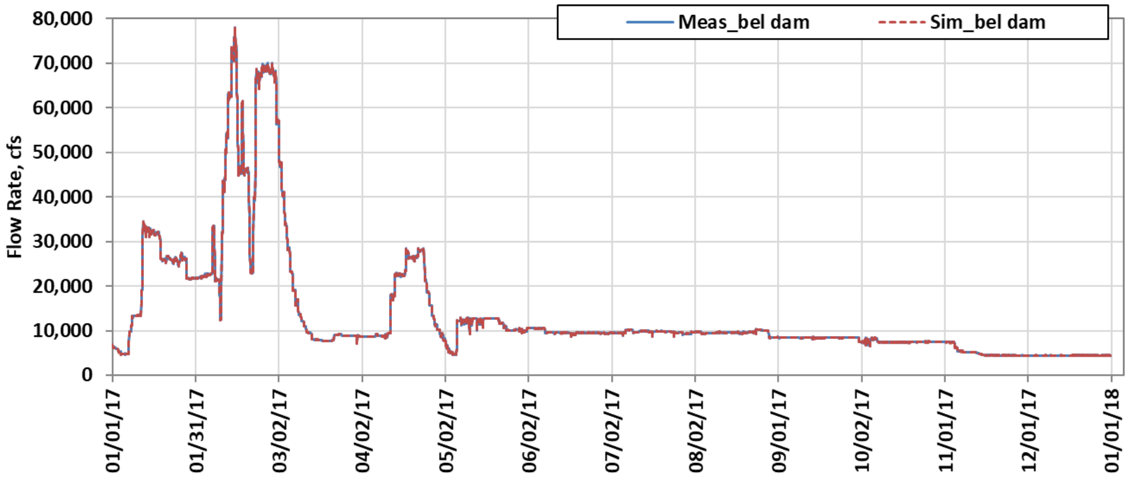


Figure E-18. Simulated versus measured flow below Keswick Dam: 2017.

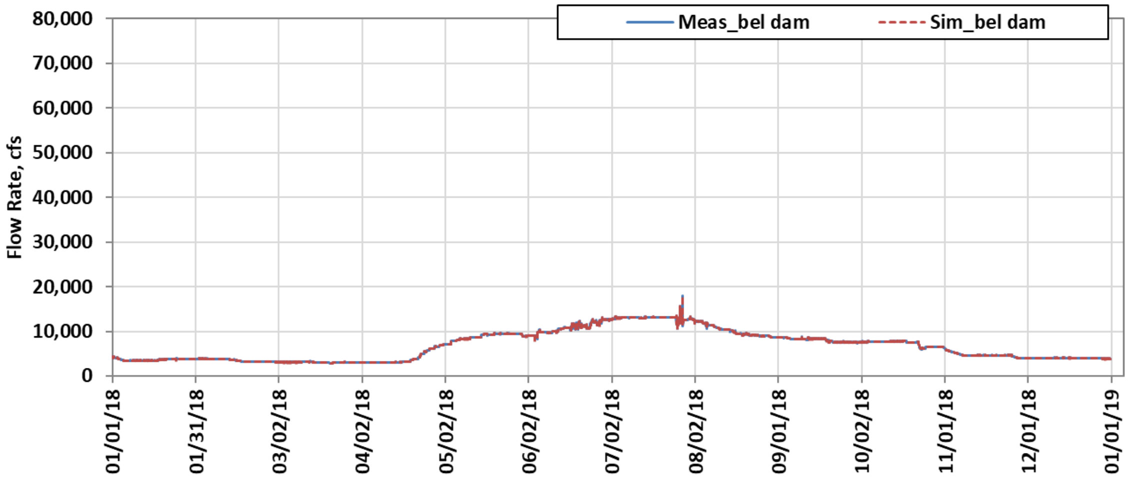


Figure E-. Simulated versus measured flow below Keswick Dam: 2018.

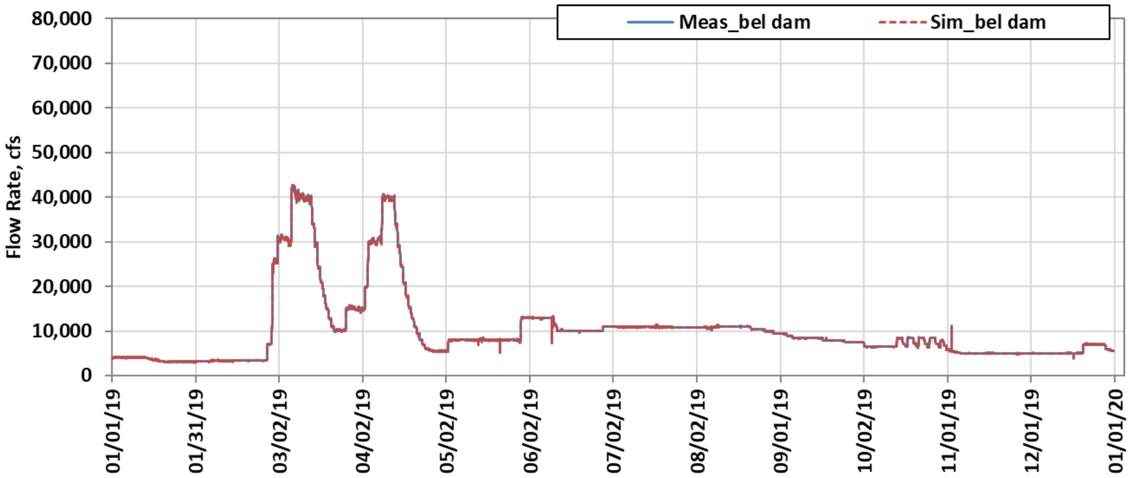


Figure E-. Simulated versus measured flow below Keswick Dam: 2019.

Table E-1. Summary statistics of Keswick Dam outflow: 2000-2019.

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

E.2. Reservoir Stage (DRAFT)

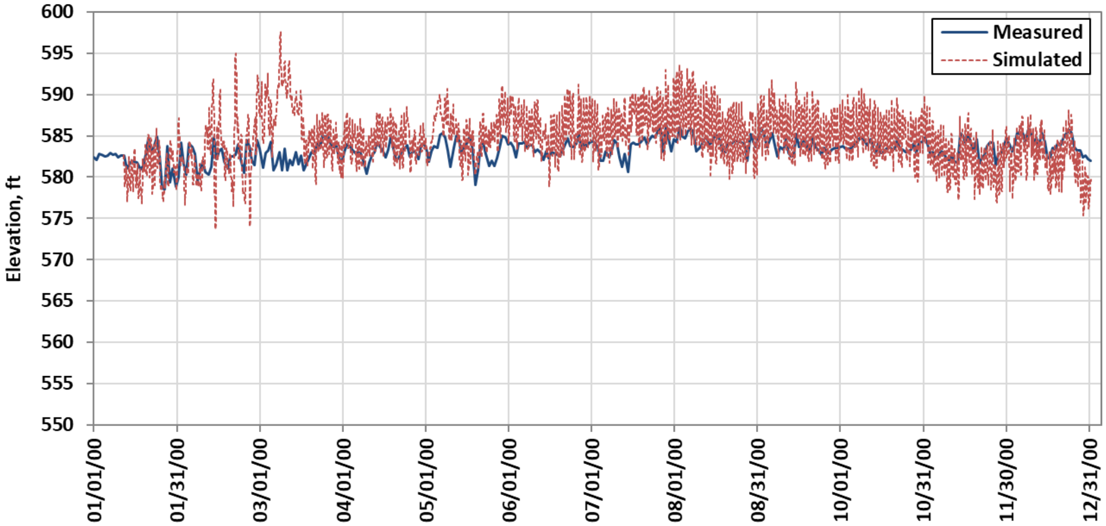


Figure E-19. Simulated versus measured Keswick Reservoir stage: 2000.

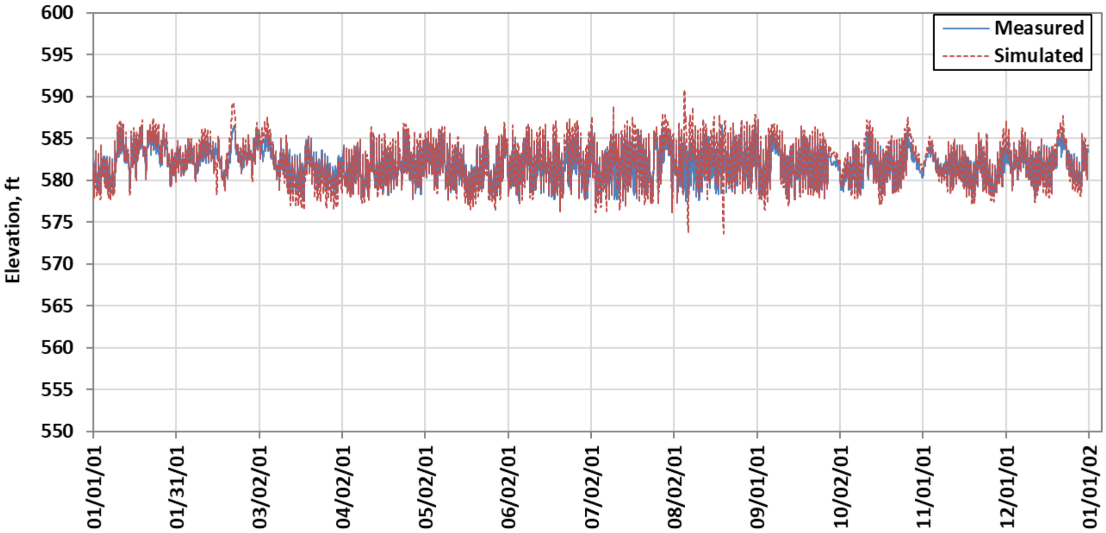


Figure E-20. Simulated versus measured Keswick Reservoir stage: 2001.

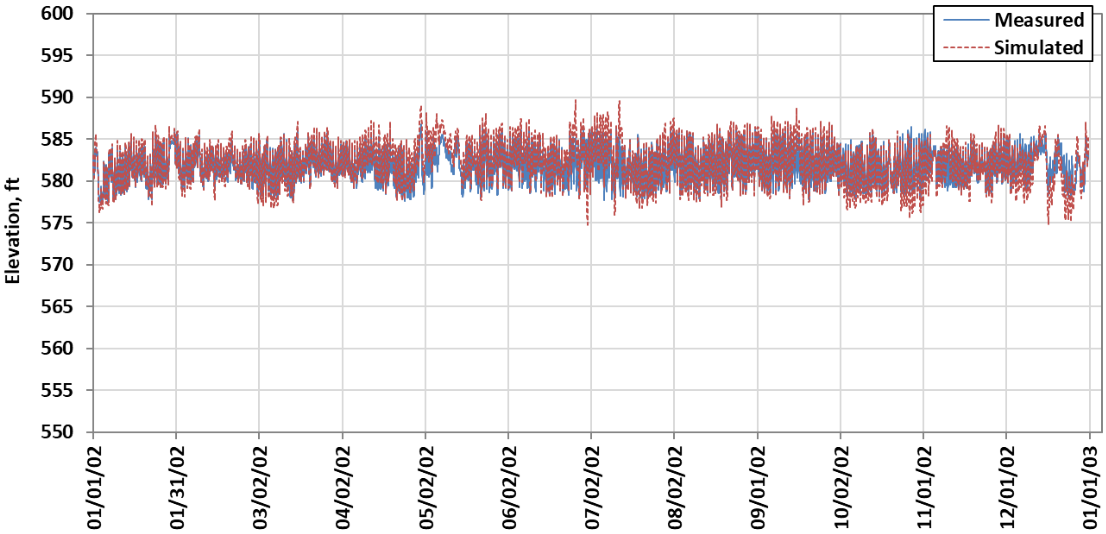


Figure E-21. Simulated versus measured Keswick Reservoir stage: 2002.

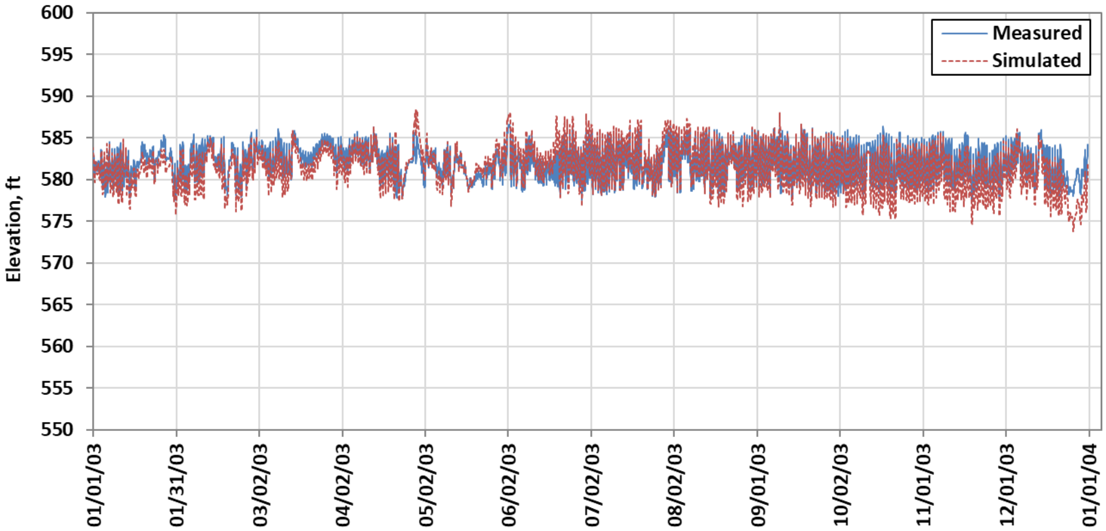


Figure E-22. Simulated versus measured Keswick Reservoir stage: 2003.

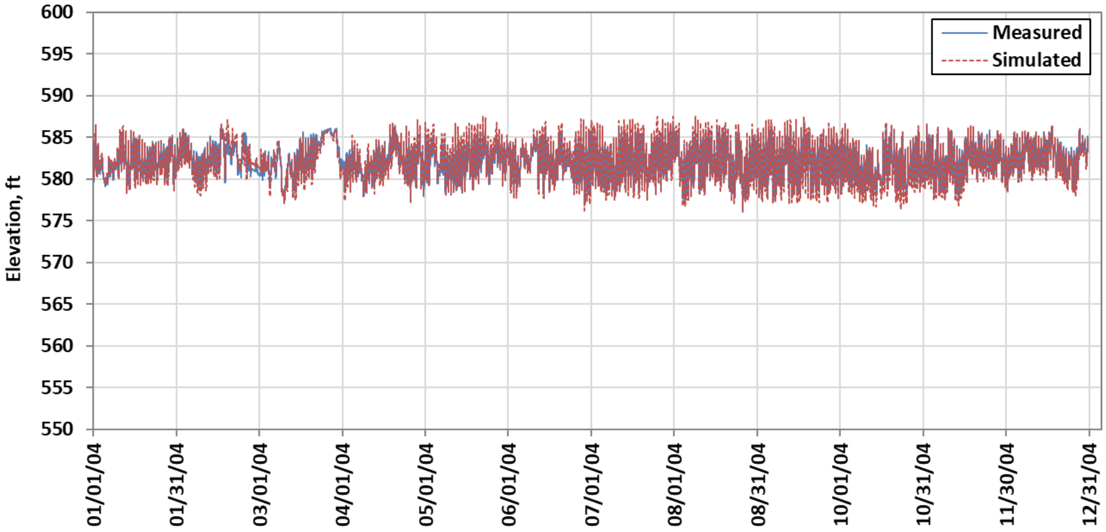


Figure E-23. Simulated versus measured Keswick Reservoir stage: 2004.

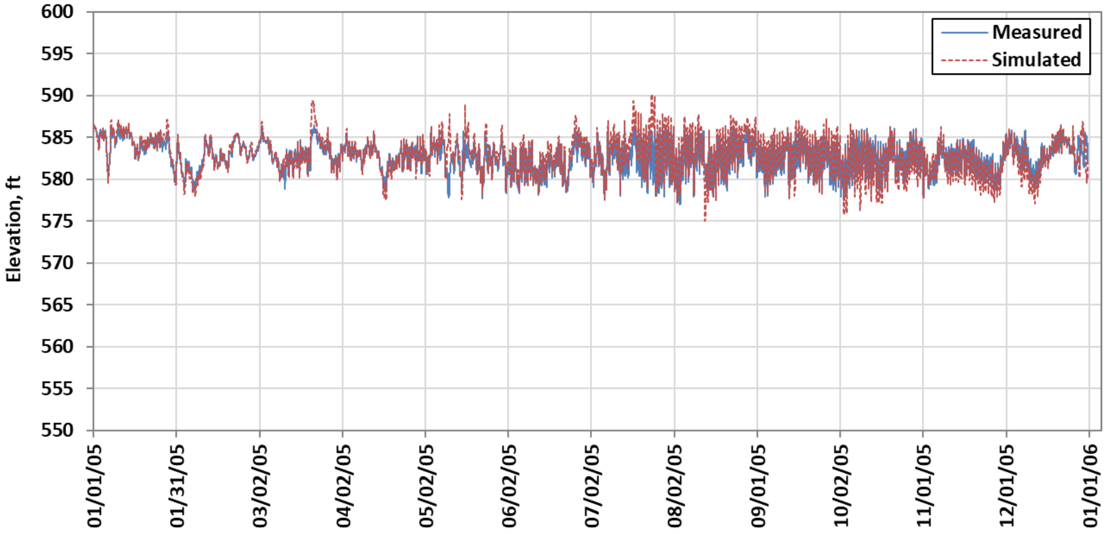


Figure E-24. Simulated versus measured Keswick Reservoir stage: 2005.

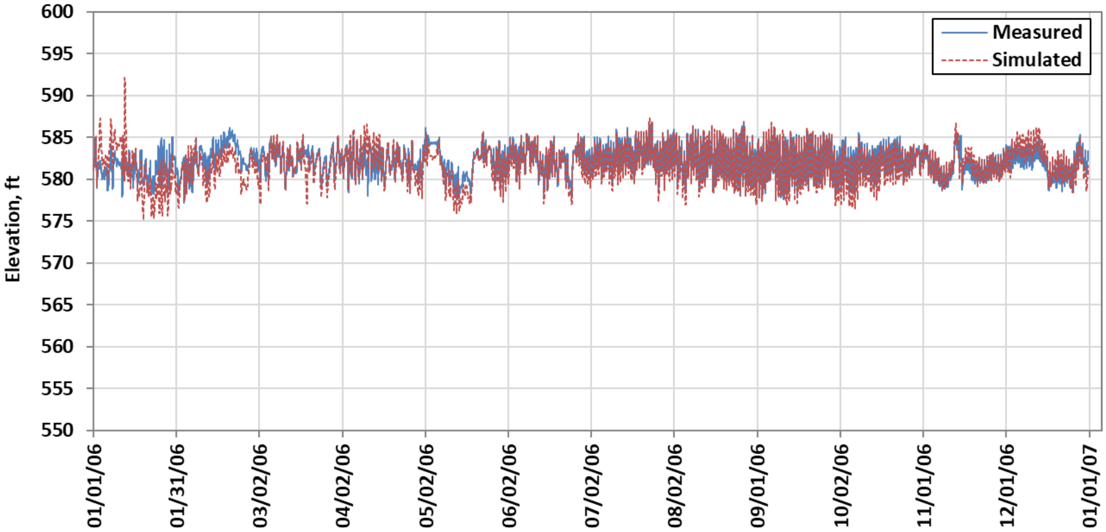


Figure E-25. Simulated versus measured Keswick Reservoir stage: 2006.

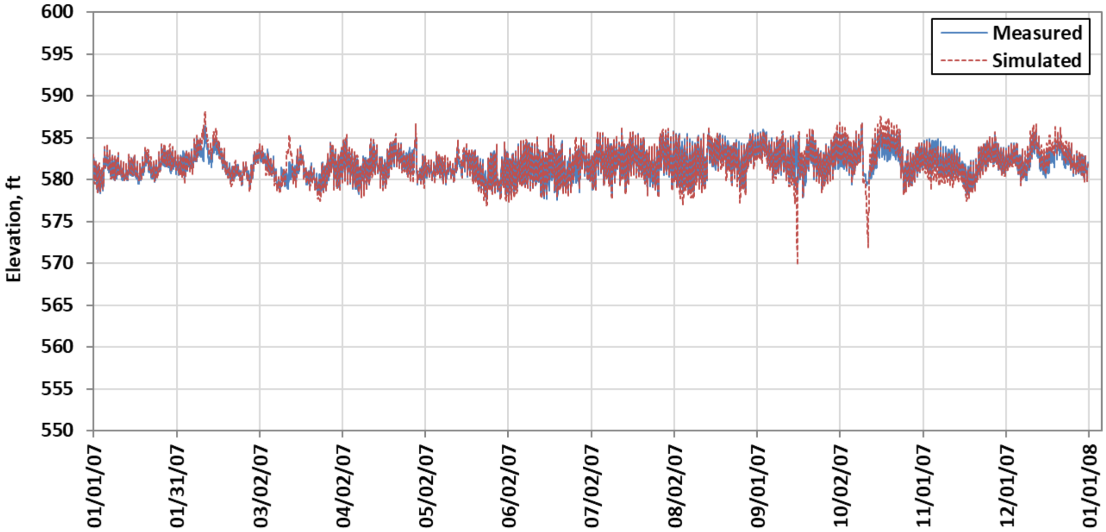


Figure E-26. Simulated versus measured Keswick Reservoir stage: 2007.

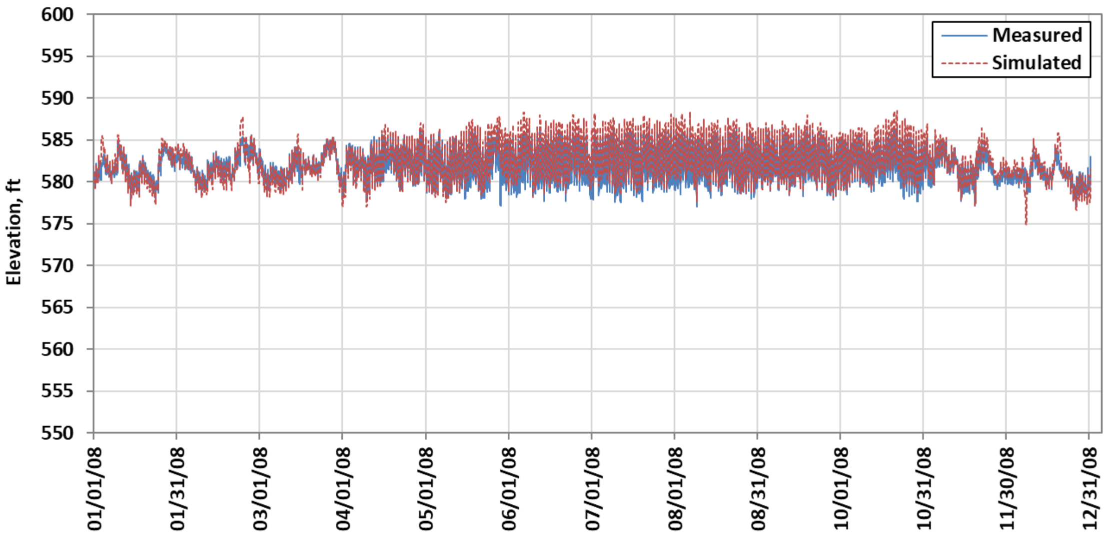


Figure E-27. Simulated versus measured Keswick Reservoir stage: 2008.

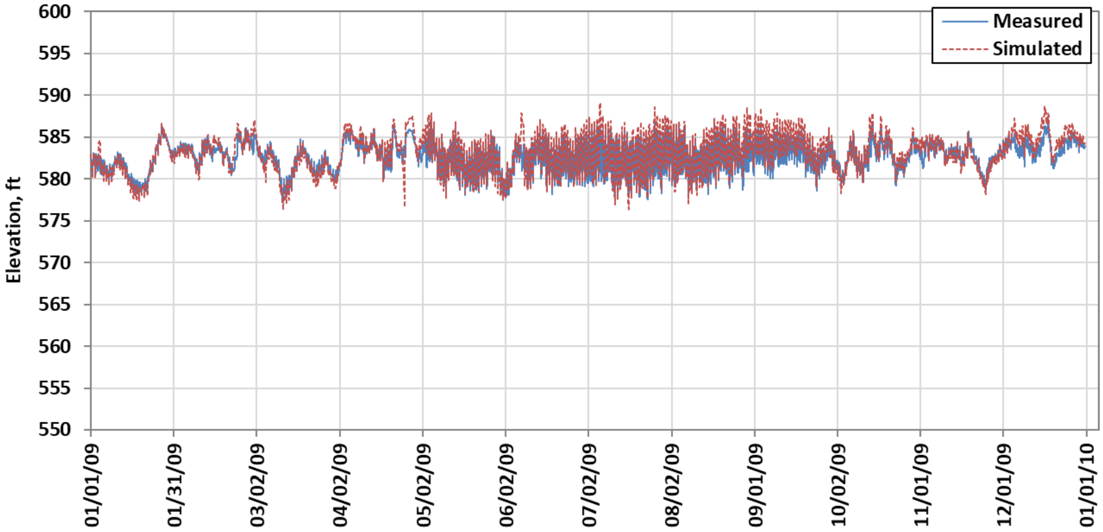


Figure E-28. Simulated versus measured Keswick Reservoir stage: 2009.

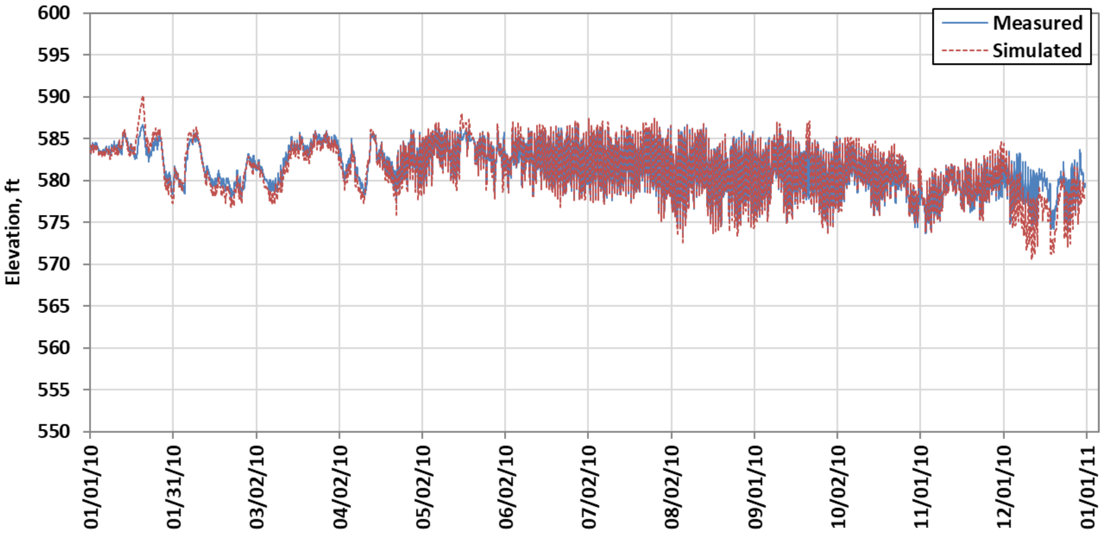


Figure E-29. Simulated versus measured Keswick Reservoir stage: 2010.

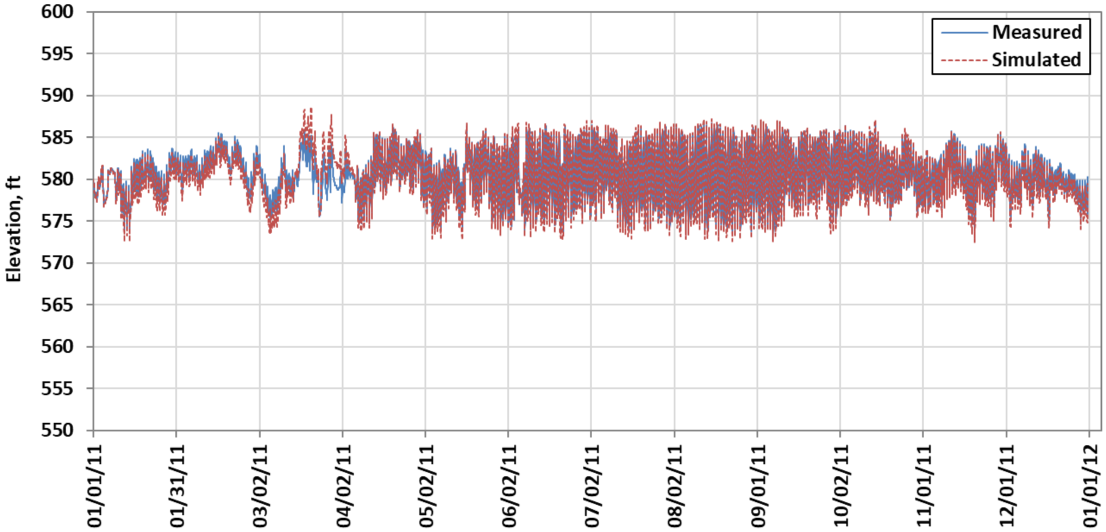


Figure E-30. Simulated versus measured Keswick Reservoir stage: 2011.

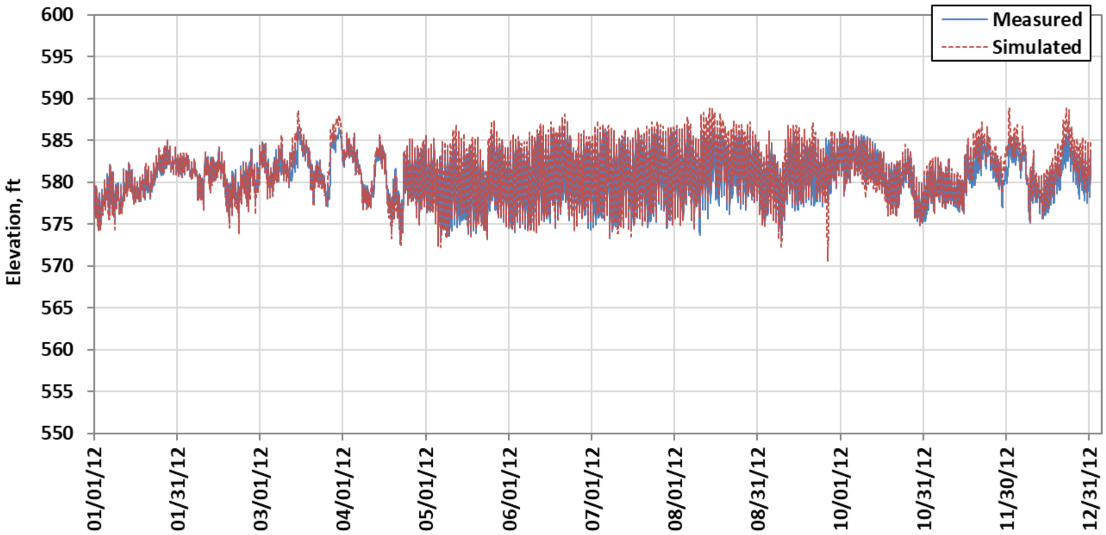


Figure E-31. Simulated versus measured Keswick Reservoir stage: 2012.

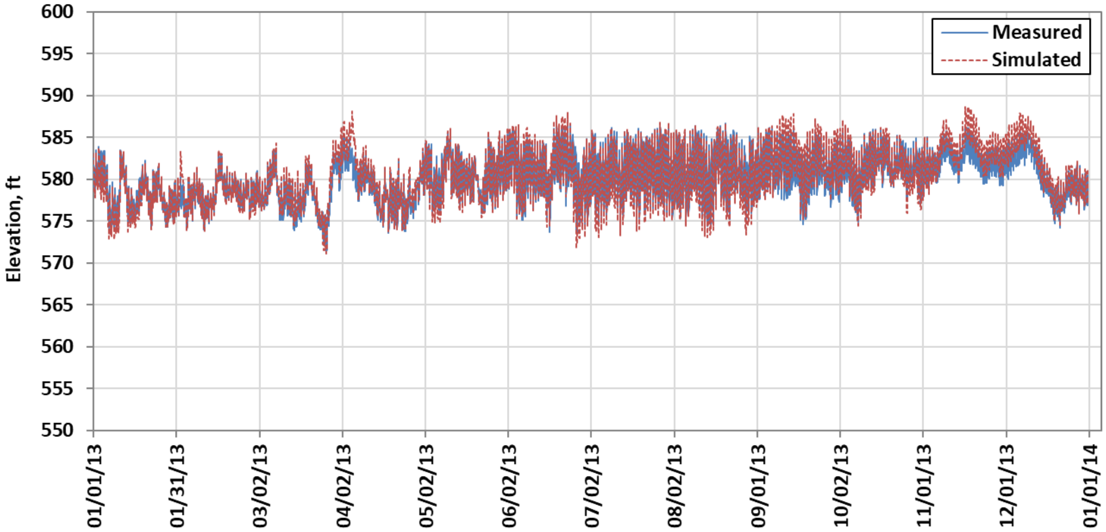


Figure E-32. Simulated versus measured Keswick Reservoir stage: 2013.

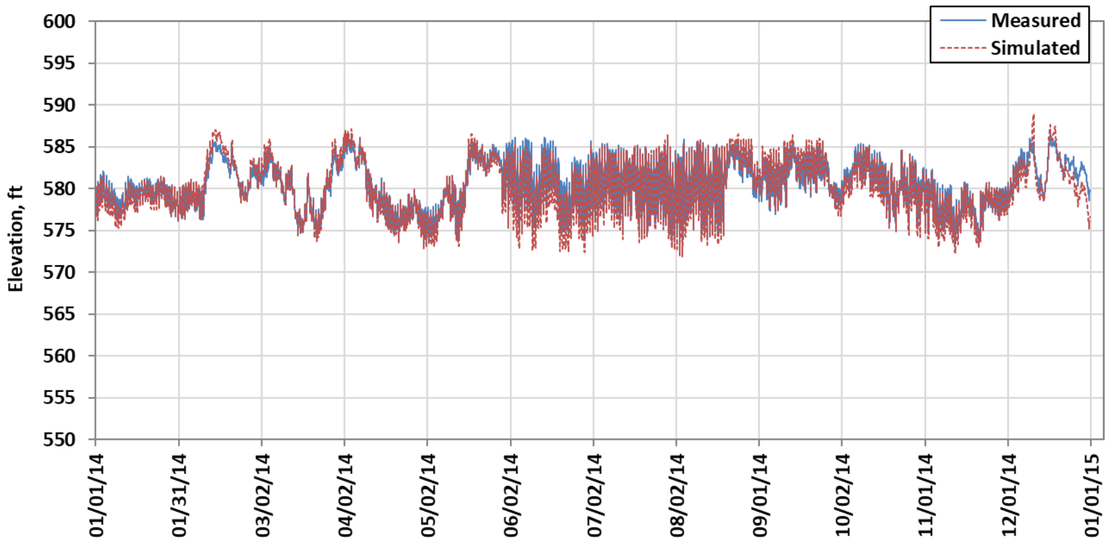


Figure E-33. Simulated versus measured Keswick Reservoir stage: 2014.

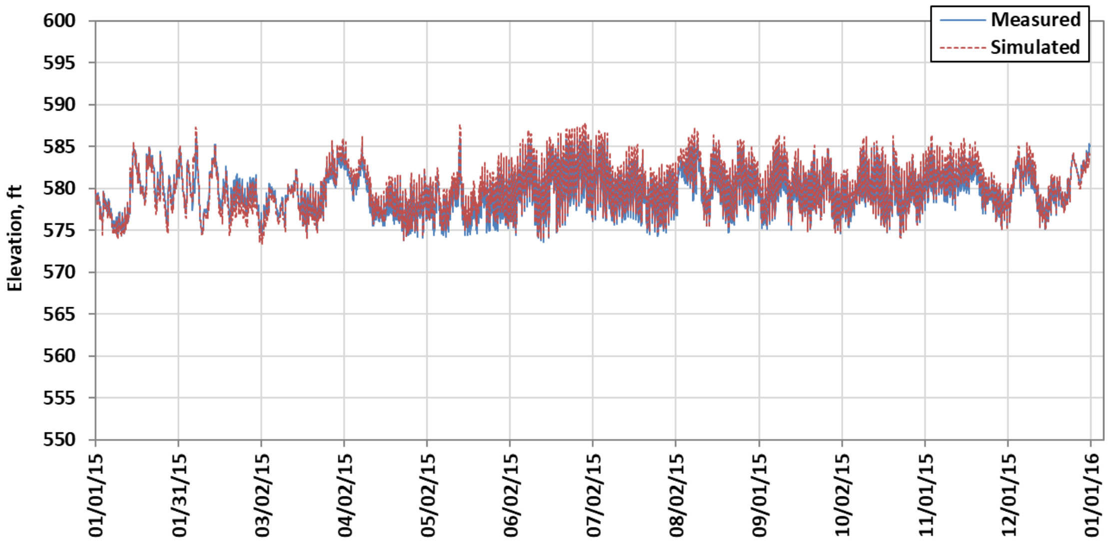


Figure E-34. Simulated versus measured Keswick Reservoir stage: 2015.

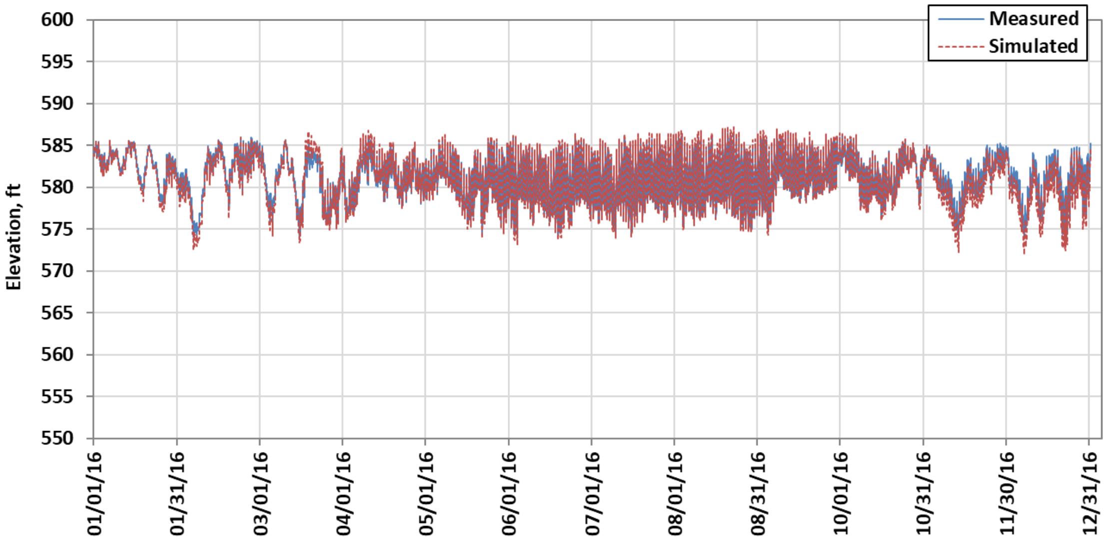


Figure E-35. Simulated versus measured Keswick Reservoir stage: 2016.

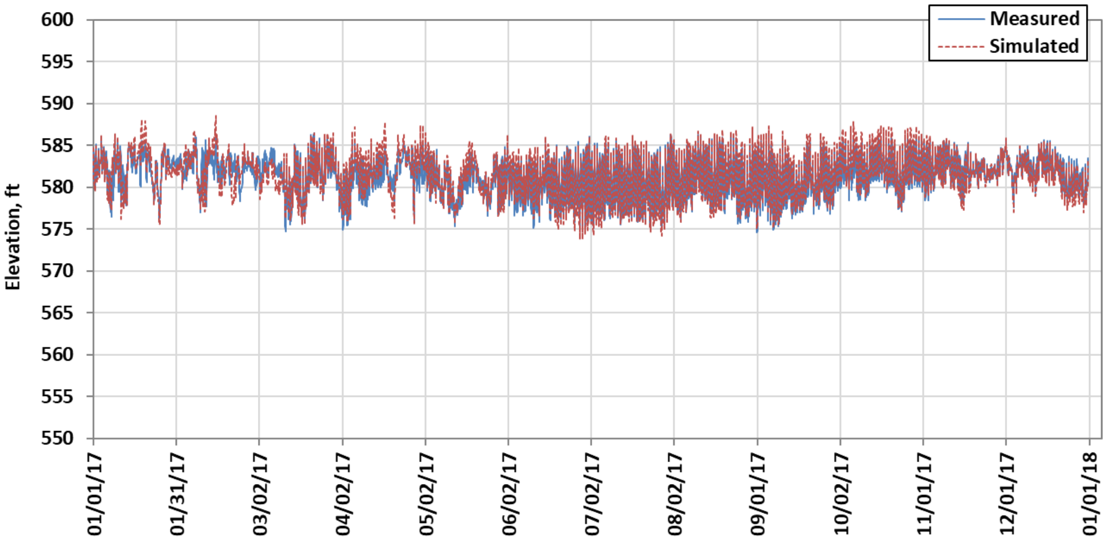


Figure E-36. Simulated versus measured Keswick Reservoir stage: 2017.

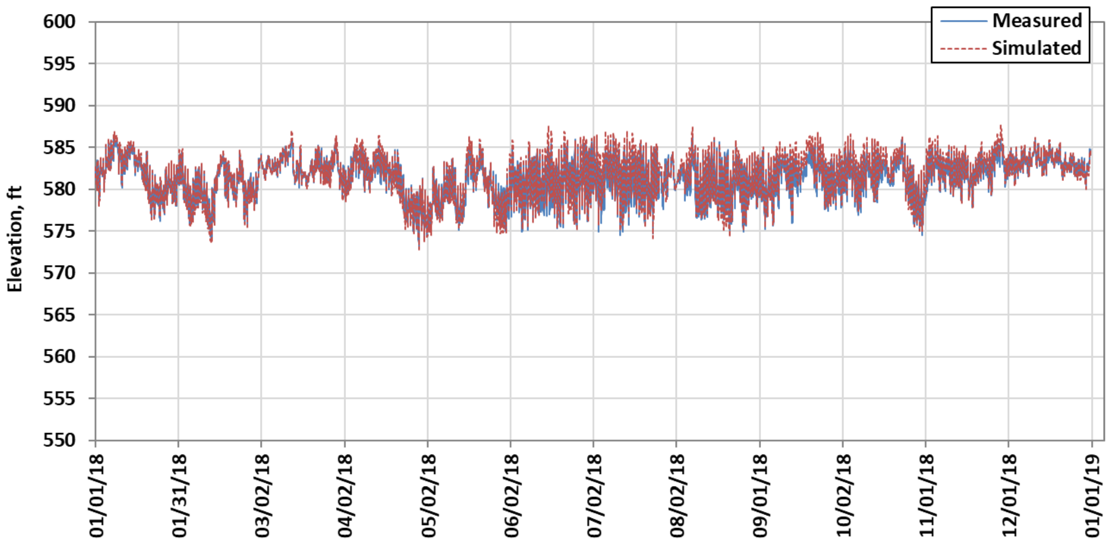


Figure E-. Simulated versus measured Keswick Reservoir stage: 2018.

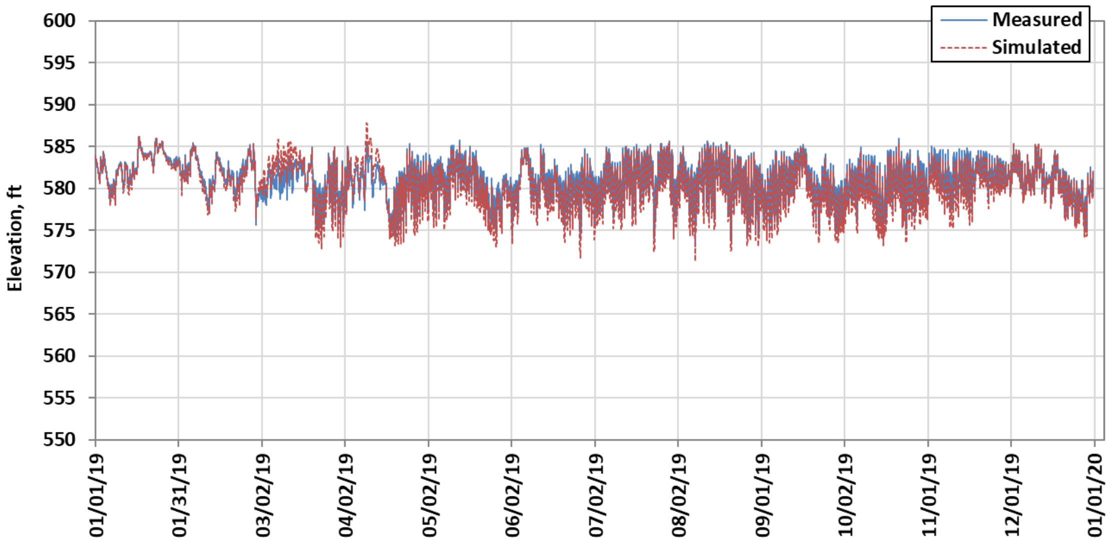


Figure E-. Simulated versus measured Keswick Reservoir stage: 2019.

Table E-2. Summary statistics of Keswick Reservoir stage: 2000-2019.

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

E.1. Outflow Temperature (DRAFT)

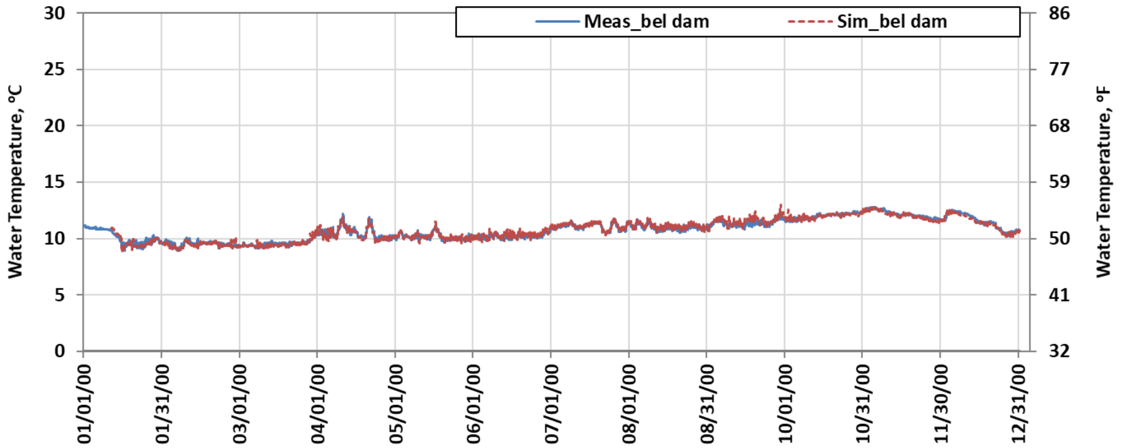


Figure E-37. Simulated versus measured temperature below Keswick Dam: 2000.

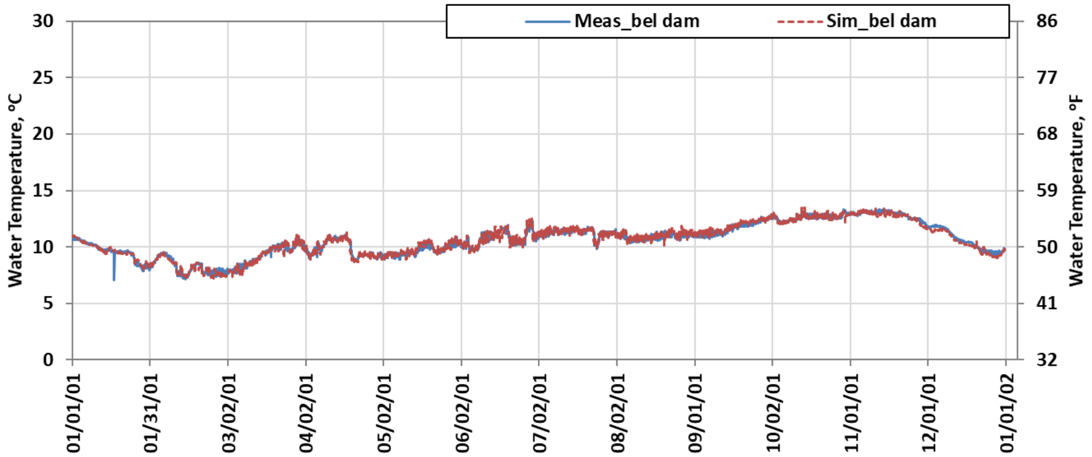


Figure E-38. Simulated versus measured temperature below Keswick Dam: 2001.

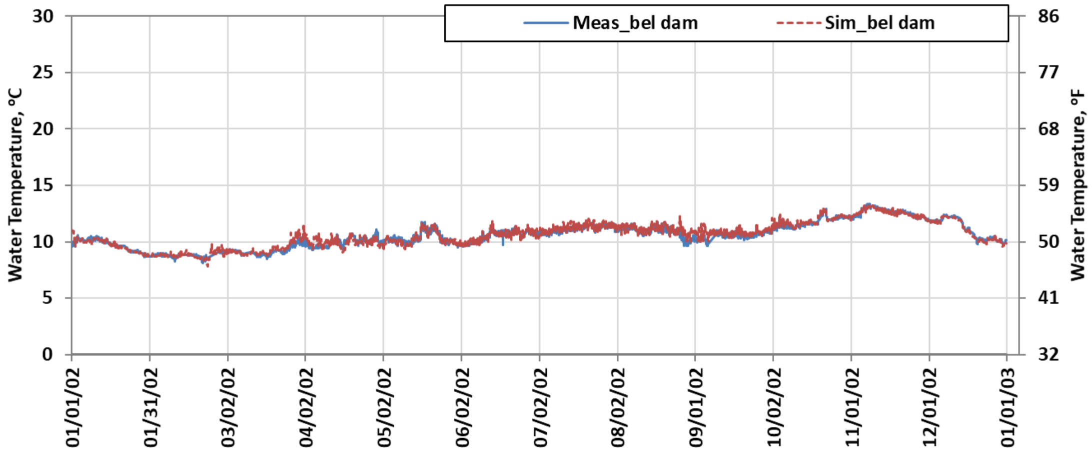


Figure E-39. Simulated versus measured temperature below Keswick Dam: 2002.

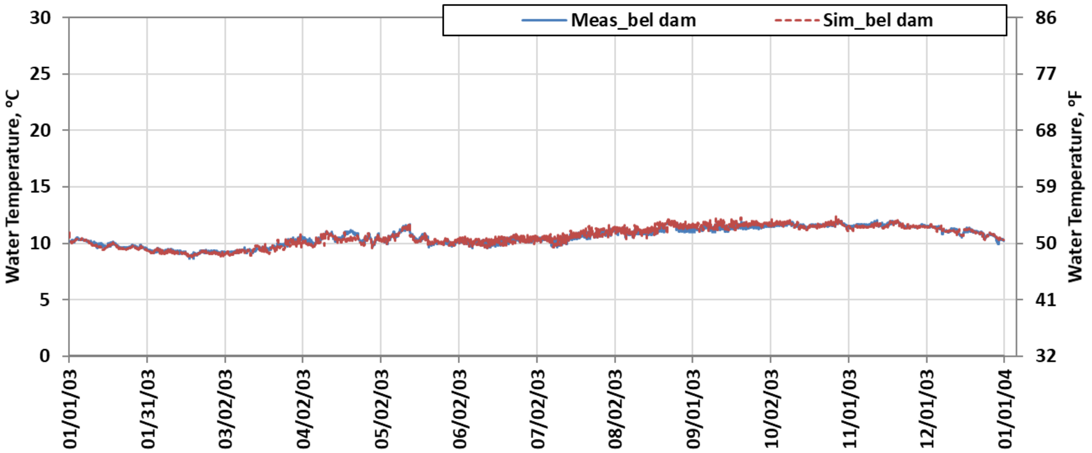


Figure E-40. Simulated versus measured temperature below Keswick Dam: 2003.

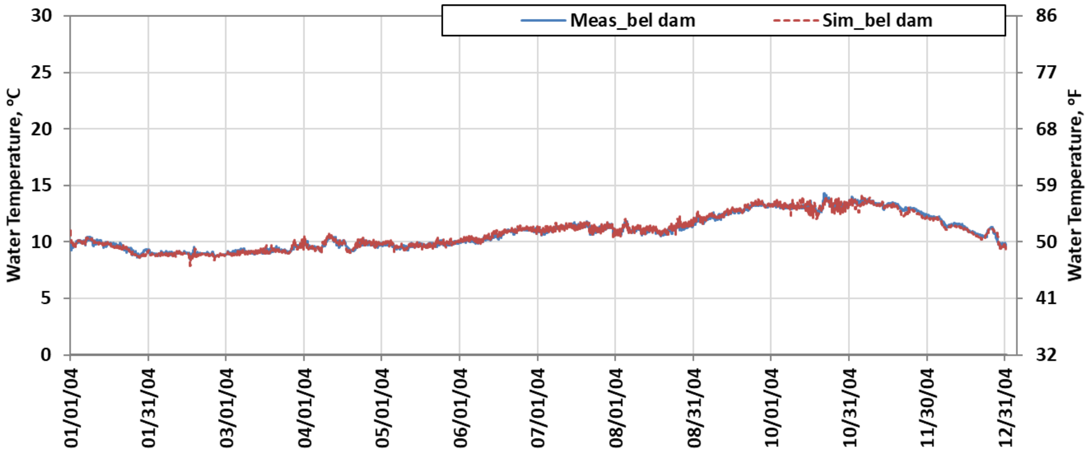


Figure E-41. Simulated versus measured temperature below Keswick Dam: 2004.

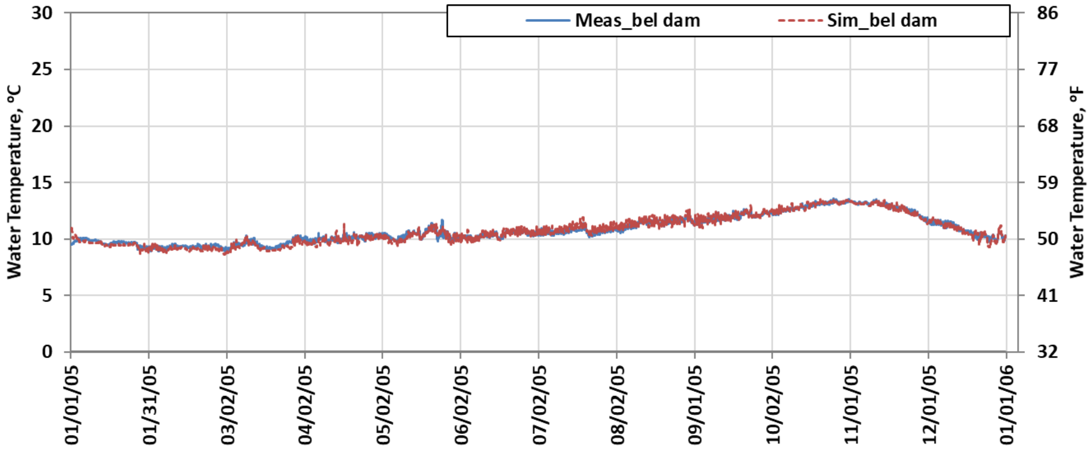


Figure E-42. Simulated versus measured temperature below Keswick Dam: 2005.

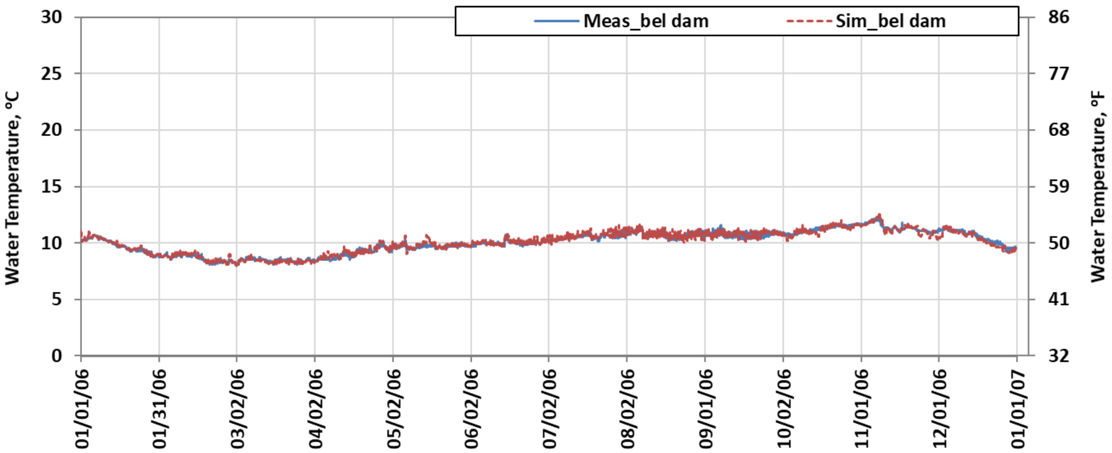


Figure E-43. Simulated versus measured temperature below Keswick Dam: 2006.

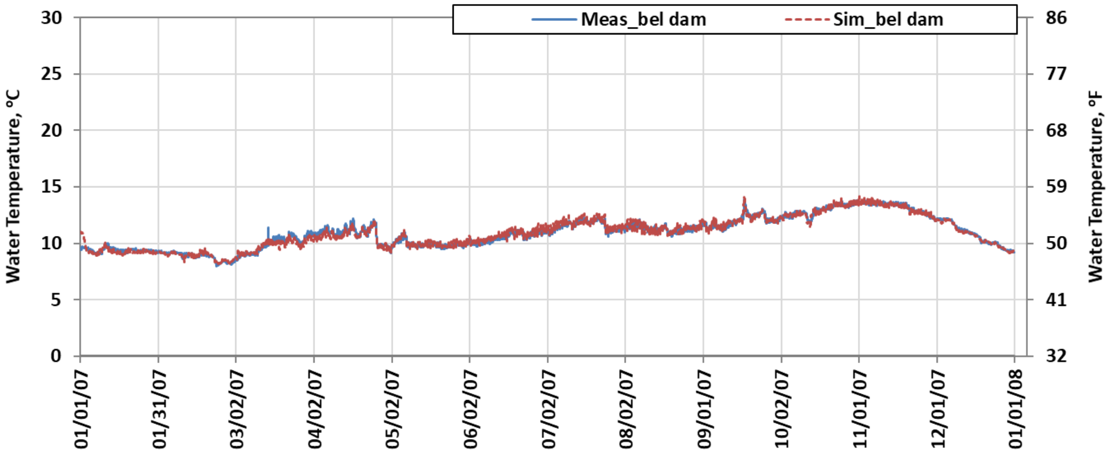


Figure E-44. Simulated versus measured temperature below Keswick Dam: 2007.

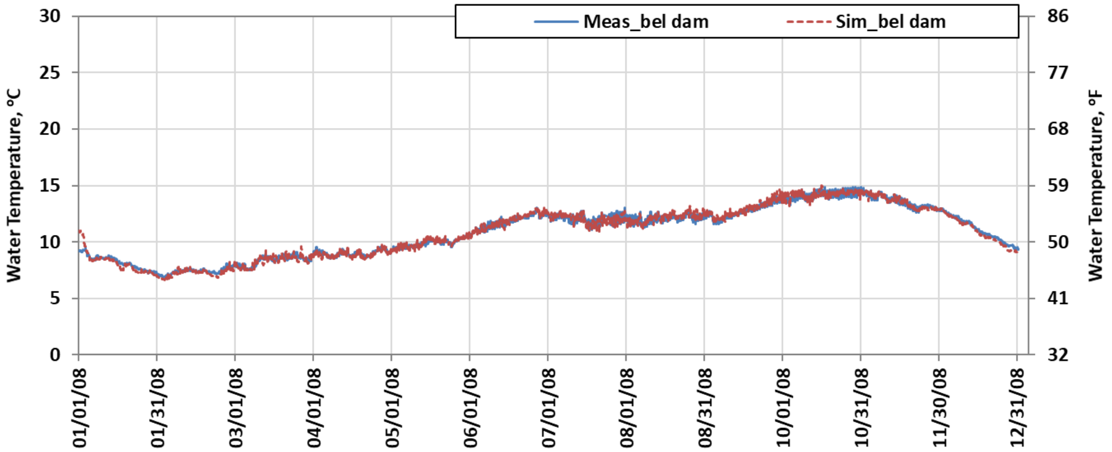


Figure E-45. Simulated versus measured temperature below Keswick Dam: 2008.

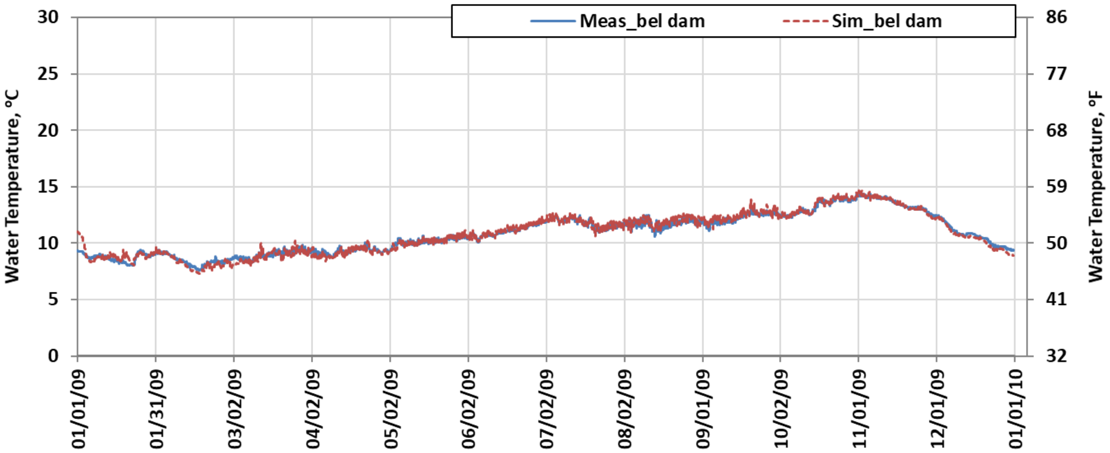


Figure E-46. Simulated versus measured temperature below Keswick Dam: 2009.

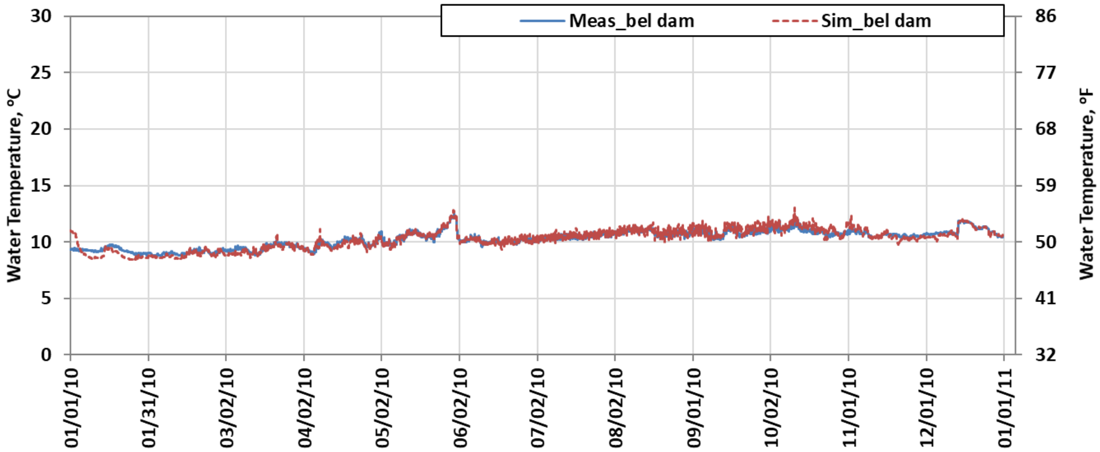


Figure E-47. Simulated versus measured temperature below Keswick Dam: 2010.

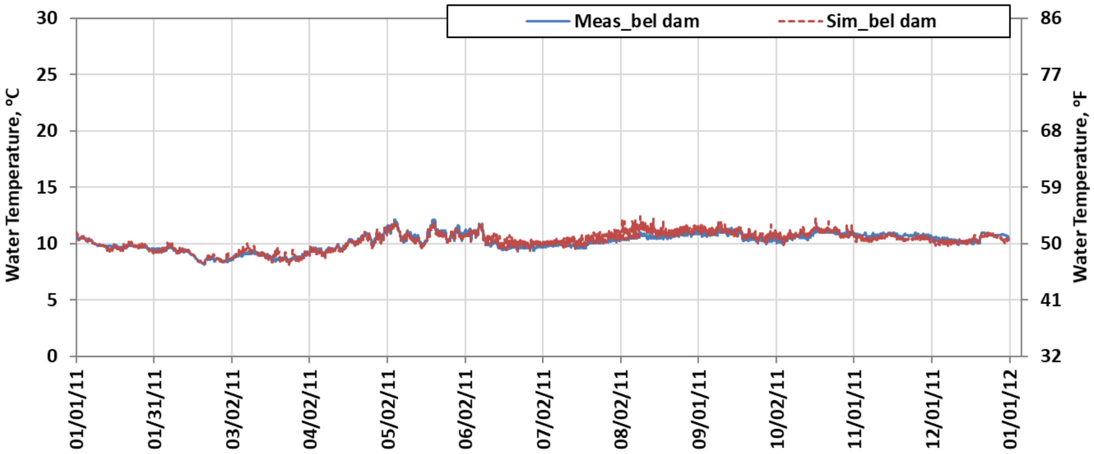


Figure E-48. Simulated versus measured temperature below Keswick Dam: 2011.

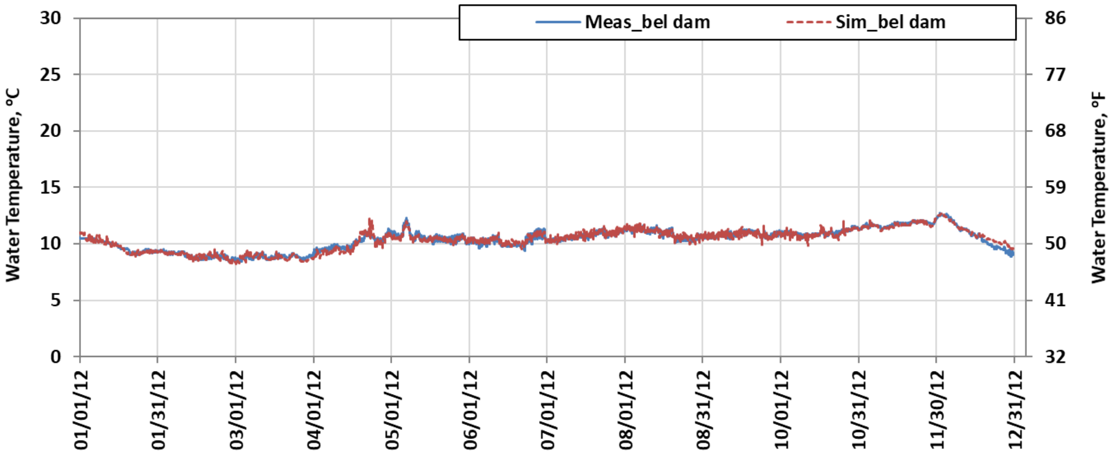


Figure E-49. Simulated versus measured temperature below Keswick Dam: 2012.

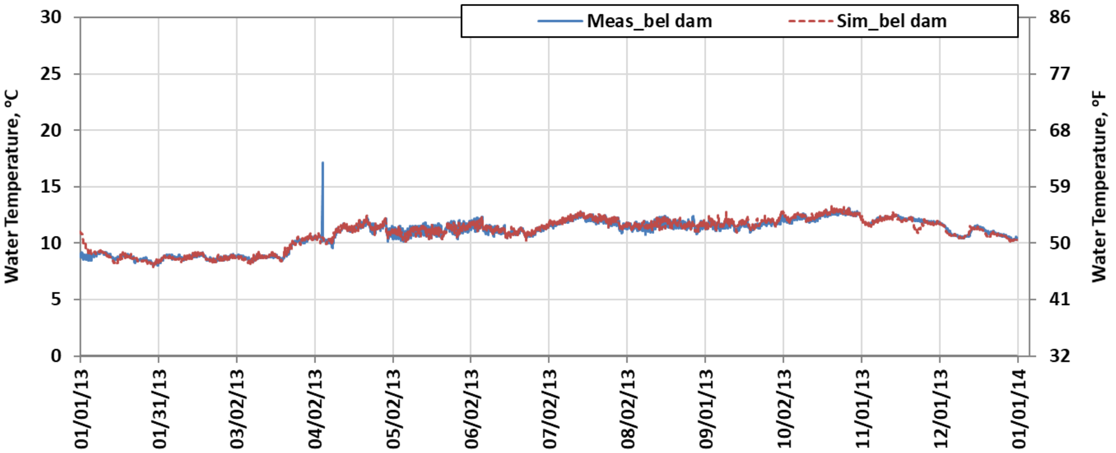


Figure E-50. Simulated versus measured temperature below Keswick Dam: 2013.

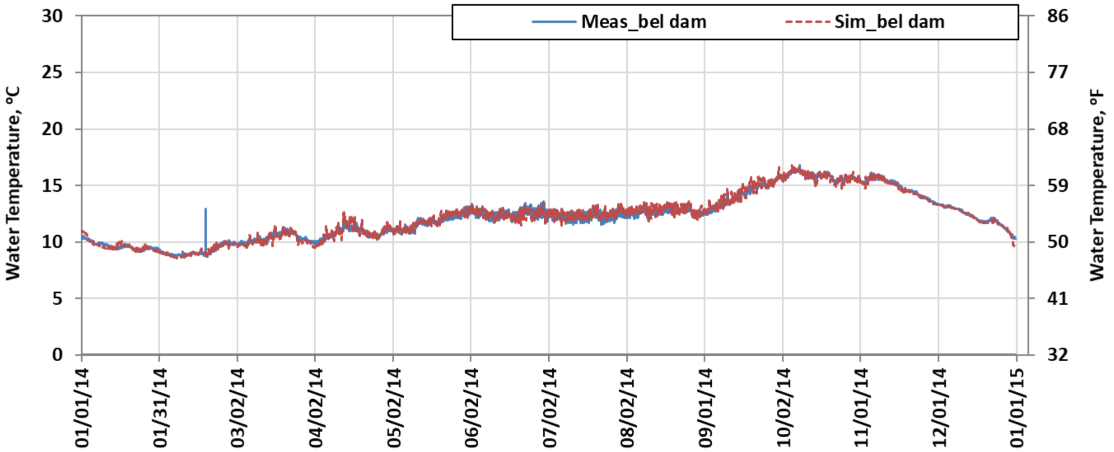


Figure E-51. Simulated versus measured temperature below Keswick Dam: 2014.

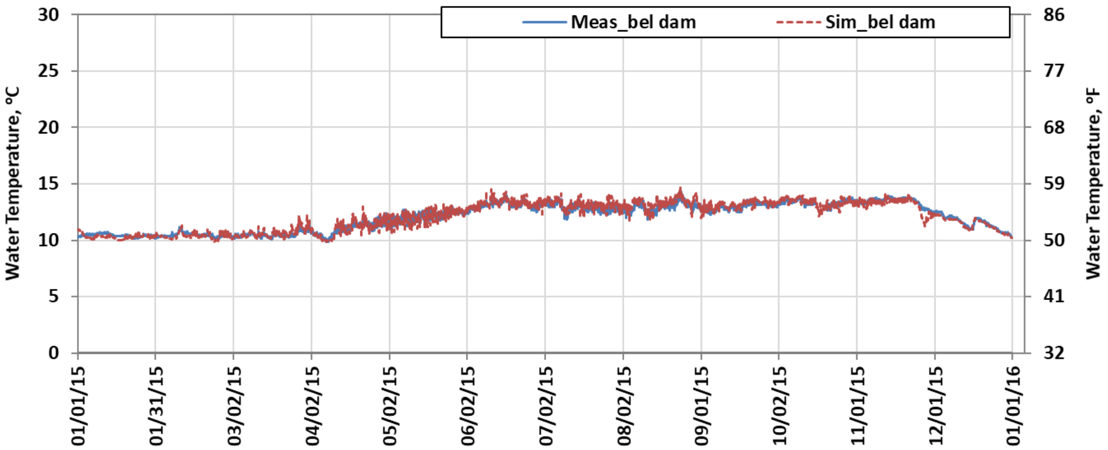


Figure E-52. Simulated versus measured temperature below Keswick Dam: 2015.

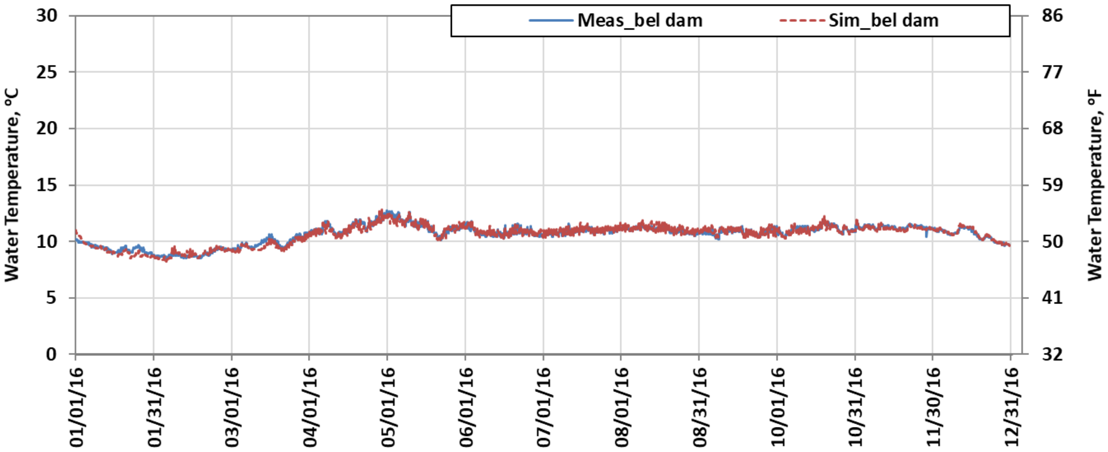


Figure E-53. Simulated versus measured temperature below Keswick Dam: 2016.

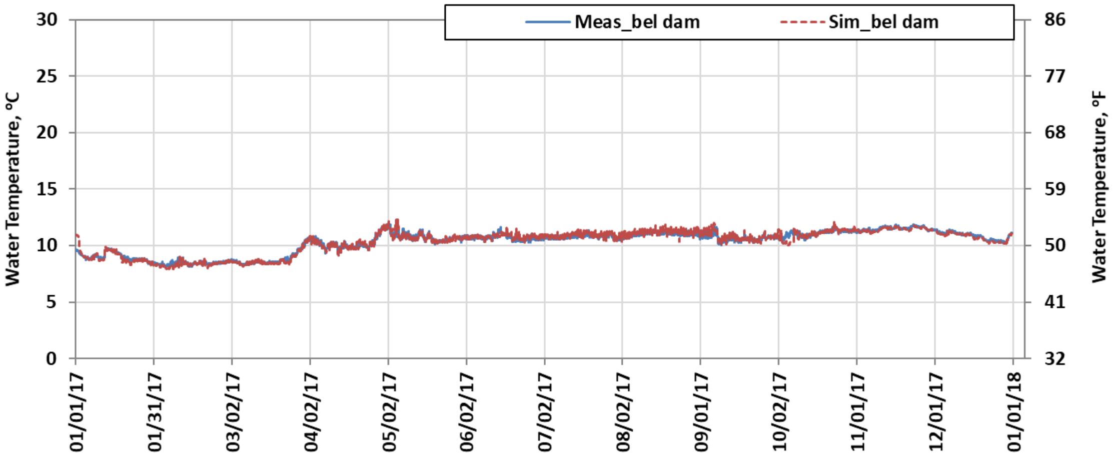


Figure E-54. Simulated versus measured temperature below Keswick Dam: 2017.

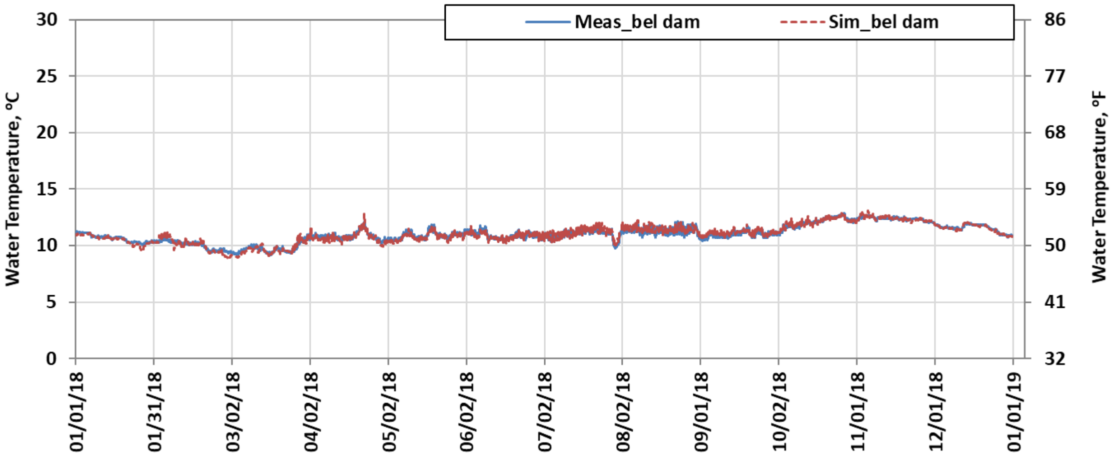


Figure E-. Simulated versus measured temperature below Keswick Dam: 2018.

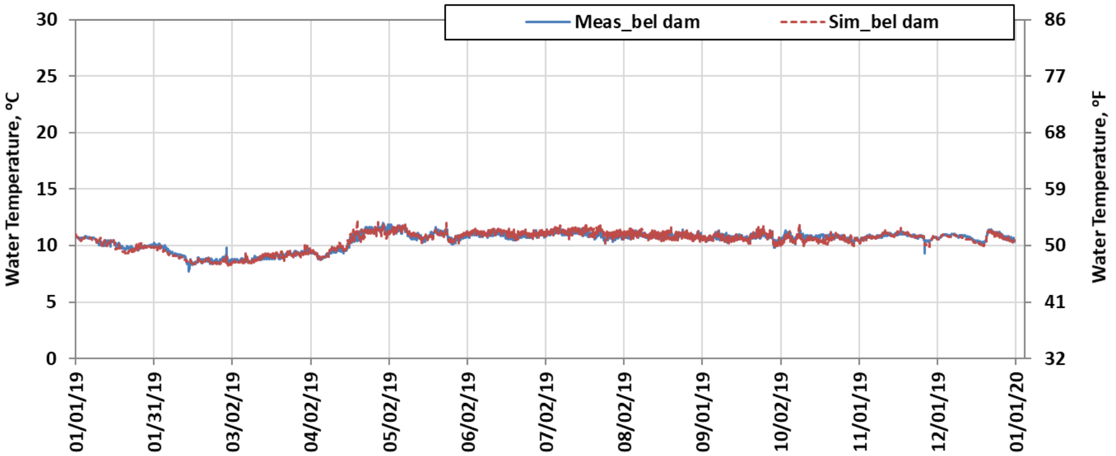


Figure E-. Simulated versus measured temperature below Keswick Dam: 2019.

Table E-3. Summary statistics of Keswick Dam outflow temperature: 2000-2019.

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