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Scientific Investigations Report 2023–5085
Version 1.1, June 2025

U.S. Department of the Interior
U.S. Geological Survey

Cover. Looking southeast at Big Cliff Dam on the North Santiam River, near Niagara, Oregon. Photograph by Brandon Overstreet, U.S. Geological Survey, April 12, 2019.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic mile (mi^3)	4.168	cubic kilometer (km^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F = (1.8 × °C) + 32.

Datums

Vertical coordinate information is referenced to National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

AgriMet	Bureau of Reclamation Cooperative Agricultural Weather Network
BCRM	Big Cliff Reservoir Model
CGRM	Cougar Reservoir Model
CWMS	Corps Water Management System
DETM	Detroit Lake Model
DTRO	Detroit Lake, Oregon AgriMet
EIS	Environmental Impact Statement
ESA	Endangered Species Act
EVC	evaporative mass loss calculation
FWSO	Foster Dam Weather Observation
GPR-FOS-M	Green Peter and Foster Lakes Model
HCLM	Hills Creek Lake Model
HCWO	Hills Creek Weather Observation station
LOP-DEX-M	Lookout Point Lake and Dexter Reservoir Model
MAE	mean absolute error
ME	mean error
MFWM	Middle Fork Willamette River Model
NOAA	National Oceanic and Atmospheric Administration
NWIS	National Water Information System
ODEQ	Oregon Department of Environmental Quality
RAWS	Remote Automated Weather Station
RM	river mile
RMSE	root mean squared error
SI	International System of Units (*Système International*)
TMDL	Total Daily Maximum Load
SRML	Solar Radiation Monitoring Laboratory
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WBAN	Weather Bureau Army Navy
WSC	wind sheltering coefficient
WVP	Willamette Valley Project

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Abstract

Mechanistic models capable of simulating hydrodynamics and water temperature in rivers and reservoirs are valuable tools for investigating thermal conditions and their relation to dam operations and streamflow in river basins where upstream water storage and management decisions have an important influence on river reaches with threatened fish populations. In particular, models allow managers to investigate how new, untried operations or hypothetical structures might influence streamflow and temperature conditions downstream. CE-QUAL-W2 is a two-dimensional (laterally averaged) hydrodynamic water-quality model that has previously been used to investigate the downstream effects of dam operations and other anthropogenic influences on stream temperature in the Willamette River Basin in northwestern Oregon, a region with two populations of fish species designated as threatened under the Endangered Species Act. By linking CE-QUAL-W2 river models to models of upstream, large Willamette Valley Project dams and reservoirs, these models can be used to investigate how dam operations at individual dams can influence streamflow and thermal conditions in downstream river reaches as an integrated system. Integrated model simulations that include the large dams and reservoirs linked to downstream river reaches can help managers develop a better understanding of tradeoffs associated with potential retrofits or operational changes across the multipurpose dams in the Willamette Valley Project, the effect of dam management on downstream tributaries and the Willamette River, and the resulting potential effect on threatened fish populations and habitat conditions.

River models capable of simulating river corridors downstream from U.S. Army Corps of Engineers dams were previously updated and integrated to simulate conditions that occurred from March through October of 2011 (a cool and wet year), 2015 (a hot and dry year), and 2016 (a moderately hot and dry year) using CE-QUAL-W2 version 4.2. These river models encompass the following:

- Coast Fork Willamette and Middle Fork Willamette Rivers, the Row River, and Fall Creek downstream from Cottage Grove, Dexter, Dorena, and Fall Creek Dams, respectively;
- South Fork McKenzie River downstream from Cougar Dam;
- McKenzie River downstream from its confluence with the South Fork McKenzie River;
- South Santiam River downstream from Foster Dam;
- North Santiam River downstream from Big Cliff Dam; and
- Willamette River from its start at the confluence of the Middle Fork Willamette and Coast Fork Willamette Rivers to Willamette Falls (river mile 26.0; near West Linn, Oregon).

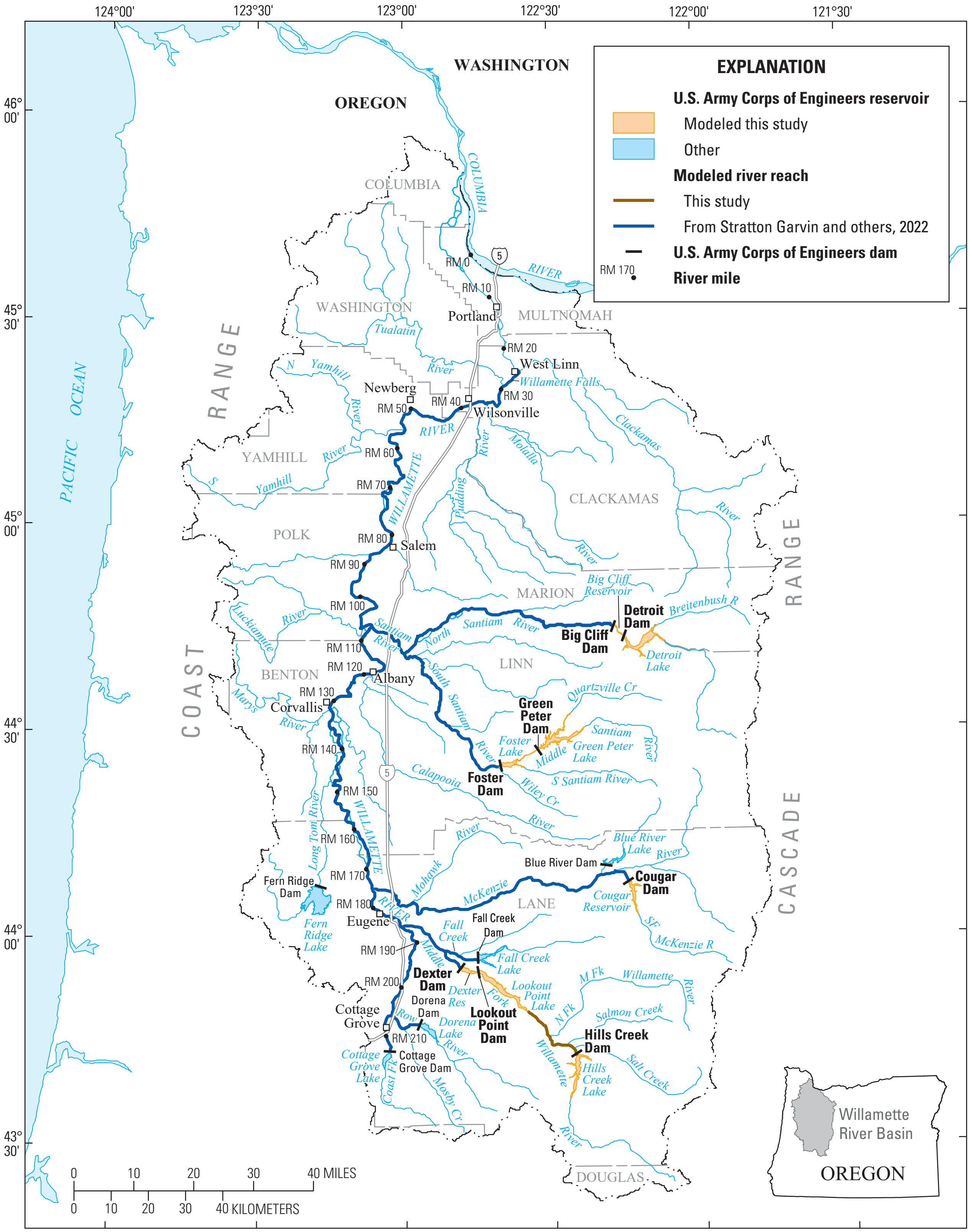
This report documents model modifications, boundary condition data sources or estimation methods, and goodness-of-fit statistics for six CE-QUAL-W2 reservoir models and one river model upstream from the existing river models. These models simulate (1) Hills Creek Lake; (2) Lookout Point Lake and Dexter Reservoir on the Middle Fork Willamette River; (3) the Middle Fork Willamette River reach between Hills Creek Dam upstream and Lookout Point Lake downstream; (4) Cougar Reservoir on the South Fork McKenzie River; (5) Green Peter Lake on the Middle Santiam River and Foster Lake on the South Santiam River; and (6) Detroit Lake and (7) Big Cliff Reservoir on the North Santiam River. These CE-QUAL-W2 models were built by a variety of researchers to simulate a range of conditions in past years; this report documents their upgrade to U.S. Geological Survey (USGS) edition 7 of version 4.2 of CE-QUAL-W2 and updates each model to simulate conditions from January through December of 2011, 2015, and 2016. Also included in this report is an explanation of modifications to the CE-QUAL-W2 source code that constitute USGS edition 7 of CE-QUAL-W2 version 4.2. Each of the models described in this report can be run in isolation or linked to downstream models as a “system model” to simulate conditions in tributaries and (or) in the Willamette Valley Project as a whole.

As part of the model updates described in this report, some model parameters were adjusted to improve stability or decrease model error, and boundary conditions including meteorological, hydrologic, and temperature inputs were developed and updated for model years 2011, 2015, and 2016, as necessary. In some cases, the data sources used to drive previous model versions were no longer available, which required the development and checking of new data sources or estimation techniques. Goodness-of-fit statistics for outflow from the dams and in simulated river reaches generally show a good model fit, with the models simulating subdaily water temperatures at most comparable locations with a mean absolute error of generally less than 1 degree Celsius (°C) and a reasonably low bias. Model simulation of the thermal vertical profiles in each reservoir also produced an overall mean absolute error of generally less than 1 °C for all 3 years, with the exception of the Hills Creek Lake Model and the Cougar Reservoir Model in years when the reservoirs did not fill (2015 and 2016). Both of these models have known calibration issues and tend to be sensitive to the choice of certain structural parameters in the model. Overall, the calibration process was focused on obtaining model settings that led to realistic water temperature predictions in all 3 years (2011, 2015, and 2016) without over-calibrating specifically to any single year. A complete investigation of model error for these reservoir submodels was beyond the scope of this investigation but could be undertaken in the future if better model performance for these two reservoirs is desired.

Introduction

The Willamette Valley Project (WVP) is a system of revetments, fish hatcheries, and 13 dams in the Willamette River Basin of northwestern Oregon operated by the U.S. Army Corps of Engineers (USACE) to provide flood risk management, irrigation, power generation, water-quality improvement, and recreational opportunities, among other authorized purposes (fig. 1). By limiting available habitat and altering the natural hydrologic and thermal regimes in the Willamette River Basin, WVP dams have negatively influenced native populations of anadromous fish, including spring-run Chinook salmon (*Oncorhynchus tshawytscha*) and winter-run steelhead (*O. mykiss*), which were designated as threatened under the Endangered Species Act (ESA) of 1973 (Public Law 93–205; 87 Stat. 884, as amended) in 1999 (National Marine Fisheries Service, 1999a, 1999b). Continuing a decades-long process, USACE began a concurrent set of assessments to evaluate and improve the conditions for threatened fish populations in the Willamette River Basin in 2019. USACE formally re-initiated consultation with National Oceanic and Atmospheric Administration (NOAA) Fisheries (formerly the National Marine Fisheries Service) on a Biological Opinion, a requirement under Section 7 of the ESA designed to help Federal agencies fulfill their duty to ensure that their actions do not jeopardize the continued existence of a species or destroy or adversely modify designated critical habitat. Concurrently, USACE moved to begin its first systemwide Environmental Impact Statement since 1980 (EIS), as required under the National Environmental Policy Act of 1969 (42 U.S.C. §§ 4321–4370m).

To better understand the thermal implications of WVP dams and their operations, including new, untested operations and hypothetical new structures, USACE requested the U.S. Geological Survey (USGS) to simulate and analyze the temperature of water released from key WVP dams and effects on river reaches downstream that might result from a variety of hypothetical management scenarios. These simulations used CE-QUAL-W2, a two-dimensional (laterally averaged) hydrodynamic and water-quality model designed for use in reservoir and river systems (Wells, 2019). CE-QUAL-W2 models of the Willamette River and key tributaries downstream from WVP dams were initially developed in the early 2000s to help the Oregon Department of Environmental Quality (ODEQ) establish a Total Daily Maximum Load (TMDL) for temperature in the Willamette River and some of its tributaries (Annear and others, 2004; Berger and others, 2004; Sullivan and Rounds, 2004; Bloom, 2016). Beginning in the early 2000s, several groups developed, with USACE support, CE-QUAL-W2 models of 8 of the 13 WVP reservoirs and a short reach of the Middle Fork Willamette River that links Hills Creek Lake and Lookout Point Lake (WEST Consultants, Inc., 2004a, 2004b, 2005; Sullivan and others, 2007; Threadgill and others, 2012; Buccola, Rounds, and others, 2013; Buccola, Stonewall, and others, 2013). These models generally include those reservoirs located on tributaries that historically supported large populations of anadromous fish, are relatively large, and can or may be managed to control the temperature of water releases. USGS has subsequently used the river models and other reservoir models to investigate a variety of management questions (for example, Buccola and others, 2015; Buccola and others, 2016; Buccola, 2017; Rounds and Stratton Garvin, 2022; Stratton Garvin and Rounds, 2022). However, the river and reservoir models had not been fully linked to allow simulation of WVP-wide management scenarios and their effects on downstream river reaches across the USACE-regulated Willamette River Basin.



Base modified from U.S. Geological Survey and other digital data sets, various scales;
Oregon Lambert Conformal Conic projection; North American Datum of 1983

Figure 1. Willamette River Basin in northwestern Oregon showing the Willamette Valley Project dams and reservoirs and the river reaches modeled in this study and in Stratton Garvin and others (2022). Modified from Stratton Garvin and others (2022).

To allow for such a systemwide analysis, USACE requested USGS to upgrade and harmonize existing CE-QUAL-W2 models of key reservoirs, downstream tributaries, and the Willamette River into a single system model capable of simulating the effects of various management scenarios at multiple WVP dams on stream temperature as far downstream as Willamette Falls (fig. 1). Additionally, an objective to simulate deep reservoir drawdowns (to near free-flowing conditions in several reservoirs) required upgrades to the CE-QUAL-W2 model code. To unify the CE-QUAL-W2 models into a single WVP system model, all individual models were updated to USGS edition 7 of version 4.2 of CE-QUAL-W2 and set up to simulate conditions representing a range of recent hydroclimatological variability, including a cool and wet year (2011), an extremely hot and dry year (2015), and a moderately hot and dry year (2016). Updates to the major river models and a discussion of conditions in the representative model years were documented by Stratton Garvin and others (2022). Updates to the reservoir models and one river model (fig. 1; table 1), as well as to the CE-QUAL-W2 model code itself, are documented in this report. By coupling reservoir with river models across the WVP, the thermal effects of various management operations (including dam operations), the sensitivity of different stream reaches to flow- and temperature-management scenarios, and their potential effects on cold-water adapted fish of the Willamette River Basin can be assessed.

Description of Study Area and Willamette Valley Project

The WVP is located in the Willamette River Basin of northwestern Oregon, an 11,500-square-mile (mi^2) basin that includes the largest metropolitan areas and most highly productive and diverse agricultural areas in the State of Oregon (Conlon and others, 2005). Bordered on the west by the Coast Range and on the east by the Cascade Range, the Willamette River Basin typically has warm, dry summers and cool, wet winters. Precipitation in the Coast Range and Willamette Valley is dominated by rain, whereas precipitation in the higher parts of the Cascade Range is dominated by snow. The Cascade Range may receive as much as 130 inches (in.) of precipitation water annually at its highest elevations (PRISM Climate Group, 2020). Streams draining the Coast Range and the relatively steep, impermeable Western Cascades geologic province tend to be highly responsive to storm events and to be relatively warm during summer; in contrast, streams draining the relatively permeable High Cascades geologic province are highly influenced by large spring complexes, with stable annual streamflow and relatively cool temperatures during summer (Tague and Grant, 2004; Tague and others, 2007; Dent and others, 2008; Rounds, 2010; Leach and others, 2017; U.S. Geological Survey, 2022). Most of the dams in the WVP are located on tributaries draining the Cascade Range (fig. 1), which contribute most of the streamflow in the Willamette River.

Table 1. CE-QUAL-W2 reservoir and river models included in this report, with associated version history and source documentation.

[Models are shown from upstream to downstream (top to bottom of table) within the Willamette River Basin. **Symbol:**—, not applicable].

Model	Relevant references	Previous model version		
		2011	2015	2016
Hills Creek Lake Model	WEST Consultants, Inc., 2004a; Buccola, Stonewall, and others, 2013; Buccola and others, 2016	3.7	—	—
Middle Fork Willamette Model	Buccola, Stonewall, and others, 2013	3.7	—	—
Lookout Point Lake and Dexter Reservoir Model	WEST Consultants, Inc., 2004b; Buccola, Stonewall, and others, 2013; Buccola and others, 2016	3.7	—	—
Cougar Reservoir Model	Threadgill and others, 2012; U.S. Army Corps of Engineers, 2019b;	—	3.7	3.7
Green Peter and Foster Lakes Model	WEST Consultants, Inc., 2005; Buccola, Stonewall, and others, 2013; Buccola, 2017; Sullivan and Rounds, 2021	4.1	—	—
Detroit Lake Model	Sullivan and others, 2007; Buccola and Rounds, 2011; Buccola, Rounds, and others, 2013; Buccola and others, 2015; Rounds and Buccola, 2015; U.S. Army Corps of Engineers, 2019c	4	4	—
Big Cliff Reservoir Model	Buccola, Rounds, and others, 2013; Buccola and others, 2015; Rounds and Buccola, 2015	—	—	—

The WVP dams are operated for flood risk management and hydropower production, among other authorized purposes. To ensure adequate available storage for winter high-flow events and to store water for hydropower production and other uses, water levels in WVP reservoirs may vary annually by about 30 meters (m) or more, according to an authorized “rule curve” that sets the target elevation for each reservoir on a given day of the year. In summer, stored water is released for downstream agricultural and municipal users and to augment streamflow in the Willamette River, which has been shown to improve water-quality conditions, including temperature, for threatened salmonids and other aquatic species (National Marine Fisheries Service, 2008; U.S. Army Corps of Engineers, 2019b). Dams in the WVP are classified by USACE as “baseload,” “power peaking,” or “reregulation” dams (U.S. Army Corps of Engineers, 2019b), depending on how they may be operated for power production. Baseload dams such as Hills Creek and Cougar Dams are typically releasing water and potentially generating power continuously. Outflow from these dams is relatively uniform from hour to hour. In contrast, power peaking dams such as Detroit, Green Peter, and Lookout Point Dams are operated to produce power mainly during those times of day when electrical demand is highest, usually in the mornings and early evenings. Releases from power peaking dams can be irregular and vary rapidly to meet changing power demands. To counteract the negative effect that these variations would have on streamflow downstream, outflows from power peaking dams are buffered by “reregulation” dams located immediately downstream. The water level in reregulation reservoirs may vary greatly and rapidly, as the available storage space within each reregulation reservoir is used to produce a more-stable streamflow downstream. Reregulation dams in the WVP include Big Cliff, Foster, and Dexter Dams downstream from Detroit, Green Peter, and Lookout Point Dams, respectively (fig. 1). More detailed descriptions of individual sub-basins and WVP dams and reservoirs are provided with the discussion of the individual models later in this report.

Purpose and Scope

This report documents model modifications, boundary condition inputs (data sources or estimation methods), and goodness-of-fit statistics for six CE-QUAL-W2 reservoir models and one river model (fig. 1) for a stream reach between two reservoirs of the WVP to simulate conditions in 2011, 2015, and 2016 using USGS edition 7 of version 4.2 of CE-QUAL-W2 (Wells, 2019; see app. 1). The models documented in this report, individually or in conjunction with the river models documented by Stratton Garvin and others (2022; these include the Coast Fork and Middle Fork Willamette River, McKenzie River, Upper Willamette River, Middle Willamette River, South Santiam River, and North Santiam-Santiam River models), have been used and may continue to be used in multiple analyses to help the USACE and other groups and agencies better understand thermal conditions in WVP reservoirs and the thermal effects of structural or operational changes to individual dams on river reaches downstream. Described from upstream to downstream within the Willamette River Basin, these models include the following:

- **Hills Creek Lake Model (HCLM).** Includes Hills Creek Lake and Hills Creek Dam. Outflow from the HCLM can be used as input to the Middle Fork Willamette River Model downstream.
- **Middle Fork Willamette River Model (MFWM).** Includes the Middle Fork Willamette River from approximately river mile (RM) 218.7 downstream to RM 206.8, the head of Lookout Point Lake. Outflow from the MFWMM can be used as inflow to the Lookout Point Lake and Dexter Reservoir Model downstream.
- **Lookout Point Lake and Dexter Reservoir Model (LOP-DEX-M).** Includes Lookout Point Lake, Lookout Point Dam, Dexter Reservoir, and Dexter Dam in a single model. Outflow from Dexter Dam can be used as input to the Middle Fork Willamette River in the Coast Fork and Middle Fork Willamette River Model documented by Stratton Garvin and others (2022).
- **Cougar Reservoir Model (CGRM).** Includes Cougar Reservoir and Cougar Dam. Outflow from the Cougar Reservoir Model can be used as input to the McKenzie River Model (which includes the South Fork McKenzie River downstream from Cougar Reservoir), as documented by Stratton Garvin and others (2022).
- **Green Peter and Foster Lakes Model (GPR-FOS-M).** Includes Green Peter Lake, Green Peter Dam, Foster Lake, and Foster Dam. Outflow from Foster Dam can be used as input to the South Santiam River Model documented by Stratton Garvin and others (2022).
- **Detroit Lake Model (DETM).** Includes Detroit Lake and Detroit Dam. Outflow from Detrpot Dam can be used as inflow to the Big Cliff Reservoir Model downstream.
- **Big Cliff Reservoir Model (BCRM).** Includes Big Cliff Reservoir and Big Cliff Dam. Outflow from Big Cliff Dam can be used as input to the North Santiam River Model documented by Stratton Garvin and others (2022).

The models described in this report were originally developed and calibrated for a range of years using different model versions by a variety of groups, including WEST Consultants, Inc.; the U.S. Army Engineer Research and Development Center; and USGS (table 1). All these models were updated from the most recent version available to USGS edition 7 of version 4.2 of CE-QUAL-W2 and, where necessary, they were set up to simulate conditions that occurred in 2011, 2015, and 2016. With minor exceptions to account for storms or other factors influencing model stability, the models run from January 1 to December 31 of those calendar years. Among other improvements, USGS edition 7 of version 4.2 improves the code controlling the wetting and drying of reservoir side branches, a critical capability for simulations to reproduce reservoir conditions during deep drawdowns in which the water level of the reservoir may become lower than the bottom elevation of a model side branch in the reservoir. The public-release version of CE-QUAL-W2 version 4.2 has been documented by Wells (2019); USGS code changes to version 4.2 were documented for USGS editions 4 and 6 by Stratton Garvin and others (2022) and Rounds and Stratton Garvin (2022), and for USGS edition 7 in appendix 1 of this report. Updated models included in this report and the executable for CE-QUAL-W2 version 4.2, USGS edition 7 are available from Stratton Garvin and others (2023; https://doi.org/10.5066/P9UJFXA5).

Terminology and Reporting Units

The units of measurement presented in this report reflect those used by streamflow and floodplain managers of the Willamette River Basin, which include a blend of International System (SI) of Units and U.S. customary units. Streamflow is given in cubic feet per second to align with the standard language used by dam operators, the original units reported by USGS streamgages, and the streamflow requirements established in the Biological Opinion (National Marine Fisheries Service, 2008). All temperatures are given in degrees Celsius. All model dimensions are provided in their original SI units, as the CE-QUAL-W2 model uses SI units. Conversion factors and equations are presented in the front matter of this report.

To help easily delineate between measured and estimated datasets used by the models, different naming conventions are used for each. Datasets derived from measured data are referred to with a station name (for example, $Q_{USGS14185000}$, indicating streamflow as measured at USGS station 14185000, South Santiam River below Cascadia, Oregon). Estimated datasets, even if derived from historical data with a station name, are referred to by their function in the model (for example, $Q_{SaltCreek}$, indicating streamflow in Salt Creek as estimated using a regression between historical measurements at USGS station 14146000, Salt Creek near Oakridge, Oregon, and several other stations).

Distances along river reaches are measured as a distance from the river mouth and termed “river miles.” All river miles (RMs) are referenced to the Willamette River unless otherwise stated. When used in reference to a streamgage or other monitoring station period of record, “present” indicates that the record was active at the time of publication.

The authors attempt to identify CE-QUAL-W2 by name in most cases, but “model” may refer to the CE-QUAL-W2 code and (or) to the individual model domains included in this report (for example, the Cougar Reservoir Model), in keeping with common usage across the modeling community.

Report Structure

This report is structured to first provide a generalized overview of CE-QUAL-W2 and the methods used to update the included models, and then to provide detailed explanations of the updates and model fits of each model. Section, “Methods and Data” provides a general introduction to CE-QUAL-W2, the various data sources or methods used to estimate streamflow or temperature conditions, a summary of updates common to all models, and an overview of calibration methods. Following section, “Methods and Data,” sub-sections within section, “Model Updates” provide detailed descriptions of each model, including a description of the model domain, model watershed, and model history, followed by a discussion of the updates made to each model and a discussion of the goodness-of-fit performance statistics. A summary and suggestions for possible future research are provided at the end of the report. Finally, a detailed discussion of updates to the model code itself is provided in appendix 1 (Code Changes for Edition 7, Version 4.2, of the CE-QUAL-W2 Model). For more detailed information on CE-QUAL-W2, readers are referred to the CE-QUAL-W2 user manual (Wells, 2019) and to previous Willamette River Basin stream temperature modeling reports (for example, Stratton Garvin and others, 2022).

Methods and Data

CE-QUAL-W2 Model

CE-QUAL-W2 is a two-dimensional (longitudinal, vertical) mechanistic model that simulates water level, streamflow, water temperature, and many water-quality constituents. The model was jointly developed by USACE and Portland State University and has been applied to a wide variety of reservoirs and rivers worldwide (Wells, 2019). For any given CE-QUAL-W2 model of a river or reservoir, the model’s spatial domain is specified as a series of “stacked boxes” that represent the average slope and cross-sectional shape of the river or reservoir at a given location. Individual “segments” (the collection of layered cells at a specific location) are grouped by the model into "branches" and then into "waterbodies," to which different model parameters and sets of boundary conditions are applied. Individual reservoirs can be modeled independently or grouped into a single CE-QUAL-W2 model. In this report, some individual models comprise a single waterbody that represents a single reservoir (for example, the Detroit Lake model), whereas in other models, multiple reservoirs are included in a single model as separate waterbodies (for example, the Green Peter and Foster Lakes Model).

CE-QUAL-W2 uses a complete heat budget in its calculations, including all incoming and outgoing environmental heat fluxes, advective energy fluxes, and a detailed representation of topographic and vegetative shading. Because it assumes lateral homogeneity but is depth-discrete, CE-QUAL-W2 is well suited to simulate long, narrow waterbodies that stratify, a condition common to many reservoirs. Reservoirs with complex geometry (for example, multiple arms) may be simulated using a set of interconnected branches of the model grid. A wide range of options for incorporating structures in the model allows the simulation of a variety of dam outlet structures ranging from spillways to diversion tunnels. Boundary conditions may be supplied at varying time steps. The internal time step of the model varies according to mass-balance and numerical stability constraints as well as user-supplied limits. Model output is user-specified and flexible, ranging from daily-averaged calculations from a specific location to subdaily output across the entire model grid.

Updated Model Parameters and Inputs

Model Grid

Each model simulation must begin with a set of initial conditions to initiate the model calculations. In the case of the water-surface elevation for each segment, the initial value is set in a model bathymetry file. For river models, which typically use a sloped grid, the initial water-surface elevation will ideally reflect conditions on the first day of the model simulation. However, because it may take some simulation time for velocity profiles to stabilize and for excess water from initial conditions to drain from the model grid, an alternative approach is to allow several days for the model to "spin up," prior to the time period of interest, after which the effect of the initial water-surface elevation will no longer be evident in the simulation results. In reservoir models, however, where internal model velocities tend to be small and both the inflow and outflow are specified, beginning the model simulation with an accurate representation of the water-surface elevation is critical to achieving a good water balance. Thus, the initial water-surface elevation for each reservoir (set as ELWS in the waterbody-specific bathymetry file) in each modeled year was set to reflect the measured water-surface elevation at the start of the simulation. No other changes were made to the model grid in any of the existing models, except to update the file format to the more-readable comma separated value (.csv) format (a new capability with CE-QUAL-W2 version 4.1; Wells, 2019).

Structures

For water to exit a CE-QUAL-W2 model, an outlet such as a spillway or structure must be specified in the model. In river models without a downstream control, water is commonly routed out of the model using a hypothetical spillway. For reservoir models, flow is more typically routed through a series of structures that can be configured to represent real structures in a dam, including an elevation, type (*point* or *line*), and width, as appropriate. The specified elevation of structures in the models used in this report were set based on a review of internal USACE as-built documentation, previous modeling reports, and internal USACE planning documentation. The number of structures included in the models and their specified elevations may differ from previous model versions but are based on the most authoritative review of historical construction documentation and confirmation of centerline-elevations completed to date (table 2). In some models, point-type outlets (instead of line-type outlets) were assigned widths in CE-QUAL-W2. These were left as artifacts of previous modeling efforts but outlet widths are ignored by CE-QUAL-W2 for point outlets. Some outlets included in the models did not have any flow routed through them in the baseline model simulations but may be used in future analyses. Some outlets included in the models have not been constructed but are included as part of the USACE planning process. Individual changes to models are documented with discussion of each model in section, "Model Updates."

Evaporation

The lake-surface evaporative mass loss calculation (EVC in the model) was turned on for consistency across all reservoir models. This calculation specifies whether evaporative mass loss is included in the water budget; heat loss from evaporation is always calculated and included in the heat budget by CE-QUAL-W2, regardless of the EVC setting. Calculation of water lost to evaporation generally tended to improve the model goodness-of-fit statistics by a few thousandths of a degree Celsius when compared to excluding it.

Table 2. Outlet structures for each dam included in CE-QUAL-W2 models, northwestern Oregon.

[All elevations are centerline except spillways, which are crest elevations. Elevations are implemented by CE-QUAL-W2 in meters, but most original documentation (as-built documents, for example) shows elevation in feet. Structures are ordered in the table from highest to lowest elevation but implementation in CE-QUAL-W2 may not retain this order (STR3 may be higher than STR1). Structure elevations may differ from previous documentation. Elevations are specific to as-built diagrams for each dam site. **Abbreviations:** BCRM, Big Cliff Reservoir Model; BR, branch; CGRM, Cougar Reservoir Model; DETM, Detroit Lake Model; EBOT, bottom elevation of the model waterbody; FSS, floating screen structure; GPR-FOS-M, Green Peter and Foster Lakes Model; HCLM, Hills Creek Lake Model; HIW, high intake weir; LIG, low intake gate; LOP-DEX-M, Lookout Point Lake and Dexter Reservoir Model; STR, structure; RO, regulating outlet; SWS, selective withdrawal structure; WTCT, water temperature control tower]

CE-QUAL-W2 model	Dam	EBOT (feet)	EBOT (meters)	Outlet name	CE-QUAL-W2 outlet designation	Structure type	Width (meters)	Elevation (feet)	Elevation (meters)
HCLM	Hills Creek	1,256.6	383.0	Spillway crest	BR1 STR3	Line	25.0	1,495.5	455.8
				ROs	BR1 STR1	Line	6.0	1,415.0	431.3
				Power penstock	BR1 STR2	Line	5.8	1,390.0	423.7
LOP-DEX-M	Lookout Point	691.3	210.7	Spillway crest	BR1 STR1	Line	75.7	887.5	270.5
				Power penstock	BR1 STR2	Line	19.0	780.0	237.7
				ROs	BR1 STR3	Line	4.0	729.3	222.3
	Dexter	641.4	195.5	Spillway crest	BR2 STR1	Line	93.9	660.0	201.2
				Power penstock	BR2 STR2	Point	[1]0	650.4	198.2
CGRM	Cougar	1,315.9	401.1	Top of WTCT	BR1 STR1	Point	[1]0	1,680.0	512.1
				ROs	BR1 STR2	Point	[1]0	1,485.0	452.6
				WTCT “leak” 1	BR1 STR3	Point	[1]0	1,640.3	500.0
				WTCT “leak” 2	BR1 STR4	Point	[1]0	1,600.6	487.9
				WTCT “leak” 3	BR1 STR5	Point	[1]0	1,561.0	475.8
				Power penstock	BR1 STR6	Point	[1]0	1,424.8	434.3
				Diversion tunnel	BR1 STR7	Point	[1]0	1,300.0	396.2
GPR-FOS-M	Green Peter	718.2	218.9	Spillway crest	BR1 STR1	Line	50.0	968.7	295.3
				Power penstock	BR1 STR2	Point	[1]4.3	810.0	246.9
				ROs	BR1 STR3	Point	[1]3.0	750.0	228.6
	Foster	533.5	162.6	Fish weir	BR7 STR2	Point	[1]1	633.5	193.1
				Hatchery intake (upper)	BR7 STR1	Point	[1]13.7	630.0	192.0
				Adult fish facility intake (upper)	BR7 STR3	Point	[1]2	599.3	182.9
				Spillway crest	BR7 STR4	Line	41.2	596.8	181.9
				Power penstock	BR7 STR5	Point	[1]3.8	590.0	179.8
				Adult fish facility intake (lower)	BR7 STR6	Point	[1]2	584.3	178.3
				Hatchery intake (lower)	BR7 STR7	Point	[1]1	576.0	175.6

Table 2. Outlet structures for each dam included in CE-QUAL-W2 models, northwestern Oregon.—Continued

[All elevations are centerline except spillways, which are crest elevations. Elevations are implemented by CE-QUAL-W2 in meters, but most original documentation (as-built documents, for example) shows elevation in feet. Structures are ordered in the table from highest to lowest elevation but implementation in CE-QUAL-W2 may not retain this order (STR3 may be higher than STR1). Structure elevations may differ from previous documentation. Elevations are specific to as-built diagrams for each dam site. **Abbreviations:** BCRM, Big Cliff Reservoir Model; BR, branch; CGRM, Cougar Reservoir Model; DETM, Detroit Lake Model; EBOT, bottom elevation of the model waterbody; FSS, floating screen structure; GPR-FOS-M, Green Peter and Foster Lakes Model; HCLM, Hills Creek Lake Model; HIW, high intake weir; LIG, low intake gate; LOP-DEX-M, Lookout Point Lake and Dexter Reservoir Model; STR, structure; RO, regulating outlet; SWS, selective withdrawal structure; WTCT, water temperature control tower]

CE-QUAL-W2 model	Dam	EBOT (feet)	EBOT (meters)	Outlet name	CE-QUAL-W2 outlet designation	Structure type	Width (meters)	Elevation (feet)	Elevation (meters)
DETM	Detroit	1,194.2	364.0	Spillway crest	BR1 STR2	Line	25.0	1,541.0	469.7
				SWS HIW	BR1 STR5	Line	25.0	1,410.1	429.8
				FSS 1	BR1 STR6	Line	25.0	1,410.1	429.8
				FSS 2	BR1 STR7	Line	25.0	1,410.1	429.8
				FSS 3	BR1 STR8	Line	25.0	1,410.1	429.8
				Power penstock	BR1 STR3	Line	6.8	1,403.0	427.6
				Upper RO	BR1 STR1	Line	6.8	1,345.0	410.0
				SWS LIG	BR1 STR9	Line	6.8	1,332.0	406.0
				Lower RO	BR1 STR4	Line	6.8	1,270.0	387.1
BCRM	Big Cliff	1,115.5	340.0	Spillway crest	BR2 STR2	Line	30.0	1,161.5	354.0
				Power Penstock	BR1 STR1	Line	6.1	1,140.0	347.5

[1]Width values may be specified for point outlet structures, but the value is ignored by CE-QUAL-W2.

Boundary Conditions

CE-QUAL-W2 requires temporal boundary conditions for six meteorological parameters along with flow and water temperature for all water inputs to the model. Ideally, these data are available from measured sources, but given the variety and number of data inputs required by CE-QUAL-W2, boundary conditions must often be estimated. Data sources used in the models, whether directly as a boundary condition or as a dataset used in the estimation of a boundary condition, are shown in table 3 and figure 2. All datasets were screened for missing values and outliers. Missing values generally were filled through interpolation, by using records from similar stations, or by using data from adjacent dates, as available and as appropriate for the dataset in question. Missing values typically spanned a few days or weeks, but there were a few instances where interpolation of missing data spanned longer periods (as much as several months). The source data used to develop the boundary conditions are in table 3, and final boundary conditions used in the model simulations are available from Stratton Garvin and others (2023).

Meteorology

CE-QUAL-W2 requires air temperature, dew-point temperature, wind speed, wind direction, cloud cover, and solar radiation (optional, but generally preferred) as meteorological inputs for each waterbody in the model. All data sources were checked for missing data, and outliers, subsampled as necessary, were interpolated to the top of the hour, and converted to the SI units required by CE-QUAL-W2. When not reported, dew-point temperature was estimated using air temperature and relative humidity (after Lawrence, 2005; Buccola, Stonewall, and others, 2013). All models used reported cloud cover from either Weather Bureau Army Navy (WBAN) 24221 (Eugene Mahlon Sweet Field) or WBAN 24232 (Salem Airport McNary Field), which was converted from reported eighths (“oktas”) to the tenths scale used by CE-QUAL-W2 (see methodology described by Stratton Garvin and others, 2022).

Although data from weather stations located at each dam (or set of dams) were generally available, in some cases other records collected farther from the model domain provided a more reliable data source and a better model fit. Wind speed from weather stations located at dams has been noted to be subject to updrafts and tends to not be representative of conditions across the reservoir (WEST Consultants, Inc., 2004a, 2004b; Buccola, Stonewall, and others, 2013). Meteorological data sources are listed in table 4 and shown in figure 2.

Precipitation is an optional input in CE-QUAL-W2. When turned on, the model requires rate and temperature of precipitation (in meters per second and degrees C, respectively). Precipitation was imposed in all reservoir models but not in the riverine MFWM model for consistency with other river models in the Willamette River domain and because precipitation is less important for a river model than a reservoir model given the smaller surface area. Data were mostly sourced from the weather stations located at the dams and converted from in. per 15 minutes to meters per second at 15-minute time steps. Specific data sources are listed in table 4.

Streamflow

Time series of streamflow data were sourced mostly from USGS streamgages and accessed through the USGS National Water Information System (NWIS; U.S. Geological Survey 2022) or from USACE databases accessible through their online portal DataQuery 2.0; all individual data sources are listed in table 3. Where data sources were unavailable, boundary conditions were estimated. In most cases, equations to estimate streamflow at certain locations were developed at the same time as the initial development of the models. For example, Buccola, Stonewall, and others (2013) developed multiple linear regressions using selected gaged streams in the region, with an effort to represent similar climatological and topographical conditions where possible and to capitalize on the most overlap in record. To minimize any bias from the movement of weather patterns, streamgage records used to estimate inflows were selected from the available records in all directions. These streamflow estimation equations were not consistently reported in Buccola, Stonewall, and others (2013); where these equations were archived and accessible, they are used and reported here. Where preexisting equations were not available, individual data-measurement stations had been discontinued, or alternate estimation methods produced a better model fit, new equations were used. All streamflow estimation equations used in updating the models are reported in individual report subsections that follow. These equations generally rely on a watershed-area-ratio method or regression-based approaches that use overlapping datasets to predict the streamflow of a tributary using records from other tributaries. The watershed-area-ratio method generally is used where no streamgage record exists and scales a streamflow time series according to the difference in watershed area between the location of the available dataset and the location of interest.

Downstream releases from all simulated reservoirs are controlled by downstream flow boundary conditions in which outflow from the model is specified as a total outflow rate through the structures specified in the model. Total outflow and flow rates through individual structures in each dam were provided by USACE in a daily time step from the Corps Water Management System (CWMS) database. These outlet-specific flow rates were applied to all dams except Cougar Dam, which used the selective withdrawal algorithm in CE-QUAL-W2, as described in section, “Methods and Data—Boundary Conditions—Selective Withdrawal and Temperature Targets.”

Table 3. Sources for all data input to the models documented in this report.

[**Data type:** "Temperature" refers to water temperature. **Model use:** "Supporting" indicates that the data source was used to estimate a boundary condition. **Source:** Web address or other citation information indicated in "Source" is available in the report References Cited section. **Source:** CWMS data are available from Dataquery 2.0 but were provided internally by USACE. USGS data from U.S. Geological Survey (2022). **Period of record:** "present" indicates that the streamgage or monitoring station was actively collecting data at the time of publication. Precision of listed period of record is as reported from the data source. **Map number:** Map location numbers correspond to numbers on figure 2. "—" (no map number) indicates that the data source is outside the mapped basin boundary. **Abbreviations:** AgriMet, Bureau of Reclamation Cooperative Agricultural Weather Network; AQWMS, Ambient Water Quality Monitoring System; BCRM, Big Cliff Reservoir Model; BOR, Bureau of Reclamation; CGRM, Cougar Reservoir Model; CWMS, Corps Water Management System; DETM, Detroit Lake Model; DRI, Desert Research Institute; GPR-FOS-M, Green Peter Lakeand Foster Reservoir Model; HCLM, Hills Creek Lake Model; LCD, Local Climatological Data; LOP-DEX-M, Lookout Point Lake and Dexter Reservoir Model; OR, Oregon; MFWM, Middle Fork Willamette River; NA, not applicable; NOAA, National Oceanic and Atmospheric Administration; mm-dd-yyyy, month, day, year; NWIS, U.S. Geological Survey National Water Information System; ODEQ, Oregon Department of Environmental Quality; RAWS, Remote Automated Weather Station; SRML, Solar Radiation Monitoring Laboratory; USACE, U.S. Army Corps of Engineers; USGS, U.S. Geological Survey; UO, University of Oregon; WBAN, Weather Bureau Army Navy, a weather station designation; WRCC, Western Regional Climate Center; yyyy, year]

Data type	Monitoring station	Model use	Agency	Source	Period of record (yyyy; mm-dd-yyyy)	Model	Map number
Flow	HCLM inflow (modeled)	Supporting	USACE	CWMS	1970–present	HCLM	—
Flow	CGRM inflow (modeled)	Supporting	USACE	CWMS	1969–present	CGRM	NA (estimated)
Flow	USGS 14146000, Salt Creek near Oakridge, OR	Supporting	USGS	NWIS	07-01-1913–09-29-1951	MFWM	1
Flow	USGS 14185000, South Santiam River below Cascadia, OR	Boundary condition, supporting	USGS	NWIS	09-01-1935–present	MFWM, HCLM, GPR-FOS-M	2
Flow	USGS 14325000, South Fork Coquille River at Powers, OR	Supporting	USGS	NWIS	10-01-1916–present	MFWM	—
Flow	USGS 14301500, Wilson River near Tillamook, OR	Supporting	USGS	NWIS	12-01-1914–present	MFWM, HCLM	—
Flow	USGS 14178000, North Santiam River below Boulder Creek, near Detroit, OR	Supporting	USGS	NWIS	01-01-1907–present	MFWM, HCLM, DETM	3
Flow	USGS 14316700, Steamboat Creek near Glide, OR	Supporting	USGS	NWIS	10-01-1956–present	HCLM	—
Flow	USGS 14171000, Marys River near Philomath, OR	Supporting	USGS	NWIS	10-01-1940–present	HCLM	4
Flow	USGS 14145500, Middle Fork Willamette River above Salt Creek, near Oakridge, OR	Calibration	USGS	NWIS	10-01-1913–present	MFWM	5
Flow	USGS 14146500, Salmon Creek near Oakridge, OR	Supporting	USGS	NWIS	02-01-1913–01-03-1994	MFWM	6
Flow	USGS 14190500, Luckiamute River near Suver, OR	Supporting	USGS	NWIS	08-01-1905–present	MFWM	7
Flow	USGS 14147500, North Fork of the Middle Fork Willamette River near Oakridge, OR	Supporting	USGS	NWIS	10-01-1909–09-30-1994	MFWM	8
Flow	USGS 14148000, Middle Fork Willamette River below North Fork, near Oakridge, OR	Calibration	USGS	NWIS	10-01-1986–present	MFWM, LOP-DEX-M	9

Table 3. Sources for all data input to the models documented in this report.—Continued

[**Data type:** "Temperature" refers to water temperature. **Model use:** "Supporting" indicates that the data source was used to estimate a boundary condition. **Source:** Web address or other citation information indicated in "Source" is available in the report References Cited section. **Source:** CWMS data are available from Dataquery 2.0 but were provided internally by USACE. USGS data from U.S. Geological Survey (2022). **Period of record:** "present" indicates that the streamgage or monitoring station was actively collecting data at the time of publication. Precision of listed period of record is as reported from the data source. **Map number:** Map location numbers correspond to numbers on figure 2. "—" (no map number) indicates that the data source is outside the mapped basin boundary. **Abbreviations:** AgriMet, Bureau of Reclamation Cooperative Agricultural Weather Network; AQWMS, Ambient Water Quality Monitoring System; BCRM, Big Cliff Reservoir Model; BOR, Bureau of Reclamation; CGRM, Cougar Reservoir Model; CWMS, Corps Water Management System; DETM, Detroit Lake Model; DRI, Desert Research Institute; GPR-FOS-M, Green Peter Lakeand Foster Reservoir Model; HCLM, Hills Creek Lake Model; LCD, Local Climatological Data; LOP-DEX-M, Lookout Point Lake and Dexter Reservoir Model; OR, Oregon; MFWM, Middle Fork Willamette River; NA, not applicable; NOAA, National Oceanic and Atmospheric Administration; mm-dd-yyyy, month, day, year; NWIS, U.S. Geological Survey National Water Information System; ODEQ, Oregon Department of Environmental Quality; RAWS, Remote Automated Weather Station; SRML, Solar Radiation Monitoring Laboratory; USACE, U.S. Army Corps of Engineers; USGS, U.S. Geological Survey; UO, University of Oregon; WBAN, Weather Bureau Army Navy, a weather station designation; WRCC, Western Regional Climate Center; yyyy, year]

Data type	Monitoring station	Model use	Agency	Source	Period of record (yyyy; mm-dd-yyyy)	Model	Map number
Flow	USGS 14144800, Middle Fork Willamette River near Oakridge, OR	Supporting	USGS	NWIS	10-01-1958–09-30-1997	HCLM	10
Flow	USGS 14318000, Little River at Peel, OR	Supporting	USGS	NWIS	10-01-1954–present	HCLM	—
Flow	USGS 14144900, Hills Creek above Hills Creek Reservoir, near Oakridge, OR	Supporting	USGS	NWIS	10-01-1958–09-29-1981	HCLM	11
Flow	USGS 14179000 Breitenbush River above French Creek, near Detroit	Boundary condition	USGS	NWIS	10-01-1998–present	DETM	12
Flow	USGS 14180300, Blowout Creek near Detroit, OR	Boundary condition	USGS	Data Grapher	10-01-1998–present	DETM	13
Flow	USGS 14185900, Quartzville Creek near Cascadia, OR	Boundary condition, supporting	USGS	NWIS	08-01-1963–present	GPR-FOS-M	14
Flow	USGS 14185700, Middle Santiam River near Upper Soda, OR	Supporting	USGS	NWIS	10-01-1988–05-25-1994	GPR-FOS-M	15
Flow	USGS 14159200, South Fork McKenzie River above Cougar Lake near Rainbow, OR	Boundary condition	USGS	NWIS	10-01-2000–present	CGRM	16
Meteorology	WBAN 24221, Eugene Airport Mahlon Sweet Field	Boundary condition	NOAA	LCD	01-01-1948–present	MFWM	17
Meteorology	WBAN 24232, Salem Airport McNary Field	Boundary condition	NOAA	LCD	01-01-1948–present	DETM, BCRM	18
Meteorology	Eugene SRML	Boundary condition	UO	SRML	1975–1995	HCLM, MFWM	19
Meteorology	CGWO, Cougar Dam Weather Observation station	Boundary condition	USACE	Dataquery 2.0	2004–present	CGRM	20
Meteorology	LPWO, Lookout Point Dam Weather Observation station	Boundary condition	USACE	Dataquery 2.0	2004–present	MFWM	21
Meteorology	FSWO, Foster Dam Weather Observation station	Boundary condition	USACE	Dataquery 2.0	2004–present (precipitation 1998–present)	GPR-FOS-M	22

Table 3. Sources for all data input to the models documented in this report.—Continued

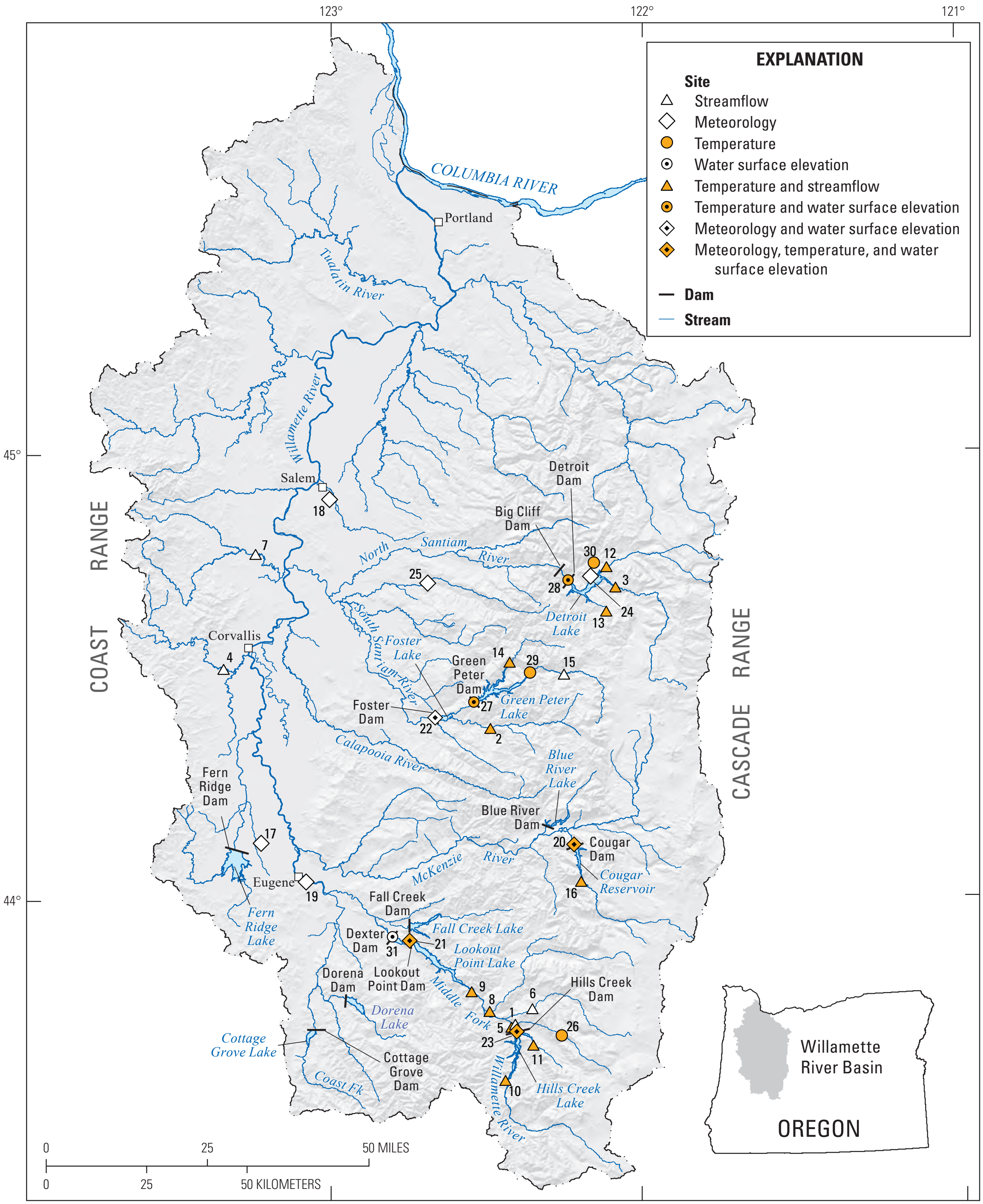
[**Data type:** “Temperature” refers to water temperature. **Model use:** “Supporting” indicates that the data source was used to estimate a boundary condition. **Source:** Web address or other citation information indicated in “Source” is available in the report References Cited section. **Source:** CWMS data are available from Dataquery 2.0 but were provided internally by USACE. USGS data from U.S. Geological Survey (2022). **Period of record:** “present” indicates that the streamgage or monitoring station was actively collecting data at the time of publication. Precision of listed period of record is as reported from the data source. **Map number:** Map location numbers correspond to numbers on figure 2. “—” (no map number) indicates that the data source is outside the mapped basin boundary. **Abbreviations:** AgriMet, Bureau of Reclamation Cooperative Agricultural Weather Network; AQWMS, Ambient Water Quality Monitoring System; BCRM, Big Cliff Reservoir Model; BOR, Bureau of Reclamation; CGRM, Cougar Reservoir Model; CWMS, Corps Water Management System; DETM, Detroit Lake Model; DRI, Desert Research Institute; GPR-FOS-M, Green Peter Lakeand Foster Reservoir Model; HCLM, Hills Creek Lake Model; LCD, Local Climatological Data; LOP-DEX-M, Lookout Point Lake and Dexter Reservoir Model; OR, Oregon; MFWM, Middle Fork Willamette River; NA, not applicable; NOAA, National Oceanic and Atmospheric Administration; mm-dd-yyyy, month, day, year; NWIS, U.S. Geological Survey National Water Information System; ODEQ, Oregon Department of Environmental Quality; RAWS, Remote Automated Weather Station; SRML, Solar Radiation Monitoring Laboratory; USACE, U.S. Army Corps of Engineers; USGS, U.S. Geological Survey; UO, University of Oregon; WBAN, Weather Bureau Army Navy, a weather station designation; WRCC, Western Regional Climate Center; yyyy, year]

Data type	Monitoring station	Model use	Agency	Source	Period of record (yyyy; mm-dd-yyyy)	Model	Map number
Meteorology	HCWO, Hills Creek Dam Weather Observation station	Boundary condition	USACE	Dataquery 2.0	2004–present	HCLM	23
Meteorology	DTRO, Detroit Lake, Oregon	Boundary condition	BOR	AgriMet	9-26-2002–present	DETM, BCRM	24
Meteorology	RAWS Jordan	Boundary condition	WRCC	DRI RAWS	2005–present	GPR-FOS-M	25
Temperature	USGS 14159200, South Fork McKenzie River above Cougar Lake near Rainbow, OR	Boundary condition	USGS	NWIS	10-01-2007–present	CGRM	16
Temperature	28007-ORDEQ, Salt Creek at Road 5875	Supporting	ODEQ	AQWMS	06-07-2001–09-30-2001	HCLM, MFWM	26
Temperature	Hills Creek Lake temperature string	Calibration	USACE	Dataquery 2.0	2010–present	HCLM	23
Temperature	Lookout Point Lake temperature string	Calibration	USACE	Dataquery 2.0	2010–present	LOP-DEX-M	21
Temperature	Green Peter Lake temperature string	Calibration	USACE	Dataquery 2.0	2010–present	GPR-FOS-M	27
Temperature	Cougar Reservoir temperature string	Calibration	USACE	Dataquery 2.0	2010–present	CGRM	20
Temperature	Detroit Lake temperature string	Calibration	USACE	Dataquery 2.0	2010–present	DETM	28
Temperature	USGS 14144800, Middle Fork Willamette River near Oakridge, OR	Boundary condition	USGS	NWIS	07-23-2010–present	HCLM	10
Temperature	USGS 14144900, Hills Creek above Hills Creek Reservoir, near Oakridge, OR	Boundary condition; supporting	USGS	NWIS	06-17-2010–present	HCLM	11
Temperature	USGS 14178000, North Santiam River below Boulder Creek, near Detroit OR	Supporting	USGS	NWIS	10-01-2007–present	HCLM, MFWM, DETM	3
Temperature	USGS 14180300, Blowout Creek near Detroit, OR	Boundary condition; supporting	USGS	Data Grapher	10-09-1998–present	HCLM, MFWM, DETM	13
Temperature	USGS 14145500, Middle Fork Willamette above Salt Creek, near Oakridge, OR	Calibration	USGS	NWIS	10-01-2008–present	HCLM, MFWM	5
Temperature	USGS 14148000, Middle Fork Willamette River below North Fork, near Oakridge, OR	Calibration	USGS	NWIS	11-14-2008–present	MFWM, LOP-DEX-M	9

Table 3. Sources for all data input to the models documented in this report.—Continued

[**Data type:** "Temperature" refers to water temperature. **Model use:** "Supporting" indicates that the data source was used to estimate a boundary condition. **Source:** Web address or other citation information indicated in "Source" is available in the report References Cited section. **Source:** CWMS data are available from Dataquery 2.0 but were provided internally by USACE. USGS data from U.S. Geological Survey (2022). **Period of record:** "present" indicates that the streamgage or monitoring station was actively collecting data at the time of publication. Precision of listed period of record is as reported from the data source. **Map number:** Map location numbers correspond to numbers on figure 2. "—" (no map number) indicates that the data source is outside the mapped basin boundary. **Abbreviations:** AgriMet, Bureau of Reclamation Cooperative Agricultural Weather Network; AQWMS, Ambient Water Quality Monitoring System; BCRM, Big Cliff Reservoir Model; BOR, Bureau of Reclamation; CGRM, Cougar Reservoir Model; CWMS, Corps Water Management System; DETM, Detroit Lake Model; DRI, Desert Research Institute; GPR-FOS-M, Green Peter Lakeand Foster Reservoir Model; HCLM, Hills Creek Lake Model; LCD, Local Climatological Data; LOP-DEX-M, Lookout Point Lake and Dexter Reservoir Model; OR, Oregon; MFWM, Middle Fork Willamette River; NA, not applicable; NOAA, National Oceanic and Atmospheric Administration; mm-dd-yyyy, month, day, year; NWIS, U.S. Geological Survey National Water Information System; ODEQ, Oregon Department of Environmental Quality; RAWS, Remote Automated Weather Station; SRML, Solar Radiation Monitoring Laboratory; USACE, U.S. Army Corps of Engineers; USGS, U.S. Geological Survey; UO, University of Oregon; WBAN, Weather Bureau Army Navy, a weather station designation; WRCC, Western Regional Climate Center; yyyy, year]

Data type	Monitoring station	Model use	Agency	Source	Period of record (yyyy; mm-dd-yyyy)	Model	Map number
Temperature	USGS 14147500, North Fork of the Middle Fork Willamette River near Oakridge, OR	Boundary condition	USGS	NWIS	05-27-2010–present	MFWM	8
Temperature	USGS 14185800, Middle Santiam River near Cascadia, OR	Boundary condition	USGS	NWIS	08-19-2010–present	GPR-FOS-M	29
Temperature	USGS 14185900, Quartzville Creek near Cascadia, OR	Boundary condition	USGS	NWIS	08-16-1963 (daily), 10-22-2008 (subdaily)–present	GPR-FOS-M	14
Temperature	USGS 14185000, South Santiam River below Cascadia	Boundary condition	USGS	NWIS	06-20-1962 (daily), 10-29-2008 (subdaily)–present	GPR-FOS-M	2
Temperature	USGS 14179000 Breitenbush River above French Creek, near Detroit	Boundary condition	USGS	NWIS	10-1-2007–present	DETM	12
Temperature	USGS 14179100 French Creek, near Detroit	Supporting	USGS	Data Grapher	07-23-2001–09-30-2005	DETM	30
Water-surface elevation	Hills Creek Lake water-surface elevation	Calibration	USACE	CWMS	1962–present	HCLM	23
Water-surface elevation	Lookout Point Lake water-surface elevation	Calibration	USACE	CWMS	1960–present	LOP-DEX-M	21
Water-surface elevation	Dexter Reservoir water-surface elevation	Calibration	USACE	CWMS	1960–present	LOP-DEX-M	31
Water-surface elevation	Cougar Reservoir water-surface elevation	Calibration	USACE	CWMS	1964–present	CGRM	20
Water-surface elevation	Green Peter Lake water-surface elevation	Calibration	USACE	CWMS	1967–present	GPR-FOS-M	27
Water-surface elevation	Foster Lake water surface-elevation	Calibration	USACE	CWMS	1968–present	GPR-FOS-M	22
Water-surface elevation	Detroit water surface-elevation	Calibration	USACE	CWMS	1960–present	DETM	28



Base map modified from U.S. Geological Survey and other digital data sets, various scales
Oregon Lambert Conformal Conic projection; North American Datum of 1983

Figure 2. Location of data sources used by the CE-QUAL-W2 models in the Willamette River Basin, northwestern Oregon. Numbered locations correspond to the data sources listed in table 3.

Table 4. Sources used for all meteorological inputs to the models.

[**Abbreviations:** BCRM, Big Cliff Reservoir Model; CGRM, Cougar Reservoir Model; CGWO, Cougar Dam Weather Observation station; DETM, Detroit Lake Model; DTRO, Detroit Lake, Oregon AgriMet (Bureau of Reclamation Cooperative Agricultural Weather Network) Weather Station; GPR-FOS-M, Green Peter and Foster Lakes Model, HCLM, Hills Creek Lake Model; HCWO, Hills Creek Dam Weather Observation station; FSWO, Foster Dam Weather Observation station; LOP-DEX-M, Lookout Point Lake and Dexter Reservoir Model; LPWO, Lookout Point Weather Observation station; MFWM, Middle Fork Willamette River; NA, not applicable; RAWS, Remote Automated Weather Station; SRML, Solar Radiation Monitoring Laboratory; WBAN, Weather Bureau Army Navy, a weather station designation]

Model	Year	Air temperature	Dew-point temperature	Wind speed	Wind direction	Cloud cover	Solar radiation	Precipitation	Precipitation temperature
HCLM	2011, 2015, 2016	HCWO	HCWO[1]	Eugene Airport (Mahlon Sweet Field) (WBAN 24221)	Eugene Airport (Mahlon Sweet Field) (WBAN 24221)	Eugene Airport (Mahlon Sweet Field) (WBAN 24221)	Eugene SRML	HCWO	Hourly air temperature from HCWO (negative values set to zero) 2011 data is daily.
MFWM	2011, 2015, 2016	LPWO	LPWO[1]	Eugene Airport (Mahlon Sweet Field) (WBAN 24221)	Eugene Airport (Mahlon Sweet Field) (WBAN 24221)	Eugene Airport (Mahlon Sweet Field) (WBAN 24221)	Eugene SRML	OFF	NA
LOP-DEX-M	2011, 2015, 2016	LPWO	LPWO[1]	Eugene Airport (Mahlon Sweet Field) (WBAN 24221)	Eugene Airport (Mahlon Sweet Field) (WBAN 24221)	Eugene Airport (Mahlon Sweet Field) (WBAN 24221)	Eugene SRML	LPWO; many suspect values deleted	Hourly air temperature from LPWO (negative values set to zero)
CGRM	2011, 2015, 2016	CGWO	CGWO[1]	Eugene Airport (Mahlon Sweet Field) (WBAN 24221)	Eugene Airport (Mahlon Sweet Field) (WBAN 24221)	Eugene Airport (Mahlon Sweet Field) (WBAN 24221)	Eugene SRML[2]	CGWO; many suspect values deleted	Hourly air temperature from CGWO (negative values set to zero)
GPR-FOS-M	2011, 2015, 2016	RAWS Jordan	RAWS Jordan	Eugene Airport (Mahlon Sweet Field) (WBAN 24221)	Eugene Airport (Mahlon Sweet Field) (WBAN 24221)	Eugene Airport (Mahlon Sweet Field) (WBAN 24221)	Eugene SRML	FSWO	Hourly air temperature from FSWO 2011, 2015; hourly air temperature from RAWS Jordan 2016 (negative values set to zero)
DETM	2011, 2015, 2016	AgriMet DTRO	AgriMet DTRO	Jordan RAWS	Jordan RAWS	Salem Municipal Airport (McNary Field) (WBAN 24232)	Eugene SRML	2011 AgriMet DTRO; 2015, 2016 RAWS Jordan	2011 DTRO, daily; 2015, 2016 RAWS Jordan (negative values set to zero)
BCRM	2011, 2015, 2016	AgriMet DTRO	AgriMet DTRO	Jordan RAWS	Jordan RAWS	Salem Municipal Airport (McNary Field) (WBAN 24232)	Eugene SRML	2011 AgriMet DTRO; 2015, 2016 RAWS Jordan	2011 DTRO, daily; 2015, 2016 RAWS Jordan (negative values set to zero)

[1]Calculated from air temperature and relative humidity after Lawrence, 2005.

[2]Included in meteorology file, but model was set to calculate solar radiation from cloud cover rather than read in observed short wave solar radiation ("SROC = OFF").

Water Temperature

Time series of water temperature were sourced mostly from USGS streamgages and accessed from NWIS (U.S. Geological Survey, 2022) or from USACE databases accessible through their online portal DataQuery 2.0 (https://www.nwd-wc.usace.army.mil/dd/common/dataquery/www/; U.S. Army Corps of Engineers, 2022); all individual data sources are listed in table 3.Where data were unavailable, the temperature of model inflows were estimated. Estimates were made by applying a proxy record from a nearby monitoring station with similar characteristics (for example, in aspect, watershed size, and underlying geology). Where historical records were available, water temperature time series were estimated using simple or multiple linear regressions with data from one or more nearby monitoring stations. The final estimation method was generally selected among several options, depending on the regression model goodness-of-fit statistics or the estimated time series that most improved the temperature fit in the CE-QUAL-W2 model. All temperature estimation equations used in updating the models are reported in individual model subsections that follow.

Selective Withdrawal and Temperature Targets

CE-QUAL-W2 is capable of using a selective blending algorithm to meet a specified downstream temperature target (Rounds and Buccola, 2015; Wells, 2019). When turned on, this option allows CE-QUAL-W2 to override the user-provided, outlet-specific flow rates for each outlet and to apportion the total user-specified outflow to the combination of dam outlets most likely to achieve the specified downstream temperature target for each time step. Bounding parameters for outlet use, including dates, minimum flow fraction (for example, 10 percent of flow might be required to be routed through the power penstock), outlet priority rank, and minimum or maximum head or flow constraints can be assigned. In the baseline (observed) model scenario, only CGRM implemented a selective blending algorithm, in keeping with the operation of the water temperature control tower at Cougar Dam, which is unique in the WVP. Details of the selective withdrawal input file and temperature target are discussed in section, “Model Updates—Cougar Reservoir Model (CGRM)—Temporal Inputs—Temperature.”

Model Calibration

Water Balance

For river models, the water balance in a CE-QUAL-W2 model is typically adjusted by comparing streamflow (or, more rarely, stage) at individual model segments with measured values from a streamgage and then adjusting one or more distributed tributaries until modeled streamflows reasonably match measured streamflows.

For reservoir models, the water budget is balanced by comparing the modeled with the measured water-surface elevation of the reservoir, calculating the difference in volume, and converting that volume to a flow rate. Unless other known conditions apply (for example, a seepage zone in a dam or a large ungaged tributary), any flows necessary to close the water budget typically are added or removed using a “distributed tributary” applied to the main branch of the reservoir. The distributed tributary can be positive or negative and is divided among the segments within the branch, weighted according to each segment’s surface area.

To close the water balance for all reservoirs included in this report, the daily average difference in water-surface elevation between measured and modeled lake elevation was converted to a daily time series of distributed tributary flow. This process is typically iterative and may require smoothing of the calculated difference between measured and modeled water levels or the computed flow to achieve reasonable values for the distributed tributary. Ideally, distributed tributary flows are small and are representative of missing surface-water flows (for example, from overland flow or small, ungaged tributaries during storms) or groundwater loss. However, given uncertainties in inflow measurements or estimates, outflow estimates, and the bathymetry, the volume of the distributed tributary may be difficult to interpret and may include undesirably large positive and negative values. This is often evident during and after large storm events, when the models may require the addition of a large volume of inflow to accurately simulate a rise in water-surface elevation and then require the removal of a similar volume to allow the reservoir water-surface elevation to decrease. Such anomalies are not ideal because small inaccuracies in the water balance can have large effects on the water-surface elevation (particularly in small reservoirs), which are then propagated through the model run. This approach does, however, allow the models to accurately simulate the water-surface elevation, which is critical for the simulation of other parameters such as water temperature. Because most large storms tend to occur during winter when the reservoirs are isothermal, the effect of adding and removing large volumes of water from the reservoir is less important than it would be during the period of reservoir stratification. Improvements to the reservoir bathymetry in models where large positive and negative distributed tributary values are an issue may allow for future refinement of the models but were outside the scope of this study.

Temperature

Temperature calibration of a CE-QUAL-W2 model can involve adjusting a wide range of parameters, including adjustment of measured or estimated boundary condition sources, the configuration of different structures within the model, extinction coefficients for light penetration with depth, or the wind-sheltering coefficient (a parameter that scales the specified wind speed), among many others. A full recalibration of model temperature was beyond the scope of this study; however, the goodness-of-fit for water temperature of all models was checked and minor adjustments were made to boundary conditions, as necessary. The reservoir models were generally checked using two datasets: (1) a “thermistor string” consisting of thermistors deployed at different depths or elevations floating in the reservoir forebay or fixed to the reservoir side of the dam, which provides a check on how well the model simulates stratification in the reservoir, and (2) the upstream-most temperature monitoring station in the river downstream from the dam, which provides a check on how well the model simulates the release temperatures from the dam. Where models were connected in series (for example, the inflow to the LOP-DEX-M uses the outflow from the MFWM, which in turn uses the outflow from the HCLM as its input), the temperature calibration was checked with two separate model runs, using (1) modeled inflow and (2) measured inflow. This approach provides a better understanding of the performance of individual models and of the suite of models connected as a whole.

In addition to time-series plots comparing measured with modeled water temperature, model performance was evaluated using several standard goodness-of-fit metrics. Mean error (ME) is a measure of model bias, with negative values indicating that the overall model results are too cool and positive values indicating that the overall model results are too warm. Root mean squared error (RMSE) and mean absolute error (MAE) are similar measures of model performance but are interpreted slightly differently (Chai and Draxler, 2014). MAE measures the average error magnitude, whereas RMSE penalizes large errors in model performance. Both measures are reported in the same units as the data (in this case, degrees Celsius). By definition, RMSE is always larger than MAE. In this report, ME, MAE, and RMSE are reported for subdaily, daily maximum, and daily minimum temperature values for all model outflows compared to the nearest downstream measured temperature time series, and subdaily fit statistics are reported for all thermistor string comparisons (tables 5–10).

Model Updates

Hills Creek Lake Model (HCLM)

Description

Hills Creek Dam is a multipurpose storage project authorized for flood risk management, irrigation, navigation, hydropower, and other uses (U.S. Army Corps of Engineers, 2019b). Located at Willamette RM 232.5, approximately 45 miles (mi) southeast of Eugene in the foothills of the Cascade Range, Hills Creek is the upstream-most USACE dam on the Middle Fork Willamette River (fig. 1). At full pool, the reservoir is approximately 286.4 ft deep. The reservoir has two main arms, extending up the Middle Fork Willamette River approximately 7.5 mi to RM 240 and up Hills Creek approximately 3 mi to Hills Creek RM 3 at full pool. Other major tributaries include Larison and Packard Creeks, which both form sub-arms of the reservoir body along the Middle Fork Willamette River.

Hills Creek Dam is approximately 290 feet (ft.; 88.4 m) high and has five outlets at three elevations: a spillway, two adjacent regulating outlets, and two adjacent power penstocks. The spillway has historically only been used in emergencies (Buccola, Stonewall, and others, 2013). The elevations of the regulating outlets and the power penstocks are relatively high in the dam; as a result, the lower 133.4 ft (40.7 m) of the reservoir is “dead storage” that cannot be released from the dam (table 2). The absence of relatively deep outlets in Hills Creek Dam limits the opportunities for temperature management from Hills Creek Lake (Buccola, Stonewall, and others, 2013).

Model History and Domain

The Hills Creek Lake Model (HCLM) was originally developed by WEST Consultants, Inc. (2004a) using data from 1971, 1972, 2001, and 2002, which was then used to perform a 33-year simulation from January 1, 1970, to December 31, 2002. WEST Consultants Inc. used 2001–02 to construct and calibrate the model and 1971–72 as a separate “validation” dataset. The original model was built in CE-QUAL-W2 version 3.1 (Cole and Wells, 2001). The HCLM was updated to CE-QUAL-W2 version 3.7 and USGS set up the model to simulate calendar years 2002, 2006, 2008, and 2011 (Buccola, Stonewall, and others, 2013). As part of that update, many of the model parameters were adjusted to improve model performance, including adjustment of the width and elevation of the structures in the model to better calibrate the reservoir temperatures.

The HCLM consists of one waterbody with four branches. Branch 1 is the main body of the reservoir, extending from the head of the reservoir on the Middle Fork Willamette River downstream from USGS monitoring station 14144800 (Middle Fork Willamette River above Hills Creek) to Hills Creek Dam (fig. 2). The other three branches are reservoir arms created by reservoir tributaries Packard Creek (branch 2), Larison Creek (branch 3), and Hills Creek (branch 4). No other tributaries are included in the model. Segment lengths vary from 259.7 to 497.4 m and layers are 0.5 m in height. Three structures are included in the model. Structure 1 represents the regulating outlets in Hills Creek Dam and structure 2 represents the power penstocks. The spillway was not included in previous version of the model (Buccola, Stonewall, and others, 2013) but was added as structure 3 in this model update (table 2).

The model changes in this report include (1) updating the 2011 HCLM documented by Buccola, Stonewall, and others (2013) to USGS edition 7, version 4.2 of CE-QUAL-W2; (2) setting up the model for calendar years 2015 and 2016; (3) adjusting the structure configuration in Hills Creek Dam by adding the spillway; and (4) checking and calibrating results for 2011, 2015, and 2016, as needed.

Table 5. Goodness-of-fit statistics comparing measured and modeled water temperatures for the Hills Creek Lake Model, northwestern Oregon, 2011, 2015, and 2016.

[**Abbreviations:** N, number; NA, not applicable; °C, degrees Celsius; ME, mean error; MAE, mean absolute error; RMSE, root mean squared error; USGS, U.S. Geological Survey]

Depth (meters)	Depth (feet)	2011				2015				2016			
		N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)
Hills Creek Lake thermistor string (floating)													
1.5	5	8,733	0.20	0.48	0.66	8,733	0.37	0.78	0.90	8,733	0.08	0.64	0.79
3	10	8,733	0.19	0.36	0.59	8,733	0.44	0.75	0.87	8,729	0.17	0.62	0.77
6.1	20	8,733	0.10	0.48	0.68	8,733	0.50	0.78	0.92	8,733	0.28	0.65	0.81
9.1	30	8,733	0.21	0.47	0.61	8,731	0.71	0.93	1.13	8,733	0.75	0.95	1.15
12.2	40	8,733	0.74	0.83	1.04	8,731	1.36	1.52	1.76	8,733	1.50	1.61	1.97
15.2	50	8,733	0.98	1.02	1.30	8,731	3.89	3.98	5.01	7,740	4.48	4.58	6.00
18.3	60	8,733	1.03	1.06	1.42	8,731	4.72	4.77	6.00	8,733	4.64	4.71	6.10
24.4	80	8,733	1.12	1.16	1.86	8,731	3.26	3.30	4.11	8,731	2.20	2.26	2.84
30.5	100	8,733	0.87	0.95	1.54	8,731	1.91	1.95	2.44	8,731	0.72	0.81	0.99
36.6	120	8,731	0.35	0.52	0.74	8,731	0.88	0.91	1.18	8,733	0.15	0.30	0.37
42.7	140	8,729	–0.05	0.34	0.42	8,731	0.22	0.31	0.42	8,733	–0.03	0.19	0.23
48.8	160	8,731	–0.22	0.27	0.35	8,731	0.00	0.15	0.17	8,733	–0.07	0.13	0.18
54.9	180	8,733	–0.17	0.73	1.06	NA	NA	NA	NA	992	0.14	0.16	0.29
	MEAN	NA	0.41	0.67	0.94	NA	1.52	1.68	2.08	NA	1.16	1.36	1.73
USGS station 14145500, Middle Fork Willamette above Salt Creek, Oregon													
	Subdaily	8,734	0.02	0.29	0.36	8,735	0.60	0.96	1.22	8,734	0.54	0.71	0.90
	Daily Maximum	363	–0.2	0.34	0.43	363	0.22	0.93	1.11	363	0.24	0.54	0.70
	Daily Minimum	363	0.23	0.31	0.39	363	0.86	1.09	1.35	363	0.81	0.91	1.09

Table 6. Goodness-of-fit statistics comparing measured and modeled water temperatures, using both measured and modeled inflow, at two comparison sites for the Middle Fork Willamette River Model, northwestern Oregon, 2011, 2015, and 2016.

[**Abbreviations:** N, number; NA, not applicable; °C, degrees Celsius; ME, mean error; MAE, mean absolute error; RMSE, root mean squared error; USGS, U.S. Geological Survey]

Metric	2011				2015				2016			
	N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)
MODELED INFLOW												
USGS 1414550, Middle Fork Willamette above Salt Creek, near Oakridge, Oregon (segment 11)												
Subdaily	8,686	0.06	0.30	0.37	8,733	0.76	1.03	1.27	8,732	0.62	0.77	1.00
Daily Maximum	361	–0.03	0.28	0.34	363	0.75	1.01	1.23	363	0.52	0.7	0.91
Daily Minimum	361	0.19	0.30	0.38	363	0.83	1.07	1.32	363	0.78	0.89	1.06
USGS 14148000, Middle Fork Willamette River below North Fork, near Oakridge, Oregon (segment 80)												
Subdaily	8,686	–0.19	0.36	0.46	8,732	0.38	0.70	0.98	8,730	0.28	0.54	0.83
Daily Maximum	361	–0.05	0.32	0.40	363	0.92	1.10	1.44	363	0.66	0.85	1.33
Daily Minimum	361	–0.24	0.26	0.32	363	0.10	0.46	0.62	363	0.07	0.33	0.42
MEASURED INFLOW												
USGS 1414550, Middle Fork Willamette above Salt Creek, near Oakridge, Oregon (segment 11)												
Subdaily	8,686	0.04	0.12	0.18	8,729	0.17	0.26	0.47	8,732	0.09	0.17	0.30
Daily Maximum	361	0.13	0.15	0.20	363	0.54	0.56	0.80	363	0.23	0.25	0.38
Daily Minimum	361	0.00	0.09	0.12	363	0.01	0.11	0.15	363	0.04	0.10	0.16
USGS 14148000, Middle Fork Willamette River below North Fork, near Oakridge, Oregon (segment 80)												
Subdaily	8,686	–0.20	0.36	0.45	8,728	0.06	0.50	0.70	8,730	0.04	0.41	0.65
Daily Maximum	361	–0.03	0.32	0.39	363	0.65	0.82	1.11	363	0.48	0.71	1.13
Daily Minimum	361	–0.24	0.25	0.31	363	–0.26	0.34	0.40	363	–0.18	0.24	0.30

Table 7. Goodness-of-fit statistics comparing measured and modeled water temperatures, simulated using both measured and modeled inflow, for the Lookout Point Lake and Dexter Reservoir Model, northwestern Oregon, 2011, 2015, and 2016.

[**Abbreviations:** N, number; NA, not applicable; °C, degrees Celsius; ME, mean error; MAE, mean absolute error; RMSE, root mean squared error; USGS, U.S. Geological Survey]

Depth (meters)	Depth (feet)	2011				2015				2016			
		N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)
MODELED INFLOW													
Lookout Point Lake thermistor string (floating)													
1.5	5	8,667	–0.53	0.92	1.11	8,729	0.13	0.45	0.57	8,731	–0.26	0.52	0.64
3.0	10	8,665	–0.54	0.88	1.07	8,729	0.16	0.43	0.56	8,731	–0.19	0.49	0.60
6.1	20	8,667	–0.33	0.82	1.03	8,729	0.22	0.51	0.72	8,731	–0.06	0.51	0.64
9.1	30	8,666	–0.06	0.72	0.92	8,729	0.32	0.75	1.04	8,731	0.19	0.61	0.79
12.2	40	8,667	0.37	0.73	0.94	8,729	0.51	0.90	1.24	8,731	0.49	0.74	1.00
18.3	60	8,669	0.41	0.68	0.95	8,727	0.71	1.09	1.48	8,731	0.79	0.92	1.30
24.4	80	8,669	0.36	0.56	0.85	8,727	0.62	1.10	1.52	8,731	0.77	0.87	1.25
30.5	100	8,669	0.40	0.55	0.85	8,729	–1.42	1.46	1.97	8,731	0.24	0.65	0.90
36.6	120	8,669	0.22	0.47	0.65	8,729	–1.91	1.93	2.22	8,731	–0.13	0.58	0.81
42.7	140	8,186	–0.08	0.32	0.44	8,728	–1.95	1.97	2.20	8,555	–0.42	0.65	0.88
48.8	160	7,258	–0.29	0.31	0.42	8,657	–1.88	1.89	2.19	4,318	–0.21	0.34	0.44
54.9	180	6,483	–0.42	0.42	0.52	NA	NA	NA	NA	3,241	–0.26	0.26	0.31
61.0	200	4,237	0.16	0.21	0.24	NA	NA	NA	NA	1,656	–0.28	0.28	0.29
	MEAN	NA	–0.03	0.58	0.77	NA	–0.41	1.14	1.43	NA	0.05	0.57	0.76
USGS station 14150000, Middle Fork Willamette River near Dexter, Oregon													
	Subdaily	8,636	–0.43	0.63	0.75	8,726	–0.40	0.90	1.10	8,729	–0.34	0.64	0.78
	Daily Maximum	360	–0.82	0.88	1.02	363	–1.26	1.36	1.36	363	–0.88	0.88	1.04
	Daily Minimum	360	–0.19	0.47	0.58	363	0.08	0.72	0.90	363	–0.04	0.57	0.71
MEASURED INFLOW													
Lookout Point Lake thermistor string (floating)													
1.5	5	8,667	–0.48	0.89	1.09	8,729	–0.02	0.39	0.53	8,733	–0.31	0.50	0.65
3.0	10	8,665	–0.50	0.84	1.06	8,729	–0.02	0.33	0.44	8,733	–0.24	0.46	0.60
6.1	20	8,667	–0.29	0.80	1.03	8,729	0.07	0.40	0.58	8,733	–0.12	0.46	0.62
9.1	30	8,666	–0.02	0.69	0.92	8,729	0.22	0.58	0.84	8,733	0.12	0.51	0.70
12.2	40	8,667	0.42	0.70	0.93	8,729	0.38	0.68	0.98	8,733	0.40	0.59	0.82
18.3	60	8,669	0.48	0.67	0.95	8,727	0.63	0.86	1.24	8,733	0.70	0.77	1.09
24.4	80	8,669	0.44	0.56	0.86	8,727	0.64	0.88	1.29	8,733	0.71	0.76	1.07

Table 7. Goodness-of-fit statistics comparing measured and modeled water temperatures, simulated using both measured and modeled inflow, for the Lookout Point Lake and Dexter Reservoir Model, northwestern Oregon, 2011, 2015, and 2016.—Continued

[**Abbreviations:** N, number; NA, not applicable; °C, degrees Celsius; ME, mean error; MAE, mean absolute error; RMSE, root mean squared error; USGS, U.S. Geological Survey]

Depth (meters)	Depth (feet)	2011				2015				2016			
		N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)
Lookout Point Lake thermistor string (floating)—Continued													
30.5	100	8,669	0.49	0.56	0.87	8,729	–1.07	1.13	1.65	8,733	0.26	0.63	0.84
36.6	120	8,669	0.33	0.51	0.69	8,729	–1.44	1.46	1.82	8,733	–0.06	0.56	0.78
42.7	140	8,245	0.00	0.32	0.43	8,728	–1.39	1.41	1.71	8,557	–0.33	0.61	0.84
48.8	160	7,283	–0.20	0.25	0.35	8,661	–1.43	1.45	1.81	4,324	–0.08	0.29	0.40
54.9	180	6,519	–0.32	0.33	0.42	33	–0.45	0.45	0.46	3,242	–0.10	0.16	0.20
61.0	200	4,282	0.24	0.26	0.29	NA	NA	NA	NA	1,658	–0.10	0.12	0.14
USGS station 14150000, Middle Fork Willamette River near Dexter, Oregon													
	Subdaily	8,682	–0.38	0.59	0.72	8,726	–0.43	0.79	0.98	8,733	–0.36	0.58	0.72
	Daily Maximum	362	–0.77	0.84	0.98	363	–1.29	1.33	1.55	363	–0.89	0.89	1.03
	Daily Minimum	362	–0.14	0.44	0.55	363	–0.05	0.58	0.74	363	–0.04	0.48	0.61

Table 8. Goodness-of-fit statistics comparing measured and modeled water temperatures for the Cougar Reservoir Model, northwestern Oregon, 2011, 2015, and 2016.

[Cougar Reservoir did not fill in 2015 or 2016, leading to a large number of "NA" values at elevations that were not submerged. Elevations are relative to the National Geodetic Vertical Datum of 1929 (NGVD 29). **Abbreviations:** N, number; NA, not applicable; °C, degrees Celsius; ME, mean error; MAE, mean absolute error; RMSE, root mean squared error; USGS, U.S. Geological Survey]

Elevation (meters)	Elevation (feet)	2011				2015				2016			
		N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)
Cougar Reservoir thermistor string (fixed elevation)													
512.1	1,680	1,697	–4.77	4.77	5.31	NA	NA	NA	NA	NA	NA	NA	NA
510.2	1,674	2,178	–3.39	3.40	4.22	NA	NA	NA	NA	NA	NA	NA	NA
508.4	1,668	2,584	–2.40	2.44	3.47	NA	NA	NA	NA	NA	NA	NA	NA
506.6	1,662	2,871	–1.79	1.94	3.08	NA	NA	NA	NA	NA	NA	NA	NA
504.7	1,656	3,138	–1.38	1.57	2.61	NA	NA	NA	NA	NA	NA	NA	NA
502.9	1,650	3,335	–1.13	1.38	2.53	NA	NA	NA	NA	NA	NA	NA	NA
501.1	1,644	3,572	–0.97	1.37	2.66	NA	NA	NA	NA	NA	NA	NA	NA
499.3	1,638	3,936	–1.33	1.63	3.07	NA	NA	NA	NA	NA	NA	NA	NA
497.4	1,632	4,335	–0.86	1.78	2.88	NA	NA	NA	NA	NA	NA	NA	NA
495.6	1,626	4,745	–0.67	1.68	2.44	NA	NA	NA	NA	NA	NA	NA	NA
493.8	1,620	4,985	–0.34	1.45	1.96	NA	NA	NA	NA	NA	NA	NA	NA
491.9	1,614	5,208	0.12	1.31	1.65	NA	NA	NA	NA	NA	NA	NA	NA
490.1	1,608	5,424	0.60	1.37	1.67	NA	NA	NA	NA	NA	NA	NA	NA
488.3	1,602	5,634	0.93	1.48	1.76	551	–5.2	5.2	5.4	NA	NA	NA	NA
486.5	1,596	5,784	0.87	1.44	1.71	1,782	–3.9	4.0	4.5	NA	NA	NA	NA
484.6	1,590	5,975	1.21	1.64	1.95	2,548	–2.7	2.8	3.4	NA	NA	NA	NA
482.8	1,584	6,091	1.50	1.80	2.15	3,153	–1.7	1.9	2.6	NA	NA	NA	NA
481.0	1,578	6,285	1.76	1.98	2.36	3,688	–0.8	1.3	1.8	719	–2.88	2.88	3.06
479.1	1,572	6,500	1.85	2.09	2.49	4,238	0.2	1.1	1.3	2,393	–3.58	3.58	4.11
475.5	1,560	7,240	1.77	2.14	2.56	5,261	1.5	1.9	2.3	4,144	–1.91	1.95	2.45
471.8	1,548	7,629	1.88	2.20	2.67	7,013	1.9	2.3	3.1	4,915	–0.49	1.24	1.41
468.2	1,536	8,104	1.82	2.12	2.64	8,213	2.3	2.8	3.9	5,875	0.34	1.34	1.59
464.5	1,524	8,724	1.46	1.94	2.45	8,425	2.7	3.2	4.4	7,410	0.75	1.54	1.96
458.4	1,504	8,732	1.60	2.04	2.59	8,454	3.4	3.9	5.1	7,770	1.49	2.10	2.77
	MEAN	NA	–0.07	1.96	2.62	NA	–0.21	2.76	3.43	NA	–0.90	2.09	2.48
USGS station 14159500, South Fork McKenzie River near Rainbow, Oregon													
	Subdaily	8,734	0.1	0.68	0.86	8,729	–0.42	0.9	1.13	8,703	–0.22	0.78	0.95
	Daily Maximum	363	–0.3	0.68	0.84	363	–0.89	1.15	1.44	363	–0.64	0.91	1.14
	Daily Minimum	363	0.52	0.82	1.13	363	0.03	0.76	0.99	363	0.09	0.76	0.97

Table 9. Goodness-of-fit statistics comparing measured and modeled water temperatures for the Green Peter and Foster Lakes Model, northwestern Oregon, 2011, 2015, and 2016.

[**Abbreviations:** N, number; NA, not applicable; °C, degrees Celsius; ME, mean error; MAE, mean absolute error; RMSE, root mean squared error; USGS, U.S. Geological Survey]

Metric		2011				2015				2016			
Depth (meters)	Depth (feet)	N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)
Green Peter Lake thermistor string (floating)													
1.5	5	8,561	0.67	0.94	1.16	6,241	–0.20	0.80	0.97	6,227	–0.48	1.01	1.17
3.0	10	8,561	–0.48	0.84	1.07	6,241	0.16	0.74	0.97	5,542	–0.27	0.91	1.10
6.1	20	8,560	–0.67	0.96	1.20	6,241	–0.38	0.90	1.12	5,542	–0.77	1.22	1.38
9.1	30	8,558	–0.57	1.02	1.31	6,240	0.31	0.91	1.40	5,542	0.04	1.09	1.42
12.2	40	8,562	–0.25	0.99	1.32	6,241	0.43	1.14	1.55	5,542	0.21	1.34	1.66
18.3	60	8,563	0.23	0.91	1.20	6,241	0.81	1.08	1.32	5,542	0.74	1.28	1.66
24.4	80	8,563	0.27	0.84	1.09	6,241	0.64	0.82	0.96	5,542	0.78	1.17	1.54
30.5	100	8,563	0.42	0.74	0.94	6,241	0.77	0.87	1.04	5,542	0.80	1.06	1.50
36.6	120	8,563	0.45	0.69	0.92	6,241	0.68	0.75	0.87	5,542	0.81	0.89	1.32
42.7	140	8,561	0.51	0.68	0.86	6,239	0.60	0.64	0.72	5,537	0.76	0.78	1.00
48.8	160	8,561	0.35	0.54	0.62	6,239	0.39	0.44	0.50	5,537	0.74	0.75	0.88
54.9	180	8,559	0.29	0.51	0.58	6,239	0.42	0.50	0.54	5,538	0.58	0.59	0.73
61.0	200	8,561	0.36	0.57	0.62	NA	NA	NA	NA	NA	NA	NA	NA
	MEAN	NA	0.02	0.79	0.99	NA	0.38	0.80	1.00	NA	0.33	1.01	1.28
USGS station 14187200, South Santiam River near Foster, Oregon													
	Subdaily	8,710	–0.21	0.64	0.79	8,527	–0.03	0.68	0.87	8,735	–0.11	0.58	0.76
	Daily Maximum	363	–0.42	0.66	0.8	356	–0.34	0.6	0.8	363	–0.26	0.59	0.76
	Daily Minimum	363	0.01	0.64	0.8	356	0.22	0.75	0.92	363	0.05	0.73	0.57

Table 10. Goodness-of-fit statistics comparing measured and modeled water temperatures for the Detroit Lake and Big Cliff Reservoir Models, northwestern Oregon, 2011, 2015, and 2016.

[Abbreviations: N, number; NA, not applicable; °C, degrees Celsius; ME, mean error; MAE, mean absolute error; RMSE, root mean squared error; USGS, U.S. Geological Survey]

Depth (meters)	Depth (feet)	2011				2015				2016			
		N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)
Detroit Lake thermistor string (floating)													
0.2	0.5	6,773	0.36	0.58	0.80	8,078	0.09	0.71	0.87	4,076	–0.31	0.79	0.92
3.0	10	6,773	0.45	0.63	0.90	8,078	0.23	0.71	0.86	4,077	–0.22	0.76	0.88
6.1	20	6,771	0.51	0.71	1.01	8,078	0.28	0.74	0.89	4,077	–0.18	0.77	0.90
9.1	30	6,771	0.02	0.69	0.97	8,078	0.23	0.72	0.86	4,077	–0.21	0.70	0.82
12.2	40	6,773	0.00	0.64	0.91	8,078	0.23	0.80	1.00	4,077	–0.27	0.66	0.79
18.3	60	6,775	0.31	0.58	0.74	8,078	0.24	0.89	1.21	4,077	–0.10	0.60	0.81
24.4	80	6,775	–0.11	0.42	0.60	8,078	–1.06	1.19	1.67	4,077	–0.05	0.62	0.87
30.5	100	6,775	–0.17	0.40	0.56	8,078	–1.89	1.98	2.83	4,077	–0.06	0.63	0.86
36.6	120	6,775	–0.18	0.41	0.57	8,078	–1.34	1.37	2.00	4,077	–0.26	0.54	0.74
42.7	140	6,773	–0.20	0.43	0.55	8,078	–1.14	1.14	1.62	4,075	–0.35	0.59	0.85
48.8	160	6,773	–0.08	0.35	0.43	8,078	–1.07	1.07	1.46	4,075	–0.41	0.51	0.69
54.9	180	6,773	–0.17	0.39	0.47	8,078	–0.96	0.96	1.18	4,075	–0.85	0.87	1.33
	MEAN	NA	0.06	0.52	0.71	NA	–0.51	1.02	1.37	NA	–0.27	0.67	0.87
USGS station 14181500, North Santiam River at Niagara, Oregon													
Outflow from Detroit Lake Model (DETM)													
	Subdaily	7,866	–0.31	0.56	0.82	7,832	0.07	0.76	1.12	7,924	–0.4	0.69	0.88
	Daily Maximum	332	–0.6	0.73	0.96	332	0.3	0.83	1.25	332	–0.39	0.72	0.86
	Daily Minimum	332	–0.08	0.41	0.6	332	–0.12	0.69	0.97	332	–0.4	0.61	0.77
Outflow from full water-balance Big Cliff Reservoir Model (BCRM)													
	Subdaily	7,866	–0.59	0.66	0.82	7,832	0.22	0.64	0.86	7,924	–0.48	0.61	0.71
	Daily Maximum	332	–0.97	0.99	1.19	332	0.17	0.64	0.85	332	–0.61	0.68	0.78
	Daily Minimum	332	–0.26	0.46	0.58	332	0.3	0.66	0.88	332	–0.36	0.56	0.66
Outflow from simplified Big Cliff Reservoir Model (BCRM)													
	Subdaily	7,866	–0.2	0.46	0.62	7,832	0.33	0.77	1.03	7,924	–0.12	0.54	0.66
	Daily Maximum	332	–0.54	0.65	0.85	332	0.3	0.77	1.02	332	–0.22	0.54	0.65
	Daily Minimum	332	0.07	0.43	0.55	332	0.39	0.78	1.05	332	–0.02	0.54	0.66

Bathymetric Grid and Non-Temporal Parameters

Most non-temporal parameters in the HCLM were unchanged from those implemented in the version 3.7 update (Buccola, Stonewall, and others, 2013). The spillway, which had not previously been included in the model, was added as a third structure within Hills Creek Dam and used as a hypothetical outlet for simulations in Buccola and others (2016). The elevation of the spillway crest was determined from internal USACE as-built drawings and the width was based on the Detroit Dam spillway, which USACE determined to be a reasonable analog. Additionally, the elevation of the power penstocks (structure 2) was adjusted 0.5 m higher to 423.7 m. This elevation matches the actual centerline elevation, as determined from internal USACE as-built drawings. The elevation of structures in the HCLM are discussed in more detail in section, “Model Updates—Hills Creek Lake Model (HCLM)—Model Fit.” The only other change to non-temporal parameters was to turn off evaporative mass loss for consistency with the other reservoir models. No changes were made to the bathymetric grid except to update it to the new, more readable .csv file format and to set the initial water-surface elevation to match the start of each simulation.

Temporal Inputs

Meteorology

Meteorological inputs to the HCLM for 2015 and 2016 used the same data sources as for 2011 and other previously calibrated years (Buccola, Stonewall, and others, 2013; table 4).

Streamflow

All inflows to the HCLM were estimated. Inflow from the Middle Fork Willamette River (branch 1) was estimated using a forward stepwise regression developed for the analysis documented by Buccola, Stonewall, and others (2013):

$$\begin{aligned}\log_{10} Q_{MiddleForkHillsCreekInflow} &= 0.6394\log_{10} Q_{USACE\_inflow\_est} \\ &+ 0.3430\log_{10} Q_{USGS14178000} \\ &+ 0.0323\log_{10} Q_{USGS14301500} \\ &+ 0.0910\log_{10} Q_{USGS14316700} \\ &- 0.0538\log_{10} Q_{USGS14185000} \\ &- 0.0221\log_{10} Q_{USGS14171000} \\ &- 0.0230\end{aligned} \tag{1}$$

where

$Q_{MiddleForkHillsCreekInflow}$ is the estimated daily mean streamflow in the Middle Fork Willamette River at historical U.S. Geological Survey (USGS) station 14144800, Middle Fork Willamette River near Oakridge, Oregon, in cubic meters per second;

$Q_{USACE\_inflow\_est}$ is the estimated daily mean inflow to Hills Creek Lake from the U.S. Army Corps of Engineers Core Water Management System database, in cubic meters per second;

$Q_{USGS14178000}$ is the daily mean streamflow measured at USGS station 14178000, North Santiam River below Boulder Creek, near Detroit, Oregon, in cubic meters per second;

$Q_{USGS14301500}$ is the daily mean streamflow measured at USGS station 14301500, Wilson River near Tillamook, Oregon, in cubic meters per second;

$Q_{USGS14316700}$ is the daily mean streamflow measured at USGS 14316700, Steamboat Creek near Glide, Oregon, in cubic meters per second;

$Q_{USGS14185000}$ is the daily mean streamflow measured at USGS station 14185000, South Santiam River below Cascadia, Oregon, in cubic meters per second; and

$Q_{USGS14171000}$ is the daily mean streamflow measured at USGS station 14171000, Marys River near Philomath, Oregon, in cubic meters per second.

Inflow to branch 2 of the HCLM (Packard Creek) was estimated using a regression developed for the analysis documented by Buccola, Stonewall, and others (2013), which compared historical data from Hills Creek and the 95th percentile of streamflow exceedance, median streamflow, and the 2-year flood for Packard Creek, as derived from the USGS streamflow-statistics web tool StreamStats (U.S. Geological Survey, 2020):

$$Q_{Packard} = 10^{-1.04\times 1.20\log_{10} Q_{HillsCreek}} \tag{2}$$

where

$Q_{Packard}$ is the estimated daily mean streamflow in Packard Creek at its confluence with Hills Creek Lake, in cubic meters per second; and

$Q_{HillsCreek}$ is the daily mean streamflow estimated at historical U.S. Geological Survey station 14144900, Hills Creek above Hills Creek Reservoir, near Oakridge, Oregon, in cubic meters per second (eq. 3).

The estimated daily streamflow at USGS station 14144900, Hills Creek above Hills Creek Reservoir, near Oakridge, Oregon, in turn, was estimated as:

$$\begin{aligned}\log_{10} Q_{HillsCreek} &= 0.7126 \log_{10} Q_{USACE\_inflow\_est} \\ &+ 0.2561 \log_{10} Q_{USGS14185000} \\ &- 0.1234 \log_{10} Q_{USGS14301500} \\ &+ 0.1426 \log_{10} Q_{USGS14318000} \\ &+ 0.1613 \log_{10} Q_{USGS14178000} \\ &- 0.0449 \log_{10} Q_{USGS14190500} \\ &- 1.1107\end{aligned} \quad (3)$$

where

$Q_{USACE\_inflow\_est}$ is the estimated daily mean inflow to Hills Creek Lake from the U.S. Army Corps of Engineers Core Water Management System database, in cubic meters per second;

$Q_{USGS14185000}$ is the daily mean streamflow measured at U.S. Geological Survey (USGS) station 14185000, South Santiam River below Cascadia, Oregon, in cubic meters per second; and

$Q_{USGS14301500}$ is the daily mean streamflow measured at USGS station 14301500, Wilson River near Tillamook, Oregon, in cubic meters per second;

$Q_{USGS14178000}$ is the daily mean streamflow measured at USGS station 14178000, North Santiam River below Boulder Creek, near Detroit, Oregon, in cubic meters per second;

$Q_{USGS14318000}$ is the daily mean streamflow measured at USGS station 14318000, Little River at Peel, Oregon, in cubic meters per second; and

$Q_{USGS14190500}$ is the daily mean streamflow measured at USGS station 14190500, Luckiamute River near Suver, Oregon, in cubic meters per second.

This equation was developed using a forward stepwise regression for the analysis documented by Buccola, Stonewall, and others (2013).

Inflow to branch 3 of the HCLM (Larison Creek) was estimated using the same approach as for $Q_{Packard}$ (after Buccola, Stonewall, and others, 2013):

$$Q_{Larison} = 10^{-1.32 \times 1.31 \log_{10} Q_{14144900}} \quad (4)$$

where

$Q_{Larison}$ is the estimated daily mean streamflow in Larison Creek at its confluence with Hills Creek Lake, in cubic meters per second; and

$Q_{HillsCreek}$ is the daily mean streamflow as estimated at historical U.S. Geological Survey station 14144900, Hills Creek above Hills Creek Reservoir, near Oakridge, Oregon, in cubic meters per second (eq. 3).

Finally, inflow to branch 4 of the HCLM (Hills Creek) was estimated using equation 3.

Outflows from Hills Creek Dam are specified on a daily basis in the HCLM. Specific release rates from the regulating outlets (structure 1) and power penstocks (structure 2) are from the CWMS database maintained by USACE.

One distributed tributary is included in the HCLM, in branch 1 (the main body of the reservoir). Values in the distributed tributary were calibrated iteratively based on a comparison with measured reservoir-surface elevations. For details, see section, “Model Updates—Hills Creek Lake Model (HCLM)—Model Fit—Water Balance.”

Temperature

Measured temperature data were available for the Middle Fork Willamette River (branch 1) and Hills Creek (branch 4) inputs to the HCLM, but water temperatures for Packard (branch 2) and Larison Creeks (branch 3) required estimation.

The temperature of inflow from the Middle Fork Willamette River to the HCLM was available from USGS station 14144800, Middle Fork Willamette River near Oakridge, Oregon, for all model years, but datasets from 2015 and 2016 were missing large intervals of data. Where data gaps were 3 hours or less, data were linearly interpolated to fill gaps. Larger gaps were filled using the regression:

$$T_{USGS14144800} = 0.8868 \times T_{14144900} + 1.2042 \quad (5)$$

where

$T_{USGS14144800}$ is the estimated hourly stream temperature at U.S. Geological Survey (USGS) 14144800, Middle Fork Willamette River near Oakridge, Oregon, in degrees Celsius; and

$T_{USGS14144900}$ is the hourly stream temperature measured at USGS 14144900, Hills Creek above Hills Creek Reservoir, near Oakridge, Oregon, in degrees Celsius.

This regression produced an adjusted coefficient of determination (R^2) value of 0.95 and was selected as producing the best fit among multiple combinations of multiple linear regression models using USGS 14144900, Hills Creek above Hills Creek Reservoir, near Oakridge, Oregon; USGS 14150290, Fall Creek above North Fork, near Lowell, Oregon; USGS 14150800, Winberry Creek near Lowell, Oregon; and USGS 14159200, South Fork McKenzie River above Cougar Lake near Rainbow, Oregon. These regression datasets were selected based on proximity and similarity in drainage characteristics. The records from Fall and Winberry Creeks were determined to be too influenced by impermeable Western Cascades-type geology (both too warm and too seasonally variable as compared to High Cascades-influenced streams) to accurately simulate the temperature of Hills Creek. Adding the South Fork McKenzie River record improved the model fit statistics, but plotting showed that the diurnal variation was too great.

Temperature data for Hills Creek (branch 2) were available from USGS 14144900 (Hills Creek above Hills Creek Reservoir, near Oakridge, Oregon). No historical or current temperature data were available for Packard or Larison Creeks. The temperatures of Packard and Larison Creeks were estimated by applying the estimated stream temperature in Salt Creek, a tributary to the Middle Fork Willamette River downstream from Hills Creek Dam, as a proxy (consistent with Buccola, Stonewall, and others, 2013; see section, “Model Updates—Middle Fork Willamette River Model (MFWM)—Temporal Inputs—Temperature” for equation and discussion). Data from Hills Creek, which is more comparable in size to Packard and Larison Creeks, was tested as a more appropriate proxy, but the resulting model fit was slightly worse, as measured at the calibration points described in section, “Model Updates—Hills Creek Lake Model (HCLM)—Model Fit—Temperature.” Given the resulting fit and for consistency with 2011 and prior model development, the temperature time series from Salt Creek was applied as a proxy.

The temperature of the distributed tributary inflow to the HCLM (branch 1) was estimated using the average annual air temperature at Hills Creek Lake and the estimated Salt Creek temperature, consistent with Buccola, Stonewall, and others (2013):

$$T_{DST1} = 0.9\,T_{air} + 0.01\,T_{Salt\ Creek} \qquad (6)$$

where

T_{DST1} is the daily mean temperature applied to distributed tributary 1, in degrees Celsius;

T_{air} is the average annual air temperature measured at Hills Creek Weather Observation station, in degrees Celsius; and

$T_{Salt\ Creek}$ is the daily mean temperature in Salt Creek as estimated for use in the MFWM (see equation in section, “Model Updates— Middle Fork Willamette River Model (MFWM)—Temporal Inputs—Temperature”), in degrees Celsius.

As discussed in section, “Model Updates—Middle Fork Willamette River Model (MFWM)—Temporal Inputs—Temperature,” the method used to estimate the temperature of Salt Creek was slightly different from that used by Buccola, Stonewall, and others (2013). For consistency and to improve model fit, the updated Salt Creek temperature estimate was applied to the 2011 HCLM (previously set up and documented by Buccola, Stonewall, and others, 2013) as well as to 2015 and 2016.

Model Fit

Water Balance

Following the protocol described in section, “Methods and Data—Model Calibration—Water Balance,” the HCLM water budget was balanced by iteratively calculating distributed tributary flow for branch 1 (the main body of the reservoir) until continued iterations did not produce a better fit between the modeled reservoir-surface elevation and the measured water-surface elevation from the CWMS database (fig. 3). Although no other parameters were changed, the 2011 HCLM water balance was recalibrated from that reported in Buccola, Stonewall, and others (2013) to account for turning off the evaporative mass loss in the model.

Temperature

The HCLM produces results of variable accuracy when modeling the thermal structure of Hills Creek Lake and the temperature of dam releases. In 2011, the model fit for the thermal structure of the lake, as compared to the floating thermistor string near Hills Creek Dam, produced a mean MAE and RMSE of about 1 degree Celsius (°C) or less, with better fit in the shallower and deeper parts of the lake and a poorer fit in the mid-depths (table 5; figs. 4–6). To depths of about 30 ft (9.1 m), the MAE is less than 0.5 °C. The temperature of release had a similar match, with the model simulating subdaily temperatures at USGS station 14145500, Middle Fork Willamette River above Salt Creek, near Oakridge, Oregon (RM 231.4, or 1.1 mi downstream from Hills Creek Dam), with a MAE of 0.29 °C (table 5). Modeled dam releases show less diurnal variation than measured temperatures (fig. 7); the larger measured variation probably reflects increases in diurnal heating and cooling over the 1.1 mi of travel from the dam to the temperature gage on the Middle Fork Willamette River.

In contrast to 2011, the HCLM does not simulate well the thermal structure of the lake or the temperature of downstream releases in 2015 and 2016. Shallow and relatively deep parts of the reservoir are simulated with reasonable accuracy in 2015 and 2016 (for example, to 30 ft [9.1 m] deep, the MAE is within 1 °C in 2015), but mid-depths in the reservoir can vary by 4 °C (MAE) or more from measured temperatures (table 5). In 2015 and 2016, the model overestimated reservoir temperature at mid-depths, mixing heat too deep into the reservoir. In 2015, for example, temperature string output suggests that the metalimnion generally remains shallower than the 60-ft (18.3-m) thermistor (fig. 5). The model, however, shows seasonal temperature variation of several degrees as deep as 120 ft (36.6 m).

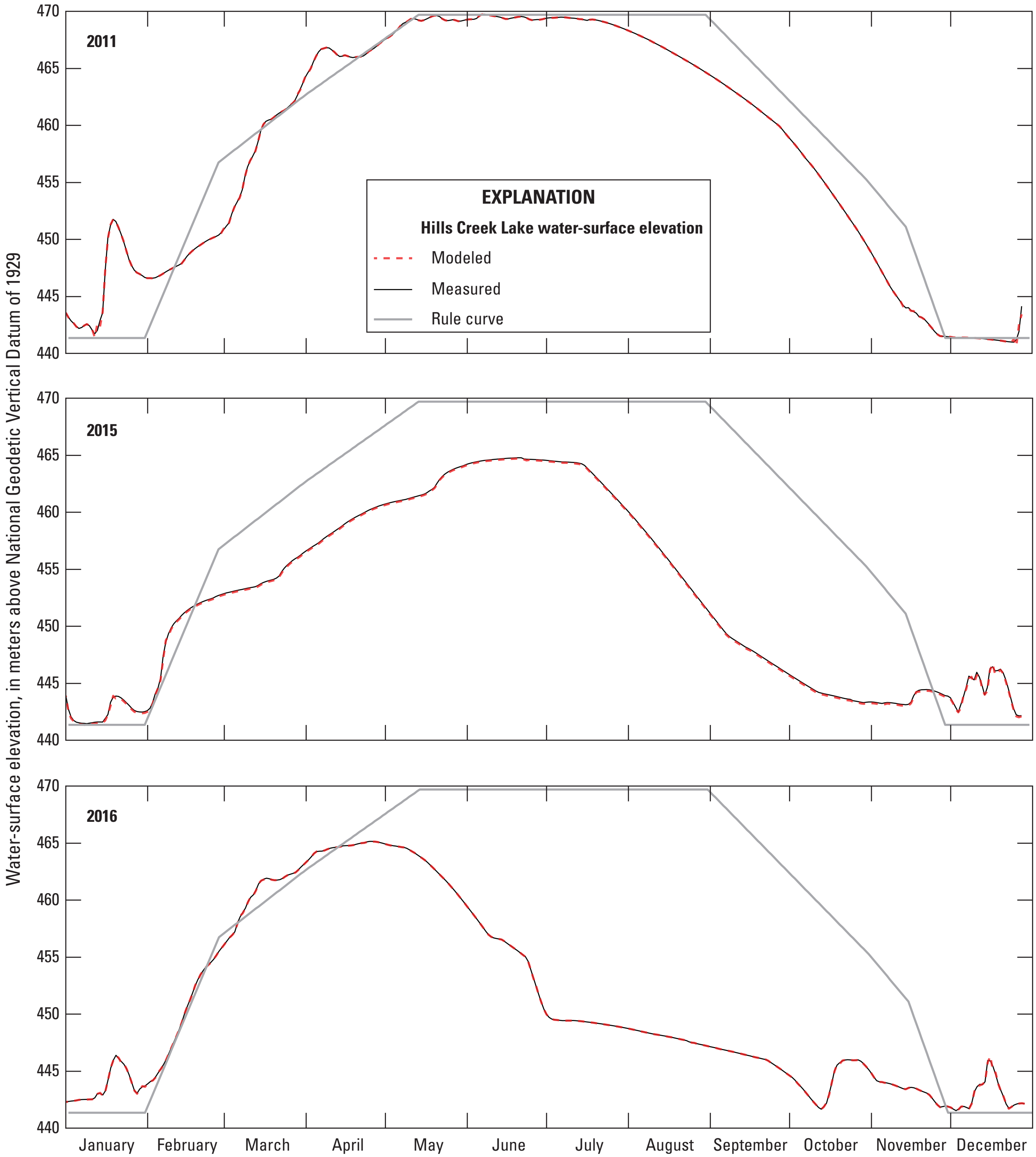


Figure 3. Daily modeled compared to measured water-surface elevation from the Hills Creek Lake Model (HCLM), northwestern Oregon, 2011, 2015, and 2016. Where not visible, red (modeled) dashed lines are plotted directly over black (measured) solid lines. The "rule curve" is the operational water-surface target for a given day and is provided for context.

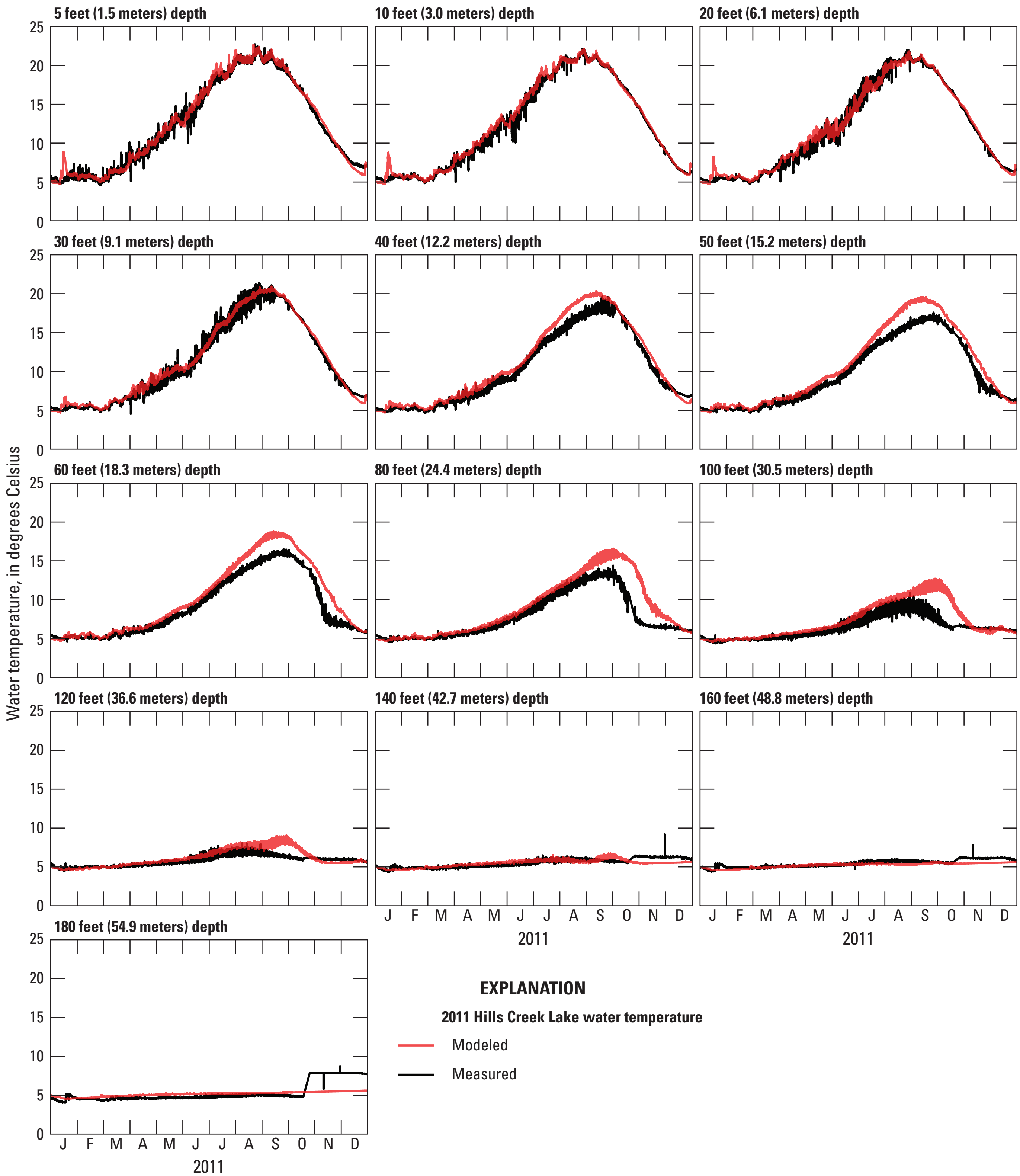


Figure 4. Continuous modeled and measured water temperatures at specific depths near the dam in Hills Creek Lake, northwestern Oregon, 2016.

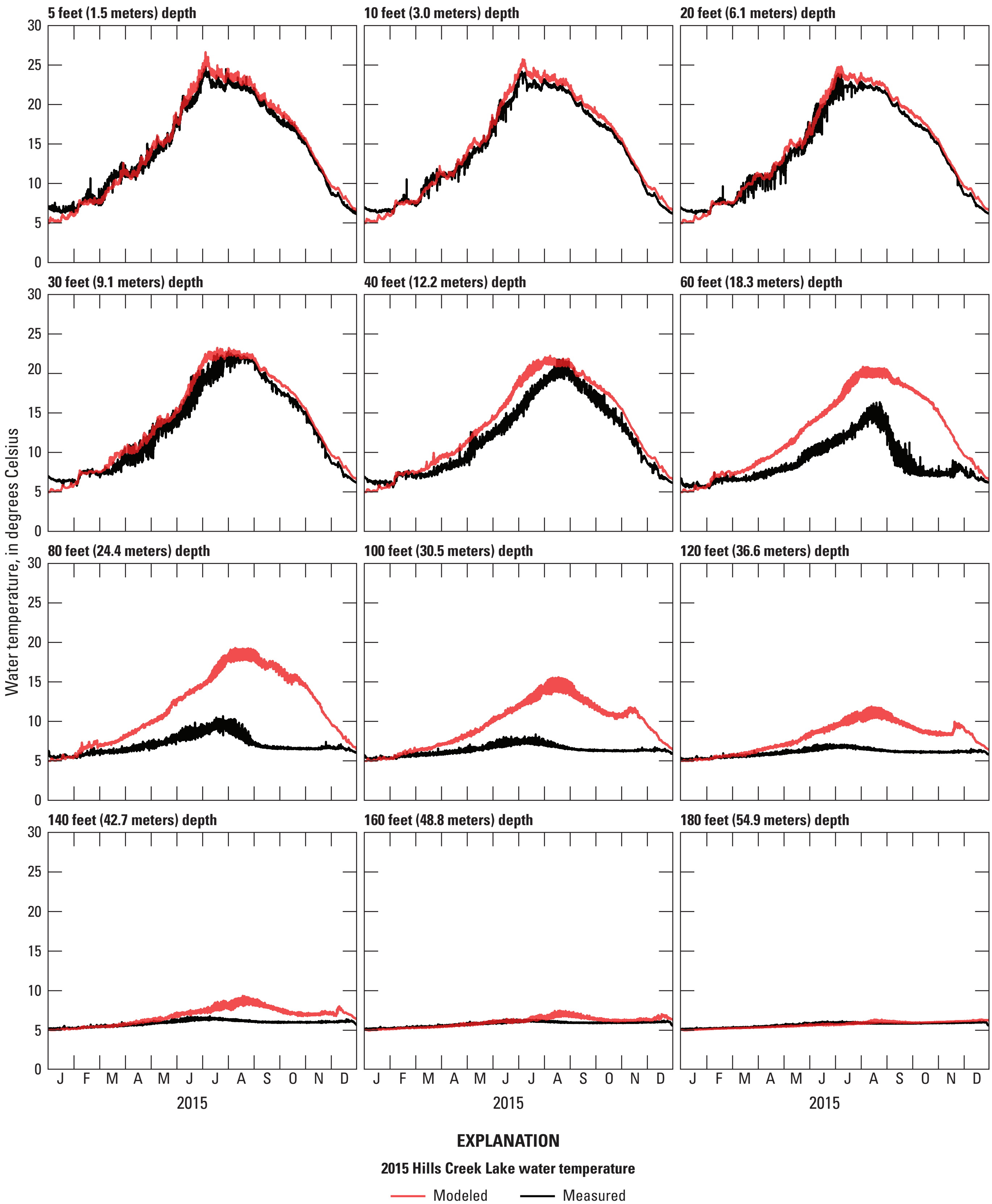


Figure 5. Continuous modeled and measured water temperatures at specific depths near the dam in Hills Creek Lake, northwestern Oregon, 2015.

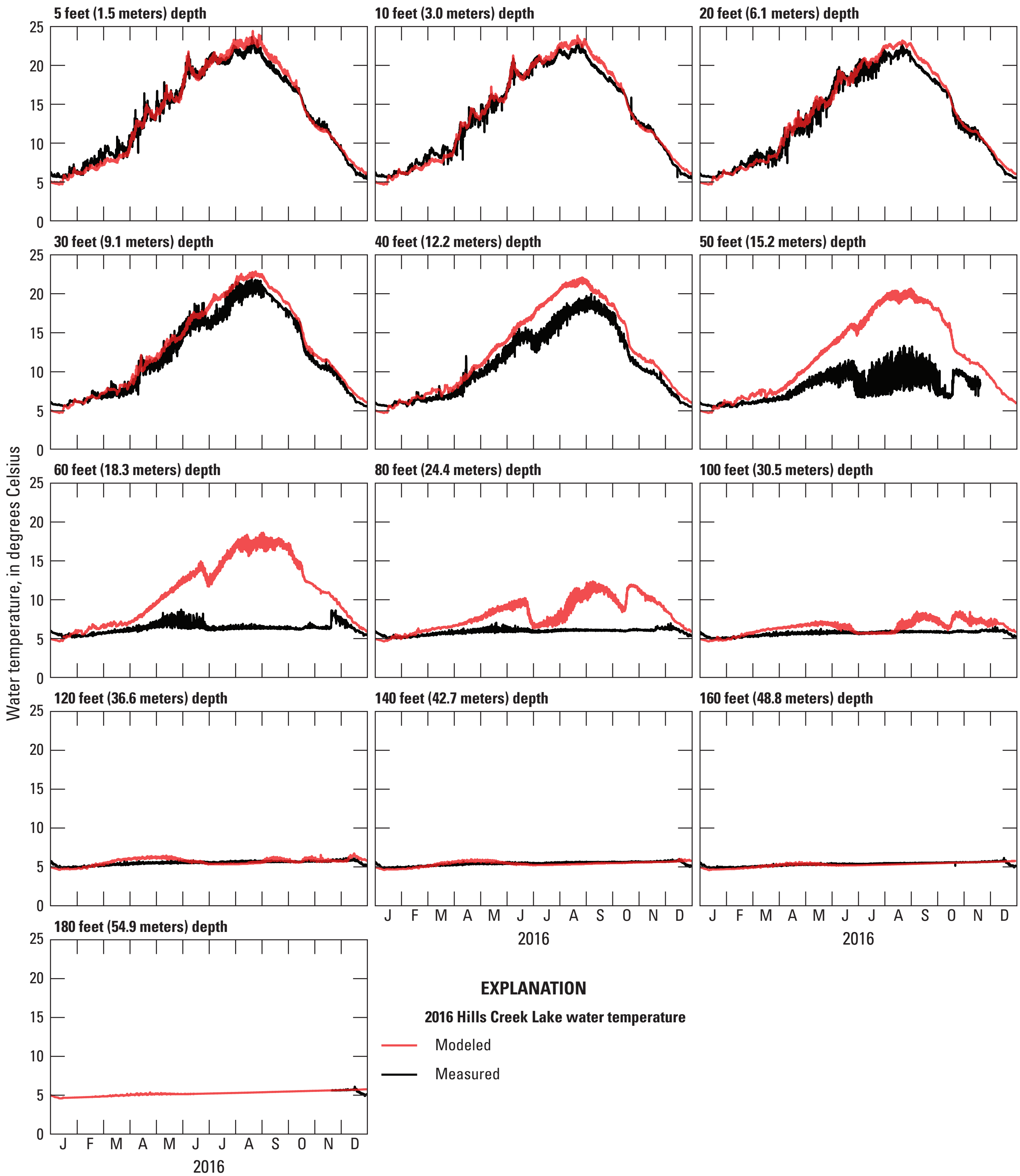


Figure 6. Continuous modeled and measured water temperatures at specific depths near the dam in Hills Creek Lake, northwestern Oregon, 2016.

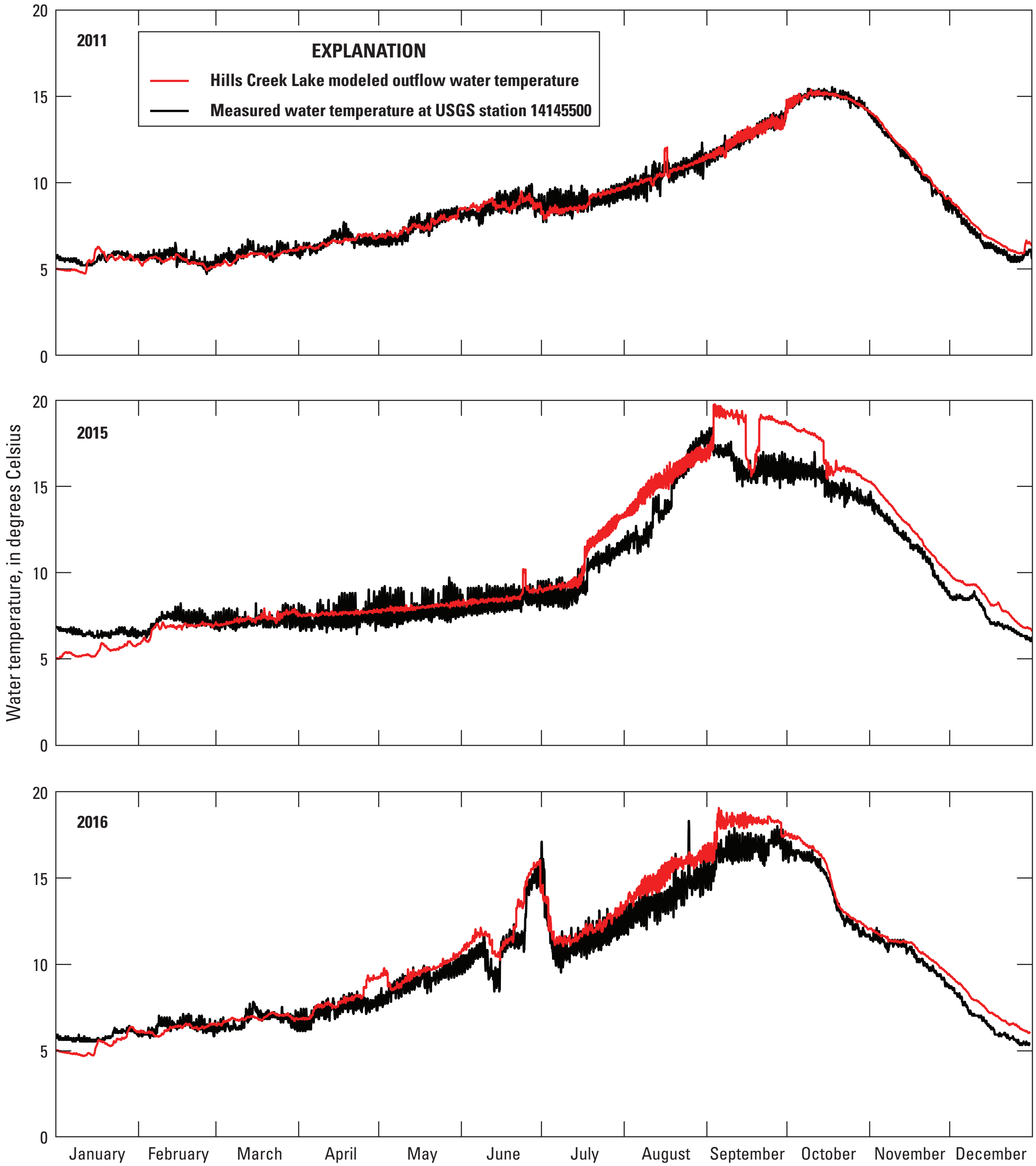


Figure 7. Continuous modeled outflow water temperatures from Hills Creek Lake and measured water temperatures at U.S. Geological Survey (USGS) station 14145500 (Middle Fork Willamette River above Salt Creek, Oregon), northwestern Oregon, 2011, 2015, and 2016.

Model performance in simulating dam release temperatures is slightly better, as the elevation of the regulating outlet and power penstocks in Hills Creek Dam often coincide with the better-performing depths of reservoir simulation. However, the model tends to overestimate release temperatures (fig. 7) and sometimes shows abrupt fluctuations in release temperatures that are not indicated in the measured temperature record. In 2015 and 2016, the ME suggests that the model overall is biased too warm by 0.60 and 0.54 °C, respectively; however, the subdaily MAE fit statistics are within 1 °C (table 5).

WEST Consultants, Inc. (2004a) and Buccola, Stonewall, and others (2013) noted that the HCLM was not always able to simulate temperatures accurately. Buccola, Stonewall, and others (2013) changed many parameters of the HCLM as originally configured by WEST Consultants, Inc. (2004a) but noted that calibration efforts to improve the simulation of thermal structure in the reservoir often resulted in poorer results for outflow temperatures, and vice versa. The model seems to be most sensitive to the configuration of the dam outflow structures, including depth, width, and their vertical range of influence (or, whether artificial limits to the depths available to draw water from were included in the model).

In large reservoirs like Hills Creek Lake, the combination of relatively long residence time and large surface area reduces the influence of inflow temperatures and increases the influence of solar radiation, wind, and structure configuration. Efforts undertaken in this study confirmed that the HCLM is relatively insensitive to inflow temperatures or rates but is more sensitive to the configuration of structures governing outflow from the dam. Substituting different meteorology datasets from alternate data sources (for example, the Lookout Point weather station instead of the Hills Creek weather station) had little effect on model results. Attempts to change the mixing dynamics of the lake by increasing or decreasing the wind sheltering coefficient (WSC, a parameter that allows the wind speed measured at a weather station to be increased or decreased at the reservoir surface) showed that the model was sensitive to this parameter, but no change in WSC value could improve the fit compared to that of Buccola, Stonewall, and others (2013). Iterative adjustments to the structure configuration in the model showed that the model is extremely sensitive to the elevation and width of structures in the dam. Like WSC, however, no combination of reasonable parameters was able to yield a better model fit than that in Buccola, Stonewall, and others (2013) for 2011, 2015, or 2016. As a result, the WSC and structure configurations in the HCLM are unchanged from those used by Buccola, Stonewall, and others (2013).

The limitations of the HCLM may reflect complex bathymetry in the reservoir that cannot be accurately simulated by a laterally averaged model, particularly when the reservoir is low and stratified. Indeed, the bathymetry of Hills Creek Lake near the dam is complex, with the interaction of the Hills Creek and Middle Fork Willamette arms of the reservoir and a narrow, “canyon-like” feature noted near the dam (WEST Consultants, Inc., 2004a; Buccola, Stonewall, and others, 2013). The HCLM was originally constructed using data from 2002 and then checked against data from 1971 and 1972 (WEST Consultants, Inc., 2004a). The 2013 model update included 2002, 2006, 2008, and 2011. The reservoir filled in all of these years (U.S. Army Corps of Engineers, 2022). In 2015, however, the reservoir reached a maximum elevation of 1,524.9 ft (464.8 m), which is 16 ft (4.9 m) below the maximum rule curve elevation of 1,541 ft (469.7 m; fig. 3). Similarly, in 2016, HCLM reached a maximum elevation of 1,525.9 ft (465.1 m), which is 15.1 ft (4.6 m) below the maximum rule curve elevation.

Given the good model fit in 2011 (including other years simulated in previous modeling exercises), the poor model fit in 2015 and 2016, the complex bathymetry, and the sensitivity to structure elevation and width, the HCLM can be considered to be reliable in years in which the reservoir fills but should be used with caution in years in which the reservoir level remains low year-round. These considerations apply to Hills Creek Lake and reaches of the Middle Fork Willamette River downstream from Hills Creek Dam. However, as discussed in greater detail in section, “Model Updates—Middle Fork Willamette River Model (MFWM)—Model Fit,” the influx of three large tributaries to the Middle Fork Willamette River between Hills Creek Dam and the uppermost reaches of Lookout Point Lake dilute the influence of Hills Creek Dam releases such that the effect on river temperature by USGS station 14148000 (Middle Fork Willamette River below North Fork, near Oakridge, Oregon) is relatively small. As a result, model fit in the LOP-DEX-M is not substantially affected when using modeled inflow temperatures compared to measured inflow temperatures.

Middle Fork Willamette River Model (MFWM)

Description

The MWFM encompasses the Middle Fork Willamette River from the outflow of Hills Creek Dam at RM 232.5 to the head of Lookout Point Lake at approximately RM 218.7, a distance of approximately 13.8 mi (22.3 km). As measured at USGS 14148000 (Middle Fork Willamette River below North Fork, near Oakridge, Oregon), near the head of Lookout Point Lake, the drainage basin is 930 mi^2, with a mean annual precipitation of 62.9 in. (U.S. Geological Survey, 2022). Much of the Middle Fork Willamette River drainage basin is in the highly permeable High Cascades geologic province, which is characterized by large spring complexes contributing abundant groundwater to headwater streams in the basin (Branscomb and others, 2002; Risley and others, 2008). Three large, unregulated tributaries enter the Middle Fork Willamette River in this reach—Salt Creek, Salmon Creek, and the North Fork Middle Fork Willamette River.

Model History and Domain

The MFWM was built by USGS (Buccola, Stonewall, and others, 2013) to connect the HCLM and LOP-DEX-M. It was originally built in CE-QUAL-W2 version 3.7 and set up for calendar years 2002, 2006, 2008, and 2011. The MWF model consists of one waterbody and one branch, comprising 86 (84 active) model segments. Model segments range from 134.11 to 804.67 m long and layers are 0.2 m high. Three tributaries are included in the model. A distributed tributary is used to balance the water budget. No structures are included in the Middle Fork Willamette River Model.

Bathymetric Grid and Non-Temporal Parameters

No changes were made to the model grid or to other non-temporal parameters in the MFWM, except to convert the model grid file to the new, more readable .csv format.

Temporal Inputs

Meteorology

Meteorological inputs to the MFWM for 2015 and 2016 used the same data sources as 2011 and other previously calibrated years (Buccola, Stonewall, and others, 2013; table 4). For consistency with the other river models in the domain (Stratton Garvin and others, 2022), precipitation was turned off in the MFWM. This change had a negligible effect on the model fit.

Streamflow

Inflow to the MFWM is the outflow from Hills Creek Dam. This can be specified based on measured data or by connecting the MFWM to the outflow from the HCLM model, depending on the desired model use. To set up and calibrate the HCLM and MFWM for calendar years 2011, 2015, and 2016, measured daily data from the USACE CWMS database were used. The modeled hourly outflow from the HCLM was implemented automatically as inflow to branch 1 in the MFWM.

No data for the tributary inflows to the MFWM were available for 2011, 2015, or 2016. However, all three tributaries to the MFWM had been gaged in the past, which allowed the development of regression models to estimate streamflow. Although they were not included in that report, equations 7, 8, and 9 were developed by Buccola, Stonewall, and others (2013) to estimate inflow from Salt Creek (tributary 1), Salmon Creek (tributary 2), and the North Fork Middle Fork Willamette River (tributary 3), respectively. Contrary to other streamflow estimation equations included in this report, equations 7, 8, and 9 were developed in cubic feet per second and then converted to cubic meters per second. The equations are:

$$\log_{10} Q_{Salt} = \begin{pmatrix} -0.0296 \\ +0.1556 \log_{10} Q_{USGS14185000} \\ +0.6601 \log_{10} Q_{HillsCreekInflow} \\ -0.0877 \log_{10} Q_{USGS14325000} \\ -0.0742 \log_{10} Q_{USGS14301500} \\ +0.1806 \log_{10} Q_{USGS14178000} \end{pmatrix} \times 0.0283 \quad (7)$$

where

Q_{Salt} is the estimated daily mean streamflow in Salt Creek at historical U.S. Geological Survey (USGS) station 14146000, Salt Creek near Oakridge, Oregon, in cubic meters per second;

$Q_{HillsCreekInflow}$ is the estimated daily mean inflow to Hills Creek Lake, in cubic feet per second (see eq. 1);

$Q_{USGS14185000}$ is the daily mean streamflow measured at USGS station 14185000, South Santiam River below Cascadia, Oregon, in cubic feet per second;

$Q_{USGS14325000}$ is the daily mean streamflow measured at USGS station 14325000, South Fork Coquille River at Powers, Oregon, in cubic feet per second;

$Q_{USGS14301500}$ is the daily mean streamflow measured at USGS station 14301500, Wilson River near Tillamook, Oregon, in cubic feet per second; and

$Q_{USGS14178000}$ is the daily mean streamflow measured at USGS station 14178000, North Santiam River below Boulder Creek, near Detroit, Oregon, in cubic feet per second.

$$\log_{10} Q_{Salmon} = \begin{pmatrix} -0.0818 \\ +0.2485 \log_{10} Q_{USGS14178000} \\ +0.5850 \log_{10} Q_{HillsCreekInflow} \\ +0.1396 \log_{10} Q_{USGS14185000} \\ -0.0815 \log_{10} Q_{USGS14325000} \\ +0.0020 \log_{10} Q_{USGS14171000} \\ -0.0398 \log_{10} Q_{USGS14301500} \\ +0.045 \log_{10} Q_{USGS14190500} \end{pmatrix} \times 0.0283 \quad (8)$$

where

Q_{Salmon} is the estimated daily mean streamflow in Salmon Creek at historical U.S. Geological Survey (USGS) station 14146500, Salmon Creek near Oakridge, Oregon, in cubic meters per second;

$Q_{USGS14178000}$ is the daily mean streamflow measured at USGS station 14178000, North Santiam River below Boulder Creek, near Detroit, Oregon, in cubic feet per second;

$Q_{HillsCreekInflow}$ is the estimated daily mean inflow to Hills Creek Lake, in cubic feet per second (see eq. 1);

$Q_{USGS14185000}$ is the daily mean streamflow measured at USGS station 14185000, South Santiam River below Cascadia, Oregon, in cubic feet per second;

$Q_{USGS14325000}$ is the daily mean streamflow measured at USGS station 14325000, South Fork Coquille River at Powers, Oregon, in cubic feet per second;

$Q_{USGS14171000}$ is the daily mean streamflow measured at USGS station 14171000, Marys River near Philomath, Oregon, in cubic feet per second;

$Q_{USGS14301500}$ is the daily mean streamflow measured at USGS station 14301500, Wilson River near Tillamook, Oregon, in cubic feet per second; and

$Q_{USGS14190500}$ is the daily mean streamflow measured at USGS station 14190500, Luckiamute River near Suver, Oregon, in cubic feet per second.

$$\log_{10} Q_{NFMK} = \begin{pmatrix} 0.1269 \\ +\,0.05980 \log_{10} Q_{USGS14171000} \\ +\,0.51500 \log_{10} Q_{HillsCreekInflow} \\ +\,0.30530 \log_{10} Q_{USGS14185000} \\ +\,0.21525 \log_{10} Q_{USGS14178000} \\ -\,0.10700 \log_{10} Q_{USGS14301500} \\ -\,0.05530 \log_{10} Q_{USGS14325000} \\ +\,0.08650 \log_{10} Q_{USGS14190500} \end{pmatrix} \times 0.0283 \quad (9)$$

where

Q_{NFMK} is the daily mean streamflow in the North Fork Middle Fork Willamette River at historical U.S. Geological Survey (USGS) station 14147500, North Fork Middle Fork Willamette River near Oakridge, Oregon, in cubic meters per second;

$Q_{USGS14171000}$ is the daily mean streamflow measured at USGS station 14171000, Marys River near Philomath, Oregon, in cubic feet per second;

$Q_{HillsCreekInflow}$ is the estimated daily mean inflow to Hills Creek Lake, in cubic feet per second (see eq. 1);

$Q_{USGS14185000}$ is the daily mean streamflow measured at USGS station 14185000, South Santiam River below Cascadia, Oregon, in cubic feet per second;

$Q_{USGS14178000}$ is the daily mean streamflow measured at USGS station 14178000, North Santiam River below Boulder Creek, near Detroit, Oregon, in cubic feet per second;

$Q_{USGS14301500}$ is the daily mean streamflow measured at USGS station 14301500, Wilson River near Tillamook, Oregon, in cubic feet per second;

$Q_{USGS14325000}$ is the daily mean streamflow measured at USGS station 14325000, South Fork Coquille River at Powers, Oregon, in cubic feet per second; and

$Q_{USGS14190500}$ is the daily mean streamflow measured at USGS station 14190500, Luckiamute River near Suver, Oregon, in cubic feet per second.

A distributed tributary was applied to the single branch in the MFWM. This was calibrated iteratively, as discussed in section, “Model Updates—Middle Fork Willamette River Model (MFWM)—Model Fit—Streamflow.”

Temperature

The temperature of inflow to the MFWM can be specified using modeled outflow from the HCLM or measured data from USGS monitoring station 14145500 (Middle Fork Willamette River above Salt Creek, near Oakridge, Oregon). Model fit statistics from simulations using modeled and measured inflow temperatures are reported in section, “Model Updates—Middle Fork Willamette Model (MFWM) —Model Fit—Temperature.”

Of the three tributaries to the MFWM, one had temperature data available, one had its temperature estimated using a proxy record, and one had its temperature estimated using a regression equation. The North Fork Middle Fork Willamette River (tributary 3) used data from USGS 14147500 (North Fork Middle Fork Willamette River near Oakridge, Oregon). Salmon Creek (tributary 2) applied temperature records from USGS 14147500 as a proxy (consistent with Buccola, Stonewall, and others, 2013).

The temperature time series for Salt Creek was estimated using a multiple linear regression between data collected by the ODEQ and two other datasets from sites in the Willamette River Basin. The final equation is:

$$\begin{aligned} T_{SaltCreek} &= (0.2954 \times T_{USGS14144800}) \\ &+ (0.4426 \times T_{USGS14180300}) \\ &+ \ 1.8106 \end{aligned} \quad (10)$$

where

$T_{SaltCreek}$ is the estimated hourly stream temperature in Salt Creek at station 28007-ORDEQ, Salt Creek at Road 5875, in degrees Celsius;

$T_{USGS14144800}$ is the hourly stream temperature measured at U.S. Geological Survey (USGS) station 14144800, Middle Fork Willamette River near Oakridge, Oregon, in degrees Celsius; and

$T_{USGS14180300}$ is the hourly stream temperature measured at USGS station 14180300, Blowout Creek near Detroit, Oregon, in degrees Celsius.

This approach is different from that used by Buccola, Stonewall, and others (2013), but it yielded a better goodness-of-fit.

Model Fit

Streamflow

Data from two streamgages on the Middle Fork Willamette River between Hills Creek Dam and Lookout Point Lake were available for comparison and calibration of model streamflow (fig. 8). Modeled streamflow near the upstream boundary of the model (segment 11) match measured streamflow at USGS station 14145500 (Middle Fork Willamette River above Salt Creek) with high accuracy, as would be expected given the specified upstream head boundary. To better simulate measured streamflow at USGS station 14148000 (Middle Fork Willamette River below North Fork, near Oakridge), a distributed tributary was applied to the single branch in the MFWM. This distributed tributary was calculated iteratively using data from USGS station 14148000 until better fit could not be achieved with continued iteration (fig. 8).

Temperature

Temperature records for comparison within the MFWM domain were available from USGS stations 14145500 (Middle Fork Willamette River above Salt Creek, Oregon) and 14148000 (Middle Fork Willamette River below North Fork near Oakridge, Oregon). The temperature at model segment 11 (USGS station 14145500, Middle Fork Willamette River above Salt Creek, Oregon) closely reflects the specified inflow temperature and, when the models are run in series, is thus dependent on the outflow temperature from the HCLM (fig. 9). For 2011, the subdaily MAE at segment 11 using modeled inflow from the HCLM is 0.30 °C (table 6). For 2015 and 2016, however, the model fit reflects the relatively poor performance of the HCLM with MAE values of 1.03 and 0.77 °C, respectively. Downstream at segment 80 (USGS 14148000, Middle Fork Willamette River below North Fork near Oakridge, Oregon), the MAE using modeled inflow improves to 0.70 °C or less. This improvement probably reflects the relative accuracy of the MFWM (which, using measured inflow, produced subdaily MAE values of 0.50 °C or less at segment 80) and the importance of the large, groundwater-dominated tributaries to the MFWM. Subdaily bias in the MFWM is minimal (≤0.20 °C, as modeled using measured inputs); however, during the relatively low-flow years of 2015 and 2016, the model tended to overestimate diurnal variation (primarily by overestimating maximum temperatures) during the late spring or summer through early autumn (fig. 10). As noted by Buccola, Stonewall, and others (2013), this may be a function of the location of the USGS 14148000 temperature sensor on the left bank of the Middle Fork Willamette River, which is deeper and shows less temperature variability than the right bank.

Lookout Point Lake and Dexter Reservoir Model (LOP-DEX-M)

Description

Lookout Point Dam is a multipurpose storage project authorized for flood risk management, irrigation, navigation, hydropower, and other purposes (U.S. Army Corps of Engineers, 2019b). It is operated jointly with Dexter Dam, a reregulation project immediately downstream. Lookout Point Dam is located on the Middle Fork Willamette River at RM 206.9, approximately 25.6 mi (41.2 km) downstream from Hills Creek Dam. Lookout Point Dam impounds Lookout Point Lake for approximately 11.8 mi (19.0 km) to approximately RM 218.7 on the Middle Fork Willamette River (the downstream boundary of the Middle Fork Willamette River Model). Lookout Point Reservoir is long and narrow and has no major tributaries. Near the dam and at full pool, the reservoir reaches a maximum depth of 237.7 ft (72.5 m). Lookout Point Dam has five spillway gates, four regulating outlets, and three power penstocks, which allow outflow from the dam at three different elevations (table 2; Buccola, Stonewall, and others, 2013). As of 2019, Lookout Point Dam is operated as a power-peaking project (U.S. Army Corps of Engineers, 2019b).

Dexter Dam is a multipurpose storage project operated primarily as a reregulation dam for Lookout Point Dam. Located at RM 203.7 near the town of Lowell, Dexter Dam impounds the Middle Fork Willamette River for approximately 3.2 mi (5.1 km) to Lookout Point Dam upstream. No major tributaries enter Dexter Reservoir. At its deepest point, Dexter Reservoir is 61.1 ft (18.6 m) deep. Dexter Dam has seven spillway gates, one power penstock, and no regulating outlets, allowing outflow from two elevations in the reservoir (table 2; Buccola, Stonewall, and others, 2013).

Model History and Domain

Lookout Point Lake and Dexter Reservoir are modeled as a single model in CE-QUAL-W2. The LOP-DEX-M was originally developed by WEST Consultants, Inc. (2004b) using data from 2002, which was then used to perform a 30-year simulation from January 1, 1970, to December 31, 2000. The LOP-DEX-M was originally built in CE-QUAL-W2 version 3.1 (Cole and Wells, 2001; it was subsequently updated to CE-QUAL-W2 version 3.7 and set up to simulate calendar years 2002, 2006, 2008, and 2011 by USGS (Buccola, Stonewall, and others, 2013). As part of that update, the number and configuration of structures included in the model was modified to conform with actual conditions (Buccola, Stonewall, and others, 2013).

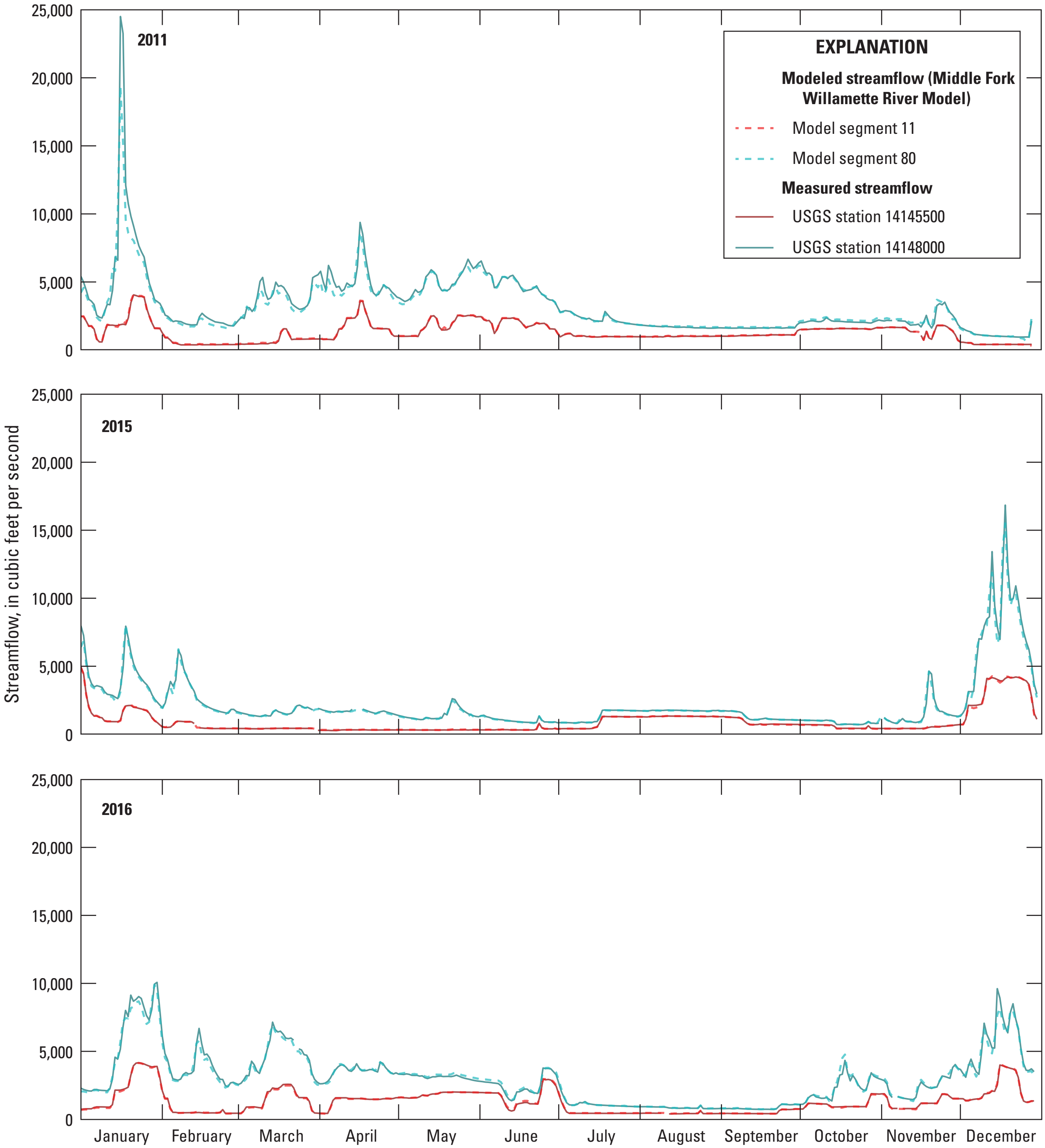


Figure 8. Daily modeled streamflow from the Middle Fork Willamette River Model (MFWM) at segments 11 and 80 and measured streamflow at U.S. Geological Survey (USGS) stations 14145500 (Middle Fork Willamette River above Salt Creek, Oregon) and 14148000 (Middle Fork Willamette River below North Fork near Oakridge, Oregon), northwestern Oregon, 2011, 2015, and 2016. Where not visible, dashed lines are plotted directly over solid lines.

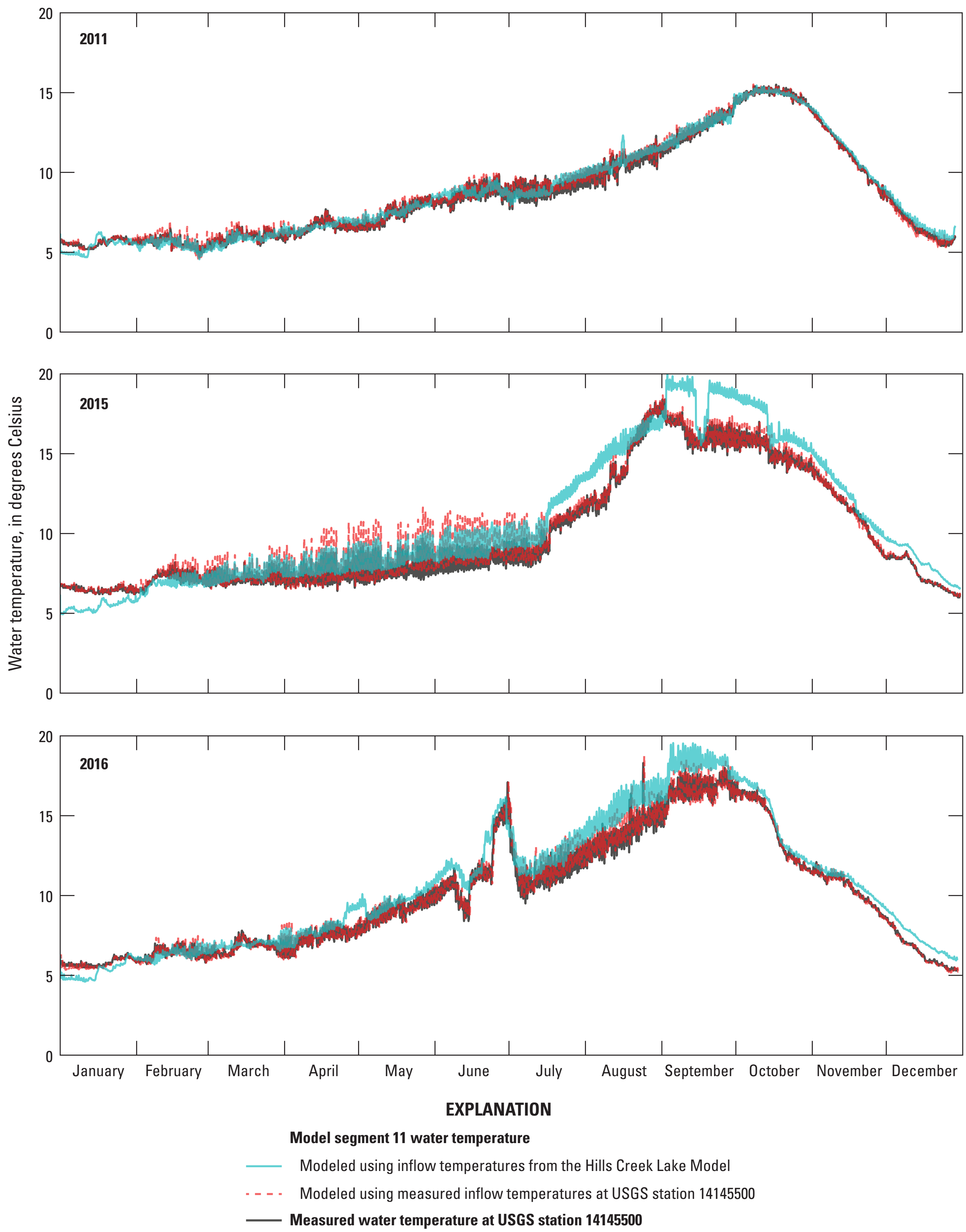


Figure 9. Continuous modeled water temperatures from the Middle Fork Willamette River Model (MFWM) at segment 11 and measured temperatures at U.S. Geological Survey (USGS) station 14145500 (Middle Fork Willamette River above Salt Creek, Oregon), northwestern Oregon, 2011, 2015, and 2016. Solid blue line indicates results simulated using inflow temperatures modeled by the Hills Creek Lake Model (HCLM) and red dashed line indicates results simulated using inflow temperatures measured at USGS station 14145500 (Middle Fork Willamette River above Salt Creek, Oregon).

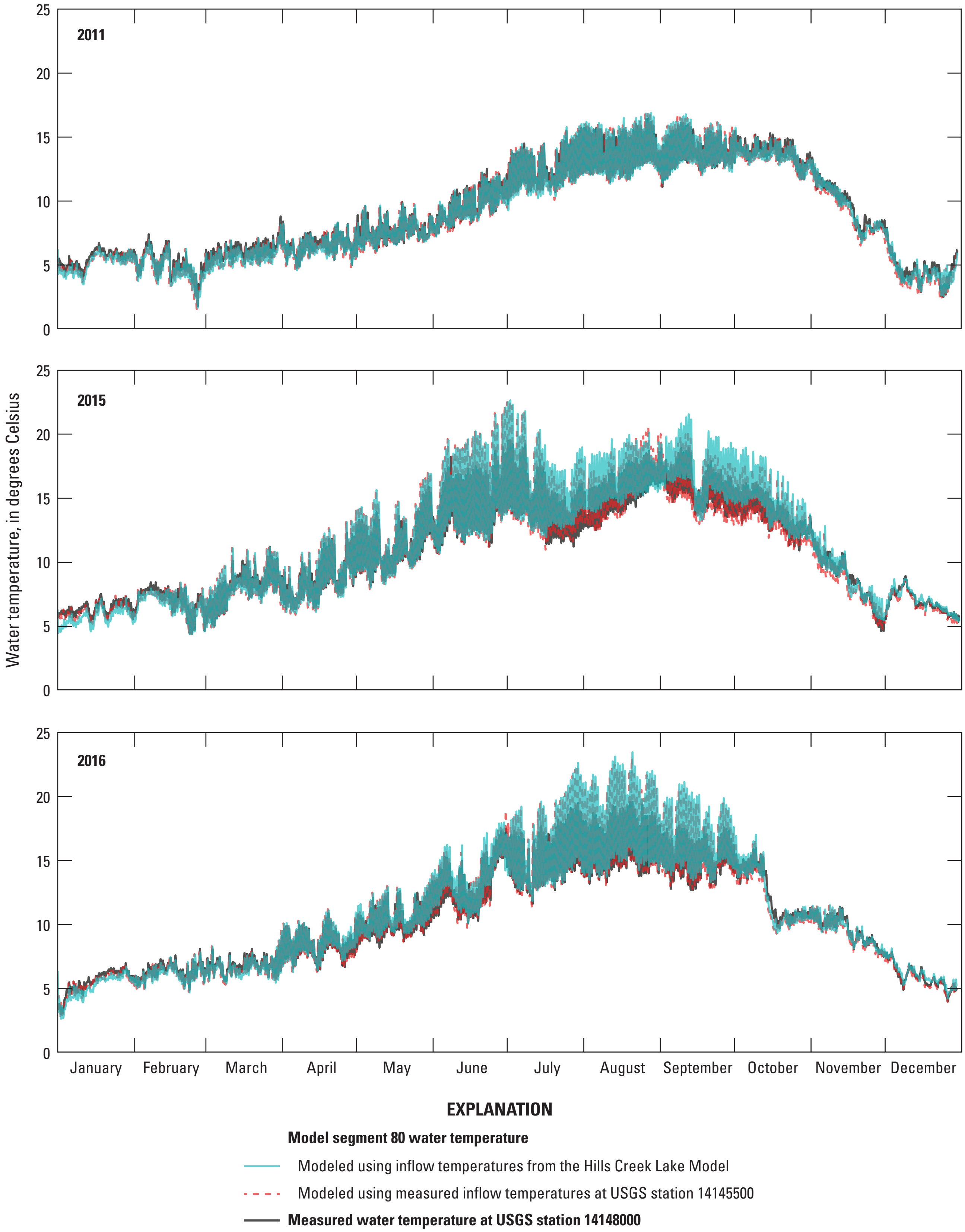


Figure 10. Continuous modeled water temperatures from the Middle Fork Willamette River Model (MFWM) at segment 80 and measured temperatures at U.S. Geological Survey (USGS) station 14148000 (Middle Fork Willamette River below North Fork near Oakridge, Oregon), northwestern Oregon, 2011, 2015, and 2016. Solid blue line indicates results simulated using inflow temperatures modeled by the Hills Creek Lake Model (HCLM) and red dashed line indicates results simulated using inflow temperatures measured at USGS station 14145500 (Middle Fork Willamette River above Salt Creek, Oregon).

The LOP-DEX-M consists of two waterbodies and two branches. Waterbody 1 and branch 1 extend from segments 2 to 36 and represent Lookout Point Lake. Waterbody 2 and branch 2 include segments 39 through 57 and represent Dexter Reservoir. No tributaries are included in the model. Segment lengths are 503 m long and in branch 1 (LOP) and 249.1 m long in branch 2 (DEX). All model layers are 1 m high. A total of five structures are included in the model: three in branch 1 and two in branch 2. The structures in branch 1 represent outlets from Lookout Point Dam and include the spillway, power penstock, and regulating outlets. The structures in branch 2 represent outlets from Dexter Dam and include the spillway and power penstocks (table 2).

The model changes in this report include (1) updating the 2011 LOP-DEX-M documented by Buccola, Stonewall, and others (2013) to CE-QUAL-W2 version 4.2 (USGS edition 7), (2) setting up the LOP-DEX-M for calendar years 2015 and 2016, and (3) checking and calibrating model results for 2011, 2015, and 2016, as needed. For a description of updates to Dexter Dam structure bottom selective withdrawal limits, see appendix 2.

Bathymetric Grid and Non-Temporal Parameters

No changes were made to the bathymetric grid except to update it to the new, more readable .csv file format and to set the initial water-surface elevation to match the start of each simulation. The only other change to non-temporal parameters was to turn off evaporative mass loss for consistency with the other reservoir models.

Temporal Inputs

Meteorology

Meteorological inputs to the LOP-DEX-M for 2015 and 2016 used the same data sources as 2011 and other previously calibrated years (Buccola, Stonewall, and others, 2013; table 4). For consistency with the other models in the domain, precipitation and evaporative mass loss were turned off in the LOP-DEX-M.

Streamflow

No tributaries are included in the LOP-DEX-M. When run independently, inflow to the LOP-DEX-M is specified with data from USGS monitoring station 14148000 (Middle Fork Willamette River below North Fork, near Oakridge, Oregon). When linked to the MFWM upstream (as in this report), inflow to the model is specified as the outflow from the MFWM.

The water budgets for the Lookout Point Lake and Dexter Reservoir waterbodies of the LOP-DEX-M were each balanced using a distributed tributary. Values in the distributed tributary were calibrated iteratively based on a comparison with measured reservoir-surface elevations as generally described in section, "Methods and Data—Model Calibration—Water Balance."

Temperature

When run independently, the temperature of inflow to the LOP-DEX-M is specified with data from USGS 14148000 (Middle Fork Willamette River below North Fork, near Oakridge, Oregon). When linked to the MFWM upstream (as in this report), the temperature of inflow to the model is specified as the outflow from the MFWM. The temperature of distributed tributaries in Lookout Point Lake and Dexter Reservoir (branches 1 and 2) was estimated using the average annual air temperature at Hills Creek Lake and the estimated Salt Creek temperature (eq. 10), identical to the approach documented by Buccola, Stonewall, and others (2013).

Model Fit

Water Balance

The LOP-DEX-M water budget was balanced in a two-step process. First, a distributed tributary for branch 1 (Lookout Point Lake) was iteratively calculated until the modeled reservoir-surface elevation matched the measured water-surface elevation from the CWMS database, following the protocol described in section, “Methods and Data—Model Calibration—Water Balance” (fig. 11). Once branch 1 was balanced, branch 2 (Dexter Reservoir) was balanced following a similar process. The volume of the Dexter Reservoir branch of the DEX-LOP-M is small relative to its inflow and outflow rates and thus is sensitive to small errors in the water balance. As a result, the water balance for branch 2 was initiated by estimating the daily average difference between inflow and outflow, then iterating until continued iteration failed to achieve a better fit between the modeled water-surface elevation and the measured water-surface elevation from the CWMS database (fig. 12). The 2011 submodel water balance was recalibrated from that reported by Buccola, Stonewall, and others (2013) because evaporative mass loss was turned off, which required a modification to the distributed tributary flow rates.

Temperature

As with the MFWM, two versions of the LOP-DEX-M were simulated: one using measured inflow temperatures and one using modeled inflow temperatures. For 2015 and 2016, the difference in MAE between measured-input and modeled-input results from the MFWM near its downstream boundary is about 0.2–0.3 °C (table 7). After routing water and heat through the LOP-DEX-M, this difference decreases to less than 0.1 °C for all years modeled when comparing modeled outflow from Dexter Dam to measured temperatures at USGS station 14150000 (Middle Fork Willamette River near Dexter, Oregon). This reduction provides further evidence that, although not ideal, errors in the HCLM for 2015 and 2016 baseline conditions are not meaningfully propagated into the Middle Fork Willamette or Willamette Rivers downstream from Dexter Dam.

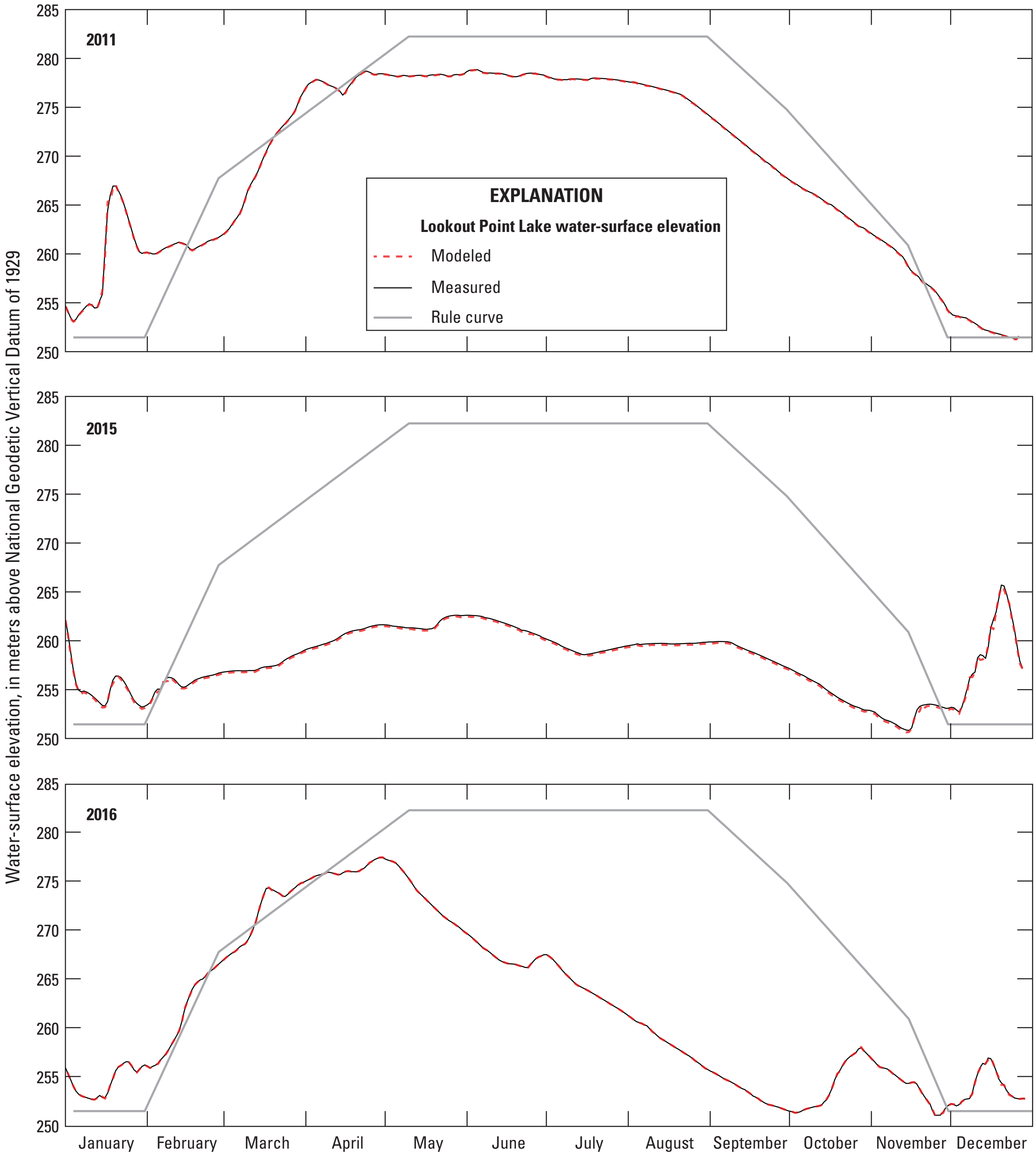


Figure 11. Daily modeled compared to measured water-surface elevation at Lookout Point Lake from the Lookout Point Lake and Dexter Reservoir Model (LOP-DEX-M), northwestern Oregon, 2011, 2015, and 2016. Where not visible, red (modeled) dashed lines are plotted directly over black (measured) solid lines. The “rule curve” is the operational water-surface target for a given day and is provided for context.

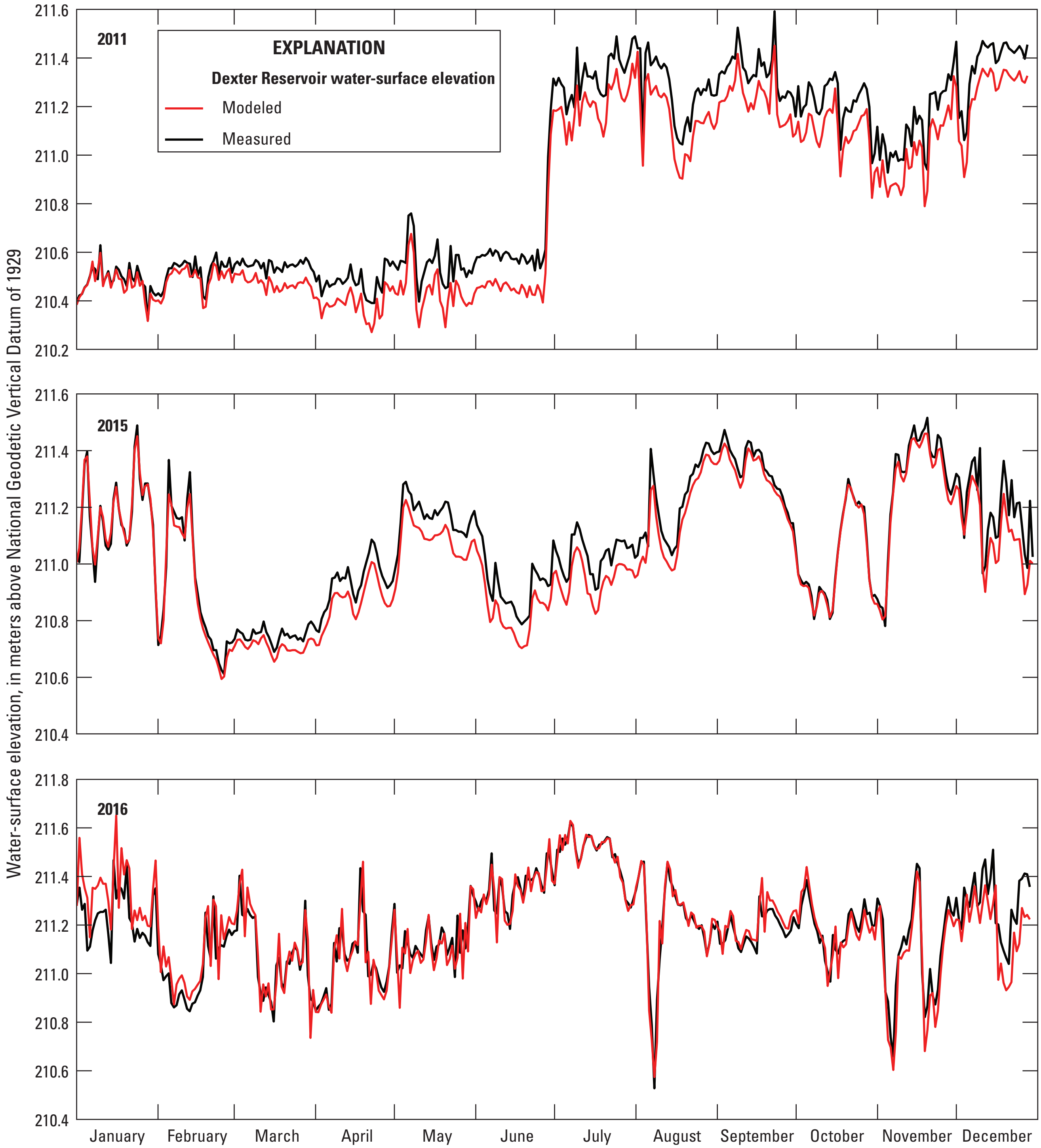


Figure 12. Daily modeled compared to measured water-surface elevation at Dexter Reservoir from the Lookout Point and Dexter Reservoir Model (LOP-DEX-M), northwestern Oregon, 2011, 2015, and 2016. Where not visible, red (modeled) lines are plotted directly over black (measured) lines.

Modeled temperatures in Lookout Point Lake match well with measured values, as compared to the floating thermistor string near Lookout Point Dam, in all modeled years to depths of at least 9 m in both versions of the model using measured and modeled inflow, consistent with results reported by Buccola, Stonewall, and others (2013; figs. 13–18). Measured temperature values without corresponding modeled values reflect periods when the lake was shallower than the total depth of the temperature string; for example, in 2015, the reservoir never filled to 180 ft (54.9 m) in depth; as a result, measured temperature values probably represent the bottom of the reservoir and have no corresponding modeled values. From below 9 m to about 37 m in depth, the model tends to slightly overpredict reservoir temperatures in the warmest parts of the year (July–September). In 2015, a year in which Lookout Point Lake did not fill (fig. 11), model performance is worse than for the other two modeled years. The model tends to overpredict temperatures in 2015 from about 9 to 24 m in depth but underpredicts temperatures at about 30 m in depth and deeper.

Goodness-of-fit statistics for outflow temperatures in all modeled years are good, however, with subdaily MAE values no greater than 0.79 °C for measured-inflow results and no greater than 0.90 °C for modeled-inflow results (table 7) as compared to water temperatures measured at USGS station 14150000 (Middle Fork Willamette River near Dexter, Oregon). Modeled outflow from Dexter Dam does not show the degree of diurnal variability as measured at USGS 14150000 (fig. 19); however, given the measurement location 2.6 mi downstream from Dexter Dam, this difference can probably be accounted for by real differences in the diurnal heat flux between Dexter Dam and the downstream river location.

Cougar Reservoir Model (CGRM)

Description

Cougar Dam is a multipurpose storage project authorized for flood risk management, irrigation, navigation, hydropower, and other purposes (U.S. Army Corps of Engineers, 2019b). Cougar Dam is located at RM 4.4 of the South Fork McKenzie River. The main body of the reservoir extends up the South Fork McKenzie River approximately 6.5 mi (10.5 km). The East Fork South Fork McKenzie River is the only significant tributary to Cougar Reservoir, forming a secondary arm approximately 1.7 mi in length. Cougar Dam is 452 ft (137.8 m) high and was originally constructed with an intake tower that included five “fish horns” at a range of elevations to allow collection of fish for downstream transport (Hansen and others, 2017). This tower was modified in 2004 when a “temperature control tower” providing selective withdrawal of water from different depths was constructed. A regulating outlet and power penstock in the original intake tower can also act as reservoir outlets. Finally, a diversion tunnel at the base of the dam is occasionally used to draw the reservoir down for construction or maintenance purposes.

Model History and Domain

The CGRM was developed by the U.S. Army Engineer Research and Development Center (Threadgill and others, 2012) using CE-QUAL-W2 version 3.7. The model was calibrated using data from calendar years 2005 and 2006 and then applied to calendar years 2001, 2004, 2006, and 2008, which were chosen to represent a range of hydrologic conditions. As originally developed, the model included the water temperature control tower, which began operation in May of 2005, by using individual structures at different depths to simulate the temperature tower’s sliding weirs. The water temperature control tower was implemented to allow dynamic mixing to meet a downstream temperature target. The model was subsequently updated to CE-QUAL-W2 version 3.72 (Cole and Wells, 2015) and modified to simplify the selective release outlets in the model by replacing the individual structures representing sliding weirs with a single, floating outlet 3.5 m (10 ft) below the water surface. This model version was then recalibrated by adding three structures designed to simulate reported leakage past the sliding weirs in the temperature control tower (U.S. Army Corps of Engineers, 2019a).

Bathymetric Grid and Non-Temporal Parameters

No changes were made to the bathymetric grid except to update it to the new, more readable .csv file format and to set the initial water-surface elevation to match the start of each simulation. Additionally, two outlet structures were added to the CGRM. Structure 6 represents the power penstock and structure 7 represents the diversion tunnel (table 2). Elevations of the new structures were specified by USACE based on as-built diagrams of Cougar Dam.

Temporal Inputs

Meteorology

Although use of observed solar radiation as model input is typically best practice (Wells, 2019), CE-QUAL-W2 provides an option to compute solar radiation from observed cloud cover, latitude, longitude, and time of day. The original CGRM was configured to compute solar radiation inputs (Threadgill and others, 2012). The option of using observed solar radiation data from the Eugene Solar Radiation Monitoring Laboratory (SRML) was tested in the CGRM, but the resulting model fit was slightly worse, so the updated CGRM retained the option of computing the solar radiation input based on cloud cover. Other meteorological inputs were as specified in table 4, identical to prior applications of the CGRM.

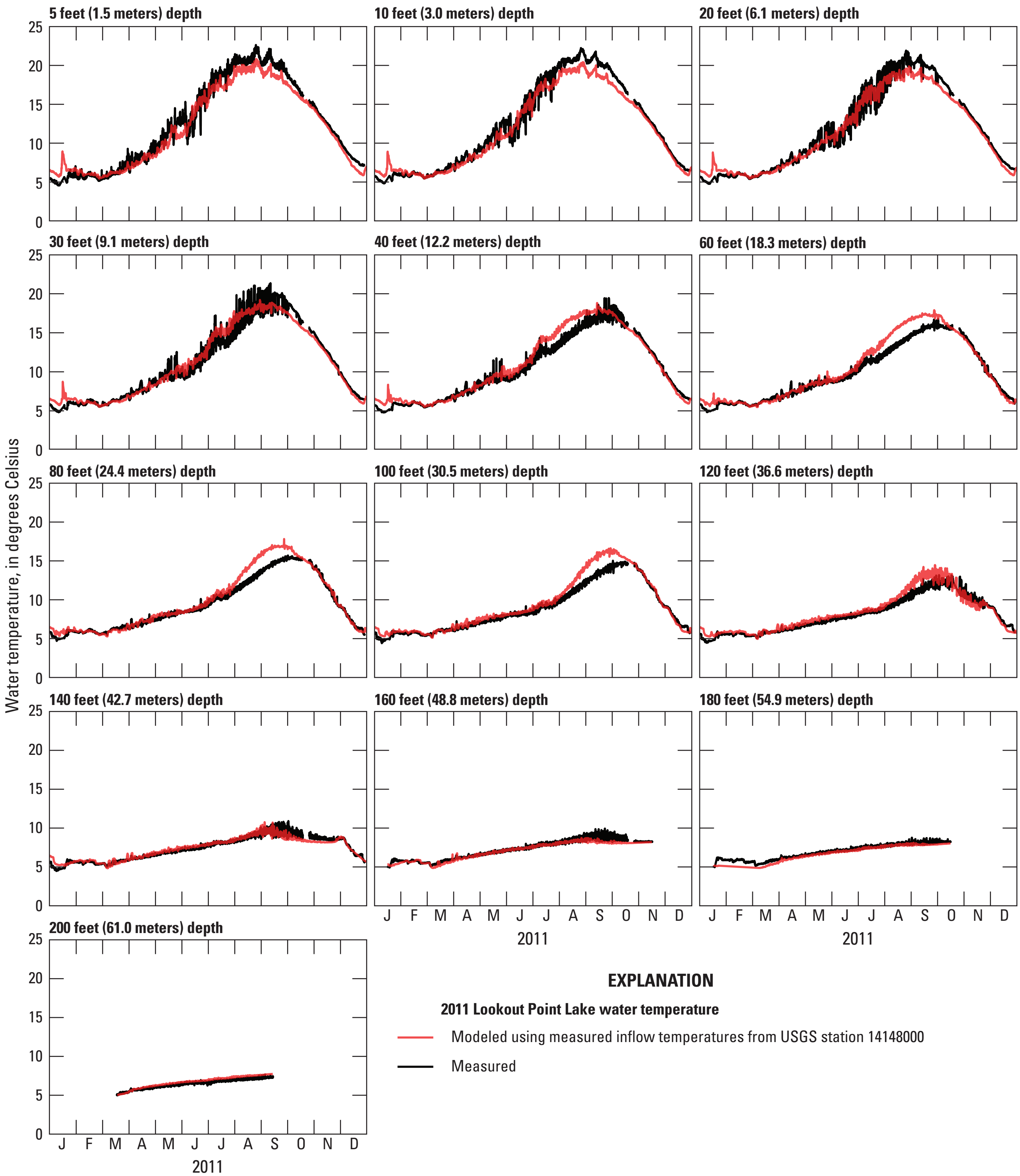


Figure 13. Continuous modeled and measured water temperatures at specific depths near the dam in Lookout Point Lake, northwestern Oregon, simulated using inflow temperatures to Lookout Point Lake from the Middle Fork Willamette River measured at U.S. Geological Survey (USGS) station 14148000 (Middle Fork Willamette River below North Fork near Oakridge, Oregon), northwestern Oregon, 2011.

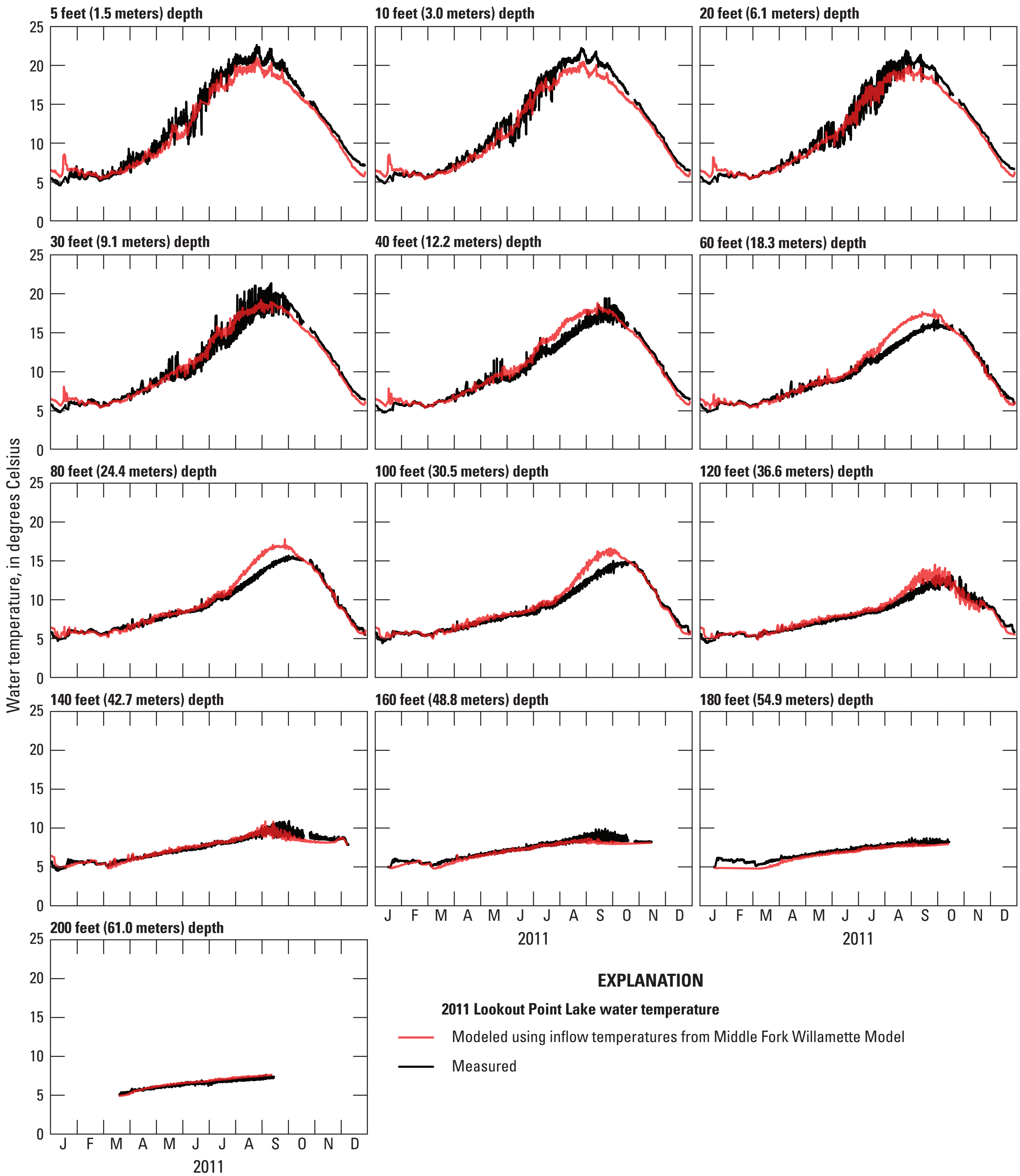


Figure 14. Continuous modeled and measured water temperatures at specific depths near the dam in Lookout Point Lake, simulated using inflow temperatures to Lookout Point Lake from the Middle Fork Willamette River as modeled by the Middle Fork Willamette Model (MFWM), northwestern Oregon, 2011.

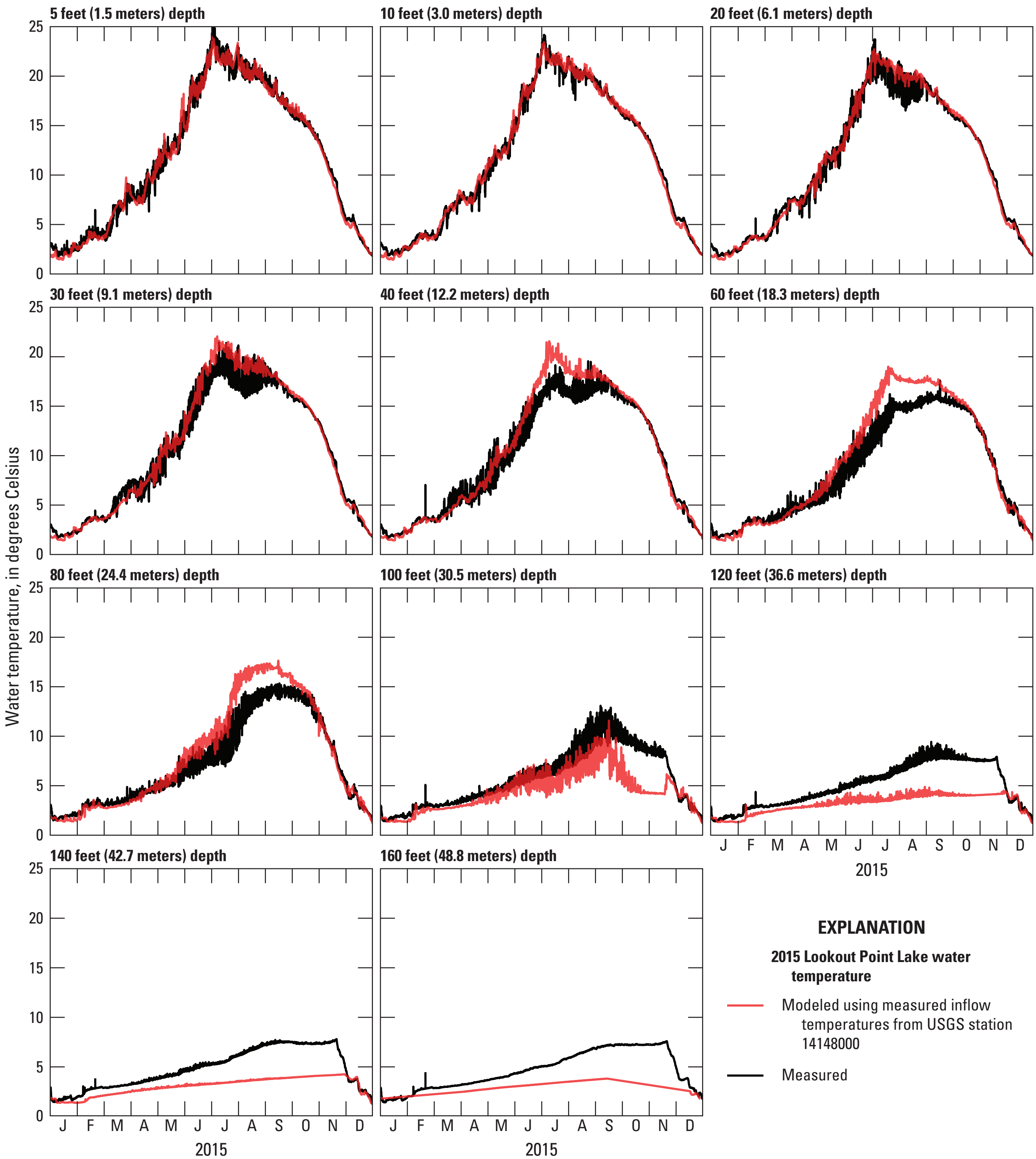


Figure 15. Continuous modeled and measured water temperatures at specific depths near the dam in Lookout Point Lake, simulated using inflow temperatures to Lookout Point Lake from the Middle Fork Willamette River measured at U.S. Geological Survey (USGS) station 14148000 (Middle Fork Willamette River below North Fork near Oakridge, Oregon), northwestern Oregon, 2015.

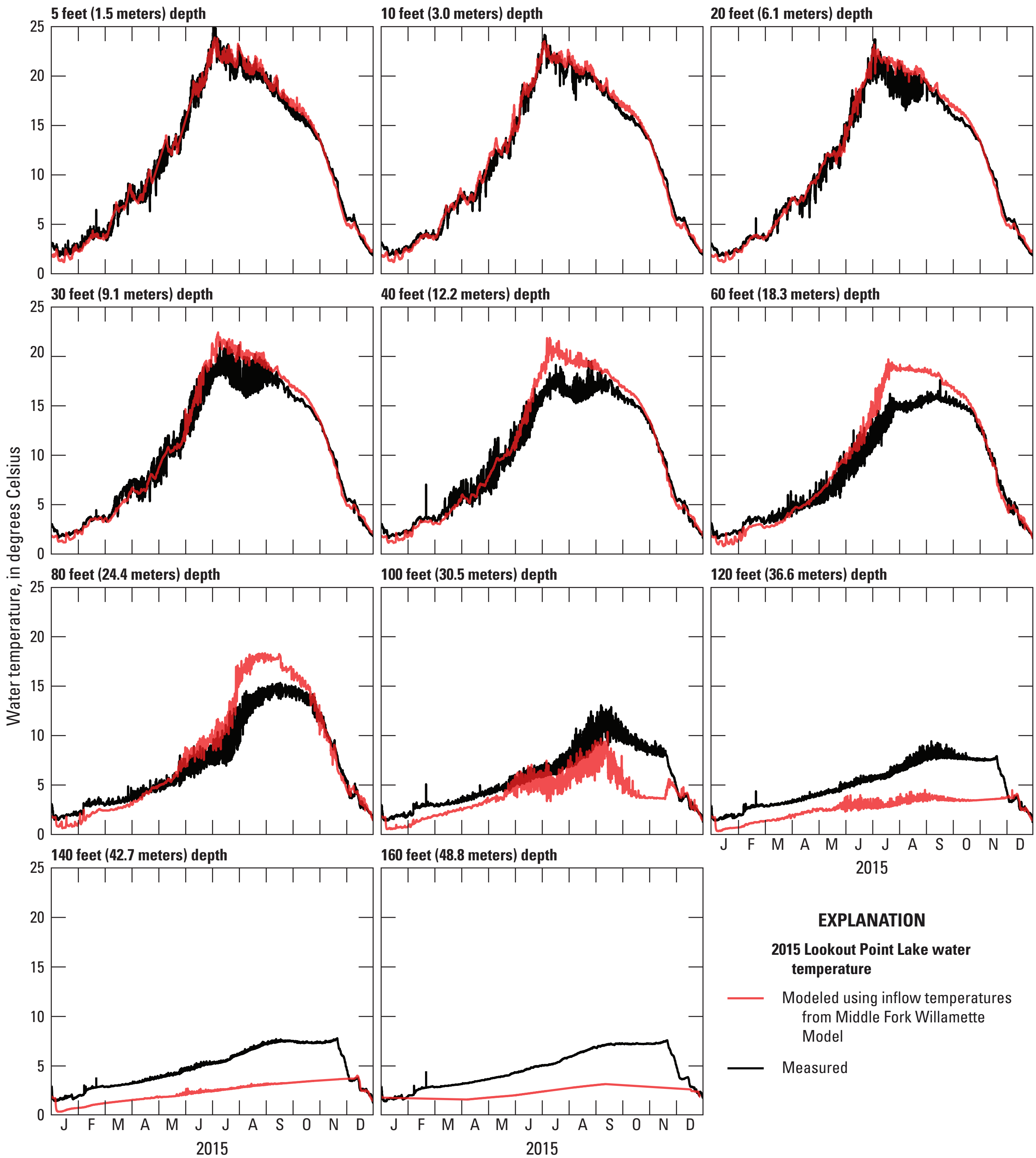


Figure 16. Continuous modeled and measured water temperatures at specific depths near the dam in Lookout Point Lake, simulated using inflow temperatures to Lookout Point Lake from the Middle Fork Willamette River as modeled by the Middle Fork Willamette Model (MFWM), northwestern Oregon, 2015.

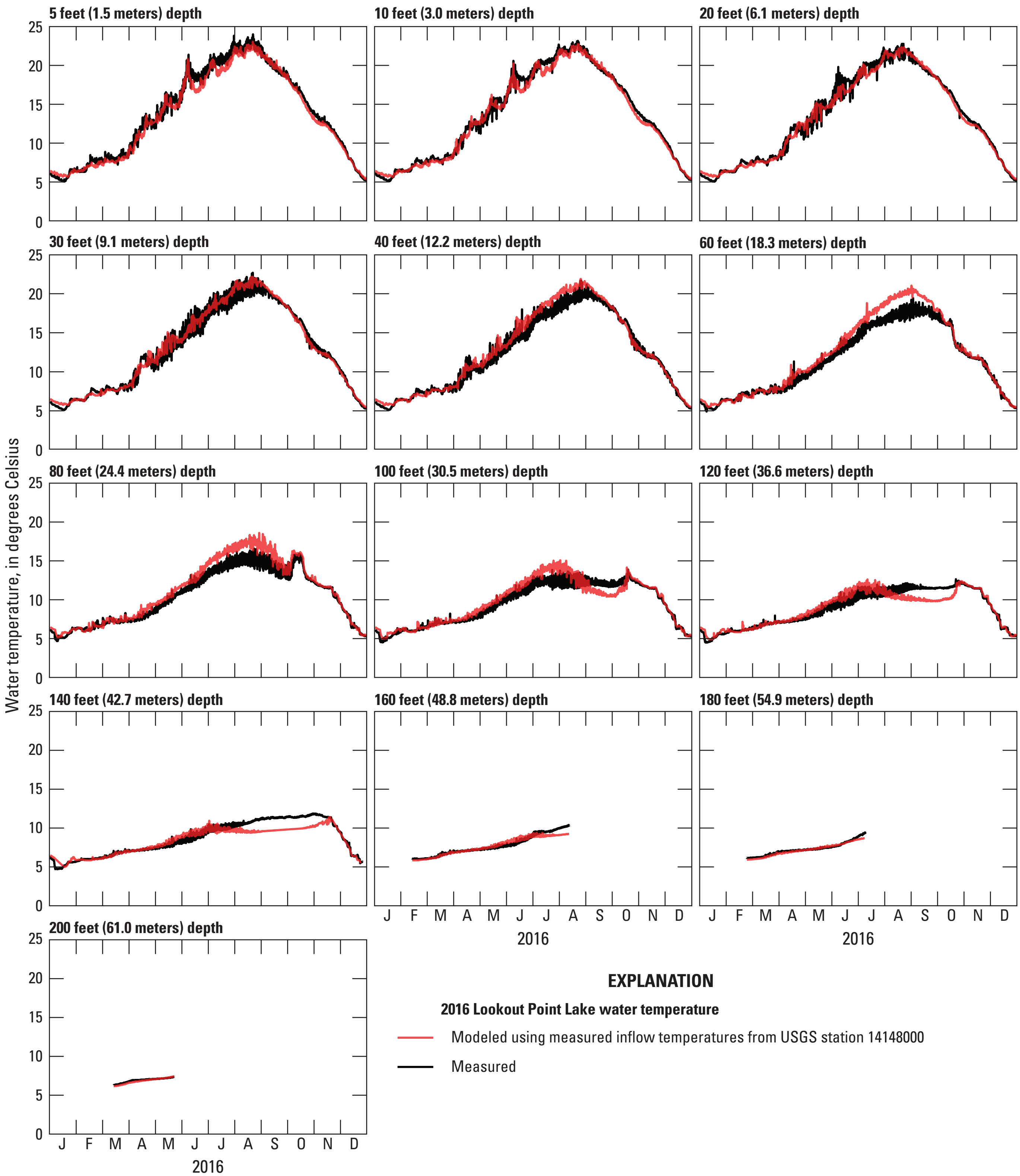


Figure 17. Continuous modeled and measured water temperatures at specific depths near the dam in Lookout Point Lake, simulated using inflow temperatures to Lookout Point Lake from the Middle Fork Willamette River measured at U.S. Geological Survey (USGS) station 14148000 (Middle Fork Willamette River below North Fork near Oakridge, Oregon), northwestern Oregon, 2016.

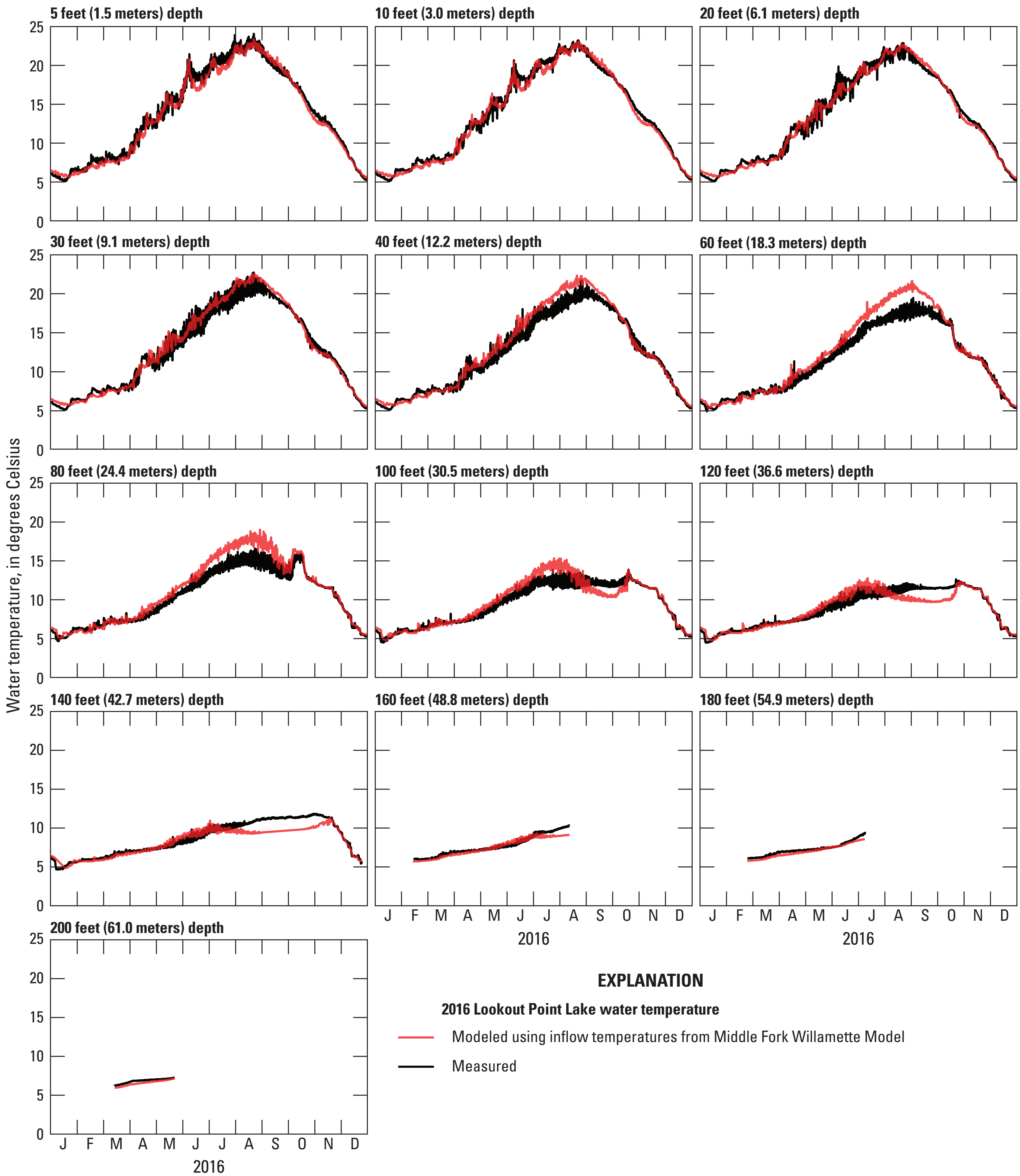


Figure 18. Continuous modeled and measured water temperatures at specific depths near the dam in Lookout Point Lake, simulated using inflow temperatures to Lookout Point Lake from the Middle Fork Willamette River as modeled by the Middle Fork Willamette Model (MFWM), northwestern Oregon, 2016.

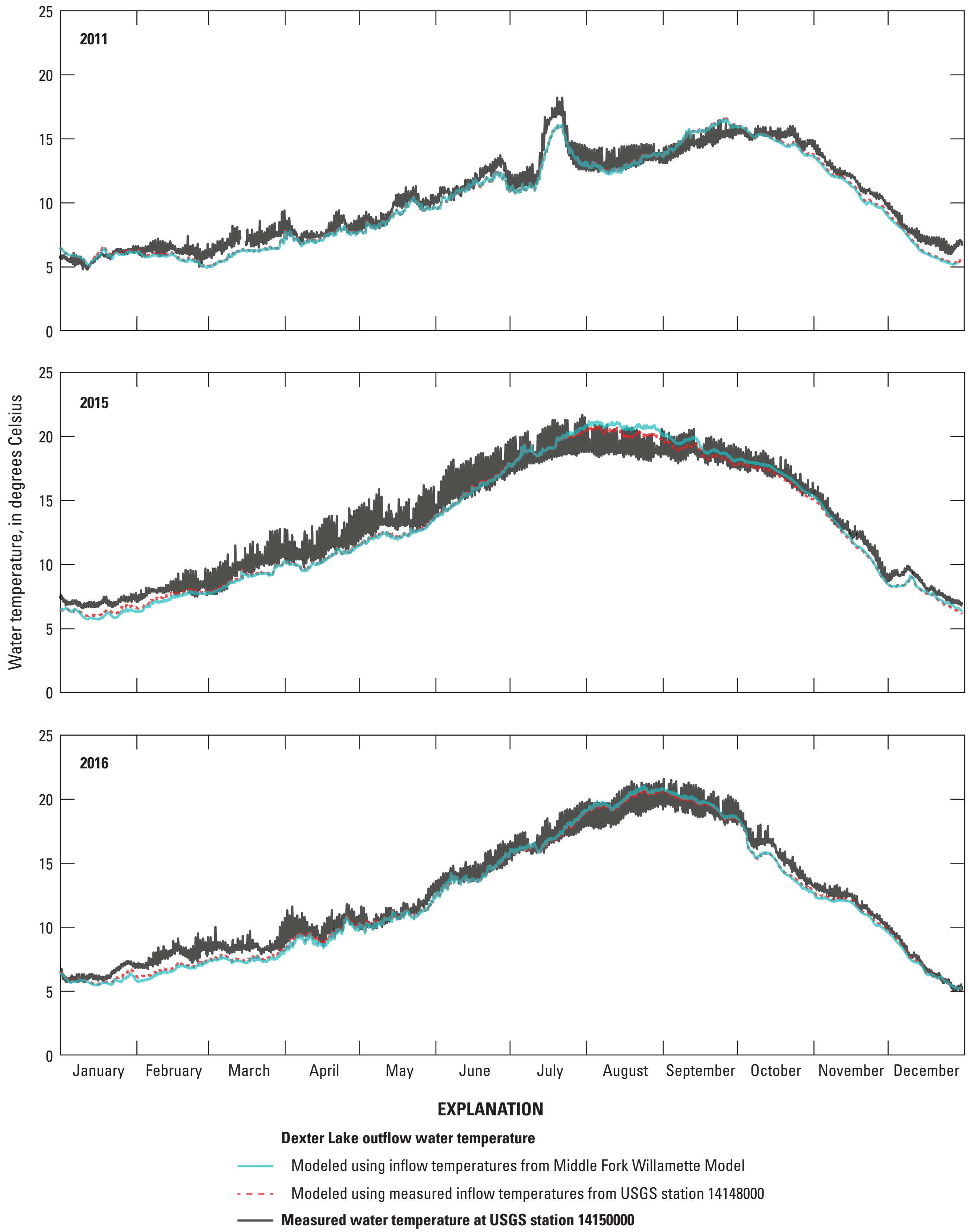


Figure 19. Continuous modeled outflow water temperatures from Dexter Reservoir and measured water temperatures at U.S. Geological Survey (USGS) station 14150000 (Middle Fork Willamette River near Dexter, Oregon), northwestern Oregon, 2011, 2015, and 2016. Modeled (measured input) dashed red line indicates outflow temperatures simulated using inflow temperatures to Lookout Point Lake from the Middle Fork Willamette River measured at USGS station 14148000 (Middle Fork Willamette River below North Fork near Oakridge, Oregon). Modeled (modeled input) solid blue line indicates outflow temperatures simulated using inflow temperatures to Lookout Point Lake from the Middle Fork Willamette River as modeled by the Middle Fork Willamette Model (MFWM).

Streamflow

Inflow to the CGRM model is specified in two branches representing the South Fork McKenzie River (branch 1) and the East Fork South Fork McKenzie River (branch 2). Inflow to branch 1 was specified using measured data from USGS 14159200 (South Fork McKenzie River above Cougar Lake near Rainbow, Oregon). Inflow to branch 2 was estimated by subtracting the record at USGS 14159200 from USACE's estimate of total inflow to Cougar Reservoir. This approach is different from that of previous versions of the CGRM, which used CWMS database estimates of total inflow to specify inflow to branch 1, with no inflow specified for branch 2. The provision of inflow to branch 2 was used as a more realistic simulation of inflow to Cougar Reservoir and internal lake circulation, as well as an effort to improve model stability.

Temperature

The temperature of inflows to branches 1 and 2 of the CGRM was specified with measured data from USGS 14159200 (South Fork McKenzie River above Cougar Lake near Rainbow, Oregon). This record was also used to estimate the temperature of the distributed tributary.

To accurately simulate temperature in Cougar Reservoir and its outflow, the operation of the water temperature control tower needed to be approximated. This is most effectively done by using the selective withdrawal algorithm available in CE-QUAL-W2, which allows the model to automatically route flow through multiple outlets (within a set of specified parameters) to attempt to match a user-specified downstream temperature target. The maximum temperature target for releases from Cougar Dam was developed in 1984 by NOAA, the U.S. Fish and Wildlife Service, and the Oregon Department of Fish and Wildlife for the benefit of downstream ESA-listed anadromous fish (National Marine Fisheries Service, 2008).

The most recent version of the CGRM (U.S. Army Corps of Engineers, 2019a) calibrated outflow temperature releases by specifying three mixing control periods. In the first and third periods, when the Cougar Reservoir water level was below the bottom of the water temperature control tower, all flow was designated to pass through the regulating outlet. During the second period, when the water-surface elevation was high enough to use the temperature control tower, the model specified that 10 percent of the total outflow be passed through each of the simulated "leaks" in the temperature tower (structures 3, 4 and 5, constituting 30 percent of total flow), whereas the remaining 70 percent of flow was passed through structure 1, which represents the water temperature control tower as a floating weir in the mixing algorithm control tower. The day of the year demarcating the boundary between periods was manually set depending on the measured water-surface elevation.

When updating the models, the approach for specifying outlet release rates described previously worked well for 2016 but required modification to reproduce measured release temperatures in 2011 and 2015. In 2011 and 2015, the measured outflow temperature from Cougar Dam decreased by about 5 °C on a single day near the end of September. This change—which does not match the temperature target or coincide with the date that the elevation of Cougar Reservoir dropped below the temperature tower—indicates a decision to route flow through the regulating outlet for reasons not included in logic of the selective withdrawal algorithm. To accurately simulate this temperature decrease, the end of the second control period was moved to coincide with the drop in temperature. In 2011, an additional selective withdrawal period was added (for a total of four periods), to attempt to improve the model fit in late autumn, when the measured temperature stayed relatively constant rather than declining during autumn to coincide with the temperature target. Although this approach yielded a good temperature fit, it has several limitations. First, it requires that the mixing control group time periods be manually adjusted for each simulated year. Second, in the case of 2011 and 2015, it required further manual adjustment of control time periods to better match the measured temperature record. This approach is acceptable when calibrating the model to measured ("baseline") conditions, but for performing hypothetical model simulations without measured water-surface elevation and (or) temperature records to measure against, such an approach is not feasible.

To address this problem, the selective withdrawal input file was simplified to a single period. Because the algorithm governing selective temperature control in CE-QUAL-W2 first checks which outlets are available for use depending on their elevation (or range of elevation, in the case of a floating outlet) and the water-surface elevation, a model user does not need to manually specify control periods based on water-surface elevation. By further specifying the priority of the regulating outlet (structure 2) as secondary to the water temperature control tower (structures 1, 3, 4, and 5), the model would prioritize flow through the water temperature control tower when it was available, but route water through the regulating outlet when the water-surface elevation was below the lowest water temperature control tower elevation. In 2016, this approach greatly improved the model fit. To reproduce the late-September temperature decrease in 2011 and 2015, however, a second period forcing flow only to the regulating outlet was required (reflecting an element of dam operations not predictable by algorithm but based on human decision). When this adjustment was made, the model fit improved in 2011 and was comparable (but slightly worse) in 2015. Given the improvement to model results for 2011 and 2016 and the simplicity of the approach, this simplification of modeled selective withdrawal operations was deemed an acceptable outcome. To allow for accurate comparison with conditions as measured in 2011, 2015, and 2016, the CGRM documented in this report as "baseline" simulations use the simplified single-period approach in 2016 and similar simplified approaches for 2011 (2 periods) and 2015 (3 periods).

Model Fit

Water Balance

The CGRM water budget was balanced by iteratively calculating a distributed tributary for branch 1 (the main body of the reservoir) until the modeled reservoir-surface elevation matched the measured water-surface elevation from the CWMS database, following the protocol described in section, “Methods and Data—Model Calibration—Water Balance” (fig. 20).

Temperature

When compared to data from a series of thermistors located at fixed elevations on the upstream face of Cougar Dam, results from the CGRM tend to overestimate temperatures at most wetted elevations in all modeled years, but, in general, the model reasonably represents seasonal warming and cooling patterns in Cougar Reservoir (figs. 21–23). These results are difficult to compare to previously calibrated model years, as older versions of the CGRM did not use the fixed temperature string at Cougar Dam for calibration data, instead relying on discrete temperature profiles from in-lake monitoring sites in the reservoir near Cougar Dam and the arms along the East Fork South Fork McKenzie and South Fork McKenzie Rivers, collected at monthly intervals (Threadgill and others, 2012). However, goodness-of-fit statistics show that depth-specific error tends to be higher than is desirable (table 8; typically, the target is to keep the MAE less than 1.0 °C), indicating that the CGRM is not capturing the thermal structure of Cougar Reservoir with sufficient accuracy. In 2016, a spike in surface temperature in late November and early December seemed to be a result of model instability (fig. 23); this error was short-lived and did not influence downstream outflow temperatures. Despite the relatively large in-reservoir error, however, goodness-of-fit statistics comparing outflow from the CGRM to the temperature measured at USGS station 14159500 (South Fork McKenzie River near Rainbow, Oregon) are good, with MAE ranging from 0.68 °C in 2011 to 0.90 °C in 2015 (table 8). Similarly, with some deviation, seasonal and operationally driven patterns in outflow temperature seem to be well-simulated by the CGRM (fig. 24). The discrepancy between the accuracy of the thermal reservoir structure and the accuracy of the outflow temperatures suggests that the model simulates thermal structure in the reservoir more accurately than is indicated by the fixed thermistors on the dam face. Future studies may benefit from additional calibration datasets for comparison.

Green Peter and Foster Lakes Model (GPR-FOS-M)

Description

Green Peter Dam is a multipurpose storage project authorized for flood risk management, irrigation, navigation, hydropower, and other uses (U.S. Army Corps of Engineers, 2019b). Located at RM 5.5 on the Middle Santiam River, Green Peter Dam has historically been operated as a power-peaking project. Green Peter Lake has a sinuous shoreline with multiple arms; significant tributaries include Quartzville, Whitcomb, Tally, Thistle, and Rumbaugh Creeks. Green Peter Dam is 327 ft (99.7 m) high and has outlets at three elevations, including a spillway, regulating outlet, and power penstock (Hansen and others, 2017; Sullivan and Rounds, 2021).

Foster Dam, located downstream at RM 38.5 on the South Santiam River, acts as a reregulation dam for Green Peter Dam (Hansen and others, 2017; U.S. Army Corps of Engineers, 2019b). Foster Lake impounds the South Santiam and Middle Santiam Rivers but has no other major tributaries. The primary outlets at Foster Dam include a spillway and power penstock. Additionally, a weir structure located in one of the spillway bays facilitates the downstream passage of juvenile salmon and adult steelhead, two small-diameter outlets located in the sidewall of one of the power intakes can be used to route flow to the adult fish facility immediately downstream, and two small-diameter outlets in the spillway embankment wall can be used to route water to the nearby fish hatchery (Hansen and others, 2017; Sullivan and Rounds, 2021).

Model History and Domain

Green Peter and Foster Lakes are modeled as a single model in CE-QUAL-W2. The GPR-FOS-M was originally developed by WEST Consultants, Inc. (2005) using data from 2001, 2002, 1996, and 1997, and that model then was used to perform a 33-year simulation from January 1, 1970 to December 31, 2002. WEST Consultants used 2001–02 to construct and calibrate the model and 1996–97 as a separate “validation” dataset. The original model was built in CE-QUAL-W2 version 3.1 (Cole and Wells, 2001). The GPR-FOS-M was updated to CE-QUAL-W2 version 3.7 and set up by USGS to simulate calendar years 2002, 2006, 2008, and 2011 (Buccola, Stonewall, and others, 2013). As part of that update, many of the model parameters were adjusted to improve model performance. Sullivan and Rounds (2021) subsequently updated the GPR-FOS-M to CE-QUAL-W2 version 4.1 for 2002, 2006/2008 (spliced conditions), and 2001. As part of this update, Sullivan and Rounds (2021) added the Foster Dam fish weir (modified in 2018), the upper and lower hatchery outlets (“Upper Hatchery Outlet” and “HatchLow” therein), and the upper and lower adult fish facility intakes (“PowerUp” and “PowerLow” therein).

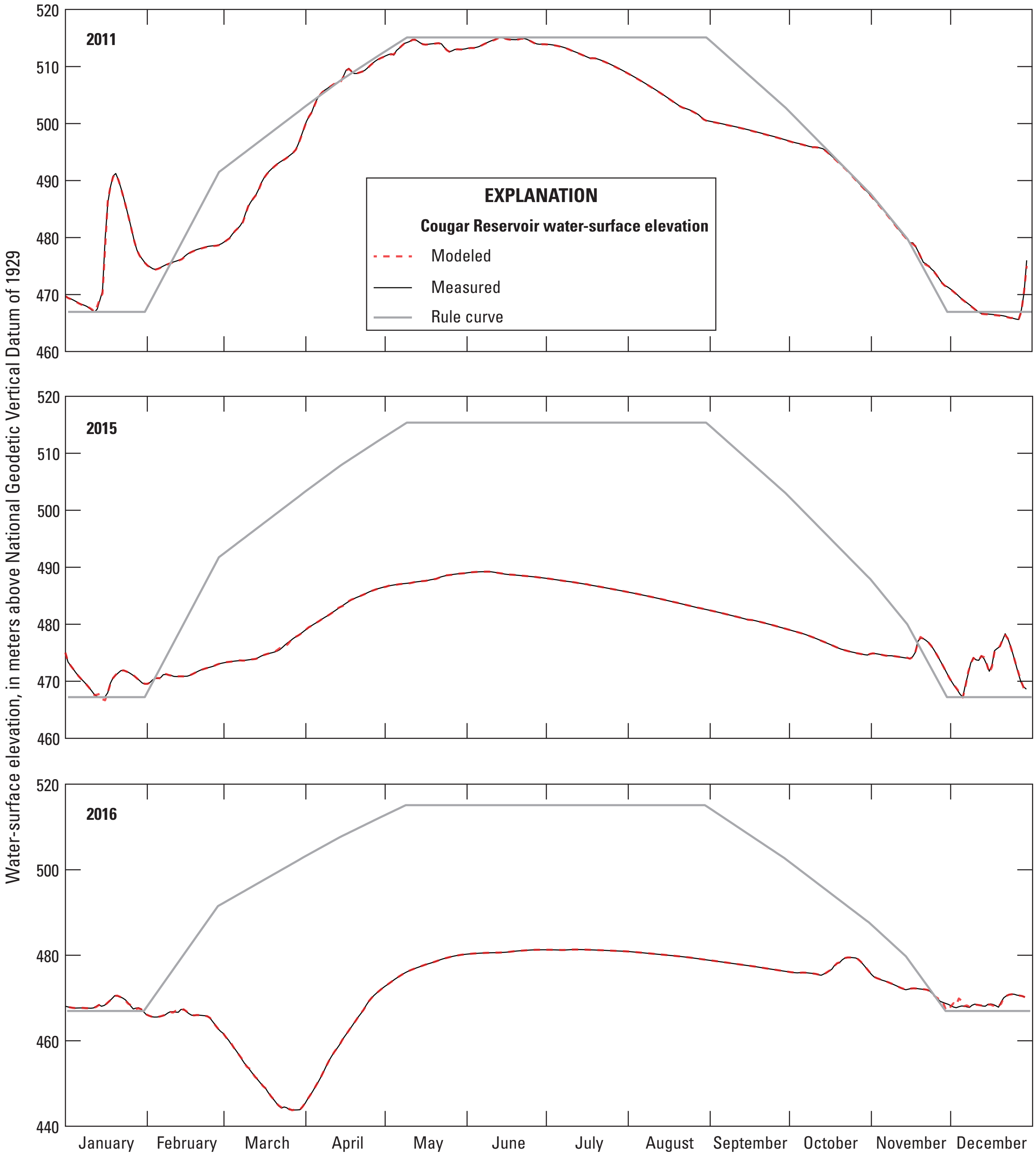


Figure 20. Daily modeled compared to measured water-surface elevation at Cougar Reservoir from the Cougar Reservoir Model (CGRM), northwestern Oregon, 2011, 2015, and 2016. Where not visible, red (modeled) dashed lines are plotted directly over black (measured) solid lines. The “rule curve” is the operational water-surface target for a given day and is provided for context.

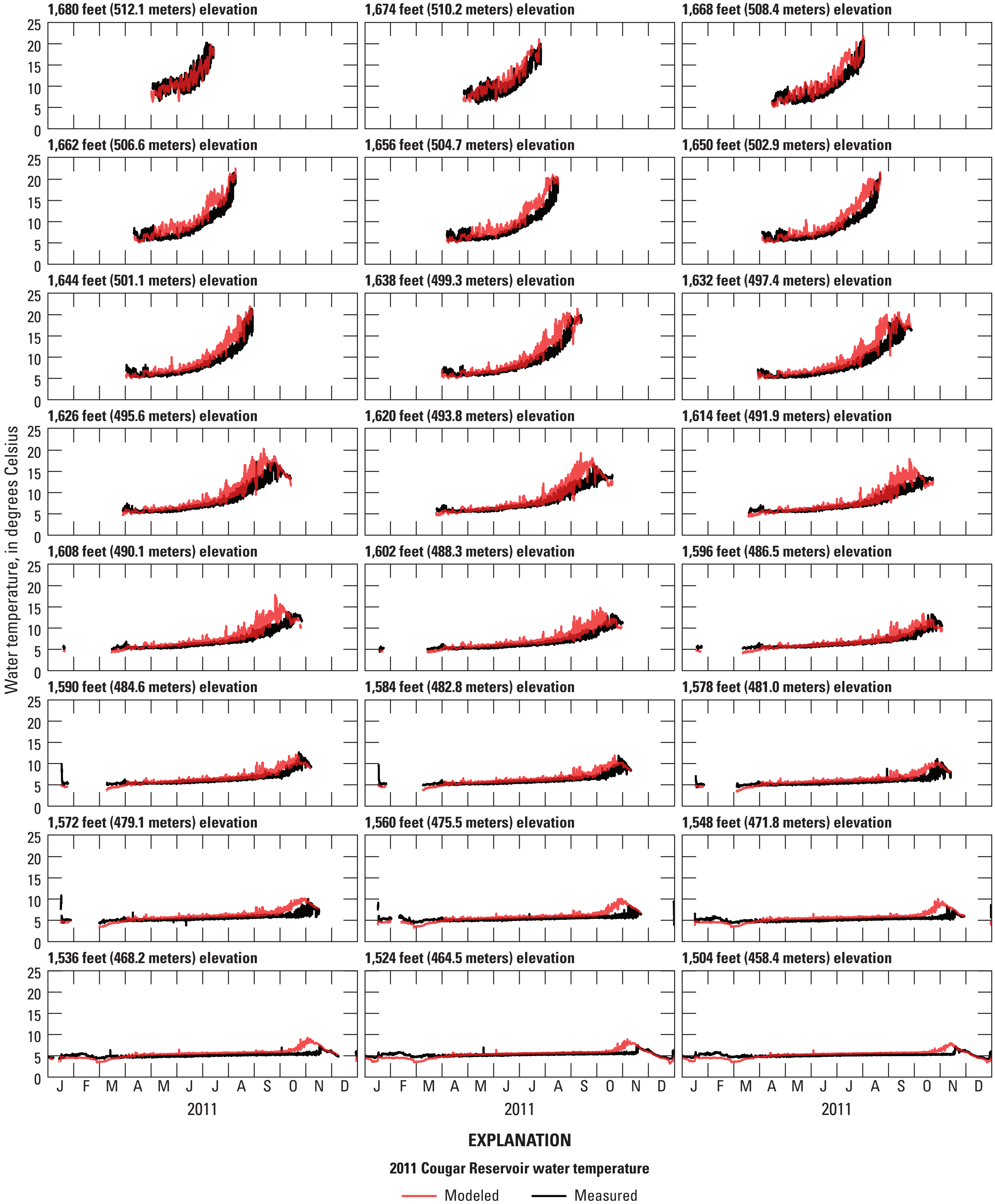


Figure 21. Continuous modeled and measured water temperatures at specific wetted elevations on the dam face in Cougar Reservoir, northwestern Oregon, 2011.

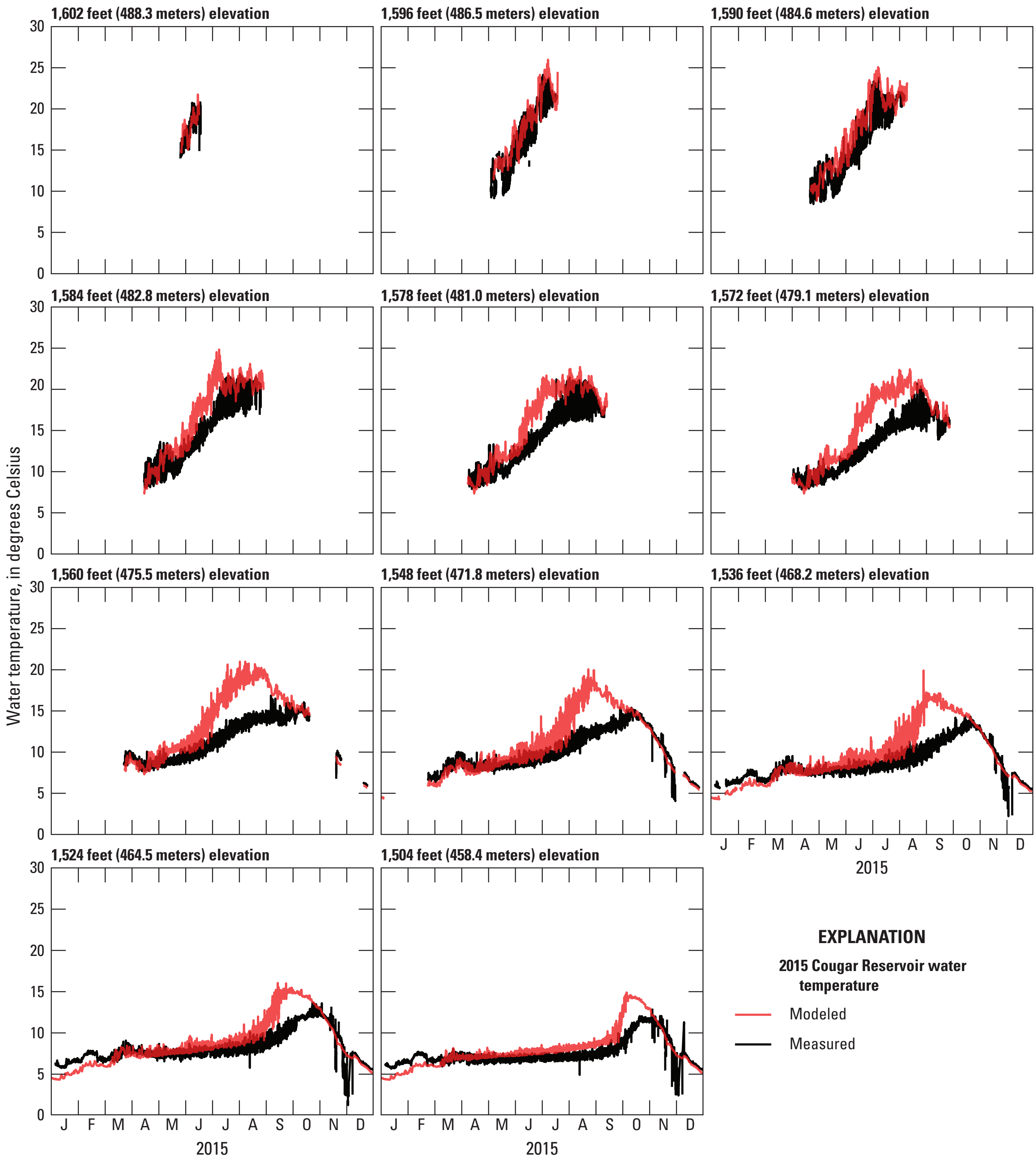


Figure 22. Continuous modeled and measured water temperatures specific wetted elevations on the dam face in Cougar Reservoir, northwestern Oregon, 2015.

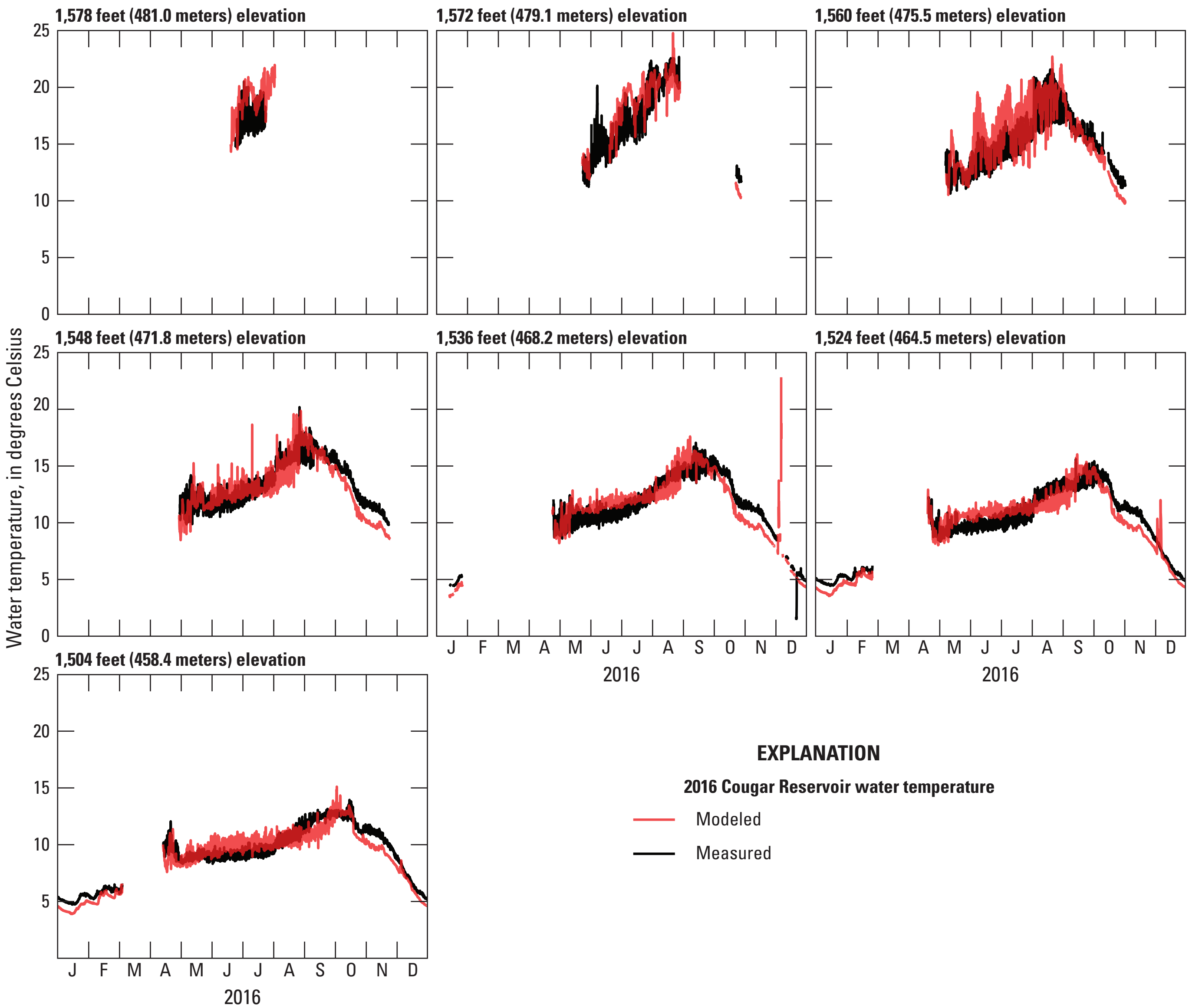


Figure 23. Continuous modeled and measured water temperatures at specific wetted elevations on the dam face in Cougar Reservoir, northwestern Oregon, 2016.

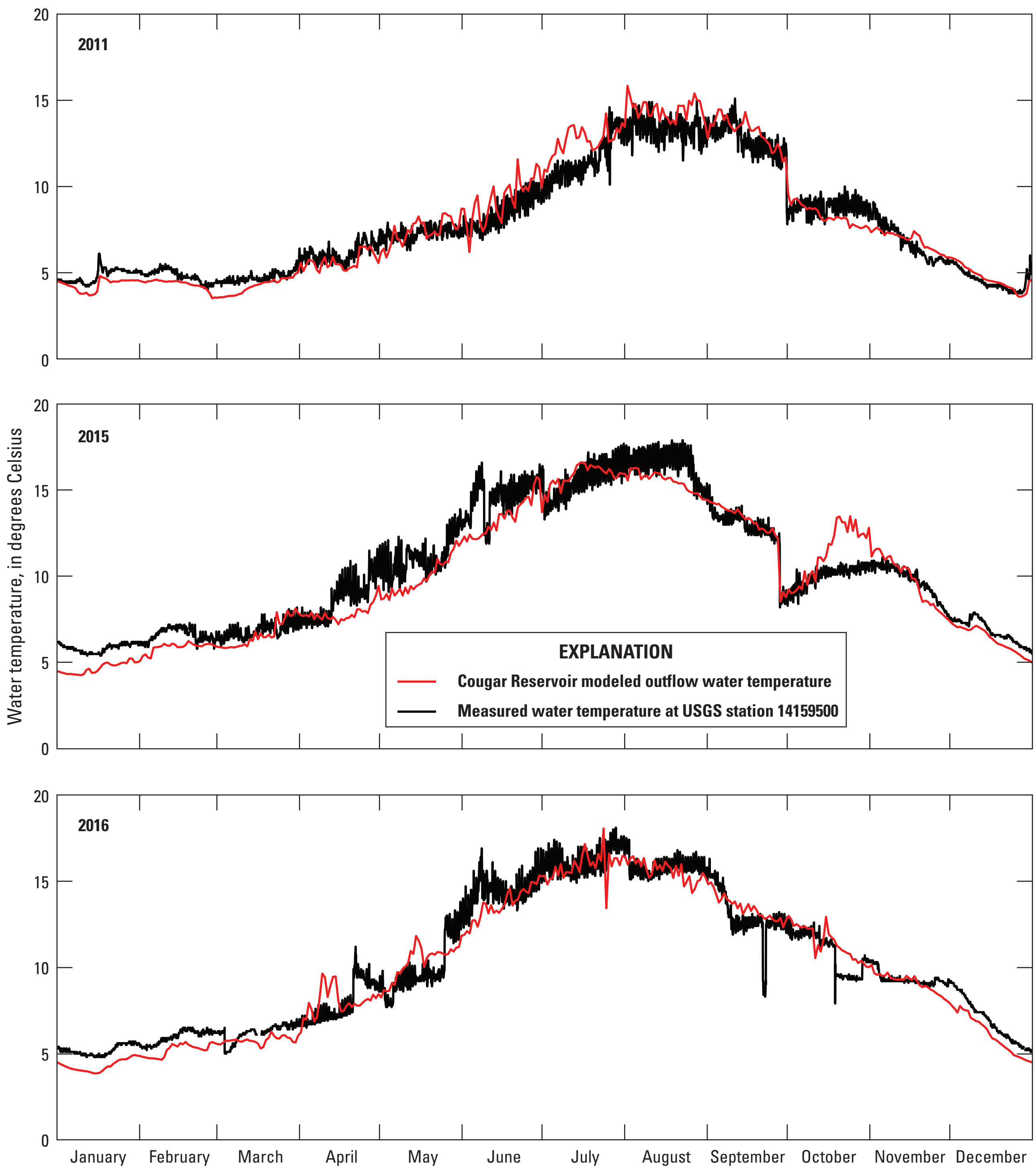


Figure 24. Continuous modeled outflow water temperatures from Cougar Reservoir and measured water temperatures at U.S. Geological Survey (USGS) station 14159500 (South Fork McKenzie River below Cougar Dam, Oregon), northwestern Oregon, 2011, 2015, and 2016.

The GPR-FOS-M consists of two waterbodies and 8 branches. Waterbody 1 represents Green Peter Lake and includes branches 1 through 6. Branch 1 extends from segment 2 to segment 17 and represents the main body of Green Peter Lake. Branches 2 through 6 represent reservoir arms that receive tributaries to Green Peter Lake, including Quartzville Creek (branch 2), Whitcomb Creek (branch 3), Thistle Creek (branch 4), Tally Creek (branch 5), and Rumbaugh Creek (branch 6). No other tributaries are included in waterbody 1. Segment lengths vary from 377.2 to 2,998.5 m in Green Peter Lake and layers are 0.5 m high. Three structures in waterbody 1 represent the spillway, power penstocks, and regulating outlets in Green Peter Dam (table 2). The water budget in Green Peter Lake was balanced using a distributed tributary in branch 1.

Waterbody 2 represents Foster Lake and includes branch 7, the main body of Foster Lake, and branch 8, the reservoir arm that receives inflow from the South Santiam River. No other tributaries are included in waterbody 2. Segment lengths vary from 505.8 to 510.4 m in Foster Lake and layers are 1 m high. Seven structures in waterbody 2 represent the fish weir , upper hatchery intake (unused), upper adult fish facility intake (unused), spillway crest, power penstock, lower adult fish facility intake (unused), and lower hatchery intake (table 2). The water budget in Foster Lake was balanced using a distributed tributary in branch 7.

The model updates described in this report include (1) updating the 2011 GPR-FOS-M documented by Sullivan and Rounds (2021) to CE-QUAL-W2 version 4.2 (USGS edition 7); (2) setting up the GPR-FOS-M for calendar years 2015 and 2016; and (3) checking and calibrating the model results against data from 2011, 2015, and 2016, as needed.

Bathymetric Grid and Non-Temporal Parameters

No changes were made to the bathymetric grid except to update it to the new, more readable .csv file format and to set the initial water-surface elevation to match the start of each simulation. Additionally, the spillway was added to the Green Peter Lake waterbody of the model (table 2). Finally, the surface-heat exchange method was changed from the equilibrium temperature method to a term-by-term accounting of surface-heat exchange. The equilibrium temperature method has been successfully used in older models but the term-by-term approach is more theoretically sound.

Temporal Inputs

Meteorology

The GPR-FOS-M was set up to use air temperature and dew-point temperature data from the Foster Dam Weather Observation, by Buccola, Stonewall, and others (2013) and Sullivan and Rounds (2021) (table 4). However, the temperature data from FWSO were unreliable in 2016 and could not be used. Testing of air temperature and dew-point temperature derived from WBAN 24221 (Eugene Airport Mahlon Sweet Field) and from the Jordan Remote Automated Weather Station (RAWS) weather station indicated that the best model fit was achieved using data from the Jordan RAWS weather station. This weather station is located approximately 20 mi north-northwest of Green Peter and Foster Lakes at an elevation of 778 ft (240.2 m), between the full-pool elevations of Green Peter and Foster Lakes (table 2). Wind speed, wind direction, and cloud cover data were sourced from WBAN 24221 (Eugene Airport Mahlon Sweet Field), consistent with previous versions of the GPR-FOS-M. Solar radiation is from the Eugene SRML.

Precipitation rates were from the FWSO weather station. The temperature of precipitation was set to the air temperature; values below zero were set to zero degrees Celsius.

Streamflow

Of the seven branches requiring inflow to the GPR-FOS-M (out of eight total branches), two had measured data available and five were estimated. Streamflow data from Quartzville Creek (branch 2) were available from USGS 14185900 (Quartzville Creek near Cascadia, Oregon). Streamflow data from the South Santiam River (branch 8) were available from USGS 14185000 (South Santiam River below Cascadia, Oregon). The remainder of this section describes how other inflows were estimated.

Streamflow for the Middle Santiam River (branch 1) was estimated using a regression with a historical record from USGS monitoring station 14185700 on the Middle Santiam River:

$$Q_{MiddleSantiam} = 0.7402 \times Q_{USGS14185900} + 3.5332 \quad (11)$$

(WEST Consultants, Inc., 2005)

where

$Q_{MiddleSantiam}$ is the daily mean streamflow in the Middle Santiam River at U.S. Geological Survey (USGS) station 14185700, Middle Santiam River near Upper Soda, Oregon, in cubic feet per second; and

$Q_{USGS14185900}$ is the daily mean streamflow measured at USGS station 14185900, Quartzville Creek near Cascadia, Oregon, in cubic feet per second.

The other inflows to the GPR-FOS-M were estimated using a watershed-area ratio method with USGS station 14185900, Quartzville Creek near Cascadia, Oregon, as developed for the analysis in Buccola, Stonewall, and others (2013):

$$Q_{WhitcombCreek} = \frac{9.1}{99.2} \times Q_{USGS14185900} \quad (12)$$

$$Q_{ThistleCreek} = \frac{3.1}{99.2} \times Q_{USGS14185900} \quad (13)$$

$$Q_{TallyCreek} = \frac{11.8}{99.2} \times Q_{USGS14185900} \quad (14)$$

$$Q_{RumbaughCreek} = \frac{4.5}{99.2} \times Q_{USGS14185900} \quad (15)$$

where

$Q_{WhitcombCreek}$ is the hourly streamflow in Whitcomb Creek where it enters branch 3 of the Green Peter and Foster Lakes Model (GPR-FOS-M), in cubic feet per second;

$Q_{ThistleCreek}$ is the hourly streamflow in Thistle Creek where it enters branch 4 of the GPR-FOS-M, in cubic feet per second;

$Q_{TallyCreek}$ is the hourly streamflow in Thistle Creek where it enters branch 5 of the GPR-FOS-M, in cubic feet per second;

$Q_{RumbaughCreek}$ is the hourly streamflow in Thistle Creek where it enters branch 6 of the GPR-FOS-M, in cubic feet per second;

$Q_{USGS14185900}$ is the hourly streamflow measured at USGS station 14185900, Quartzville Creek near Cascadia, Oregon, in cubic feet per second; and

the coefficients represent the ratios between each respective tributary watershed area, in square miles, and the watershed area upstream from the Quartzville Creek station (99.2 cubic miles).

Two distributed tributaries are included in the GPR-FOS-M, for branch 1 (the main body of Green Peter Lake) and branch 7 (the main body of Foster Lake). Values in the distributed tributary were calibrated iteratively based on a comparison with measured reservoir-surface elevations. For details on the methodology, see section, "Methods and Data—Model Calibration—Water Balance."

Temperature

Inflow temperatures were available for three inputs to the GPR-FOS-M, whereas the other inflow temperatures were estimated by applying a proxy record from another location. The temperature of inflow from the Middle Santiam River (branch 1) was available as subdaily data from USGS station 14185800 (Middle Santiam River near Cascadia, Oregon). The temperature of inflow from Quartzville Creek (branch 2) was available as subdaily data from USGS station 14185900 (Quartzville Creek near Cascadia, Oregon). The temperature of inflow from the South Santiam River (branch 8) was available from USGS 14185000 (South Santiam River below Cascadia, Oregon). The temperature of Whitcomb (branch 3), Thistle (branch 4), Tally (branch 5), and Rumbaugh (branch 6) Creeks were all estimated using USGS station 14185900 (Quartzville Creek near Cascadia, Oregon) as a proxy record.

The temperature of the distributed tributary in Green Peter Lake (branch 1) was estimated following the method established for the analysis in Buccola, Stonewall, and others (2013):

$$T_{DST1} = 0.20 \times 11.1 + 0.80 \times T_{USGS14185900} \quad (16)$$

where

T_{DST1} is the estimated subdaily temperature in distributed tributary 1, in degrees Celsius;

11.1 is the estimated temperature of groundwater, in degrees Celsius; and

$T_{USGS14185900}$ is the subdaily temperature measured at U.S. Geological Survey station 14185900, Quartzville Creek near Cascadia, Oregon, in degrees Celsius.

The temperature of the distributed tributary in Foster Lake (branch 7) was estimated following the method established for the analysis in Buccola, Stonewall, and others (2013):

$$T_{DST2} = 0.20 \times 11.1 + 0.80 \times T_{USGS14185000} \quad (17)$$

where

T_{DST2} is the estimated subdaily temperature in distributed tributary 2, in degrees Celsius;

11.1 is the estimated temperature of groundwater, in degrees Celsius; and

$T_{USGS14185000}$ is the subdaily temperature measured at U.S. Geological Survey station 14185000, South Santiam River below Cascadia, Oregon, in degrees Celsius.

Model Fit

Water Balance

The GPR-FOS-M water budget was balanced in a two-step process. First, a distributed tributary for branch 1 (Green Peter Lake) was iteratively calculated until the modeled reservoir-surface elevation matched the measured water-surface elevation from the CWMS database, following the protocol described in section, "Methods and Data—Model Calibration—Water Balance" (fig. 25). Once branch 1 was balanced, branch 7 (Foster Lake) was balanced following an identical process. The volume of the Foster Lake branch of the CE-QUAL-W2 model is small relative to its inflow and outflow rates and thus is sensitive to small errors in the water balance. As a result, the water balance for branch 7 was initiated by estimating the daily average difference between inflow and outflow, and then iterating until continued iteration did not achieve a closer match between the modeled water-surface elevation and the measured water-surface elevation from the CWMS database (fig. 26). To account for turning off the evaporative mass loss, the 2011 model was recalibrated from the model developed by Sullivan and Rounds (2021).

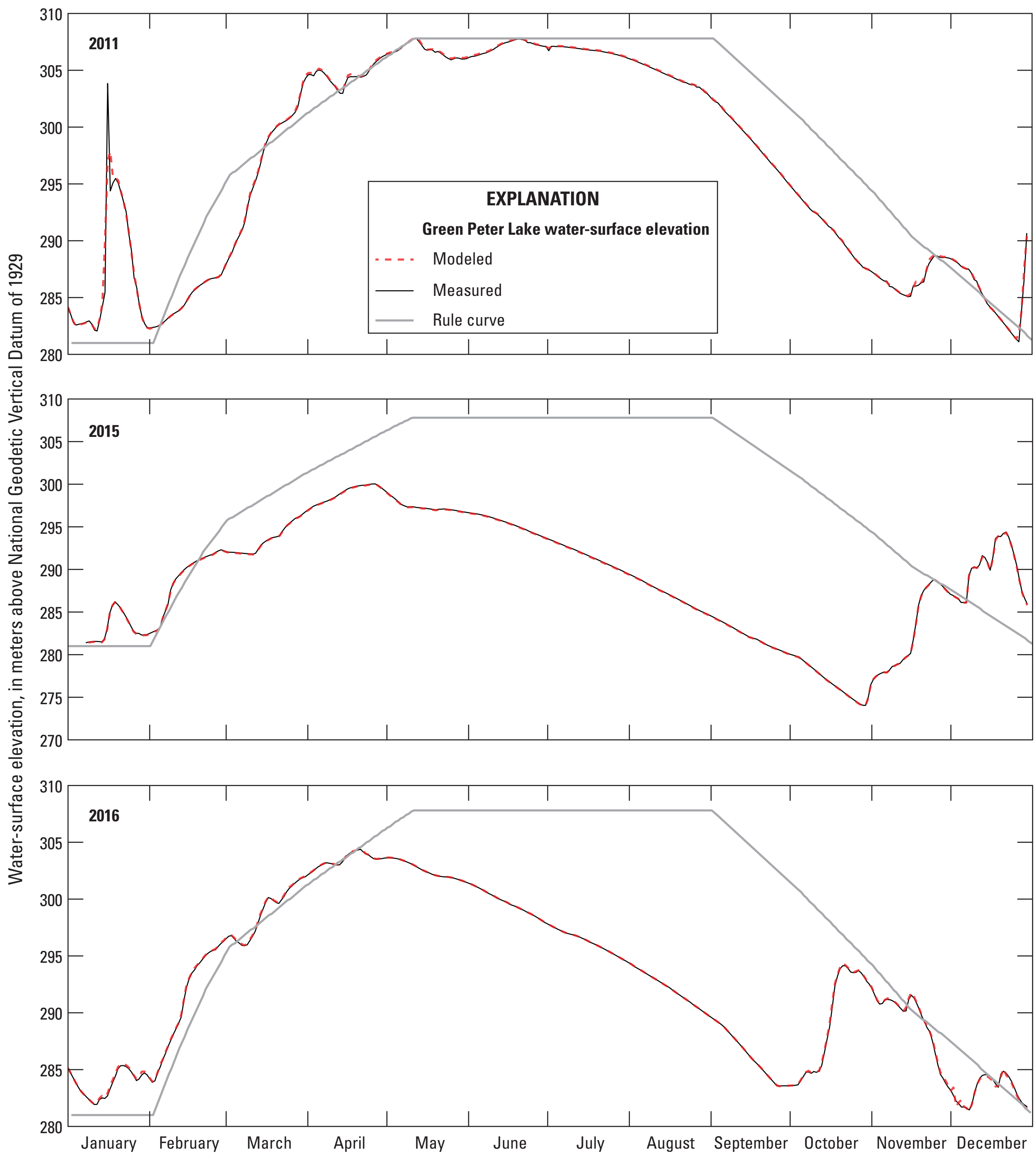


Figure 25. Daily modeled compared to measured water-surface elevation at Green Peter Lake from the Green Peter and Foster Lakes Model (GPR-FOS-M), northwestern Oregon, 2011, 2015, and 2016. Where not visible, red (modeled) dashed lines are plotted directly over black (measured) solid lines. The "rule curve" is the operational water-surface target for a given day and is provided for context.

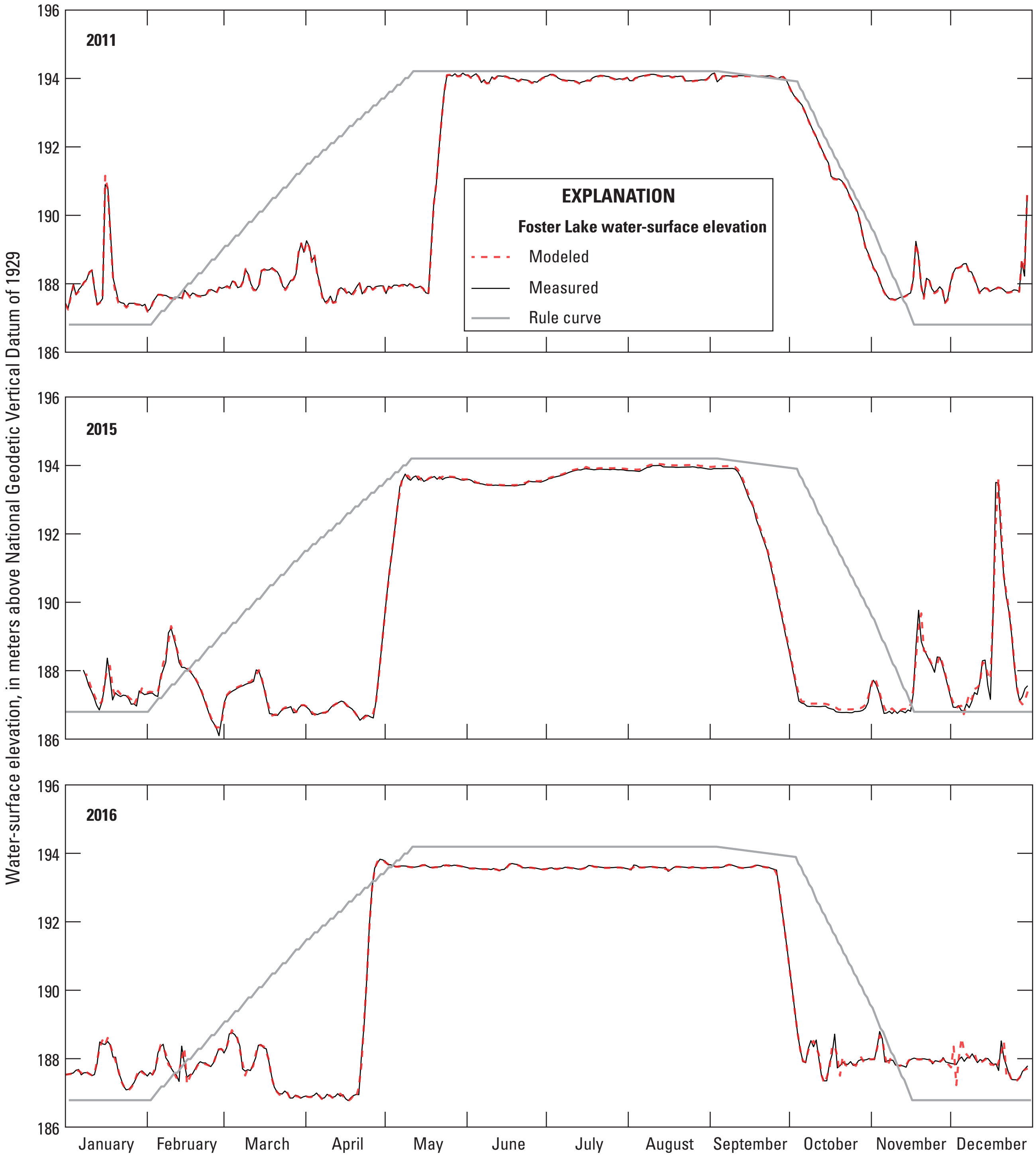


Figure 26. Daily modeled compared to measured water-surface elevation at Foster Lake from the Green Peter and Foster Lakes Model (GPR-FOS-M), northwestern Oregon, 2011, 2015, and 2016. Where not visible, red (modeled) dashed lines are plotted directly over black (measured) solid lines. The “rule curve” is the operational water-surface target for a given day and is provided for context.

Temperature

Temperature results from the GPR-FOS-M were evaluated by comparing modeled temperatures to those measured from a floating thermistor string in Green Peter Lake and by comparing the modeled outflow temperature from Foster Lake to measurements at USGS station 14187200 (South Santiam River near Foster, Oregon) downstream. Time series plots indicate that the model tends to slightly overestimate reservoir temperatures below about 18.3 m (60 ft) from spring through autumn and to underestimate reservoir temperatures below about 18.3 m (60 ft) from autumn into early winter (figs. 27–29). Seasonal patterns are generally well-replicated, however, and the MAE is less than or equal to 1.0 °C at most depths, except for 2016 (table 9). Outflow temperatures are also well represented across all years (fig. 30) and the subdaily MAE does not exceed 0.68 °C in any year modeled (table 9).

Detroit Lake Model (DETM)

Description

Detroit Dam is a multipurpose storage project authorized for flood risk management, irrigation, navigation, hydropower, and other uses (U.S. Army Corps of Engineers, 2019b). Located at RM 60.9 on the North Santiam River, Detroit Dam has historically been operated as a power-peaking project. Big Cliff Dam, located about 3 mi downstream, acts as a reregulation dam for Detroit Dam (Hansen and others, 2017; see section, “Model Updates—Big Cliff Reservoir Model (BCRM)” for discussion of the BCRM). Detroit Lake has two primary inputs, the North Santiam and Breitenbush Rivers, and several smaller tributaries, including French, Blowout, Box Canyon, and Kinney Creeks. Detroit Dam is 463 ft (141.1 m) high and has outlets at four elevations, including a spillway, power penstocks, and upper and lower sets of regulating outlets.

Model History and Domain

The Detroit Lake Model (DETM) was developed by USGS to model calendar years 2002 and 2003 and a period of storm runoff from December 1, 2005, to February, 2006 (Sullivan and others, 2007), and has been used extensively for additional model runs since its initial development. (table 1). The DETM consists of one waterbody and four branches, representing the four major arms of the reservoir. Branches 1 and 2 represent the North Santiam and Breitenbush Rivers, respectively. Branch 3 represents the Blowout Creek arm of the reservoir. Branch 4 represents the Kinney Creek arm of the reservoir. Additionally, French and Box Canyon Creeks are included as tributaries to the model. Segment lengths range from 229.8 m to 638 m. Layers are 1 m thick. Unlike the LOP-DEX-M and GPR-FOS-M, which model the two in-series reservoirs as a single model, Detroit Lake and Big Cliff Reservoir are separate models. The BCRM is described in section, “Model Updates—Big Cliff Reservoir Model (BCRM).”

The model changes described in this report include (1) updating the 2011 and 2015 DETMs to CE-QUAL-W2 version 4.2 (USGS edition 7); (2) setting up the DETM for calendar year 2016; (3) adding hypothetical outlet structures to the DETM; and (4) checking and calibrating the models against measurements from 2011, 2015, and 2016, as needed. In addition to the four real structures, five hypothetical structures were added to the DETM, representing possible structural changes to the dam under consideration as part of the Willamette River Environmental Impact Statement (EIS) process. These hypothetical structures include a floating screen structure (for fish collection) represented by three structures at different elevations in the model, a high-elevation intake weir in a hypothetical selective withdrawal structure, and a lower-elevation intake gate in the hypothetical selective withdrawal structure (U.S. Army Corps of Engineers, 2019c). Elevations and widths of all structures are detailed in table 2.

Bathymetric and Non-Temporal Parameters

No changes were made to the bathymetric grid except to update it to the new, more readable .csv file format and to set the initial water-surface elevation to match the start of each simulation.

Temporal Inputs

Meteorology

The DETM was originally constructed using air temperature, dew-point temperature, wind speed, and wind direction data from the Stayton RAWS station (Sullivan and others, 2007). This station was decommissioned in 2010, requiring a replacement source for meteorological data for models from 2011 onward. The Bureau of Reclamation Cooperative Agricultural Weather Network (AgriMet) maintains a weather station near Detroit Lake (DTRO), and a RAWS station at Jordan (closer to Detroit Lake than the former Stayton RAWS station) was installed in 2005. Air temperature and dew-point temperature (calculated using relative humidity; Lawrence, 2005) from both stations were tested. Air and dew-point temperature from the Jordan RAWS station yielded a slightly better temperature fit when compared to the Detroit Lake temperature string, but improvements were mainly in the lower elevations of the lake, whereas the upper elevations of the lake and the fit downstream were slightly worse. For this reason, air and dew-point temperature data from DTRO were selected for the model updates (table 4). However, wind speed and direction as measured at the Jordan RAWS station yielded a better fit compared to using wind data from the DTRO station and were used for all three models.

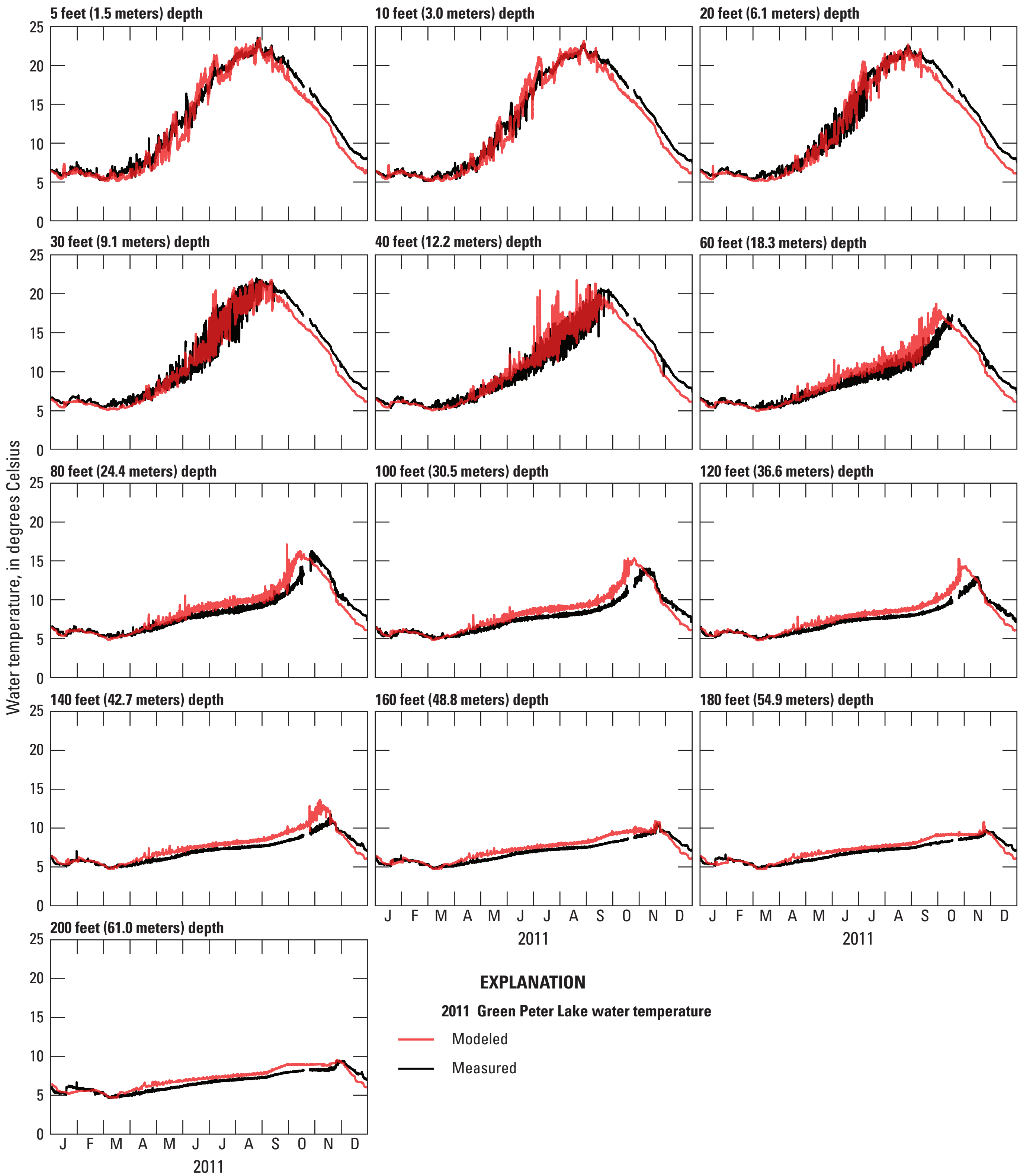


Figure 27. Continuous modeled and measured water temperatures at specific depths near the dam in Green Peter Lake, northwestern Oregon, 2011.

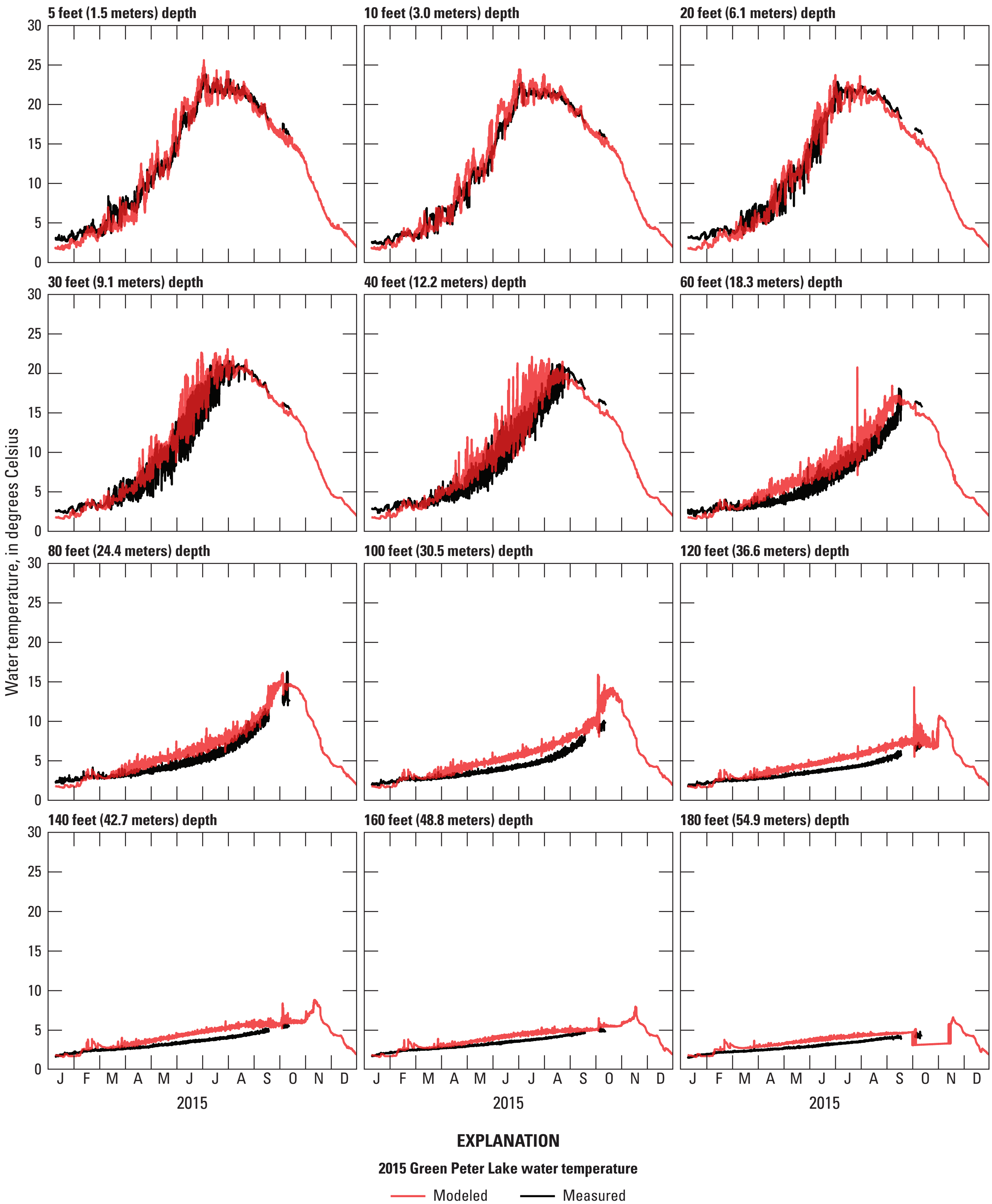


Figure 28. Continuous modeled and measured water temperatures at specific depths near the dam in Green Peter Lake, northwestern Oregon, 2015.

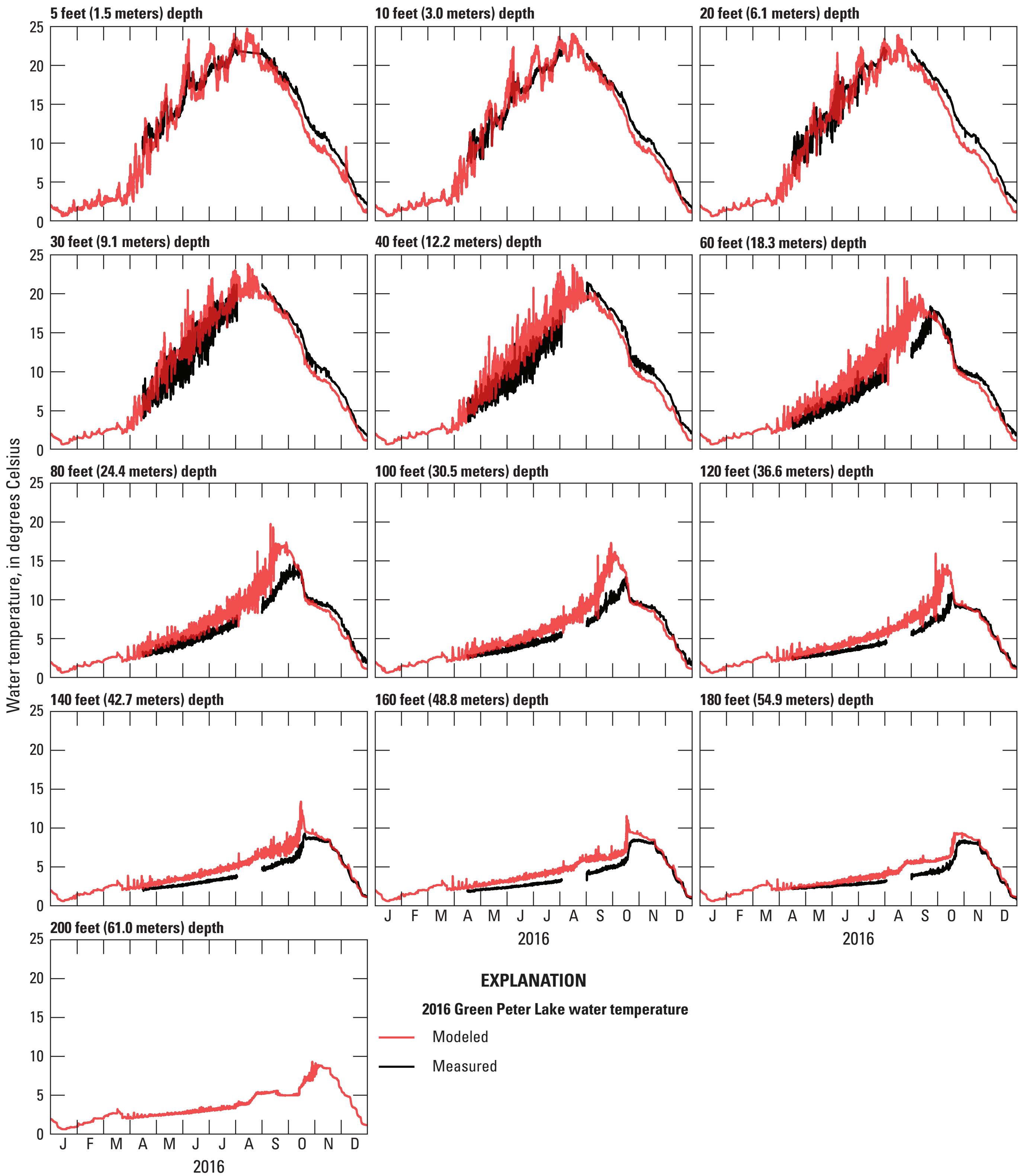


Figure 29. Continuous modeled and measured water temperatures at specific depths near the dam in Green Peter Lake. Northwestern Oregon, 2016.

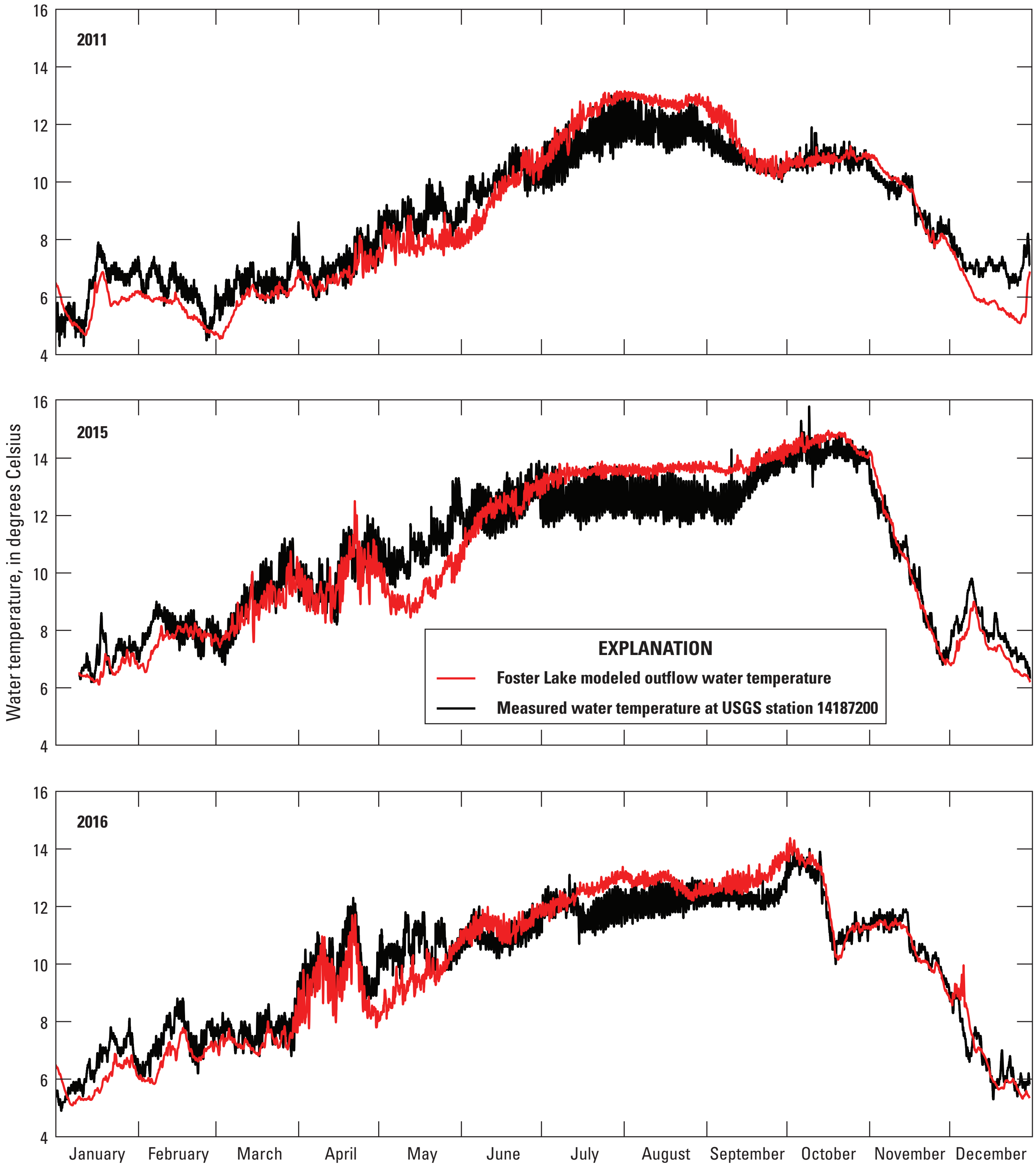


Figure 30. Continuous modeled outflow water temperatures from Foster Dam and measured water temperatures at U.S. Geological Survey (USGS) station 14187200 (South Santiam River near Foster, Oregon), northwestern Oregon, 2011, 2015, and 2016.

The original DETM used solar radiation data from the Eugene SRML and calculated cloud cover by comparing measured and theoretical solar insolation rates. This approach for cloud cover can yield good results but requires interpolation at night when measured and theoretical solar radiation are zero. For this reason, cloud cover was instead calculated as described by Stratton Garvin and others (2022) from cloud cover reported at WBAN 24232 (Salem Airport McNary Field). Cloud cover reported at WBAN 24221 (Eugene Airport Mahlon Sweet Field) was also tested but yielded a slightly worse fit. Similarly, solar radiation data from the DTRO AgriMet station was tested as an alternate to the Eugene SRML data, but the fit was slightly worse. The final meteorological inputs for all 3 years of the model updates used air and dew-point temperature from DTRO, wind speed and direction data from Jordan RAWS, observed cloud cover from WBAN 24232 (Salem Airport McNary Field), and solar radiation from the Eugene SRML.

Streamflow

Of the six inflows to the DETM, three had measured time series data and three were estimated using a watershed-area scaling method. Streamflow from USGS 14178000 (North Santiam River below Boulder Creek, near Detroit, Oregon) was available for the branch 1 inflow to the DETM. Branch 2 inflow used data from USGS 14179000 (Breitenbush River above French Creek near Detroit, Oregon). Branch 3 used data from USGS 14180300 (Blowout Creek near Detroit, Oregon). The remaining inflows were estimated using a watershed-area scaling method based on data from USGS 14180300 (Blowout Creek near Detroit, Oregon) and watershed areas computed using USGS StreamStats (U.S. Geological Survey, 2020):

$$Q_{KinneyCreek} = \frac{13.7}{26.0} \times Q_{USGS14180300} \tag{18}$$

$$Q_{FrenchCreek} = \frac{9.9}{26.0} \times Q_{USGS14180300} \tag{19}$$

$$Q_{BoxCanyonCreek} = \frac{10.7}{26.0} \times Q_{USGS14180300} \tag{20}$$

where

$Q_{KinneyCreek}$ is the daily streamflow in Kinney Creek where it enters branch 4 of the Detroit Lake Model (DETM), in cubic feet per second;

$Q_{FrenchCreek}$ is the daily streamflow in French Creek where it enters the DETM as tributary 1, in cubic feet per second;

$Q_{BoxCanyonCreek}$ is the daily streamflow in Box Canyon Creek where it enters the DETM as tributary 2, in cubic feet per second;

$Q_{USGS14180300}$ is the daily streamflow measured at U.S. Geological Survey station 14180300 (Blowout Creek near Detroit, Oregon), in cubic feet per second; and

the coefficients represent the ratios between each respective tributary watershed area, in square miles, and the watershed area of Blowout Creek upstream from its measurement station (26.0 square miles).

Temperature

Temperature data for inflows to the DETM were available from three continuous monitoring stations. The temperature of branch 1 inflow from the North Santiam River was derived from hourly measurements at USGS 14178000 (North Santiam River below Boulder Creek, near Detroit, Oregon). The temperature of inflow from the Breitenbush River (branch 2) was specified using hourly data from USGS 14179000 (Breitenbush River above French Creek near Detroit, Oregon). The temperature of branch 3 inflow from Blowout Creek was specified using hourly temperature data from USGS 14180300 (Blowout Creek near Detroit, Oregon).

The temperatures of the remaining inflows to the DETM were estimated using a combination of proxy records and regression methods. The temperature of USGS 14180300 (Blowout Creek near Detroit, Oregon) was used as a proxy for Kinney (branch 4) and Box Canyon (tributary 2) Creeks. The temperature of French Creek was estimated using a regression with the Breitenbush River and discontinued monitoring site USGS 14179100 (French Creek near Detroit, Oregon):

$$T_{FrenchCreek} = 0.92 \times T_{USGS14179000} + 0.27 \tag{21}$$

where

$T_{FrenchCreek}$ is the estimated subdaily temperature of French Creek at its confluence with Detroit Lake, in degrees Celsius; and

$T_{USGS14179000}$ is the subdaily temperature measured at U.S. Geological Survey station 14179000 (Breitenbush River above French Creek near Detroit, Oregon), in degrees Celsius.

Model Fit

Water Balance

The DETM water budget was balanced by iteratively calculating a distributed tributary for branch 1 (the main body of the reservoir) until the modeled reservoir surface elevation matched the measured water surface elevation from the CWMS database, following the protocol described in section Methods and Data: Water Balance (fig. 31). Detroit Lake filled in 2011 but did not fill in 2015 or 2016 when it remained well below its rule curve throughout the summer.

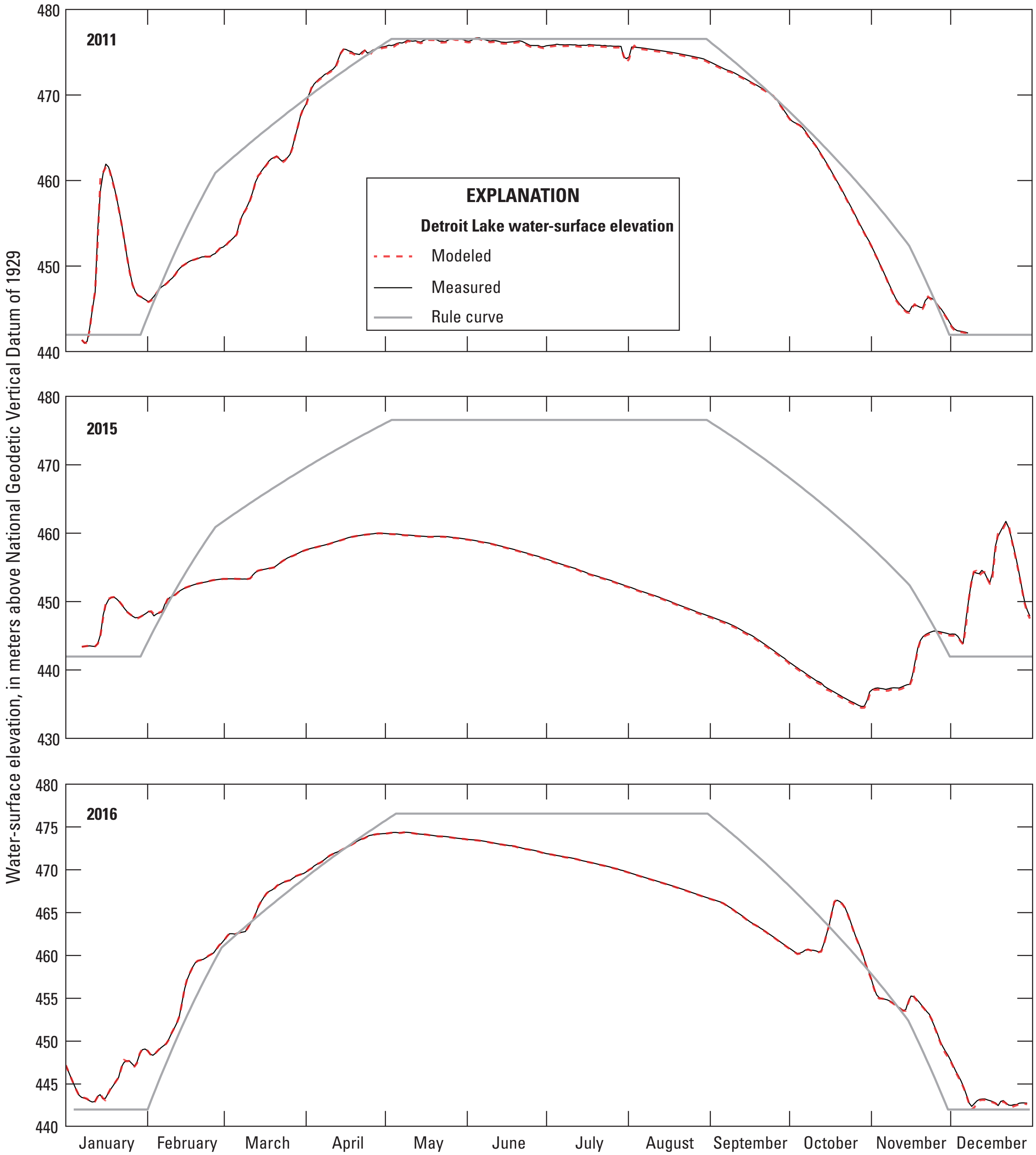


Figure 31. Daily modeled compared to measured water-surface elevation at Detroit Lake from the Detroit Lake Model (DETM), northwestern Oregon, 2011, 2015, and 2016. Where not visible, red (modeled) dashed lines are plotted directly over black (measured) solid lines. The “rule curve” is the operational water-surface target for a given day and is provided for context.

Temperature

Comparison of modeled temperatures with data from the floating thermistor string in Detroit Lake shows that the DETM produces good results at all depths except in 2015, when the model failed to simulate the timing of autumn turnover (when the reservoir becomes isothermal following a season of thermal stratification) in early November (figs. 32–34). In contrast, the 2016 model reproduces autumn turnover well. Subdaily outflow temperature MAE for all years does not exceed 0.76 °C when comparing modeled outflow from Detroit Dam with data from USGS station 14181500 (North Santiam River at Niagara, Oregon), which is located downstream from Big Cliff Dam and tends to reflect warming and smoothing of variability that outflow from Detroit undergoes when traveling through Big Cliff Reservoir (table 10). As discussed in section, “Model Updates—Big Cliff Reservoir Model (BCRM)—Model Fit—Temperature,” fit improves after routing outflow from the DETM through the BCRM. Some error in the simulated thermal structure of the lake might be a result of the use of a daily time step in the user-specified outflow rates from Detroit Dam, when in reality outlet use and outflow rates may vary widely throughout the day to account for power production needs at the Detroit powerhouse.

Big Cliff Reservoir Model (BCRM)

Description

Big Cliff Reservoir is the reregulating reservoir immediately downstream from Detroit Dam on the North Santiam River at approximately RM 58.1. Because its storage volume is used to smooth the releases from Detroit Dam to the North Santiam River downstream, it is subject to substantial changes in elevation on a daily basis (as much as 24 ft; Buccola, Rounds, and others, 2013). Big Cliff Dam is 191 ft high and has outlets at two elevations, including a spillway and power penstocks (Hansen and others, 2017).

Model History and Domain

The Big Cliff Reservoir Model (BCRM) was developed by USGS to simulate model years 2002 and 2003 using CE-QUAL-W2 version 3.12 (Cole and Wells, 2001; Buccola, Rounds, and others, 2013). The model was updated to CE-QUAL-W2 version 3.72 with USGS modifications in 2015 (Buccola and others, 2015; Cole and Wells, 2015; Rounds and Buccola, 2015). USGS and USACE updated the model to version 4.1 for a synthetic “hot/dry” scenario as part of an unpublished study investigating operational and management scenarios at Detroit Lake; this version of the BCRM was used to develop boundary conditions for 2011, 2015, and 2016.

Because of Big Cliff Reservoir’s small size compared to the volume of inputs, the water-surface elevation simulated by the BCRM is extremely sensitive to minor imbalances between inflow and outflow. As a result, closing the water balance can be challenging and time-consuming, requiring many attempts to force the model to completion while balancing a few days at a time. This approach was not considered to be reasonable for the EIS modeling effort because of timeline constraints. As a result, two versions of the BCRM were developed. The first version includes a complete water balance as originally developed by Buccola, Rounds, and others (2013). The second version was developed for use with the EIS scenarios and simplifies the model to remove all sources or sinks of water except for the inflow and outflow, which were set to be equal on a daily basis. In this way, water moving through the BCRM is exposed to environmental heat fluxes during its time of travel through Big Cliff Reservoir, improving the estimate of water temperature in the North Santiam River as compared to the outflow from Detroit Dam, while also providing a simple enough model to be useful within the given constraints. A comparison of the goodness-of-fit for both approaches is included in section, “Model Updates—Big Cliff Reservoir Model (BCRM)—Model Fit”.

Bathymetric Grid and Non-Temporal Parameters

No changes were made to the bathymetric grid except to update it to the new, more readable .csv file format and to set the initial water-surface elevation to match the start of each simulation.

Temporal Inputs

Meteorology

The original setup of the BCRM used air temperature, dew-point temperature, wind speed, and wind direction data from the Stayton RAWS station (Sullivan and others, 2007). This station was decommissioned in 2010, requiring a new data source to be found for these parameters, as discussed in section, “Model Updates—Detroit Lake Model (DETM)—Temporal Inputs—Meteorology.” The BCRM used the same meteorology file as the DETM. Evaporative mass loss was turned on for the “full water balance” version of the model but turned off for the simplified version.

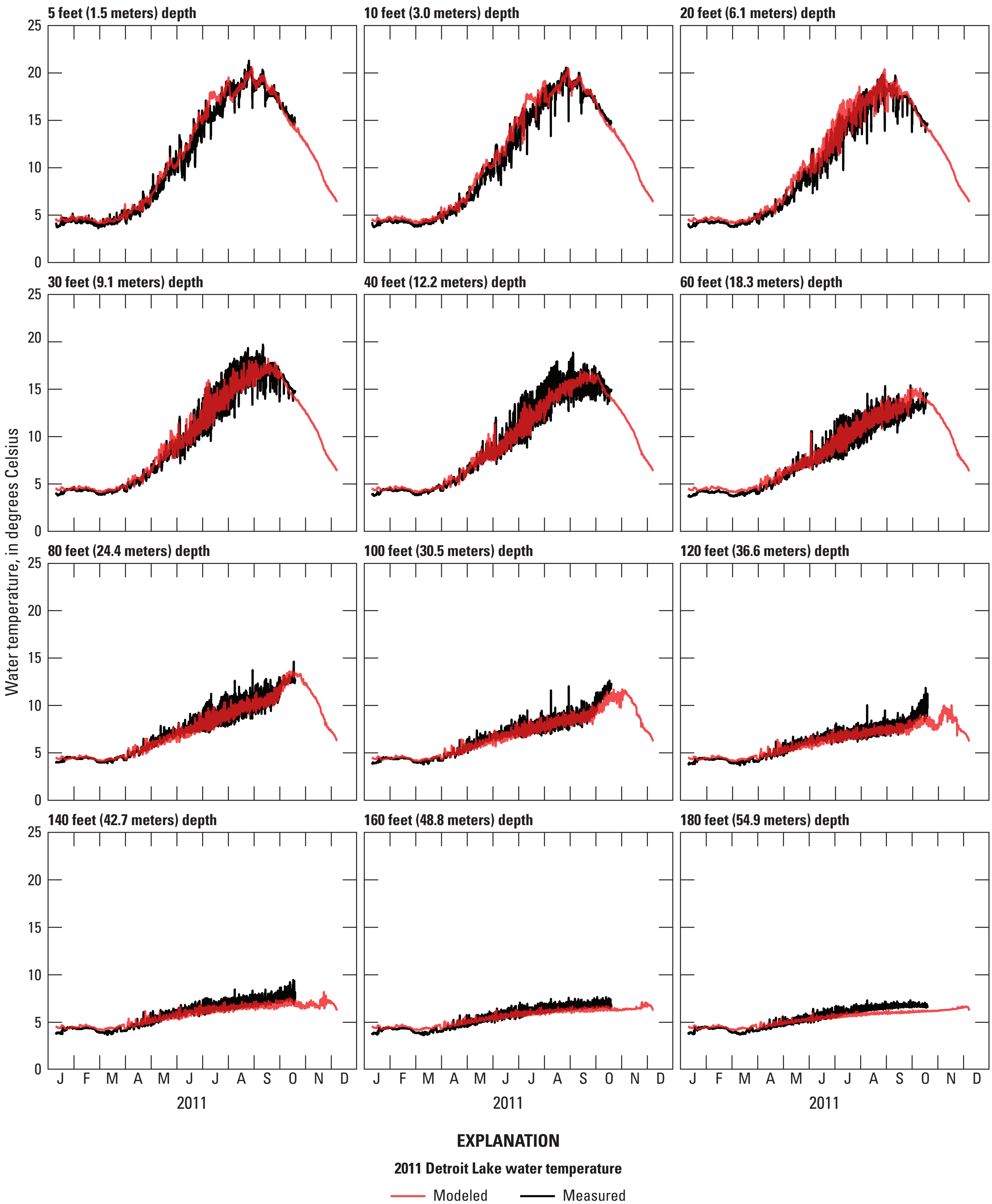


Figure 32. Continuous modeled and measured water temperatures at specific depths near the dam in Detroit Lake, northwestern Oregon, 2011.

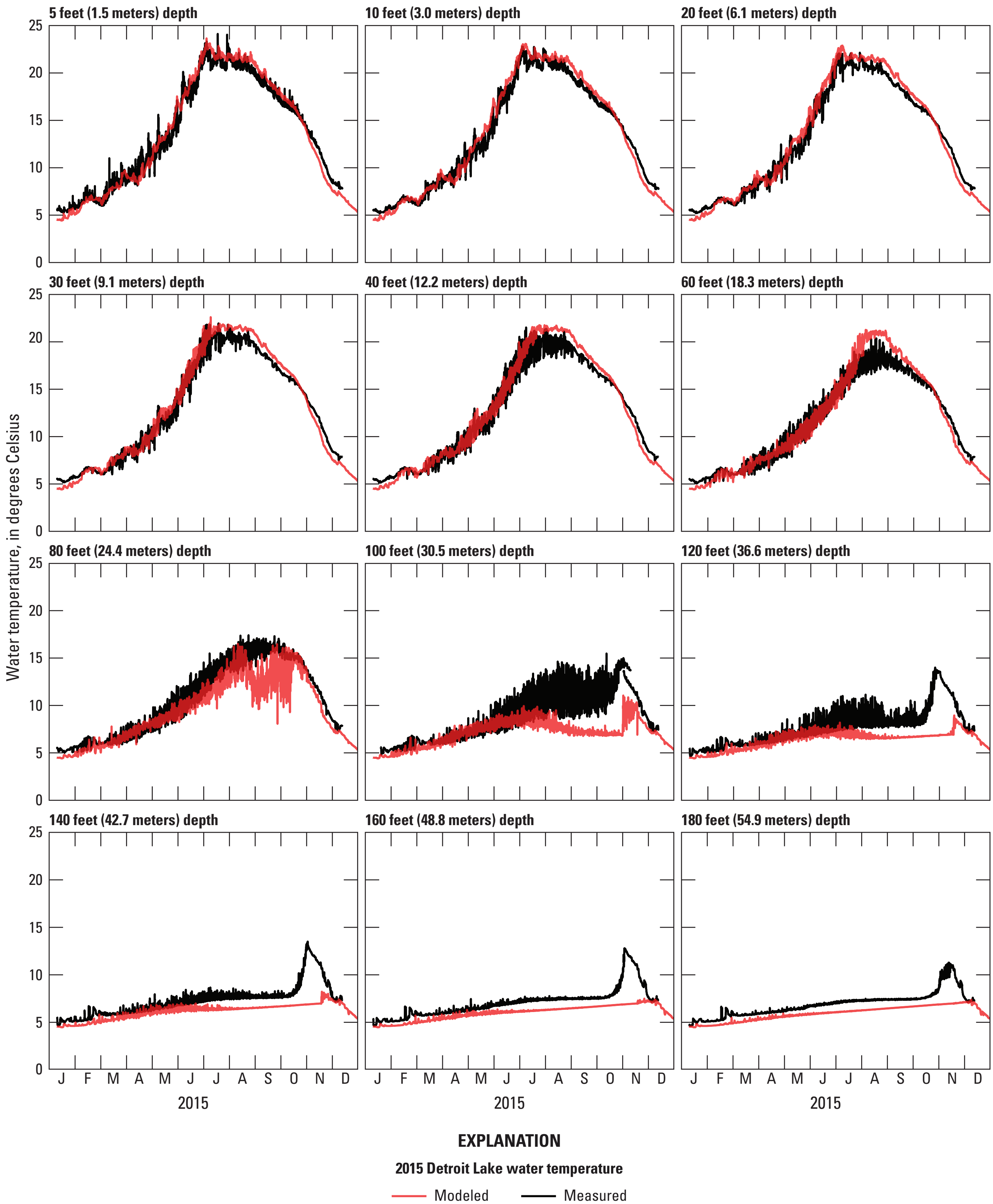


Figure 33. Continuous modeled and measured water temperatures at specific depths near the dam in Detroit Lake, northwestern Oregon, 2015.

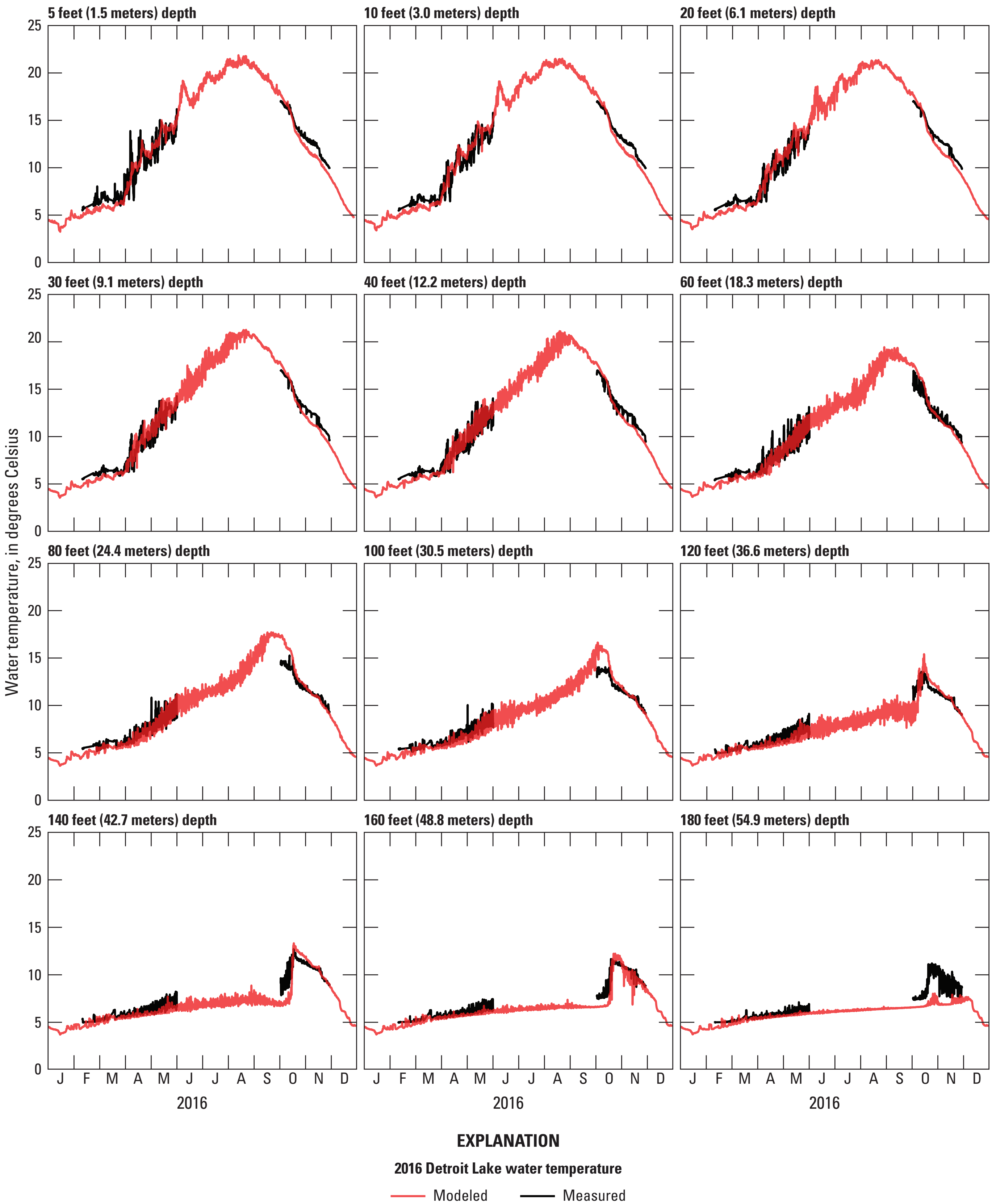


Figure 34. Continuous modeled and measured water temperatures at specific depths near the dam in Detroit Lake, northwestern Oregon, 2016.

Streamflow

As originally built and calibrated, the BCRM included inflow from Detroit Dam (branch 1) and from two tributaries, Lawhead and Sardine Creeks. Streamflow from these tributaries was estimated using a watershed-area scaling method as documented by Buccola, Rounds, and others (2013):

$$Q_{LawheadCreek} = \frac{13.7}{26.0} \times Q_{USGS14180300} \quad (22)$$

$$Q_{SardineCreek} = \frac{10.7}{26.0} \times Q_{USGS14180300} \quad (23)$$

where

$Q_{LawheadCreek}$ is the daily streamflow in Lawhead Creek where it enters the Big Cliff Reservoir Model (BCRM), in cubic feet per second;

$Q_{SardineCreek}$ is the daily streamflow in Sardine Creek where it enters the BCRM, in cubic feet per second; and

$Q_{USGS14180300}$ is the daily streamflow measured at U.S. Geological Survey station 14180300 (Blowout Creek near Detroit, Oregon), in cubic feet per second; and

the coefficients represent the ratios between each respective tributary watershed area, in square miles, and the watershed area upstream from the measurement station for Blowout Creek (26.0 square miles).

In the simplified version of the BCRM, streamflow from the tributaries and distributed tributary were set to zero. Daily outflow from Big Cliff Dam was set to equal the inflow from Detroit Dam.

Temperature

In the “full water balance” version of the BCRM, both tributaries used the estimated temperature of French Creek as proxy records (eq. 21). The temperature of the distributed tributary was set to the temperature of outflow from Detroit Lake. No tributary or distributed tributary temperatures were applied in the simplified versions of the BCRM.

Model Fit

Water Balance

Big Cliff Reservoir is a relatively small reservoir with a water level that varies rapidly to allow irregular inflows from Detroit Dam to be smoothed prior to release to the North Santiam River downstream. This dynamic tends to make the water balance in the model difficult to calibrate, as the model tends to crash when the water budget is out of balance (the model either dries up or overflows). Multiple approaches to calibrate the water balance in the BCRM have been taken, but all require an iterative and time-consuming process to achieve a water-surface elevation that is stable enough to allow the model to run to completion (for example, see Buccola and others, 2015). To run multiple model scenarios investigating a range of operational and management changes at Detroit Dam, simplification of this process was required using the following approach:(1) removing flows from the tributaries, distributed tributary, and precipitation; (2) turning off evaporative mass losses; and (3) setting daily inflow from Detroit Dam equal to daily outflow from Big Cliff Dam. Using this approach, the BCRM can be simplified to pass all inflow as outflow and effectively hold the water-surface elevation constant while still allowing water passing out of Detroit Dam to be exposed to the heating or cooling effects of passage through Big Cliff Reservoir (fig. 35). Conditions in Big Cliff Reservoir were simulated using the existing, “complete” model and the simplified model, and the results were compared between model versions. As discussed further in section, “Model Updates—Big Cliff Reservoir Model (BCRM)—Model Fit—Temperature,” the simplified approach provided a reasonable shortcut to use the BCRM with minimal increase in the model error when comparing measured temperatures in the North Santiam River to outflow temperatures from the BCRM.

Temperature

Big Cliff Reservoir has a short residence time for outflow from Detroit Lake. At the time of recalibration, in-reservoir temperature data was not available for comparison. As a result, model calibration is limited to a comparison of the outflow temperature from Big Cliff Dam to the temperature measured at USGS station 14181500 (North Santiam River at Niagara, Oregon). The full-water-balance and simplified versions of the BCRM both show subdaily MAEs of 0.77 °C or less in all years modeled, with the simplified version showing improved error statistics in 2011 and 2016 and a MAE only 0.13 °C greater in 2015 (table 10). A comparison of time series plots from both versions of the BCRM with temperature measured at USGS station 14181500 (North Santiam River at Niagara, Oregon) shows a tendency to slightly underestimate outflow temperature in 2011 and 2016 and to overestimate outflow temperature in August 2015—likely a carryover of simulated Detroit Dam releases that also were too warm in August 2015 (figs. 36 and 37).

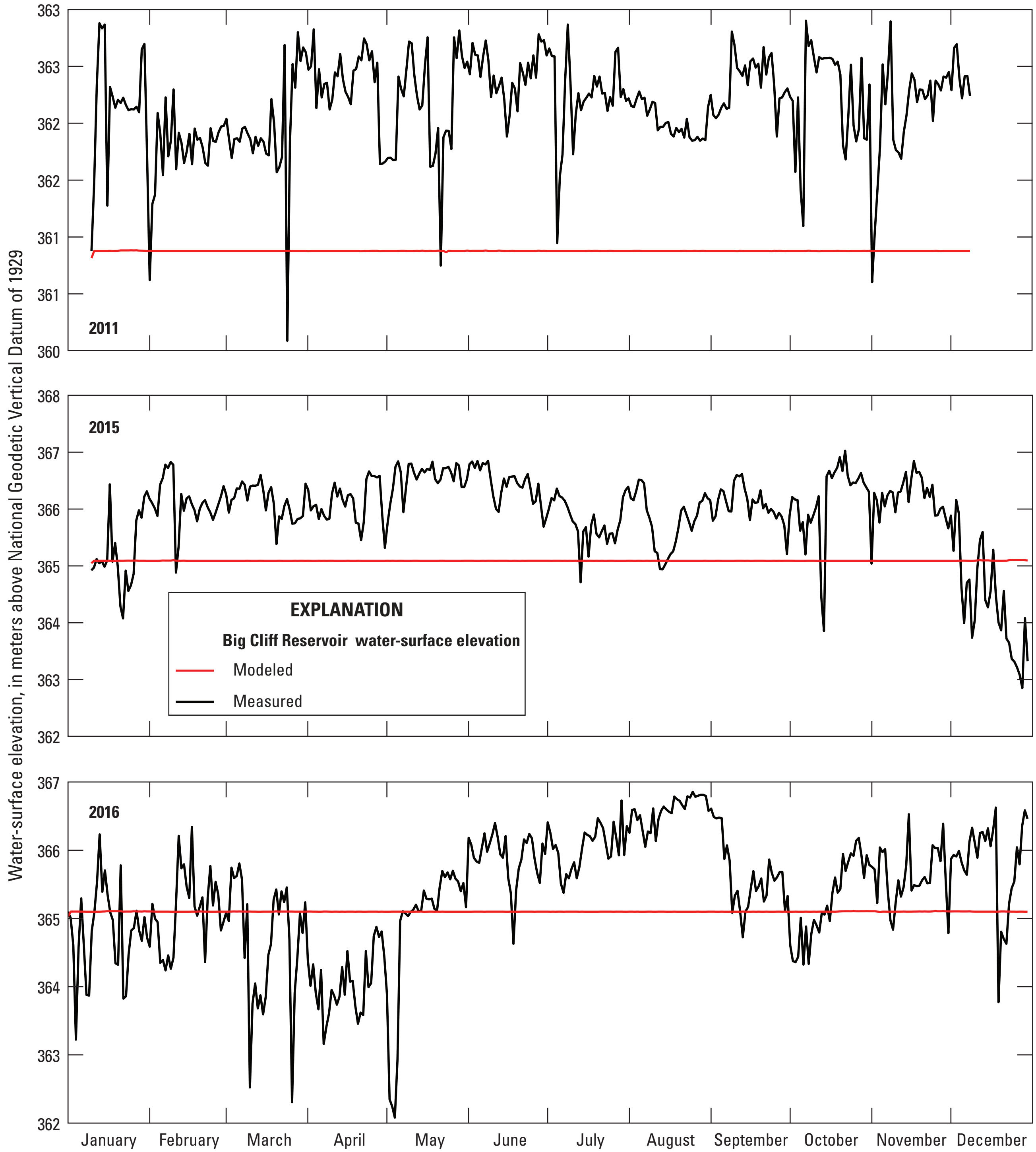


Figure 35. Daily modeled compared to measured water-surface elevation in Big Cliff Reservoir from the simplified water-balance version of the Big Cliff Reservoir Model (BCRM), northwestern Oregon, 2011, 2015, and 2016.

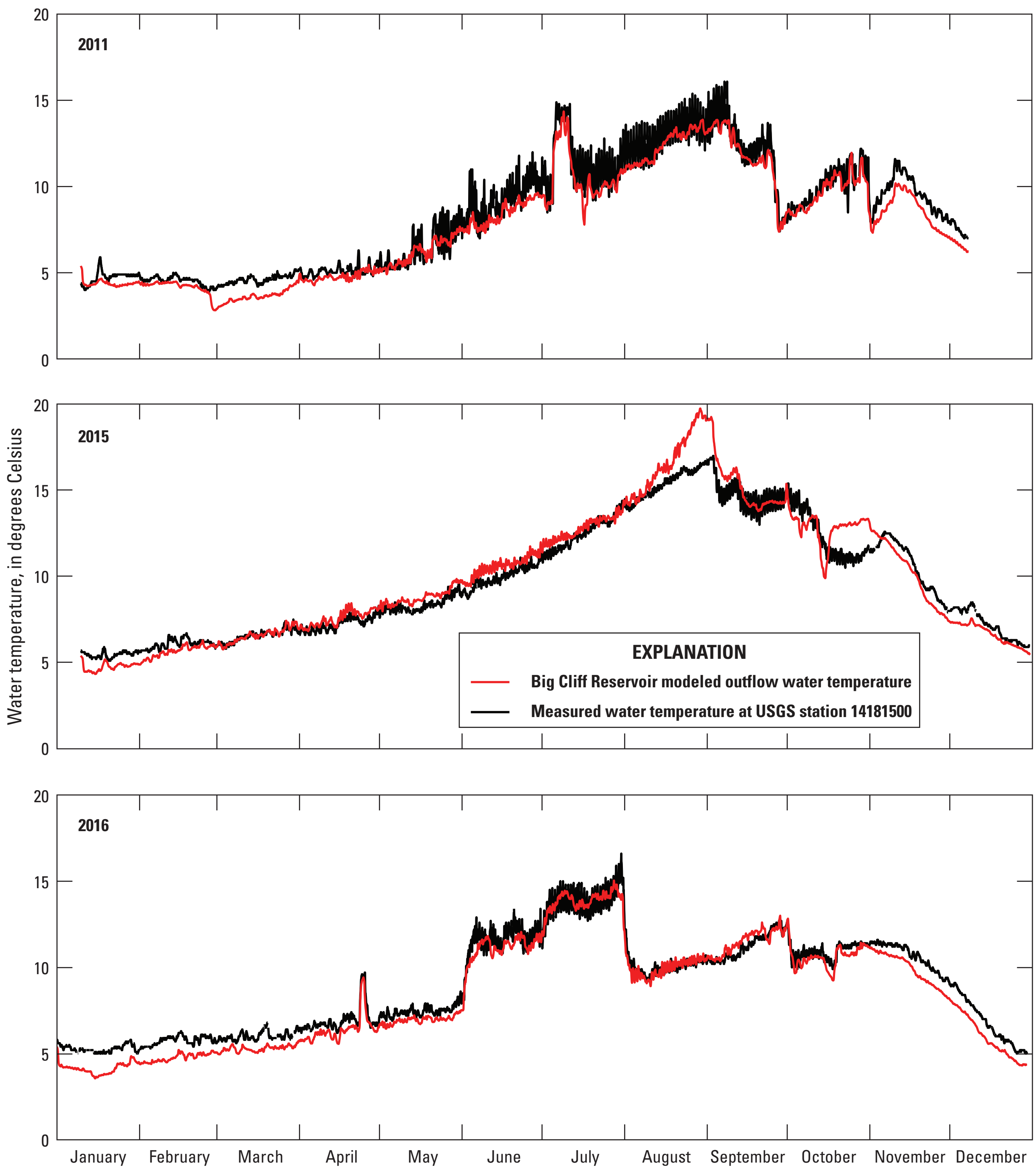


Figure 36. Continuous modeled outflow water temperatures from Big Cliff Reservoir and measured water temperatures at U.S. Geological Survey (USGS) station 14181500 (North Santiam River at Niagara, Oregon), simulated using the full-water-balance version of the Big Cliff Reservoir Model (BCRM), northwestern Oregon, 2011, 2015, and 2016.

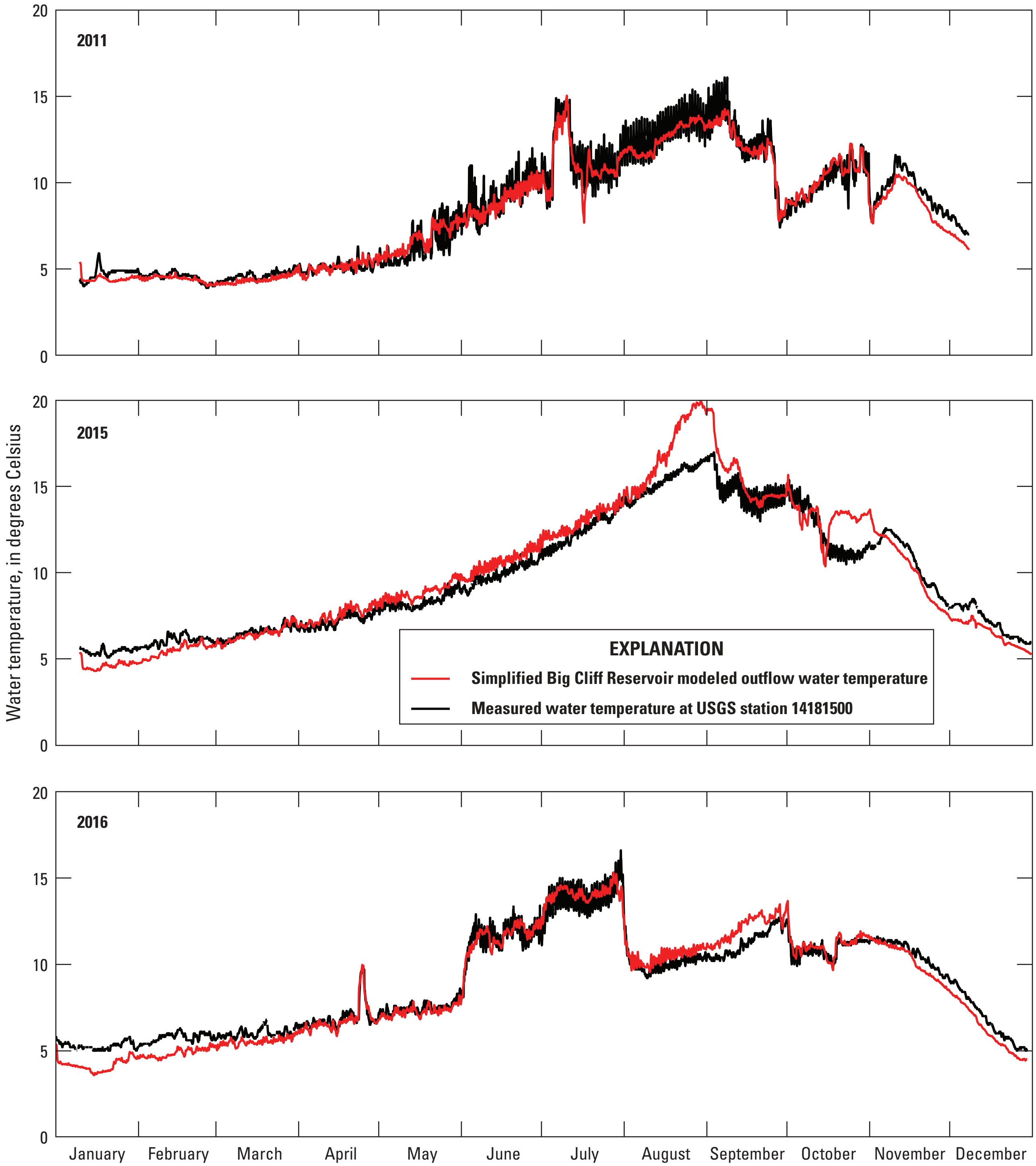


Figure 37. Continuous modeled outflow water temperatures from Big Cliff Reservoir and measured water temperatures at U.S. Geological Survey (USGS) station 14181500 (North Santiam River at Niagara, Oregon), simulated using the simplified-water-balance version of the Big Cliff Reservoir Model (BCRM), northwestern Oregon, 2011, 2015, and 2016.

Summary and Possible Future Research

This report documents (1) the modernization to U.S. Geological Survey (USGS) edition 7 of version 4.2 of CE-QUAL-W2, a two-dimensional (laterally averaged) hydrodynamic and water-quality model designed for use in reservoir and river systems; and (2) the configuration to simulate calendar years 2011 (a “cool, wet” year), 2015 (a “hot, dry” year) and 2016 (a “more-normal” year) of a set of reservoir and river models within the Willamette Valley Project in northwestern Oregon. These models include (1) Hills Creek Lake and Dam (HCLM); (2) the Middle Fork Willamette River between Hills Creek Dam and the head of Lookout Point Lake (MFWM); (3) Lookout Point Lake, Lookout Point Dam, Dexter Reservoir, and Dexter Dam (LOP-DEX-M); (4) Cougar Reservoir and Cougar Dam (CGRM); (5) Green Peter Lake, Green Peter Dam, Foster Lake, and Foster Dam (GPR-FOS-M); (6) Detroit Lake and Detroit Dam (DETM); and (7) Big Cliff Reservoir and Big Cliff Dam (BCRM model). All these models were developed by other researchers to simulate the hydrodynamics, thermal structure, and dam operations for the reservoirs and streams listed above, for a range of years and hydroclimatological conditions. As part of the model updates described here, some model parameters were adjusted to improve stability or decrease model error; additionally, boundary conditions including meteorological, hydrologic, and thermal parameters were developed and updated for model years 2011, 2015, and 2016. In some cases, the data sources used to drive the previous model versions were no longer available, which required the development and checking of new data sources or estimation techniques.

Goodness-of-fit statistics for outflow from the dams and in simulated river reaches generally show a good model fit, with the models simulating subdaily water temperatures at most comparable locations with a mean absolute error of generally less than 1 degree Celsius (°C) and a bias near zero. Model simulation of the thermal structure in each reservoir was also generally characterized by a mean absolute error goodness-of-fit of less than 1 °C, with the exception of Hills Creek Lake and Cougar Reservoir in years when the reservoirs did not fill (2015 and 2016). Both of these models have known calibration issues and tend to be very sensitive to the configuration of parameters describing model outflow structures. Notably, most of the reservoir models tend to be less accurate in 2015, when reservoir elevations were generally low throughout the summer. This observation may reflect the increased importance of accurately simulating the depth of the thermocline when the water-surface elevation is lower and therefore closer to the elevation of many dam outlets. It may also reflect the enhanced influence of minor inaccuracies in the model grid relative to actual reservoir bathymetry at lower elevations, the increased influence of inflow temperature (which, in many cases, is estimated) relative to a smaller reservoir pool, or variations in wind speed and fetch between calibrated full versus lower pool elevations. In the case of Cougar Dam, however, some error may be a result of data-quality and comparability issues with the fixed thermistor string on the face of Cougar Dam. The discrepancy between relatively large in-reservoir model error and relatively small error in outflow temperature suggests that the model might be simulating reservoir thermal structure more accurately than is suggested by comparisons to data from in-reservoir temperature strings. Future updates to the CGRM (or other reservoir models) might include collecting in-reservoir data away from the dam faces, which is consistent with practices used for the original CGRM calibration and verification (Threadgill and others, 2012).

The updated reservoir and river models included in this report are set up for the same model years and in a compatible version of CE-QUAL-W2 to be linked with the downstream river models documented by Stratton Garvin and others (2022), allowing integrated simulation of operations at the large Willamette Valley Project Dams and their influence on downstream tributaries and the Willamette River as far downstream as Willamette Falls. This integrated, “basin-wide” CE-QUAL-W2 system model can provide managers with tools to understand management tradeoffs between dams and reservoirs within the Willamette Valley Project, the effect of dam operations on downstream tributaries and the Willamette River, and their potential effect on threatened fish populations and the quality of their habitat. Individually or collectively, the reservoir and river models of the Willamette Valley Project allow managers to test potential outcomes from new operations

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Appendix 1. Code Changes for Edition 7, Version 4.2, of the CE-QUAL-W2 Model

A customized edition of the CE-QUAL-W2 model, a two-dimensional (laterally averaged) hydrodynamic water-quality model, was used in this study. Modified by U.S. Geological Survey (USGS), the 7th USGS edition of version 4.2 is based on model code released by Portland State University on September 20, 2019. Previous USGS editions of version 4.2 have added a variety of new capabilities and fixed a number of problems, such as:

- the ability to track individual sources of water or heat, the average age of heat, and the ages of individual sources of water or heat;
- the creation of several customized output files for analyzing heat fluxes and making systemwide visualizations of model results;
- a modification of the model's ability to run multiple models simultaneously, such that downstream models can run at the same time as upstream models by pausing to wait for new inputs from upstream models;
- updates to the code for adsorption of phosphorus and silica; and
- the ability to use potential of hydrogen (pH) as a boundary condition rather than the concentration of total inorganic carbon.

Edition 7 builds on these features and bug fixes of previous editions of version 4.2. The main focus of code changes in edition 7 was on fixing issues related to branch inactivation and reactivation. Recall that a "branch" in the CE-QUAL-W2 model is a sequential collection of model segments, where a segment is the longitudinal discretization unit of the model grid and each segment is composed of a vertical stack of model cells of various widths. Edition 7 also fixed problems in the downstream and lateral withdrawal subroutines and modified the snapshot output to better communicate when branches or tributaries were active or inactive. All changes for edition 7 were marked in the code with a "!SR 11/30/2021" comment.

The modified code and more extensive documentation of the code changes are available from Stratton Garvin and others (2023; https://doi.org/10.5066/P9UJFXA5).

Branch Inactivation and Reactivation

Most of the code changes in USGS edition 7 were made to fix problems relative to branch deactivation and reactivation. When simulating a reservoir with side arms that are represented with separate model branches, a deep drawdown of that reservoir may dry up the side arm and cause the model to deactivate that branch. If the water level in the reservoir later rises and sufficient water once again resides in the side arm, the model will reactivate that branch. Branch deactivation must be done in such a way that any upstream inflows and tributary inputs to a deactivated branch are translated downstream to the active waterbody, and branch reactivation must be done in a way that properly initializes all the required model variables. The original version 4.2 model code addressed branch inactivation and reactivation, but the code was inconsistent in its methods and numerous variables were not properly initialized upon branch reactivation, such that the model produced inaccurate results after a branch was reactivated.

Relocating Flows into Inactive Branches

In subroutine HYDROINOUT, some code was present in the original version 4.2 model to handle situations when one or more branches of the model were inactive. The intent of the original code was to try to translate upstream inflows for any inactive model branches to an active receiving segment so that the inflow would remain part of the model water budget. The code in the HYDROINOUT subroutine that was supposed to make this reassignment, however, contained several errors and was not optimal in its approach.

First, the original code moved the inactive branch inflow to the current upstream segment of branch 1 (rather than the downstream connection point of the inactive branch), as a simple default. In some ways, this default was acceptable because branch 1 should be the main branch of the model and should never be inactivated. A better solution, however, would be to assign the inactive branch inflow to the segment that would normally receive downstream outflow from that branch. In the case of a downstream internal head boundary condition, which is the most common model linkage for a side arm of a reservoir, that location would be the segment defined with the model variable DHS(JB) for the inactive branch, where JB is the branch index. Assigning the flow to branch 1, as was the procedure in the original code, may result in problems. For example, if a model includes two reservoirs and a branch arm of the downstream reservoir is inactivated, the upstream inflow for that branch would be reassigned to branch 1, which likely is the main branch of the upstream reservoir, thus putting the inflow into the wrong waterbody. The newer version 4.5 code changed the inflow destination from the current upstream segment of branch 1 to the current upstream segment of the downstream-most branch in the same waterbody, but the version 4.5 code still had other problems with that reassignment.

Second, the original code created a new "fake" or "temporary" tributary in the model as a means of relocating the inactive branch inflow to a reassigned segment location. This is a good means of temporarily reassigning the flow to a new location. However, the flow assigned to the temporary tributary was taken from the QIN(JB) variable, which normally would hold the upstream inflow rate for the branch being inactivated when that branch has an upstream flow boundary condition. The problem is that the QIN(JB) variable is not updated to the user-specified flow input when branch JB is inactivated because the part of the code that would set QIN(JB) is bypassed when branch JB is inactive. Instead, the code should use the variable QIND(JB), as that is the flow rate read in from the boundary condition input file and, if requested by the user, is interpolated over time.

The third original code issue is essentially the same as the second issue, but for water temperature rather than flow. The original code assigned the water temperature of the temporary tributary using the TIN(JB) variable, but the variable TIND(JB) should have been used instead.

All tributaries in the model are assigned a variable that holds the model branch number for the segment into which the tributary flows. The original version 4.2 code assigned the temporary tributary location to the current upstream segment of branch 1, so this tributary branch index (JBTR) was originally set to 1. In version 4.5, the temporary tributary segment location was changed to the current upstream segment of the downstream-most branch in the same waterbody as the branch being deactivated (JBDN(JW), where JW is the waterbody index), but the updated version 4.5 code failed to set the tributary branch index to JBDN(JW). The updated code fixes these issues.

The temporary tributaries are useless unless the model knows that tributaries are present, whether real or fake. A logical variable in the model (TRIBUTARIES) is defined as TRUE when the number of tributaries is more than zero. The original code neglected to reset this variable after creating any temporary tributaries, meaning that in the absence of any user-defined "real" tributaries, the model would still use a value of FALSE for the TRIBUTARIES variable and therefore would fail to apply the inputs of newly created temporary tributaries.

Finally, if a user-specified tributary was set to flow into a branch that becomes inactive, the original code failed to reassign that tributary flow to a downstream active location and the flow was "lost" from the model. The updated code creates a new temporary tributary to help relocate any user-defined tributary flow downstream to the segment where the inactive branch flows would normally be placed.

The updated code accounts for multiple inactive branches in a downstream sequence, such that any inflows to those inactive branches and any tributaries that normally would discharge into those inactive branches are reassigned downstream to the active segment where that water would normally flow. The updated code follows internal downstream head boundary conditions or flow connections made by gates, spillways, pumps, or pipes. However, branch reactivation in another part of the code assumes that a downstream head linkage exists.

In summary, the original version 4.2 code that attempted to account for upstream inflows to inactive branches assigned the wrong flow and the wrong temperature to the wrong location, did not account for user-specified tributaries flowing into inactive branches, and also did not apply any temporary tributaries when no other tributaries were specified in the model. The updates in USGS edition 7 fix all these problems related to flows into inactive branches.

Inactivating or Reactivating a Branch

Subroutine LAYERADDSUB in the CE-QUAL-W2 model contains code enabling the surface-layer index to be moved up or down in the model grid in response to changes in the water-surface elevation, effectively activating ("adding") a new layer of active cells or inactivating ("subtracting") a layer of cells at the water surface. When adding a layer, the model also can activate (add) any inactive segments on the upstream side of a branch that meet a certain activation criterion. Similarly, when subtracting a layer, the model may inactivate (subtract) active segments that fail to meet another criterion. This subroutine also is the location in the model code where active branches can be inactivated, inactive branches can be reactivated, or the model can be terminated if a main branch no longer has any viable segments.

The model code that defines initial conditions in CE-QUAL-W2 (in subroutine INITGEOM) will NOT initially activate a branch unless that branch has at least two active segments. In contrast, the original version 4.2 and 4.5 model codes were configured to inactivate a branch when it had fewer than one active segment rather than two active segments. The code changes in USGS edition 7 eliminate this inconsistency by requiring that branches must have at least two active segments to become active and to remain active.

The criterion used in the original version 4.2 and 4.5 model codes for reactivating an inactive branch was convoluted and did not honor the user-specified minimum number of active cells for a segment to be active. The original reactivation criterion instead required the current water level in the segment specified by a downstream head linkage to be higher than the top of the bottom-most layer of the inactive branch at a point either two or three segments from the downstream end of that inactive branch. As a result, water might be present in a reactivated branch, but branch reactivation could be followed closely by branch inactivation if the user-specified minimum number of active cells in a segment (NLMIN input) was more than 1.

Any code changes regarding branch inactivation and reactivation should be consistent with regard to the number of active segments, and the reactivation criterion should honor the NLMIN input for each branch. Given that the initial conditions require at least two active segments for a branch to be active, other criteria for branch inactivation and reactivation should be similar. The updated code requires at least two active segments for branch reactivation and fewer than two active segments for branch inactivation, except for the downstream-most branch in each waterbody. The downstream-most branches typically are the main branches of a river or reservoir and normally would never be inactivated; therefore, failure to keep at least one active segment in the downstream-most branch of each waterbody should terminate the model. This is a small change, as the original code would only terminate the model when branch 1 had no active segments. Rather than hard-wiring branch inactivation to fewer than two active segments and branch reactivation to at least two segments, the user could have been allowed to specify the number of segments for branch inactivation or reactivation in the control file, but this criterion is rather sensitive and is best not left to the model user. Specifying a single segment to keep a branch active, for example, might cause oscillations, and specifying a larger number could be problematic for continuing to simulate as much of the grid as possible. The decision was made, therefore, to require at least two segments for branch reactivation and fewer than two active segments for branch inactivation.

The code in the original LAYERADDSUB subroutine did not seem to be complete with respect to branch reactivation. Some variables in the original code were not set properly, and many variables for the newly activated branch and its activated cells were not initialized at all. It was difficult to determine which variables needed to be initialized. The original code for adding layers and adding segments was used as a partial template for adding new code for branch reactivation. Some groups of variables were omitted for this edition, such as code that is relevant only for macrophytes or epiphytes or flux calculations; those refinements are left for a future edition. Importantly, however, calls were added to subroutines that serve to refresh some critical variables. The call to the INTERPOLATION_MULTIPLIERS subroutine, for example, was particularly important because variables set there depend partly on the updated surface-layer heights, and that subroutine call had been left out of the original code. Without that subroutine call, the model tended to produce highly inaccurate results after branch reactivation.

The branch reactivation code relies on the reactivated branch having an internal downstream head boundary condition. Without that type of linkage, the code will fail to reactivate a branch. For reservoirs, a downstream head boundary condition would be the typical linkage for a side arm that might become inactivated at low water levels; therefore, this restriction in the code should not be a problem for most model applications. Future refinements might address any shortcomings and make the code more robust.

In the process of making these changes for branch reactivation and inactivation, code was added to fix a few other variables that were not set properly. The original code had a couple of errors in computing the number of active model cells, along with the running minimum and maximum of that number; these values are now reported out at the end of the snapshot file as general information. Additionally, the code was updated with respect to the variables that keep track of the running temporal sums of heat and constituent mass. When a branch is inactivated, that heat and mass are subtracted. Conversely, when a branch is reactivated, that heat and mass are added back to the running total. The original code had omitted some of this code when segments were added and subtracted and had errors when a branch was inactivated. The updated code fixes these problems.

Downstream and Lateral Withdrawals

Four subroutines are used to determine the vertical distribution of horizontal velocities for water flowing toward a downstream outlet or a lateral withdrawal. These subroutines form the basis of the selective withdrawal algorithms and determine how much water is drawn from each model layer when water is released through a dam outlet or removed from a lateral withdrawal. Water moving toward the outlet generally is drawn from layers with a similar density; for example, a dam outlet located below a strong thermocline generally will release water only from layers below that thermocline. The vertical size of the withdrawal zone depends on a number of factors, but the total withdrawal or release rate and the vertical density profile are strong influences.

The original model code was written with an assumption that water density always increases with depth. That assumption may be valid most of the time, but small water-temperature differences can cause the maximum density difference relative to the outlet location to occur in an unexpected layer. Given the algorithm later used to compute the horizontal velocity in each layer above or below an outflow or withdrawal, it is critical to find the maximum density difference rather than assume that the greatest density difference occurs at the farthest extent of the withdrawal zone; otherwise, the computed velocity distribution for the outflow can have substantial anomalies. To find the maximum density difference, the computations were placed in a loop over the appropriate layers for the each of the zones above and below the outlet layer. These changes were implemented for each of the DOWNSTREAM_WITHDRAWAL, DOWNSTREAM_WITHDRAWAL_ESTIMATE, LATERAL_WITHDRAWAL, and LATERAL_WITHDRAWAL_ESTIMATE subroutines.

Snapshot Output File

The OUTPUTA subroutine was modified to more clearly communicate whether branches and tributaries were active or inactive in the snapshot output and to fix a couple of errors. Snapshot output files are specific to each waterbody in the model, but not all outputs from the original model code were filtered to provide information specific to the branches or tributaries in the waterbody of a given snapshot file. Two of the meteorological parameters had been hard-wired to the first branch instead of being drawn from the waterbody of interest. For many of the branch- and tributary-specific outputs, the updated code now checks to see whether that branch or tributary is active before printing out a value. If the branch or tributary is inactive, a message to that effect is substituted for the intended variable value. This check applies to upstream inflows, distributed tributaries, regular tributaries, evaporation and precipitation rates, and the current upstream segment number.

Selective Withdrawal Input File Name

CE-QUAL-W2 reads a number of input files whose names are hard-coded into the model. One of these input files is "w2_selective.npt," which provides user-specified inputs relative to selective withdrawal details and constraints as well as habitat computations. In some studies that evaluate multiple operational scenarios, a different name may be conveniently used for this input file based on the scenario of interest. Therefore, code was added to read three extra lines at the end of the control file ("w2_con.npt" is the control file) if present. Those three extra input lines provide the name of the selective withdrawal user-input file if the user did not wish to use the default name. If those extra lines are not present in the control file, then the default of "w2_selective.npt" is retained. This new input was placed at the end of the control file so as not to break the pre-processor or create problems with older existing models. A few other changes were made to the model code to allow a variable to hold that user-supplied file name and to use that variable when opening the input file.

Error Dump File

If a CE-QUAL-W2 model run is terminated with an error, an output file named W2Errordump.csv is created with the values of many important variables for each segment in the model. These values may be useful for the model user to diagnose the reason for the model termination. That file, however, did not previously indicate which segments of the model were active at the time of termination. Code was modified to add a new field to the W2Errordump.csv file. The new field is the third field, and it indicates whether the segment denoted on that row of output was active ("A") or inactive ("I") at the time of model termination.

Appendix 2. Updates to Dexter Dam Structure Bottom Selective Withdrawal Limits

In version 1.1 of this report and the associated data release (Stratton Garvin and others, 2023; https://doi.org/10.5066/P9UJFXA5), the structure bottom selective withdrawal limit was updated for both Dexter Dam structures in waterbody 2 of the Lookout Point and Dexter Lakes model. The two model versions are hence referred to as "version 1.1," which includes the updated models, and "original version," which was originally published in August 2023 (Stratton Garvin and others, 2023) and documented in this report. The structure bottom selective withdrawal limit for the spillway crest, structure 1 of branch 2, was updated from 28 (in the original version) to 75 (in version 1.1). The structure bottom selective withdrawal limit for the power penstock, structure 2 of branch 2, was updated from 30 (in the original version) to 75 (in version 1.1). Layers 28 and 30, which were used as the structure bottom selective withdrawal limits in the original version of the model, are rarely, if ever, active, and that caused outflow from the structure(s) in use at any given time during the model run to be routed from the surface layer and the layer immediately below the surface layer of the model rather than from layers adjacent to and near the outlet elevation.

Table 2.1 shows goodness-of-fit statistics for the original version of the Lookout Point and Dexter Lakes model (originally published August 2023; Stratton Garvin and others, 2023) using structure bottom selective withdrawal limits of 28 and 30 for Dexter Dam. Figure 2.1 compares outflow temperatures from the Lookout Point and Dexter Lakes models from both the original version and from version 1.1 of the Lookout Point and Dexter Lakes model.

Table 2.1. Goodness-of-fit statistics from the original model version comparing measured and modeled water temperatures using a structure bottom selective withdrawal limit of 28 and 30 for the Dexter Dam spillway and power penstock structures, respectively, simulated using both measured and modeled inflow, for the Lookout Point Lake and Dexter Lake Model, northwestern Oregon, 2011, 2015, and 2016.

[Goodness-of-fit statistics reflect results from the original version of the model published in August 2023 (Stratton Garvin and others, 2023) and shown in table 7 of original publication. Values shown in table 2.1 are the same as those shown in table 7 of the original publication, except for two values that have been updated with trailing zeroes. These values are noted with an asterisk (*). Abbreviations: N, number; NA, not applicable; °C, degrees Celsius; ME, mean error; MAE, mean absolute error; RMSE, root mean squared error; USGS, U.S. Geological Survey]

Depth (meters)	Depth (feet)	2011				2015				2016			
		N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)
MODELED INFLOW													
Lookout Point Lake thermistor string (floating)													
1.5	5	8,667	–0.53	0.92	1.11	8,729	0.13	0.45	0.57	8,731	–0.26	0.52	0.64
3.0	10	8,665	–0.54	0.88	1.07	8,729	0.16	0.43	0.56	8,731	–0.19	0.49	0.60
6.1	20	8,667	–0.33	0.82	1.03	8,729	0.22	0.51	0.72	8,731	–0.06	0.51	0.64
9.1	30	8,666	–0.06	0.72	0.92	8,729	0.32	0.75	1.04	8,731	0.19	0.61	0.79
12.2	40	8,667	0.37	0.73	0.94	8,729	0.51	0.90	1.24	8,731	0.49	0.74	1.00
18.3	60	8,669	0.41	0.68	0.95	8,727	0.71	1.09	1.48	8,731	0.79	0.92	1.30
24.4	80	8,669	0.36	0.56	0.85	8,727	0.62	1.10	1.52	8,731	0.77	0.87	1.25
30.5	100	8,669	0.40	0.55	0.85	8,729	–1.42	1.46	1.97	8,731	0.24	0.65	0.90
36.6	120	8,669	0.22	0.47	0.65	8,729	–1.91	1.93	2.22	8,731	–0.13	0.58	0.81
42.7	140	8,186	–0.08	0.32	0.44	8,728	–1.95	1.97	2.20	8,555	–0.42	0.65	0.88
48.8	160	7,258	–0.29	0.31	0.42	8,657	–1.88	1.89	2.19	4,318	–0.21	0.34	0.44
54.9	180	6,483	–0.42	0.42	0.52	NA	NA	NA	NA	3,241	–0.26	0.26	0.31
61.0	200	4,237	0.16	0.21	0.24	NA	NA	NA	NA	1,656	–0.28	0.28	0.29
	MEAN	NA	–0.03	0.58	0.77	NA	–0.41	1.14	1.43	NA	0.05	0.57	0.76
USGS station 14150000, Middle Fork Willamette River near Dexter, Oregon													
	Subdaily	8,636	–0.31	0.65	0.77	8,726	–0.17	0.87	1.07	8,729	–0.23	0.68	0.83
	Daily Maximum	360	–0.48	0.69	0.83	363	–0.73	1.00*	1.14	363	–0.54	0.76	0.9
	Daily Minimum	360	–0.23	0.51	0.61	363	0.10*	0.74	0.94	363	–0.06	0.61	0.75

Table 2.1. Goodness-of-fit statistics from the original model version comparing measured and modeled water temperatures using a structure bottom selective withdrawal limit of 28 and 30 for the Dexter Dam spillway and power penstock structures, respectively, simulated using both measured and modeled inflow, for the Lookout Point Lake and Dexter Lake Model, northwestern Oregon, 2011, 2015, and 2016.—Continued

[Goodness-of-fit statistics reflect results from the original version of the model published in August 2023 (Stratton Garvin and others, 2023) and shown in table 7 of original publication. Values shown in table 2.1 are the same as those shown in table 7 of the original publication, except for two values that have been updated with trailing zeroes. These values are noted with an asterisk (*). Abbreviations: N, number; NA, not applicable; °C, degrees Celsius; ME, mean error; MAE, mean absolute error; RMSE, root mean squared error; USGS, U.S. Geological Survey]

Depth (meters)	Depth (feet)	2011				2015				2016			
		N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)	N	ME (°C)	MAE (°C)	RMSE (°C)
MEASURED INFLOW													
Lookout Point Lake thermistor string (floating)													
1.5	5	8,667	–0.48	0.89	1.09	8,729	–0.02	0.39	0.53	8,733	–0.31	0.50	0.65
3.0	10	8,665	–0.50	0.84	1.06	8,729	–0.02	0.33	0.44	8,733	–0.24	0.46	0.60
6.1	20	8,667	–0.29	0.80	1.03	8,729	0.07	0.40	0.58	8,733	–0.12	0.46	0.62
9.1	30	8,666	–0.02	0.69	0.92	8,729	0.22	0.58	0.84	8,733	0.12	0.51	0.70
12.2	40	8,667	0.42	0.70	0.93	8,729	0.38	0.68	0.98	8,733	0.40	0.59	0.82
Lookout Point Lake thermistor string (floating)—Continued													
18.3	60	8,669	0.48	0.67	0.95	8,727	0.63	0.86	1.24	8,733	0.70	0.77	1.09
24.4	80	8,669	0.44	0.56	0.86	8,727	0.64	0.88	1.29	8,733	0.71	0.76	1.07
30.5	100	8,669	0.49	0.56	0.87	8,729	–1.07	1.13	1.65	8,733	0.26	0.63	0.84
36.6	120	8,669	0.33	0.51	0.69	8,729	–1.44	1.46	1.82	8,733	–0.06	0.56	0.78
42.7	140	8,245	0.00	0.32	0.43	8,728	–1.39	1.41	1.71	8,557	–0.33	0.61	0.84
48.8	160	7,283	–0.20	0.25	0.35	8,661	–1.43	1.45	1.81	4,324	–0.08	0.29	0.40
54.9	180	6,519	–0.32	0.33	0.42	33	–0.45	0.45	0.46	3,242	–0.10	0.16	0.20
61.0	200	4,282	0.24	0.26	0.29	NA	NA	NA	NA	1,658	–0.10	0.12	0.14
USGS station 14150000, Middle Fork Willamette River near Dexter, Oregon													
	Subdaily	8,682	–0.26	0.61	0.74	8,726	–0.19	0.78	0.96	8,733	–0.23	0.62	0.76
	Daily Maximum	362	–0.46	0.64	0.78	363	–0.76	0.96	1.08	363	–0.54	0.71	0.85
	Daily Minimum	362	–0.18	0.48	0.59	363	0.08	0.62	0.78	363	–0.07	0.54	0.66

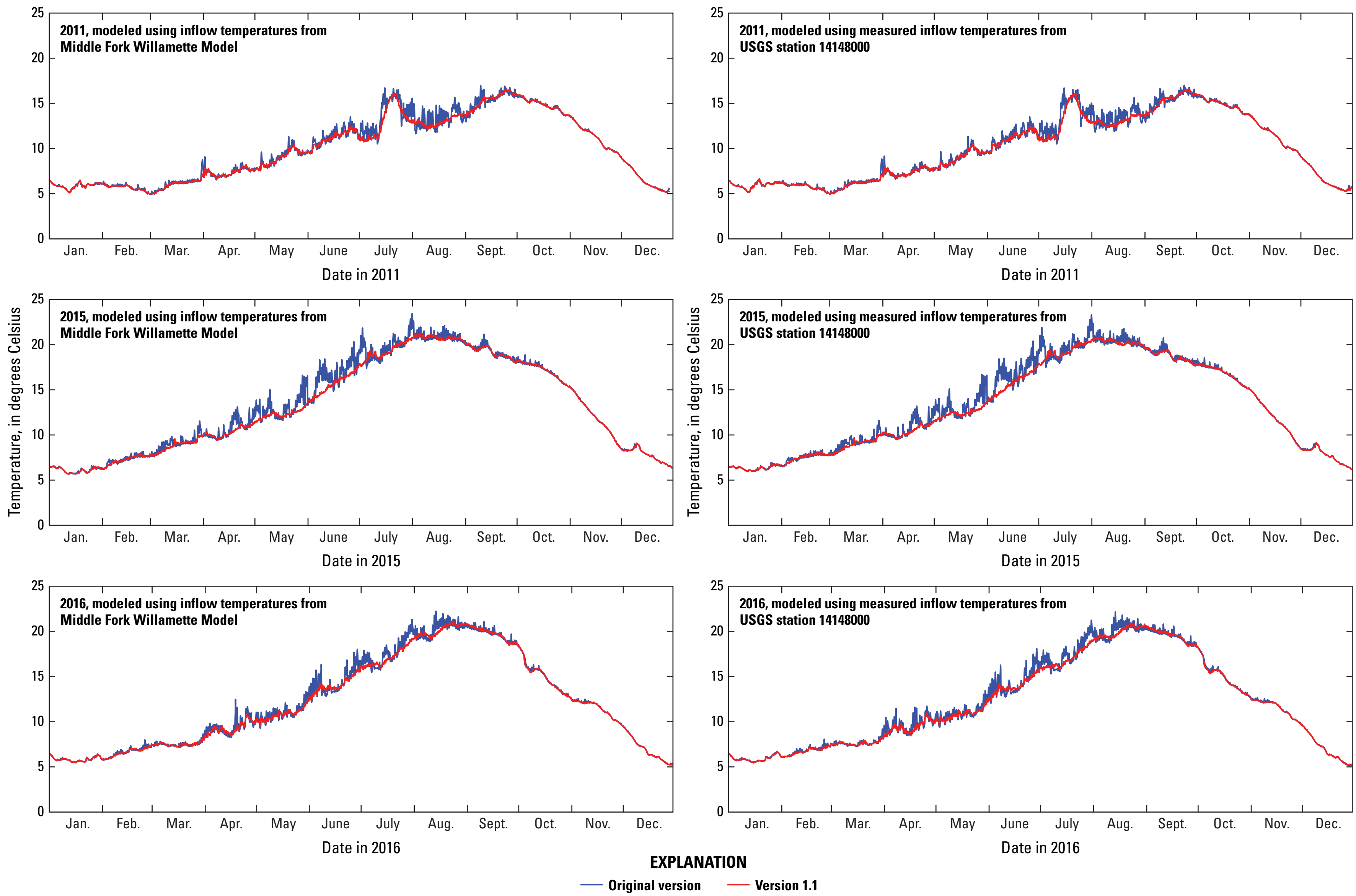

Figure 2.1. Continuous modeled outflow water temperatures from Dexter Lake in northwestern Oregon for 2011, 2015, and 2016. Modeled blue line indicates outflow temperatures simulated using the original version of the Lookout Point and Dexter Lakes model. Modeled red line indicates outflow temperatures simulated using version 1.1 of the Lookout Point and Dexter Lakes model.

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