Appendix A. Big Cliff Reservoir Model Development—Construction and Calibration

Abstract

A hydrodynamic and water temperature model was developed for Big Cliff Reservoir on the North Santiam River in western Oregon for calendar years 2002 and 2003. This model allows the connection of an existing model of Detroit Lake upstream to an existing model of the North Santiam River downstream. The Big Cliff Reservoir model was able to reproduce the daily as well as hourly fluctuations in water surface elevation well. Initial runs showed that the magnitude and seasonal patterns in modeled water temperature released from Big Cliff Dam matched measured temperature just downstream in the North Santiam River generally well; however, model temperatures were 2 to 3°C too warm in late October to early November. Sensitivity testing and other investigations into this issue led to modifications in the setup of the modeled Detroit Lake model releases, which formed the upstream boundary of the Big Cliff Reservoir model. These changes led to somewhat higher water temperature errors within the Detroit Lake model, but improved the measured-to-modeled fit for the Big Cliff release in late October to early November in both 2002 and 2003.

Introduction

Big Cliff Reservoir and Big Cliff Dam are part of the USACE water management system in the Willamette River basin in northwest Oregon (fig. 1). Big Cliff Dam was constructed in 1953 along with the larger Detroit Dam, about 2.8 mi upstream. At a full-pool water surface elevation of 1,206 ft, Big Cliff Reservoir stores 6,450 acre-ft of water. Big Cliff Dam releases water through a power generating facility or through radial spillway gates to the North Santiam River.

A primary purpose of Big Cliff Dam is to regulate the fluctuating power-generating water releases from Detroit Dam so that relatively smooth flows are released to the North Santiam River. In the years modeled, the Big Cliff Reservoir water surface elevation often fluctuated on a daily or hourly basis as much as 24 ft due to the hydropower peaking releases from Detroit Dam. Other purposes of Big Cliff Reservoir and Dam include flood damage protection, power generation, water quality improvement, fish and wildlife habitat, and recreation.

Purpose and Scope

The purpose of this work was to develop a model of Big Cliff Reservoir that could (1) simulate stage, flow, velocity, and water temperature, (2) provide information on processes that control water temperature in this reach, and (3) act as the connecting model between the existing Detroit Lake CE-QUAL-W2 model and the existing North Santiam and Santiam River CE-QUAL-W2 model so that model scenarios for the entire system could be run and analyzed. Separate Big Cliff Reservoir models were developed for calendar years 2002 and 2003 and were calibrated for flow and water temperature.

Methods and Data

The Big Cliff Reservoir model was constructed using version 3.12 of CE-QUAL-W2, a hydrodynamic and water quality model from the USACE (Cole and Wells, 2002). CE-QUAL-W2 is two-dimensional, simulating vertical and longitudinal variation from upstream to downstream; it is laterally averaged across the channel. For a long, narrow, pooled reach such as Big Cliff Reservoir, a two-dimensional laterally averaged model is a good choice. CE-QUAL-W2 can simulate streamflow, water velocity, water temperature, and a number of water quality constituents, including total dissolved solids, nutrients, algae, oxygen, and suspended sediment. CE-QUAL-W2 also was used to build the upstream Detroit Lake model (Sullivan and others, 2007) and the downstream North Santiam River model (Sullivan and Rounds, 2004) as well as models of other rivers and reservoirs in the Willamette River basin.

The CE-QUAL-W2 model code was modified by USGS project personnel to (1) fix coding errors, (2) add new model flux outputs, (3) add a new subroutine to automatically blend outflows from multiple reservoir outlets to match a user-supplied downstream temperature target, and (4) update the selective withdrawal algorithms. The blending routines were documented previously by Sullivan and Rounds (2006); further updates are documented in appendix C.

The Big Cliff Reservoir model was constructed in several steps. Initially, a model grid was built. Then, model input data were collected, processed, and formatted to provide flow, water temperature, meteorological, and shade boundary conditions. Finally, the model was calibrated by comparing model output to measured water surface elevation and water temperature data.

Model Grid

A CE-QUAL-W2 model grid is composed of model segments that connect together in the direction of flow. Each individual segment has layers with defined height that increase in width from the channel bottom upwards, resembling a cross section in shape. Only limited bathymetric data were available to construct the Big Cliff model grid. As a first step, a pre-dam topographic map from USACE of the Big Cliff reach with only few contour lines was digitized into a geographic information system (GIS). Model segment boundaries were designated in this GIS coverage. Then, 10 equally spaced cross sections were sampled within each segment using GIS techniques; the ten subsections were averaged to obtain a representative cross section shape for each model segment. Layer widths were adjusted until the volume-elevation curve matched the volume-elevation curve from the USACE Big Cliff Reservoir storage table (USACE table dated November 15, 2002) (fig. A1). After checking that none of the layer widths were less than 5 m, as recommended by the CE-QUAL-W2 development team (Cole and Wells, 2008), the segment cross sections were formatted into a CE-QUAL-W2 bathymetry input file. The Big Cliff CE-QUAL-W2 model grid consisted of 15 model segments. Segment length ranged from 281.2 to 307.0 m, with an average length of 297.3 m. Layer height throughout the bathymetry grid was 1.0 m.

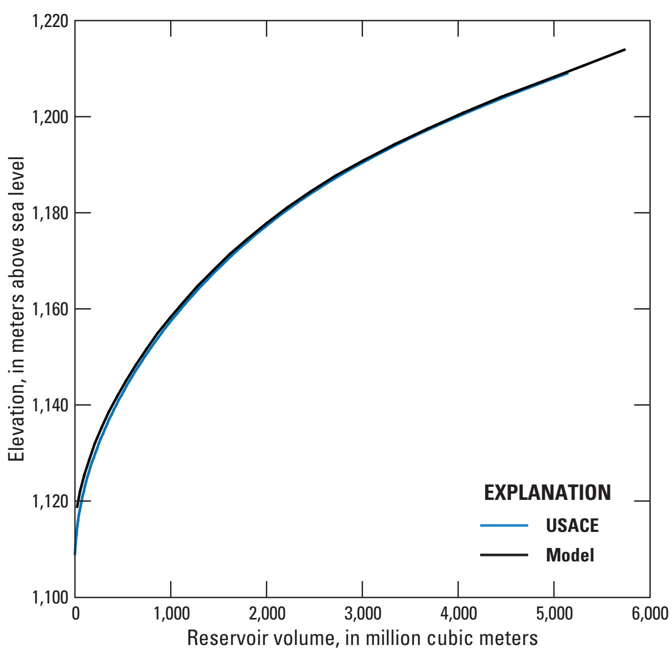

Figure A1. Volume-elevation curves for Big Cliff Reservoir, Oregon, from the U.S. Army Corps of Engineers (USACE) and as represented by the model grid (Model).

Model Data

Because the Detroit Lake and Big Cliff Reservoir models are adjacent, some CE-QUAL-W2 inputs from the Detroit Lake model could be used for the Big Cliff Reservoir model. Shared inputs included the meteorological conditions input file, the precipitation input file, the precipitation temperature input file, and many control file parameters. Data for other input files and calibration had to be obtained specifically for the Big Cliff model. Although the Detroit Lake model simulated total dissolved solids and suspended sediment, those constituents were not included in the Big Cliff model because the North Santiam River model does not simulate those constituents.

Hydrologic Data

The main inflow to the Big Cliff Reservoir model was the outflow from the Detroit Lake model. These releases often fluctuated greatly on an hourly basis, from zero to hundreds or thousands of cubic feet per second. Flows from Detroit Dam were released in this manner to respond to hydropower demands. During high flow events, flows were released from Detroit Dam in a more continuous fashion.

Other inflows to Big Cliff Reservoir included tributary flows from Sardine Creek and Lawhead Creek. Because neither of those inflows were gaged, the inflows were estimated by multiplying the ratio of each creek's watershed (drainage) area to the watershed area of Blowout Creek by the gaged flow of Blowout Creek. Blowout Creek is a gaged tributary on the south side of Detroit Lake that has a long record of data. Sardine Creek drains 5.5 mi^2 and Lawhead Creek drains 4.6 mi^2 of watershed area.

Water releases from Big Cliff Dam were routed through the power penstocks or over the spillway. Data on hourly flow through these two outlets were obtained from USACE. The power penstocks' intake centerline elevation is 1,140 ft (347.5 m), and the spillway crest is located at 1,161.5 ft (354.0 m). These water release elevations were set in the model control file.

The measured water surface elevation of Big Cliff Reservoir was used to close the water balance during model calibration and set the inflows from other ungaged tributaries and groundwater as a distributed tributary input to the model. Hourly values of the Big Cliff Reservoir forebay water surface elevation were obtained from USACE. In 2002–03, the water surface elevation in Big Cliff Reservoir fluctuated between 1,181.0 and 1,205.9 ft.

Water Temperature Data

The water temperature for the inflow from Detroit Lake came from Detroit Lake model output. Water temperatures of Sardine Creek and Lawhead Creek were not measured, but they were estimated to be similar to that of French Creek, a tributary in the Detroit Lake drainage.

Water temperature data with which to compare modeled water temperature during calibration was limited. For instance, during the years modeled, no in-reservoir temperature profiles had been collected. Measured water temperature data were available for the North Santiam River at Niagara, about 0.7 mi downstream of Big Cliff Dam. In addition, some intermittent measured temperature data were available from the base of Detroit Dam from the Oregon Department of Environmental Quality LASAR database.

Some water temperature data in Big Cliff Reservoir for more recent years (parts of 2008 and 2009) were provided by USACE. Although these data were not used directly to calibrate the 2002 and 2003 Big Cliff Reservoir models, the data were useful for helping to understand the general trend in water temperature as water moved from Detroit Dam through Big Cliff Reservoir and farther downstream.

Shade

Because Big Cliff Reservoir is located in a canyon, the effect of topographic shading was important and included in the model simulations. Eighteen topographic inclination angles, every 20 degrees, from the water surface of each model segment to the nearby ridgetops, were calculated using GIS techniques. These angles then were formatted into a CE-QUAL-W2 shade file to describe the shading provided by topographic features. Shading provided by any riparian vegetation was assumed to be negligible.

Model Development/Calibration

During the process of model calibration, measured data are compared to model outputs. Parameters and other factors can be modified within reasonable bounds to optimize the comparison between model outputs and measured data for this specific reach. For the Big Cliff Reservoir model calibration, the water balance was completed first. Then, the model was calibrated for water temperature.

Water Balance

Results from initial model runs that included inflows, outflows, precipitation, and evaporation showed differences between modeled and measured water surface elevations in Big Cliff Reservoir. This indicated that some additional inflows or outflows were needed to close the water balance. Typically, missing flows in a CE-QUAL-W2 model occur due to the presence of small ungaged tributaries, overland flows, groundwater sources or sinks, or error in the measurement of the included inflows and outflows.

For the Big Cliff model, a distributed tributary was used to describe and include these missing flows; this is a common way to close the water balance in CE-QUAL-W2 (Cole and Wells, 2002). In brief, the distributed tributary flow was calculated by subtracting the sum of inflows from the sum of outflows on an hourly basis, applying a moving daily average to that time series, running the model with that distributed tributary file, and making minor adjustments to the distributed tributary inputs until the measured and modeled water surface elevations matched reasonably well. The flow associated with the distributed tributary was small relative to total inflows and outflows, accounting for only 1 and 4 percent of total inflows and 1 and 0 percent of total outflows in 2002 and 2003, respectively. The flows that make up the distributed tributary flows are likely sourced mostly from surface water because the flow imbalance was greatest during storm events. The final modeled water surface elevations were in good agreement with the measured values for both 2002 and 2003 (fig. A2). The water-surface elevations in that figure show a large amount of daily variation, which is typical of how Big Cliff Reservoir is used to moderate (reregulate) the greatly varying releases from Detroit Dam.

Water Temperature

Initial Testing of Big Cliff Reservoir Model

After the water balance was complete, the modeled water temperature of the Big Cliff Dam release was compared to measured water temperature 0.7 mi downstream at the USGS gaging station at Niagara on the North Santiam River. Travel time is short between these locations and although the water temperatures would not be expected to match exactly, they were likely to be close. In this first comparison, the seasonal pattern of water temperature from the modeled Big Cliff release matched the seasonal pattern in the measured data at Niagara for most of the year. However, the annual maximum modeled temperature for the period from late October to early November was as much as 2 or 3°C warmer than the measured temperature.

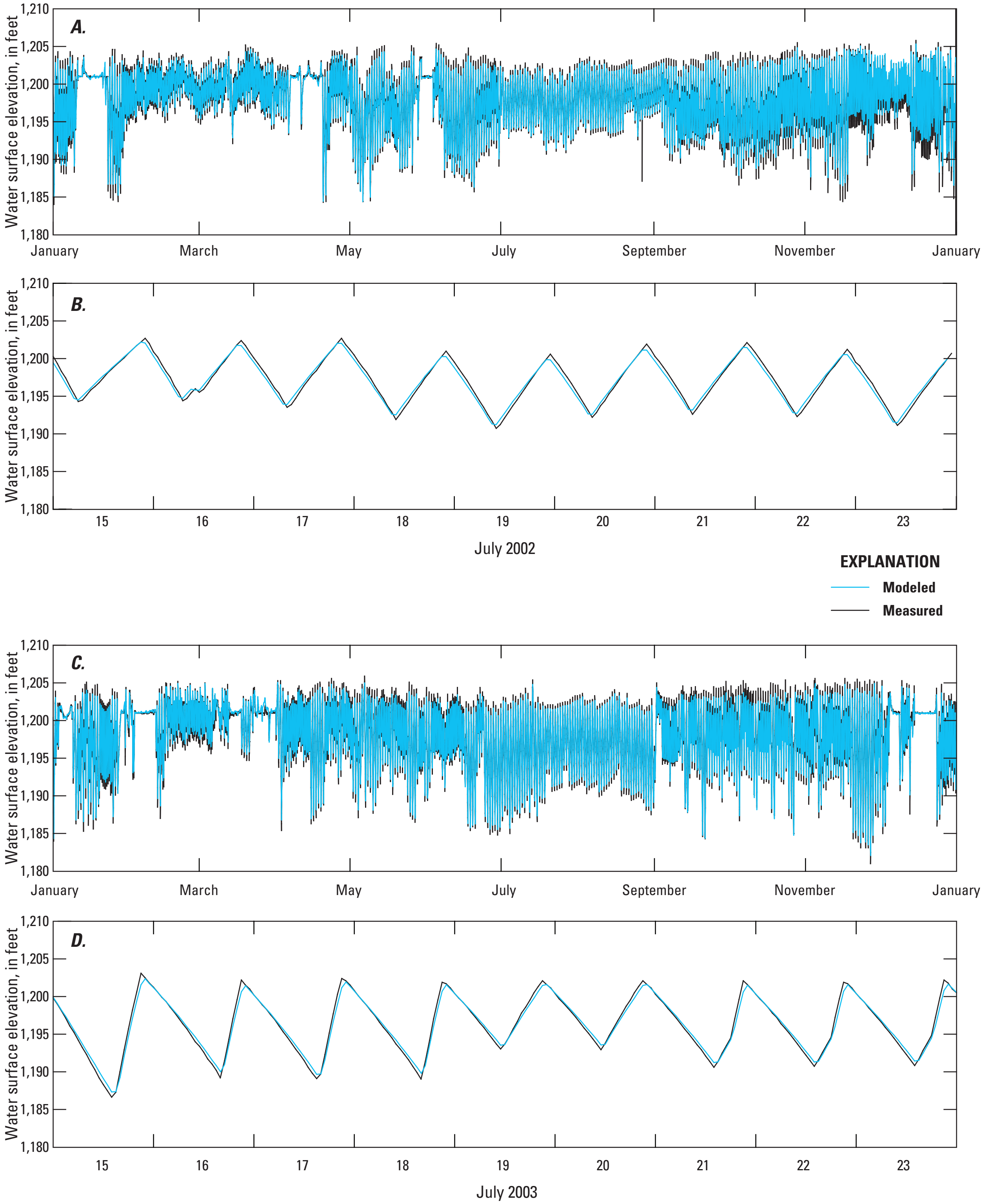

Figure A2. Modeled and measured Big Cliff Reservoir water surface elevations for the entire calendar years of 2002 and 2003. A closer look at 9 days in July shows the nature of the daily variation in water surface elevation.

To test whether model calibration factors within the Big Cliff model could be adjusted to provide a better water temperature match in late October and early November, a series of sensitivity tests were run. The sensitivity tests modified one factor at a time and examined the effect on Big Cliff outflow water temperatures. Factors examined in this analysis included friction factors, the coefficient of bottom heat exchange, the surface heat exchange calculation method, the vertical turbulence closure algorithm, and the elevation of the outflows at Big Cliff Dam. Version 3.6 of CE-QUAL-W2 (Cole and Wells, 2008) also was tested. None of these tests could explain the late October to early November temperature difference and most produced less than a 0.3°C change in the Big Cliff Dam outflow water temperature. The insensitivity of Big Cliff release temperatures to Big Cliff model parameters was likely due to the short model reach and brief residence time of water within Big Cliff Reservoir.

Detroit Lake Model Tests and Adjustments

Because Big Cliff Reservoir model parameters could not explain the 2–3°C discrepancy in late October and early November, the next step was to look farther upstream at the Detroit Lake model and its outflow water temperature. Testing of the Detroit Lake model first took the form of sensitivity testing for parameters that affected temperature both within Detroit Lake and for the Detroit Lake outflow. Through this testing, it was determined that the modeled in-lake water temperature and associated water temperature parameters were constrained by calibration to the in-lake data; therefore, the main variable that could be adjusted was the setup of the Detroit Dam outlet structures and the interaction of the withdrawal outlets with the CE-QUAL-W2 selective withdrawal algorithm.

To address this, several updates and adjustments were made to the CE-QUAL-W2 code for the Detroit Lake model. First, the DOWNSTREAM_WITHDRAWAL and LATERAL_WITHDRAWAL subroutines in the USGS-modified version 3.12 model were modified to make the velocity profile equations similar to those in CE-QUAL-W2 version 3.6. Secondly, the LATERAL_WITHDRAWAL subroutine was modified to allow both point and line withdrawals, using equations from the DOWNSTREAM_WITHDRAWAL subroutine. A point withdrawal is an outlet structure that is narrow in relation to the dam width, whereas a line withdrawal is wide in relation to dam width (>1/10). In the previous version of the Detroit Lake model code, the default was to specify point withdrawal outlets at Detroit Dam, which has no associated width specification. A line withdrawal, on the other hand, requires an associated outlet width to be specified, and varying the width of the outlet line affects which lake depths (or model layers) from which the resulting outflow are drawn. If the lake is well-mixed with similar temperatures from surface to bottom, the outlet line width has little effect on outflow water temperature; however, if the lake is stratified with variable water temperature with depth, then this parameter does affect the outflow water temperature.

More specifically, the equations for point and line withdrawals are (Cole and Wells, 2008):

$$\text{point: } d = \left(\frac{c_{bi}Q}{N}\right)^{0.3333}$$

$$\text{line: } d = \left(\frac{c_{bi}2q}{N}\right)^{0.5}$$

where

d is withdrawal zone half height, m;
Q is total outflow, in m^3/s;
N is internal buoyance frequency, Hz;
q is outflow per unit width, m^2/s; and
c_{bi} is boundary interference coefficient.

As the outlet line width increases, the model withdraws more of its releases from model layers (or reservoir depths) close to the elevation of the outlet. As the line width decreases, the model withdraws water from a greater range of depths. Similarly, greater release rates tend to draw water from more model layers, whereas small releases tend to be from layers near the outlet elevation. Changing the line width then, changes release water temperatures during stratified conditions in Detroit Lake. For the Detroit Lake model, the line width was used as a calibration parameter to better match the late October to early November water temperature downstream at Niagara. The final structure widths used for the Detroit Lake model were 6.8 m for the power penstocks and 4.0 m for the upper ROs; the spillway was not used in 2002–03. These are calibration parameters, and the selective withdrawal algorithms in the model are not perfect representations of mixing near the dam; therefore, these values are not expected to have an actual physical meaning.

Changing these outlet parameters for Detroit Dam did somewhat affect modeled water temperatures within Detroit Lake. A tradeoff was made between water temperature errors in Detroit Lake and water temperature errors downstream. Goodness-of-fit statistics for the updated Detroit Lake model are compared to those of the original model in table A1. The mean error (ME) is the sum of the differences between modeled and measured temperatures, where they coincide in space and time, and is an overall measure of bias; a ME close to zero is desirable. The mean absolute error (MAE) is the average of the absolute value of modeled-measured differences and represents a typical error for any data point; an MAE less than 1.0°C has been noted in previous model applications as a reasonable metric denoting a good fit to the data (Sullivan and others, 2007). The root mean square error (RMSE) is the square root of the average squared error between modeled-measured data comparisons and is equal to the square of the mean plus the square of the standard deviation. If the ME is zero, then the RMSE is equal to the standard deviation of the errors—a good measure of the magnitude of the typical error of the prediction; RMSE values less than 1.0 to 1.5°C have been deemed a good fit in previous applications.

Final Big Cliff Modeled Water Temperature

Changing the outlet setup of the Detroit Lake model outlets provided a better match between the Big Cliff Dam release temperatures and the measured water temperatures at Niagara (fig. A3). Agreement with those measured data downstream was good, with a mean absolute error less than 0.4°C in both 2002 and 2003 (table A2). The construction and calibration of the Big Cliff Reservoir model now allows the Detroit Lake model to be connected with the existing North Santiam River model and other Willamette River basin models downstream.

Table A1. Detroit Lake model goodness-of-fit statistics for calendar years 2002 and 2003 for the original Detroit Lake model (Sullivan and others, 2007) and the updated Detroit Lake model used as the upstream boundary for the Big Cliff Reservoir model.

Detroit Lake model	Year 2002		Year 2003	
	Original model	Updated model	Original model	Updated model
Mean error	-0.02	-0.39	-0.34	-0.55
Mean absolute error	0.52	0.77	0.58	0.77
Root mean square error	0.69	1.00	0.76	0.99

Table A2. Big Cliff model goodness-of-fit statistics for calendar years 2002 and 2003 using the updated Detroit Lake model as the upstream boundary condition.

Statistic	Year 2002	Year 2003
Mean error	-0.05	-0.09
Mean absolute error	0.31	0.39
Root mean square error	0.39	0.48

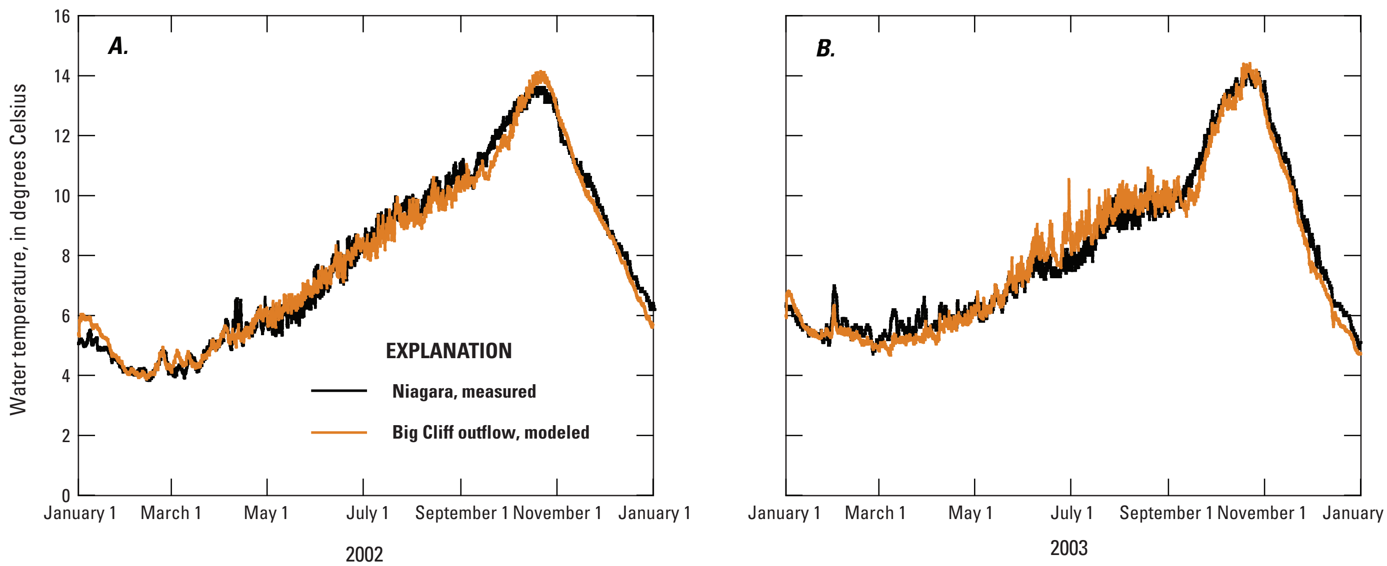

Figure A3. Modeled water temperatures released from Big Cliff Dam compared to measured water temperatures in the North Santiam River at Niagara, Oregon, 0.7 mile downstream.