Update of the RBM10 Temperature Model of the Columbia and Snake Rivers

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1.0 INTRODUCTION

This report describes the process and information used to update and calibrate the RBM10 temperature model of the Columbia and Snake Rivers in Washington and Oregon. The model simulates mainstem river temperatures from the Columbia River at the International Boundary (River Mile 745.0) to the mouth at Astoria, Oregon and the Snake River from Anatone, Washington (Snake River Mile 168) to its confluence with the Columbia River near Pasco, Washington.

This model update was conducted by Tetra Tech under contract to the U.S. Environmental Protection Agency (USEPA). The primary purpose of this work is the planned development of a Total Maximum Daily Load (TMDL) for temperature in the Columbia and Snake River mainstems. This work is occurring concurrently with the development of the Columbia River Systems Operation Environmental Impact Statement (CRSO EIS). As part of the CRSO EIS, the U.S. Army Corps of Engineers (USACE), Bonneville Power, and the U.S. Bureau of Reclamation are developing both one- and two-dimensional models that include analysis of temperature in the Columbia and Snake mainstems. EPA is collaborating with the above federal agencies, particularly in circumstances where model scenarios for the TMDL are similar to CRSO EIS model scenarios.

This project updates the database, simulation period, and calibration of the RBM10 model while retaining the core mathematical structure of the model, which was originally developed by USEPA Region 10. This report explains the general model structure with details of the model update. Additional details on the model structure can be found in the original model documentation (Yearsley et al. 2001) and a subsequent journal paper (Yearsley 2009).

The model update was conducted in two phases in 2017 and 2018. This report documents the updates and refinements from both phases. Summaries of the activities conducted during the phases of this project are presented below.

1.1 Phase I –RBM10 model Development and Code Modifications

In Phase I of the project, Tetra Tech updated the FORTRAN code of the RBM10 model and preprocessing utilities (Tetra Tech 2017) and extended the model simulation period through 2016. The details for these updates, including the changes performed to the FORTRAN codes, are presented in a technical memorandum for the Phase 1 work (Tetra Tech 2017). This memo also includes the initial calibration to available observations from Phase 1.

1.2 Phase II –RBM10 model Recalibration and Alternative Model Setups

In Phase II of the project, Tetra Tech evaluated potential sources of error, adjusted the model setup, and recalibrated the RBM10 model to improve the model performance reported in Tetra Tech (2017). The recalibrated model is identified hereafter as the 2018 RBM10 model and the results of the recalibration efforts are summarized in Section 3.0. During Phase II of the project, further code modifications were included in the RBM10 code to output simulations of river flow and velocity along the simulated reaches. The simulations of flow were compared against available observations of flow along the Columbia and Snake Rivers. The results of these comparisons are presented in Appendix B.

During Phase II, two alternative model setups were created by moving the location of the upstream boundary of the Columbia River model from the international boundary downstream to two alternative locations: (1) Grand Coulee dam tailrace (2018 “RBM10B” model), and (2) Priest Rapids dam tailrace (2018 “RBM10C” model). The purpose of these two model setups was to evaluate the effect of the Columbia River upstream boundary and model representation of Grand

Coulee operations on the predictive capability of the model in downstream reaches. These evaluations of the 2018 RBM10 model are presented in Appendix C and Appendix D respectively.

A summary of the information in the appendices of this report is presented below.

1) **Appendix A** presents the atmospheric input datasets used to force the model as well as the flow and temperature boundary conditions used at the upstream boundaries of the Columbia River, Snake River, Clearwater River, and Dworshak Dam. Appendix A also explains how temperature gaps were filled to construct continuous daily temperature time series to force the model boundaries.

2) **Appendix B** presents comparison plots between simulated and observed flow at different locations over the Columbia and Snake Rivers. Appendix B also presents model simulations of velocity in the simulated domain

3) **Appendix C** presents comparison plots between simulated and observed temperature and flow for the 2018 RBM10B Model. This model setup was obtained by moving the upstream boundary of the Columbia River from the international boundary to the Grand Coulee dam tailrace.

4) **Appendix D** presents comparison plots between simulated and observed temperature and flow for the 2018 RBM10C Model. This model setup was obtained by moving the upstream boundary of the Columbia River from the international boundary to the Priest Rapids dam tailrace.

4) **Appendix E** presents the 2018 RBM10 geometric properties of the Columbia and Snake Rivers.

5) **Appendix F** presents the results of a sensitivity analysis of the 2018 RBM10 model. The sensitivity analysis was performed to identify the major drivers of water temperature on the Columbia River and Snake River. Appendix F shows how simulated water temperatures change in response to variations in: upstream boundary inflows, tributary inflows, upstream boundary temperatures, evaporation coefficient values, and air temperature.

This phase of the project also included a review of an earlier draft of this report by technical staff from the three federal agencies that operate the hydroelectric dams along the Columbia and Snake rivers (USACE, BOR, and BPA). This review led to a number of improvements and clarifications in this document.
With the update and refinement of the RBM10 model completed, the next phase of work in the TMDL project is to apply the RBM10 model to evaluate impacts on mainstem river temperatures.

1.3 Columbia River Watershed Description

The Columbia River drains more than 259,000 square miles of southeastern British Columbia in Canada and the Pacific Northwest in the United States. Most of the approximately 219,000 square miles of the watershed in the United States are in Idaho, Oregon, and Washington, while a small portion of the watershed is in Wyoming, Nevada, and Utah. The Columbia River flows more than 400 miles through British Columbia before reaching the U.S.-Canada border near Castlegar, British Columbia. It then flows south through Washington before turning west near Wallulla Junction, Washington, forming the Washington-Oregon state border. The headwaters of its largest tributary, the Snake River, are in the Teton Mountains of Wyoming. The Snake River flows through Idaho before forming the Oregon-Idaho state border and discharging to the Columbia River near Pasco, Washington. Other major tributaries to the Columbia River include the

Kootenai, Clark Fork-Pend Oreille, Spokane, Deschutes, and Willamette rivers. As discussed below, the RBM10 model domain consists of those segments of the lower Columbia and Snake Rivers in the states of Washington and Oregon.

The Columbia River and its largest tributaries are controlled by dams. There are 11 mainstem hydroelectric projects on the Columbia River in the United States. The Snake River is also heavily controlled with 19 dams on the mainstem and several impoundments on its tributaries. The only segment of the Columbia River above Bonneville Dam that remains unimpounded is the Hanford Reach between Priest Rapids Dam (River Mile 397) and the confluence with the Snake River (River Mile 324).

Despite the modifications from dams and other flood control structures, the hydrograph has the general characteristics of a snowmelt regime. Stream flows are low during the winter but increase beginning in spring and early summer as the snowpack melts. After the snowpack melts, flows then recede gradually during the summer and fall.

The climate of most of the Columbia River watershed is primarily of continental character, with cold winters and hot, dry summers. Precipitation varies widely, depending primarily on topographic influences. The interior Columbia Basin and Snake Plain generally receive less than 15 inches of precipitation annually, while annual precipitation can exceed 100 inches per year in some of the mountainous regions of Canada. Air temperature also varies considerably, depending on location. Summertime temperatures in the Columbia Basin and Snake Plain exceed 100ºF (37.8ºC) for extended periods, while temperatures at higher elevations remain cooler. Winters in this area are cold throughout the basin with heavy snow in the mountains.

West of the Cascade Mountains, which includes the lower 150 miles of the Columbia River and all the Willamette River, the climate has a more maritime character. Winter air temperatures at lower elevations are seldom below freezing, and summer air temperatures are seldom above 100ºF (37.8ºC) for long periods. Average annual precipitation west of the Cascade Mountains is more than 40 inches in most areas. Below about 5,000 feet, most of the precipitation falls as rain, with 70% or more falling between October and March.

1.4 RBM10 model Description

The RBM10 model is a one-dimensional mathematical model of the thermal energy budget of the mainstem Columbia and Snake Rivers. It simulates daily average water temperature under conditions of gradually varied flow. Similar models of this type have been used since the 1960s to assess temperature conditions in the Columbia and Snake Rivers (Yearsley 1969, Bonneville Power Administration et al. 1994, Normandeau Associates 1999). The fast run time and simplicity of the model setup for RBM10 affords the opportunity to simulate long time periods. The long simulation periods can provide information on how both natural and man-made changes interact and impact the system under a variety of different climate and operational conditions.

The technical underpinning of the RBM10 model has been peer-reviewed, documented, and applied in a number of settings since 2001. The model was initially developed and peer-reviewed by USEPA in 2001 and was used to evaluate conditions in the Columbia and Snake Rivers from 1970 through 2000 (Yearsley et al. 2001). Revised and updated versions of the model were developed and further documented as part of a Total Maximum Daily Load (TMDL) project (Yearsley 2003). The model developer, Dr. John Yearsley, retired from USEPA and continued to document the model theory and test applications at the University of Washington (Yearsley 2009). Other organizations have successfully applied versions of this model framework to rivers in the United States and abroad, including published studies by researchers at the U.S. Geological Survey (USGS) (Perry et al. 2011), University of California at Los Angeles (Cao et al. 2016), and Wageningen University in the Netherlands (van Vliet et al. 2012).

The RBM10 model of the Columbia River and Snake River mainstems simulates the following inputs and processes: upstream boundary inputs (flow, temperature), hydrodynamics within each model segment (flow, velocity, channel geometry), surface heat exchange within each model segment, and heat inputs from tributaries (Figure 1-1). The model inputs for each of these processes are described in the model setup section (Section 2.0).

The following processes are not simulated and are believed to be relatively minor influences on the cross-sectional average temperature of these large mainstem rivers: groundwater and hyporheic flow interactions, topographical and riparian shade, and heat exchange at the water/sediment interface. In addition, point source discharges are not currently included in the model. An USEPA assessment of point source influences on mainstem Columbia River and Snake River temperatures indicated that cumulative impacts of these sources are minor, so exclusion of these sources in this phase of model development should not significantly impact the quality of the calibration (USEPA 2003).

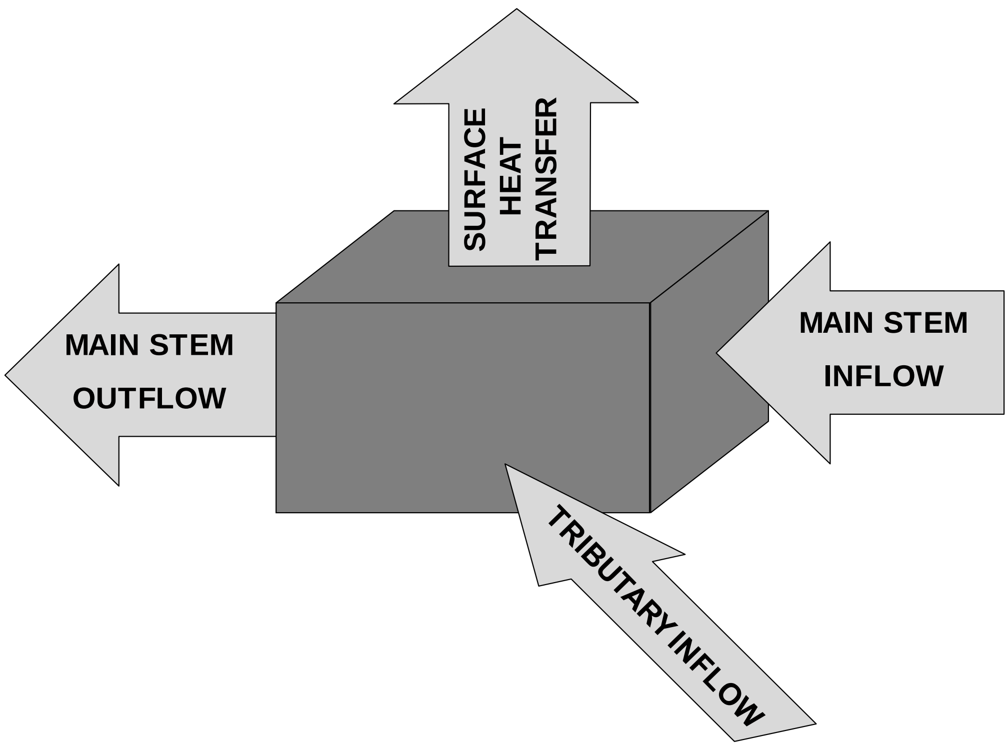

Figure 1-1 Conceptual representation of model segment in one-dimensional temperature model

The model implements a mixed Eulerian-Lagrangian method for solving the dynamic energy budget equation, and this approach provides the fast run times of the model. The model uses reverse particle tracking to locate the starting point of a water parcel at each computational time step. The water temperature at the starting point of each time step for a parcel is determined by polynomial interpolation of simulated temperatures stored on a fixed grid in the previous time step. The energy budget method (Wunderlich and Gras 1967) is used to simulate the time history of temperature as the parcel moves from its starting point at time t-Δt to ending point at time t. Additional details about the reverse particle tracking methodology and testing are included in the 2001 RBM10 model development report (Yearsely et al. 2001) and a journal paper (Yearsley 2009).

The new 2018 RBM10 model is an update of the code, database, and calibration of the 2002 version of the RBM10 model. The model was initially developed and peer-reviewed in 2001 and was used to evaluate conditions in the Columbia and Snake Rivers from 1970 through 2000 (Yearsley et al. 2001). The model was then under active development from 2001 through 2003 in support of a TMDL project. Updated versions of the model were developed in both 2002 and 2003 (Yearsley 2003). The 2002 RBM10 model supported the problem assessment phase of the TMDL project. This version was selected as the foundation for this update because it pre-dated the addition of specialized code for the 2003 TMDL related to point sources and future growth allocations that were outdated and/or extraneous to the model update and recalibration process.

The 2018 RBM10 model retains several aspects of the 2002 RBM10 model. The preprocessing of atmospheric, flow, and temperature datasets to fill data gaps and generate continuous input time series for the model are identical in both models. Similarly, the statistics of goodness of fit used during model calibration are similar in both models.

A description of the 2018 RBM10 model setup and calibration results are presented in the following sections.

2.0 2018 RBM10 model Structure and Data Inputs

2.1 Temporal Resolution

The 2018 RBM10 model simulates temperatures in the Columbia and Snake Rivers from 1970 through 2016. The simulation period is constrained by the completion of the hydroelectric system and availability of publicly available data necessary to setup and run the model. For historic analysis, the model was bounded by the completion of the hydroelectric and reservoir operating system. The last hydroelectric project, Lower Granite Dam and Reservoir, was completed in 1975.

The model code allows the user to specify simulation of daily or hourly temperatures. This project, like previous RBM10 assessments, focuses on daily average temperature simulation. One limitation in using RBM10 to simulate hourly temperatures is that the model uses daily boundary inputs for river flows and temperatures. Hourly meteorology inputs provide the hourly forcing in the heat budget. The additional development and evaluation effort to apply hourly simulation of temperatures is beyond the scope of this project.

2.2 Spatial Representation

The 2018 RBM10 model simulates the Columbia River from the International Boundary (River Mile 745.0) to the mouth at Astoria, Oregon, the Snake River from Anatone, Washington (Snake River Mile 168) to its confluence with the Columbia River near Pasco, Washington (Figure 2-1) and the Clearwater River from Orofino, Idaho (Clearwater River Mile 44.6) to its confluence with the Snake River near Lewiston, Idaho (Snake River Mile 139.3). The Clearwater River is included in the model domain to represent the cold water releases from Dworshak Dam. All other major tributaries are represented as model boundary inputs, and the model is forced with flow and temperature at their confluences with the mainstem.

Existing hydroelectric projects on the Columbia River within the model domain are listed in Table 2-1. With the exception of the Grand Coulee Dam, all hydroelectric projects are run-of-the-river projects. This means that the dams are operated in such a way that approximately all the water entering the reservoirs are passed through the reservoirs and released. These operations only cause small changes in the water levels; therefore, the water levels can be assumed constant for temperature estimation.

The reservoir behind Grand Coulee Dam (Lake Roosevelt) is used for flood control purposes and, in consequence, the fluctuations in water elevations and volume can be significant and must be modeled. These fluctuations are simulated in RBM10 by prescribing the water surface elevations. The model uses the input water levels to calculate the changes in velocity and residence time of the water moving throughout the reservoir.

Table 2-1 Hydroelectric projects on the mainstem Columbia and Snake rivers included in the scope of the analysis

Project	River Mile	Start of Operation	Generating Capacity (megawatts)	Storage Capacity (1000s acre-feet)
Grand Coulee	596.6	1942	6,494	8,290
Chief Joseph	545.1	1961	2,069	588
Wells	515.8	1967	774	281
Rocky Reach	473.7	1961	1,347	440
Rock Island	453.4	1933	622	132
Wanapum	415.8	1963	1,038	710
Priest Rapids	397.1	1961	907	231
McNary	292.0	1957	980	1,295
John Day	215.6	1971	2,160	2,294
The Dalles	191.5	1960	1,780	311
Bonneville	146.1	1938	1,050	761
Lower Granite	107.5	1975	810	474
Little Goose	70.3	1970	810	541
Lower Monumental	41.6	1969	810	351
Ice Harbor	9.7	1962	603	400

2.3 Hydrodynamics

RBM10 uses model reaches and computational segments to represent the Columbia, Snake, and Clearwater Rivers. A model reach is a longitudinal portion of the river where the geometry of the cross-section is uniform and constant. The length of the reaches in the RBM10 model usually varies between 1 mile and 10 miles. In the master input file, the geometry of the rivers is prescribed for each reach from the upstream boundary to the downstream boundary. Reaches are then divided into segments which are the computational units used by the RBM10 model to perform the mass and heat balance computations. The typical length of a segment in the RBM10 model is 1 mile, although some segments are approximately 2 miles in length. The spatial resolution of the 2018 RBM10 model is similar to the resolution of the 2001 and 2002 RBM10 models.

The geometry of the model reaches is defined in the RBM10 model as follows (Yearsley 2001). For the impounded reaches with run-of-the-river dams, the water surface elevation is prescribed and assumed to remain constant, such that the depth and width remain constant at any cross-section. The velocity, U, is calculated from the simple continuity equation as follows:

$$U = Q/(W_x*D) \qquad \textbf{(1)}$$

where

U = river velocity, feet/second

Q = river flow, cfs

W_x = river width, feet

D = river depth, feet

The geometric properties of the run-of-the-river reaches were initially obtained from the 2001 RBM10 model (see Appendix C in Yearsley et al. 2001). This geometry was then compared against available geometry of the run-of-the-river dams provided for this project by the USACE. In most areas, the 2001 RBM10 model geometry was retained because there were no significant differences in the geometry of the run-of-the-river dams. Updates were performed in the geometric information for Rocky Reach, Wanapum, McNary, and Bonneville reaches to reflect the latest information available from USACE. A summary of the geometry of the run-of-the-river reaches is presented in Appendix E.

The hydraulic characteristics of reaches subject to significant changes in volume due to dam operations are modeled as functions of the reservoir depth and water surface elevations. For this purpose water surface elevation must be prescribed to the model. Because significant storage operations only occur at the Grand Coulee Dam, this approach is used in the RBM10 model only for the impounded model reaches behind the Grand Coulee Dam. The expressions for the velocity (U), cross-section area (A_x), and width (W_x) of these reaches are:

$$U = Q/ A_x \quad \textbf{(2)}$$

$$A_x = A_a\, e^{(H*Ba)} \quad \textbf{(3)}$$

$$W_x = A_w\, e^{(H*Bw)} \quad \textbf{(4)}$$

where H is the reservoir depth calculated as the difference between the water surface elevation and the reservoir dead storage elevation. The coefficients A_a - B_a and A_w - B_w are inputs in RBM10 and are calculated from known relationships between storage volume and depth, and between area and depth. The geometric coefficients used in the 2018 RBM10 model to represent the impounded reaches behind Grand Coulee Dam were obtained from the original model (see Appendix C in Yearsley et al. 2001) and are presented in Appendix E. The coefficients were reviewed during this project to ensure the input geometry was correctly representing the existing reservoir storage capacity curve. The existing reservoir capacity curve was obtained from the U.S. Bureau of Reclamation (https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/HYD/HYD-440.pdf).

The hydraulic characteristics of the unimpounded reaches of the river system were estimated from power equations relating mean velocity, area, and width (Leopold and Maddock 1953):

$$U = A_u\, Q^{Bu} \quad \textbf{(5)}$$

$$A_x = A_a\, Q^{Ba} \quad \textbf{(6)}$$

$$W_x = A_w\, Q^{Bw} \quad \textbf{(7)}$$

The coefficients, A_u, B_u, A_a, B_a, A_w, and B_w, were estimated using nonlinear regression analysis (Levemberg-Marquardt) of cross-sectional area (A_x) versus flow (Q) and channel width (W_x) versus flow (Q). The variation of area and channel width with flow was derived from steady and gradually varied flow simulations of river hydraulics using HEC-RAS (USACE-HEC 1995). To calculate the coefficients of Eqs. 5 through 7, the existing USACE Hydrologic Engineering Center's River Analysis System (HEC-RAS) models of the Columbia and Snake Rivers were used to simulate channel hydraulics for flow conditions between 20,000 cfs and 300,000 cfs in the Columbia River and between 10,000 cfs and 200,000 cfs in the Snake River. In total, 25 flow simulations were performed in the Columbia River HEC-RAS model, and 20 flow simulations were performed in the Snake River HEC-RAS model. For each flow condition/simulation, HEC-RAS provided outputs of cross-section area (A_x) and width (W_x) at different locations along the Columbia River and Snake River channels. These model outputs were used in a nonlinear regression analysis to calculate the coefficients A_u, B_u, A_a, B_a, A_w, and B_w.

The coefficients obtained from the nonlinear regression analysis are presented in Appendix E.

Daily flow at any mainstem location is the sum of headwater flow and cumulative upstream tributary inflows. The 2018 RBM10 model assumes the following:

- Flow changes are transmitted instantaneously to locations downstream. Flows are transmitted from the upstream to the downstream end of a reach assuming that no changes in flow occurs within the reach unless there is an external source of flow such as a tributary. This approach provides accurate representation of flow transport in unimpounded and run-of-the river reaches but underestimates the impacts of dam operations on flow at the Grand Coulee Dam. Some discrepancies between the simulated and observed flows at the Grand Coulee tailrace are experienced, although these discrepancies are reduced/smoothed out in downstream locations as the system of tributaries enter the Columbia River (a comparison of simulated and observed flows is presented in Appendix B). The limitation to simulate flow changes in response to dam operations at the Grand Coulee tailrace have, however, minor impacts on the model's ability to reproduce water temperatures in the Columbia River. Appendix C and Appendix D shows that the model's ability to reproduce temperatures in the Columbia River is not significantly improved or altered by changing the location of the upstream boundary from the international boundary to other locations downstream of Grand Coulee.
- Tributary sources other than those included as model inputs are negligible (the tributaries included in the model are presented in Section 2.4).
- The river gradient is sufficiently high such that the slope terms dominate, and flow can be routed as a kinematic wave. This means that a flow hydrograph is not attenuated moving downstream and the routing reduces to calculating the travel time through each model segment.

As part of the evaluation of this update, simulated flow has been output at each dam and compared to the measured flow (see Appendix B). The reasonable agreement between the model outputs and measurements for mainstem river flow indicate that: (1) the model incorporates sufficient tributary inflows to represent the system, and (2) groundwater inflows are minor and can be neglected without substantial errors in the water balance.

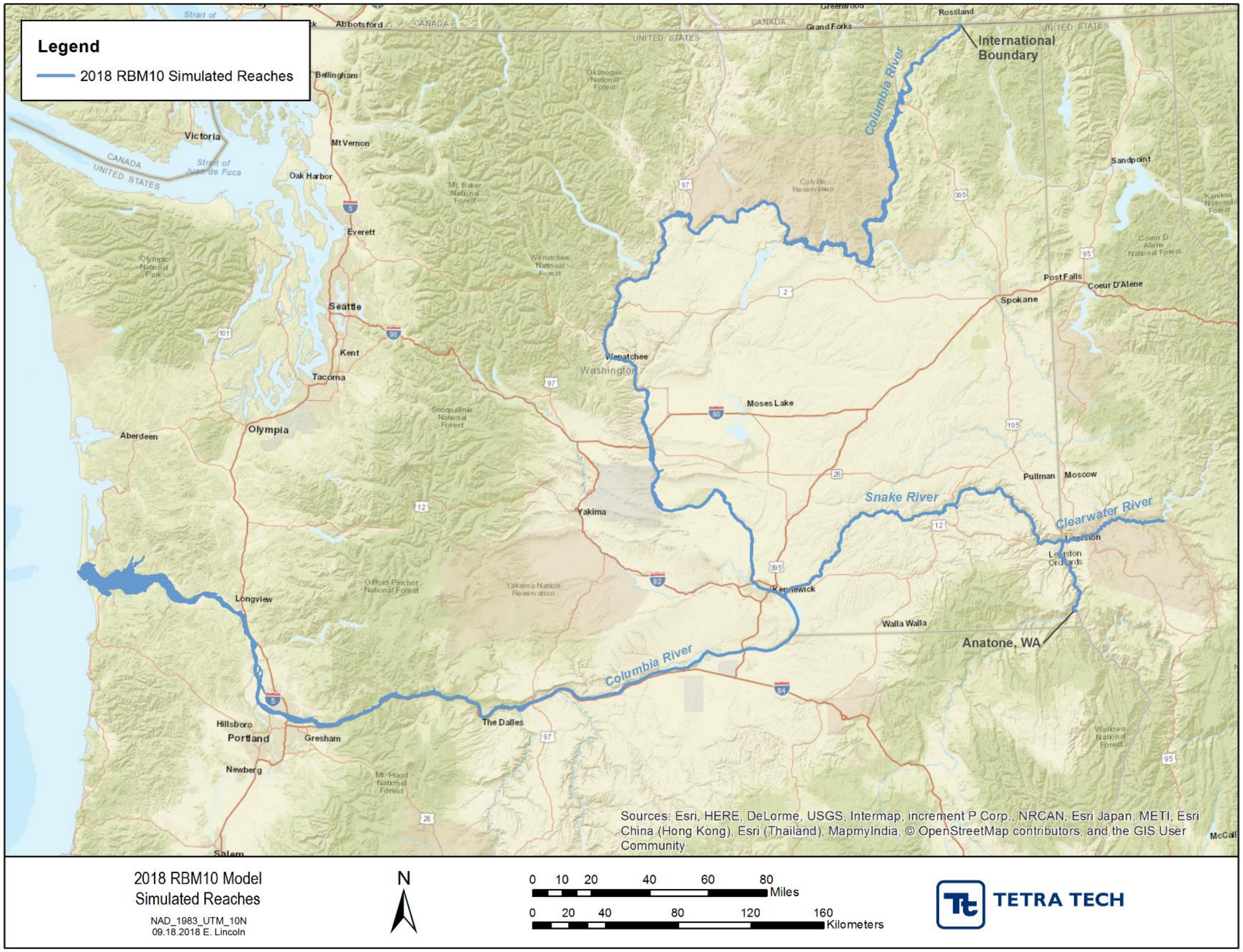

Figure 2-1 RBM10 model domain: Columbia River and Snake River mainstems

2.4 Upstream Boundary and Tributary Inputs

Flows and temperatures at the upstream boundaries of the Columbia River, Snake River, and their major tributaries are used as forcing conditions for the 2018 RBM10 model. The model uses flow observations from USGS and temperature observations from USGS, USACE (Columbia Basin Research Data Access in Real Time [DART] website), the Washington Department of Ecology (DOE), and the Oregon Department of Environmental Quality (DEQ). The tributaries included in the model are presented in Table 2-2 and Figure 2-2, and their flows and temperatures were inputs to the mainstem rivers.

2.5 Data retrieval and QA/QC procedure

The flow and temperature records retrieved from the USGS, USACE, DOE and DEQ agencies were subject to a quality assurance/quality control (QA/QC) analysis before they were used to construct the input time series of flow and temperature for the 2018 RBM10 model. The purpose of the QA/QC analysis was to identify and remove errors in the records. The QA/QC analysis started by identifying suspicious records in each monitoring station through a combination of box-plots analyses and best professional data interpretation. The records identified as outliers or suspicious in a particular monitoring station were later compared against data records in other stations to determine if they were supported by other observations in nearby areas. Data records were only removed if there were no similar records in nearby stations. Less than 2% of the available observations were flagged as suspicious records and removed from the input datasets.

Despite this QA/QC effort, it is likely that errors remain in the temperature monitoring datasets that were not flagged through this process. Given the relatively low error in model predictions (presented in the calibration section of this report), there are likely to be situations where model-simulated temperatures are more accurate than observed temperatures, particularly when simulated-versus-observed temperature differences are unusually large at a particular time and location.

Table 2-2 Tributaries included in the 2018 RBM10 model

Tributary Source	Receiving Waterbody
Dworshak Dam[1]	Clearwater River
Clearwater River	Snake River
Tucannon River	Snake River
Palouse River	Snake River
Chelan River	Columbia River
Colville River	Columbia River
Cowlitz River	Columbia River
Crab Creek	Columbia River
Deschutes River	Columbia River
Entiat River	Columbia River
Hood River	Columbia River
John Day River	Columbia River
Kalama River	Columbia River
Kettle River	Columbia River
Klickitat River	Columbia River
Lewis River	Columbia River
Methow River	Columbia River

Tributary Source	Receiving Waterbody
Okanogan River	Columbia River
Sandy River	Columbia River
Spokane River	Columbia River
Umatilla River	Columbia River
Walla Walla River	Columbia River
Wenatchee River	Columbia River
Willamette River	Columbia River
Yakima River	Columbia River

[1] Dworshak Dam is on the North Fork Clearwater River near its confluence with the Clearwater River.

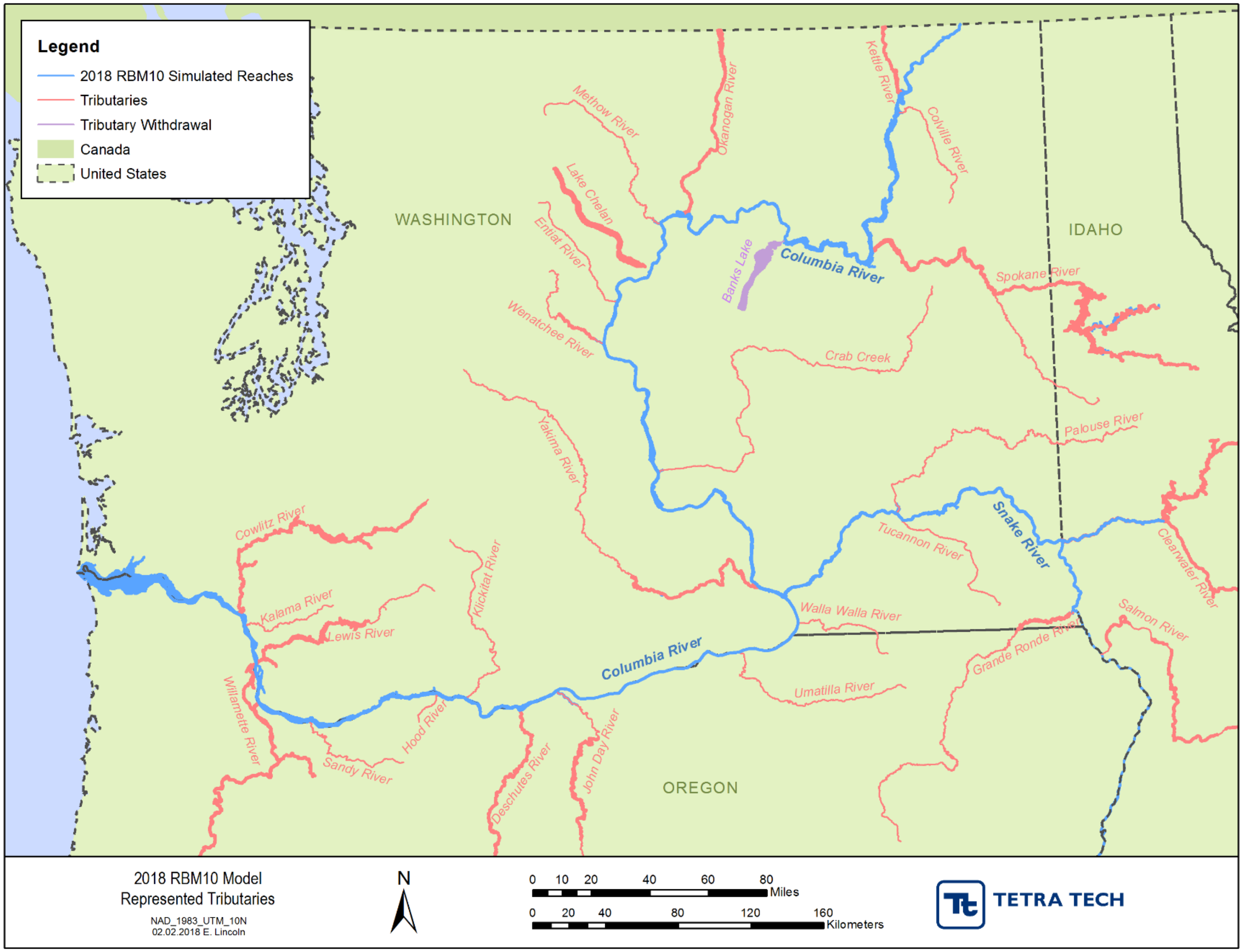

Figure 2-2 Columbia and Snake River tributaries represented in the 2018 RBM10 model

2.5.1 Flow Inputs

Flow inputs for the headwaters and tributaries included in the 2018 RBM10 model were developed based on daily flow data obtained from the USGS National Water Information System website for the simulation period January 1,1970 – December 31,2016 (Figure 2-3). The USGS maintains streamflow gages on the Columbia and Snake Rivers, as well as on major tributaries. Table 2-3 lists the stations used to extract flow data for the 2018 RBM10 model. These stations are the same USGS stations that were used for the 2001 RBM10 model. The QA/QC checked flow records from the USGS were processed with the RBM10 model preprocessing tools to fill data gaps and construct continuous daily time series of flows to force the model. Data gaps were filled using the long-term daily average flows. A detailed discussion of the RBM10 model utilities used to process and fill data gaps is presented in Tetra Tech 2017.

Table 2-3 List of USGS gaging stations used to extract flow daily flow data for the 2018 RBM10 model

River Name	Station Name	Station Number	Latitude	Longitude
Headwater				
Clearwater River	Clearwater River at Orofino, ID	13340000	46°28'42.0"	116°15'27.0"
Snake River	Snake River near Anatone, WA	13334300	46°05'50.0"	116°58'36.1"
Columbia River	Columbia River at the International Boundary	12399500	49°00'03.0"	117°37'41.9"
Tributaries				
Dworshak Dam	North Fork Clearwater at Dworshak Dam	DART-DWR	--	--
Tucannon River	Tucannon near Starbuck, WA	13344500	46°30'20.0"	118°03'55.1"
Palouse River	Palouse River near Hooper, WA	13351000	46°45'31.0"	118°08'52.1"
Kettle River	Kettle River near Laurier, WA	12404500	48°59'03.9"	118°12'55.1"
Colville River	Colville River at Kettle Falls, WA	12409000	48°35'40.0"	118°03'41.0"
Spokane River	Spokane River at Long Lake	12433000	47°50'12.0"	117°50'25.1"
Feeder Canal*	Feeder Canal at Grand Coulee, WA	12435500	47°57'05.0"	118°59'39.8"
Okanogan River	Okanogan River at Malott, WA	12447200	48°16'53.0"	119°42'11.9"
Methow River	Methow River near Pateros, WA	12449950	48°04'39.0"	119°59'02.0"
Chelan River	Chelan River at Chelan, WA	12452500	47°50'05.0"	120°00'42.8"
Entiat River	Entiat River near Ardenvoir, WA	12452800	47°49'07.0"	120°25'18.8"
Wenatchee River	Wenatchee River at Monitor, WA	12462500	47°29'58.0"	120°25'23.9"
Crab Creek	Crab Creek near Moses Lake, WA	12467000	47°11'22.0"	119°15'52.9"
Yakima River	Yakima River at Kiona, WA	12510500	46°15'13.0"	119°28'36.8"
Walla Walla River	Walla Walla River at Touchet, WA	14018500	46°01'40.0"	118°43'43.0"
Umatilla River	Umatilla River near Umatilla, OR	14033500	45°54'11.0"	119°19'32.9"
John Day River	John Day River at McDonald Ferry, OR	14048000	45°35'16.0"	120°24'29.9"
Deschutes River	Deschutes River at Moody, near Biggs, OR	14103000	45°37'20.0"	120°54'15.8"
Klickitat	Klickitat River near Pitt, WA	14113000	45°45'24.0"	121°12'32.0"
Hood River	Hood River at Tucker Bridge, near hood River, OR	14120000	45°39'16.2"	121°32'55.7"
Sandy River	Sandy River below Bull Run Reservoir, OR	14142500	45°26'57.0"	122°14'38.0"
Willamette River	Willamette River at Portland, OR	14191000	44°56'40.0"	123°02'30.1"
Lewis River	Lewis River at Ariel, WA	14220500	45°57'07.0"	122°33'46.1"
Kalama River	Kalama River, WA (Hood River area-weighted)	14120000	45°39'16.2"	121°32'55.7"
Cowlitz River	Cowlitz River at Castle Rock, OR	14243000	46°16'30.0"	122°54'47.9"

* Banks Lake - Banks Lake Pump Storage Project

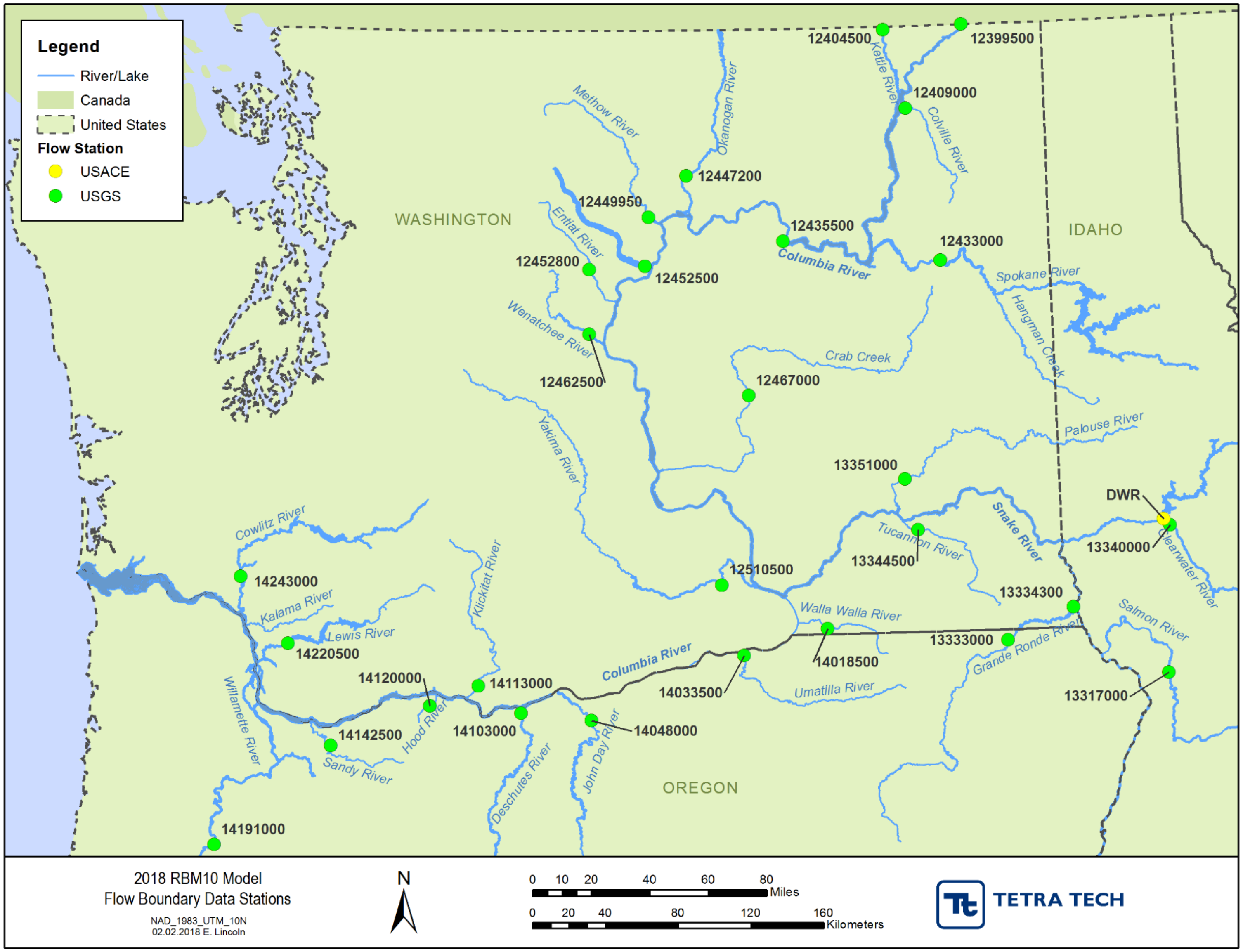

Figure 2-3 Stations used to generate flow boundary conditions for the Columbia and Snake Rivers

2.5.2 Temperature Inputs

Temperature inputs for the 2018 RBM10 model were developed based on data collected by multiple agencies including the USGS, USACE, DOE, and DEQ. The list of monitoring stations used to extract temperature data for the mainstem reaches and tributaries included in the model is presented in Table 2-4. The 2018 RBM10 model uses temperature inputs from the same stations used in previous model applications, although the DOE stations listed in Table 2-4 reflect new identification numbers.

To generate the daily temperature inputs for each tributary and headwater included in the 2018 RBM10 model (Table 2-4), the available daily temperature observations for the period 2000 – 2016 were subject to a QA/QC and later appended to the 2002 RBM10 model temperature files which had daily data for the period 1970 – 2000.

Preprocessing tools were used to automatically fill data gaps (Yearsley 2003). Data gaps of a week or less than a week were filled by linear interpolation. For larger gap periods, the gaps were filled with long-term daily average temperatures and a lag-one Markov model. Details of the data gap filling procedure including examples are presented in Appendix A. Table 2-5 shows a summary of available data and major data gaps at the mainstem upstream boundary monitoring stations.

Due to data limitations for the Hood, Sandy, and Kalama rivers, these rivers are assigned temperatures from the Deschutes River.

Table 2-4 List of monitoring stations used to extract temperature data for the 2018 RBM10 model

River Name	Station Name	Agency	Station Number	Latitude	Longitude
Headwater					
Clearwater River	Clearwater River at Orofino, ID	USGS	13340000	46°28'42.0"	116°15'27.0"
Snake River	Snake River near Anatone, WA	USGS	13334300	46°05'50.0"	116°58'36.1"
Columbia River	CIBW-Boundary (Columbia R US/Canada)	USACE	CIBW	--	--
Tributaries					
Dworshak Dam	North Fork Clearwater at Dworshak Dam	USACE	DWR	--	--
Tucannon River	Tucannon River at Powers	DOE	35B060	46°32'15.4"	118°09'19.8"
Palouse River	Palouse River at Hooper	DOE	34A070	46°45'31.0"	118°08'52.8"
Kettle River	Kettle River near Barstow	DOE	60A070	48°47'04.6"	118°07'31.1"
Colville River	Colville River at Kettle Falls	DOE	59A070	48°35'39.5"	118°03'45.0"
	Colville River at Greenwood Loop Rd	DOE	59A080	48°35'19.0"	117°59'32.3"
Spokane River	Spokane River at Stateline Br	DOE	57A150	47°41'54.6"	117°02'40.6"
Okanogan River	Okanogan River at Malott	DOE	49A070	48°16'49.4"	119°42'16.2"
Methow River	Methow River at Pateros	DOE	48A070	48°04'28.6"	119°57'24.5"
Chelan River	Chelan River at Chelan	DOE	47A070	47°48'52.6"	119°58'22.1"
Entiat River	Entiat River near Entiat	DOE	46A070	47°39'47.5"	120°15'2.2"
Wenatchee River	Wenatchee River at Wenatchee	DOE	45A070	47°27'31.7"	120°20'11.4"
Crab Creek	Crab Creek near Beverly	DOE	41A070	46°49'52.7"	119°48'58.3"
Yakima River	Yakima River near Richland	DOE	37A090	46°15'10.4"	119°28'31.1"
Walla Walla River	Walla Walla River near Touchet	DOE	32A070	46°02'15.4"	118°45'59.0"

River Name	Station Name	Agency	Station Number	Latitude	Longitude
Umatilla River	Umatilla River	DEQ	11489	45°50'08.2"	119°19'58.4"
John Day River	John Day River	DEQ	11478	44°47'31.9"	120°00'13.3"
		DEQ	11479	44°27'57.6"	119°28'17.4"
		DEQ	11386	45°28'37.3"	120°28'10.2"
Deschutes River	Deschutes River at Moody, near Biggs, OR	USGS	14103000	45°37'20.0"	120°54'15.8"
Klickitat River	Klickitat River near Lyle	DOE	30B060	45°42'41.0"	121°15'58.0"
	Klickitat River near Pitt	DOE	30B070	45°45'23.4"	121°12'36.4"
Hood River	Setup uses data from Deschutes	USGS	14103000	45°37'20.0"	120°54'15.8"
Sandy River	Setup uses data from Deschutes	USGS	14103000	45°37'20.0"	120°54'15.8"
Willamette River	Willamette River at Portland, OR	USGS	14211720	44°56'40.0"	123°02'30.1"
Lewis River	Lewis River at Co Rd 16	DOE	27C080	45°54'20.5"	122°44'14.3"
	Lewis River at Ariel	DOE	27C110	45°57'20.5"	122°33'24.5"
Kalama River	Setup uses data from Deschutes	USGS	14103000	45°37'20.0"	120°54'15.8"
Cowlitz River	Cowlitz River at Kelso	DOE	26B070	46°08'43.4"	122°54'51.5"

Table 2-5 Summary of available water temperature records for the period 2000 – 2016 at mainstem headwater boundaries

River	Station ID	Data Frequency	Records Available	Periods with gaps of 10 or more days	Top 3 data gaps
Clearwater	USGS 13340000	Daily	6145	1	18 (1/10/2013 – 1/28/2013)
Snake	USGS 13334300	Daily	6160	2	16 Days (10/23/2012 – 11/8/2012) 13 Days (10/2/2008 – 10/15/2008)
Columbia	USACE CIBW	Daily	5735	3	397 Days (11/30/2008 – 1/1/2010) 20 Days (2/19/2013 – 3/11/2013) 10 Days (9/22/2003 – 10/2/2003)

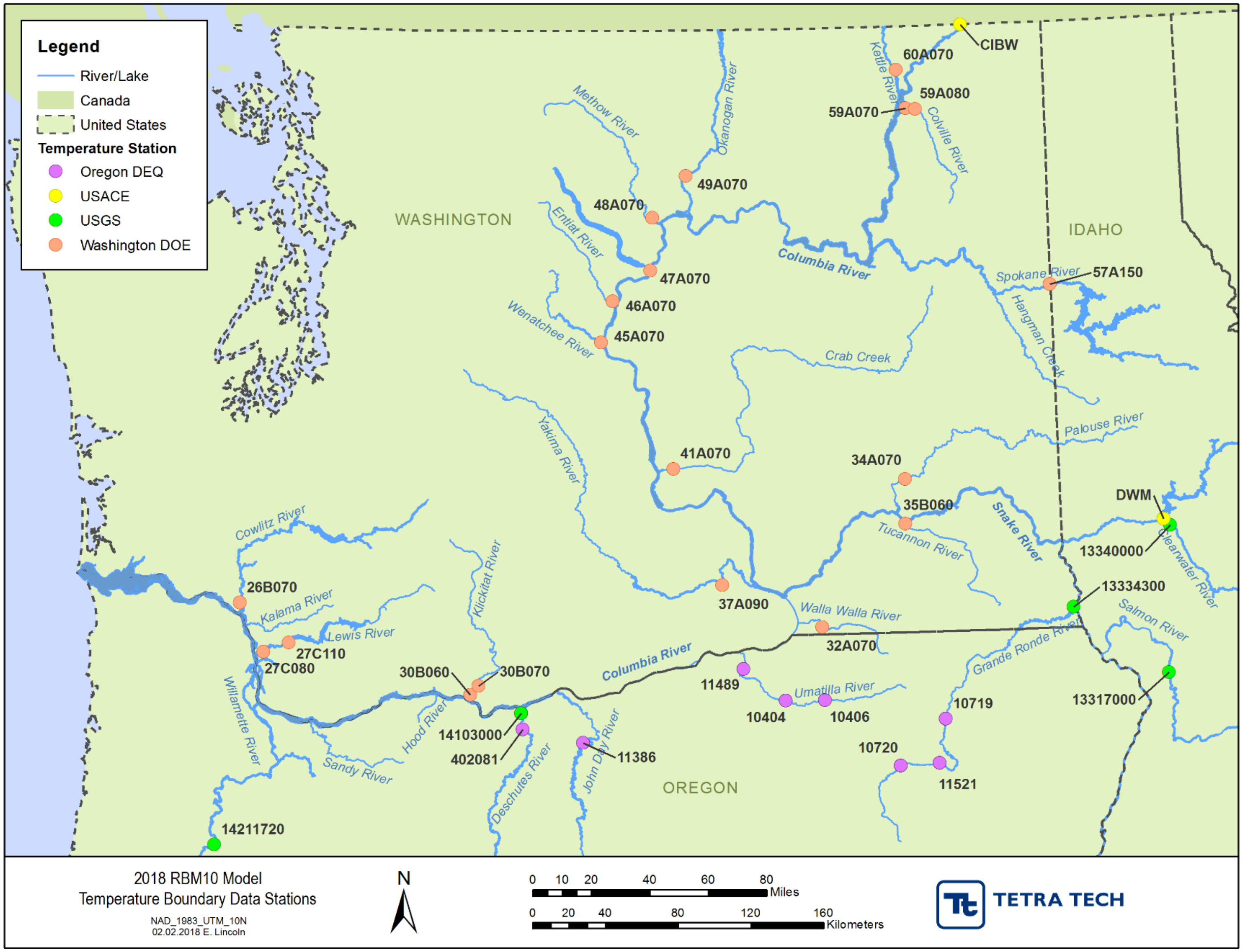

Figure 2-4 Stations used to generate temperature boundary conditions for the Columbia and Snake Rivers

2.6 Surface Heat Exchange and Meteorological Inputs

Heat exchange across the air-water interface is generally the major source of thermal energy for lakes, rivers, and reservoirs. The RBM10 model calculates the net exchange of thermal energy, H_{net}, across the air-water interface for the following processes:

$$H_{net} = (H_s - H_{rs}) + (H_a - H_{ra}) +/- H_{evap} +/- H_{cond} - H_{back} \quad \textbf{(8)}$$

where

H_{net} = Net heat exchange across the air-water interface, kcal/meter^2/second

H_s = Shortwave solar radiation, kcal/meter^2/second

H_{rs} = Reflected shortwave solar radiation, kcal/meter^2/second

H_a = Longwave atmospheric radiation, kcal/meter^2/second

H_{ra} = Reflected atmospheric radiation, kcal/meter^2/second

H_{evap} = Evaporative heat flux, kcal/meter^2/second

H_{cond} = Conductive heat flux, kcal/meter^2/second

H_{back} = Blackbody radiation from the water surface, kcal/meter^2/second

The specific form for each of the terms in the heat budget formulation above is based on a compilation of heat budget studies by Wunderlich and Gras (1967), with individual elements of the heat budget as follows:

Shortwave (Solar) Radiation

$$(H_s - H_{rs}) = F(\Phi,\delta,D_y) \quad \textbf{(9)}$$

where

Φ = the latitude of the site

δ = the declination of the sun at the site

D_y = the day of the year

Longwave (Atmospheric) Radiation

$$(H_a - H_{ra}) = (1-\alpha_{ar})\ 1.23 \times 10^{-16}\ (1.0 + 0.17\ C^2)\ (T_{DB} + 273.)^6 \quad \textbf{(10)}$$

where

α_{ar} = reflectivity of the water surface for atmospheric radiation, ~ 0.03

C = cloud cover, decimal fraction

T_{DB} = dry bulb temperature, ^oC

Evaporative Heat Flux

$$H_{evap} = \rho\ \lambda\ E_v\ W\ (e_o - e_a) \quad \textbf{(11)}$$

where

ρ = water density, kg/meter^3

λ = latent heat of vaporization, kcal/kg

E_v = empirical constant, mb^{-1}

W = wind speed, meters/second

e_o = saturation vapor pressure at the temperature of the water surface, mb

e_a = vapor pressure of the air near the water surface, mb

Conductive Heat Flux

$$H_{cond} = R_B \left[\frac{T - T_a}{e_0 - e_a} \right] \frac{p_a}{1013.3} \quad \textbf{(12)}$$

where

R_B = an empirical constant, 0.66

p_a = atmospheric pressure, mb

Black Body (Water Surface) Radiation

$$H_{back} = 0.97\,\sigma\,(T + 273.)^4 \quad \textbf{(13)}$$

where

Φ = Stefan-Boltzman constant, 1.357×10^{-11} cal/meter^2/second/^{o}K

In the RBM10 model, surface heat exchange balance is driven by meteorological data. The RBM10 model requires dew point temperature, air temperature, wind speed, atmospheric pressure, and cloud cover. The above information is obtained from a weather monitoring station and provided to the model in a file containing time series of records for each atmospheric variable. Multiple weather files can be created and used by the model. The weather files are then paired or assigned by the user to each reach in the model (usually based on proximity). This way the model can execute the heat balance at each reach using information from a specific weather station. When multiple weather files are available, weather file assignment is performed as part of the model calibration as performed during this project.

For this project, the weather information was obtained from four Weather Bureau Army Navy (WBAN) meteorological stations and three Global Historical Climatology Network – Daily (GHCND) meteorological stations (Figure 2-5). All meteorological data sources and station locations are unchanged from the 2001 model.

The WBAN stations reported all the required meteorological variables for the model (Table 2-6). For the 2001 through 2003 RBM10 models, data for these stations were available from the National Climatic Data Center (NCDC) Solar and Meteorological Surface Observation Network (SAMSON) at 3-hour intervals (Yearsley 2003). For the 2018 RBM10 model data were available and obtained from the National Climatic Data Center (NCDC) National Oceanic and Atmospheric Administration (NOAA) website at hourly intervals.

Table 2-6 WBAN stations used in 2018 RBM10 model

Station Name	Station Number	2017 Data Source	2002 Data Source
Lewiston, Idaho	24149	WBAN	SAMSON
Portland, Oregon	24229	WBAN	SAMSON
Spokane, Washington	24157	WBAN	SAMSON
Yakima, Washington	24243	WBAN	SAMSON

The GHCND stations only reported daily maximum and minimum air temperature (Table 2-7). The closest WBAN station was used to append the remaining meteorological data parameters to the GHCND time series. Previously, data for the GHCND stations were gathered from the NCDC

Local Climatological Data (LCD) datasets. For the 2018 RBM10 model, data were downloaded from NCDC NOAA website.

Table 2-7 GHCND stations used in 2018 RBM10 model

Station Name	Station Number	2017 Data Source	2002 Data Source	WBAN Appended Data
Coulee Dam	1767	GHCND	LCD	Spokane
Richland	7015	GHCND	LCD	Lewiston
Wenatchee	9074	GHCND	LCD	Spokane

The atmospheric records downloaded from the WBAN and GHCND stations were processed to fill data gaps and construct a continuous daily time series of atmospheric forcings for the model. The data gaps were filled automatically by the meteorological preprocessing tools by replacing the gaps with long-term daily average values.

The WBAN and GHCND stations were selected during the original modeling because they provided continuous data for the entire simulation period and had a robust data set. For the 2018 RBM10 model, the meteorological data needed to span from 1970 through 2016, and many current sources of weather information did not exist in the 1970s. In addition, the meteorological data were similar between most of the selected stations, indicating that the number and distribution of stations provided adequate spatial resolution of meteorological conditions throughout the model domain area. A station was added to the model near Portland, Oregon because there were differences at that location as compared to others in the model. No other changes were made to the meteorological station selection.

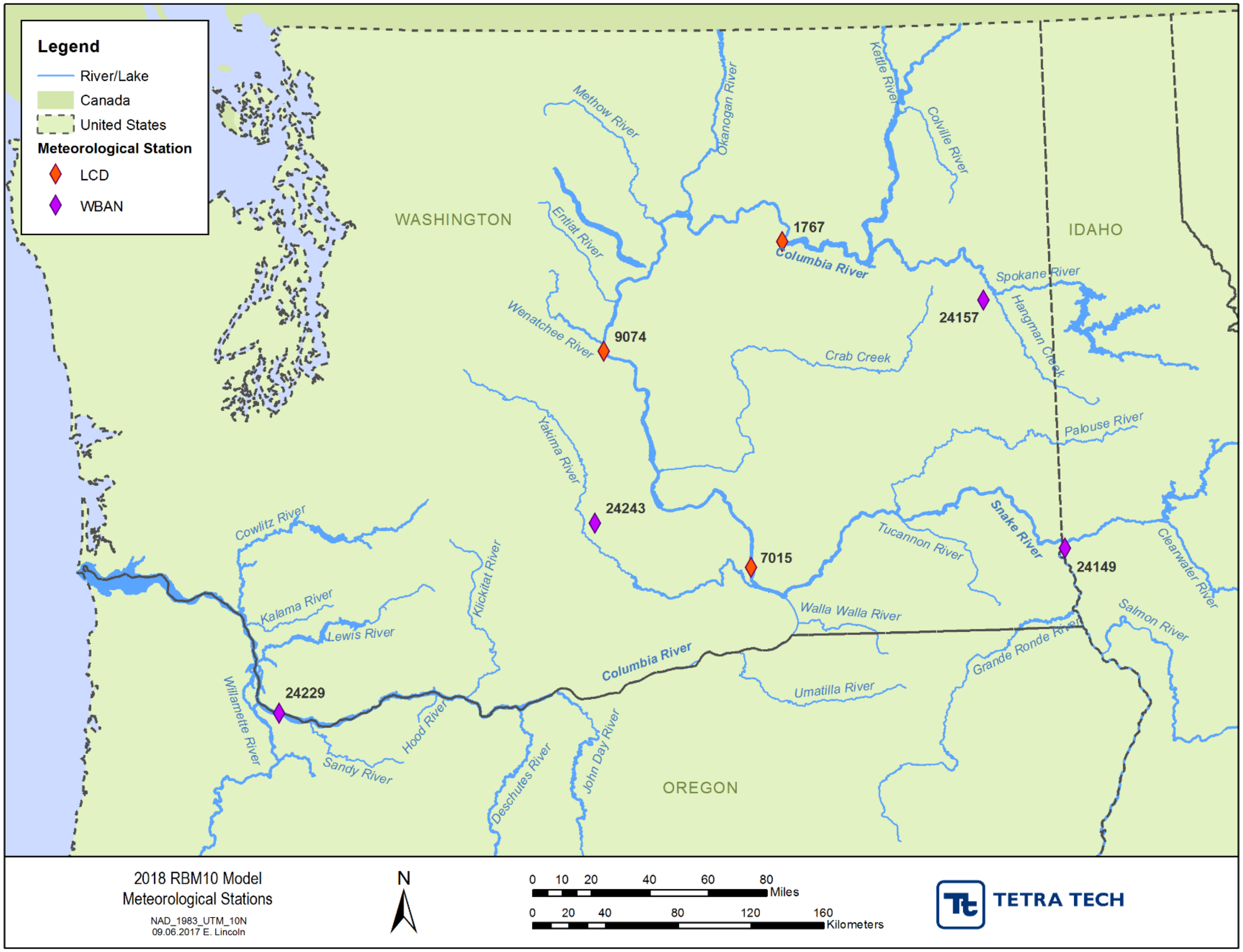

Figure 2-5 Meteorological stations within the simulated area

3.0 Model Calibration Process and Results

3.1 Calibration Approach

The calibration of the model was performed using all available USACE tailrace water temperature monitoring data (approximately 25 years) for comparison of model simulations and observations. During calibration, weather files were initially assigned to the Columbia and Snake River reaches solely based on the proximity of each reach to the available weather stations and following the weather assignements used in the 2001 RBM10 model. The list of weather stations used by the 2001 RBM10 model is shown in Table 3-1. Final weather file assignments was based on reach proximity to the weather station and model perfomance to statistically and graphically match observed water temperatures. The list of weather stations used by the 2018 RBM10 model is shown in Table 3-2.

Using a similar approach to that taken in the original model development in 2001, the empirical constants (E_v) from Eq. (11) were iteratively adjusted during calibration to achieve a close match between observed and simulated water temperatures along the Colombia and Snake Rivers. The empirical constants E_v control the evaporative heat flux between the water and the atmosphere and are defined for each weather station. Recalling Eq. (11), the evaporative heat flux is computed in the RBM10 model using the following model (Yearsley et al. 2001):

$$H_{evap} = \rho \, \lambda \, E_v \, W \, (e_o - e_a)$$

The 2018 RBM10 model uses three Ev coefficients for each meteorological station to simulate annual seasonal changes in the evaporative heat fluxes. Yearsley et al. (2001) used two E_v coefficients in the 2001 RBM10 model (Table 3-1). In the 2001 RBM10 model, one value of E_v was used to simulate evaporative heat transfer between January 1 and September 8 (Julian days 0 – 250) and a second value of E_v was used to simulate evaporative heat transfer between September 9 and December 31 (Julian days 251 – 365) (Table 3-1). In the 2018 RBM10 model, one value of E_v was used to simulate evaporative heat transfer between April 1 and August 13 (Julian days 91 – 225), a second value of E_v was used to simulate evaporative transfer between August 14 and November 26 (Julian days 226 – 330), and a third value of E_v was used to simulate evaporative heat transfer between November 27 and March 31 (Julian day 330 – 90). The seasonal period as well as the calibrated values of E_v for each season are presented in Table 3-2. The calibrated values of E_v are within the values typically found in the literature, which generally range from 0 to 3.0E-9 (see Edinger et al. 1974; Bowie et al. 1985).

Table 3-1 2001 RBM10 model evaporative heat flux transfer constants Ev

	2001 RBM10 model	
Station Name	Ev (January 1 – September 8)	Ev (September 9 December 31)
Wenatchee	1.40e-9	1.40e-9
Yakima	1.30e-9	1.47e-9
Lewiston	2.40e-9	0.86e-9
Richland	1.60e-9	1.51e-9
Coulee	1.90e-9	0.83e-9

Table 3-2 2018 RBM10 model calibrated evaporative heat flux transfer constants Ev

	2018 RBM10 model		
Station Name	Ev (April 1 – August 13)	Ev (August 14 – November 26)	Ev (November 27 – March 31)
Wenatchee	1.40e-9	1.15e-9	0.50e-9
Yakima	1.30e-9	1.20e-9	1.50e-9
Lewiston	2.40e-9	1.90e-9	0.20e-9
Portland	1.60e-9	1.25e-9	0.01e-9
Spokane	1.90e-9	1.00e-9	0.55e-9

During calibration, the values of E_v were iteratively adjusted for each meteorological station to minimize the bias and residual errors (produce the closest fit) between the model simuations and available temperature observations. During calibration, simulated temperatures were compared graphically and statistically to measured temperatures collected from 1995 through 2016 at USACE tailrace monitoring stations located along the Columbia River (Table 3-3) and Snake River (Table 3-4). Focus was placed on tailwater stations as usually these are locations where water is well mixed vertically and laterally due to the turbulence caused by the upstream dam releases and due to local shallow depths. Therefore, mixing conditions at these locations most closely match the assumptions of the RBM10 transport model. It is noted that differences between forebay and tailrace water temperatures are in most cases negligible, because most reservoirs along the Columbia and Snake Rivers are operated as run-of-the-river systems with minor vertical stratification. This is illustrated from Figure 3-2 through Figure 3-4, where available observations of water temperatures at forebay and tailrace locations are compared forRocky Reach Dam, The Dalles Dam, and Bonneville Dam. These figures show that forebay and tailrace temperatures are very similar with differences rarely exceeding ±1 °C.

The stations listed in Table 3-3, Table 3-4 and Table 3-5 with exception of stations WRNO (Warrandale, OR), CWMN (Camas/Washougal, WA) and PEKI (Clearwater River NR Peck) were also used for model perfomance assessment in previous implementations of the RBM10 model (Yearsley et al. 2001; Yearsley 2003).

Table 3-3 Temperature monitoring stations on the Columbia River used for model comparisons

Station	Station ID	Station Description
Camas/Washougal WA	CWMW	Columbia RM 119: Columbia River at RM 119
Warrandale OR	WRNO	Columbia RM 140: Six miles D/s of dam
Bonneville Dam tailwater	BON	Columbia RM 146: Right end of spillway near dam center
The Dalles Dam tailwater	TDDO	Columbia RM 190: Left bank one mile d/s of dam
John Day Dam tailwater	JHAW	Columbia RM 215: Dam tailwater Right bank of river
McNary Dam tailwater-Washington	MCPW	Columbia RM 291: Dam Tailwater Right bank of river
Priest Rapids tailwater	PRXW	Columbia RM 396: Tailwater D/s of dam
Wanapum Dam tailwater	WANW	Columbia RM 415: Tailwater D/s of dam
Rock Island Dam tailwater	RIGW	Columbia RM 452: Tailwater D/s of dam
Rocky Reach Dam tailwater	RRDW	Columbia RM 472 Tailwater D/s of dam
Wells Dam tailwater	WELW	Columbia RM 514: Tailwater D/s of dam
Chief Joseph Dam tailwater	CHQW	Columbia RM 545: Tailwater D/s of dam
Grand Coulee Dam tailwater	GCGW	Columbia RM 590: Six miles D/s of dam

Table 3-4 Temperature monitoring stations on the Snake River used for model comparisons

Station	Station ID	Station Description
Ice Harbor Dam tailwater	IDSW	Snake RM 6.8: Right bank 15,400 feet d/s of dam
Lower Monumental Dam tailwater	LMNW	Snake RM 40.8: Left bank 4,300 feet d/s of dam
Little Goose Dam tailwater	LGSW	Snake RM 69.5: Right bank 3,900 feet d/s of dam
Lower Granite Dan tailwater	LGNW	Snake RM 106.8: Right bank 3,500 feet d/s of dam

Table 3-5 Temperature monitoring stations on the Clearwater River used for model comparisons

Station	Station ID	Station Description
Clearwater River NR Peck	PEKI	Clearwater RM 30.0: Clearwater River at RM 33

3.2 Data retrieval and QA/QC procedure

Tailrace water temperatures along the Columbia and Snake Rivers (Table 3-3 and Table 3-4) were retrieved from the Columbia River DART website (http://www.cbr.washington.edu/dart). For each station, data errors were flagged and removed before the temperature datasets were used for the graphical and statistical analyses. A statistical analysis of the observed water temperatures was conducted to identify outliers at each station using box and whisker plots. The outliers identified during this process were then compared to air temperatures and records at nearby water temperature stations to determine, using professional judgement, if they were errors. The records flagged as errors were removed from the datasets. An example of outliers and errors identified and removed at the Ice Harbor Dam tailrace is presented in Figure 3-5 and Figure 3-6. For all stations, a small fraction (less than 2%) of the available observations were flagged as suspicious records and removed from the calibration dataset.

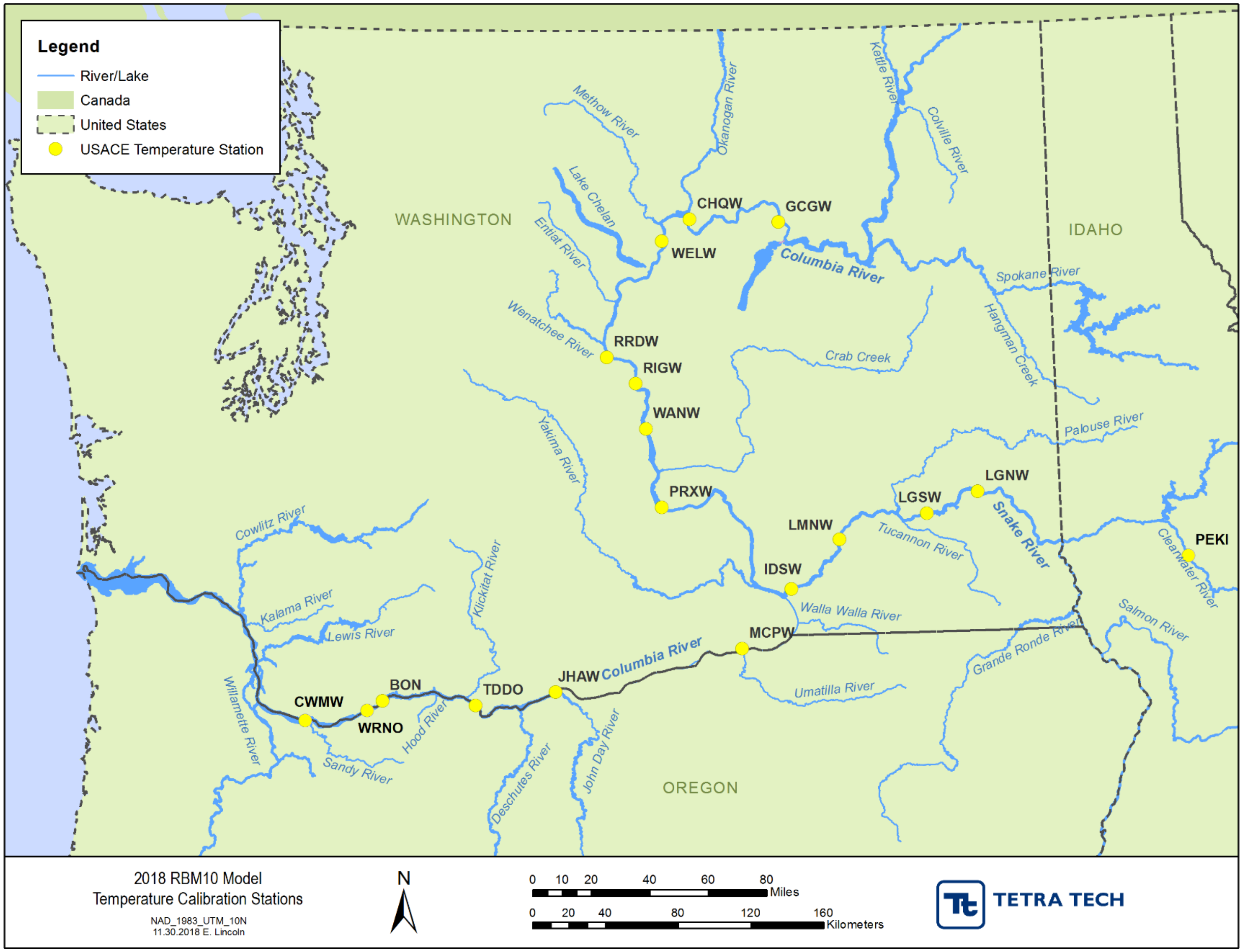

Figure 3-1 Temperature calibration stations for the RBM10 model

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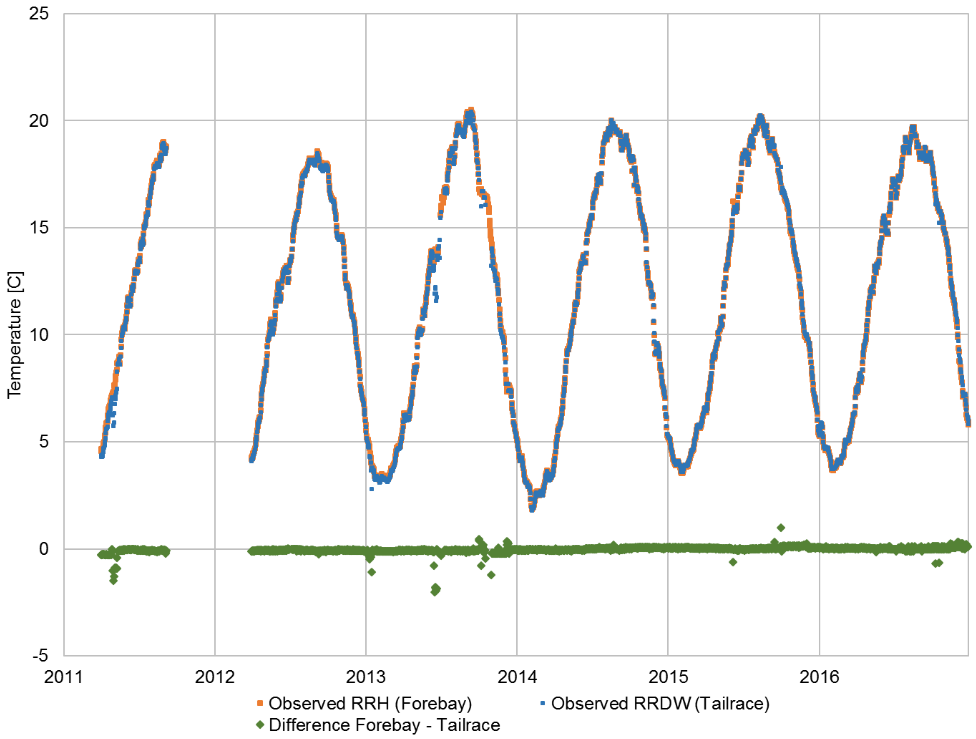

Figure 3-2 Comparison between forebay and tailrace water temperatures at the Rocky Reach Dam

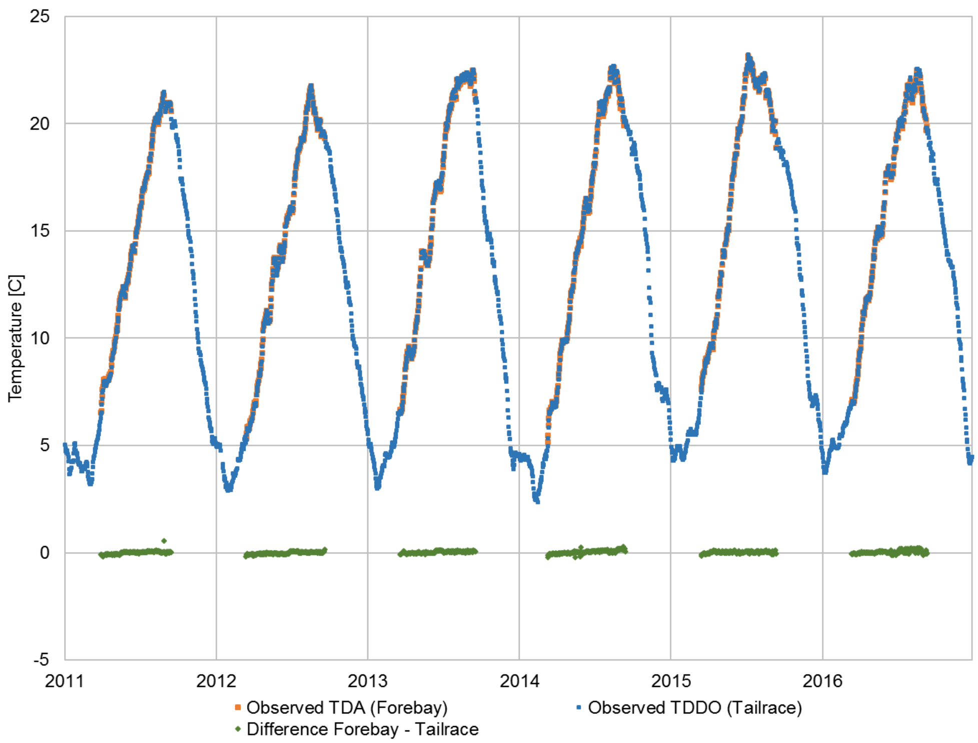

Figure 3-3 Comparison between forebay and tailrace water temperatures at The Dalles Dam

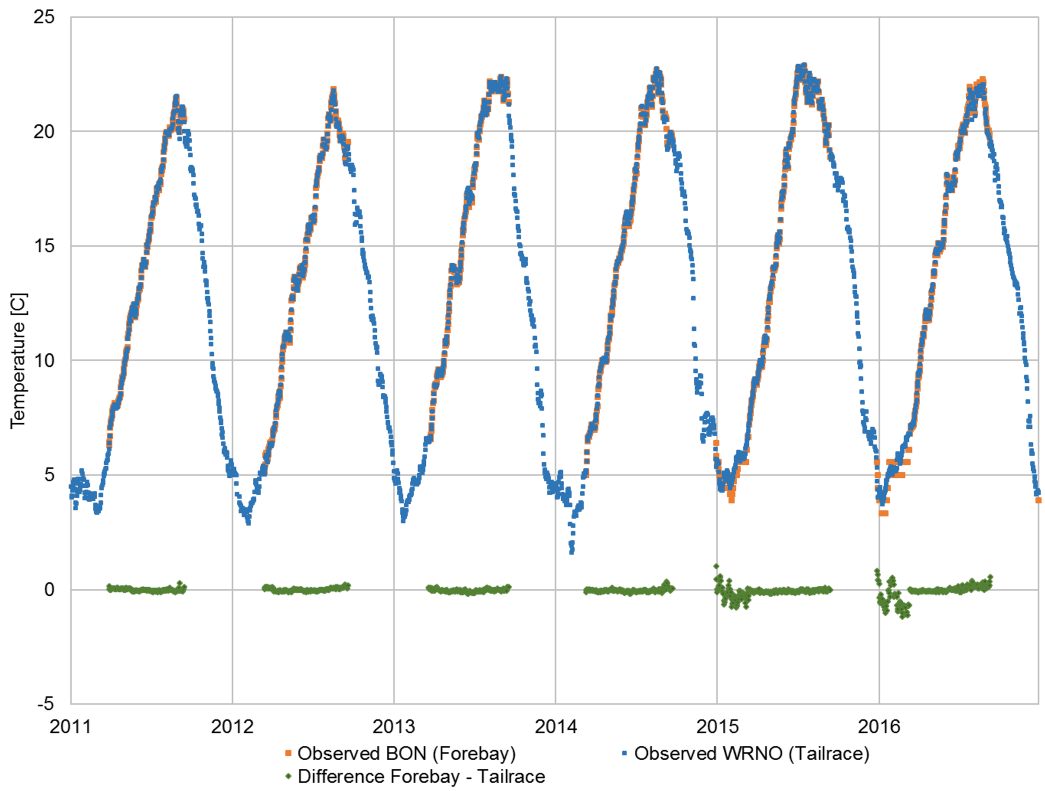

Figure 3-4 Comparison between forebay and tailrace water temperatures at the Bonneville Dam

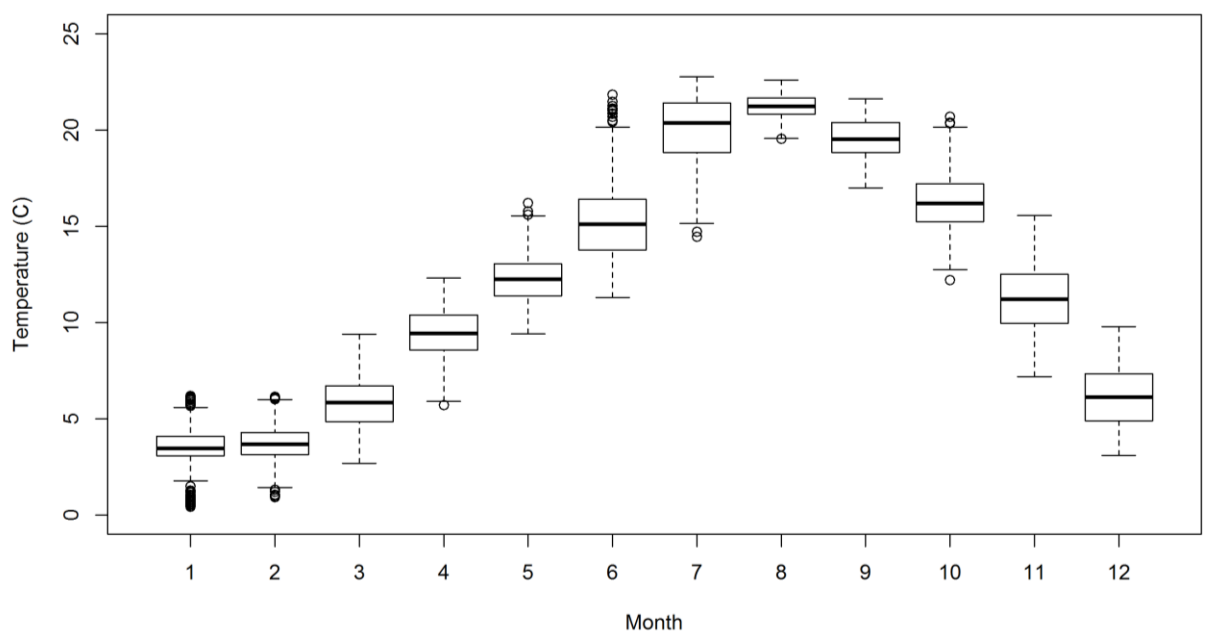

Figure 3-5 Monthly Box and Whisker plots of water temperature at Ice Harbor Dam tailrace with temperature outliers shown in circles

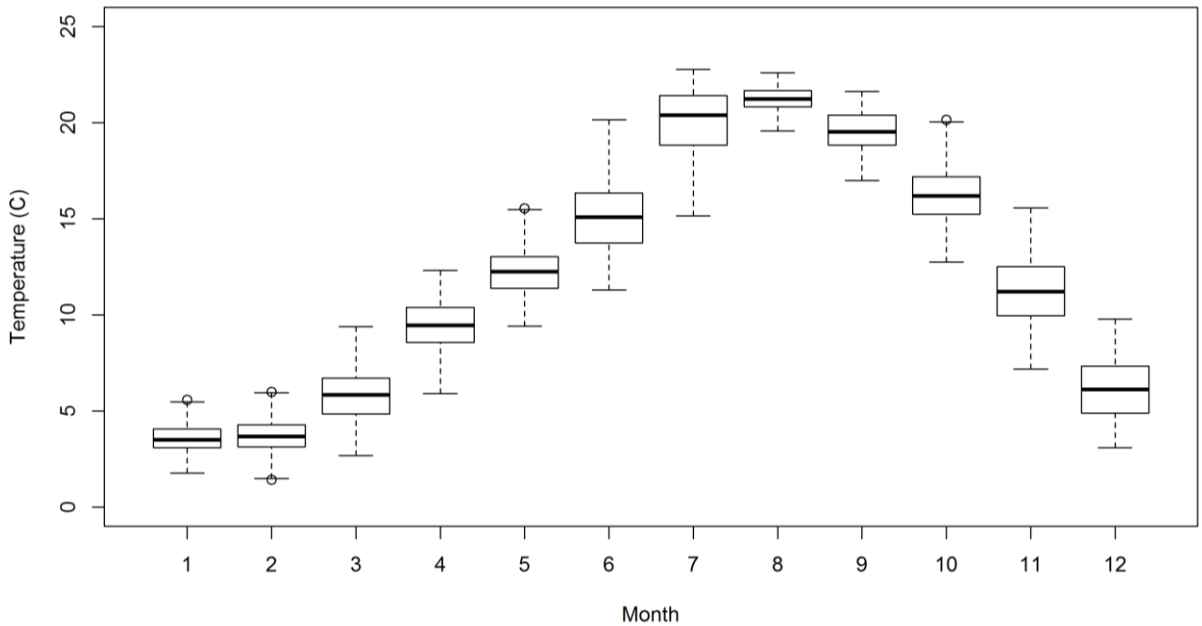

Figure 3-6 Monthly Box and Whisker plots of water temperature at Ice Harbor Dam tailrace with temperature outliers flagged as errors removed from the dataset

3.3 Model Performance Statistics

The statistics of model performance, including mean error, mean absolute error, root mean square error, and correlation coefficient were used to assess the predictive capability of the 2018 RBM10 model. These statistics are similar to those used by Yearsley et al. (2001) and Yearsley (2003). The equations to calculate each statistic given a time series of model predictions P and a time series of observations O are given by:

Mean Error: $ME = \frac{\sum_{i=1}^{n} P_i - O_i}{n}$

Mean Absolute Error: $MAE = \frac{\sum_{i=1}^{n} \left| P_i - O_i \right|}{n}$

Root Mean Squared Error: $RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(P_i - O_i \right)^2}{n}}$

Correlation coefficient: $R = \frac{\left(n \sum_{i=1}^{n}(P_i \times O_i)\right) - \left(\sum_{i=1}^{n} P_i \times \sum_{i=1}^{n} O_i\right)}{\sqrt{\left[n \sum_{i=1}^{n}(P_i{}^2) - \sum_{i=1}^{n}(P_i)^2\right] \times \left[n \sum_{i=1}^{n}(O_i{}^2) - \sum_{i=1}^{n}(O_i)^2\right]}}$

The calibration effort focused on maximizing the ability of the model to reproduce the seasonal changes (timing and magnitude) of water temperatures along the Columbia and Snake Rivers. For this purpose, the model parameters were adjusted to capture different characteristics of the temperature time series such as the positive slope of the rising temperatures during the spring season, the duration and magnitude of peak temperatures during the summer season, and the negative slope of the temperatures during the fall season. The ability of the model to capture these temperature variations was evaluated by both plotting the simulated/observed temperatures and by calculating the goodness of fit of the simulations for different periods of time. Model performance statistics were calculated for the following periods: January – December, April – November, July – August, and September – October. The model parameters were iteratively adjusted to match observed temperature patterns and minimize the differences between the simulated and observed temperatures.

Statistical results obtained at each station in the Columbia and Snakes Rivers are presented in Table 3-6 through Table 3-9. The tables present the statistical analyses resulting from the comparison of the model simulations against all available observations within the period 2007 – 2016. The statistics focused on the 2007-2016 period because this time frame will be used to develop the temperature load allocations for the Columbia River Temperature TMDL. Long term statistics of model performance for the period 1990-2016 were also evaluated and in general were similar to those presented in Table 3-6 through Table 3-9. Data collected prior to 1990 was not considered to be high quality and useful for model calibration. DART data were unavailable at many stations prior to 1990, and data that were available tended to have data gaps and discrepancies. Prior to 1984, measurements of water temperature in the Columbia and Snake River consisted of manual observations of temperature from thermometers placed in the cooling system of each dam's turbines and there were several quality assurance issues in the instruments, location of instruments, and protocols for collecting and reporting data.

Overall, the statistics of model performance shown in Table 3-6 through Table 3-9 are similar and in most cases improved compared to those reported by Yearsley (2003). The performance statistics indicate that the 2018 RBM10 model is able to simulate temperatures in the Columbia River with average MAEs of 0.4°C – 0.5°C, and average RMSEs of 0.5°C – 0.6°C, and in the Snake River with average MAEs of 0.4°C – 0.5°C and an average RMSE of 0.6°C. The timing and seasonal temperature changes are well captured by the model and the average correlation coefficient between the observations and model simulations in the Columbia and Snake Rivers is 0.99.

Summer temperatures, which are of interest for management purposes, are well captured by the model without systematic overpredictions or underpredictions in any of the monitoring statations evaluated (Table 3-8). The average MAE between the simulations and observations of temperature for the months of July – August was 0.4 °C in the Columbia and Snake Rivers and and the RMSE was an average 0.5 °C in both rivers.

Graphical comparisons between simulated and observed temperatures are presented from Figure 3-11 through Figure 3-33 and comparisons between simulated and observed river flows are presented in Appendix B. The graphical comparisons show that the 2018 RBM10 model is able to predict the annual trends and seasonal variations of temperature along the Columbia and Snake Rivers. The model is able to capture the slope of the rising limb of the temperature hydrograph during the heating period between winter and summer, the peak temperatures during the summer months, and the slope of the receding limb of the temperature hydrograph during the cooling period between summer and winter (Figure 3-7 through Figure 3-42). The ability of the model to capture the timing and interseasonal changes of temperature is reflected in the high correlation coefficients obtained during calibration, which were typically above or equal to 0.97 at all of the evaluated stations.

Table 3-6 Model performance statistics all months (2007-2016; January – December)

Columbia River Stations					
	Observations	**ME**	**MAE**	**RMSE**	**R**
CWMW	4639	-0.139	0.488	0.609	0.994
WRNO	7865	-0.136	0.476	0.607	0.995
BON	8383	-0.153	0.447	0.558	0.996
TDDO	5626	0.064	0.420	0.521	0.997
JHAW	5857	0.105	0.417	0.519	0.997
MCPW	7306	0.168	0.429	0.533	0.997
PRXW	5493	-0.119	0.418	0.533	0.996
WANW	5380	-0.176	0.461	0.588	0.996
RIGW	4250	-0.039	0.496	0.650	0.993
RRDW	4028	-0.076	0.486	0.622	0.994
WELW	3482	0.100	0.436	0.544	0.994
CHQW	3853	-0.064	0.414	0.529	0.995
GCGW	6498	-0.012	0.389	0.495	0.996
Average		**-0.037**	**0.444**	**0.562**	**0.995**

Snake River Stations					
	Observations	**ME**	**MAE**	**RMSE**	**R**
IDSW	7635	0.141	0.460	0.588	0.996
LMNW	6052	0.090	0.521	0.658	0.994
LGSW	5859	0.093	0.531	0.667	0.994
LGNW	7345	0.087	0.494	0.625	0.994
	Average	**0.103**	**0.501**	**0.634**	**0.995**
Clearwater River Stations					
	Observations	**ME**	**MAE**	**RMSE**	**R**
PEKI	5157	0.077	0.377	0.506	0.990
	Average	**0.077**	**0.377**	**0.506**	**0.990**

Table 3-7 Model performance statistics (2007-2016; April – November)

Columbia River Stations					
	Observations	**ME**	**MAE**	**RMSE**	**R**
CWMW	3993	-0.092	0.481	0.602	0.992
WRNO	5496	-0.136	0.453	0.569	0.992
BON	6150	-0.161	0.437	0.549	0.994
TDDO	4345	0.070	0.412	0.510	0.993
JHAW	4560	-0.088	0.403	0.498	0.994
MCPW	5110	0.154	0.409	0.502	0.994
PRXW	4348	-0.137	0.429	0.544	0.992
WANW	4028	-0.109	0.436	0.555	0.992
RIGW	3632	-0.036	0.515	0.679	0.988
RRDW	3489	-0.080	0.508	0.651	0.990
WELW	3140	0.115	0.455	0.563	0.991
CHQW	3699	-0.069	0.417	0.534	0.993
GCGW	4380	-0.014	0.440	0.549	0.992
	Average	**-0.045**	**0.446**	**0.562**	**0.992**
Snake River Stations					
	Observations	**ME**	**MAE**	**RMSE**	**R**
IDSW	5379	0.160	0.436	0.557	0.993
LMNW	4721	0.241	0.499	0.636	0.991
LGSW	4579	0.225	0.536	0.674	0.990
LGNW	5109	0.200	0.519	0.651	0.991
	Average	**0.206**	**0.498**	**0.630**	**0.991**
Clearwater River Stations					
	Observations	**ME**	**MAE**	**RMSE**	**R**
PEKI	4100	0.095	0.372	0.501	0.979
	Average	**0.095**	**0.372**	**0.501**	**0.979**

Table 3-8 Model performance statistics (2007-2016; July – August)

Columbia River Stations					
	Observations	**ME**	**MAE**	**RMSE**	**R**
CWMW	1376	0.143	0.505	0.624	0.934
WRNO	1383	0.042	0.391	0.486	0.959
BON	1792	0.002	0.418	0.533	0.949
TDDO	1284	0.197	0.409	0.499	0.962
JHAW	1355	0.205	0.399	0.480	0.969
MCPW	1356	0.226	0.353	0.429	0.975
PRXW	1249	-0.186	0.390	0.494	0.957
WANW	1118	-0.052	0.352	0.448	0.961
RIGW	1154	0.036	0.449	0.586	0.931
RRDW	1158	-0.032	0.425	0.522	0.938
WELW	1065	0.178	0.424	0.517	0.949
CHQW	1170	-0.041	0.392	0.491	0.951
GCGW	1081	-0.072	0.426	0.543	0.944
	Average	**0.050**	**0.410**	**0.512**	**0.952**
Snake River Stations					
	Observations	**ME**	**MAE**	**RMSE**	**R**
IDSW	1414	0.145	0.410	0.516	0.960
LMNW	1352	0.081	0.465	0.580	0.922
LGSW	1334	-0.060	0.494	0.616	0.873
LGNW	1324	-0.199	0.496	0.647	0.769
	Average	**-0.008**	**0.466**	**0.590**	**0.881**
Clearwater River Stations					
	Observations	**ME**	**MAE**	**RMSE**	**R**
PEKI	1337	0.174	0.377	0.500	0.918
	Average	**0.174**	**0.377**	**0.500**	**0.918**

Table 3-9 Model performance statistics (2007-2016; September – October)

Columbia River Stations					
	Observations	**ME**	**MAE**	**RMSE**	**R**
CWMW	500	-0.643	0.666	0.817	0.876
WRNO	1370	-0.322	0.544	0.689	0.969
BON	1200	-0.562	0.625	0.783	0.812
TDDO	901	0.057	0.439	0.548	0.974
JHAW	892	0.108	0.421	0.535	0.976
MCPW	1243	0.171	0.415	0.516	0.976
PRXW	1032	-0.039	0.382	0.478	0.959
WANW	973	-0.080	0.396	0.484	0.957
RIGW	632	-0.018	0.555	0.719	0.883
RRDW	547	0.023	0.472	0.634	0.895
WELW	518	-0.147	0.478	0.621	0.866
CHQW	821	-0.312	0.495	0.663	0.741
GCGW	1083	-0.226	0.499	0.618	0.862
	Average	**-0.153**	**0.491**	**0.623**	**0.904**
Snake River Stations					
	Observations	**ME**	**MAE**	**RMSE**	**R**
IDSW	1306	0.057	0.418	0.525	0.971
LMNW	1021	0.117	0.438	0.557	0.966
LGSW	939	0.459	0.637	0.771	0.953
LGNW	1198	0.274	0.532	0.640	0.970
	Average	**0.227**	**0.506**	**0.623**	**0.965**
Clearwater River Stations					
	Observations	**ME**	**MAE**	**RMSE**	**R**
PEKI	768	0.057	0.271	0.357	0.962
	Average	**0.057**	**0.271**	**0.357**	**0.962**

3.4 Model Calibration Plots

The following plots are comparisons of simulated and measured temperatures at tailrace monitoring locations. These plots were reviewed in conjuction with the error statistics to evaluate model performance and identify potential areas of concern in the model setup and/or data inputs.

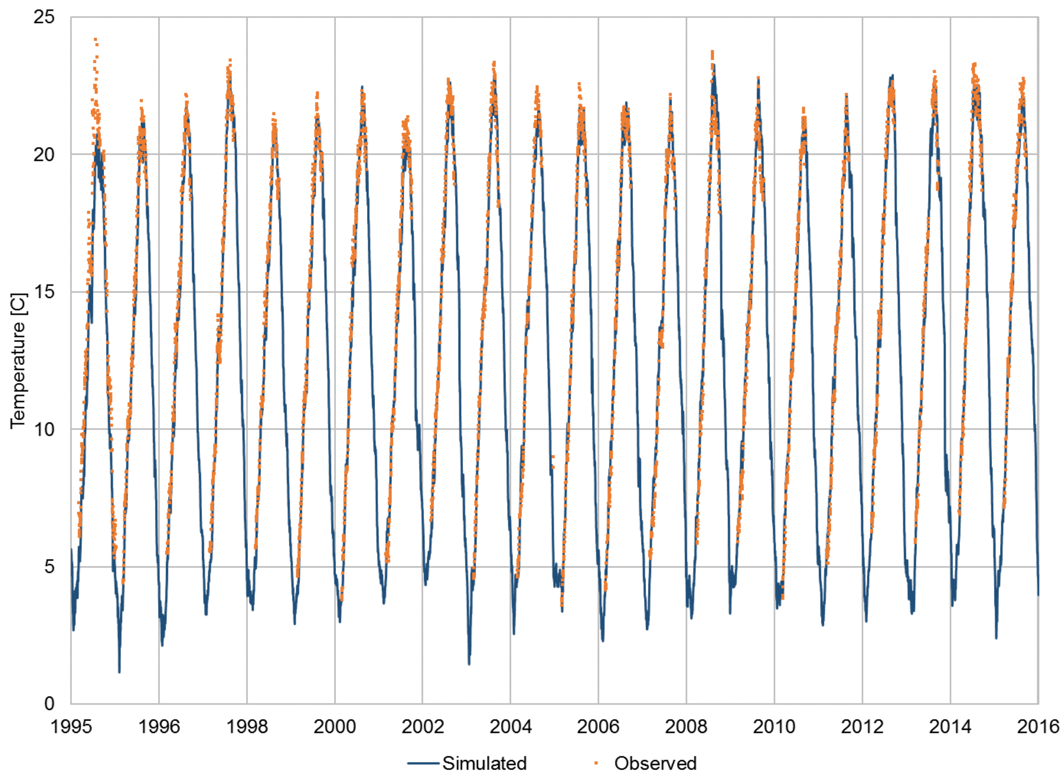

Figure 3-7 Simulated versus observed temperature at CWMW, Columbia River RM 119

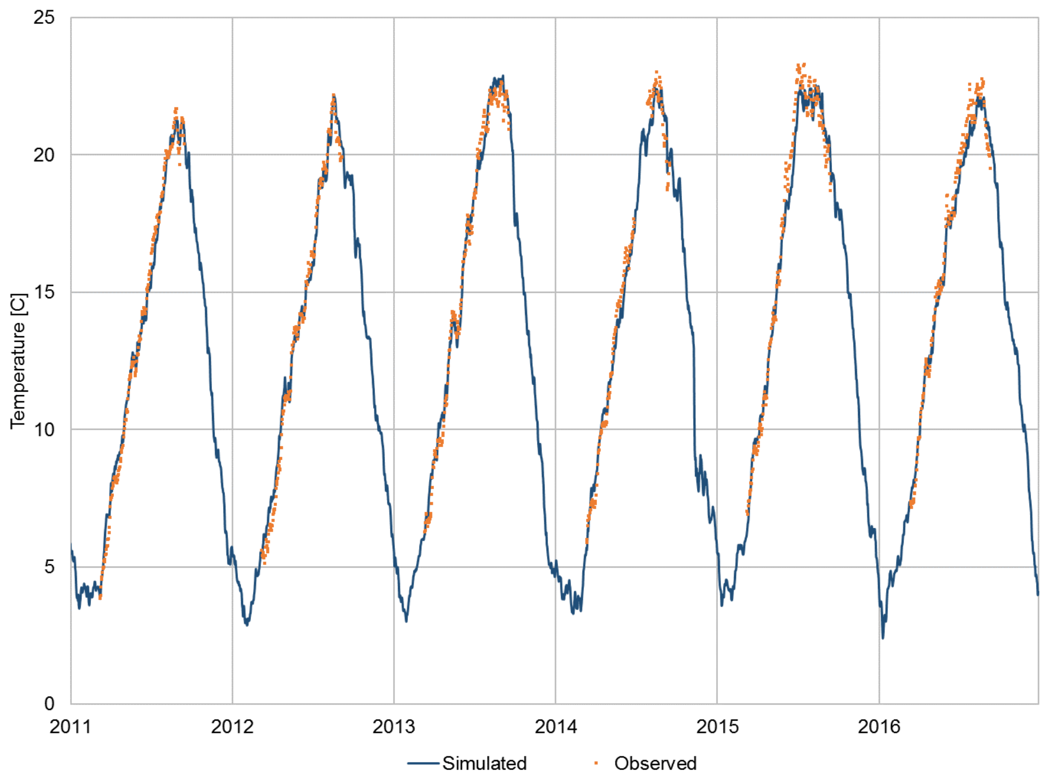

Figure 3-8 Simulated versus observed temperature at CWMW, period 2011 – 2016

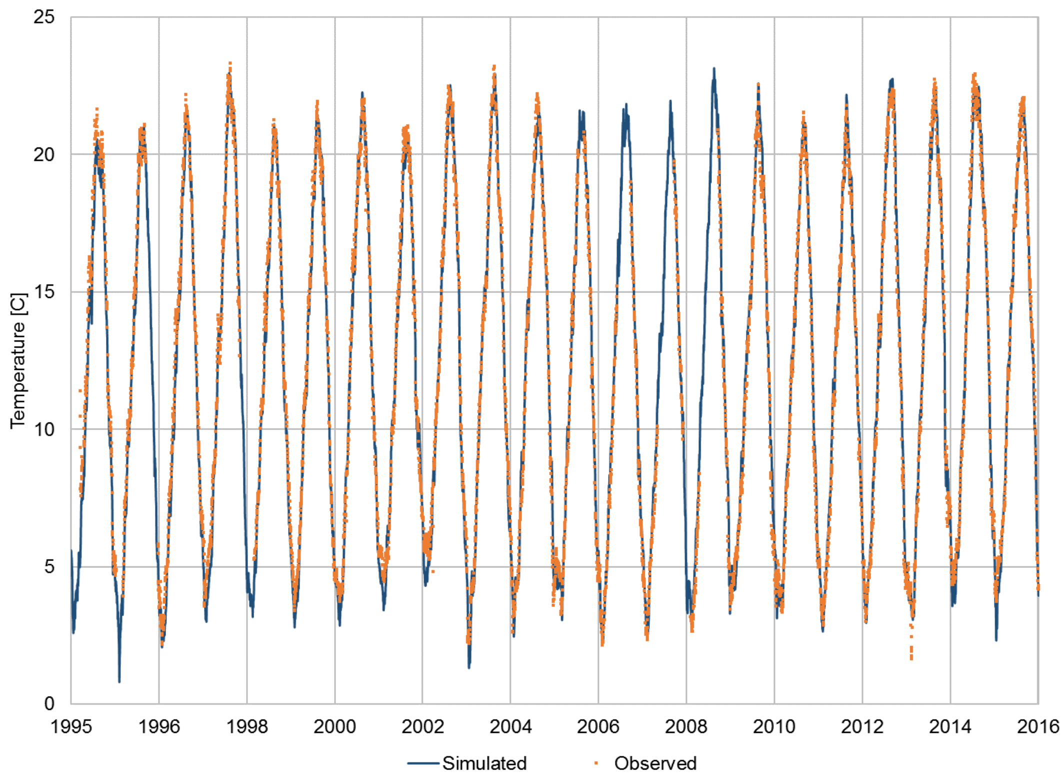

Figure 3-9 Simulated versus observed temperature at WRNO, Columbia River RM 140

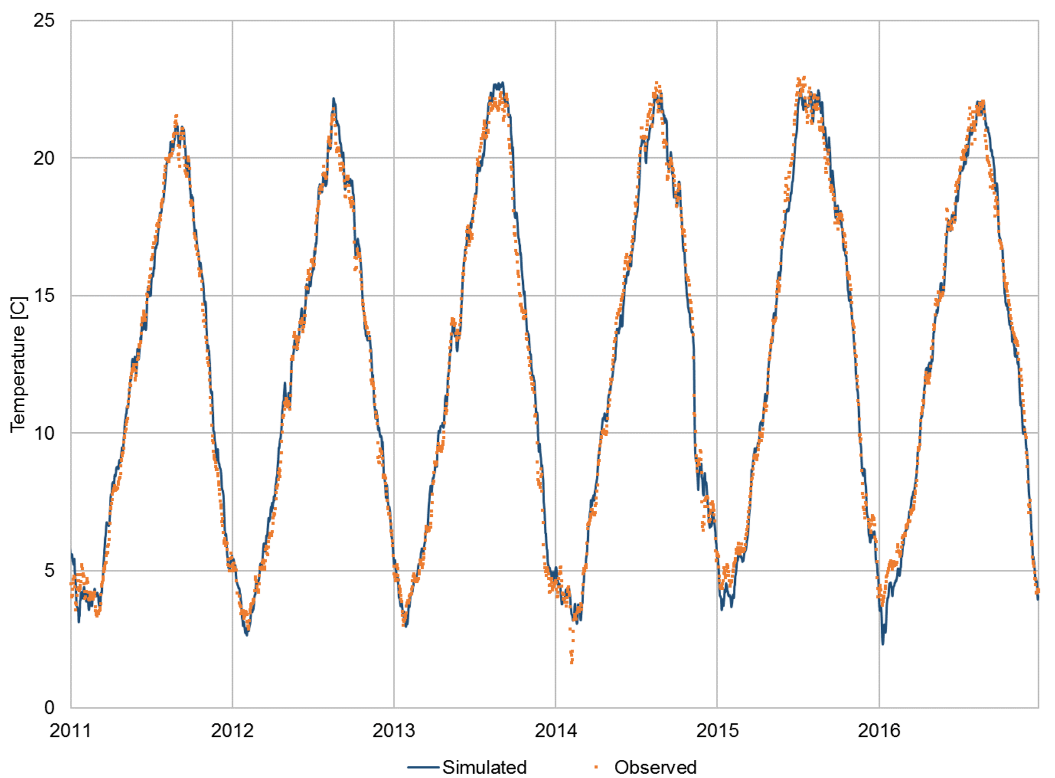

Figure 3-10 Simulated versus observed temperature at WRNO, period 2011 – 2016

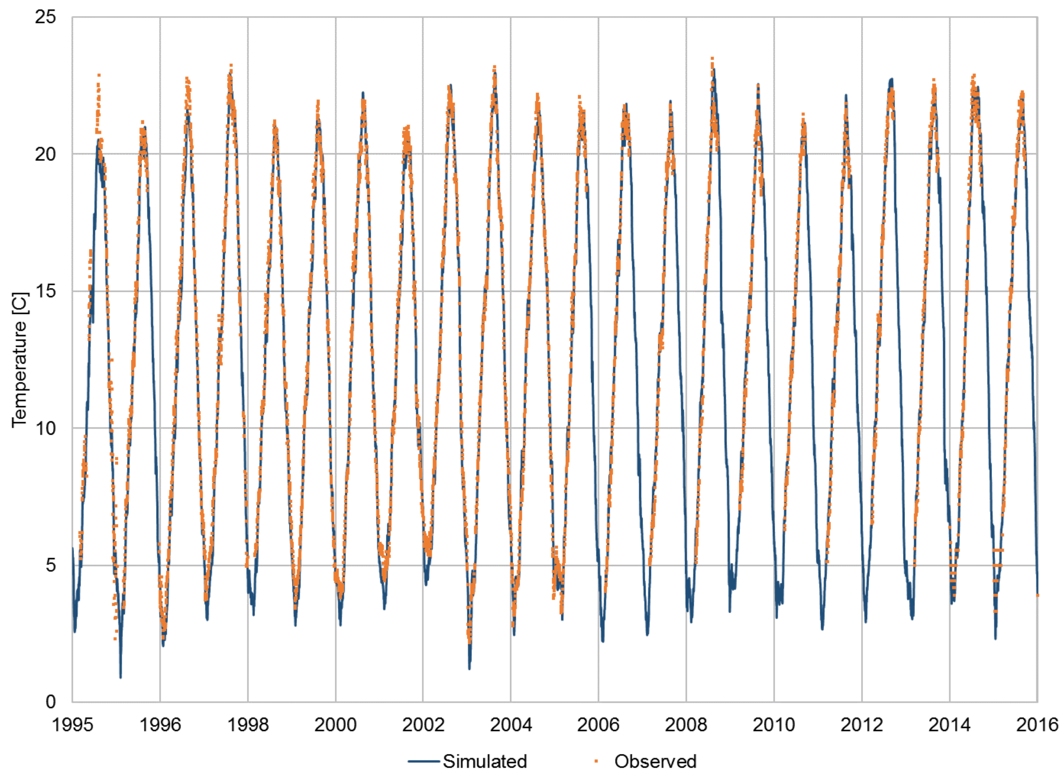

Figure 3-11 Simulated versus observed temperature at BON, Columbia River RM 146

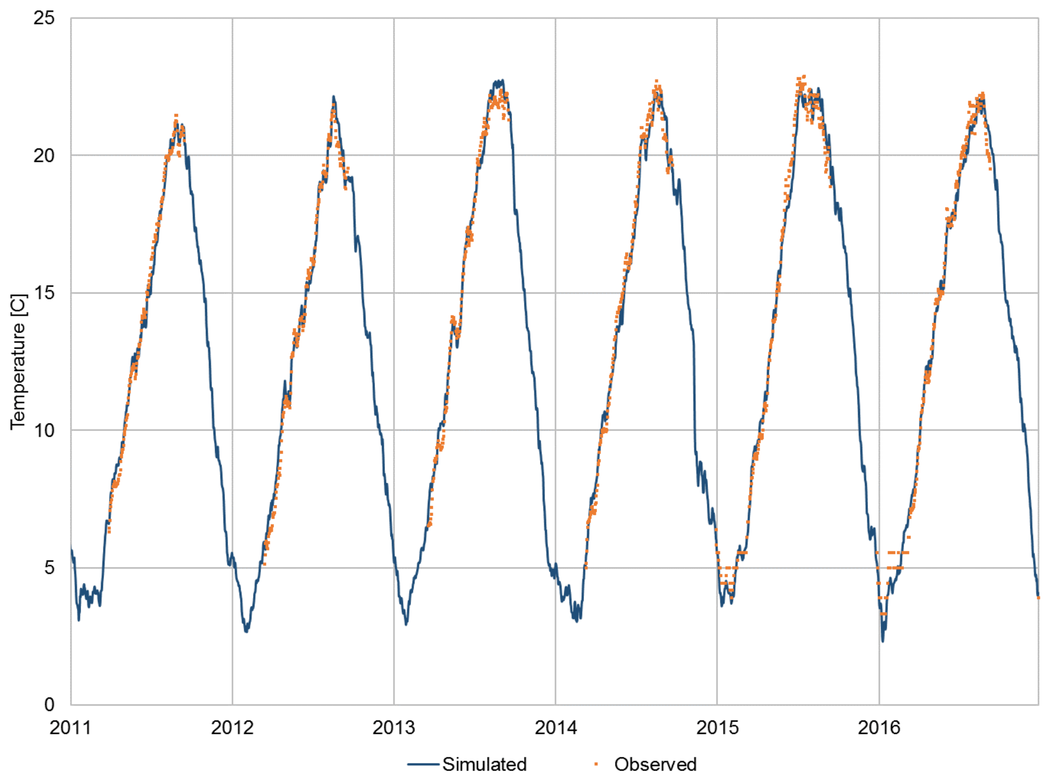

Figure 3-12 Simulated versus observed temperature at BON, period 2011 – 2016

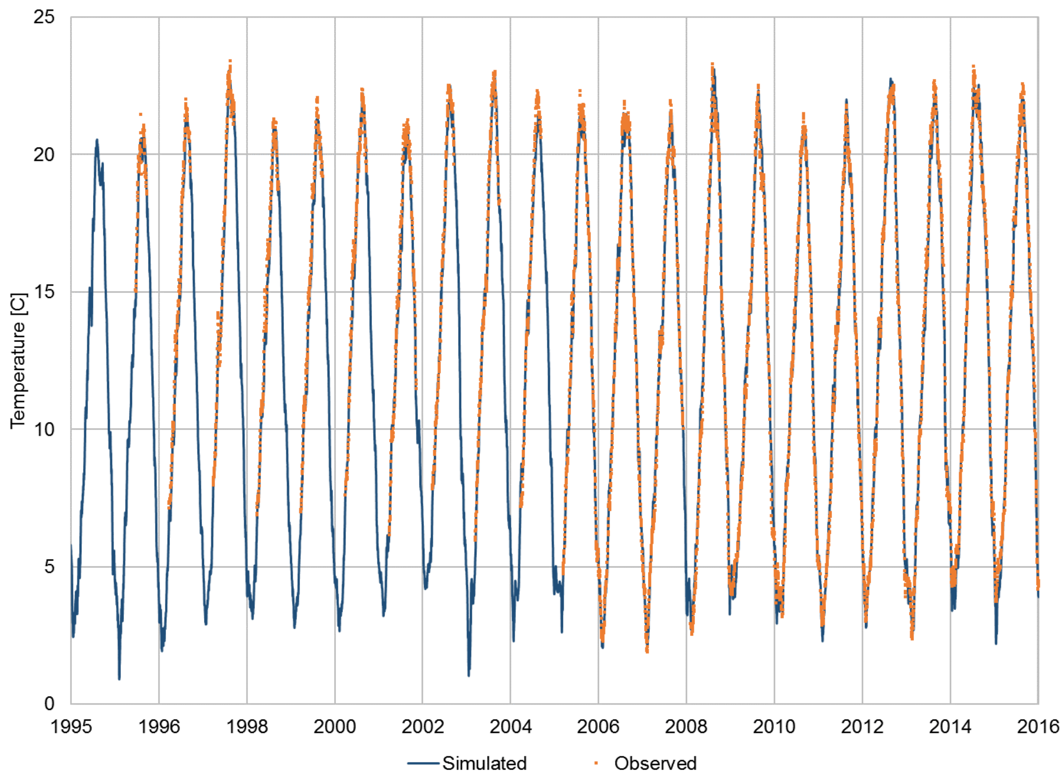

Figure 3-13 Simulated versus observed temperature at TDDO, Columbia River RM 190

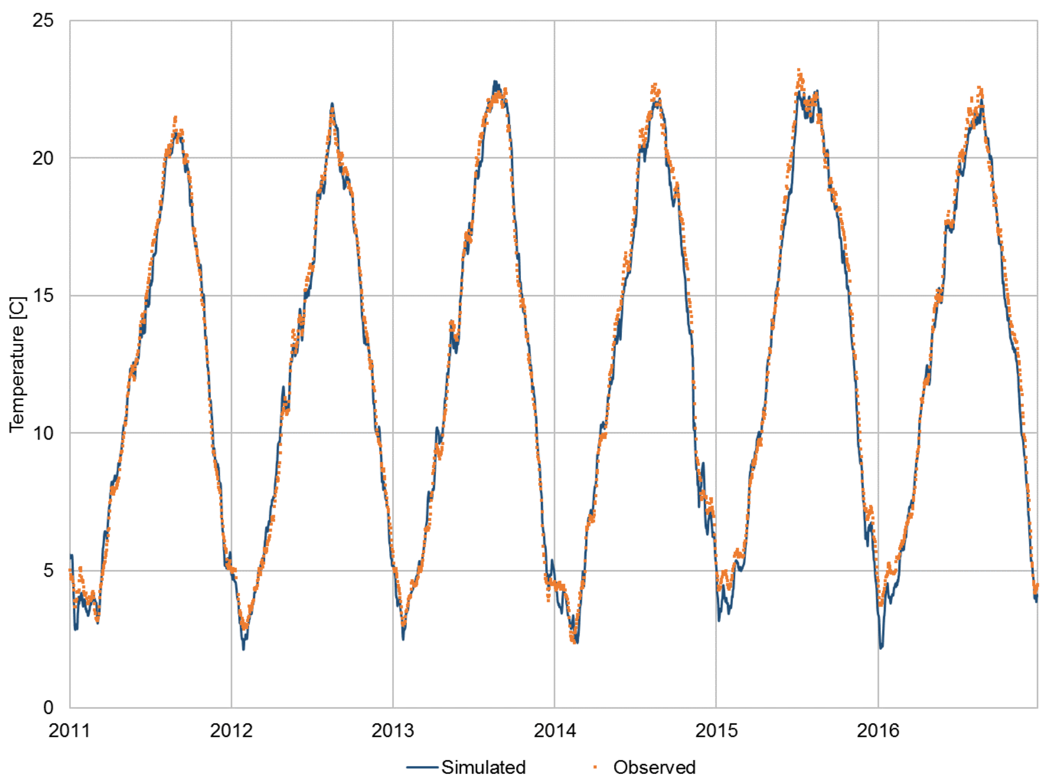

Figure 3-14 Simulated versus observed temperature at TDDO, period 2011 – 2016

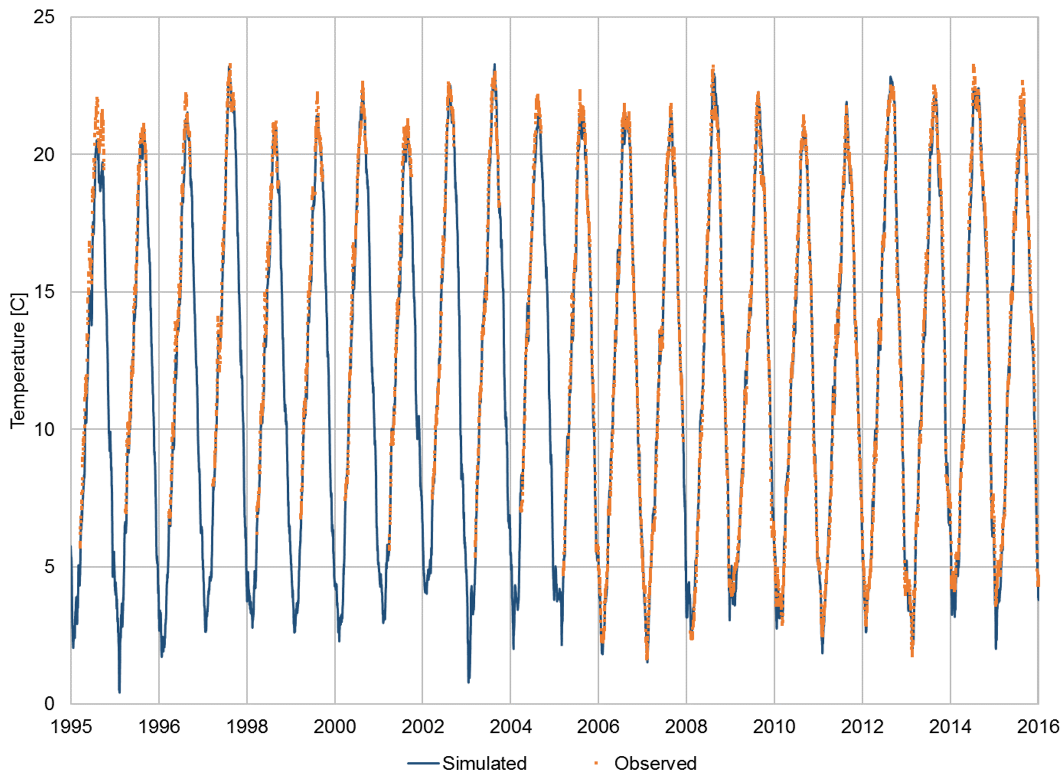

Figure 3-15 Simulated versus observed temperature at JHAW, Columbia River RM 215

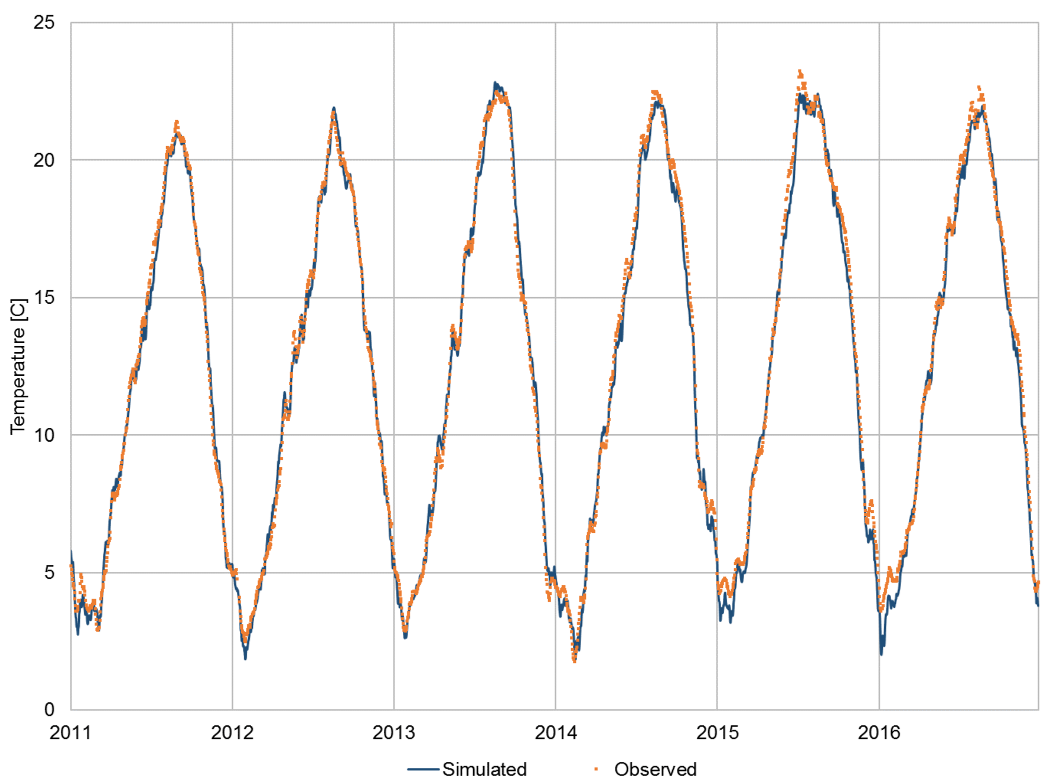

Figure 3-16 Simulated versus observed temperature at JHAW, period 2011 – 2016

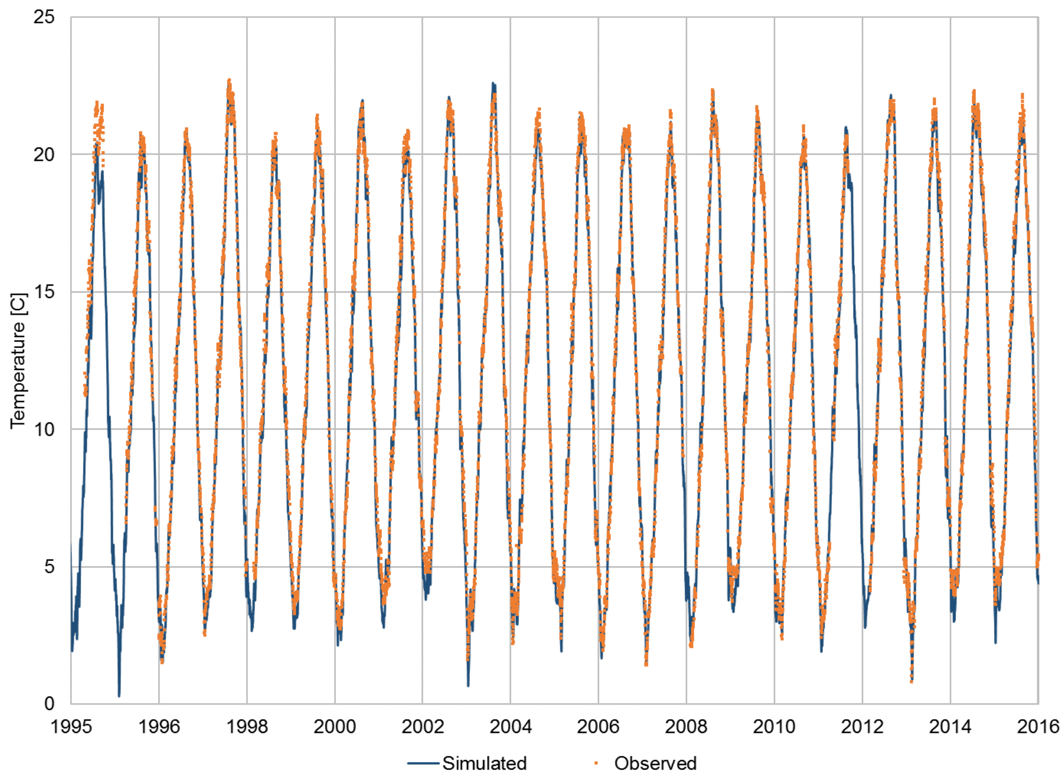

Figure 3-17 Simulated versus observed temperature at MCPW, Columbia River RM 291

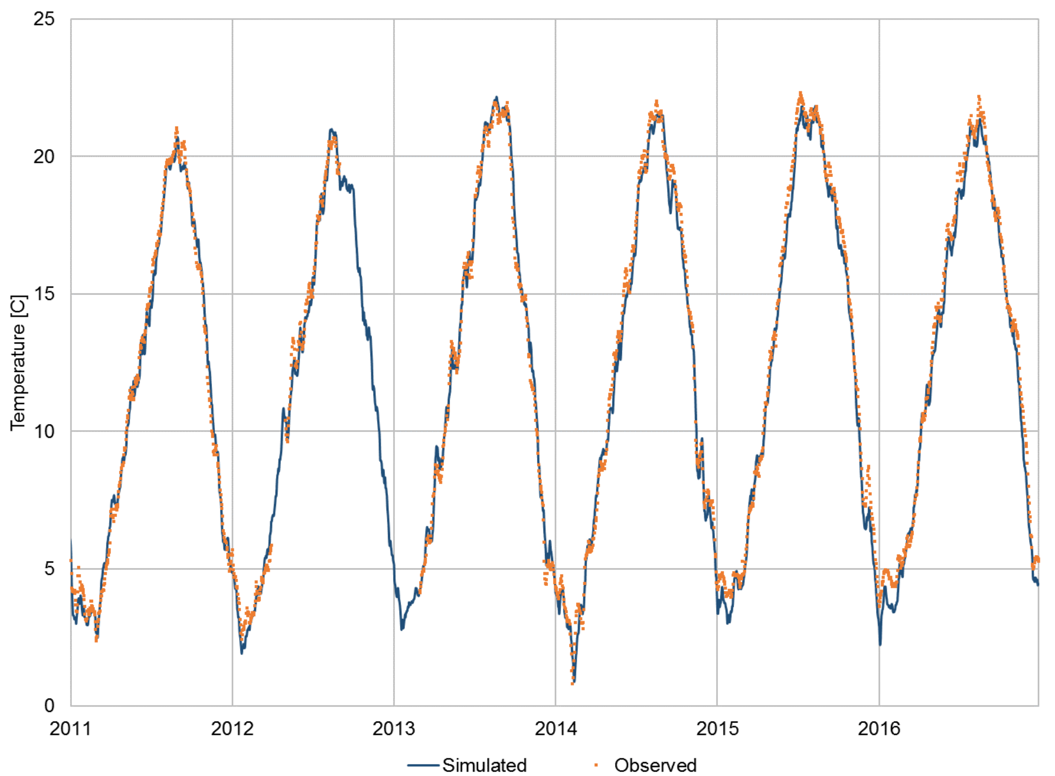

Figure 3-18 Simulated versus observed temperature at MCPW, period 2011 – 2016

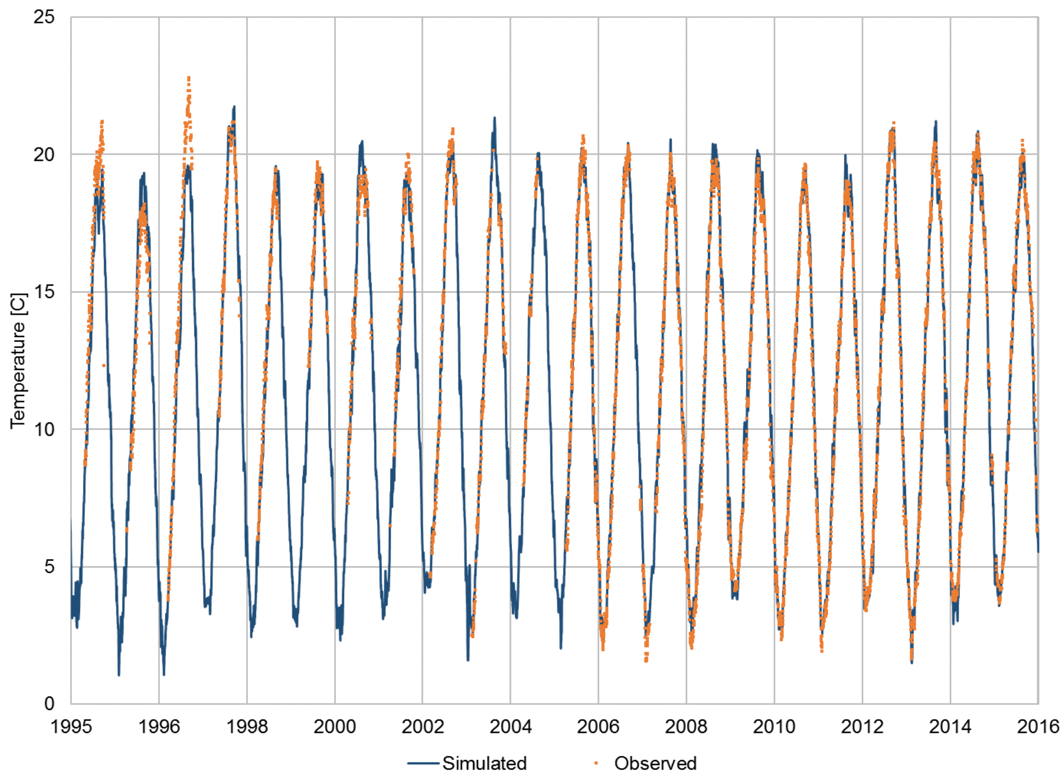

Figure 3-19 Simulated versus observed temperature at PRXW, Columbia River RM 396

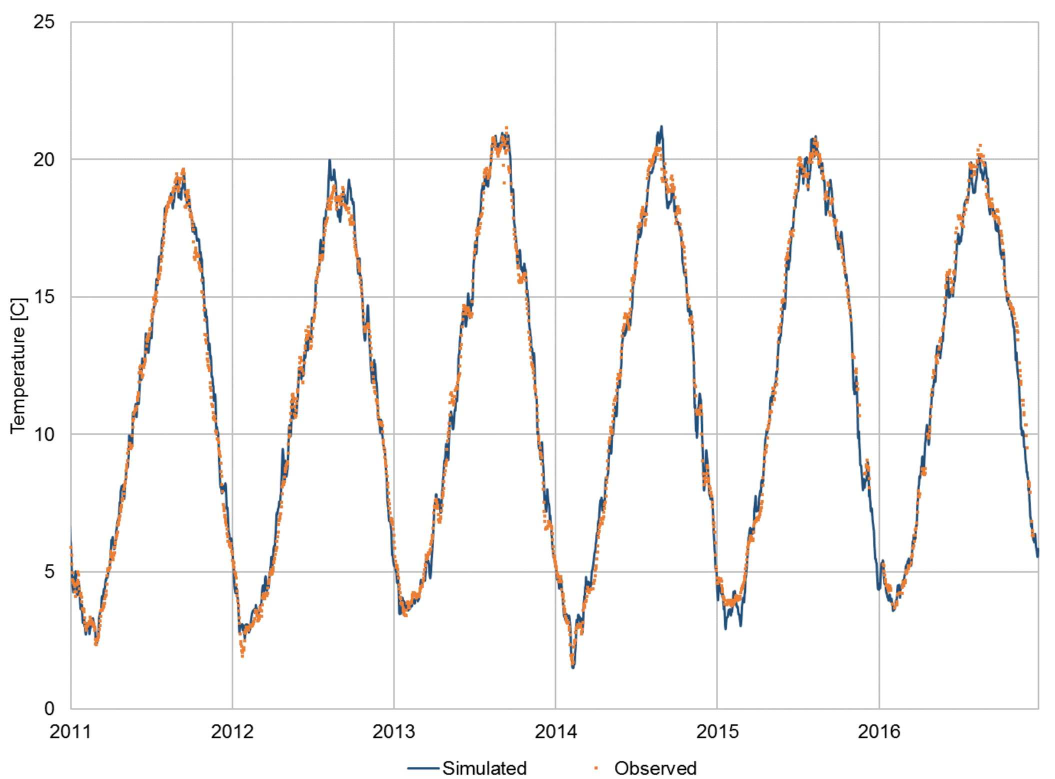

Figure 3-20 Simulated versus observed temperature at PRXW, period 2011 – 2016

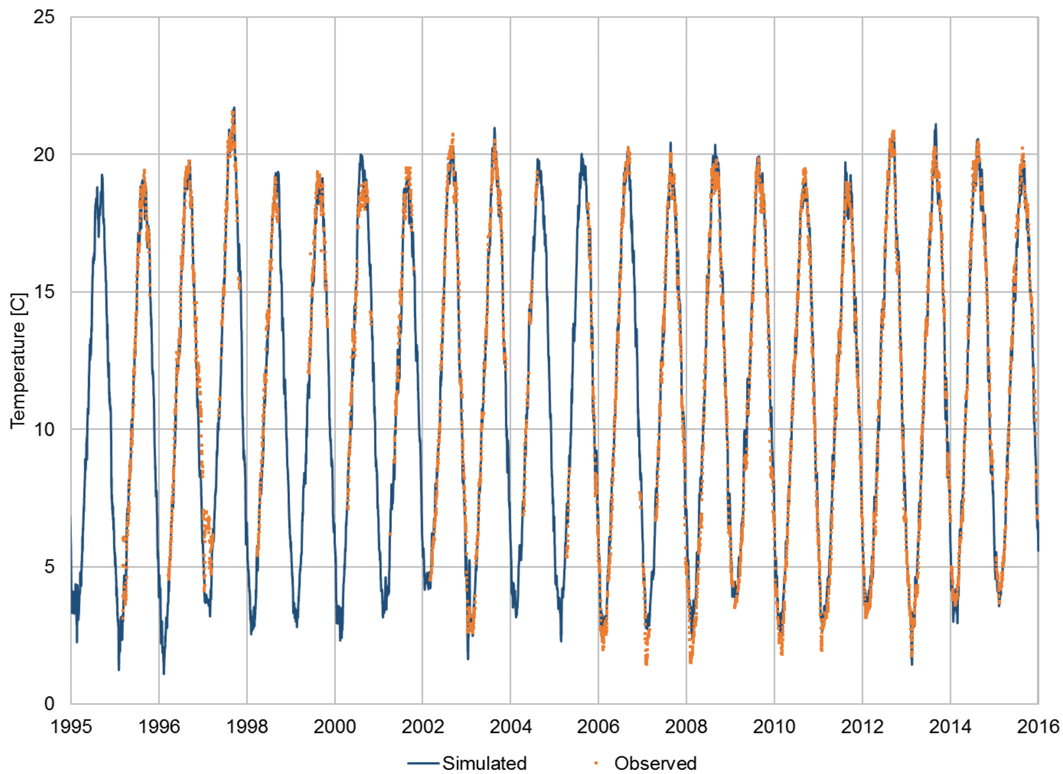

Figure 3-21 Simulated versus observed temperature at WANW, Columbia River RM 415

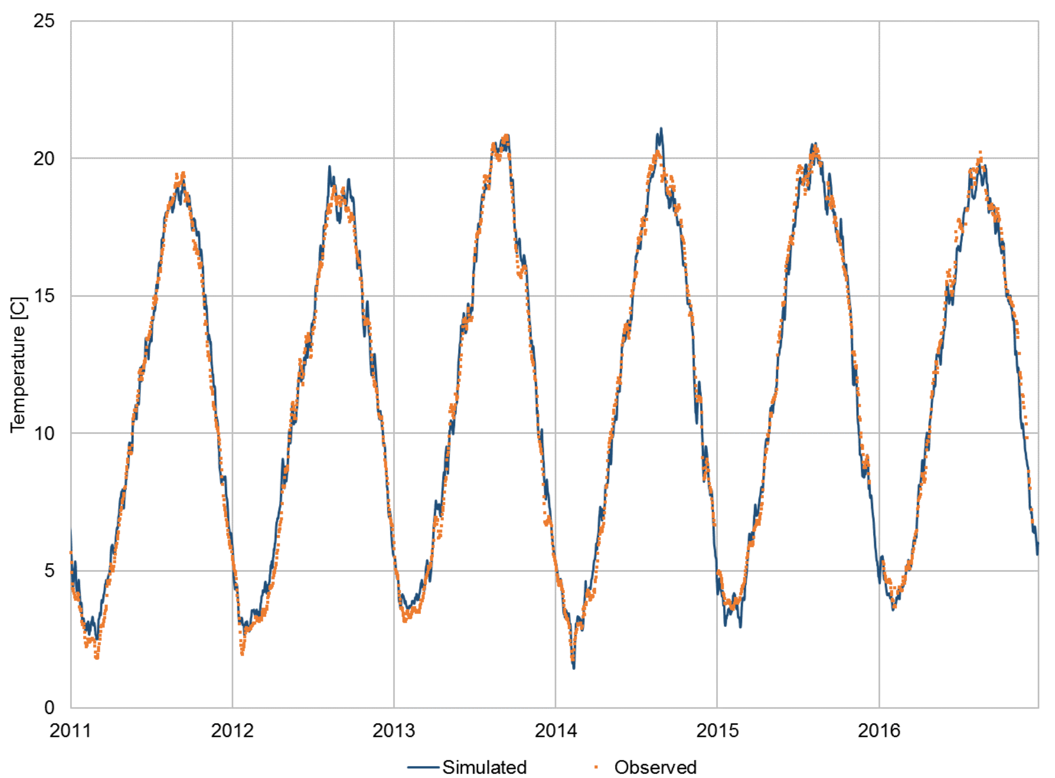

Figure 3-22 Simulated versus observed temperature at WANW, period 2011 – 2016

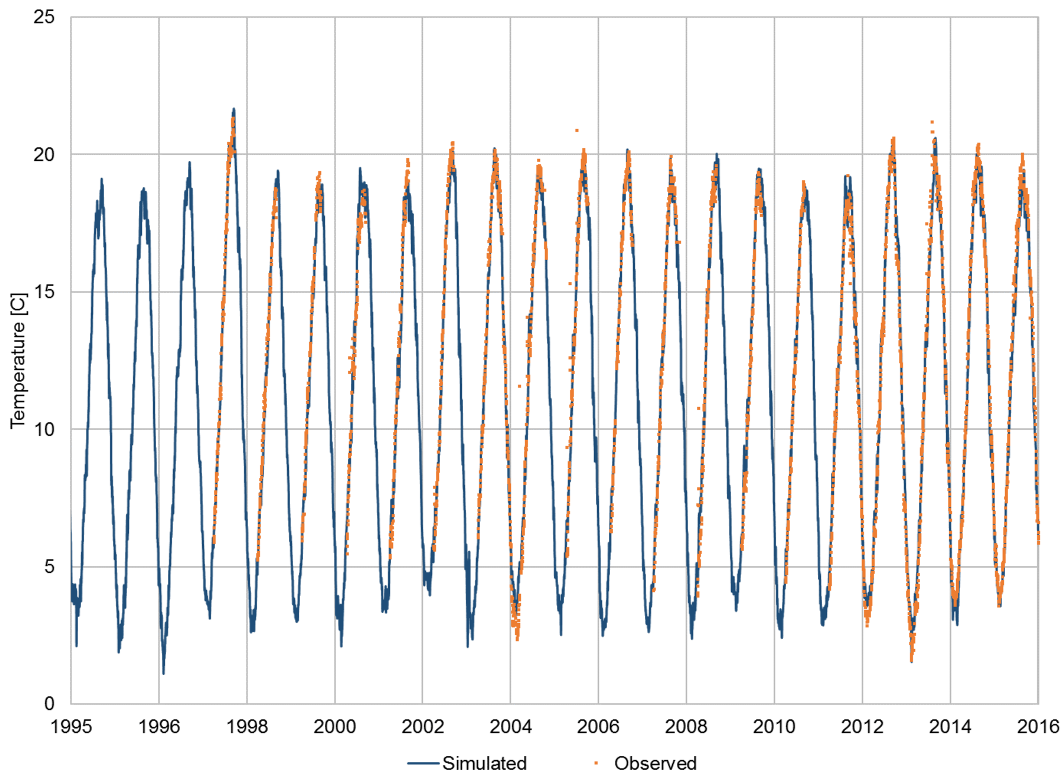

Figure 3-23 Simulated versus observed temperature at RIGW, Columbia River RM 452

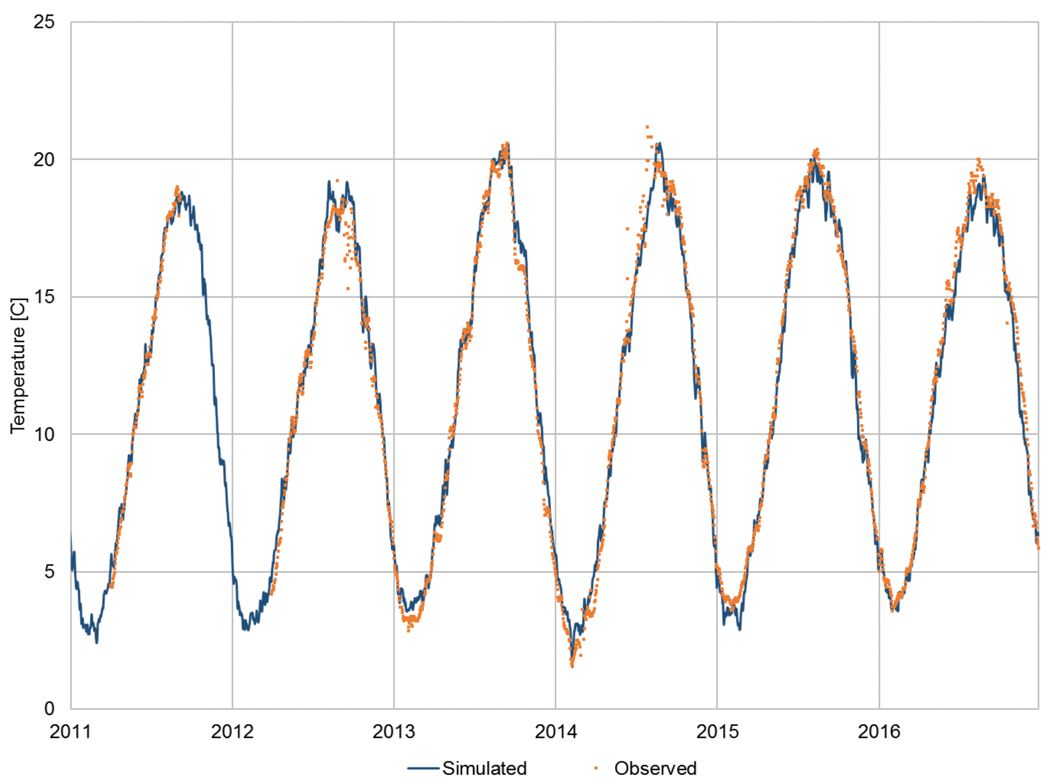

Figure 3-24 Simulated versus observed temperature at RIGW, period 2011 – 2016

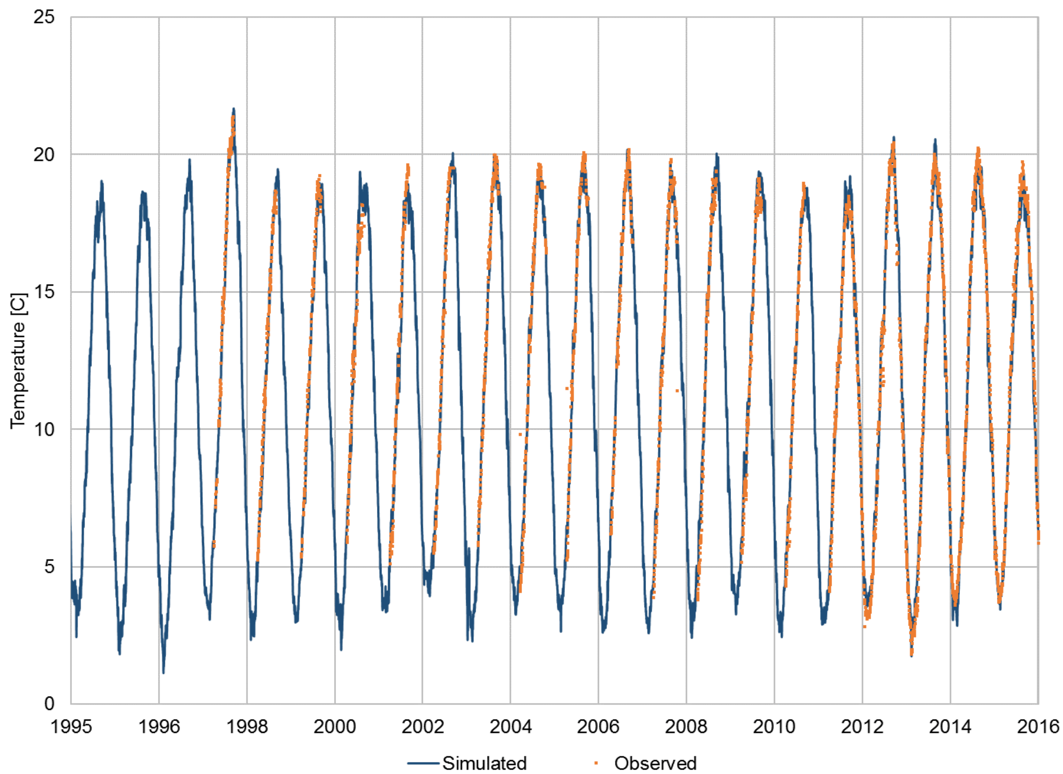

Figure 3-25 Simulated versus observed temperature at RRDW, Columbia River RM 472

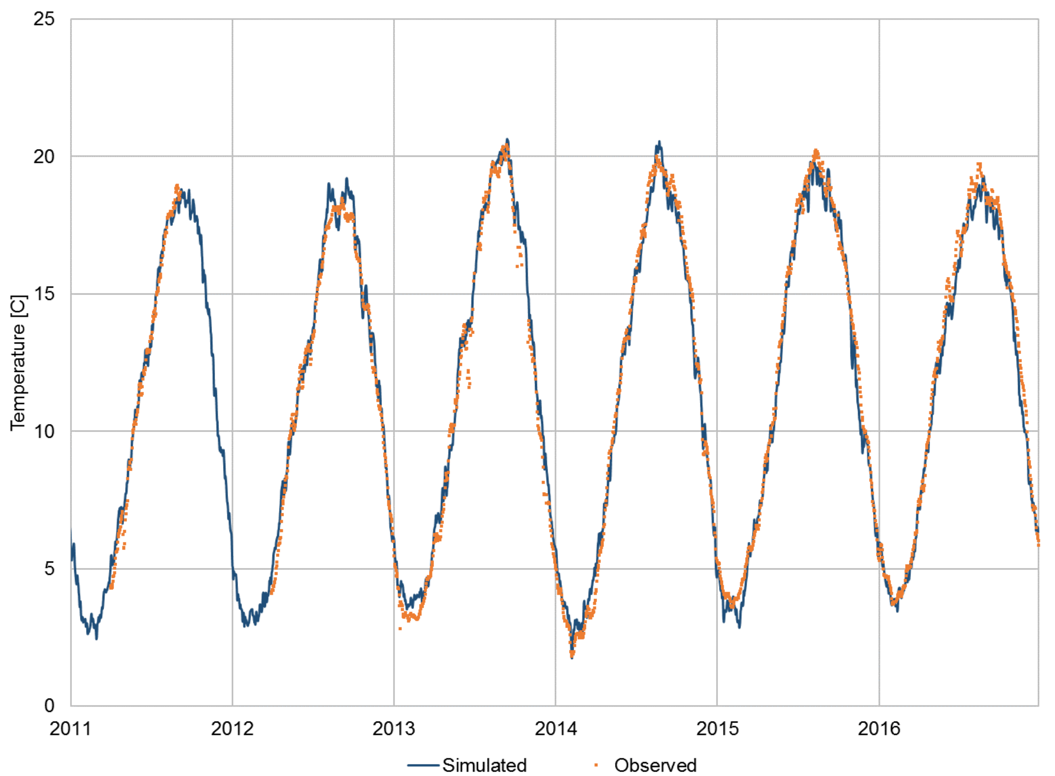

Figure 3-26 Simulated versus observed temperature at RRDW, period 2011 – 2016

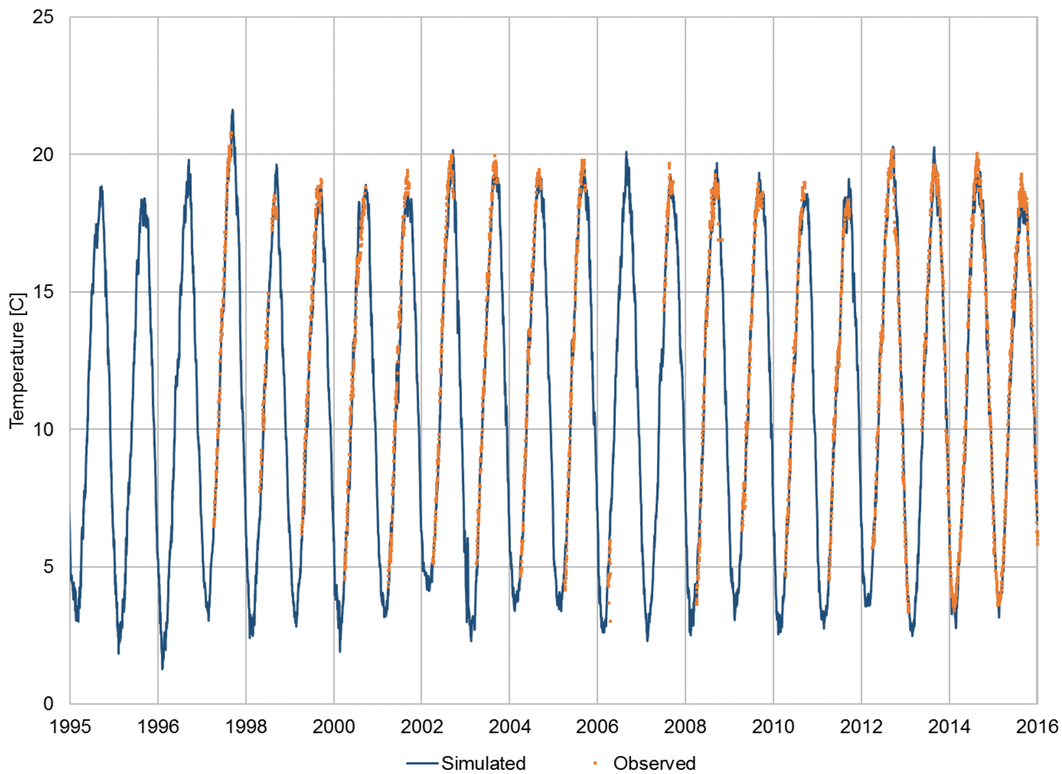

Figure 3-27 Simulated versus observed temperature at WELW, Columbia River RM 514

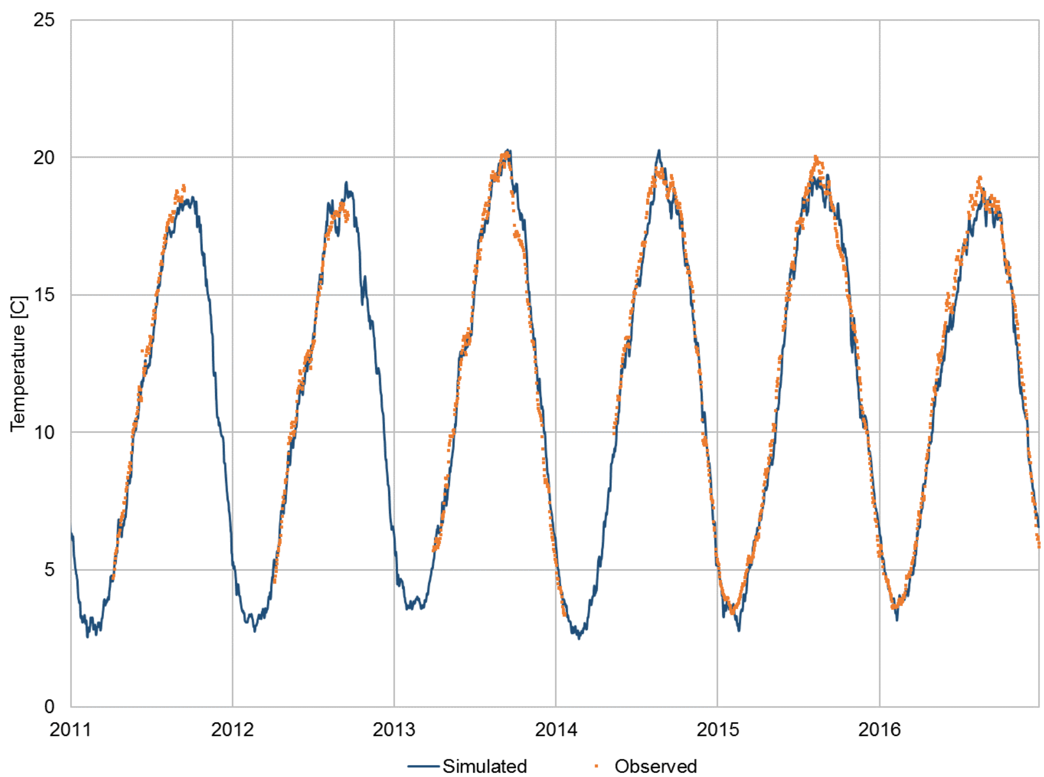

Figure 3-28 Simulated versus observed temperature at WELW, period 2011 – 2016

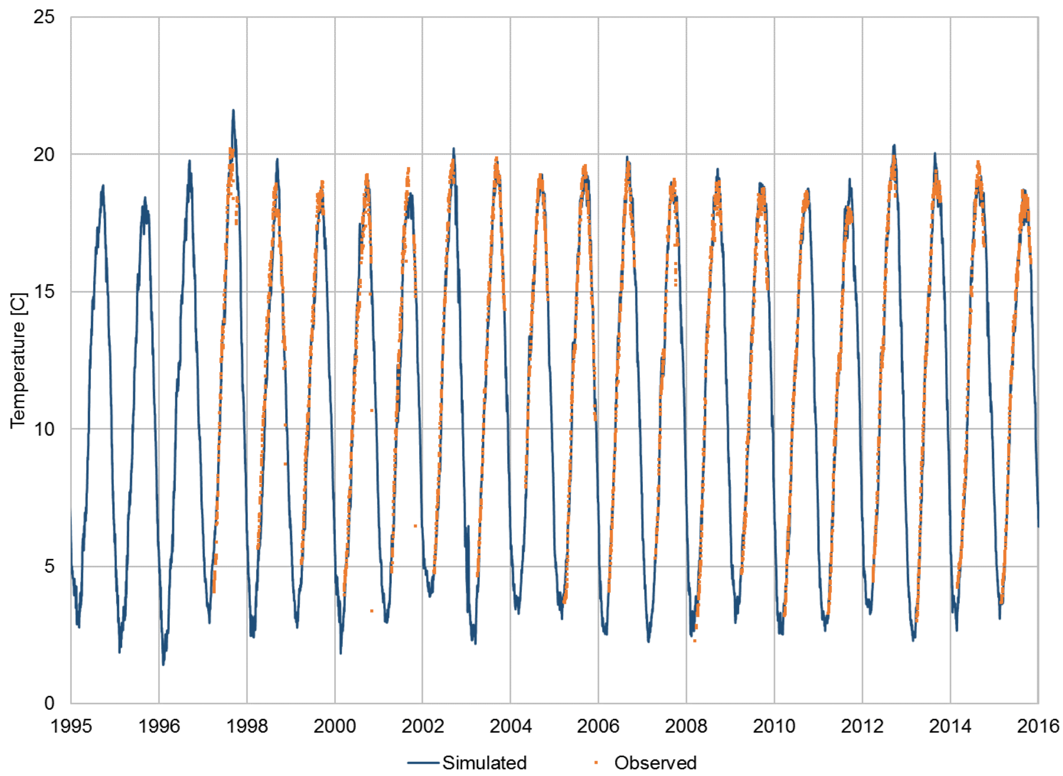

Figure 3-29 Simulated versus observed temperature at CHQW, Columbia River RM 545

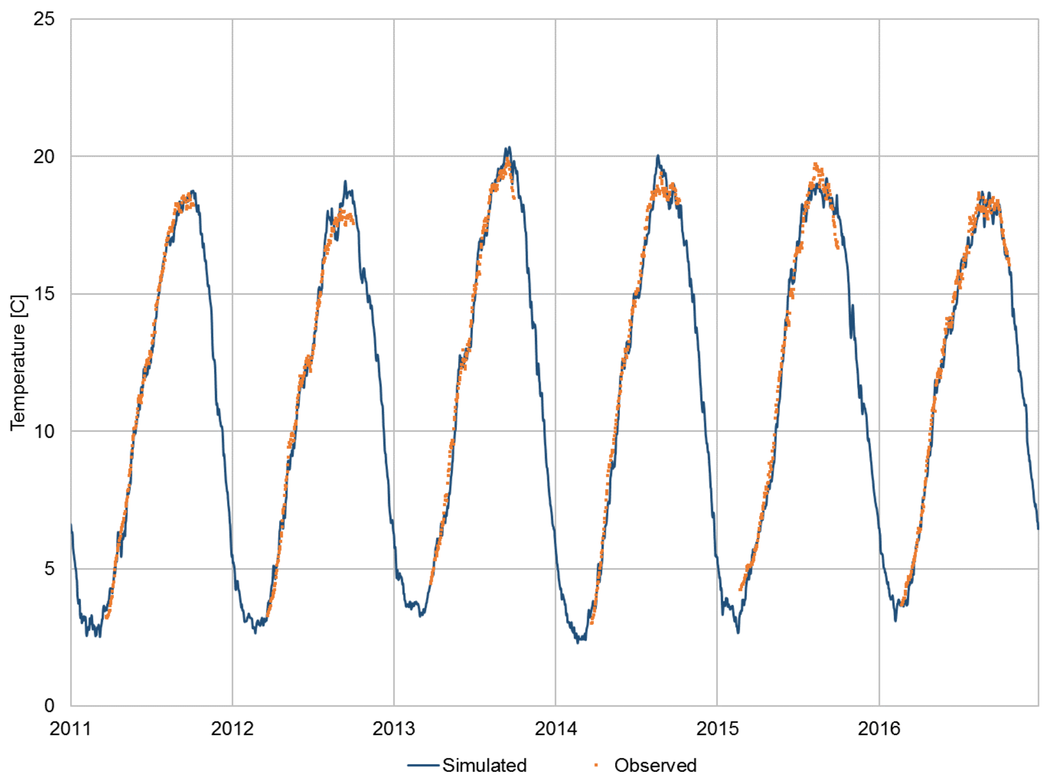

Figure 3-30 Simulated versus observed temperature at CHQW, period 2011 – 2016

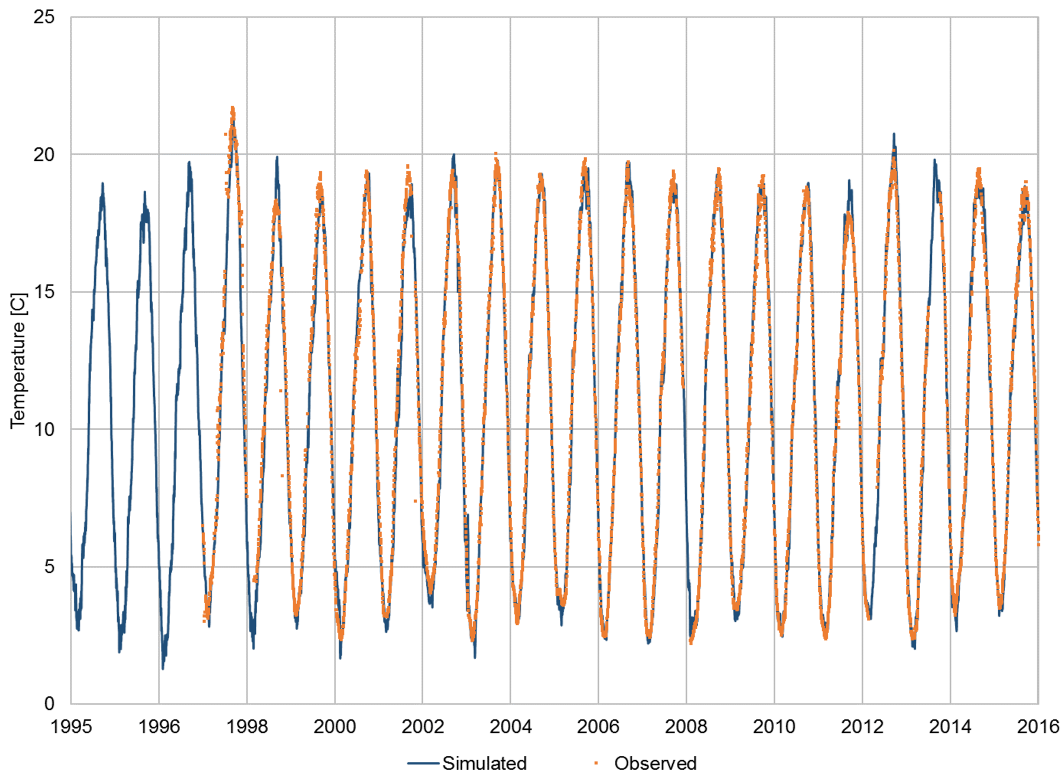

Figure 3-31 Simulated versus observed temperature at GCGW, Columbia River RM 590

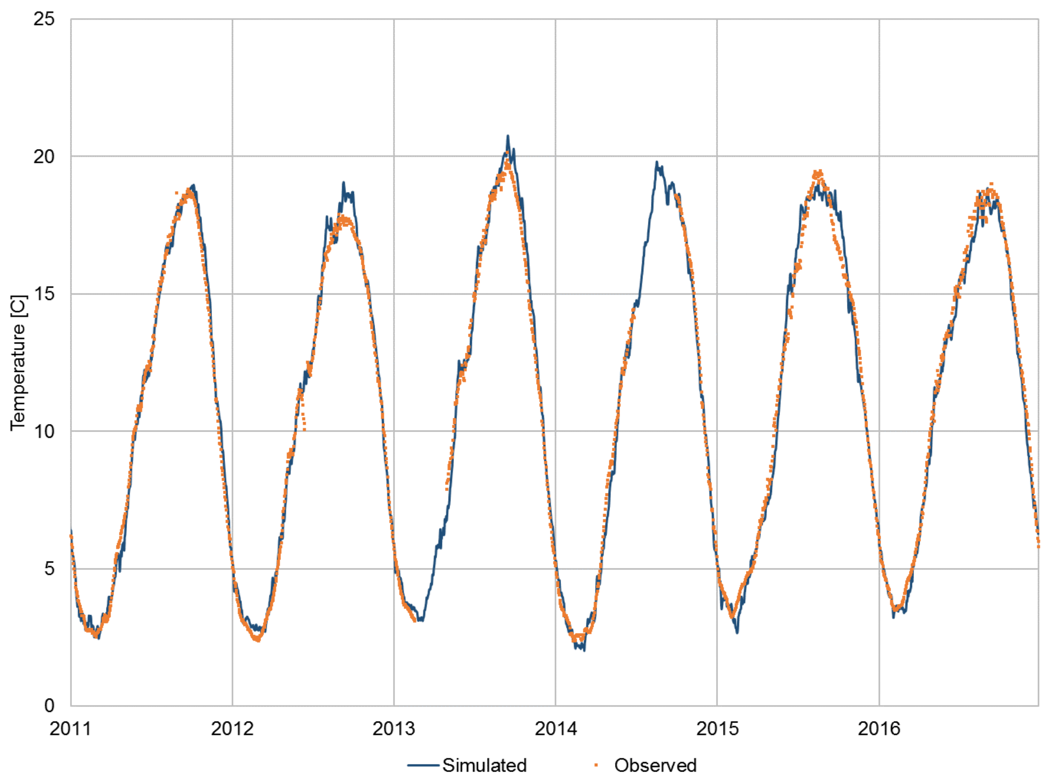

Figure 3-32 Simulated versus observed temperature at GCGW, period 2011 – 2016

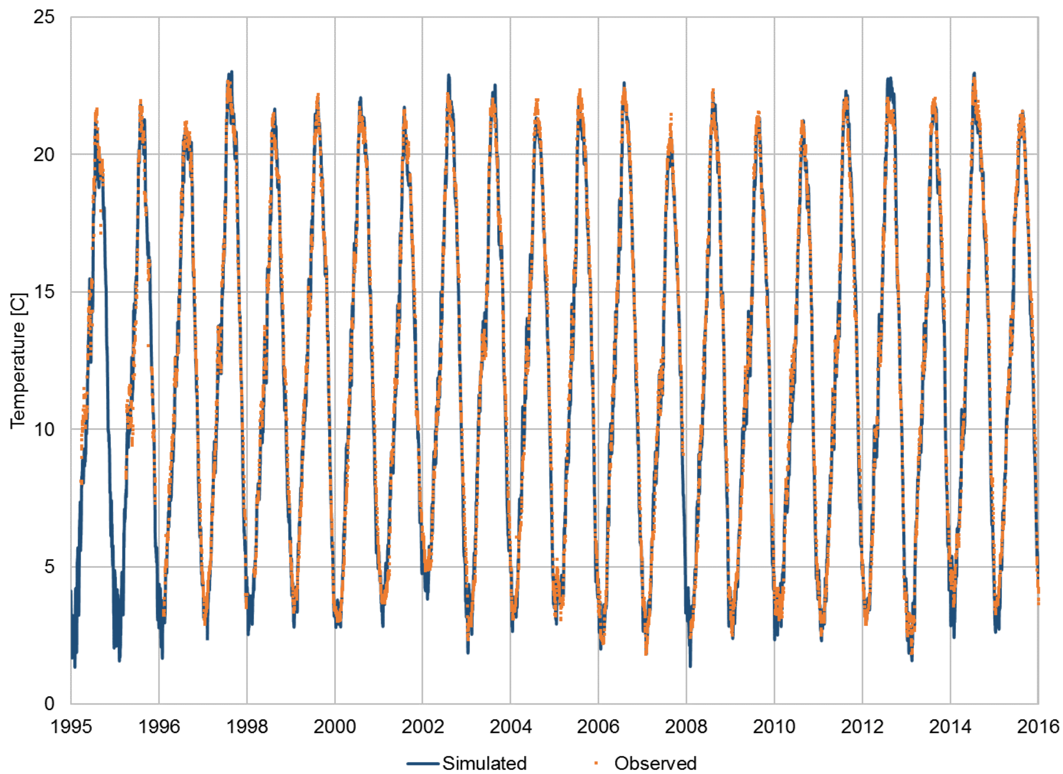

Figure 3-33 Simulated versus observed temperature at IDSW, Snake River RM 6.8

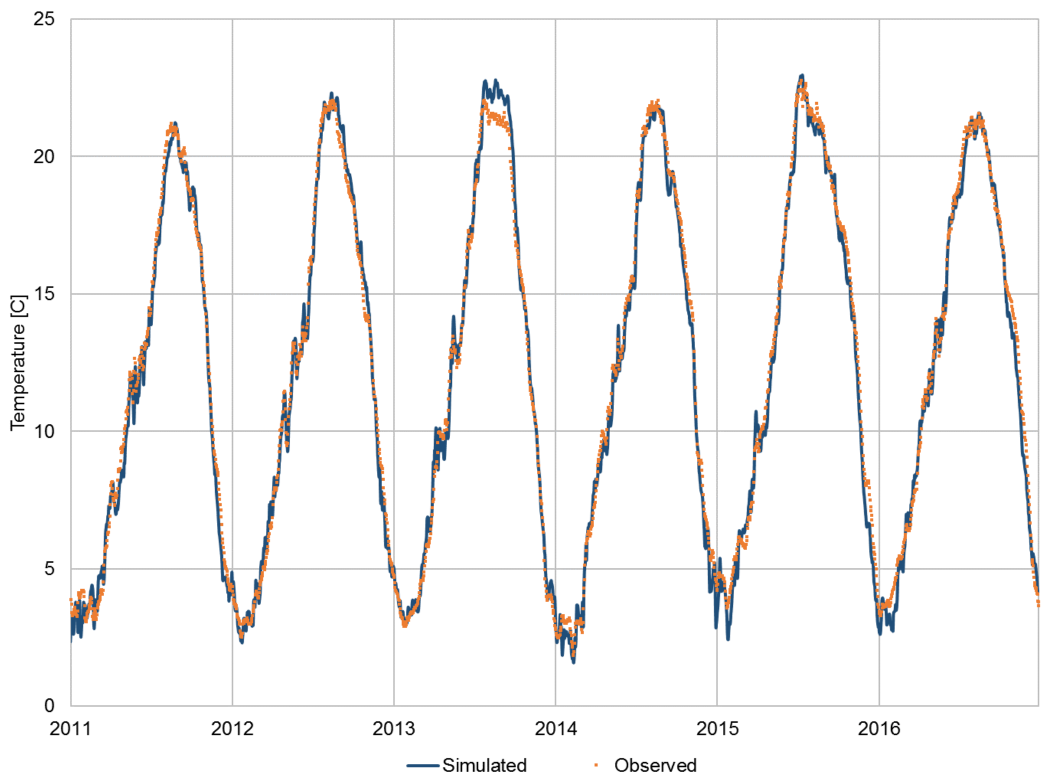

Figure 3-34 Simulated versus observed temperature at IDSW, period 2011 – 2016

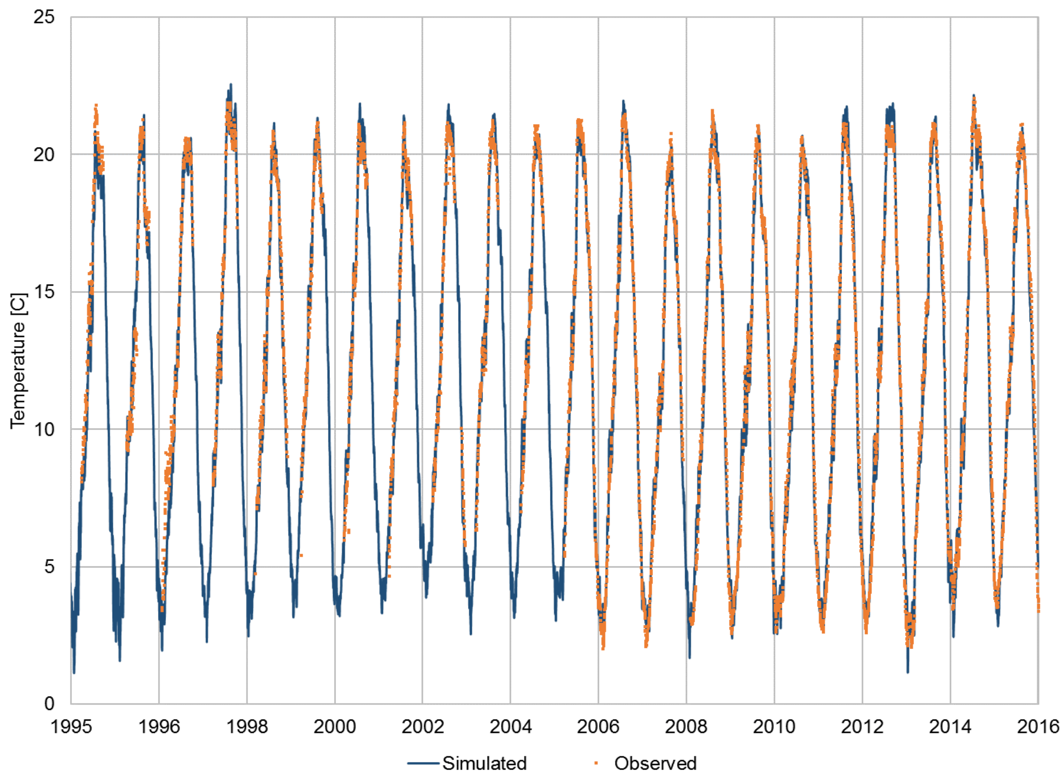

Figure 3-35 Simulated versus observed temperature at LMNW, Snake River RM 40.8

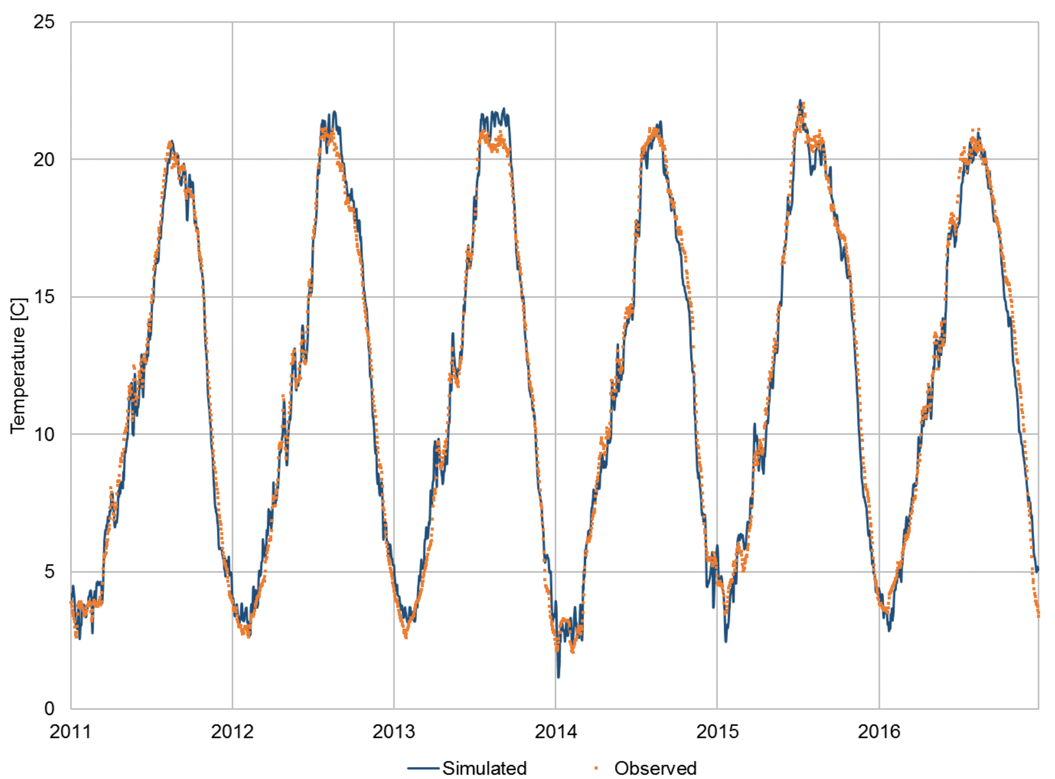

Figure 3-36 Simulated versus observed temperature at LMNW, period 2011 – 2016

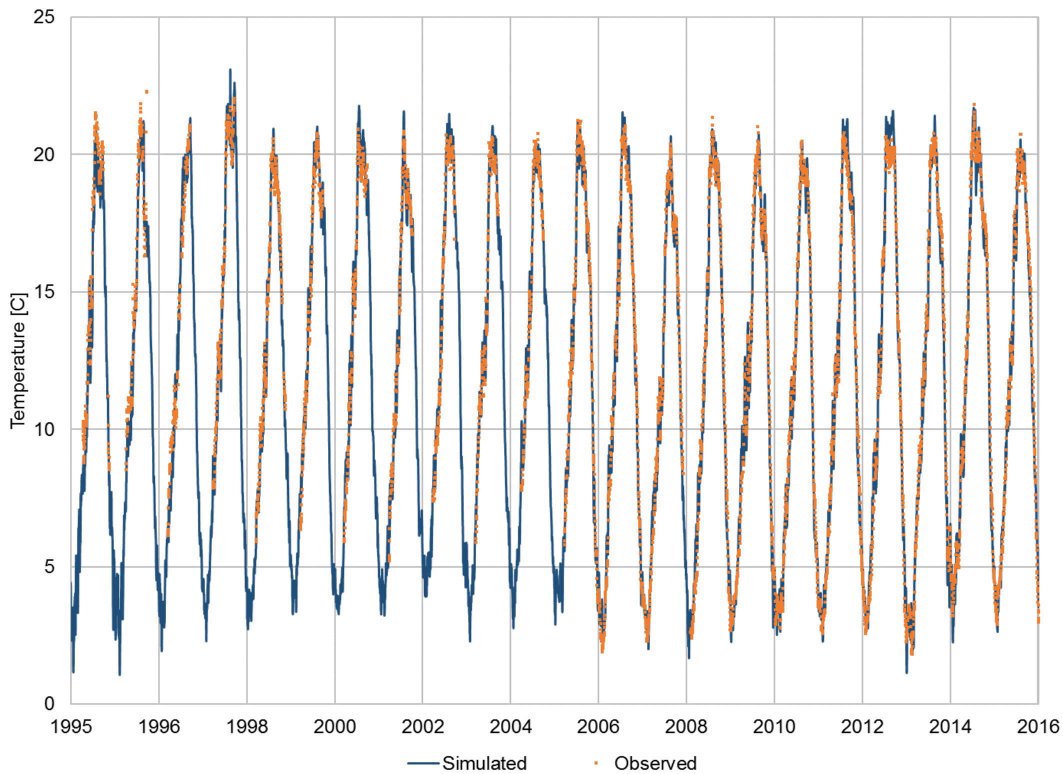

Figure 3-37 Simulated versus observed temperature at LGSW, Snake River RM 69.5

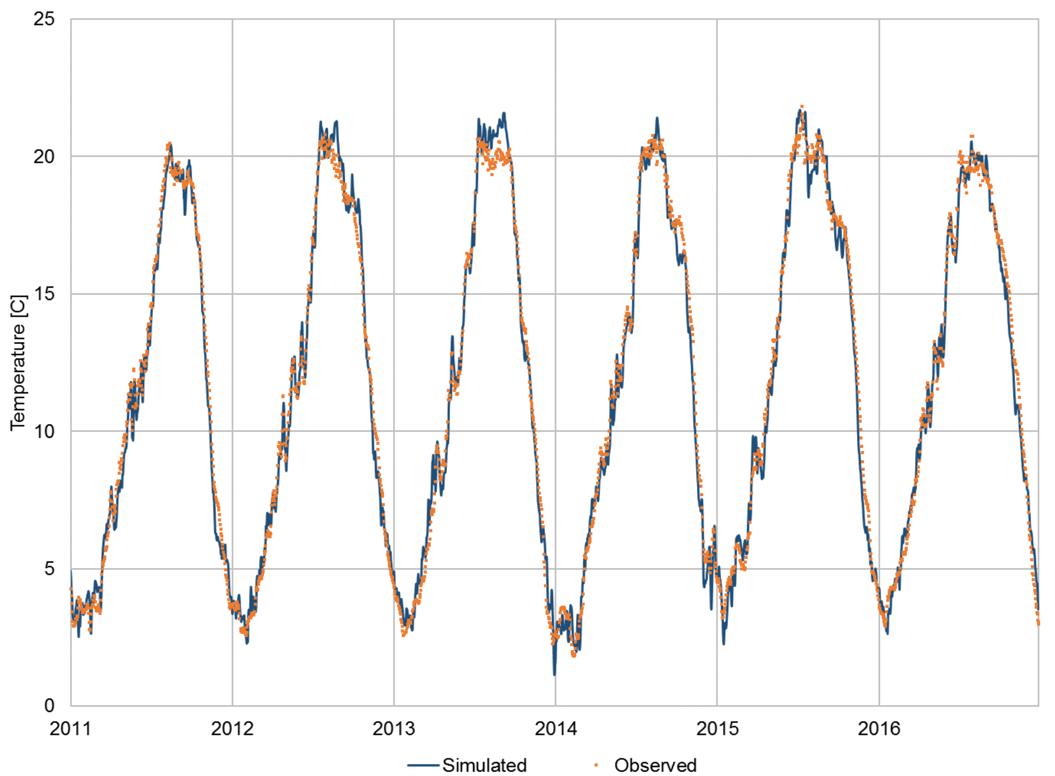

Figure 3-38 Simulated versus observed temperature at LGSW, period 2011 – 2016

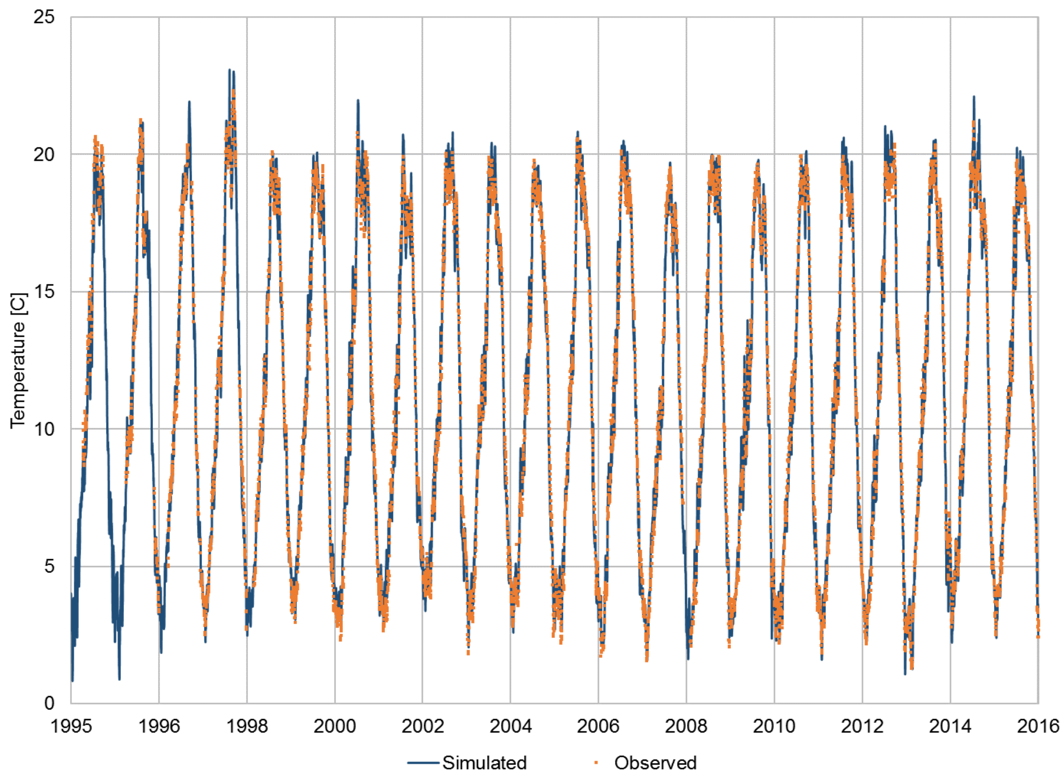

Figure 3-39 Simulated versus observed temperature at LGNW, Snake River RM 106.8

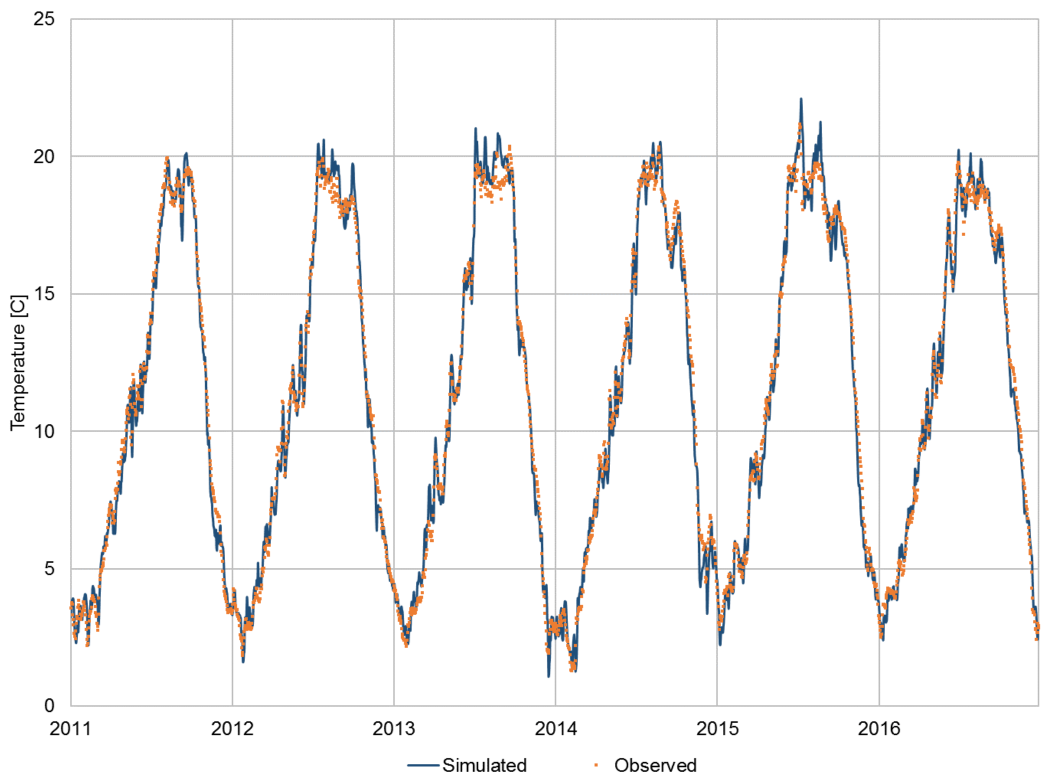

Figure 3-40 Simulated versus observed temperature at LGNW, period 2011 – 2016

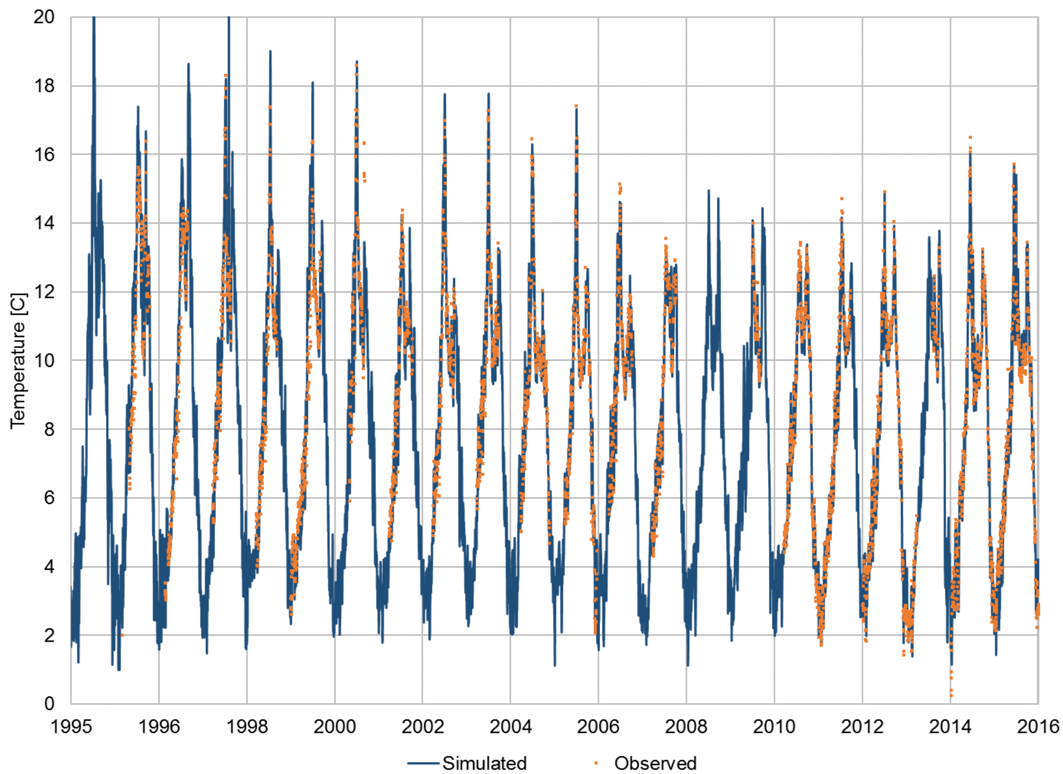

Figure 3-41 Simulated versus observed temperature at PEKI, Clearwater River RM 33

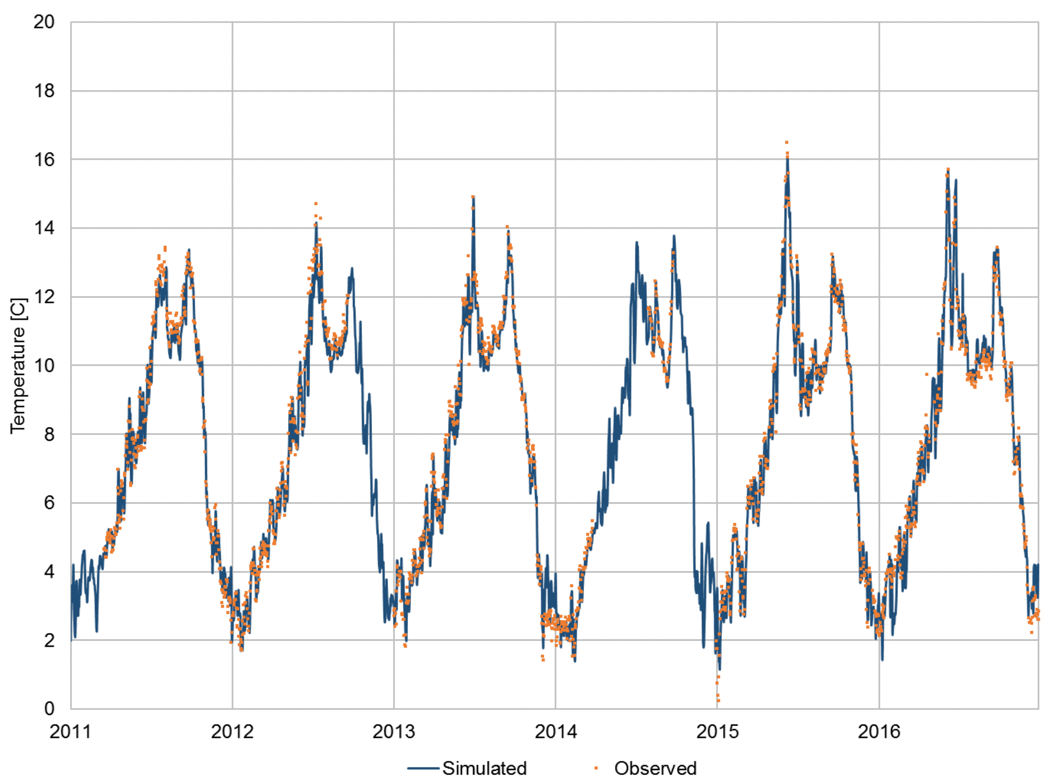

Figure 3-42 Simulated versus observed temperature at PEKI, period 2011 – 2016

3.5 10-Year Daily Average Temperature Comparisons

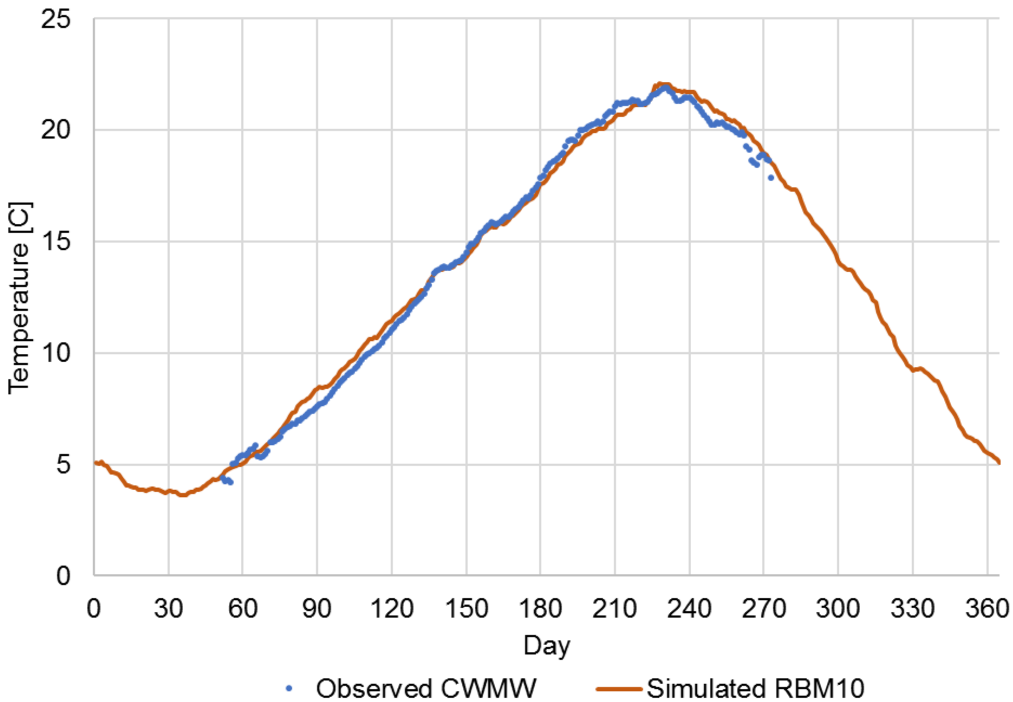

Figure 3-43 10-year daily average temperature comparison at CWMW

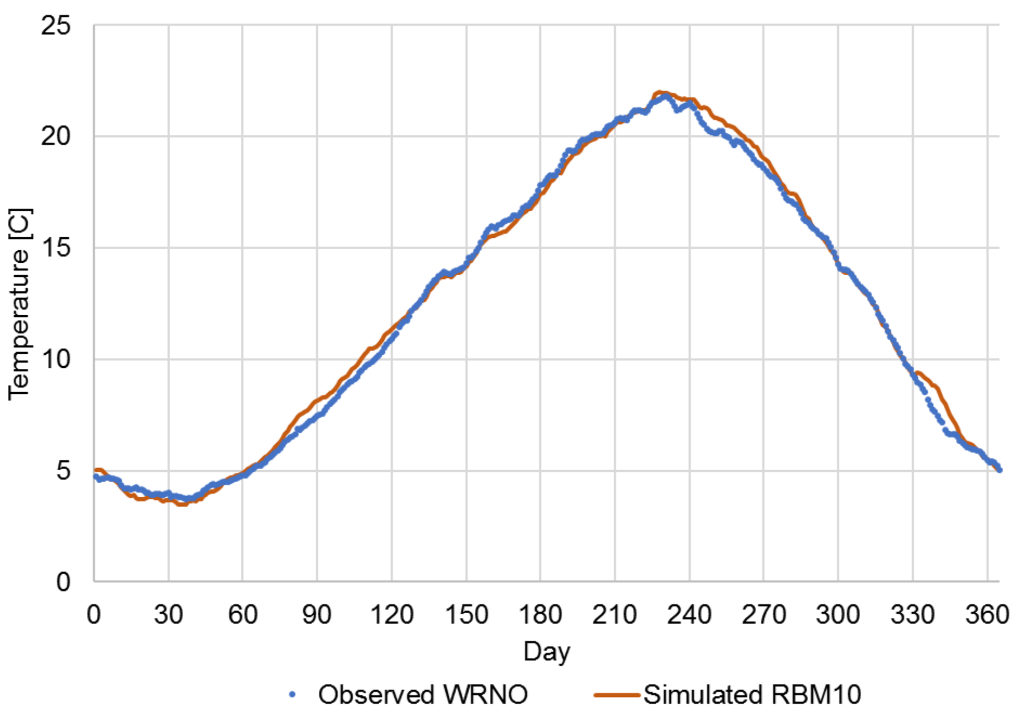

Figure 3-44 10-year daily average temperature comparison at WRNO

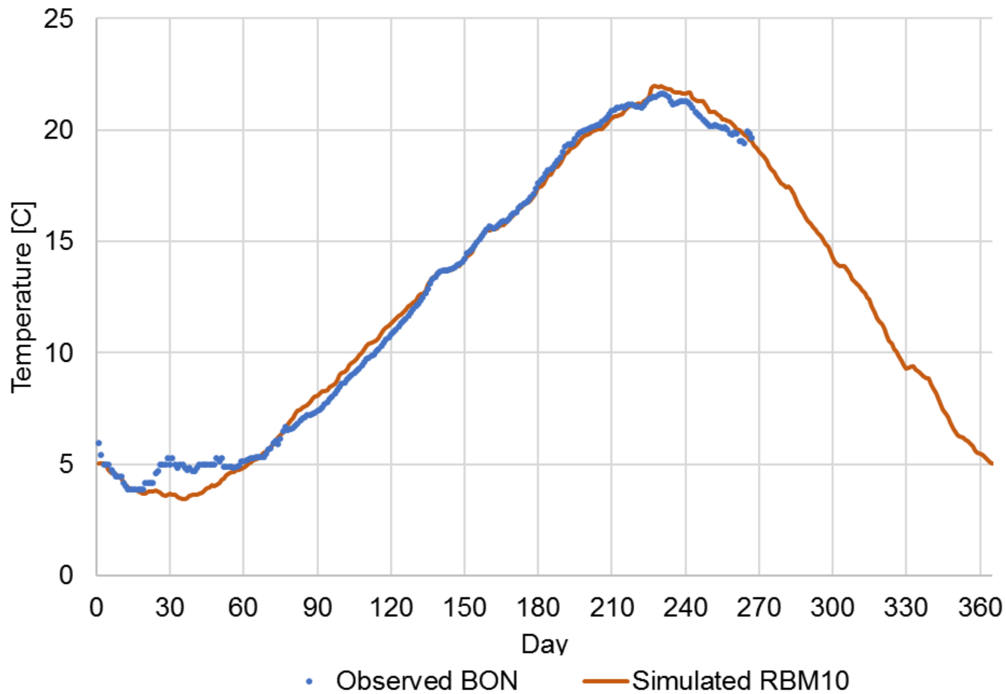

Figure 3-45 10-year daily average temperature comparison at BON

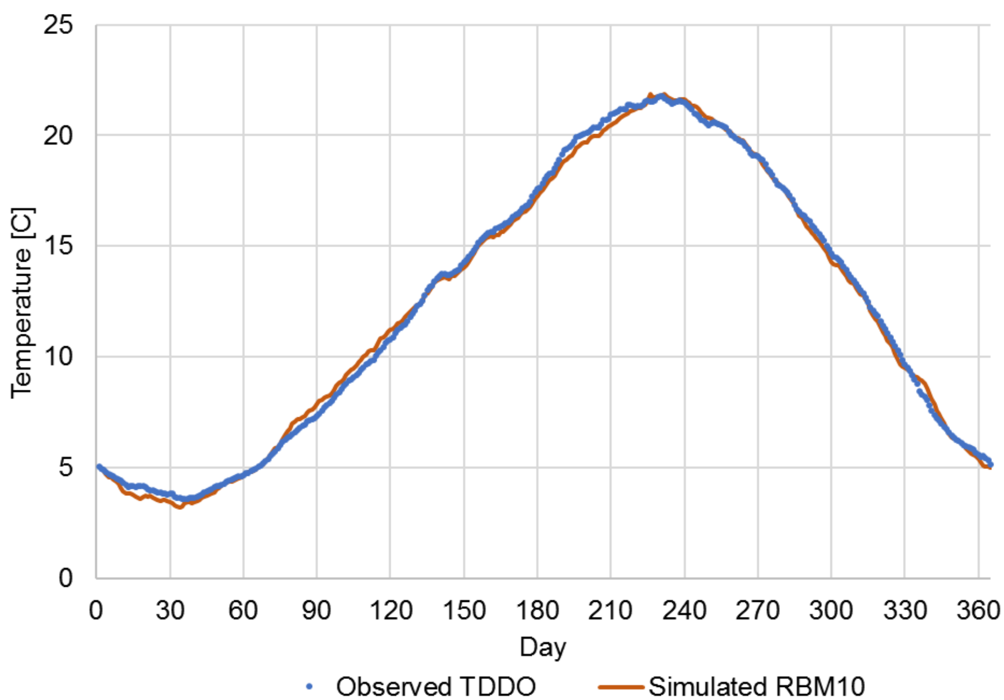

Figure 3-46 10-year daily average temperature comparison at TDDO

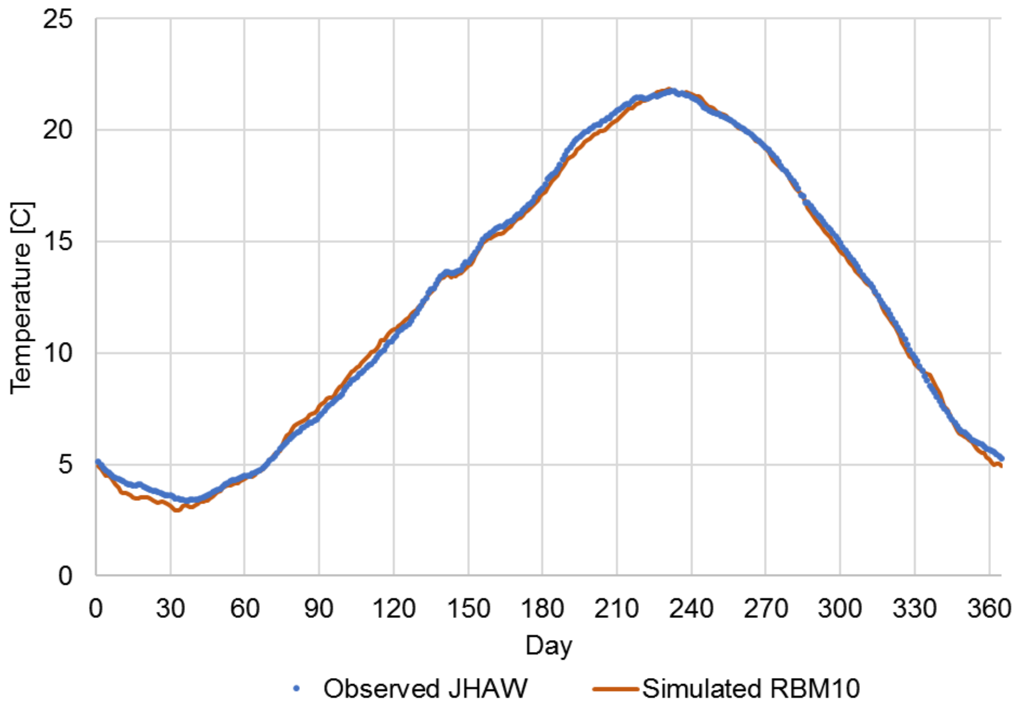

Figure 3-47 10-year daily average temperature comparison at JHAW

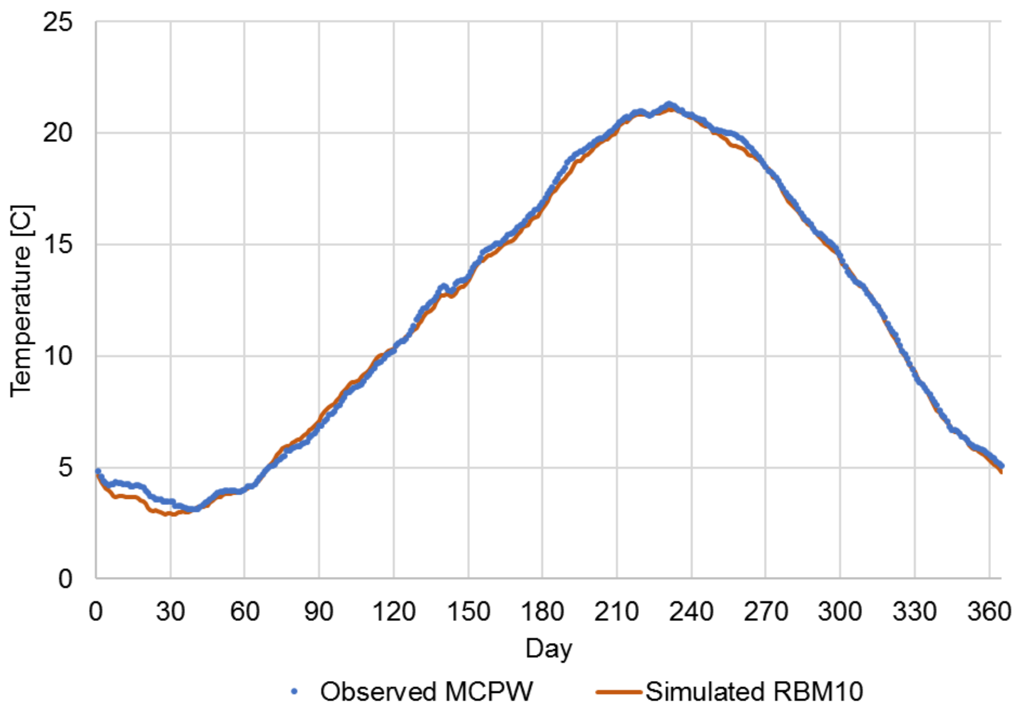

Figure 3-48 10-year daily average temperature comparison at MCPW

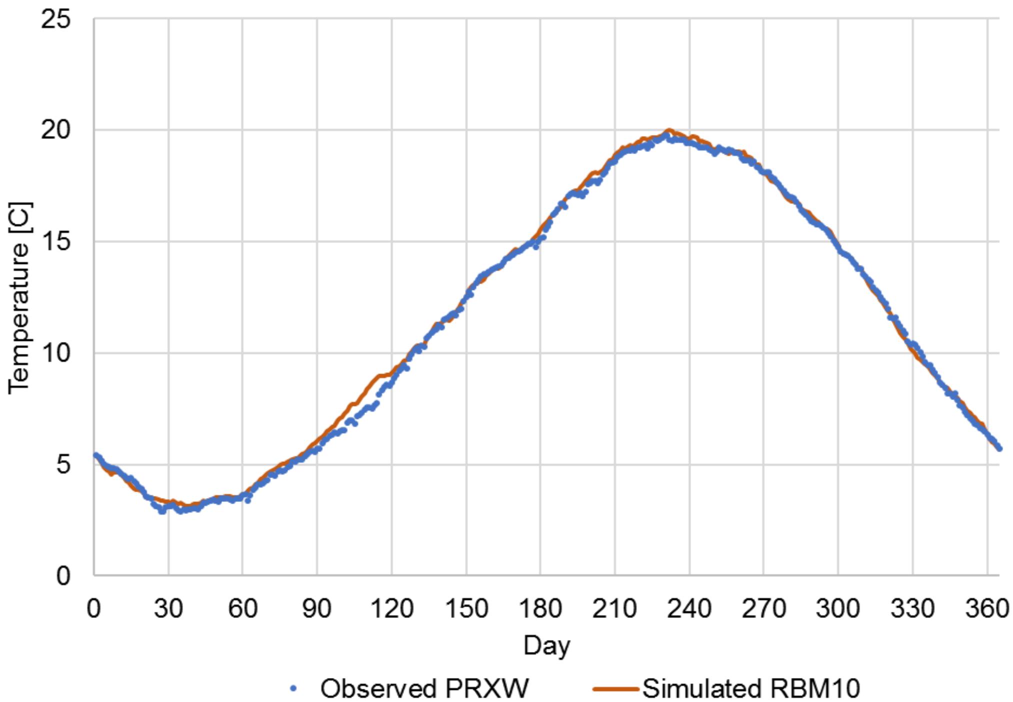

Figure 3-49 10-year daily average temperature comparison at PRXW

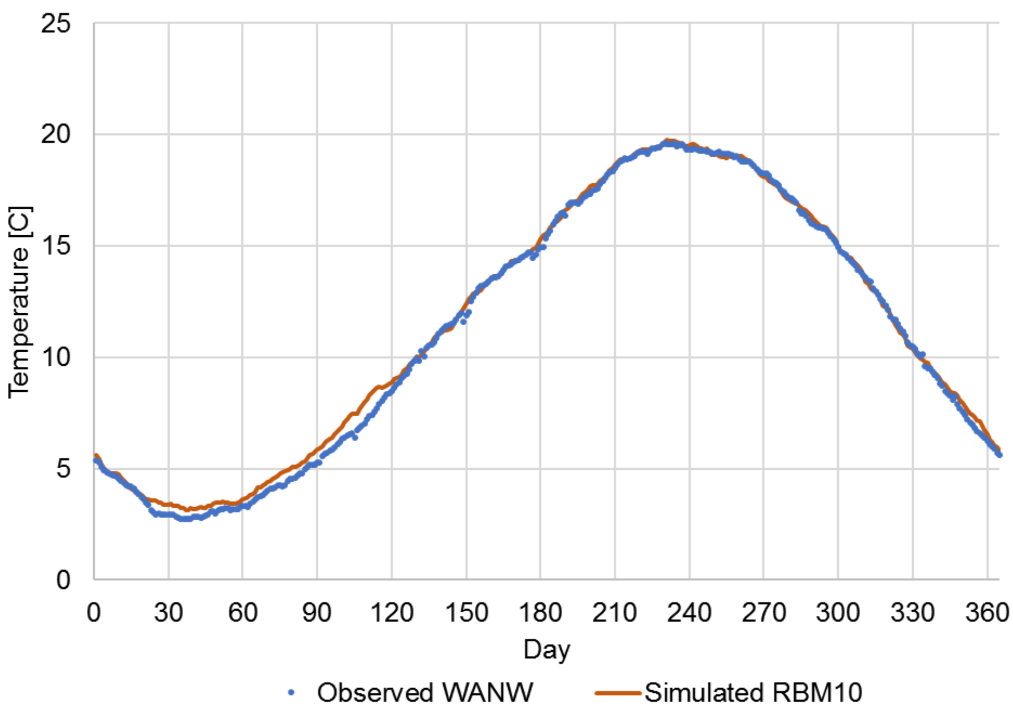

Figure 3-50 10-year daily average temperature comparison at WANW

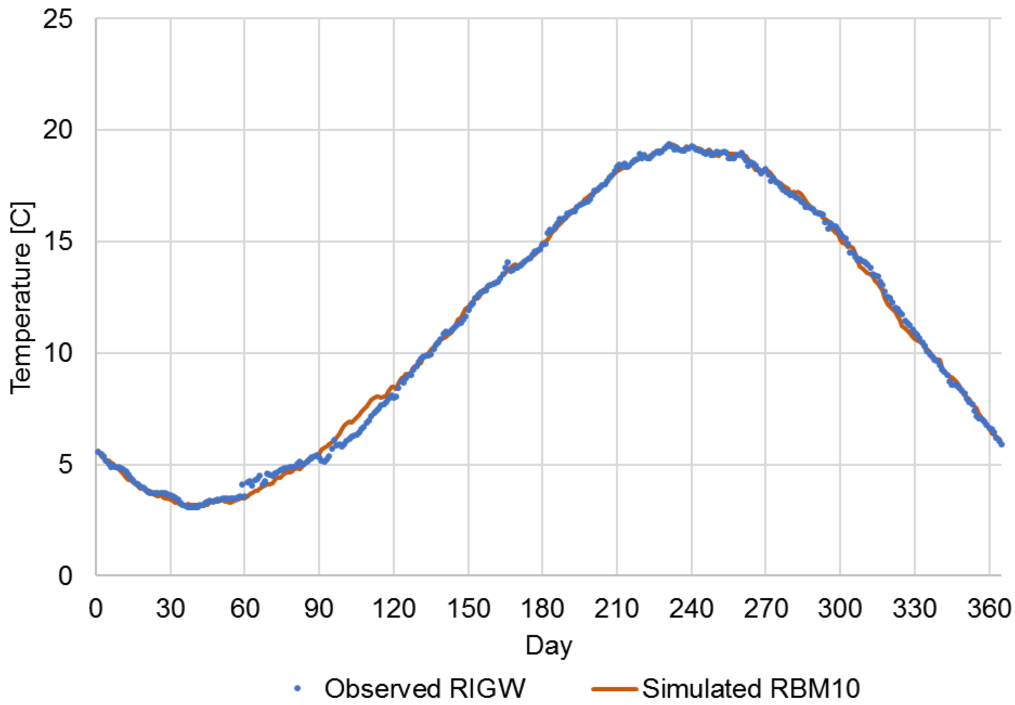

Figure 3-51 10-year daily average temperature comparison at RIGW

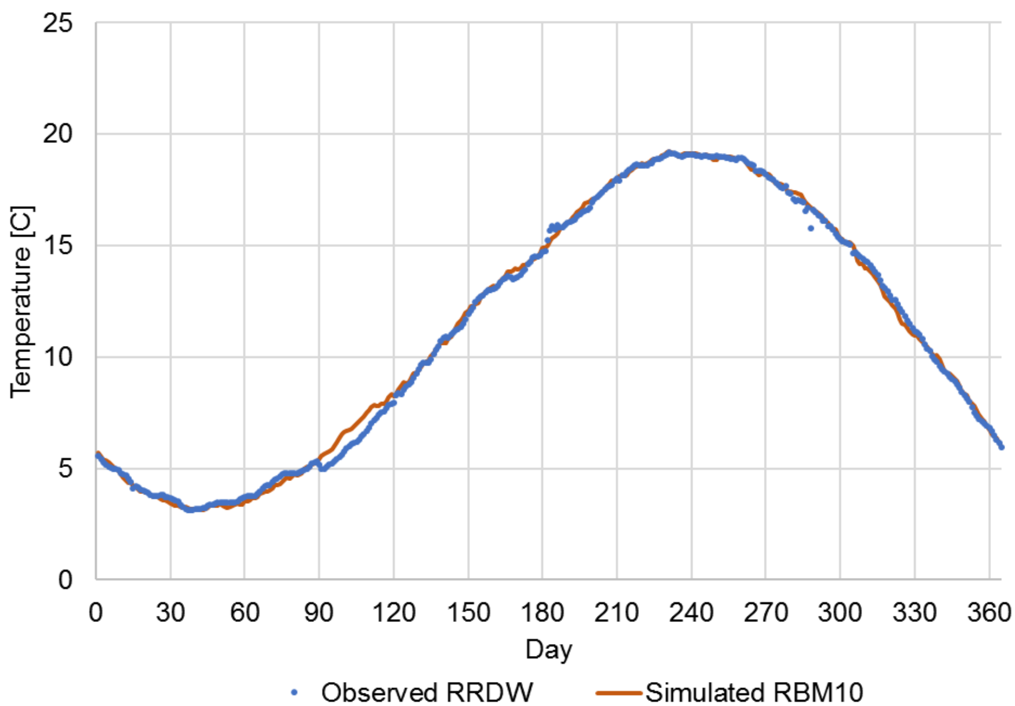

Figure 3-52 10-year daily average temperature comparison at RRDW

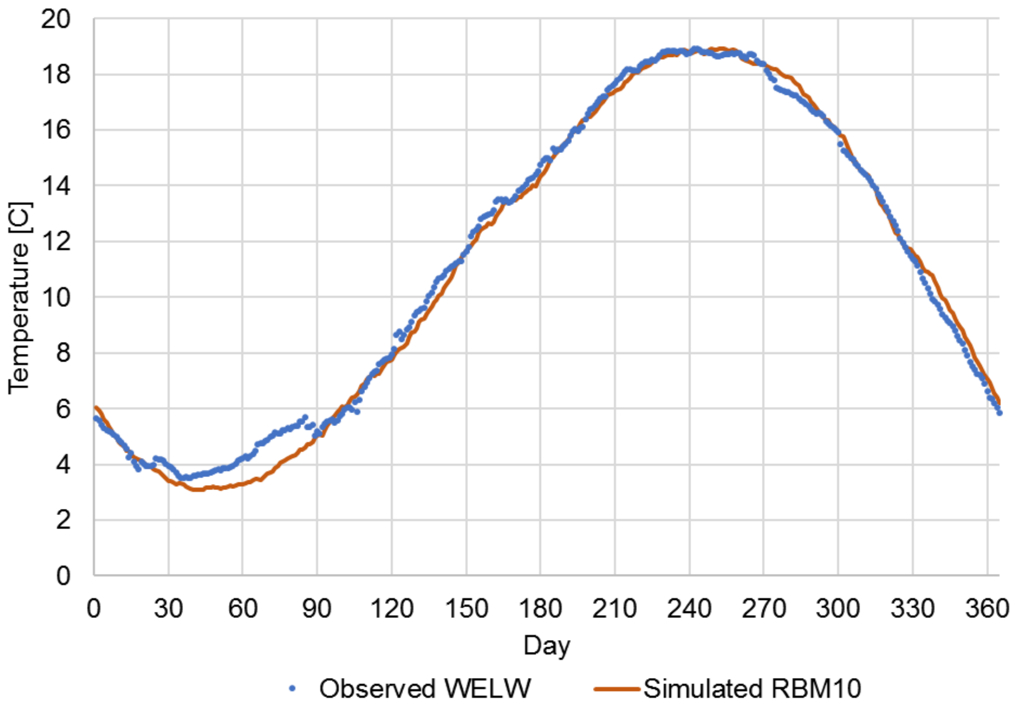

Figure 3-53 10-year daily average temperature comparison at WELW

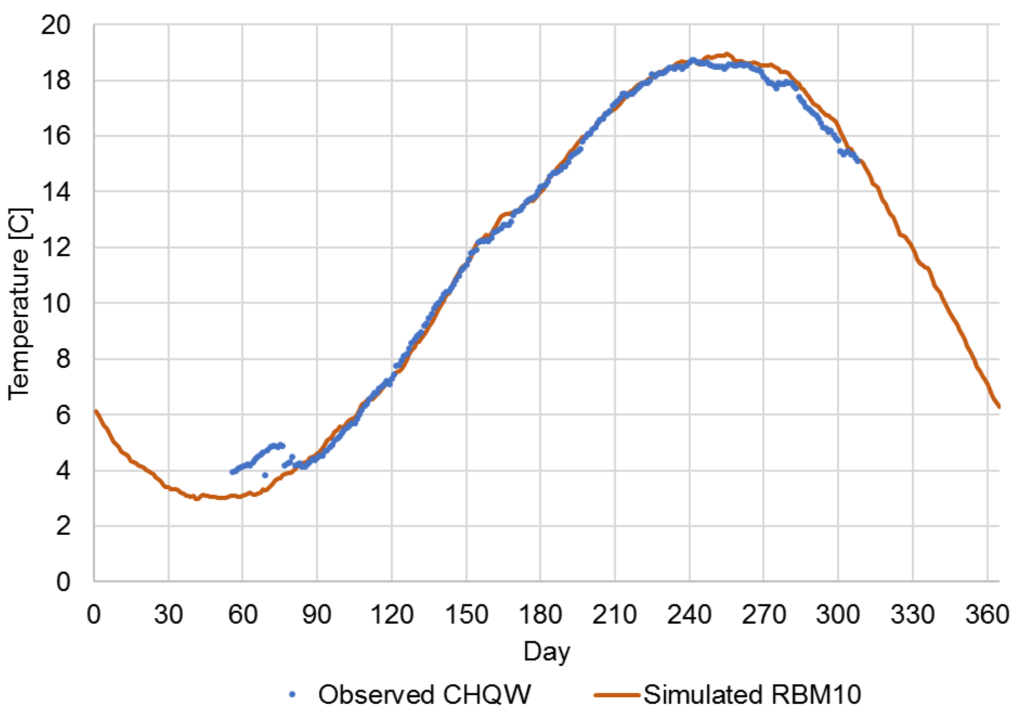

Figure 3-54 10-year daily average temperature comparison at CHQW

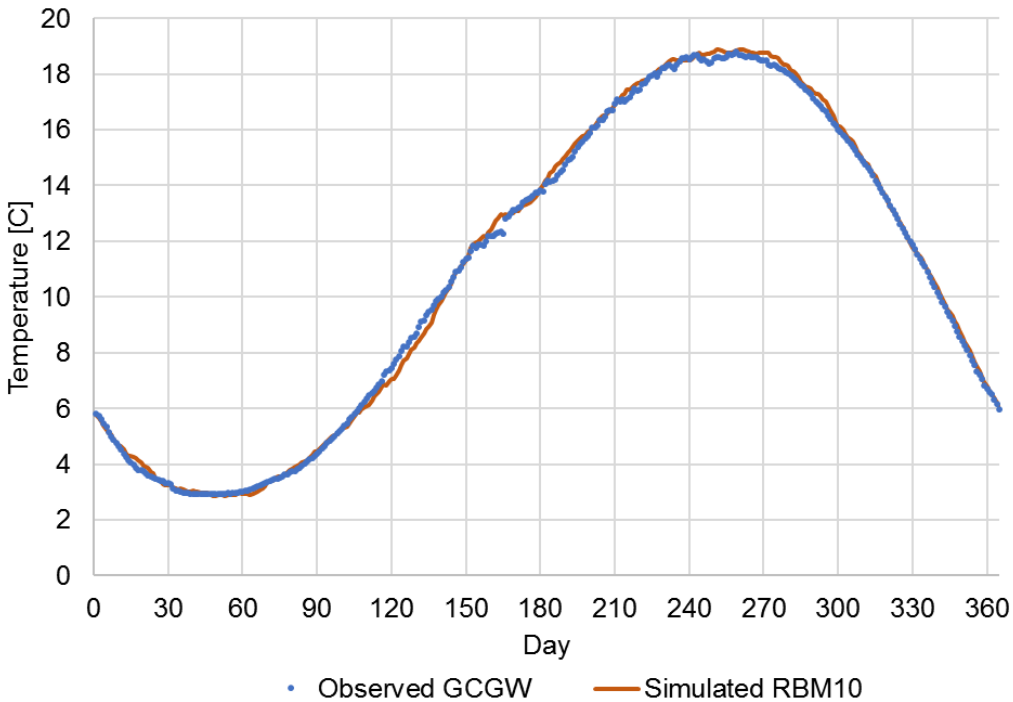

Figure 3-55 10-year daily average temperature comparison at GCGW

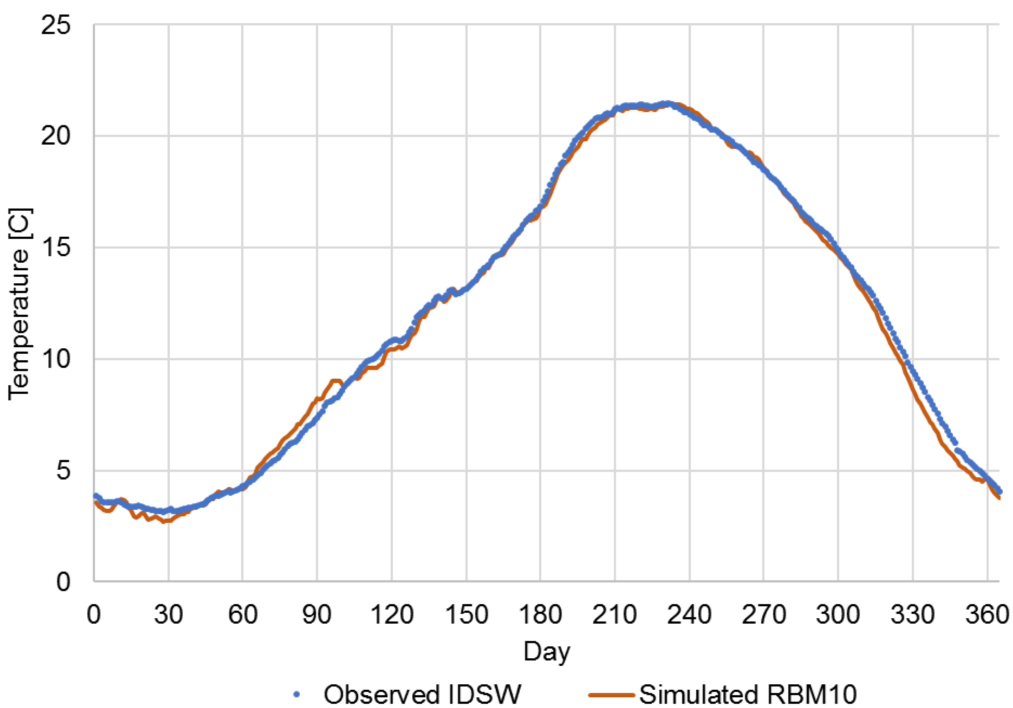

Figure 3-56 10-year daily average temperature comparison at IDSW

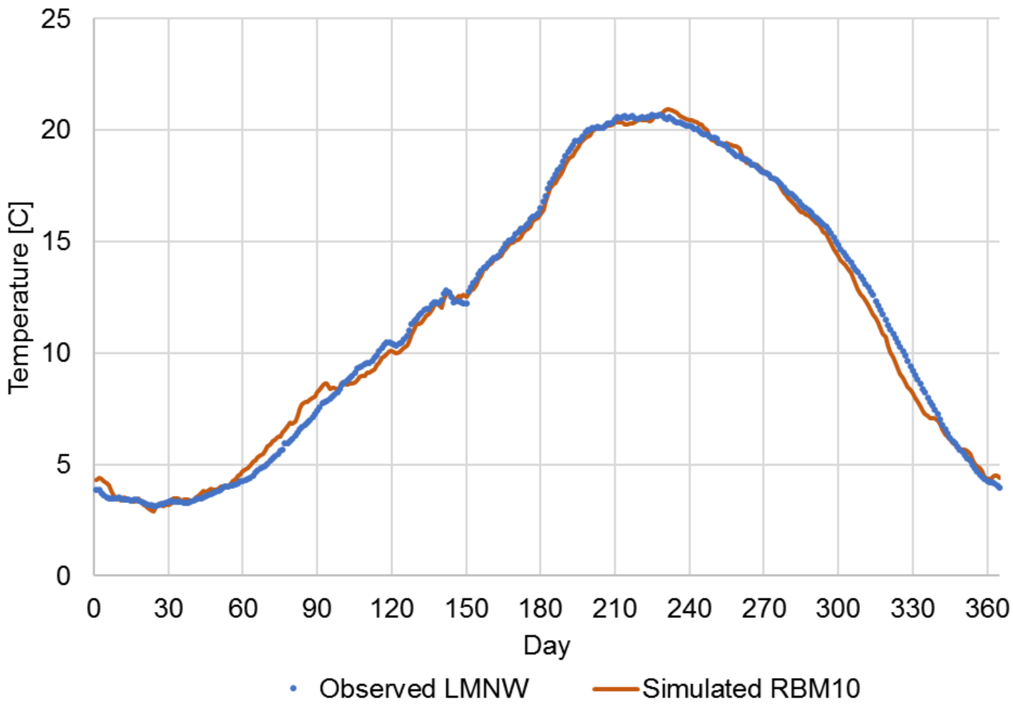

Figure 3-57 10-year daily average temperature comparison at LMNW

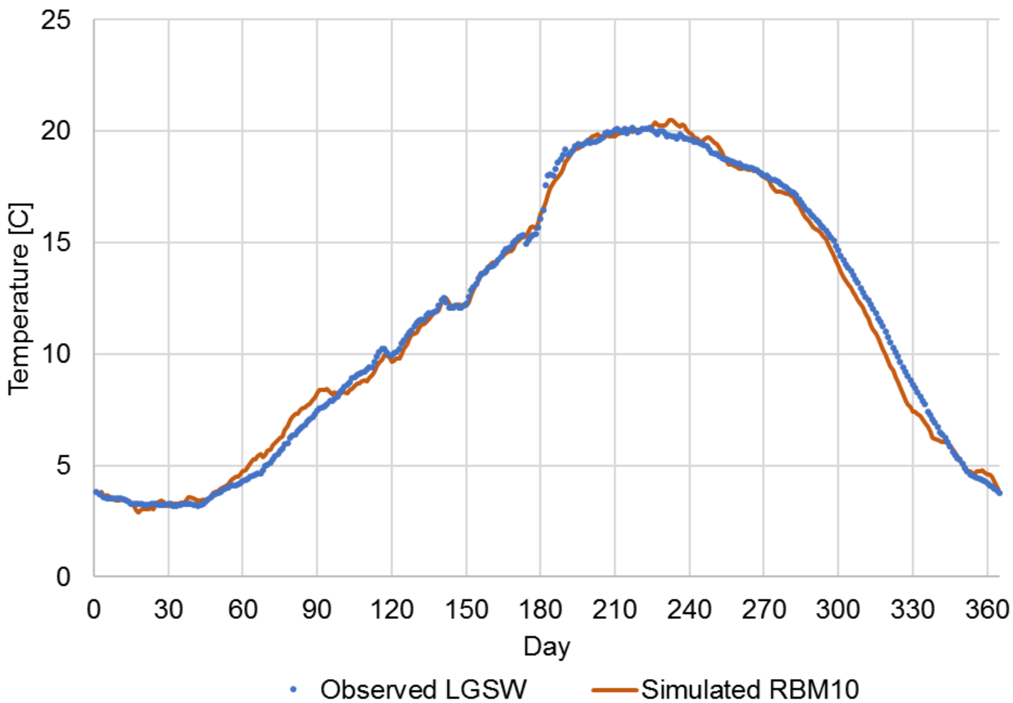

Figure 3-58 10-year daily average temperature comparison at LGSW

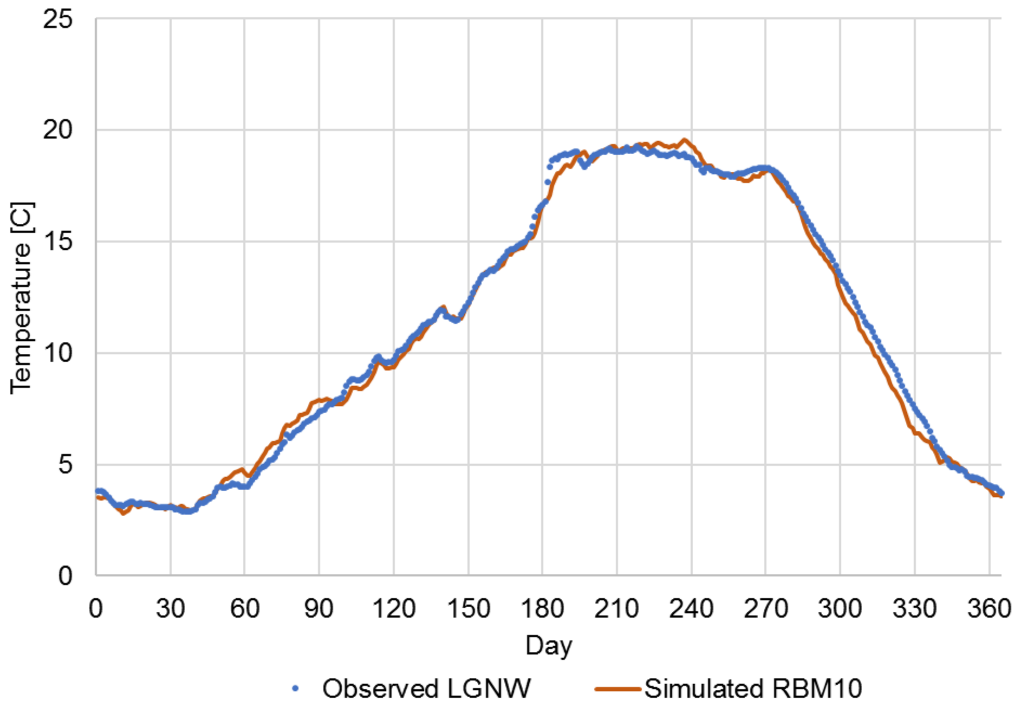

Figure 3-59 10-year daily average temperature comparison at LGNW

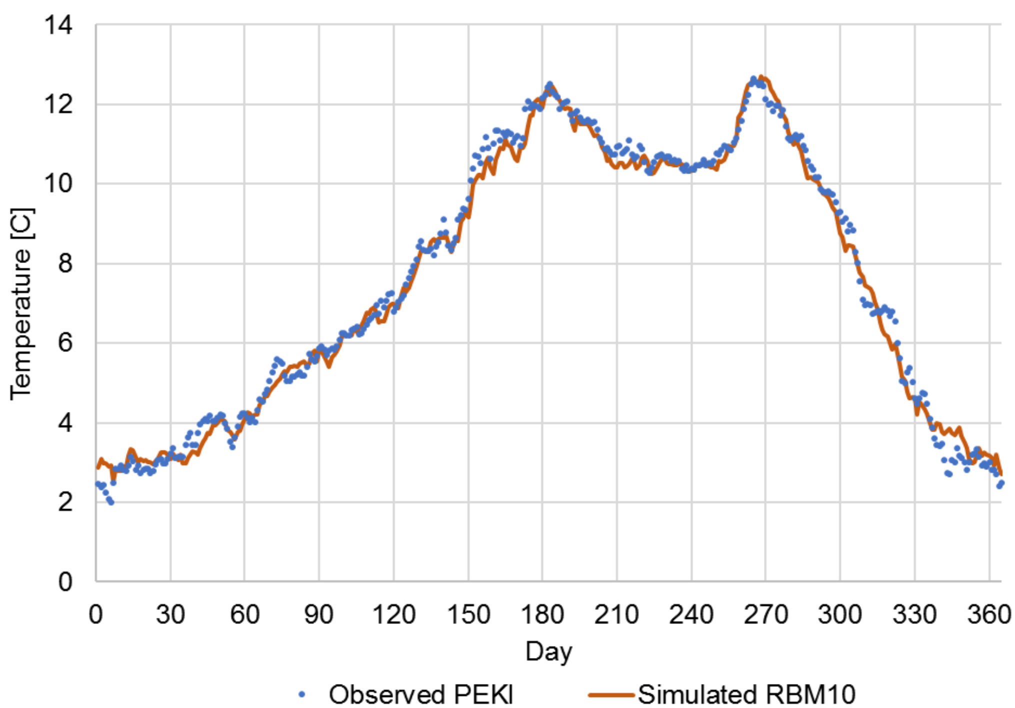

Figure 3-60 10-year daily average temperature comparison at PEKI

4.0 Alternative Columbia River Boundaries

The Grand Coulee Dam is subject to flood control operations, which result in variable flow discharges through the dam. Because these flow releases are not prescribed but are simulated in the 2018 RBM10 model as a function of the reservoir water surface elevations, some errors are expected in the representation of flows (Figure B.1-21 and Figure B.1-22) from the Grand Coulee Dam. To investigate how much these errors can impact the performance of the 2018 RBM10 model, two alternative model setups were developed during the project: (1) starting the Columbia River model at the Grand Coulee tailrace, and (2) starting the Columbia River model at the Priest Rapids tailrace. The evaluation of these alternative models helped identify the sensitivity of the 2018 RBM10 model performance to the location of the Columbia River upstream boundary.

The first alternate setup, hereafter labeled the 2018 RBM10B Model, was developed by moving the Columbia River upstream boundary from the international border to the Grand Coulee tailrace. The 2018 RBM10B Model upstream boundary was forced with observed flows and temperatures from USACE station GCGW. The second alternative setup, hereafter labeled the 2018 RBM10C Model, was developed by moving the location of the Columbia River boundary even further downstream, from the international boundary to the Priest Rapids tailrace. The 2018 RBM10C upstream boundary was forced with observed flows and temperatures from USACE station PRXW.

A detailed performance evaluation of the alternative models is presented in Appendix C and Appendix D respectively.

The 2018 RBM10B Model results indicate that by moving the location of the Columbia River from the international boundary to the Grand Coulee dam tailrace, the model performance is only marginally improved in downstream stations on the Columbia River. The statistics of model performance for the 2018 RBM10B Model indicate that the model can reproduce water temperatures with an average MAE of 0.4°C and an average RMSE of 0.52°C. Compared to the 2018 RBM10 model performance statistics, the above statistics represent an approximate 10% improvement of the MAE (from 0.44°C to 0.40°C) and a 6% improvement of the RMSE (from 0.56°C to 0.52°C).

The 2018 RBM10C Model results indicate that by moving the location of the Columbia River from the international boundary to the Priest Rapids dam tailrace, the model performance was improved to a greater degree in downstream stations on the Columbia River. The statistics of model performance for the 2018 RBM10C Model indicate that the model can reproduce water temperatures with an average MAE of 0.34°C and an average RMSE of 0.44°C. Compared to the 2018 RBM10 model, the above statistics represent an approximate 22% improvement of the MAE (from 0.44 °C to 0.34 °C) and a 16% improvement of the RMSE (from 0.55 °C to 0.44°C). A limitation of the 2018 RBM10C Model setup is that the length of the model domain is reduced and the model cannot be used to simulate temperature in regions upstream of the Priest Rapids Dam.

5.0 Sensitivity Analysis

A sensitivity analysis of the 2018 RBM10 model was conducted to identify the major drivers of water temperature on the Columbia River and Snake River. The results of the sensitivity analysis are presented in Appendix F. Sensitivity analyses assess and evaluate how model outputs respond to perturbations of model inputs, parameters, and model structure changes. This process can identify the important drivers of the simulated physical processes (Perumal and Gunawan, 2011) and help identify the model parameters that have the largest impacts on the model outputs, which in turn can help focus the calibration efforts only on the most critical parameters (Saltelli et al. 2000; White and Chaubey 2005). The sensitivity analysis can also be used to prioritize data collection efforts to reduce uncertainties in important input variables and model parameters.

A sensitivity analysis generally requires the perturbation of multiple parameters or model inputs from a reference model condition. This reference condition is usually a calibrated model setup. The perturbations can be performed simultaneously or alternatively by changing each parameter or input one at a time while keeping the others as defined in the reference condition. The later approach, as performed in this project, is commonly known as "one-at-a-time sensitivity analysis" (OAT-SA) and is a widely applied approach for sensitivity analyses (Saltelli et al. 2006; Loosvelt et al. 2013). One of the most important aspects of OAT-SA is that the impacts of each parameter or input variable on the model predictions can be isolated from the other aspects of the model, so it is easy to identify its relevance in the modeling effort. However, OAT-SA has the limitation that it cannot be used to identify correlation between parameters or model inputs.

An OAT-SA sensitivity analysis was performed using the calibrated 2018 RBM10 model as the baseline condition. The analysis focused on the last decade of model outputs from 2007 through 2016. The purpose of the sensitivity analysis was to identify the most important drivers of water temperature in the Columbia River and Snake River.

5.1 Sensitivity Scenarios

Eight model runs were executed as part of the sensitivity analysis (Table 5-1). Five scenarios were performed by increasing upstream boundary flows and water temperatures by 20% at the boundaries of the model, one scenario was performed by increasing the air temperatures by 2°C, and two scenarios were performed by increasing the model air evaporation coefficients by 15%. The evaluated scenarios were conducted to identify if flow increments at the model boundaries can attenuate the longitudinal increases of water temperatures along the Columbia and Snake Rivers and to determine if increments of water temperatures at the boundaries of the Columbia and Snake Rivers propagate along the rivers in the same magnitude or if they are magnified or attenuated. The scenarios with modified evaporation coefficients and air temperatures were performed to evaluate the impacts of changes in air temperature and atmospheric conditions on water temperatures.

The results of the sensitivity analysis are presented in Sections F.1 and F.2. The results include longitudinal plots of decadal averaged water temperatures along the Columbia (Section F.1) and Snake (Section F.2) Rivers, decadal daily averaged water temperatures at USACE tailrace monitoring stations on the Columbia and Snake Rivers, and summary tables showing the percent changes in water temperature from the baseline condition for each simulated scenario.

The results indicated that water temperatures along the Columbia and Snake Rivers were primarily sensitive to changes in upstream boundary water temperatures followed by changes in air temperature and evaporation coefficients. The changes in the Columbia and Snake River upstream boundary temperatures mostly impacted the regions close to the boundaries and were attenuated longitudinally by the entrance of the tributaries into the main channels (Figure F.1-1 through Figure F.1-3). In the Columbia River, the 20% increase in upstream water temperatures caused approximately an 8% increase in water temperatures (1.2°C – 1.4°C) at Grand Coulee (GCGW) and a 1.5% increase in water temperatures (0.2°C – 0.3°C) at Bonneville (BON) (Table F.1-1 through Table F.1-6). The increase in the Snake River upstream water temperatures mostly impacted the temperatures in the Snake River (Figure F.2-1 through Figure F.2-3), but had a minor impact on the Columbia River water temperatures. The 20% increase in Snake River upstream boundary temperature was attenuated longitudinally and caused an approximately 5% increase in water temperatures (0.6°C – 0.7°C) at Ice Harbor Dam (IDSW) (Table F.2-1 through Table F.2-6) and approximately a 1% increase in water temperature (0.1°C – 0.2°C) in the Columbia River below the confluence, at McNary Dam (MCPW).

Changes in air temperature, on the other hand, were slightly magnified longitudinally in the Colombia and Snake Rivers (Figure F.1-1 through Figure F.1-3). The 2°C increase in air temperatures, which represents an approximately 7% increase in average peak summer temperatures (30°C), caused on average a 2% overall increase in water temperatures in the Columbia and Snake Rivers (0.2°C – 0.3°C). In the Colombia River, water temperatures increased by 1.9% at GCGW (0.25°C – 0.30°C) and by 2.4% at BON (0.3°C - 0.4°C) (Table F.1-1 and Table F.1-5). In the Snake Rivers, water temperatures increased by 1.2% at LGNW (0.15°C – 0.2°C) and by 1.9% at IDSW (0.25°C – 0.3°C) (Table F.2-1, Table F.2-5).

The increments in the model evaporation coefficients caused reductions in the simulated Columbia and Snake River water temperatures. These temperature reductions were relatively homogeneous longitudinally. By increasing by 15% the summer and fall evaporation coefficients, summer water temperatures were reduced between 1% and 2% (0.25°C – 0.4°C) (Table F.1-3 and Table F.2-3), while fall temperatures were reduced between 2% and 3% (0.3°C – 0.5°C) (Table F.1-5 and Table F.2-5) in the Columbia and Snake Rivers. The sensitivity of the simulated water temperatures to changes in the evaporation coefficients reveal a high importance of these parameters in the setup and calibration of the model.

Finally, the 20% increases in Columbia and Snake River boundary flows and tributary flows generally caused mild changes of 1% or less (0.1°C – 0.2°C) in simulated Columbia River water temperatures. These results suggest that flows are relatively minor drivers of temperature if other factors such as upstream temperatures and air temperatures are not changed from the baseline conditions.

Table 5-1 Sensitivity analysis scenarios

Scenario	Description
Columbia Flow + 20%	Flows at the Columbia River upstream boundary increased by 20%
Snake Flow + 20%	Flows at the Snake River upstream boundary increased by 20%
Tributaries Flow + 20%	Tributary flows increased by 20%
Columbia Temp + 20%	Water temperature at the Columbia River upstream boundary increased by 20%
Snake Temp + 20%	Water temperature at the Snake River upstream boundary increased by 20%
Fall Ev Coeff + 15%	Fall evaporation coefficient (Ev) increased by 15%
Summer Ev Coeff + 15%	Summer evaporation coefficient (Ev) increased by 15%
Air Temp + 2 C	Air temperature increased by 2 °C

6.0 Conclusions

This project has completed an update and refinement of EPA's RBM10 temperature model of the Columbia and Snake river mainstems. The original model simulation period (1970-2000) has been extended and now incorporates the period 1970-2016. The latest river geometry and impoundment volume data from the U.S. Army Corps of Engineers and Bureau of Reclamation has been used to improve the river geometry representation in RBM10. In addition, a quality assurance review was undertaken to remove weather and water temperature data of questionable accuracy and to compare temperature measurements taken in dam tailraces compared to those taken in forebays. Finally, the model was recalibrated using 18 temperature monitoring stations on the Columbia, Snake, and Clearwater rivers.

Model performance in simulating daily average river temperatures was evaluated using a variety of graphical comparisons and statistical metrics. The information supporting the calibration process has been expanded to include seasonal error statistics and decadal-averaged simulated/observed temperature plots. In general, the update and refinement has improved the accuracy of the model.

Like any environmental assessment tool, the RBM10 model has both strengths and limitations. Strengths include the long-term simulation period (1970-2016), fast run times, simplicity of the model setup, breadth of peer review, and overall model accuracy. Limitations include the spatial and temporal resolution of the model. The one-dimensional representation provides cross-sectional average predictions and does not represent vertical stratification. The daily time step simulates daily average temperatures; daily maximum and minimums are not estimated.

For Grand Coulee Dam, the only flood-controlled reservoir in the model domain, changes in volumes and outflows are simulated as a function of measured water surface elevations.

Two additional RBM10 models starting at the Grand Coulee Dam tailrace and at the Priest Rapids tailrace were developed as a sensitivity analysis to evaluate how potential errors in the simulation of dam flow operations at Grand Coulee Dam impacted temperature simulations in downstream reaches of the model. Only slight improvements in the performance of the model were achieved by moving the upstream boundary to the alternative locations. The results of the alternative RBM10 models indicate that the mid-Columbia River temperatures are not strongly influenced by flow variation, and this finding is consistent with results in a recent statistical analysis of Columbia River temperatures (Isaak 2017). Given the limited benefit of using a sub-model that excludes the Grand Coulee reach, the full 2018 RBM10 model will likely be used for future analysis, particularly to estimate temperatures without dams.

The RBM10 model can be applied to answer a variety of assessment questions about temperature conditions in the mainstem Columbia, Snake, and Clearwater rivers. This report documents the development and performance of the "core model" simulation of existing conditions, from input data compilation through the calibration process. The next step is to apply the model to answer assessment questions, using model "scenarios" that alter one or more of the model inputs to isolate the effects of specified changes in the system. This scenario work will be documented in separate reports. As the assessment moves forward, this report will be updated or amended if substantive changes are made to the core model based on peer review and/or new information.

7.0 References

Bonneville Power Administration et al. 1994. Columbia River system operation review. Appendix M, Water quality. DOE/EIS-0170. Bonneville Power Administration, U.S. Army Corps of Engineers, and U.S. Bureau of Reclamation, Portland, Oregon.

Bowie, G.L., Mills, W.B., Porcella, D.B., Campbell, C.L., Pagenkopf, J.R., Rupp, G.L., Johnson, K.M., Chan, P.W.H., Gherini, S.A. and Chamberlin, C.E. 1985. Rates, Constants, and Kinetic Formulations in Surface Water Quality Modeling. U.S. Envir. Prot. Agency, ORD, Athens, GA, ERL, EPA/600/3-85/040.

Cao, Q., Sun, N., Yearsley, J., Nijssen, B., and Lettenmaier, D. P. 2016. Climate and land cover effects on the temperature of Puget Sound streams. Hydrol. Process., 30: 2286–2304. *doi:* 10.1002/hyp.10784.

Edinger, J.E., Brady, D.K., and Geyer, J.C. 1974. Heat Exchange and Transport in the Environment. Report No. 14, EPRI Pub. No. EA-74-049-00-3, Electric Power Research Institute, Palo Alto, CA.

EPA. 2003. Preliminary Draft Columbia/Snake Rivers Temperature TMDL. EPA Region 10. July 2003. Figure 4-1.

Isaak, D., S. Wenger, E. Peterson, J. Ver Hoef, D. Nagel, C. Luce, S. Hostetler, J. Dunham, B. Roper, S. Wollrab, G. Chandler, D. Horan, S. Parkes-Payne. 2017. The NorWeST summer stream temperature model and scenarios for the western U.S.: A crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. Water Resources Research 53.11 (2017): 9181-9205.

Leopold, L.B., and T. Maddock. 1953. The hydraulic geometry of stream channels and some physiographic implications. U.S. Geological Survey Professional Paper 252. U.S. Geological Survey.

Loosvelt, L., Vernieuwe, H., Pauwels, V.R.N., Baets, B.D. and Verhoest, N.E.C., 2013. Local sensitivity analysis for compositional data with application to soil texture in hydrologic modelling. Hydrology and Earth System Sciences, 17(2), pp.461-478.

Normandeau Associates. 1999. Lower Snake River temperature and biological productivity modeling. R-16031.007. Preliminary review draft. Prepared for the Department of the Army, Corps of Engineers, Walla Walla, Washington.

Perry, R.W., Risley, J.C., Brewer, S.J., Jones, E.C., and Rondorf, D.W. 2011. Simulating daily water temperatures of the Klamath River under dam removal and climate change scenarios. U.S. Geological Survey. Open-File Report 2011-1243.

Perumal, T.M. and Gunawan, R., 2011. Understanding dynamics using sensitivity analysis: caveat and solution. BMC systems biology, 5(1), p.1.

Saltelli, A., Chan, K. and Scott, E.M. eds., 2000. Sensitivity analysis (Vol. 1). New York: Wiley. Vancouver

Saltelli, A., Ratto, M., Tarantola, S., Campolongo, F. and Commission, E., 2006. Sensitivity analysis practices: Strategies for model-based inference. Reliability Engineering & System Safety, 91(10), pp.1109-1125.

Tetra Tech. 2017. Final Technical Memorandum for 2017 RBM10 Columbia and Snake Rivers Model. Prepared for U.S. Environmental Protection Agency. September 2017.

USACE-HEC (U.S. Army Corps of Engineers). 1995. HEC-RAS: River analysis system. U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, California.

van Vliet, M. T. H., J. R. Yearsley, W. H. P. Franssen, F. Ludwig, I. Haddeland, D. P. Lettenmaier, and P. Kabat. 2012. Coupled daily streamflow and water temperature modelling in large river basins. Hydrol. Earth Syst. Sci., 16, 4303–4321. doi:10.5194.

White, K.L. and Chaubey, I., 2005. Sensitivity analysis, calibration, and validations for a multisite and multivariable swat model1.

Wunderlich, W.O., and R. Gras. 1967. Heat and mass transfer between a water surface and the atmosphere. Tennessee Valley Authority, Division of Water Cont. Planning, Norris, Tennessee.

Yearsley, J.R. 1969. A mathematical model for predicting temperatures in rivers and river-run reservoirs. Working Paper No. 65, Federal Water Pollution Control Agency, Portland, Oregon.

Yearsley, J. R. 2003. Developing a temperature Total Maximum Daily Load for the Columbia and Snake Rivers: Simulation methods. Report 910-R-03-003 by the U.S. Environmental Protection Agency, Region 10, Seattle, Washington.

Yearsley, J. R. 2009. A semi-Lagrangian water temperature model for advection-dominated river systems. Water Resour. Res., 45, W12405. doi:10.1029/2008WR007629.

Yearsley, J. R., Karna, R., Peene, S. and Watson, B. 2001. Application of a 1-D heat budget model to the Columbia River system. Final report 901-R-01-001 by the U.S. Environmental Protection Agency, Region 10, Seattle, Washington.

Appendix A Atmospheric, Flow, and Temperature Inputs

A.1 Atmospheric Inputs

A graphical summary of the atmospheric inputs (air temperature, atmospheric radiation, and wind speed) derived from available observations from 2001 through 2016 at the weather stations Lewiston (WBAN 24149), Wenatchee (GHCND 9074), Yakima (WBAN 24243), Portland (GHCND 24229), and Spokane (WBAN 24157) (Table 2-6 and Table 2-7) are presented from Figure A.1-1 through Figure A.1-6. In general, the coldest air temperatures are registered at Spokane (average temperature 8.8°C) while the warmest are registered at Portland (average temperature 12°C). These changes in temperature are primarily associated to the elevation of the meteorological stations.

The highest wind speeds are registered at Spokane (average velocity 4.1 m/s) and the lowest at Lewiston (average velocity 2.8 m/s). Wind speed differences among stations can be associated to local conditions and the presence or absence of major fluid obstacles such as mountains and trees and also to changes in macro scale atmospheric circulation in the region.

The most homogeneous atmospheric input variable is radiation with an average value of 0.07 Kcal/m^2-s and an annual variation between 0.04 Kcal/m^2-s (winter) and 0.1 Kcal/m^2-s (summer).

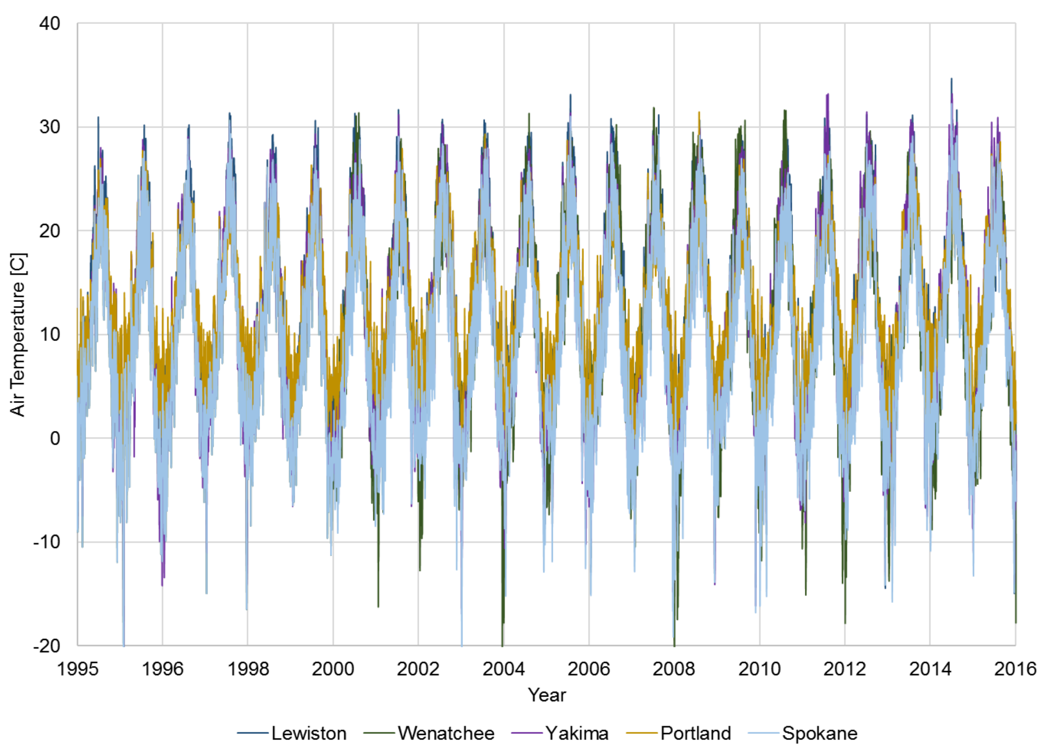

Figure A.1-1 RBM10 air temperature inputs 1995 – 2016 period

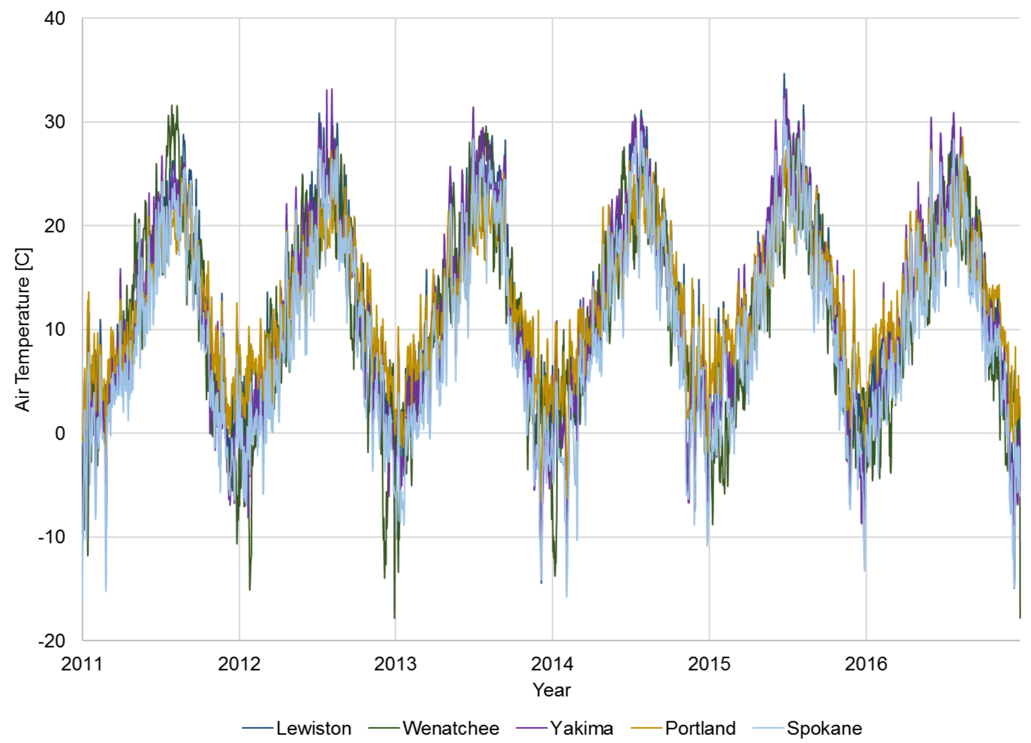

Figure A.1-2 RBM10 air temperature inputs 2011 – 2016 period

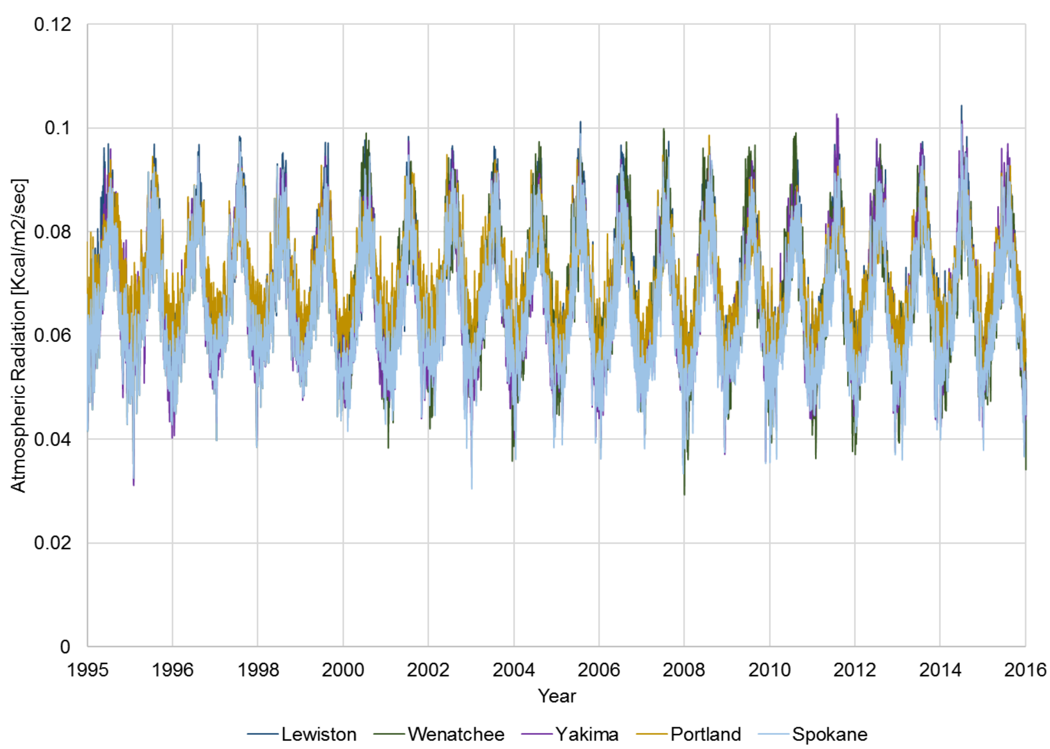

Figure A.1-3 RBM10 atmospheric radiation inputs 1995 – 2016 period

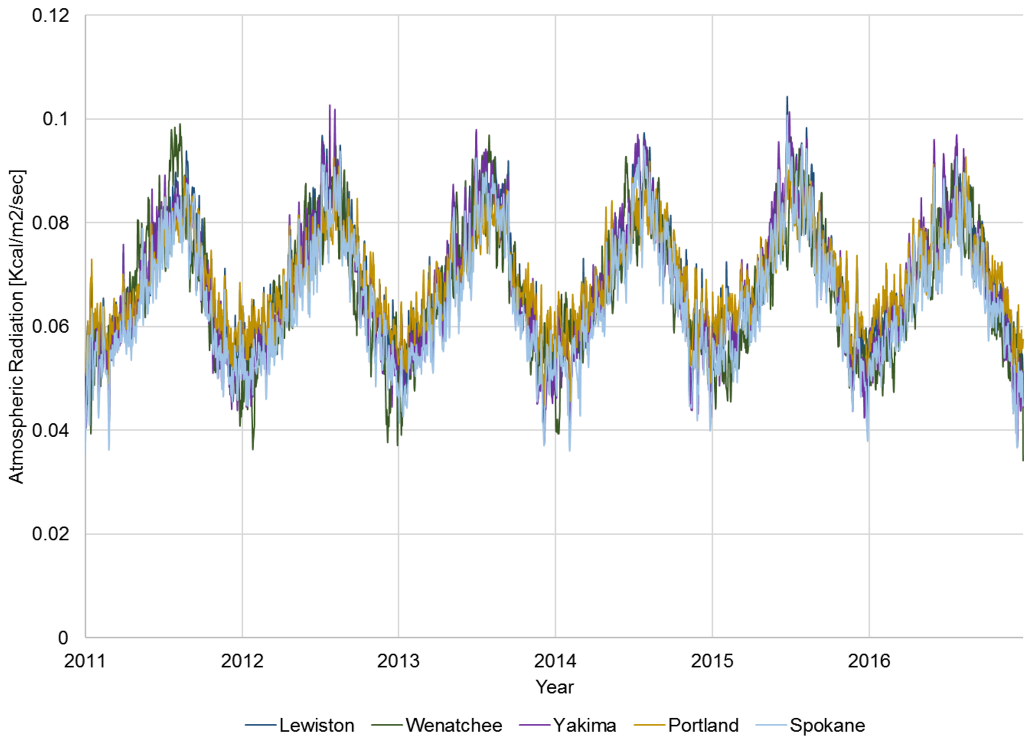

Figure A.1-4 RBM10 atmospheric radiation inputs 2011 – 2016 period

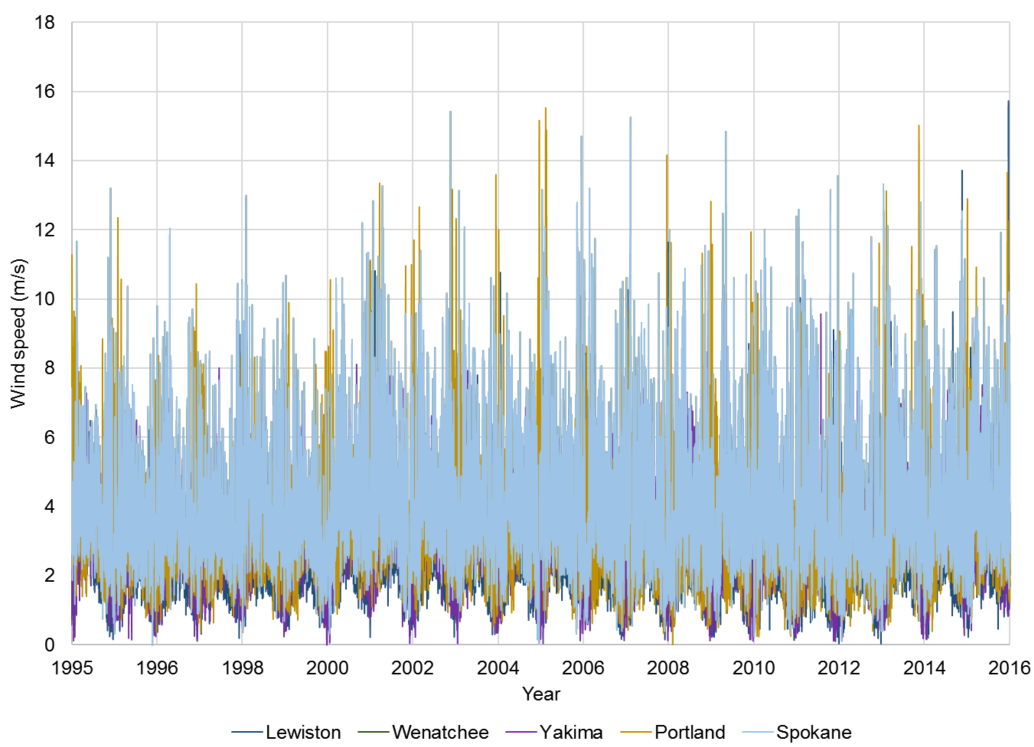

Figure A.1-5 RBM10 wind speed inputs 1995 – 2016 period

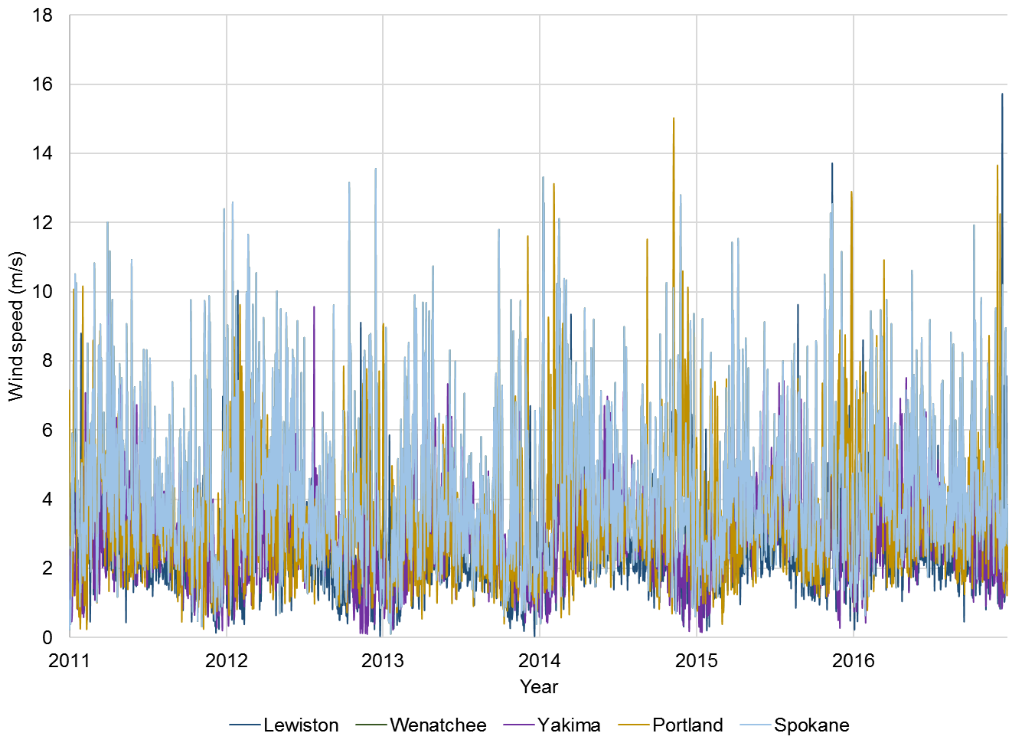

Figure A.1-6 RBM10 wind speed inputs 2011 – 2016 period

A.2 Headwater Flow Boundary Inputs

A graphical summary of the flow boundary conditions prescribed at the upstream end of the Columbia River, Snake River, Clearwater River, and Dworshak Dam (spatial domain shown in Figure 2-1) is presented from Figure A.2-1 through Figure A.2-4. The average flow discharge at the Columbia River upstream boundary is 100 kcfs (thousand cubic feet per seconds) and represents the major source of flows in the RBM10 model. The second largest source of flows in the model is the Snake River which contributes an average flow of 34 kcfs.

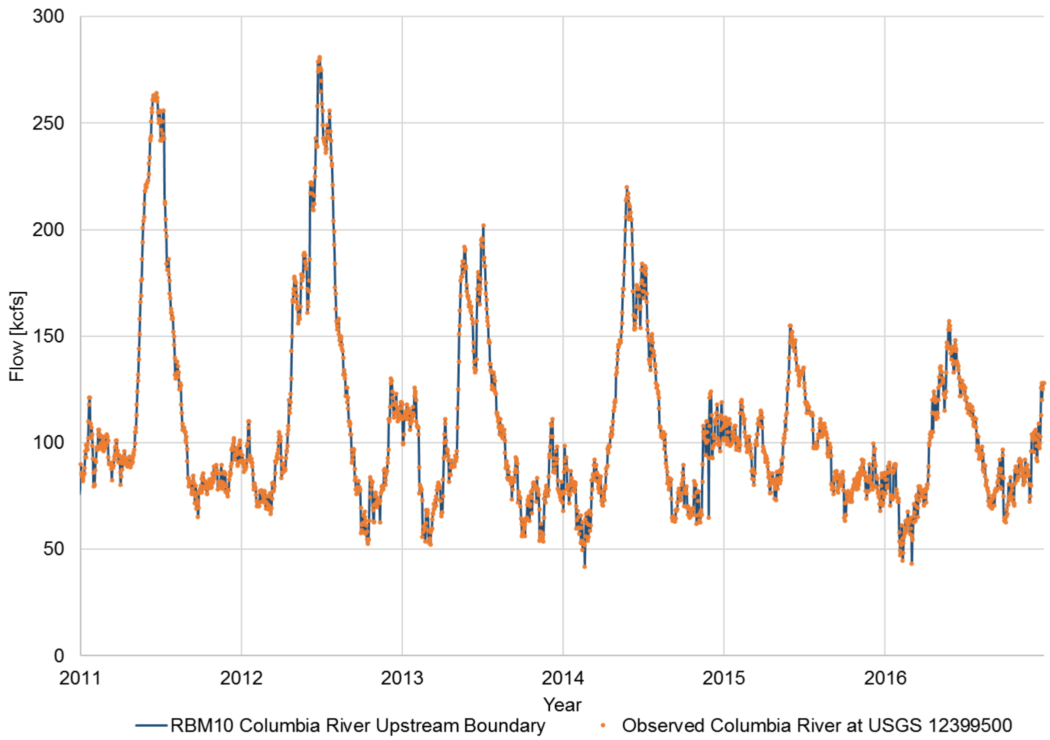

Figure A.2-1 Columbia River upstream boundary flow inputs

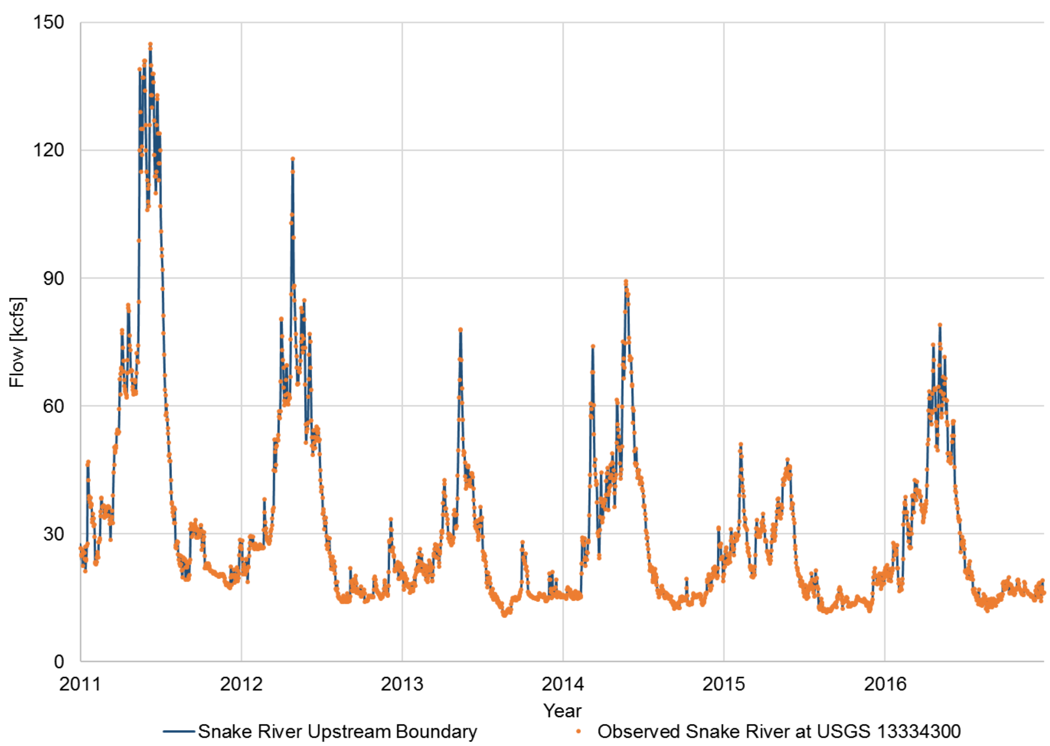

Figure A.2-2 Snake River upstream boundary flow inputs

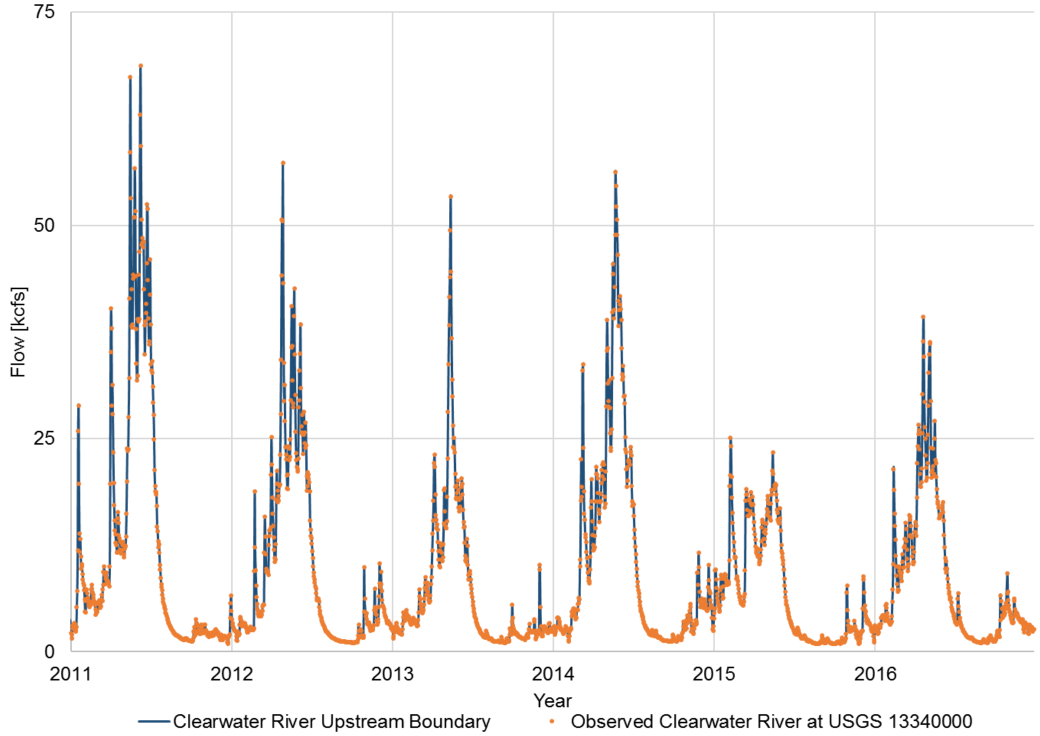

Figure A.2-3 Clearwater River upstream boundary flow inputs

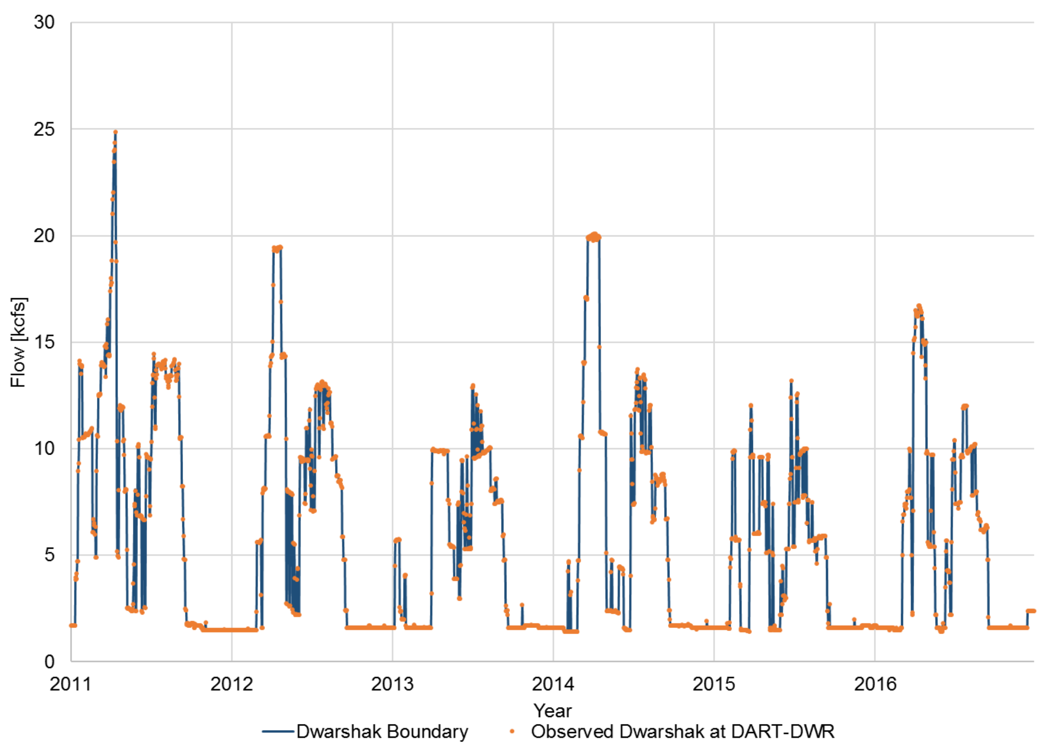

Figure A.2-4 Dworshak Dam boundary flow inputs

A.3 Temperature Boundary Inputs

A graphical summary of the temperature boundary conditions prescribed at the upstream end of the Columbia River, Snake River, Clearwater River, and Dworshak Dam is presented from Figure A.3-1 through Figure A.3-4. Water temperatures at the upstream boundaries of the Columbia River are typically colder than those at the upstream boundary of the Snake River. Temperatures at the Columbia River upstream boundary generally varied between 3°C and 19°C with an average value of 10°C whereas temperatures at the Snake River generally vary between 2°C and 22°C with an average value of 11.7°C. The Snake River receives cold water discharges from the Dworshak Dam, which generally vary between 4°C and 10°C with an average value of 7°C.

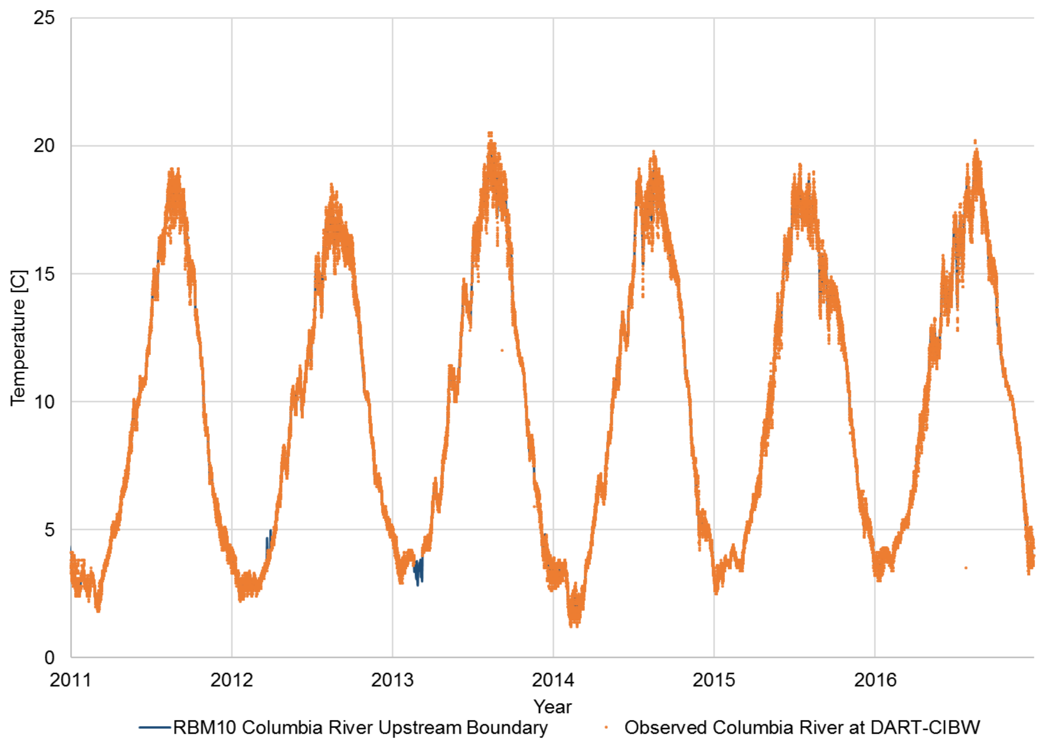

Figure A.3-1 Columbia River upstream boundary temperature inputs

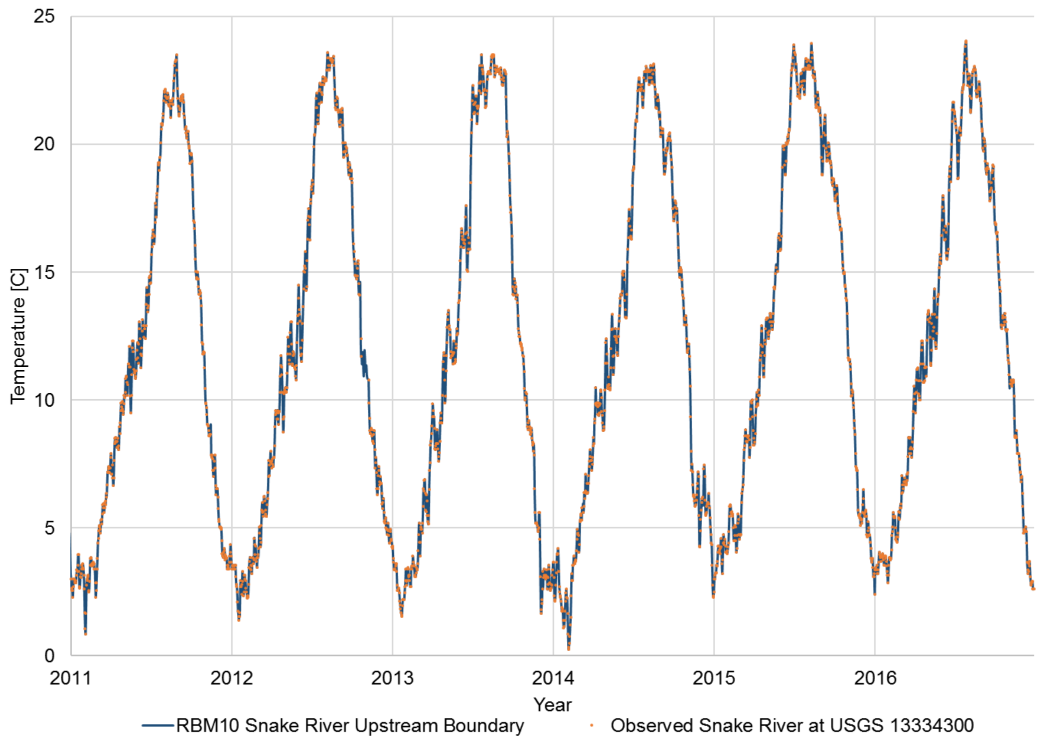

Figure A.3-2 Snake River upstream boundary temperature inputs

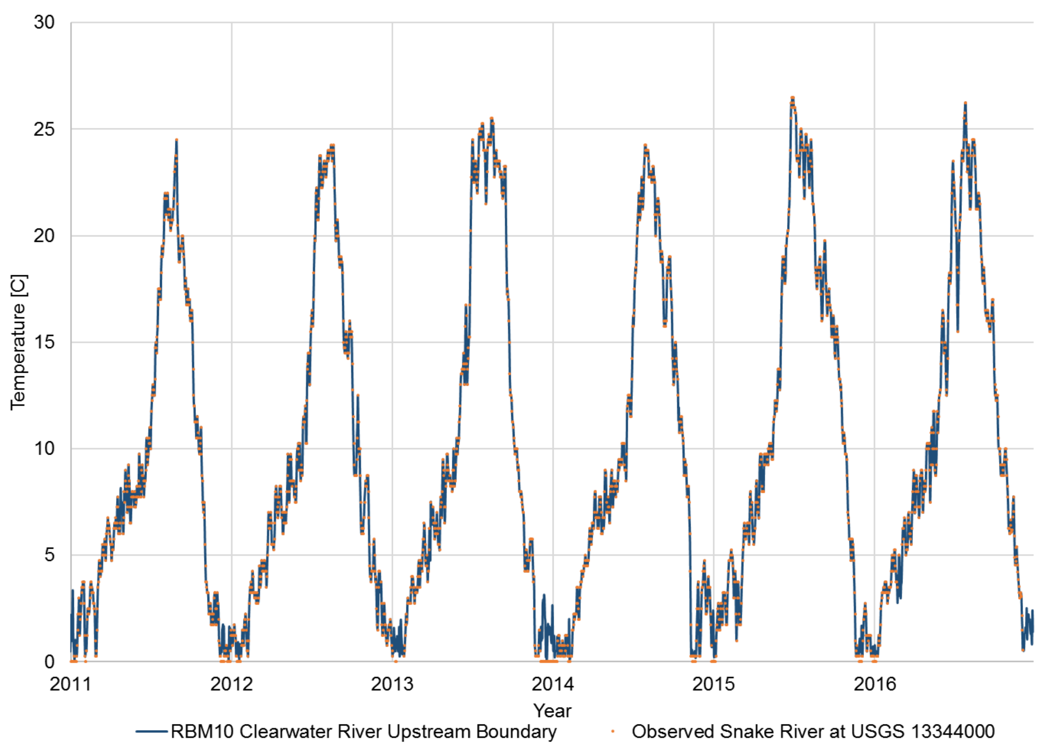

Figure A.3-3 Clearwater River upstream boundary temperature inputs

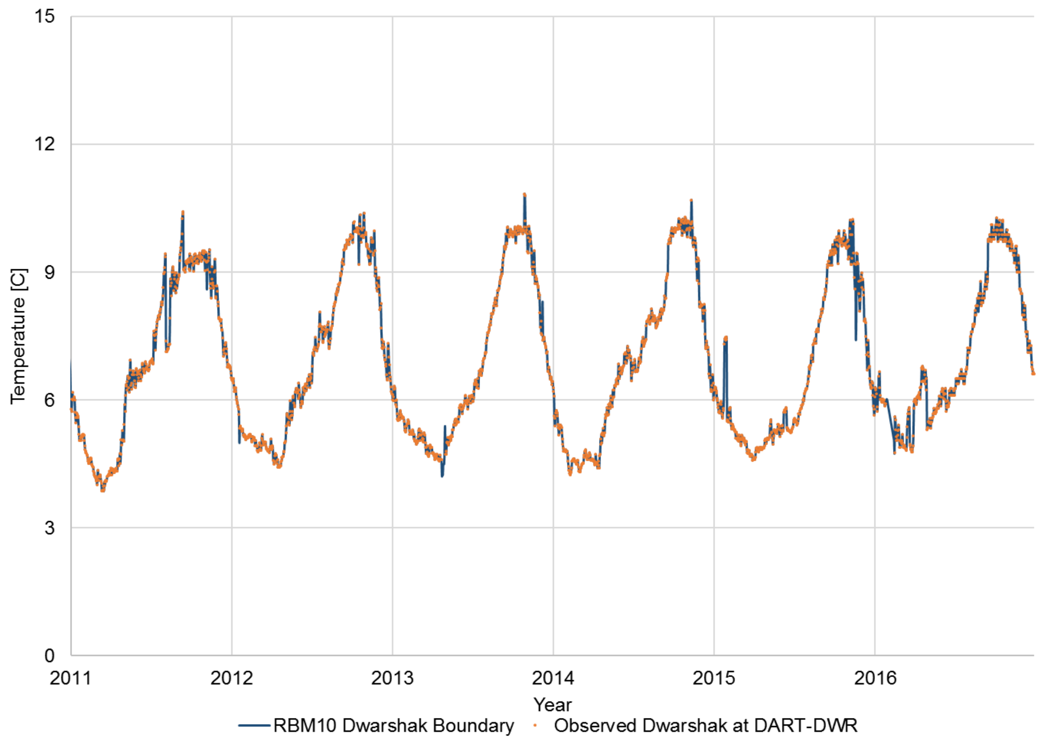

Figure A.3-4 Dworshak Dam boundary temperature inputs

A.4 Data Gap Filling Procedure for Water Temperature Inputs

As discussed in Section 2.0, the RBM10 model requires a continuous time series of water temperature at the upstream boundaries of the modeled river reaches and for every tributary entering the Columbia River and Snake River (Table 2-4). To provide the appropriate water temperature boundary conditions to the model, the forcing temperature time series must be created by compiling available observations of water temperature in the vicinity of the upstream boundaries and on the tributaries located along the Columbia River and Snake River. The available observations can be obtained from monitoring stations controlled by the USGS, USACE, and DOE (Table 2-4). A summary of the water temperature data sources and locations of monitoring stations used to develop the input time series in this project is presented in Table 2-4 and Figure 2-4.

The purpose of this appendix is to illustrate how the available observations of water temperature are processed by the RBM10 model processing tools and, in particular, to show how the data gaps are filled to generate the continuous input time series required by the model.

The process to generate forcing time series of water temperature for the RBM10 model can be summarized in three steps as follows

- Step 1: The first step is to download the available water temperature observations from USGS, USACE, or Oregon DOE for the stations located at the upstream boundaries of the modeled reaches and on the tributaries along the Columbia and Snake Rivers. Once downloaded, the observations of water temperature are organized and saved in a text file with extension .F6 which contains the date and measured temperature for each record available. An example of the data available from 2009 to 2011 at the USACE station DART-CIBW (upstream boundary of the Columbia River) is presented in Figure A.4-1. The records in the .F6 file can be discontinuous as illustrated in Figure A.4-1.
- Step 2: The second step is to run the long-term average temperature calculation tool "Avg_temp_updt_intel.exe." The Avg_temp_updt_intel.exe program reads the temperature observations stored in the .F6 file and calculates a regular and smoothed long-term daily average time series of temperatures for the station under analysis.
- Step 3: The third step is to run the processing tool "build_temp_updt_intel.exe" to fill in data gaps and generate a continuous daily time series of water temperatures. Data gaps on the order of one week or less are filled by linear interpolation. For larger gap periods, the processing tool uses the long-term average temperatures and a lag-one Markov model to fill in the missing data (Yearsley 2003).

Figure A.4-2 shows, for the period 2008 – 2011, the processed time series of water temperatures used as upstream boundary conditions for the Columbia River. In this case, the data gap in the observations available at station DART-CIBW during the year 2009 has been filled with a continuous time series of water temperatures for the RBM10 model. Additional examples of long-term data gap reconstruction for the Snake River upstream boundary and Clearwater River upstream boundary are presented from Figure A.4-3 through Figure A.4-6.

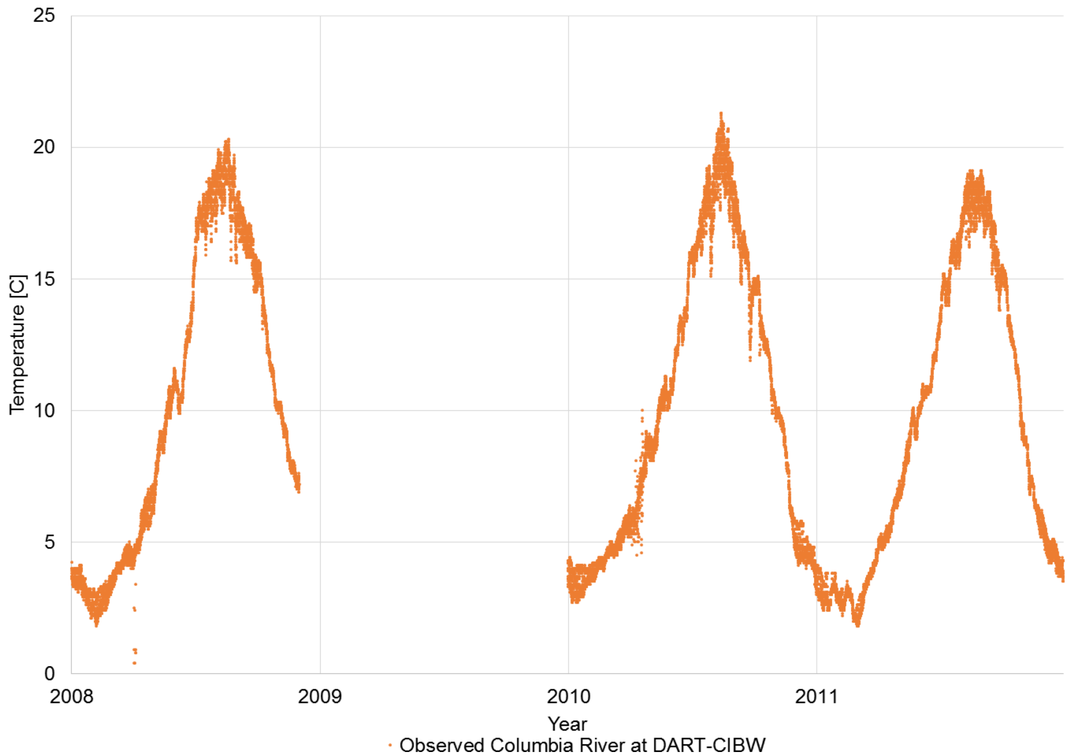

Figure A.4-1 Available water temperature observations at DART-CIBW station (2008 – 2011)

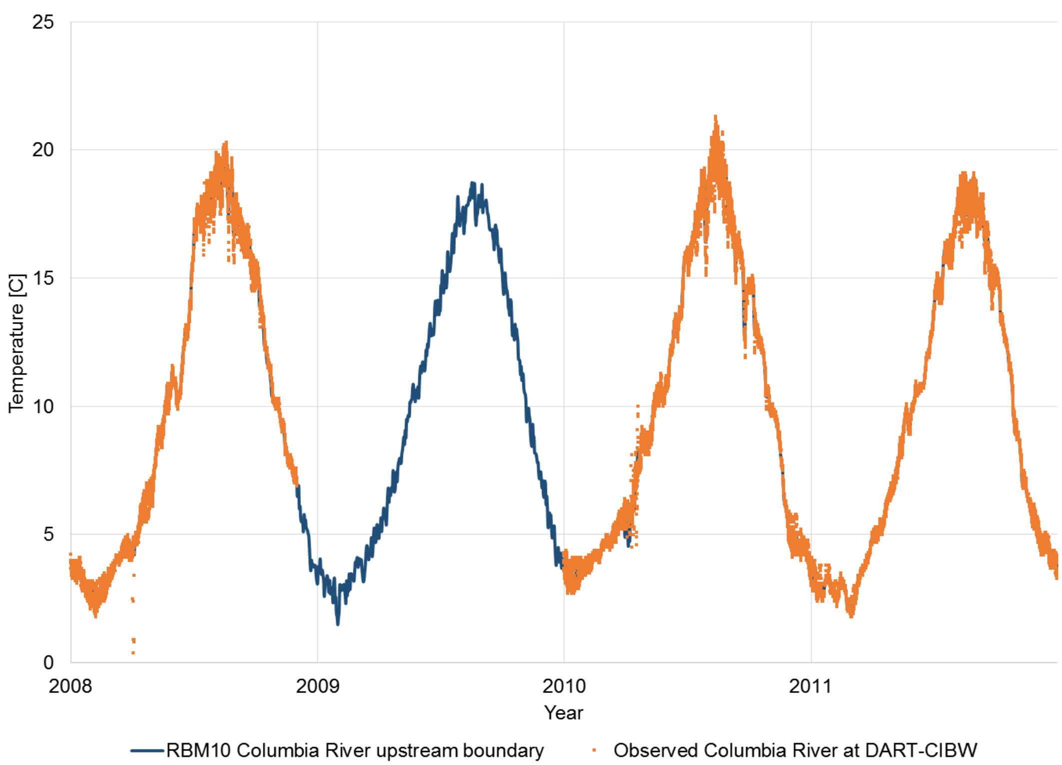

Figure A.4-2 Water temperature boundary conditions at the Columbia River upstream boundary (blue line) from observations available at DART-CIBW station (2008 – 2011)

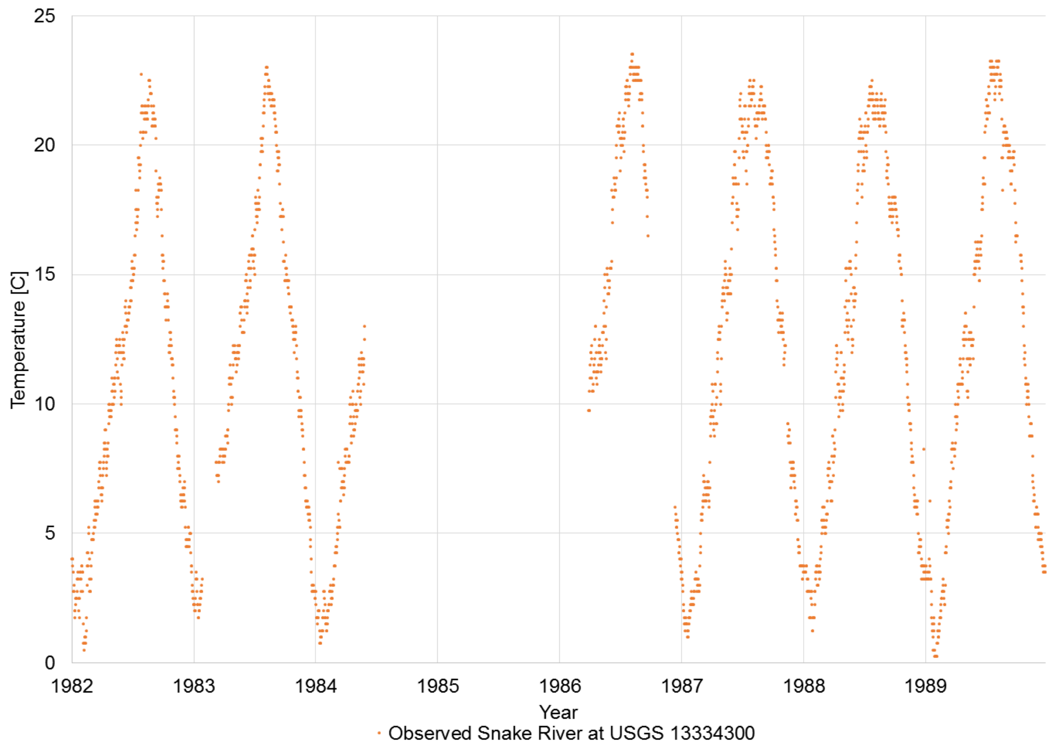

Figure A.4-3 Available water temperature observations at USGS 13334300 (1982 – 1990)

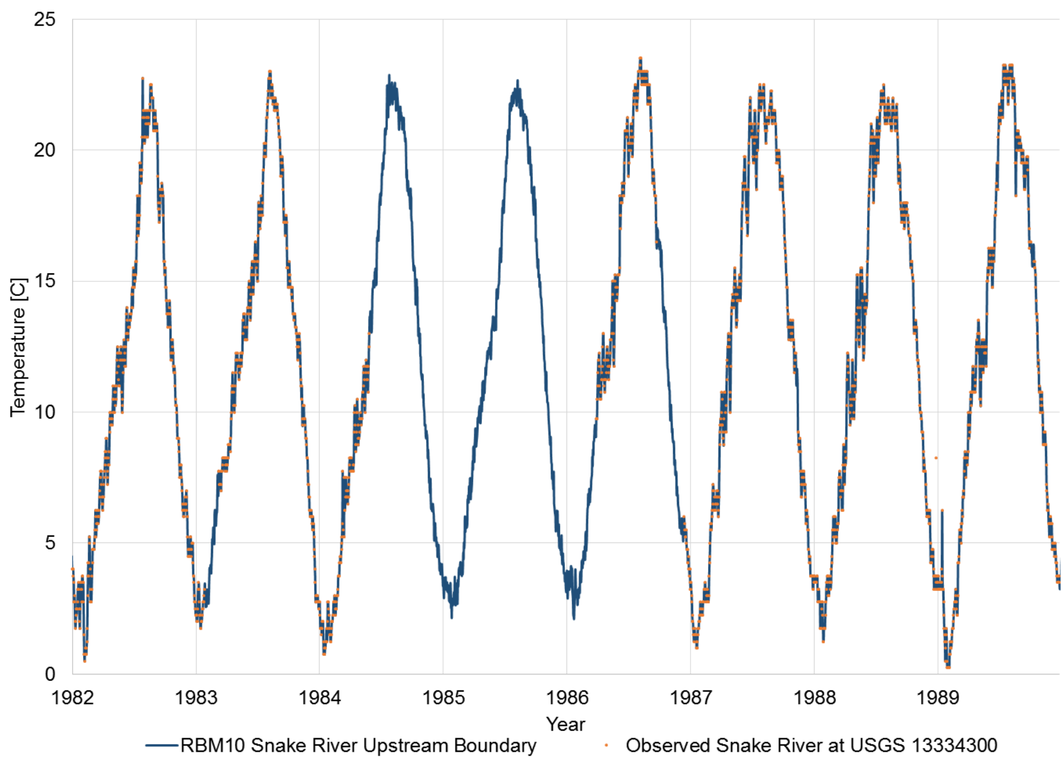

Figure A.4-4 Water temperature boundary conditions at the Snake River upstream boundary (blue line) from observations available at USGS 13334300 (1982 – 1990)

Figure A.4-5 Available water temperature observations at USGS 13344000 (1996 – 2001)

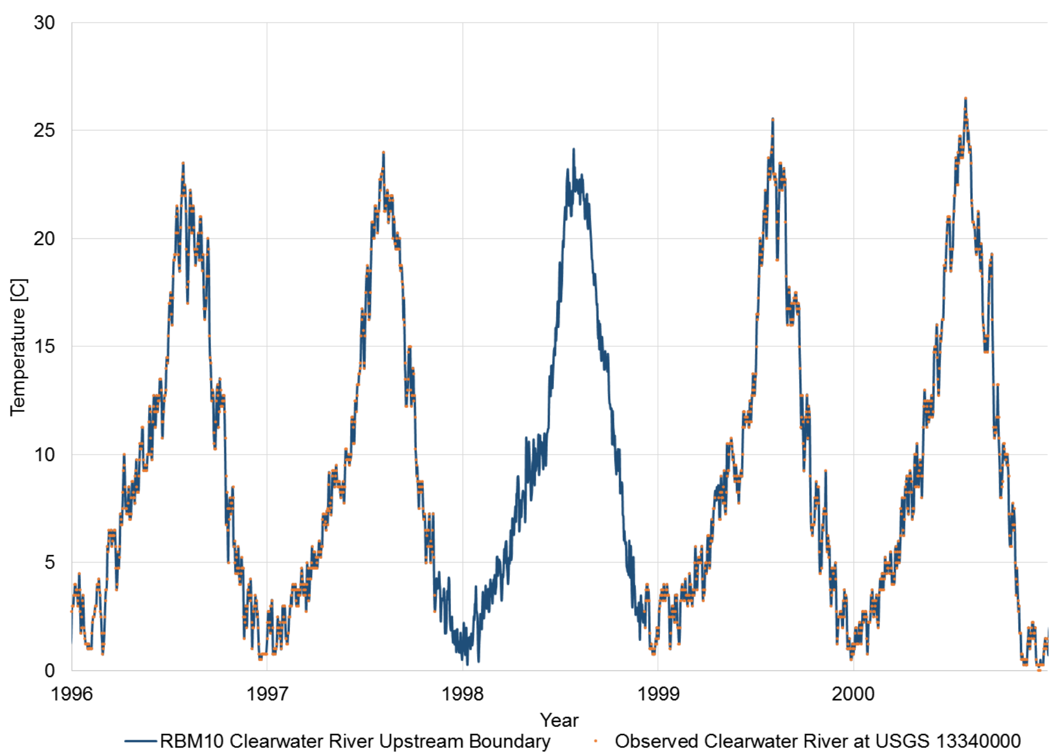

Figure A.4-6 Water temperature boundary conditions at the Clearwater River upstream boundary (blue line) from observations available at USGS 13340000 (1996 – 2001)

Appendix B Flow and Velocity Simulation Results

B.1 Flow Simulation

Graphical comparisons between observed and simulated flow discharges along the Columbia River and Snake River are presented from Figure B.1-1 through Figure B.1-30.

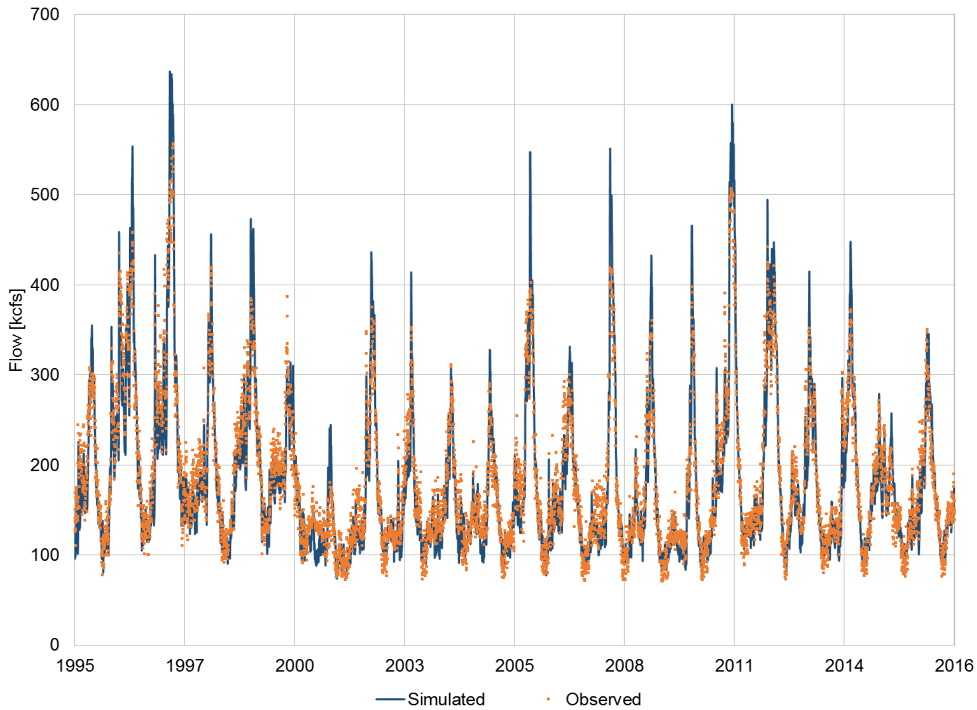

Figure B.1-1 Simulated versus observed flow at BON, Columbia River RM 146

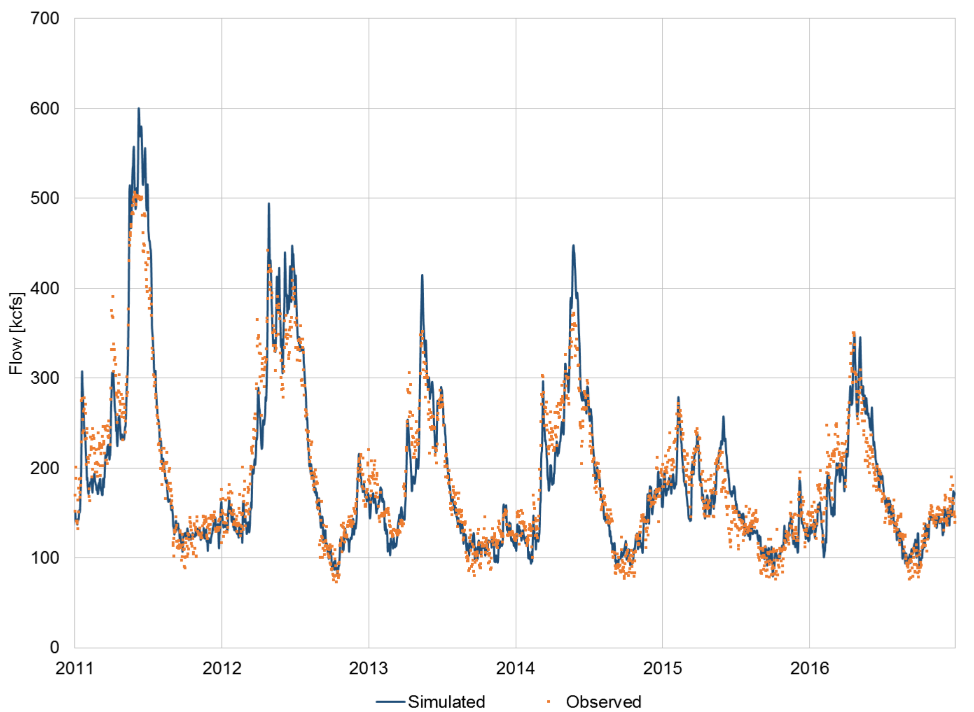

Figure B.1-2 Simulated versus observed flow at BON, period 2011 – 2016

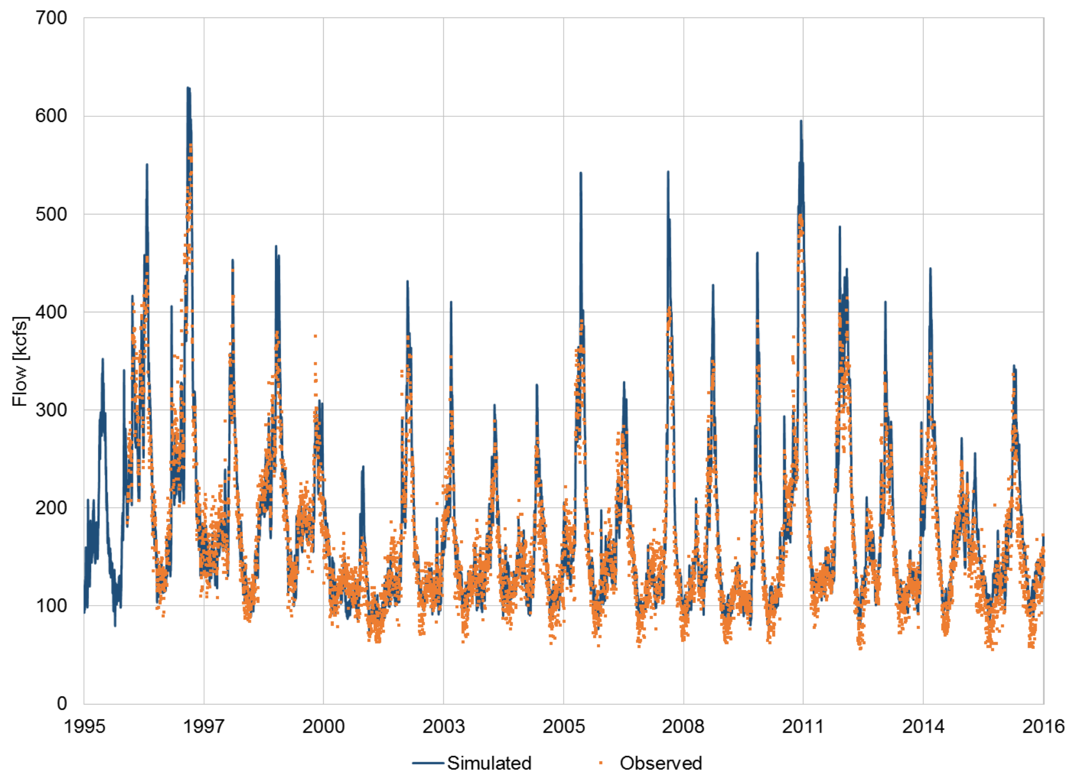

Figure B.1-3 Simulated versus observed flow at TDDO, Columbia River RM 190

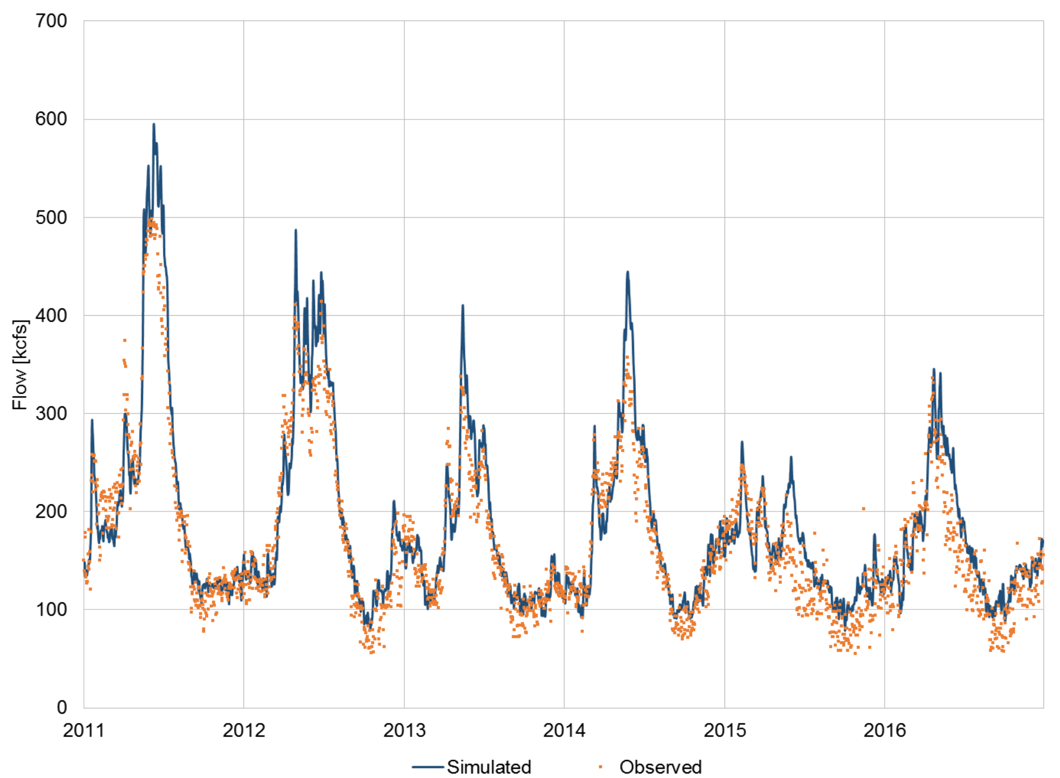

Figure B.1-4 Simulated versus observed flow at TDDO, period 2011 – 2016

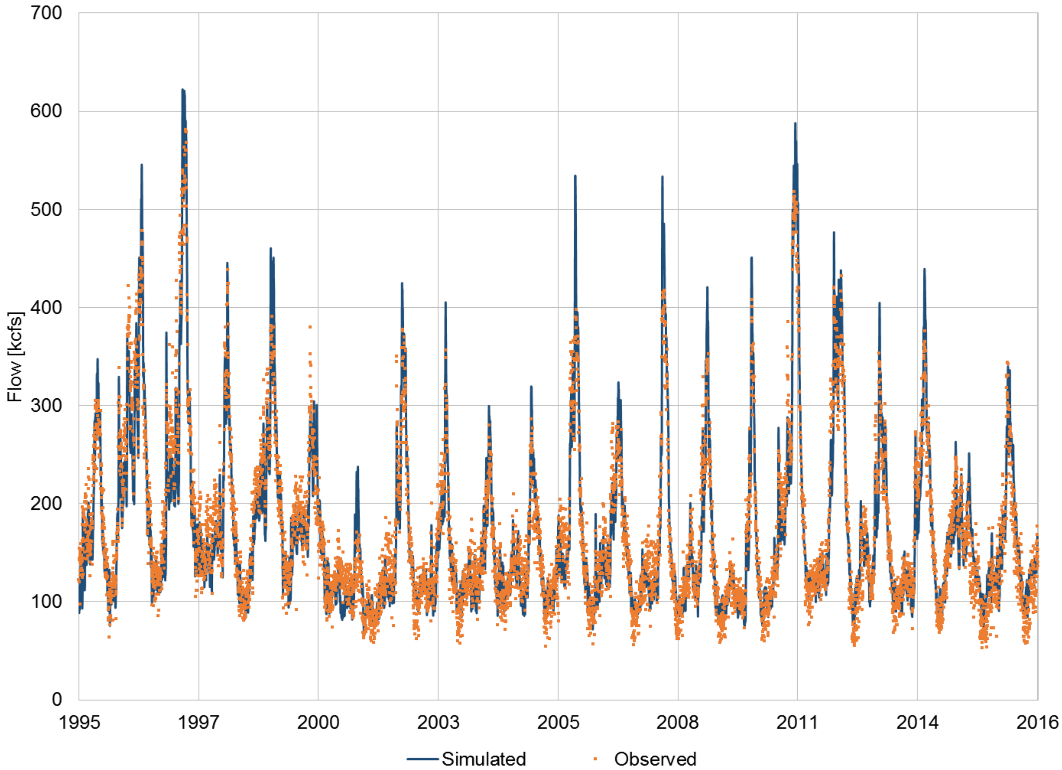

Figure B.1-5 Simulated versus observed flow at JHAW, Columbia River RM 215

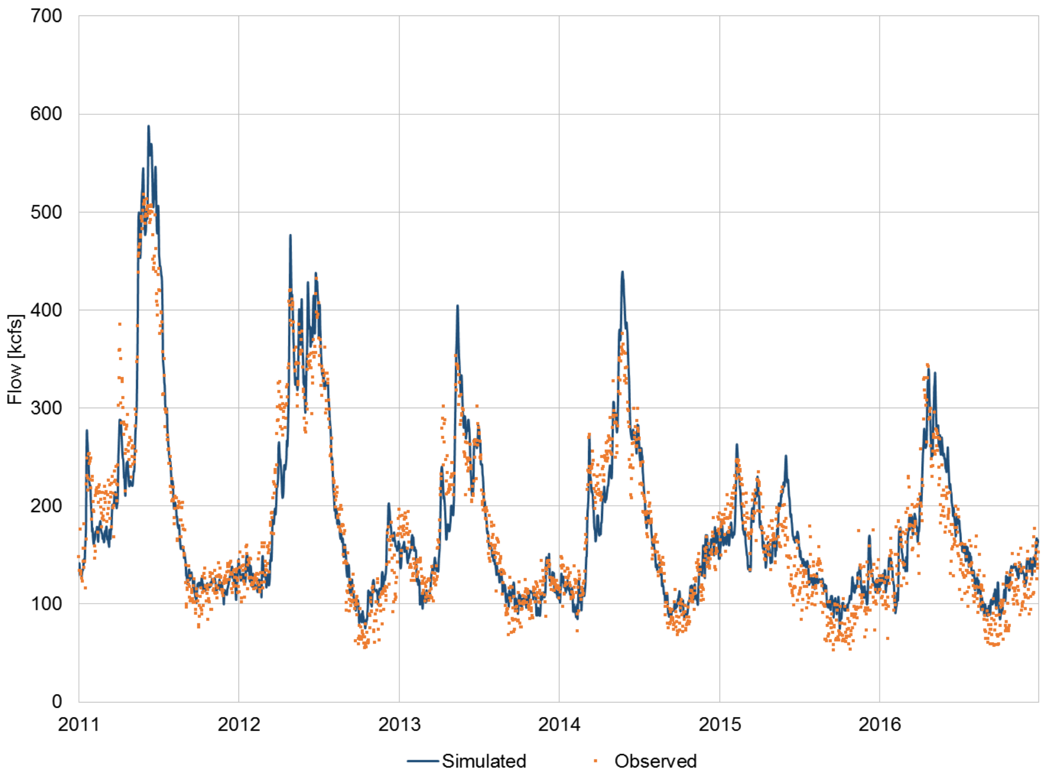

Figure B.1-6 Simulated versus observed flow at JHAW, period 2011 – 2016

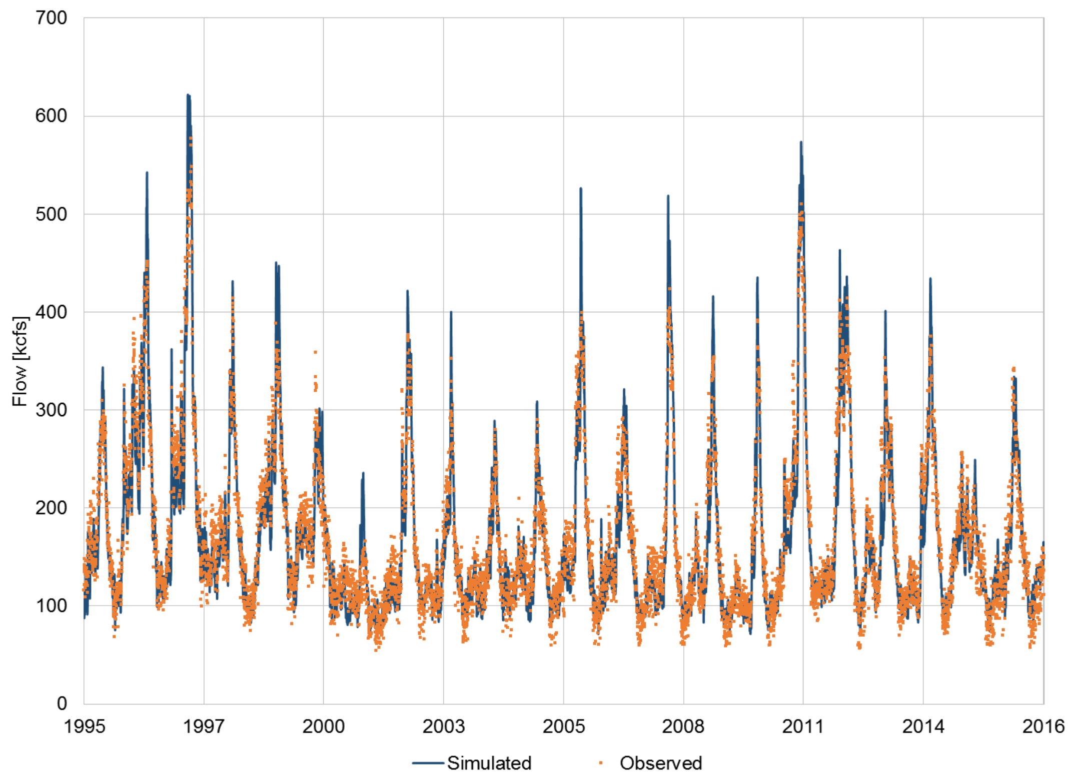

Figure B.1-7 Simulated versus observed flow at MCPW, Columbia River RM 291

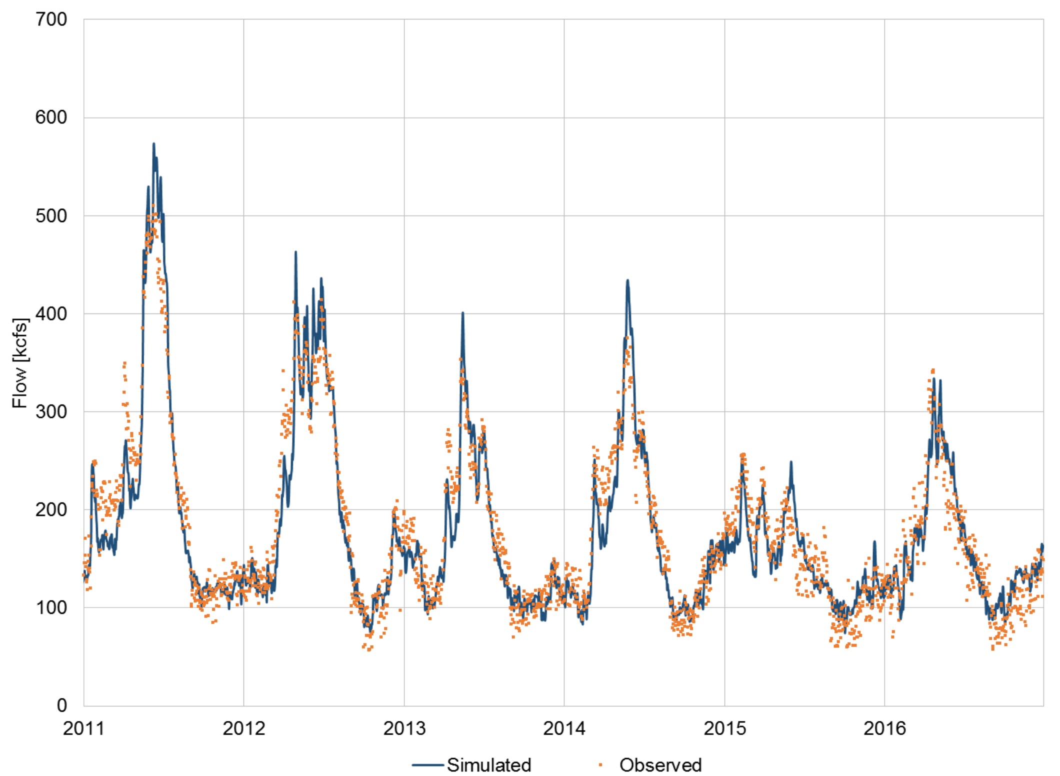

Figure B.1-8 Simulated versus observed flow at MCPW, period 2011 – 2016

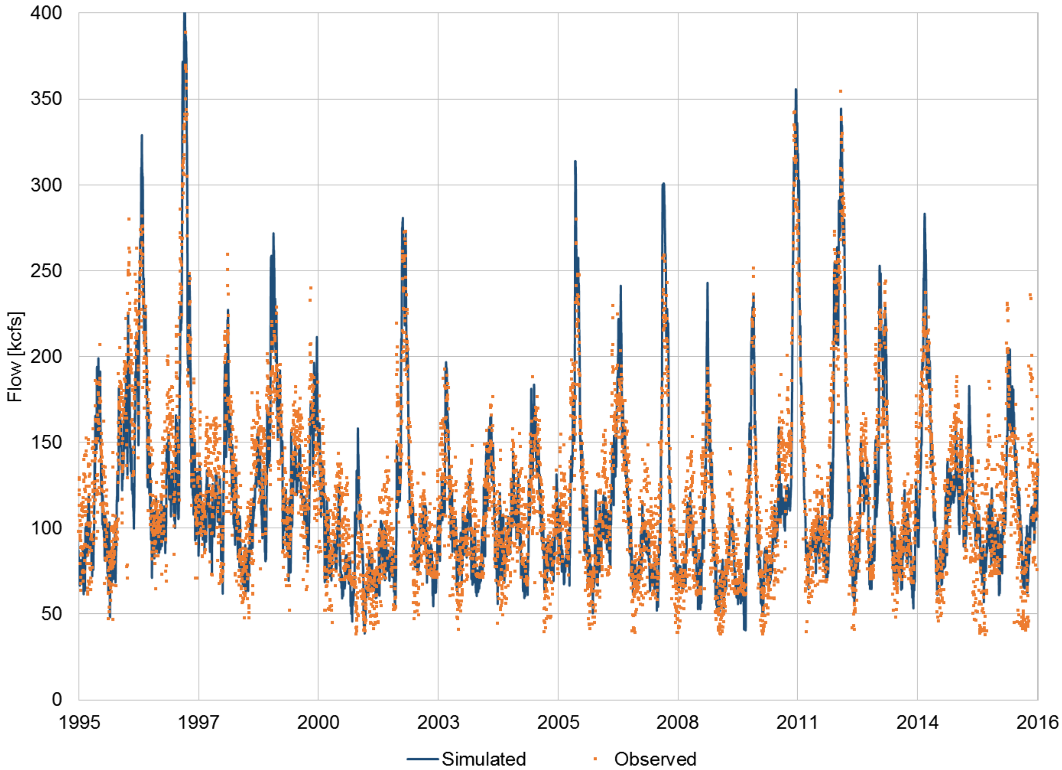

Figure B.1-9 Simulated versus observed flow at PRXW, Columbia River RM 396

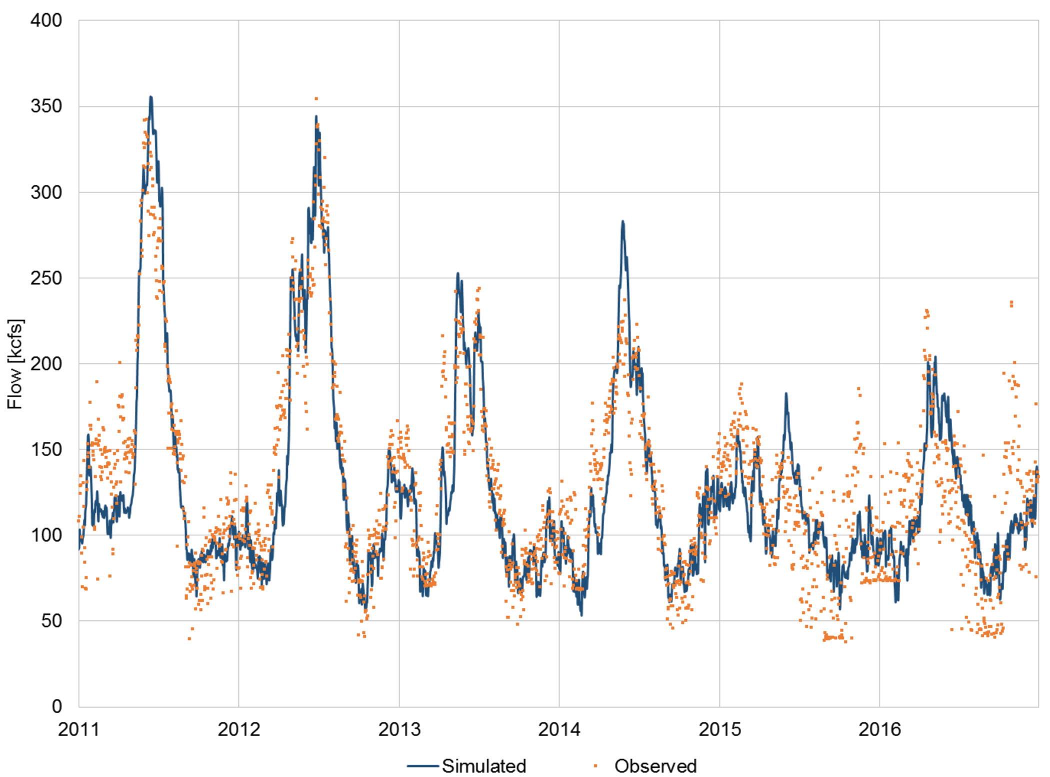

Figure B.1-10 Simulated versus observed flow at PRXW, period 2011 – 2016

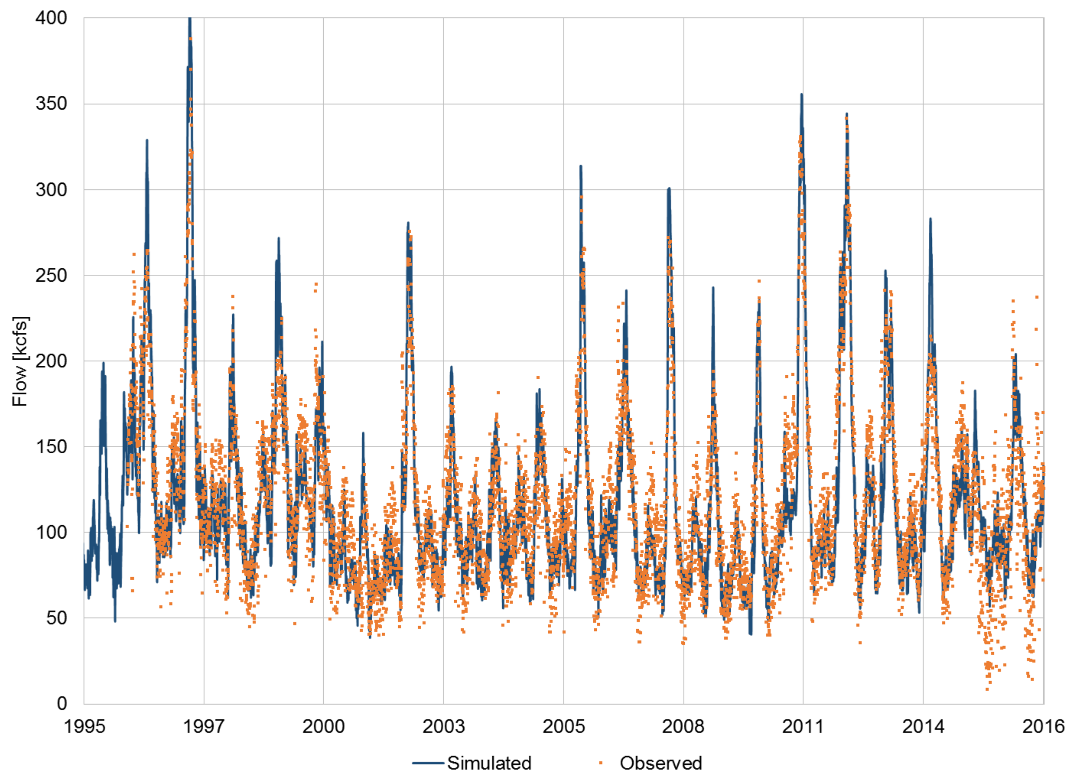

Figure B.1-11 Simulated versus observed flow at WANW, Columbia River RM 415

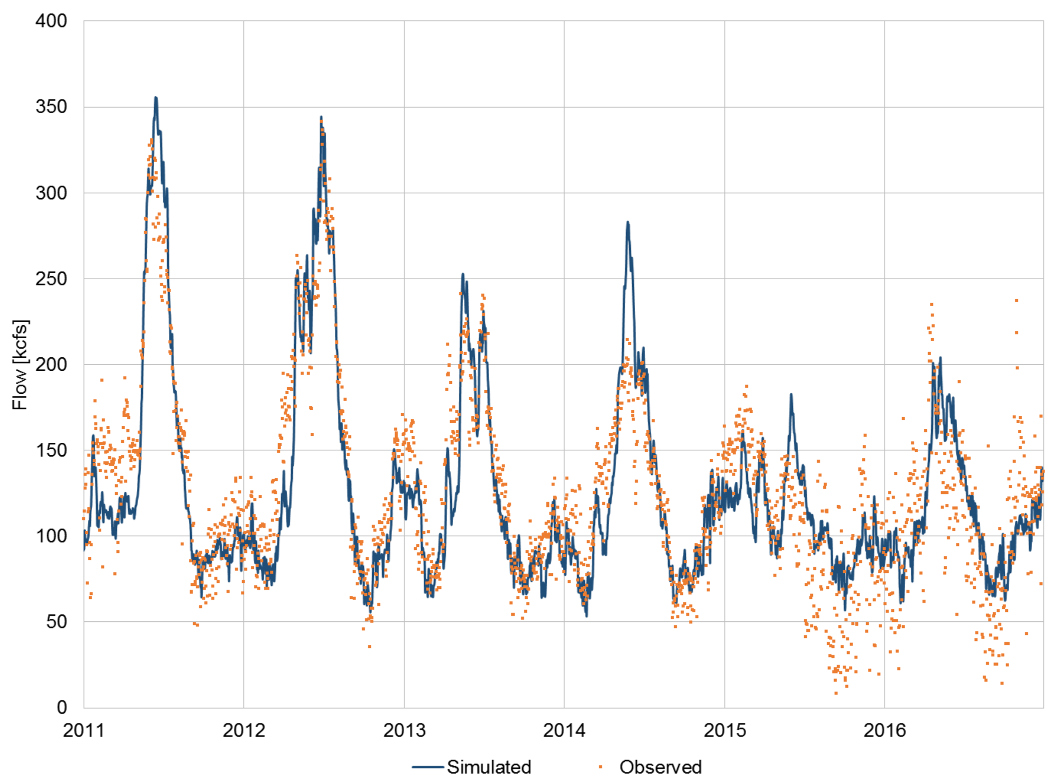

Figure B.1-12 Simulated versus observed flow at WANW, period 2011 – 2016

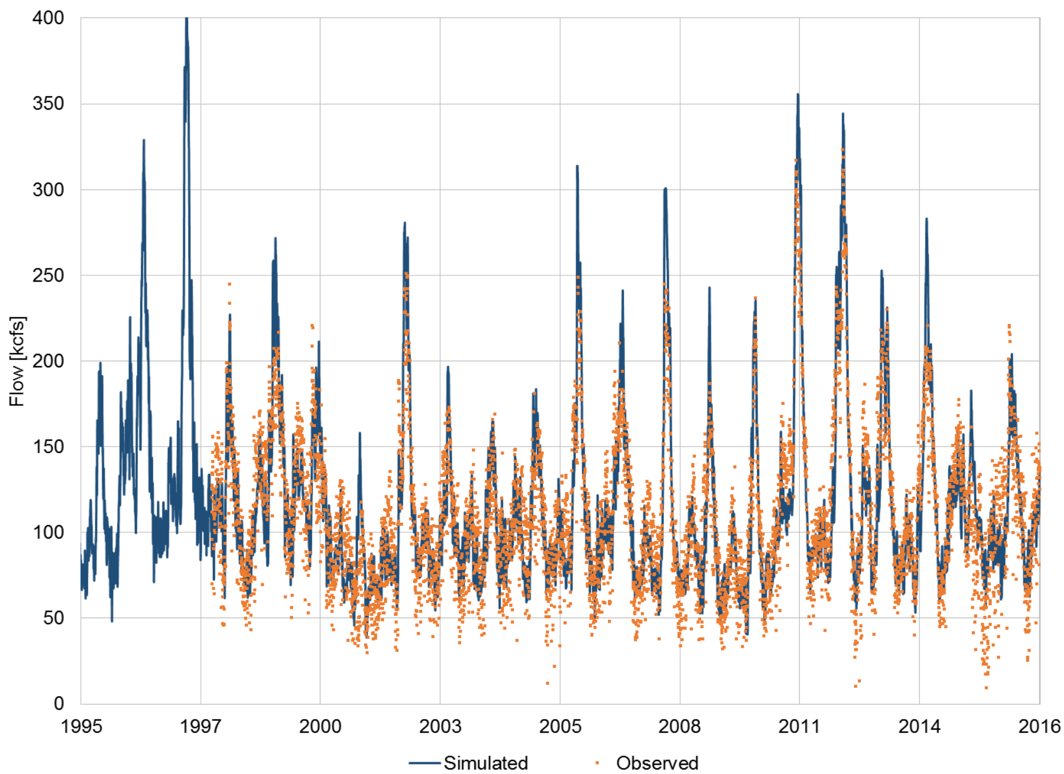

Figure B.1-13 Simulated versus observed flow at RIGW, Columbia River RM 452

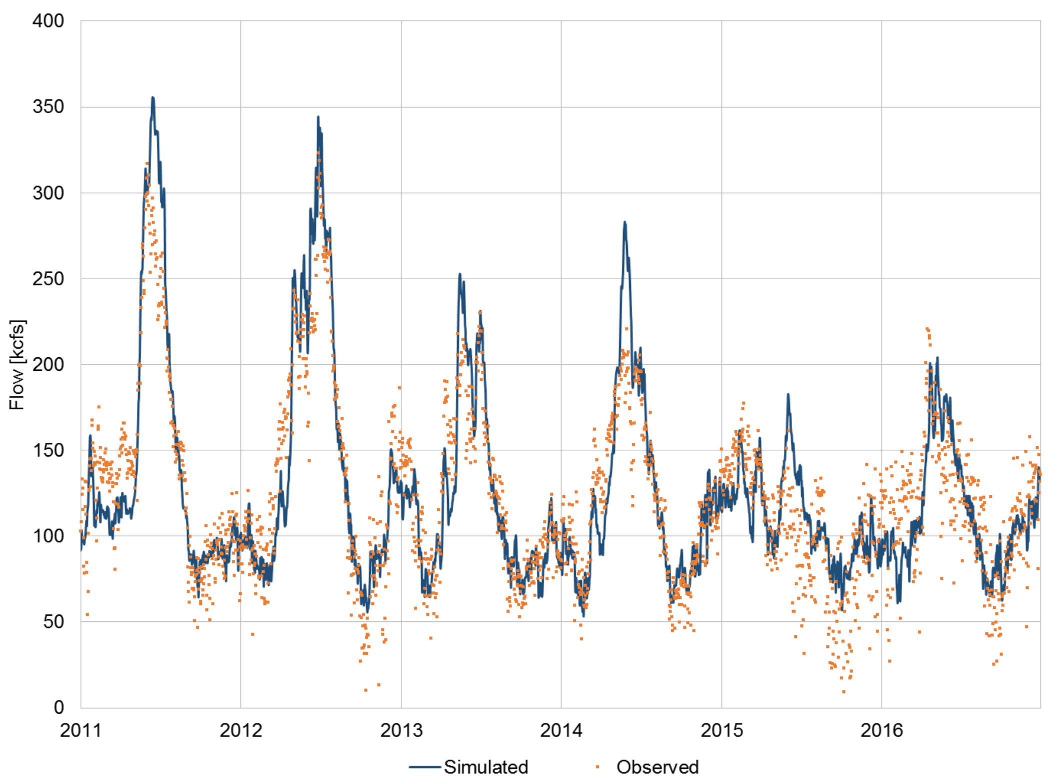

Figure B.1-14 Simulated versus observed flow at RIGW, period 2011 – 2016

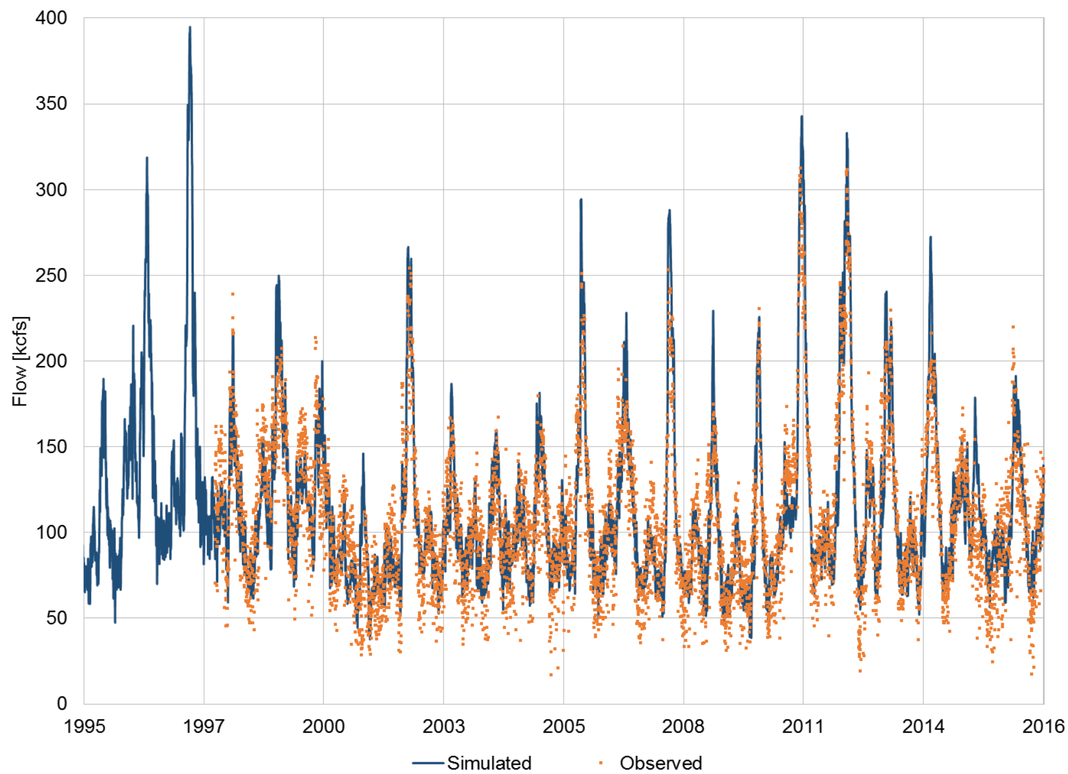

Figure B.1-15 Simulated versus observed flow at RRDW, Columbia River RM 472

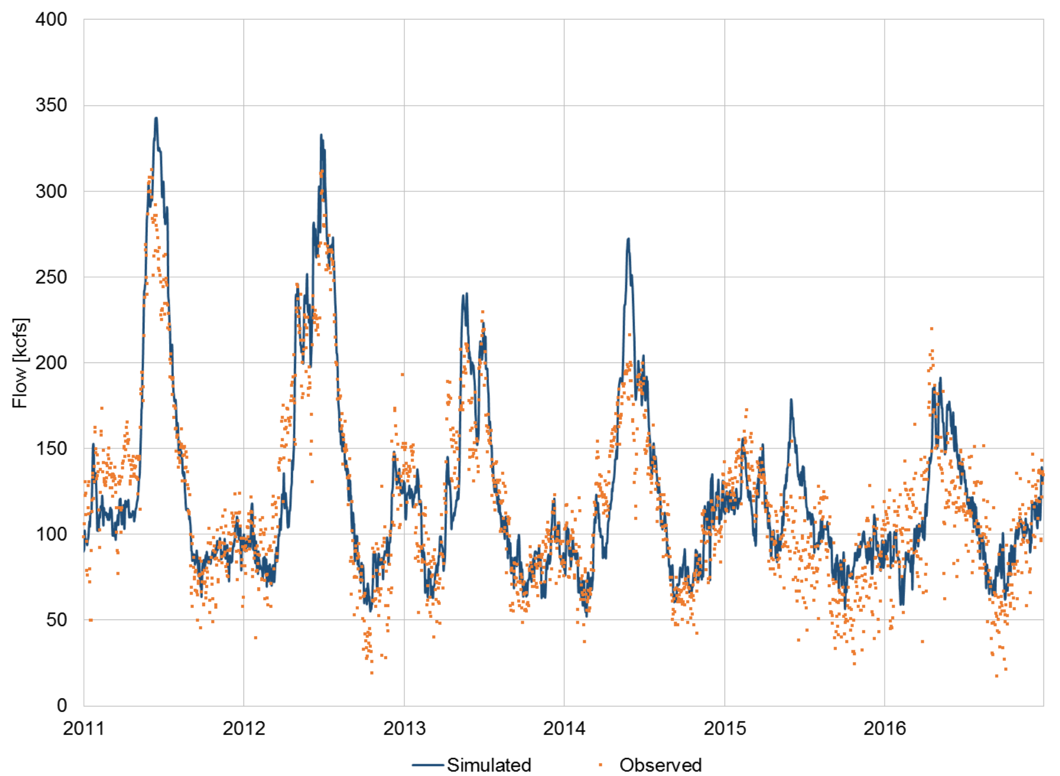

Figure B.1-16 Simulated versus observed flow at RRDW, period 2011 – 2016

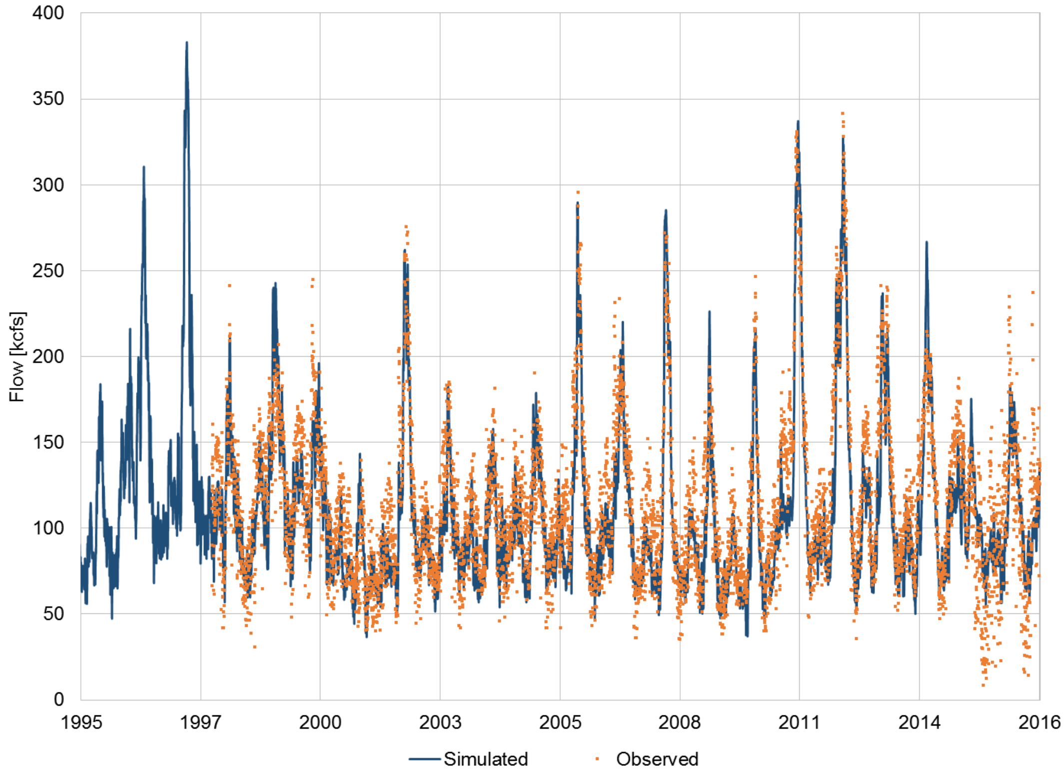

Figure B.1-17 Simulated versus observed flow at WELW, Columbia River RM 514

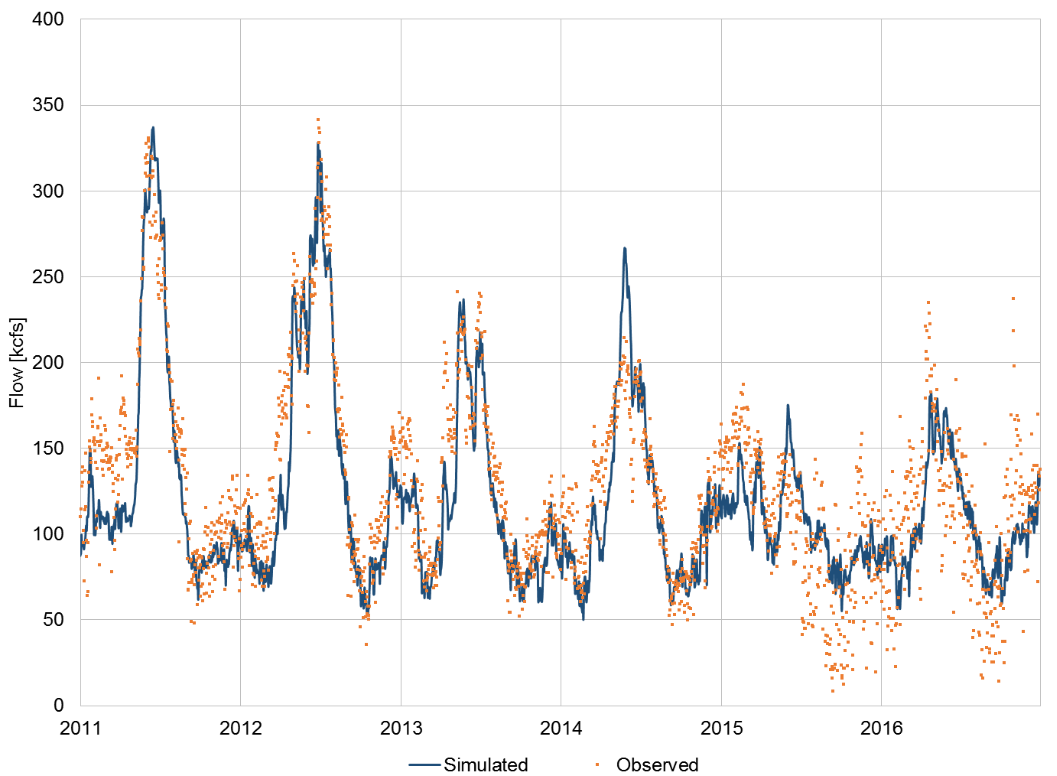

Figure B.1-18 Simulated versus observed flow at WELW, period 2011 – 2016

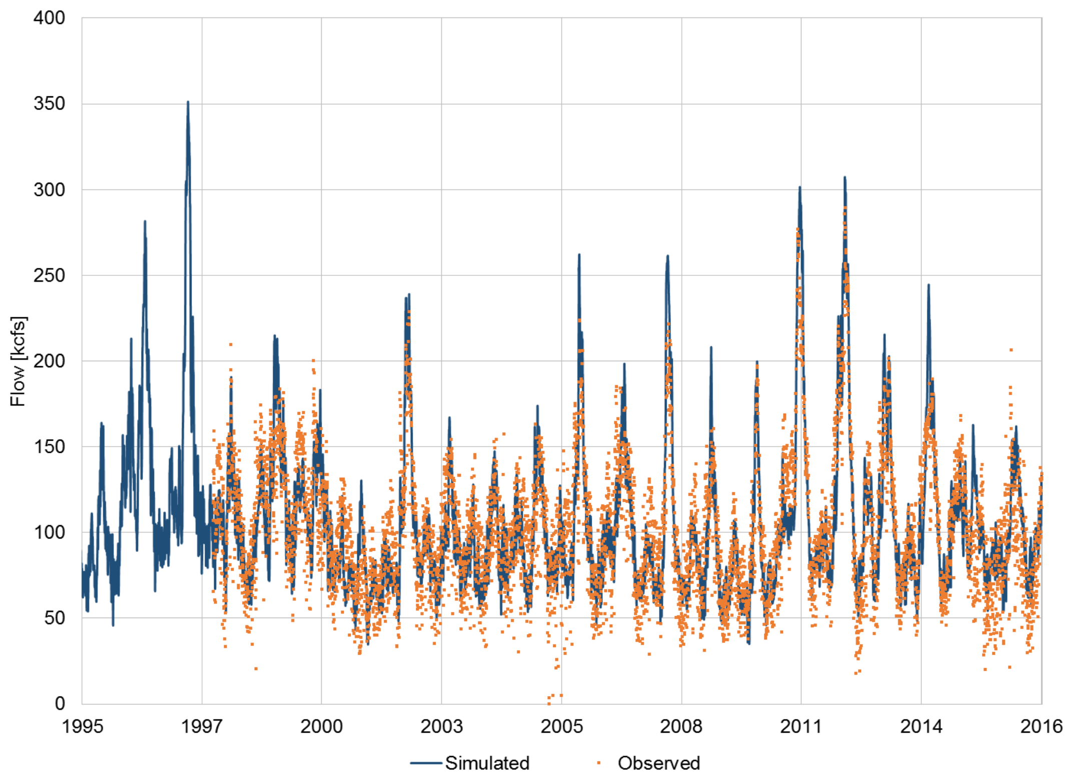

Figure B.1-19 Simulated versus observed flow at CHQW, Columbia River RM 545

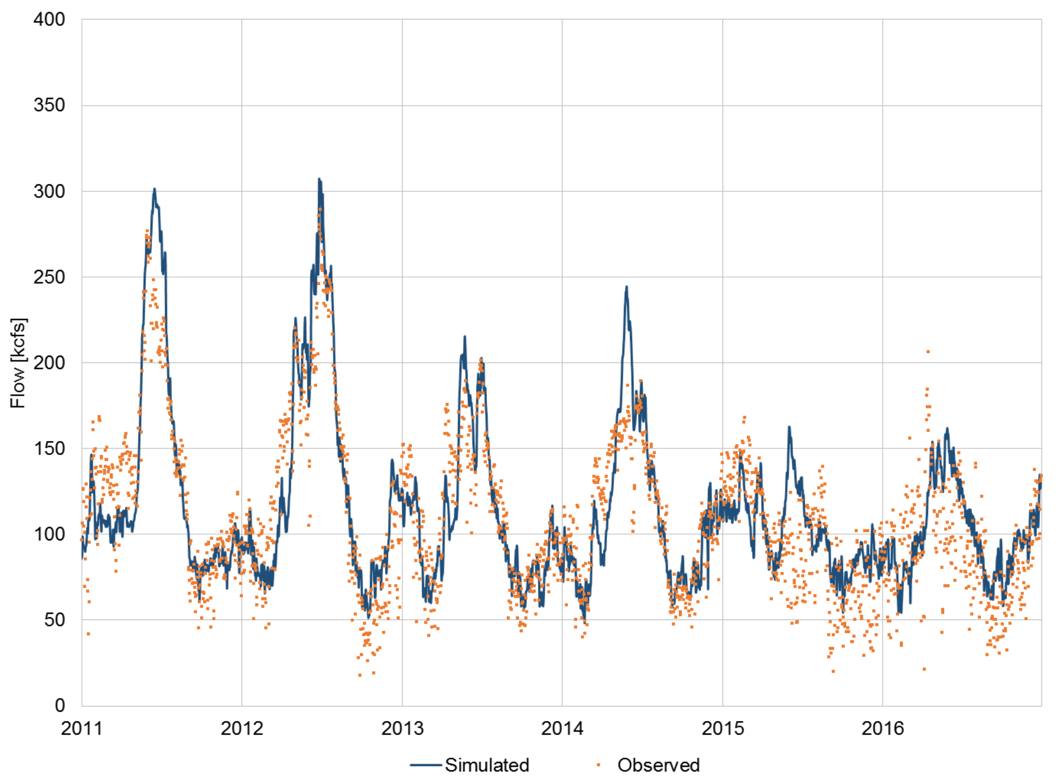

Figure B.1-20 Simulated versus observed flow at CHQW, period 2011 – 2016

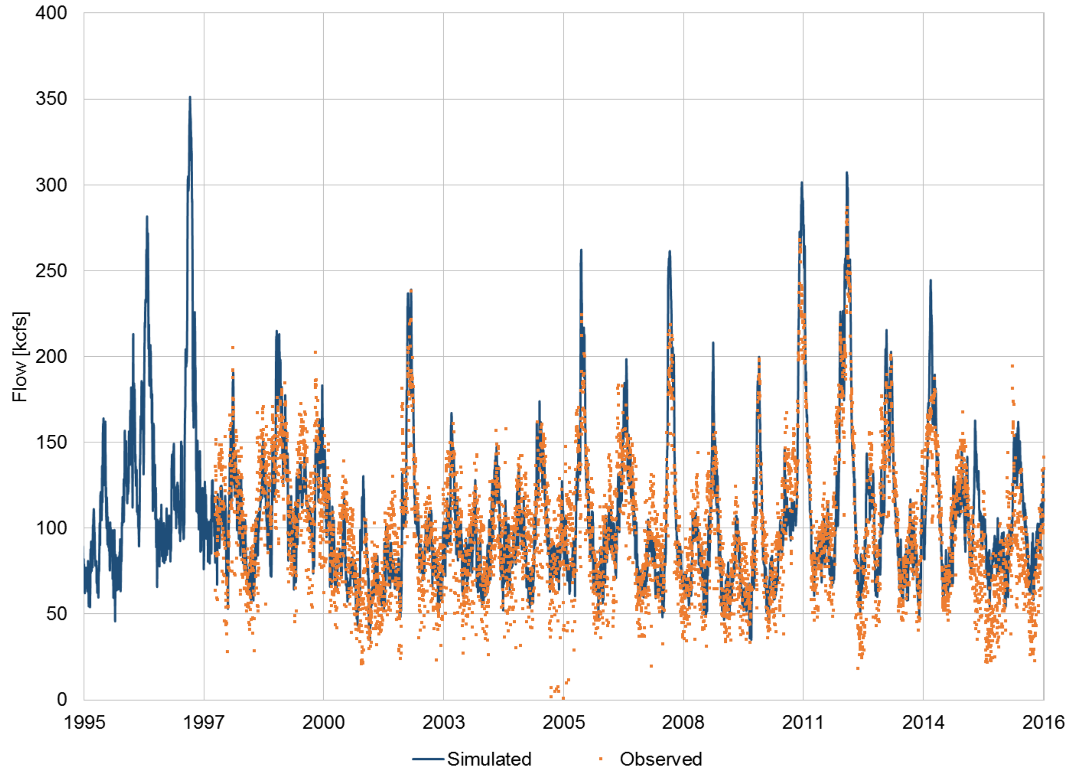

Figure B.1-21 Simulated versus observed flow at GCGW, Columbia River RM 590

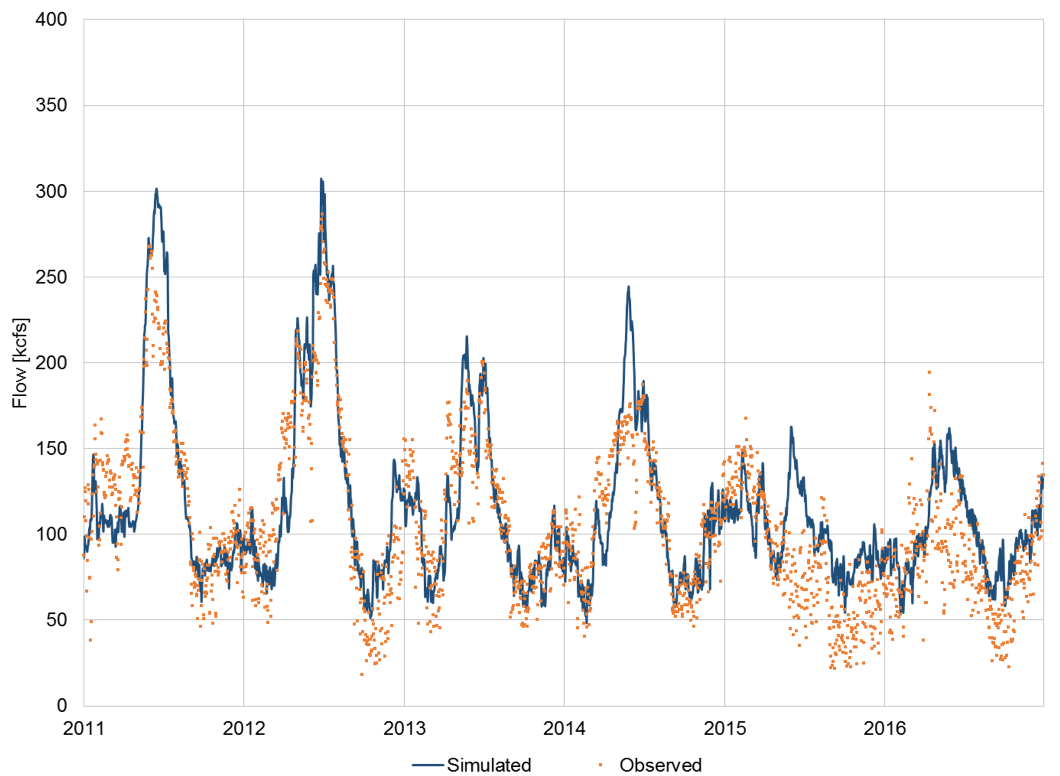

Figure B.1-22 Simulated versus observed flow at GCGW, period 2011 – 2016

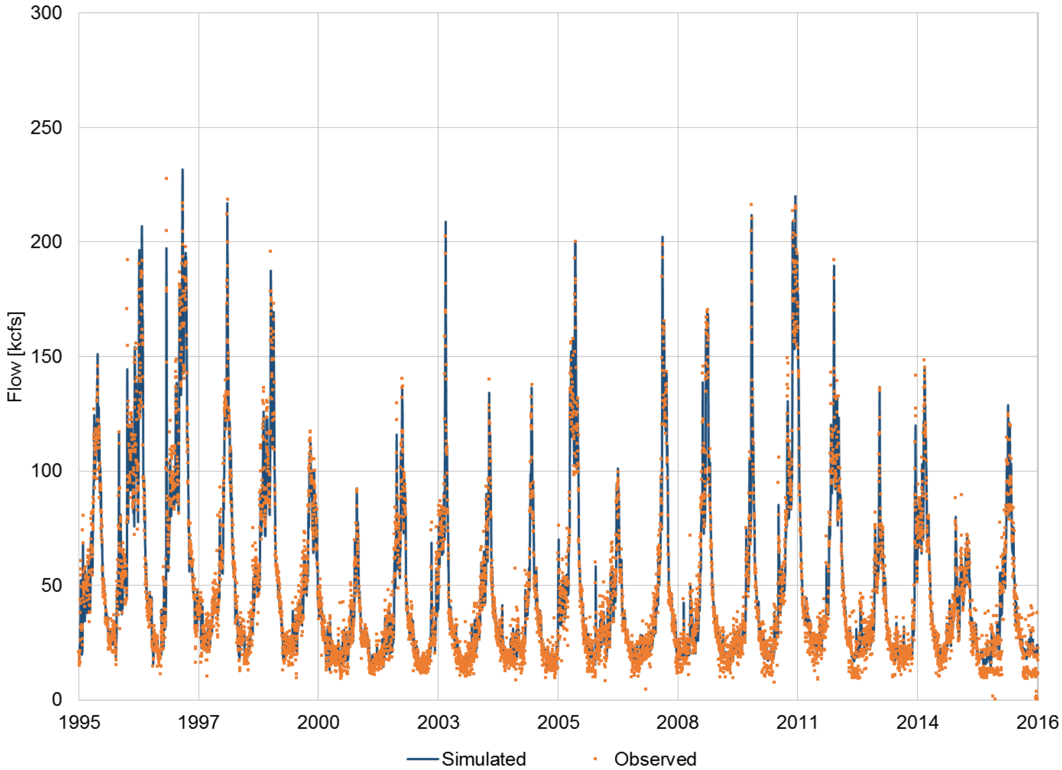

Figure B.1-23 Simulated versus observed flow at IDSW, Snake River RM 6.8

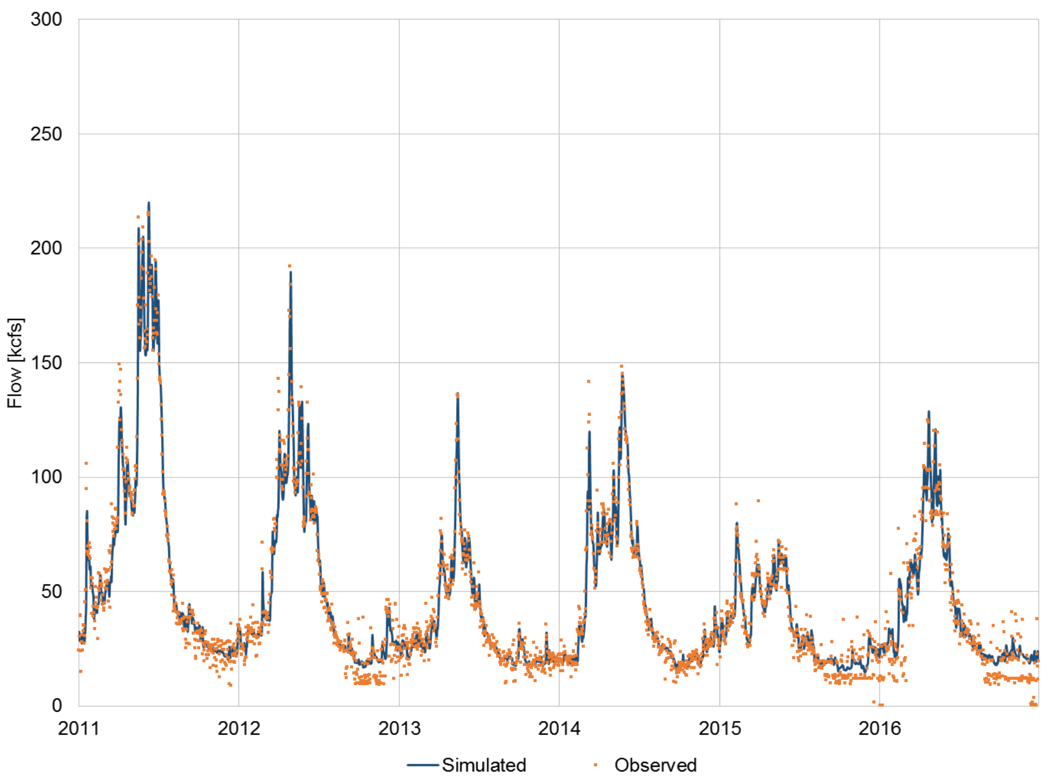

Figure B.1-24 Simulated versus observed flow at IDSW, period 2011 – 2016

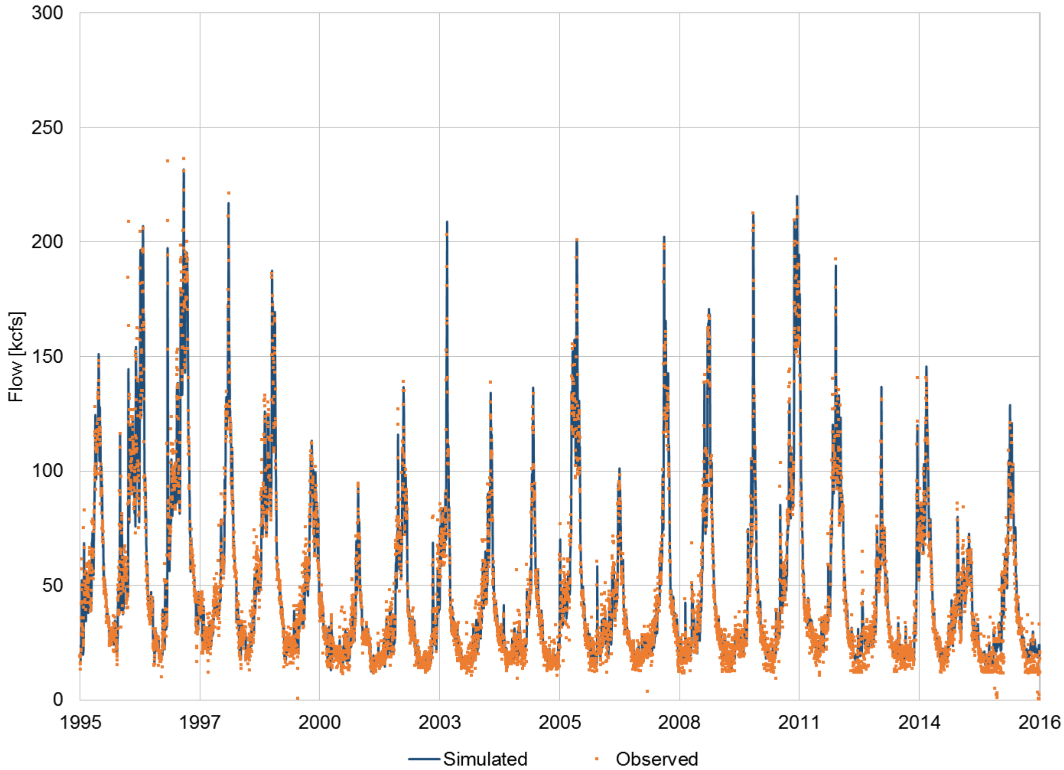

Figure B.1-25 Simulated versus observed flow at LMNW, Snake River RM 40.8

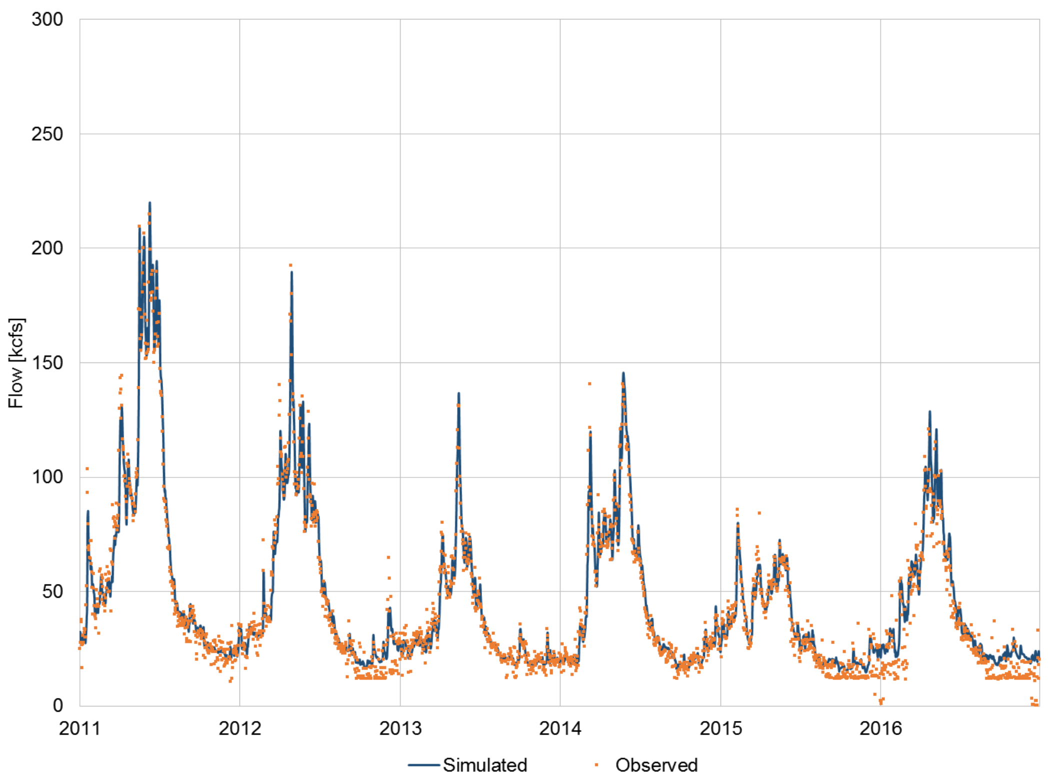

Figure B.1-26 Simulated versus observed flow at LMNW, period 2011 – 2016

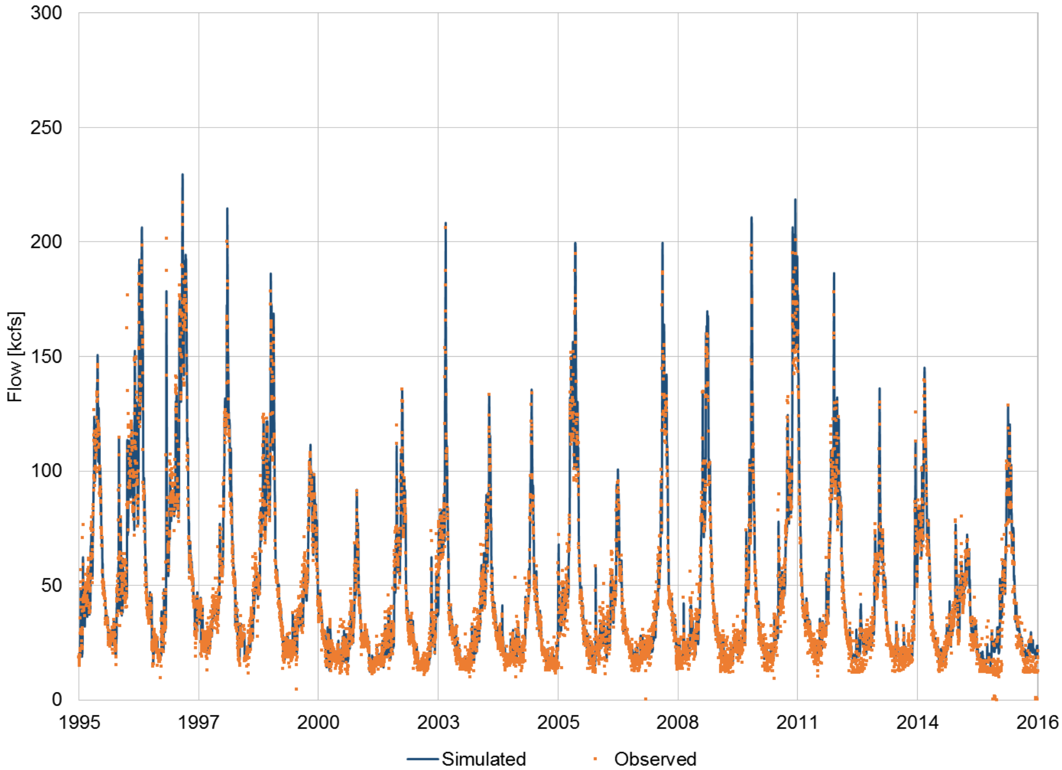

Figure B.1-27 Simulated versus observed flow at LGSW, Snake River RM 69.5

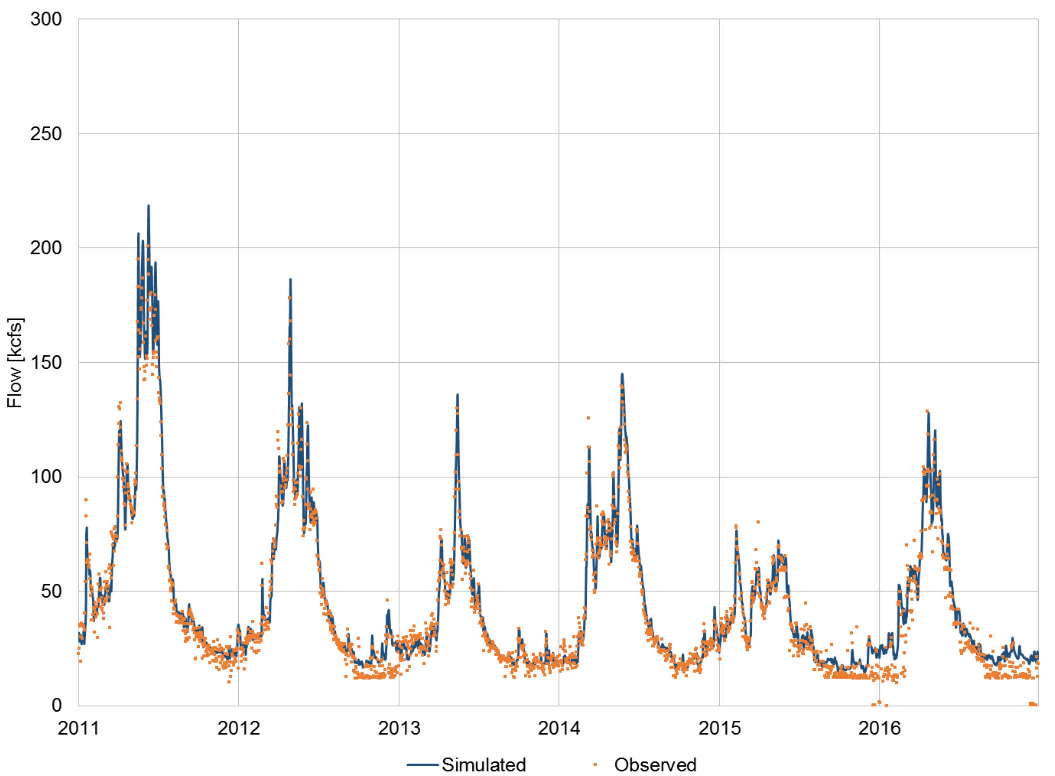

Figure B.1-28 Simulated versus observed flow at LGSW, period 2011 – 2016

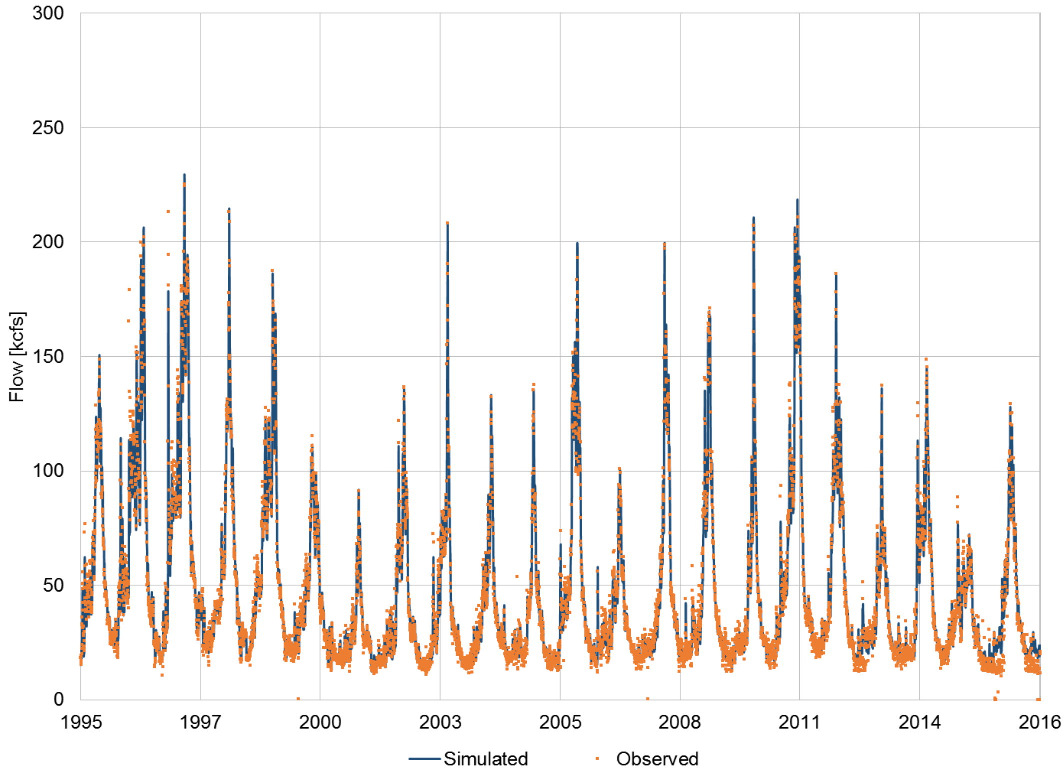

Figure B.1-29 Simulated versus observed flow at LGNW, Snake River RM 106.8

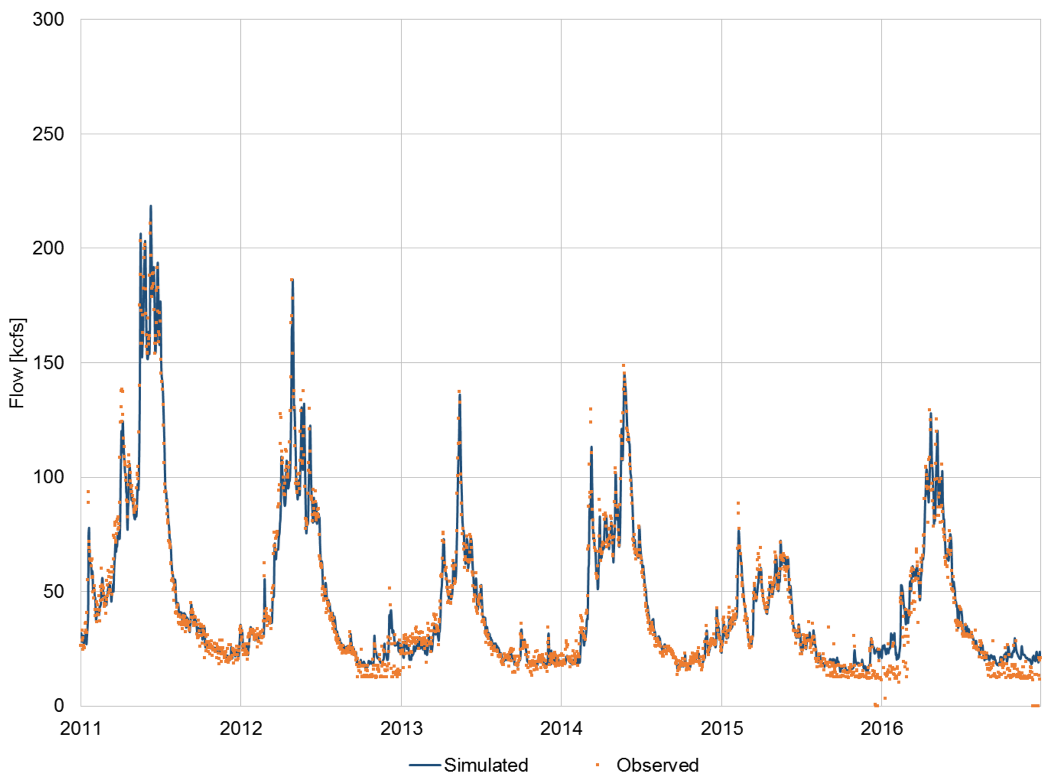

Figure B.1-30 Simulated versus observed flow at LGNW, period 2011 – 2016

B.2 Velocity Results

Simulation results of velocity along the Columbia River and Snake River are presented from Figure B.2-1 through Figure B.2-30

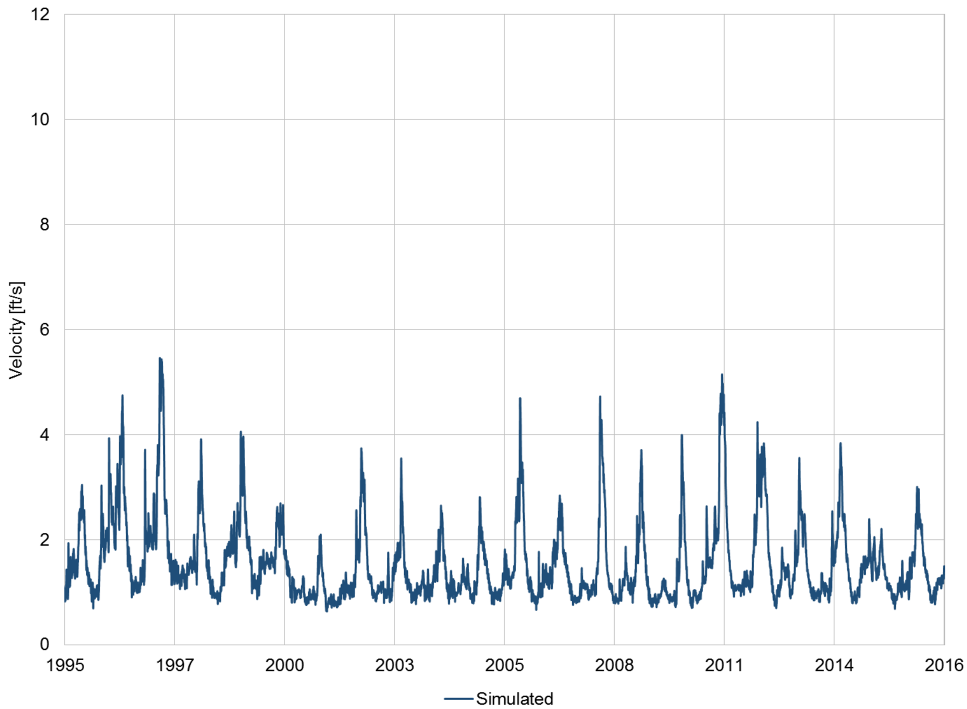

Figure B.2-1 Simulated velocity at BON, Columbia River RM 146

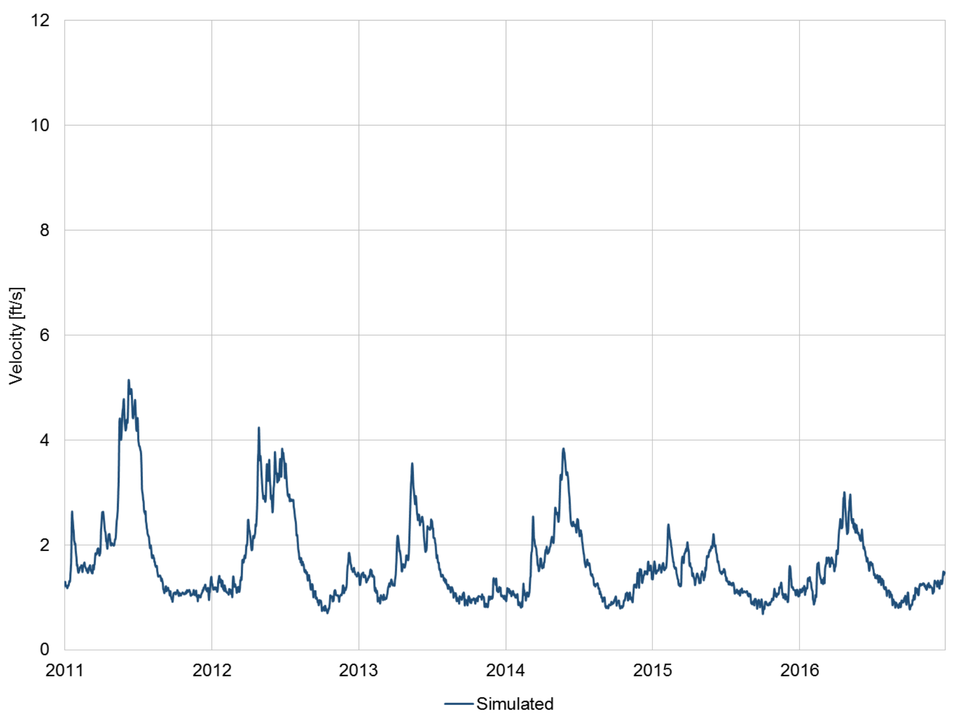

Figure B.2-2 Simulated velocity at BON, period 2011 – 2016

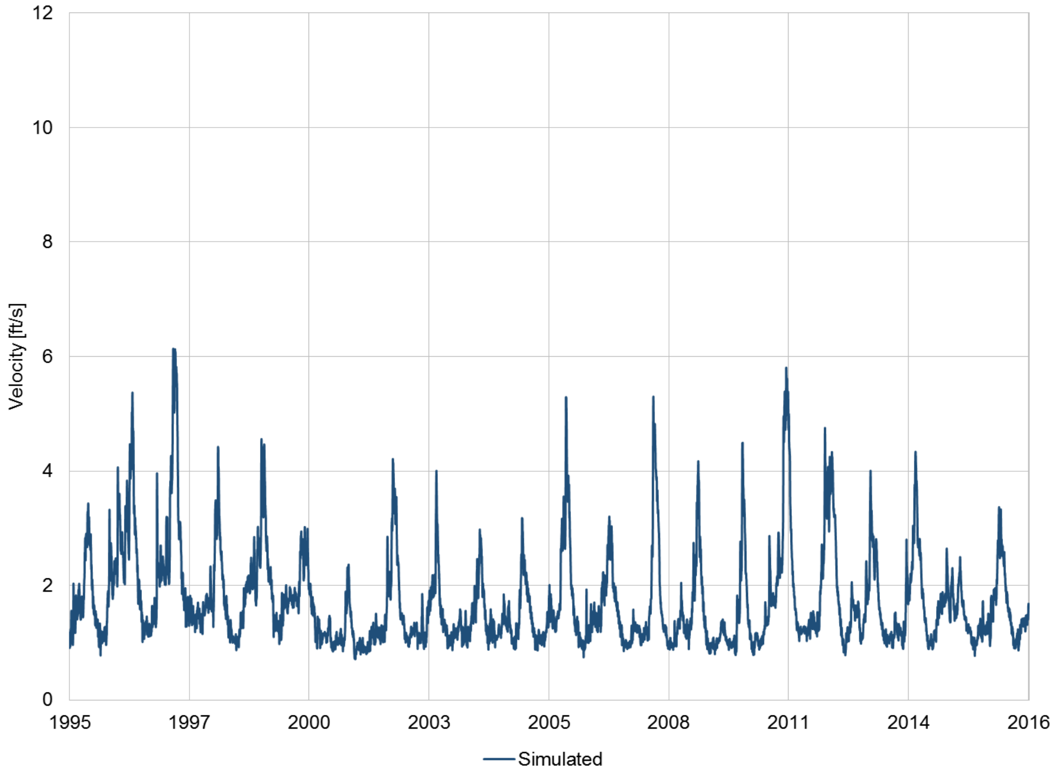

Figure B.2-3 Simulated velocity at TDDO, Columbia River RM 190

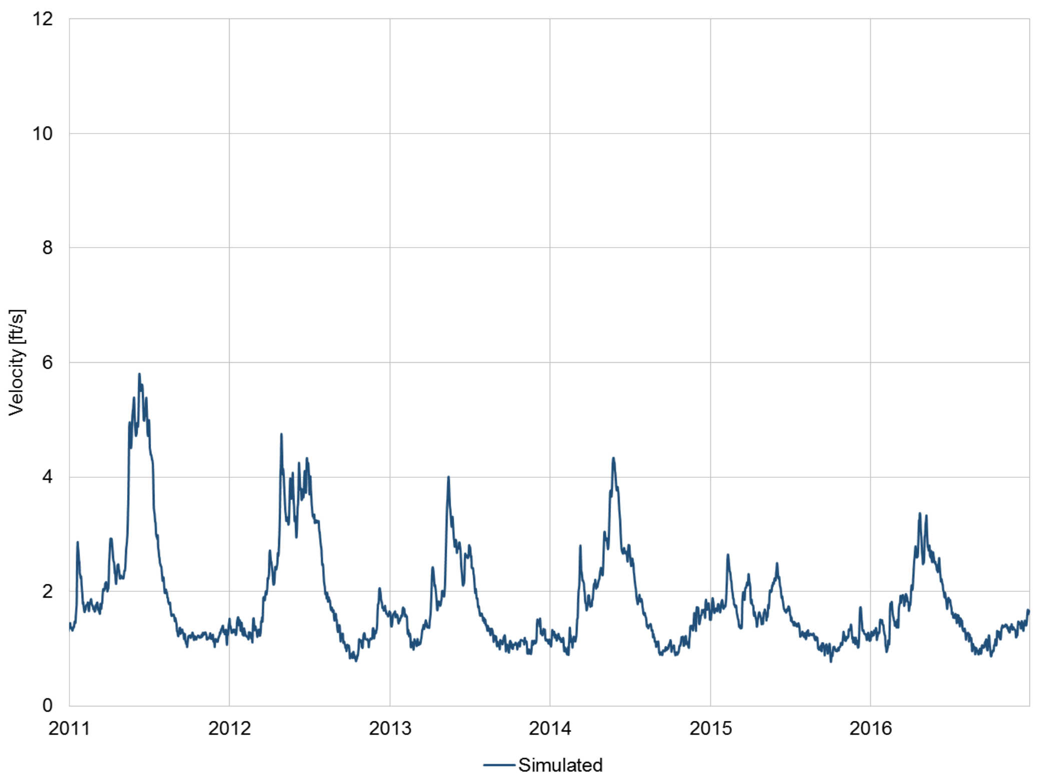

Figure B.2-4 Simulated velocity at TDDO, period 2011 – 2016

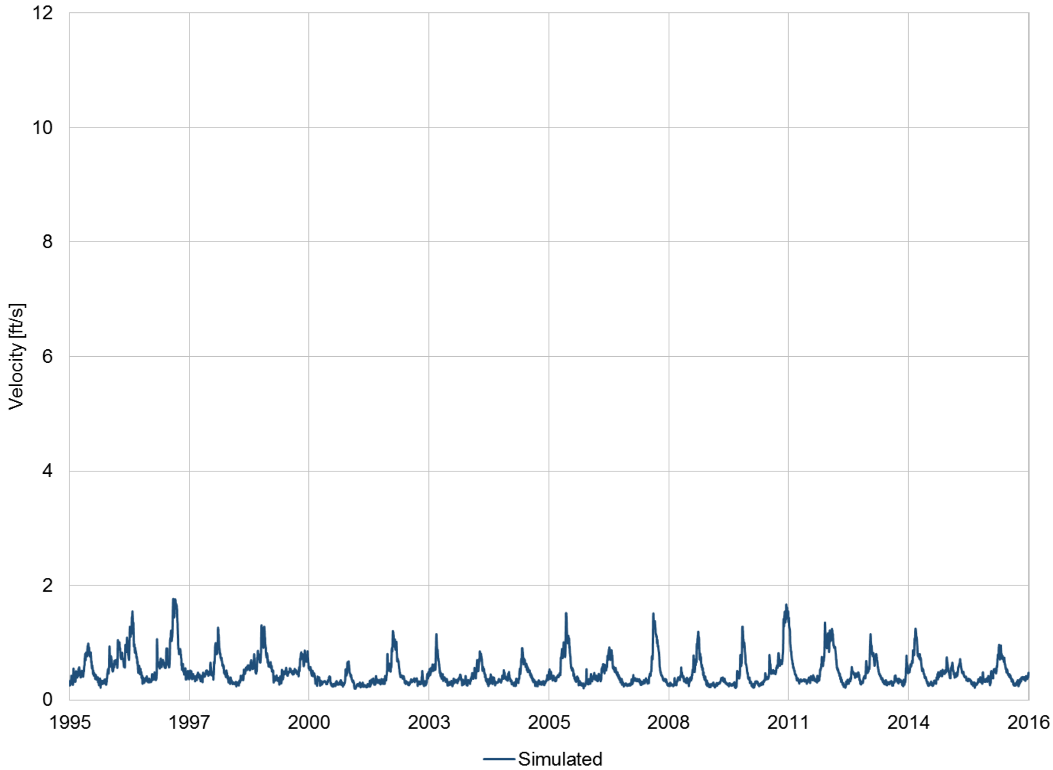

Figure B.2-5 Simulated velocity at JHAW, Columbia River RM 215

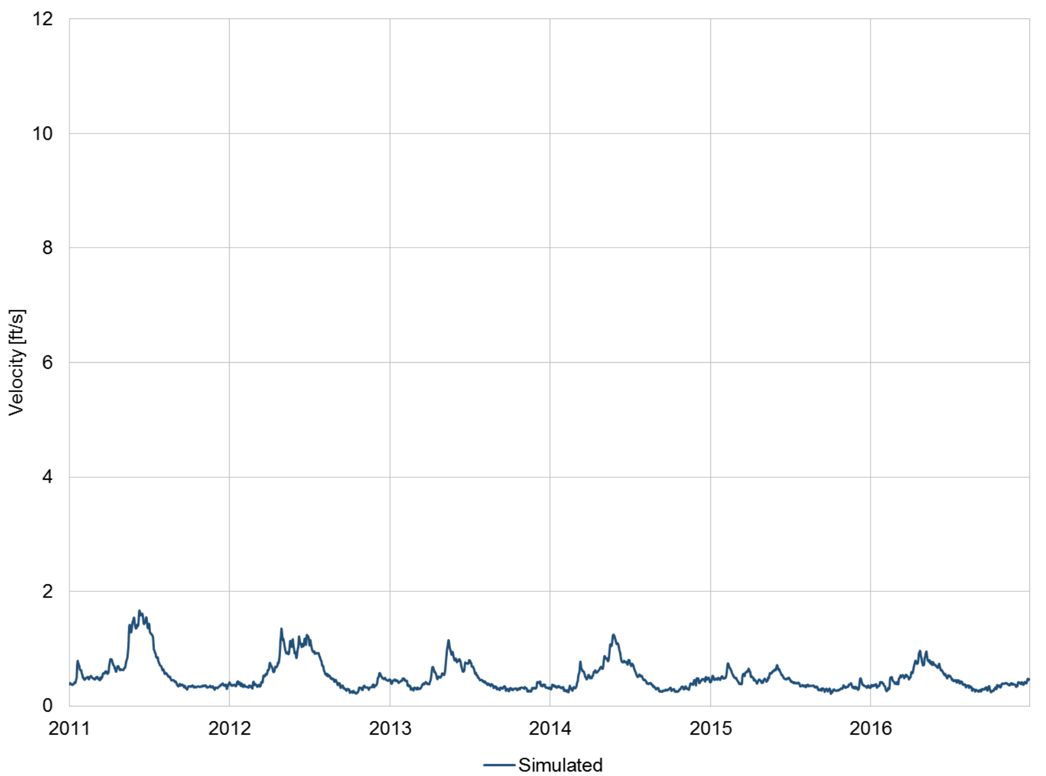

Figure B.2-6 Simulated velocity at JHAW, period 2011 – 2016

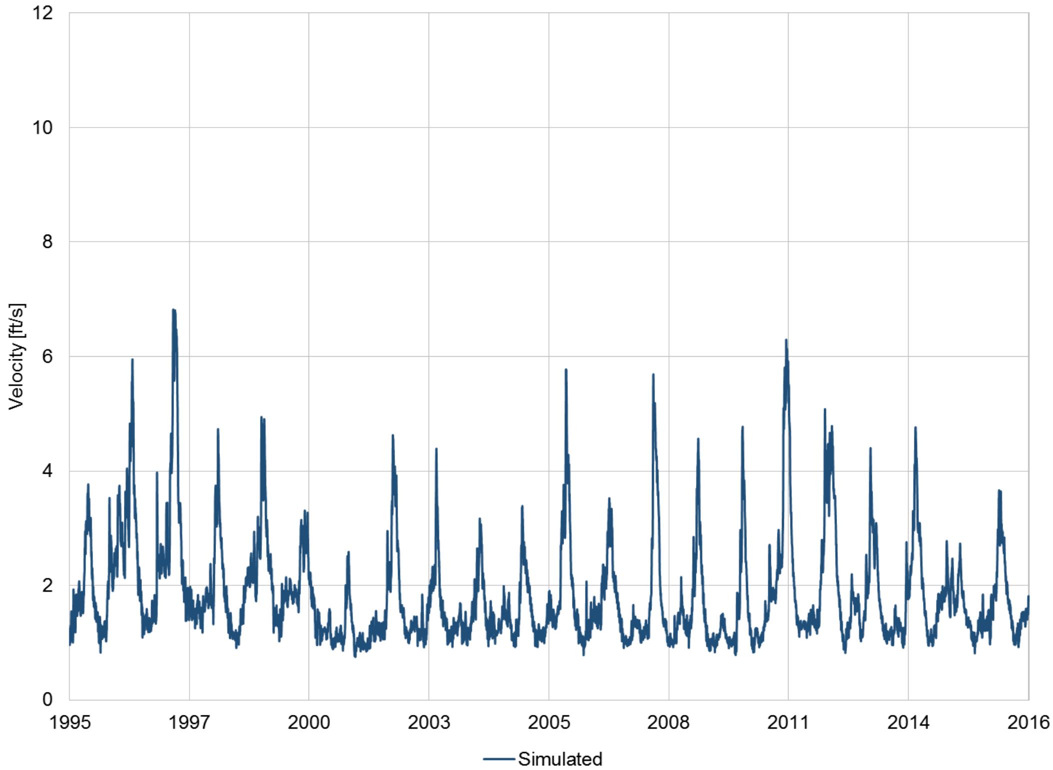

Figure B.2-7 Simulated velocity at MCPW, Columbia River RM 291

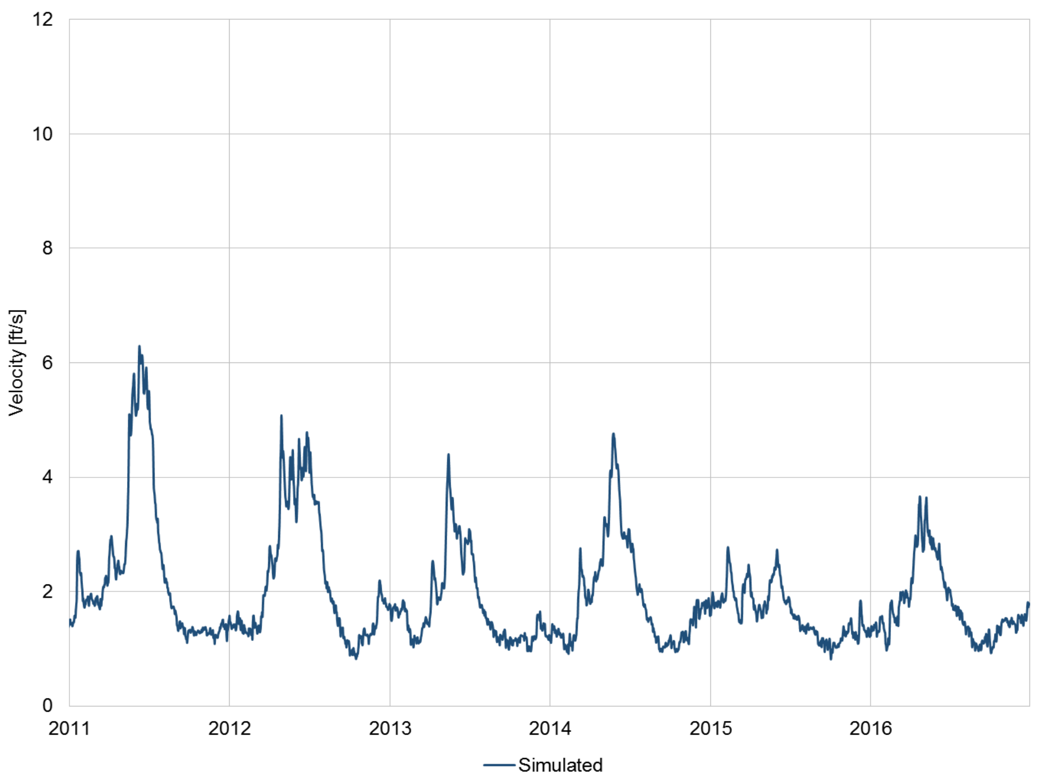

Figure B.2-8 Simulated velocity at MCPW, period 2011 – 2016

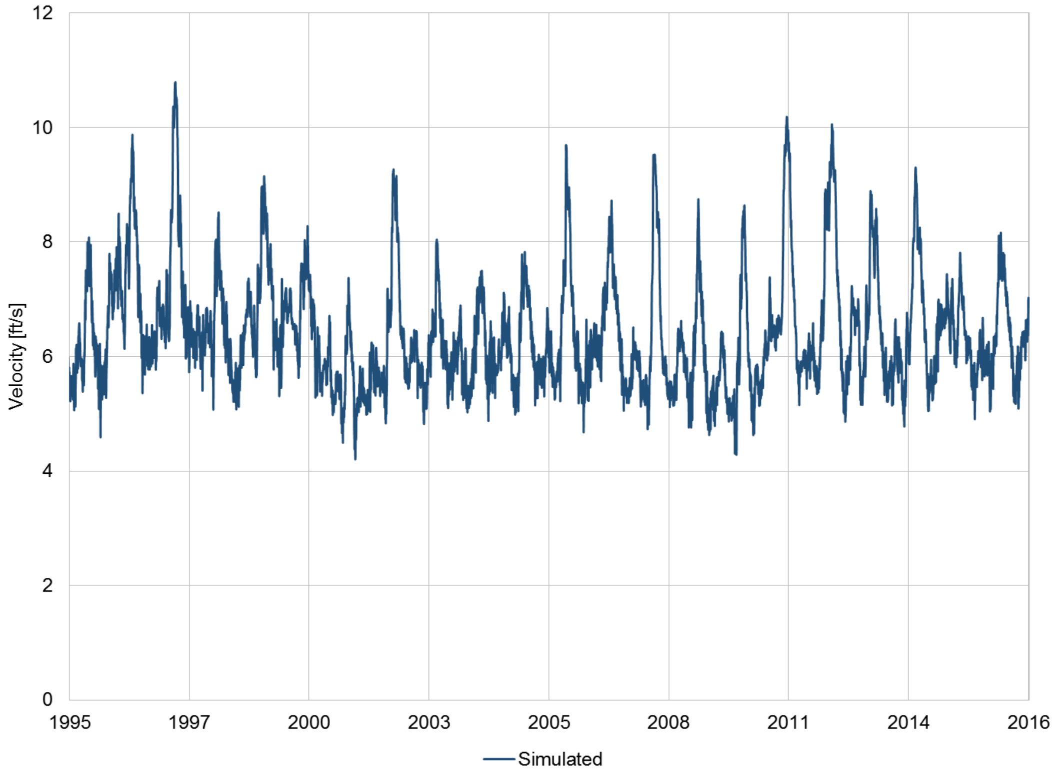

Figure B.2-9 Simulated velocity at PRXW, Columbia River RM 396

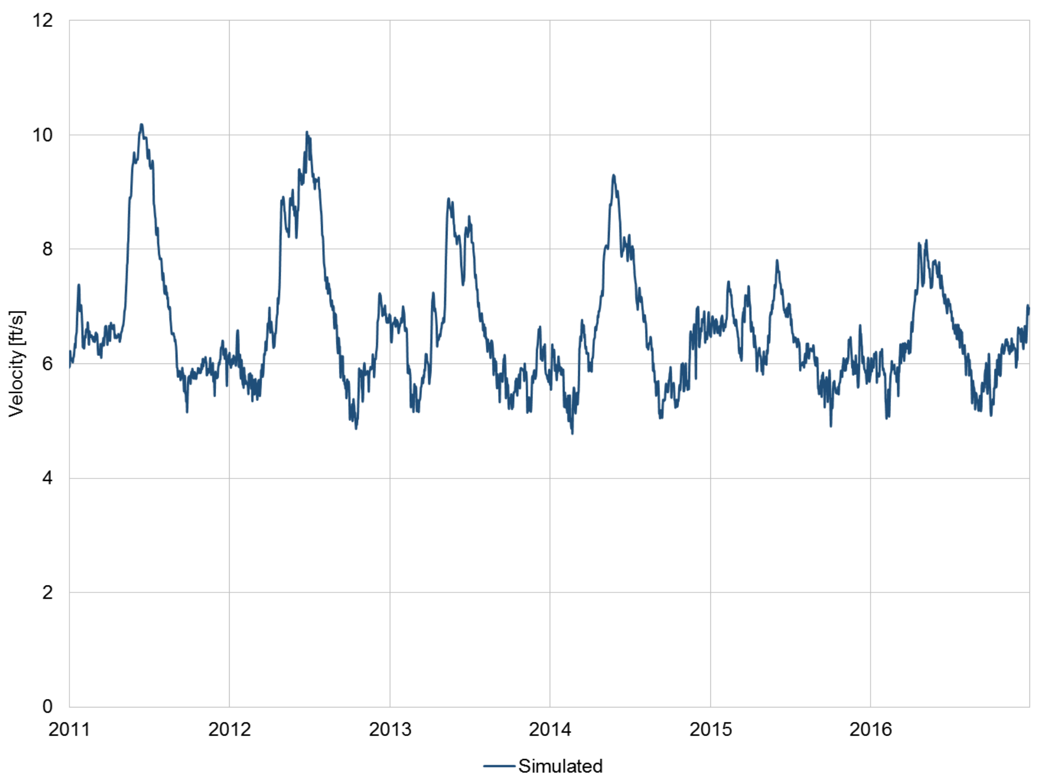

Figure B.2-10 Simulated velocity at PRXW, period 2011 – 2016

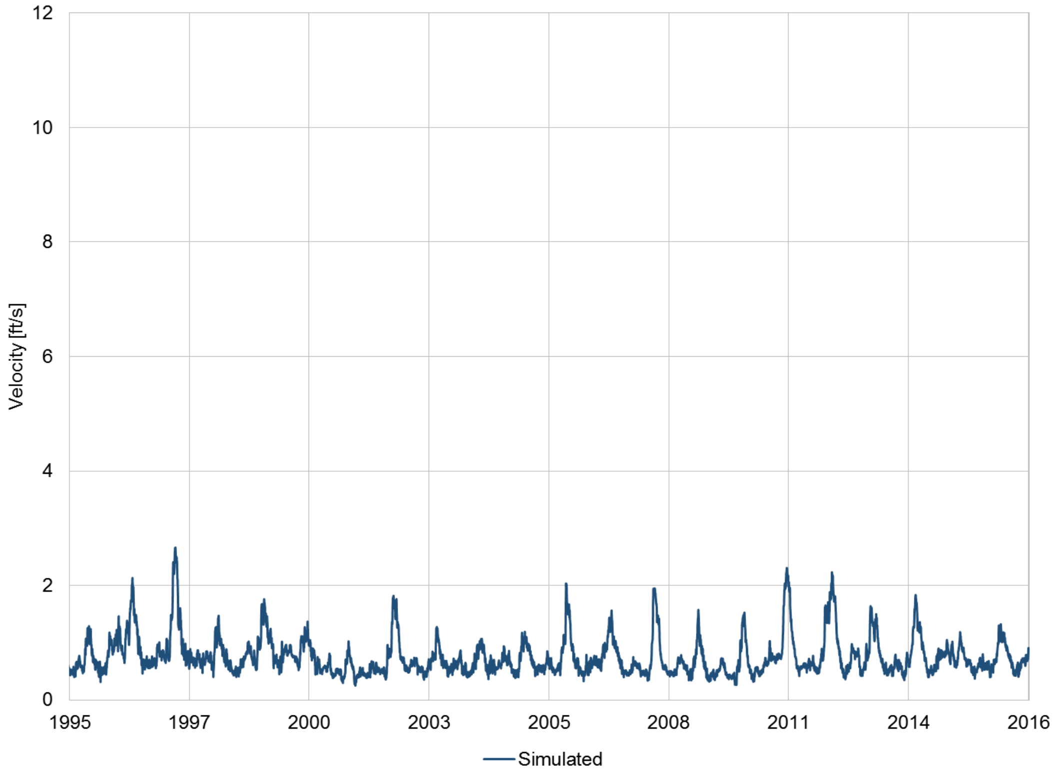

Figure B.2-11 Simulated velocity at WANW, Columbia River RM 415

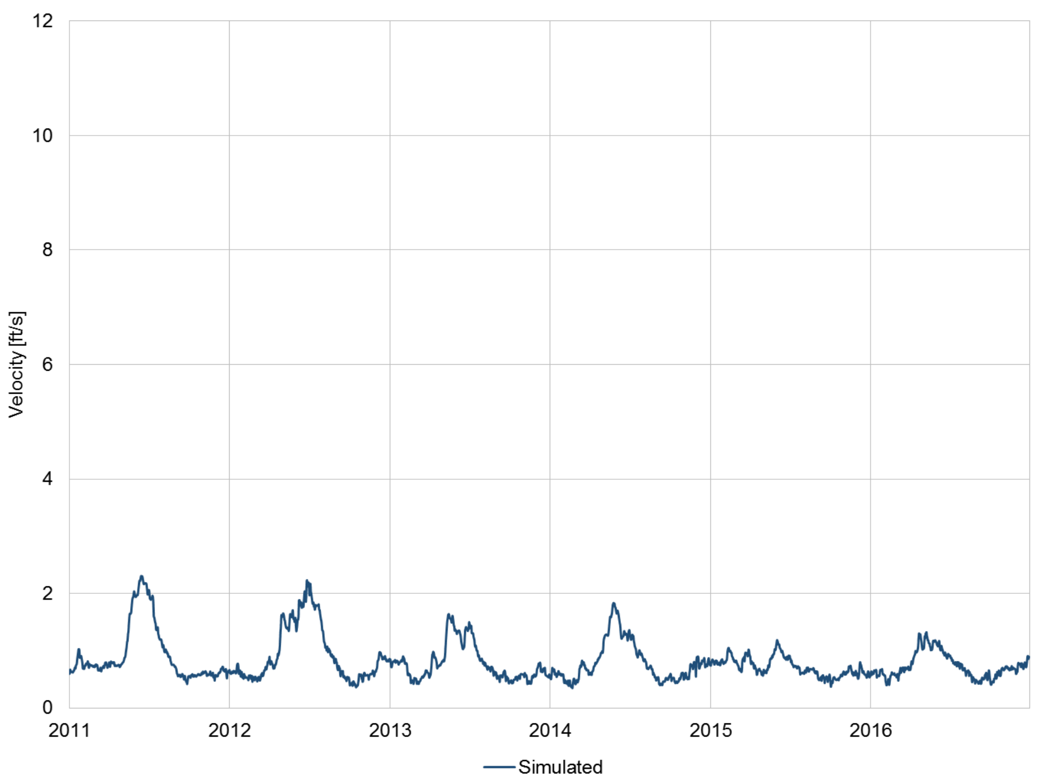

Figure B.2-12 Simulated velocity at WANW, period 2011 – 2016

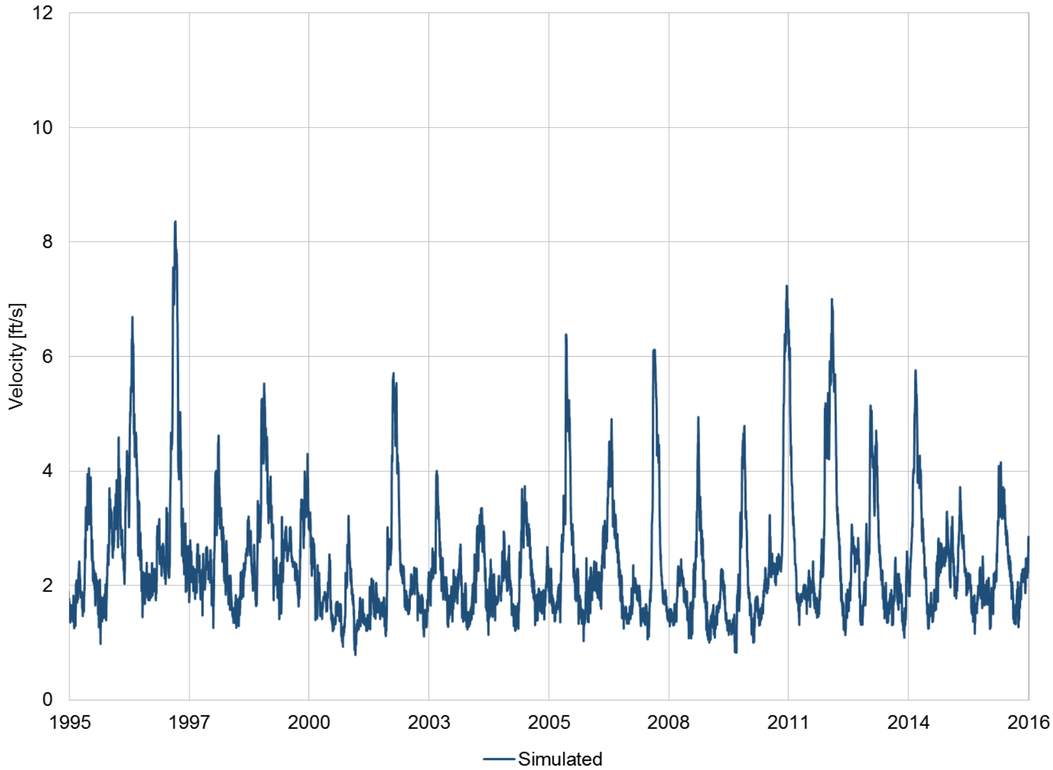

Figure B.2-13 Simulated velocity at RIGW, Columbia River RM 452

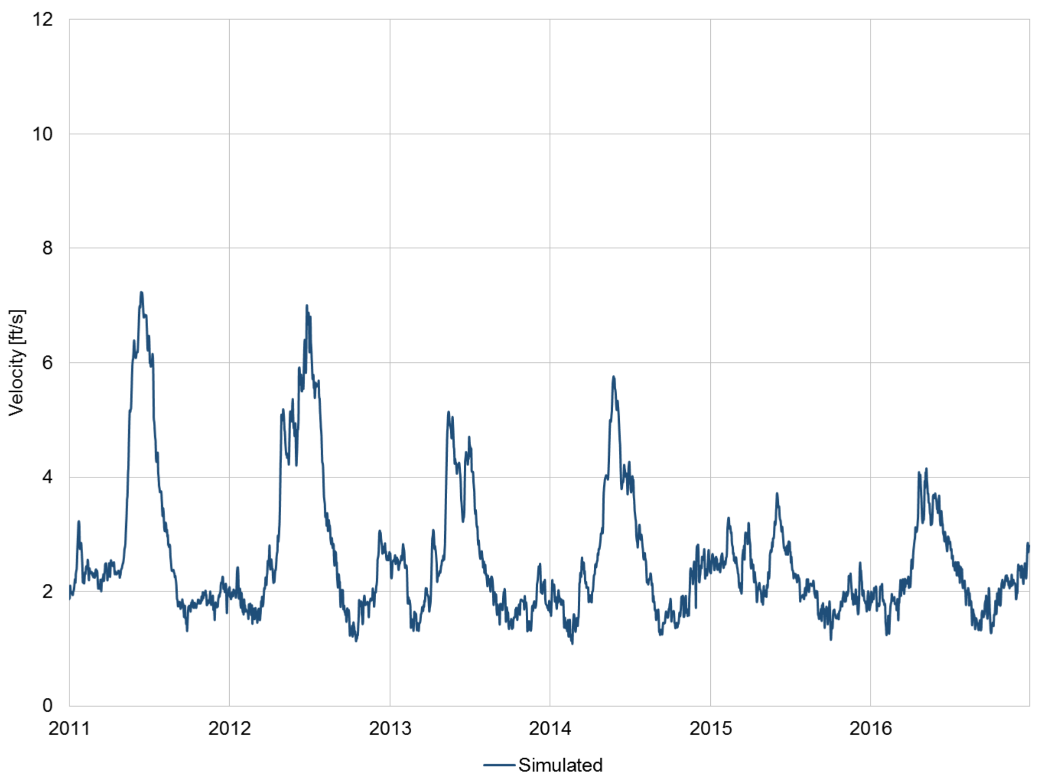

Figure B.2-14 Simulated velocity at RIGW, period 2011 – 2016

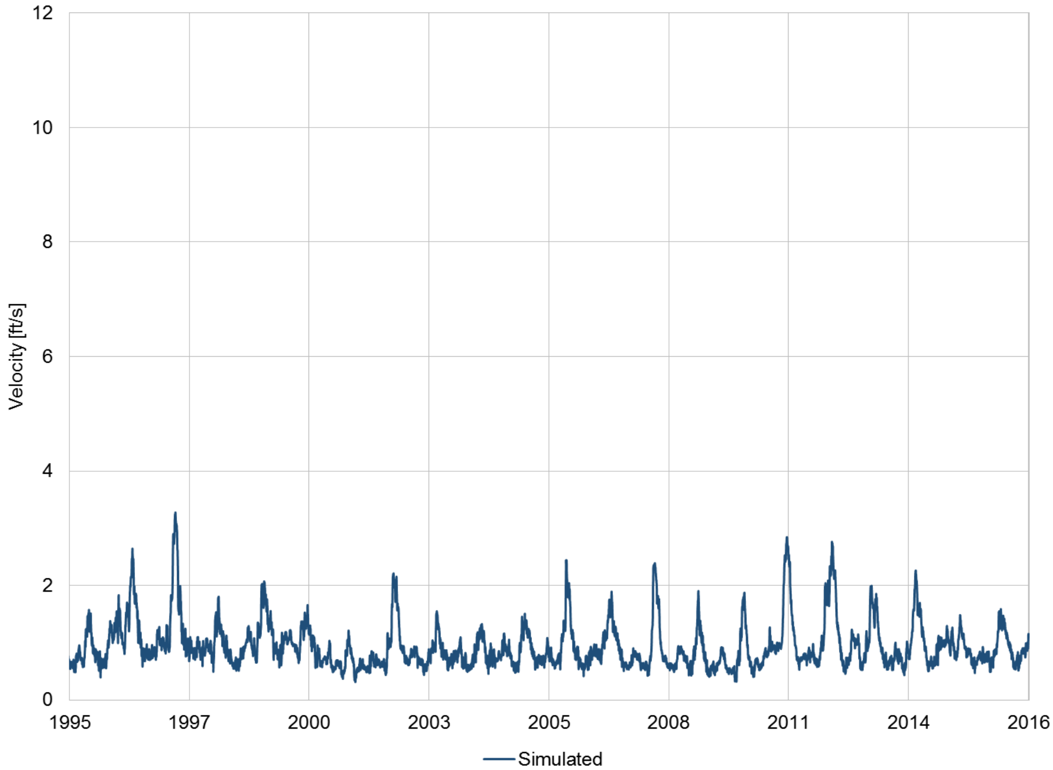

Figure B.2-15 Simulated velocity at RRDW, Columbia River RM 472

Figure B.2-16 Simulated velocity at RRDW, period 2011 – 2016

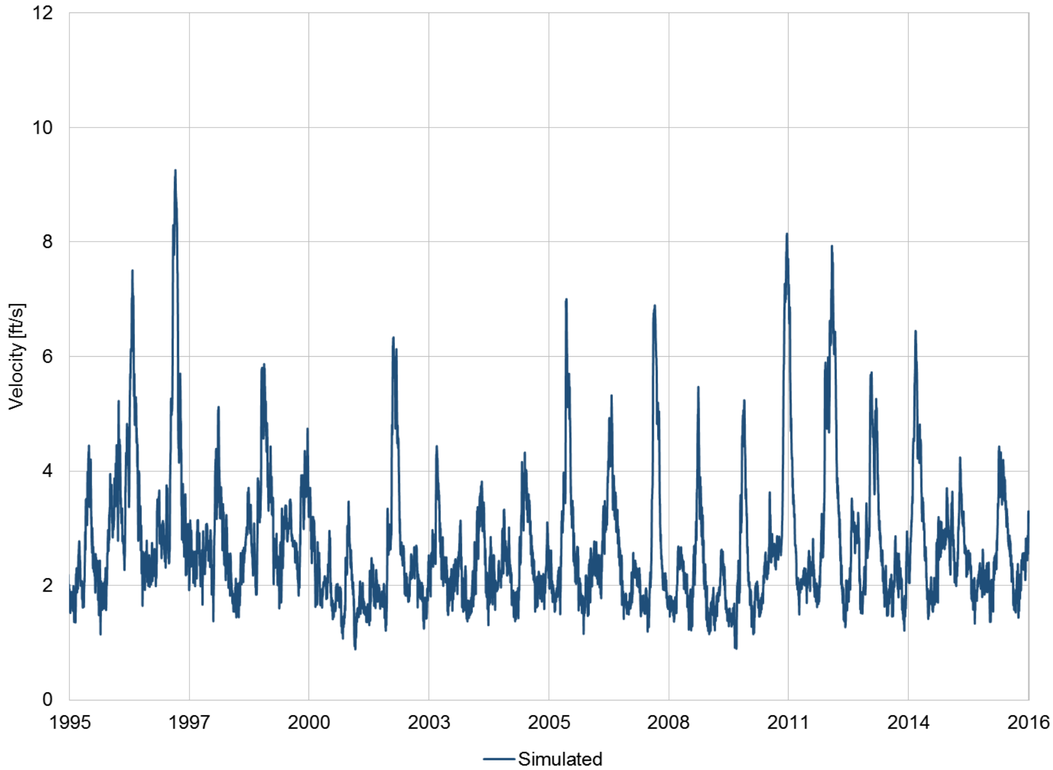

Figure B.2-17 Simulated velocity at WELW, Columbia River RM 514

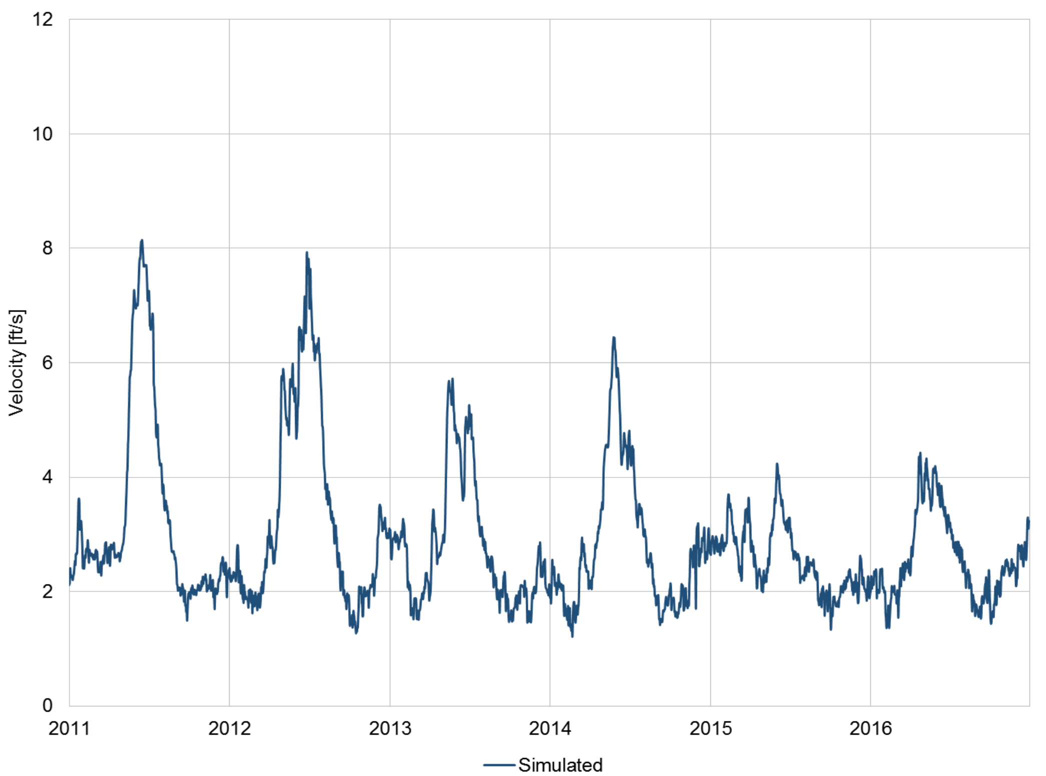

Figure B.2-18 Simulated velocity at WELW, period 2011 – 2016

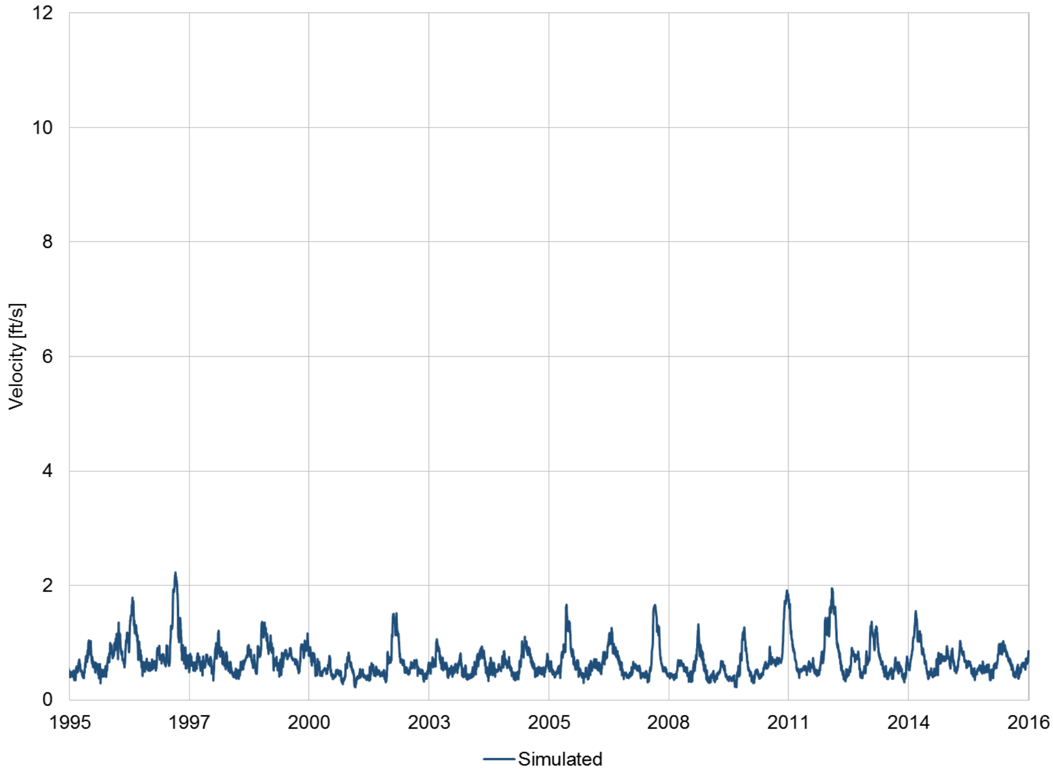

Figure B.2-19 Simulated velocity at CHQW, Columbia River RM 545

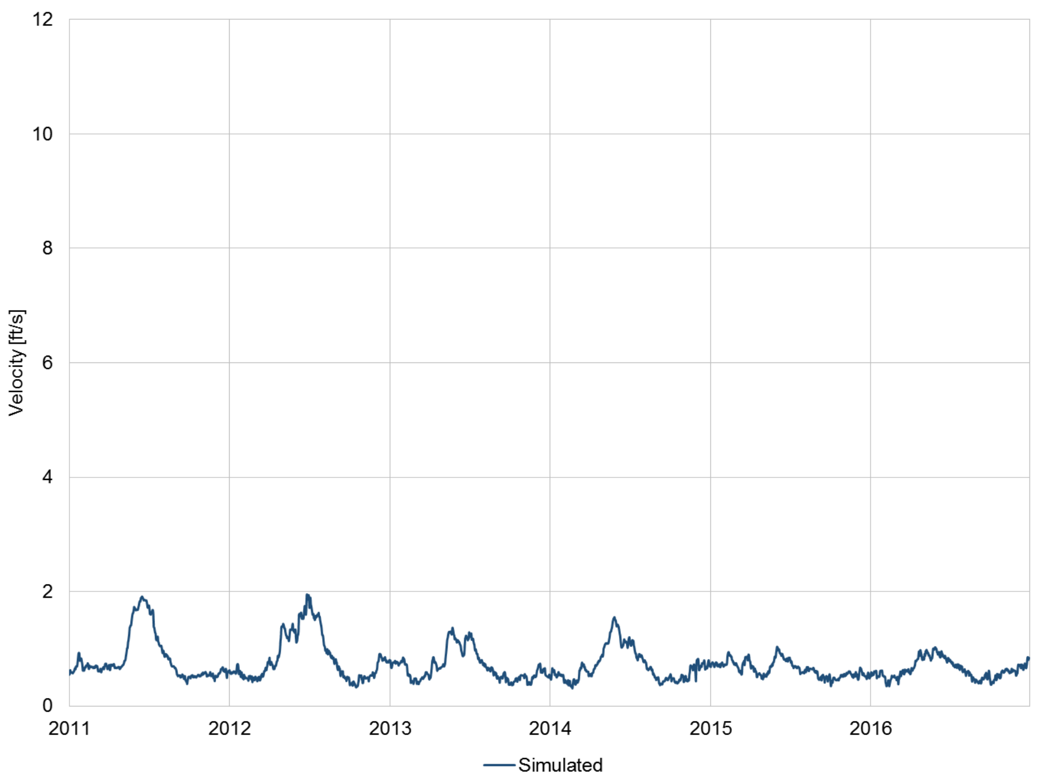

Figure B.2-20 Simulated velocity at CHQW, period 2011 – 2016

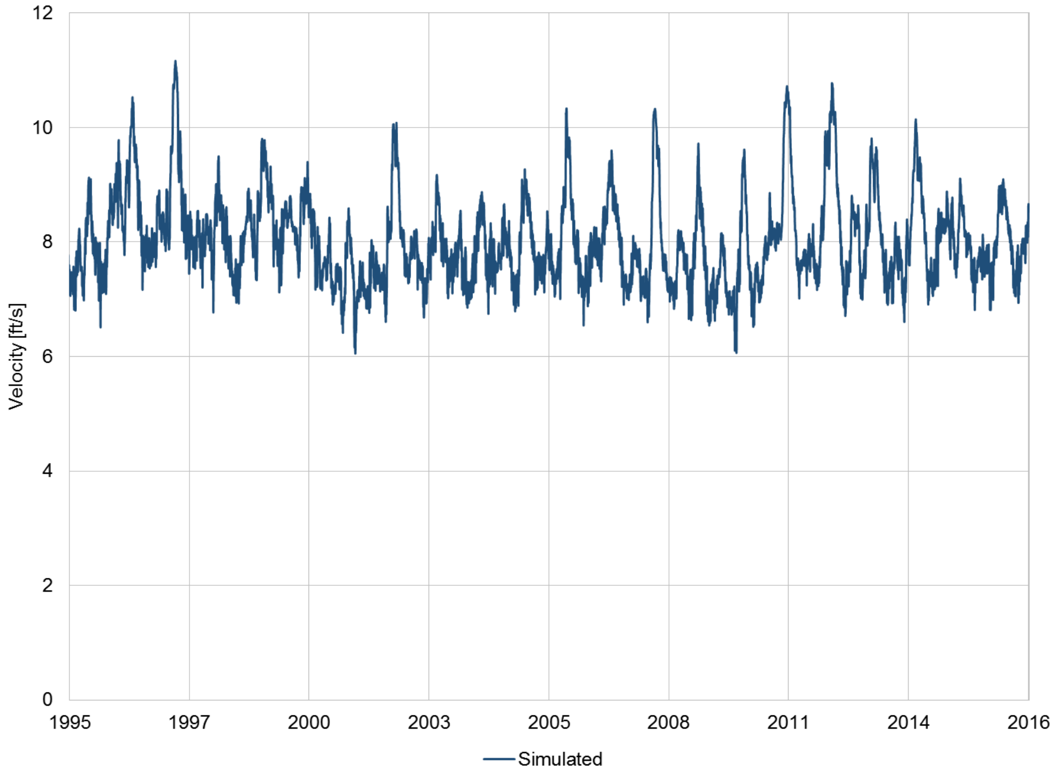

Figure B.2-21 Simulated velocity at GCGW, Columbia River RM 590

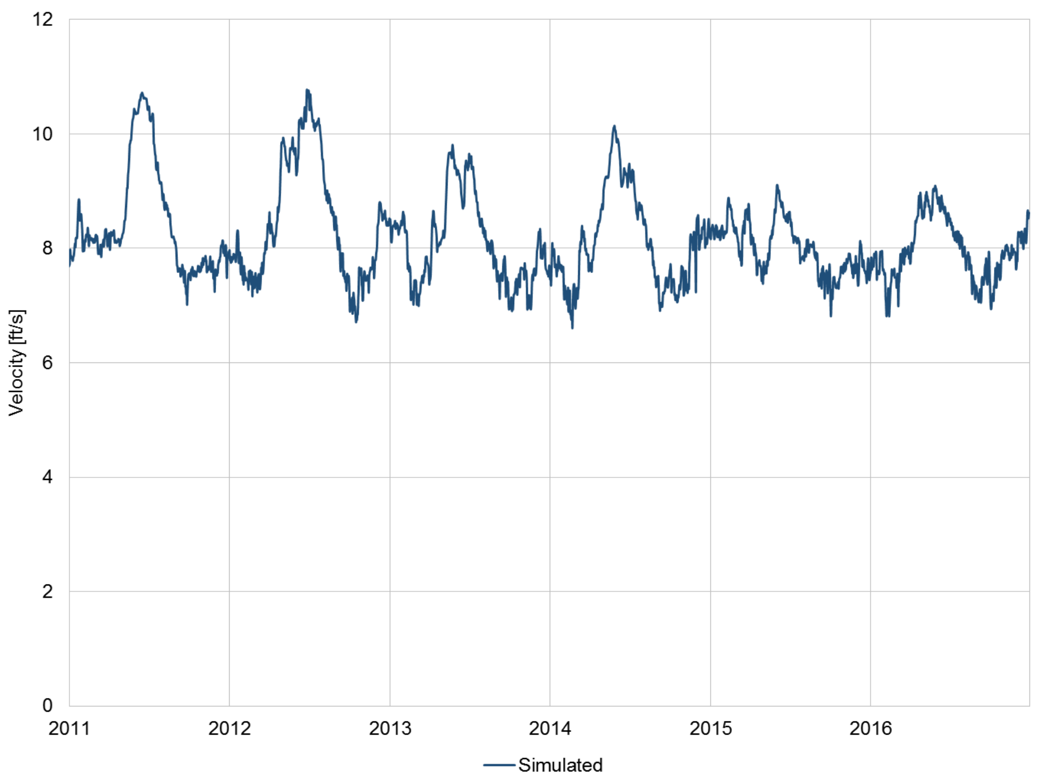

Figure B.2-22 Simulated velocity at GCGW, period 2011 – 2016

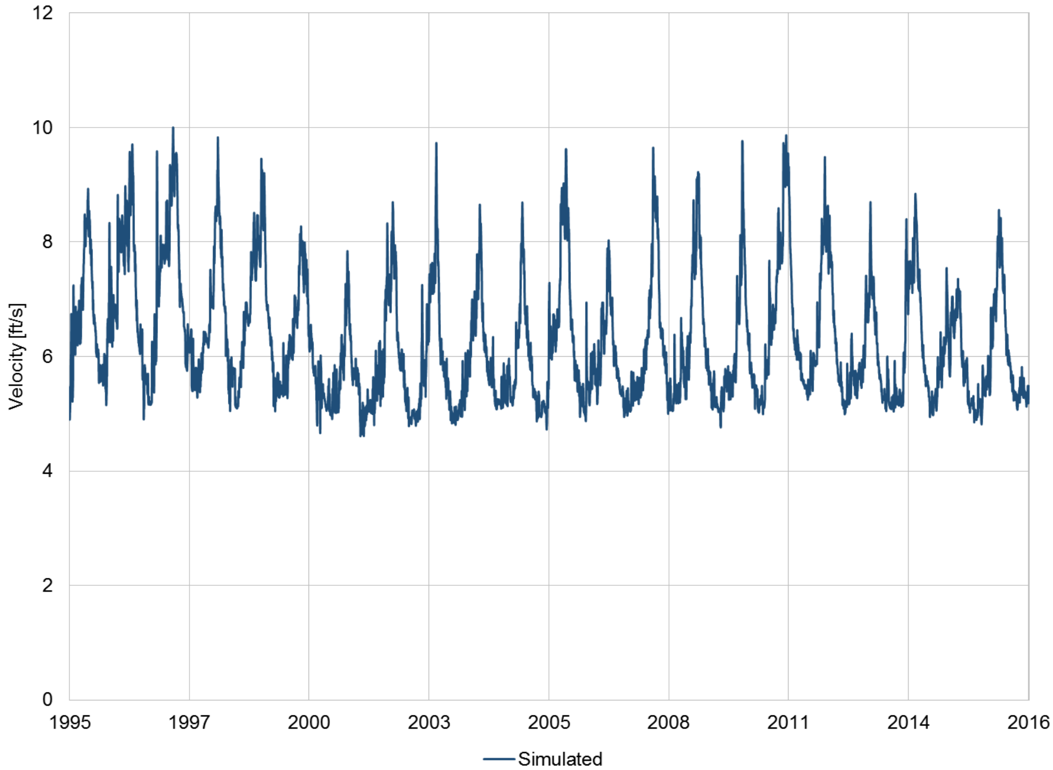

Figure B.2-23 Simulated velocity at IDSW, Snake River RM 6.8

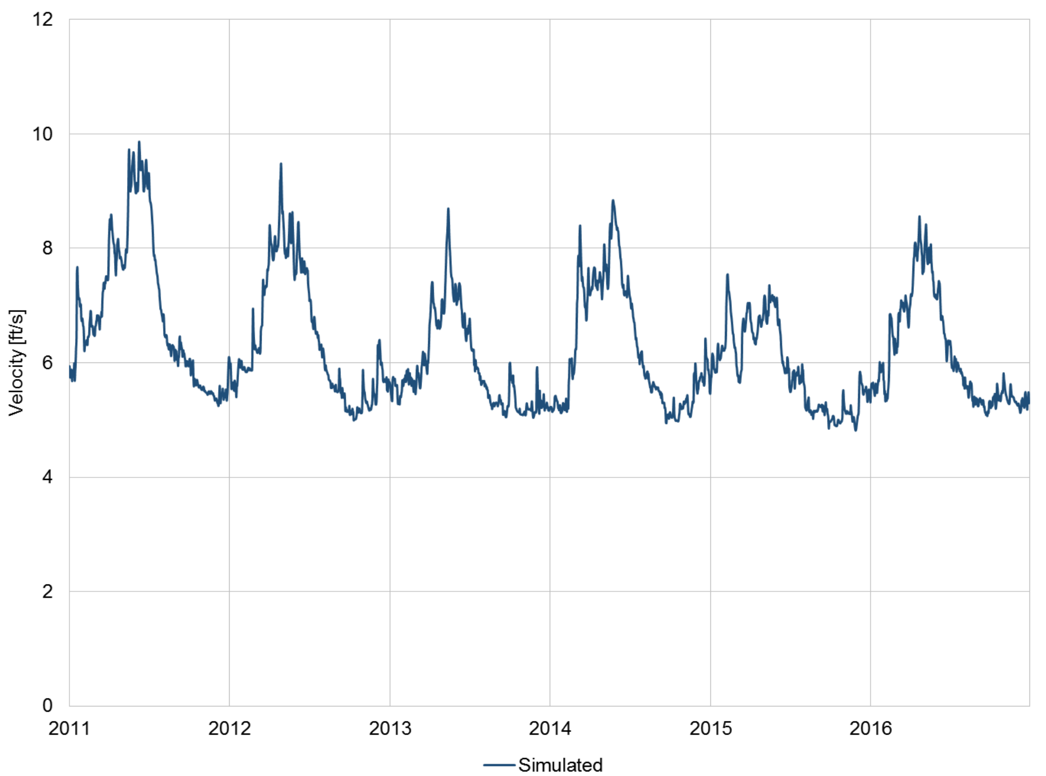

Figure B.2-24 Simulated velocity at IDSW, period 2011 – 2016

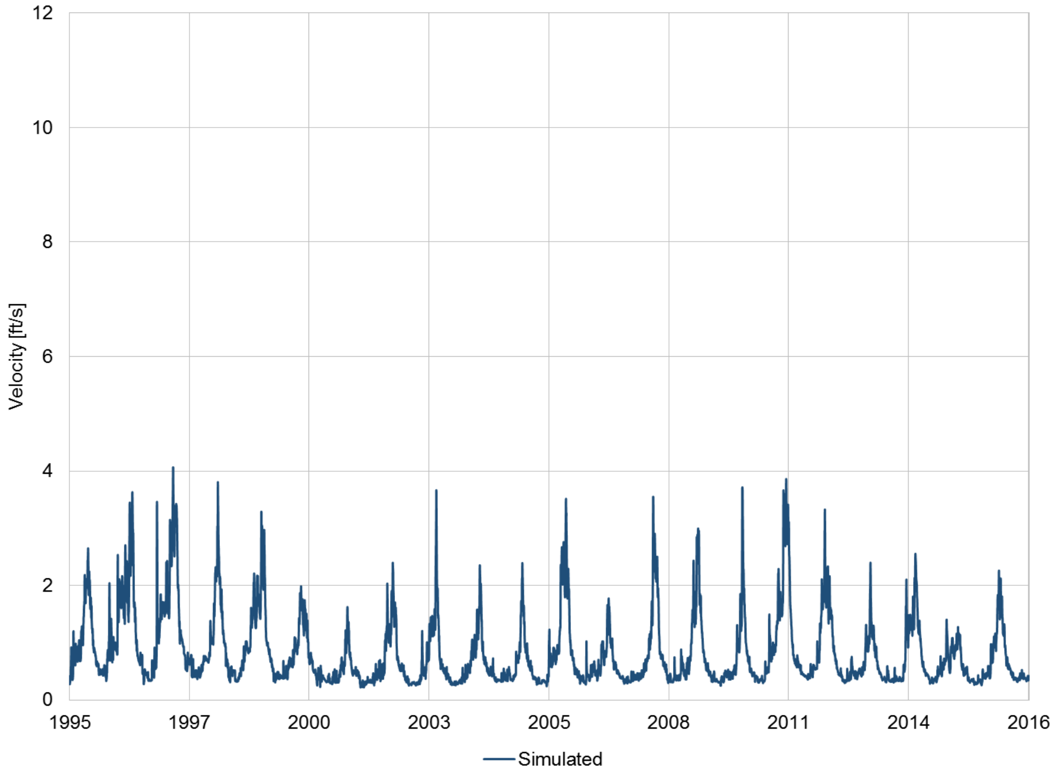

Figure B.2-25 Simulated velocity at LMNW, Snake River RM 40.8

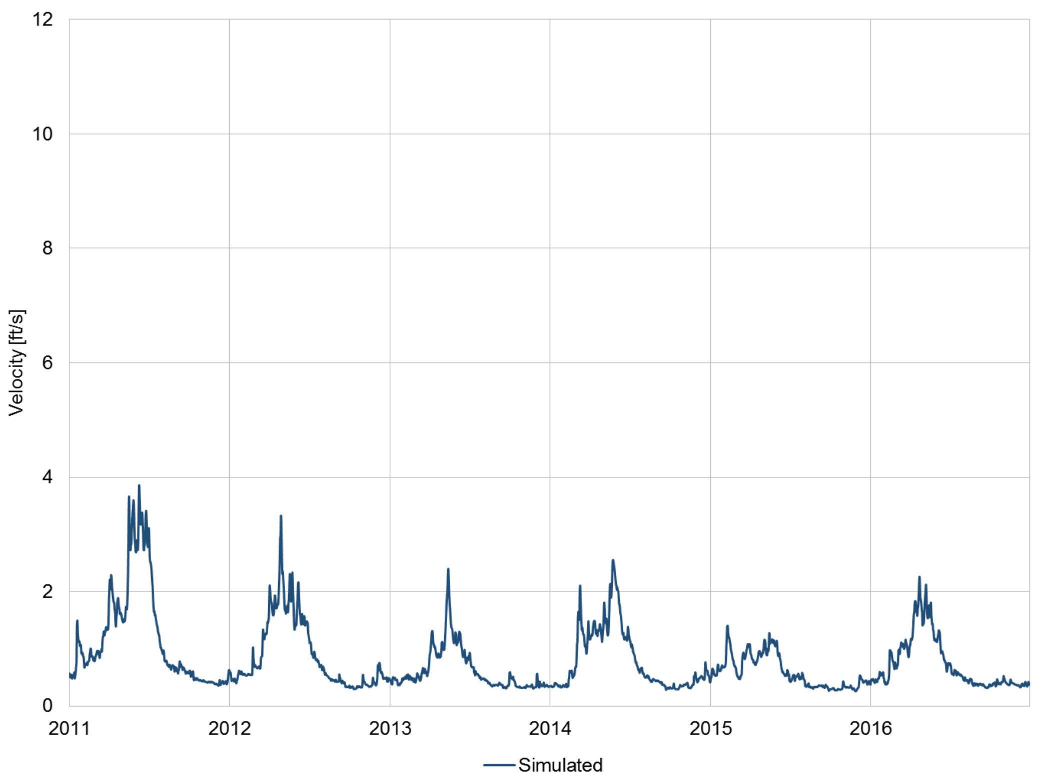

Figure B.2-26 Simulated velocity at LMNW, period 2011 – 2016

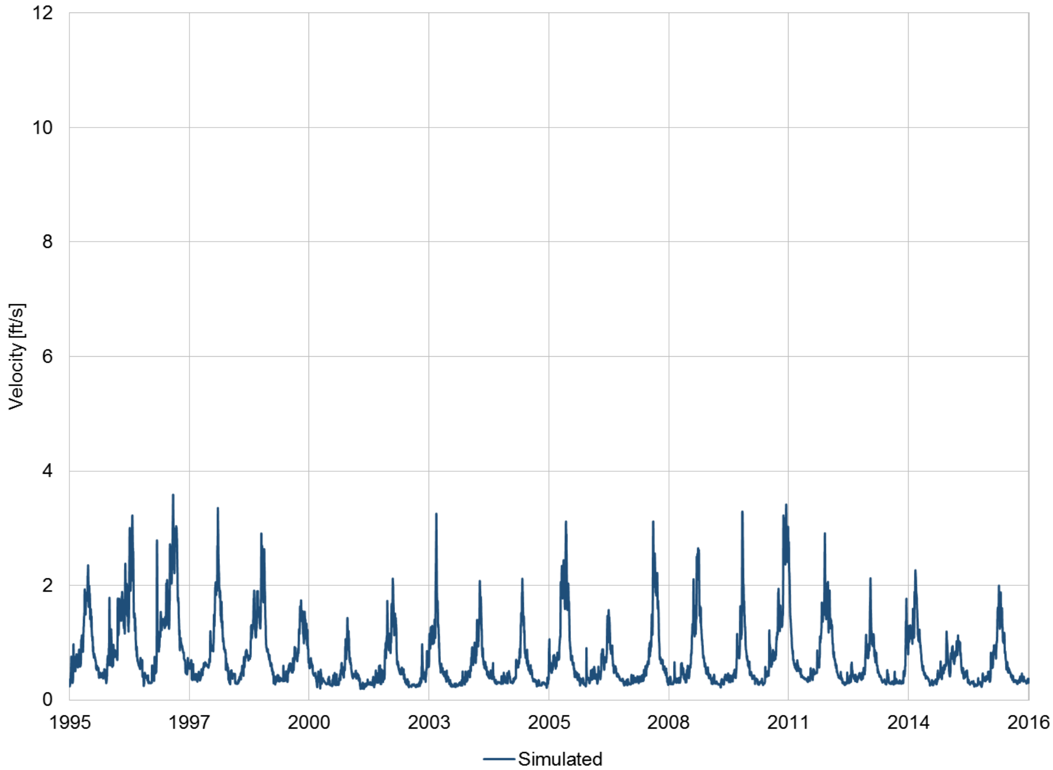

Figure B.2-27 Simulated velocity at LGSW, Snake River RM 69.5

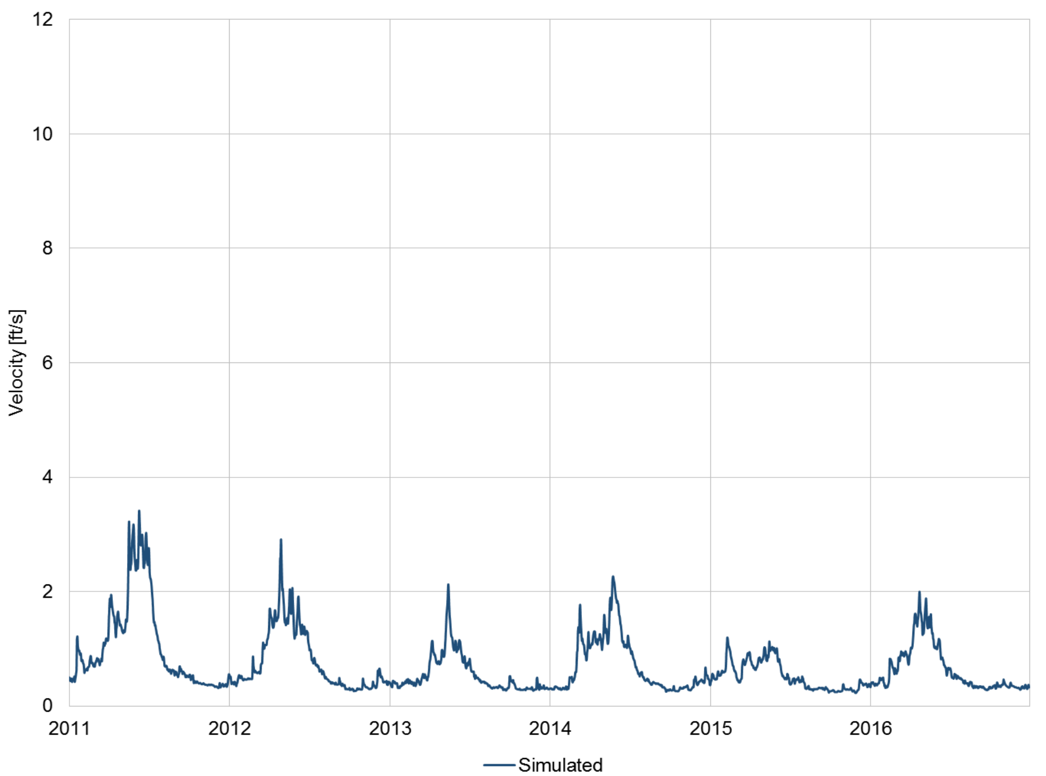

Figure B.2-28 Simulated velocity at LGSW, period 2011 – 2016

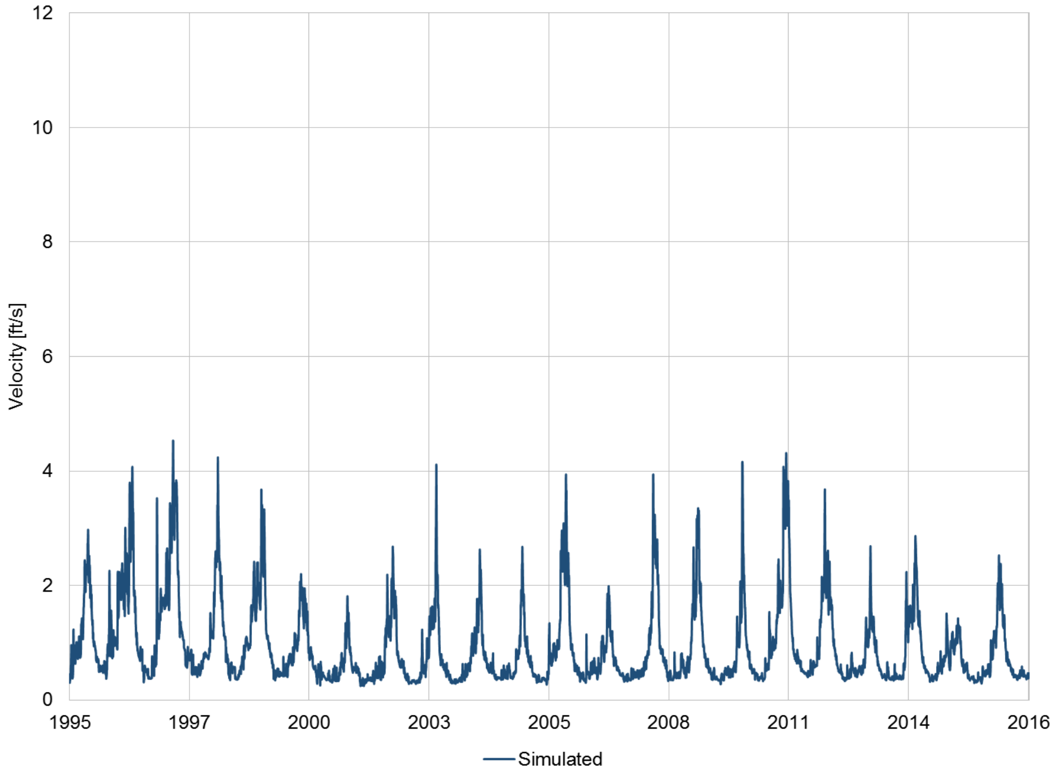

Figure B.2-29 Simulated velocity at LGNW, Snake River RM 106.8

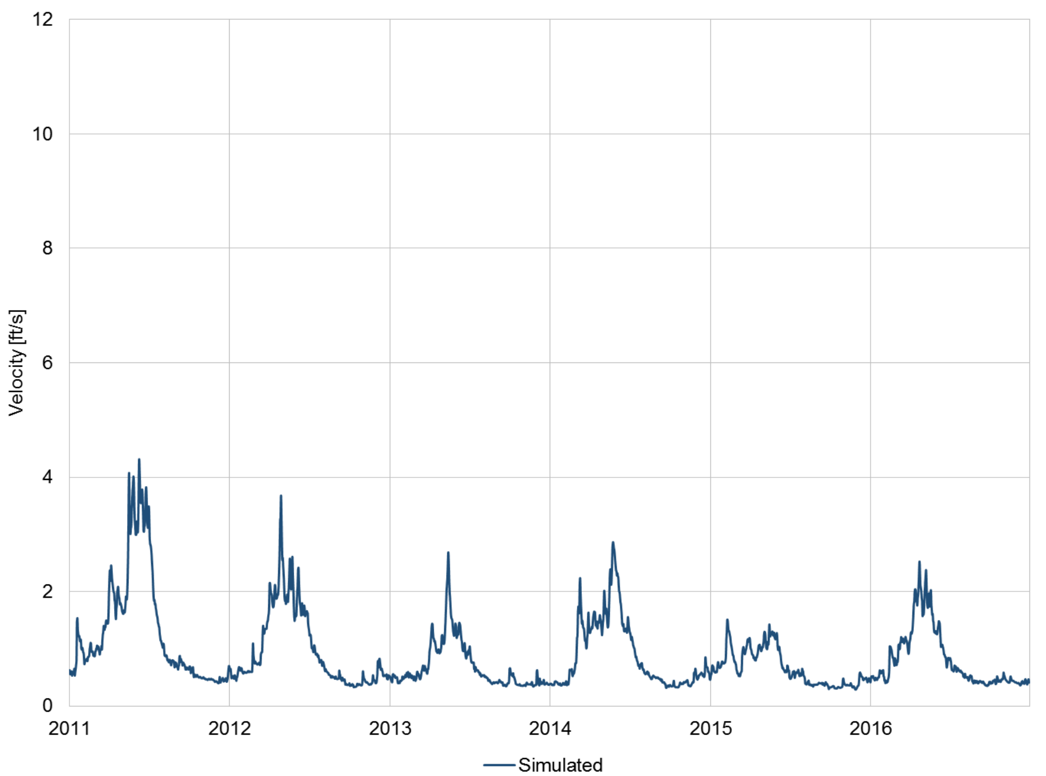

Figure B.2-30 Simulated velocity at LGNW, period 2011 – 2016

Appendix C 2018 RBM10B Model Setup

C.1 Introduction

To investigate the impacts of the Columbia River upstream boundary location on the performance of the 2018 RBM10 model, an alternative model setup starting at the Grand Coulee Dam was developed. The spatial representation of the simulated domain is presented in Figure C.1-1 and a summary of the model results for temperature, flow, and velocity is presented in the following sections. The monitoring stations located within the simulated reaches (Figure C.1-2) and used to compare the model results against observations of temperature are listed in Table C.1-1 through Table C.1-3. The evaporative heat flux coefficients used for this model domain are summarized Table C.1-4.

Table C.1-1 Temperature monitoring stations on the Columbia River used for model comparisons

Station	Station ID	Station Description
Camas/Washougal WA	**CWMW**	Columbia RM 119: Columbia River at RM 119
Warrandale OR	**WRNO**	Columbia RM 140: Six miles D/s of dam
Bonneville Dam tailwater	**BON**	Columbia RM 146: Right end of spillway near dam center
The Dalles Dam tailwater	**TDDO**	Columbia RM 190: Left bank one mile d/s of dam
John Day Dam tailwater	**JHAW**	Columbia RM 215: Dam tailwater Right bank of river
McNary Dam tailwater-Washington	**MCPW**	Columbia RM 291: Dam Tailwater Right bank of river
Priest Rapids tailwater	**PRXW**	Columbia RM 396: Tailwater D/s of dam
Wanapum Dam tailwater	**WANW**	Columbia RM 415: Tailwater D/s of dam
Rock Island Dam tailwater	**RIGW**	Columbia RM 452: Tailwater D/s of dam
Rocky Reach Dam tailwater	**RRDW**	Columbia RM 472 Tailwater D/s of dam
Wells Dam tailwater	**WELW**	Columbia RM 514: Tailwater D/s of dam
Chief Joseph Dam tailwater	**CHQW**	Columbia RM 545: Tailwater D/s of dam

Table C.1-2 Temperature monitoring stations on the Snake River used for model comparisons

Station	Station ID	Station Description
Ice Harbor Dam tailwater	**IDSW**	Snake RM 6.8: Right bank 15,400 feet d/s of dam
Lower Monumental Dam tailwater	**LMNW**	Snake RM 40.8:Left bank 4,300 feet d/s of dam
Little Goose Dam tailwater	**LGSW**	Snake RM 69.5:Right bank 3,900 feet d/s of dam
Lower Granite Dan tailwater	**LGNW**	Snake RM 106.8: Right bank 3,500 feet d/s of dam

Table C.1-3 Temperature monitoring stations on the Clearwater River used for model comparisons

Station	Station ID	Station Description
Clearwater River NR Peck	**PEKI**	Clearwater RM 30.0: Clearwater River at RM 33

Table C.1-4 Calibrated evaporative heat flux transfer constants Ev

	2018 RBM10 model		
Station Name	Ev (April 1 – August 13)	Ev (August 14 – November 26)	Ev (November 27 – March 31)
Wenatchee	1.40e-9	1.15e-9	0.50e-9
Yakima	1.30e-9	1.20e-9	1.50e-9
Lewiston	2.40e-9	1.90e-9	0.20e-9
Portland	1.60e-9	1.25e-9	0.01e-9
Spokane	1.90e-9	1.00e-9	0.55e-9

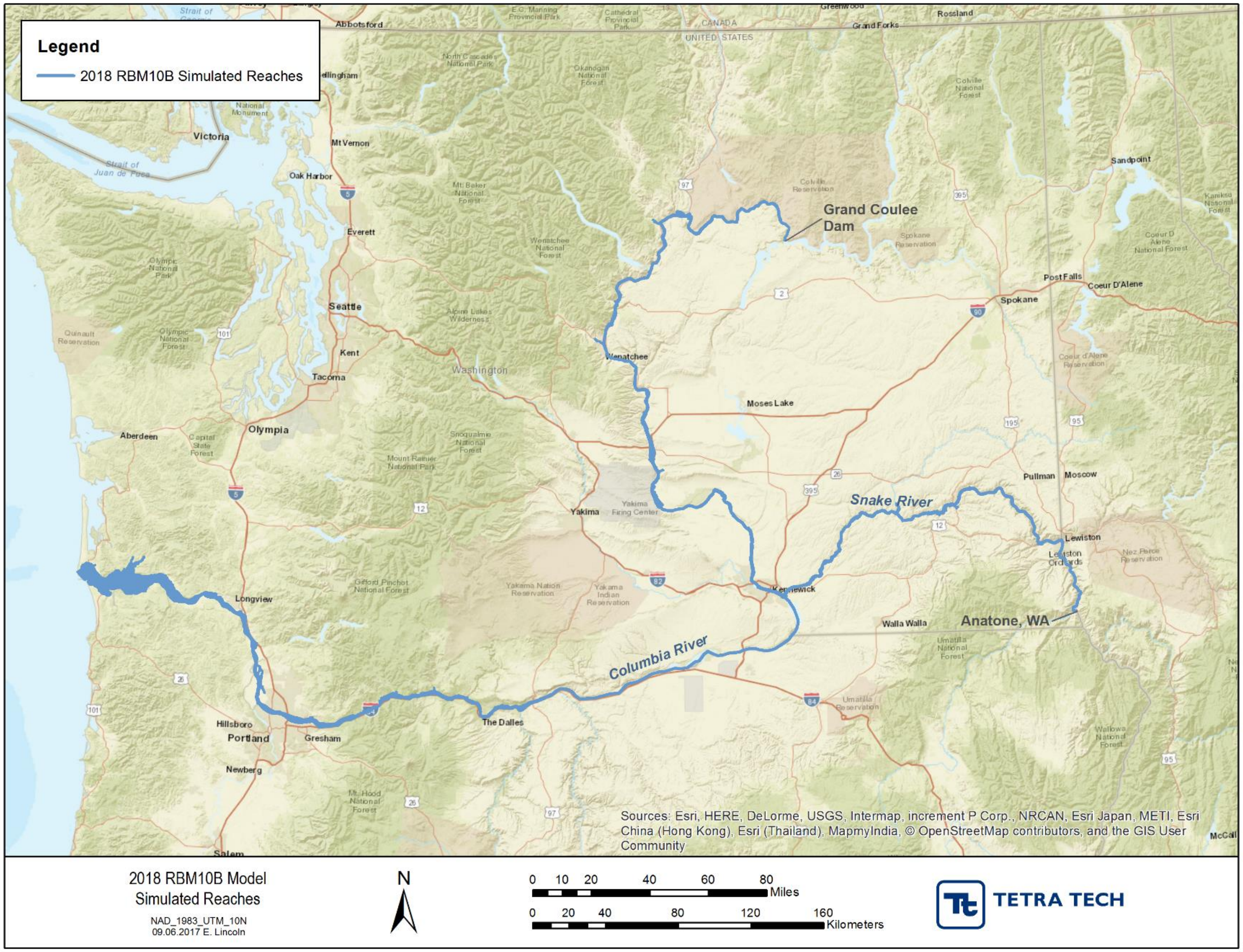

Figure C.1-1 2018 RBM10B spatial model representation of the Columbia and Snake Rivers

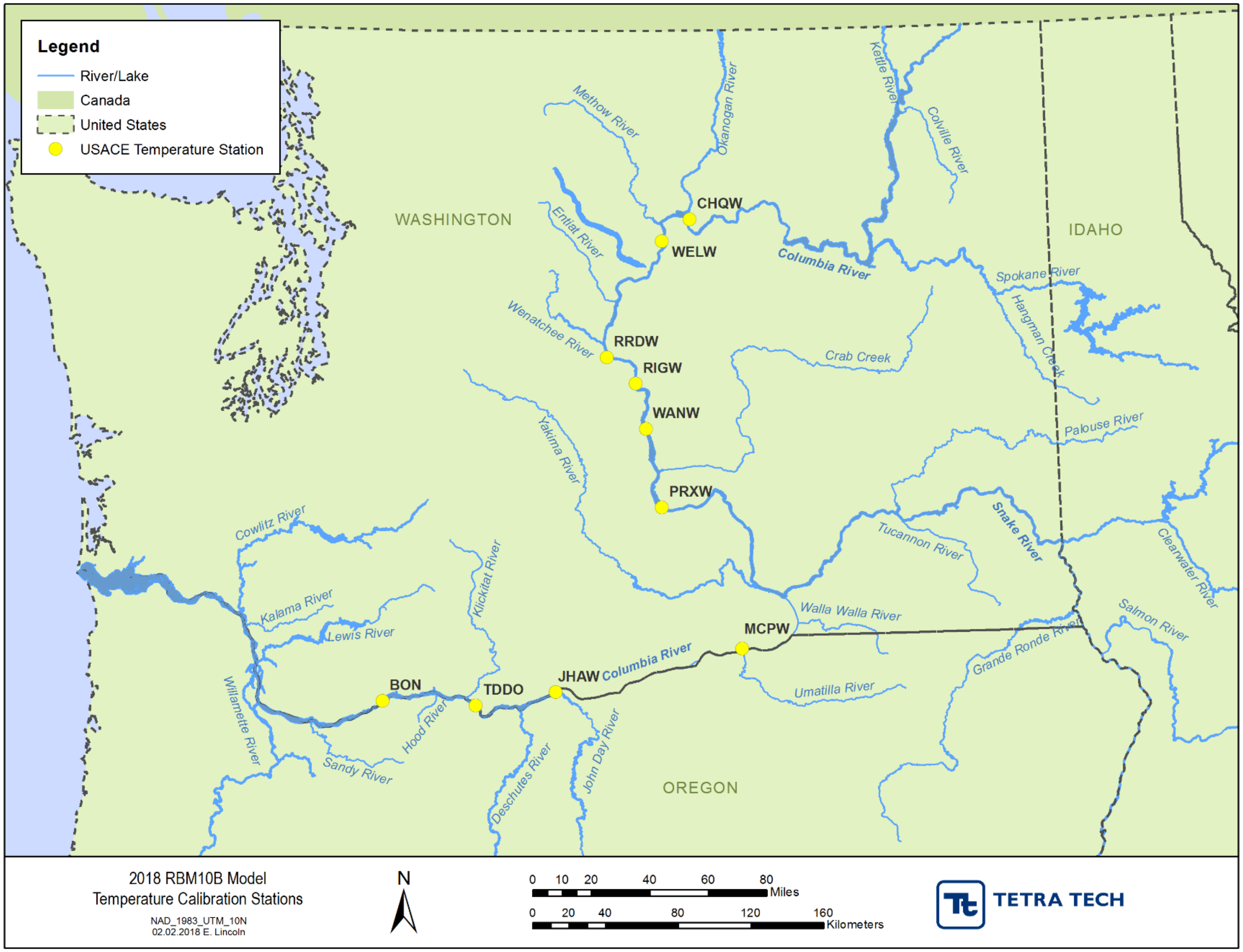

Figure C.1-2 2018 RBM10B Columbia and Snake Rivers temperature calibration stations

C.2 Water Temperature Model Performance Statistics

Statistical results obtained at each station in the Columbia and Snakes Rivers are presented in Table C.2-1 through Table C.2-4. Table C.2-1 and Table C.2-2 present the statistical analyses resulting from the comparison of the model simulations against all available observations within the period 2007 - 2016. Table C.2-3 and Table C.2-4 present the statistical analysis obtained by comparing the temperature model simulations to measured observations between April 1 and November 30 within the period of 1975 through 2016. Graphical comparisons between observed and simulated water temperatures are presented from Figure C.3-1 through Figure C.3-18 and from Figure C.4-1 through Figure C.4-9.

Table C.2-1 Model performance statistics, all months (January – December)

Columbia River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
CWMW	4639	-0.184	0.417	0.535	0.996
WRNO	7865	-0.150	0.452	0.595	0.996
BON	8383	-0.193	0.404	0.517	0.996
TDDO	5626	0.041	0.377	0.491	0.997
JHAW	5857	0.080	0.378	0.495	0.997
MCPW	7306	0.242	0.448	0.591	0.996
PRXW	5493	-0.087	0.383	0.494	0.996
WANW	5380	-0.129	0.399	0.519	0.996
RIGW	4250	-0.033	0.436	0.591	0.994
RRDW	4028	-0.087	0.429	0.566	0.995
WELW	3482	0.110	0.369	0.502	0.995
CHQW	3853	-0.044	0.289	0.437	0.996
	Average	**-0.036**	**0.398**	**0.528**	**0.996**
Snake River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
IDSW	7635	0.141	0.460	0.588	0.996
LMNW	6052	0.090	0.521	0.658	0.994
LGSW	5859	0.093	0.531	0.667	0.994
LGNW	7345	0.087	0.494	0.625	0.994
	Average	**0.103**	**0.501**	**0.634**	**0.995**
Clearwater River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
PEKI	5157	0.077	0.377	0.506	0.990
	Average	**0.077**	**0.377**	**0.506**	**0.990**

Table C.2-2 Model performance statistics (April – November)

Station	Observations	ME	MAE	RMSE	R
Columbia River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
CWMW	3993	-0.154	0.408	0.524	0.994
WRNO	5496	-0.192	0.428	0.555	0.993
BON	6150	-0.218	0.385	0.497	0.995
TDDO	4345	0.011	0.358	0.462	0.994
JHAW	4560	0.024	0.350	0.451	0.995
MCPW	5110	0.233	0.416	0.548	0.994
PRXW	4348	-0.131	0.402	0.510	0.993
WANW	4028	-0.082	0.396	0.516	0.993
RIGW	3632	-0.008	0.454	0.621	0.991
RRDW	3489	-0.066	0.455	0.600	0.992
WELW	3140	0.153	0.375	0.499	0.994
CHQW	3699	-0.040	0.295	0.444	0.995
	Average	**-0.039**	**0.393**	**0.519**	**0.994**
Snake River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
IDSW	7635	0.141	0.460	0.588	0.996
LMNW	6052	0.090	0.521	0.658	0.994
LGSW	5859	0.093	0.531	0.667	0.994
LGNW	7345	0.087	0.494	0.625	0.994
	Average	**0.103**	**0.501**	**0.634**	**0.995**
Clearwater River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
PEKI	5157	0.077	0.377	0.506	0.990
	Average	**0.077**	**0.377**	**0.506**	**0.990**

Table C.2-3 Model performance statistics (July – August)

Columbia River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
CWMW	1376	0.081	0.439	0.557	0.945
WRNO	1383	-0.017	0.369	0.456	0.965
BON	1792	-0.057	0.386	0.502	0.956
TDDO	1284	0.139	0.361	0.451	0.967
JHAW	1355	0.150	0.349	0.429	0.974
MCPW	1356	0.249	0.356	0.422	0.977
PRXW	1249	-0.122	0.319	0.404	0.970
WANW	1118	0.014	0.289	0.375	0.972
RIGW	1154	0.097	0.328	0.492	0.953
RRDW	1158	0.045	0.314	0.410	0.962
WELW	1065	0.305	0.380	0.492	0.968
CHQW	1170	0.113	0.284	0.392	0.972
	Average	**0.083**	**0.348**	**0.448**	**0.965**
Snake River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
IDSW	7635	0.141	0.460	0.588	0.996
LMNW	6052	0.090	0.521	0.658	0.994
LGSW	5859	0.093	0.531	0.667	0.994
LGNW	7345	0.087	0.494	0.625	0.994
	Average	**0.103**	**0.501**	**0.634**	**0.995**
Clearwater River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
PEKI	5157	0.077	0.377	0.506	0.990
	Average	**0.077**	**0.377**	**0.506**	**0.990**

Table C.2-4 Model performance statistics (September – October)

Columbia River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
CWMW	500	-0.622	0.650	0.784	0.890
WRNO	1370	-0.408	0.587	0.744	0.967
BON	1200	-0.530	0.599	0.755	0.813
TDDO	901	-0.027	0.435	0.559	0.971
JHAW	892	-0.006	0.424	0.550	0.973
MCPW	1243	0.477	0.538	0.677	0.978
PRXW	1032	0.165	0.415	0.519	0.960
WANW	973	0.076	0.385	0.482	0.959
RIGW	632	0.233	0.535	0.682	0.918
RRDW	547	0.261	0.493	0.651	0.919
WELW	518	0.067	0.433	0.542	0.896
CHQW	821	-0.145	0.344	0.522	0.815
	Average	**-0.038**	**0.487**	**0.622**	**0.922**
Snake River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
IDSW	7635	0.141	0.460	0.588	0.996
LMNW	6052	0.090	0.521	0.658	0.994
LGSW	5859	0.093	0.531	0.667	0.994
LGNW	7345	0.087	0.494	0.625	0.994
	Average	**0.103**	**0.501**	**0.634**	**0.995**
Clearwater River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
PEKI	5157	0.077	0.377	0.506	0.990
	Average	**0.077**	**0.377**	**0.506**	**0.990**

C.3 Temperature Model Results

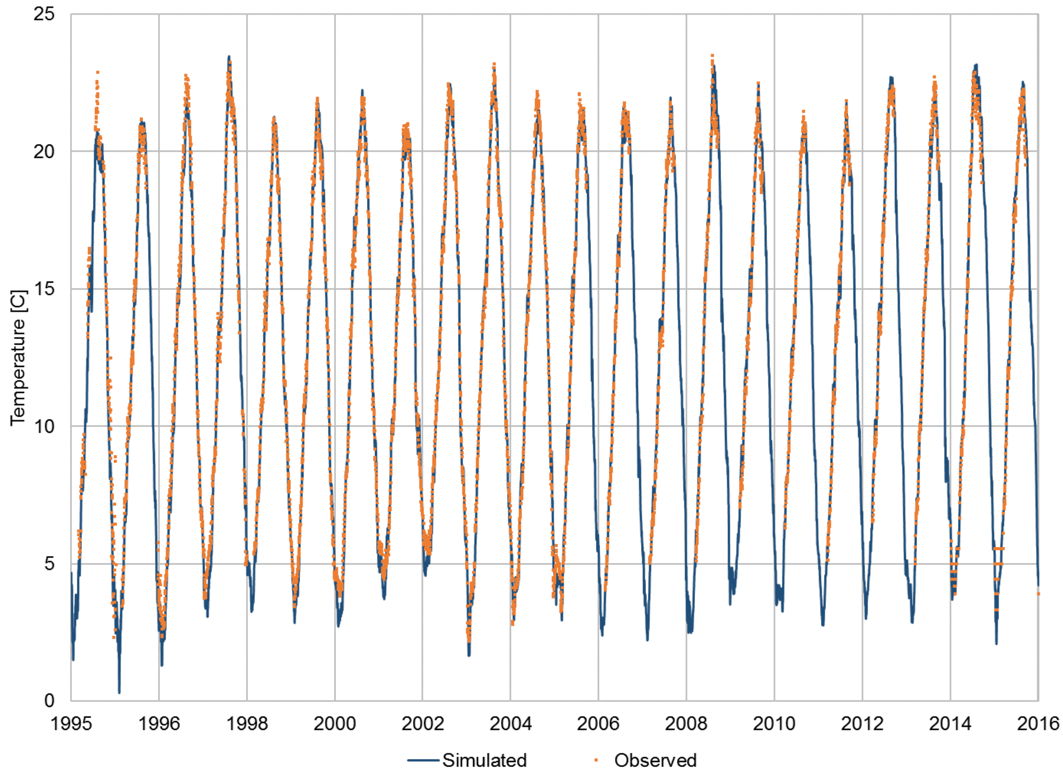

Figure C.3-1 Simulated versus observed temperature at BON, Columbia River RM 146

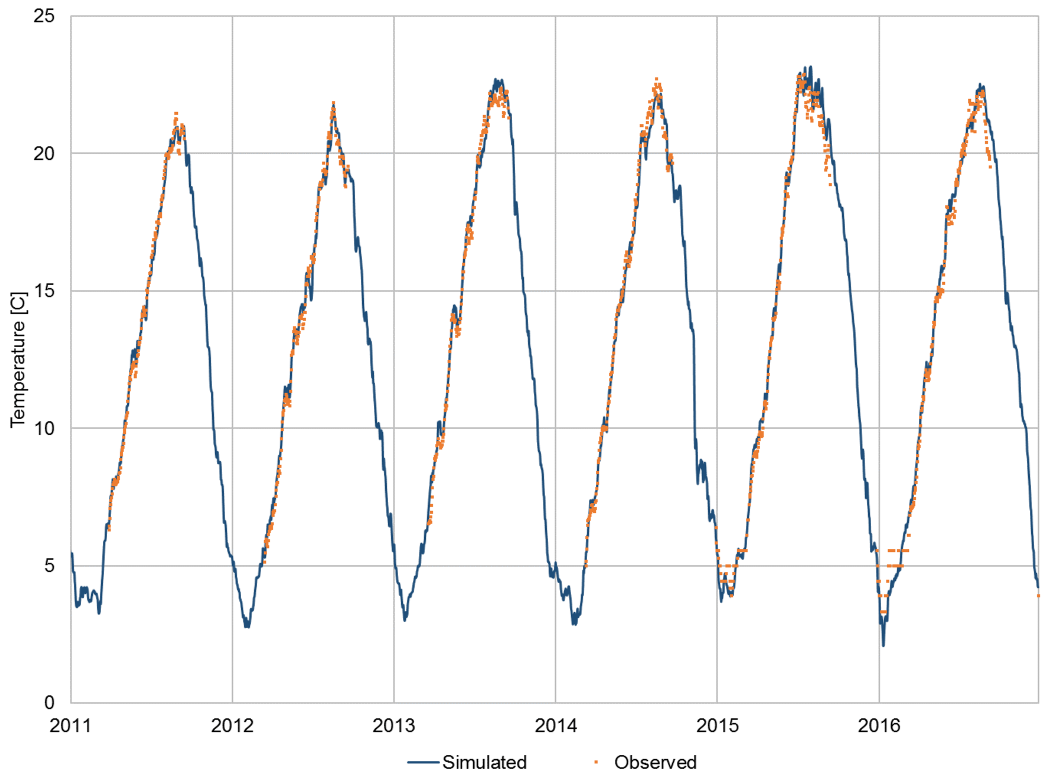

Figure C.3-2 Simulated versus observed temperature at BON, period 2011 – 2016

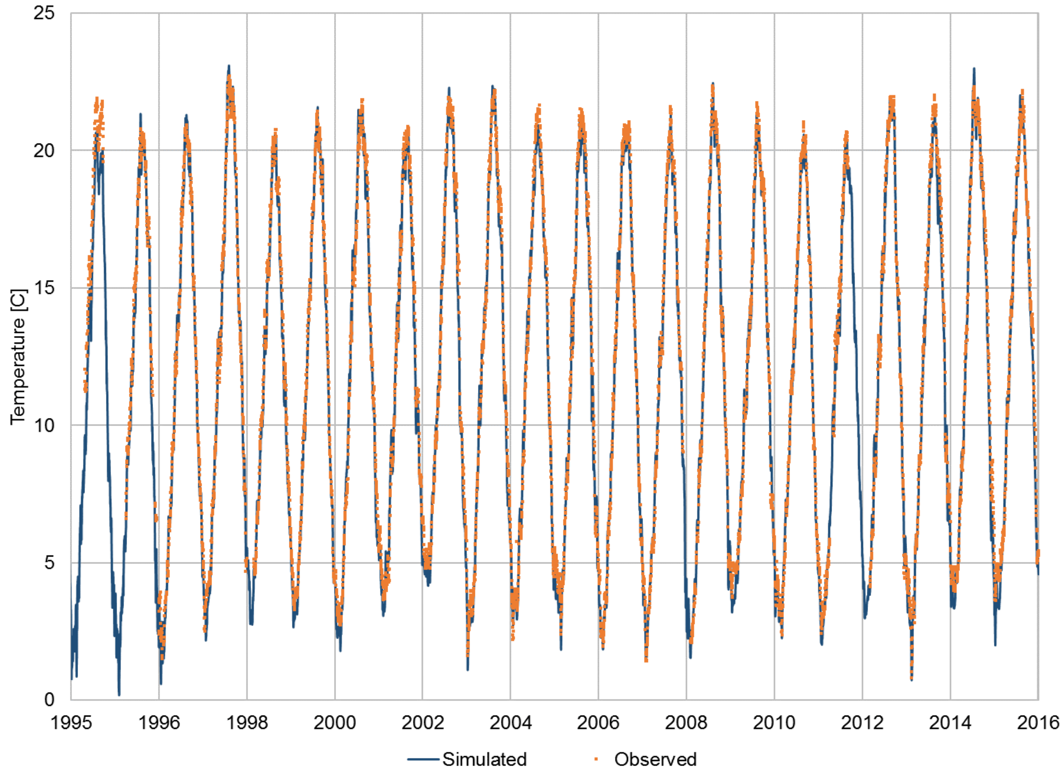

Figure C.3-3 Simulated versus observed temperature at MCPW, Columbia River RM 291

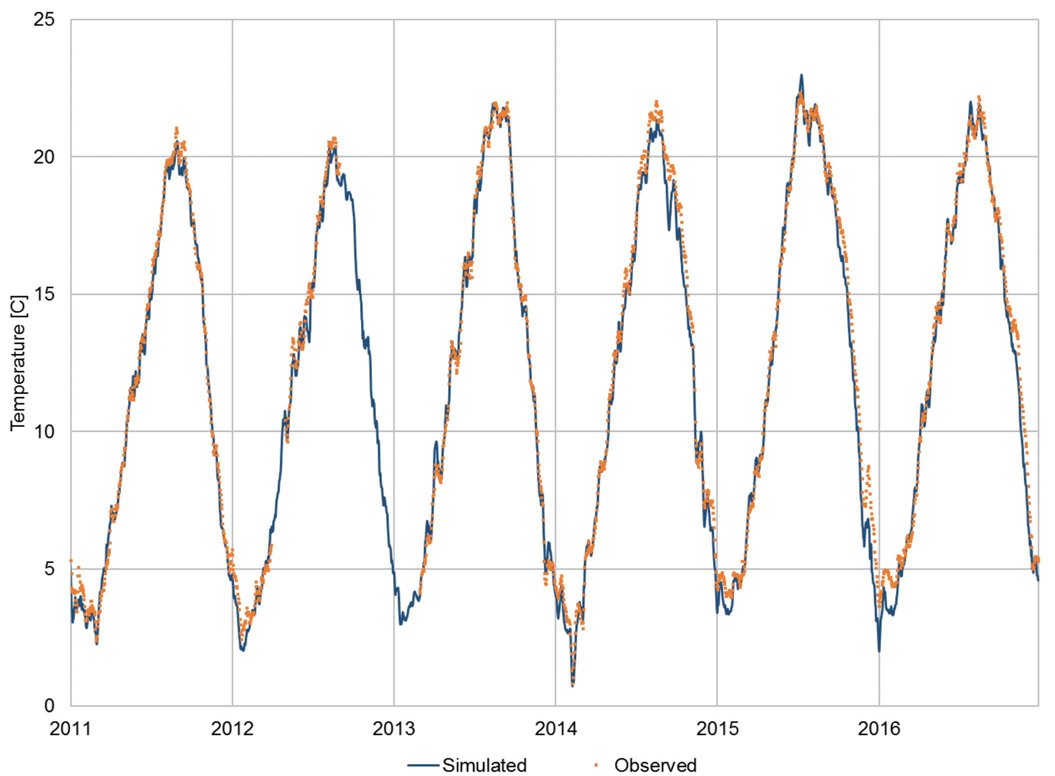

Figure C.3-4 Simulated versus observed temperature at MCPW, period 2011 – 2016

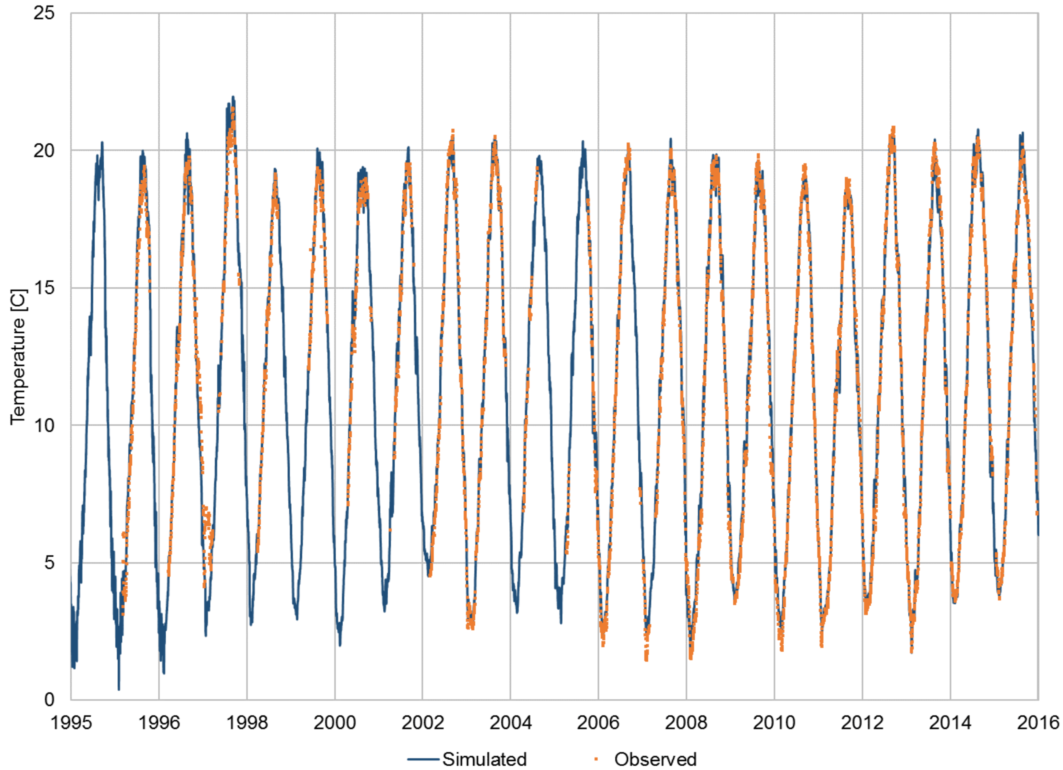

Figure C.3-5 Simulated versus observed temperature at WANW, Columbia River RM 415

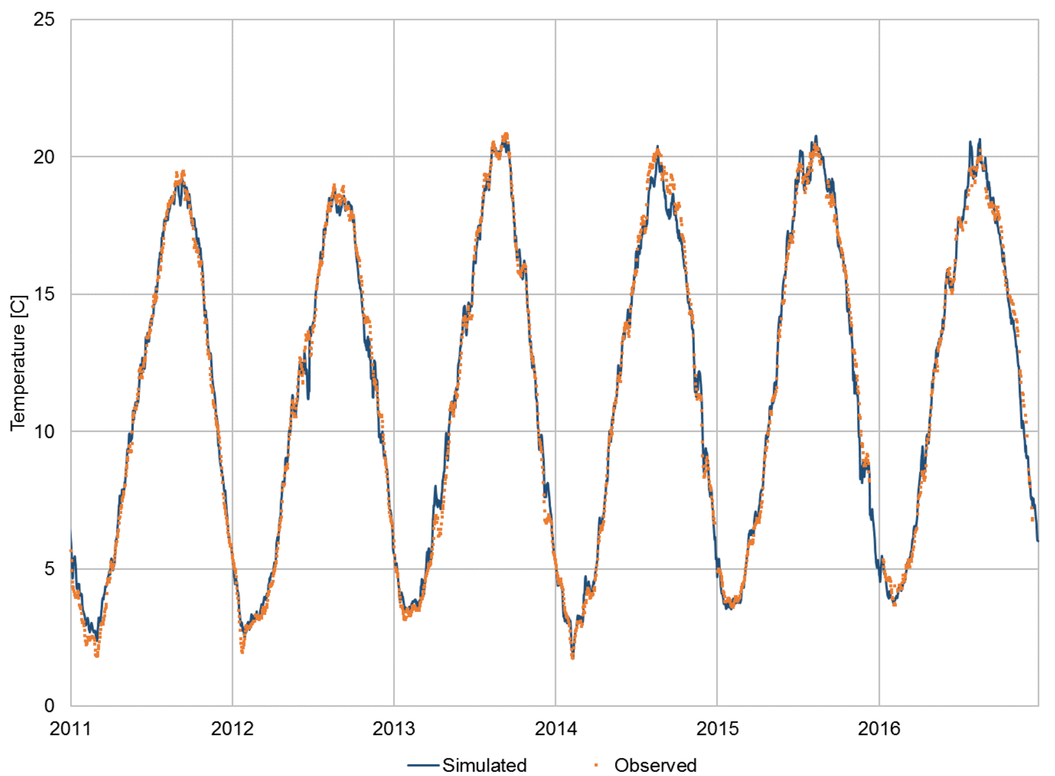

Figure C.3-6 Simulated versus observed temperature at WANW, period 2011 – 2016

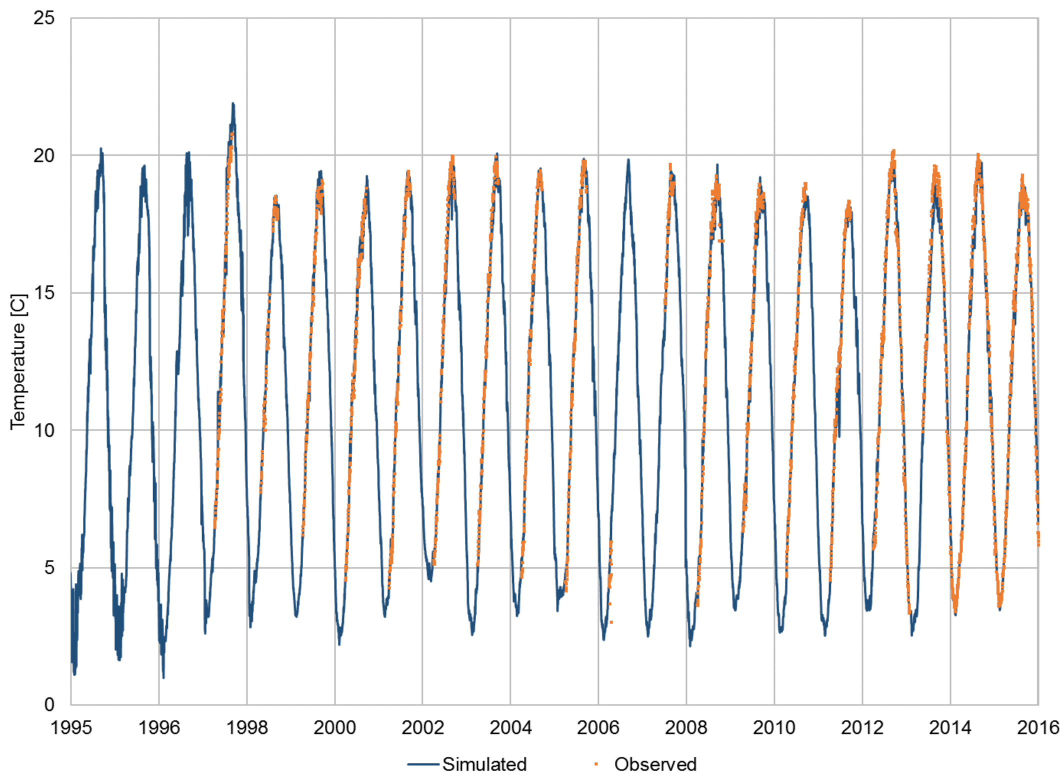

Figure C.3-7 Simulated versus observed temperature at WELW, Columbia River RM 514

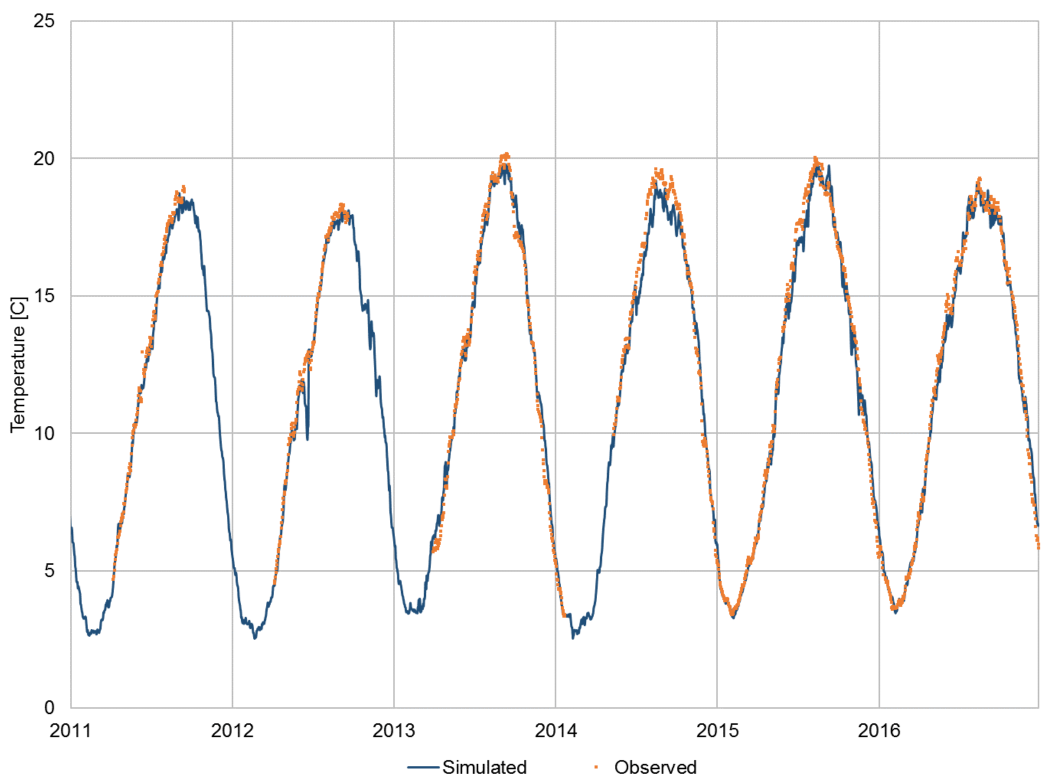

Figure C.3-8 Simulated versus observed temperature at WELW, period 2011 – 2016

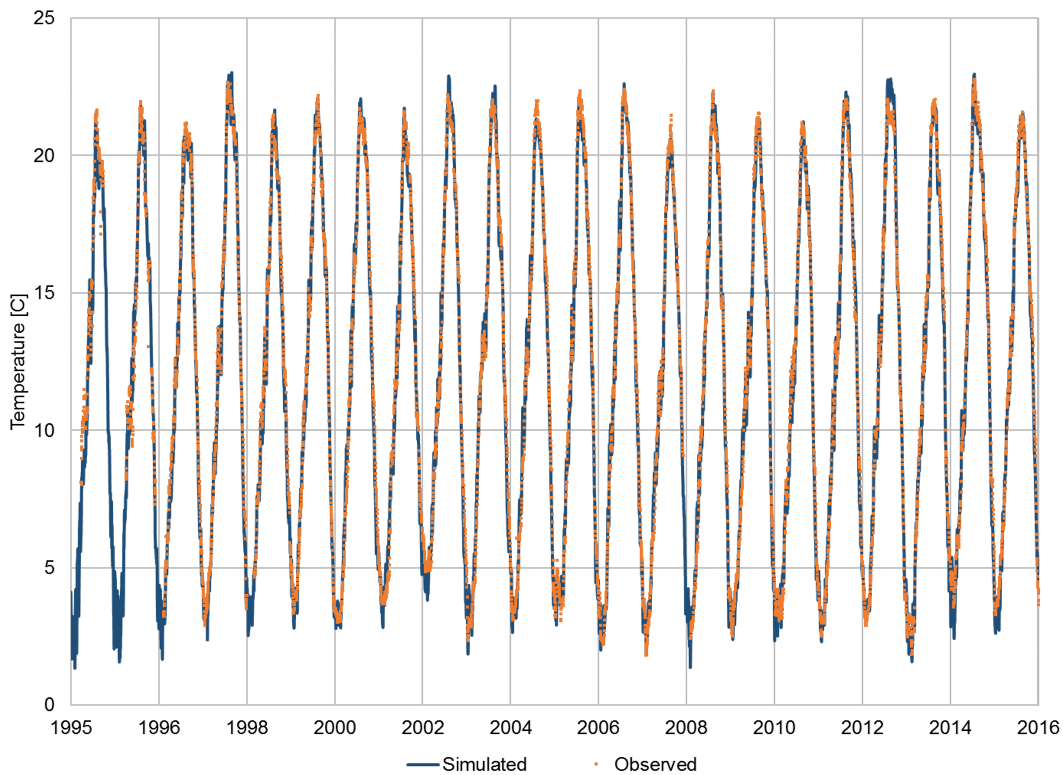

Figure C.3-9 Simulated versus observed temperature at IDSW, Snake River RM 6.8

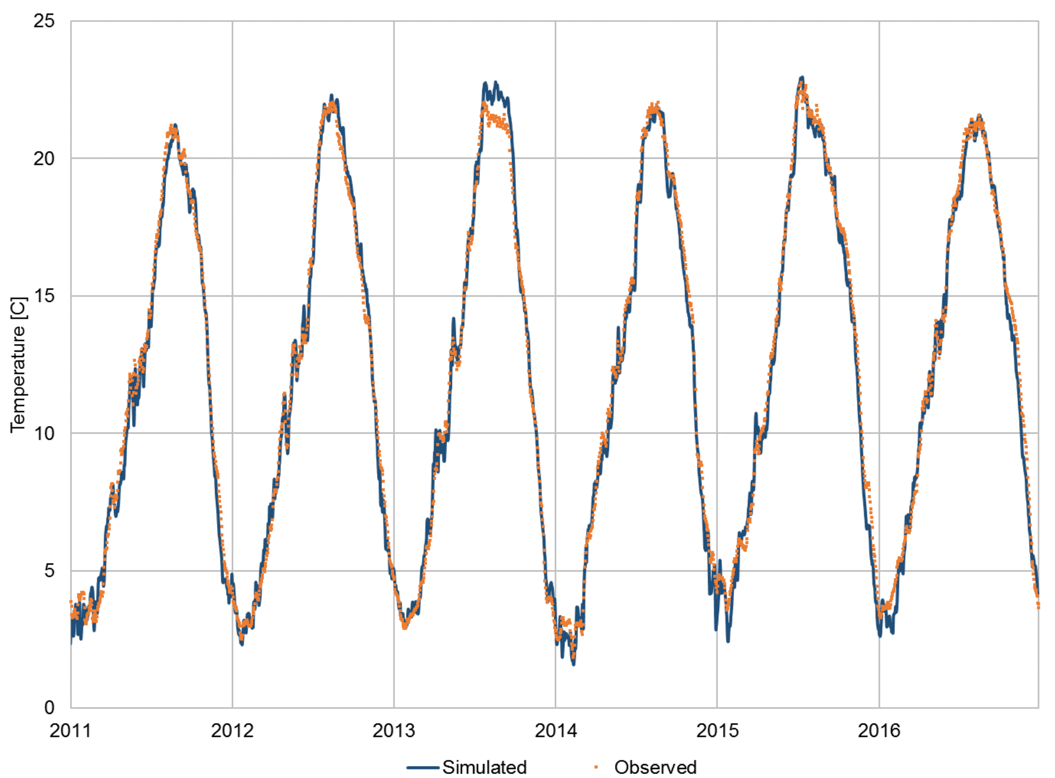

Figure C.3-10 Simulated versus observed temperature at IDSW, period 2011 – 2016

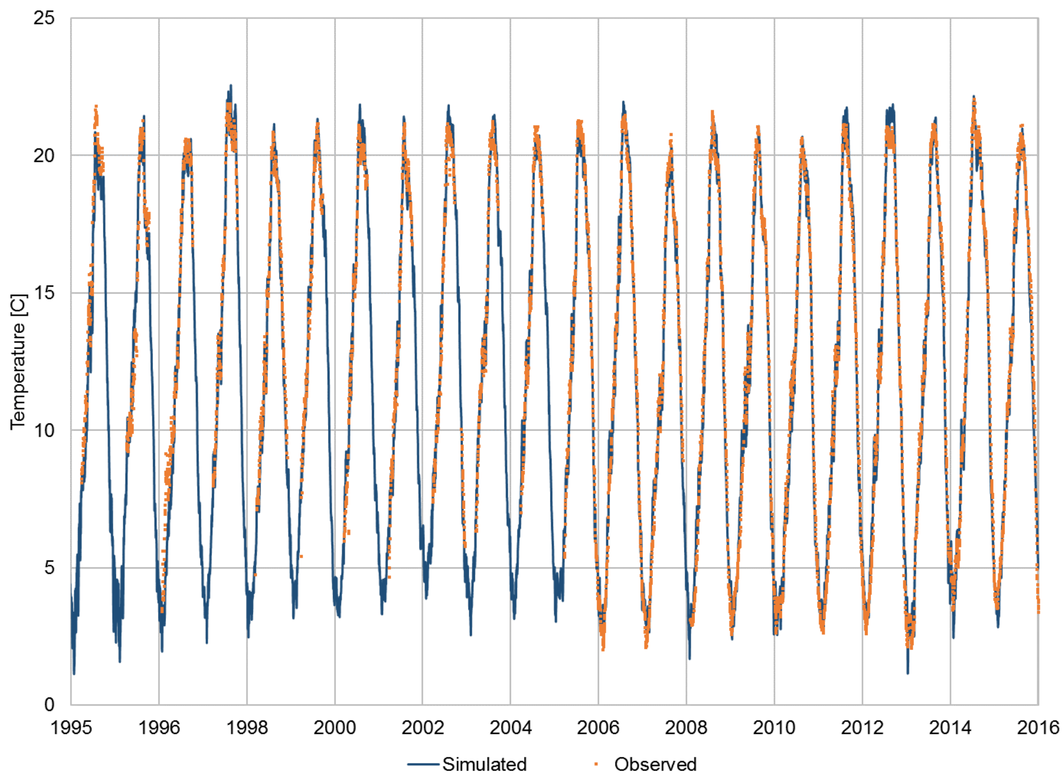

Figure C.3-11 Simulated versus observed temperature at LMNW, Snake River RM 40.8

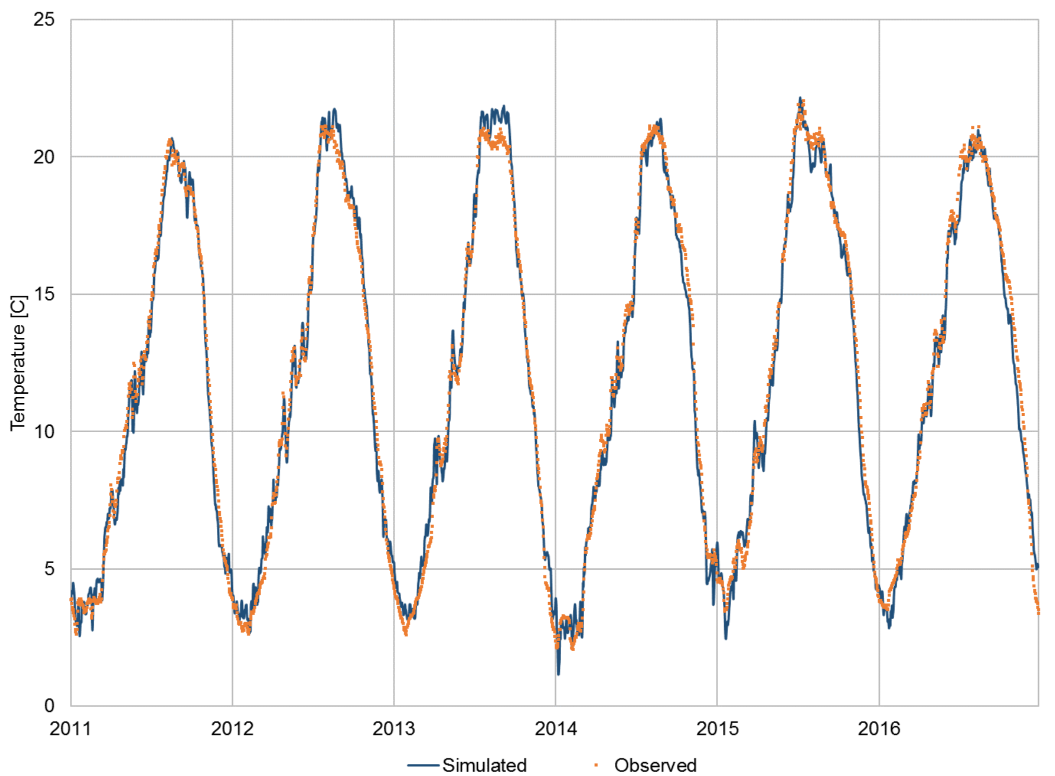

Figure C.3-12 Simulated versus observed temperature at LMNW, period 2011 – 2016

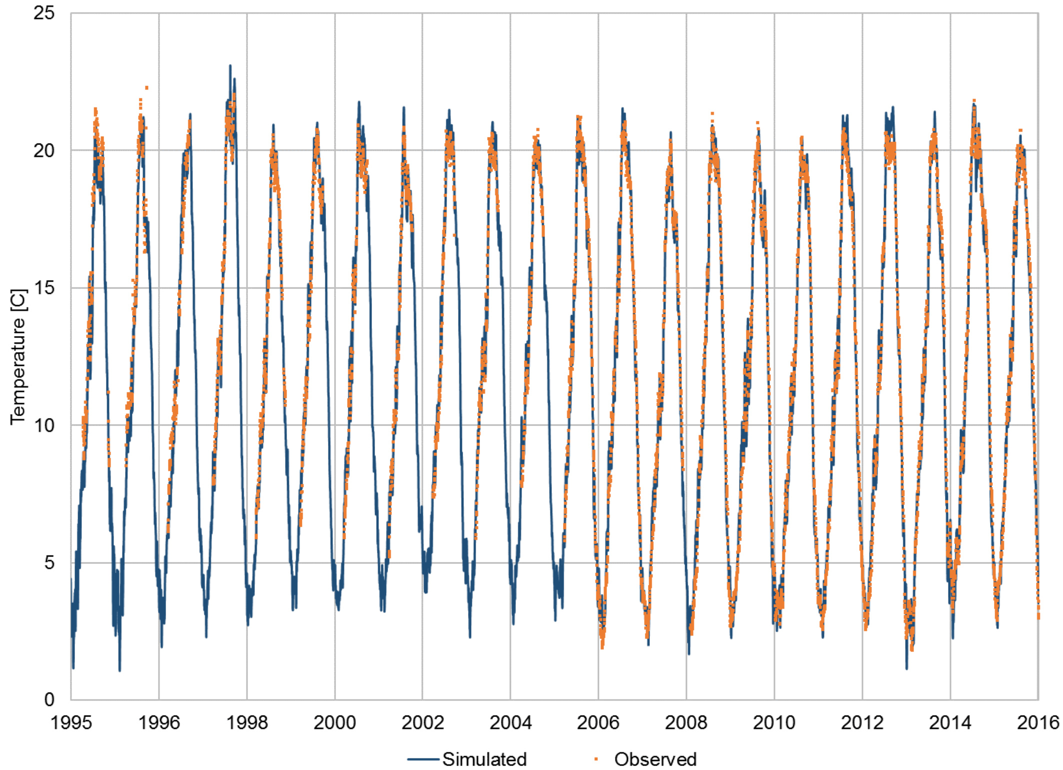

Figure C.3-13 Simulated versus observed temperature at LGSW, Snake River RM 69.5

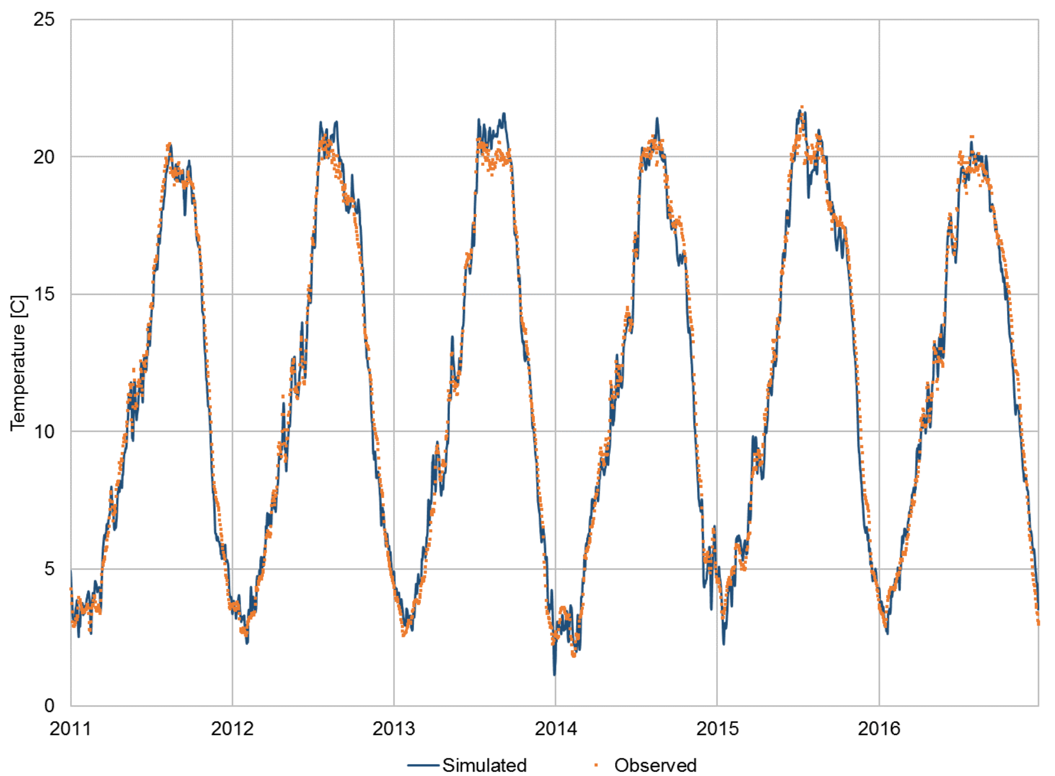

Figure C.3-14 Simulated versus observed temperature at LGSW, period 2011 – 2016

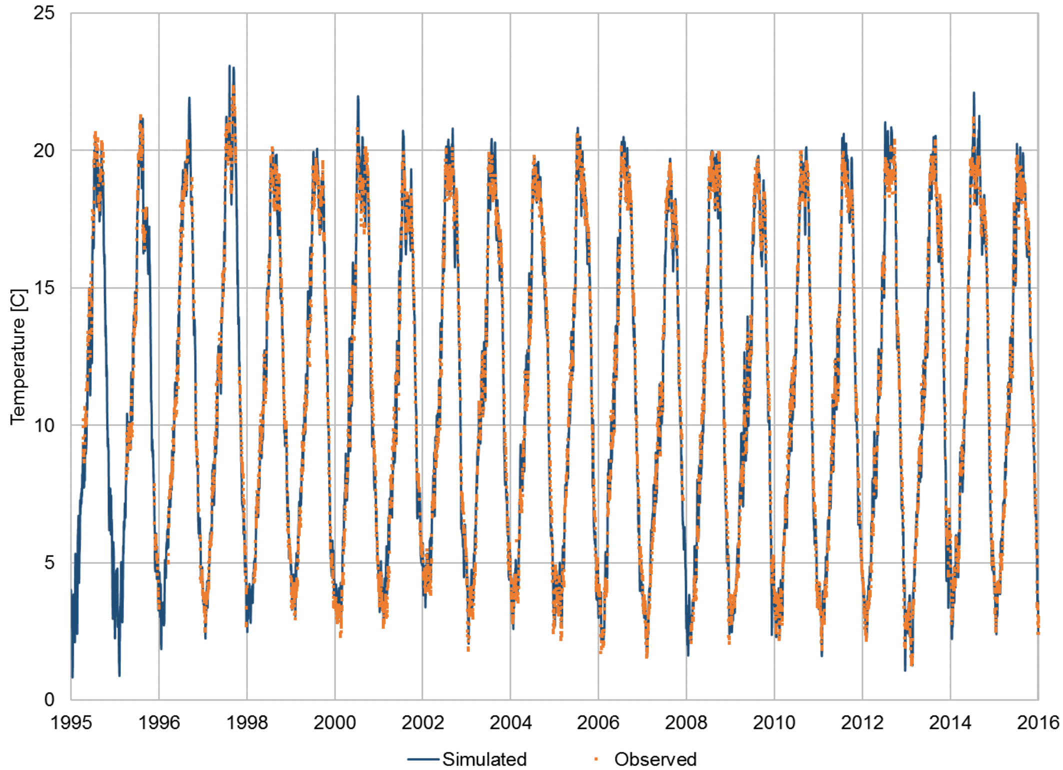

Figure C.3-15 Simulated versus observed temperature at LGNW, Snake River RM 106.8

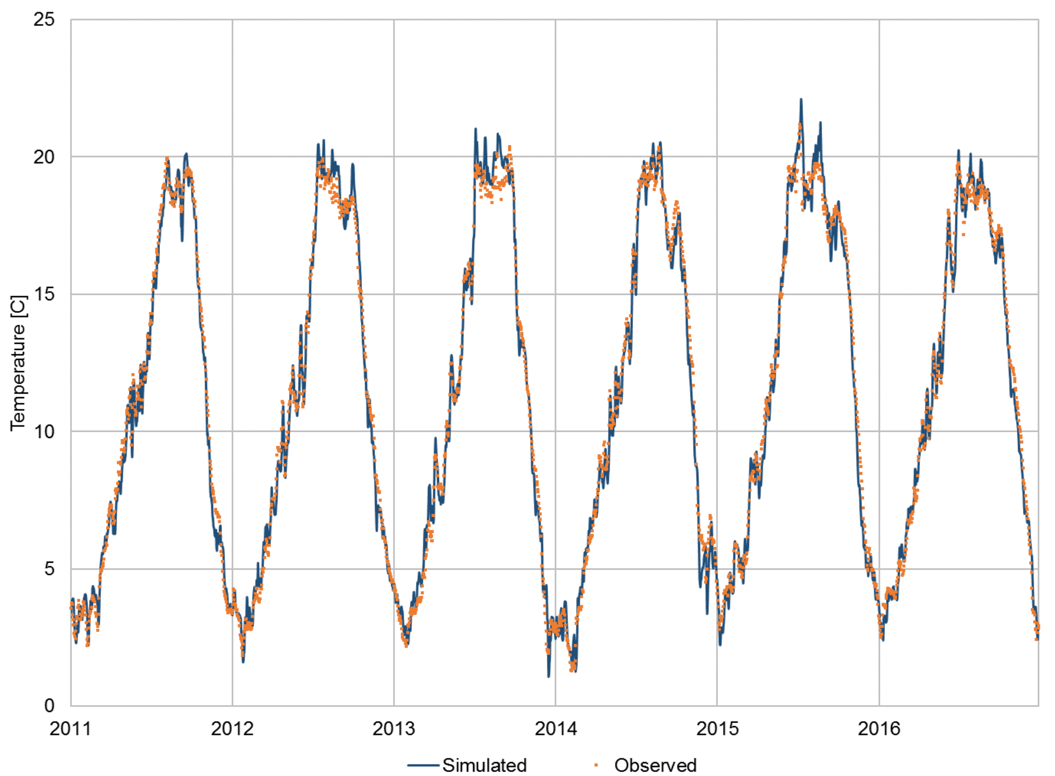

Figure C.3-16 Simulated versus observed temperature at LGNW, period 2011 – 2016

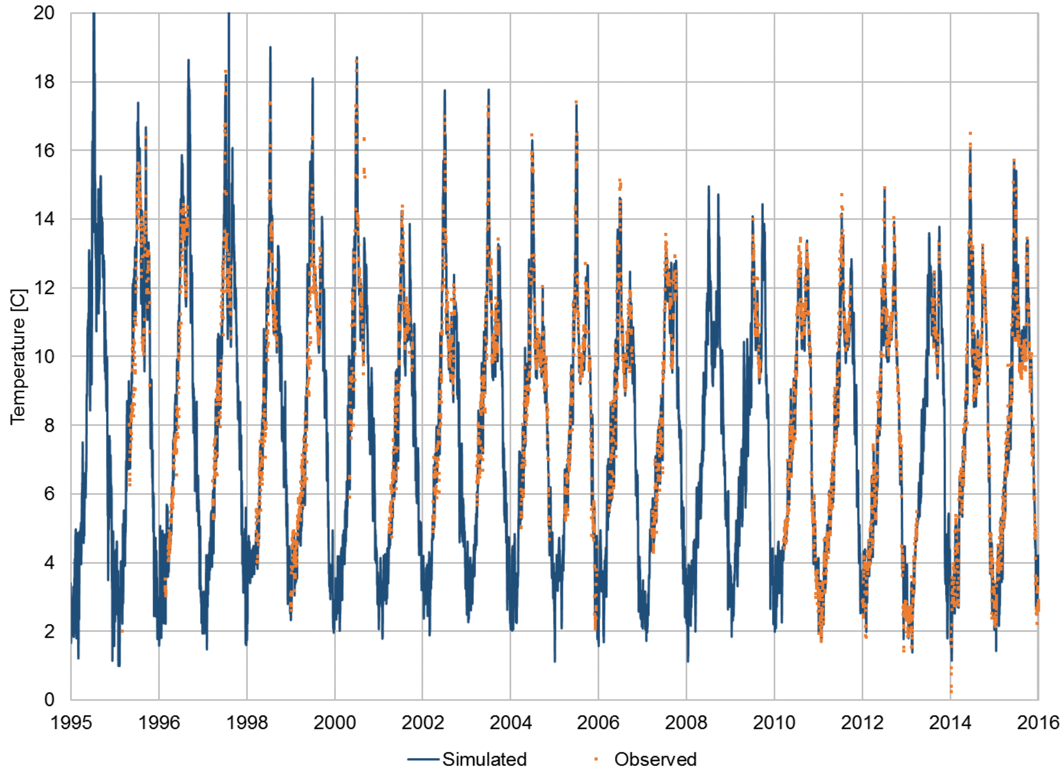

Figure C.3-17 Simulated versus observed temperature at PEKI, Clearwater River RM 33

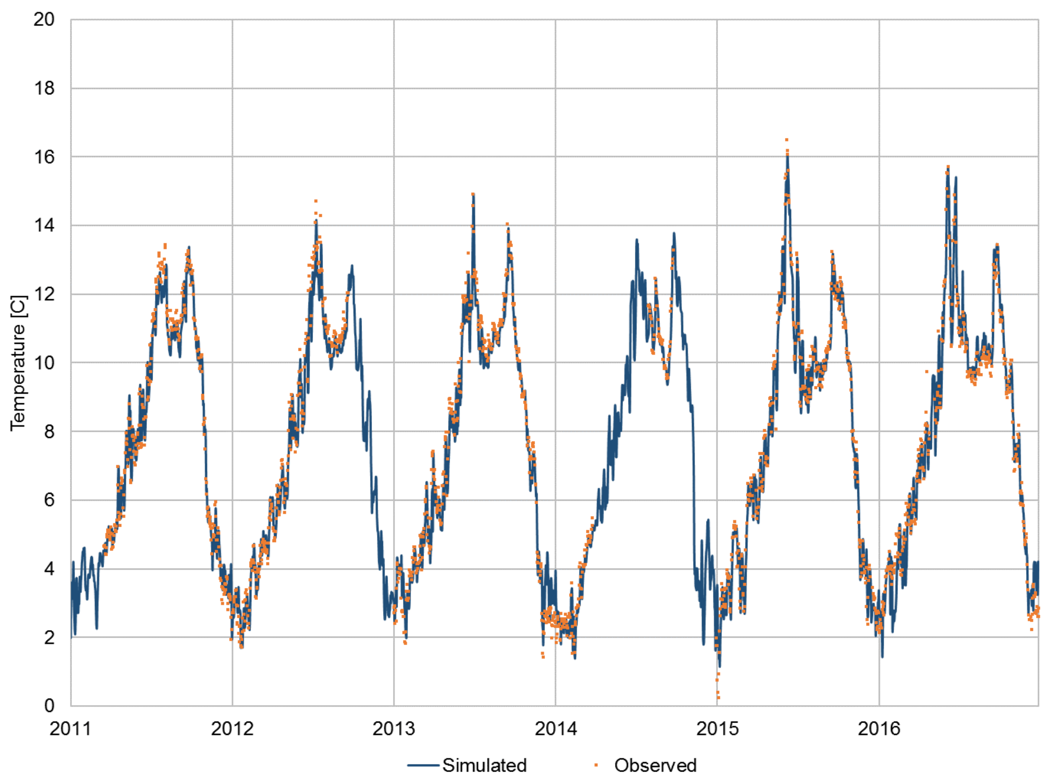

Figure C.3-18 Simulated versus observed temperature at PEKI, period 2011 – 2016

C.4 10-year Daily Average Temperature Comparisons

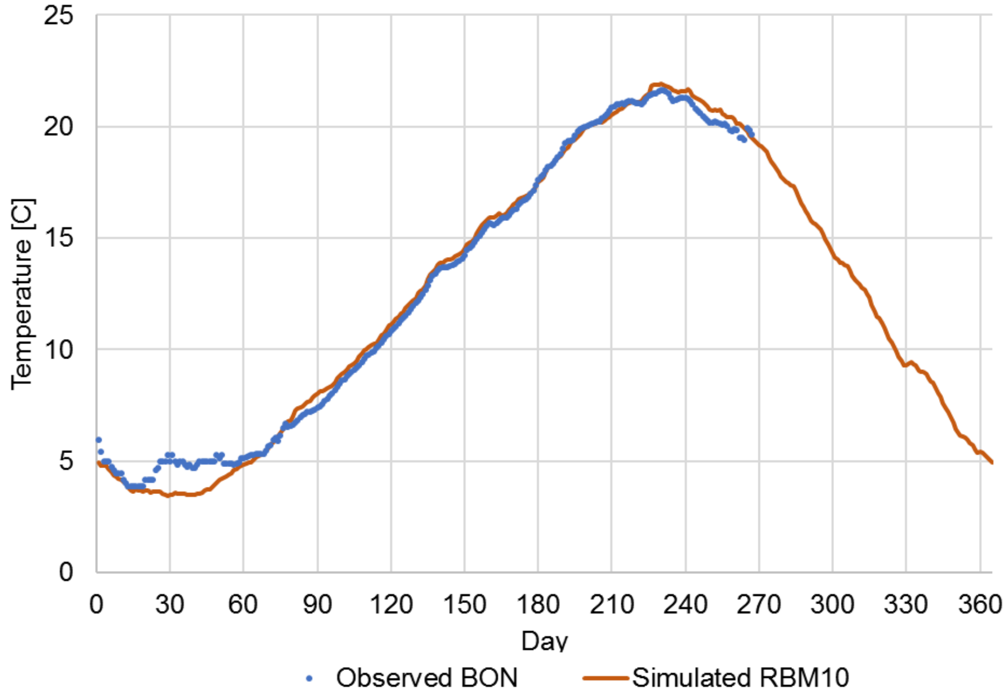

Figure C.4-1 10-year daily average temperature comparison at BON

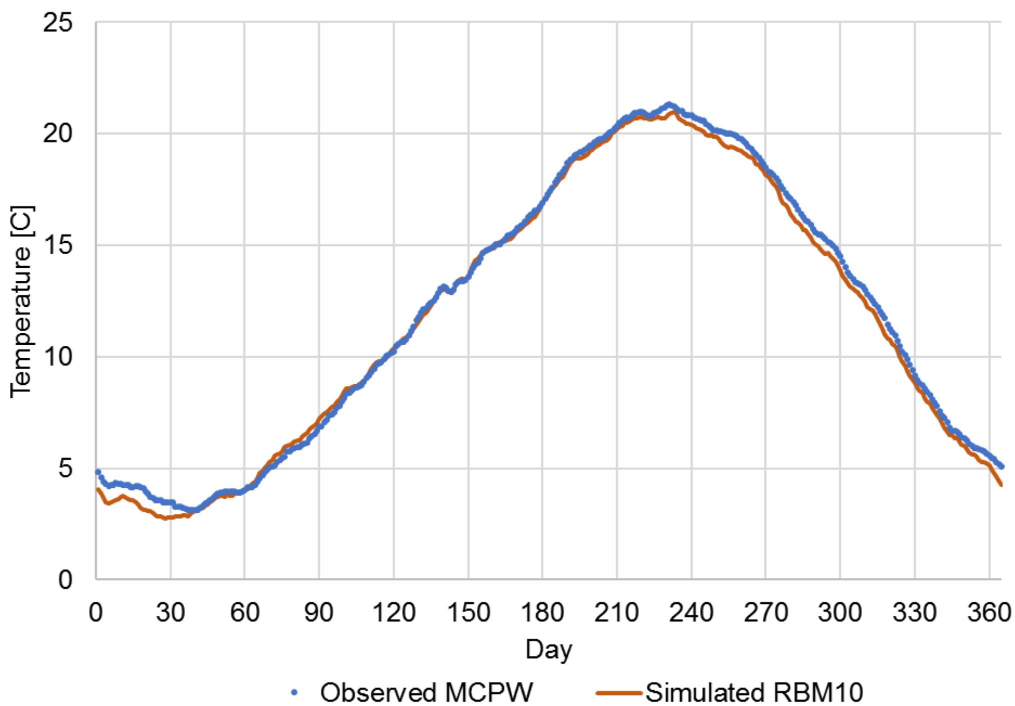

Figure C.4-2 10-year daily average temperature comparison at MCPW

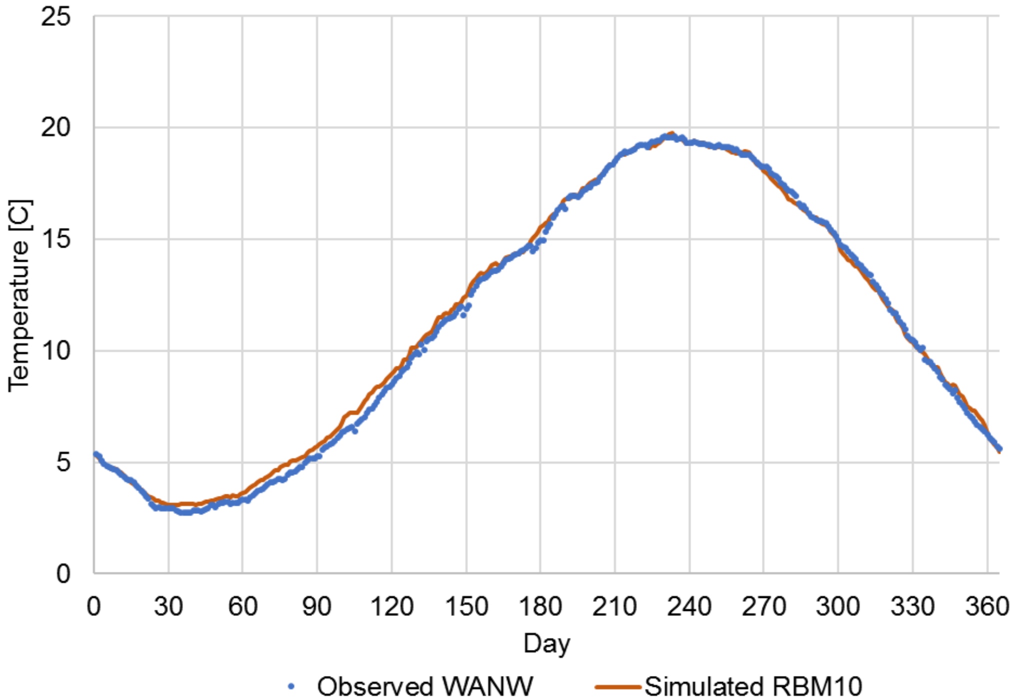

Figure C.4-3 10-year daily average temperature comparison at WANW

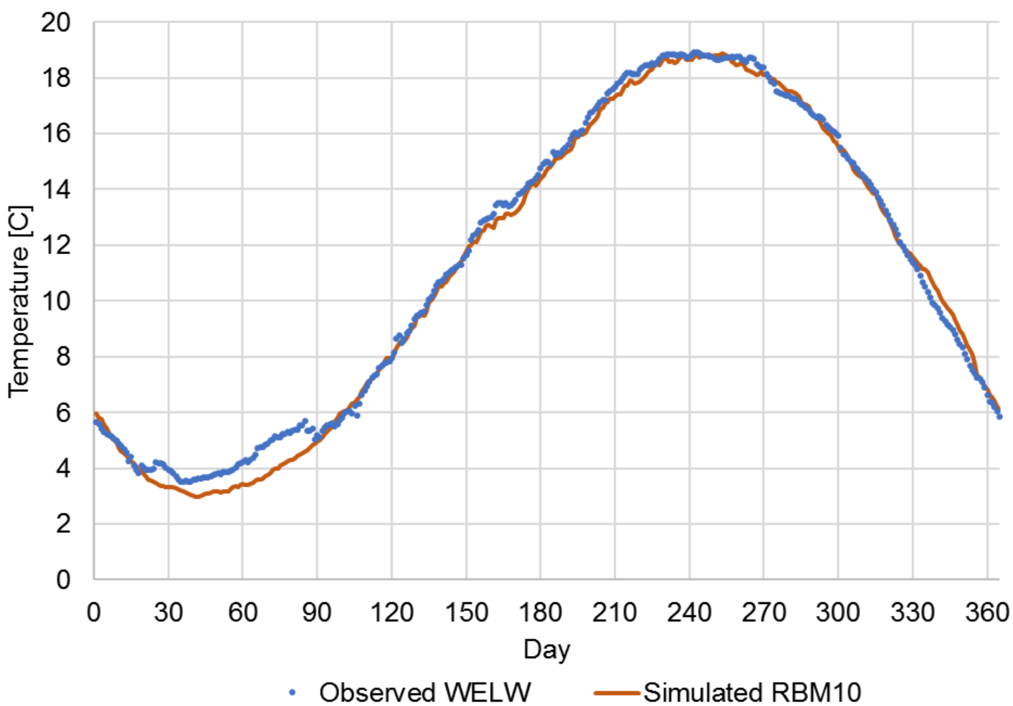

Figure C.4-4 10-year daily average temperature comparison at WELW

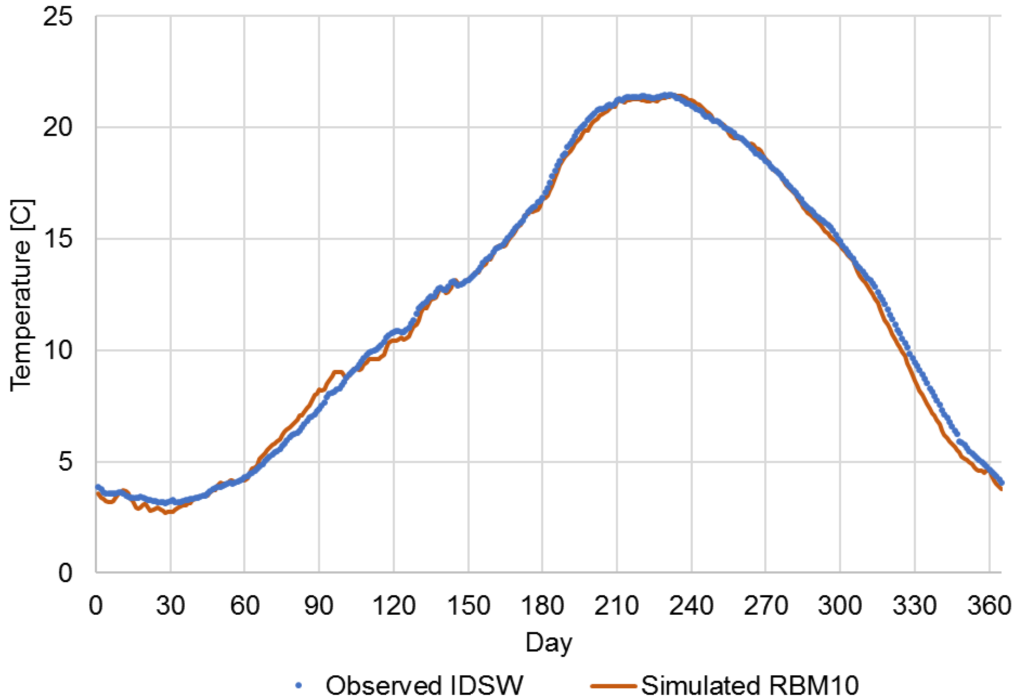

Figure C.4-5 10-year daily average temperature comparison at IDSW

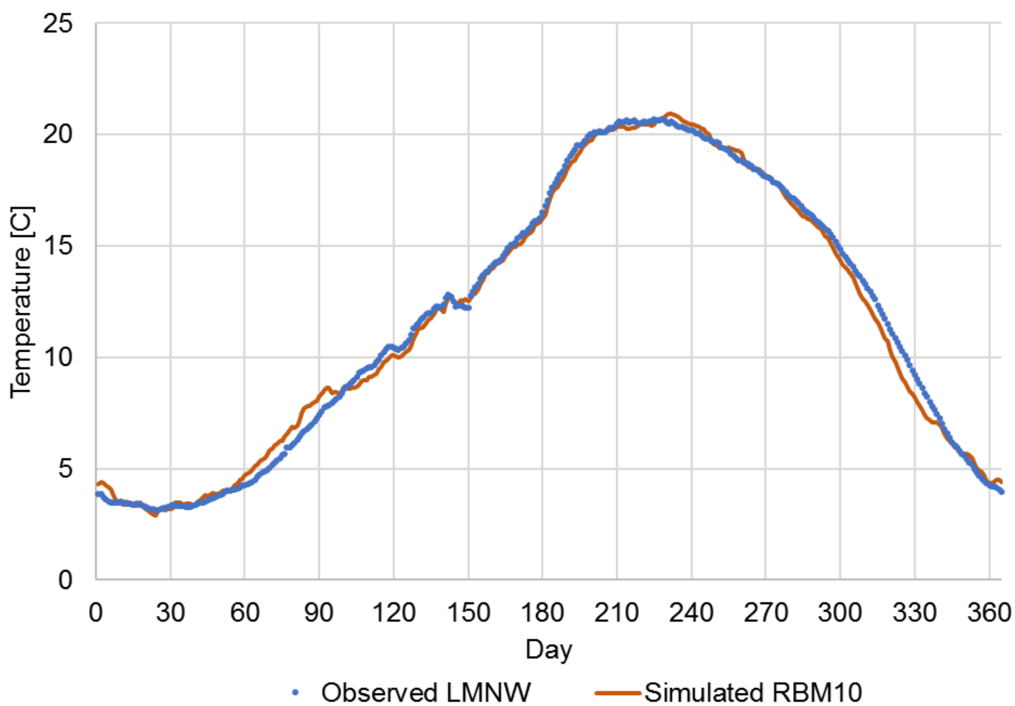

Figure C.4-6 10-year daily average temperature comparison at LMNW

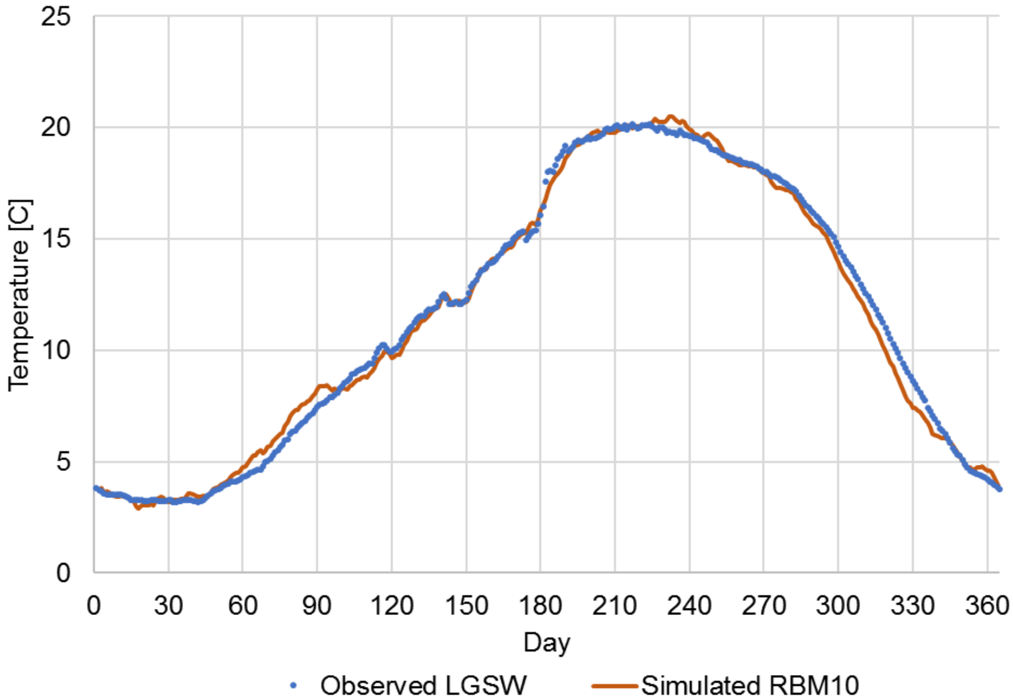

Figure C.4-7 10-year daily average temperature comparison at LGSW

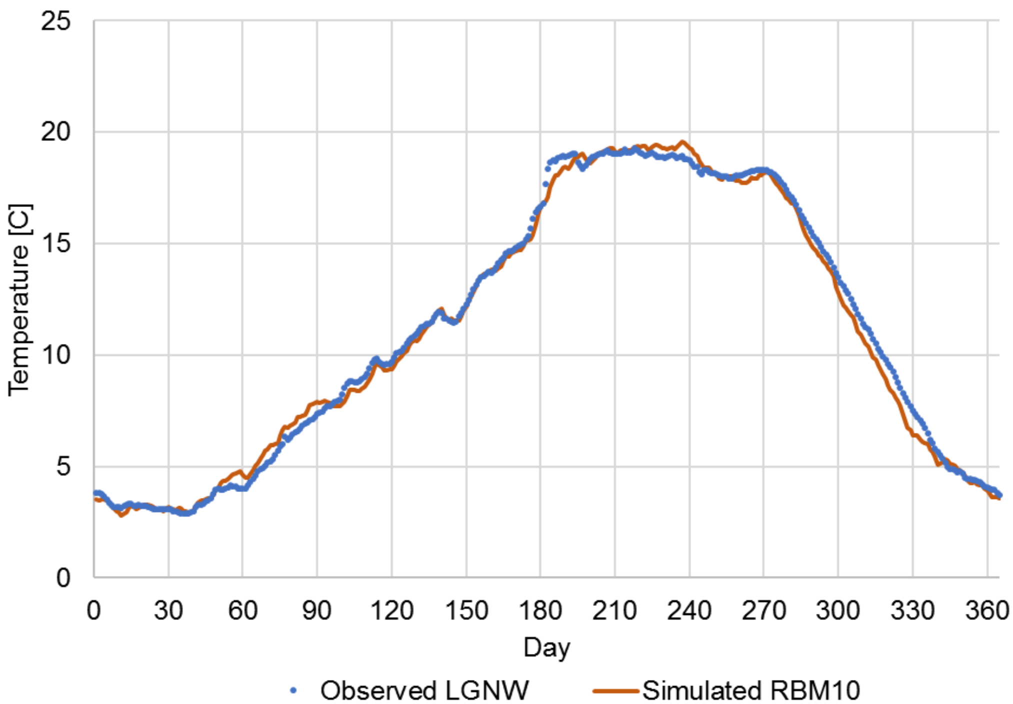

Figure C.4-8 10-year daily average temperature comparison at LGNW

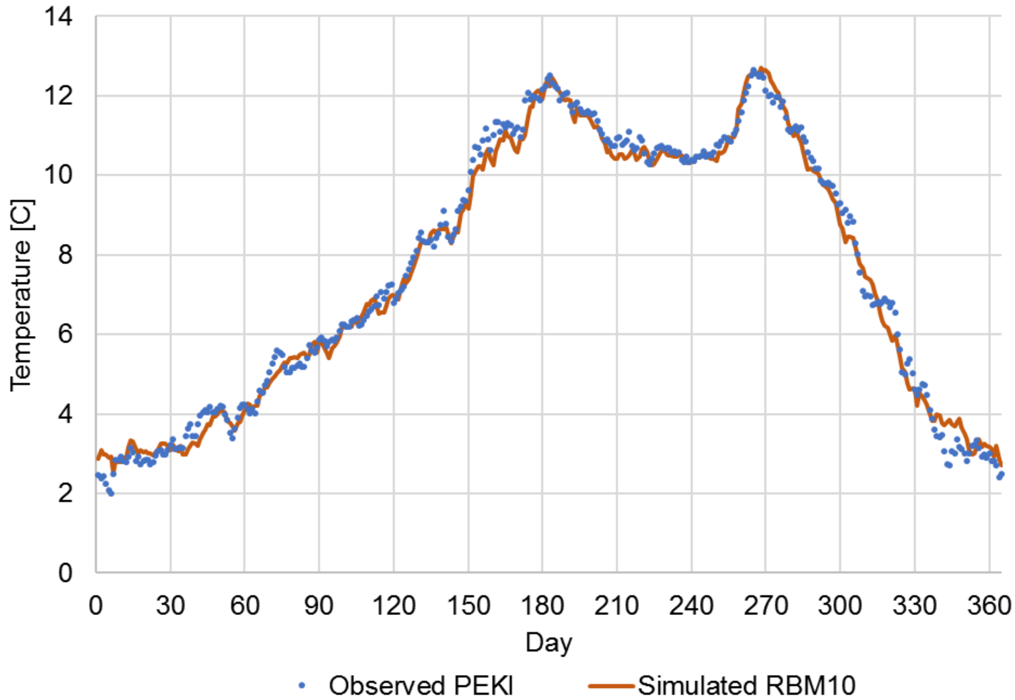

Figure C.4-9 10-year daily average temperature comparison at PEKI

C.5 Flow Discharge Model Results

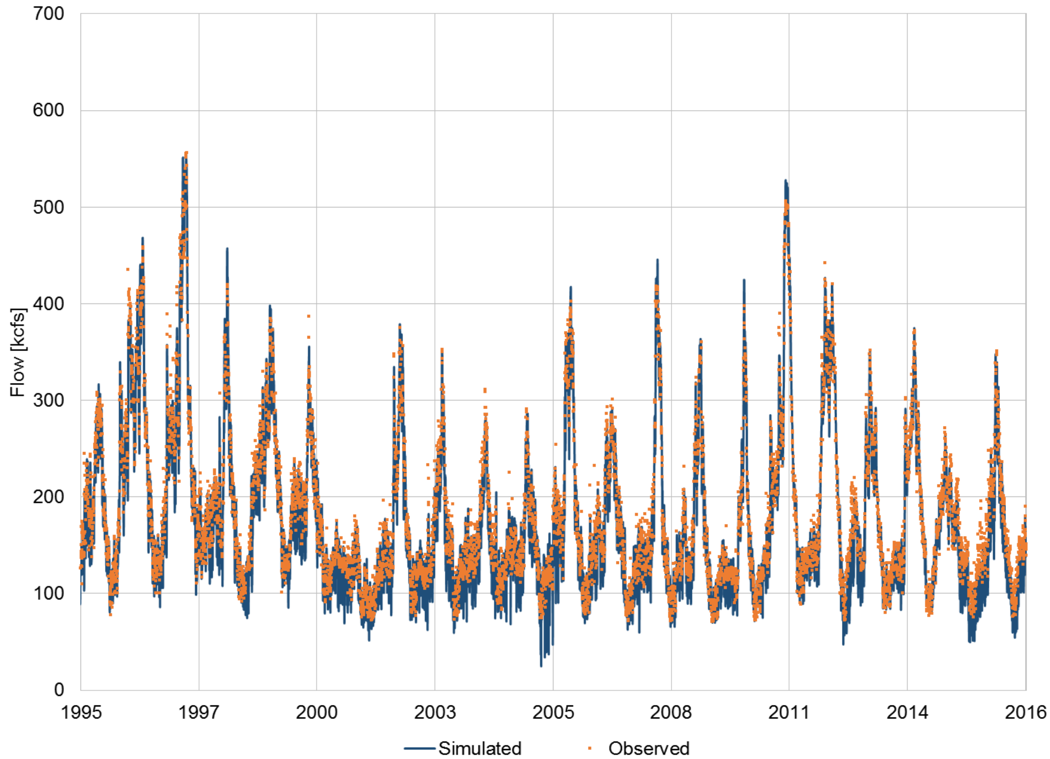

Figure C.5-1 Simulated versus observed flow at BON, Columbia River RM 146

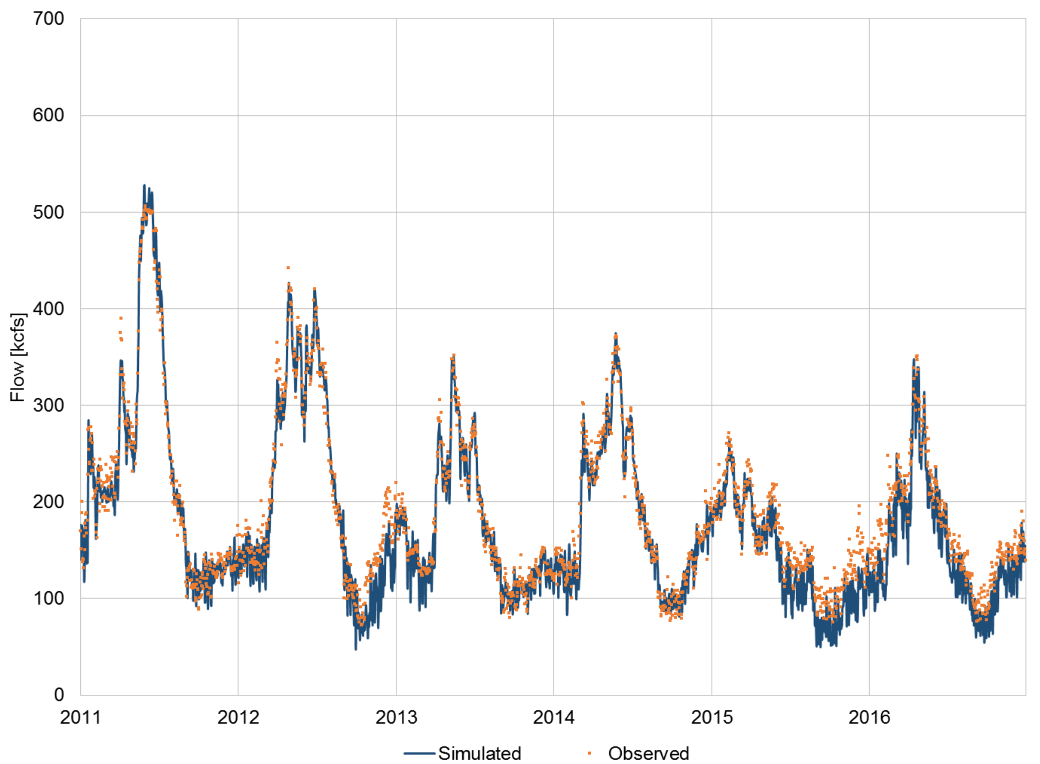

Figure C.5-2 Simulated versus observed flow at BON, period 2011 – 2016

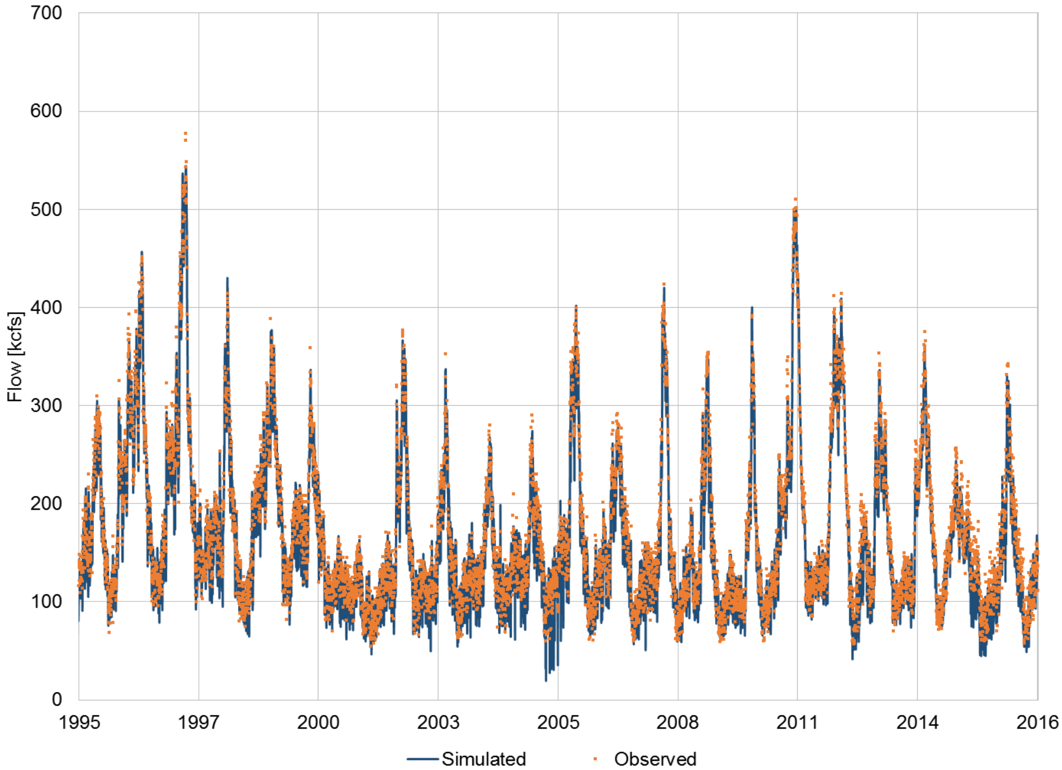

Figure C.5-3 Simulated versus observed flow at MCPW, Columbia River RM 291

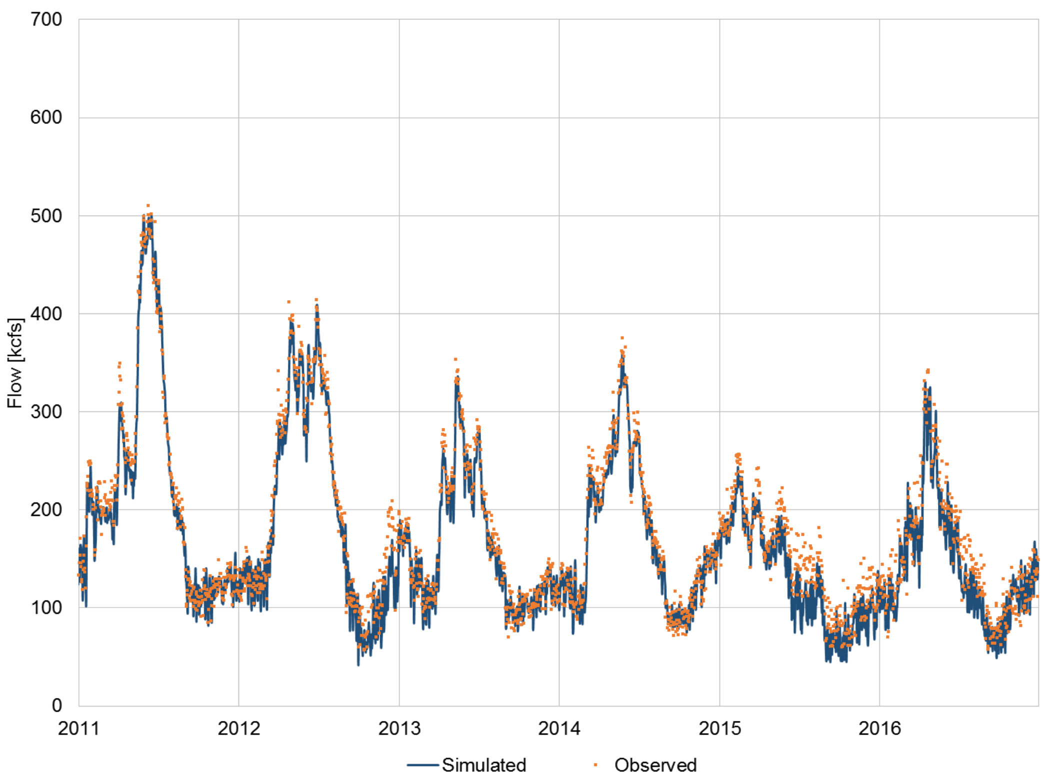

Figure C.5-4 Simulated versus observed flow at MCPW, period 2011 – 2016

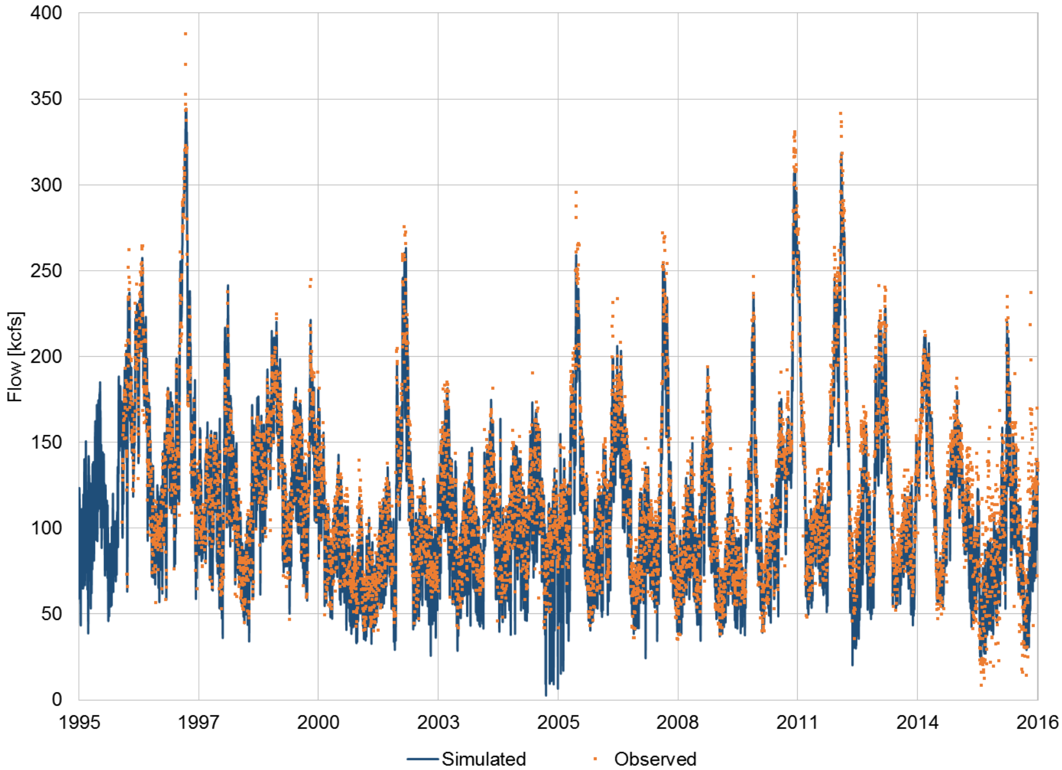

Figure C.5-5 Simulated versus observed flow at WANW, Columbia River RM 415

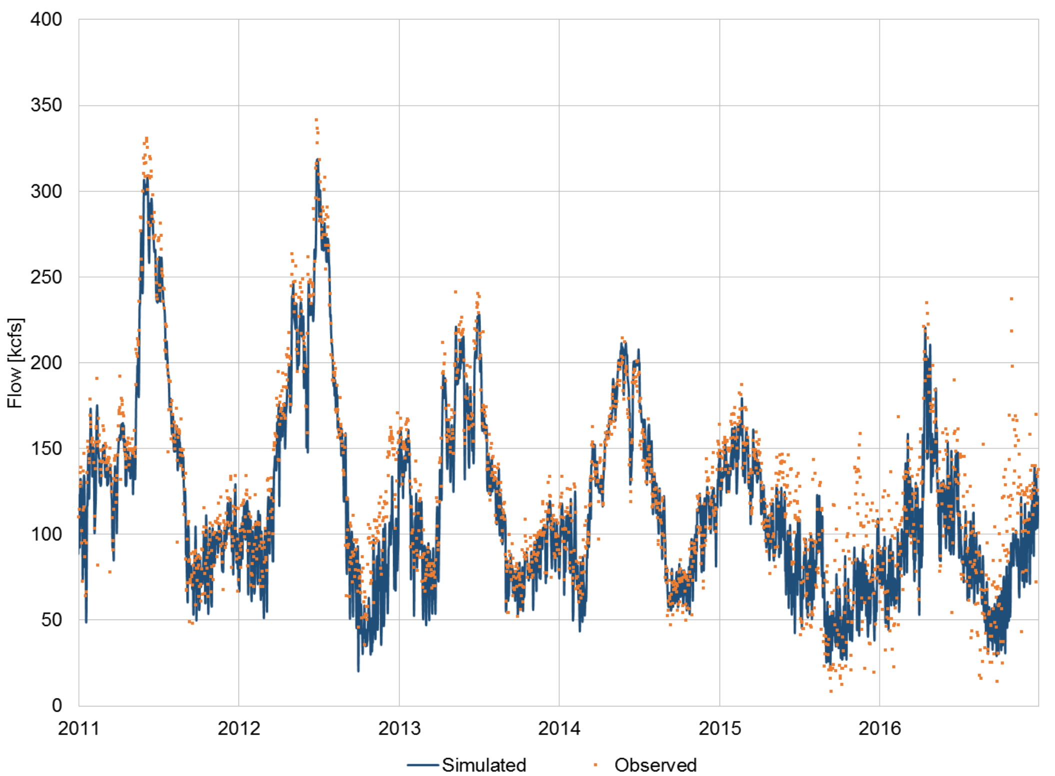

Figure C.5-6 Simulated versus observed flow at WANW, period 2011 – 2016

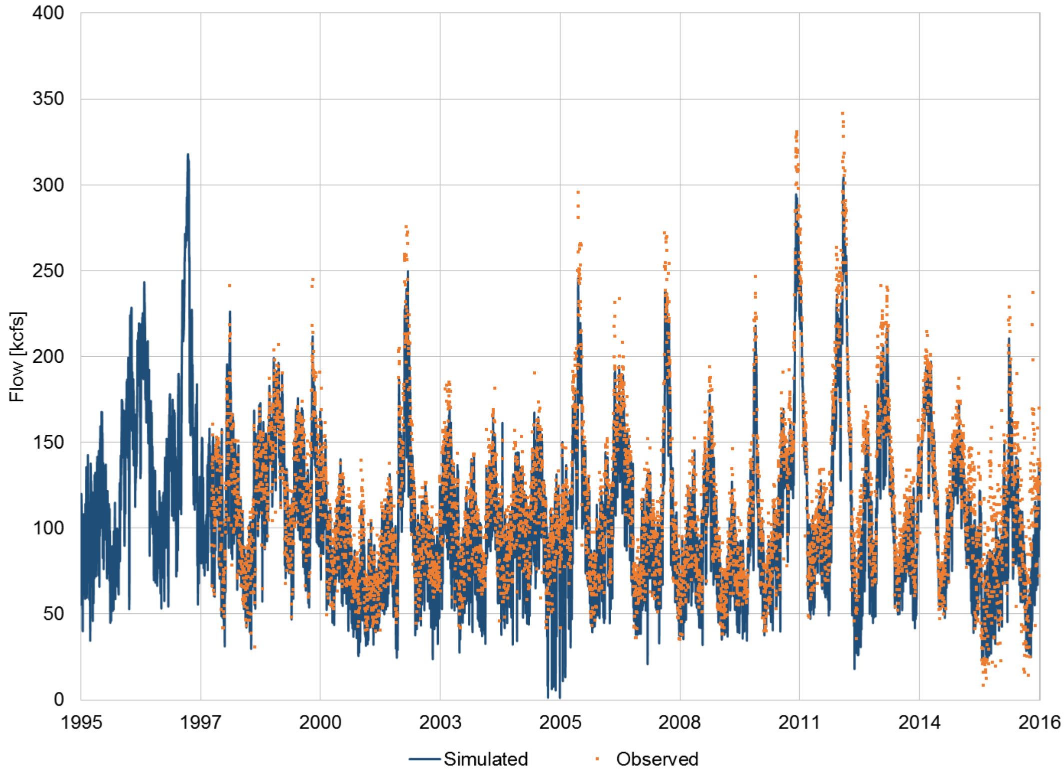

Figure C.5-7 Simulated versus observed flow at WELW, Columbia River RM 514

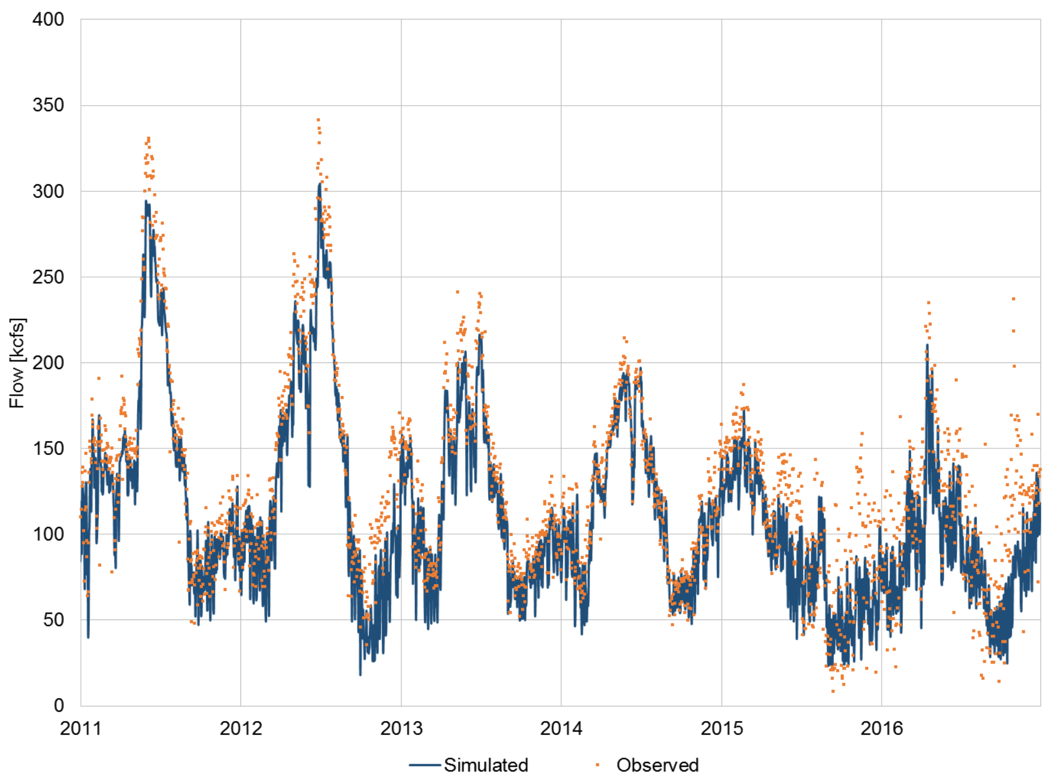

Figure C.5-8 Simulated versus observed flow at WELW, period 2011 – 2016

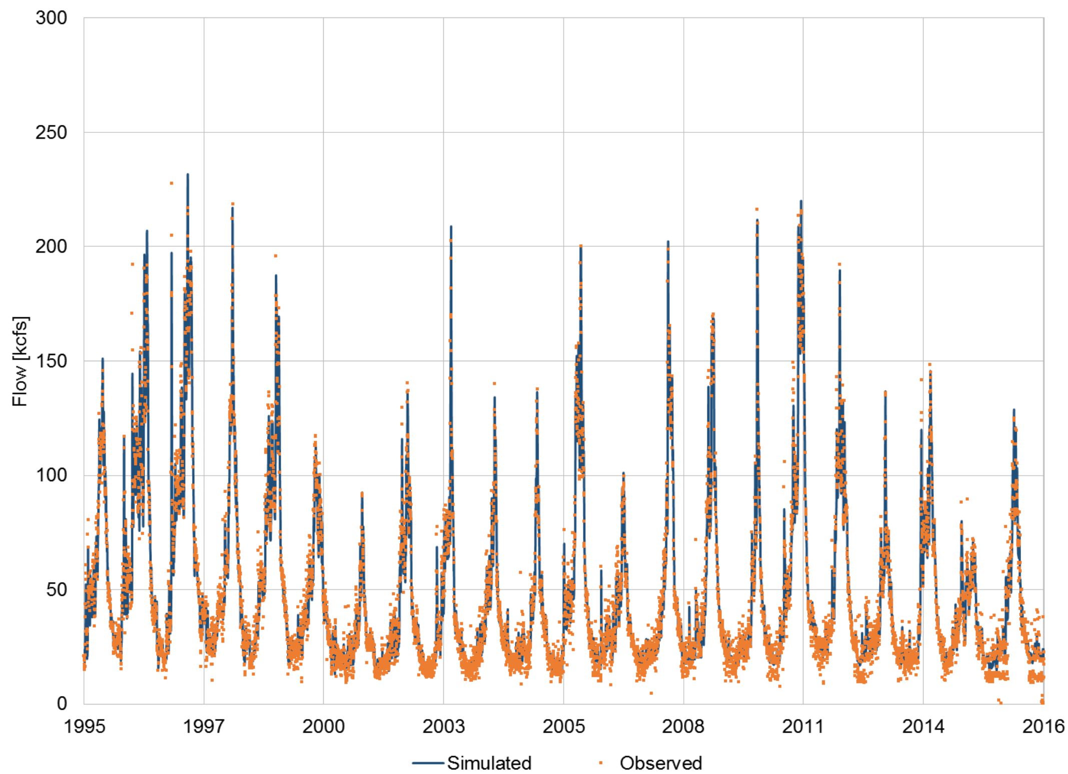

Figure C.5-9 Simulated versus observed flow at IDSW, Snake River RM 6.8

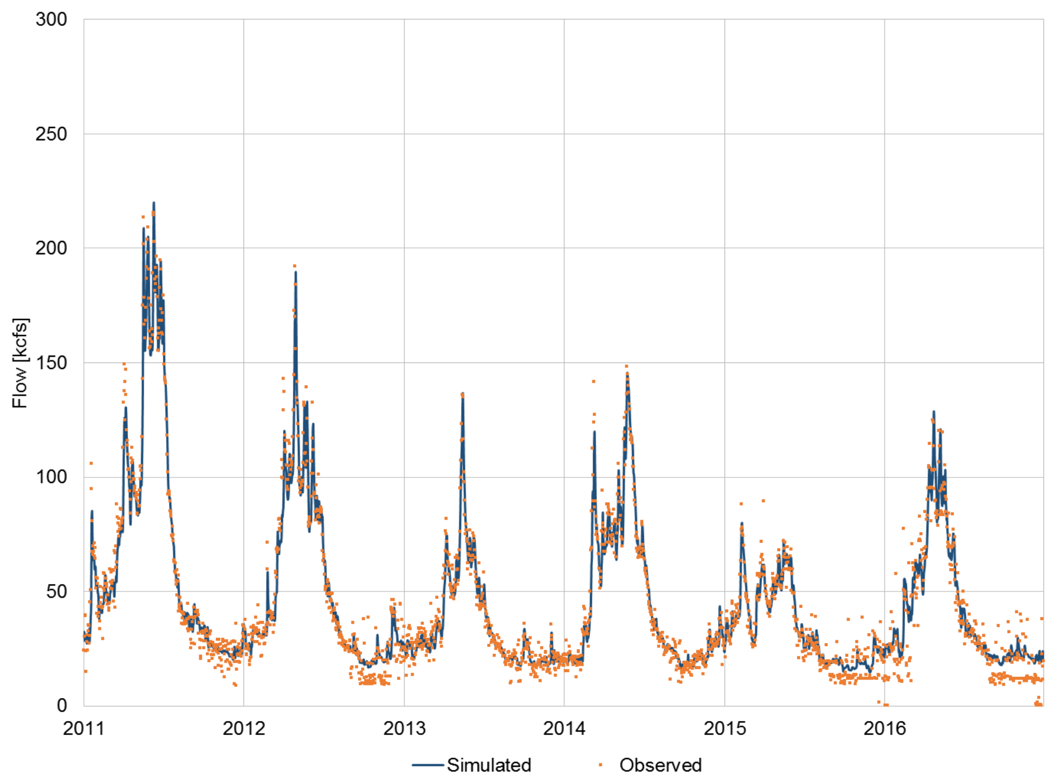

Figure C.5-10 Simulated versus observed flow at IDSW, period 2011 – 2016

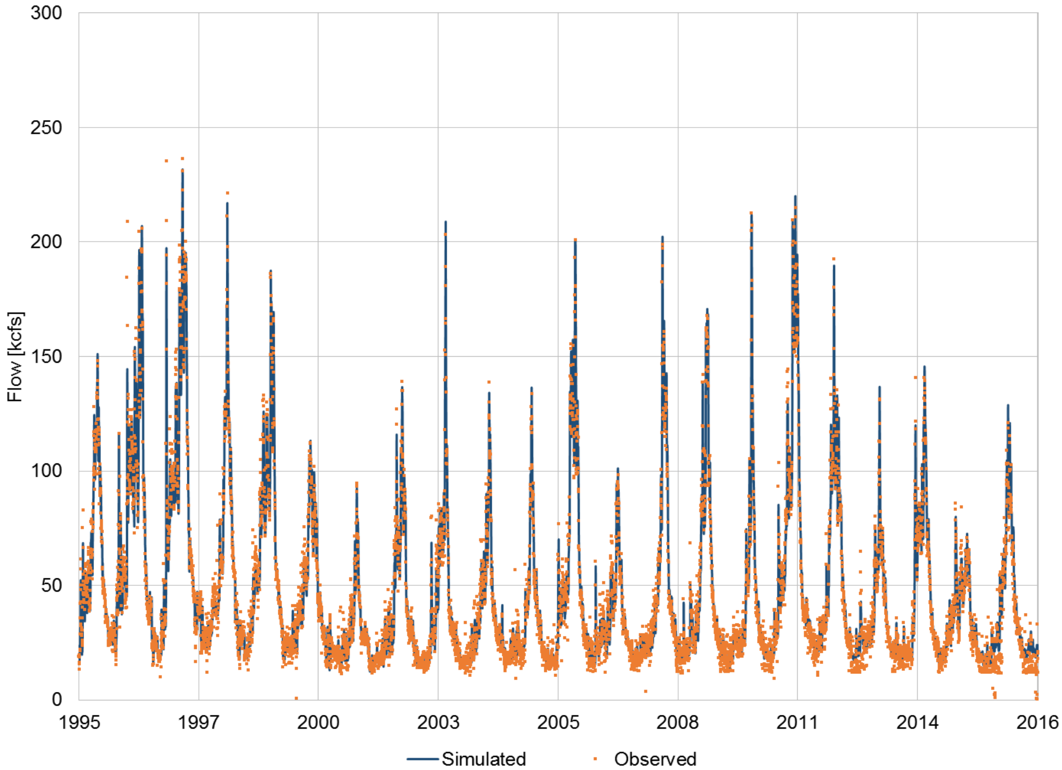

Figure C.5-11 Simulated versus observed flow at LMNW, Snake River RM 40.8

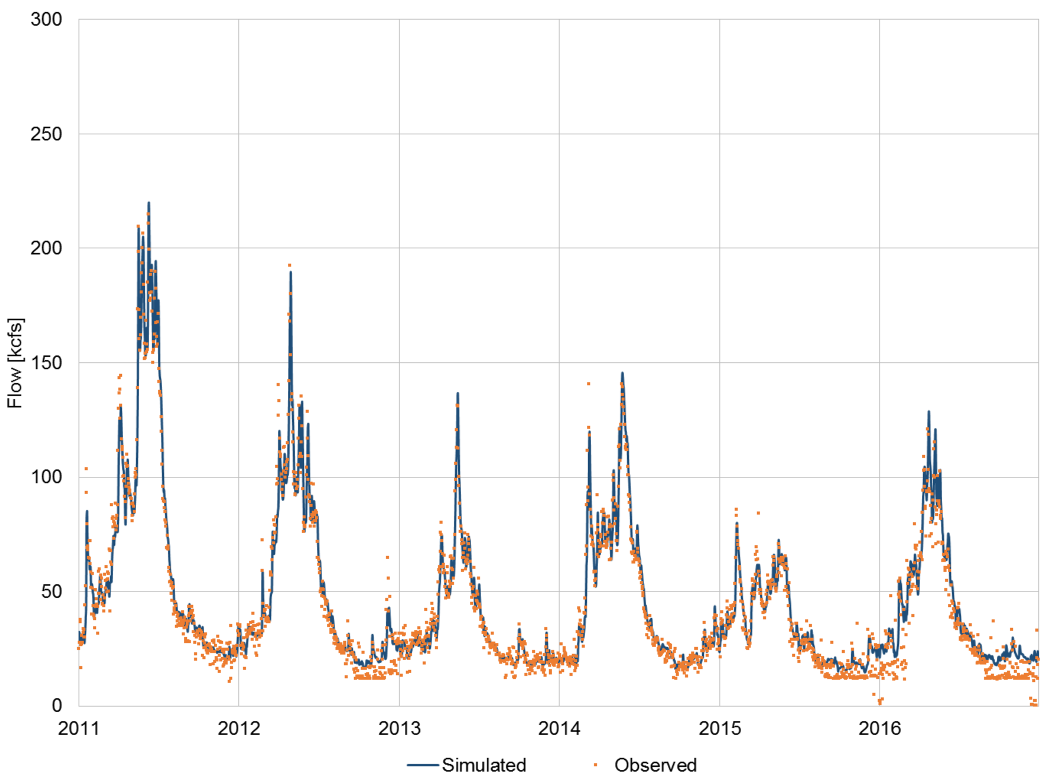

Figure C.5-12 Simulated versus observed flow at LMNW, period 2011 – 2016

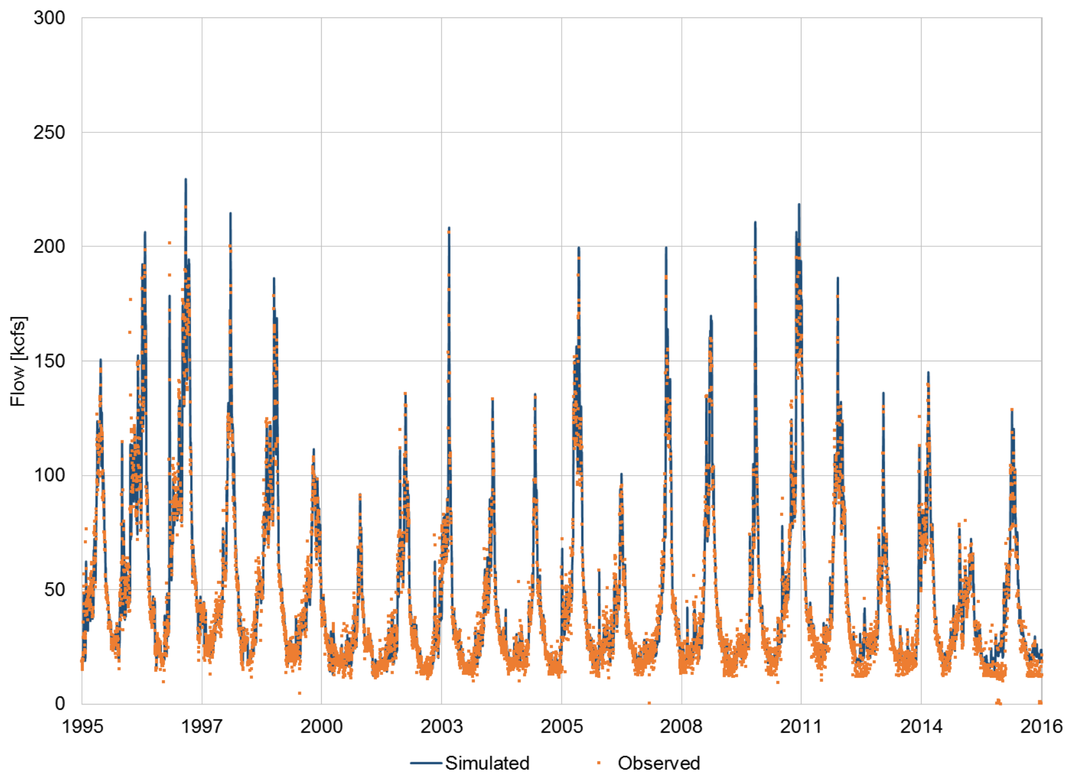

Figure C.5-13 Simulated versus observed flow at LGSW, Snake River RM 69.5

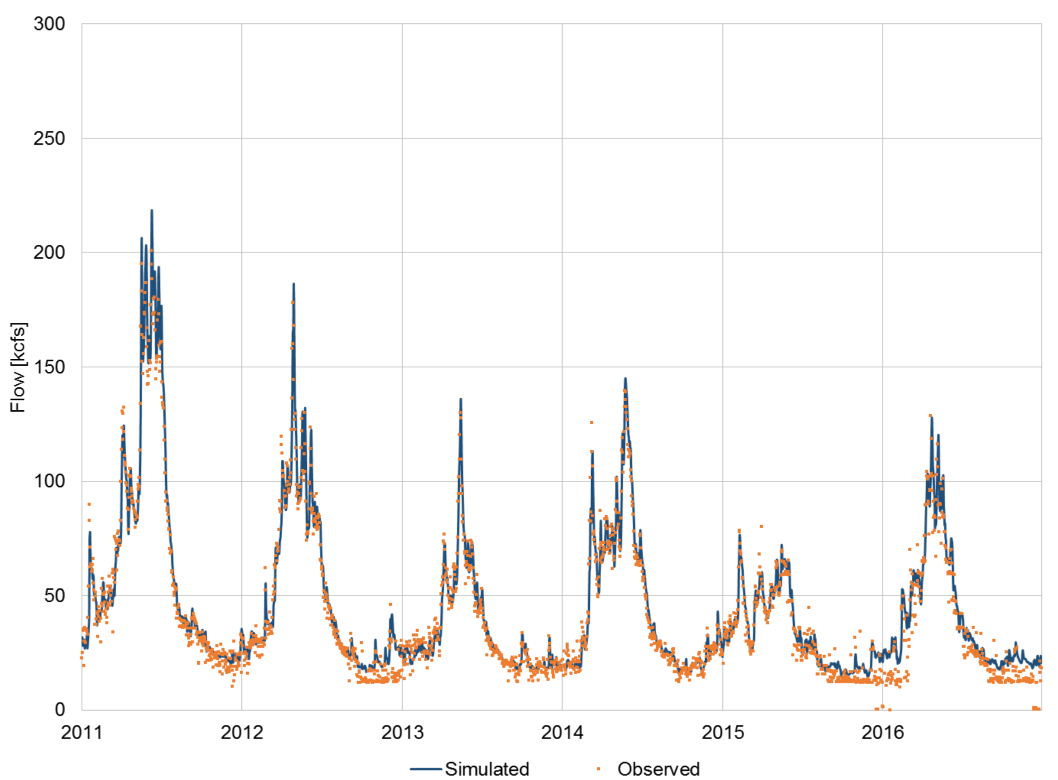

Figure C.5-14 Simulated versus observed flow at LGSW, period 2011 – 2016

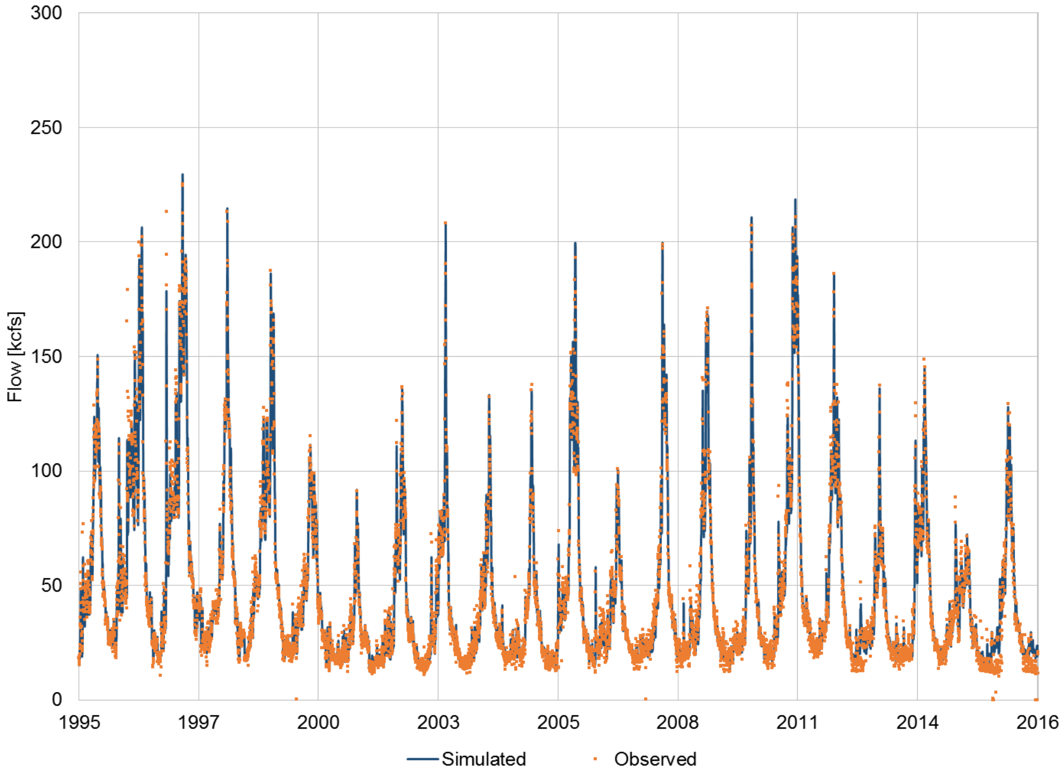

Figure C.5-15 Simulated versus observed flow at LGNW, Snake River RM 106.8

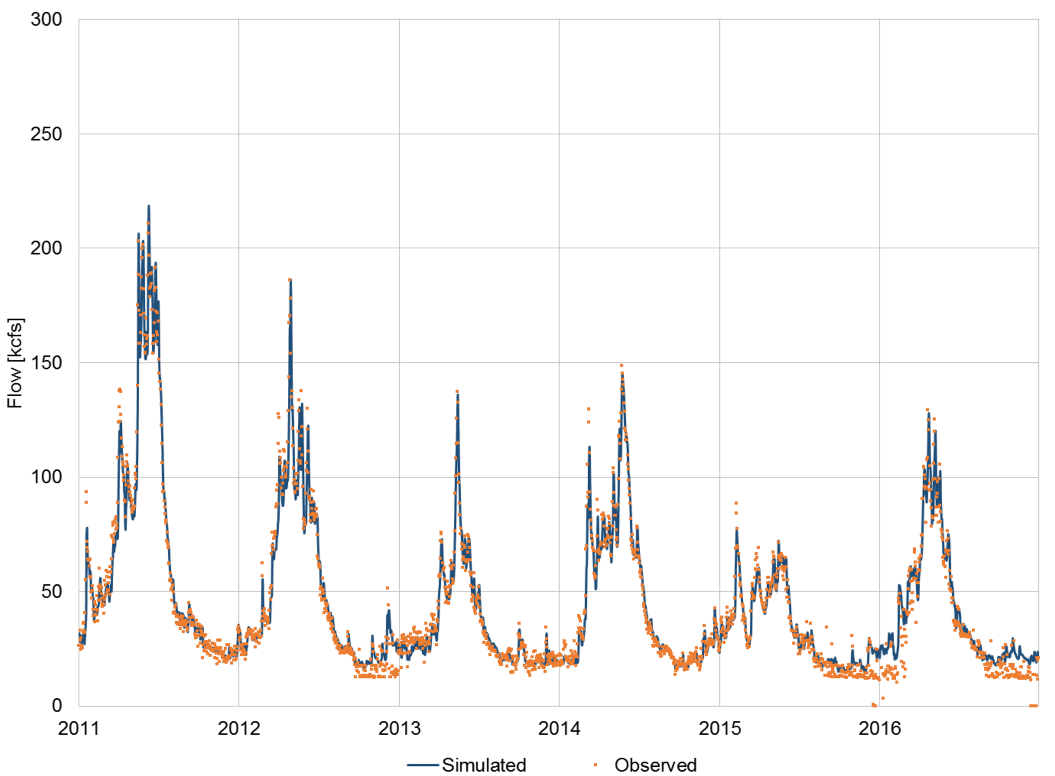

Figure C.5-16 Simulated versus observed flow at LGNW, period 2011 – 2016

Appendix D 2018 RBM10C Model Setup

D.1 Introduction

To investigate the impacts of the Columbia River upstream boundary location on the performance of the 2018 RBM10 model, an alternative model setup starting at the Priests Rapids Dam was developed. The spatial representation of the simulated domain is presented in Figure D.1-1 and a summary of the model results for temperature, flow, and velocity is presented in the following sections. The monitoring stations located within the simulated reaches (Figure D.1-2) and used to compare the model results against observations of temperature are listed in Table D.1-1 through Table D.1-3. The evaporative heat flux coefficients used for this model domain are summarized Table D.1-4.

Table D.1-1 Temperature monitoring stations on the Columbia River used for model comparisons

Station	Station ID	Station Description
Camas/Washougal WA	**CWMW**	Columbia RM 119: Columbia River at RM 119
Warrandale OR	**WRNO**	Columbia RM 140: Six miles D/s of dam
Bonneville Dam tailwater	**BON**	Columbia RM 146: Right end of spillway near dam center
The Dalles Dam tailwater	**TDDO**	Columbia RM 190: Left bank one mile d/s of dam
John Day Dam tailwater	**JHAW**	Columbia RM 215: Dam tailwater Right bank of river
McNary Dam tailwater-Washington	**MCPW**	Columbia RM 291: Dam Tailwater Right bank of river

Table D.1-2 Temperature monitoring stations on the Snake River used for model comparisons

Station	Station ID	Station Description
Ice Harbor Dam tailwater	**IDSW**	Snake RM 6.8: Right bank 15,400 feet d/s of dam
Lower Monumental Dam tailwater	**LMNW**	Snake RM 40.8:Left bank 4,300 feet d/s of dam
Little Goose Dam tailwater	**LGSW**	Snake RM 69.5:Right bank 3,900 feet d/s of dam
Lower Granite Dan tailwater	**LGNW**	Snake RM 106.8: Right bank 3,500 feet d/s of dam

Table D.1-3 Temperature monitoring stations on the Clearwater River used for model comparisons

Station	Station ID	Station Description
Clearwater River NR Peck	**PEKI**	Clearwater RM 30.0: Clearwater River at RM 33

Table D.1-4 Calibrated evaporative heat flux transfer constants Ev

	2018 RBM10 model		
Station Name	Ev (April 1 – August 13)	Ev (August 14 – November 26)	Ev (November 27 – March 31)
Wenatchee	1.40e-9	1.15e-9	0.50e-9
Yakima	1.30e-9	1.20e-9	1.50e-9
Lewiston	2.40e-9	1.90e-9	0.20e-9
Portland	1.60e-9	1.25e-9	0.01e-9
Spokane	1.90e-9	1.00e-9	0.55e-9

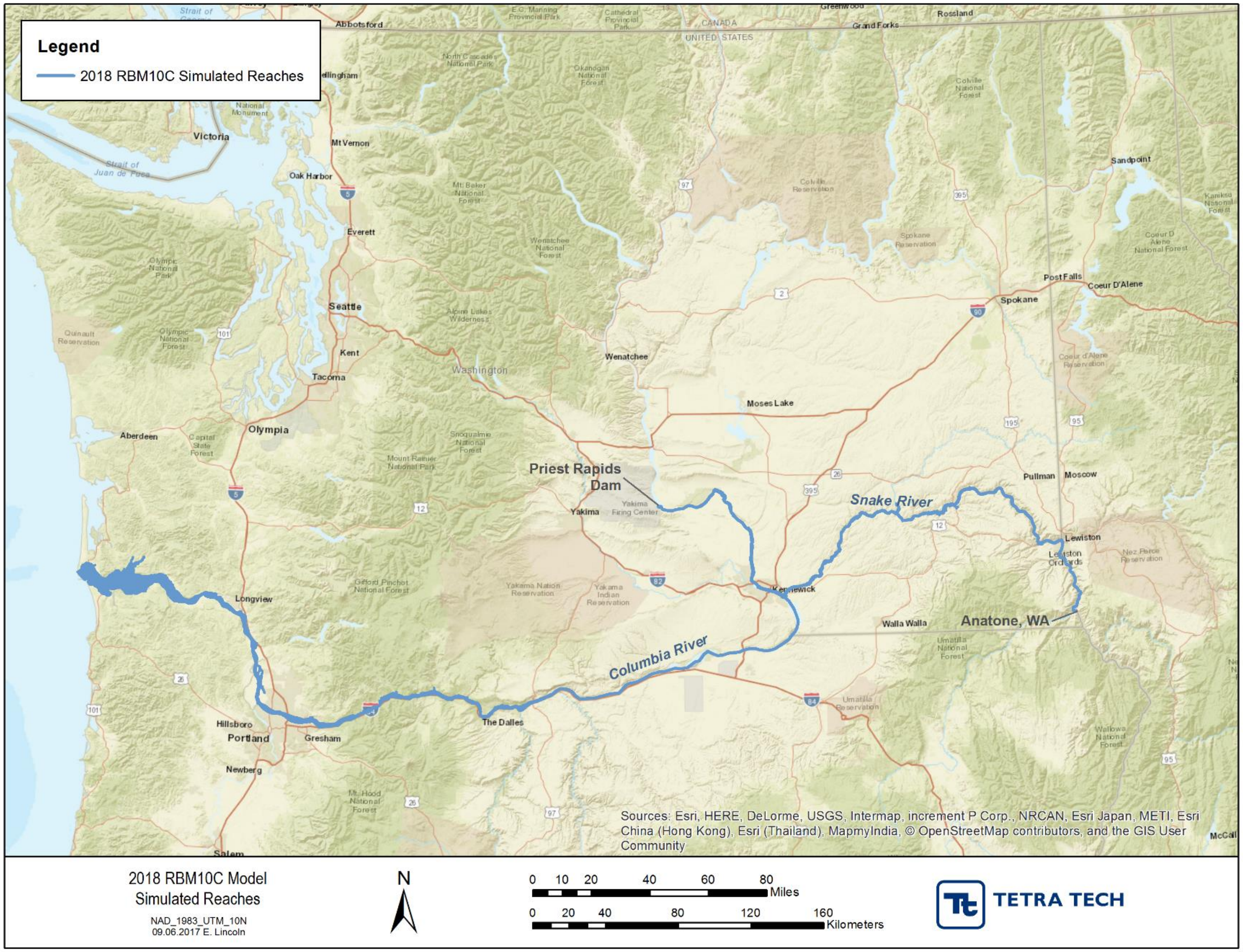

Figure D.1-1 2018 RBM10C spatial model representation of the Columbia and Snake Rivers

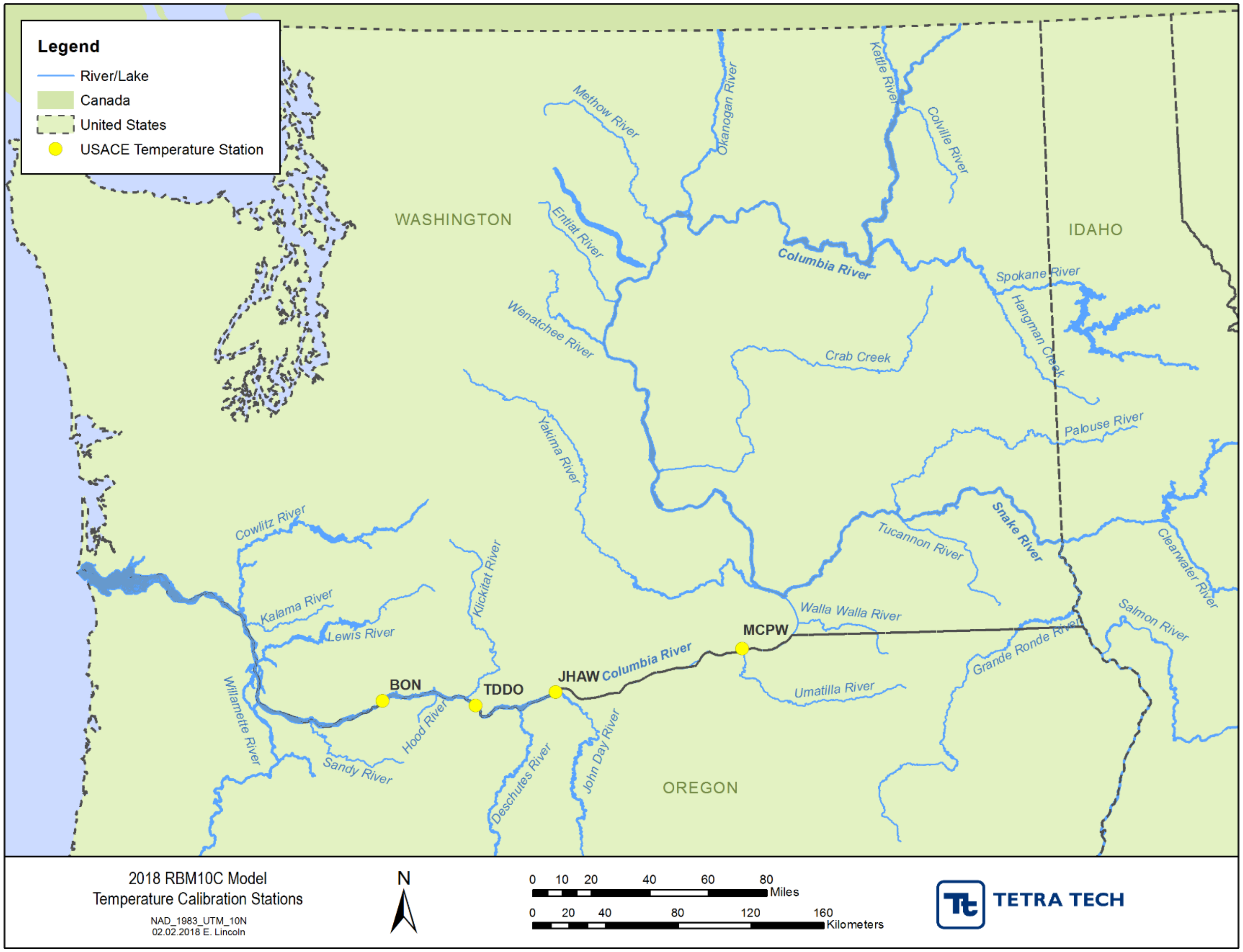

Figure D.1-2 2018 RBM10C Columbia and Snake Rivers temperature calibration stations

D.2 Water Temperature Model Performance Statistics

Statistical results obtained at each station in the Columbia and Snakes Rivers are presented in Table D.2-1 through Table D.2-4. Table D.2-1 and Table D.2-2 present the statistical analyses resulting from the comparison of the model simulations against all available observations within the period 2007 – 2016.

Table D.2-3 and Table D.2-4 present the statistical analysis obtained by comparing the temperature model simulations to measured observations between April 1 and November 30 within the period of 1975 – 2016. Graphical comparisons between observed and simulated water temperatures are presented from Figure D.1-1 through Figure D.3-14 and from Figure D.4-1 though Figure D.4-7.

Table D.2-1 Model performance statistics, all months (January – December)

Columbia River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
CWMW	4639	-0.051	0.400	0.515	0.996
WRNO	7865	-0.111	0.422	0.561	0.996
BON	8383	-0.079	0.353	0.462	0.997
TDDO	5626	0.092	0.356	0.455	0.997
JHAW	5857	0.134	0.352	0.445	0.998
MCPW	7306	0.201	0.367	0.456	0.998
PRXW	5493	-0.005	0.146	0.196	0.999
	Average	**0.026**	**0.342**	**0.441**	**0.997**
Snake River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
IDSW	7635	0.141	0.460	0.588	0.996
LMNW	6052	0.090	0.521	0.658	0.994
LGSW	5859	0.093	0.531	0.667	0.994
LGNW	7345	0.087	0.494	0.625	0.994
	Average	**0.103**	**0.501**	**0.634**	**0.995**
Clearwater River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
PEKI	5157	0.077	0.377	0.506	0.990
	Average	**0.077**	**0.377**	**0.506**	**0.990**

Table D.2-2 Model performance statistics (April – November)

Columbia River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
CWMW	3993	-0.015	0.400	0.513	0.994
WRNO	5496	-0.105	0.400	0.524	0.993
BON	6150	-0.080	0.347	0.456	0.995
TDDO	4345	0.112	0.354	0.451	0.995
JHAW	4560	0.135	0.349	0.439	0.996
MCPW	5110	0.206	0.368	0.450	0.996
PRXW	4348	0.011	0.156	0.206	0.999
	Average	**0.038**	**0.339**	**0.434**	**0.995**
Snake River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
IDSW	7635	0.141	0.460	0.588	0.996
LMNW	6052	0.090	0.521	0.658	0.994
LGSW	5859	0.093	0.531	0.667	0.994
LGNW	7345	0.087	0.494	0.625	0.994
	Average	**0.103**	**0.501**	**0.634**	**0.995**
Clearwater River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
PEKI	5157	0.077	0.377	0.506	0.990
	Average	**0.077**	**0.377**	**0.506**	**0.990**

Table D.2-3 Model performance statistics (July – August)

Columbia River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
CWMW	1376	0.210	0.472	0.583	0.949
WRNO	1383	0.110	0.368	0.447	0.970
BON	1792	0.067	0.385	0.489	0.960
TDDO	1284	0.267	0.405	0.489	0.971
JHAW	1355	0.289	0.404	0.474	0.978
MCPW	1356	0.337	0.391	0.455	0.983
PRXW	1249	0.051	0.154	0.194	0.993
	Average	**0.190**	**0.368**	**0.447**	**0.972**
Snake River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
IDSW	7635	0.141	0.460	0.588	0.996
LMNW	6052	0.090	0.521	0.658	0.994
LGSW	5859	0.093	0.531	0.667	0.994
LGNW	7345	0.087	0.494	0.625	0.994
	Average	**0.103**	**0.501**	**0.634**	**0.995**
Clearwater River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
PEKI	5157	0.077	0.377	0.506	0.990
	Average	**0.077**	**0.377**	**0.506**	**0.990**

Table D.2-4 Model performance statistics (September – October)

Columbia River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
CWMW	500	-0.576	0.606	0.739	0.897
WRNO	1370	-0.359	0.550	0.698	0.969
BON	1200	-0.501	0.569	0.715	0.830
TDDO	901	0.040	0.418	0.529	0.975
JHAW	892	0.078	0.402	0.511	0.977
MCPW	1243	0.169	0.378	0.469	0.981
PRXW	1032	-0.085	0.160	0.228	0.992
	Average	**-0.176**	**0.440**	**0.556**	**0.946**
Snake River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
IDSW	7635	0.141	0.460	0.588	0.996
LMNW	6052	0.090	0.521	0.658	0.994
LGSW	5859	0.093	0.531	0.667	0.994
LGNW	7345	0.087	0.494	0.625	0.994
	Average	**0.103**	**0.501**	**0.634**	**0.995**
Clearwater River Stations					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R**
PEKI	5157	0.077	0.377	0.506	0.990
	Average	**0.077**	**0.377**	**0.506**	**0.990**

D.3 Temperature Model Results

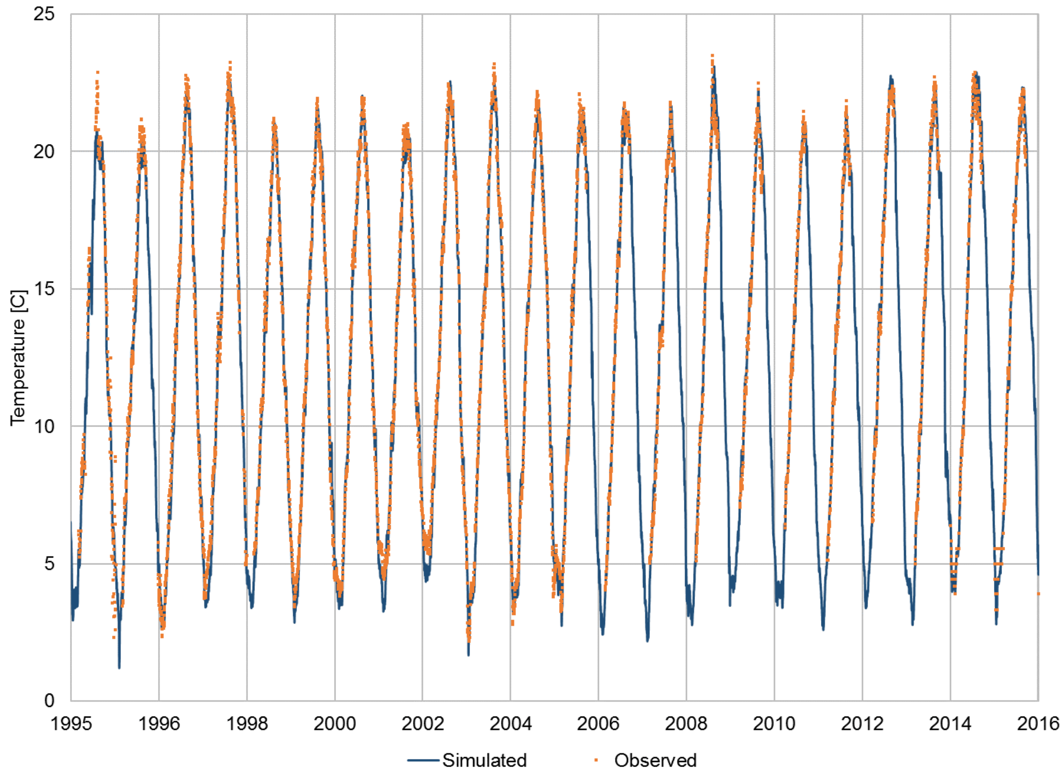

Figure D.3-1 Simulated versus observed temperature at BON, Columbia River RM 146

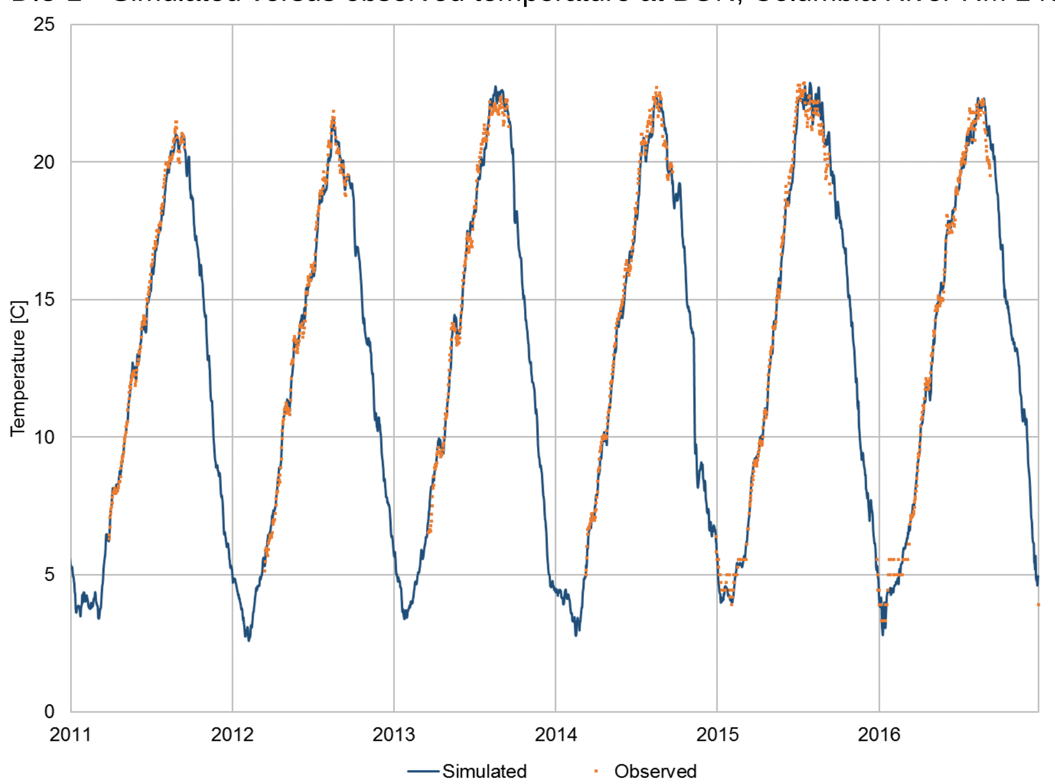

Figure D.3-2 Simulated versus observed temperature at BON, period 2011 – 2016

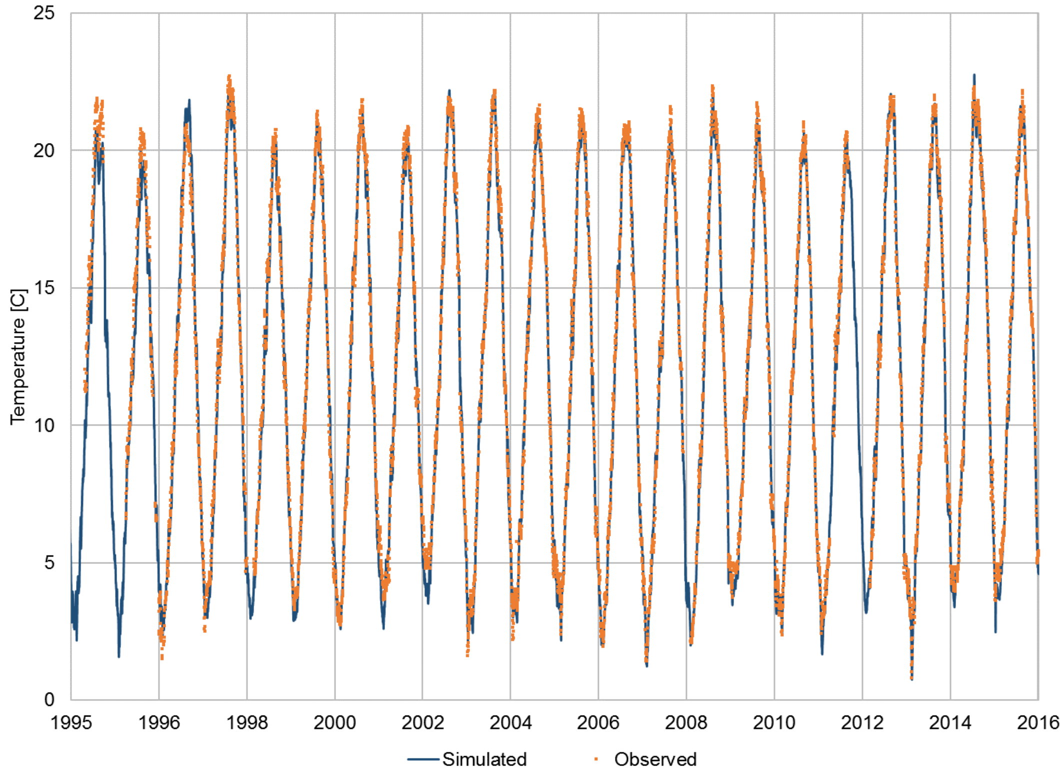

Figure D.3-3 Simulated versus observed temperature at MCPW, Columbia River RM 291

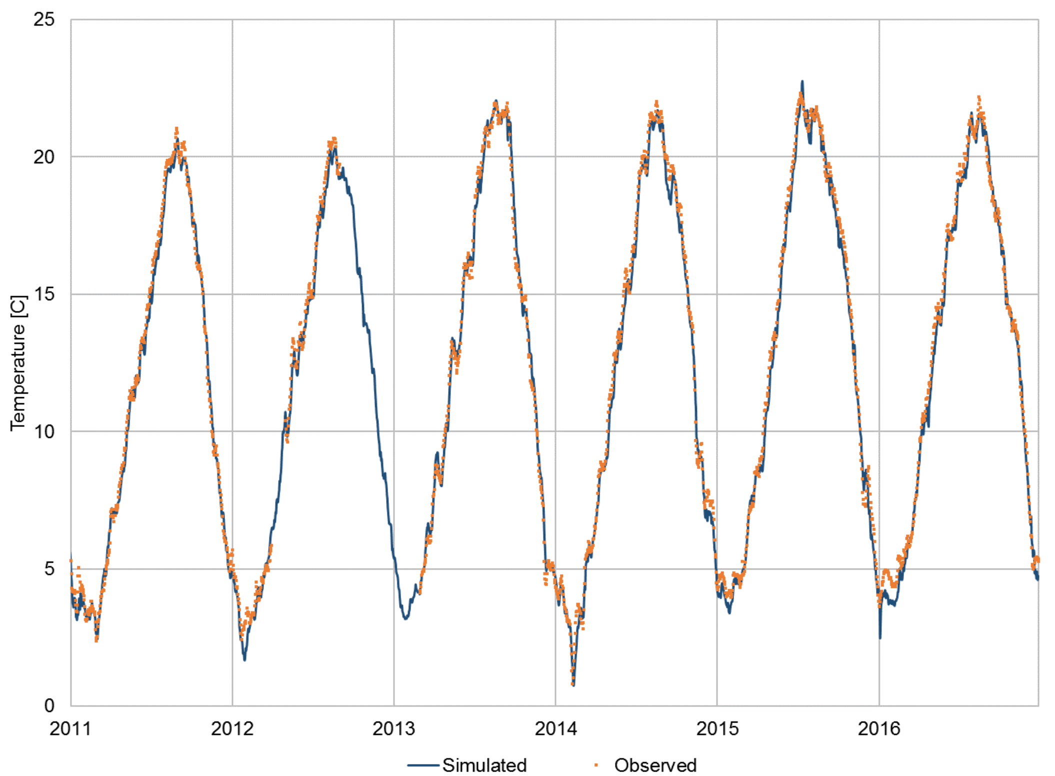

Figure D.3-4 Simulated versus observed temperature at MCPW, period 2011 – 2016

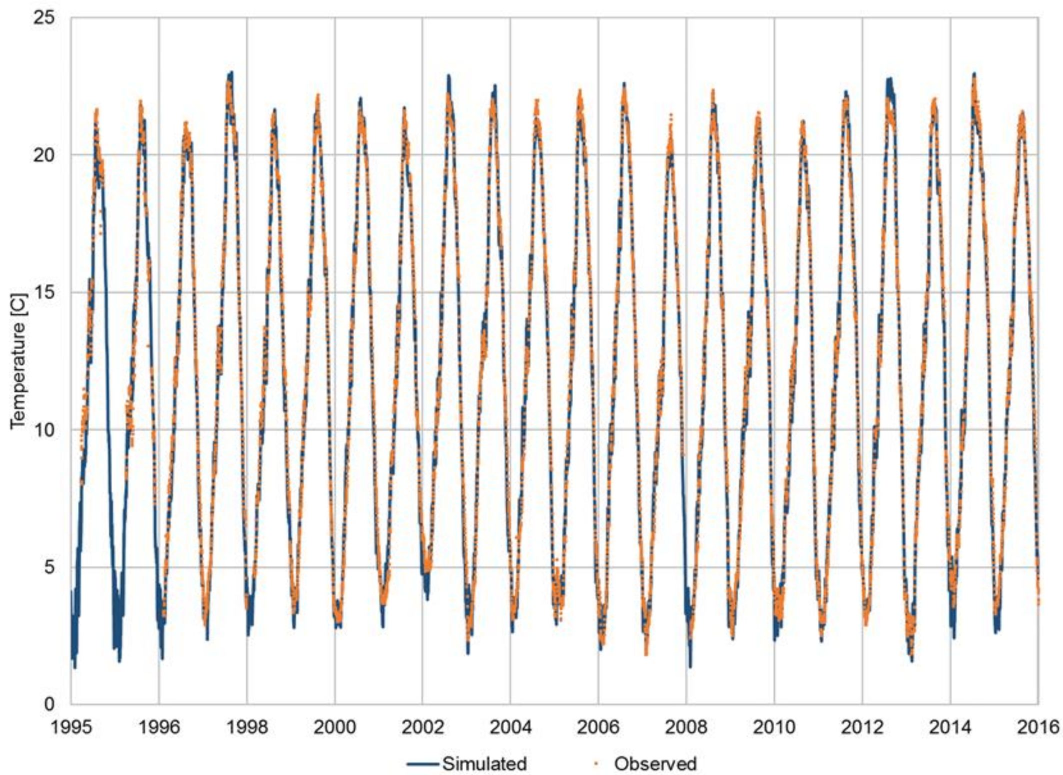

Figure D.3-5 Simulated versus observed temperature at IDSW, Snake River RM 6.8

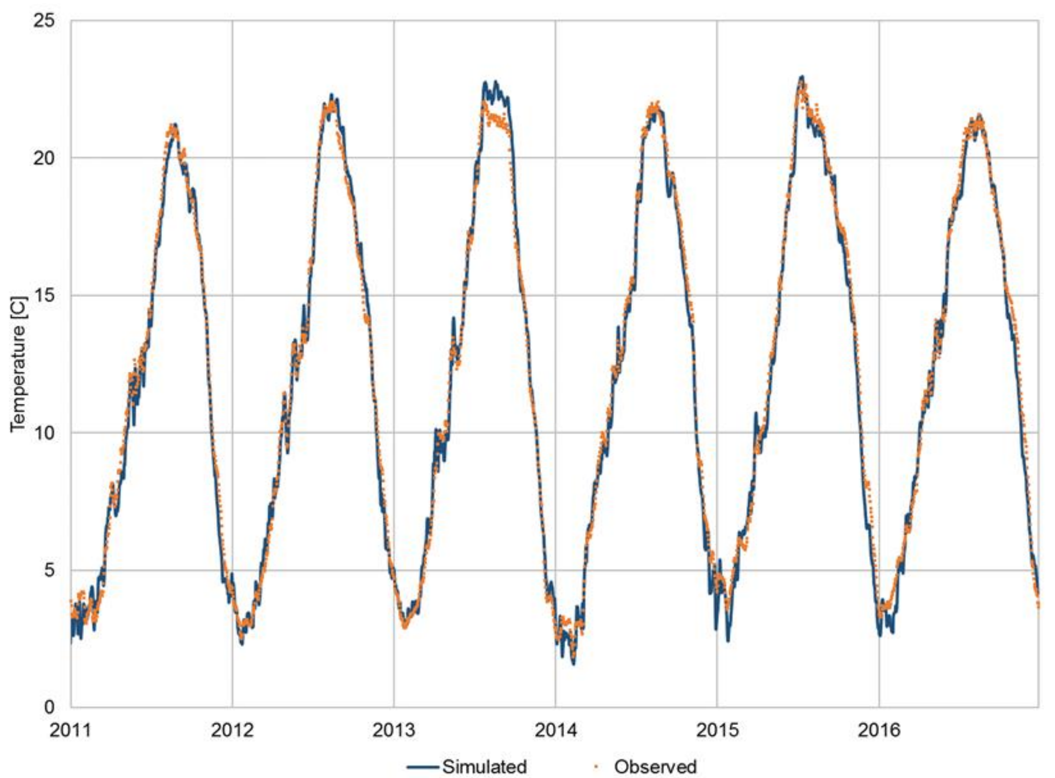

Figure D.3-6 Simulated versus observed temperature at IDSW, period 2011 – 2016

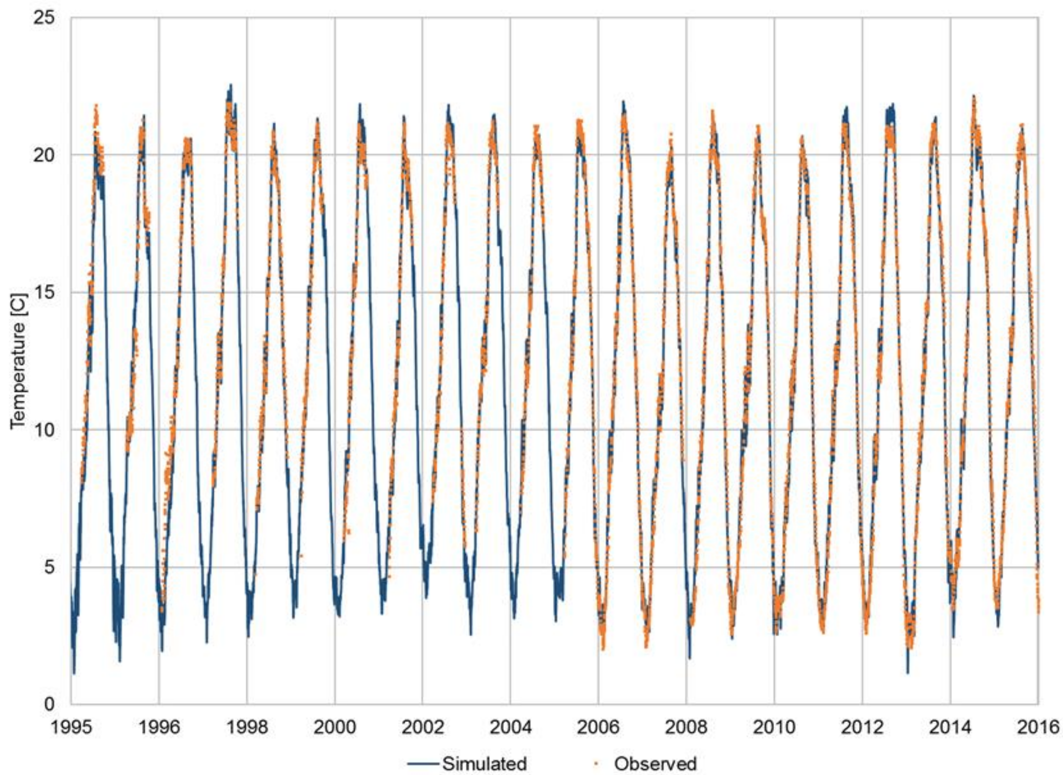

Figure D.3-7 Simulated versus observed temperature at LMNW, Snake River RM 40.8

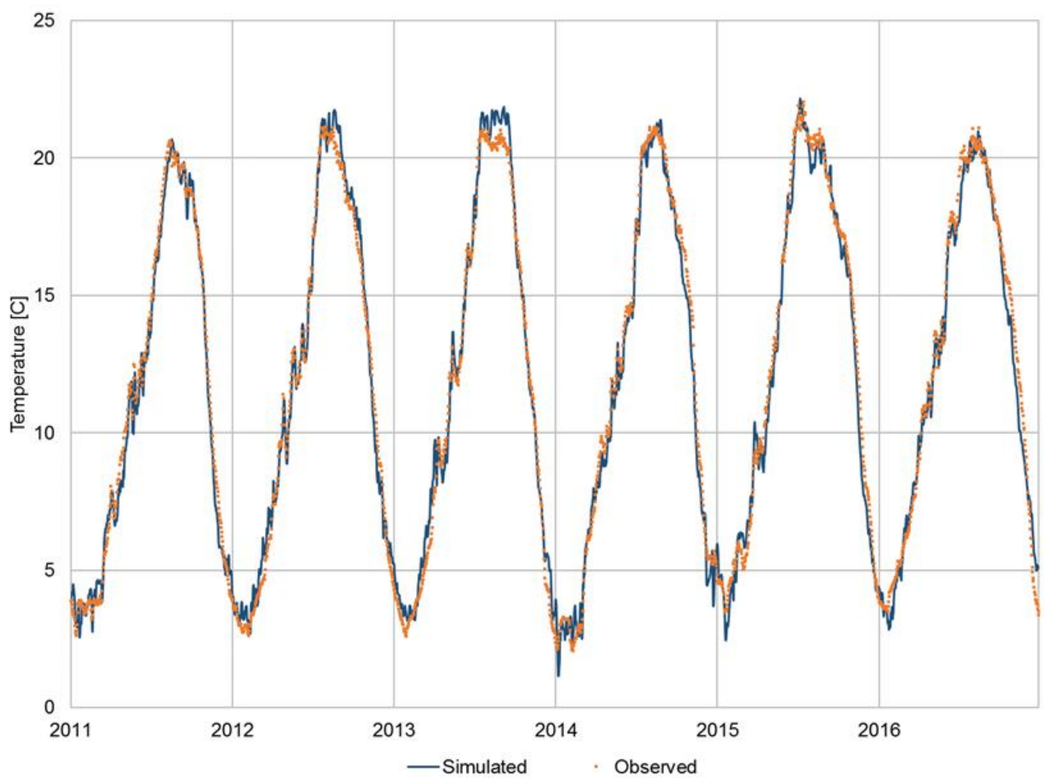

Figure D.3-8 Simulated versus observed temperature at LMNW, period 2011 – 2016

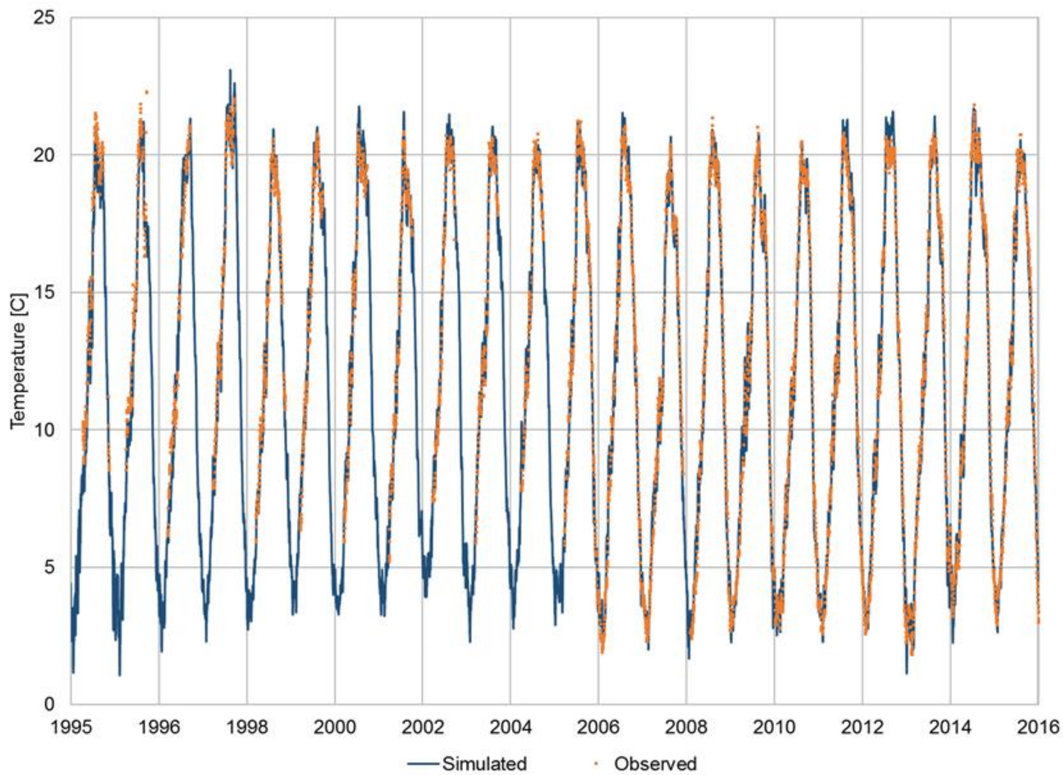

Figure D.3-9 Simulated versus observed temperature at LGSW, Snake River RM 69.5

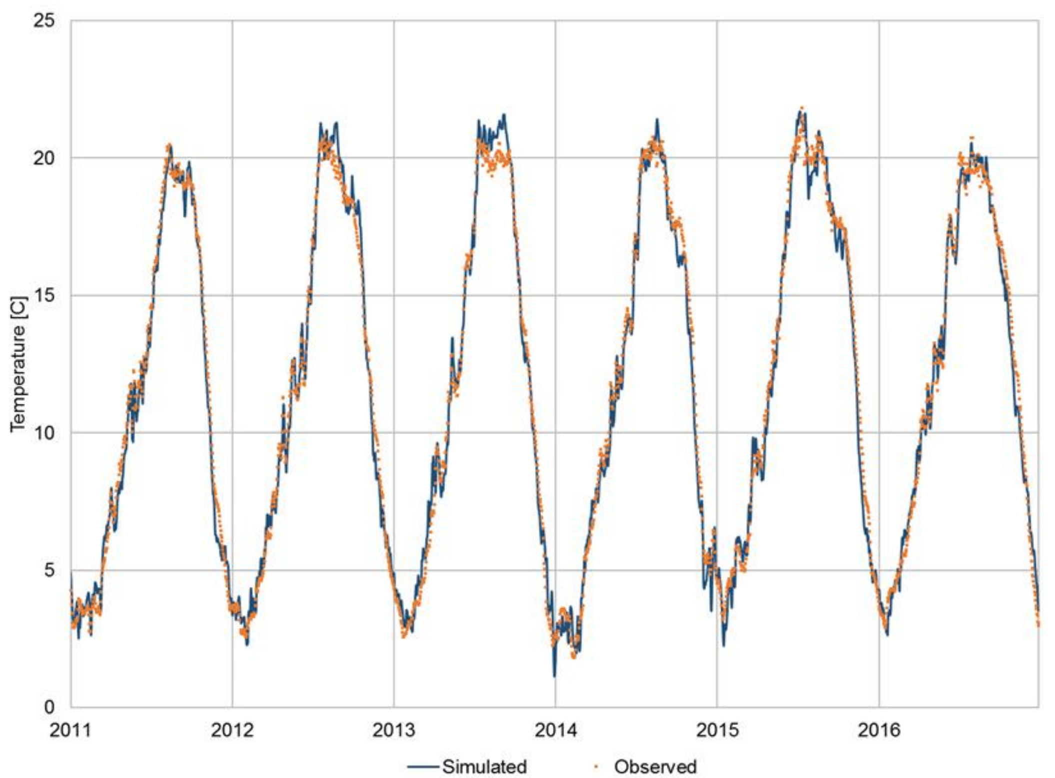

Figure D.3-10 Simulated versus observed temperature at LGSW, period 2011 – 2016

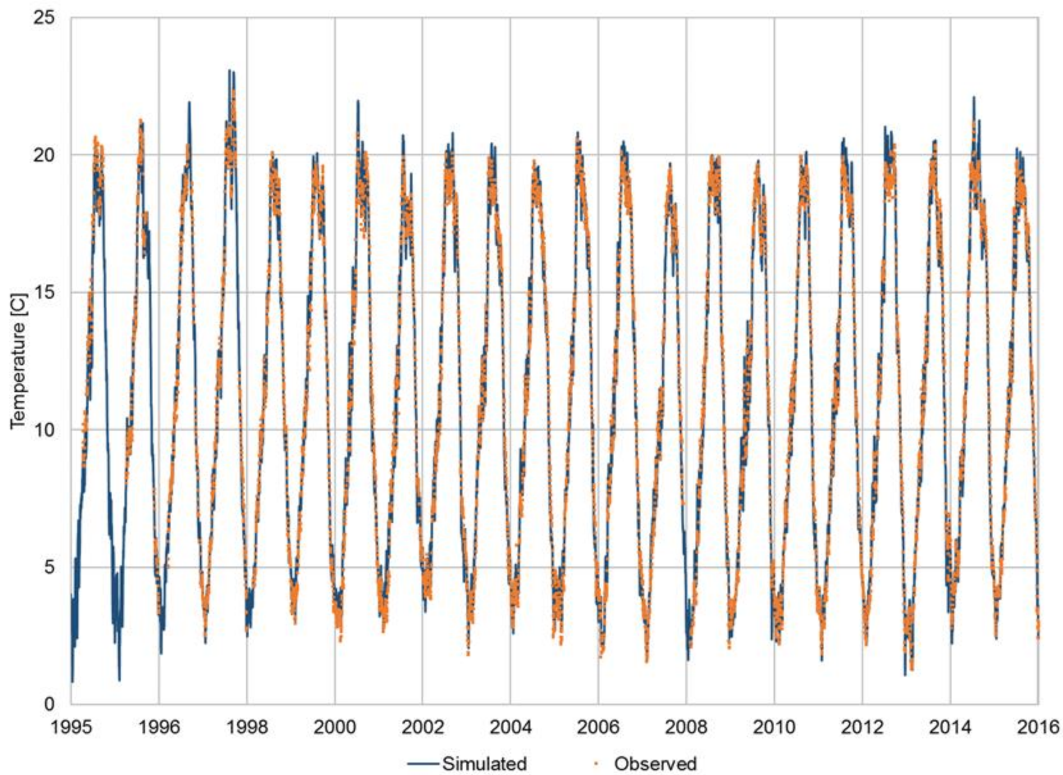

Figure D.3-11 Simulated versus observed temperature at LGNW, Snake River RM 106.8

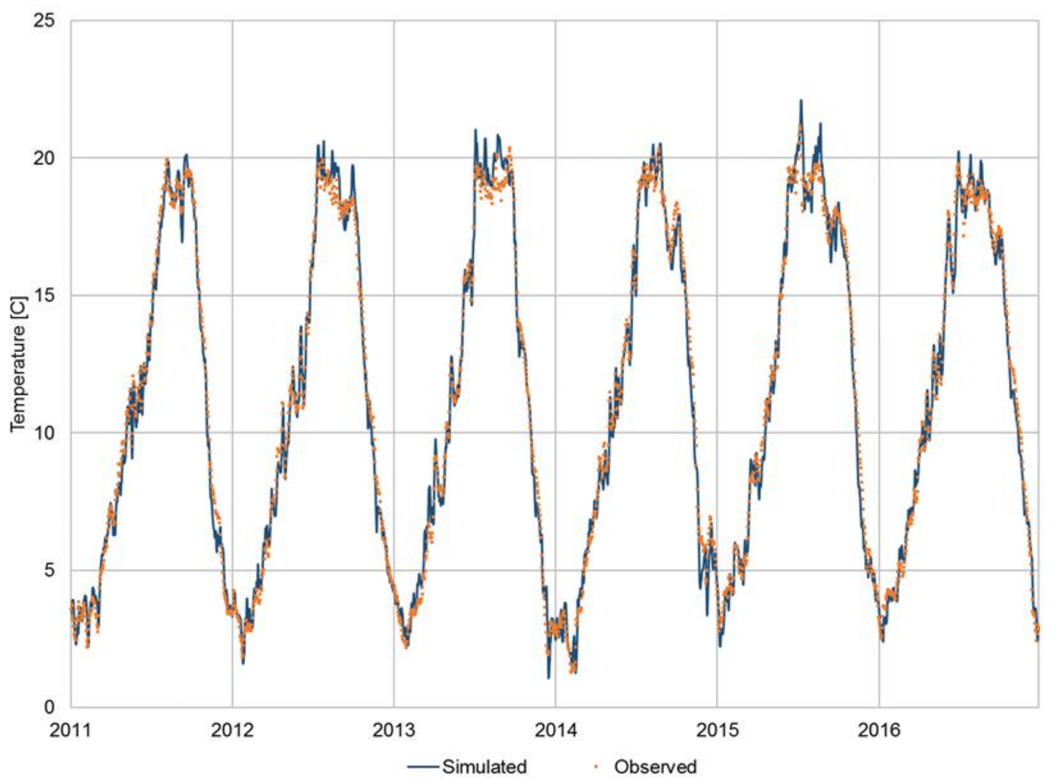

Figure D.3-12 Simulated versus observed temperature at LGNW, period 2011 – 2016

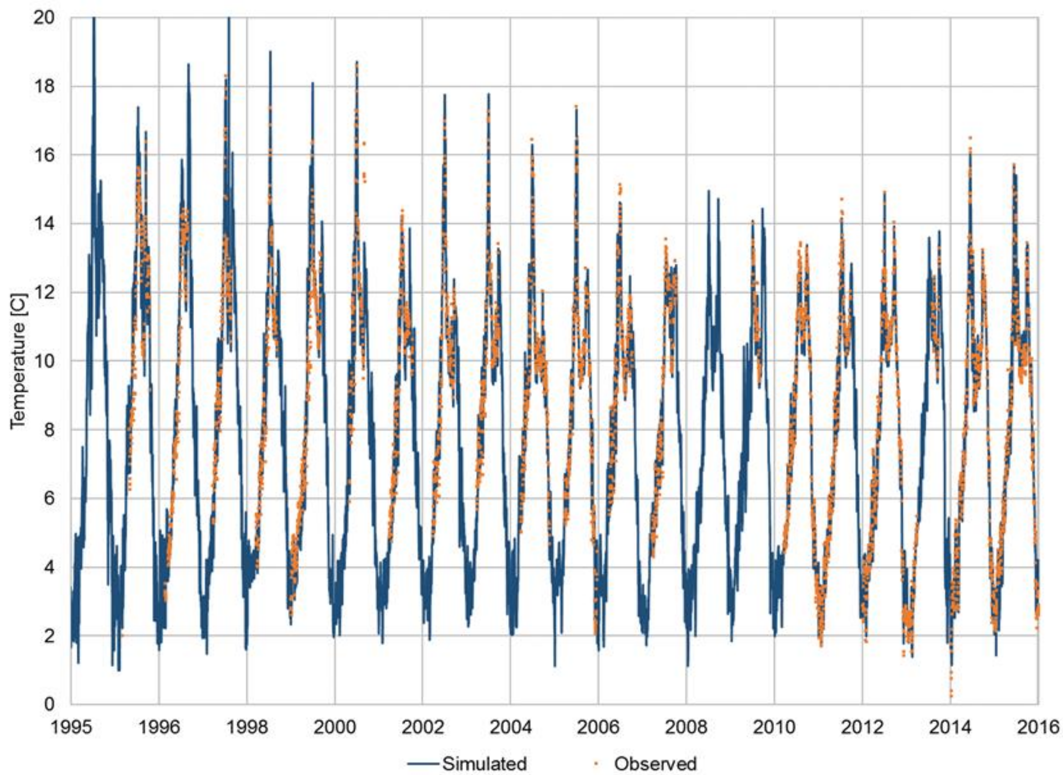

Figure D.3-13 Simulated versus observed temperature at PEKI, Clearwater River RM 33

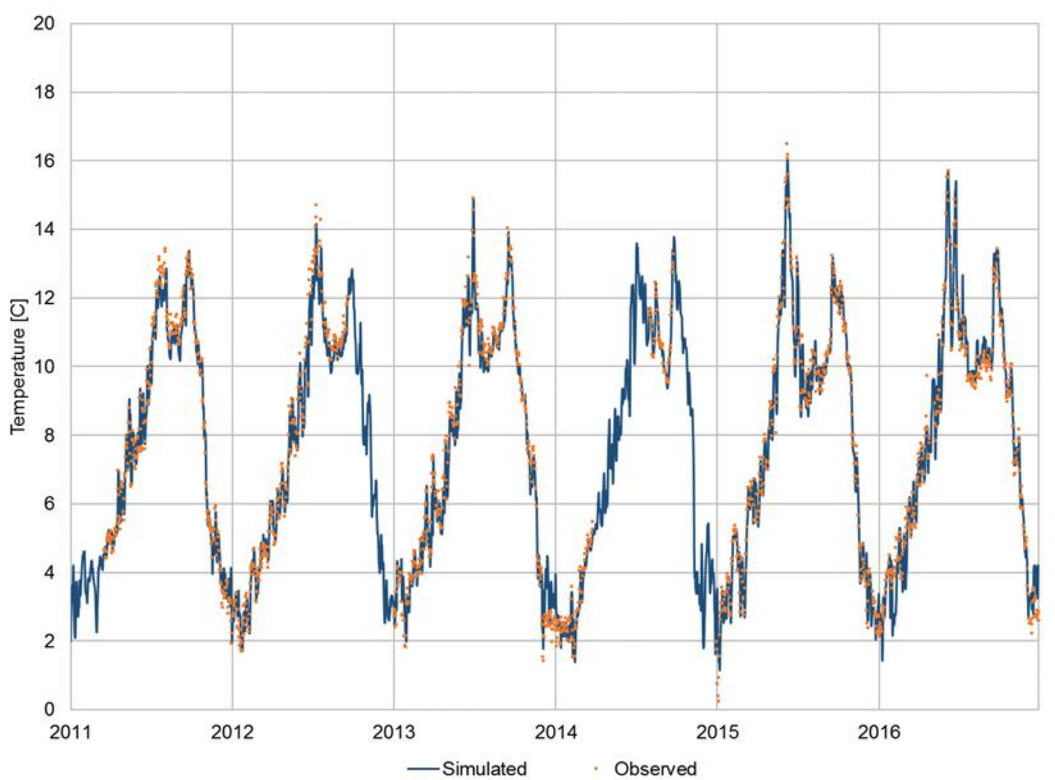

Figure D.3-14 Simulated versus observed temperature at LGNW, period 2011 – 2016

D.4 10-year Daily Average Temperature Comparisons

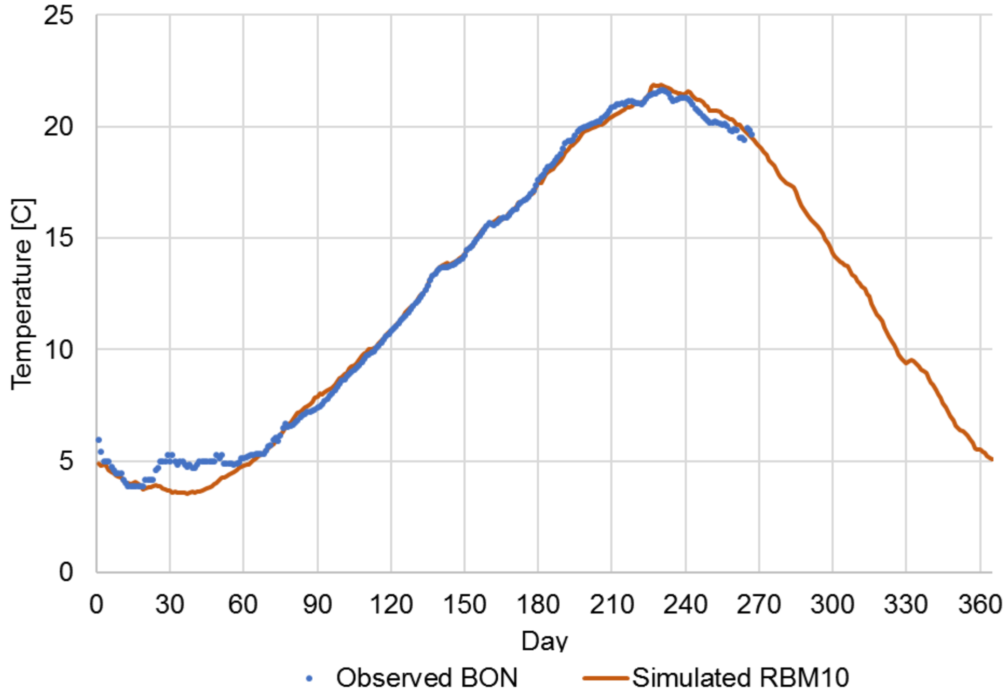

Figure D.4-1 10-year daily average temperature comparison at BON

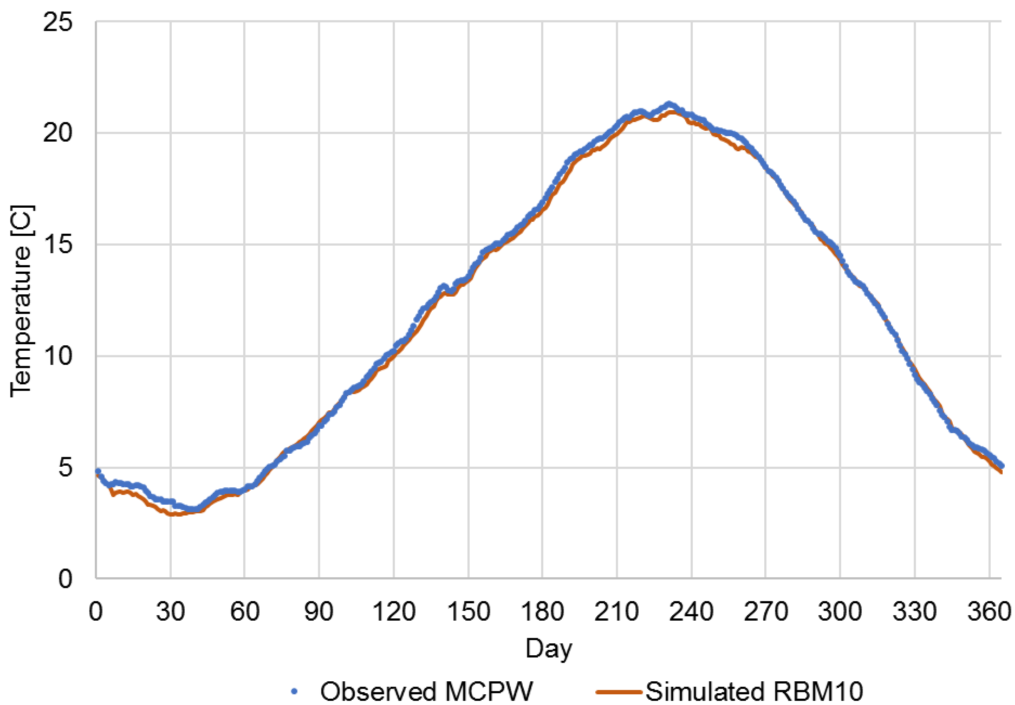

Figure D.4-2 10-year daily average temperature comparison at MCPW

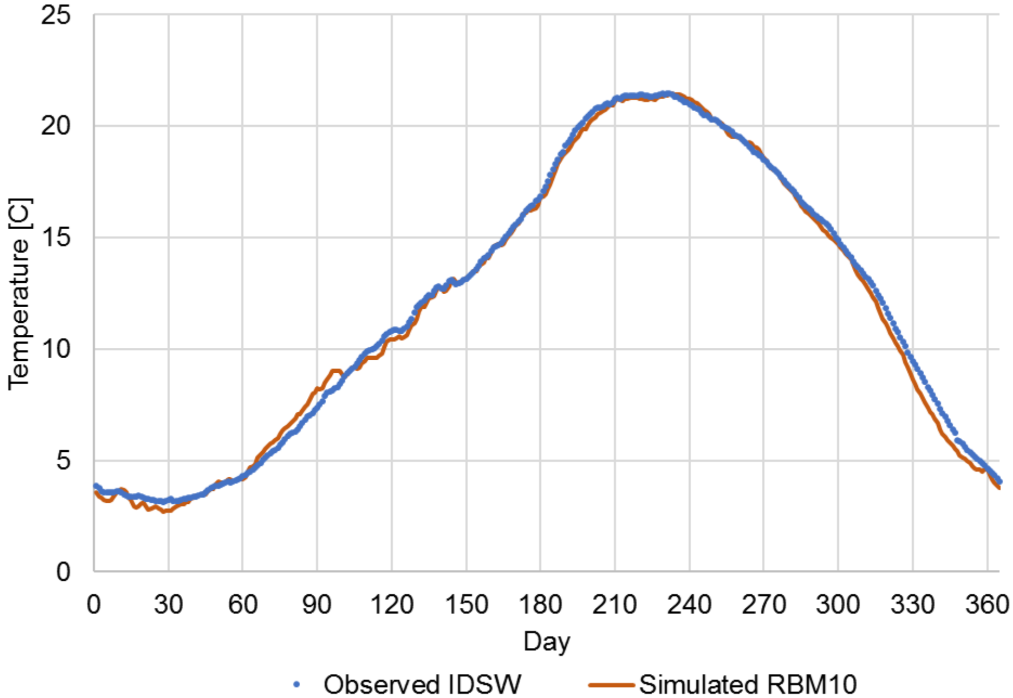

Figure D.4-3 10-year daily average temperature comparison at IDSW

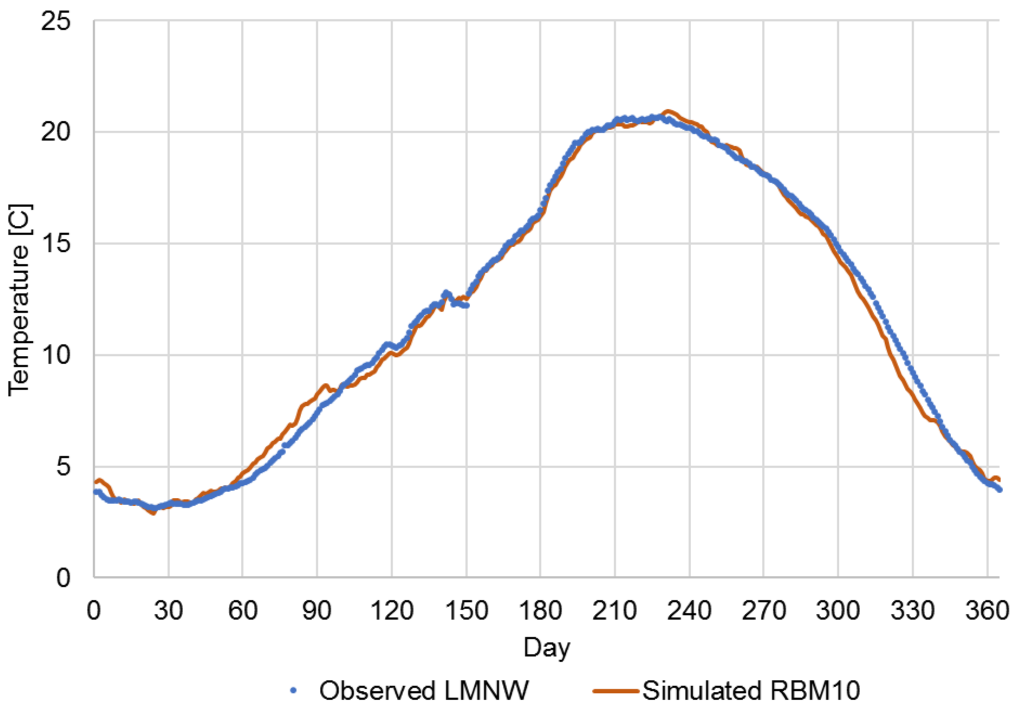

Figure D.4-4 10-year daily average temperature comparison at LMNW

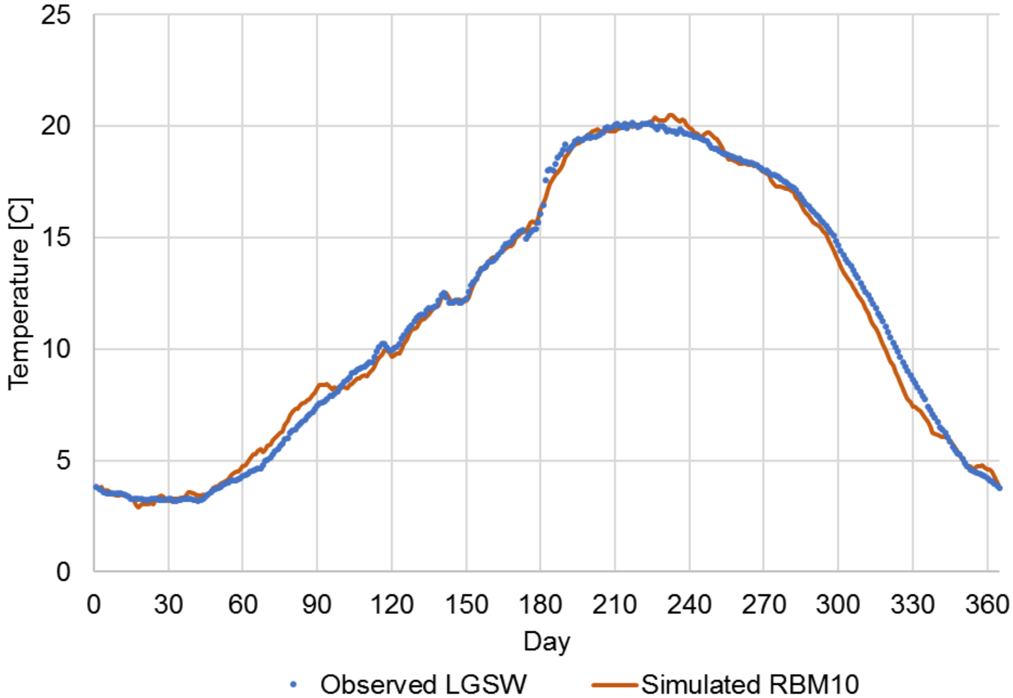

Figure D.4-5 10-year daily average temperature comparison at LGSW

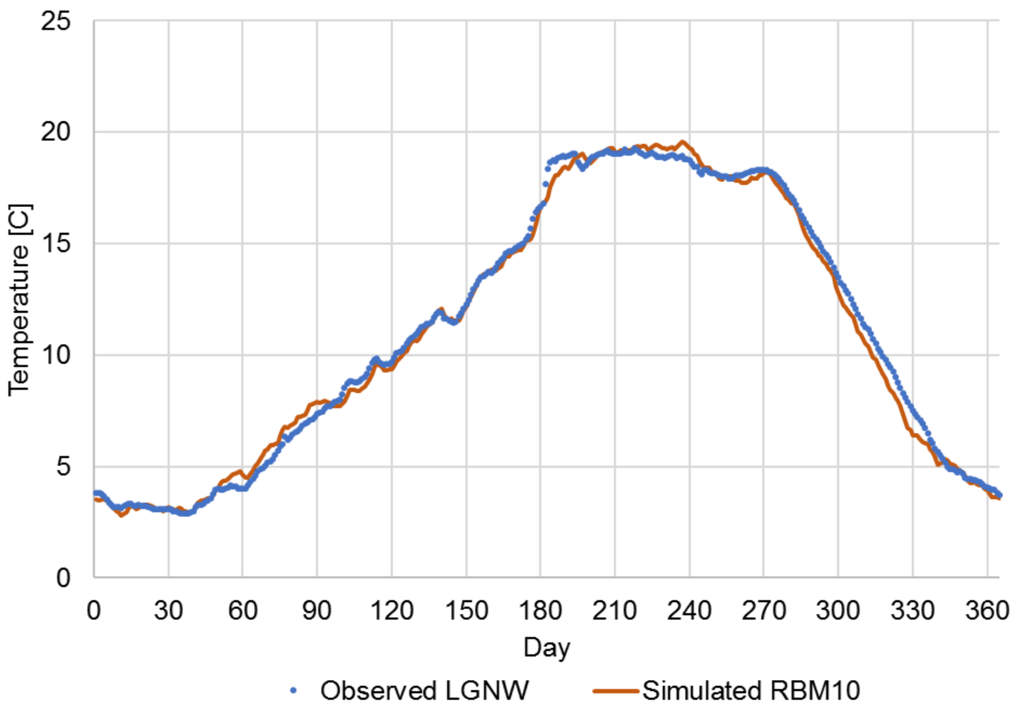

Figure D.4-6 10-year daily average temperature comparison at LGNW

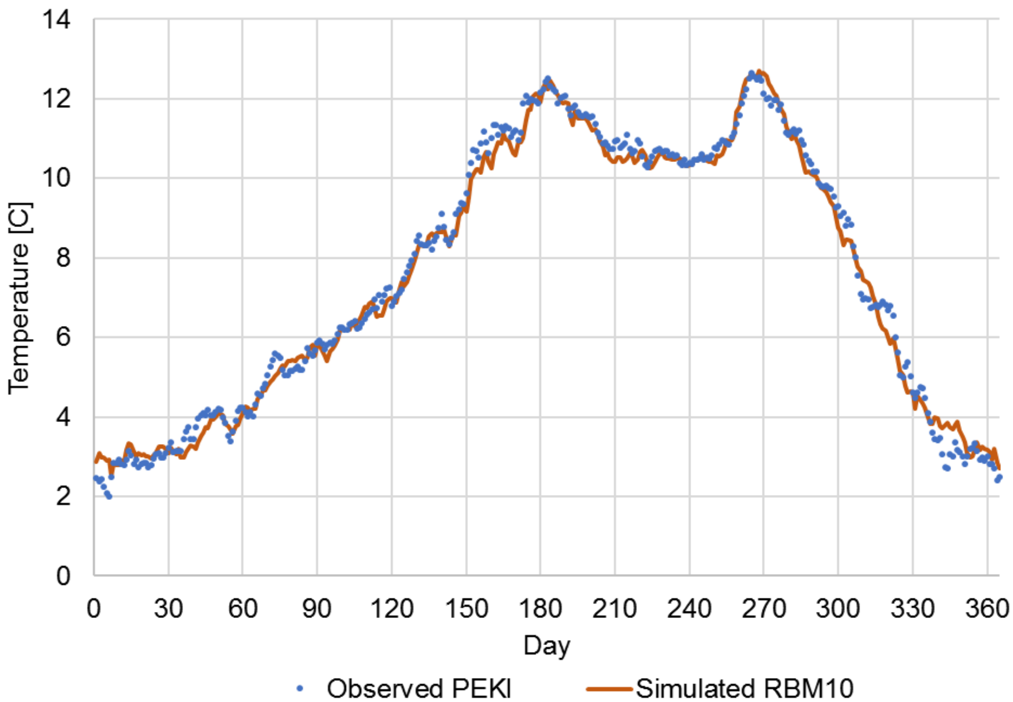

Figure D.4-7 10-year daily average temperature comparison at PEKI

D.5 Flow Discharge Model Results

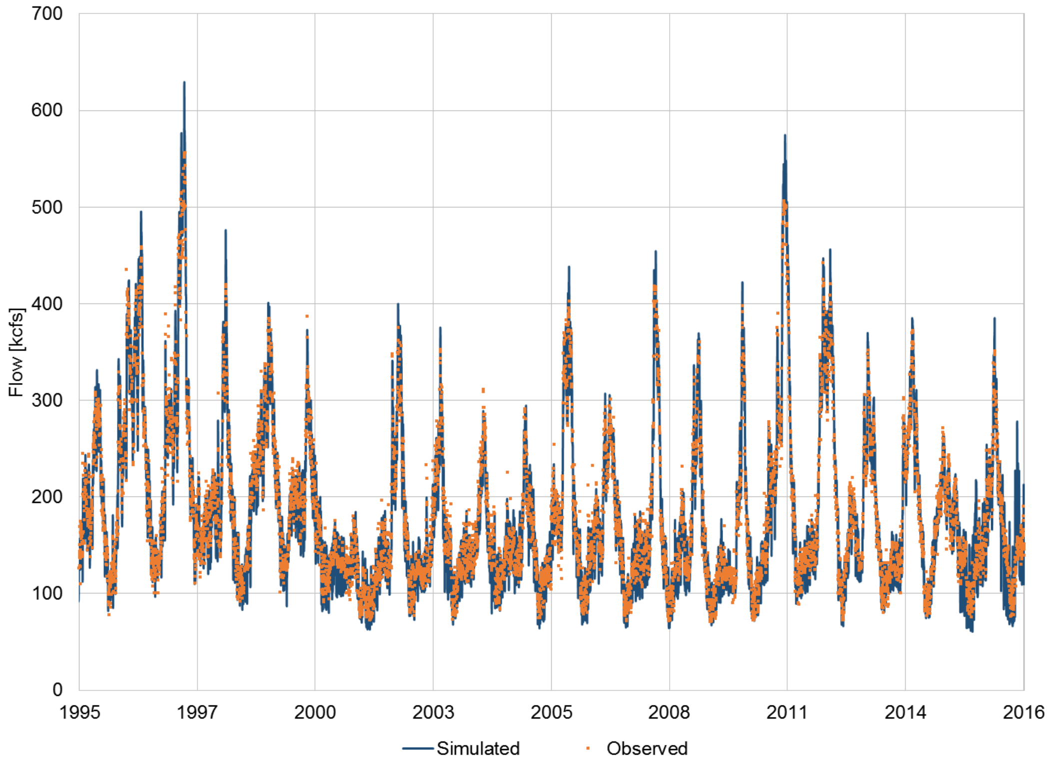

Figure D.5-1 Simulated versus observed flow at BON, Columbia River RM 146

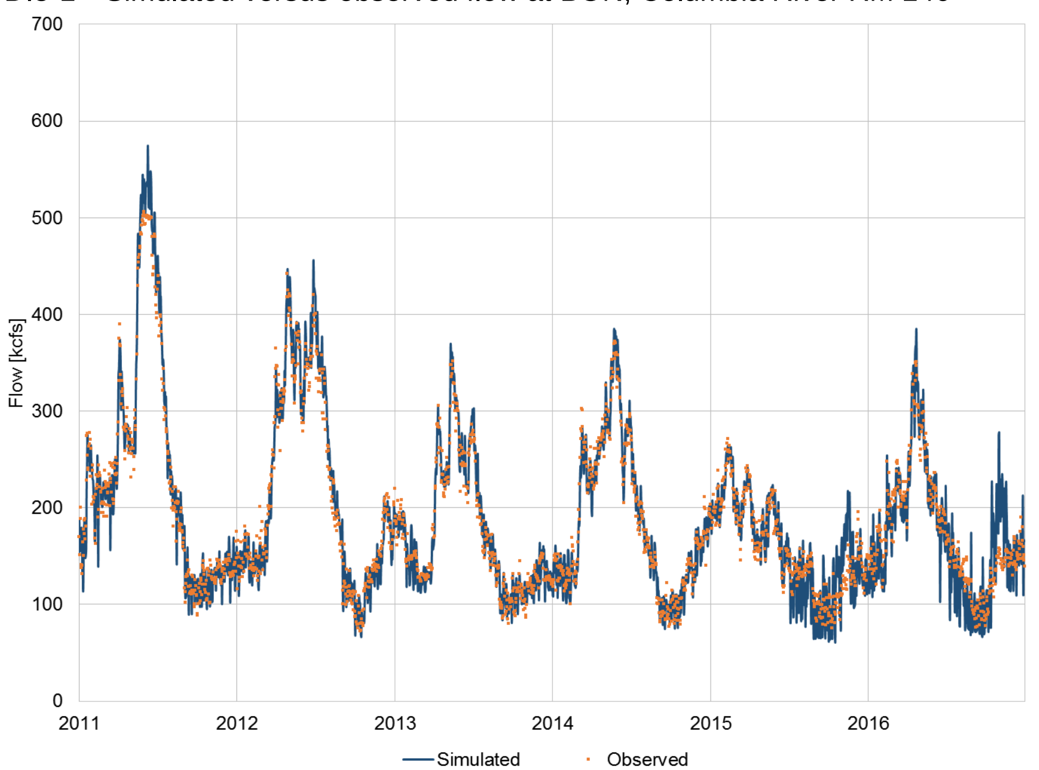

Figure D.5-2 Simulated versus observed flow at BON, period 2011 – 2016

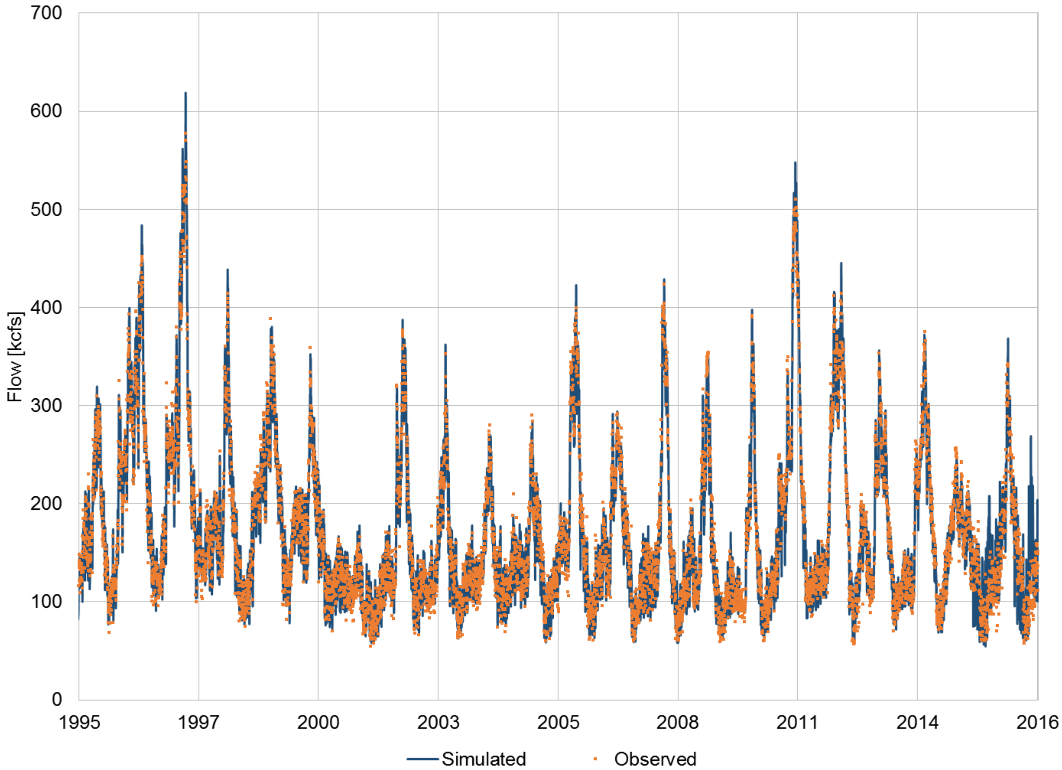

Figure D.5-3 Simulated versus observed flow at MCPW, Columbia River RM 291

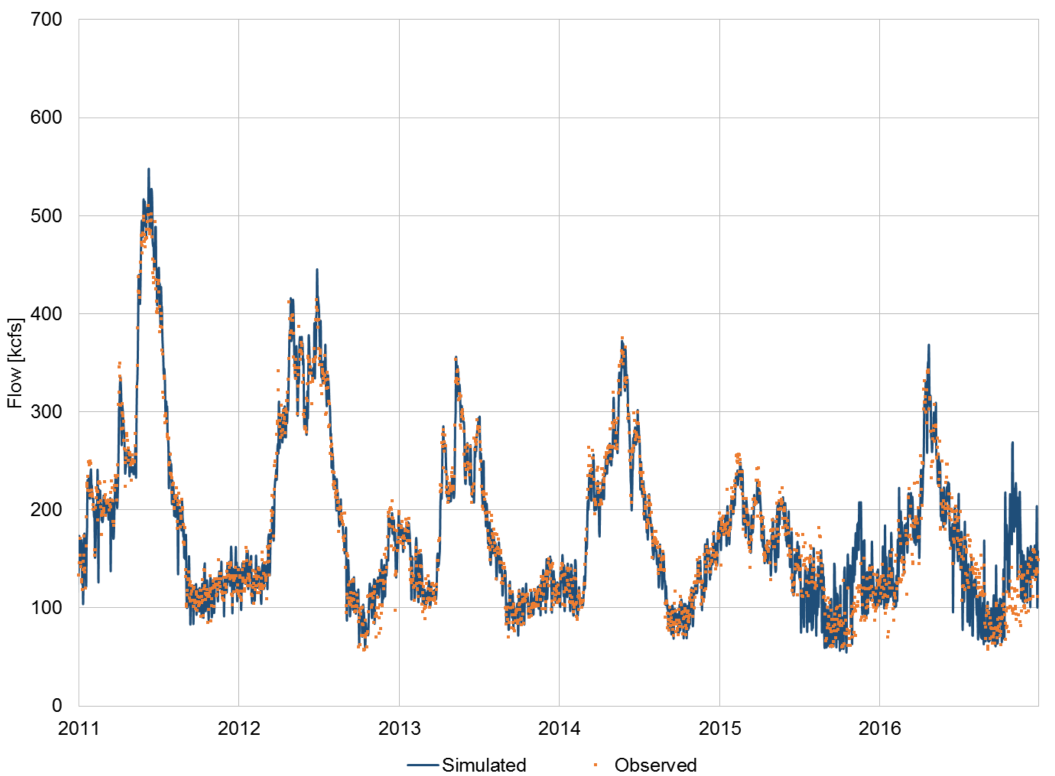

Figure D.5-4 Simulated versus observed flow at MCPW, period 2011 – 2016

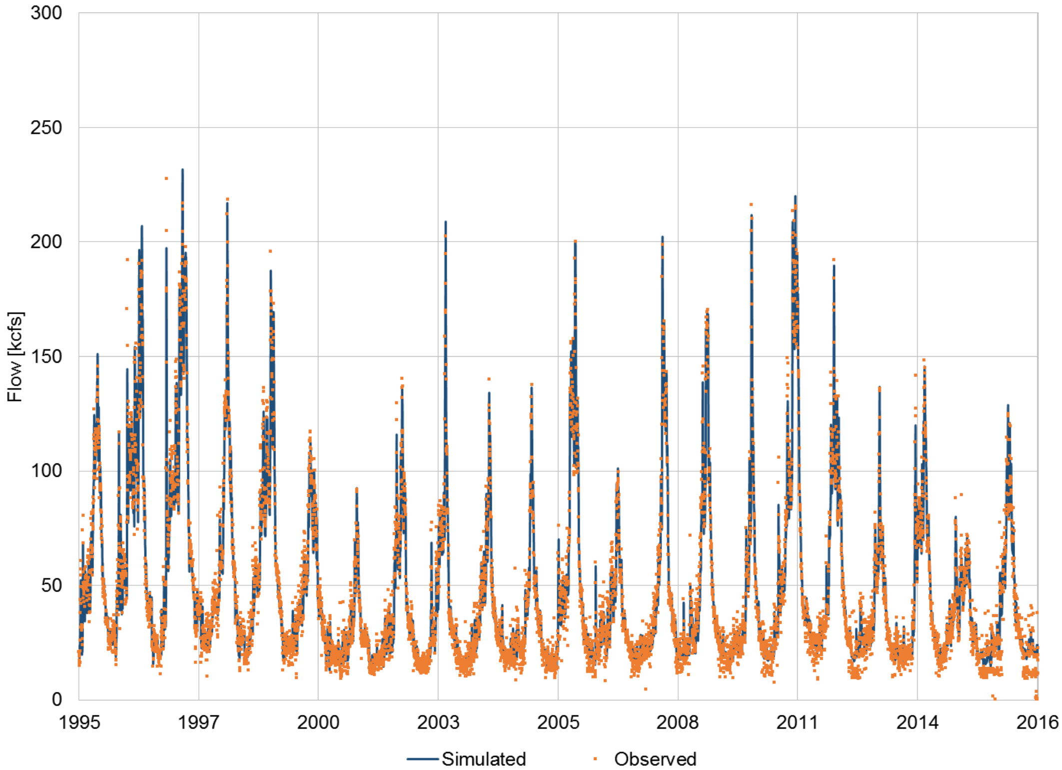

Figure D.5-5 Simulated versus observed flow at IDSW, Snake River RM 6.8

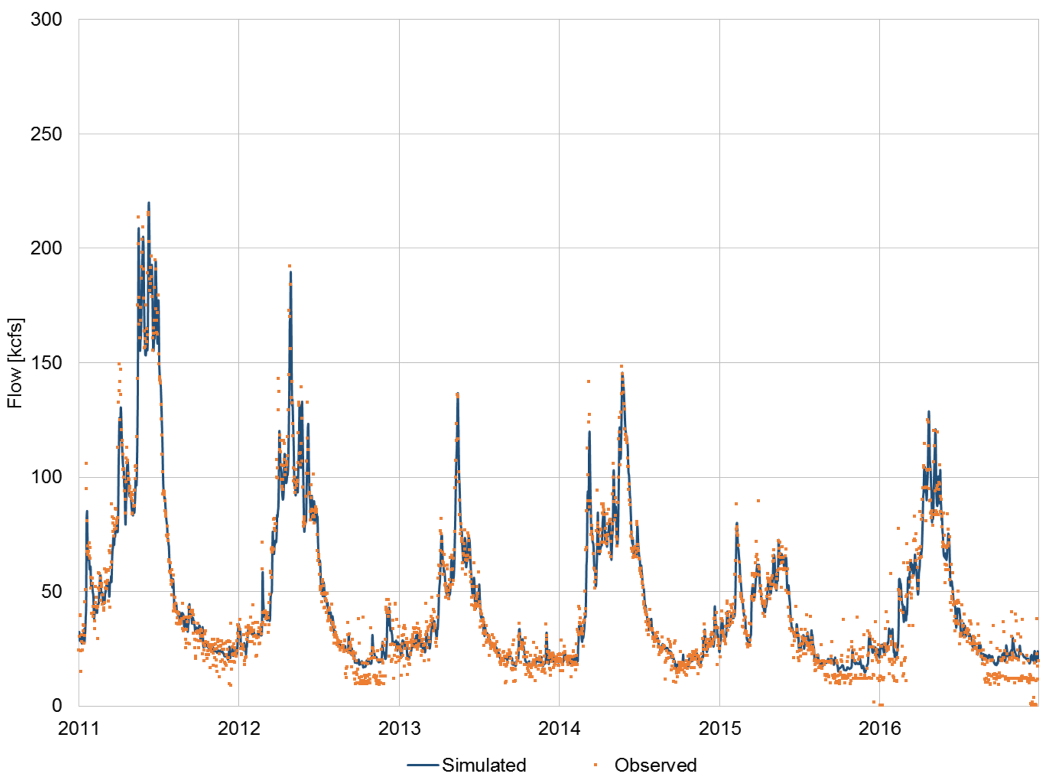

Figure D.5-6 Simulated versus observed flow at IDSW, period 2011 – 2016

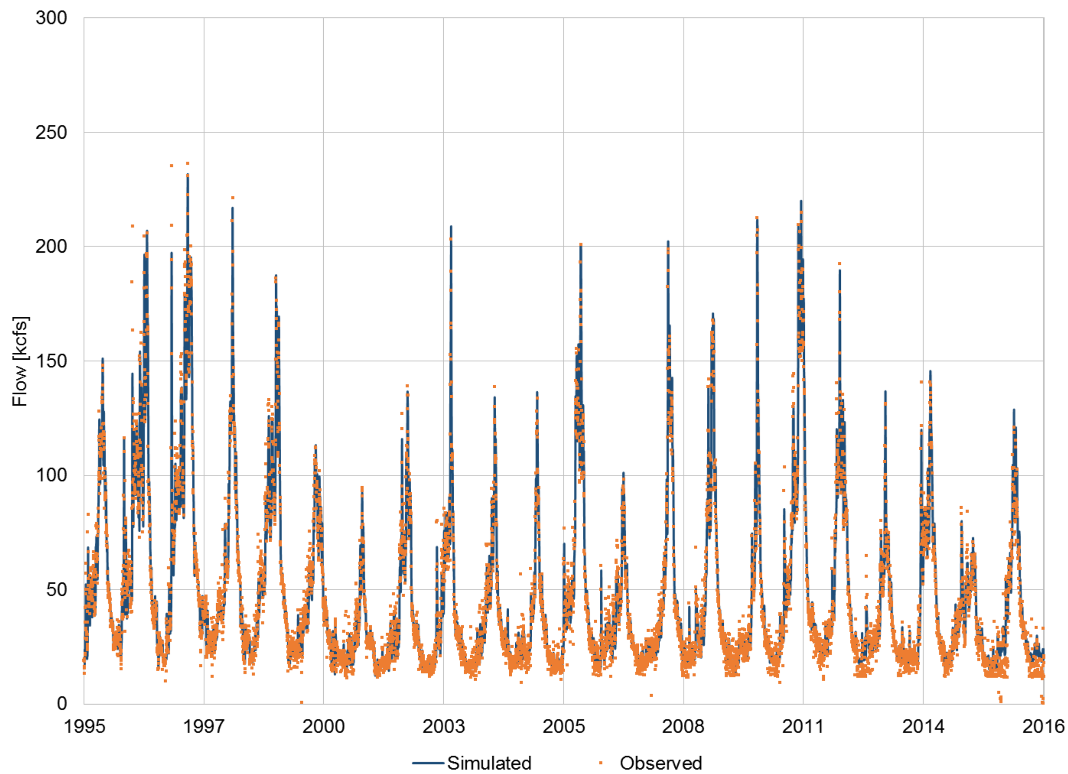

Figure D.5-7 Simulated versus observed flow at LMNW, Snake River RM 40.8

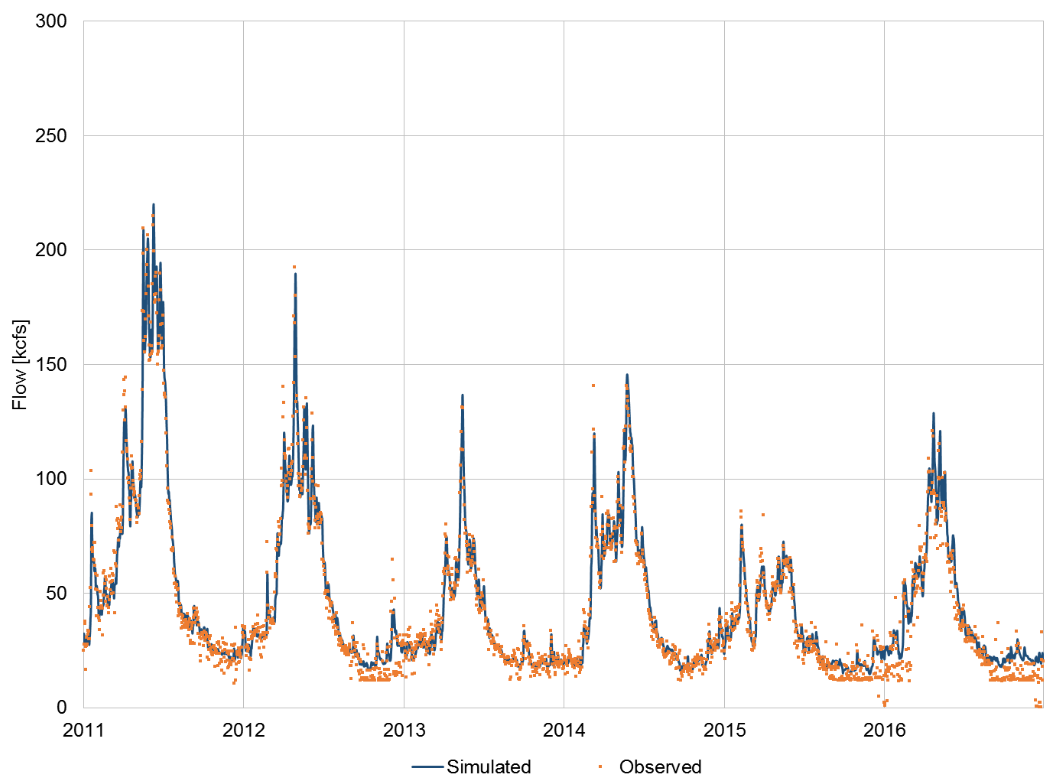

Figure D.5-8 Simulated versus observed flow at LMNW, period 2011 – 2016

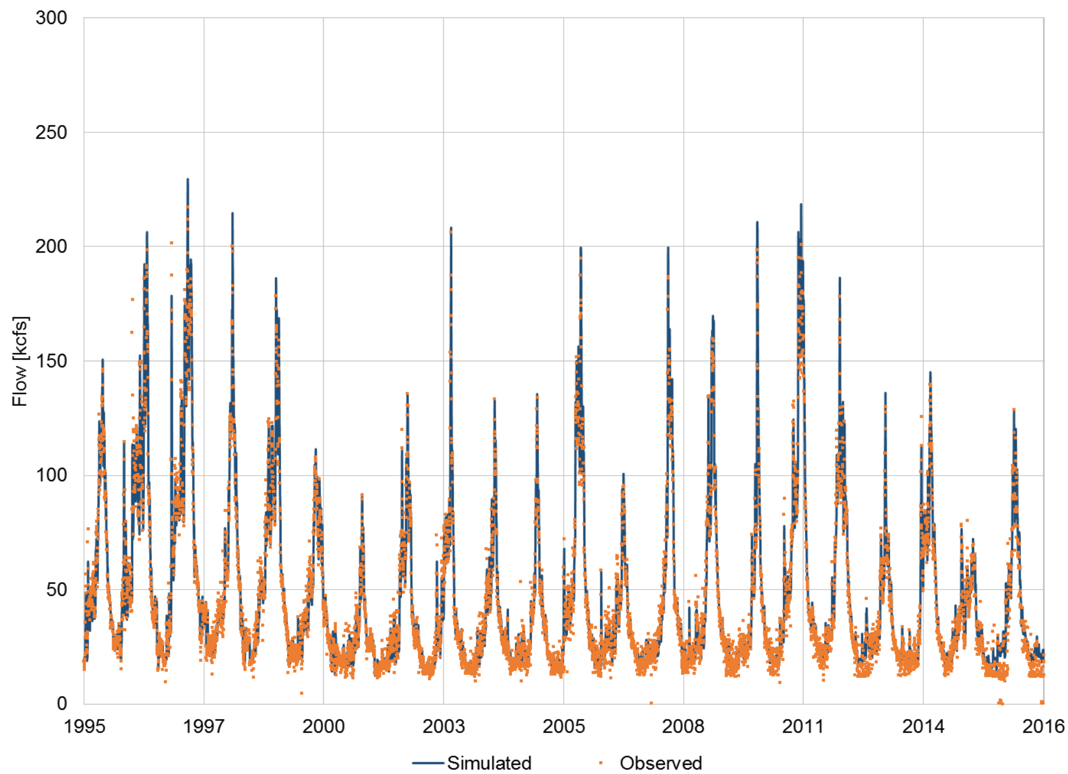

Figure D.5-9 Simulated versus observed flow at LGSW, Snake River RM 69.5

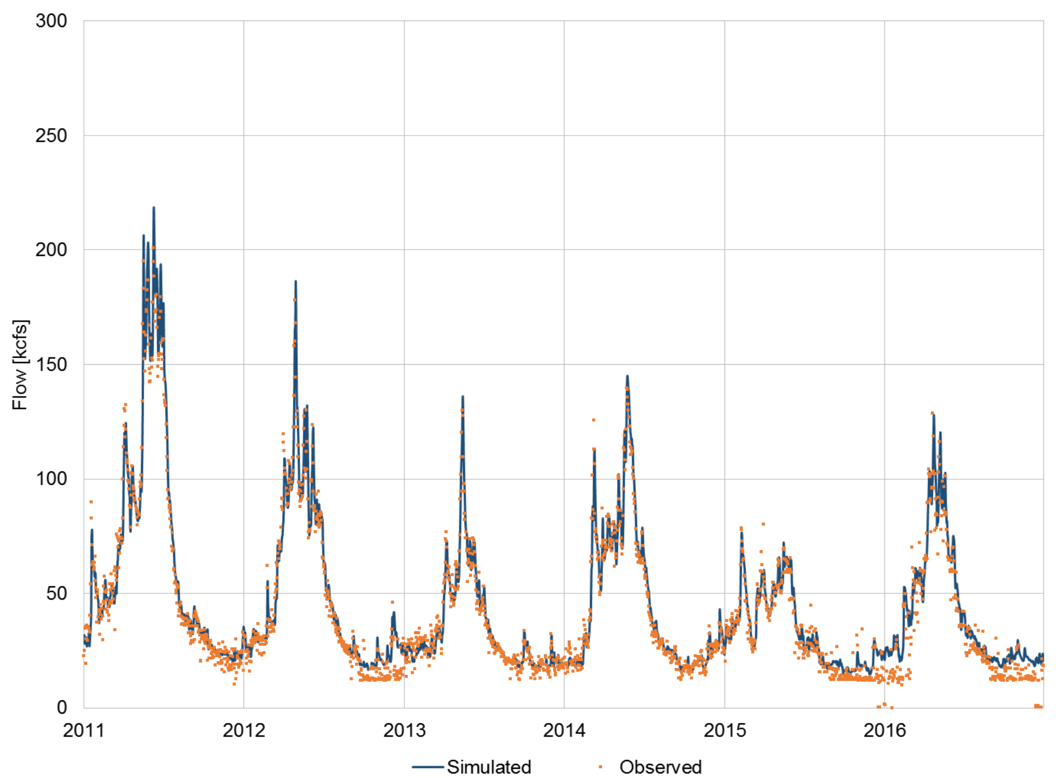

Figure D.5-10 Simulated versus observed flow at LGSW, period 2011 – 2016

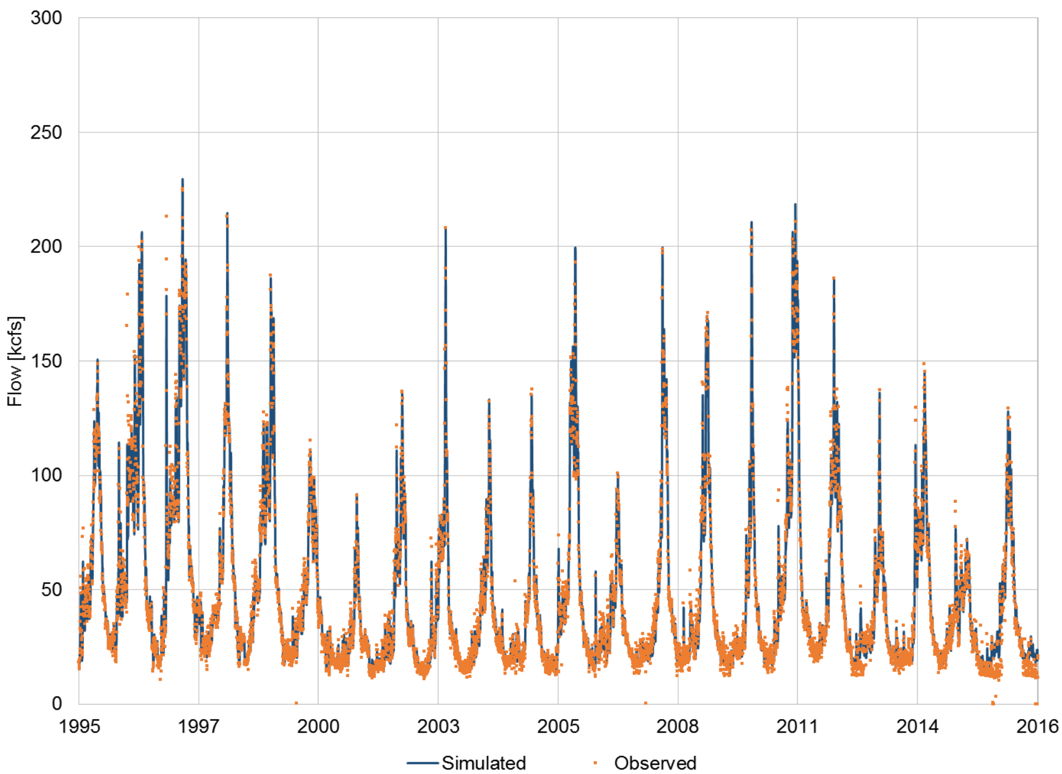

Figure D.5-11 Simulated versus observed flow at LGNW, Snake River RM 106.8

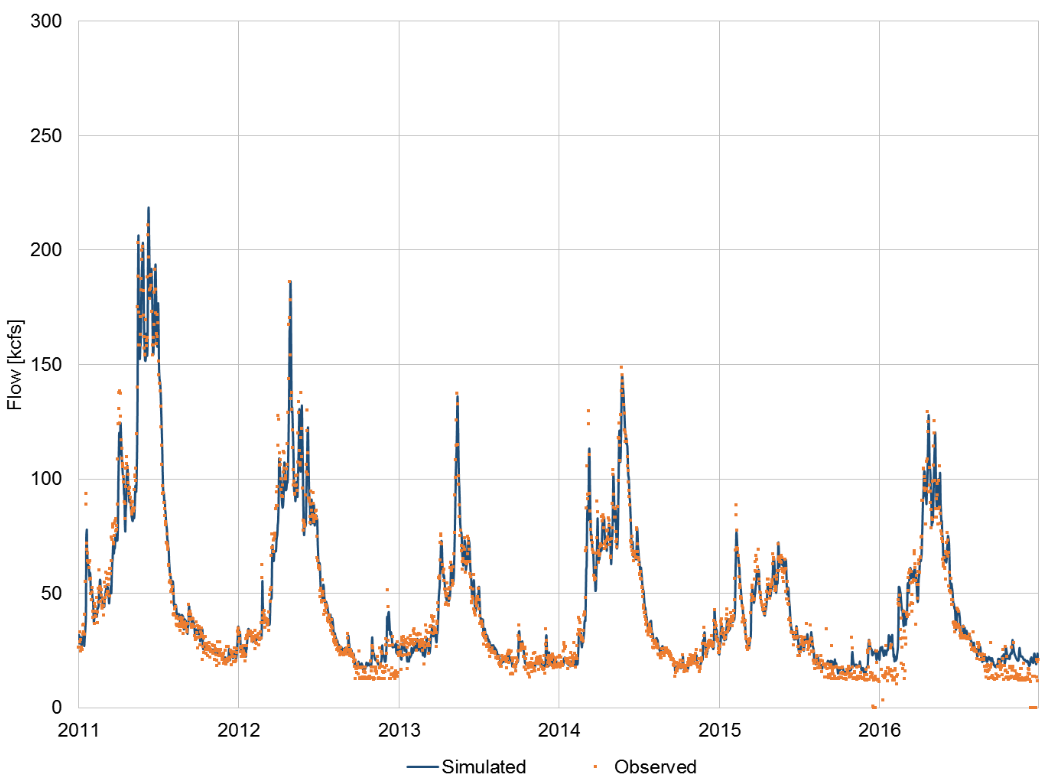

Figure D.5-12 Simulated versus observed flow at LGNW, period 2011 – 2016

Appendix E Geometric Properties of the Columbia and Snake River Reaches

E.1 Geometry of Channels and Reservoirs – Existing Conditions

Table E.1-1 Surface elevation, volume, and surface area of run-of-the-river reservoir segments in the Snake River from Lewiston, Idaho to Ice Harbor Dam

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	Volume (acre-feet)	Area (acres)
140.0	137.3	746	20825.0	597
137.3	134.6	746	20825.0	597
134.6	131.9	746	20825.0	597
131.9	129.2	746	20825.0	597
129.2	126.5	746	20825.0	597
126.5	123.8	746	35044.0	558
123.8	121.1	746	35044.0	558
121.1	118.4	746	35044.0	558
118.4	116.3	746	38586.0	524
116.3	114.3	746	38586.0	524
114.3	112.3	746	38586.0	524
112.3	110.1	746	57027.0	718
110.1	107.9	746	57027.0	718
107.9	104.5	646	20883.2	580
104.5	101.0	646	20883.2	580
101.0	97.6	646	20883.2	580
97.6	94.1	646	20883.2	580
94.1	90.7	646	20883.2	580
90.7	87.4	646	50635.0	905
87.4	84.0	646	50635.0	905
84.0	81.5	646	56622.0	814
81.5	78.9	646	56622.0	814
78.9	76.6	646	55658.0	727
76.6	74.2	646	55658.0	728
74.2	70.8	646	75002.0	956
70.8	67.5	548	25614.6	518
67.5	64.2	548	25614.6	518
64.2	60.9	548	25614.6	518
60.9	57.6	548	25614.6	518
57.6	54.2	548	25614.6	518
54.2	50.7	548	51914.0	717
50.7	47.1	548	53397.0	738
47.1	44.6	548	57812.0	735
44.6	42.0	548	60125.0	764
42.0	38.3	446	25571.6	752
38.3	34.7	446	25571.6	752
34.7	31.0	446	25571.6	752
31.0	27.4	446	25571.6	752
27.4	23.7	446	25571.6	752
23.7	21.1	446	44783.3	772
21.1	18.5	446	44783.3	772
18.5	16.0	446	44783.3	772
16.0	13.9	446	40202.7	574
13.9	11.8	446	40202.7	574
11.8	9.7	446	40202.7	574

Table E.1-2 Surface elevation, volume, and surface area of run-of-the-river reservoir segments on the Columbia River between Grand Coulee Dam and Bonneville Dam

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	Volume (acre-feet)	Area (acres)
590.0	584.9	978	46717.0	734
584.9	579.9	978	46717.0	734
579.9	574.8	978	46717.0	734
574.8	569.8	978	46717.0	734
569.8	564.7	978	46717.0	734
564.7	559.7	978	46717.0	734
559.7	554.8	978	91643.0	459
554.8	549.9	978	91643.0	459
549.9	545.1	978	91643.0	459
545.1	543.5	803	4094.0	180
543.5	536.0	803	51608.0	1194
536.0	524.1	803	120985.0	2296
524.1	522.6	803	19249.0	346
522.6	515.6	803	104064.0	1765
515.6	505.1	719	58363.0	2737
505.1	494.7	719	58363.0	2711
494.7	484.3	719	58363.0	2711
484.3	480.8	719	58303.0	912
480.8	477.3	719	58303.0	912
477.3	473.7	719	58303.0	938
473.7	466.9	619	42688.0	997
466.9	460.1	619	42688.0	997
460.1	453.4	619	42688.0	997
453.4	424.2	580	294506.0	7728
424.2	415.8	580	265974.0	5412
415.8	397.1	491	184014.0	7014
324.0	314.4	357	401976.0	10049
314.4	301.1	357	386913.0	8867
301.1	292.0	357	463002.0	6253
292.0	273.3	276	206635.0	8712
273.3	265.0	276	227752.0	9325
265.0	256.6	276	235460.0	5771
256.6	249.1	276	214530.0	4184
249.1	243.7	276	213204.0	3533
243.7	236.3	276	241671.0	3348
236.3	229.1	276	292632.0	3711
229.1	222.3	276	295188.0	4068
222.3	215.6	276	286356.0	3175
215.6	191.5	182	299532.0	8567
191.5	178.6	82	84242.0	2097
178.6	165.7	82	84242.0	2097
165.7	145.5	82	338617.0	9072

Table E.1-3 Surface elevation and parameters for equations 6 and 7. Hydraulics of unimpounded reaches in the Hanford Reach of the Columbia River

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	A_a	B_a	A_w	B_w
397.1	392.4	450	31.5606	0.5789	153.4414	0.1837
392.4	386.7	450	15.1295	0.6340	82.3124	0.2403
386.7	382.1	450	40.4673	0.5534	112.3547	0.2240
382.1	377.4	450	21.6529	0.6059	35.6177	0.3234
377.4	371.6	450	37.0496	0.5780	108.5132	0.2558
371.6	364.4	450	14.0766	0.6577	11.6300	0.4528
364.4	358.3	450	12.5432	0.6580	135.2675	0.2168
358.3	353.6	450	241.4399	0.4239	44.7010	0.3096
353.6	346.3	450	4.9438	0.7356	22.2377	0.3925
346.3	339.5	450	20.2489	0.6085	72.7417	0.2837
339.5	333.6	450	243.9695	0.4058	107.0497	0.2304
333.6	329.4	450	31.4766	0.5732	149.4212	0.2183
329.4	324.0	450	455.1888	0.3585	88.4076	0.2657

E.2 Geometry of Channels and Reservoirs – Dams Removed

Table E.2-1 Surface elevation and parameters for equations 6 and 7. Hydraulics of unimpounded reaches in the Snake River with dams removed

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	A_a	B_a	A_w	B_w
168.7	150.0	812	7.7187	0.6541	70.9226	0.2078
150.0	144.0	800	5.9800	0.6549	106.2291	0.1821
144.0	140.0	760	4.1713	0.6881	106.4711	0.1852
140.0	135.1	727	106.5232	0.4315	201.6670	0.1414
135.1	130.0	714	98.9285	0.4455	200.5298	0.1294
130.0	124.9	700	32.2671	0.5285	87.1929	0.1923
124.9	120.5	683	630.9459	0.3003	285.6511	0.0958
120.5	114.9	675	163.4107	0.3943	154.8179	0.1505
114.9	111.2	657	33.9991	0.5358	165.4843	0.1498
111.2	105.0	650	81.4161	0.4550	178.8500	0.1490
105.0	100.0	634	69.5631	0.4792	164.1594	0.1735
100.0	95.0	616	2.9459	0.7291	32.9600	0.2933
95.0	90.0	604	47.6104	0.5026	137.3326	0.1653
90.0	85.0	591	0.1085	1.0176	2.3597	0.5197
85.0	80.0	578	0.0088	1.2802	20.1629	0.3723
80.0	75.0	564	0.3738	1.0024	37.7921	0.3261
75.0	70.0	550	50.1404	0.6099	277.2079	0.1425
70.0	65.0	536	28.0869	0.5563	161.7569	0.1813
65.0	64.1	519	10.4819	0.6178	284.8547	0.1013
64.1	60.0	519	3.4710	0.6950	140.7562	0.1531
60.0	55.0	497	6.3505	0.6602	103.6262	0.1916
55.0	50.0	484	5.8877	0.6735	98.4345	0.1912
50.0	45.2	470	4.8022	0.6967	159.5878	0.1558
45.2	39.6	456	1.2579	0.8314	216.3742	0.1528
39.6	34.7	440	4.5489	0.7038	146.1067	0.1872
34.7	29.7	426	55.6236	0.5090	220.7035	0.1553
29.7	24.9	413	119.6431	0.4403	128.1916	0.1875
24.9	20.5	401	11.3383	0.6247	35.1737	0.2947
20.5	15.0	389	80.3594	0.4661	93.1568	0.2130
15.0	10.1	371	1.8818	0.8035	27.3681	0.3441
10.1	5.1	356	12.8612	0.6260	307.1769	0.1186
5.1	0.0	344	3.1882	0.7395	236.7204	0.1704

Table E.2-2 Surface elevation and parameters for equations 6 and 7. Hydraulics of unimpounded reaches in the Columbia River with dams removed. RM 740 – RM 600

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	A_a	B_a	A_w	B_w
738.2	731.4	1255.0	44.6579	0.5584	36.4799	0.2913
731.4	724.6	1233.0	82.7897	0.5014	83.3763	0.2135
724.6	717.8	1218.0	45.6788	0.5338	188.4850	0.1534
717.8	711.6	1211.0	54.0968	0.5183	167.8987	0.1531
711.6	705.6	1203.0	71.3479	0.5087	20.3333	0.3692
705.6	700.8	1189.0	327.2225	0.3970	371.4008	0.1181
700.8	696.5	1159.0	0.9141	0.8887	2.7299	0.5506
696.5	691.6	1128.0	19.0743	0.6415	27.4688	0.3349
691.6	686.7	1119.0	18.6975	0.6385	65.2029	0.2559
686.7	681.8	1117.0	38.5909	0.5949	143.1136	0.2032
681.8	678.0	1115.0	320.0048	0.4325	115.5199	0.2173
678.0	672.9	1100.0	1001.2389	0.3101	277.7493	0.0979
672.9	667.1	1091.0	56.8500	0.5513	83.1533	0.2500
667.1	663.3	1106.0	0.3274	0.9451	2.5498	0.5501
663.3	659.0	1089.0	2.9552	0.7795	54.4666	0.2795
659.0	654.0	1071.0	1.0046	0.8632	3.3353	0.5015
654.0	649.9	1052.0	6.7526	0.6904	51.2543	0.2454
649.9	645.6	1054.0	20.4480	0.6101	82.1068	0.2067
645.6	640.8	1041.0	46.1797	0.5185	61.8110	0.2017
640.8	634.6	1034.0	2.6447	0.7403	9.6688	0.3826
634.6	629.8	1010.0	4.4783	0.7234	45.8156	0.2484
629.8	625.7	996.9	112.4502	0.4662	71.9251	0.1974
625.7	620.0	992.6	13.8482	0.6394	61.3483	0.2400
620.0	616.3	975.1	94.2052	0.5106	46.4156	0.2770
616.3	612.1	953.2	993.6177	0.3371	264.2475	0.1284
612.1	607.7	946.6	1787.4376	0.3073	476.9973	0.0937
607.7	601.6	926.9	3985.4725	0.2546	462.8197	0.0996
601.6	596.6	905.1	4166.8963	0.2401	356.4680	0.1090

Table E.2-3 Surface elevation and parameters for equations 6 and 7. Hydraulics of unimpounded reaches in the Columbia River with dams removed. RM 600 – RM 416

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	A_a	B_a	A_w	B_w
596.6	593.3	1000	63.2581	0.4902	53.8357	0.2040
593.3	590.0	980	63.3358	0.5028	145.0753	0.1499
590.0	584.9	900	1.9812	0.7776	24.6645	0.3029
584.9	579.9	900	21.0540	0.6061	50.9888	0.2633
579.9	574.8	900	13.4895	0.6142	85.0871	0.1924
574.8	569.8	900	206.5641	0.3995	159.4924	0.1281
569.8	564.7	900	6.6427	0.6786	121.5886	0.1844
564.7	559.7	900	8.3673	0.6401	27.5162	0.2552
559.7	554.8	900	686.4039	0.3562	157.9005	0.1426
554.8	549.9	900	1.2514	0.8084	29.4744	0.2658
549.9	545.1	900	3.6328	0.6947	11.6800	0.3479
545.1	543.5	750	4.2461	0.7068	80.6680	0.2022
543.5	536.0	750	32.1228	0.5673	43.0408	0.2882
536.0	524.1	750	3.2566	0.7622	8.9014	0.4461
524.1	522.6	750	98.2811	0.4622	95.0016	0.1844
522.6	515.6	750	78.0606	0.4781	71.5874	0.2215
515.6	505.1	690	2.8414	0.7465	60.2659	0.2371
505.1	494.7	690	30.2005	0.5577	46.8850	0.2384
494.7	484.3	690	64.3158	0.5022	110.1743	0.1771
484.3	480.8	690	6.3695	0.6658	36.0287	0.2739
480.8	477.3	690	30.6490	0.5615	84.7111	0.2122
477.3	473.7	690	1.4414	0.7895	13.7299	0.3512
473.7	466.9	590	10.0867	0.6420	72.7227	0.2350
466.9	460.1	590	75.3660	0.4772	49.6587	0.2322
460.1	453.4	590	1467.2271	0.2697	78.6971	0.2106
453.4	424.2	500	4.4798	0.7084	12.4150	0.3700
424.2	415.8	500	2.4335	0.7604	6.5870	0.4357

Table E.2-4 Surface elevation and parameters for equations 6 and 7. Hydraulics of unimpounded reaches in the Columbia River with dams removed. RM 415 – RM 165

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	A_a	B_a	A_w	B_w
415.8	397.1	450	3.3563	0.7446	7.4465	0.4446
397.1	392.4	450	34.5416	0.5709	207.6239	0.1560
392.4	386.7	450	10.9966	0.6625	34.2419	0.3199
386.7	382.1	450	24.8849	0.5969	75.0587	0.2607
382.1	377.4	450	14.1346	0.6439	26.2289	0.3512
377.4	371.6	450	31.3949	0.5928	97.3136	0.2656
371.6	364.4	450	8.6027	0.7015	24.5650	0.3852
364.4	358.3	450	13.0791	0.6542	90.4279	0.2534
358.3	353.6	450	128.7905	0.4804	26.4022	0.3573
353.6	346.3	450	5.0872	0.7331	24.8791	0.3825
346.3	339.5	450	14.7627	0.6367	92.8002	0.2616
339.5	333.6	450	119.6021	0.4700	71.8547	0.2667
333.6	329.4	450	26.0197	0.5903	146.9509	0.2198
329.4	324.0	450	253.6713	0.4113	89.7111	0.2644
324.0	314.4	300	157.8708	0.4520	247.0500	0.2053
314.4	301.1	300	28.7002	0.5865	35.7668	0.3564
301.1	292.0	300	59.4761	0.5248	146.7489	0.2403
292.0	273.3	250	92.1021	0.5034	184.4085	0.2164
273.3	265.0	250	13.0995	0.6606	44.3810	0.3557
265.0	256.6	250	87.0843	0.5123	189.4475	0.2129
256.6	249.1	250	19.5999	0.6280	80.7308	0.2883
249.1	243.7	250	9.2135	0.6827	45.5035	0.3371
243.7	236.3	250	95.4752	0.4953	197.7407	0.1951
236.3	229.1	250	8.7544	0.6997	76.0817	0.2793
229.1	222.3	250	10.6410	0.6947	58.3905	0.3035
222.3	215.6	250	58.6465	0.5847	132.0937	0.2447
215.6	191.5	120	1044.3774	0.3247	92.0860	0.2569
191.5	178.6	50	3545.4392	0.2541	414.3888	0.1200
178.6	165.7	50	976.9627	0.3624	297.5893	0.1827
165.7	145.5	50	289.8918	0.4386	76.2070	0.2884

Appendix F Sensitivity Analysis

F.1 Columbia River Sensitivity Analysis Results

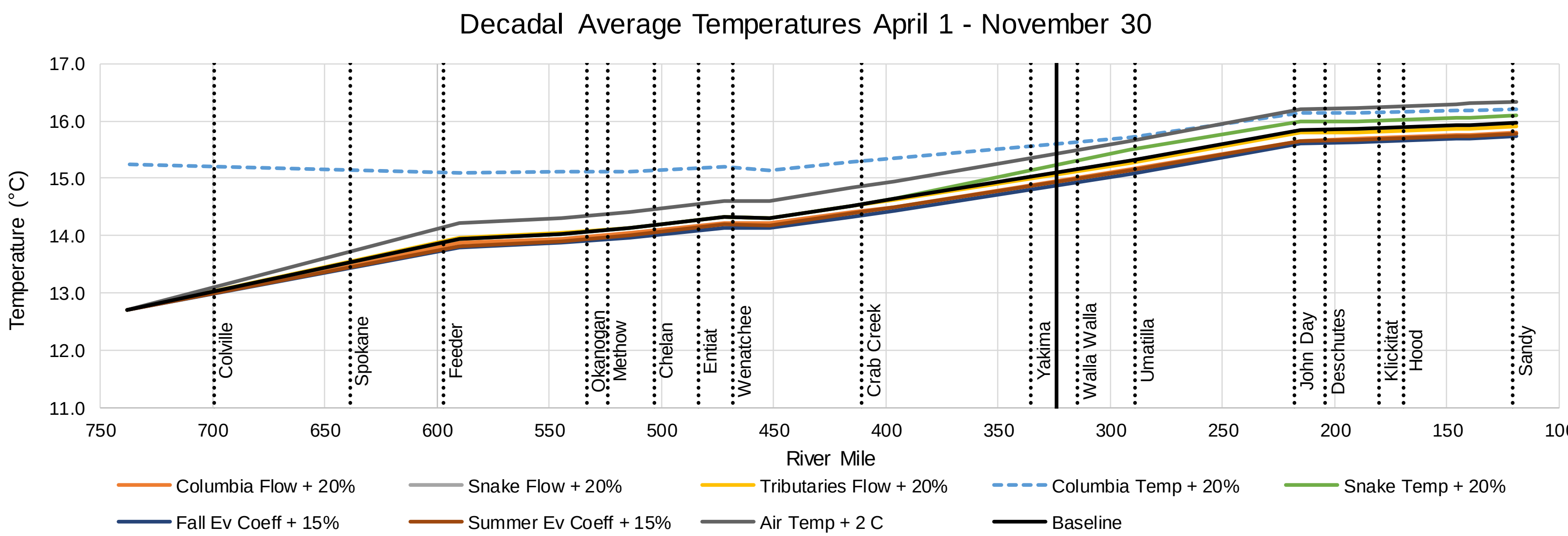

Figure F.1-1 Longitudinal changes in 10-year (April - November) average Columbia River water temperatures for each scenario evaluated

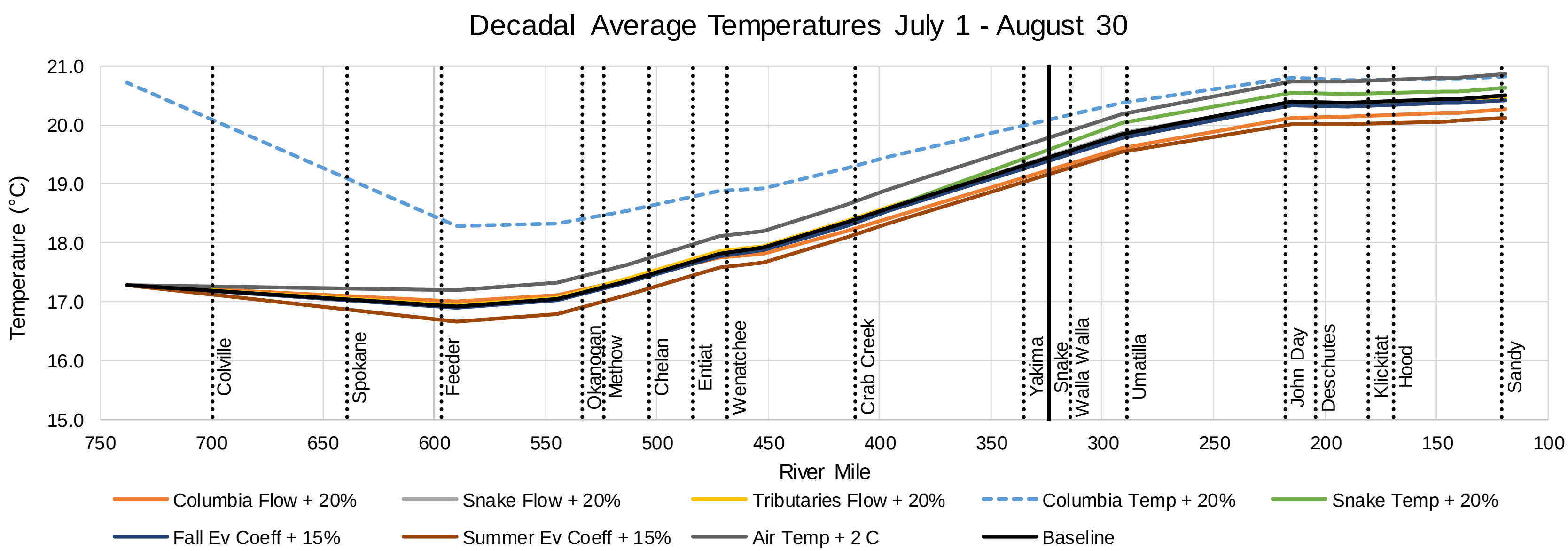

Figure F.1-2 Longitudinal changes in 10-year (July - August) average Columbia River water temperatures for each scenario evaluated

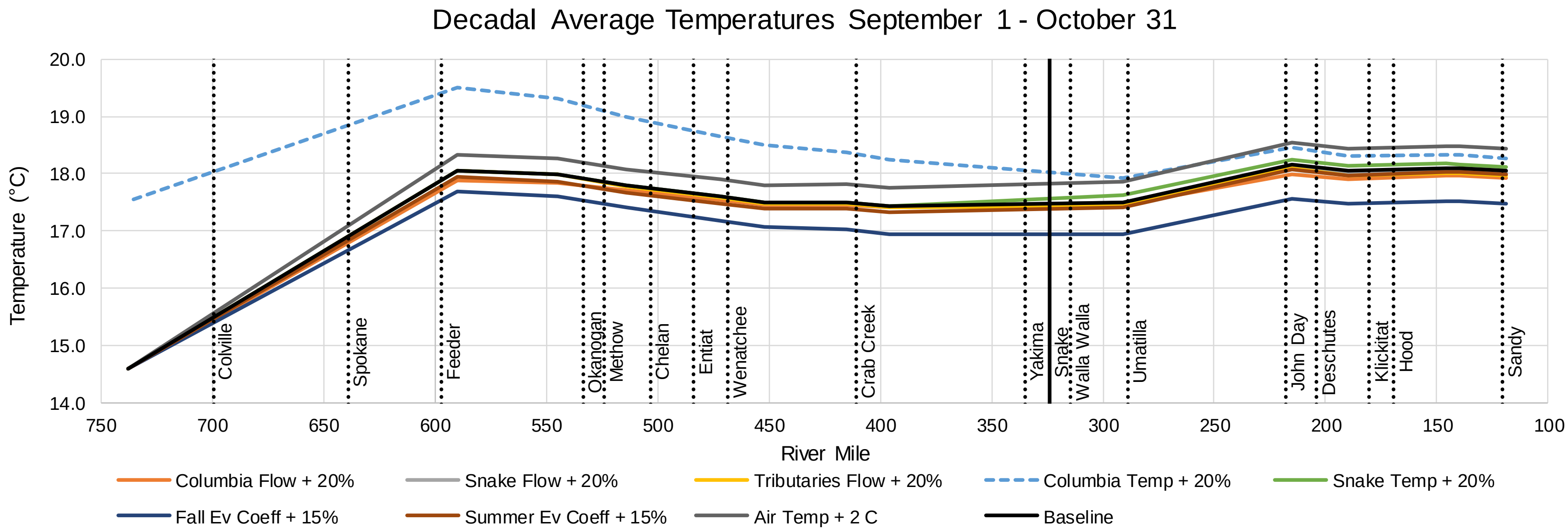

Figure F.1-3 Longitudinal changes in 10-year (September - October) average Columbia River water temperatures for each scenario evaluated

Table F.1-1 Percent changes in decadal (April - November) average water temperature along the Columbia River under different sensitivity scenarios

Station ID*	Baseline Temp. (°C)	Mean Change in Temperature from Baseline (%) (April 1 - November 30)							
		Columbia Flow + 20%	Snake Flow + 20%	Tributaries Flow + 20%	Columbia Temp + 20%	Snake Temp + 20%	Fall Ev Coeff + 15%	Summer Ev Coeff + 15%	Air Temp + 2 C
CWMW	16.0	-1.0	-0.1	-0.3	1.5	0.8	-1.5	-1.2	2.4
WRNO	15.9	-1.0	-0.1	-0.3	1.6	0.8	-1.4	-1.2	2.4
BON	15.9	-1.1	-0.1	-0.4	1.6	0.8	-1.4	-1.2	2.3
TDDO	15.9	-1.1	-0.1	-0.3	1.8	0.9	-1.5	-1.2	2.3
JHAW	15.8	-1.2	-0.1	-0.3	1.9	1.0	-1.5	-1.2	2.3
MCPW	15.3	-1.0	0.0	-0.3	2.6	1.3	-1.5	-1.1	2.2
PRXW	14.6	-0.9	0.0	-0.1	4.9	0.0	-1.4	-0.9	2.2
WANW	14.5	-0.8	0.0	-0.1	5.2	0.0	-1.3	-0.9	2.1
RIGW	14.3	-0.7	0.0	-0.1	5.8	0.0	-1.3	-0.9	2.0
RRDW	14.3	-0.7	0.0	0.0	6.1	0.0	-1.3	-0.9	2.0
WELW	14.1	-0.6	0.0	0.0	6.9	0.0	-1.2	-0.9	2.0
CHQW	14.0	-0.6	0.0	0.1	7.7	0.0	-1.2	-1.0	2.0
GCGW	13.9	-0.6	0.0	0.1	8.3	0.0	-1.1	-1.0	1.9

* Station location shown in Figure 3-1

Table F.1-2 Percent changes in decadal (April - November) minimum, maximum and average water temperature along the Columbia River under different sensitivity scenarios

Station ID*	Baseline Temp. (°C)			Change in Temperature from Baseline (%) (April 1 - November 30)																										
				Columbia Flow + 20%			Snake Flow + 20%			Tributaries Flow + 20%			Columbia Temp + 20%			Snake Temp + 20%			Fall Ev Coeff + 15%			Summer Ev Coeff + 15%			Air Temp + 2 C		
	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
CWMW	16.0	7.5	23.3	-1.0	-1.2	-1.6	-0.1	0.6	-0.3	-0.3	0.1	-0.4	1.5	1.0	0.8	0.8	1.4	0.8	-1.5	-5.6	0.0	-1.2	-0.5	-2.2	2.4	4.1	1.5
WRNO	15.9	7.3	23.1	-1.0	-1.2	-1.6	-0.1	0.4	-0.4	-0.3	0.8	-0.5	1.6	1.3	0.8	0.8	1.5	0.8	-1.4	-1.4	0.0	-1.2	-0.4	-2.2	2.4	4.3	1.6
BON	15.9	7.3	23.1	-1.1	-1.5	-1.4	-0.1	0.1	-0.4	-0.4	0.4	-0.5	1.6	1.3	0.8	0.8	1.5	0.8	-1.4	-0.9	0.0	-1.2	-0.4	-2.1	2.3	4.3	1.6
TDDO	15.9	7.1	23.1	-1.1	-0.3	-1.4	-0.1	0.5	0.1	-0.3	0.5	-0.1	1.8	1.2	0.9	0.9	0.5	0.8	-1.5	0.0	0.0	-1.2	-0.3	-2.1	2.3	5.7	1.5
JHAW	15.8	6.7	22.9	-1.2	-0.8	-1.0	-0.1	1.4	-0.1	-0.3	1.3	0.0	1.9	1.3	1.4	1.0	0.6	1.0	-1.5	0.0	0.0	-1.2	0.0	-2.0	2.3	6.0	1.6
MCPW	15.3	6.2	22.3	-1.0	-4.2	-1.3	0.0	-0.5	-0.3	-0.3	-0.2	-0.4	2.6	2.0	2.0	1.3	1.8	1.2	-1.5	0.0	0.0	-1.1	-0.2	-1.6	2.2	5.9	1.6
PRXW	14.6	5.0	21.2	-0.9	-1.7	-0.1	0.0	0.0	0.0	-0.1	0.2	0.1	4.9	5.1	4.5	0.0	0.0	0.0	-1.4	0.0	-1.2	-0.9	-0.5	-1.1	2.2	6.6	1.5
WANW	14.5	4.9	21.1	-0.8	-4.4	0.6	0.0	0.0	0.0	-0.1	1.0	0.1	5.2	6.0	4.9	0.0	0.0	0.0	-1.3	0.0	-1.0	-0.9	-0.3	-1.2	2.1	6.6	1.5
RIGW	14.3	4.4	20.6	-0.7	4.6	1.9	0.0	0.0	0.0	-0.1	4.9	0.1	5.8	5.4	5.6	0.0	0.0	0.0	-1.3	0.0	-0.4	-0.9	0.0	-0.9	2.0	6.2	1.4
RRDW	14.3	4.6	20.6	-0.7	-3.2	1.1	0.0	0.0	0.0	0.0	-3.6	-0.1	6.1	6.4	5.6	0.0	0.0	0.0	-1.3	0.0	-1.0	-0.9	-0.6	-0.8	2.0	5.5	1.3
WELW	14.1	3.8	20.3	-0.6	4.9	2.5	0.0	0.0	0.0	0.0	2.7	0.0	6.9	8.1	7.4	0.0	0.0	0.0	-1.2	0.0	-0.5	-0.9	-0.2	-0.8	2.0	5.0	1.3
CHQW	14.0	3.5	20.3	-0.6	3.0	2.1	0.0	0.0	0.0	0.1	-2.0	0.1	7.7	7.1	8.2	0.0	0.0	0.0	-1.2	0.0	-1.0	-1.0	0.1	-0.7	2.0	6.4	1.2
GCGW	13.9	3.2	20.8	-0.6	10.5	0.5	0.0	0.0	0.0	0.1	0.2	0.0	8.3	6.2	8.8	0.0	0.0	0.0	-1.1	0.0	-1.0	-1.0	0.0	-0.8	1.9	6.4	1.0

* Station location shown in Figure 3-1

Table F.1-3 Percent changes in decadal (July - August) average water temperature along the Columbia River under different sensitivity scenarios

Station ID*	Baseline Temp. (°C)	Change in Temperature from Baseline (%) (July 1 - August 31)							
		Columbia Flow + 20%	Snake Flow + 20%	Tributaries Flow + 20%	Columbia Temp + 20%	Snake Temp + 20%	Fall Ev Coeff + 15%	Summer Ev Coeff + 15%	Air Temp + 2 C
CWMW	20.5	-1.1	-0.1	-0.2	1.6	0.6	-0.3	-1.9	1.8
WRNO	20.4	-1.1	-0.1	-0.2	1.7	0.7	-0.3	-1.8	1.8
BON	20.4	-1.2	-0.1	-0.2	1.7	0.7	-0.3	-1.8	1.8
TDDO	20.4	-1.2	0.0	-0.2	1.8	0.7	-0.3	-1.8	1.7
JHAW	20.4	-1.3	0.0	-0.1	2.0	0.8	-0.3	-1.8	1.8
MCPW	19.8	-1.3	0.0	-0.1	2.6	0.9	-0.3	-1.6	1.7
PRXW	18.6	-1.0	0.0	0.1	4.7	0.0	-0.3	-1.4	1.7
WANW	18.3	-0.8	0.0	0.2	5.1	0.0	-0.3	-1.3	1.7
RIGW	17.9	-0.5	0.0	0.2	5.7	0.0	-0.2	-1.4	1.6
RRDW	17.8	-0.4	0.0	0.2	6.0	0.0	-0.2	-1.4	1.6
WELW	17.3	0.0	0.0	0.2	6.8	0.0	-0.2	-1.4	1.6
CHQW	17.0	0.3	0.0	0.1	7.5	0.0	-0.1	-1.5	1.6
GCGW	16.9	0.5	0.0	0.1	8.0	0.0	-0.1	-1.5	1.6

* Station location shown in Figure 3-1

Table F.1-4 Percent changes in decadal (July - August) minimum, maximum and average water temperature along the Columbia River under different sensitivity scenarios

Station ID*	**Baseline Temp. (°C)**			**Change in Temperature from Baseline (%) (July 1 - August 31)**																							
				Columbia Flow + 20%			**Snake Flow + 20%**			**Tributaries Flow + 20%**			**Columbia Temp + 20%**			**Snake Temp + 20%**			**Fall Ev Coeff + 15%**			**Summer Ev Coeff + 15%**			**Air Temp + 2 C**		
	Avg	**Min**	**Max**	**Avg**	**Min**	**Max**	**Avg**	**Min**	**Max**	**Avg**	**Min**	**Max**	**Avg**	**Min**	**Max**	**Avg**	**Min**	**Max**	**Avg**	**Min**	**Max**	**Avg**	**Min**	**Max**	**Avg**	**Min**	**Max**
CWMW	20.5	15.4	23.3	-1.1	-1.4	-1.6	-0.1	0.0	-0.3	-0.2	0.1	-0.4	1.6	3.3	0.8	0.6	2.7	0.8	-0.3	0.0	0.0	-1.9	-1.0	-2.2	1.8	1.5	1.5
WRNO	20.4	15.4	23.1	-1.1	-1.5	-1.6	-0.1	0.1	-0.4	-0.2	0.2	-0.5	1.7	3.5	0.8	0.7	2.7	0.8	-0.3	0.0	0.0	-1.8	-0.9	-2.2	1.8	1.5	1.6
BON	20.4	15.4	23.1	-1.2	-1.5	-1.4	-0.1	0.0	-0.4	-0.2	0.1	-0.5	1.7	3.5	0.8	0.7	2.7	0.8	-0.3	0.0	0.0	-1.8	-0.9	-2.2	1.8	1.5	1.6
TDDO	20.4	15.5	23.1	-1.2	-1.8	-1.4	0.0	-1.2	0.1	-0.2	-0.5	-0.1	1.8	3.4	0.9	0.7	2.8	0.8	-0.3	0.0	0.0	-1.8	-0.9	-2.1	1.7	1.5	1.5
JHAW	20.4	15.3	22.9	-1.3	-1.5	-1.0	0.0	-0.9	-0.1	-0.1	-0.4	0.0	2.0	3.6	1.4	0.8	2.9	1.0	-0.3	0.0	0.0	-1.8	-0.9	-2.0	1.8	1.5	1.6
MCPW	19.8	14.5	22.3	-1.3	-0.9	-1.3	0.0	-0.5	-0.3	-0.1	0.3	-0.4	2.6	4.2	2.0	0.9	3.4	1.2	-0.3	0.0	0.0	-1.6	-0.7	-1.6	1.7	1.3	1.6
PRXW	18.6	13.5	21.2	-1.0	-0.3	-0.1	0.0	0.0	0.0	0.1	-0.1	0.1	4.7	7.9	4.5	0.0	0.0	0.0	-0.3	0.0	-1.2	-1.4	-0.8	-1.1	1.7	1.4	1.5
WANW	18.3	13.4	21.1	-0.8	-1.3	-0.5	0.0	0.0	0.0	0.2	-0.1	0.1	5.1	8.1	4.9	0.0	0.0	0.0	-0.3	0.0	-1.0	-1.3	-0.7	-1.2	1.7	1.3	1.5
RIGW	17.9	13.0	20.6	-0.5	1.0	-0.1	0.0	0.0	0.0	0.2	0.3	0.1	5.7	8.5	5.6	0.0	0.0	0.0	-0.2	0.0	-0.4	-1.4	-0.7	-1.4	1.6	1.3	1.4
RRDW	17.8	13.1	20.6	-0.4	0.4	-0.7	0.0	0.0	0.0	0.2	0.4	0.1	6.0	8.9	5.9	0.0	0.0	0.0	-0.2	0.0	-0.7	-1.4	-0.7	-1.4	1.6	1.3	1.4
WELW	17.3	13.0	20.3	0.0	-0.8	-1.4	0.0	0.0	0.0	0.2	0.6	0.1	6.8	9.7	6.7	0.0	0.0	0.0	-0.2	0.0	-0.4	-1.4	-0.6	-1.6	1.6	1.3	1.4
CHQW	17.0	12.8	20.0	0.3	-0.8	-1.5	0.0	0.0	0.0	0.1	0.2	0.0	7.5	11.0	7.3	0.0	0.0	0.0	-0.1	0.0	-0.3	-1.5	-0.5	-1.8	1.6	1.3	1.4
GCGW	16.9	12.6	19.8	0.5	0.3	-0.1	0.0	0.0	0.0	0.1	1.5	0.1	8.0	11.5	7.9	0.0	0.0	0.0	-0.1	0.0	-0.1	-1.5	-0.6	-1.9	1.6	1.2	1.4

* Station location shown in Figure 3-1

Table F.1-5 Percent changes in decadal (September - October) average water temperature along the Columbia River under different sensitivity scenarios

Station ID*	Baseline Temp. (°C)	Mean Change in Temperature from Baseline (%) (Sept 1 - Oct 31)							
		Columbia Flow + 20%	Snake Flow + 20%	Tributaries Flow + 20%	Columbia Temp + 20%	Snake Temp + 20%	Fall Ev Coeff + 15%	Summer Ev Coeff + 15%	Air Temp + 2 C
CWMW	18.0	-0.7	-0.1	-0.5	1.3	0.4	-3.2	-0.3	2.2
WRNO	18.1	-0.8	-0.1	-0.5	1.3	0.4	-3.2	-0.4	2.2
BON	18.1	-0.8	-0.1	-0.5	1.4	0.4	-3.2	-0.4	2.2
TDDO	18.0	-0.7	-0.1	-0.4	1.5	0.5	-3.2	-0.4	2.1
JHAW	18.2	-0.8	-0.1	-0.3	1.7	0.5	-3.3	-0.4	2.2
MCPW	17.5	-0.3	0.0	-0.4	2.5	0.8	-3.2	-0.4	2.1
PRXW	17.4	-0.1	0.0	-0.1	4.7	0.0	-2.8	-0.6	1.9
WANW	17.5	-0.2	0.0	-0.1	5.0	0.0	-2.6	-0.6	1.9
RIGW	17.5	-0.2	0.0	-0.2	5.7	0.0	-2.4	-0.6	1.7
RRDW	17.6	-0.3	0.0	-0.1	6.0	0.0	-2.4	-0.6	1.7
WELW	17.8	-0.5	0.0	-0.1	6.8	0.0	-2.2	-0.7	1.6
CHQW	18.0	-0.8	0.0	0.0	7.4	0.0	-2.1	-0.7	1.6
GCGW	18.1	-1.0	0.0	0.0	8.1	0.0	-2.0	-0.6	1.5

* Station location shown in Figure 3-1

Table F.1-6 Percent changes in decadal (September - October) minimum, maximum and average water temperature along the Columbia River under different sensitivity scenarios

Station ID*	Baseline Temp. (°C)			Change in Temperature from Baseline (%) (Sept 1 - Oct 31)																								
				Columbia Flow + 20%			Snake Flow + 20%			Tributaries Flow + 20%			Columbia Temp + 20%			Snake Temp + 20%			Fall Ev Coeff + 15%			Summer Ev Coeff + 15%			Air Temp + 2 C		
	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
CWMW	18.0	12.7	22.9	-0.7	3.4	-1.5	-0.1	1.5	-0.1	-0.5	0.9	-0.4	1.3	1.1	1.5	0.4	0.5	0.3	-3.2	-5.0	-1.9	-0.3	-0.2	-0.6	2.2	3.5	1.5
WRNO	18.1	12.9	22.8	-0.8	2.5	-1.5	-0.1	0.2	0.0	-0.5	-0.9	-0.2	1.3	1.1	1.6	0.4	0.5	0.3	-3.2	-4.9	-1.8	-0.4	-0.3	-0.6	2.2	3.4	1.5
BON	18.1	12.9	22.8	-0.8	2.2	-1.5	-0.1	0.6	0.0	-0.5	-0.7	-0.2	1.4	1.1	1.6	0.4	0.5	0.3	-3.2	-5.0	-1.8	-0.4	-0.2	-0.6	2.2	3.4	1.5
TDDO	18.0	13.3	22.6	-0.7	-1.7	-2.1	-0.1	-0.4	0.1	-0.4	-0.2	0.0	1.5	1.8	1.8	0.5	0.7	0.3	-3.2	-4.7	-1.7	-0.4	-0.4	-0.7	2.1	3.0	1.5
JHAW	18.2	13.3	22.6	-0.8	-0.7	-2.2	-0.1	-1.1	0.0	-0.3	-1.6	-0.1	1.7	1.7	2.1	0.5	0.9	0.3	-3.3	-5.0	-1.8	-0.4	-0.4	-0.7	2.2	3.1	1.5
MCPW	17.5	13.1	21.8	-0.3	-1.1	-0.8	0.0	0.1	-0.1	-0.4	-0.3	-0.3	2.5	2.9	2.6	0.8	0.9	0.4	-3.2	-5.4	-1.8	-0.4	-0.3	-0.6	2.1	2.8	1.5
PRXW	17.4	13.4	21.0	-0.1	-0.4	0.8	0.0	0.0	0.0	-0.1	-0.5	0.0	4.7	6.2	4.8	0.0	0.0	0.0	-2.8	-4.4	-1.2	-0.6	0.0	-0.8	1.9	2.2	1.4
WANW	17.5	13.5	20.8	-0.2	-0.2	1.8	0.0	0.0	0.0	-0.1	-0.7	-0.1	5.0	4.9	4.6	0.0	0.0	0.0	-2.6	-4.6	-1.3	-0.6	-0.1	-0.7	1.9	2.1	1.4
RIGW	17.5	13.7	20.6	-0.2	1.2	2.0	0.0	0.0	0.0	-0.2	-0.8	0.0	5.7	6.2	5.5	0.0	0.0	0.0	-2.4	-4.2	-1.1	-0.6	0.0	-0.8	1.7	2.2	1.3
RRDW	17.6	14.0	20.6	-0.3	-0.5	1.1	0.0	0.0	0.0	-0.1	-0.5	-0.1	6.0	7.5	5.6	0.0	0.0	0.0	-2.4	-4.1	-1.1	-0.6	0.0	-0.8	1.7	2.2	1.3
WELW	17.8	14.4	20.3	-0.5	-1.5	2.5	0.0	0.0	0.0	-0.1	-0.5	0.0	6.8	9.0	7.4	0.0	0.0	0.0	-2.2	-2.9	-1.0	-0.7	0.0	-0.8	1.6	1.9	1.2
CHQW	18.0	13.9	20.3	-0.8	1.6	2.1	0.0	0.0	0.0	0.0	-0.2	0.1	7.4	9.4	8.2	0.0	0.0	0.0	-2.1	-2.5	-1.0	-0.7	0.0	-0.7	1.6	1.8	1.2
GCGW	18.1	14.3	20.8	-1.0	0.6	0.5	0.0	0.0	0.0	0.0	-0.1	0.0	8.1	9.9	8.8	0.0	0.0	0.0	-2.0	-2.1	-1.0	-0.6	0.0	-0.8	1.5	1.6	1.0

* Station location shown in Figure 3-1

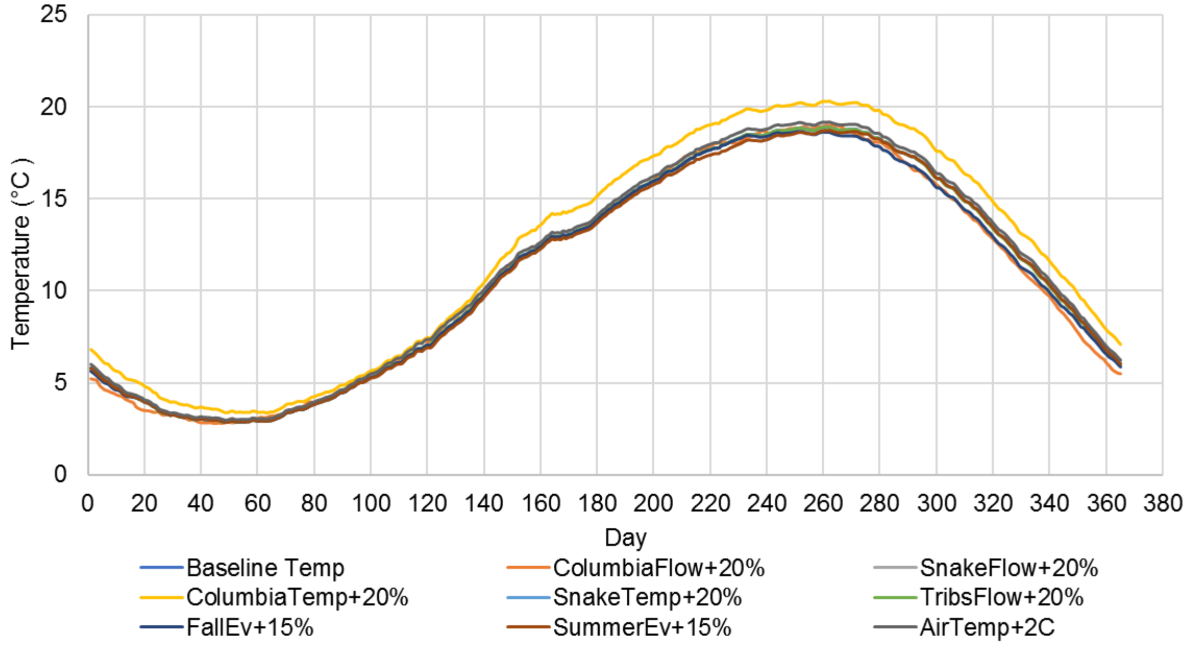

Figure F.1-4 Sensitivity of 10-year daily average temperatures at GCGW

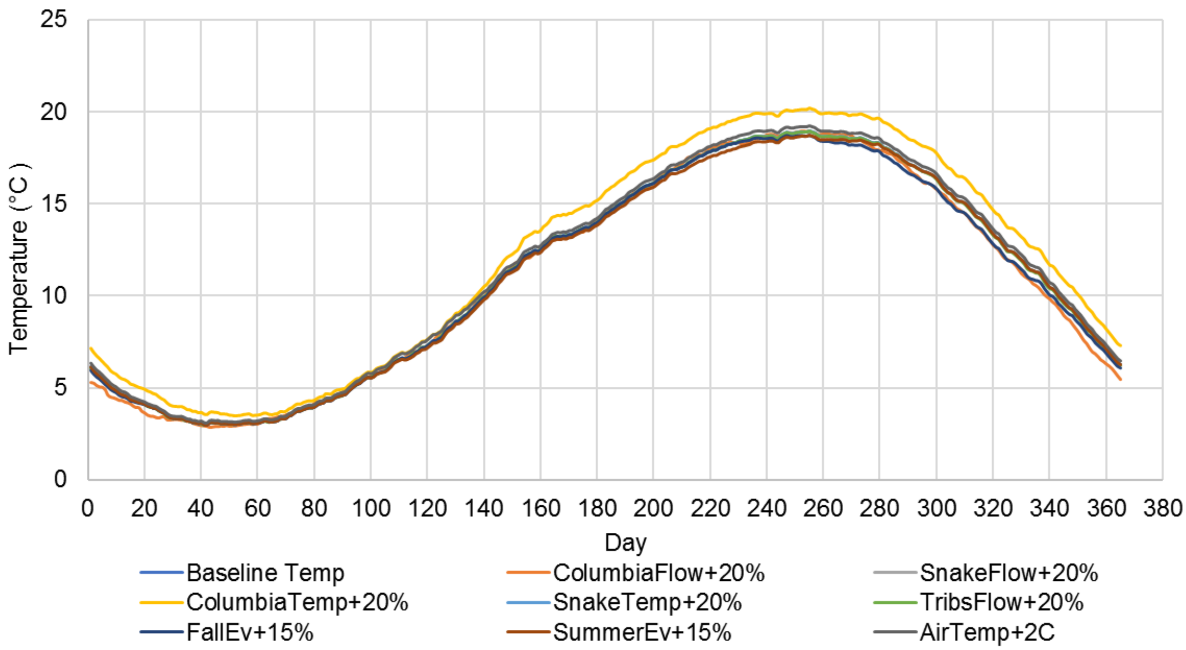

Figure F.1-5 Sensitivity of 10-year daily average temperatures at CHQW

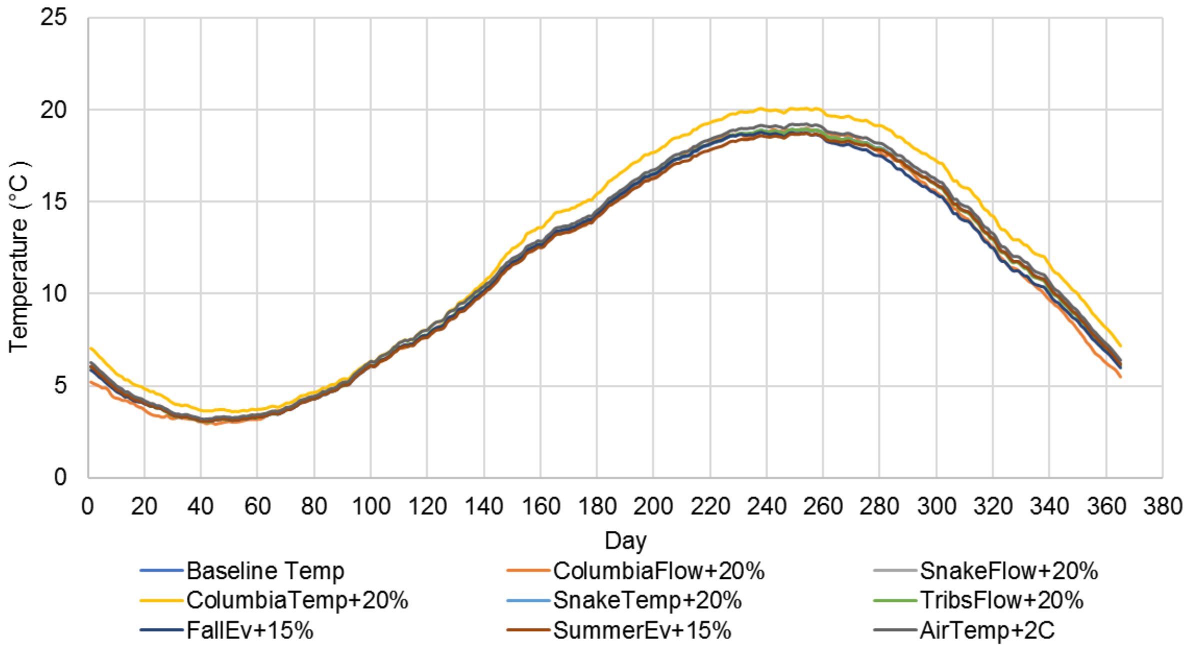

Figure F.1-6 Sensitivity of 10-year daily average temperatures at WELW

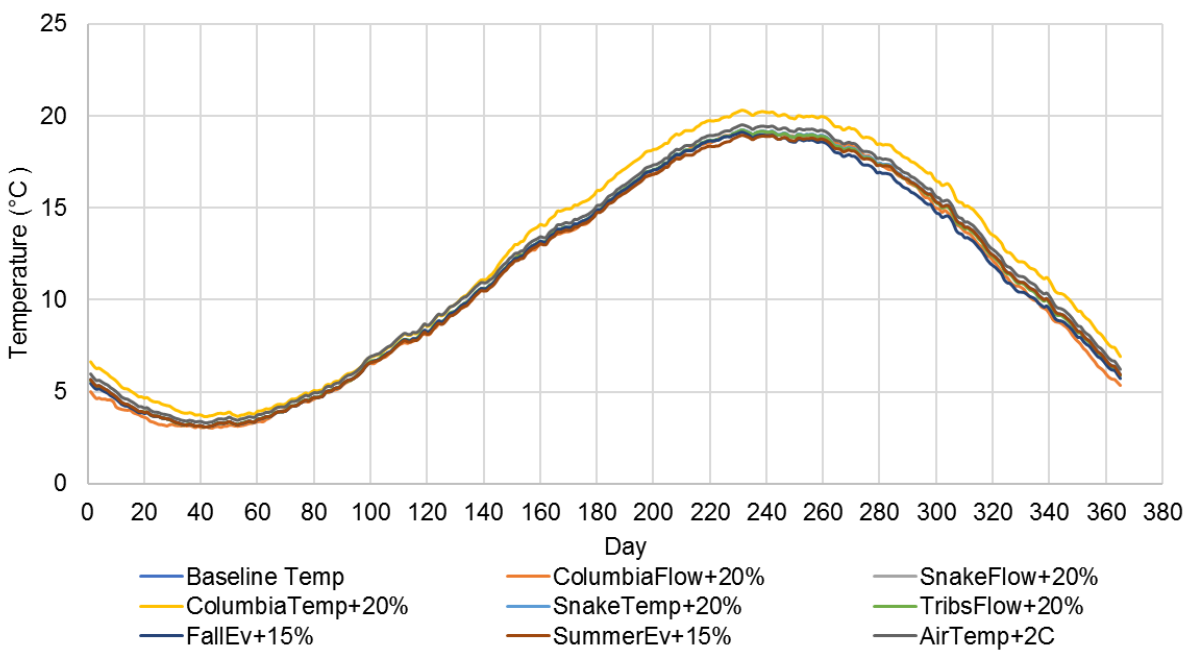

Figure F.1-7 Sensitivity of 10-year daily average temperatures at RRDW

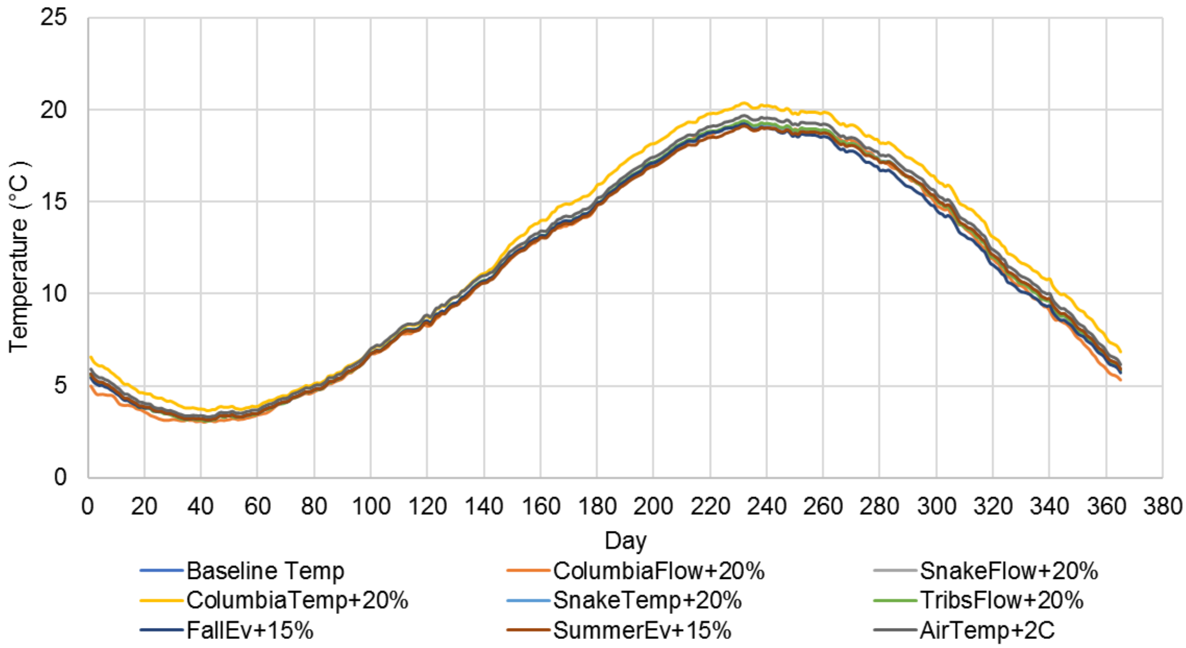

Figure F.1-8 Sensitivity of 10-year daily average temperatures at RIGW

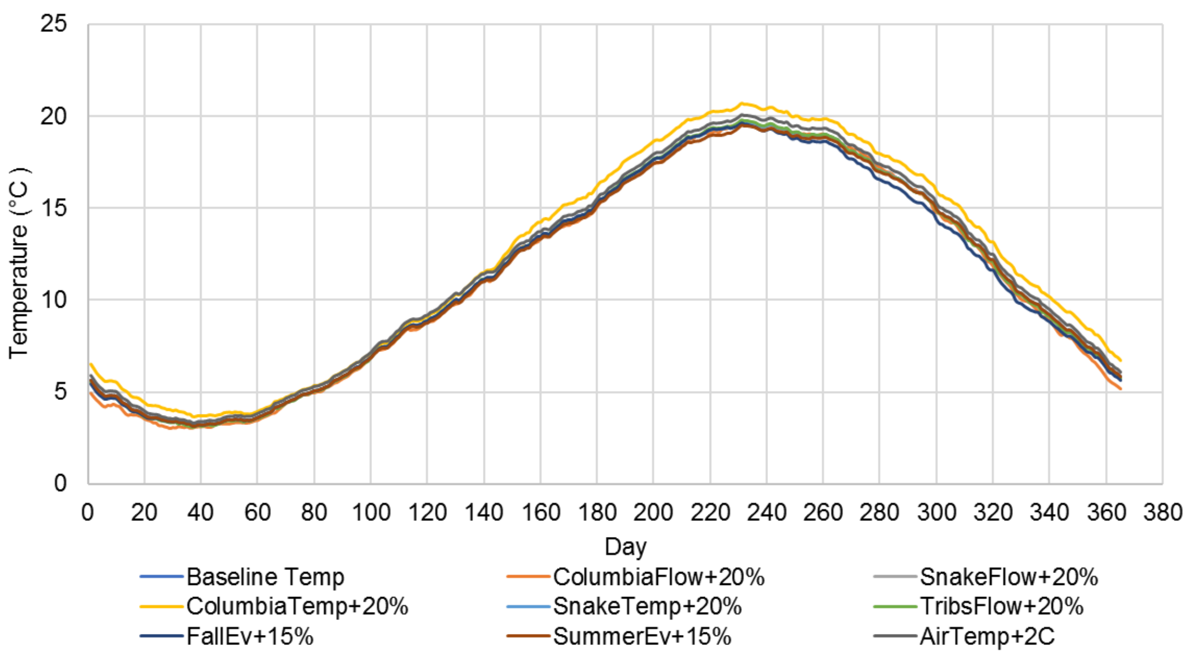

Figure F.1-9 Sensitivity of 10-year daily average temperatures at WANW

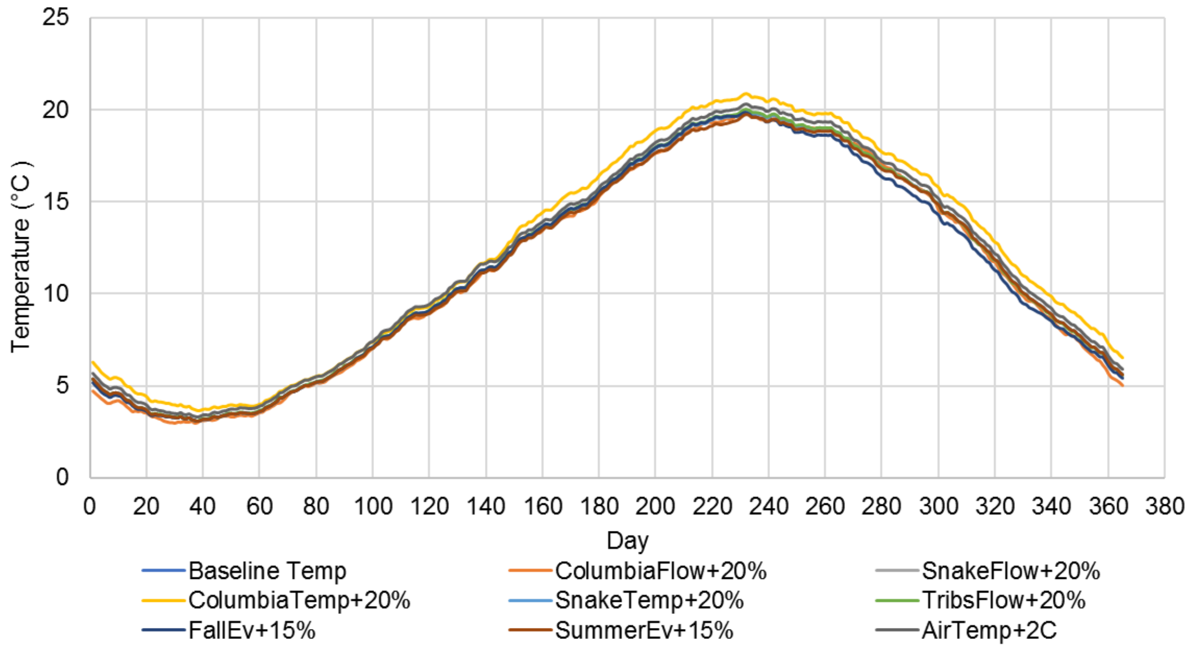

Figure F.1-10 Sensitivity of 10-year daily average temperatures at PRXW

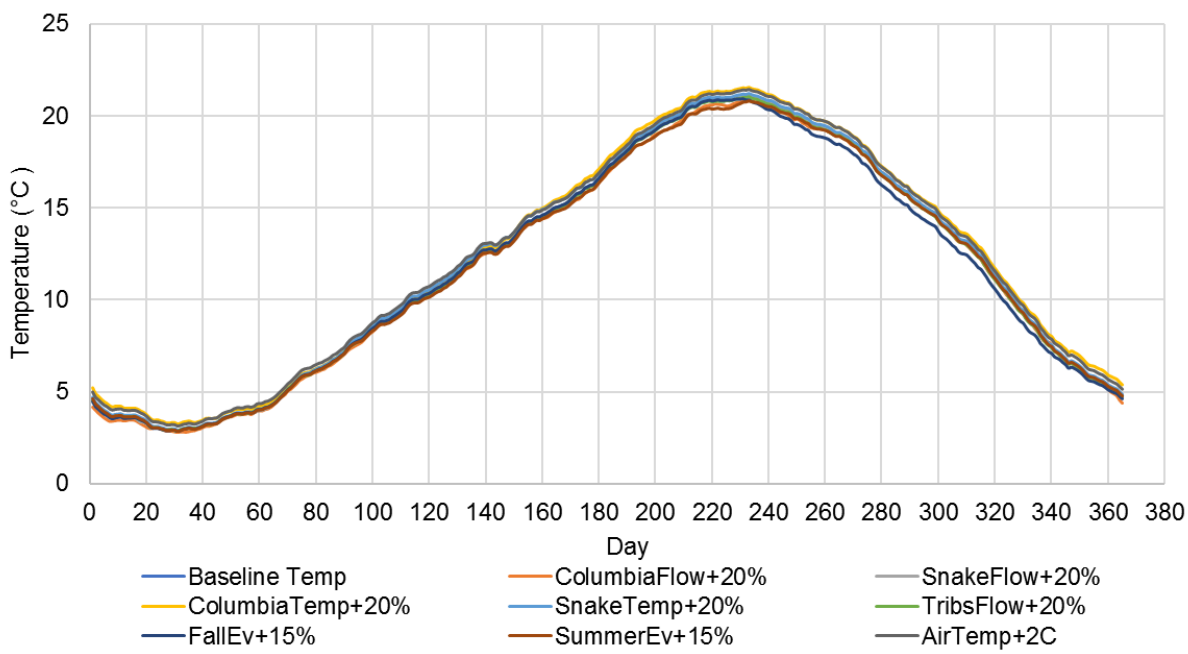

Figure F.1-11 Sensitivity of 10-year daily average temperatures at MCPW

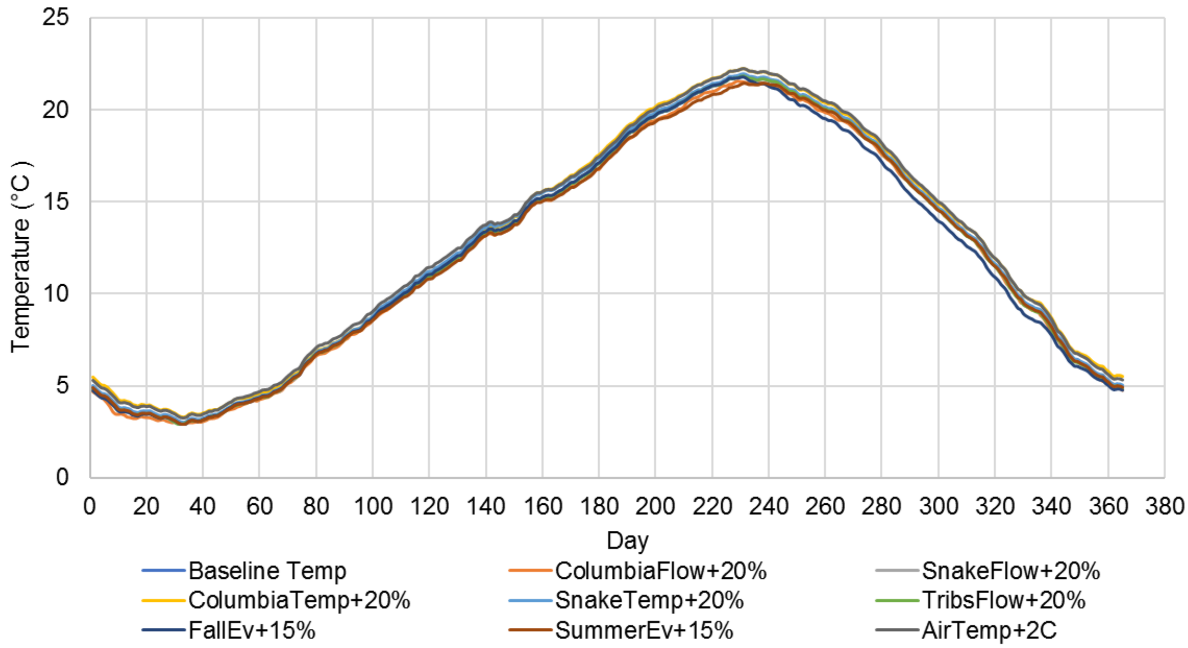

Figure F.1-12 Sensitivity of 10-year daily average temperatures at JHAW

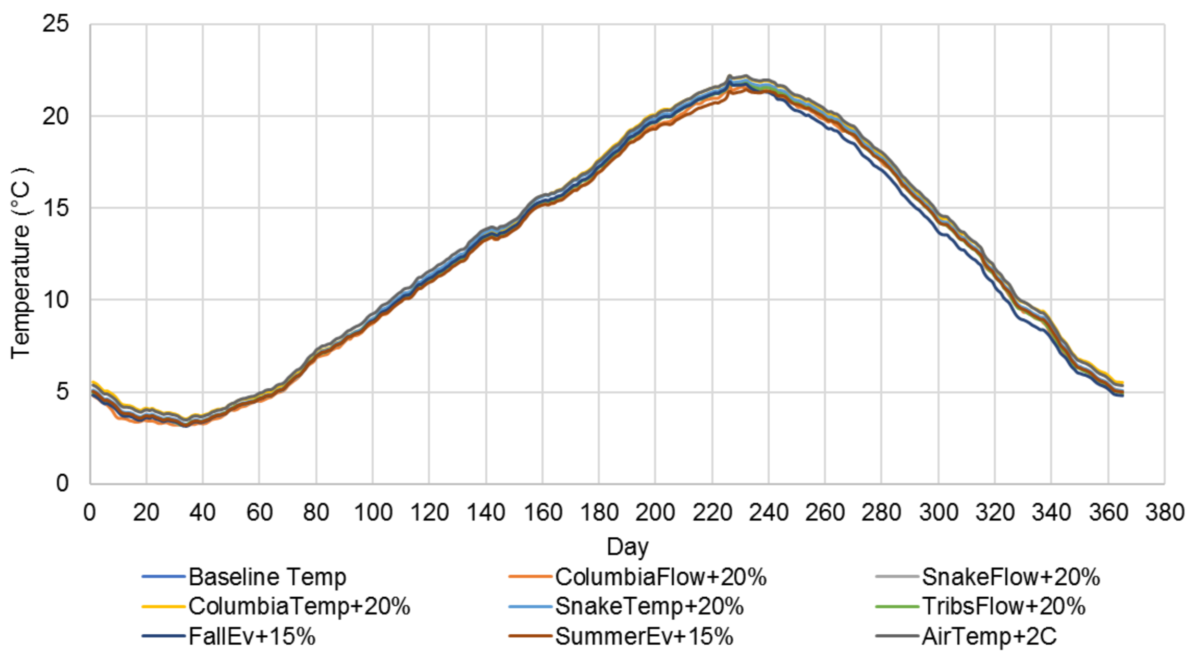

Figure F.1-13 Sensitivity of 10-year daily average temperatures at TDDO

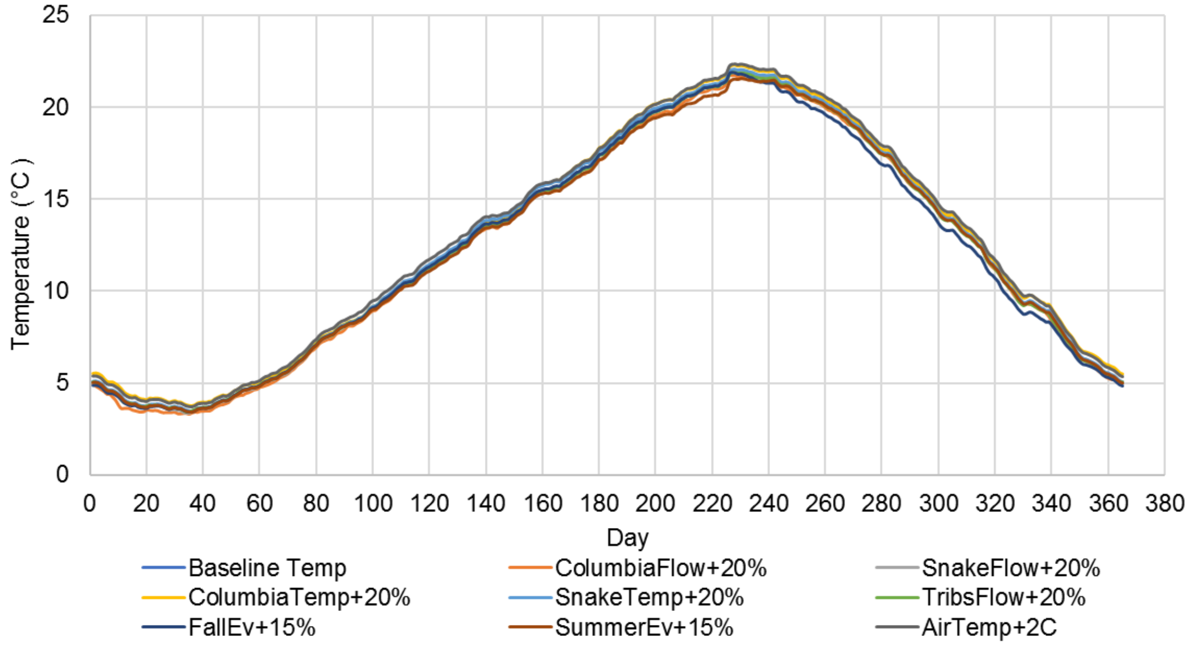

Figure F.1-14 Sensitivity of 10-year daily average temperatures at BON

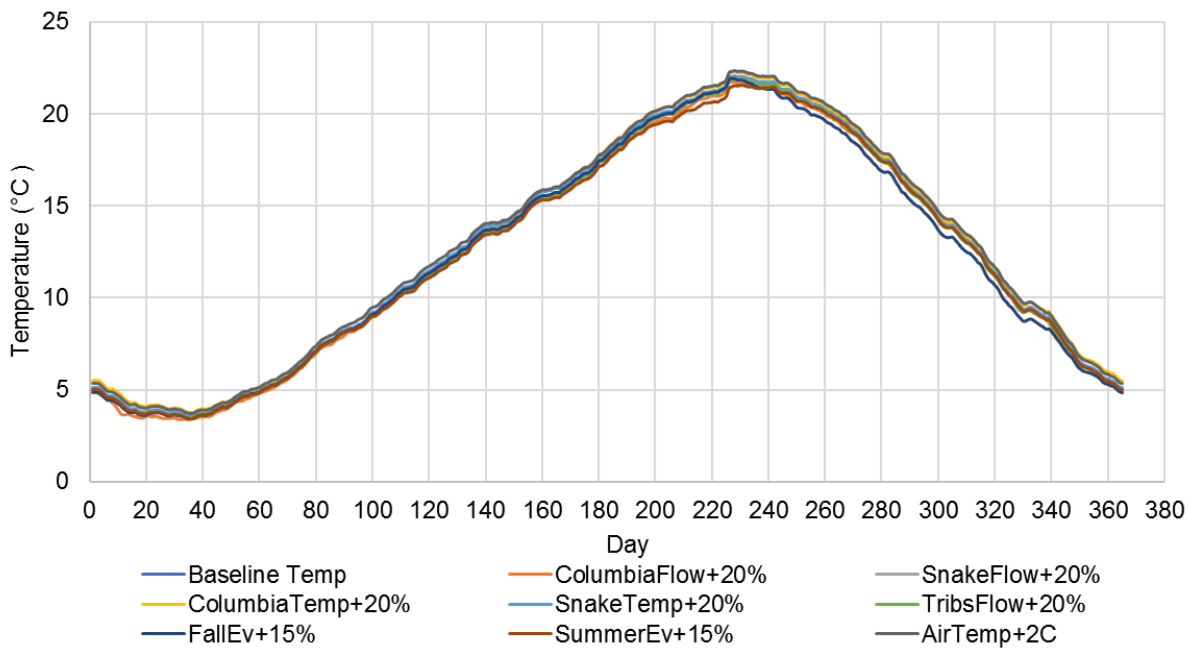

Figure F.1-15 Sensitivity of 10-year daily average temperatures at WRNO

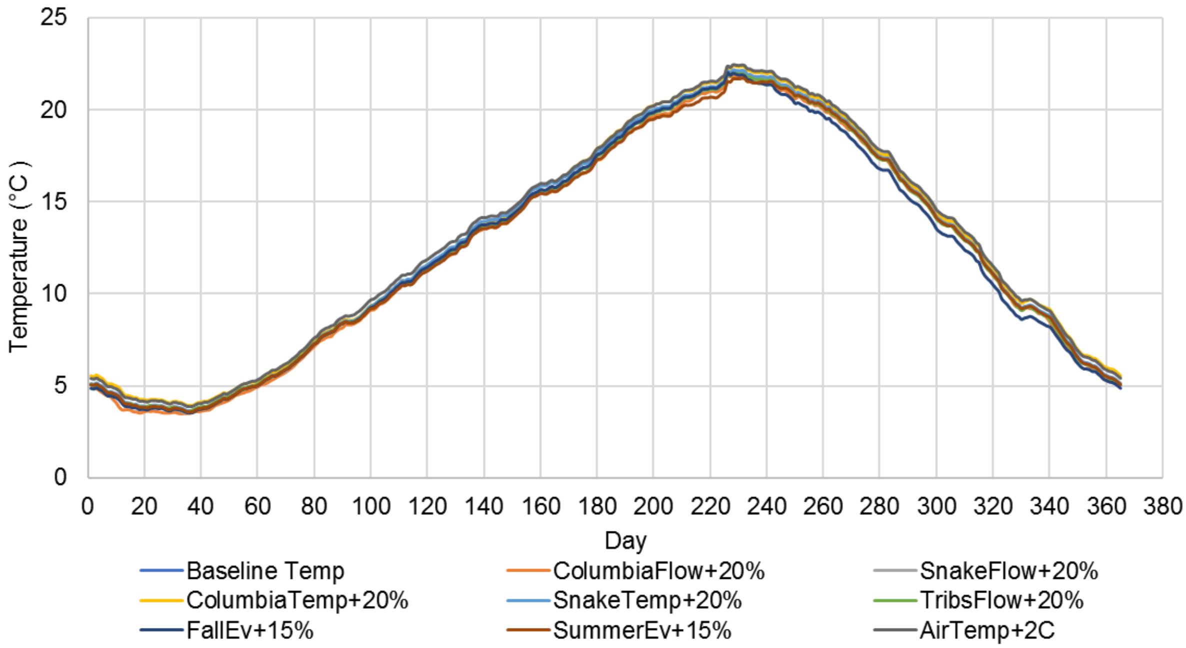

Figure F.1-16 Sensitivity of 10-year daily average temperatures at CMWN

F.2 Snake River Sensitivity Analysis Results

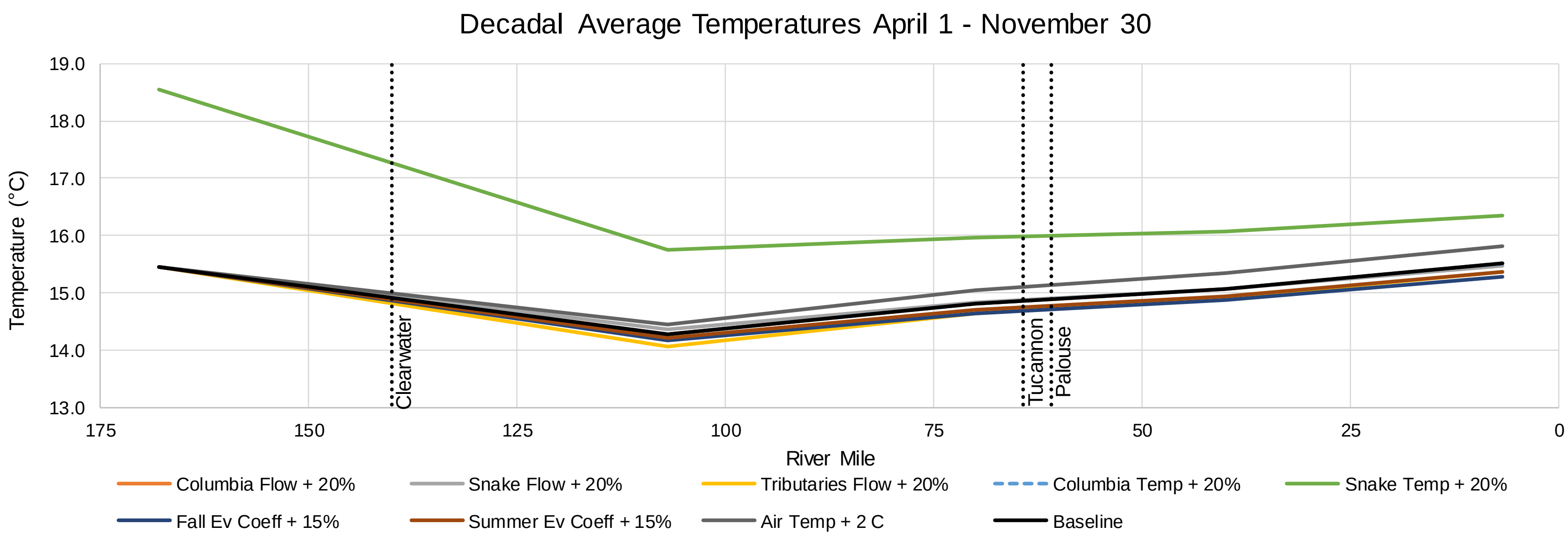

Figure F.2-1 Longitudinal changes in 10-year (April - November) average Snake River water temperatures for each scenario evaluated

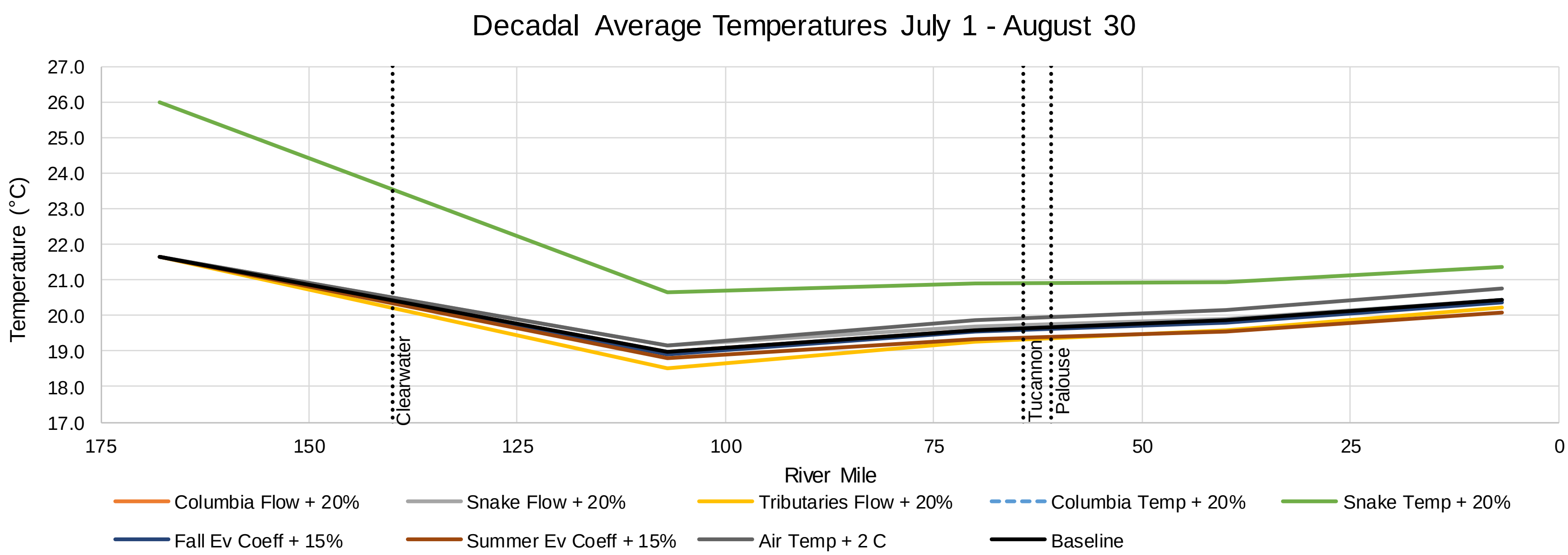

Figure F.2-2 Longitudinal changes in 10-year (July - August) average Snake River water temperatures for each scenario evaluated

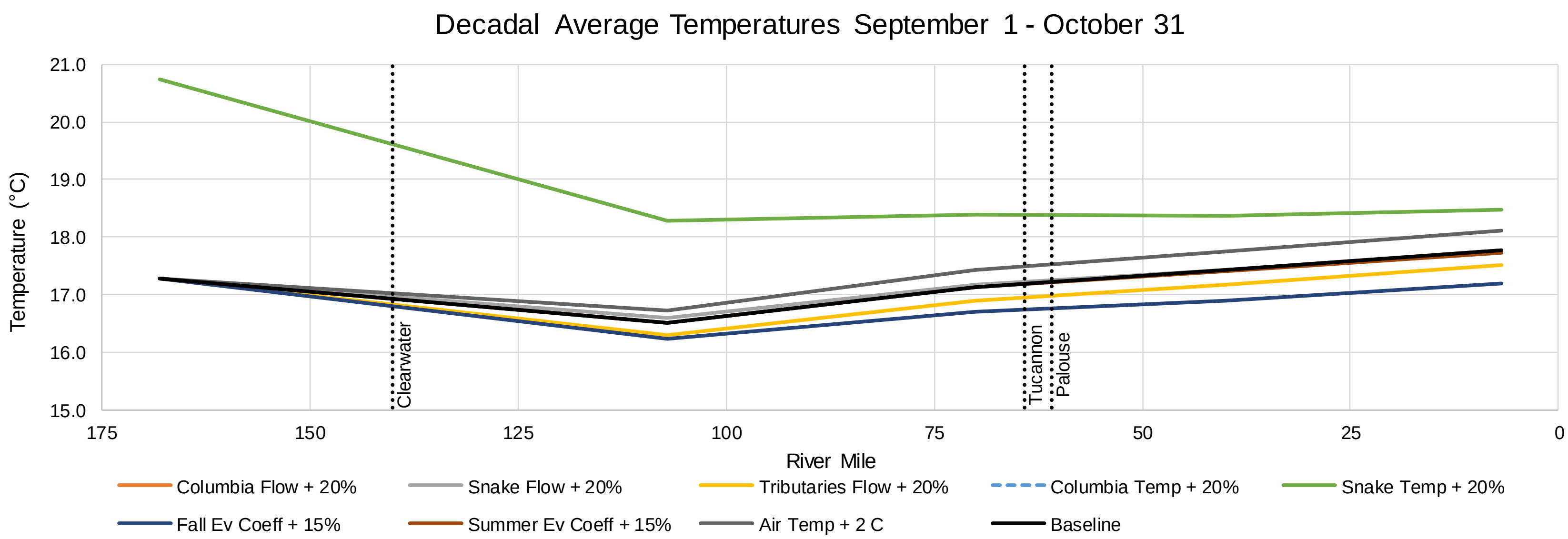

Figure F.2-3 Longitudinal changes in 10-year (September - October) average Snake River water temperatures for each scenario evaluated

Table F.2-1 Percent changes in decadal (April - November) average water temperature along the Snake River under different sensitivity scenarios

Station ID*	Baseline Temp. (°C)	Mean Change in Temperature from Baseline (%) (April 1 - November 30)							
		Columbia Flow + 20%	Snake Flow + 20%	Tributaries Flow + 20%	Columbia Temp + 20%	Snake Temp + 20%	Fall Ev Coeff + 15%	Summer Ev Coeff + 15%	Air Temp + 2 C
IDSW	15.5	0.0	-0.3	-0.9	0.0	5.4	-1.5	-1.0	1.9
LMNW	15.1	0.0	-0.1	-1.1	0.0	6.5	-1.3	-0.9	1.8
LGSW	14.8	0.0	0.1	-1.2	0.0	7.9	-1.1	-0.7	1.6
LGNW	14.3	0.0	0.6	-1.4	0.0	10.4	-0.8	-0.5	1.2

* Station location shown in Figure 3-1

Table F.2-2 Percent changes in decadal (April - November) minimum, maximum and average water temperature along the Snake River under different sensitivity scenarios

Station ID*	Baseline Temp. (°C)			Change in Temperature from Baseline (%) (April 1 - November 30)																							
				Columbia Flow + 20%			Snake Flow + 20%			Tributaries Flow + 20%			Columbia Temp + 20%			Snake Temp + 20%			Fall Ev Coeff + 15%			Summer Ev Coeff + 15%			Air Temp + 2 C		
	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
IDSW	15.5	6.7	23.0	0.0	0.0	0.0	-0.3	-5.0	0.0	-0.9	0.2	-0.6	0.0	0.0	0.0	5.4	4.7	3.0	-1.5	-2.7	0.0	-1.0	-0.8	-2.4	1.9	1.9	1.6
LMNW	15.1	6.3	22.2	0.0	0.0	0.0	-0.1	-2.8	-0.7	-1.1	-0.4	-1.0	0.0	0.0	0.0	6.5	5.7	3.9	-1.3	-4.1	0.0	-0.9	0.0	-1.7	1.8	0.7	1.5
LGSW	14.8	6.0	21.7	0.0	0.0	0.0	0.1	-0.1	0.2	-1.2	-0.7	-1.3	0.0	0.0	0.0	7.9	11.9	5.6	-1.1	-4.7	0.0	-0.7	0.0	-0.5	1.6	5.8	1.3
LGNW	14.3	4.3	22.1	0.0	0.0	0.0	0.6	7.9	0.8	-1.4	2.1	-2.1	0.0	0.0	0.0	10.4	18.2	7.4	-0.8	-5.1	0.0	-0.5	0.0	-1.6	1.2	5.6	1.1

* Station location shown in Figure 3-1

Table F.2-3 Percent changes in decadal (July - August) average water temperature along the Snake River under different sensitivity scenarios

Station ID*	Baseline Temp. (°C)	Change in Temperature from Baseline (%) (July 1 - August 31)							
		Columbia Flow + 20%	Snake Flow + 20%	Tributaries Flow + 20%	Columbia Temp + 20%	Snake Temp + 20%	Fall Ev Coeff + 15%	Summer Ev Coeff + 15%	Air Temp + 2 C
IDSW	20.4	0.0	0.0	-1.1	0.0	4.5	-0.3	-1.7	1.5
LMNW	19.9	0.0	0.2	-1.4	0.0	5.5	-0.3	-1.6	1.4
LGSW	19.6	0.0	0.4	-1.8	0.0	6.6	-0.3	-1.3	1.3
LGNW	19.0	0.0	1.0	-2.4	0.0	9.0	-0.2	-0.8	0.9

* Station location shown in Figure 3-1

Table F.2-4 Percent changes in decadal (July - August) average water temperature along the Snake River under different sensitivity scenarios

Station ID*	Baseline Temp. (°C)			Change in Temperature from Baseline (%) (July 1 - August 31)																							
				Columbia Flow + 20%			Snake Flow + 20%			Tributaries Flow + 20%			Columbia Temp + 20%			Snake Temp + 20%			Fall Ev Coeff + 15%			Summer Ev Coeff + 15%			Air Temp + 2 C		
	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
IDSW	20.4	13.9	23.0	0.0	0.0	0.0	0.0	2.1	0.0	-1.1	-0.4	-0.6	0.0	0.0	0.0	4.5	10.9	3.0	-0.3	0.0	0.0	-1.7	-0.4	-2.4	1.5	1.0	1.6
LMNW	19.9	13.9	22.2	0.0	0.0	0.0	0.2	1.8	-0.7	-1.4	-0.3	-1.0	0.0	0.0	0.0	5.5	11.3	3.9	-0.3	0.0	0.0	-1.6	-0.3	-2.1	1.4	0.8	1.5
LGSW	19.6	14.1	21.7	0.0	0.0	0.0	0.4	2.1	0.0	-1.8	-0.5	-1.3	0.0	0.0	0.0	6.6	12.4	5.6	-0.3	0.0	0.0	-1.3	-0.2	-1.7	1.3	0.7	1.3
LGNW	19.0	13.9	22.1	0.0	0.0	0.0	1.0	0.8	0.8	-2.4	-0.4	-2.1	0.0	0.0	0.0	9.0	13.2	7.4	-0.2	0.0	0.0	-0.8	-0.3	-1.6	0.9	0.5	1.1

* Station location shown in Figure 3-1

Table F.2-5 Percent changes in decadal (September - October) average water temperature along the Snake River under different sensitivity scenarios

Station ID*	Baseline Temp. (°C)	Mean Change in Temperature from Baseline (%) (Sept 1 - Oct 31)							
		Columbia Flow + 20%	Snake Flow + 20%	Tributaries Flow + 20%	Columbia Temp + 20%	Snake Temp + 20%	Fall Ev Coeff + 15%	Summer Ev Coeff + 15%	Air Temp + 2 C
IDSW	17.8	0.0	-0.1	-1.4	0.0	4.1	-3.2	-0.1	2.0
LMNW	17.4	0.0	0.0	-1.4	0.0	5.5	-3.0	-0.1	1.9
LGSW	17.1	0.0	0.2	-1.4	0.0	7.3	-2.6	0.0	1.7
LGNW	16.5	0.0	0.5	-1.3	0.0	10.7	-1.8	0.0	1.2

* Station location shown in Figure 3-1

Table F.2-6 Percent changes in decadal (September - October) average water temperature along the Snake River under different sensitivity scenarios

Station ID*	Baseline Temp. (°C)			Change in Temperature from Baseline (%) (Sept 1 - Oct 31)																							
				Columbia Flow + 20%			Snake Flow + 20%			Tributaries Flow + 20%			Columbia Temp + 20%			Snake Temp + 20%			Fall Ev Coeff + 15%			Summer Ev Coeff + 15%			Air Temp + 2 C		
	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
IDSW	17.8	13.2	22.4	0.0	0.0	0.0	-0.1	-6.1	-0.4	-1.4	-0.5	-2.2	0.0	0.0	0.0	4.1	5.3	2.6	-3.2	-5.4	-1.6	-0.1	0.0	-0.9	2.0	3.0	1.5
LMNW	17.4	11.9	21.9	0.0	0.0	0.0	0.0	-1.7	0.0	-1.4	-1.0	-1.8	0.0	0.0	0.0	5.5	8.7	3.6	-3.0	-5.0	-1.7	-0.1	0.0	-0.4	1.9	3.2	1.4
LGSW	17.1	11.6	21.6	0.0	0.0	0.0	0.2	-0.4	0.7	-1.4	-0.2	-1.5	0.0	0.0	0.0	7.3	8.4	5.2	-2.6	-3.5	-1.8	0.0	0.0	0.0	1.7	3.1	1.3
LGNW	16.5	10.7	20.1	0.0	0.0	0.0	0.5	1.0	1.0	-1.3	-0.4	-0.8	0.0	0.0	0.0	10.7	10.9	13.1	-1.8	-2.6	-0.9	0.0	0.0	0.0	1.2	3.0	0.5

* Station location shown in Figure 3-1

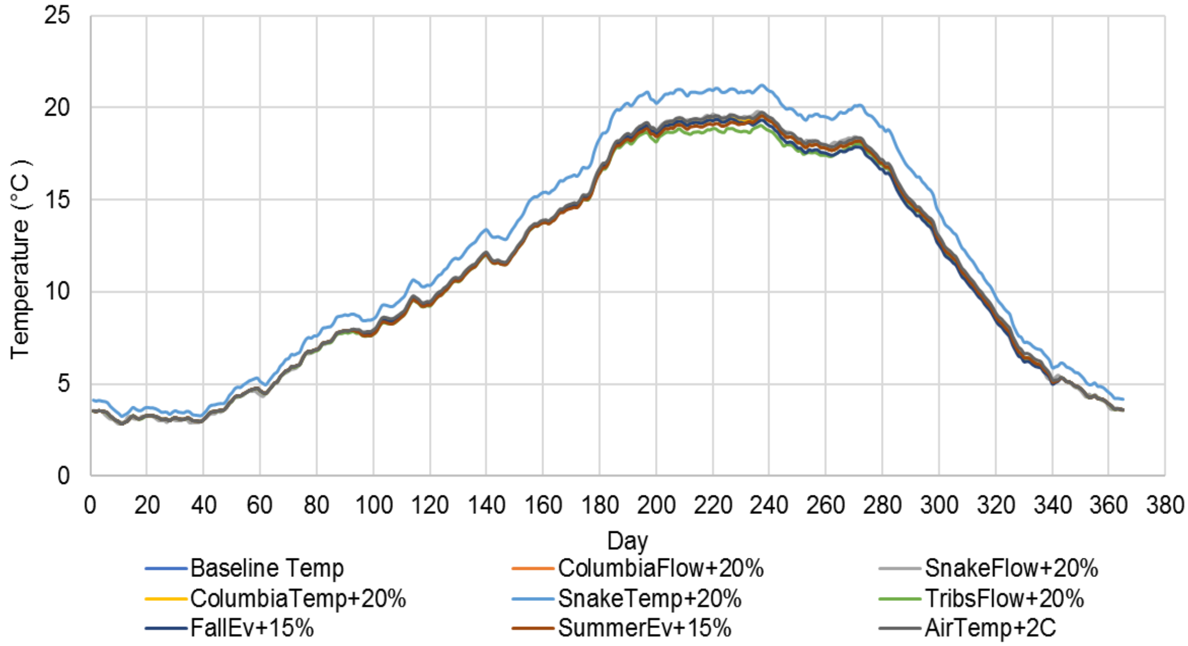

Figure F.2-4 Sensitivity of 10-year daily average temperatures at LGNW

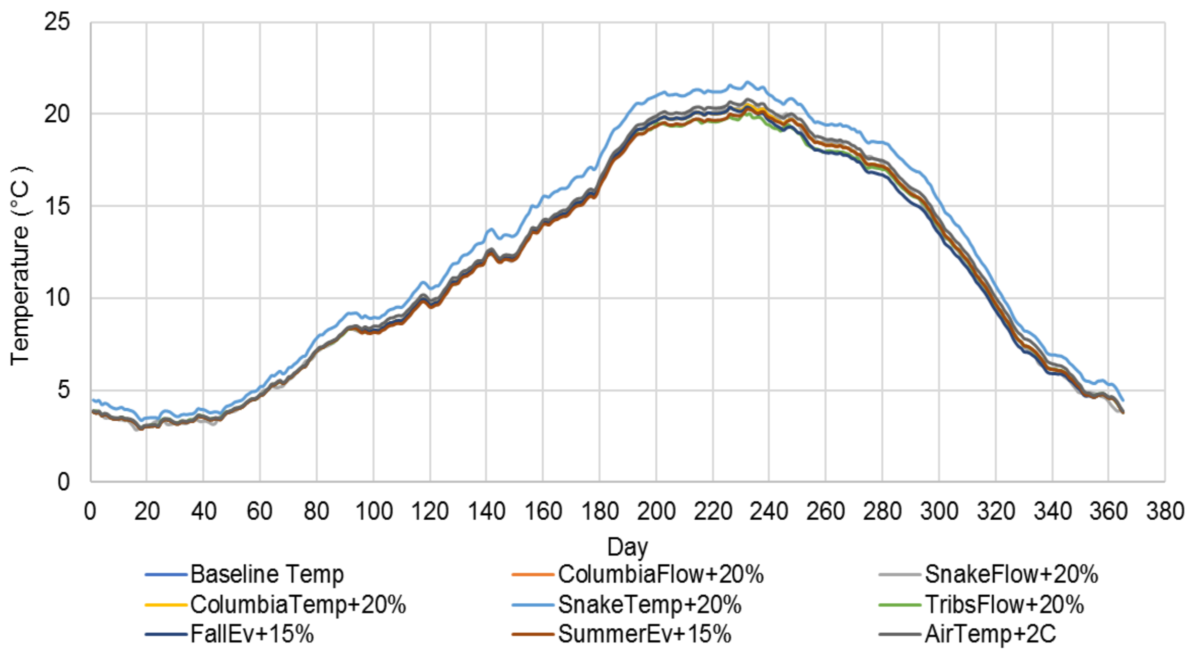

Figure F.2-5 Sensitivity of 10-year daily average temperatures at LGSW

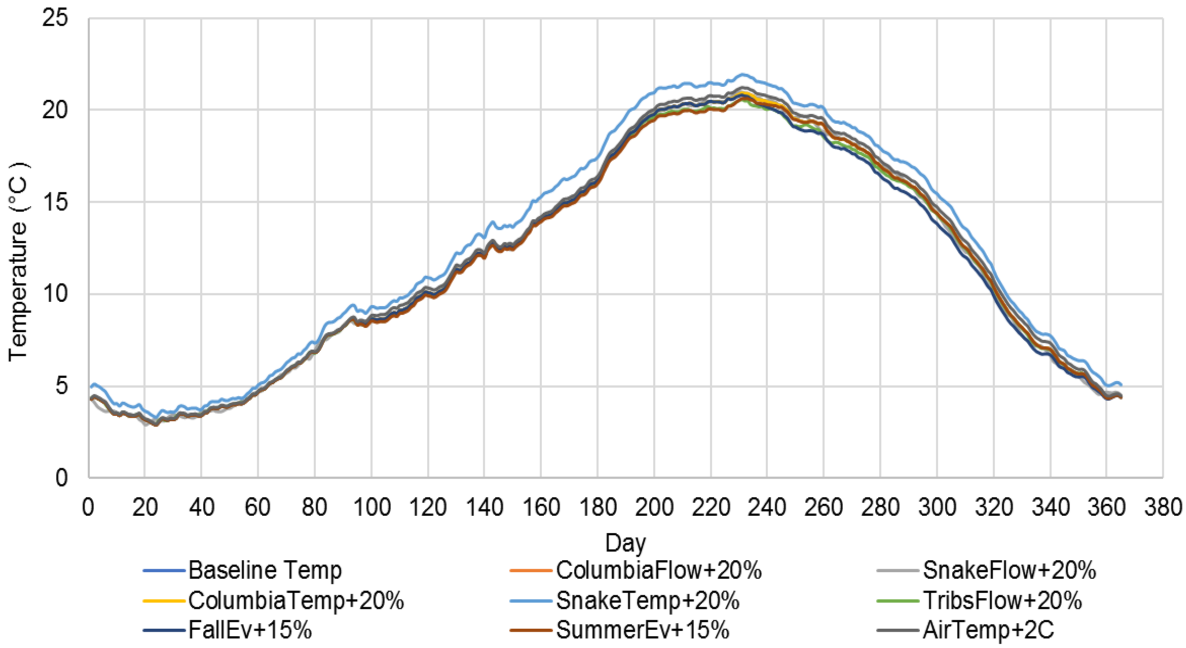

Figure F.2-6 Sensitivity of 10-year daily average temperatures at LMNW

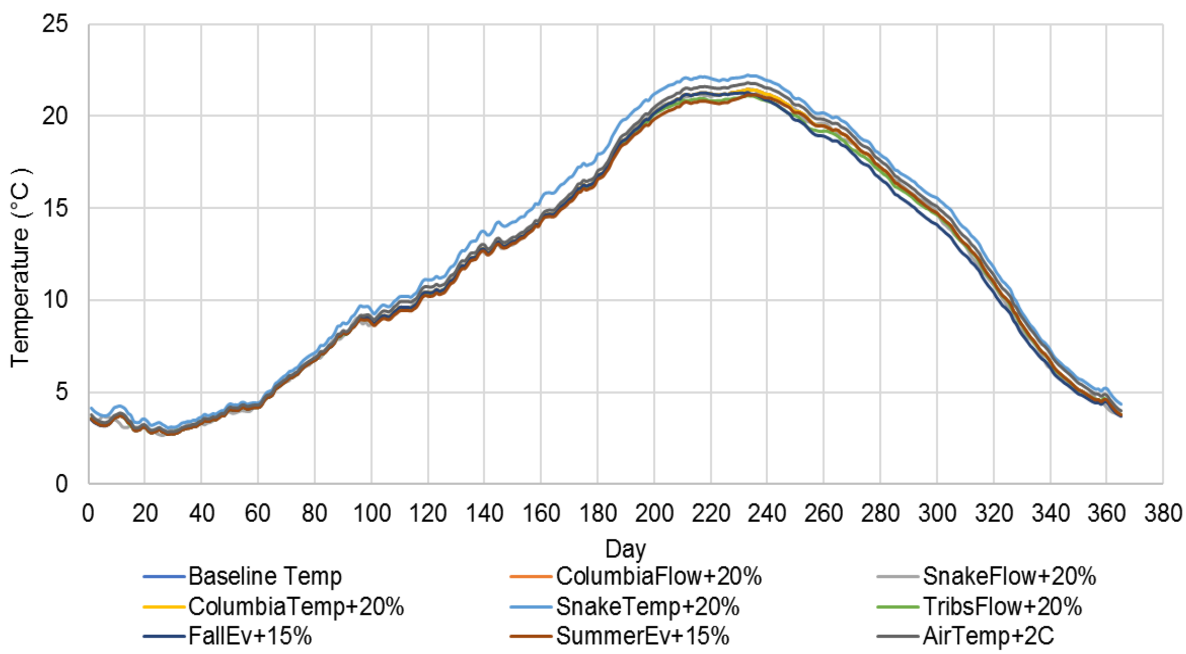

Figure F.2-7 Sensitivity of 10-year daily average temperatures at IDSW