Snake River CE-QUAL-W2 Temperature TMDL Model Development and Calibration (DRAFT)

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ACRONYMS/ABBREVIATIONS

Acronyms/Abbreviations	Definition
7DADMax	7-day Average of Daily Maxima
AgriMet	Agricultural Meteorology
AWQMS	Ambient Water Quality Monitoring System
W2	CE-QUAL-W2
ECD	Empirical Cumulative Distribution
HCC	Hells Canyon Complex
IDEQ	Idaho Department of Environmental Quality
IPC	Idaho Power Company
MetTool	Gridded Weather Data Processing Tool
NARR	North American Regional Reanalysis
NAVD88	North American Vertical Datum of 1988
NGVD 29	National Geodetic Vertical Datum of 1929
NLDAS	North American Land Data Assimilation System
NWIS	National Water Information System
ODEQ	Oregon Department of Environmental Quality
PSU	Portland State University
PRISM	Parameter Elevation Regression on Independent Slopes Model
RM	River Mile
Tt	Tetra Tech
TTools	Shade calculation software
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USGS	U.S. Geological Survey
WSDOE	Washington State Department of Ecology
WLA	Waste Load Allocation

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1.0 INTRODUCTION

On October 4, 2019, U.S. EPA was issued a final order and judgment to replace 15 Oregon temperature TMDLs that cumulatively address over 700 temperature impaired segments. The TMDLs must be replaced over an eight-year period with most of the technical work completed in the first two years starting January 2020 through December 2021. Oregon Department of Environmental Quality (ODEQ) is generally leading the effort to develop replacement TMDLs with contract and staff support from EPA but has asked EPA to be the technical lead for the TMDL for the Snake River - Hells Canyon segments, which contain portions of the Snake River located on the Oregon/Idaho border. To meet the court-mandated schedule, the approach to complete these TMDLs relies on previously completed technical work as much as possible with a streamlined development process.

The previous iteration of the Snake River – Hells Canyon temperature TMDL (ODEQ and IDEQ, 2004) incorporated a CE-QUAL-W2 (“W2”) model for temperature within the Hells Canyon Complex (HCC) hydropower reservoirs operated by Idaho Power Company (IPC). Subsequently, IPC funded Portland State University (PSU) to update the W2 model for temperature using the period from the calendar year 2014 through 2018 (Wells, Berger, & Garstecki, 2021b). Based on these existing and pending modeling capabilities, EPA anticipates that this W2 model will provide information for the revised temperature TMDL. However, the current geographic extent of the model does not align with the extent of the temperature impairments listed on the 2022 303(d) list. The listed segments of the Snake River extend both upstream and downstream of the Hells Canyon reservoir complex to include free-flowing segments of the river from the Idaho border near Adrian, OR (River Mile (RM) 409) to the state line between Oregon, Idaho, and Washington (RM 176) (Figure 1). The 2004 Snake River – Hells Canyon TMDL ended upstream of the Washington-Oregon border just above the confluence with the Salmon River (RM 188). Additionally, EPA used the RBM10 model as the basis for its 2020 temperature TMDL for the Columbia and Lower Snake Rivers, which has an upstream extent in the Snake River at its confluence with the Clearwater River near the state line between Idaho and Washington (RM 139). RBM10 extends upstream from this TMDL boundary to the monitoring station at Anatone, Washington (RM168). This is also the upstream boundary of a U.S. Army Corp of Engineers (USACE) W2 model for the Lower Snake River. For this project, the existing IPC model must be extended so the revised Snake River-Hells Canyon TMDL will cover the impaired segments from RM 409 to RM 176. EPA and ODEQ decided to extend the model farther downstream to RM 139 to overlap with the EPA and USACE models and bridge the gap to the upper extent of the 2020 Lower Snake TMDL. Since the Snake River – Hells Canyon TMDL project area as well as the gap between it and the Lower Snake TMDL is part of the contributing source area to the Lower Snake, extending the model downstream to RM 139 is anticipated to aid EPA and the states in future analyses and implementation of temperature reduction measures.

In summary, PSU has developed W2 models for Hells Canyon Complex (“HCC”; Brownlee, Oxbow, and Hells Canyon reservoirs) to simulate the vertical and horizontal profiles of water temperature of HCC reservoirs and their outflows from 2014-2018 (Wells, Berger, & Garstecki, 2021b). Tetra Tech developed W2 models for the extent of the Snake River and Hells Canyon Reservoir complex which includes free-flowing segments of the river from the Oregon\Idaho border near Adrian, or near river mile 399 to the state line between Oregon, Idaho and

Washington and river mile 176. The model also includes the Snake River downstream of Oregon in Idaho and Washington to river mile 139.

The purpose of this report is to document the development and calibration of the W2 model for simulating water temperature for the Snake River near Adrian (RM 399) to the head of Brownlee Reservoir and from Hells Canyon Dam (RM 247) to Clearwater River (RM 139) for 2014-2018 to support the development of the Snake River-Hells Canyon temperature TMDL. W2 models are linked to PSU HCC models and model development and calibration followed procedures described in the Model QAPP (Tetra Tech, 2022).

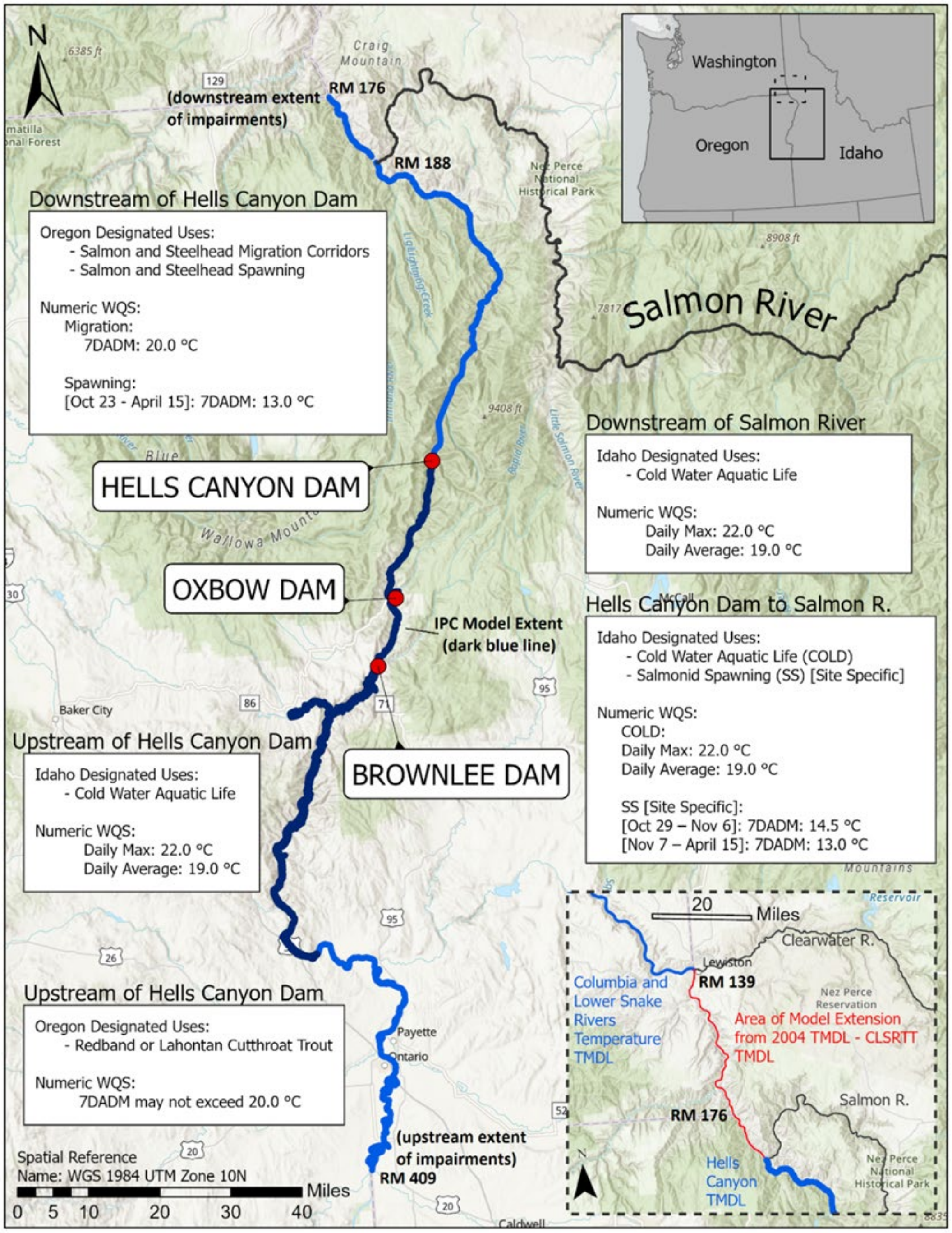


Figure 1. Snake River - Hells Canyon TMDL Extent and Model Extent.

2.0 MODEL DEVELOPMENT

2.1 CE-QUAL-W2 MODEL

CE-QUAL-W2 is a two-dimensional (vertical and horizontal) hydrodynamic and water quality model for rivers, lakes, reservoirs, and estuaries (Wells S. A., 2021a). The model is capable of simulating water balance, velocities, temperature, and a number of water quality constituents such as dissolved oxygen, total dissolved and suspended solids, and nutrients. W2 is widely used to simulate temperature and water quality of waterbodies around the world (Shabani, Zhang, & Ell, 2017; Noori, Berndtsson, Franklin Adamowski, & Rabiee Abyaneh, 2018; Lindenschmidt, Carr, Sadeghian, & Morales-Marin, 2019). The model in the past was applied to simulate water temperature of several water bodies in Oregon including the Willamette River and multiple tributaries of the Willamette River (Annear, McKillip, Khan, Berger, & Wells, 2004; Berger, McKillip, Annear, Khan, & Wells, 2004; Sullivan & Rounds, 2004; Stratton Garvin, Rounds, & Buccola, 2022) Middle Fork Willamette and South Santiam River (Buccola N. S., Stonewall, Sullivan, Kim, & Rounds, 2013), Crystal Spring Lake (Buccola & Stonewall, 2016), and the Hells Canyon Complex (Wells, Berger, & Garstecki, 2021b). CE-QUAL-W2 version 4.5 was applied in this study and the model includes updated modules for atmospheric deposition, sediment diagenesis, and nutrients simulation (Wells S. A., 2021a).

2.2 STUDY AREA

The study area is free flowing reaches of Snake River from near Adrian (RM 399) to the Clearwater River (RM 139). The river near Adrian to the head of the Brownlee Dam (RM 345) is 90 km long with a mean slope of slightly more than 0.044 percent (Figure 2a and Figure 3). The river meanders through an agricultural valley before entering Hells Canyon. Five major tributaries (Owyhee River, Boise River, Malheur River, Payette River, and Weiser River) flow into the Snake River mainstream in this section of the model (Figure 3).The river channel in this area is wide (> 100 m) and has a narrow riparian zone covered by vegetation (trees and bushes) and farmlands.

The Hells Canyon Complex is a series of three dams owned and operated by the Idaho Power Company (IPC). Brownlee Dam is the highest dam and operates as a storage reservoir, while the Oxbow and Hells Canyon dams are head run-of-river dams that generally pass Snake River flows without substantial storage. Water balance and temperature profile of these reservoirs are simulated by PSU W2 models for the modeling period (Wells, Berger, & Garstecki, 2021b).The Snake River from Hells Canyon Dam to Clearwater River is 171 km long. Salmon River, Imnaha River, and Grande Ronde are major tributaries that flow into this section of the model. In addition, flow in the lower Snake River is controlled by dam outflow and upstream storage. Upstream of the Oregon and Washington border, the river flows through Hells Canyon and is steeper than its downstream path to Clearwater (Figure 2b and Figure 2c). Because of the length and slope of the river, the lower Snake River was divided into two W2 models, Hells Canyon Dam to the Oregon and Washington State line and OR and WA border to Clearwater River.

To better understand the W2 performance and reduce the uncertainty associated with model calibration, downstream models (from Hells Canyon to Clearwater) are first developed and calibrated using Snake River flow and temperature observations. The calibrated models are then linked to PSU's Hells Canyon models to simulate Snake River water temperature from Adrian to Clearwater.

2.3 MODEL PERIOD

The model period for Snake River temperature TMDL study spans from January 1, 2014, to December 31, 2018. This timeframe aligns with the Hells Canyon complex of models developed by PSU (Wells, Berger, & Garstecki, 2021b) enabling sharing flow and temperature boundaries between the models.

2.4 BATHYMETRY

Adequate information on channel geometry is essential to building a W2 model. Detailed geometry is already established for the Hells Canyon complex (Wells, Berger, & Garstecki, 2021b), but was needed for the free-flowing reaches where the model is being extended.

IPC provided bathymetry data for reaches upstream and downstream of the Hells Canyon complex in HEC-RAS geometry and geographical information system (GIS) shapefiles. The shapefiles are exports of the HEC-RAS geometry files and are georeferenced. The upstream cross section covers the Snake River between the head of Brownlee Reservoir and upstream of Adrian. These data were collected by Ayres Associates in June 1997 and April 1999 using a sonic depth sounder that was linked to a survey-grade, real-time kinematic geographic positioning system (GPS) data. The downstream cross sections provided by IPC cover from Hells Canyon Dam to the Washington State line and were developed using 2017 bathymetric data and topographic data from USACE LiDAR collected in 2010. Cross sections present elevation in ellipsoidal height and there was no geoid associated with these data.

For the Snake River from the Oregon-Washington State line to the confluence with the Clearwater River USACE has developed a HEC-RAS model. Tetra Tech had a copy of the USACE HEC-RAS model of the Snake River obtained in a previous project on the Columbia River system (USACE, 2020). This contains the river Thalweg line cross sections that extend from RM 178 to RM 138. The model segments and bathymetry file for the Hells Canyon complex were provided by PSU in Surfer format. These have been converted to GIS shapefiles and were used to ensure a smooth transition between the Hells Canyon complex and the extended model section.

The vertical datum for the IPC upstream cross sections was North American Vertical Datum of 1988 [NAVD88] (Geoid 3) and for the downstream cross sections (from HC to Oregon and Washington State line) the measurements were NAVD88 ellipsoid heights. The vertical datum for USACE HEC-RAS cross sections was also NAVD88 and the cross sections were not georeferenced. The vertical datums for all cross sections needed to be converted to National Geodetic Vertical Datum of 1929 [NGVD29] datum to be consistent with the existing Hells Canyon complex W2 model. To generate a computational grid for the W2 model, cross-sections were converted into a Digital Elevation Models (DEM) in HEC RAS v.6.0 RAS Mapper. For Hells Canyon dam to OR and WA State line, ellipsoidal heights were converted to orthometric heights by subtracting DEM from the geoid 3 height, downloaded from Hydromagic (hydrography survey software), in ArcMap. For the OR and WA State line to Clearwater DEM was georeferenced using an aerial imagery. Elevations in the NAVD88 datum are approximately 1 m higher than NGVD29. DEMs' vertical datums were converted to NGVD29 by subtracting the elevations. The DEM geographic horizontal projection was also converted to UTM zone 11 for measuring horizontal distances. Figure 2 shows Snake River channel DEM. Tetra Tech developed a Python program to generate bathymetry input for the W2 model. The inputs for the program are DEM in raster format (e.g., GeoTIFF) and river cross sections and model segments in shapefiles. The program uses open-source scientific computational packages such as Whitebox for advanced geospatial data analysis developed by the University of Guelph's Geomorphometry and Hydrogeomatics Research Group (Whitebox Geospatial Home - Whitebox Geospatial Inc), Numpy (https://numpy.org), Pandas (https://pandas.pydata.org), and Geopandas (https://geopandas.org) to convert DEM into a series of contour polygons at a user-specified interval. The program calculates the profile width of the river channel by either overlapping the cross-sections or segments with contour polygons. The former calculates the channel width by measuring the length of cross-sections within a contour polygon at the segment center while the latter uses area, depth, and volume relation computed from the trapezoidal (Equation 1) or prismoid methods (Equation 2) to calculate the channel width (Equation 3). Compared to cross-section method, trapezoidal and prismoid methods calculate the average width for a segment. Therefore, these methods are preferred where there is spatial variability in river channel width, or the model segments are so large that a single cross section cannot accurately represent variation of width within a segment. Prismoid method also is preferred over trapezoidal (average area) method since it results in more accurate volume estimation by assuming a mid cross section area between upper and lower layers (Equation 2). In addition to width, the bathymetry program calculates and populates essential fields such as the length and orientation (relative azimuth) of the segments for the W2 bathymetry input.

$$\text{Volume}=H\times 1/2(A1+A2) \quad (1) \quad \text{Trapezoidal method} \qquad (1)$$

$$\text{Volume}=H/3(A1+\sqrt{A1\times A2}+A2) \quad \text{Prismoid method} \qquad (2)$$

$$\text{Width}=Volume/(H\times L) \qquad (3)$$

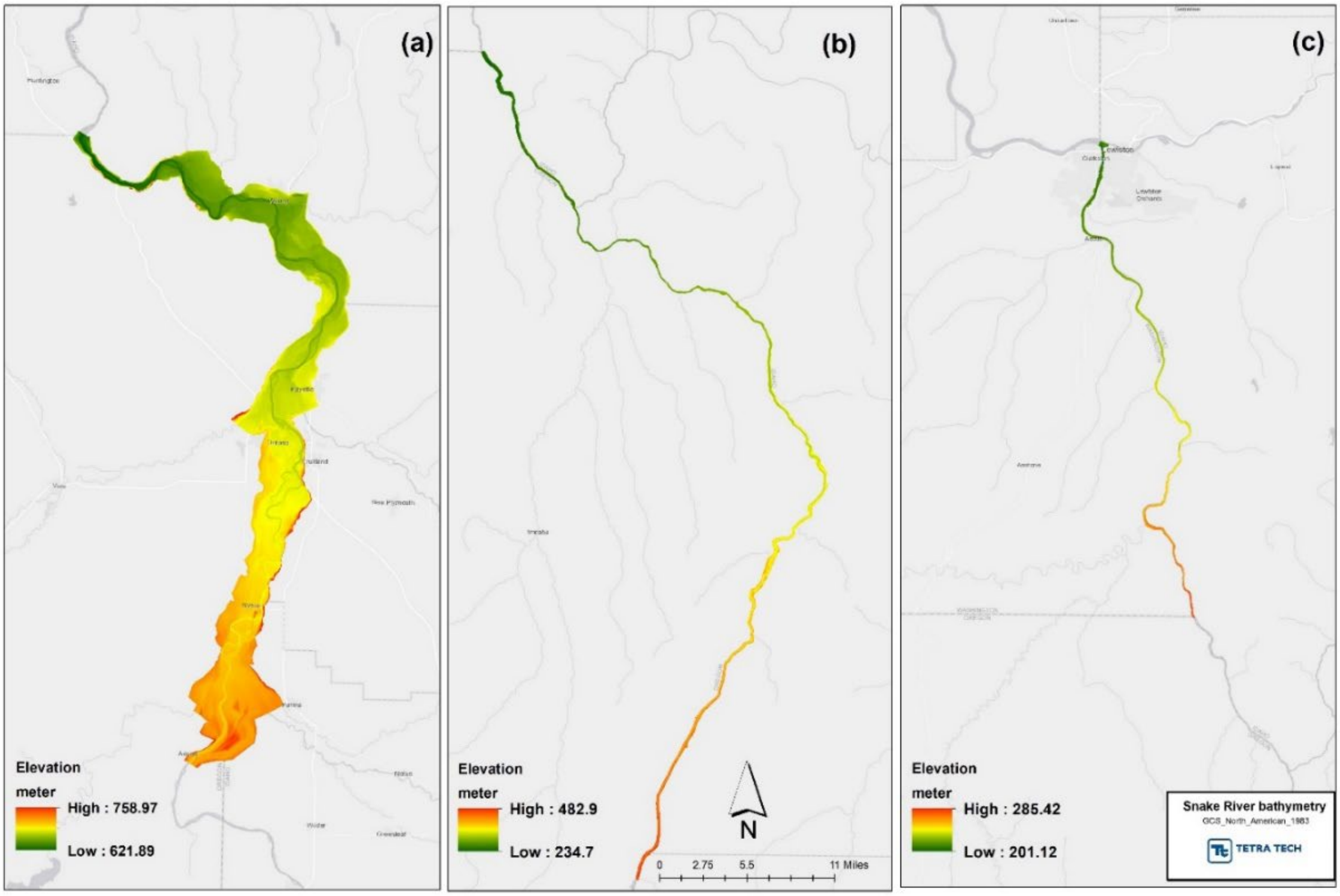


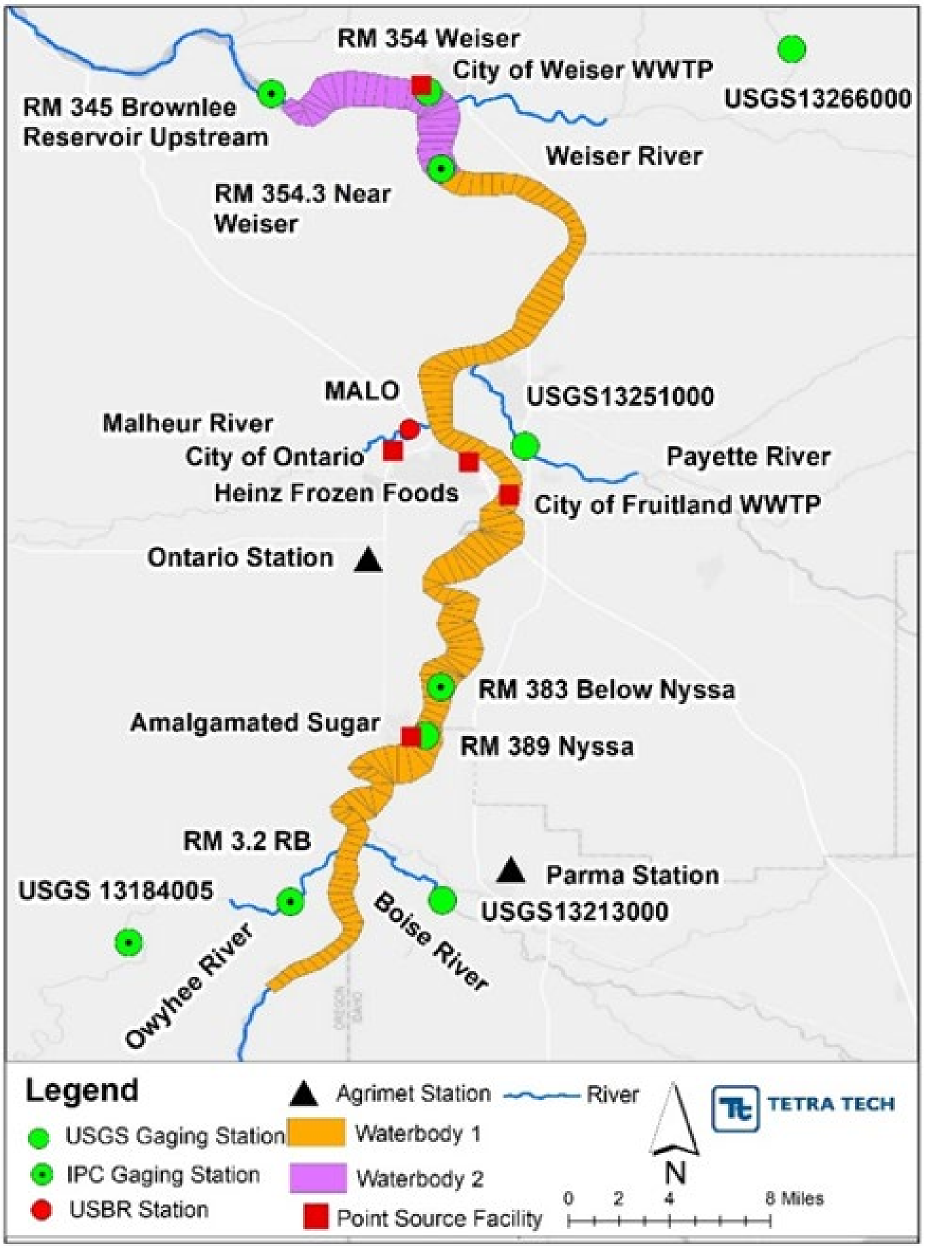
Figure 2. Snake River channel Digital Elevation Model (DEM) (a) upstream of Adrian to Head of Brownlee Reservoir, (b) Hells Canyon Dam to Oregon-Washington State line, (c) Oregon-Washington State line to Clearwater River

Note: Vertical datum for DEM is NGVD29.

2.4.1 Adrian to Brownlee

The Snake River from Adrian to Brownlee model was divided into two waterbodies for water temperature simulation to maintain stability during flow calculation (see Section 3.5). The Snake River bathymetry was represented in the W2 model using 503 m horizontal segments and 1 m vertical layers (Figure 3). The W2 model is comprised of 183 segments (including boundaries) and 11-40 active vertical layers. The large number of vertical layers in the model is because the W2 model uses one value for the maximum number of layers (KMX) for the model segments and there is 37 m elevation difference between upstream and downstream segments. The topmost layer has a fixed elevation that must encompass the water surface in all segments; thus, for any individual segment many of the vertical layers are not used.

In the model, waterbody 1 is upstream and contains segment numbers 2 to 150. Waterbody 2 is downstream and connected to waterbody 1 through segment boundaries 151 and 152. The typical W2 longitudinal and vertical resolutions are between 100-1000 m and 0.5-2 m, respectively (Wells, Berger, & Garstecki, 2021b). The generated computational grid provides sufficient details of vertical and longitudinal profiles of the river channel for the model to simulate flow and water temperature. Using the Tetra Tech W2 bathymetry program the prismoid method



was applied to process the river channel DEM and generate an input bathymetry for the model.

Figure 3. Snake River near Adrian to Brownlee.

Note: The location of USBR MALO station is approximated on the map. The orange and purple segments show CE-QUAL-W2 waterbodies 1 and 2.

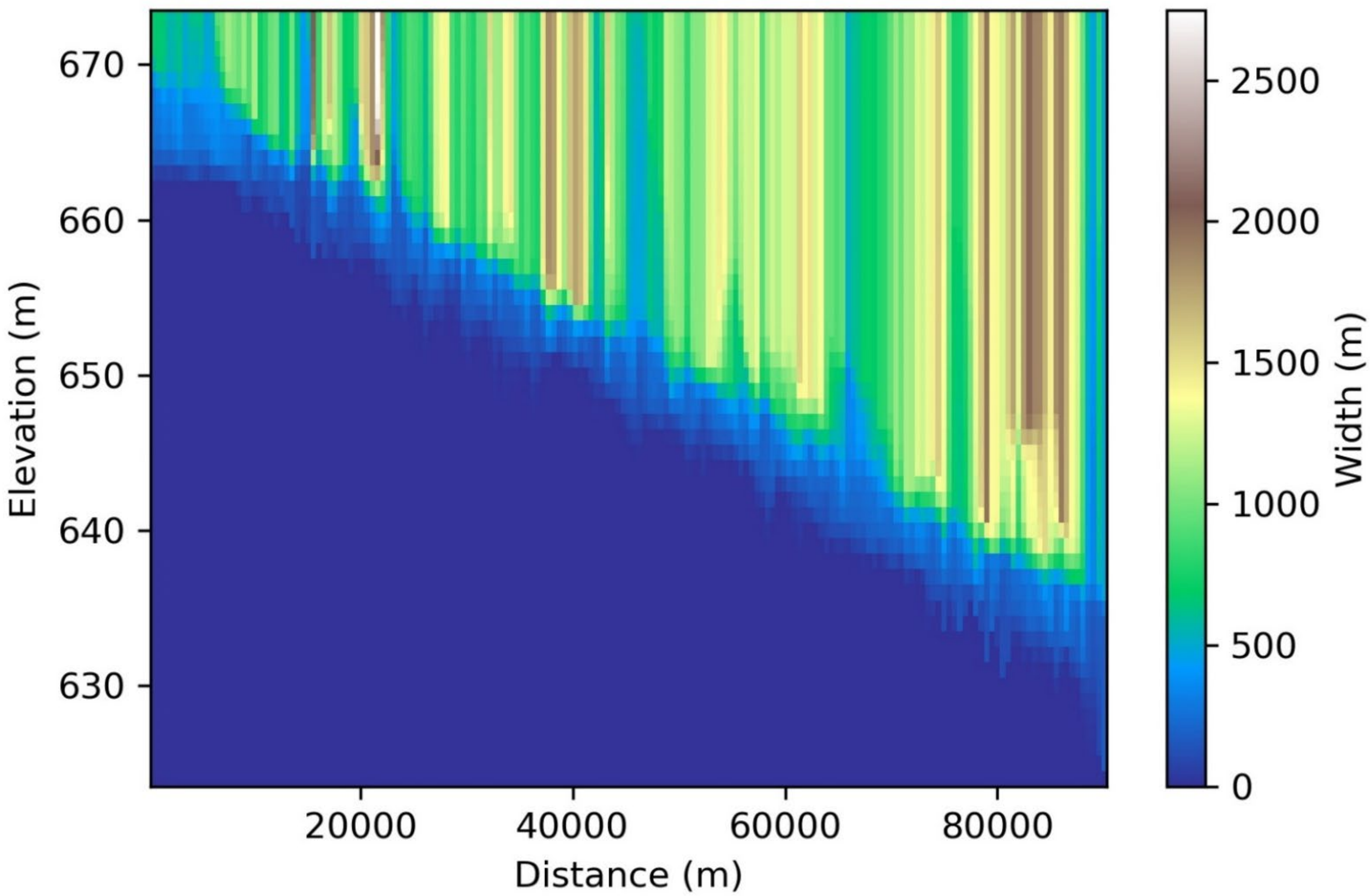


Figure 4. Side view of model segments width starting at 2 (on the left; upstream) and ending at segment 182 (on the right; downstream).

2.4.2 Hells Canyon Dam to Oregon and Washington State line

The W2 model from Hells Canyon Dam to Washington State line extends from RM 247 to RM 176. The model is composed of a single waterbody representing the river channel bathymetry (Figure 5). The W2 model is configured using 501 m horizontal segments and 1 m vertical layers (Figure 6). The model contains 235 segments (including the model boundaries) and 241 vertical layers that are varying in width. The bathymetry input for W2 was generated using the Tetra Tech bathymetry program and prismoid method. Salmon River and Imnaha River are two tributaries included in the model, and they flow into River Miles 200 and 188 (model segments 183 and 194), respectively (Figure 5).

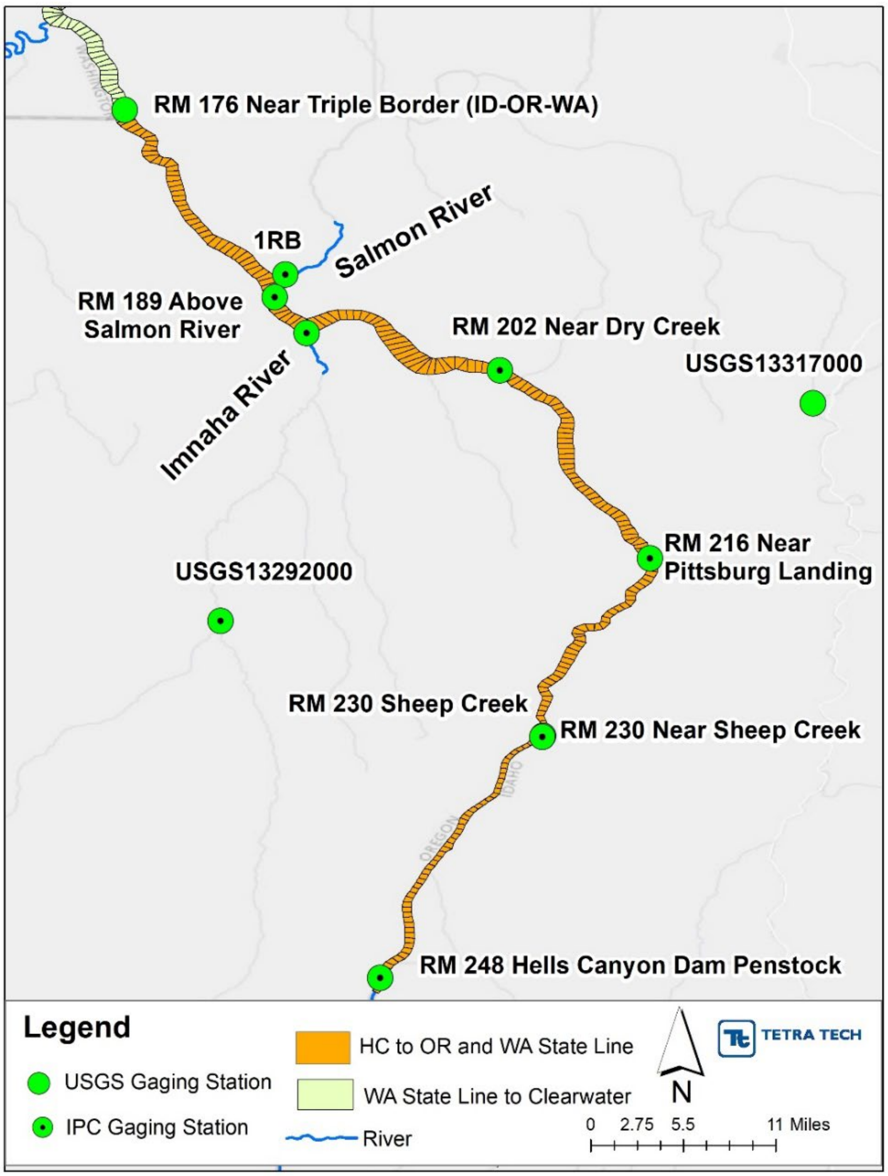


Figure 5. Snake River from Hells Canyon Dam to Oregon and Washington State line.

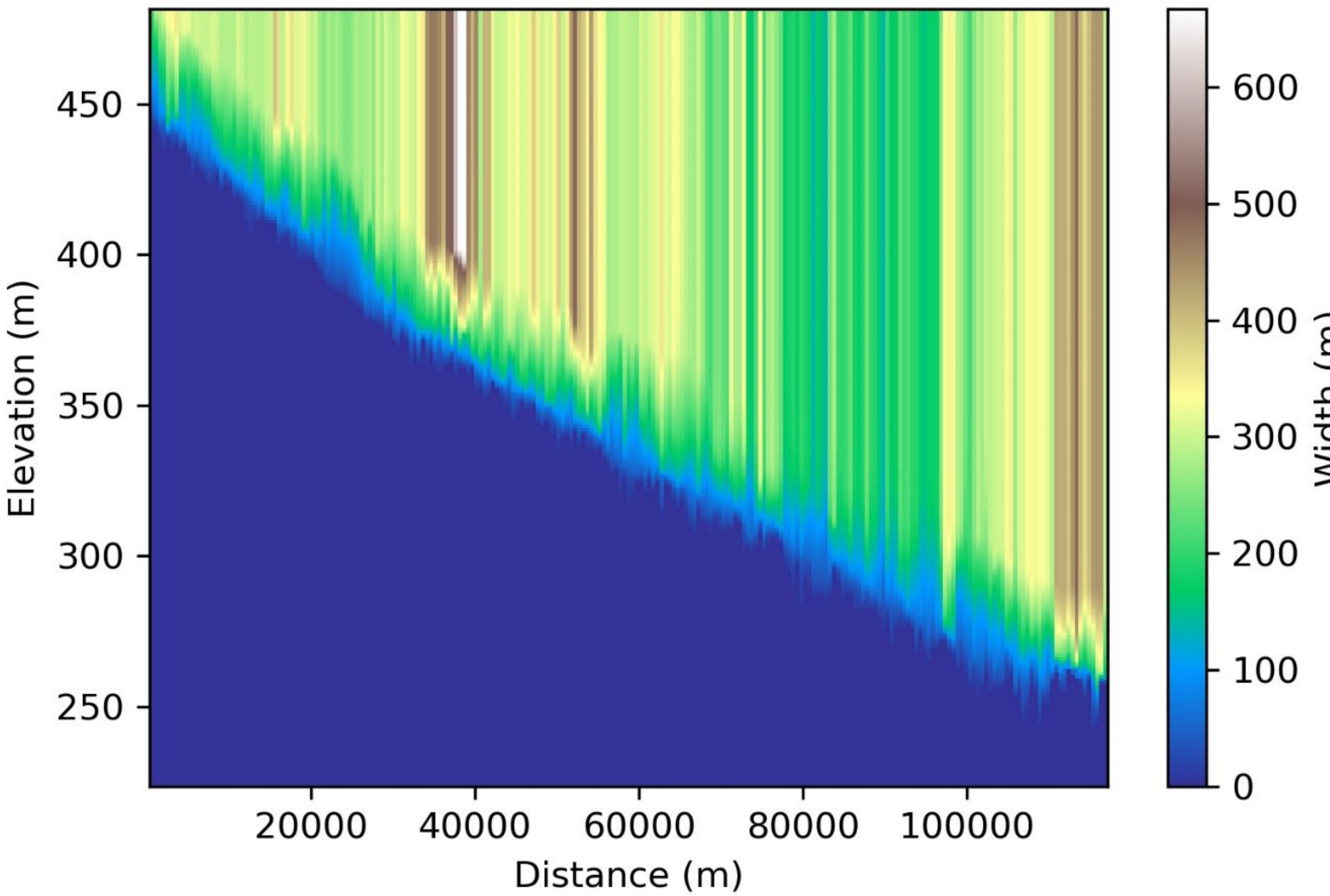


Figure 6. Side view of Hells Canyon Dam to Oregon and Washington State line W2 model segments width starting at 2 (on the left; upstream) and ending at segment 234 (on the right; downstream).

2.4.3 Oregon and Washington State line to Clearwater River

This model represents the Snake River from RM 176 to RM 139. The model is composed of a single waterbody and contains 119 segments (504 m in length) and 63 vertical layers (1m in height) (Figure 7 and Figure 8). Like upstream W2 models the channel width was calculated using the Tetra Tech bathymetry program and prismoid method. Grande Ronde and Asotin Creek are two tributaries included in the model.

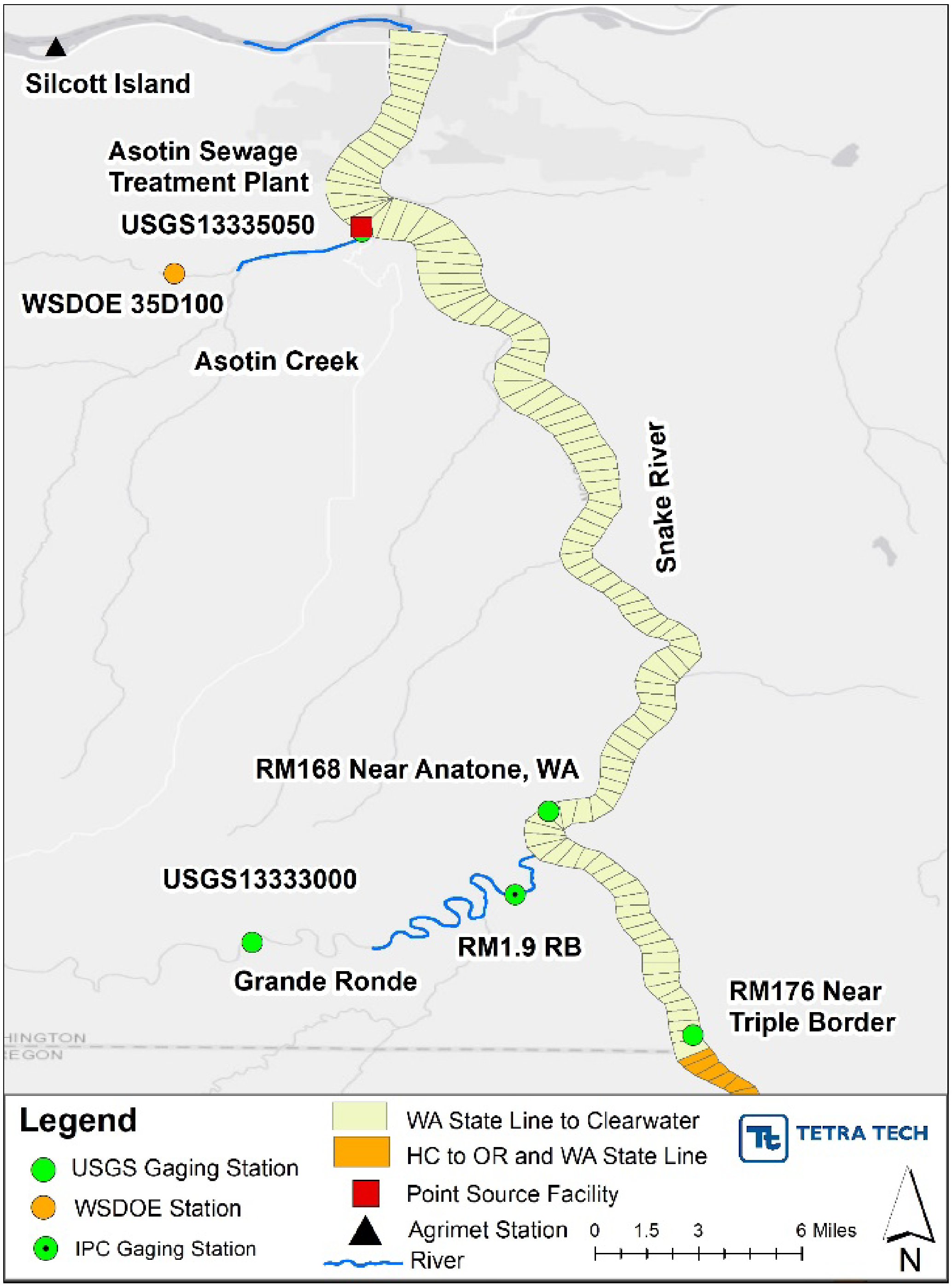


Figure 7. Snake River from Oregon and Washington state line to Clearwater River.

Note: The location of USGS 13333000 station is approximated on the map.

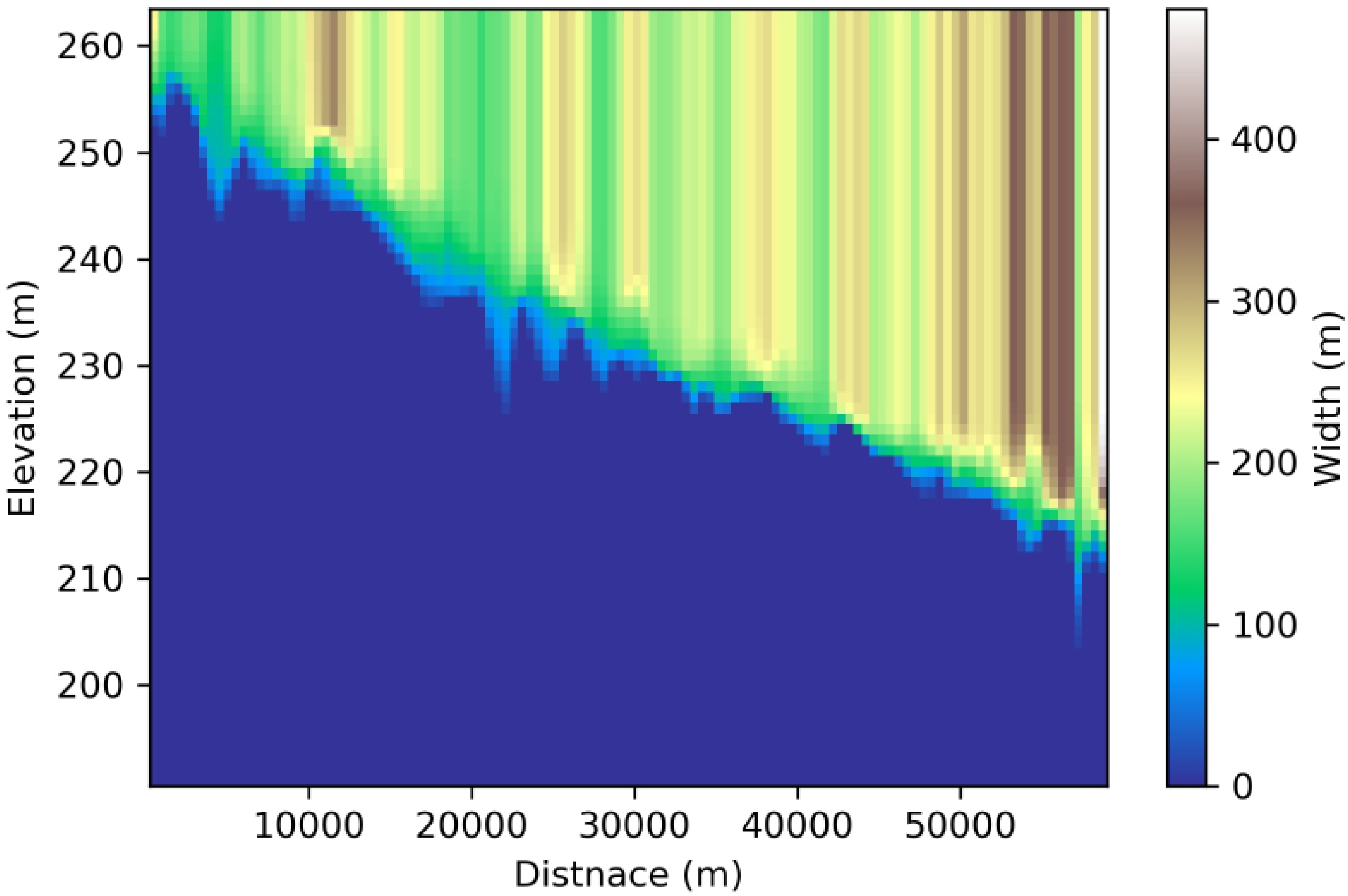


Figure 8. Side view of Oregon and Washington State line to Clearwater River W2 model segments width starting at 2 (on the left; upstream) and ending at segment 118 (on the right; downstream).

3.0 DATA SOURCES

3.1 METEOROLOGY

Meteorological data, including air temperature, dew point temperature, wind speed and direction, and cloud cover must be included in the meteorological input for the W2 Model. Where available, shortwave solar radiation can also be input directly into the model. The U.S Bureau of Reclamation (USBR) maintains a network of agricultural weather stations called AgriMet stations. These stations provide all the required meteorological inputs, including solar radiation, with exception of cloud cover for the study area. Hourly satellite-based meteorological data are also available online in gridded formats such as Parameter Elevation Regression on Independent Slopes Model (PRISM), North American Land Data Assimilation System (NLDAS), and North American Regional Reanalysis (NARR) for the study area. For instance, NLDAS provides hourly temperature, dew point, solar radiation, and wind speed in a 1/8-degree resolution and NARR provides cloud cover in a 3-hour resolution on a 32 km grid.

3.1.1 Adrian to Brownlee

Hourly meteorological observations were available for the upstream model from AgriMet stations (Figure 3). The hourly meteorological data for Ontario, OR and Parma, ID stations were downloaded from the Bureau of Reclamation website (AgriMet Columbia-Pacific Northwest Region | Bureau of Reclamation (usbr.gov)). The meteorological data were screened for outliers and converted to metric units for W2 input. Wind directions in AgriMet stations are measured in units of azimuth and were converted to radians for the model, where 0 radians indicates wind from the north. Solar radiation values were converted from Langleys per hour to watts per square meter. The Gridded Weather Data Processing Tool (MetTool), developed by Tetra Tech for Minnesota Pollution Control Agency (Tetra Tech, 2020), was used to extract, and process hourly meteorological data for the study area. Tetra Tech frequently utilizes the MetTool and grided weather data for watershed and receiving waterboy modeling. The outputs have undergone rigorous testing in the past. The NARR 3-hour cloud cover was resampled to 1-hour by MetTool and scaled between 0 and 10 indicating clear and overcast skies, respectively. The gaps in the calculated cloud cover were filled by the linear interpolation method. NLDAS products were also used to gap-fill meteorological inputs such as air temperature, dew point, and solar radiation for dates that were missing in AgriMet meteorological observations. Figure 9 shows observed hourly air temperature, dew point, wind speed, and solar radiation for the Ontario and Parma AgriMet stations. The hourly and average monthly cloud cover values calculated from NLDAS for these stations are also presented in this figure. In general, the two stations have similar observations, e.g., air temperature ranges from -28 to 40 °C. Only wind speeds appear to be slightly greater at Parma station. Calculated monthly cloud cover for both stations exhibit a reasonable pattern, peaking during winter and decreasing during summer. Parma’s meteorological observations were input for waterbody 1 and Ontario’s observations were used for waterbody 2 in the W2 model.

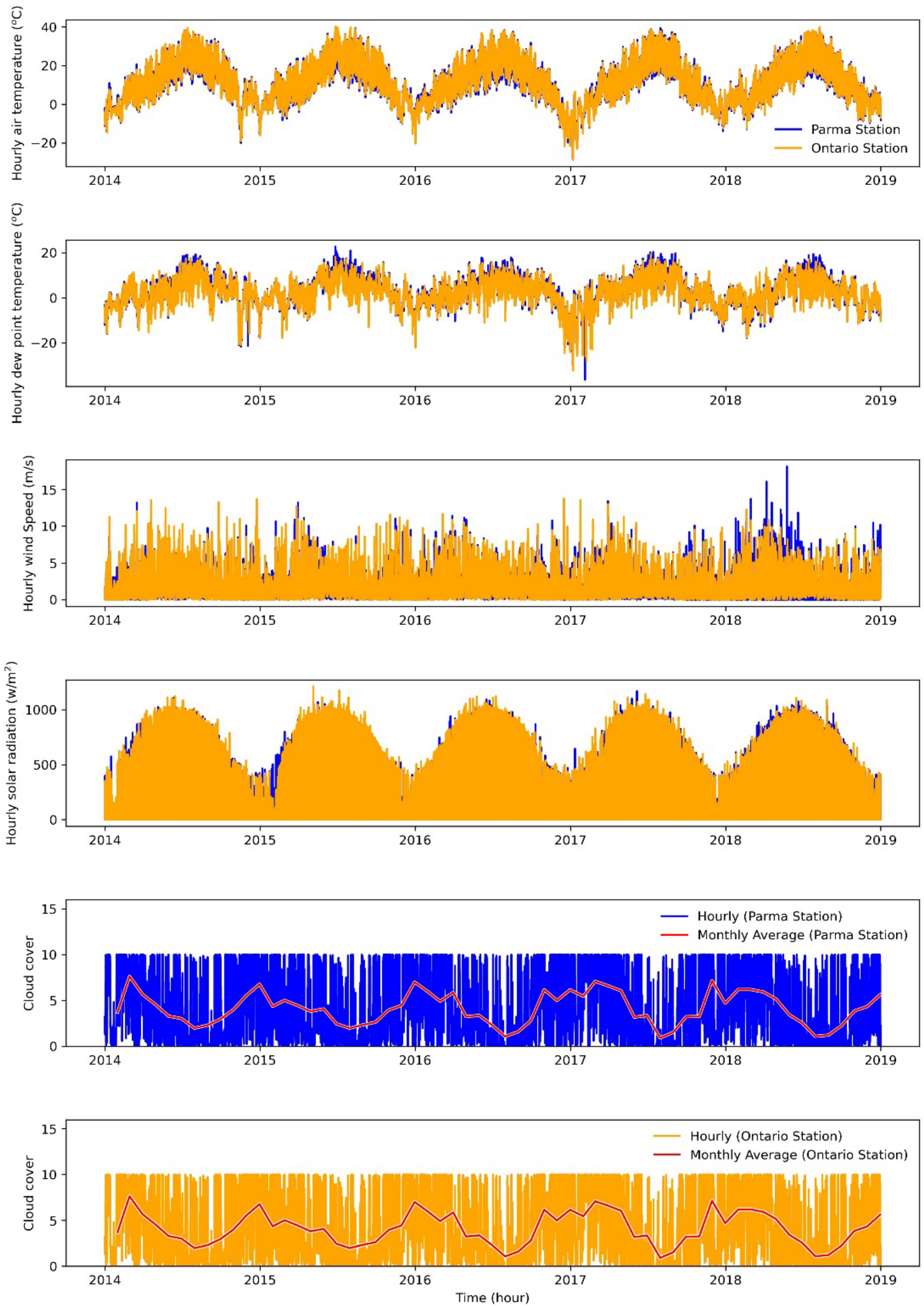


Figure 9. Observed hourly air temperature, dew point, wind speed, and solar radiation for Parma (blue) and Ontario (orange) AgriMet stations. The observations are gap-filled for missing dates

and hours using NLDAS data. Hourly (blue/orange) and average monthly (red) cloud covers calculated from NLDAS are presented in the two last rows.

3.1.2 Hells Canyon Dam to Oregon and Washington State Line

AgriMet stations or first order weather stations are not available for Hells Canyon Dam to Washington State line. For this part of the river, hourly meteorological observations (temperature, dew point, solar radiation, wind speed, and wind direction) were calculated from NLDAS, and cloud cover was computed from NARR gridded products (Figure 10). Within the modeling domain air temperature ranges from -21 to 36 °C and wind speed varies between 0 to 10 m/s. The wind speeds are greater in the fall and winter and summer has minimum wind speed; average wind speed in July and November are 1.8 m/s and 2.7 m/s, respectively.

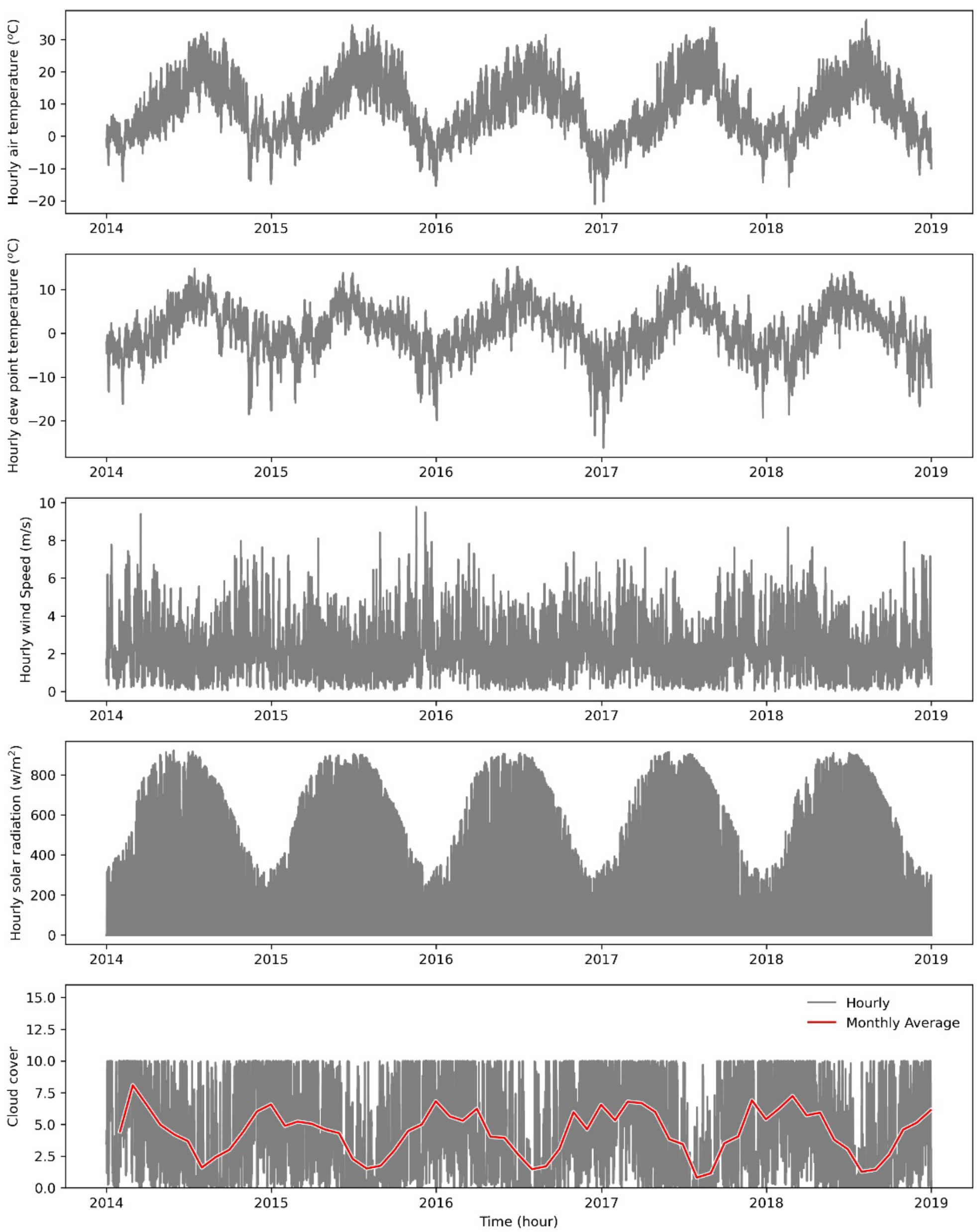
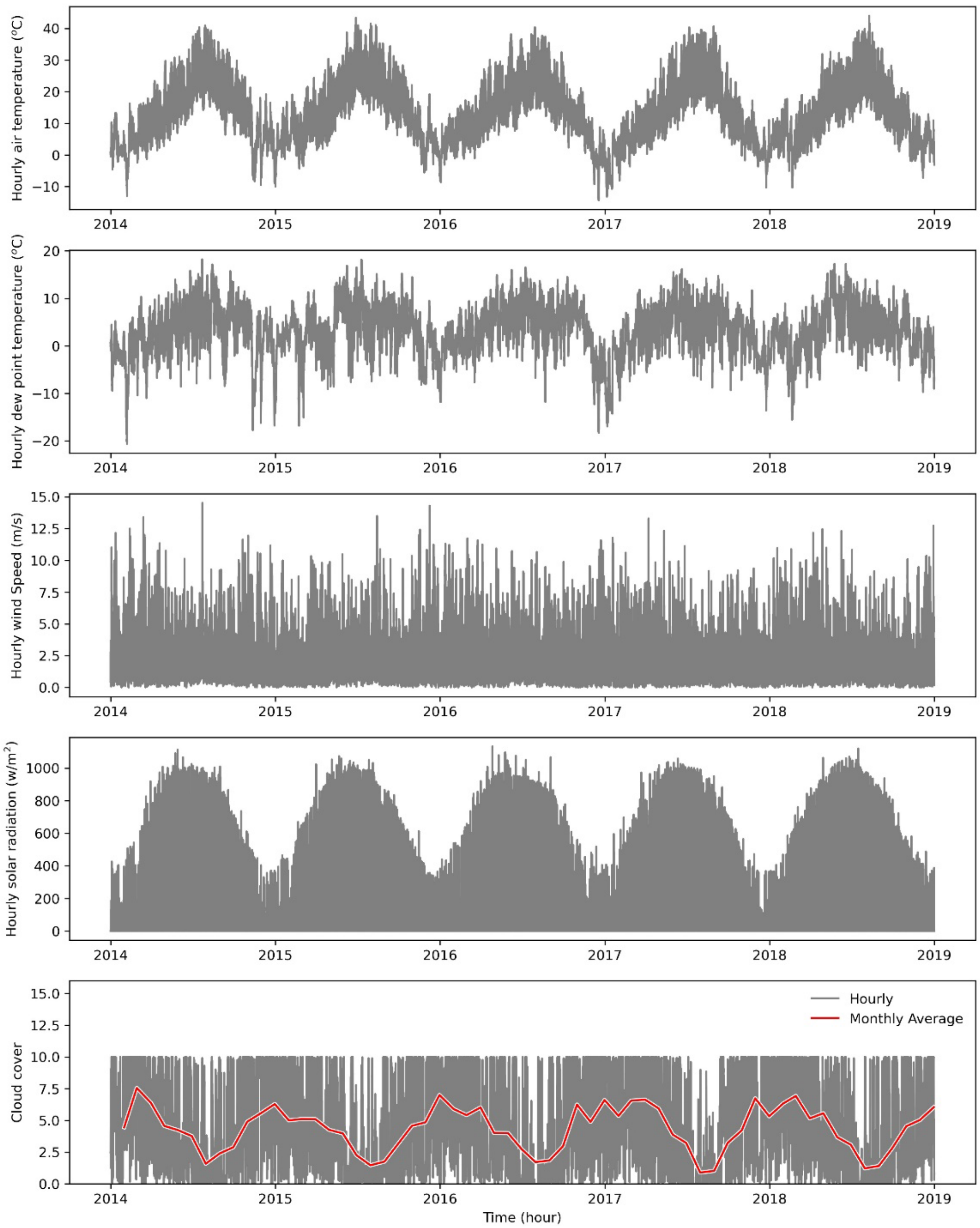


Figure 10. Calculated hourly air temperature, dew point, wind speed, and solar radiation from NLDAS and NARR products, Hells Canyon Dam to Oregon and Washington State line. Hourly and monthly average cloud covers are presented in the last row.

3.1.3 Oregon and Washington State Line to Clearwater River

Hourly Meteorological observations are available from AgriMet stations for the downstream W2 model. The hourly meteorological data for Silcott Island, WA were downloaded from the Bureau of Reclamation website (AgriMet Columbia-Pacific Northwest Region | Bureau of Reclamation (usbr.gov)). The meteorological data were screened for outliers and converted to metric units for W2 input. Cloud cover was calculated from NARR products. NLDAS products were used to gap-fill meteorological inputs for dates that were missing in AgriMet meteorological observations. Figure 11 shows hourly meteorological boundary for W2 input.

Figure 11. Observed hourly air temperature, dew point, wind speed, and solar radiation for Silcott Island AgriMet station. The observations are gap-filled for missing dates and hours using NLDAS



data. Hourly and monthly average cloud covers are presented in the last row.

3.2 FLOW AND TEMPERATURE DATA

Continuous flow and water temperature observations for Snake River and tributaries are needed to initiate the model boundaries. There are nine major tributaries (Owyhee River, Boise River, Malheur River, Payette River, Weiser River, Imnaha River, Salmon River, Grande Ronde River, and Asotin Creek) that flow into the Snake River mainstream in the study modeling domain (Table 1). Flow and temperature data for the model tributaries were obtained for these stations for the modeling period and gap-filled using the approach described below in sections 3.2.1 and 3.2.2. Table 1 and Table 2 summarize available flow and temperature observations for the model tributaries.

Table 1. Flow observations for Snake River tributaries from 2014-2018.

Gage	Location	Model Segment	Downloaded Records	Missing records (days)	Time Scale
IPC 13184005	Owyhee River near Adrian, OR	23	2014-2018	2	Daily average
USGS 13213000	Boise River	25	2014-2018	0	Daily average
Bureau of Reclamation MALO	Malheur River	107	2014-2018	47	Daily average
USGS 13251000	Payette River	119	2014-2018	0	Daily average
USGS 13266000	Weiser River	168	2014-2018	0	Daily average
Idaho Power gage, Imnaha River 13292000	Imnaha River	183	2014-2018	20	Daily average
USGS 13317000	Salmon River	194	2014-2018	1	Daily average
USGS 13333000	Grande Ronde	25	2014-2018	0	Daily average
USGS 13335050	Asotin Creek	99	2014-2018	0	Daily average

Table 2. Temperature observations for model tributaries from 2014-2018.

Gage	Location	W2 Model	Model Segment	Observations (days)	Missing records (days)	Time Scale
IPC, Owyhee River RM 3.2	Owyhee River	Adrian to Brownlee	23	1,325	501	15-minute
USGS 13213000	Boise River	Adrian to Brownlee	25	1,815	11	15-minute
USBOR MALO	Malheur River	Adrian To Brownlee	107	1,826	0	15-minute
USGS 13251000	Payette River	Adrian To Brownlee	119	914	912	15-minute
USGS 13266000	Weiser River	Adrian To Brownlee	168	911	915	15-minute
IPC, Imnaha River RM 0.1 RB	Imnaha River	HC Dam to OR and WA State Line	183	1,771	55	30-minute
IPC, Salmon River RM 1 RB	Salmon River	HC Dam to OR and WA State Line	194	1,791	35	30-minute
IPC, Grande Ronde RM 1.9 RB	Grande Ronde	OR and WA State Line to Clearwater	25	1,602	224	30-minute
Washington State Department of Ecology 35D 100	Asotin Creek	OR and WA State Line to Clearwater	99	1,795	31	15-mintue

3.2.1 Flow

3.2.1.1 Adrian to Brownlee

USGS daily average streamflow observations were available for three tributaries (Boise, Payette, and Weiser) and daily flow records for Malheur River were obtained from the USBR website (https://www.usbr.gov/pn-bin/inventory.pl?site=MALO&ui=true&interval=daily). Daily observations for Owyhee River were available from IPC website (https://idastream.idahopower.com). The daily discharge data for the model tributaries were downloaded from USGS and USBR websites and screened for outliers. Available tributary flow observations during the model application period are summarized in Table 1. Most tributaries had daily flow records for the simulation period and only the Owyhee River and Malheur River were missing flows for a short period of the simulation. Owyhee River was missing two flow records (1/16/2017 and 6/2/2018) which were estimated using the average flow for the adjacent days with measurements. The Malheur River was missing 47 flows and 28 days of these were consecutive and at the beginning of the simulation (1/15/2014 – 2/12/2014). For this period (28 days), the flow was gap-filled using the average daily flow for the same date from 2015-2018, and for the remaining the flow was gap-filled using the average value for the adjacent days with measurements. The Malheur River has the second smallest discharge, after Owyhee River, among the model tributaries and the missing flows for the river occurred during low flow seasons. As a result, the interpolated discharges were not expected to significantly impact the model discharge and water temperature simulations. The W2 model upstream boundary approximately coincides with USGS gage 13173600 (Snake River near Adrian, OR), and flow records are not available at this gaging station for the modeling period. Flow for the model upstream boundary was back-calculated from gage records at Nyssa (USGS 1321300 or RM389 Nyssa in Figure 3) after subtracting the contributions from the Owyhee River (13184005) and Boise River (13213000). The back-calculated flow was compared against Adrian flow observations from 10/1/2009 to 9/29/2010 and the calculated flow bias was approximately 3 percent. Figure 12 shows daily average flow for model tributaries and the Snake River at the upstream boundary.

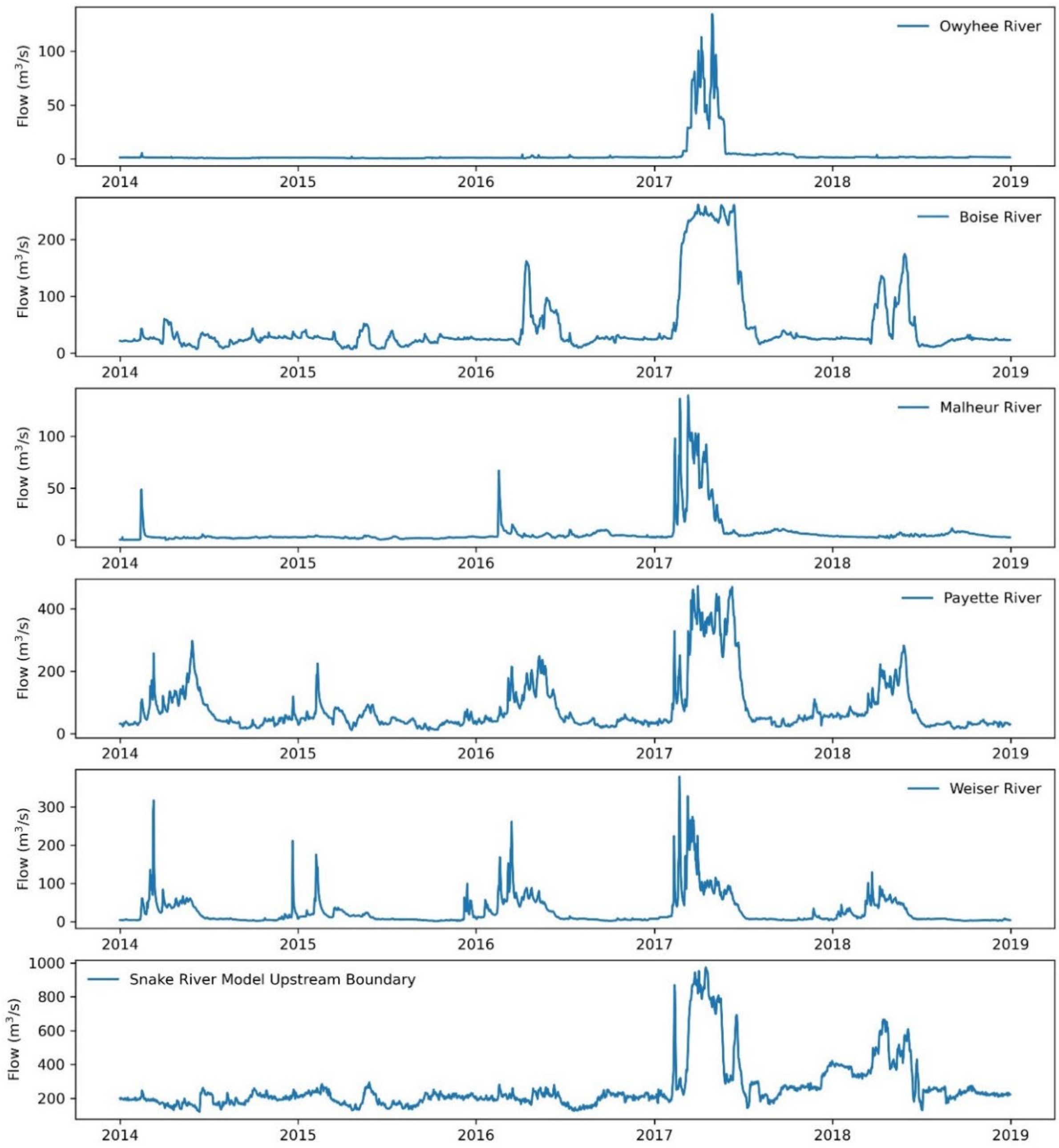


Figure 12. Adrian to Brownlee CE-QUAL-W2 tributary and upstream flow boundaries.

3.2.1.2 Hells Canyon Dam to Oregon and Washington State line

USGS daily average streamflow observations were available for Snake River RM 248 Hells Canyon Dam Penstock (IPC 13290450), Imnaha River (IPC, 13292000), and Salmon River (USGS 13317000), gages presented in Figure 5. The streamflow observations were downloaded from the USGS National Water Information System (NWIS) and screened for outliers. Imnaha River was missing 20 observations which were gap-filled using the average daily flow for the same date from 2015-2018. Salmon River was missing one observation which was gap filled using the average flow for the adjacent days with measurements. Observed streamflow for Imnaha River, Salmon River, and Snake River were used to initiate upstream flow boundary for W2 model (Figure 13). **Note:** after calibrating W2 to flow observations (see Section 3.6), this downstream model was linked to the HCC model, and the simulated outflow from Hells Canyon Dam became the inflow for this model reach.

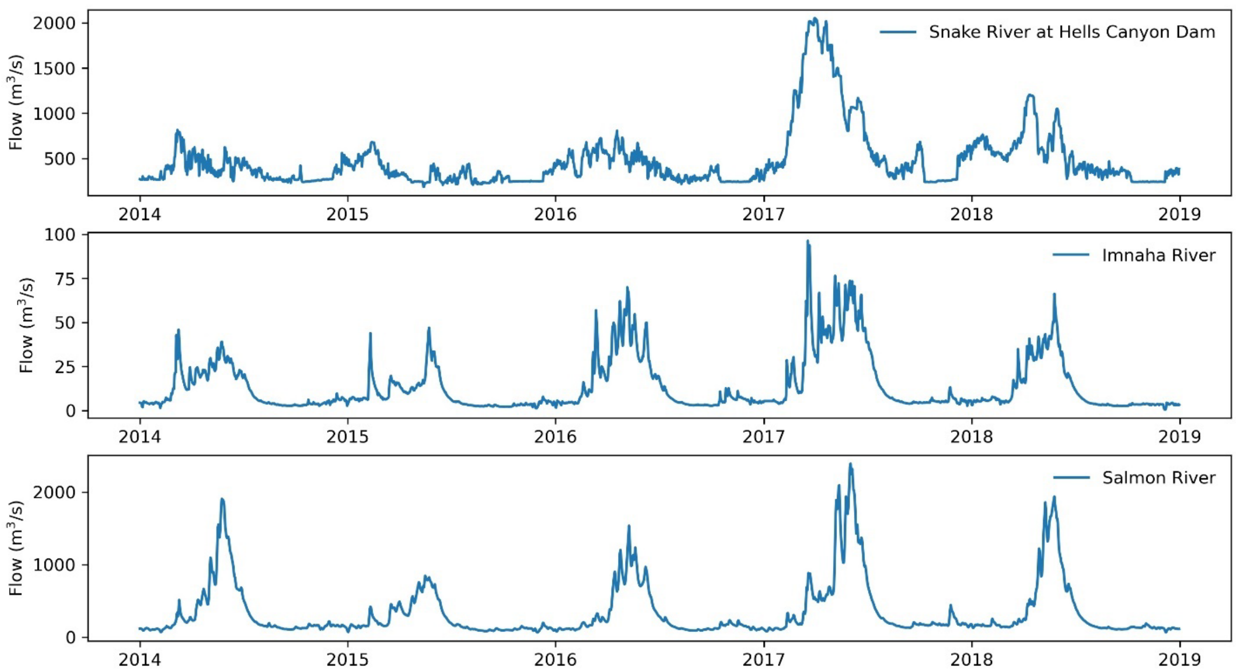


Figure 13. CE-QUAL-W2 upstream boundary and tributary flows for the model reach from Hells Canyon Dam to Oregon and Washington State line.

3.2.1.3 Oregon and Washington State line to Clearwater River

USGS daily average streamflow observations were available for Grande Ronde and Asotin Creek (Figure 14). The streamflow observations were downloaded from USGS NWIS and screened for outliers. The upstream boundary flow for the Snake River was specified using the simulated outflow from the upstream (Hells Canyon to Oregon and Washington State line) W2 model.

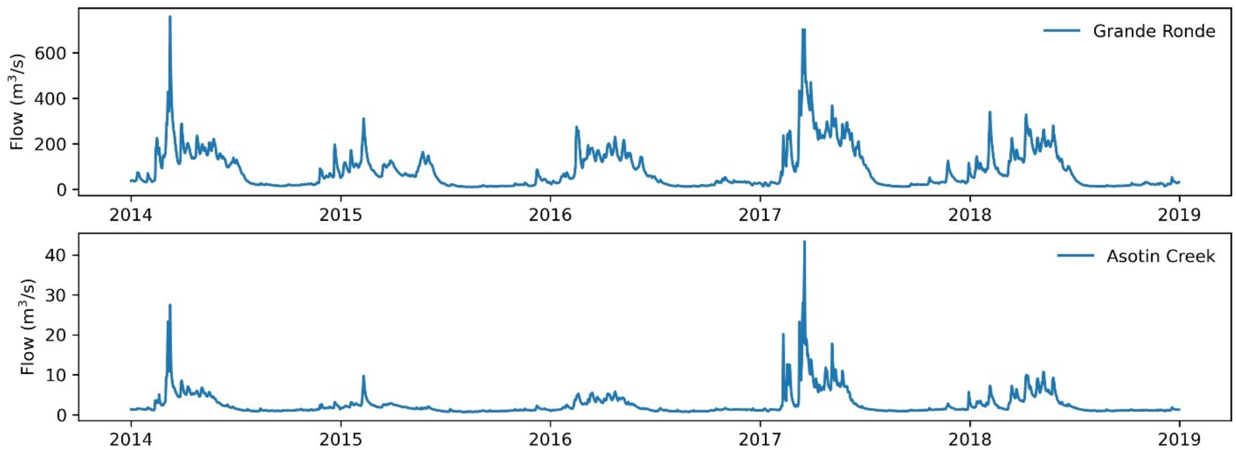


Figure 14. CE-QUAL-W2 upstream boundary and tributary flows for model reach from Oregon and Washington State line to Clearwater River confluence.

3.2.2 Water Temperature

3.2.2.1 Adrian to Brownlee

Among the model tributaries, water temperature observations are available for Malheur River (MALO station) for the entire modeling period. Malheur temperature observations were received in 15 minutes intervals from USBR (personal communications with Bryan Horsburg and Rich Jakson, February 8, 2022). Sub-hourly water temperature observations for Owyhee River (IPC RM 3.2), Boise River (USGS 13213000), Weiser River (USGS 13266000), and Snake River (USGS 13213100) were received from ODEQ, temperature data were downloaded from Oregon DEQ's Ambient Water Quality Monitoring System (AWQMS) and USGS website using R package. Sub-hourly temperatures for Payette River (USGS 13251000) were not available online and they were received from Idaho Water Science Center (personal communication with Christopher Mebane and Ross Dickinson, May 25, 2023). The time zone for tributary temperature observations was converted to Mountain Standard Time, and the data were subsequently plotted and visually inspected for any outliers. The Boise River had a nearly complete temperature record. Only 11 non-consecutive days were missing for this station, and they were gap-filled using daily average temperatures estimated from observations using a linear interpolation. Owyhee River, Payette River, and Weiser River were missing water temperature observations for a part of the simulation (Table 2). Strong correlations were found between tributary water temperatures and Boise and Malheur observations for the modeling period. Multi-linear regression models were established using hourly air temperature from Parma Station to estimate missing water temperatures for the tributaries (Figure 15-Figure 17). Since Ontario Station exhibits similar air temperature records to Parma Station (Figure 9), separate regression models using this station were not developed. For each tributary, two separate regression models were developed using Boise and Malheur observations and the best fit model, with the largest R^2 and smallest RMSE, was employed to estimate missing temperatures (Table 3). The Snake River upstream temperature boundary was specified using measurements at RM 389 Nyssa (USGS 13213100). Like the model tributaries, the Nyssa station did not have a full record of observations for the modeling period. Nyssa's missing hourly water temperatures were gap-filled by establishing a multi-linear regression model using observations at IPC RM 345.2 LB (Brownlee Reservoir upstream) and Parma’s hourly air temperature observations (Figure 18).The developed regression model had R^2=0.98 and RMSE=0.95 °C and accurately predicted river water temperatures, especially temperatures warmer than 20 °C that are important for TMDL assessment. Figure 19 shows the model inputs for the Snake River mainstream and tributaries.

Table 3. The Multi-linear regression models applied for gap filling of the model tributaries' water temperature observations and Snake River water temperature observations at Nyssa.

Gage	Location	Regression Model				Coefficient of Determination (R^2)	RMSE (°C)
		Observation	Period	No. Observations	Model		
Idaho Power gage, Owyhee River 3.2 RB	Owyhee River	Boise	2014-2018	31176	$T_{Owyhee}=0.94 \times T_{Boise}+0.07xT_{air}-0.4$	0.89	2.21
		Malheur	2014-2018	31560	$T_{Owyhee}=1.01 \times T_{Malheur}+0.01xT_{air}-1.3$	0.94	1.68
USGS 13251000	Payette River	Boise	2014-2018	21542	$T_{Payette}=1.09 \times T_{Boise}+0.06xT_{air}-2.49$	0.97	1.34
		Malheur	2014-2018	21912	$T_{Payette}=1.08 \times T_{Malheur}+0.07xT_{air}-3.91$	0.92	2.13
USGS 13266000	Weiser River	Boise	2014-2018	21404	$T_{Weiser}=1.1 \times T_{Boise}+0.09xT_{air}-3.6$	0.94	1.93
		Malheur	2014-2018	21774	$T_{Weiser}=1.15 \times T_{Malheur}+0.07xT_{air}-5.48$	0.91	2.34
USGS 13213100	RM 389 Nyssa	Snake River at RM 345.2	2014-2018	15738	$T_{Nyssa}=0.98 \times T_{RM\ 345.2}-0.08xT_{air}+1.45$	0.98	0.95

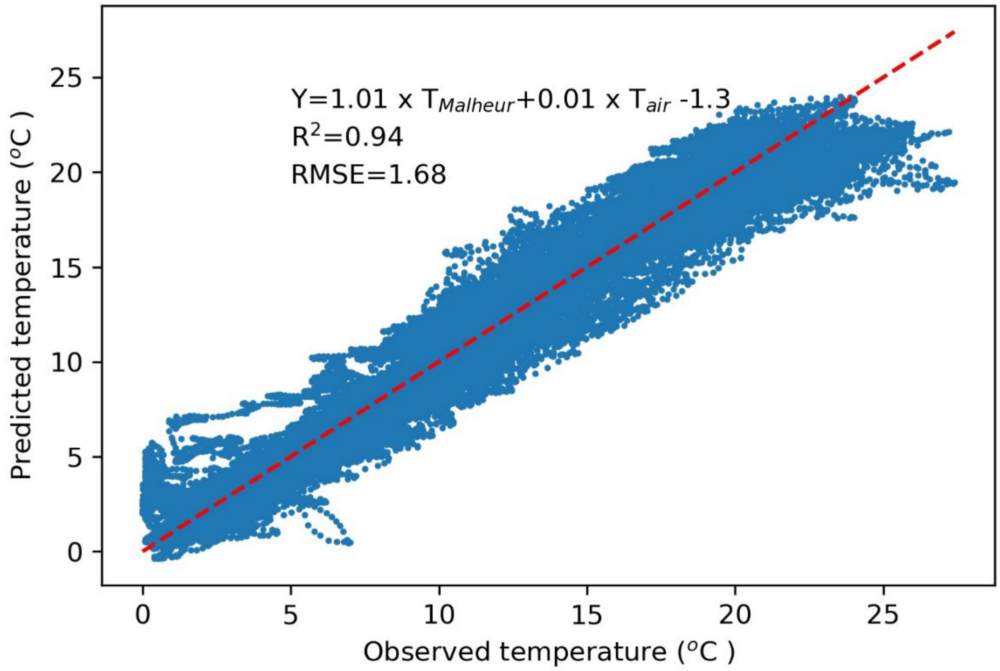


Figure 15. Owyhee River predicted hourly water temperatures versus observations.

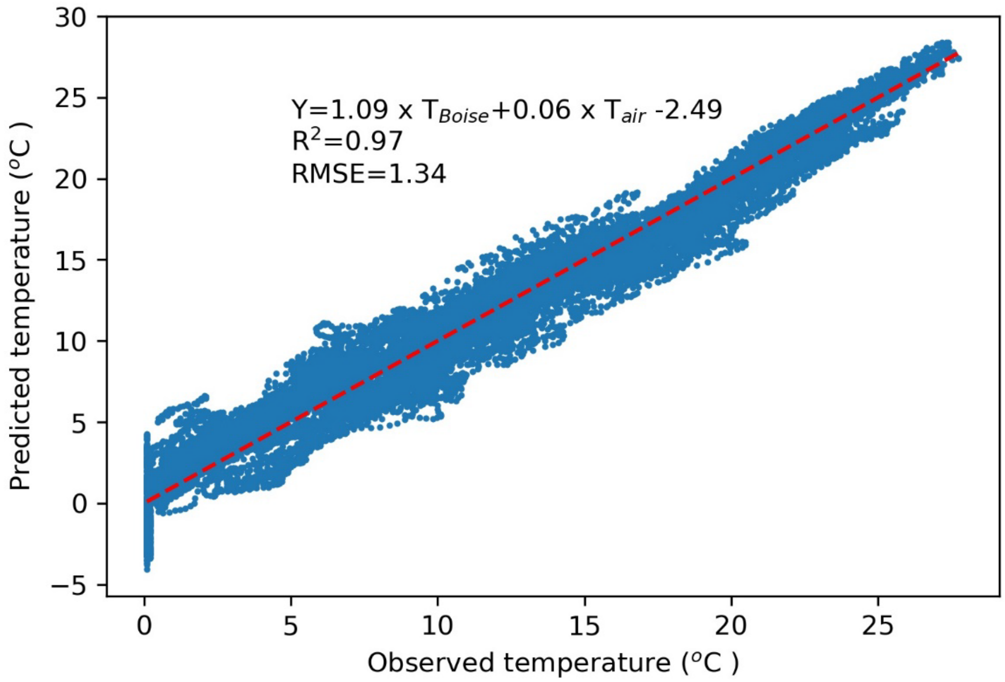


Figure 16. Payette River predicted hourly water temperatures versus observations.

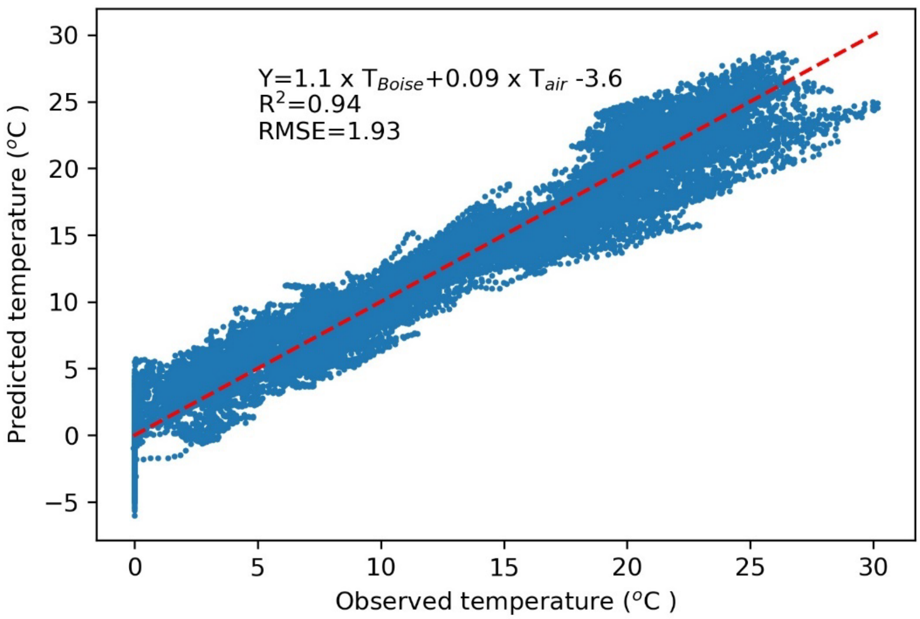


Figure 17. Weiser River predicted hourly water temperatures versus observations.

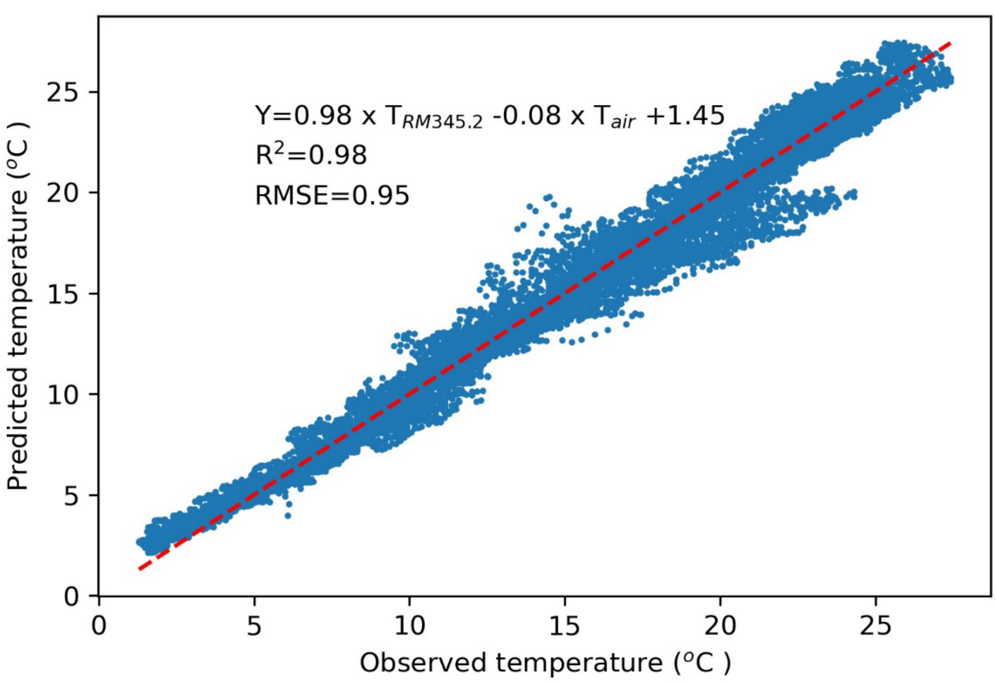


Figure 18. Snake River predicted hourly water temperatures versus observations at Nyssa.

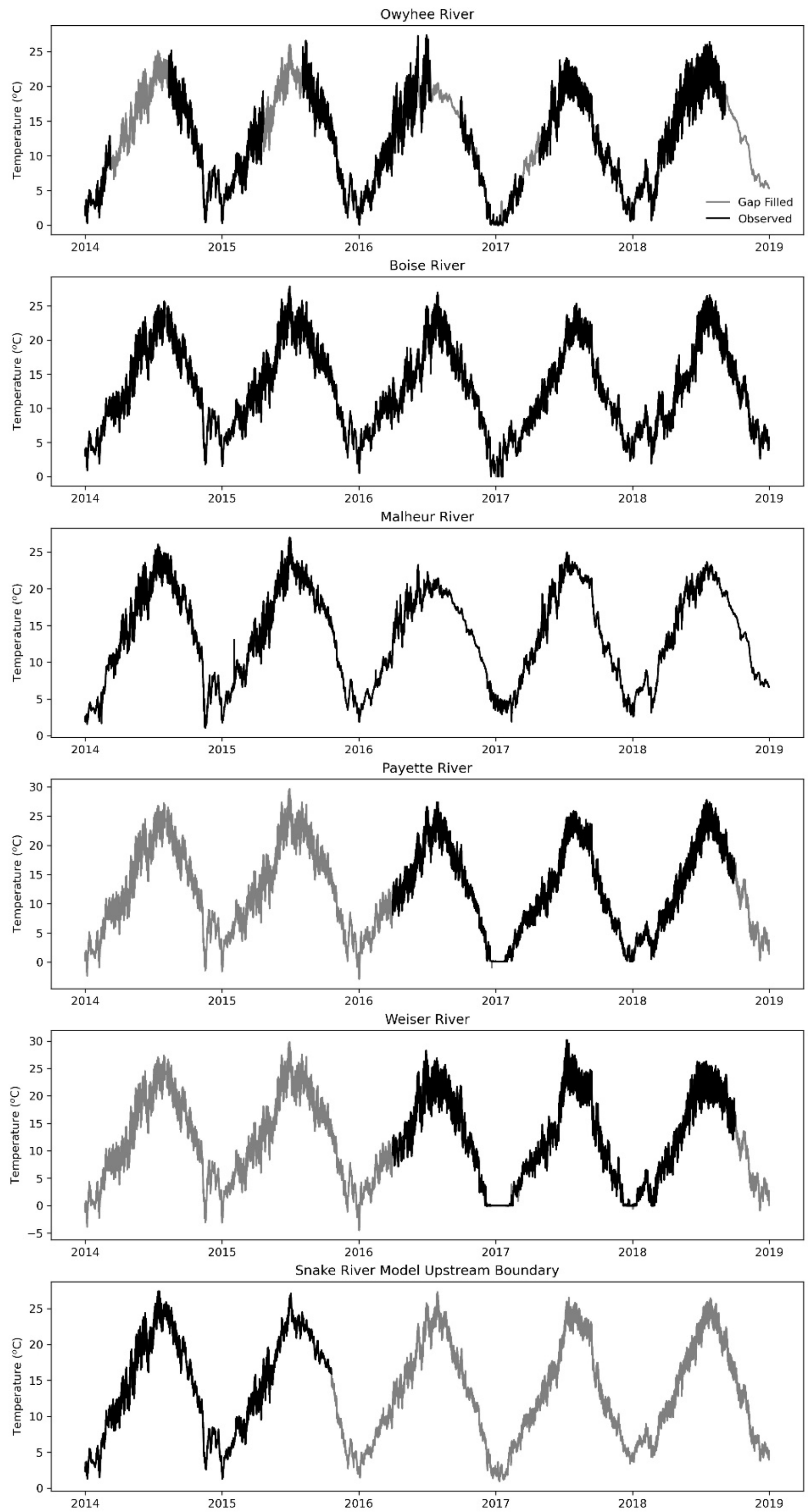


Figure 19. Observed (black) and gap-filled (grey) hourly water temperature boundary time series.

3.2.2.2 Hells Canyon Dam to Oregon and Washington State line

Sub-hourly water temperature observations for Salmon River (IPC Salmon River 1 RB) and Imnaha River (IPC Imnaha River RM 189) were received from ODEQ for the modeling period. Salmon River was missing 35 days which were gap-filled using hourly temperature observations at White Bird (USGS 13317000, Figure 5). Imnaha River lacked 55-day observations and most of missing records occurred at the beginning of simulation. Missing water temperatures were gap filled for Imnaha River by establishing a multi-linear regression model using hourly observations at IPC Salmon River 1 RB and air temperature observations. The developed regression model had R^2= 0.96 and RMSE= 1.62 °C (Figure 20).

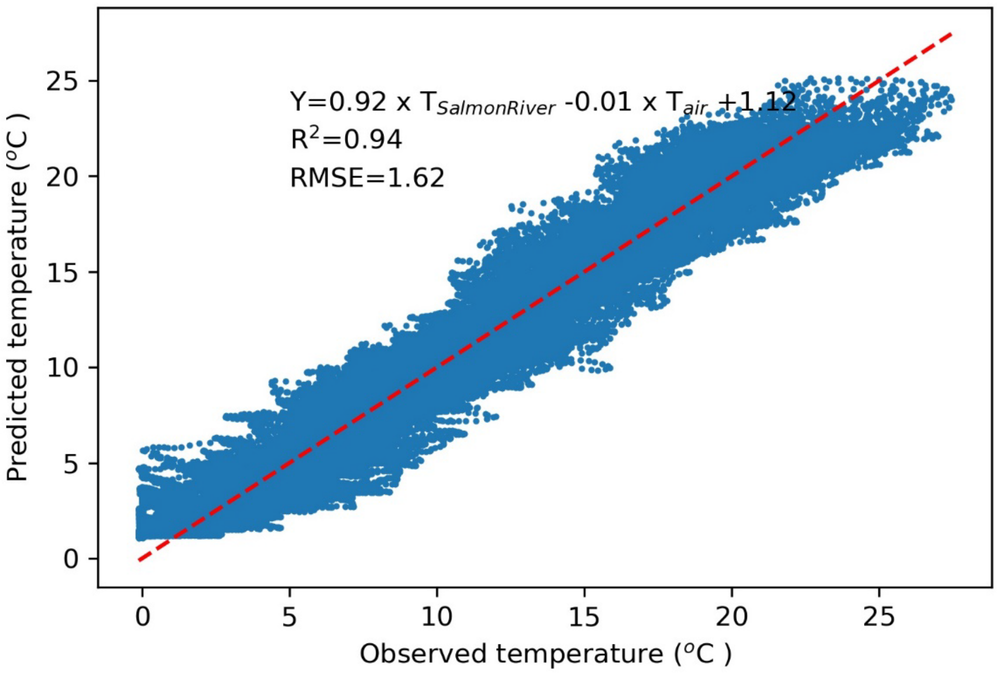


Figure 20. Imnaha River predicted hourly water temperatures versus observations.

The Snake River temperature boundary was specified using daily average observations below Hells Canyon Dam, IPC Snake River at RM 229.8 LB (near Sheep Creek). The gage station was missing 406 records which were gap-filled by establishing a multi-linear regression model using observations at IPC Snake River at RM 216.3 LB (near Pittsburg Landing, Figure 5) and daily average air temperature observations. Figure 21 shows water temperature boundaries for the W2 model. **Note:** after calibrating W2 to flow observations (see Section 3.6), this downstream model was linked to the HCC model, and the simulated outflow from Hells Canyon Dam became the inflow for this model reach.

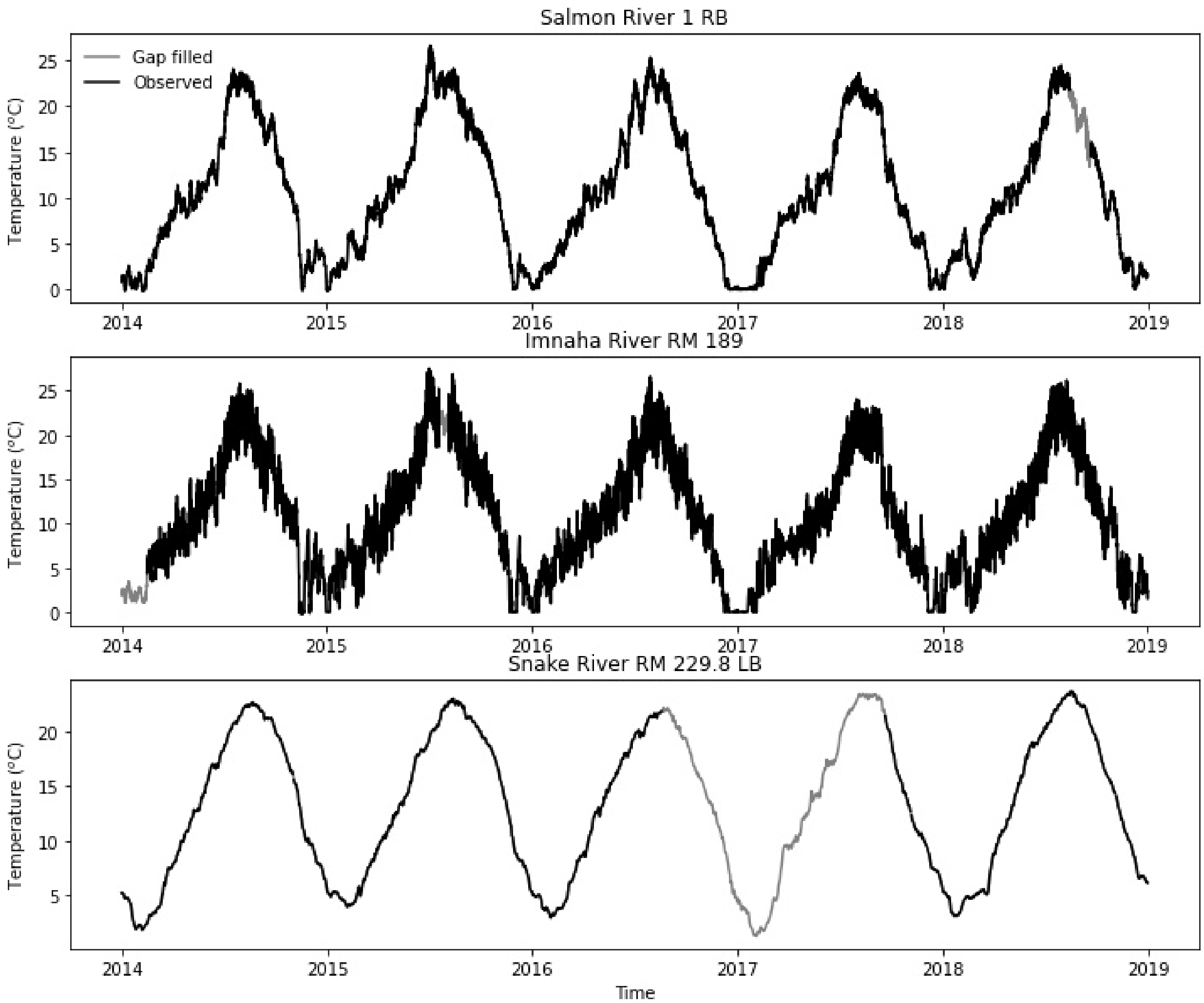


Figure 21. Observed (black) and gap-filled (grey) water temperature boundary time series, Hells Canyon Dam to Oregon and Washington State line.

3.2.2.3 Oregon and Washington State Line to Clearwater River

Sub-hourly water temperature observations for Grande Ronde River (Grande Ronde RM 1.9 RB) were received from ODEQ. The river was missing 224 observations for the modeling period which were gap filled by establishing a multi-linear regression model using observations at Salmon River 1 RB (Figure 22) and Silcott's Island hourly air temperature observations. Sub-hourly (15 minutes) water temperature observations for Asotin Creek were downloaded from Washington State Department of Ecology (WDOE) and screened for outliers. The station was missing temperatures for August 2018 which were gap-filled using average observations for same dates from 2014-2017. Figure 23 shows Grande Ronde River and Asotin Creek water temperatures used in the W2 model.

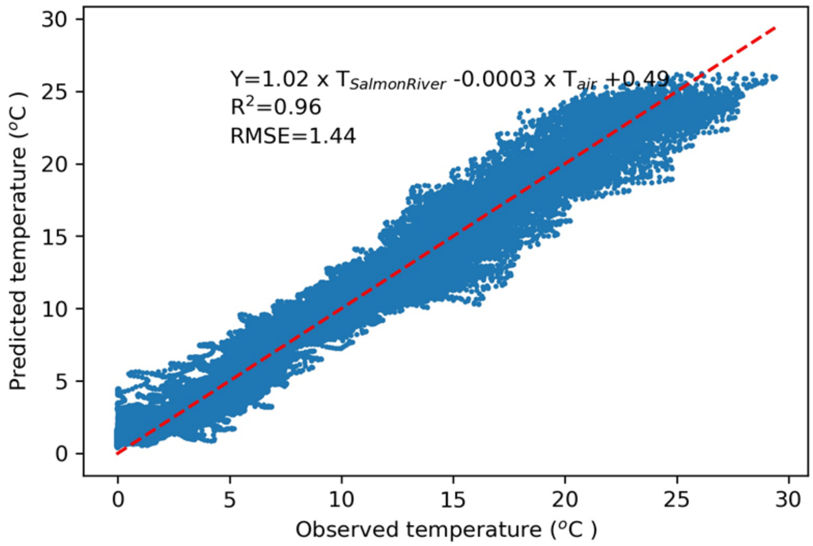


Figure 22. Grande Ronde River predicted hourly water temperatures versus observations.

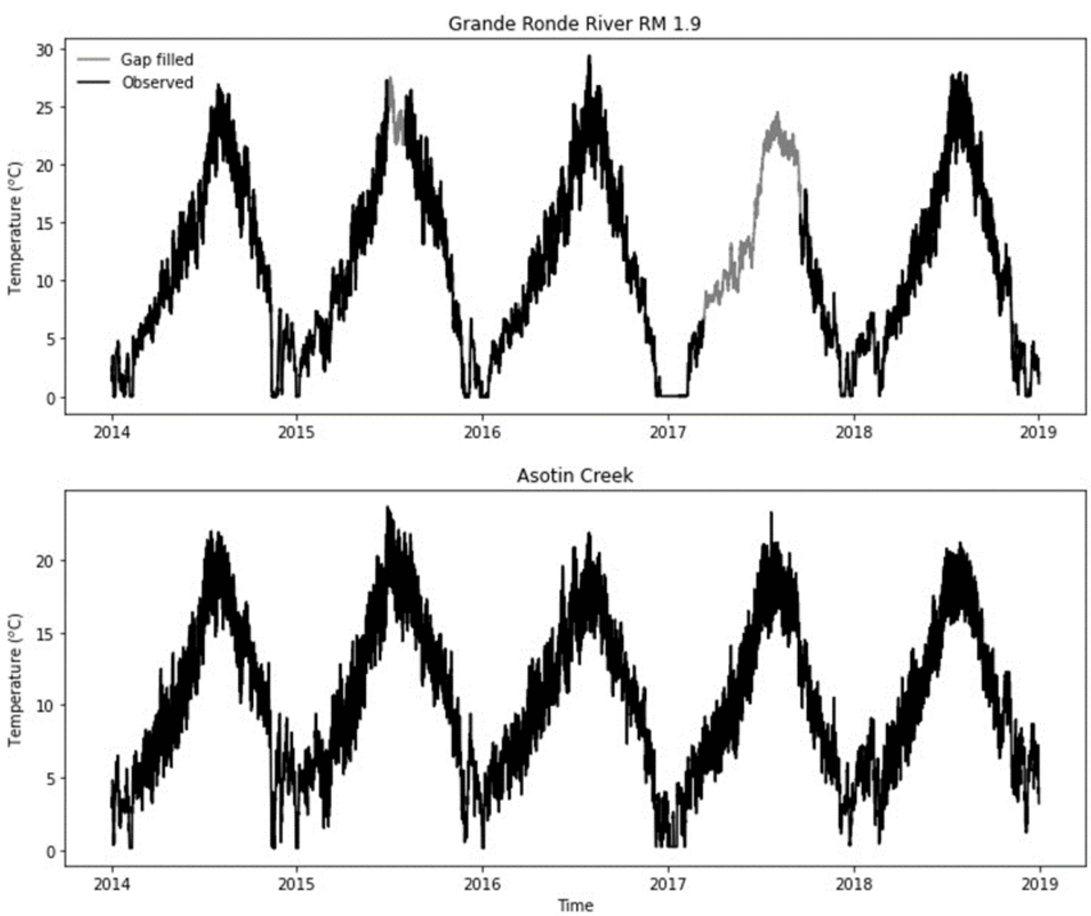


Figure 23. Observed (black) and gap-filled (grey) water temperature boundary time series, Oregon and Washington State Line to Clearwater River.

3.3 POINT SOURCES

Several point source facilities within the model domain are permitted to directly discharge water to the Snake River TMDL reach between RM 399 to RM139. These facilities, along with their respective permits, are listed in the Table 4.

Table 4. Permitted point sources discharge directly to the Snake River within the Snake River-Hells Canyon TMDL reach.

Point Source	NPDES Permit Number	Location (RM)	Treatment Type	Current Design-flow (MGD)
Amalgamated Sugar	OR2002526	385	Seepage ponds	Seepage (no direct discharge)
City of Fruitland	ID0020338	373	Facultative lagoon	0.5
Heinz Frozen Foods	OR0002402	370	Activated sludge	3.1 max monthly average 4.3 max daily average
City of Ontario	OR0020621	369	Facultative lagoon	3.06 (No discharge May 1 – Oct 31)
City of Weiser	ID0020290	352	Activated sludge	2.4
Brownlee Dam (IPC)	ID0020907	285	See note 1	15
Oxbow Dam (IPC)	OR0027286	272.5	See note 1	Turbine non-contact cooling water: 12 Wastewater: 0.15
Hells Canyon Dam (IPC)	OR0027278	247	See note 1	Turbine non-contact cooling water: 9 Wastewater: 1.5
Asotin Sewage Treatment Plant	WA0020818	145	Activated sludge	0.33

1. Facilities sump discharge and turbine cooling water, not a waste treatment source.
NPDES = National Pollution Discharge Elimination System; MGD = Million Gallons per Day; WTP = Water Treatment Plant; WWTP = Wastewater Treatment Plant

The Adrian to Brownlee model (Figure 3) includes Amalgamated Sugar, City of Fruitland, Heinz Frozen Foods, City of Ontario, and City of Weiser, while the Oregon and Washington State Line to Clearwater W2 model (Figure 7) includes Asotin Sewage Treatment Plant discharge. There are no point source discharges between Hells Canyon Dam and the OR and WA state line. Non-contact cooling and wastewater discharges from Brownlee Dam, Oxbow Dam, and Hells

Canyon Dam are covered under NPDES permits. These NPDES related discharges add small heat loads to the Snake River, but they are not simulated in the PSU reservoir models. The available discharge and temperature data for point source facilities are discussed and summarized below. All point source facilities are simulated as a tributary in the W2 models.

Amalgamated Sugar

While this facility has an active permit for a pond that is authorized to discharge to the Snake River, there is currently no discharge data indicated for the modeling period through the National Pollutant Discharge Elimination System. According to personal communication with ODEQ on December 15, 2022, the pond has been dry since 2005, as Amalgamated Sugar reported in their DMRs that “The 2004-2005 sugar production season ended sugar production at the Nyssa Factory. The volume of water discharge to the ponds have significantly been reduced. Consequently, the ponds have dried up.” As a result, for the purpose of the model calibration, the facility has been added to the model with zero discharge.

City of Fruitland

Within the modeling domain, there are two Fruitland WWTP facilities (ID0021199 and ID0020338). ID0021199 is included in the model as part of the Payette River discharge and temperature boundaries because it discharges to the Payette River. ID0020338, on the other hand, directly discharges to the Snake River. For this permit (ID0020338), flow and temperature data were downloaded from NPDES. The daily maximum and monthly average flow and temperature were available until March 2016. However, no data were available after that date, and this discharge has been assumed to have ceased in the model.

Heinz Frozen Foods

ODEQ provided daily discharge and temperature observations for the facility during the modeling period. However, there were some gaps in the observations: (1) flow and temperature data were missing for September 2018, (2) temperature data was absent for January 1 to May 31, 2014, and (3) flow data was missing for March 2016. To address these gaps, the daily flow for September 2019 was estimated using the NPDES monthly total flow, while the daily temperature for this month was filled in using the weekly average temperature. The missing temperature records for January to May 2014 were filled by using the average daily temperature values calculated for the same dates using observations from 2015-2018. For March 2016, the facility's maximum daily average design flow (4.3 MGD or 0.226 m^3/s), which was provided by ODEQ during a personal communication with EPA and ODEQ on December 14, 2014, was used.

City of Ontario

The current NPDES permit prohibits the facility from discharging water to the Snake River from May 1 to October 31. During this period the discharge was set to zero in the model. From November 1 – April 30 discharge was characterized using DMR daily flow and temperature data provided by ODEQ. There were some missing temperature records for a few days within each monthly report. To address this issue, the missing temperature values were filled in by using the average daily temperature from the corresponding report.

City of Weiser

For this facility monthly maximum flow and monthly average temperature for the modeling period were available from NPDES. These data were downloaded and used for the model input.

Brownlee Dam

The monthly maximum discharge (million gallons per minute) and temperature (°F) data for Brownlee Dam's non-contact cooling and wastewater discharges were obtained from the Idaho Department of Quality (IDEQ) and EPA Region 10. The dataset includes a total of 5 outfalls. For outfalls 1-4, observations were available for Generator Air Cooler and Turbine Cooler, with wastewater flow and average temperature discharge provided in separate columns.

Outfall 5 at the dam comprises 4 units (Generator Air Cooler, Turbine Cooler, Generator Guide, and Turbine Guide), and temperature and discharge data were provided for each unit. To standardize the units, the temperature and discharge values of the outfalls were converted to °C and m^3/s respectively.

To integrate these data into the Oxbow Reservoir model, the sum of outfall discharges and the flow-weighted average temperature for outfalls 1-5 were calculated and added as a new tributary. This additional tributary contributes to segment 2 of the Oxbow model. During the modeling period, the average wastewater discharge from Brownlee Dam was 0.357 m^3/s. This value is significantly smaller in comparison to the overall dam outflow of 443.47 m^3/s.

Oxbow Dam

The dam has five outfalls, with non-contact cooling discharging through outfalls 1-4, having a maximum permit discharge of 12 MGD. Outfall 5 discharges powerhouse sump wastewater, and its current permit allows a discharge of 0.15 MGD. The current regulations limit outfalls' temperature to be within background temperature plus 10 F (5.5 °C) or a maximum of 68 F (20 °C) (NPDES, 2004)

Quarterly maximum discharge and temperature data for Oxbow outfalls were provided by ODEQ. Temperature observations were reported as ΔT (the difference between outfall temperature and background water temperature) for most of the modeling period, except that actual maximum temperatures were reported for winter and fall of 2014 and winter of 2015. Temperature for the dam's outfalls was calculated by adding ΔT to the PSU simulated outflow temperature for the Oxbow Dam. For periods when actual maximum outfall temperatures were reported, the average ΔT for the same period from 2015-2018 observations was calculated and used to generate input for the model. The calculated temperature and discharge data were incorporated as a new tributary into the segment 13 of the Hells Canyon Reservoir model.

Hells Canyon Dam

The dam consists of five outfalls. Outfalls 1-3 discharge non-contact cooling with a maximum permitted discharge of 9 MGD. Additionally, wastewater is collected in the powerhouse sump and discharged via outfall 4 into Snake River, with a permitted maximum discharge of 1.5 MGD. Outfall 5 discharges sanitary wastewater into a holding tank, which is then pumped and transported off-site every two weeks. The current NPDES permit restricts discharge temperatures to be no more than background temperature (ambient temperature) plus 5.5 °C when background temperature is higher than 7.2°C (NPDES, 2004).

Quarterly maximum discharge and temperature data for Hells Canyon outfalls (1-4) were provided by ODEQ. Temperature was reported as ΔT for the modeling period, except no data were available for November- December 2018. The average quarterly discharge and temperature for the same period from 2014-2017 was used to gap fill data for missing months. Temperature for the dam's outfall discharge was calculated by adding ΔT to the simulated temperature outflow for the Hells Canyon Dam using the PSU model. The calculated temperature and discharge data were incorporated as a new tributary into the segment 2 of the Hells Canyon Dam to Oregon and Washington State Line W2 model.

Asotin

Monthly maximum flow and temperature observations for the facility were obtained from the NPDES, with temperature records available from January 2014 to August 2018, while the flow records ended in May 2014. We assumed that the facility had discharged water during the period when temperature data were available, and the missing flow data were filled in by using the facility's design discharge (0.33 MGD).

3.4 TOPOGRAPHIC AND VEGETATIVE SHADING

Local topography and vegetation can block solar shortwave radiation resulting in less heat gain and lower water temperatures. The W2 model simulates both topographic and vegetative shading using static and dynamic methods. The model needs topographic inclination angles in 20-degree increments, starting from the north and in a clockwise direction around the segment center, to calculate the influence of topography. Vegetation data inputs for the model are height, density, distance from riverbanks, and leaf-in and leaf-out times for deciduous vegetation. The model uses topographic and vegetation information and the position of the sun to calculate shade for a model segment; for details see (Cole & Wells, 2003).

TTools, a GIS toolbox provided by the Oregon Department of Environmental Quality (Department of Environmental Quality : Analysis Tools and Modeling Review : Total Maximum Daily Loads : State of Oregon) calculates the topographic inclination angle from the DEM. The TTools Python program is available on the ODEQ's GitHub account GitHub - OR-Dept-Environmental-Quality/TTools: TTools. The program uses ArcGIS ArcPy library and was modified to calculate the topographic inclination angles and shading for W2 in 20-degree increments (see Figure 24). For an increment, the program extracted an array of elevation points within a 10 km radius from the segments' center from the 30 m DEM. Using the point distances and elevations the program calculated the largest topographic angle relative to the segments' center in the unit of a degree. Topographic angles were converted to radians for W2 input. The riverbank distance from the centerline of the river was also calculated using TTools. Tree elevations on the riverbanks were calculated from Lidar Highest Hits downloaded from Oregon Department of Geology and Mineral Industries (ArcGIS Web Application (oregon.gov)) for the models upstream of Oregon and Washington border. For downstream W2 model (Oregon and Washington border to Clearwater River) tree elevations were calculated by adding LANDFIRE 2016 trees' height to DEM. W2 shade input contains two layers of vegetation and the reduction factors for these layers were set to 0.25. Leaf-in and leaf-out times for deciduous vegetation were specified as in the HCC water temperature study (Wells, Berger, & Garstecki, 2021b).

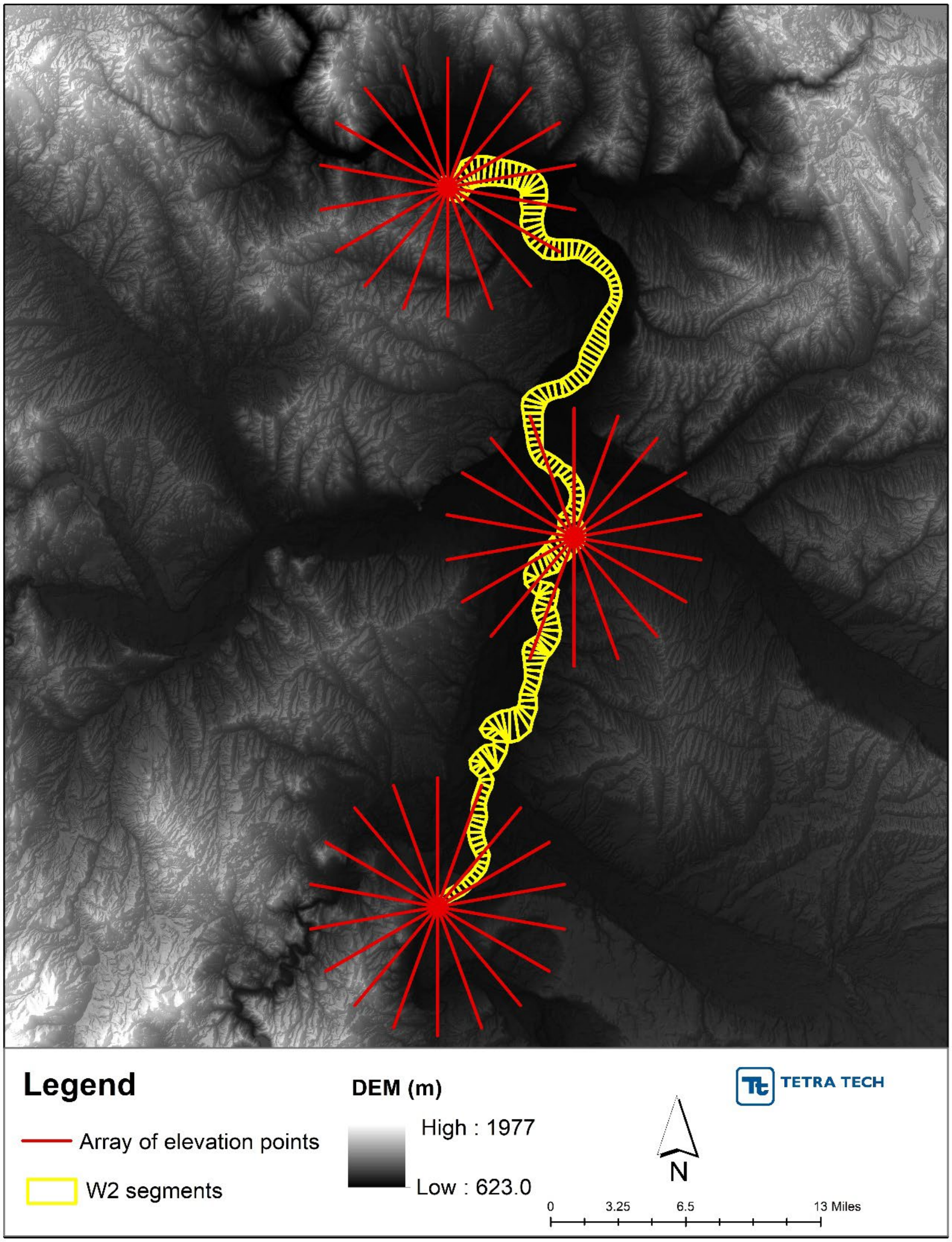


Figure 24. Arrays of elevation point in 20-degreee increments generated to calculate topographic angle for the Adrian to Brownlee model segments 2, 85, and 179.

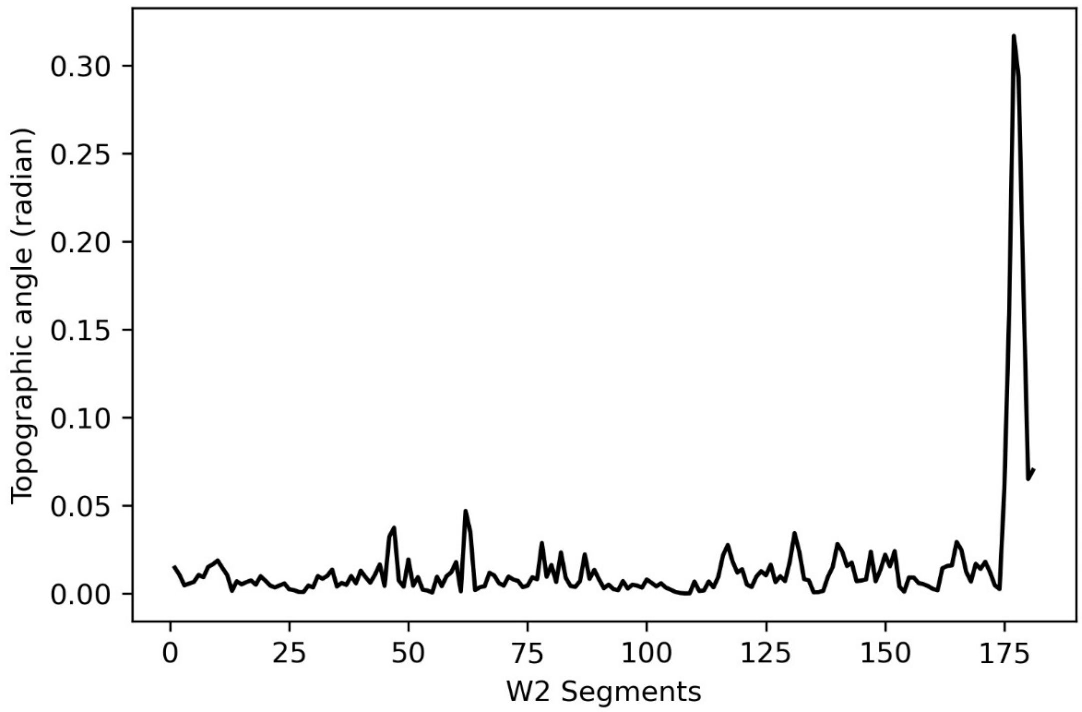


Figure 25. TTools calculated topographic angle in 180-degree (South) direction for Adrian to Brownlee model.

3.5 STREAMFLOW SIMULATION

Maintaining stability in a W2 model for a fast-flowing river is challenging since model segments can become dry either during the initial time steps or in the middle of the simulation (Cole & Wells, 2003). A dry segment results in instability in the water balance simulation and causes the model to stop running. Snake River is shallow and relatively steep which caused the model segments to become dry during the initial time steps when the model starts from static conditions. To resolve the instability for Adrian to Brownlee, the model was divided into two waterbodies and the maximum computational time step was set to 1 second for the first 5 days of stimulation to allow the system to equilibrate, then increased to 10 seconds after day 5 and maintained the same until day 1100 before it was reduced to 5 second for the rest of the simulation. Using this setup, the model was able to simulate the streamflow for the first 200 days of simulation before it became unstable again. Analyzing the W2 simulated flow output showed that the model removes dry segments from the headwater to remain stable during simulation when the slope for a model waterbody is set to zero. To prevent the W2 model from removing dry segments a minimal slope of 0.000001 was used for the waterbodies and a spillway representation was set for the model downstream boundary to help maintain stability (approach based on Tetra tech communication with Scott Wells and Chris Berger at PSU). To keep water in the system during the initial start-up and later during low flow conditions, the friction coefficient (Manning's roughness) value for the model segments was set between 0.065 to 0.085. A few segments, however, still dried at times due to the river slope. These segments were maintained wet by slightly increasing their bottom width or adding an active layer to the bottom per W2 guidance (Cole & Wells, 2003). Note that W2 combines the volume of multiple vertical cells in a segment into a single computational segment in order to remain stable in a relatively steep and shallow river (personal communication with Chris Berger, July 6, 2022). This caused the model to output a single temperature for a vertically combined segment that is assumed to be vertically mixed.

Because of the high slope of the lower reaches in the study area, several W2 segments below Hells Canyon Dam dried during trial flow simulation. The W2 model was unstable during initial time steps when the model started from static conditions (velocity=0). Enabling InitUWL in the W2 setup allows the model to calculate an initial velocity for flow at time=0. However, this approach was not successful due to the significantly large slope of the reach at this section of the Snake River. The models' instability was resolved by specifying high initial water surface elevation for the segments and using a small maximum computational time step. Hells Canyon Dam to Oregon and Washington State line W2 model was stable when the slope of initial water surface elevation was 0.1%. The initial water surface elevations for the model segments were calculated by reducing a segment's upstream water surface elevation by 0.5 meters. This set-up caused flooding for the downstream segments on the first day of simulation since the initial water surface elevation exceeded the river channel maximum elevation. This did not impact the model flow and temperature simulations because flood water recedes within the Snake River channel on the second day of simulation. In addition, a 1-second maximum computational time step was used for first 5 days of simulation to maintain the model stable during initial start-up. The maximum computational time was then increased to 5 seconds for days between 5 to 20 and set to 20 seconds after Day 20 and maintained the same for the rest of the simulation. As in the upstream model, the downstream reach was simulated using a spillway and waterbody slope was set to 0.000001. The Manning's roughness was also set to 0.044.

The downstream W2 model (Oregon and Washington State line to Clearwater) was stable during initial time steps when the slope of the initial water surface elevation was 0.02%. The initial water surface elevations for the model segments were calculated by reducing upstream segment's water surface elevation by 0.1 meters. As in the upstream model, this setup only caused flooding for the model on the first day of simulation. The maximum computational time step for the model was set to 10 seconds for first 50 days of simulation and increased to 20 seconds for the rest of the simulation. The downstream boundary for the W2 model was simulated using a spillway and a waterbody slope of 0.000001. The Manning's roughness was also set to 0.044 for the model.

3.6 FLOW AND TEMPERATURE CALIBRATION APPROACH

The W2 model was calibrated to flow and water temperature gage observations following Tetra Tech's Quality Assurance Project Plan (Tetra Tech, 2022). The calibration was performed using a graphical and statistical comparison between the model predictions and the observations. The W2 parameters were initially defined based on knowledge of the study area and literature.

The flow calibration process involved calculating the discharge for the un-gaged tributaries and adjusting the model parameter values for temperature simulation. Five statistical measures, the Coefficient of Determination (R^2), Root Mean Square Error (RMSE), Mean Error (ME), Mean Absolute Error (MAE), and Nash-Sutcliffe coefficient of model fit efficiency (NSE) were calculated to evaluate the calibration:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (4)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \quad (5)$$

$$ME = \frac{\sum_{i=1}^{n}(P_i - O_i)}{n} \quad (6)$$

$$MAE = \frac{\sum_{i=1}^{n}|(P_i - O_i)|}{n} \quad (7)$$

$$\text{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O}_i)^2}\right] \quad (8)$$

where *P* and *O* are prediction and observation; $\overline{O}$ is the average value of observation; *i* is the observation number, and *n* is the total number of observations.

NSE and RMSE were the main objective functions for flow and temperature calibrations. During W2 temperature calibration the model parameter values were adjusted using a joined manual and automatic calibration method. The model was first manually calibrated for temperature based on knowledge of study area and literature. The Particle Swarm Optimization (PSO) algorithm was then used to further explore the model solution space within identified parameter ranges to achieve a better calibration. PSO is a well-known optimization method and previously was used for calibration of W2 model (Shojaei, 2014; Shabani A. , Zhang, Chu, & Zheng, 2021). The W2 model was calibrated to hourly and average daily water temperature observations by adjusting values of the 10 model parameters listed in Table 5. These parameters and their typical values are selected from the Hells Canyon Complex W2 model study (Wells, Berger, & Garstecki, 2021b).

The statistics measuring calibration performance were calculated for discharge and flow at the stations shown in Table 6. The IPC station at RM345.2 LB is located downstream of the Adrian to Brownlee modeling boundary (Figure 3) and the W2 temperature output for segment 182 in the model was compared against observations at this station. USGS 13317660 is also located downstream of the Hells Canyon to Oregon and Washington State border (Figure 5) and the W2 flow and temperature output for the segment 234 in the model was compared against observations at this station. Sub-hourly and daily water temperature observations for IPC RM 383 MC, IPC 354.3 LB, IPC 345.2 LB, IPC 229.8, IPC 216.3, IPC 202.3, and IPC 189 from the state of Oregon’s AWQMS database were provided by EPA Region 10. The sub-hourly observations were aggregated into hourly temperatures, and 7-day average of daily maxima (7DADMax) temperatures were calculated using a rolling 7-day window. Due to the critical role of warm water temperatures in TMDL calculation, the model performance was also evaluated for the warm/summer season (May-November) separately for all stations.

Table 5. CE-QUAL-W2 model temperature parameters and their calibrated values.

Parameter	Description	Units	Typical value	Calibration value		
				Adrian to Brownlee	HC to OR and WA State line	OR and WA State Line to Clearwater
AX	Longitudinal eddy viscosity for momentum dispersion)	$m^2 sec^{-1}$	1.0	Waterbody 1: 1.0* Waterbody 2: 1.0*	0.89	1.0*
DX	Longitudinal eddy diffusivity (for dispersion of heat and constituents)	$m^2 sec^{-1}$	1.0	Waterbody 1: 1.0* Waterbody 2: 1.0*	0.4	1.0*
CBHE	Coefficient of bottom heat exchange	$Wm^2 sec^{-1}$	0.3	Waterbody 1: 0.3* Waterbody 2: 0.48	0.68	0.3*
TSED	Sediment (ground) temperature	°C		Waterbody 1: 11.7* Waterbody 2: 10.02	11.74	11.5
TSEDF	Fraction of heat lost sediments that is added back to water column			Waterbody 1: 1.0 Waterbody 2: 1.0	0.84	0.1
WSC	Wind sheltering coefficient		0.5-3	0.5 - 1.17	1.43	1.38
BETA	Fraction of incident solar radiation absorbed at the water surface		0.45	Waterbody 1: 0.65 Waterbody 2: 0.34	0.45*	0.65
EXH2O	Extinction rate of water	per meter	0.25-0.45	Waterbody 1: 0.45 Waterbody 2: 0.33	0.37	0.5
AFW	*a* coefficient in the wind speed formulation	Wm^{-2} mm Hg^{-1}		Waterbody 1: 8 Waterbody 2: 8	7.34	8.8*
BFW	*b* coefficient in the wind speed formulation	Wm^{-2} mm Hg^{-1}		Waterbody 1: 1.94 Waterbody 2: 1.94	0.2*	2.94
CFW	*c* coefficient in the wind speed formulation	Wm^{-2} mm Hg^{-1}		Waterbody 1: 1.0* Waterbody 2: 1.0*	1.0*	1.0*

*Value is adopted from HCC W2 models (Wells, Berger, & Garstecki, 2021b).

Table 6. Stations used for the W2 model flow and temperature calibrations.

Gage	Location	River Mile (RM)	Source	Calibration	
				Flow	Temperature
USGS 13213100	Snake River at Nyssa	389	USGS	✓	✓
IPC RM 383 MC	Snake River below Nyssa	383	IPC	X	✓
IPC RM 354.3 LB	Snake River near Weiser	345.3	IPC	X	✓
USGS 13269000	Snake River at Weiser	354	USGS	✓	✓
IPC RM 345.2 LB	Snake River Brownlee Reservoir upstream	345	IPC	X	✓
IPC RM 283.9 LC	Snake River below Brownlee Dam, left channel	284	IPC	X	✓
IPC RM 283.9 RC	Snake River below Brownlee Dam, right channel	284	IPC	X	✓
IPC RM 269.8 LC	Snake River below Oxbow Dam	270	IPC	X	✓
IPC RM 247.6	Snake River Hells Canyon Dam Penstock	248	IPC	X	✓
IPC RM 229.8	Snake River near Sheep Creek	230	IPC	X	✓
USGS 13290460	Snake River at Sheep Creek	230	USGS	✓	X
IPC RM 216.3	Snake River near Pittsburg Landing	216	IPC	X	✓
IPC RM 202.3	Snake River near Dry Creek	202	IPC	X	✓
IPC RM 189	Snake River above Salmon River	189	IPC	X	✓
USGS 13317660	Snake River near Triple Border (ID-OR-WA)	176	USGS	✓	✓

USGS 13334300	Snake River near Anatone, WA	168	USGS	✓	✓

3.7 LINKING W2 MODELS TO PSU HCC MODEL

A W2 model of the Hells Canyon Complex (HCC model) has been developed by PSU using model version 4.5 (Wells, Berger, & Garstecki, 2021b). The PSU model covers the three linked IPC reservoirs (in upstream to downstream order): Brownlee, Oxbow, and Hells Canyon (see Figure 1). It does not include the free-flowing river reaches upstream of Brownlee reservoir and downstream of Hells Canyon Dam. The boundary between Brownlee Reservoir and the upstream free-flowing Snake River is variable, depending on the reservoir water surface elevation. The PSU model domain is extended upstream to RM 345.6 to include the extent of Brownlee at full pool but does not include the river reaches upstream of that point. The total mainstem length included in the PSU model is 95.9 miles (Hells Canyon Dam to upper extent of Brownlee pool).

The HCC model is constructed at a high spatial resolution. Brownlee, which is the largest reservoir, is represented with 239 lateral segments in 7 branches, with a maximum of 102 layers (1 m resolution) and is divided into 5 separate water bodies that allow specification of different meteorological inputs to different portions of the reservoir. Oxbow has 53 lateral segments in 57 layers, while Hells Canyon has 112 lateral segments in 81 layers. The model boundary includes inflow and temperature from Burnt River, Powder River, Daily Creek, Wildhorse River, Pine Creek, and Snake River mainstream. There are no external permitted point source discharges to the HCC model. The model contains a detailed representation of topographic shading, which has important effects on solar radiation input. The model is calibrated to an extensive series of vertical profiles and outflow temperatures collected by IPC and runs for calendar years 2014-2018.

Snake River flow and temperature boundaries for the HCC model at the head of Brownlee Reservoir are specified using USGS streamflow observations at Weiser (13269000, RM 354) and IPC temperature observations at RM 345 (Figure 3). The Adrian to Brownlee model was linked to the HCC model, so flows and temperatures entering Brownlee Reservoir are the simulated values from the upstream model (simulated flow and water temperature for segment 182). Similarly, downstream of the HCC model, the W2 downstream models were linked to the HCC model, and the flows and temperatures entering the downstream models are the simulated outflow and temperature from the HCC model at Hells Canyon Dam. The evaluation of reservoir-linked models was conducted using sub-hourly water temperature observations from IPC RM 283.9 LC and IPC RM 283.9 RC for Brownlee Dam, and IPC RM 269.8 LC and IPC RM 247.6 for Oxbow Dam and Hells Canyon Dam downstream segments, respectively.

The main body of this report presents the results of Snake River simulated discharge and water temperature produced by the linked Tetra Tech and PSU models to be used to support the TMDL. To provide supplemental information related to the model linkage, the calibration results of W2 models below Hells Canyon Dam using flow and water temperature observations (IPC 13290450 and IPC RM 229.8 LB) for the upstream boundary are presented in Appendix B (Section 8.0).

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4.0 CALIBRATION RESULTS

4.1 FLOW AND WATER BALANCE

4.1.1 Adrian to Brownlee

The model daily simulated flows are compared against observations at Nyssa (USGS 13213100) and Weiser (USGS 13269000) in Table 7 and Figure 26 - Figure 29. The W2 model simulated the Snake River streamflow very well with $R^2 \geq 0.98$ and NSE ≥ 0.82 (Figure 26 and Figure 28).

Under typical flow conditions for 2014-2016, the Snake River streamflow ranged between 200-400 m^3/s and 250-800 m^3/s at Nyssa and Weiser, respectively. During the high flow events in 2017 and 2018, the river flow significantly increased and reached 1,291 and 1,953 m^3/s, respectively. The calibrated W2 model provides a good match to the gaged flow spectra in the Snake River, especially the 2017 and 2018 flood peaks. The simulated flows were sorted and their probabilities computed and compared against observations using the Empirical Cumulative Distribution (ECD) method. ECD graphs show the model tends to slightly underestimate the high flows (discharge > 350 m^3/s), but the bias on average is limited to 8% of flow. The difference between simulated and observed discharge was larger at Weiser (downstream station). The discrepancy between model flow simulation and observations at Weiser was likely due to a combination of the representation of river channel morphology in the W2 model and potential flow gain from unmodeled sources such as small tributaries and groundwater discharge. The Snake River was simulated as a single-strand channel in the W2 model, but in fact the river meanders through its path from Adrian to Brownlee and is braided by small islands in several locations. Flow and velocity typically are different in braided river channels, resulting in smaller discharge estimates for the Snake River than when it is simulated as a single unified channel.

The underestimation of flow could impact the Snake River water temperature simulation during high flow events. A sensitivity test was performed to evaluate impact of flow bias on W2 water temperature simulation by adding 40 m^3/s distributed flow to waterbody 2 in the model. The result of flow sensitivity analysis did not show a significant impact on W2 water temperature simulation because the simulated temperature was mainly driven by the Snake River upstream boundary. Distributed flow however degraded temperature fit for the downstream reservoir models by impacting HCC reservoirs water balance and was removed from the Adrian to Brownlee model.

During the simulation of initial time or day=1, there are small sudden jumps and drops in simulated flows. These are due to the initial water surface elevations that were estimated from USGS rating curves (USGS WaterWatch -- Streamflow conditions); these initial elevations were adjusted to help with model stability. These flow discrepancies however had minimal impact on water balance and temperature of PSU Brownlee Reservoir model.

Table 7. Performance of W2 in simulating Snake River discharge, Adrian to Brownlee.

Gage	Location	River Mile (RM)	Number of observations	R^2	NSE
USGS 13213100	Snake River at Nyssa	389	1,826	1.0	0.95
USGS 13269000	Snake River at Weiser	354	1,826	0.98	0.82

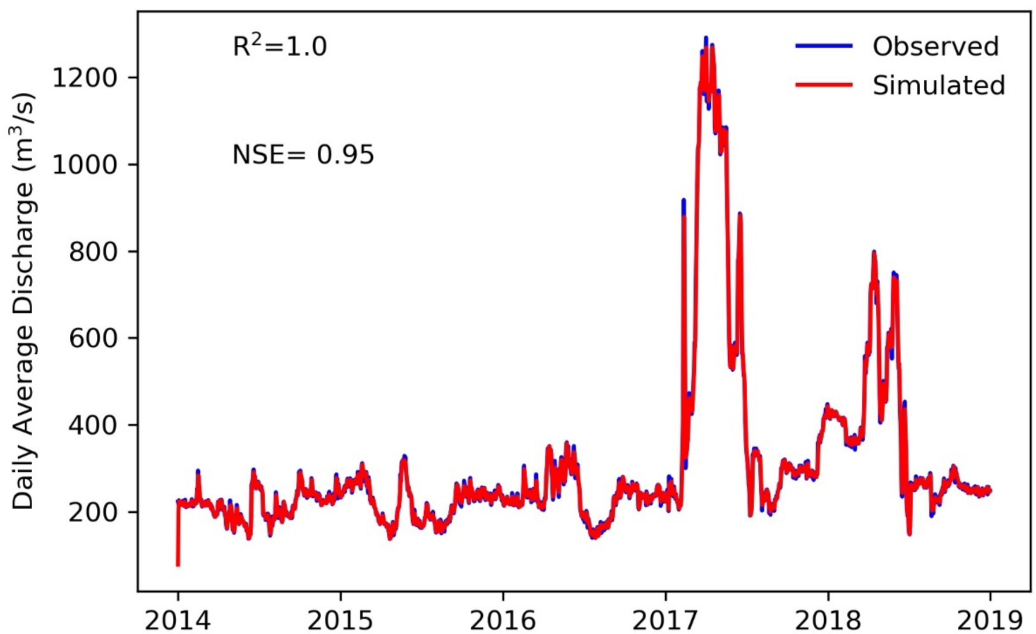

Figure 26. W2 simulated daily streamflow (red) versus USGS flow observations (blue) at Nyssa (USGS 13213100).

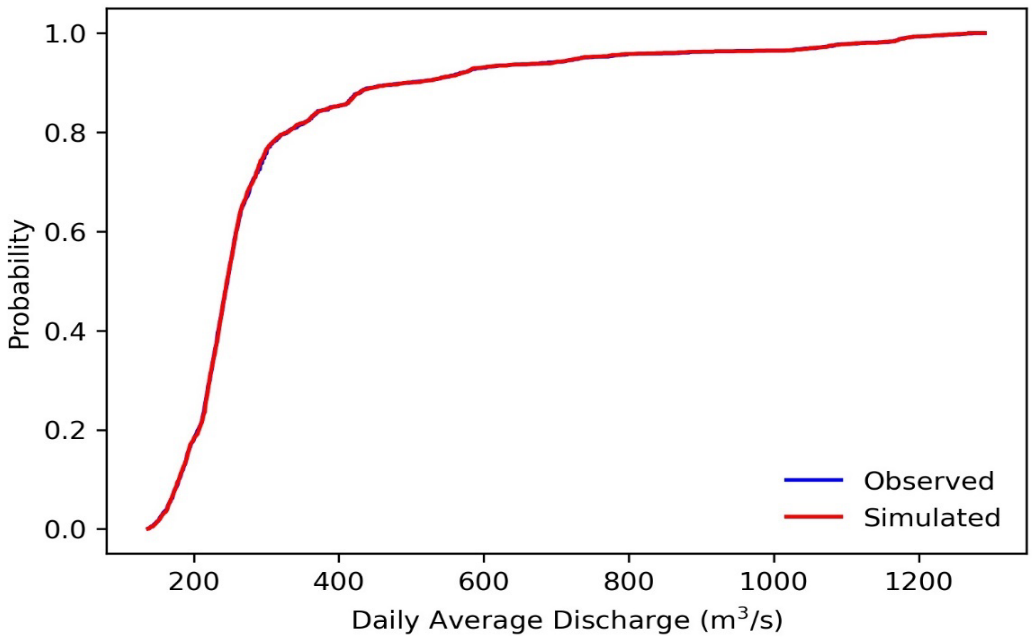

Figure 27. Observed (blue) and W2 simulated (red) streamflow at Nyssa (USGS 13213100), ECD graph.

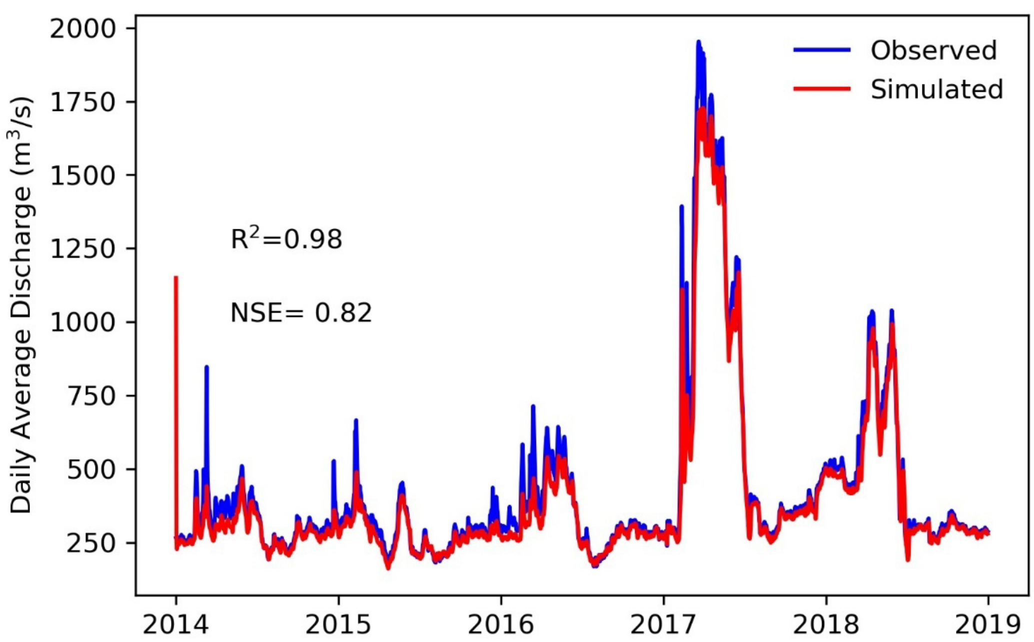

Figure 28. W2 simulated daily streamflow (red) versus USGS flow observations (blue) at Weiser (USGS 13269000).

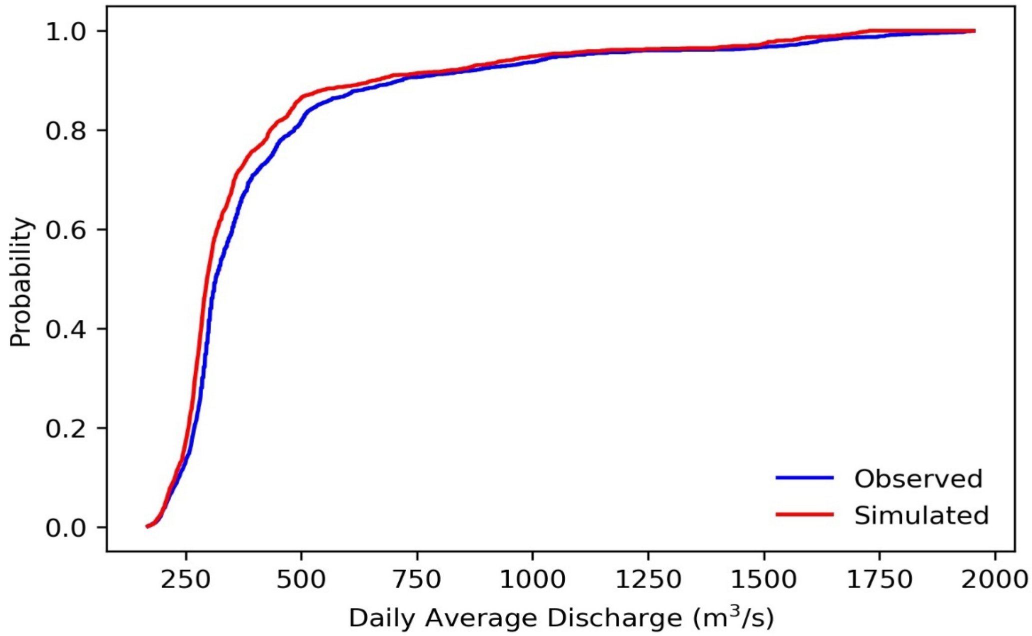

Figure 29. Observed (blue) and W2 simulated (red) daily streamflow at Weiser (USGS 13269000), ECD graphs.

4.1.2 Hells Canyon Dam to Washington State Line

Snake River simulated discharges are compared to daily average flow observations at Snake River RM 230 Sheep Creek (USGS 13290460) and RM 176 near Triple Border (ID-OR-WA, USGS 13317660) in Table 8 and Figure 30 - Figure 33. The model simulated streamflow well with $R^2 \geq 0.98$ and NSE ≥ 0.82. ECD graphs show the model tends to slightly underestimate the low flows, discharges < 750 m^3/s at Sheep Creek and discharges < 1,000 m^3/s at Near Triple Border, but the bias is limited to less than 5% of flow.

Table 8. Performance of W2 in simulating Snake River discharge.

Gage	Location	River Mile (RM)	Number of observations	R^2	NSE
USGS 13290460	Snake River at Sheep Creek	230	1,826	0.98	0.82
USGS 13317660	Snake River Near Triple Border (ID-OR-WA)	176	1,826	0.99	0.89

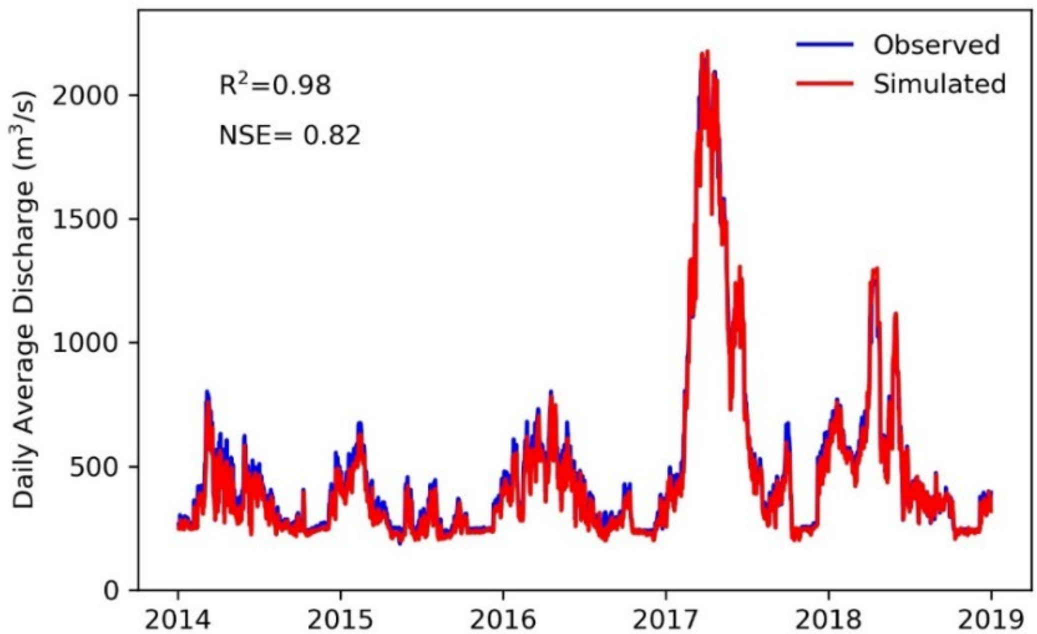

Figure 30. W2 simulated daily streamflow (red) versus USGS flow observations (blue) Sheep Creek at RM 230 (USGS 13290460)

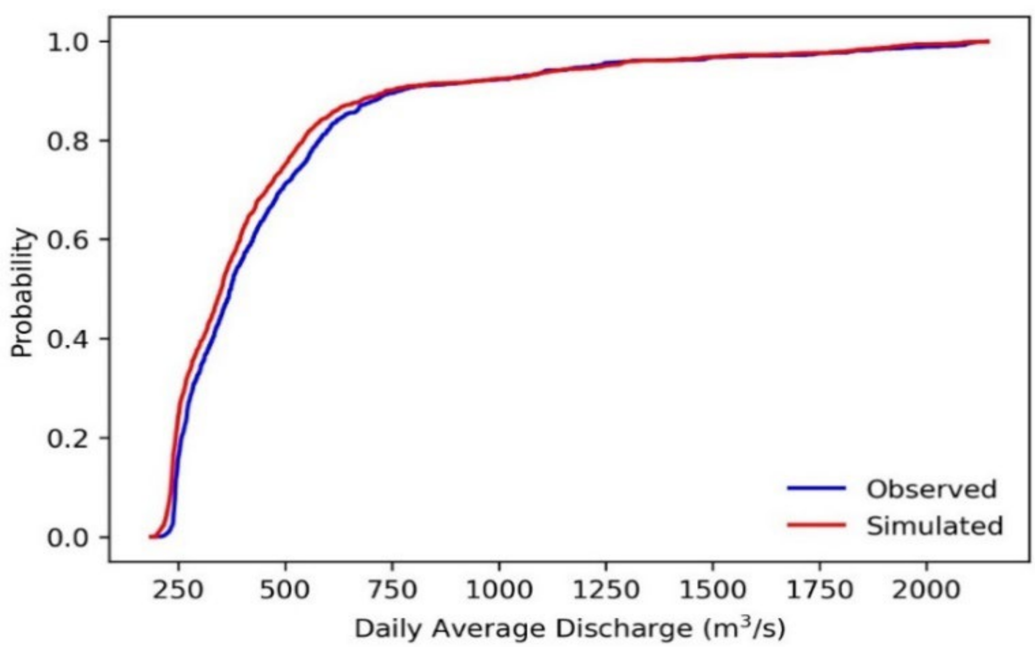

Figure 31. Observed (blue) and W2 simulated (red) streamflow Sheep Creek at RM 230 (USGS 13290460), ECD graph.

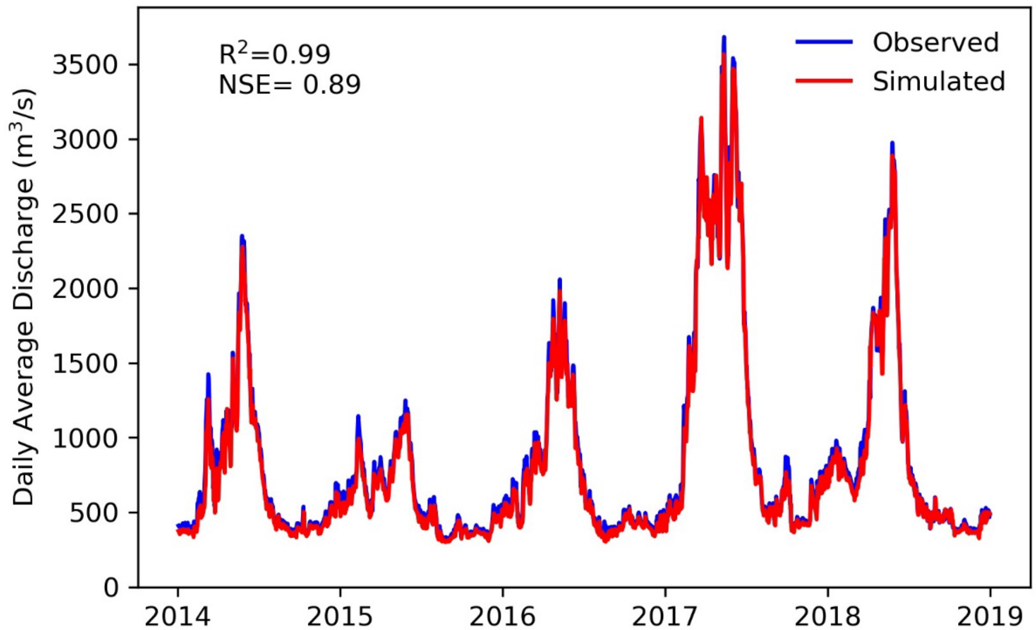

Figure 32. W2 simulated daily streamflow (red) versus USGS flow observations (blue) Near Triple Border at RM 176 (ID-OR-WA, USGS 13317660).

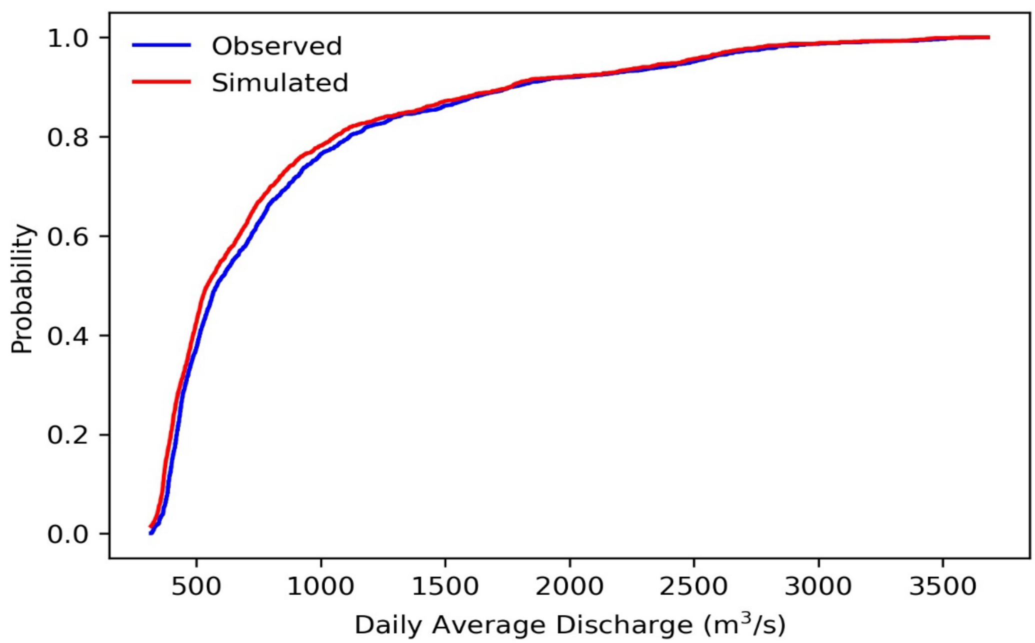

Figure 33. Observed (blue) and W2 simulated (red) streamflow Near Triple Border at RM 176 (ID-OR-WA, USGS 13317660), ECD graph.

4.1.3 Oregon and Washington State Line to Clearwater

Snake River simulated streamflow are compared against daily average flow observations near Anatone, WA (USGS 13334300) in Table 9 and Figure 34. The model well predicted the observed flows with $R^2 = 0.99$ and NSE = 0.9. ECD graph (Figure 35) shows a minimal (maximum less than 4%) bias between simulated and observed flows below about 1,500 m^3/s.

Table 9. Performance of W2 in simulating Snake River discharge.

Gage	Location	River Mile (RM)	Number of observations	R^2	NSE
USGS 13334300	Snake River Near Anatone, WA	168	1,826	0.99	0.9

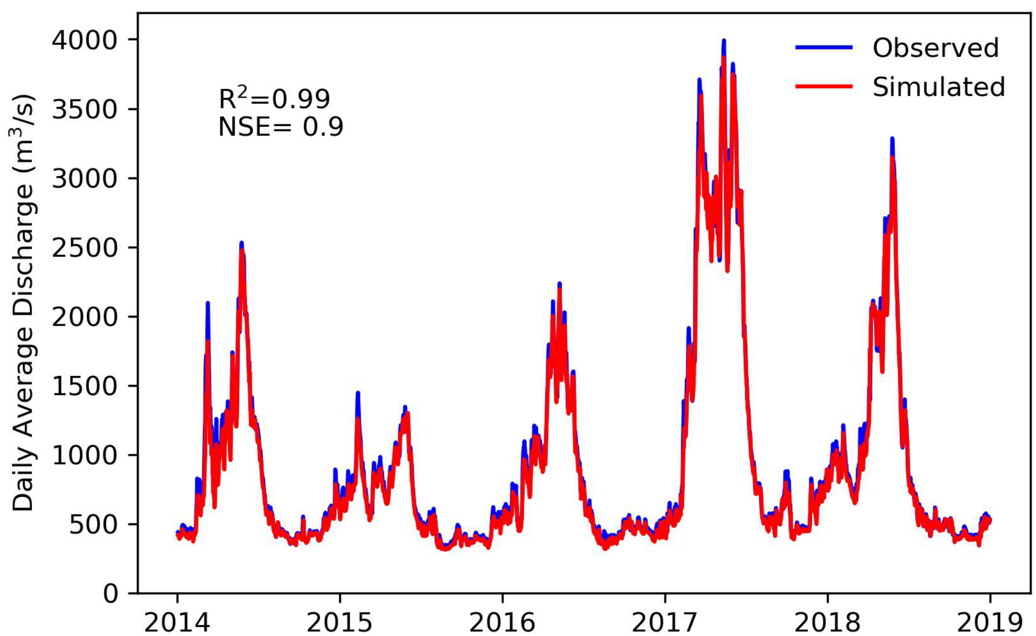

Figure 34. W2 simulated daily streamflow (red) versus USGS flow observations (blue) near Anatone at RM 168 (USGS 13334300).

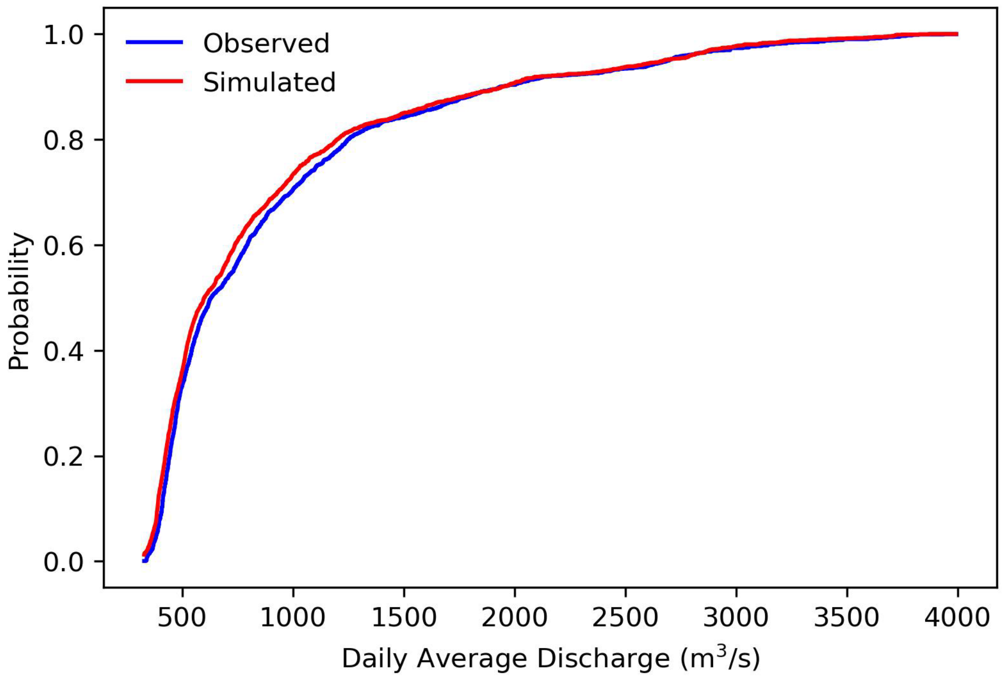

Figure 35. Observed (blue) and W2 simulated (red) streamflow near Anatone at RM 168, ECD graph.

4.2 WATER TEMPERATURE

4.2.1 Adrian To Brownlee

4.2.1.1 Hourly Comparison

W2 hourly simulated water temperatures are compared against observations at RM 383 (Nyssa), RM 354.3 (Near Weiser), and RM 345 (Brownlee Reservoir Upstream) in Figure 36 through Figure 41. Statistics evaluating the model fit for whole year and the warmer season (May-November) are presented in Table 10. The model simulated the hourly water temperature observations well with RMSE ≤ 1.31°C and NSE ≥ 0.83. The simulated temperatures deviated from observations by less than 0.94°C measured by RMSE, ME, and MAE for RM 383 and RM 345. For RM 354.3 (Weiser) the model RMSE were 1.31°C and 1.53°C for the modeling period and summer. Analysis of simulated temperatures shows the model overestimated the measured water temperatures above 20°C at this station (Figure 38 and Figure 39). This contrasts to the W2 outputs for the neighboring stations where the model slightly underestimated the similar range of temperature. This suggests it is unlikely that the temperature discrepancies at RM 354.3 were related to the model water temperature parameters or boundary conditions. The model performance was investigated by comparing temperature observations at RM 383, RM 354.3, and RM 345 (Figure 42). Interestingly, the RM 383 and RM 345, upstream and downstream of RM 354.3, had similar observations (Figure 42a) and RM 354.3 observations were a couple of degrees cooler in summer and a little warmer in winter compared to two other stations (Figure 42b). The river channel at RM 354.3 is single strand and there is no significant topographic or vegetative shading at this station. Sensitivity analysis of the model also showed the W2 is not sensitive to Weiser River temperature boundary tested within range of 0-5 °C. The reasons for the discrepancies at the Weiser station (RM 354.3) are apparently due to data quality issues at this station (particularly in 2015). This was confirmed by IPC after reviewing water temperature measurements at RM 354.3 (IPC communication with EPA, May4 2023). The temperature diel cycle at this station appears subdued and potentially delayed in comparison to the upstream and downstream locations. This discrepancy is attributed to sediment accumulation that covered the temperature sensor, leading to the station being decommissioned in 2018.

In addition, USGS station (13269000) is situated on the right bank of the Snake River (Figure 3) and may be influenced by the Weiser River, which flows approximately 0.5 miles upstream. Consequently, the temperature recorded at this station could be impacted by the Weiser River flow and may not accurately represent the conditions in the main channel of the Snake River, especially during varying flow conditions.

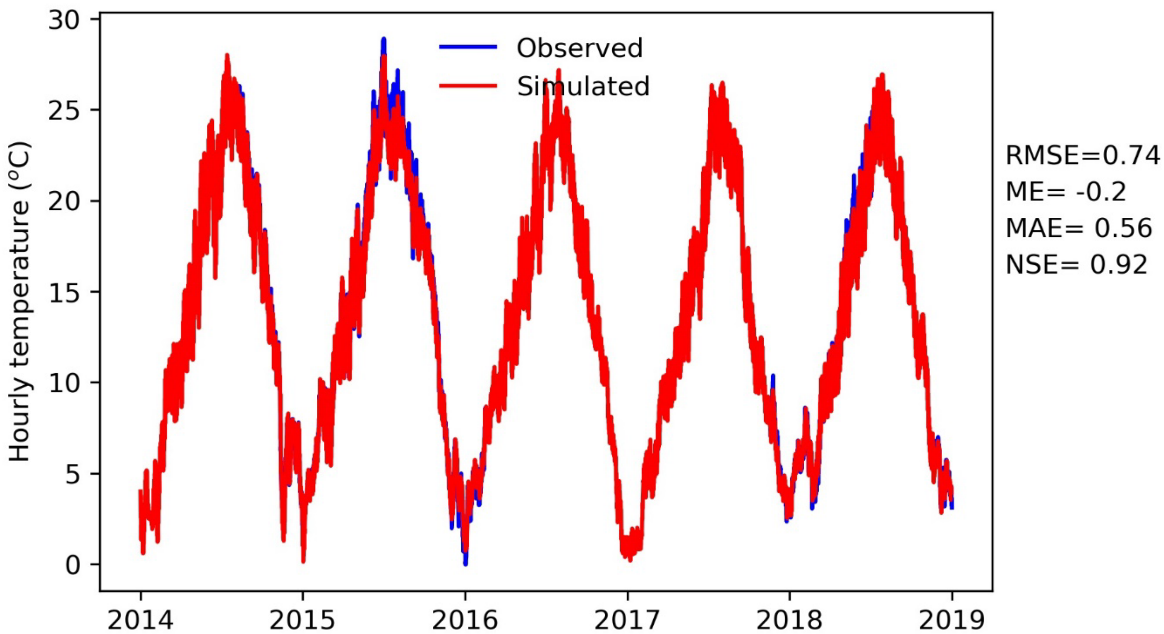

Figure 36. W2 hourly simulated water temperatures versus observations below Nyssa at RM 383.

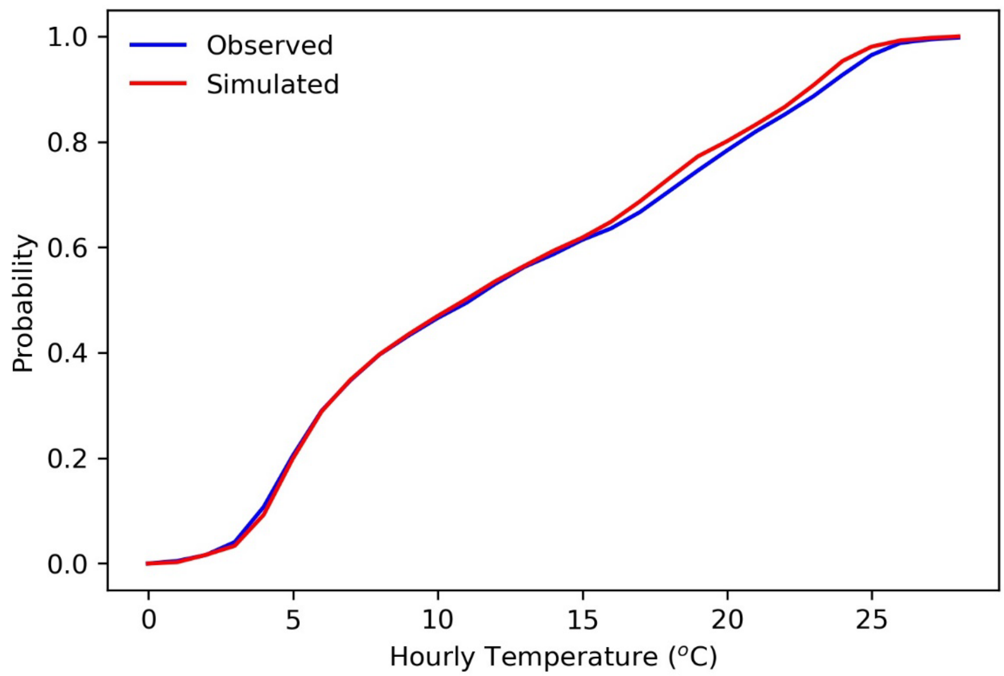

Figure 37. W2 simulated water temperatures versus observations below Nyssa at RM 383, ECD graph.

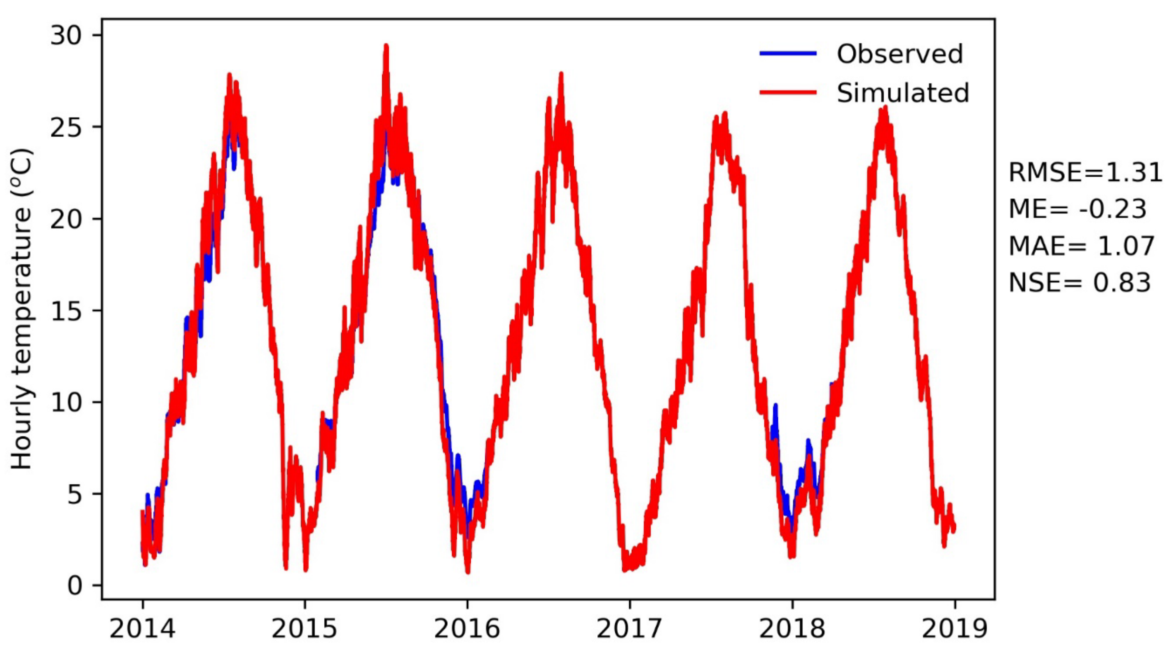

Figure 38. W2 hourly simulated water temperatures versus observations near Weiser at RM 354.3.

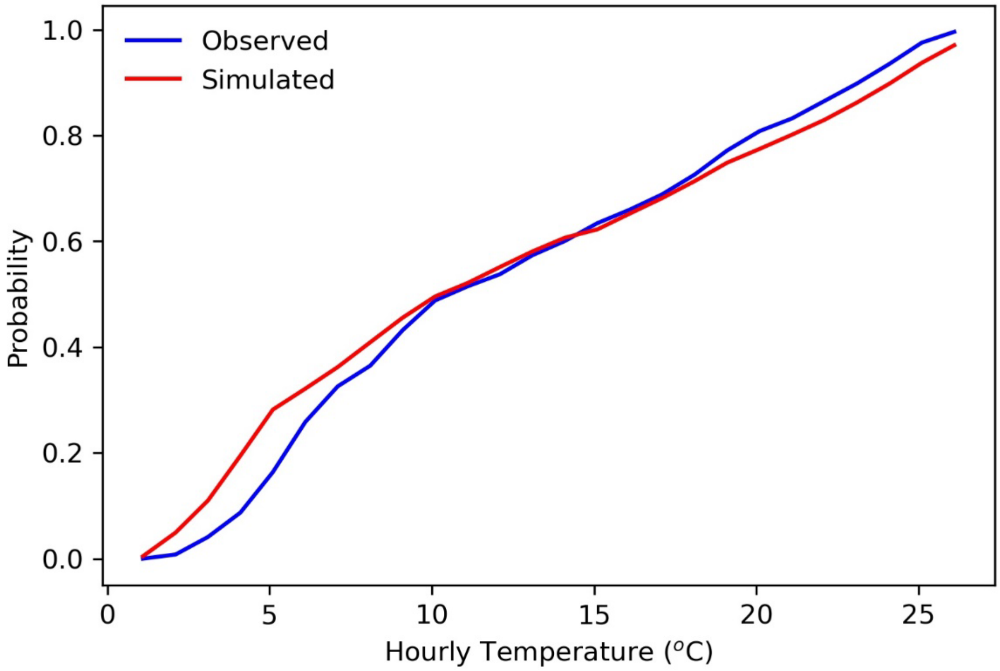

Figure 39. W2 hourly simulated water temperatures versus observations near Weiser at RM 354.3, ECD graph.

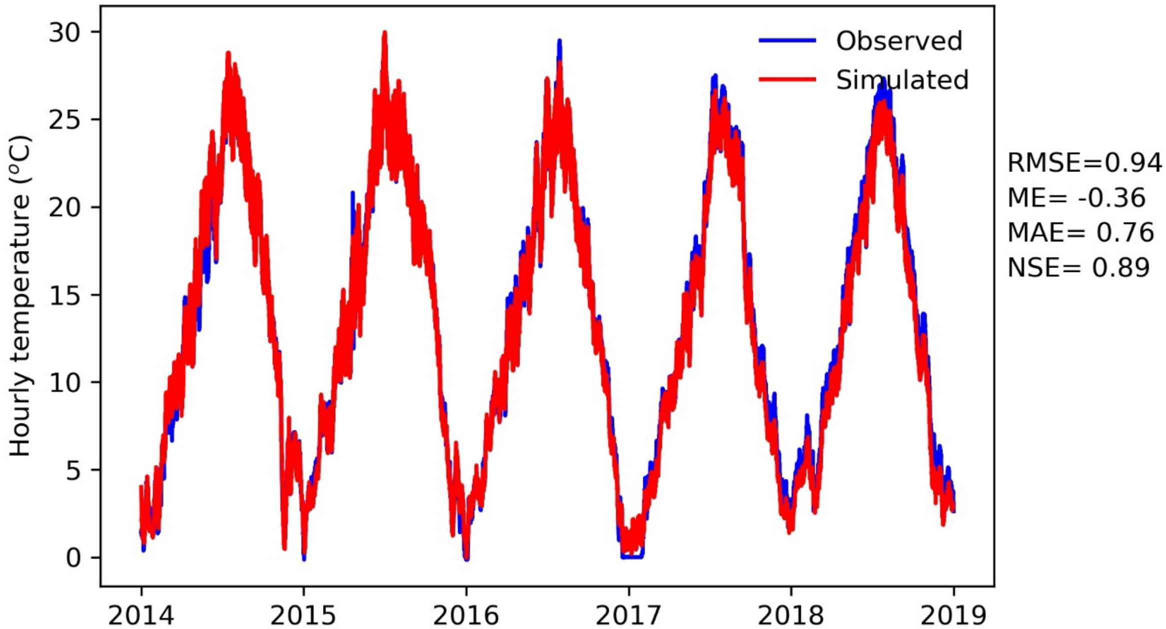

Figure 40. W2 hourly simulated water temperatures at segment 182 versus observations at Brownlee Reservoir upstream RM 345.

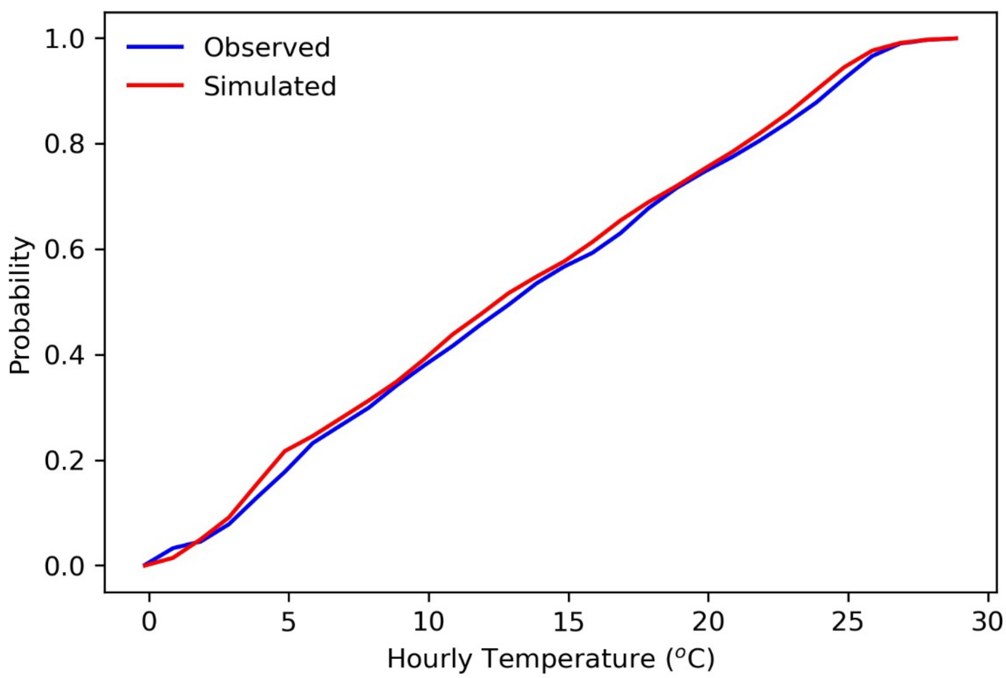

Figure 41. Hourly simulated water temperatures versus observations at Brownlee Reservoir upstream RM 345, ECD graph.

Table 10. Performance of W2 in simulating Snake River hourly water temperature. Error units are in °C.

Gage	Location	River Mile (RM)	Count	Full Year				Summer (May-November)			
				NSE	RMSE	ME	MAE	NSE	RMSE	ME	MAE
IPC 383 MC	Below Nyssa	383	20,010	0.92	0.74	-0.20	0.56	0.87	0.87	-0.47	0.66
IPC 354.3 LB	Weiser	354.3	17,493	0.83	1.31	-0.23	1.07	0.68	1.53	0.37	1.25
IPC 345.2 LB	Brownlee Reservoir Upstream	345	43,438	0.89	0.94	-0.36	0.76	0.82	1.05	-0.47	0.86

Note: NSE = Nash Sutcliffe coefficient of model fit efficiency, RMSE = root mean squared error, ME = mean error, MAE = mean absolute error.

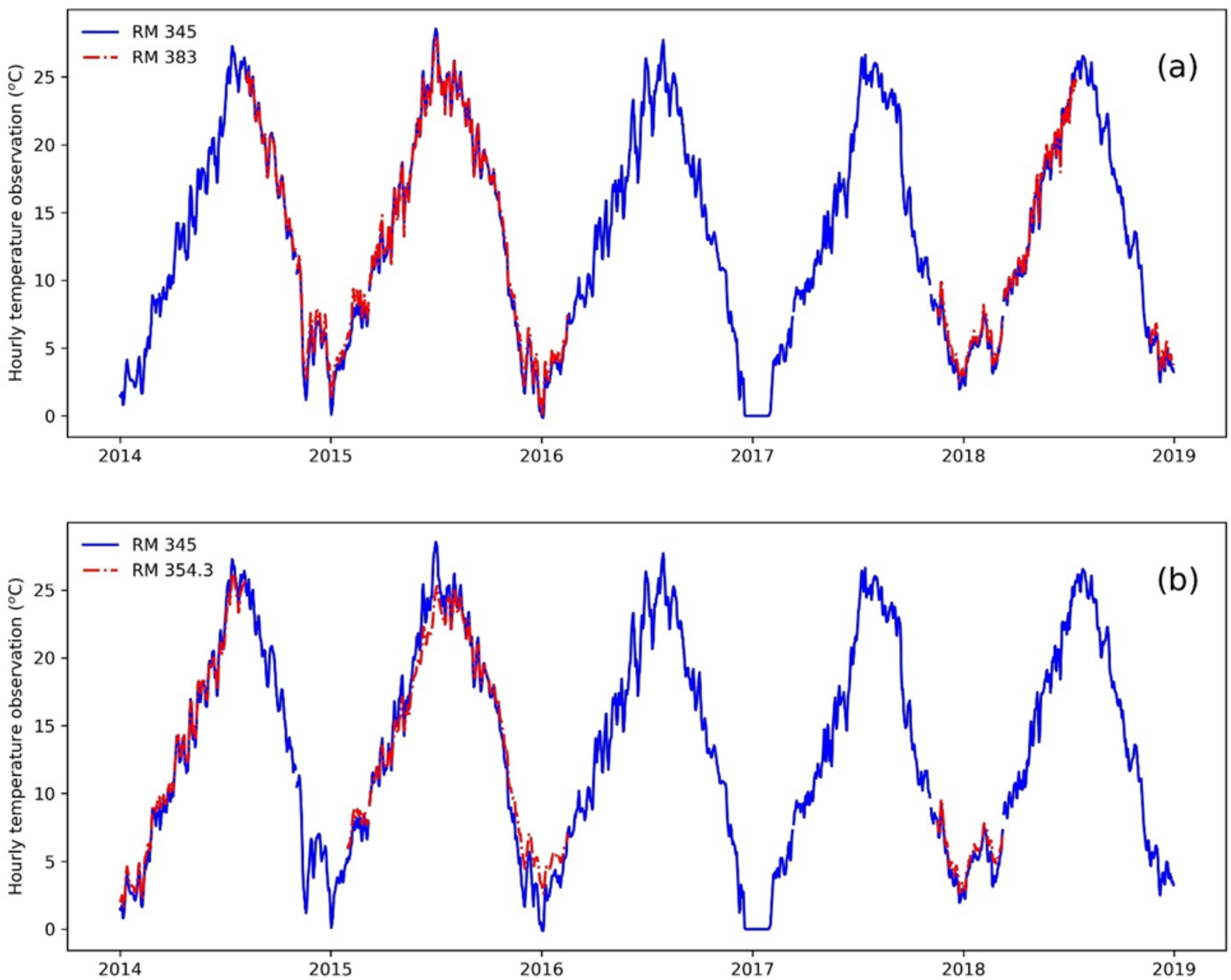

Figure 42. Hourly water temperature observations, (a) RM 345 versus RM 383 and (b) RM 345 versus RM 354.3

4.2.1.2 Daily Average Water Temperature Comparison

W2 simulated hourly water temperatures are averaged and compared to daily observations for six stations in Table 11 and Figure 65 through Figure 74 in the Appendix A (Section 7.1.1). The model simulated temporal variation of daily water temperature observations well with NSE≥ 0.82 for modeling period and NSE ≥ 0.71 for summer for all stations. The model had RMSE ≤ 0.79°C and 0.86°C for full year and summer simulations for USGS 13213100, RM 383, and RM 354.2. For stations near Weiser, RM 354.3 and USGS 13269000, the RMSE were 1.25°C and 1.8°C for modeling period and 1.41°C to1.49°C for the summer. As was discussed in Section 4.2.1.1, the temperature observations near Weiser are influenced by various local effects.

Table 11. Performance of W2 in simulating Snake River daily average water temperatures (°C).

Gage	Location	River Mile (RM)	Count	Full Year				Summer (May-November)			
				NSE	RMSE	ME	MAE	NSE	RMSE	ME	MAE
USGS 13213100	Nyssa	389	656	0.91	0.68	0.10	0.54	0.85	0.68	0.32	0.52
IPC RM 383 MC	Below Nyssa	383	835	0.93	0.63	-0.20	0.49	0.88	0.75	-0.46	0.60
IPC RM 354.3 LB	Near Weiser	354.3	710	0.84	1.25	-0.23	1.02	0.71	1.41	0.39	1.13
USGS 13269000	Weiser	354	656	0.82	1.80	1.07	1.30	0.80	1.49	0.52	0.90
IPC RM 345.2 LB	Brownlee Reservoir Upstrea m	345	1,816	0.90	0.79	-0.36	0.65	0.86	0.86	-0.46	0.70

Note: NSE = Nash Sutcliffe coefficient of model fit efficiency, RMSE = root mean squared error, ME = mean error, MAE = mean absolute error.

4.2.1.3 Daily Maximum Temperature Comparison

W2 simulated daily maximum water temperatures are calculated from the hourly output and compared to observations for six stations in Table 12 and Figure 75 through Figure 84 in the Appendix A (Section 7.1.2). The model simulated temporal variation of daily maximum temperature observations well, with NSE≥ 0.82 for annual and NSE ≥ 0.65 for summer results for all stations. The model had RMSE ≤ 0.95 °C and 1.0°C for modeling period and summer for USGS 13213100, RM 383, and RM 354.2. For stations near Weiser, RM 354.3 and USGS 13269000, the RMSEs were 1.42°C and 1.72 °C for annual results and 1.7°C and 1.39 °C for the summer results.

Table 12. Performance of W2 in simulating Snake River daily maximum water temperatures. Error units are in °C.

Gage	Location	River Mile (RM)	Count	Full Year				Summer (May-November)			
				NSE	RMSE	ME	MAE	NSE	RMSE	ME	MAE
USGS 13213100	Nyssa	389	656	0.87	0.95	0.26	0.79	0.77	1.00	0.62	0.83
IPC RM 383 MC	Below Nyssa	383	835	0.93	0.66	-0.24	0.51	0.88	0.78	-0.51	0.62
IPC RM 354.3 LB	Near Weiser	354.3	710	0.82	1.42	-0.02	1.16	0.65	1.70	0.73	1.38
USGS 13269000	Weiser	354	656	0.83	1.72	0.99	1.32	0.78	1.39	0.46	0.99
IPC RM 345.2 LB	Brownlee Reservoir Upstream	346	1,816	0.90	0.89	-0.16	0.71	0.85	0.94	-0.16	0.74

Note: NSE = Nash Sutcliffe coefficient of model fit efficiency, RMSE = root mean squared error, ME = mean error, MAE = mean absolute error.

4.2.1.4 7DADMax Temperature Comparison

7DADMax water temperatures were calculated from W2 hourly simulations and are compared to observations for six stations in Table 13 and Figure 85 through Figure 94 in the Appendix A (Section 7.1.3). The model simulated temporal variation of 7DADMax temperature observations with NSE≥ 0.82 for modeling period and NSE ≥ 0.62 for summer for all stations. The model had RMSE ≤ 0.79°C and 0.84°C for modeling period and summer for USGS 13213100, RM 383, and RM 354.2. For stations near Weiser, RM 354.3 and USGS 13269000, the RMSE were 1.41°C and 1.58°C for the annual period and 1.67°C and1.18°C for the summer, respectively.

Table 13. Performance of CE-QUAL-W2 in simulating Snake River 7DADMax water temperatures. Error units are °C.

Gage	Location	River Mile (RM)	Count	Full Year				Summer (May-November)			
				NSE	RMSE	ME	MAE	NSE	RMSE	ME	MAE
USGS 13213100	Nyssa	389	650	0.91	0.69	0.26	0.57	0.80	0.80	0.62	0.70
IPC RM 383 MC	Below Nyssa	383	739	0.94	0.51	-0.25	0.38	0.87	0.67	-0.53	0.56
IPC RM 354.3 LB	Near Weiser	354.3	674	0.82	1.41	-0.01	1.15	0.62	1.67	0.85	1.36
USGS 13269000	Weiser	354	650	0.84	1.58	0.99	1.19	0.82	1.18	0.45	0.77
IPC RM 345.2 LB	Brownlee Reservoir Upstream	346	1,750	0.91	0.79	-0.16	0.63	0.86	0.84	-0.15	0.67

Note: NSE = Nash Sutcliffe coefficient of model fit efficiency, RMSE = root mean squared error, ME = mean error, MAE = mean absolute error.

4.2.2 Hells Canyon Complex

Linking the Adrian and Brownlee model to PSU calibrated W2 models could potentially introduce bias in reservoir water temperature simulation, as the simulated temperature and flow data are utilized for the upstream boundary of Brownlee Reservoir. In order to assess the performance of the linked reservoir models, a holistic evaluation is conducted by comparing the simulated temperature against observations for stations located below HCC dams. This step ensures that the reservoir models are performing well before they are connected to the downstream W2 models.

Table 14 and Figure 43-Figure 50 provide statistical summaries of the performance of the reservoir-linked models in simulating hourly water temperature for the Snake River. The W2 linked models exhibited a good performance, with RMSE, ME, and MAE ≤ 0.95 °C for the modeling period. In particular, the summer model showed better performance, with bias less than 0.8 °C based on the three statistics. However, Adrian to the Brownlee W2 model introduced an error of approximately 0.2 °C in the temperature simulated by the PSU reservoir models, as observed in the downstream segments of dams.

Table 14. Performance of linked PSU reservoir models in simulating Snake River hourly water temperature. Error units are in °C.

Gage	Location	River Mile (RM)	Count	Full Year				Summer (May-November)			
				NSE	RMSE	ME	MAE	NSE	RMSE	ME	MAE
IPC RM 283.9 LC	Below Brownlee Dam, Left Channel	284	41,503	0.87	0.92	-0.35	0.73	0.79	0.80	-0.17	0.64
IPC RM 283.9 RC	Below Brownlee Dam, Right Channel	284	42,773	0.87	0.95	-0.52	0.77	0.83	0.79	-0.40	0.69
IPC RM 269.8 LC	Below Oxbow Dam	270	42,415	0.88	0.93	-0.54	0.72	0.82	0.76	-0.38	0.59
IPC RM 247.6	Hells Canyon Dam Penstock	248	40,333	0.88	0.93	-0.59	0.73	0.83	0.71	-0.34	0.56

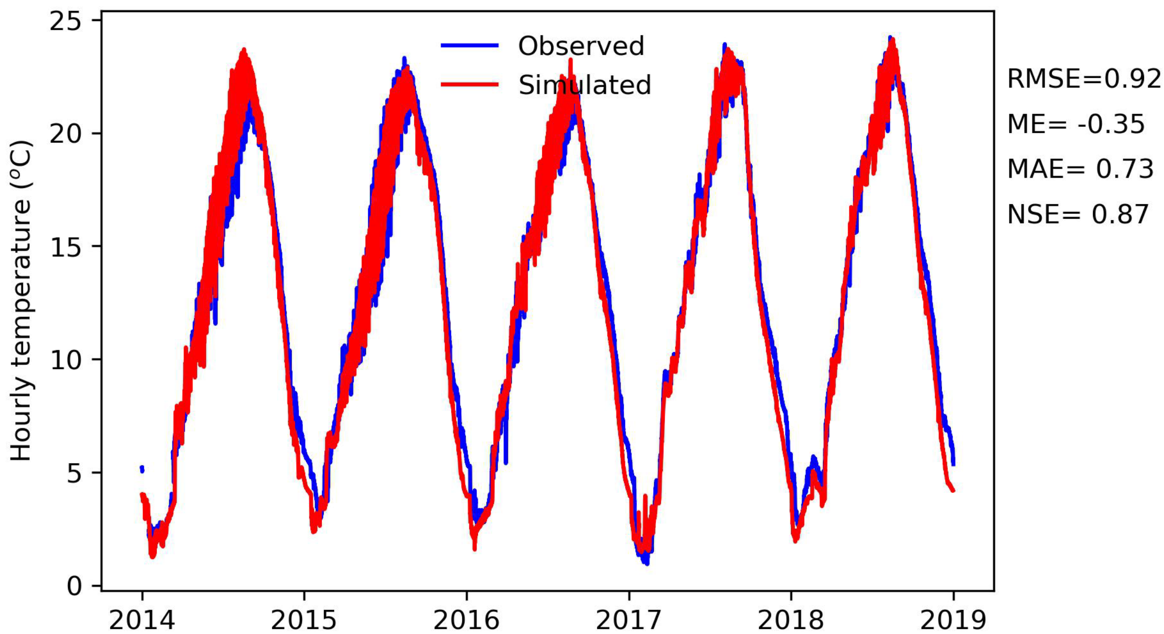

Figure 43. Hourly simulated water temperatures versus observations below Brownlee Dam at RM 284 LC.

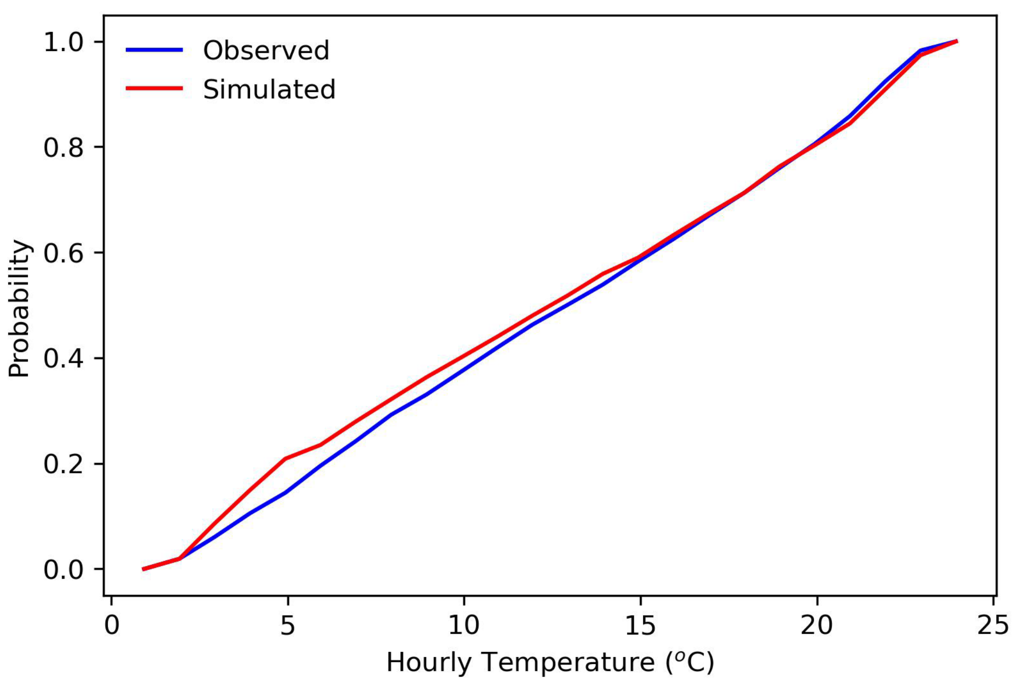

Figure 44. Hourly simulated water temperatures versus observations below Brownlee Dam at RM 284 LC, ECD graph.

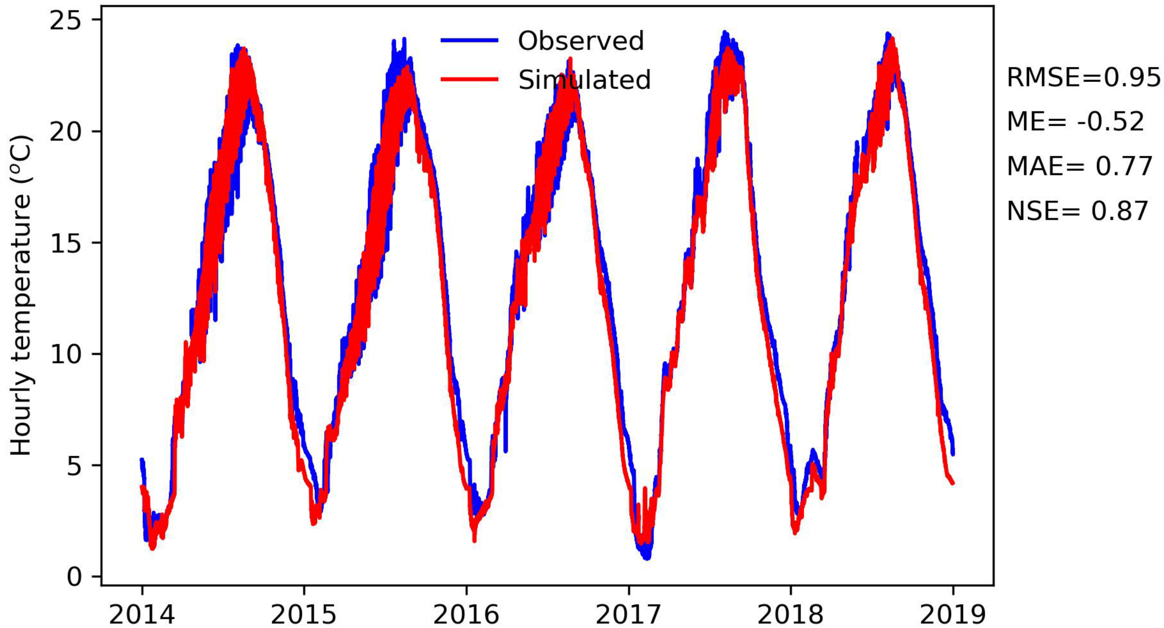

Figure 45. Hourly simulated water temperatures versus observations below Brownlee Dam at RM 284 RC.

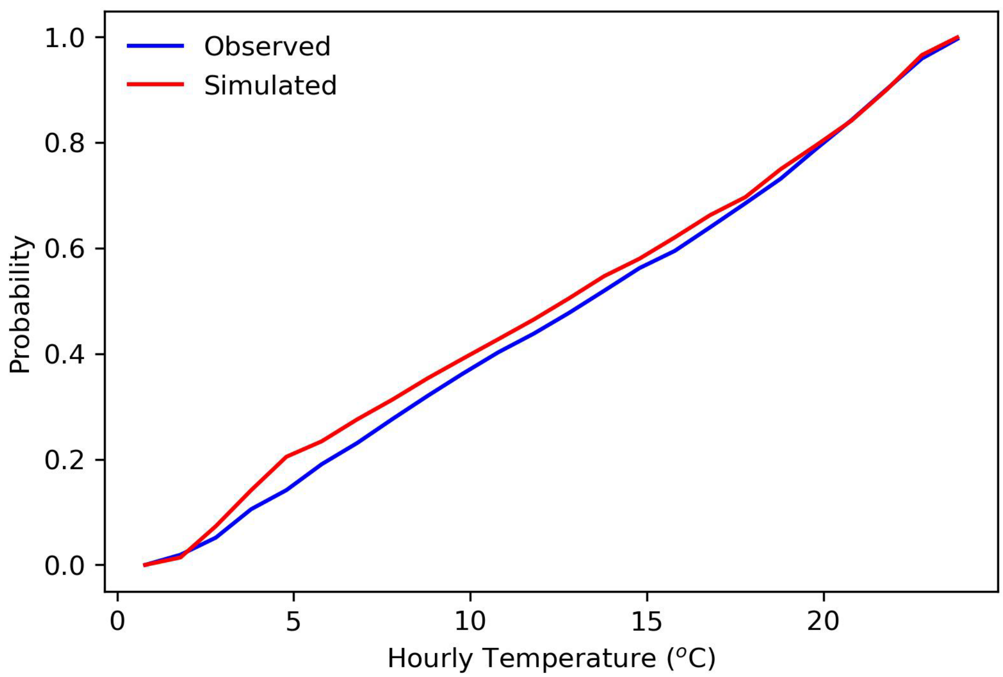

Figure 46. Hourly simulated water temperatures versus observations below Brownlee Dam at RM 284 RC, ECD graph.

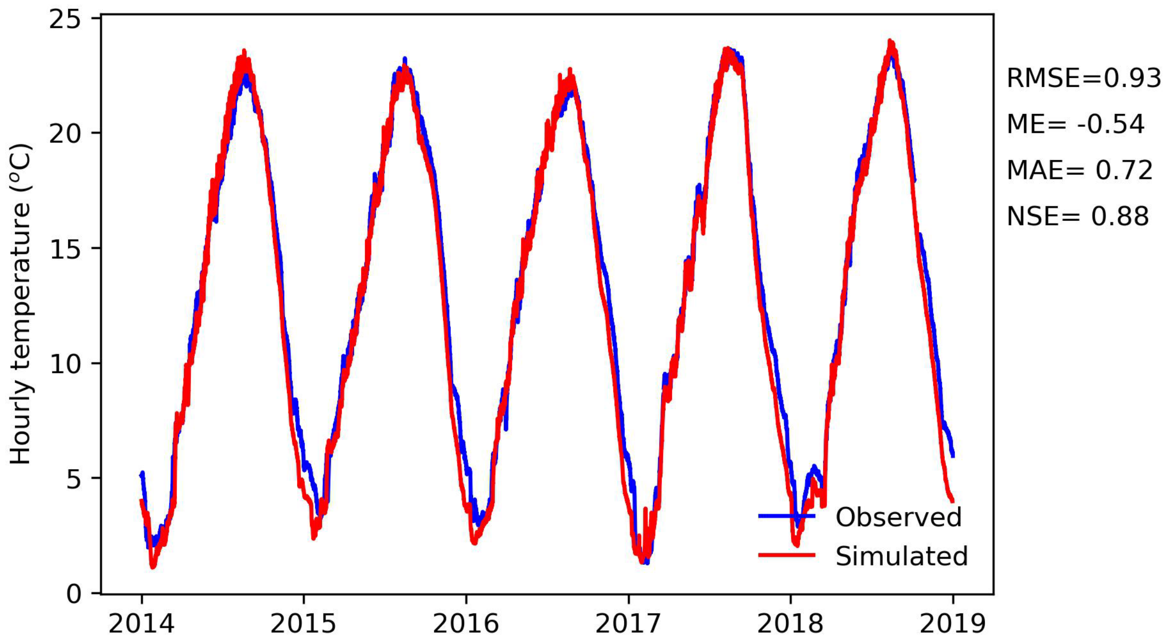

Figure 47. Hourly simulated water temperatures versus observations below Oxbow Dam at RM 270.

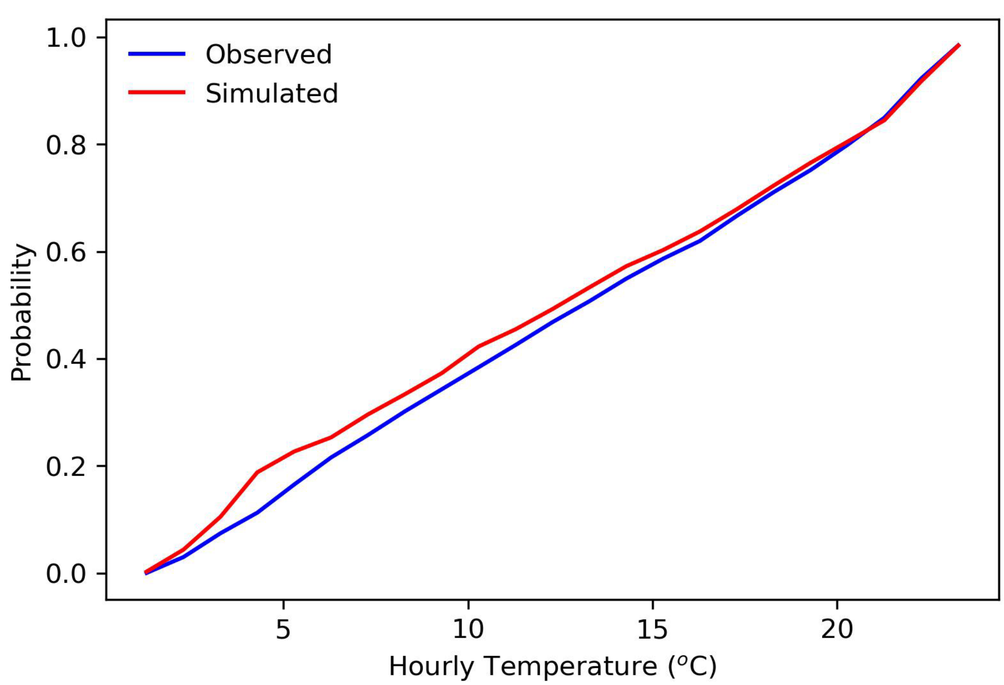

Figure 48. Hourly simulated water temperatures versus observations below Oxbow Dam at RM 270, ECD graph.

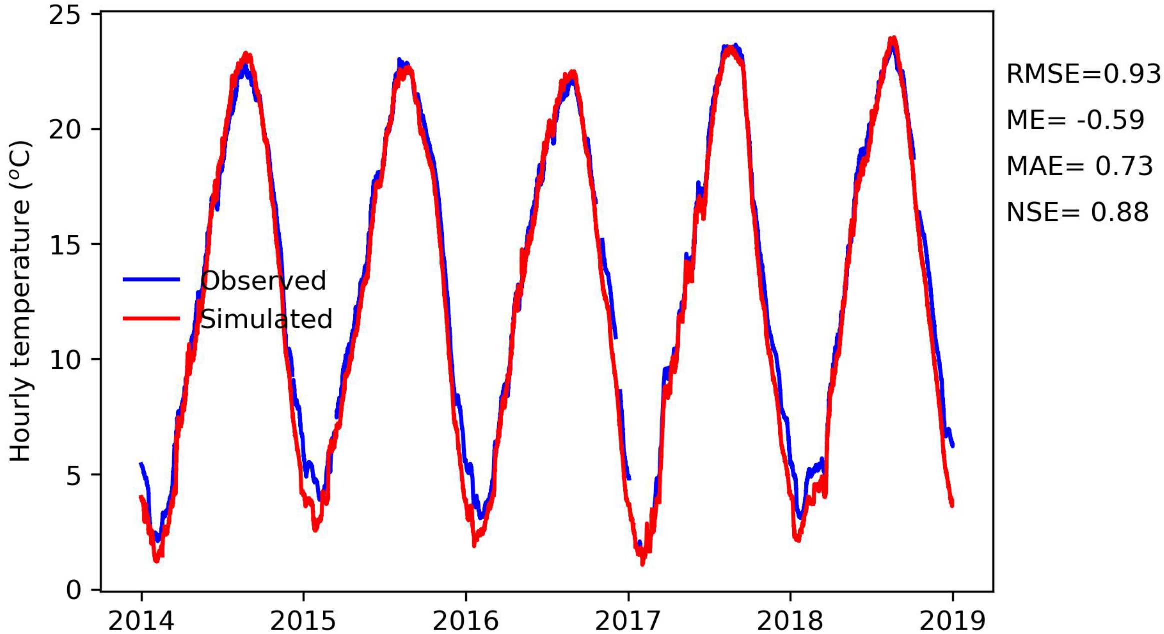

Figure 49. Hourly simulated water temperatures versus observations below Hells Canyon Dam at RM 248.

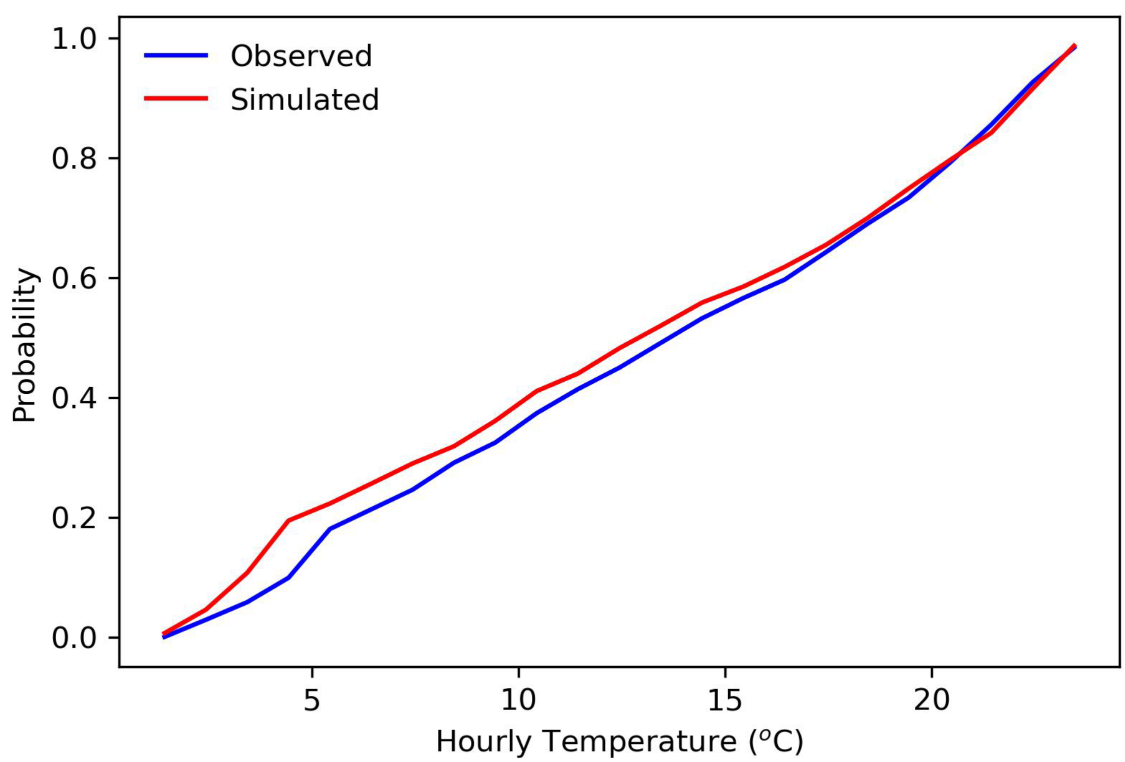

Figure 50. Hourly simulated water temperatures versus observations below Hells Canyon Dam at RM 248, ECD graph.

4.2.3 Hells Canyon to Oregon and Washington State Line

This section 4.2.3, presents results of Snake River water temperature simulation for Hells Canyon to Oregon and Washington State Line using the linked W2 model. Similarly, section 4.2.4 presents result of temperature simulation for Oregon and Washington State Line to Clear Water using linked W2 model. These linked models will be used for TMDL study. Additionally, the results of unlinked models, set up using Snake River water temperature observation, are presented in section 8.0 Appendix B which provides insight into accuracy of the calibrated models before they were linked to the upstream models.

4.2.3.1 Hourly Comparison

W2 hourly simulated water temperatures are compared against observations at RM 230, RM 216, RM 202, RM 189 in Table 15 and Figure 51 through Figure 58. Statistics evaluating the model fit for whole year and the warmer season (May-November) are presented in Table 15. The model simulated the hourly water temperature observations with RMSE ≤ 1.14°C and NSE ≥ 0.84 for the modeling period. The simulated temperatures deviated from observations by less than 0.85°C measured by RMSE, ME, and MAE for the warm season. In general, there is a small cold bias in simulated temperatures compared to observations. The bias is larger during winter and is consistent with results of simulated temperatures by the unlinked model (Table 23 and Figure 125 -Figure 130). However, for the linked W2 model the bias is approximately 0.5 °C larger than in the unlinked model where the upstream boundary is set using temperature observations.

Table 15. Performance of W2 in simulating Snake River hourly water temperature. Error units are in °C.

Gage	Location	River Mile (RM)	Count	Full Year				Summer (May-November)			
				NSE	RMSE	ME	MAE	NSE	RMSE	ME	MAE
IPC RM 229.8	Near Sheep Creek	230	33,986	0.87	0.95	-0.59	0.77	0.82	0.71	-0.29	0.57
IPC RM 216.3	Near Pittsburg Landing	216	43,436	0.86	1.02	-0.67	0.82	0.81	0.77	-0.38	0.61
IPC RM 202.3	Near Dry Creek	202	41,438	0.85	1.08	-0.77	0.87	0.81	0.80	-0.46	0.62
IPC RM 189	Above Salmon River	189	43,436	0.84	1.14	-0.87	0.93	0.80	0.85	-0.58	0.68
USGS 13317660	Near Triple Border (ID-OR-WA)	176	33,986	0.87	0.95	-0.59	0.77	0.82	0.71	-0.29	0.57

Note: NSE = Nash Sutcliffe coefficient of model fit efficiency, RMSE = root mean squared error, ME = mean error, MAE = mean absolute error.

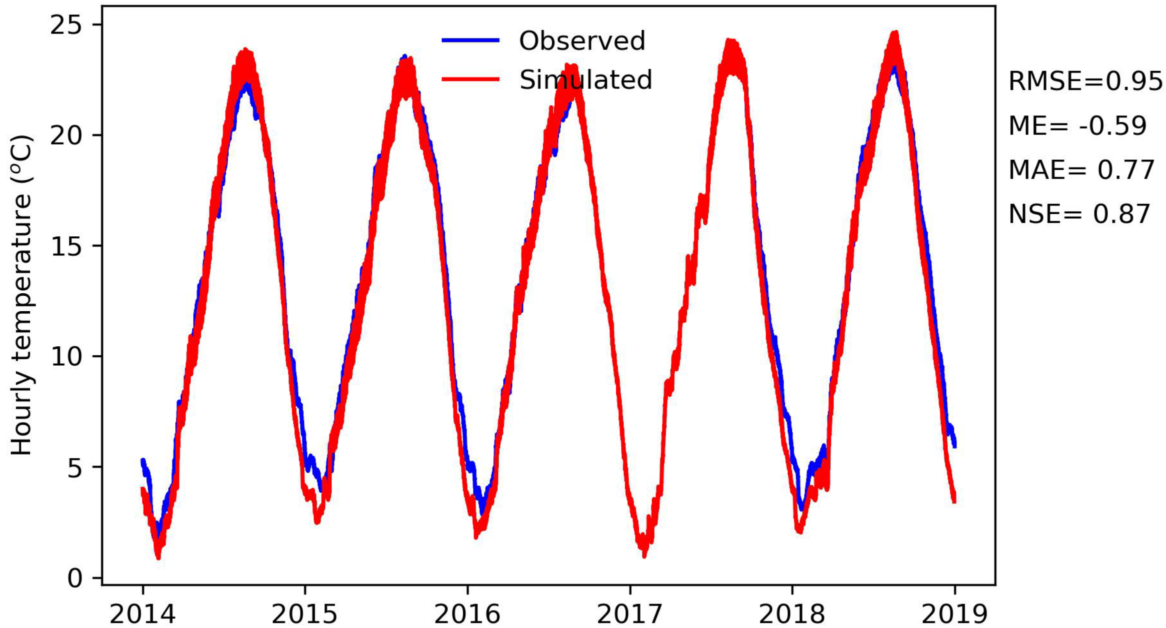

Figure 51. W2 hourly simulated water temperatures versus observations near Sheep Creek at RM 230.

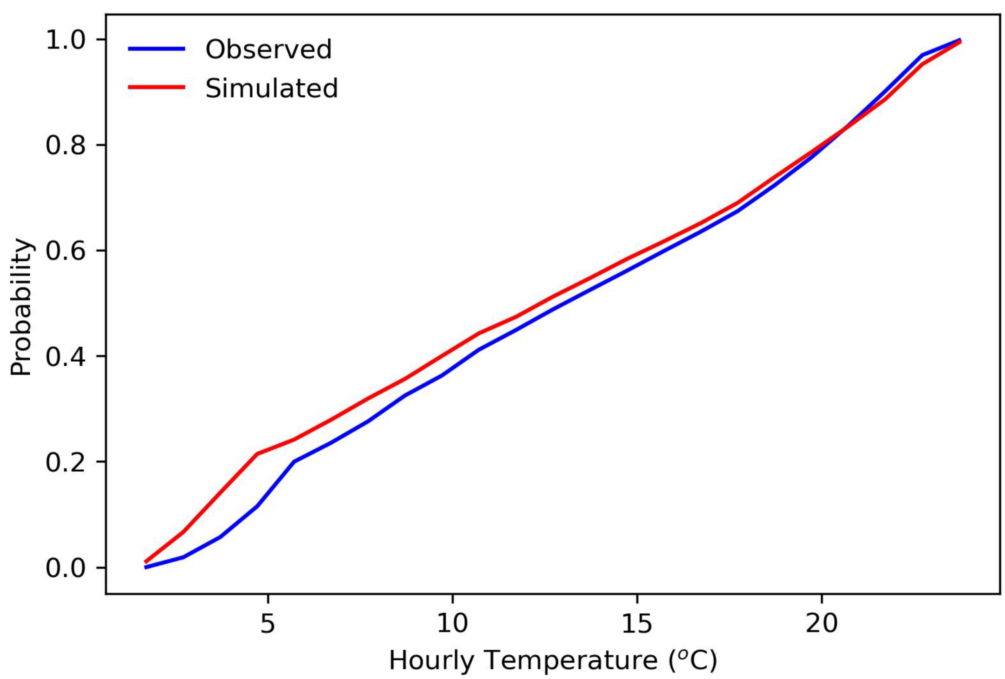

Figure 52. W2 Hourly simulated water temperatures versus observations near Sheep Creek at RM 230, ECD graph.

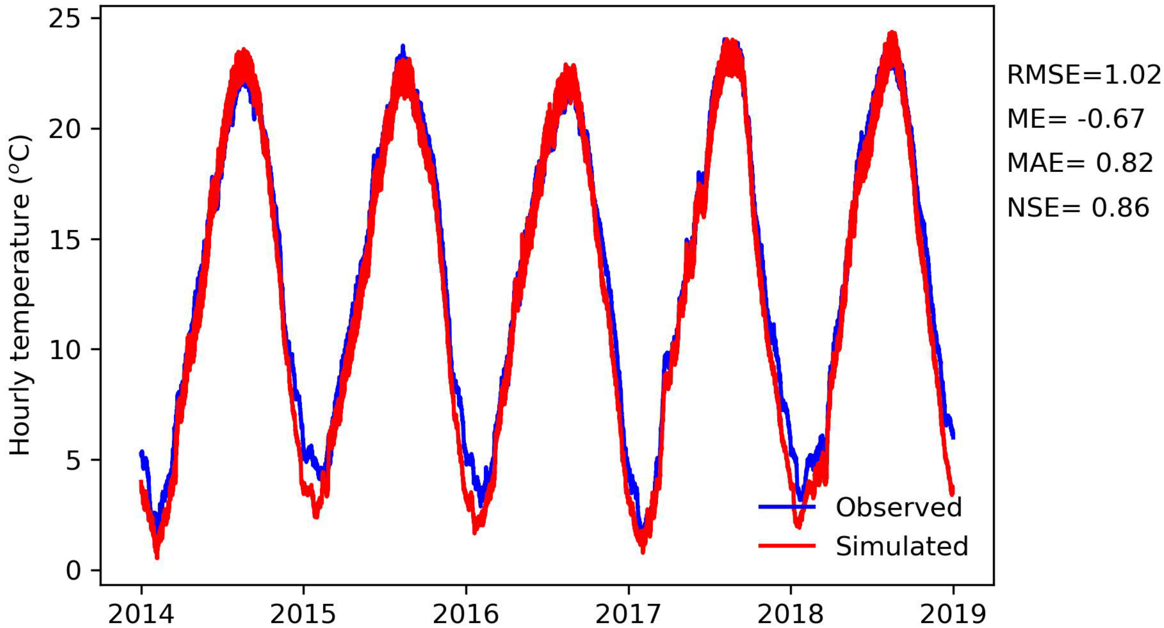

Figure 53. Hourly simulated water temperatures versus observations near Pittsburg Landing at RM 216.

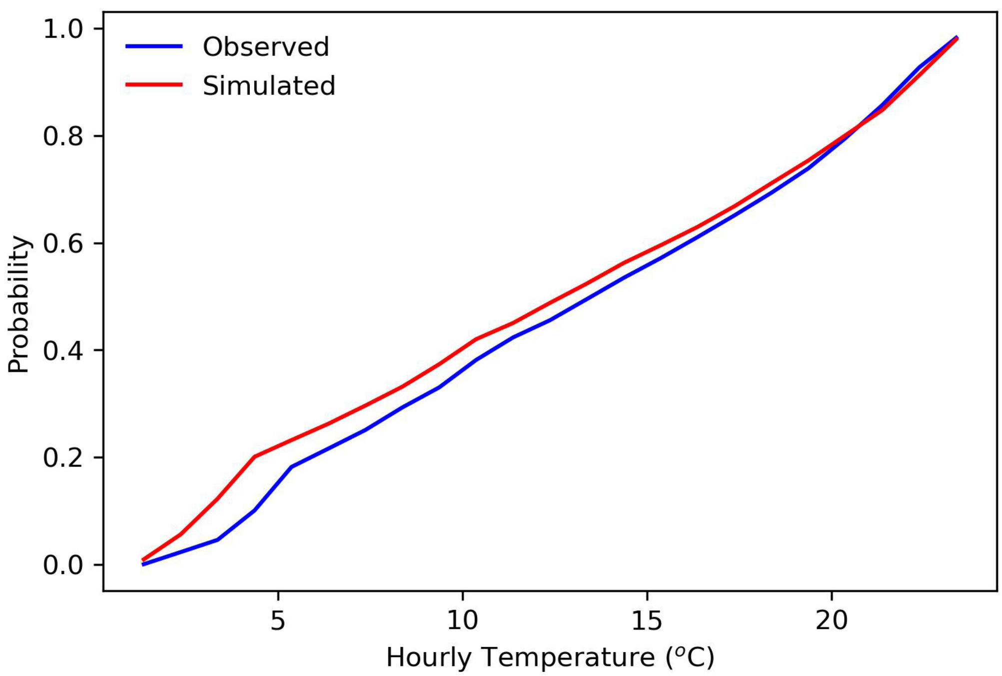

Figure 54. Hourly simulated water temperatures versus observations near Pittsburg Landing at RM 216, ECD graph.

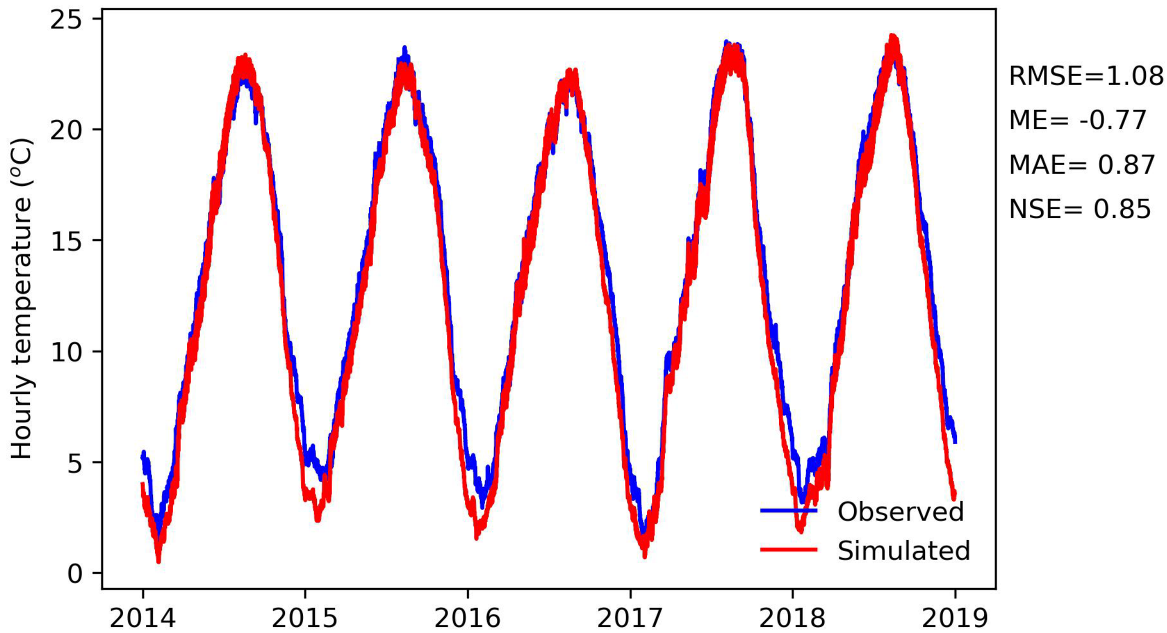

Figure 55. W2 hourly simulated water temperatures versus observations near Dry Creek at RM 202.

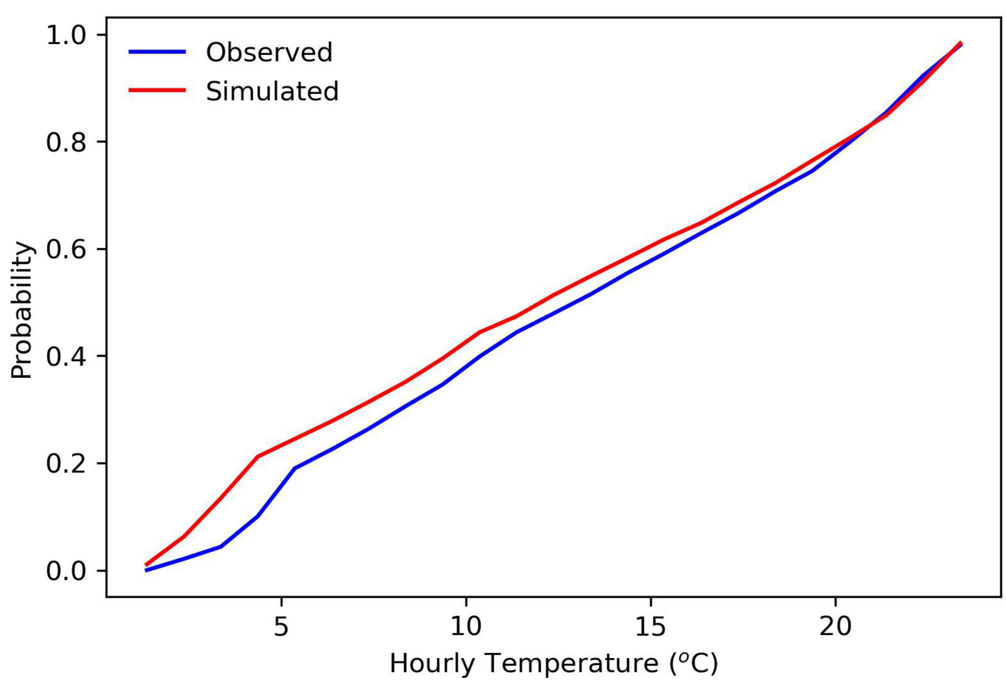

Figure 56. Hourly simulated water temperatures versus observations near Dry Creek at RM 202, ECD graph.

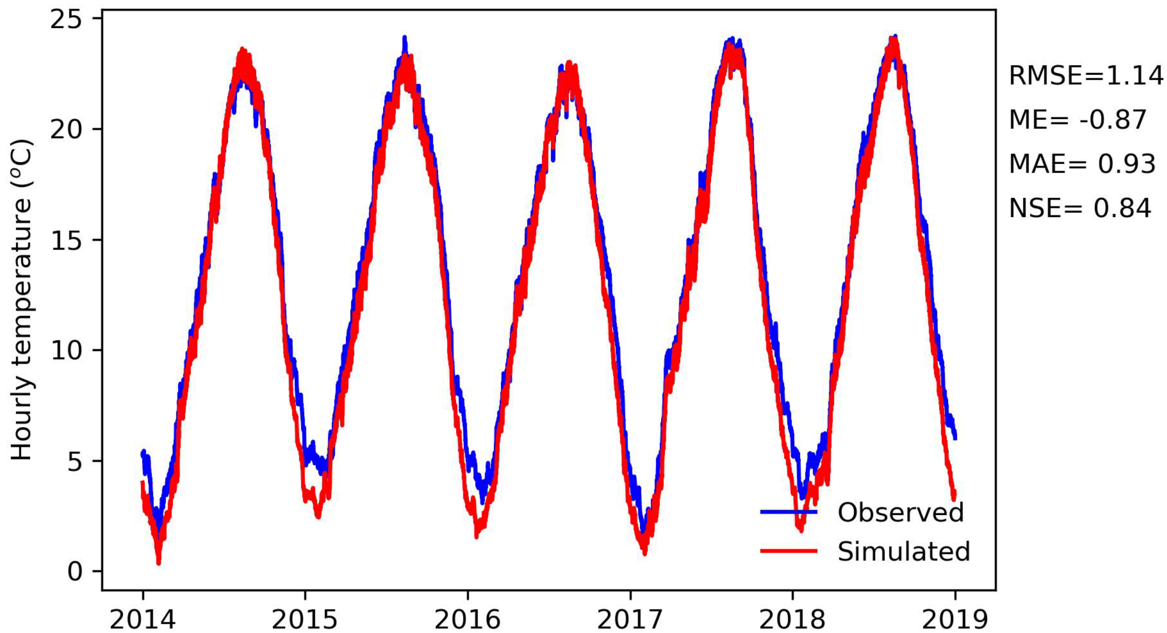

Figure 57. W2 hourly simulated water temperatures versus observations above Salmon River at RM189.

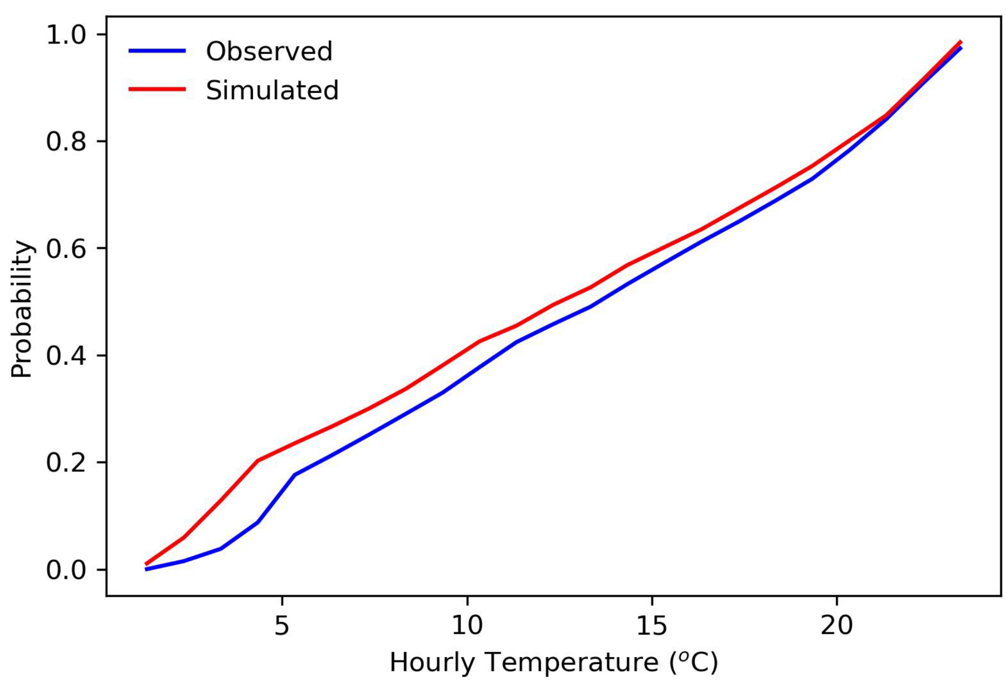

Figure 58. Hourly simulated water temperatures versus observations above Salmon River at RM189, ECD graph.

4.2.3.2 Daily Average Water Temperature Comparison

W2 simulated hourly water temperatures are averaged and compared to daily observations for five stations in Table 16 and Figure 95 through Figure 104 in the Appendix A (Section 7.2.1). The model simulated temporal variation of daily water temperature observations with RMSE ≤ 1.12 °C for modeling period and RMSE ≤ 0.81 °C for summer for all stations. The model simulated Snake River water temperature observations at USGS 13317660 (near triple boarder) with RMSE ≤ 0.82 °C for modeling period and summer season. Like hourly simulations there is a cold bias in simulated temperatures compared to observations. The bias is larger during cold season and is consistent with results of simulated temperatures by the unlinked model (Table 23 and Figure 133 -Figure 142). For the linked W2 model the bias is approximately 0.5 °C larger than the unlinked model.

Table 16. Performance of W2 in simulating Snake River daily average water temperatures (°C).

Gage	Location	River Mile (RM)	Count	Full Year				Summer (May-November)			
				NSE	RMSE	ME	MAE	NSE	RMSE	ME	MAE
IPC RM 229.8	Near Sheep Creek	230	1,421	0.87	0.93	-0.59	0.74	0.83	0.66	-0.29	0.53
IPC RM 216.3	Near Pittsburg Landing	216	1,816	0.86	1.00	-0.67	0.79	0.83	0.71	-0.37	0.55
IPC RM 202.3	Near Dry Creek	202	1,816	0.86	1.05	-0.76	0.84	0.82	0.75	-0.45	0.59
IPC RM 189	Above Salmon River	189	1,816	0.84	1.12	-0.87	0.92	0.80	0.82	-0.57	0.65
USGS 13317660	Near Triple Border (ID-OR-WA)	176	1,714	0.89	0.81	-0.60	0.65	0.90	0.54	-0.37	0.43

Note: NSE = Nash Sutcliffe coefficient of model fit efficiency, RMSE = root mean squared error, ME = mean error, MAE = mean absolute error.

4.2.3.3 Daily Maximum Temperature Comparison

W2 simulated daily maximum water temperatures are calculated from the hourly output and compared to observations for 5 stations in Table 17 and Figure 105 through Figure 114 in the Appendix A (Section 7.2.2). The model simulated temporal variation of daily maximum temperature observations, with NSE≥ 0.85 and RMSE ≤ 1.14 °C for annual results and NSE ≥ 0.80 and RMSE ≤ 0.82 °C for summer results for all stations. For Snake River near triple border at RM 176 (USGS 13317660) the RMSEs were 0.85 °C and 0.57 °C for the annual period and summer, respectively. There is a cold bias in simulated temperatures compared to observations. The bias is larger during cold seasons and is consistent with results of simulated temperatures by the unlinked model (Table 24 and Figure 145 and Figure 154). For the linked W2 model the bias is approximately 0.5 °C larger than for the unlinked model.

Table 17. Performance of W2 in simulating Snake River daily maximum water temperatures. Error units are in °C.

Gage	Location	River Mile (RM)	Count	Full Year				Summer (May-November)			
				NSE	RMSE	ME	MAE	NSE	RMSE	ME	MAE
IPC RM 229.8	Near Sheep Creek	230	1,421	0.87	0.92	-0.50	0.73	0.84	0.65	-0.15	0.53
IPC RM 216.3	Near Pittsburg Landing	216	1,816	0.87	1.00	-0.64	0.79	0.83	0.71	-0.31	0.55
IPC RM 202.3	Near Dry Creek	202	1,816	0.85	1.08	-0.79	0.88	0.81	0.79	-0.47	0.62
IPC RM 189	Above Salmon River	189	1,816	0.84	1.14	-0.88	0.94	0.80	0.82	-0.57	0.66
USGS 13317660	Near Triple Border (ID-OR-WA)	176	1,714	0.88	0.85	-0.62	0.68	0.89	0.57	-0.36	0.46

Note: NSE = Nash Sutcliffe coefficient of model fit efficiency, RMSE = root mean squared error, ME = mean error, MAE = mean absolute error.

4.2.3.4 7DADMax Temperature Comparison

7DADMax water temperatures were calculated from W2 hourly simulations and are compared to observations for 5 stations in Table 18 and Figure 115 through Figure 124 in the Appendix A (Section 7.2.3). The model simulated temporal variation of 7DADMax temperature observations with NSE≥ 0.85 for modeling period and NSE ≥ 0.82 for summer for all stations. The model had RMSE ≤ 1.1°C and 0.74°C for modeling period and summer, respectively, for all stations. For Snake River near triple border (USGS 13317660), the RMSEs were 0.81 °C and 0.49°C for the annual period and summer. The bias is larger during cold seasons and is consistent with results of simulated temperatures by unlinked model (Table 25 and Figure 157 - Figure 166). For the linked W2 model the bias is approximately 0.5 °C larger than for the unlinked model.

Table 18. Performance of CE-QUAL-W2 in simulating Snake River 7DADMax water temperatures. Error units are °C.

Gage	Location	River Mile (RM)	Count	Full Year				Summer (May-November)			
				NSE	RMSE	ME	MAE	NSE	RMSE	ME	MAE
IPC RM 229.8	Near Sheep Creek	230	1,421	0.88	0.89	-0.49	0.70	0.85	0.59	-0.11	0.48
IPC RM 216.3	Near Pittsburg Landing	216	1,816	0.87	0.96	-0.62	0.75	0.85	0.63	-0.26	0.49
IPC RM 202.3	Near Dry Creek	202	1,816	0.86	1.05	-0.77	0.84	0.82	0.71	-0.43	0.56
IPC RM 189	Above Salmon River	189	1,816	0.85	1.10	-0.87	0.90	0.82	0.74	-0.53	0.60
USGS 13317660	Near Triple Border (ID-OR-WA)	176	1,714	0.89	0.81	-0.62	0.64	0.91	0.49	-0.35	0.39

Note: NSE = Nash Sutcliffe coefficient of model fit efficiency, RMSE = root mean squared error, ME = mean error, MAE = mean absolute error.

4.2.4 Oregon and Washington State Line to Clearwater River

4.2.4.1 Daily Average Water Temperature Comparison

W2 simulated hourly water temperatures are averaged and compared to daily average observations for USGS 13334300 in Table 19 and Figure 59 -Figure 60. The simulated temperatures deviated from observations by less than 0.73°C as measured by RMSE, ME, and MAE for the annual and summer period. In general, there is a small cold bias in simulated temperatures compared to observations. The bias is partially due to the upstream simulated temperature boundary; see results for the unlinked model in Table 23 and Figure 143-Figure 144.

Table 19. Performance of W2 in simulating Snake River daily average water temperatures (°C).

Gage	Location	River Mile (RM)	Count	Full Year				Summer (May-November)			
				NSE	RMSE	ME	MAE	NSE	RMSE	ME	MAE
USGS 13334300	Near Anatone	168	1,810	0.90	0.73	-0.52	0.60	0.89	0.57	-0.37	0.48

Note: NSE = Nash Sutcliffe coefficient of model fit efficiency, RMSE = root mean squared error, ME = mean error, MAE = mean absolute error.

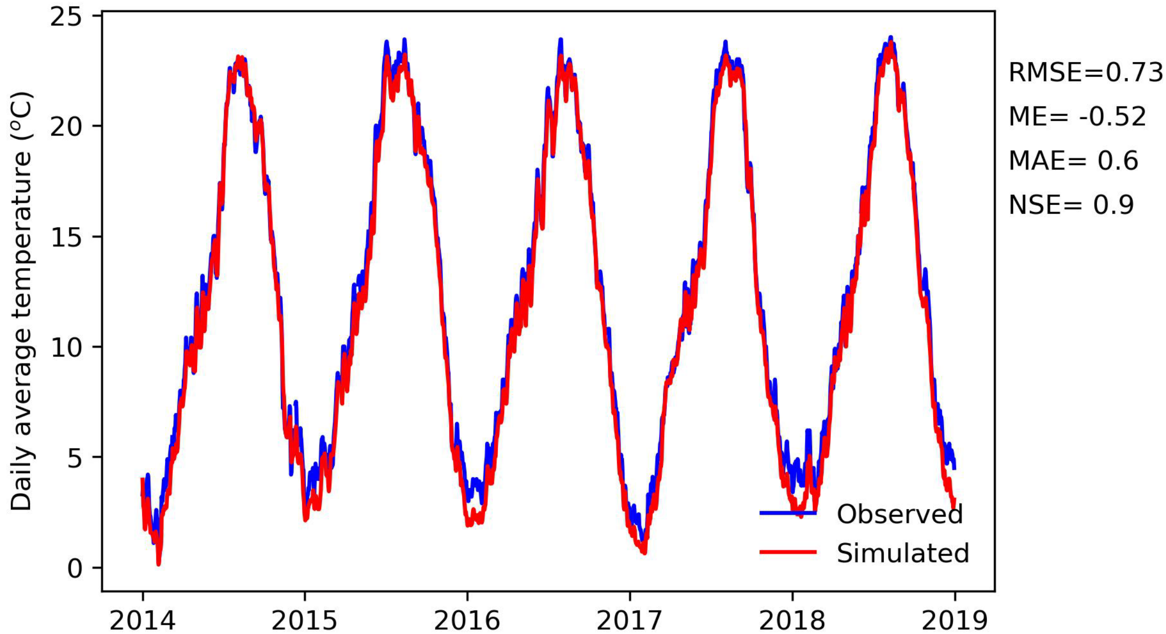

Figure 59. W2 daily average simulated water temperatures versus observations near Anatone at RM 168.

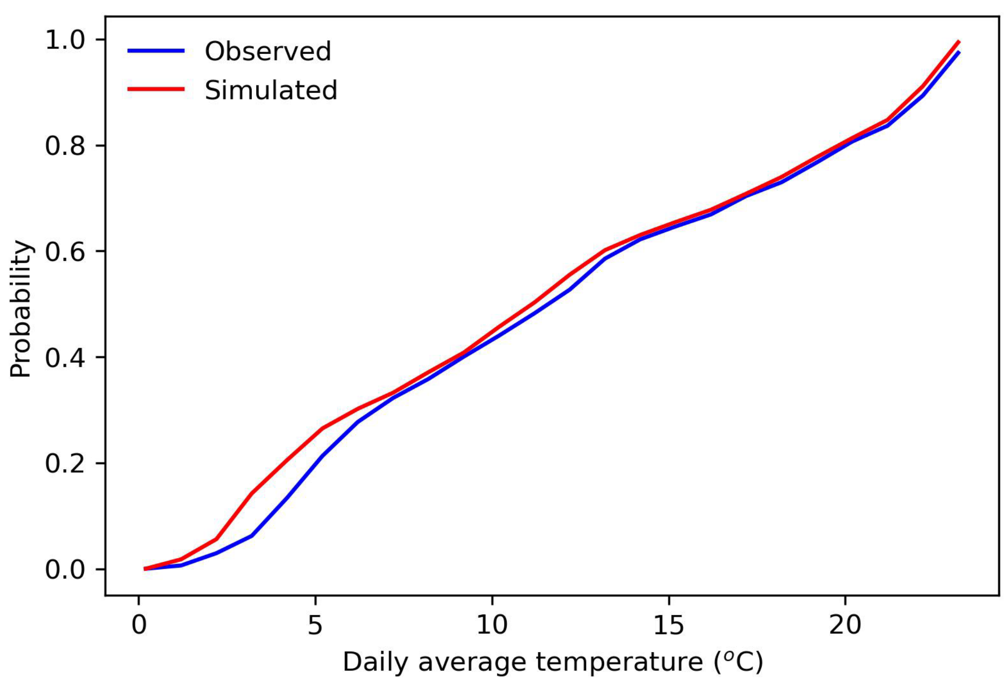

Figure 60. Daily average simulated water temperatures versus observations near Anatone at RM 168, ECD graph.

4.2.4.2 Daily Maximum Temperature Comparison

W2 simulated daily maximum water temperatures are calculated from the hourly output and compared to observations for USGS 13334300 in Table 20 and Figure 61 -Figure 62. The model simulated temporal variation of daily maximum water temperature observations well with RMSE = 0.87 °C and 0.74 °C for the annual and summer period. In general, there is a small cold bias in simulated temperatures compared to observations. The bias is partially due to the upstream simulated temperature boundary, see results for the unlinked model in Table 24 and Figure 155-Figure 156.

Table 20. Performance of W2 in simulating Snake River daily average water temperatures (°C).

Gage	Location	River Mile (RM)	Count	Full Year				Summer (May-November)			
				NSE	RMSE	ME	MAE	NSE	RMSE	ME	MAE
USGS 13334300	Near Anatone	168	1,810	0.88	0.87	-0.66	0.73	0.86	0.74	-0.51	0.62

Note: NSE = Nash Sutcliffe coefficient of model fit efficiency, RMSE = root mean squared error, ME = mean error, MAE = mean absolute error.

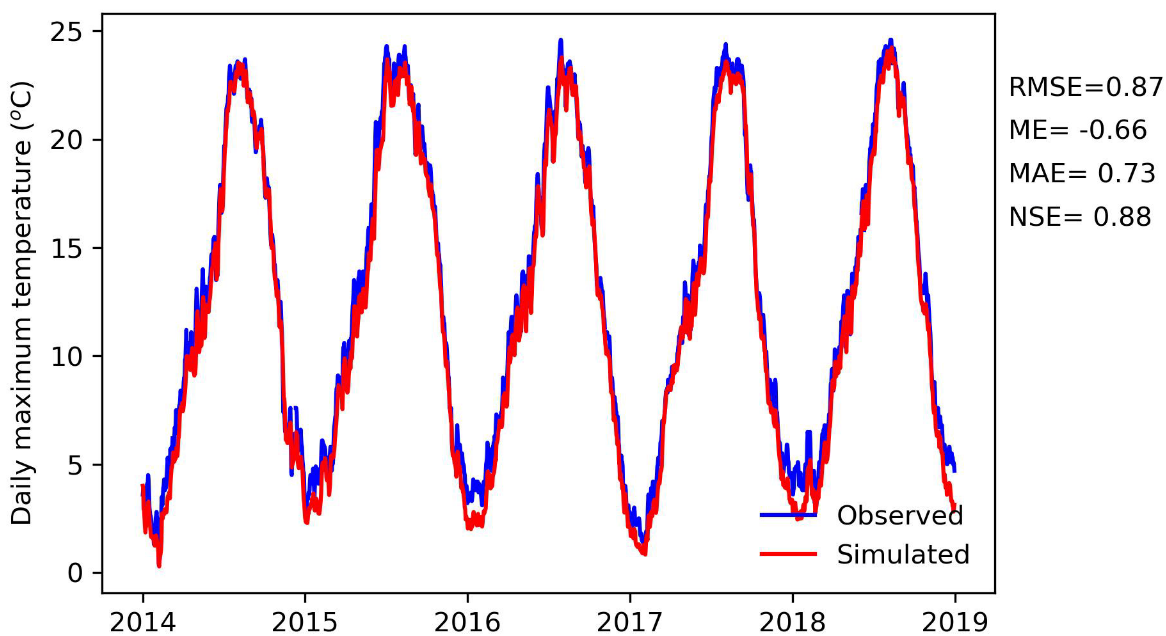

Figure 61. W2 daily maximum simulated water temperatures versus observations near Anatone at RM 168.

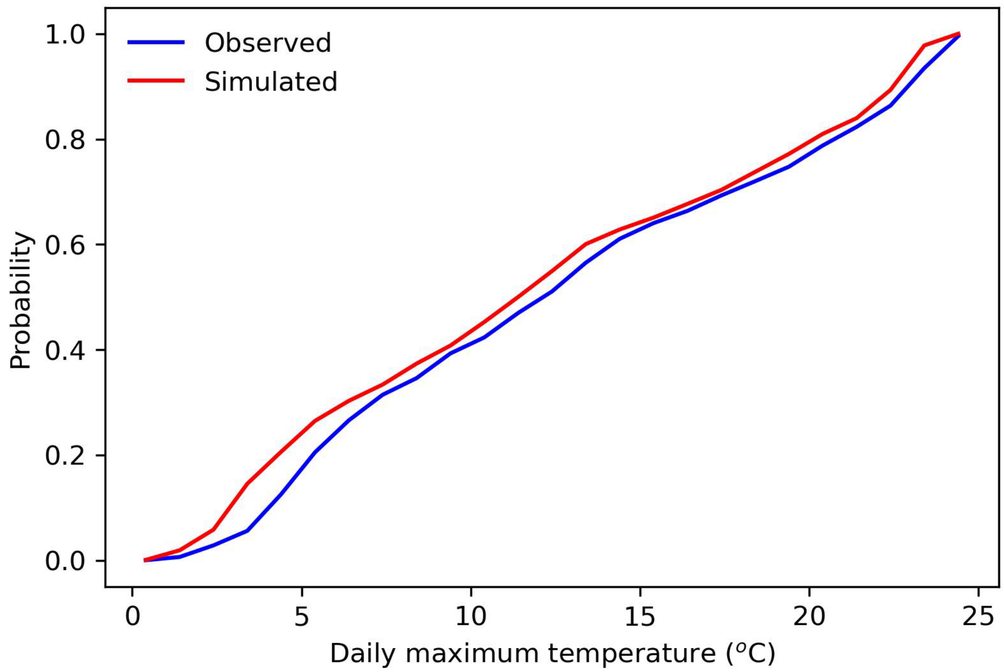

Figure 62. Daily maximum simulated water temperatures versus observations near Anatone at RM 168, ECD graph.

4.2.4.3 7DADMax Temperature Comparison

7DADMax water temperatures were calculated from W2 hourly simulations and are compared to observations for USGS 13334300 in Table 21 and Figure 63 -Figure 64. The model simulated temporal variation of 7DADMax temperature observations well with NSE= 0.89 and RMSE= 0.79 °C for modeling period and NSE =0.87 and RMSE= 0.64 °C for summer. In general, there is a small cold bias in simulated temperatures. The bias is partially due to the upstream simulated temperature boundary, see results for the unlinked model in Table 25 and Figure 167-Figure 168.

Table 21. Performance of CE-QUAL-W2 in simulating Snake River 7DADMax water temperatures. Error units are °C.

Gage	Location	River Mile (RM)	Count	Full Year				Summer (May-November)			
				NSE	RMSE	ME	MAE	NSE	RMSE	ME	MAE
USGS 13334300	Near Anatone	168	1,810	0.89	0.79	-0.66	0.68	0.87	0.64	-0.51	0.54

Note: NSE = Nash Sutcliffe coefficient of model fit efficiency, RMSE = root mean squared error, ME = mean error, MAE = mean absolute error.

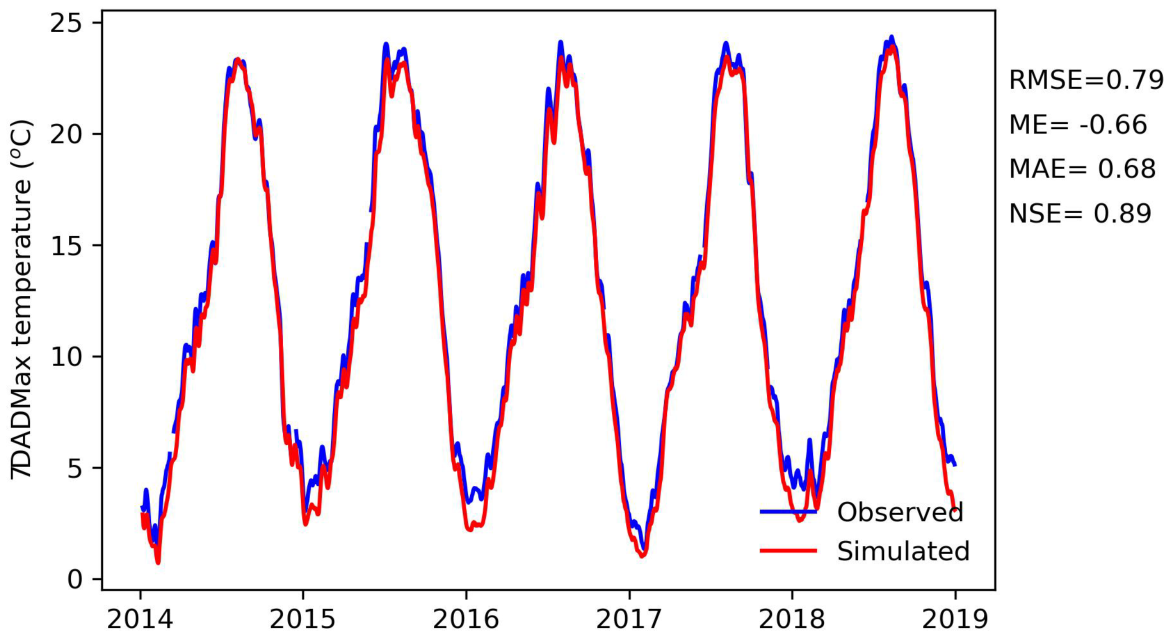

Figure 63. W2 7DADMax simulated water temperatures versus observations near Anatone at RM 168.

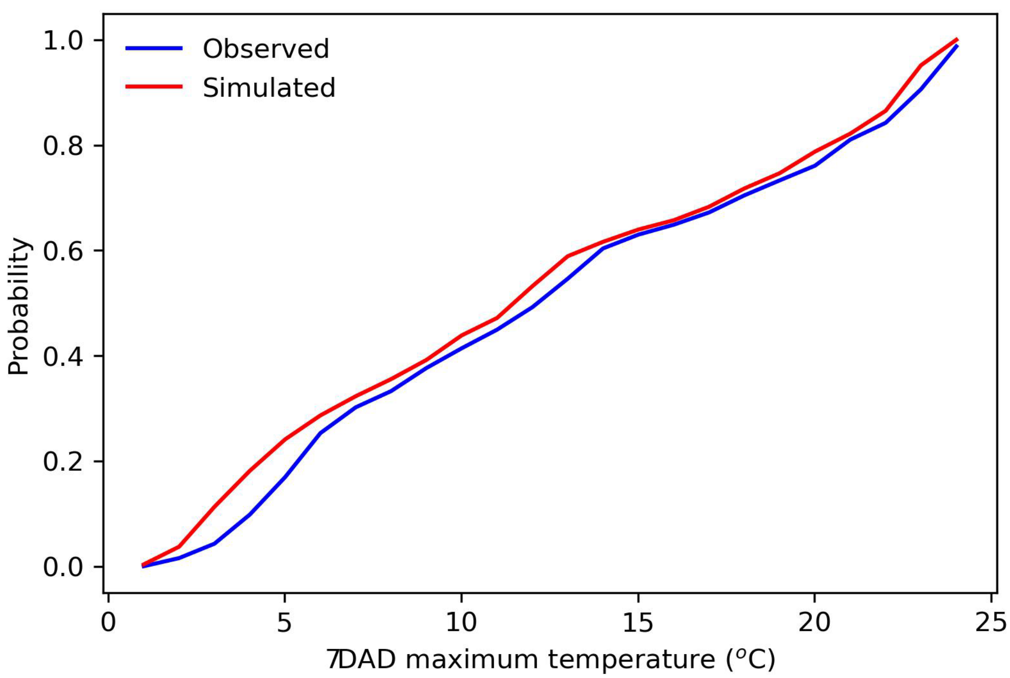

Figure 64. 7DADMax simulated water temperatures versus observations near Anatone at RM 168, ECD graph.

5.0 SUMMARY

This report documents development and calibration of CE-QUAL-W2 models (V.4.5) for simulating water temperature of Snake River from near Adrian (RM 399) to the head of the Brownlee Dam and from Hells Canyon Dam (RM 247) to Clearwater River (RM 139). The developed models were linked to the PSU HCC W2 models to support development of the Snake River-Hells Canyon temperature TMDL. Three W2 models were set up using hourly meteorological observations and flow and water temperature measurements to simulate Snake River discharge and temperature for the period from 2014 to 2018. The model outputs were calibrated and evaluated against observations. From Adrian to Brownlee, the calibrated model simulated the hourly, daily average, daily maxima, and 7ADMAX water temperatures of Snake River with RMSE ranges between 0.5 to 1.83 °C for modeling period and warm season (May to November). For the Snake River reach below Hells Canyon Dam to Clearwater the simulated temperature error ranged between 0.16 and 0.64°C for both modeling periods when the upstream temperature boundary was set for the river using observations (see Appendix 8.0). The models' temperature fit was degraded approximately by 0.5 °C and ranged between 0.49 to 1.14 °C when were linked to the upstream models. Some degradation in fit is expected, because the simulated outflow temperature from the Hells Canyon Dam does not perfectly match observations at that location, and the model error is carried into the downstream reach of the Snake River. In summary, the W2 temperature simulation errors are in an acceptable range and the models are ready to be used to assess management scenarios.

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7.0 APPENDIX A: DETAILED RESULTS FOR LINKED W2 MODELS

7.1 ADRIAN TO BROWNLEE

7.1.1 Daily Average Water Temperature Results

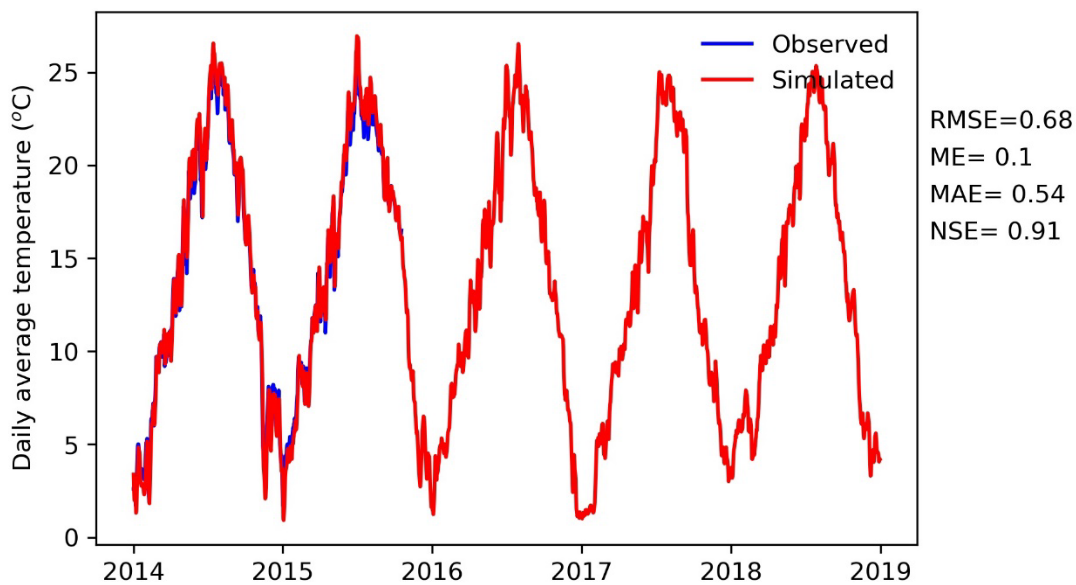


Figure 65. Daily average temperature Snake River at Nyssa RM 389.

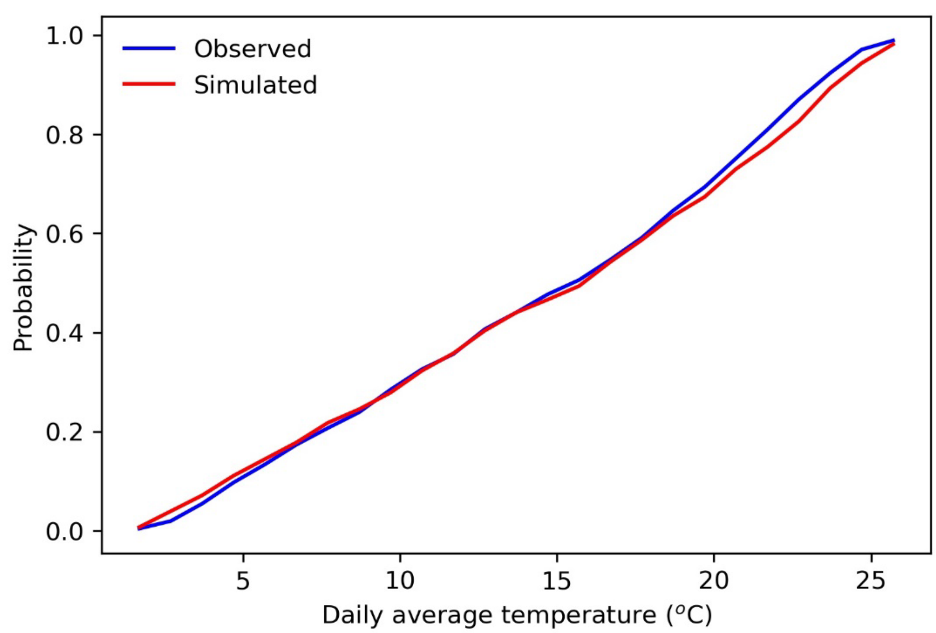


Figure 66. Daily average temperature Snake River at Nyssa RM 389.

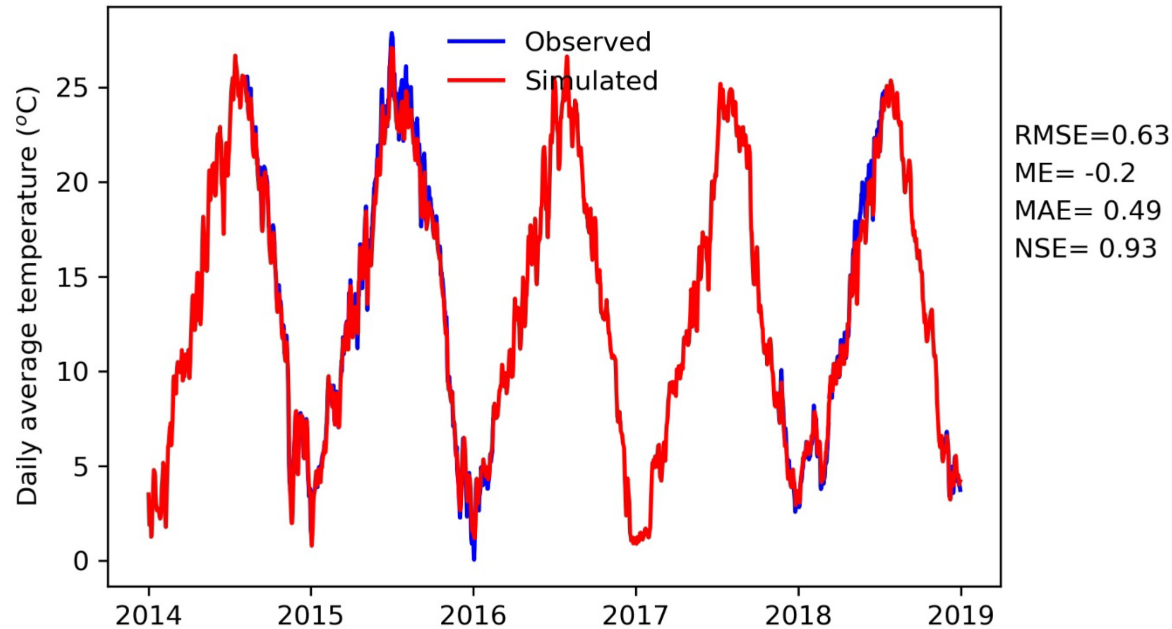


Figure 67. Daily average temperature Snake River below Nyssa at RM 383.

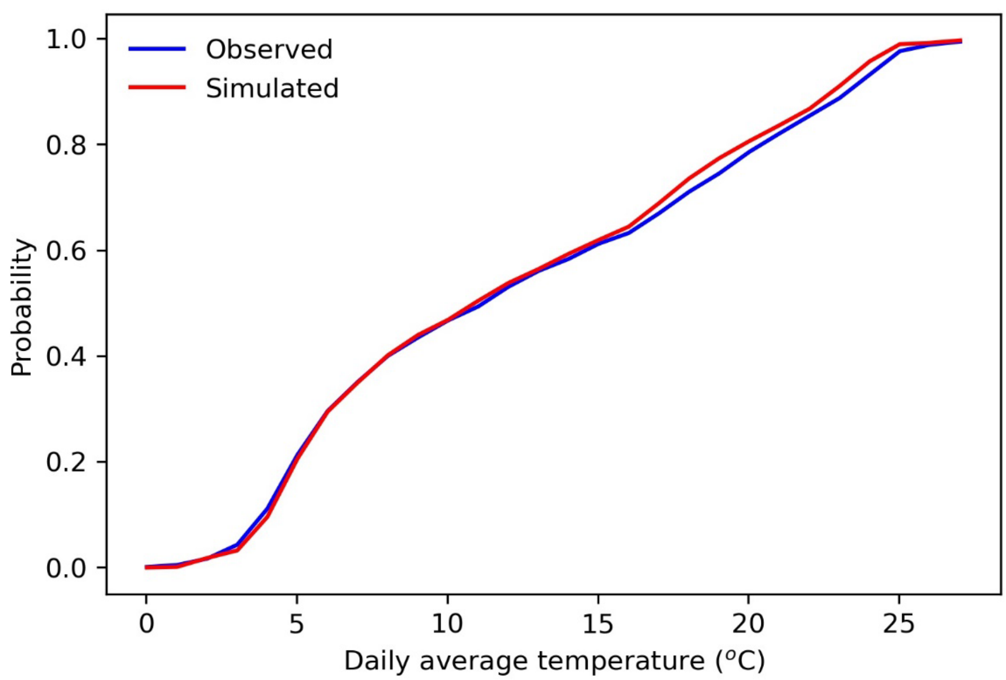


Figure 68. Daily average temperature Snake River below Nyssa at RM 383.

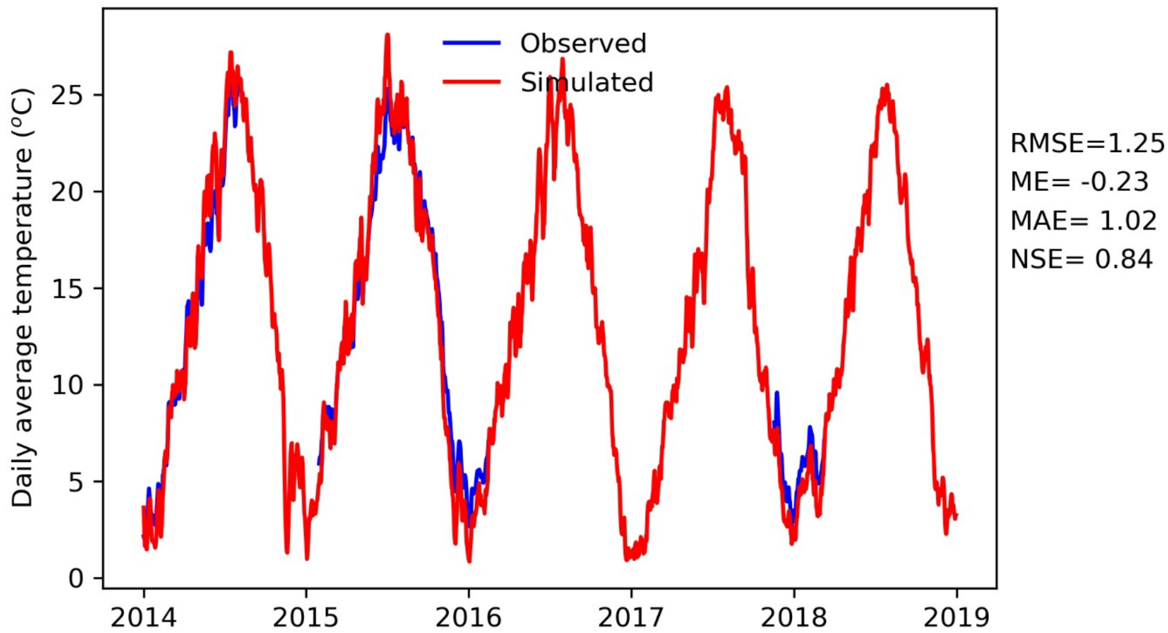


Figure 69. Daily average temperature Snake River near Weiser at RM 354.3.

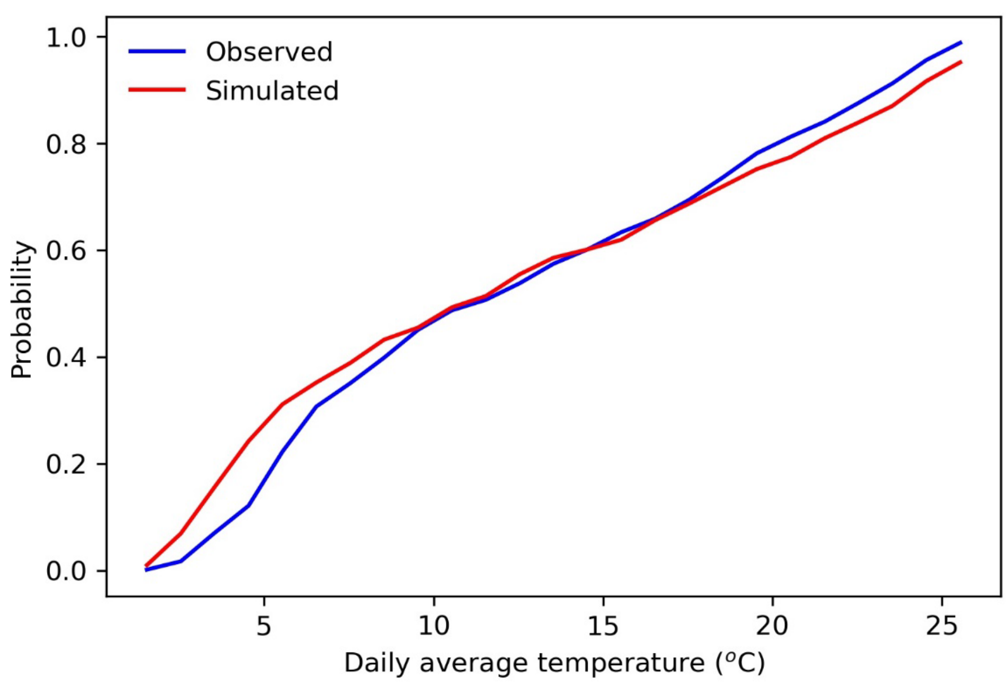


Figure 70. Daily average temperature Snake River near Weiser at RM 354.3.

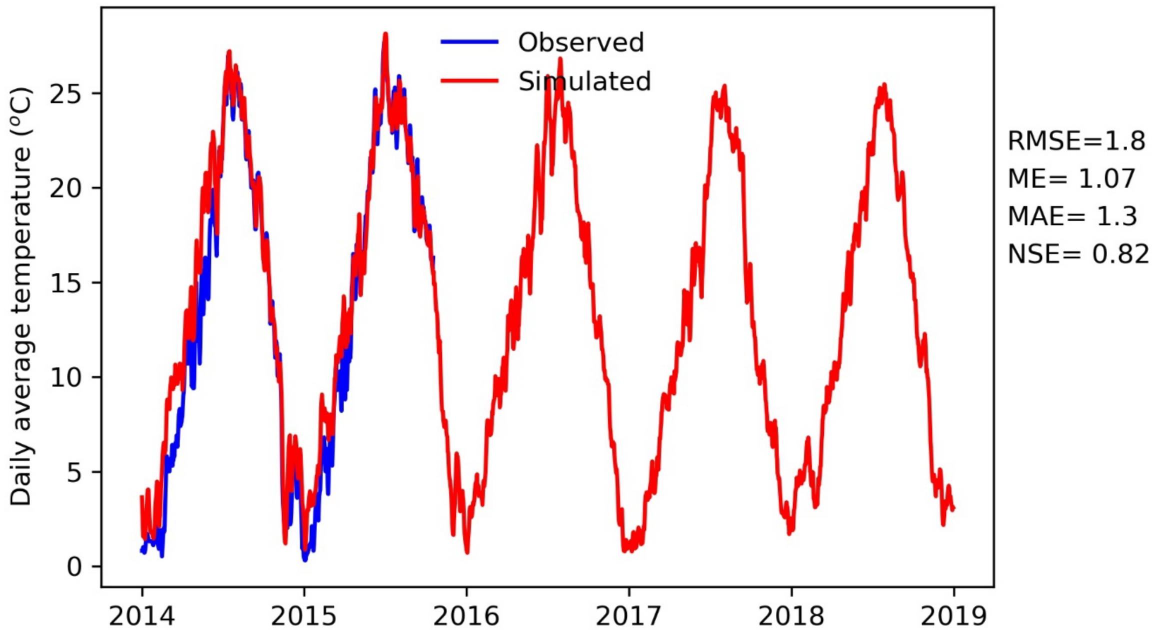


Figure 71. Daily average temperature Snake River at Weiser RM 354.

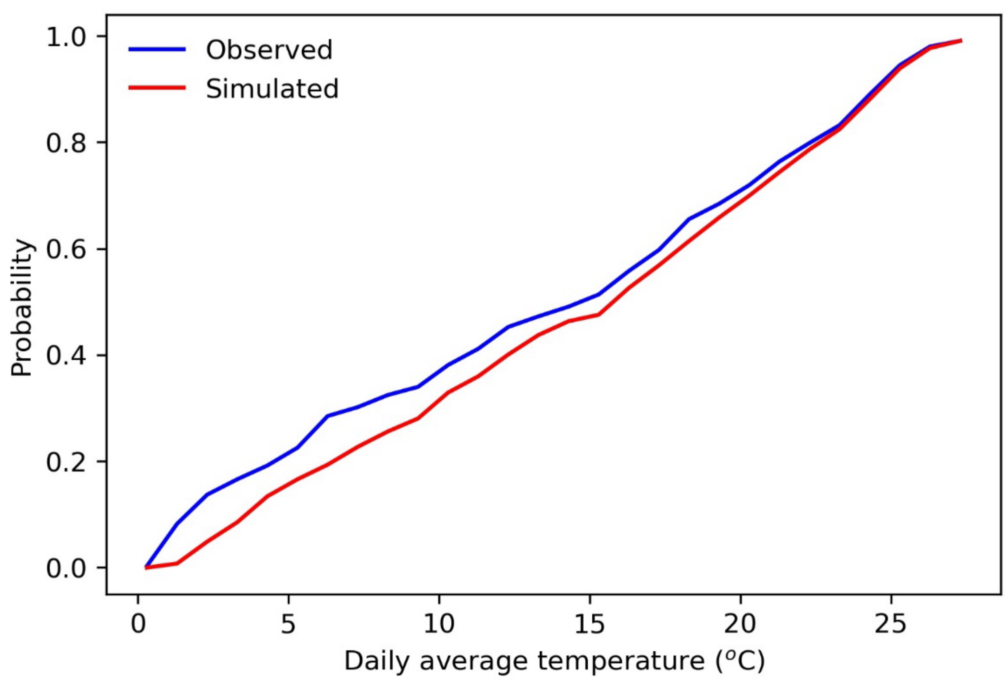


Figure 72. Daily average temperature Snake River at Weiser at RM 354.

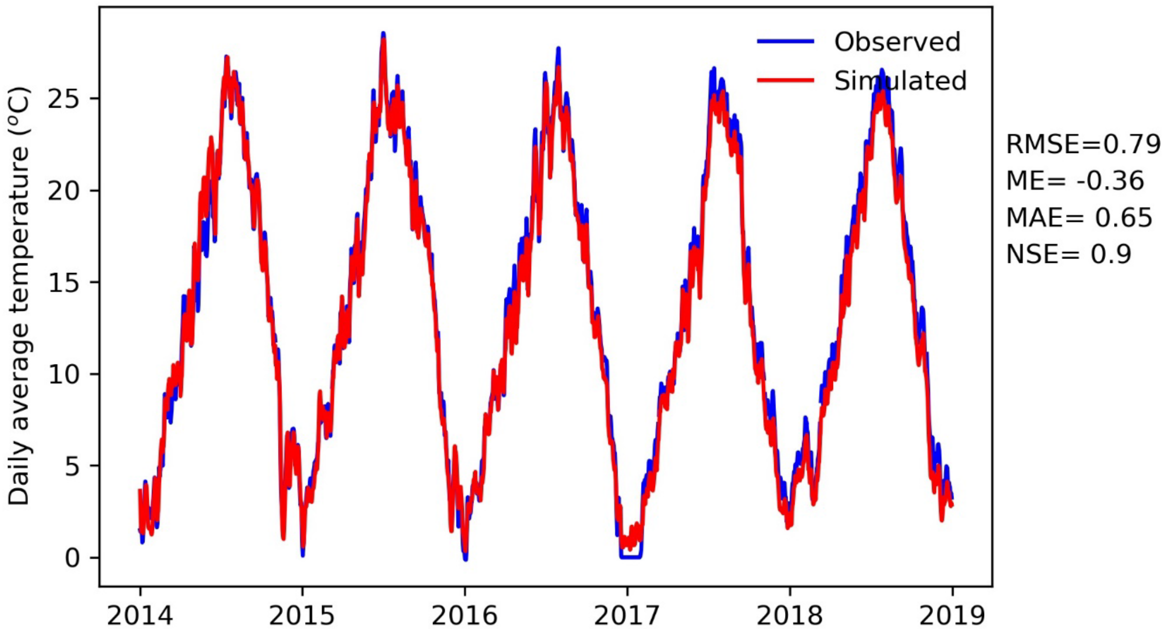


Figure 73. Daily average temperature Snake River at Brownlee Reservoir upstream, RM 345.2.

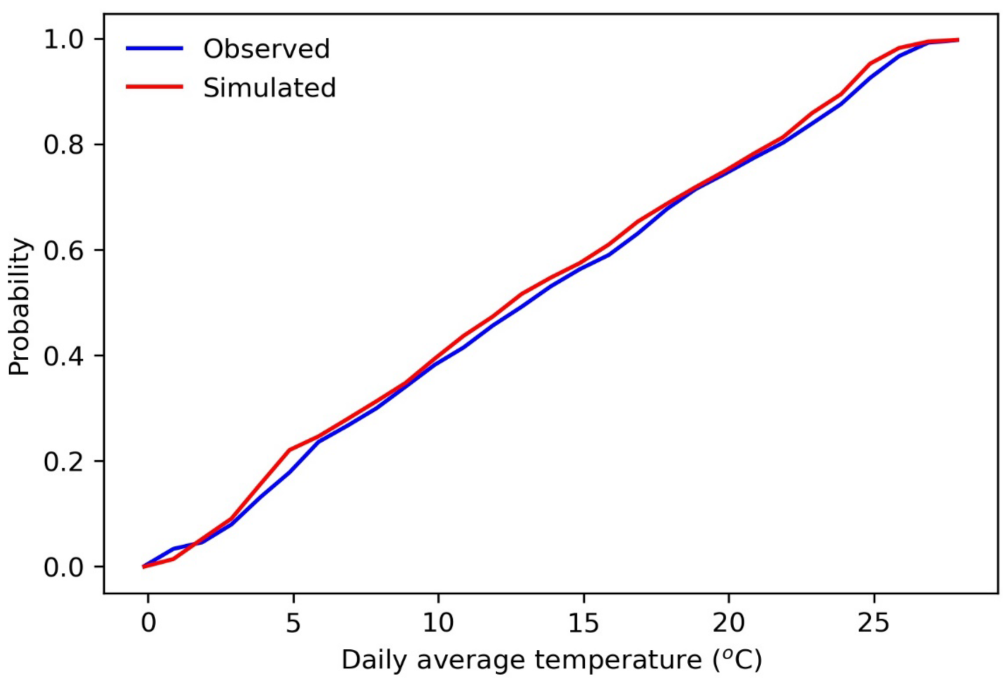


Figure 74. Daily average temperature Snake River at Brownlee Reservoir upstream, RM 345.2.

7.1.2 Daily Maximum Water Temperature Results

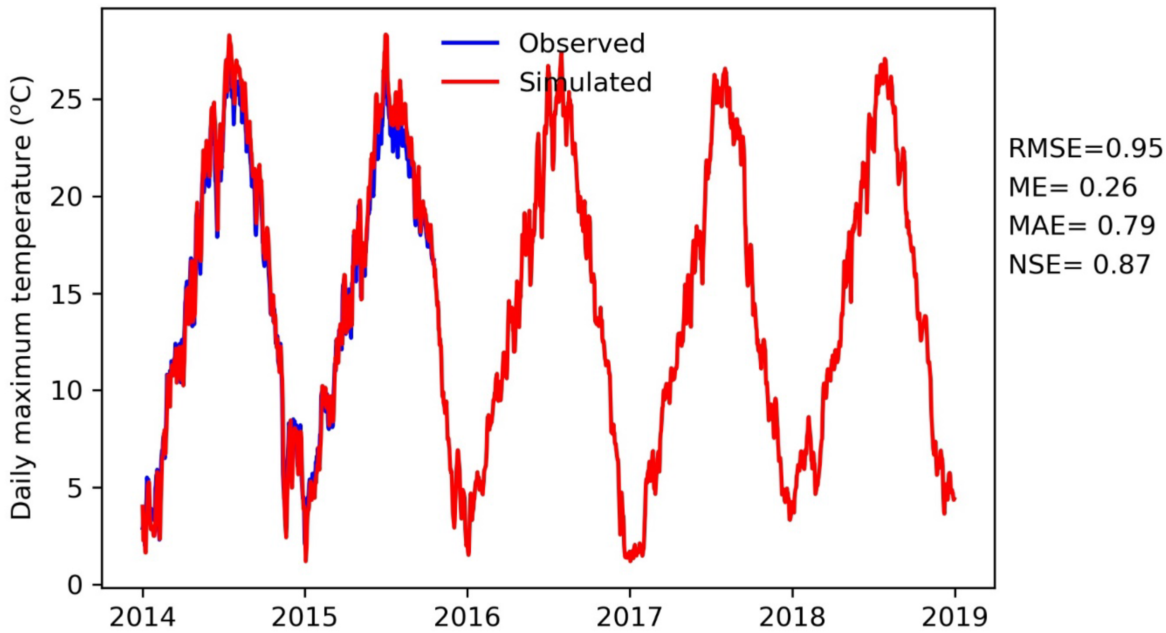


Figure 75. Daily maximum temperature Snake River at Nyssa RM 389.

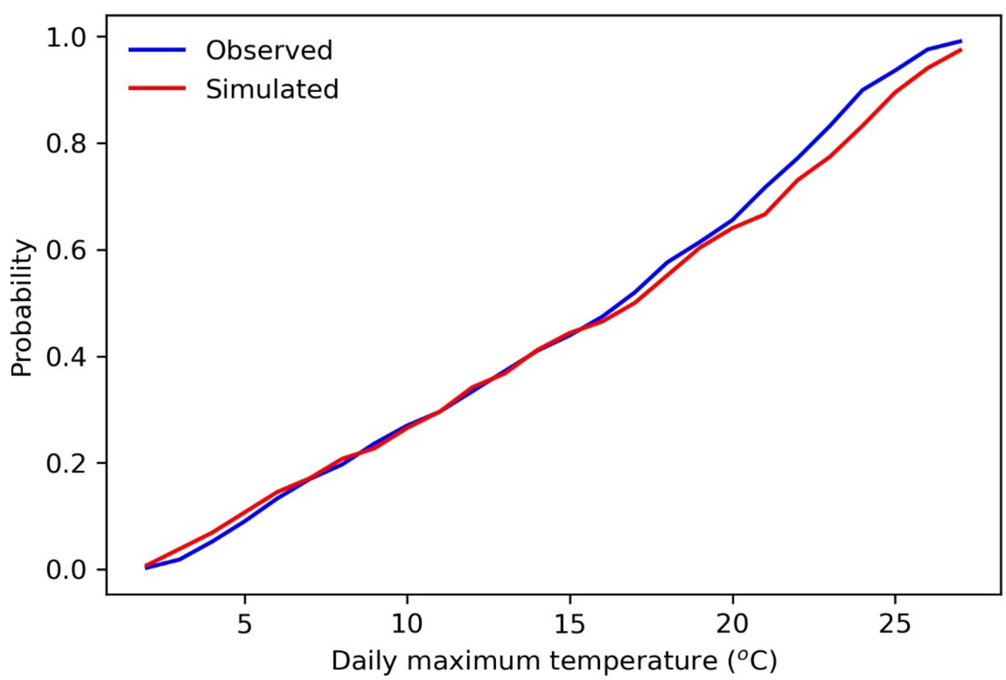


Figure 76. Daily maximum temperature Snake River at Nyssa RM 389

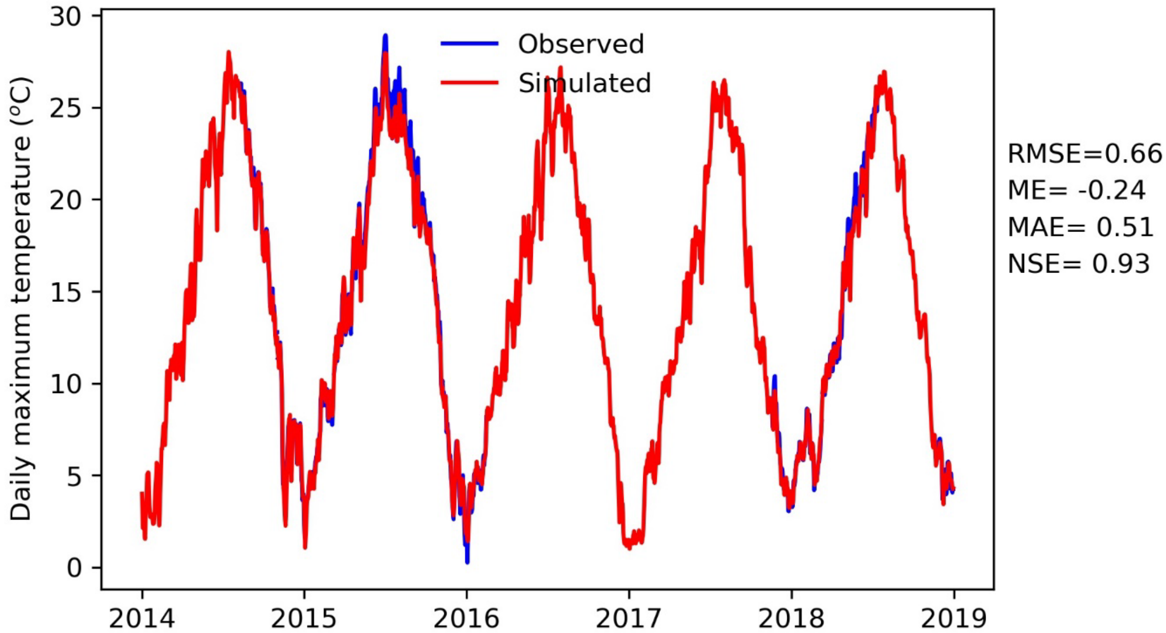


Figure 77. Daily maximum temperature Snake River below Nyssa at RM 383.

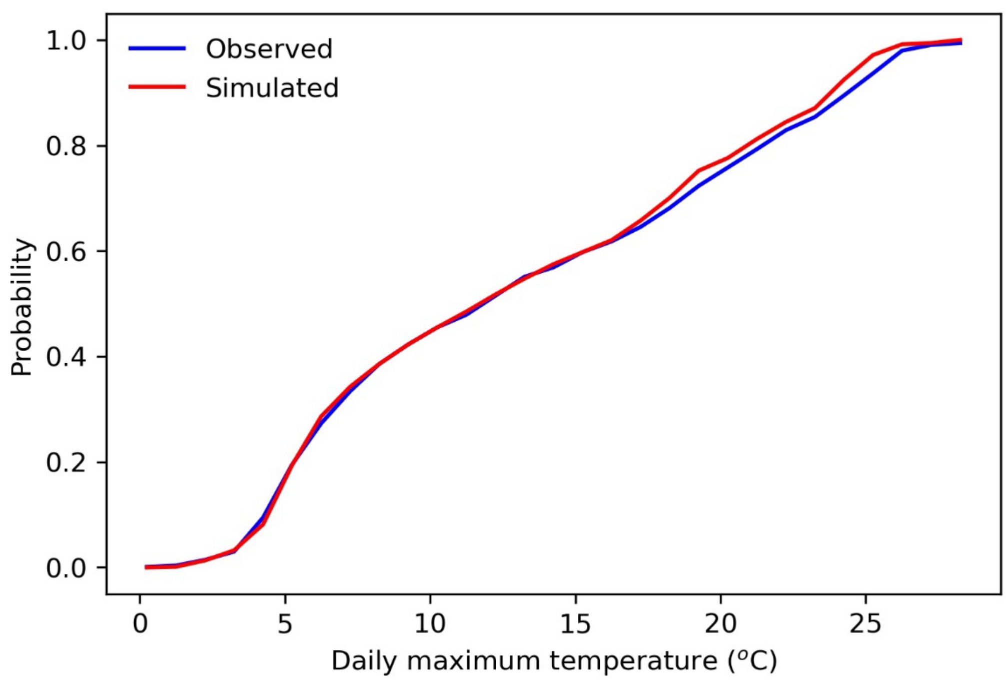


Figure 78. Daily maximum temperature Snake River below Nyssa at RM 383.

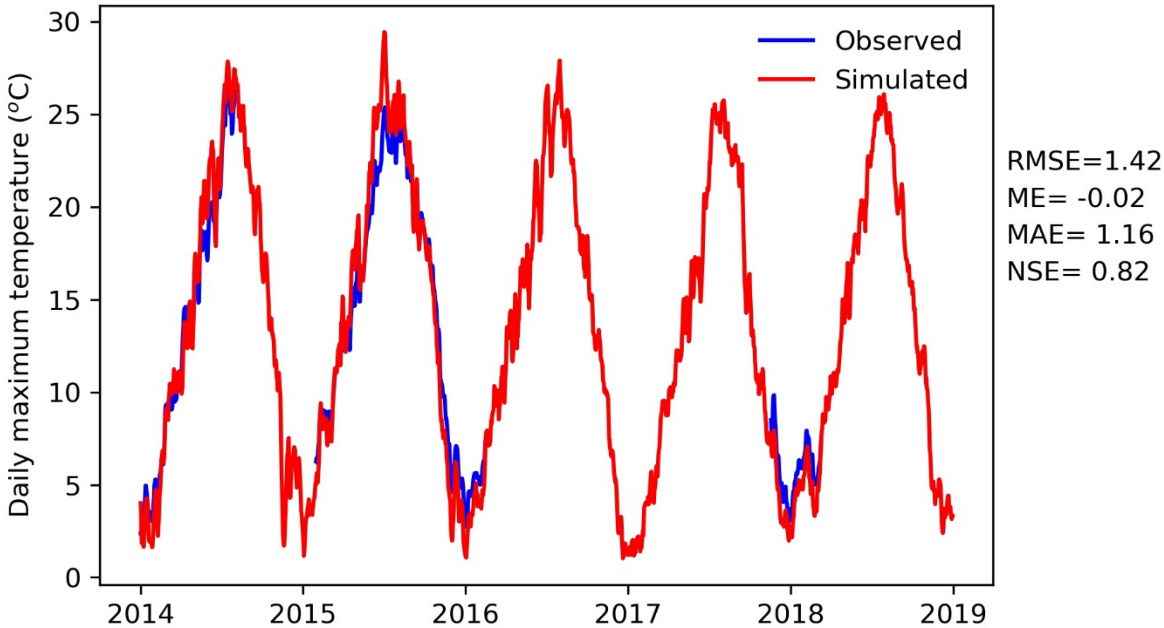


Figure 79. Daily maximum temperature Snake River near Weiser at RM 354.3.

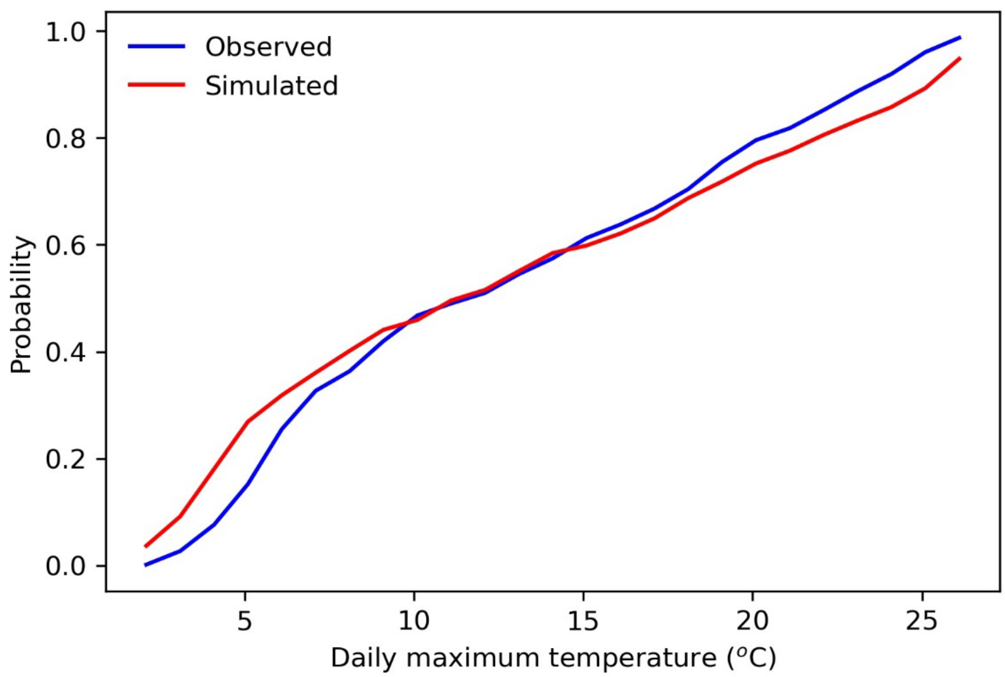


Figure 80. Daily maximum temperature near Weiser at RM 354.3.

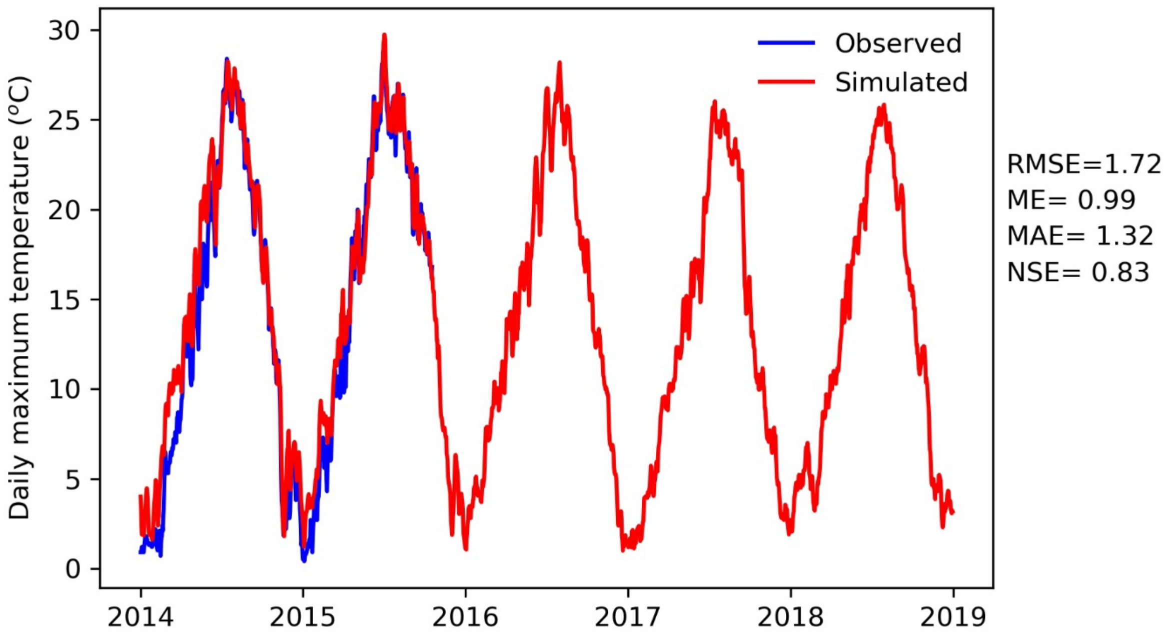


Figure 81. Daily maximum temperature at Weiser RM 354.

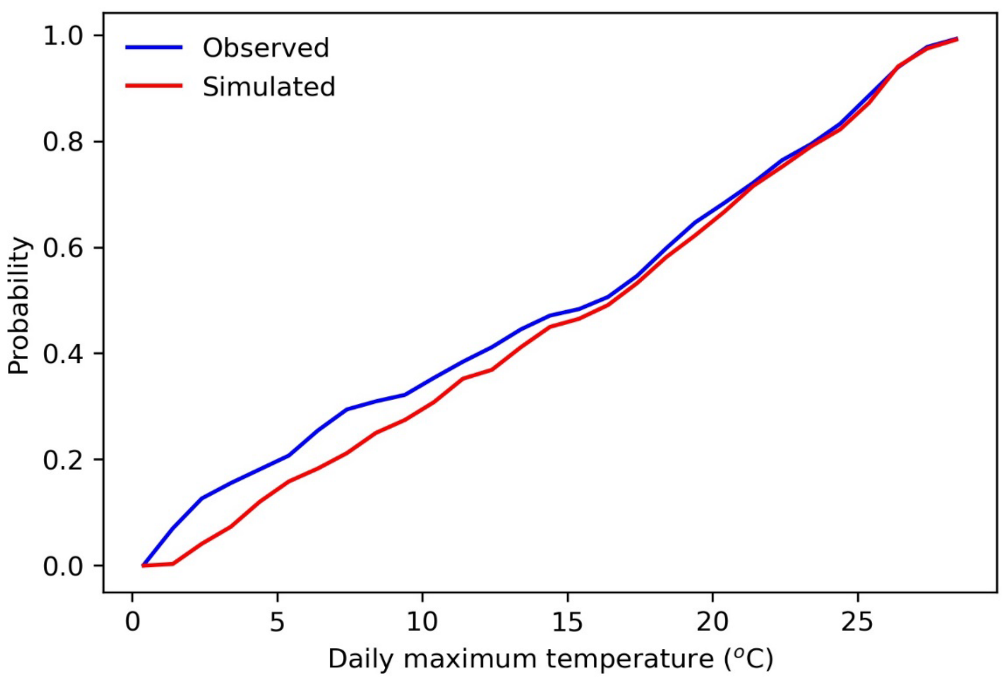


Figure 82. Daily maximum temperature at Weiser RM 354

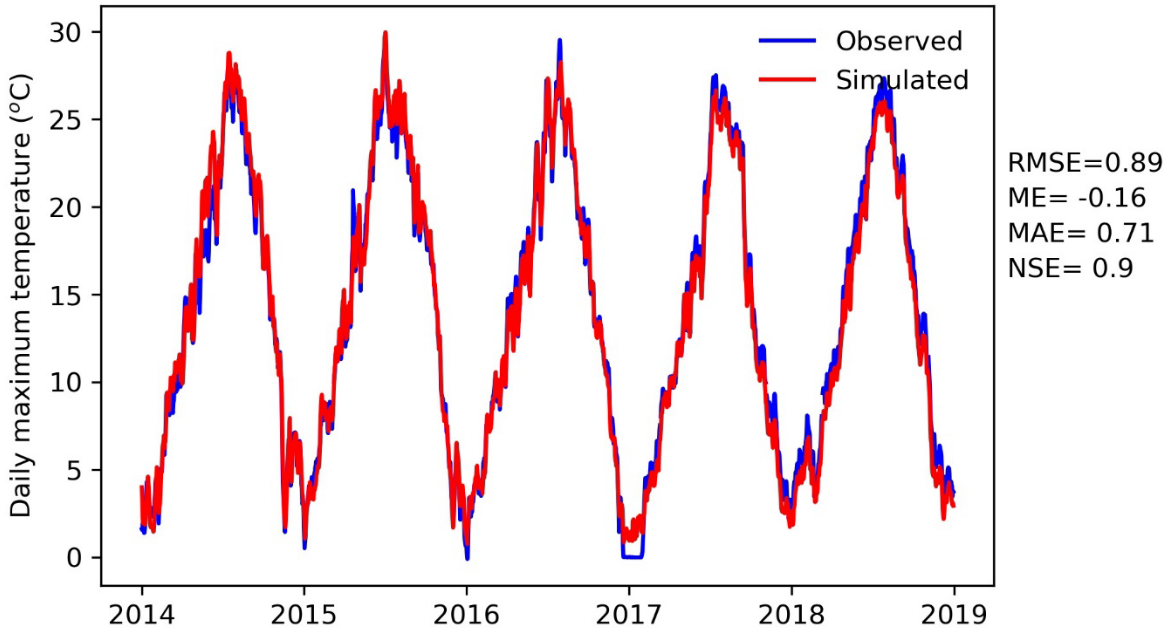


Figure 83. Daily maximum temperature at Brownlee Reservoir upstream, RM 345.2.

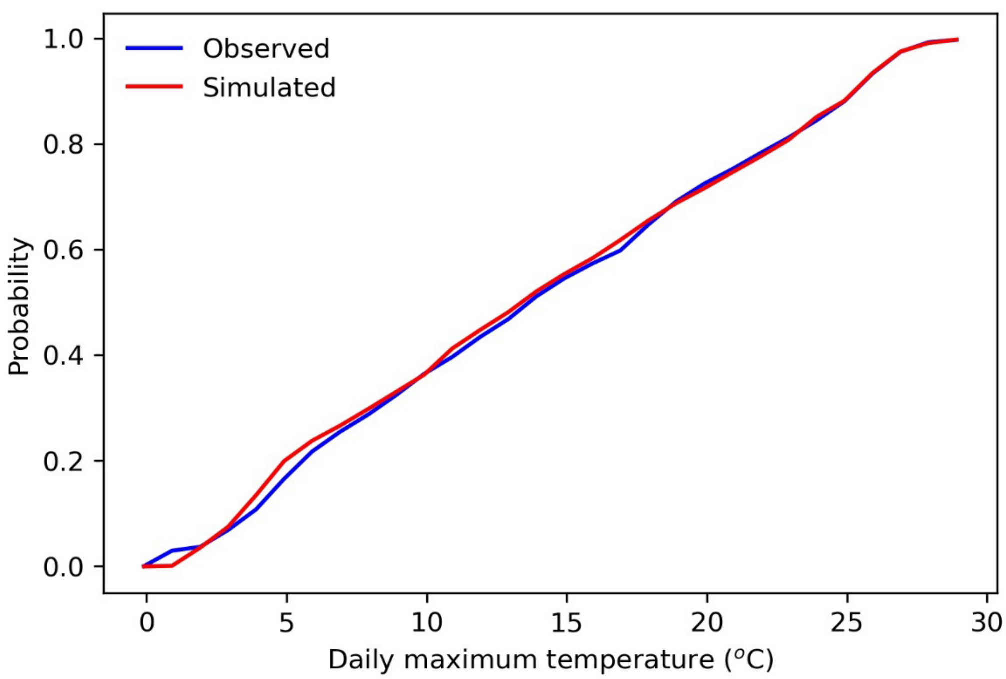


Figure 84. Daily maximum temperature at Brownlee Reservoir upstream, RM 345.2.

7.1.3 7-Day Average of Daily Maxima Water Temperature Results

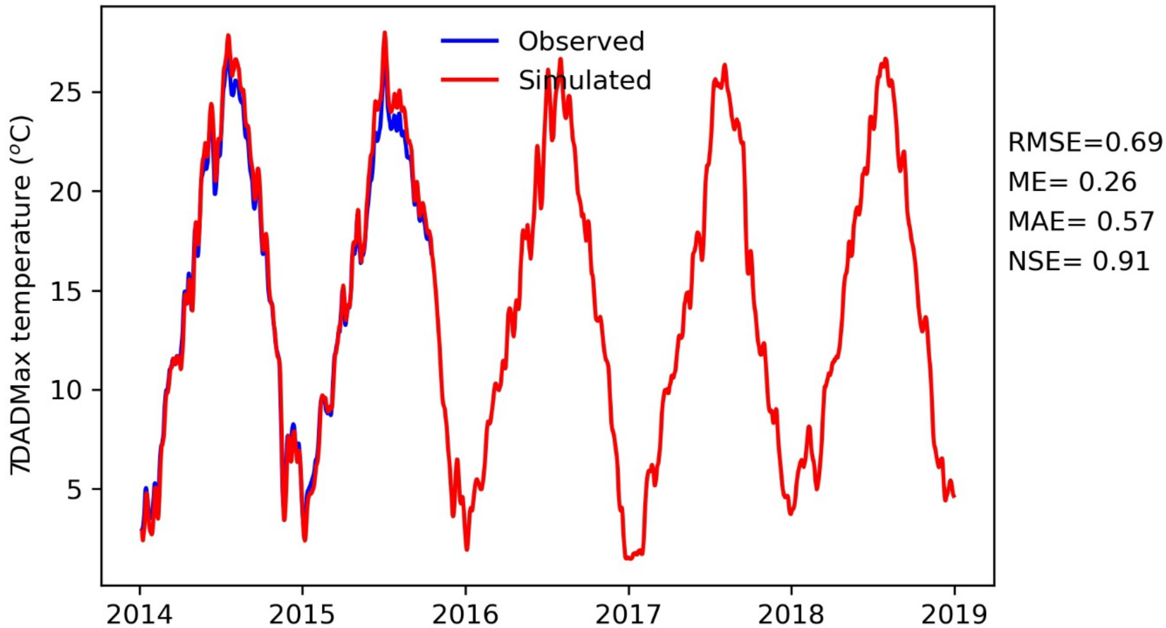


Figure 85. 7DADMax temperature Snake River at Nyssa RM 389.

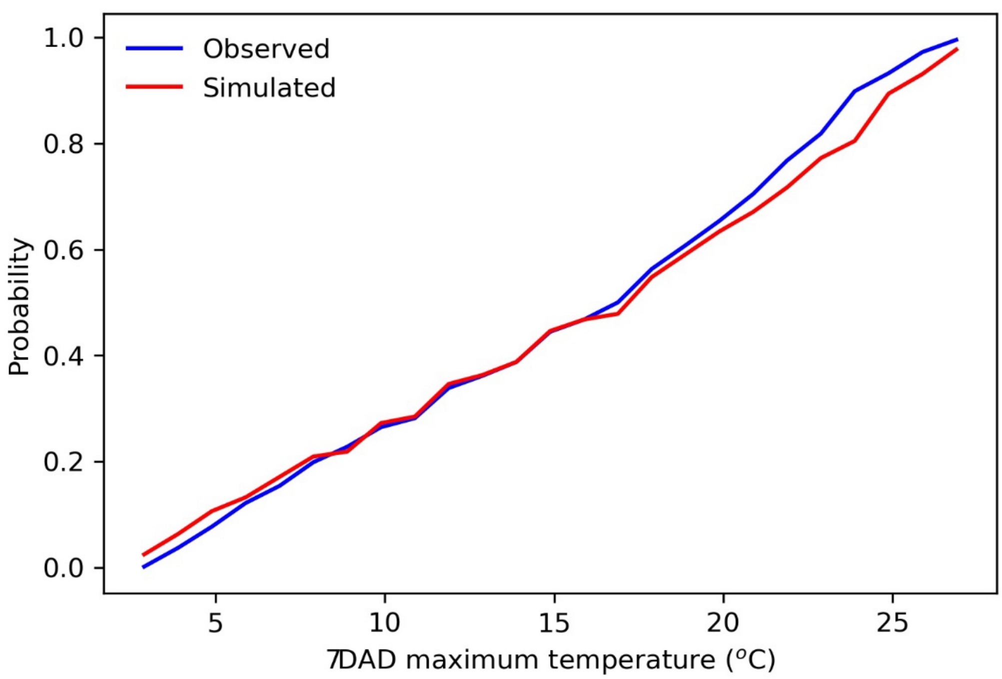


Figure 86. 7DADMax temperature Snake River at Nyssa RM 389.

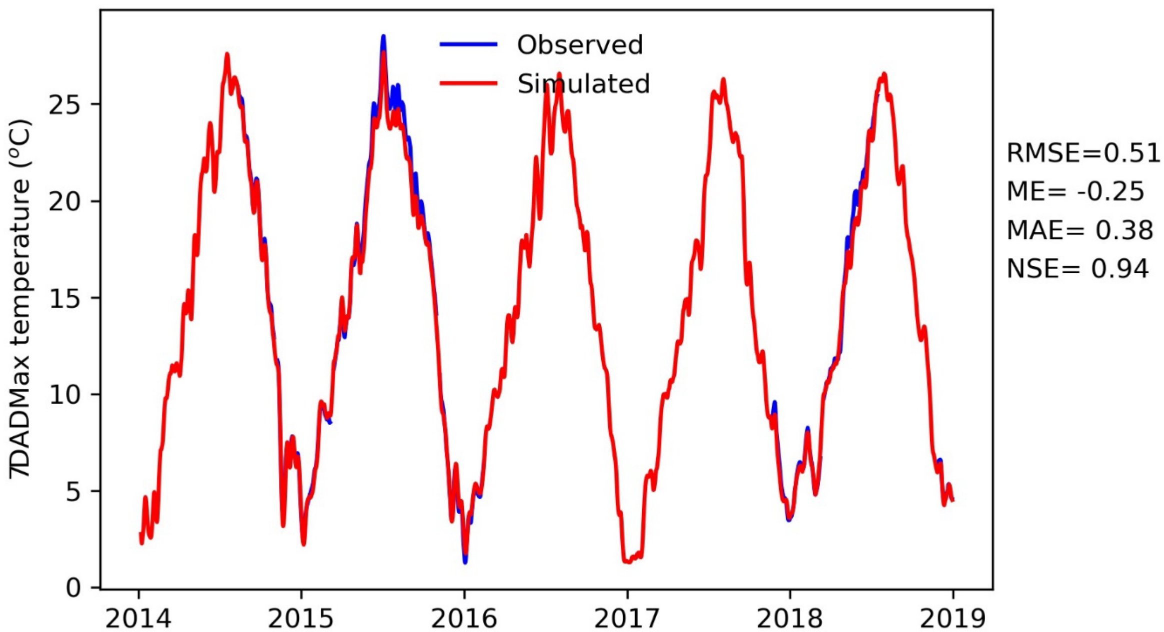


Figure 87. 7DADMax temperature Snake River below Nyssa at RM 383.

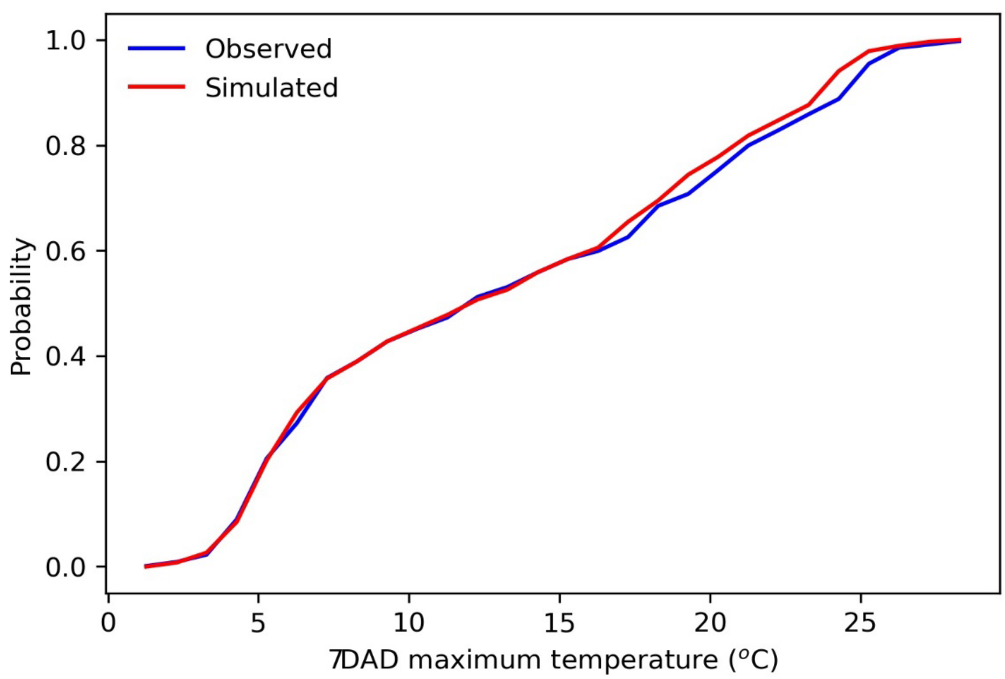


Figure 88. 7DADMax temperature Snake River below Nyssa at RM 383.

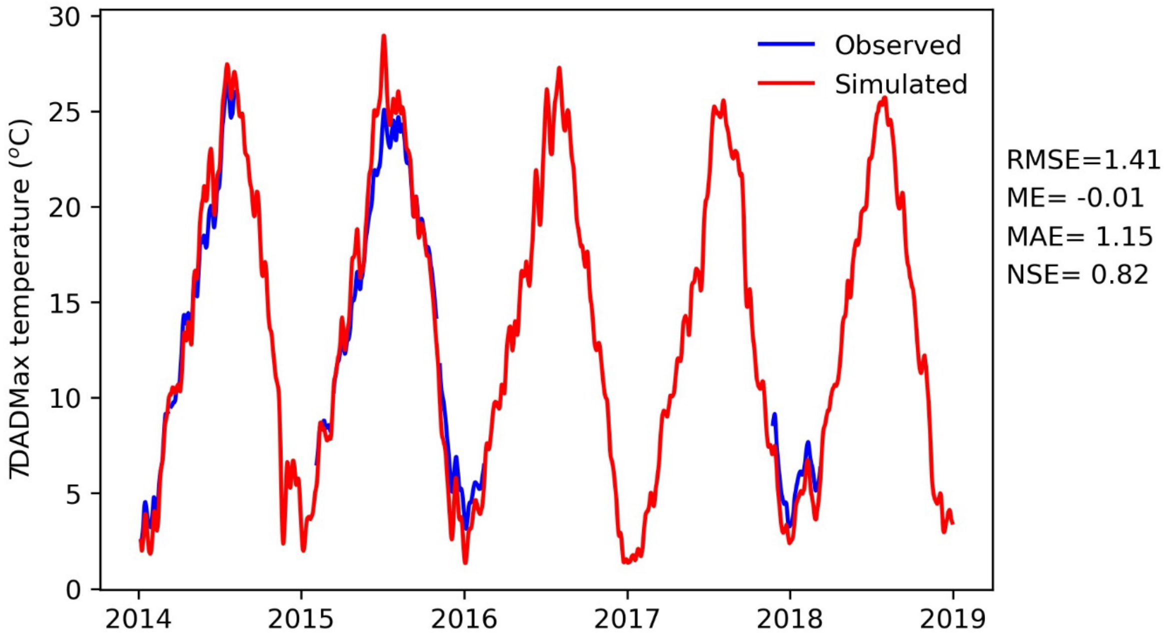


Figure 89. 7DADMax temperature Snake River near Weiser at RM 354.3.

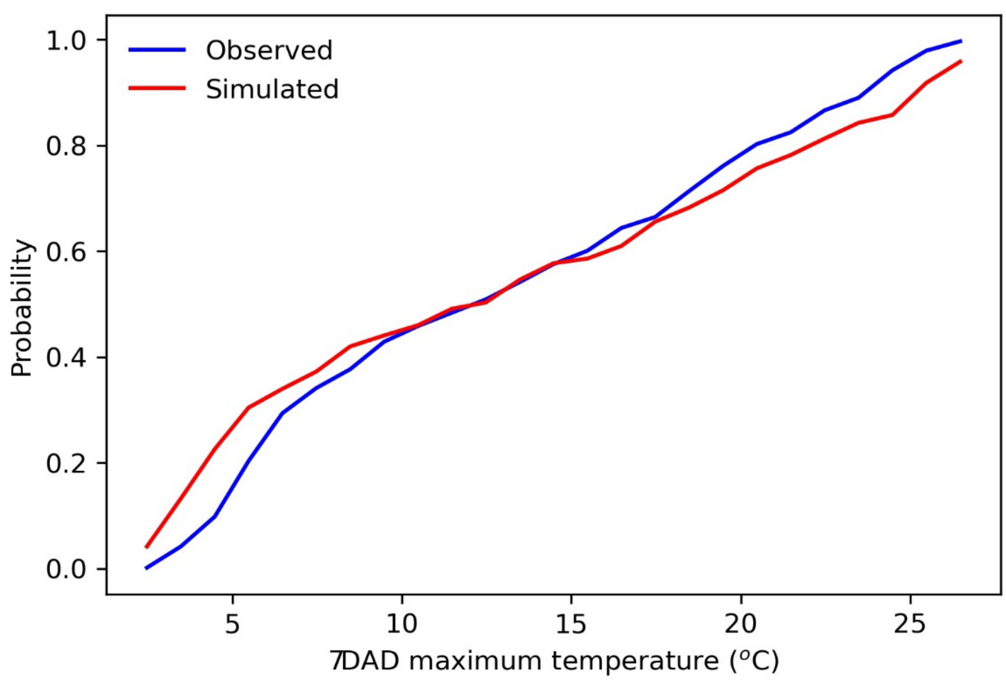


Figure 90. 7DADMax temperature Snake River near Weiser at RM 354.3.

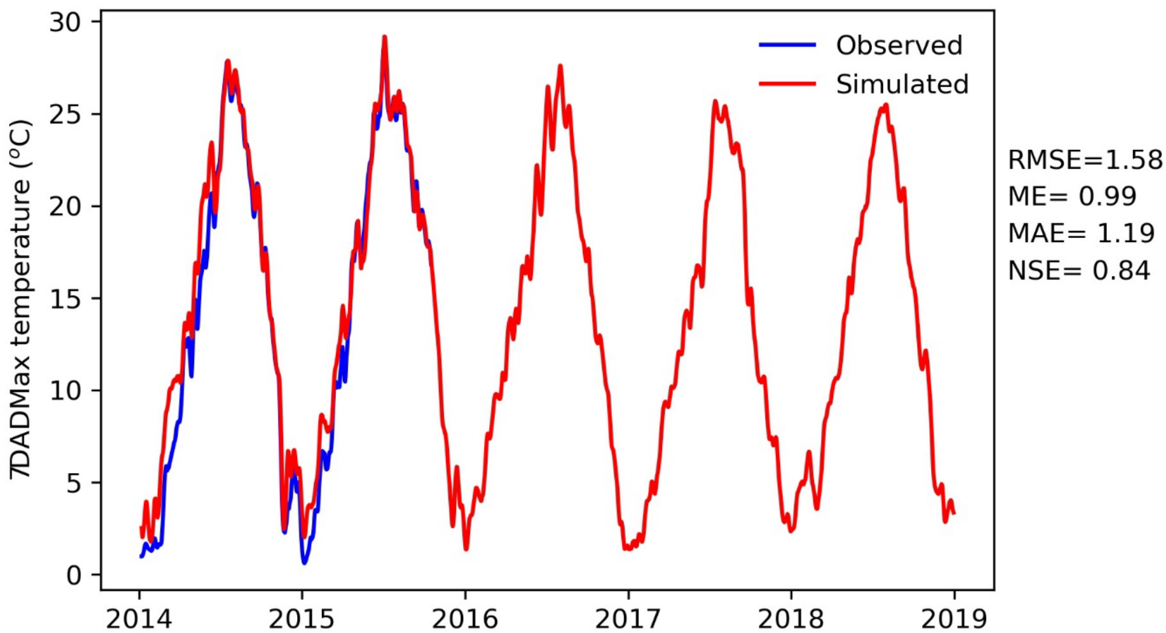


Figure 91. 7DADMax temperature Snake River at Weiser RM 354.

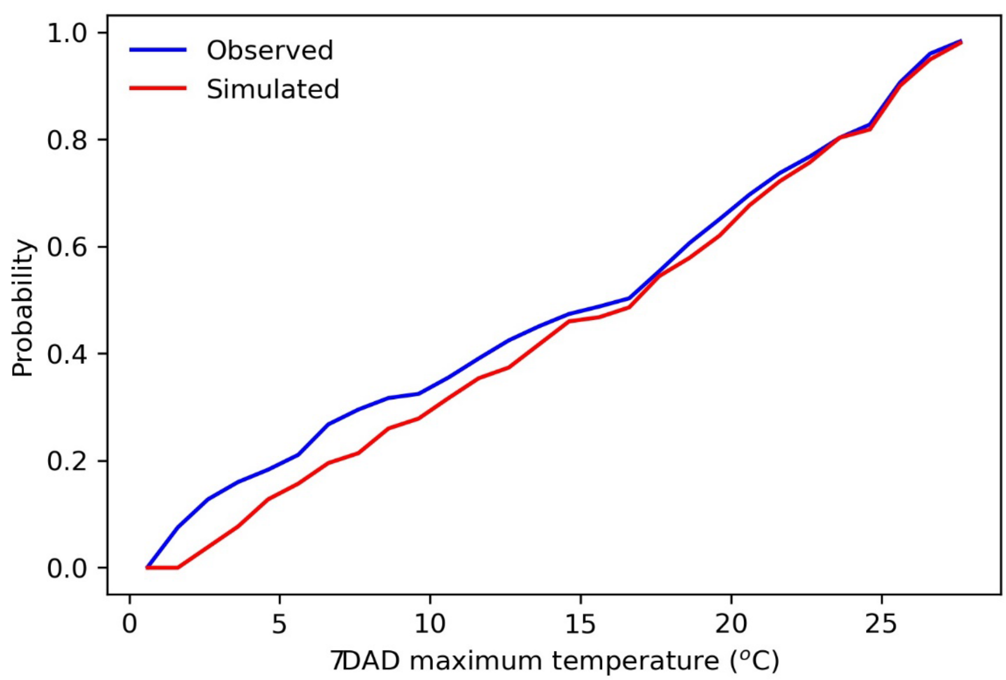


Figure 92. 7DADMax temperature Snake River at Weiser RM 354.

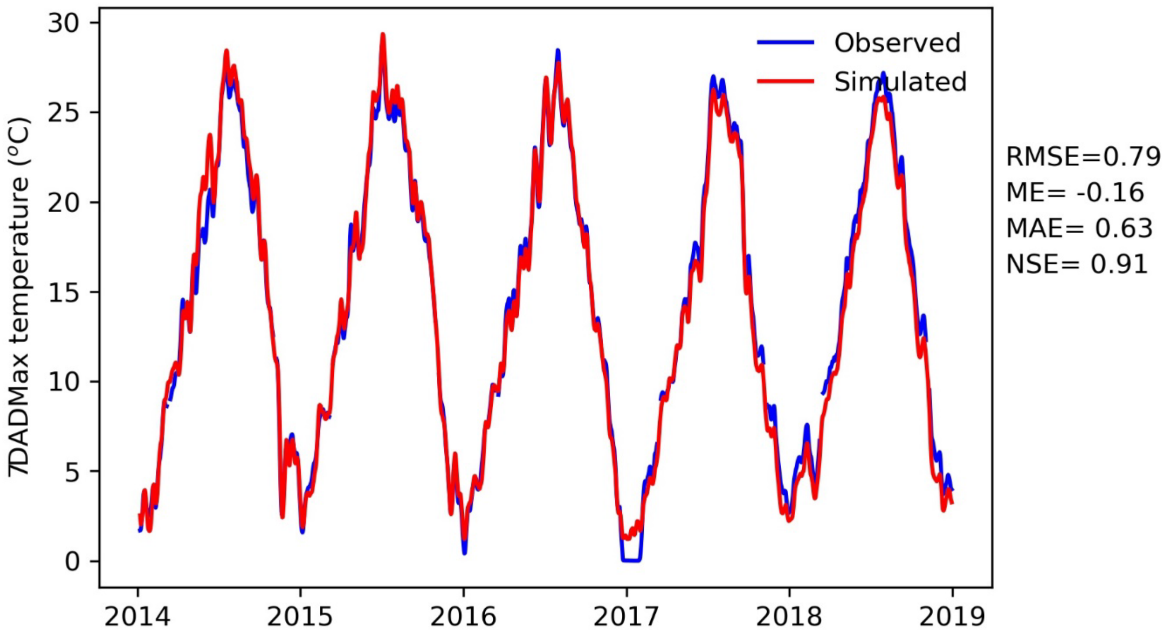


Figure 93. 7DADMax temperature Snake River at Brownlee Reservoir upstream, RM 345.2.

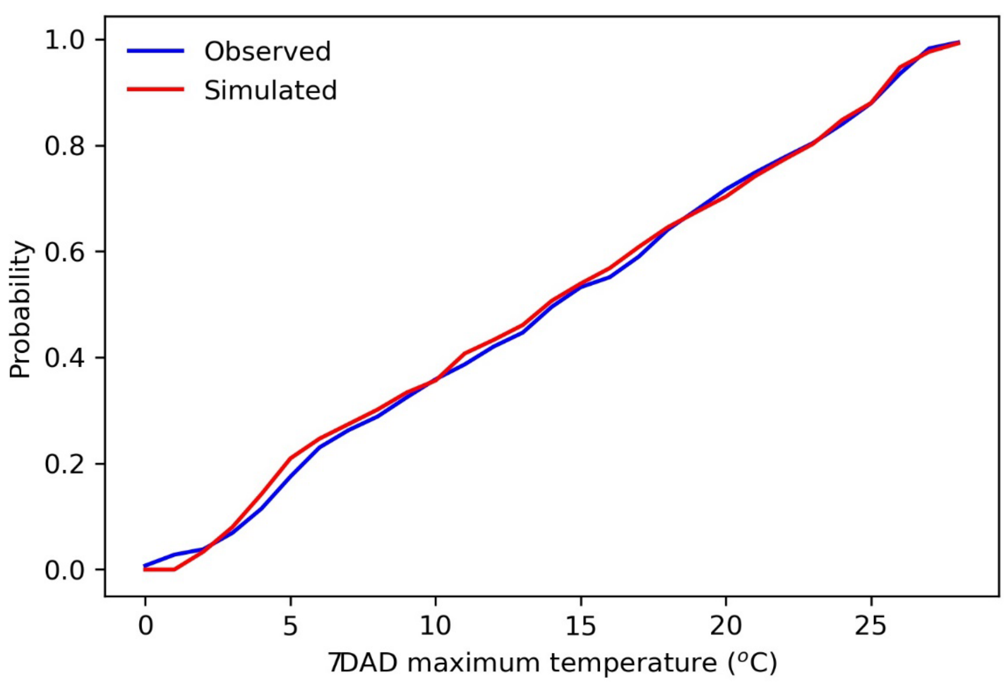


Figure 94. 7DADMax temperature Snake River at Brownlee Reservoir upstream, RM 345.2.

7.2 HELLS CANYON TO OREGON AND WASHINGTON STATE LINE

7.2.1 Daily Average Water Temperature Results

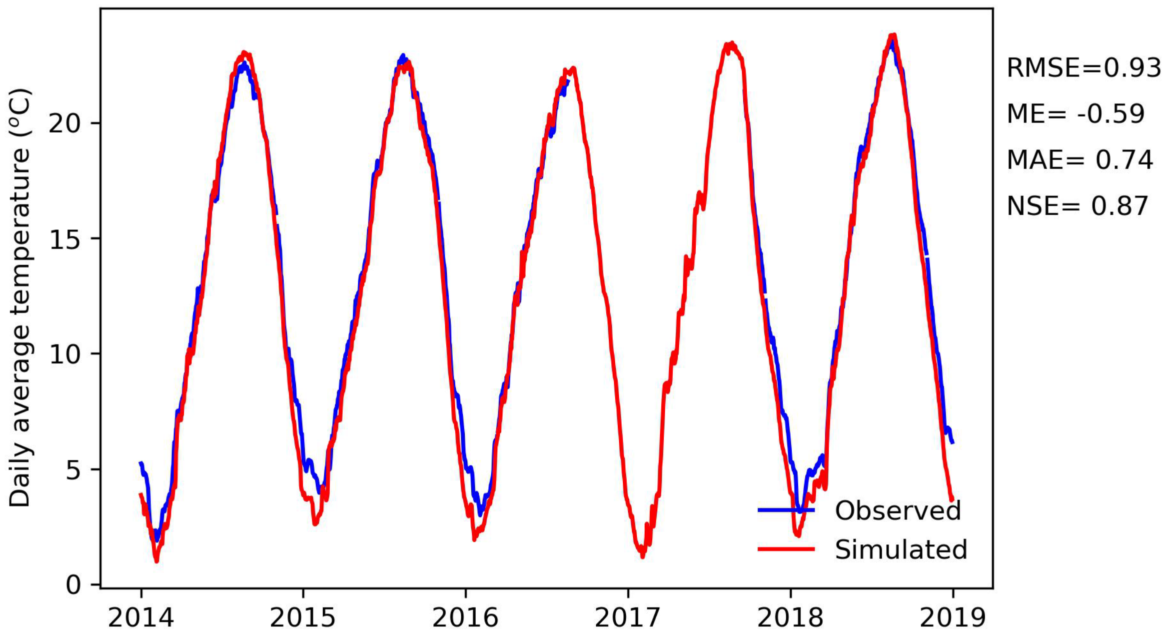


Figure 95. Daily average temperature Snake River near Sheep Creek at RM 230.

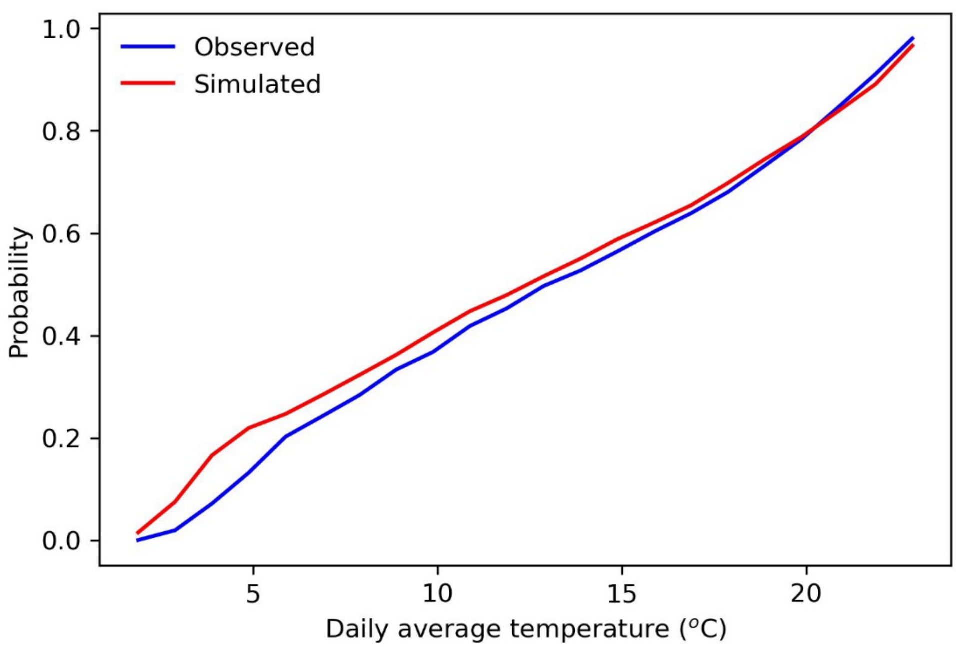


Figure 96. Daily average temperature Snake River Near Sheep Creek at RM 230.

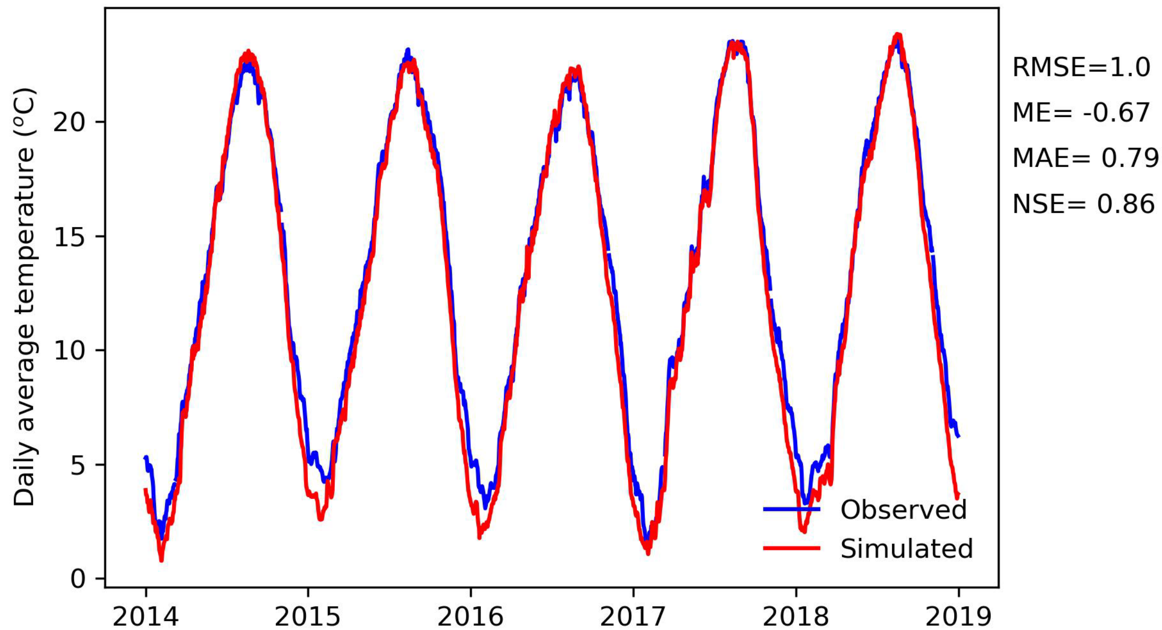


Figure 97. Daily average temperature Snake River near Pittsburg Landing at RM 216.

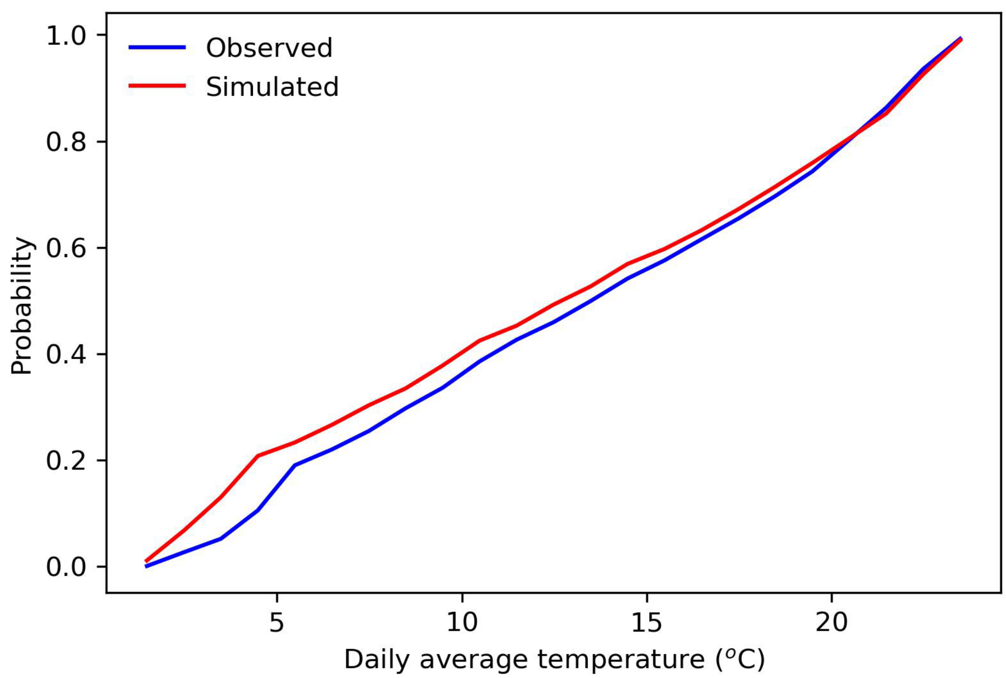


Figure 98. Daily average temperature Snake River Pittsburg Landing at RM 216.

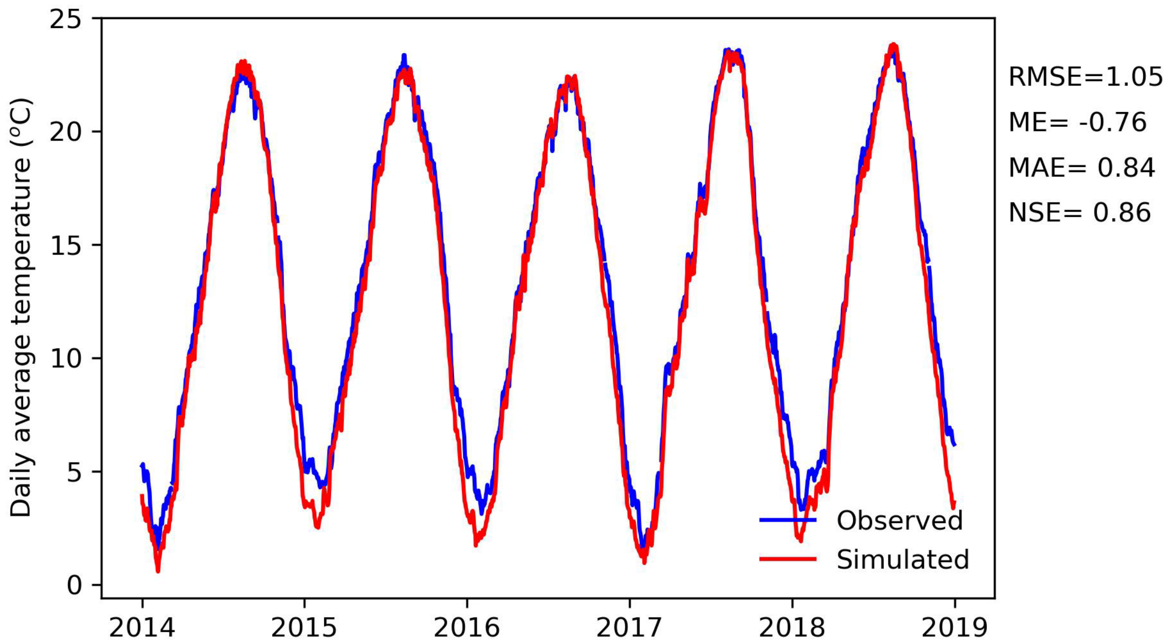


Figure 99. Daily average temperature Snake River near Dry Creek at RM 202.

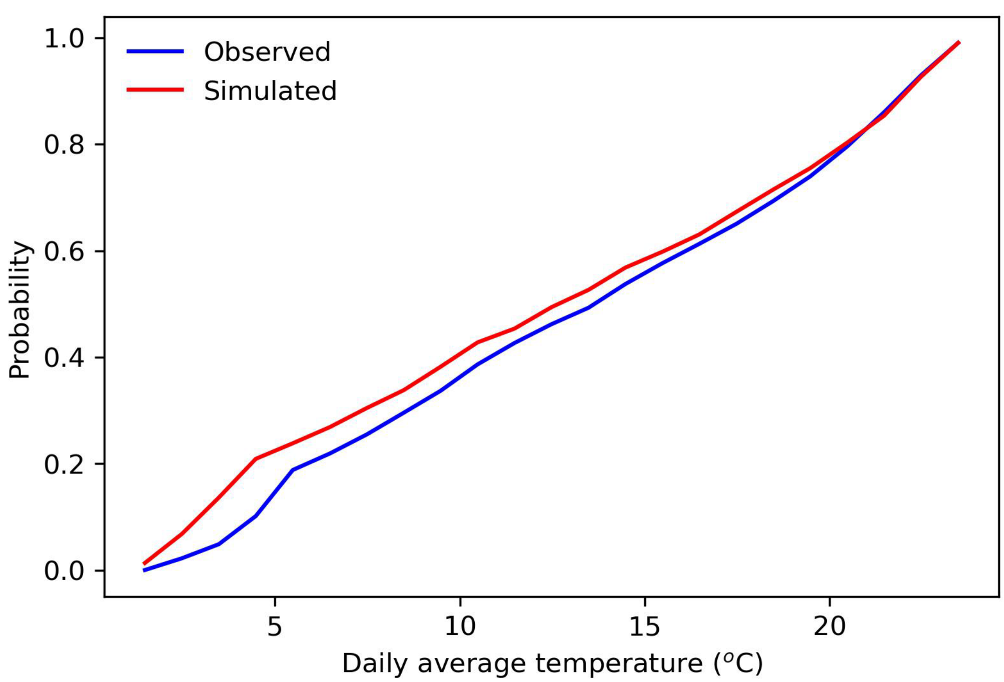


Figure 100. Daily average temperature Snake River near Dry Creek at RM 202.

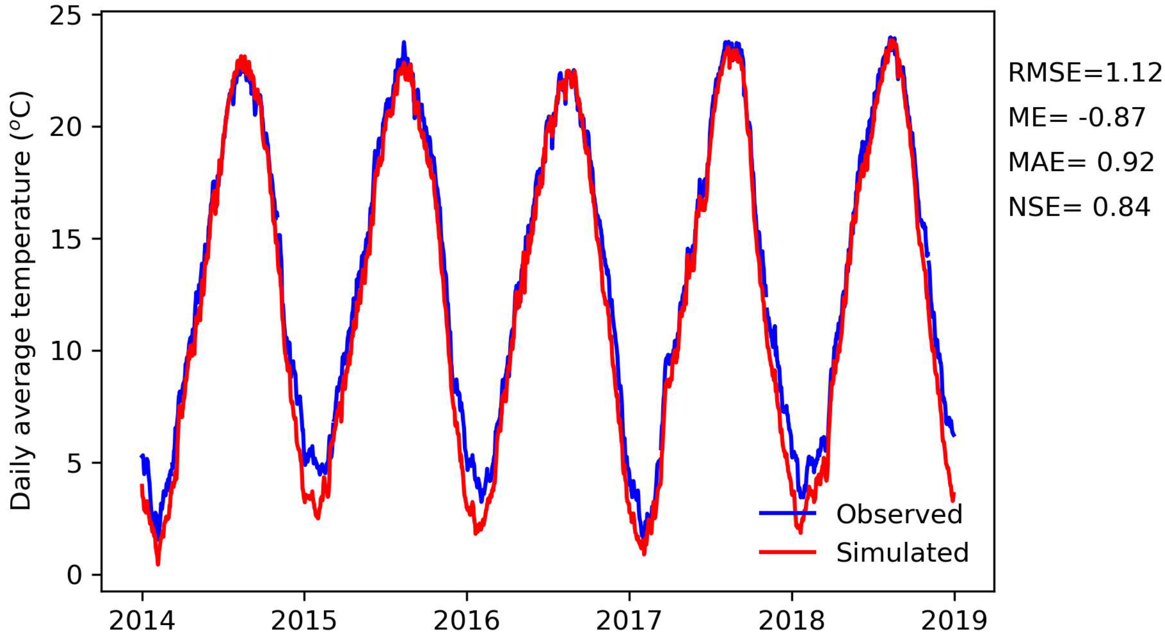


Figure 101. Daily average temperature Snake River above Salmon River at RM 189.

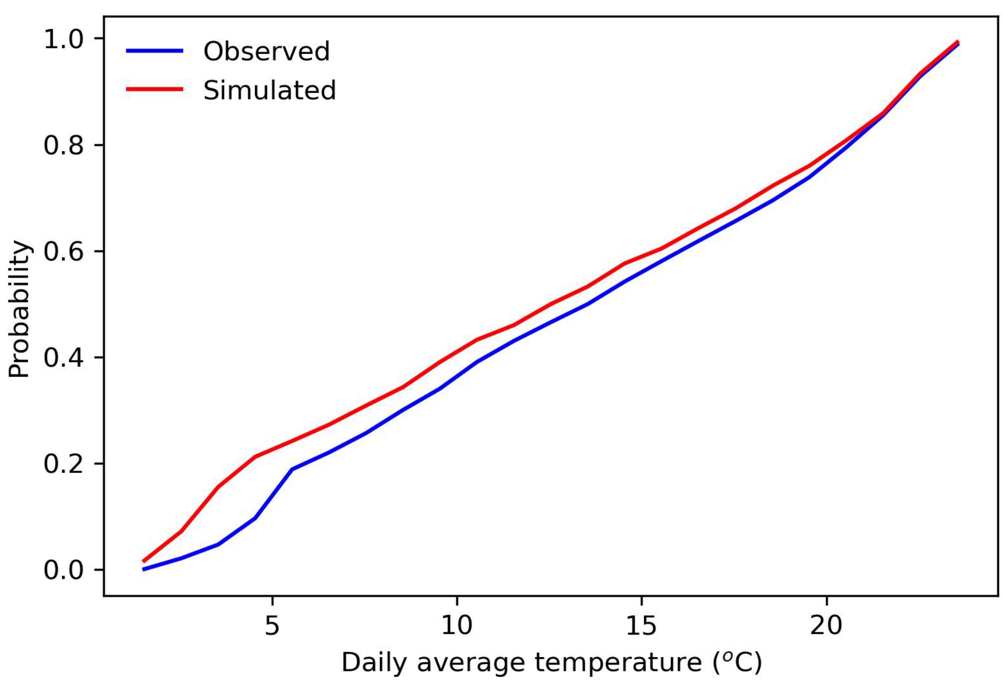


Figure 102. Daily average temperature Snake River above Salmon River at RM 189.

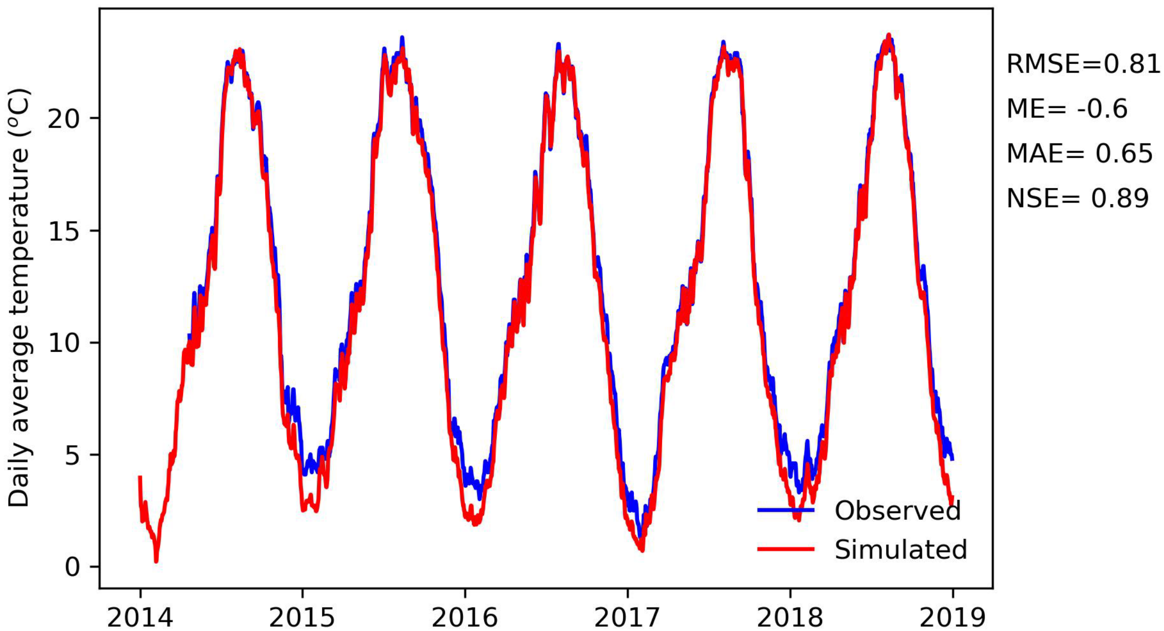


Figure 103. Daily average temperature Snake River near triple border at RM 176.

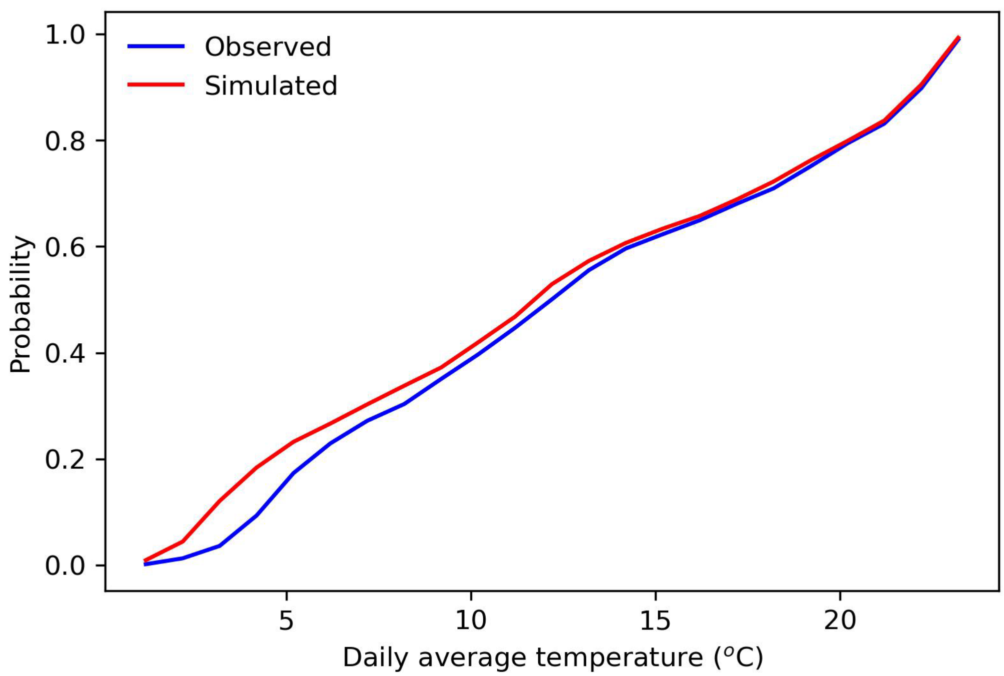


Figure 104. Daily average temperature Snake River near triple border at RM176.

7.2.2 Daily Maximum Water Temperature Results

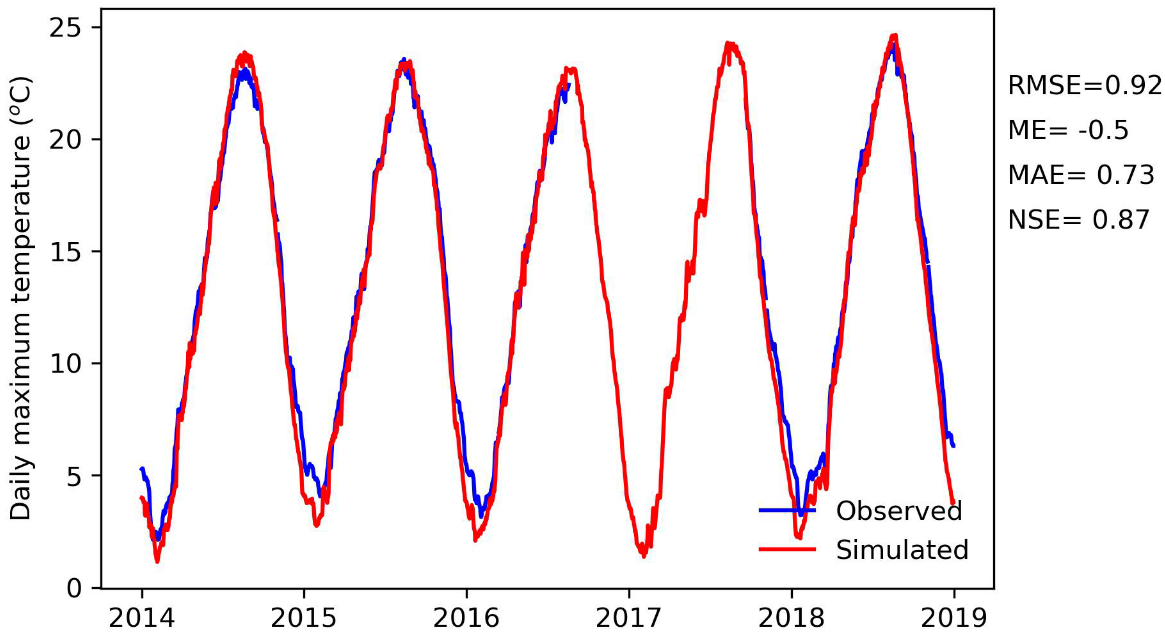


Figure 105. Daily maximum temperature Snake River near Sheep Creek at RM 230.

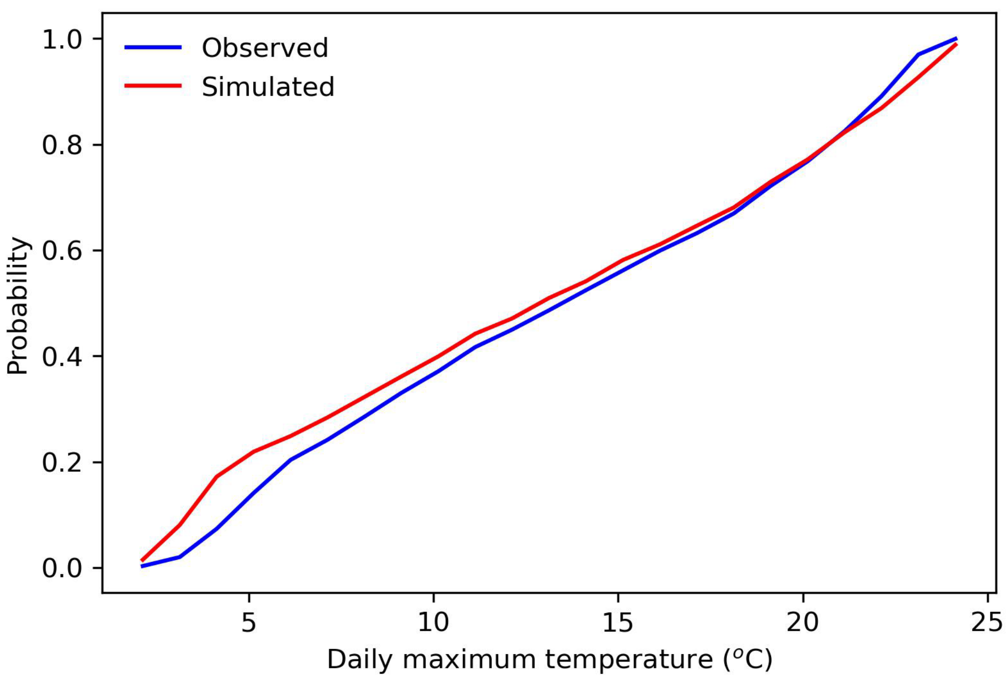


Figure 106. Daily maximum temperature Snake River near Sheep Creek at RM 230.

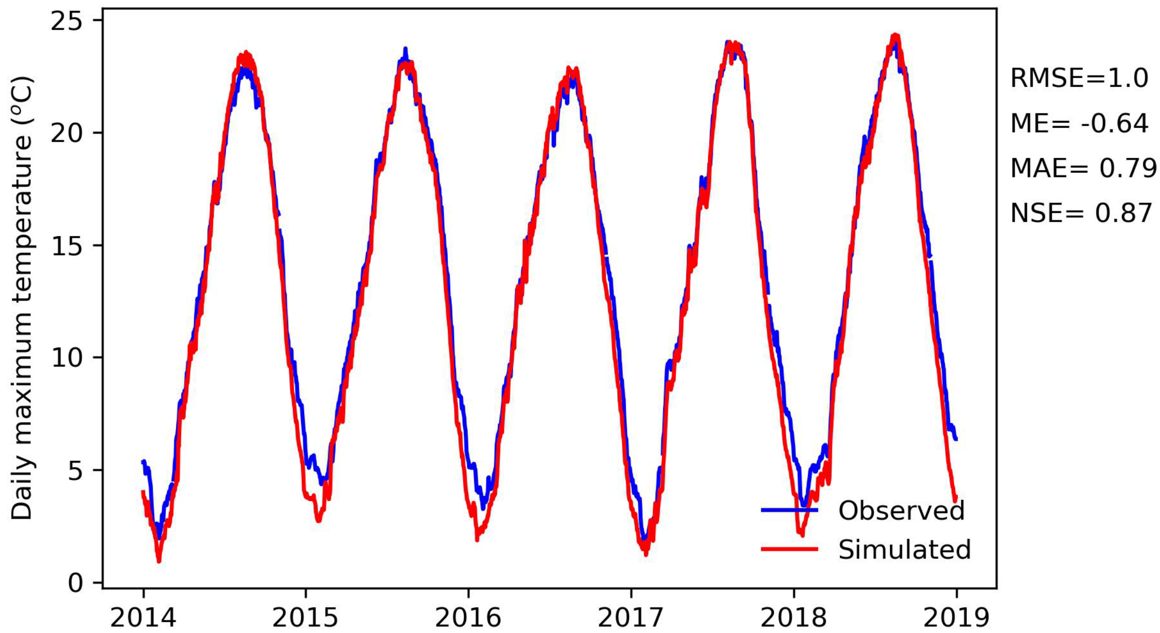


Figure 107. Daily maximum temperature Snake River near Pittsburg Landing at RM 216.

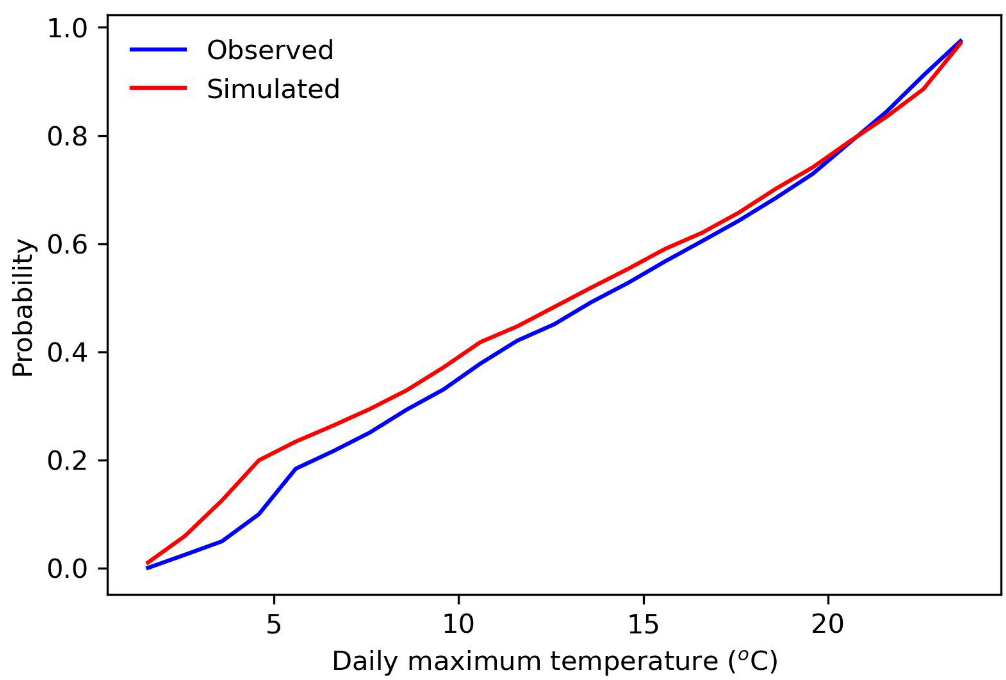


Figure 108. Daily maximum temperature Snake River near Pittsburg Landing at RM 216.

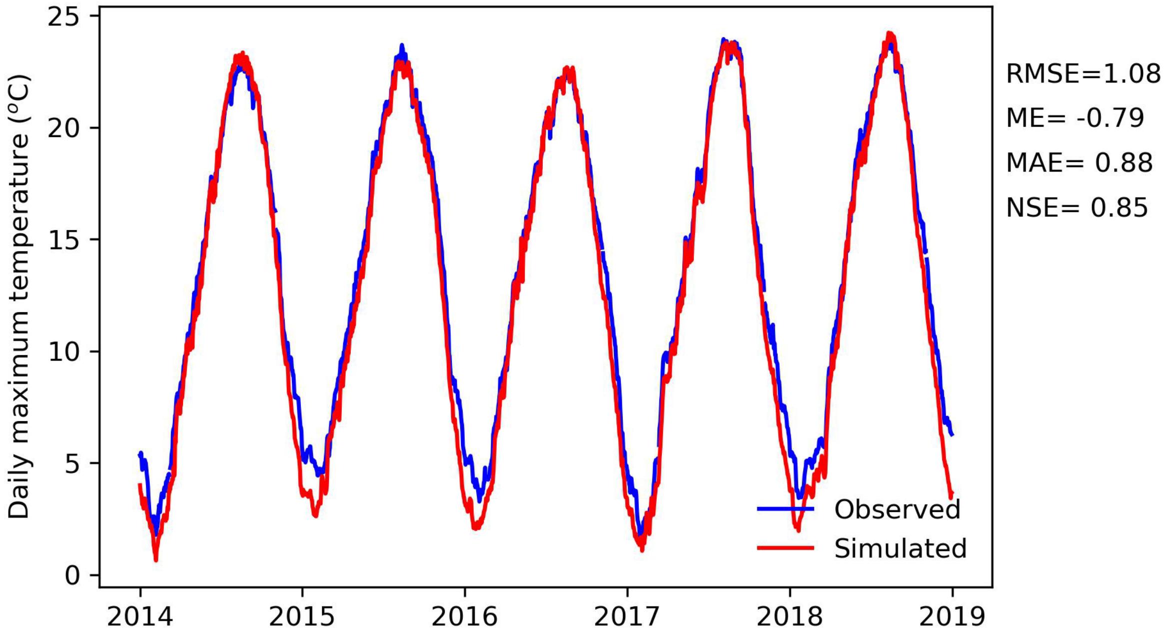


Figure 109. Daily maximum temperature Snake River near Dry Creek at RM 202.

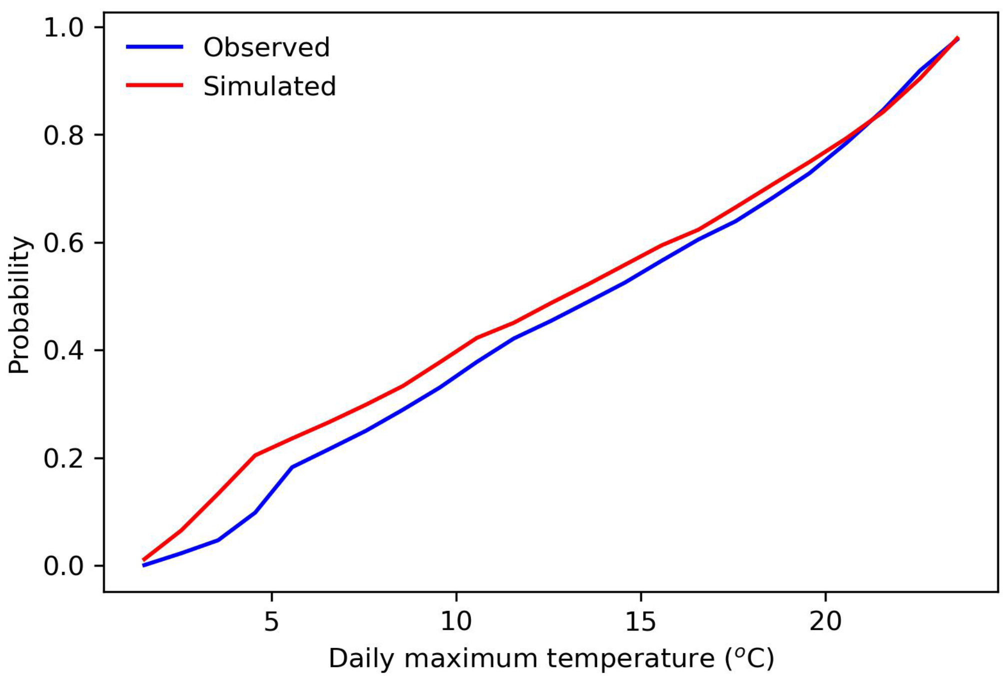


Figure 110. Daily maximum temperature Snake River near Dry Creek at RM 202.

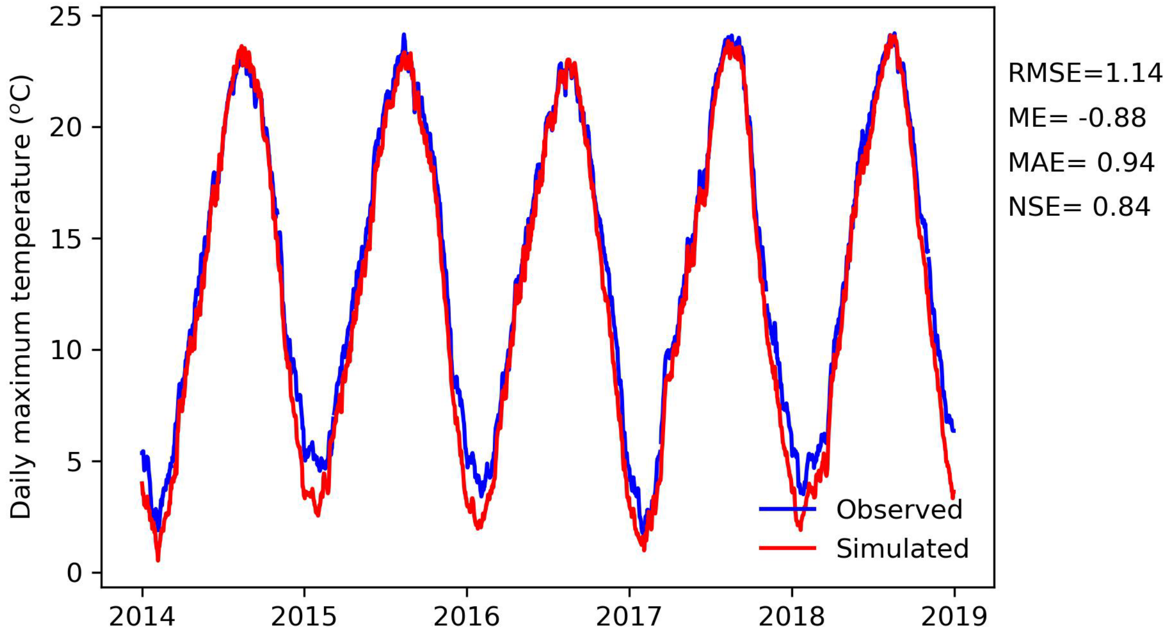


Figure 111. Daily maximum temperature Snake River above Salmon River at RM 189.

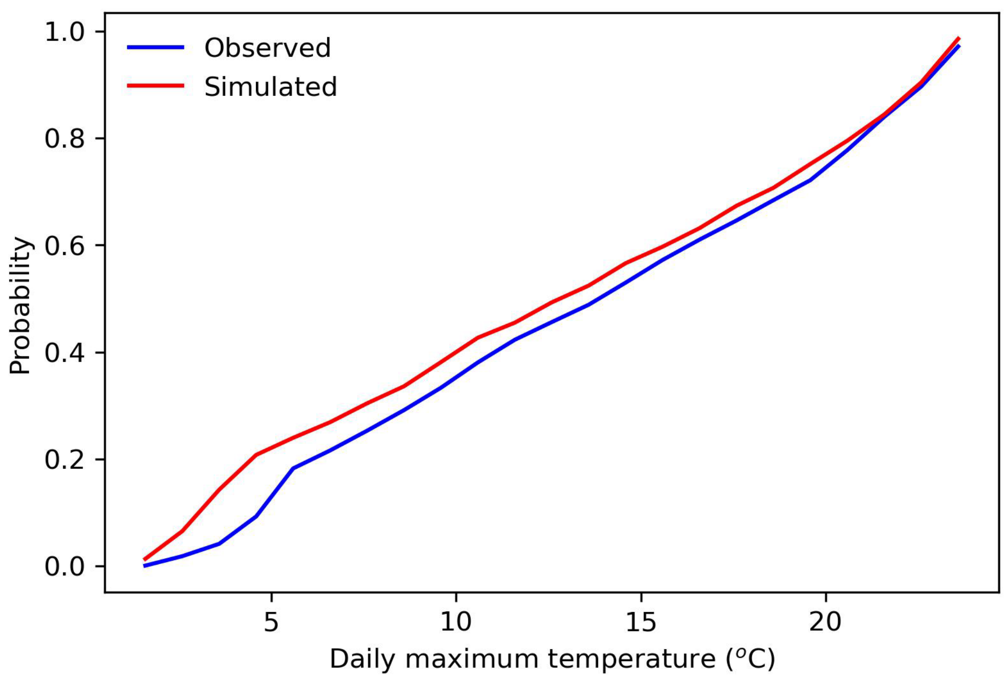


Figure 112. Daily maximum temperature Snake River above Salmon River at RM 189.

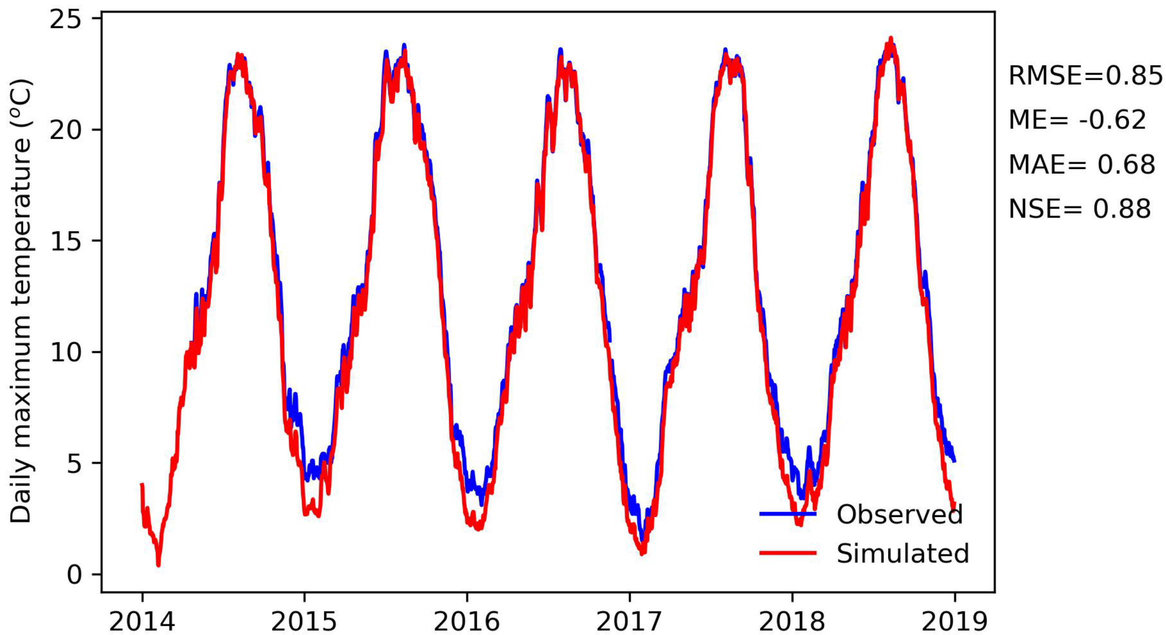


Figure 113. Daily maximum temperature Snake River near triple border at RM 176.

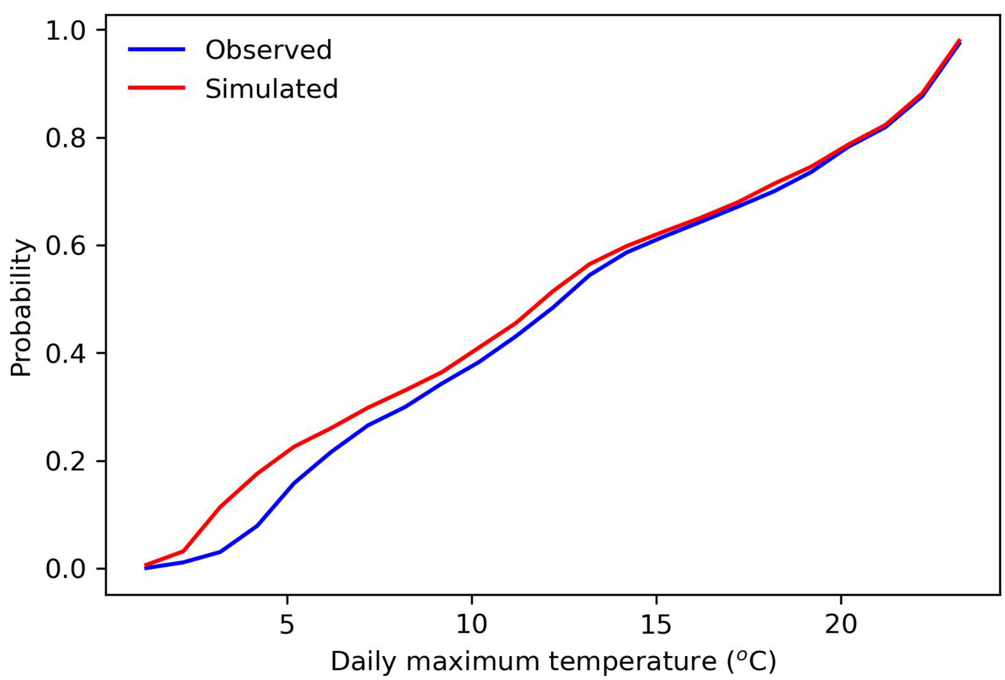


Figure 114. Daily maximum temperature Snake River near triple border at RM 176.

7.2.3 7-Day Average of Daily Maxima Water Temperature Results

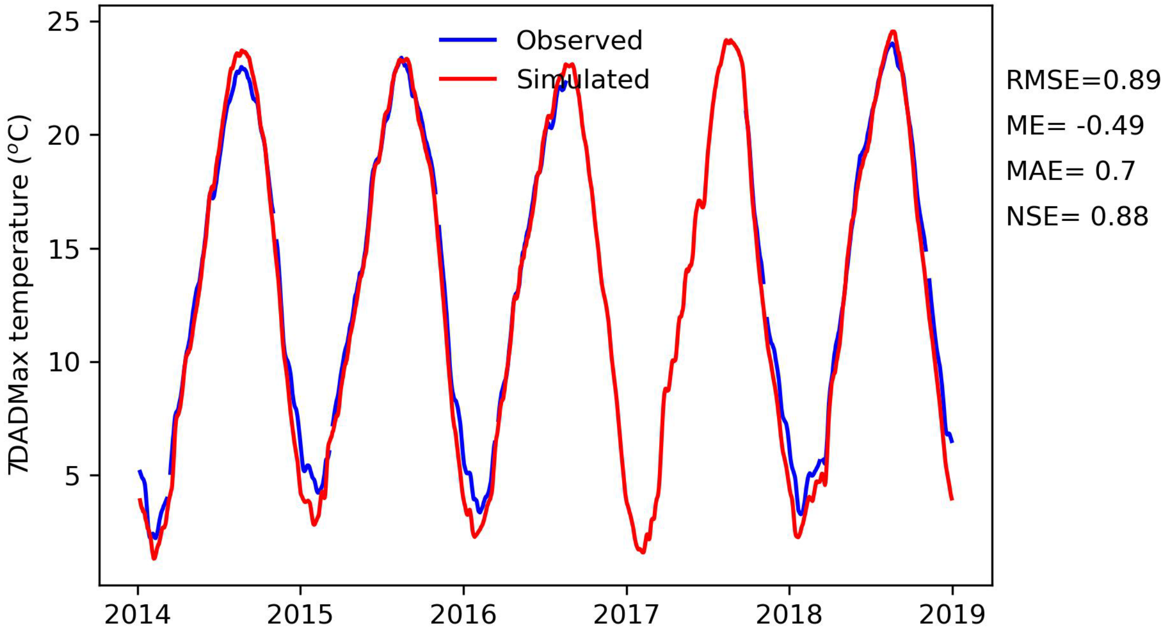


Figure 115. 7DADMax temperature Snake River near Sheep Creek at RM 230.

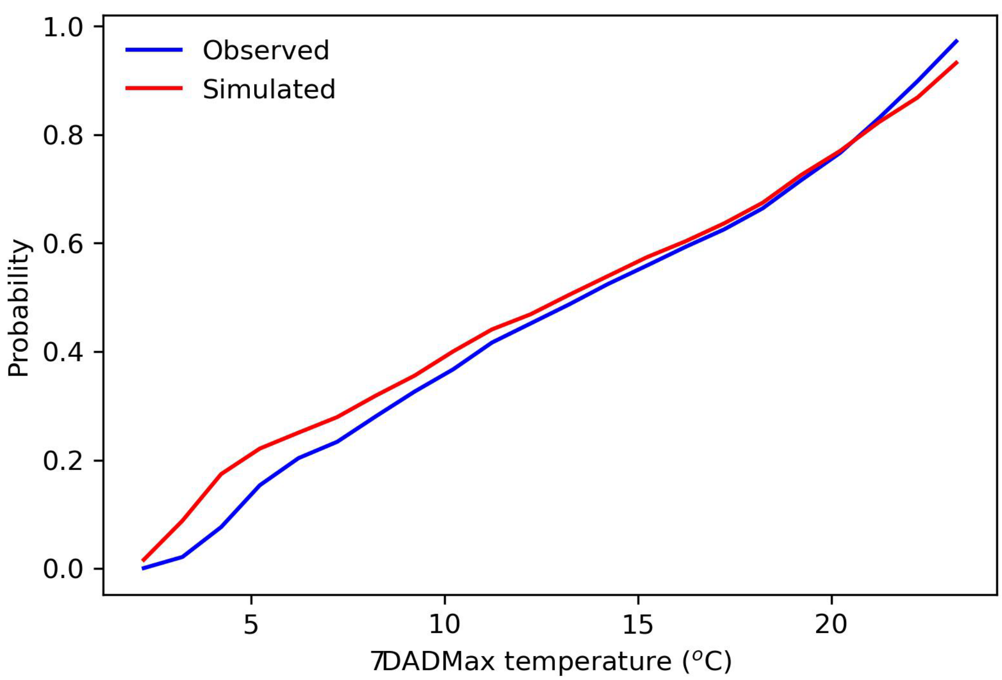


Figure 116. 7DADMax temperature Snake River near Sheep Creek at RM 230.

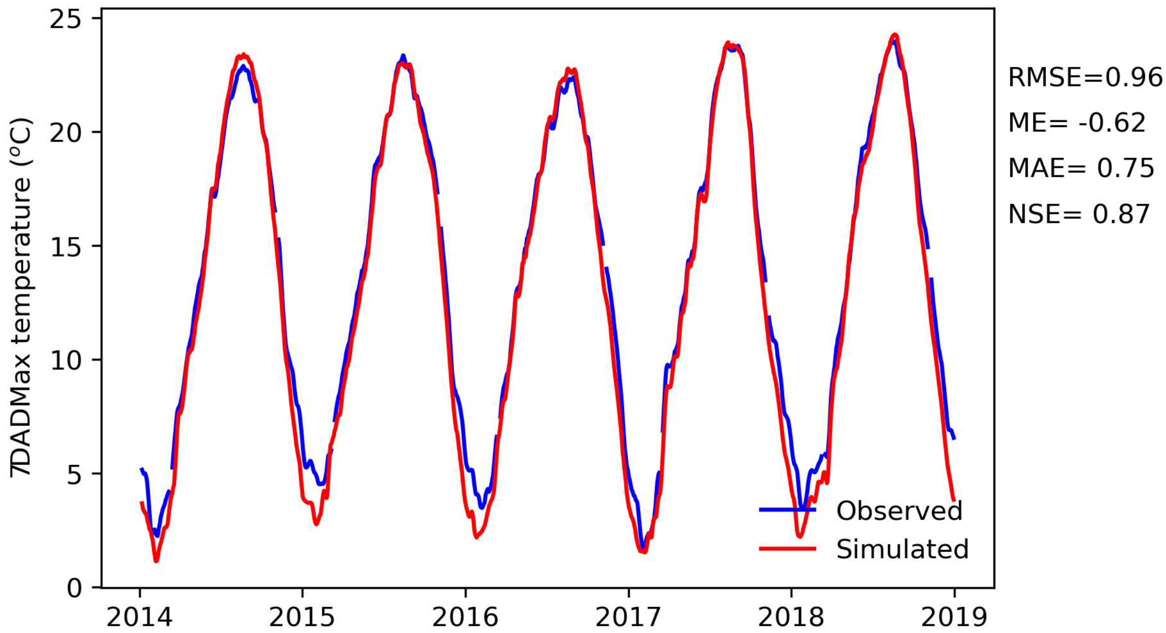


Figure 117. 7DADMax temperature Snake River near Pittsburg Landing at RM 216.

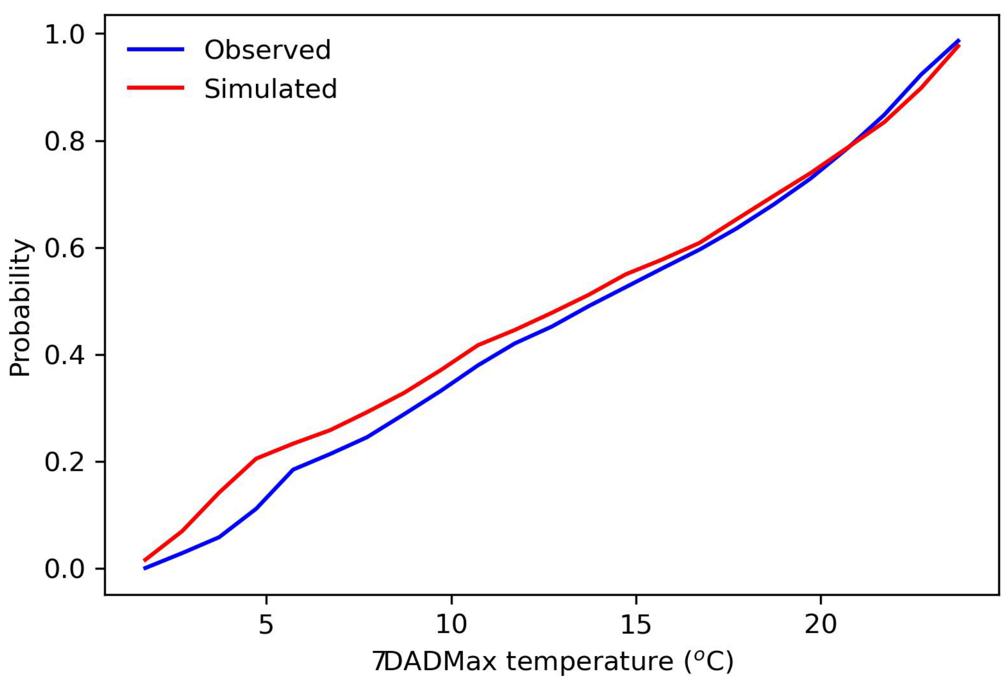


Figure 118. 7DADMax temperature Snake River near Pittsburg Landing at RM 216.

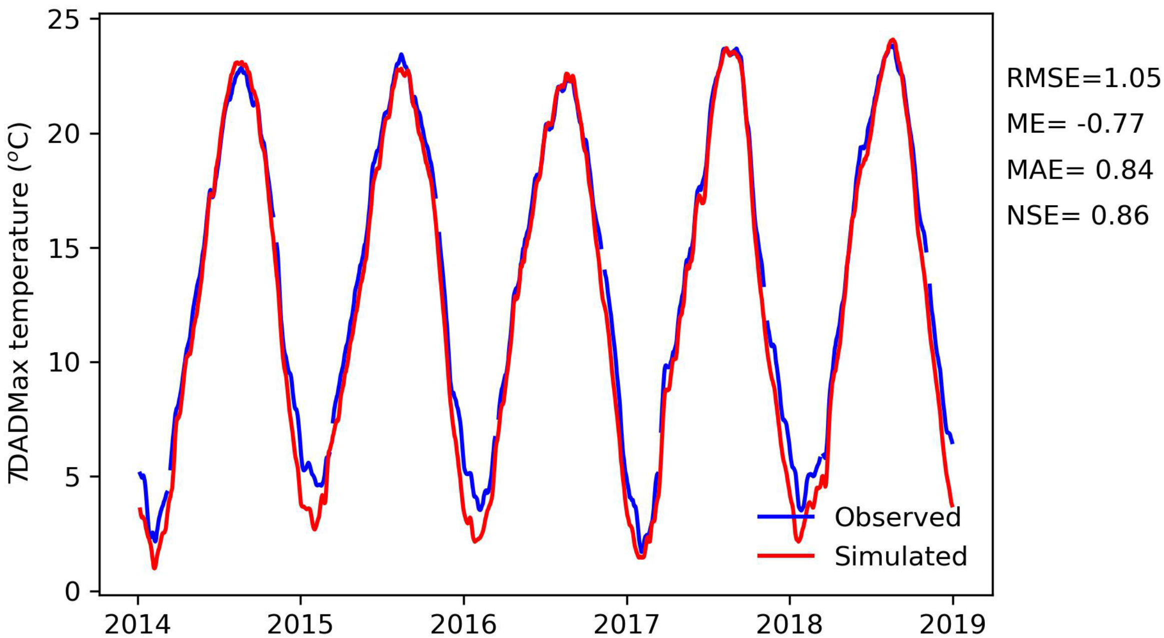


Figure 119. 7DADMax temperature Snake River near Dry Creek at RM 202.

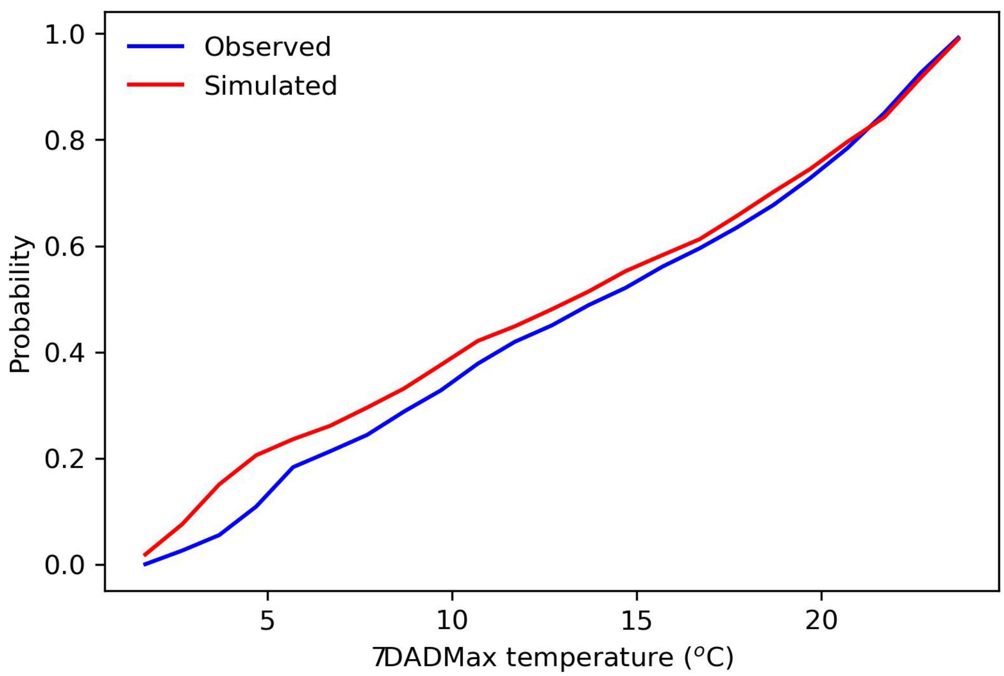


Figure 120. 7DADMax temperature Snake River near Dry Creek at RM 202.

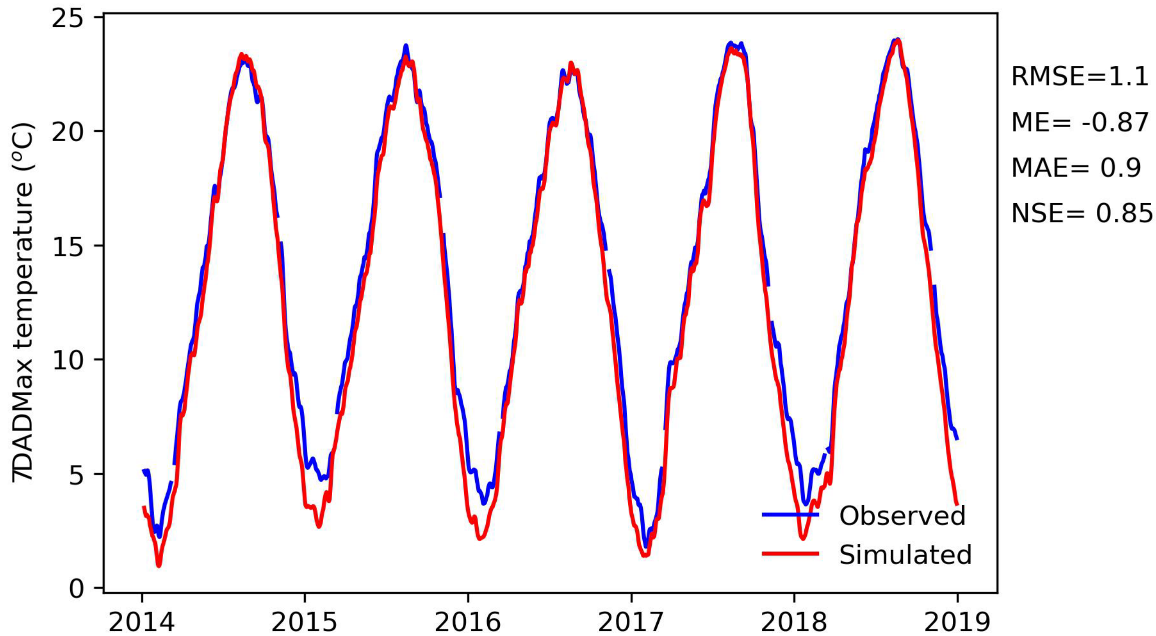


Figure 121. 7DADMax temperature Snake River above Salmon River at RM 189.

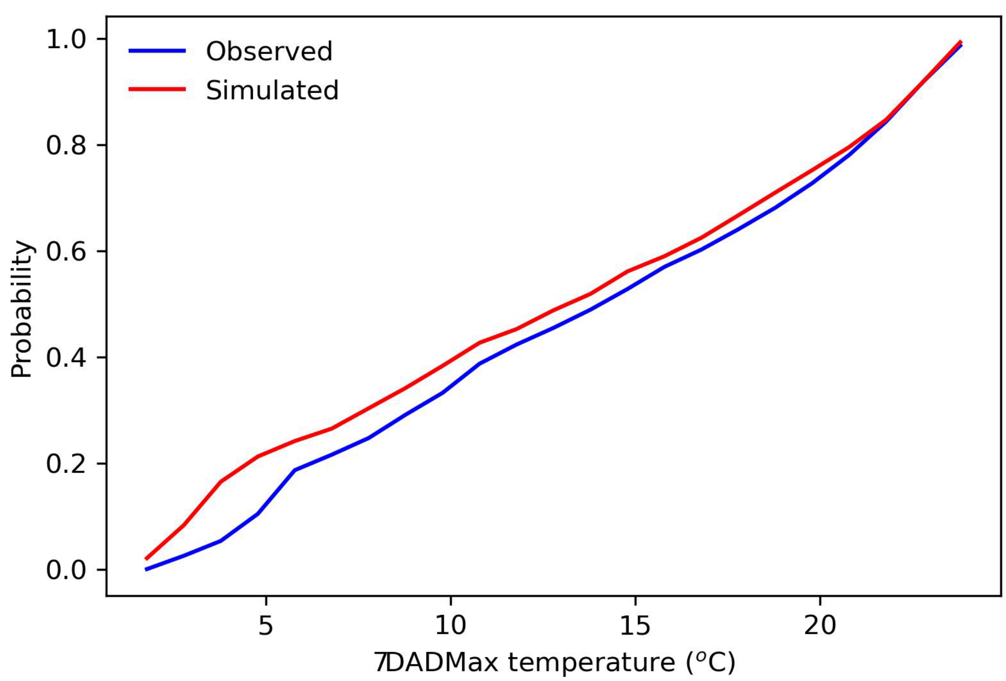


Figure 122. 7DADMax temperature Snake River above Salmon River at RM 189.

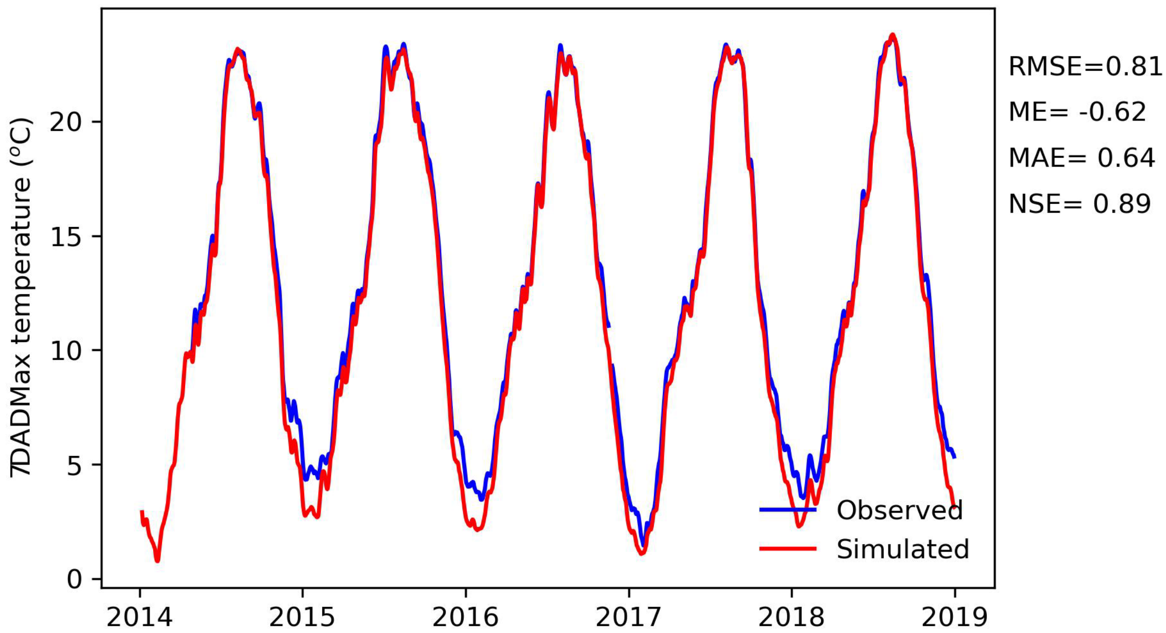


Figure 123. 7DADMax temperature Snake River near triple border at RM 176.

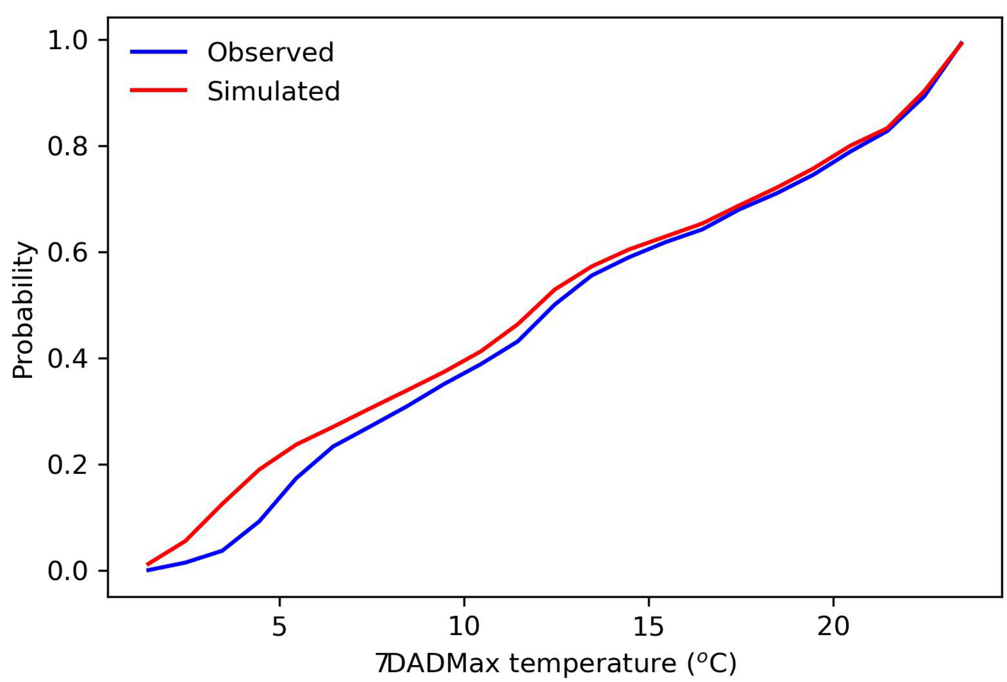


Figure 124. 7DADMax temperature Snake River near triple border at RM 176.

8.0 APPENDIX B: HELLS CANYON TO CLEARWATER RIVER USING OBSERVED UPSTREAM BOUNDARY CONDITIONS

This section present results of simulated temperature for Snake River from Hells Canyon to Clearwater River using the calibrated W2 models that utilize flow and temperature observations at IPC 13290450 and IPC RM 229.8 LB for the river upstream boundaries.

8.1 HOURLY COMPARISON

W2 hourly simulated water temperatures are compared against observations at RM 299.8, RM 216.3, RM 202.3, RM 189 in Table 22 and Figure 125 through Figure 132. Statistics evaluating the model fit for whole year and the warmer season (May-November) are presented in Table 22. The model simulated the hourly water temperature observations with RMSE ≤ 0.49°C and NSE ≥ 0.93 for the modeling period. The simulated temperatures deviated from observations by less than 0.47°C measured by RMSE, ME, and MAE for the warm season.

Table 22. Performance of W2 in simulating Snake River hourly water temperature. Error units are in °C.

Gage	Location	River Mile (RM)	Count	Full Year				Summer (May-November)			
				NSE	RMSE	ME	MAE	NSE	RMSE	ME	MAE
IPC RM 229.8	Near Sheep Creek	230	33,986	0.97	0.24	-0.07	0.19	0.92	0.29	-0.07	0.24
IPC RM 216.3	Near Pittsburg Landing	216	43,436	0.95	0.34	-0.20	0.29	0.91	0.36	-0.17	0.30
IPC RM 202.3	Near Dry Creek	202	41,438	0.94	0.38	-0.30	0.32	0.91	0.36	-0.26	0.30
IPC RM 189	Above Salmon River	189	43,436	0.93	0.49	-0.41	0.42	0.88	0.47	-0.37	0.39

Note: NSE = Nash Sutcliffe coefficient of model fit efficiency, RMSE = root mean squared error, ME = mean error, MAE = mean absolute error.

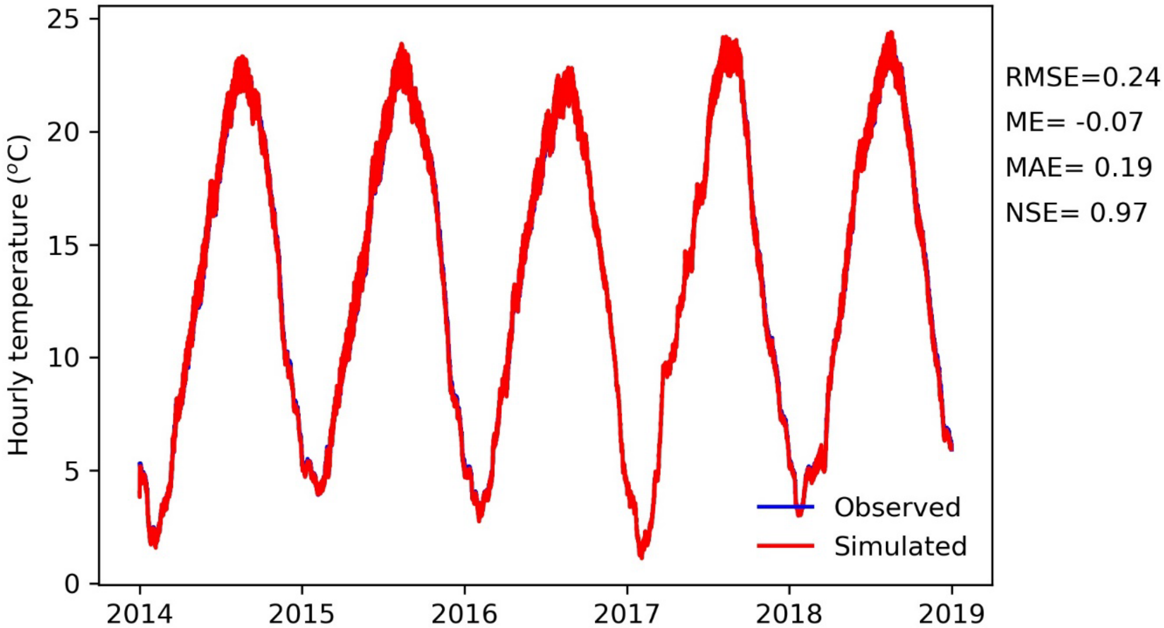


Figure 125. W2 hourly simulated water temperatures versus observations near Sheep Creek at RM 230.

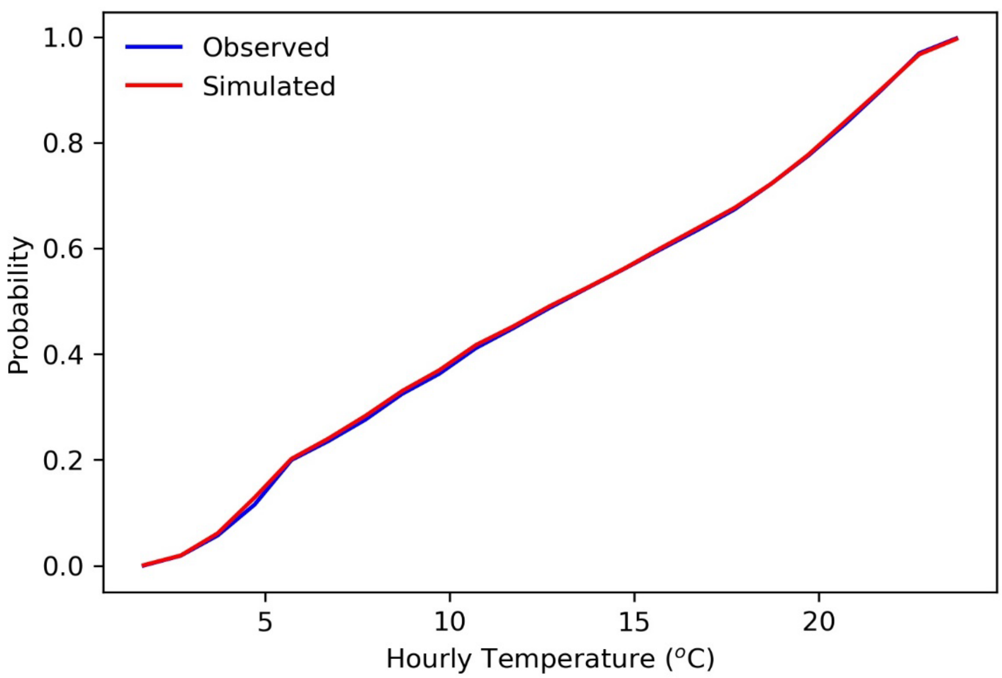


Figure 126. W2 simulated water temperatures versus observations near Sheep Creek at RM 230, ECD graph.

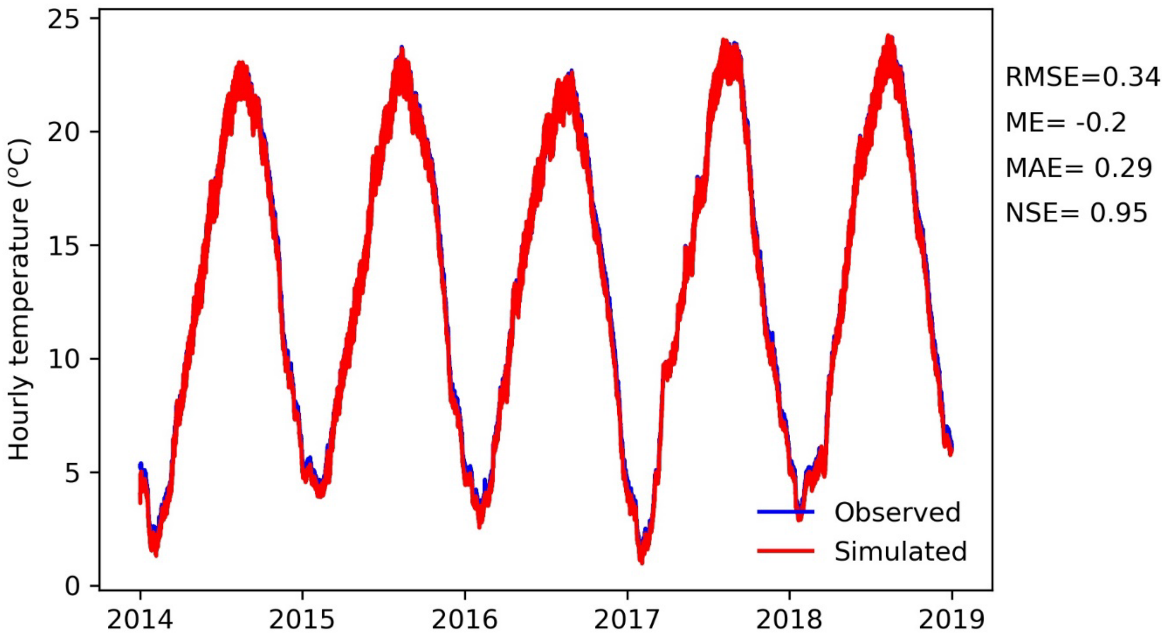


Figure 127. W2 hourly simulated water temperatures versus observations near Pittsburg Landing at RM 216.

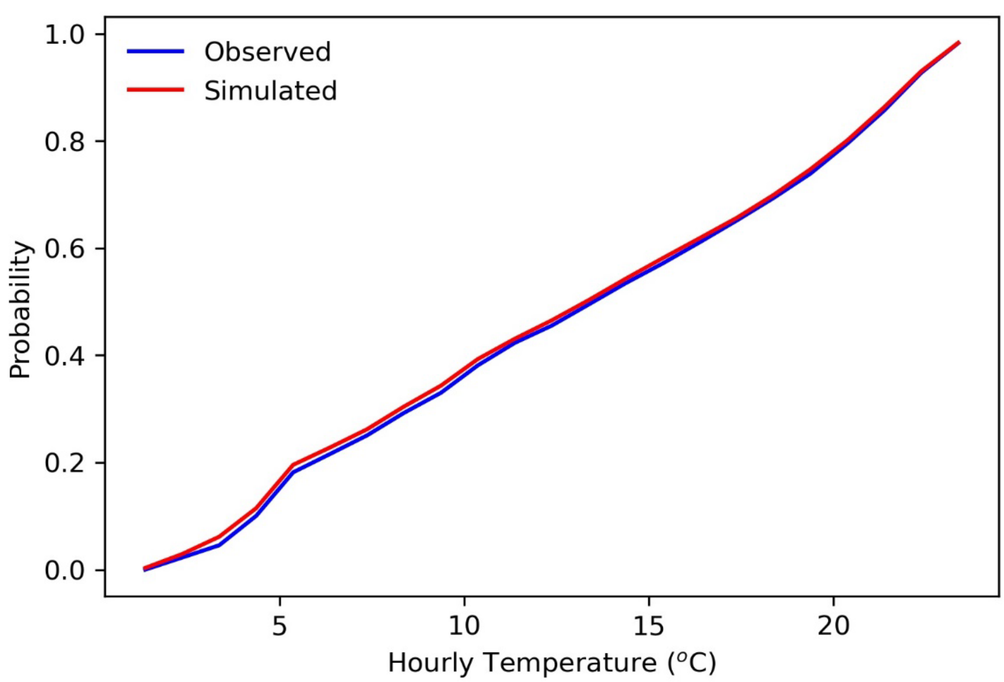


Figure 128. W2 simulated water temperatures versus observations near Pittsburg Landing at RM 216, ECD graph.

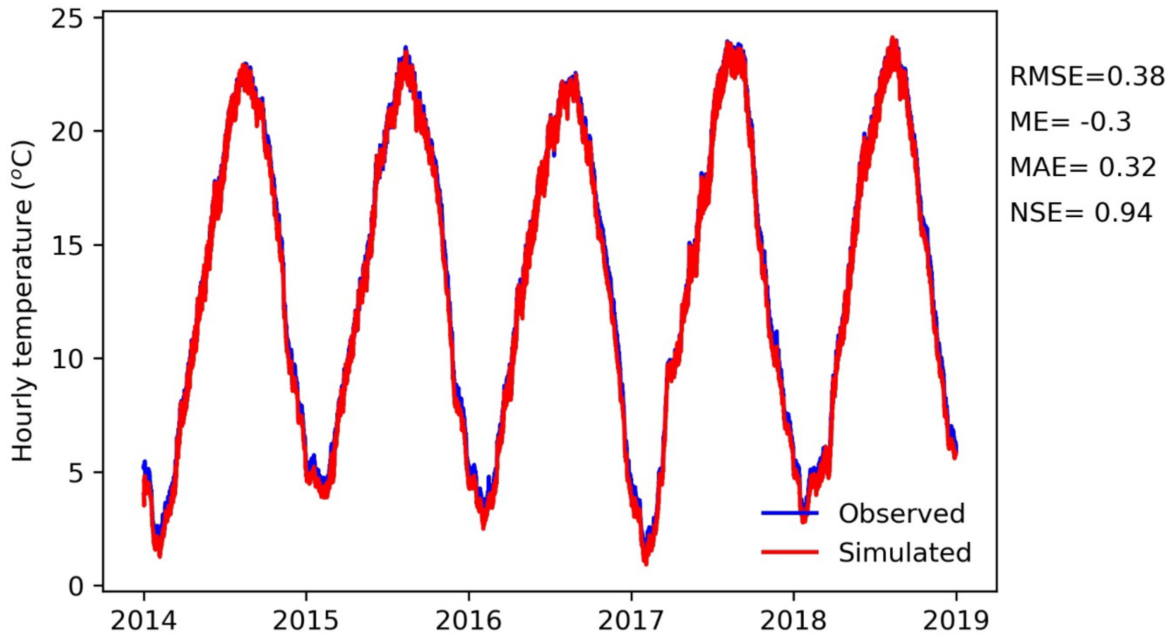
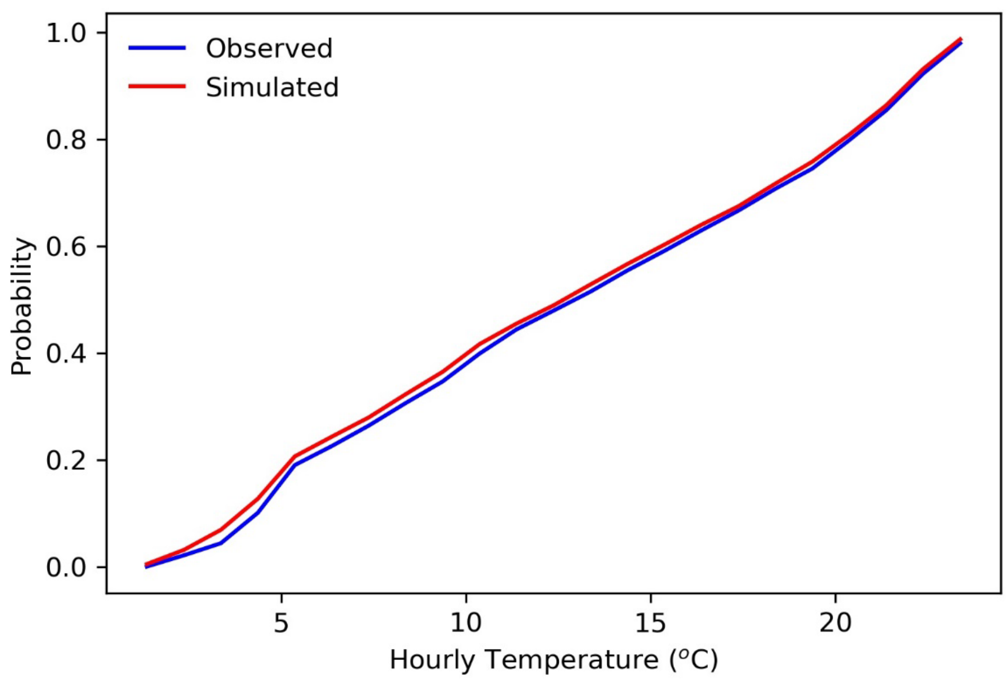


Figure 129. W2 hourly simulated water temperatures versus observations near Dry Creek at RM



202.

Figure 130. W2 simulated water temperatures versus observations near Dry Creek at RM 202, ECD graph.

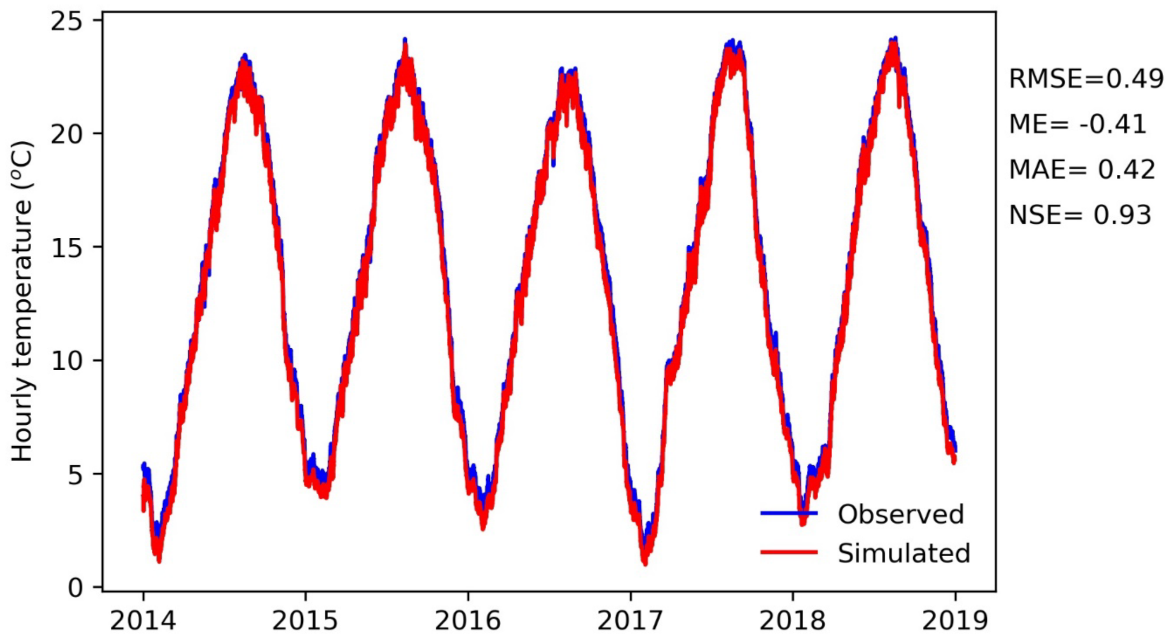


Figure 131. W2 hourly simulated water temperatures versus observations above Salmon River at RM 189.

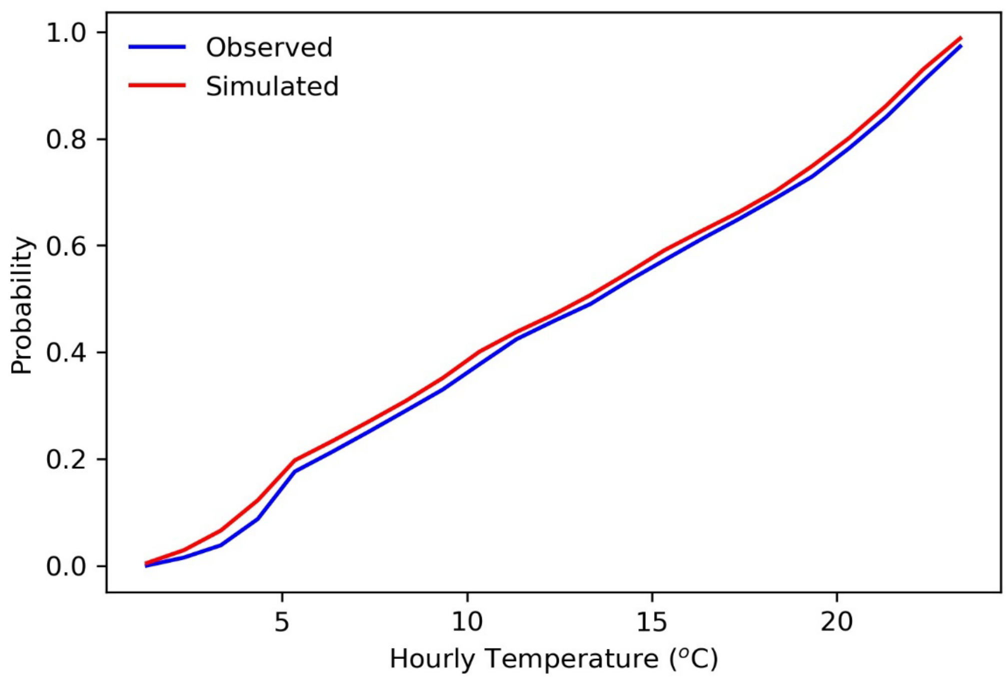


Figure 132. W2 simulated water temperatures versus observations above Salmon River at RM 189, ECD graph.

8.2 DAILY AVERAGE WATER TEMPERATURE COMPARISON

W2 simulated hourly water temperatures are averaged and compared to daily observations for six stations in Table 23and Figure 133 through Figure 144. The model simulated temporal variation of daily water temperature observations with RMSE ≤ 0.47 °C for modeling period and summer for all stations. The model simulated Snake River water temperature observations at China Garden (USGS 13317660) and near Anatone (USGS 13334300) with RMSE ≤0.39 °C and 0.47 °C, respectively, for both modeling period and summer season.

Table 23. Performance of W2 in simulating Snake River daily average water temperature. Error units are in °C.

Gage	Location	River Mile (RM)	Count	Full Year				Summer (May-November)			
				NSE	RMSE	ME	MAE	NSE	RMSE	ME	MAE
IPC RM 229.8	Near Sheep Creek	230	1,421	0.98	0.16	-0.07	0.12	0.95	0.17	-0.06	0.14
IPC RM 216.3	Near Pittsburg Landing	216	1,816	0.96	0.28	-0.20	0.23	0.94	0.26	-0.16	0.21
IPC RM 202.3	Near Dry Creek	202	1,816	0.95	0.36	-0.29	0.30	0.92	0.33	-0.24	0.27
IPC RM 189	Above Salmon River	189	1,816	0.93	0.46	-0.41	0.41	0.89	0.43	-0.36	0.37
USGS 13317660	Near Triple Border (ID-OR-WA)	176	1,714	0.94	0.39	-0.29	0.33	0.93	0.37	-0.24	0.30
USGS 13334300	Near Anatone	168	1,810	0.94	0.47	-0.24	0.38	0.91	0.47	-0.26	0.37

Note: NSE = Nash Sutcliffe coefficient of model fit efficiency, RMSE = root mean squared error, ME = mean error, MAE = mean absolute error.

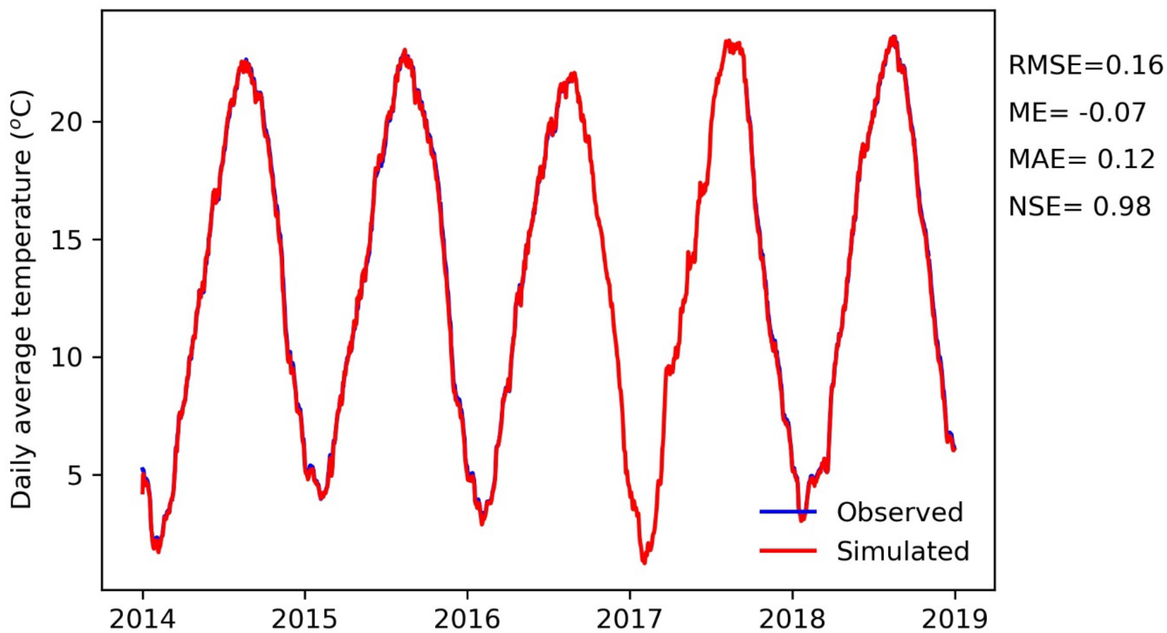


Figure 133. W2 daily average simulated water temperatures versus observations at Sheep Creek, RM 230.

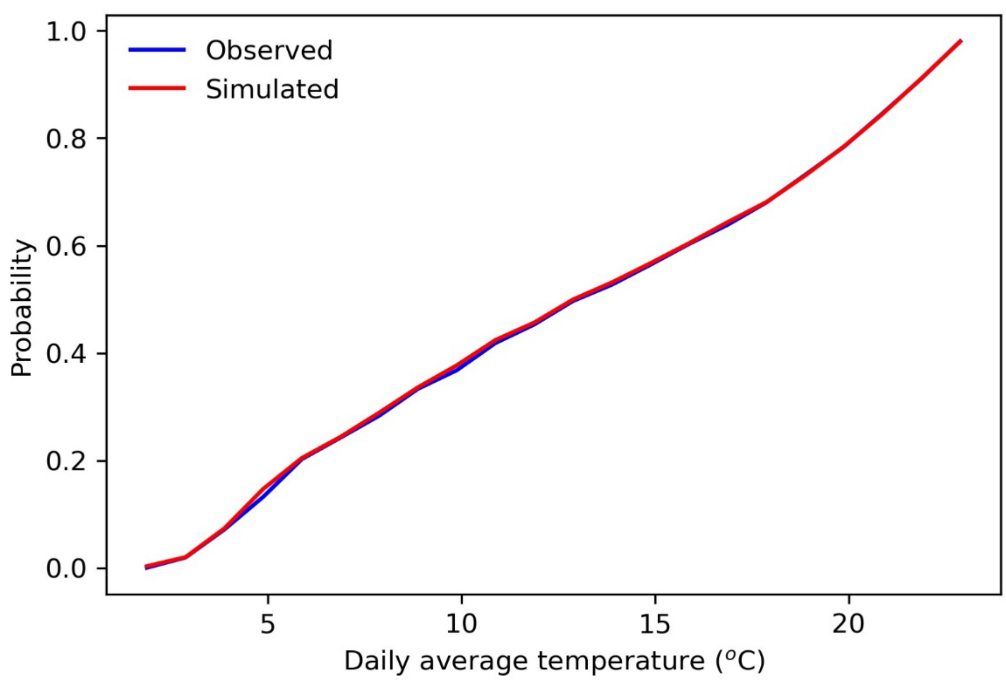


Figure 134. W2 simulated water temperatures versus observations at Sheep Creek (RM 230), ECD graph.

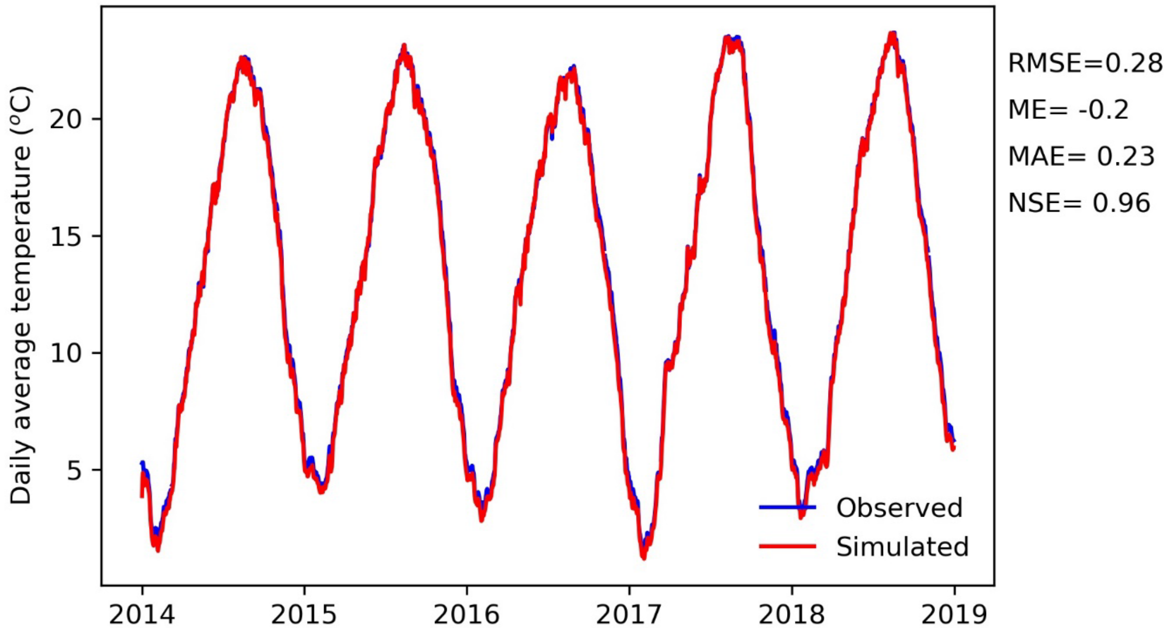


Figure 135. W2 daily average simulated water temperatures versus observations Near Pittsburg at RM 216.

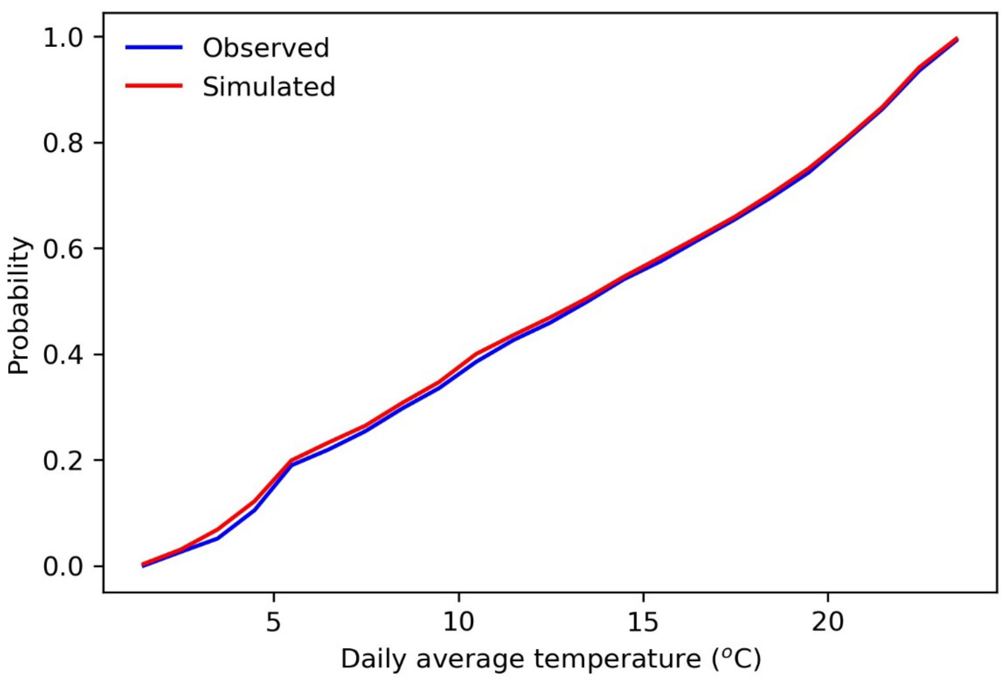


Figure 136. W2 simulated water temperatures versus observations Near Pittsburg at RM 216, ECD graph.

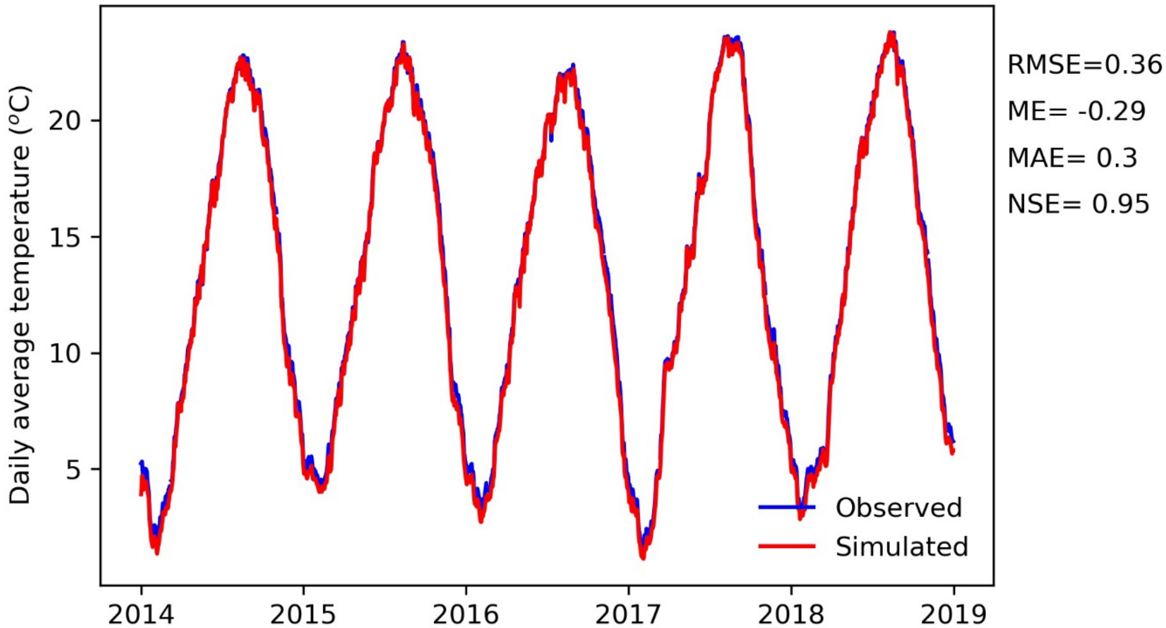


Figure 137. W2 daily average simulated water temperatures versus observations near Dry Creek at RM 202.

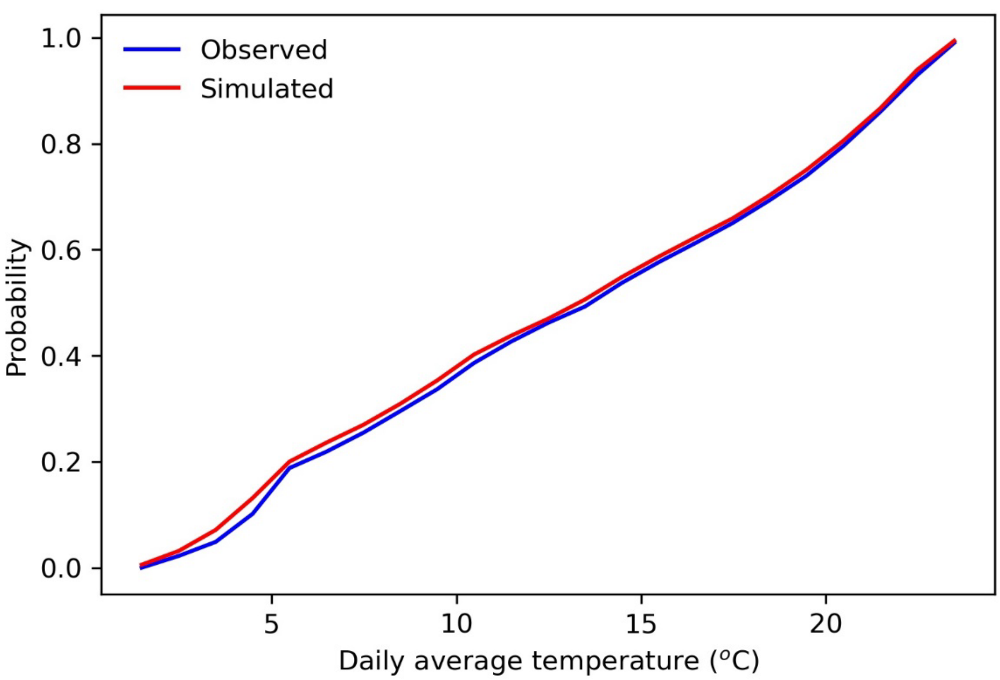


Figure 138. W2 simulated water temperatures versus observations near Dry Creek at RM 202, ECD graph.

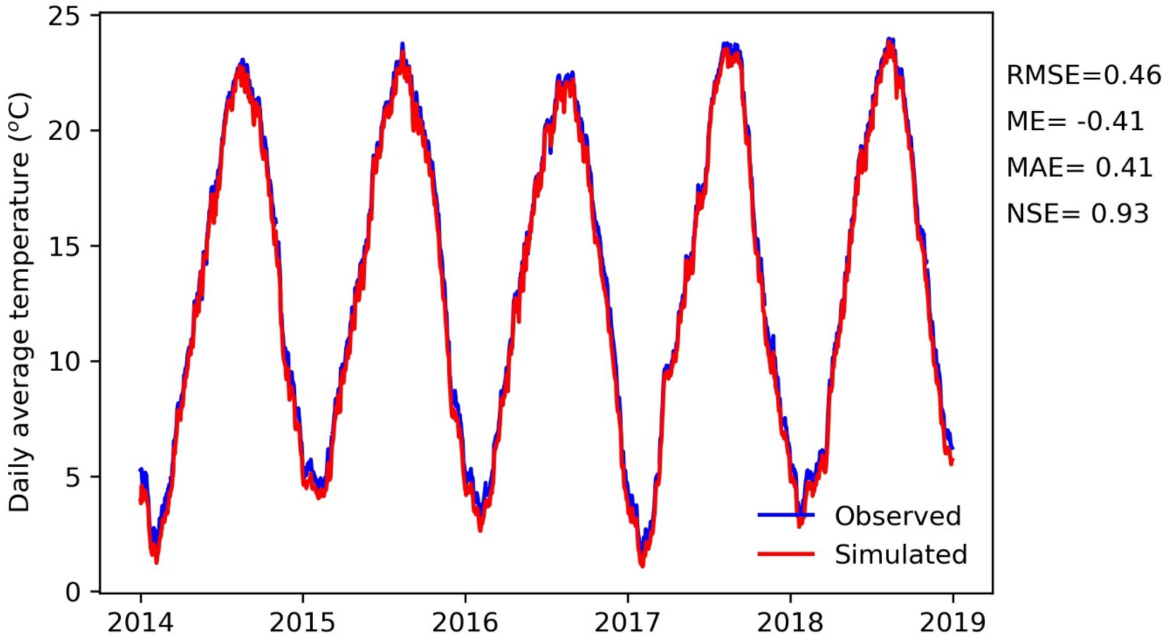


Figure 139. W2 daily average simulated water temperatures versus observations above Salmon River at RM 189.

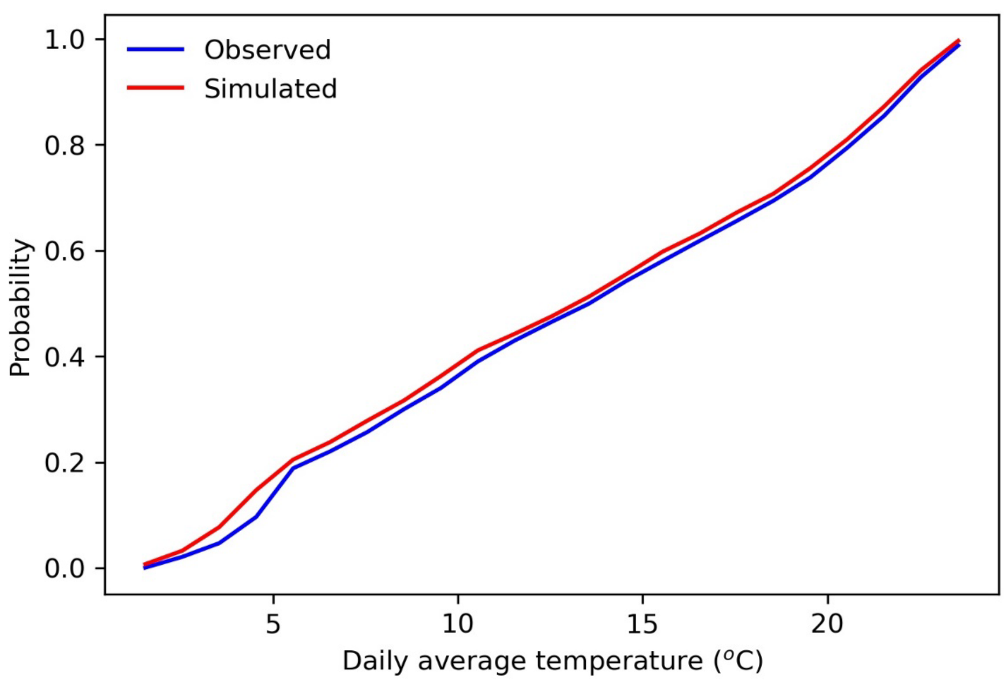


Figure 140. W2 simulated water temperatures versus observations above Salmon River at RM 189, ECD graph.

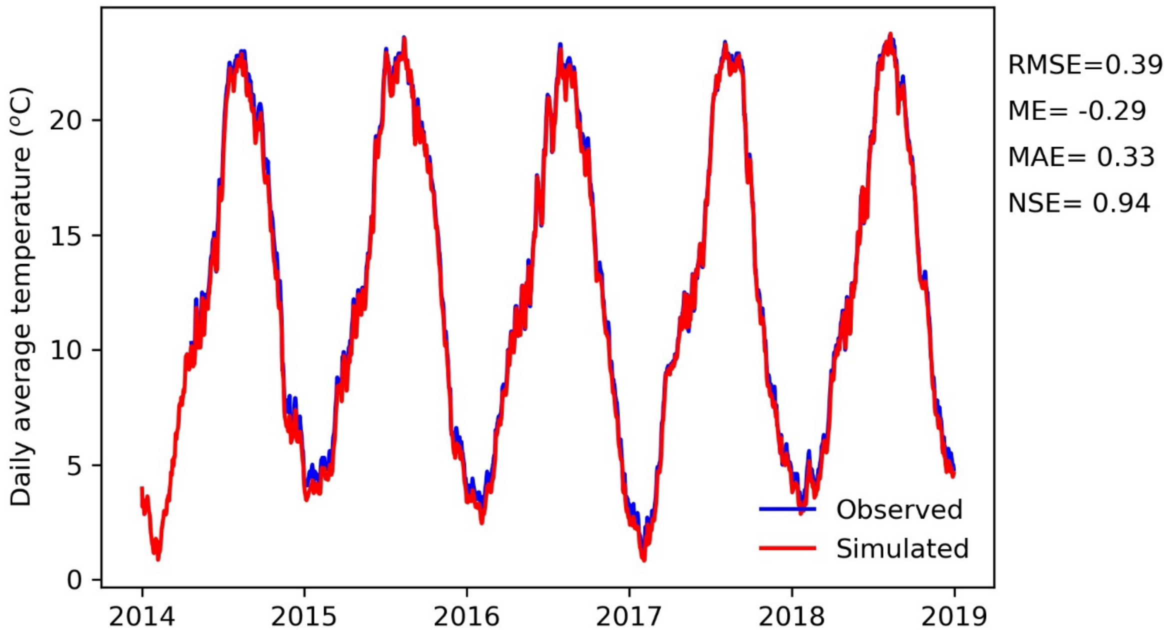


Figure 141. W2 daily average simulated water temperatures versus observations near triple border at RM176.

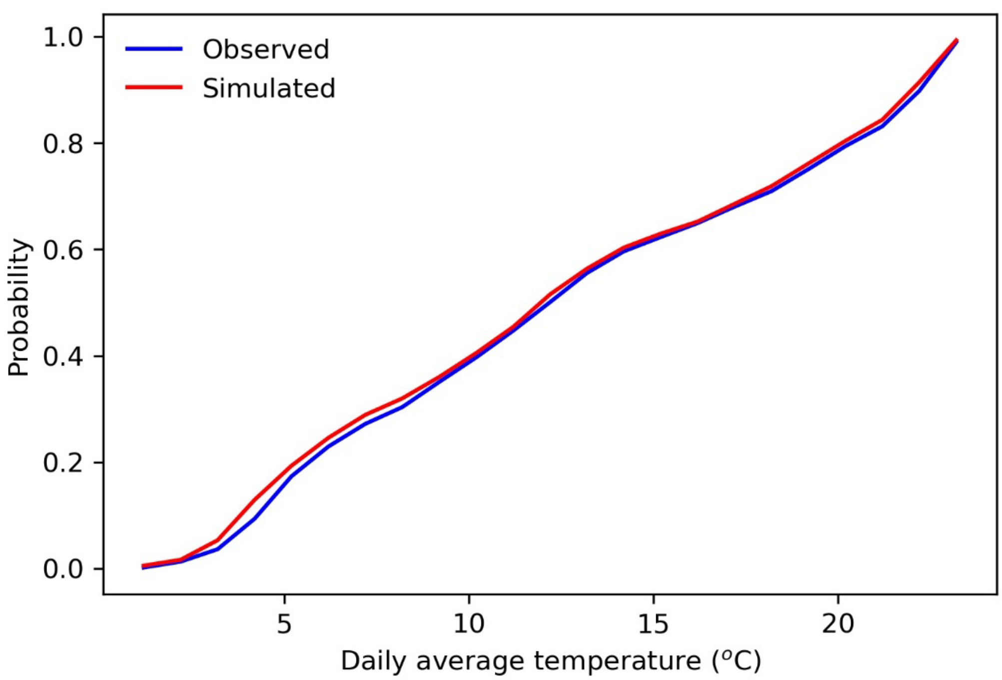


Figure 142. W2 simulated water temperatures versus observations near triple border RM 176, ECD graph.

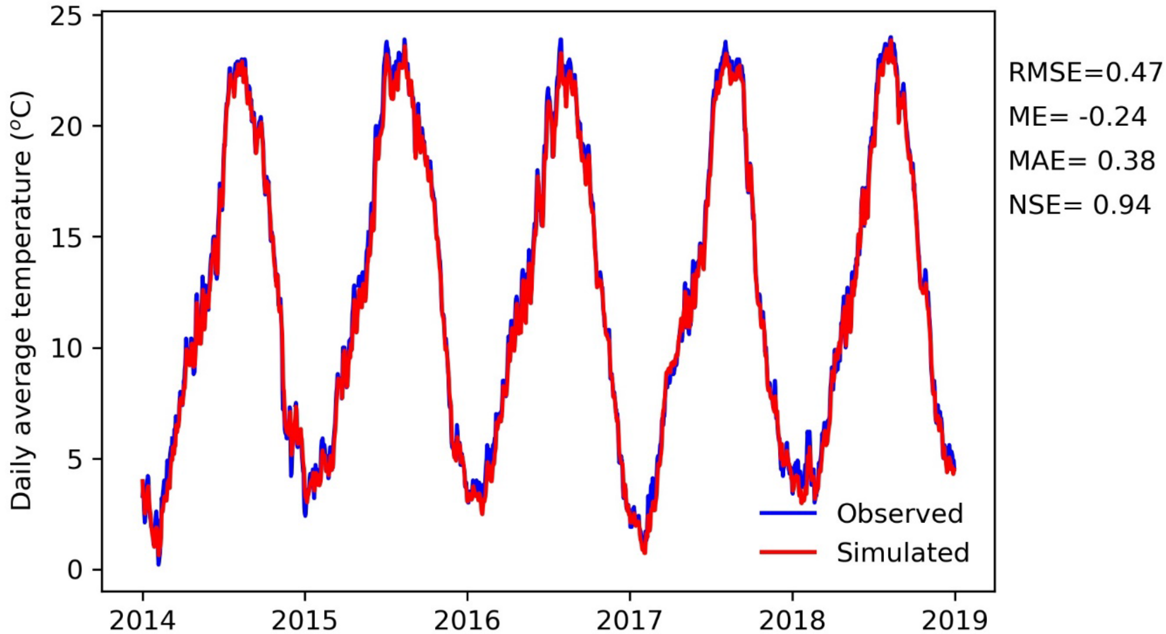


Figure 143. W2 daily average simulated water temperatures versus observations near Anatone at RM 168.

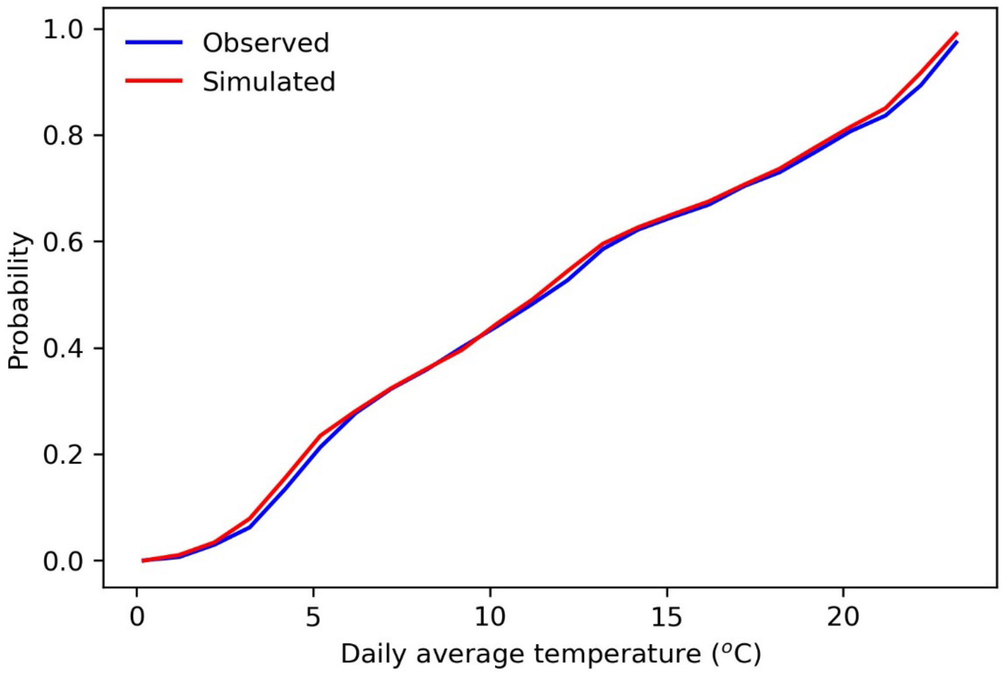


Figure 144. W2 simulated water temperatures versus observations near Anatone at RM 168, ECD graph.

8.3 DAILY MAXIMUM TEMPERATURE COMPARISON

W2 simulated daily maximum water temperatures are calculated from the hourly output and compared to observations for 6 stations in Table 24 and Figure 145 through Figure 156. The model simulated temporal variation of daily maximum temperature observations, with NSE≥ 0.92 and RMSE ≤ 0.64 °C and with NSE≥ 0.88 and RMSE ≤0.66 °C, respectively, for both modeling period and summer season for all stations. The model simulated Snake River water temperature observations at China Garden (USGS 13317660) and near Anatone (USGS 13334300) with RMSE ≤ 0.45 °C and 0.66 °C, respectively, for both modeling period and summer season.

Table 24. Performance of W2 in simulating Snake River daily maximum water temperature. Error units are in °C.

Gage	Location	River Mile (RM)	Count	Full Year				Summer (May-November)			
				NSE	RMSE	ME	MAE	NSE	RMSE	ME	MAE
IPC RM 229.8	Near Sheep Creek	230	1,421	0.97	0.21	0.01	0.17	0.94	0.24	0.06	0.19

IPC RM 216.3	Near Pittsburg Landing	216	1,816	0.96	0.29	-0.16	0.24	0.93	0.27	-0.09	0.22
IPC RM 202.3	Near Dry Creek	202	1,816	0.94	0.41	-0.33	0.35	0.90	0.38	-0.28	0.31
IPC RM 189	Above Salmon River	189	1,816	0.92	0.50	-0.43	0.44	0.88	0.45	-0.38	0.39
USGS 13317660	Near Triple Border (ID-OR-WA)	176	1,714	0.93	0.45	-0.33	0.38	0.92	0.42	-0.26	0.34
USGS 13334300	Near Anatone	168	1,810	0.92	0.64	-0.38	0.51	0.88	0.66	-0.41	0.53

Note: NSE = Nash Sutcliffe coefficient of model fit efficiency, RMSE = root mean squared error, ME = mean error, MAE = mean absolute error.

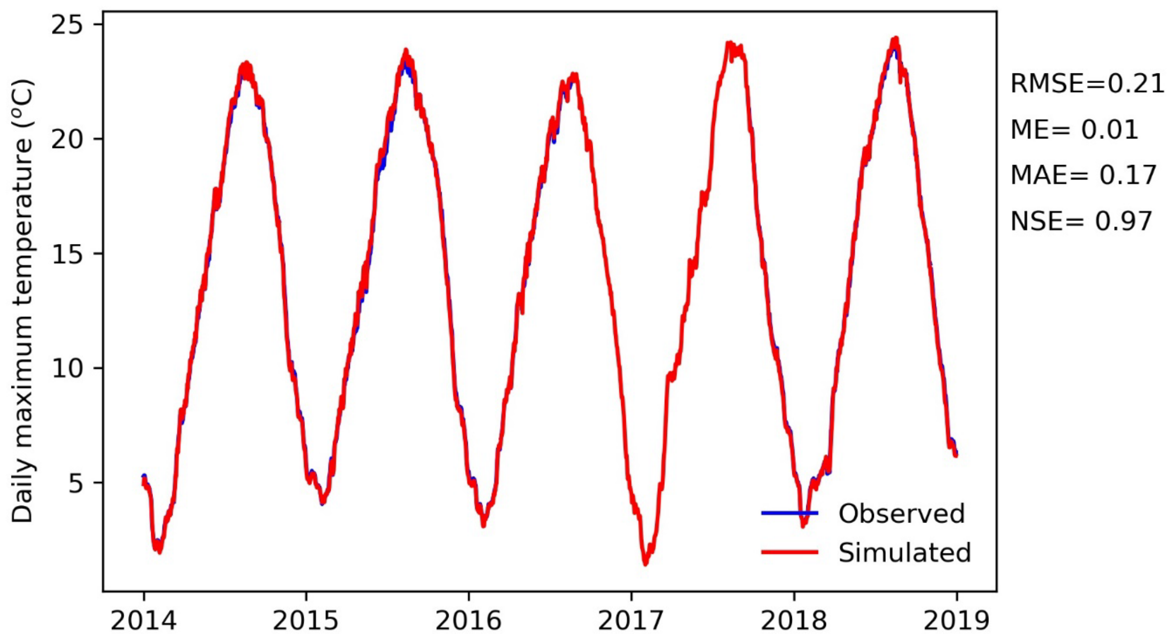


Figure 145. W2 daily maxima simulated water temperatures versus observations near Sheep Creek at RM 230.

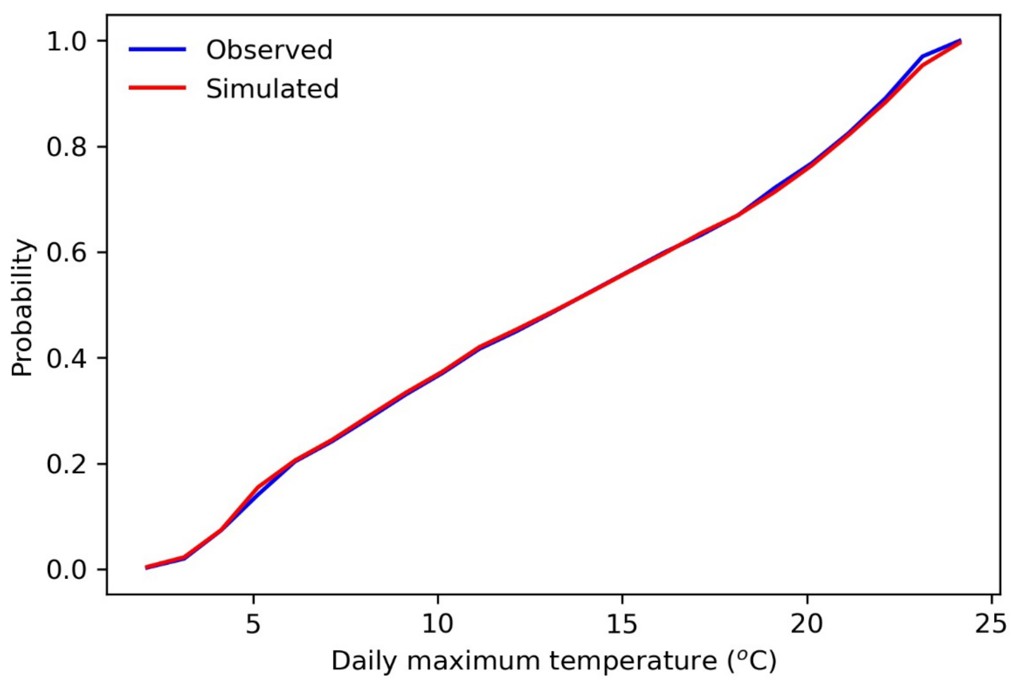


Figure 146. W2 simulated water temperatures versus observations near Sheep Creek at RM 230, ECD graph.

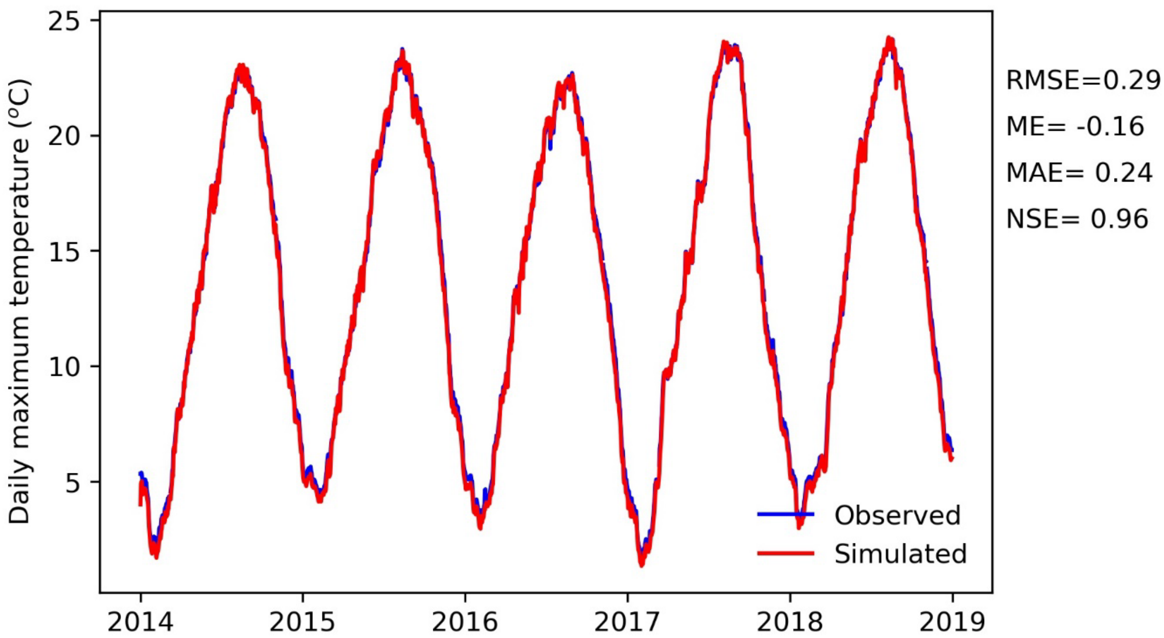


Figure 147. W2 daily maxima simulated water temperatures versus observations near Pittsburg Landing at RM 216.

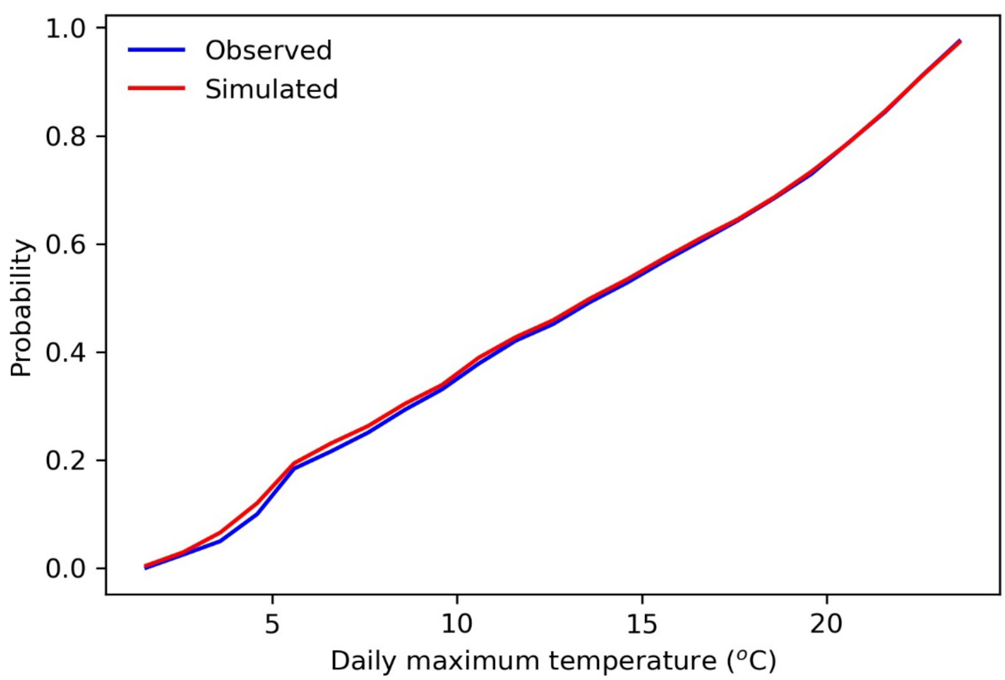


Figure 148. W2 simulated water temperatures versus observations near Pittsburg Landing at RM 216, ECD graph.

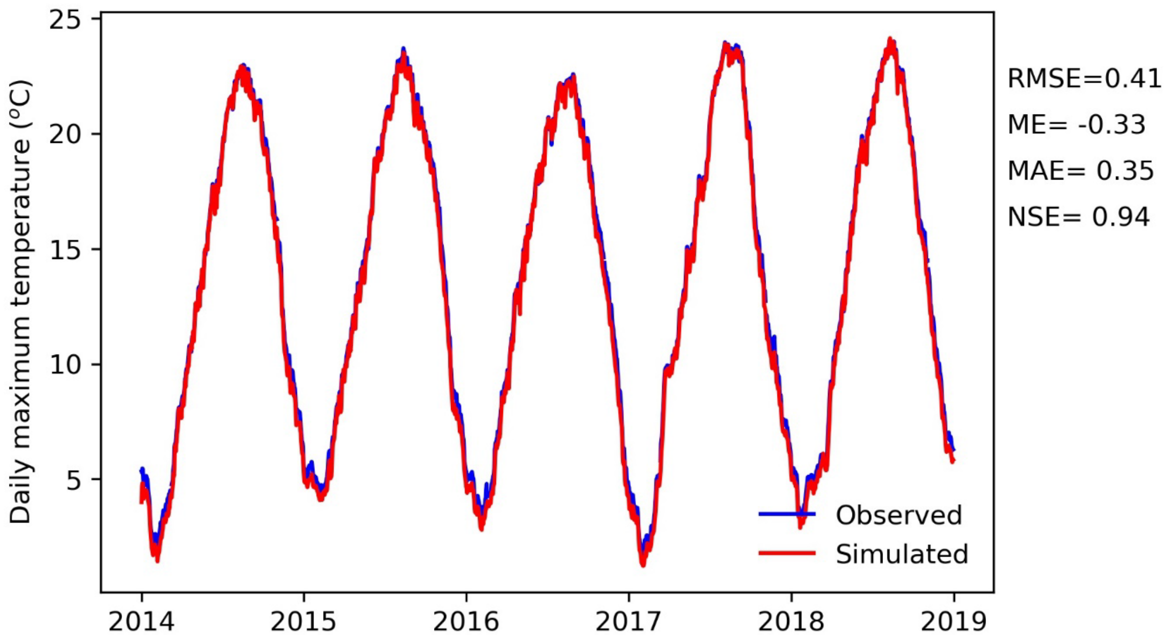


Figure 149. W2 daily maxima simulated water temperatures versus observations near Dry Creek at RM 202.

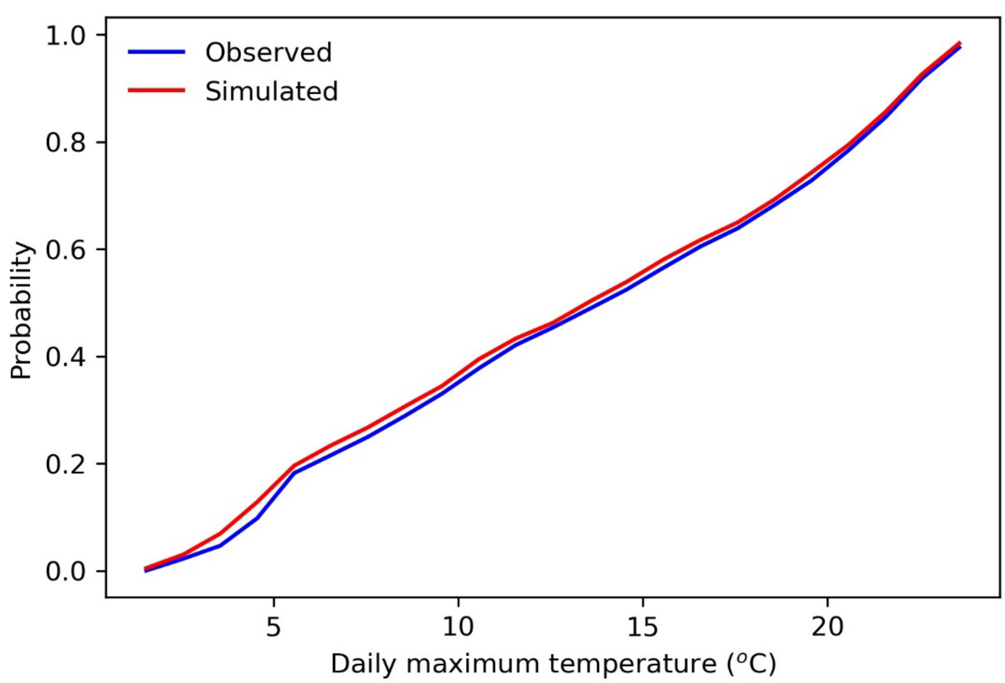


Figure 150. W2 simulated water temperatures versus observations near Dry Creek at RM 202, ECD graph.

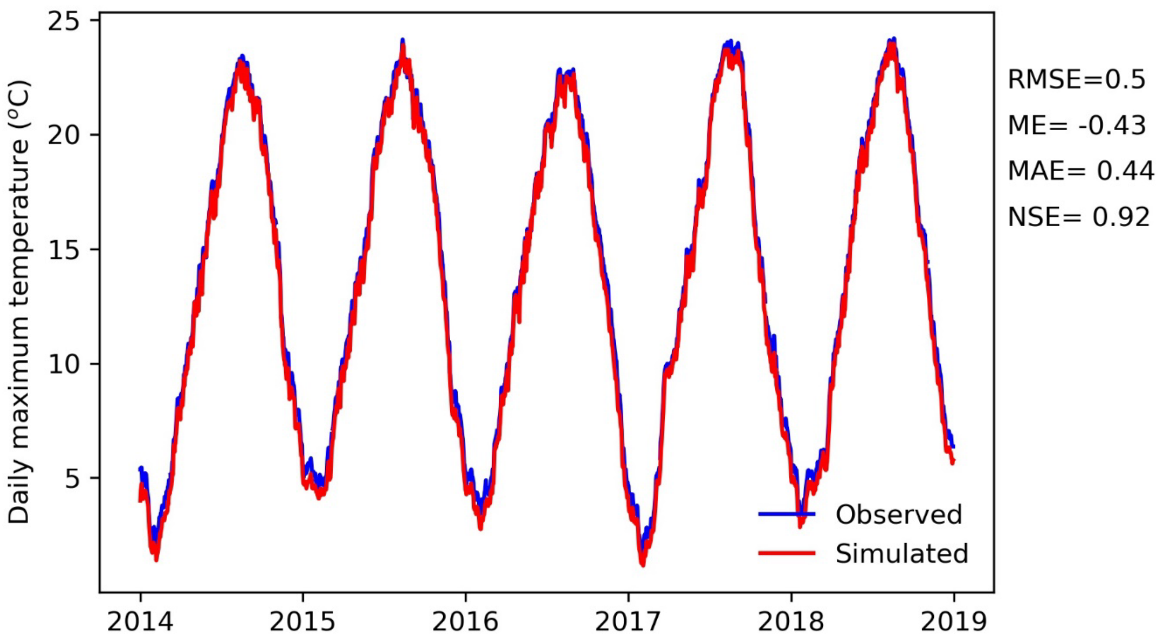


Figure 151. W2 daily maxima simulated water temperatures versus observations above Salmon River at RM 189.

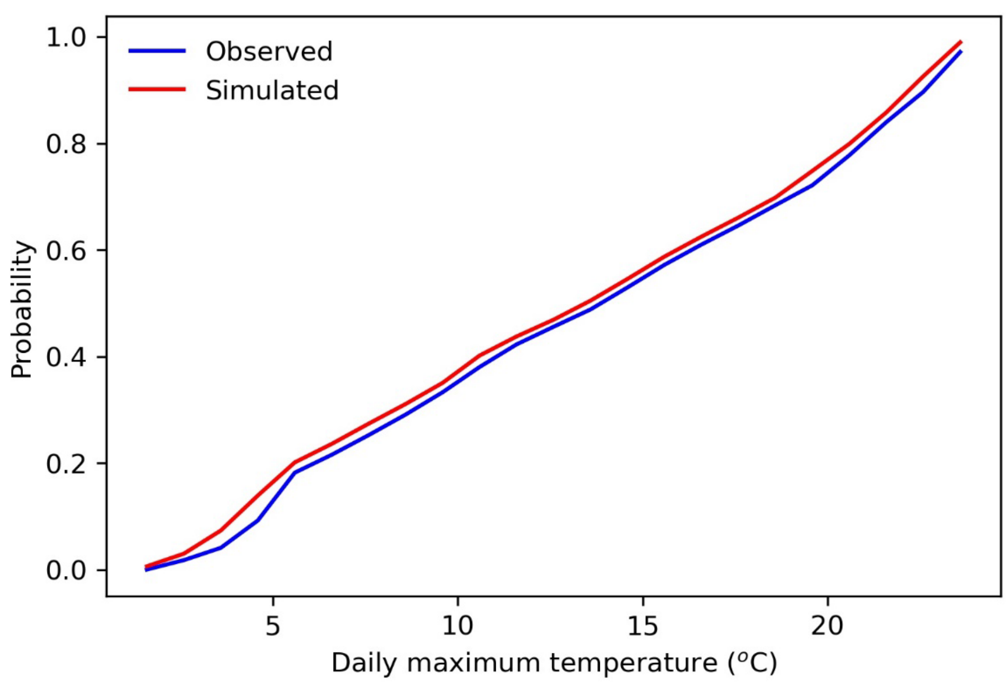


Figure 152. W2 simulated water temperatures versus observations above Salmon River at RM 189, ECD graph.

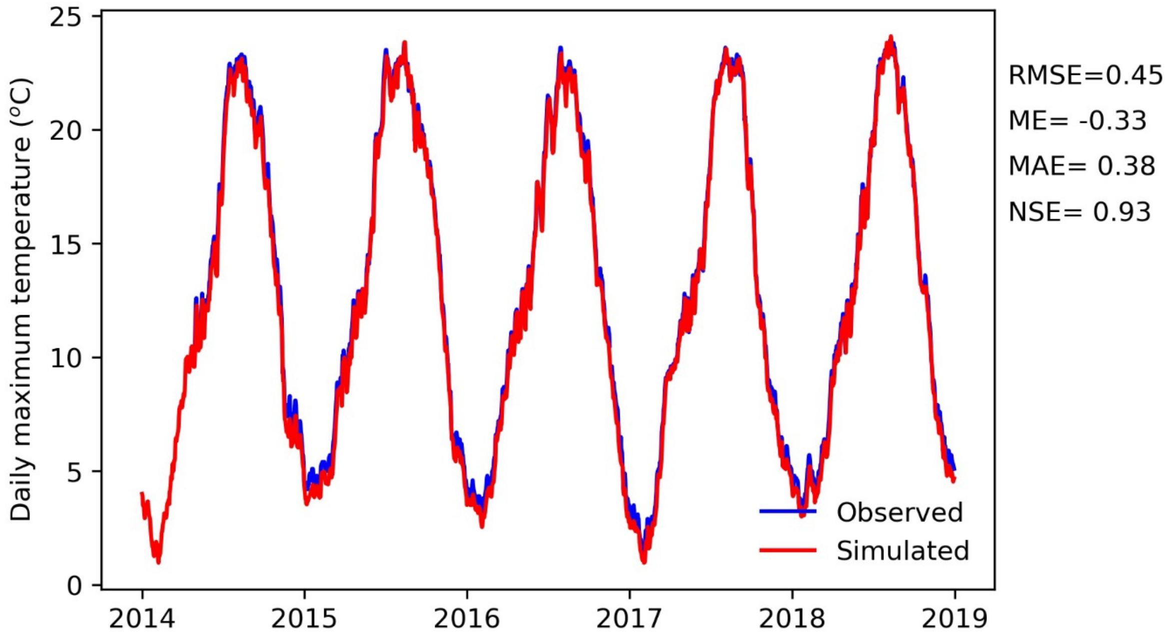


Figure 153. W2 daily maxima simulated water temperatures versus observations near triple border at RM 176.

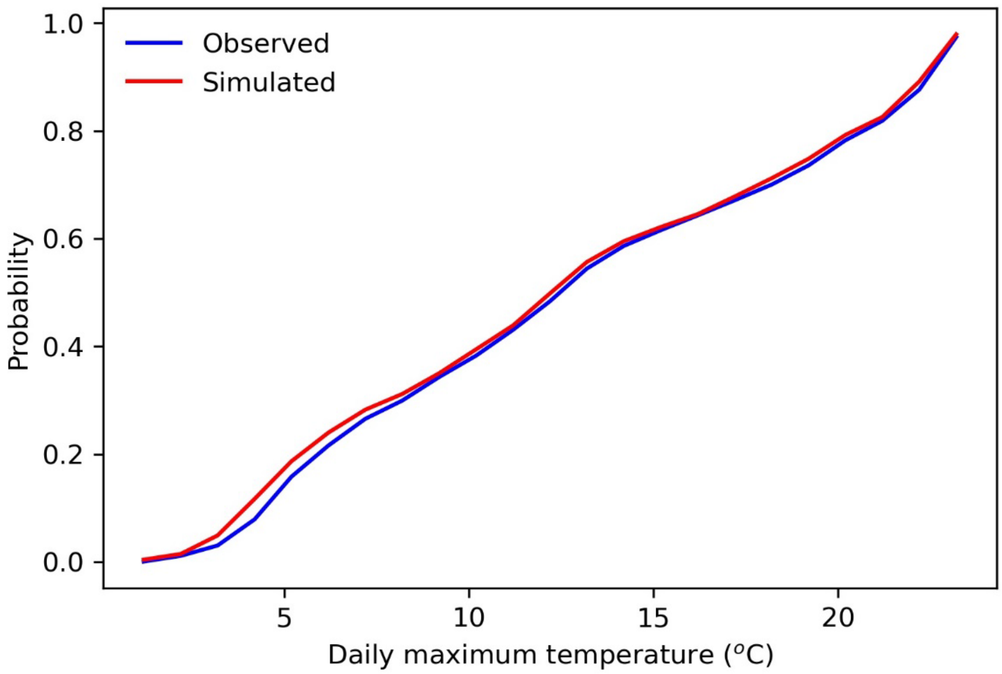


Figure 154. W2 simulated water temperatures versus observations near triple border at RM 176, ECD graph.

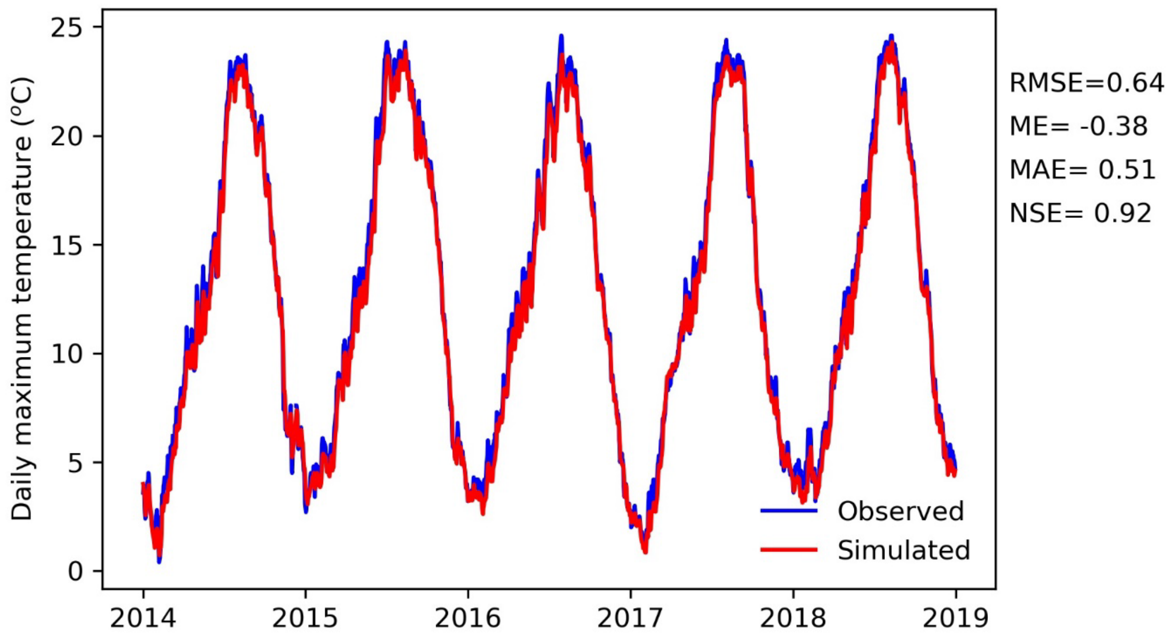


Figure 155. W2 daily maxima simulated water temperatures versus observations near Anatone RM 168.

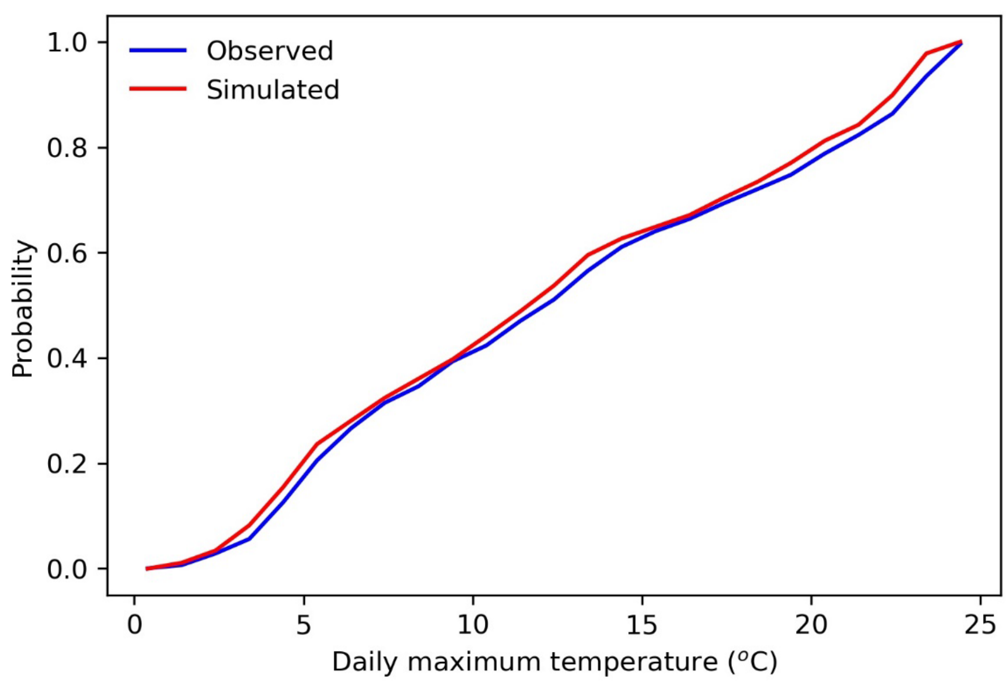


Figure 156. W2 simulated water temperatures versus observations near Anatone at RM 168, ECD graph.

8.4 7-DAY AVERAGE OF DAILY MAXIMA WATER TEMPERATURE RESULTS

7DADMax water temperatures were calculated from W2 hourly simulations and are compared to observations for six stations in Table 25 and Figure 157 through Figure 168. The model simulated temporal variation of 7DADMax temperature observations well with NSE > 0.93 and RMSE≤ 0.53 °C for modeling period and NSE ≥ 0.9 and RMSE ≤ 0.55 °C for summer. The model simulated Snake River water temperature observations at China Garden (USGS 13317660) and near Anatone (USGS 13334300) with RMSE < 0.39 °C and 0.55 °C, respectively, for both modeling period and summer season.

Table 25. Performance of W2 in simulating Snake River 7DADMax water temperature. Error units are in °C.

Gage	Location	River Mile (RM)	Count	Full Year				Summer (May-November)			
				NSE	RMSE	ME	MAE	NSE	RMSE	ME	MAE
IPC RM 229.8	Near Sheep Creek	230	1,421	0.98	0.17	0.02	0.13	0.95	0.19	0.07	0.15
IPC RM 216.3	Near Pittsburg Landing	216	1,816	0.96	0.25	-0.15	0.21	0.95	0.22	-0.07	0.17
IPC RM 202.3	Near Dry Creek	202	1,816	0.95	0.37	-0.32	0.32	0.92	0.32	-0.26	0.27
IPC RM 189	Above Salmon River	189	1,816	0.93	0.46	-0.43	0.43	0.89	0.40	-0.37	0.37
USGS 13317660	Near Triple Border (ID-OR-WA)	176	1,714	0.94	0.39	-0.33	0.34	0.93	0.33	-0.26	0.27
USGS 13334300	Near Anatone	168	1,810	0.93	0.53	-0.38	0.43	0.90	0.55	-0.41	0.45

Note: NSE = Nash Sutcliffe coefficient of model fit efficiency, RMSE = root mean squared error, ME = mean error, MAE = mean absolute error.

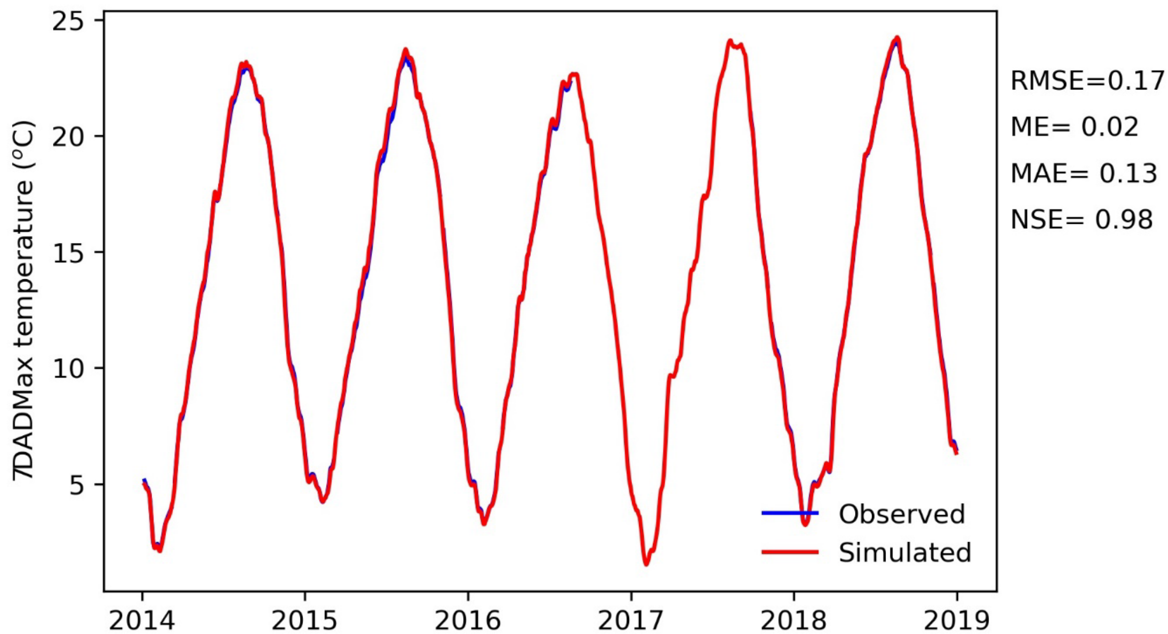


Figure 157. 7DADMax temperature Snake River at Sheep Creek, RM 230.

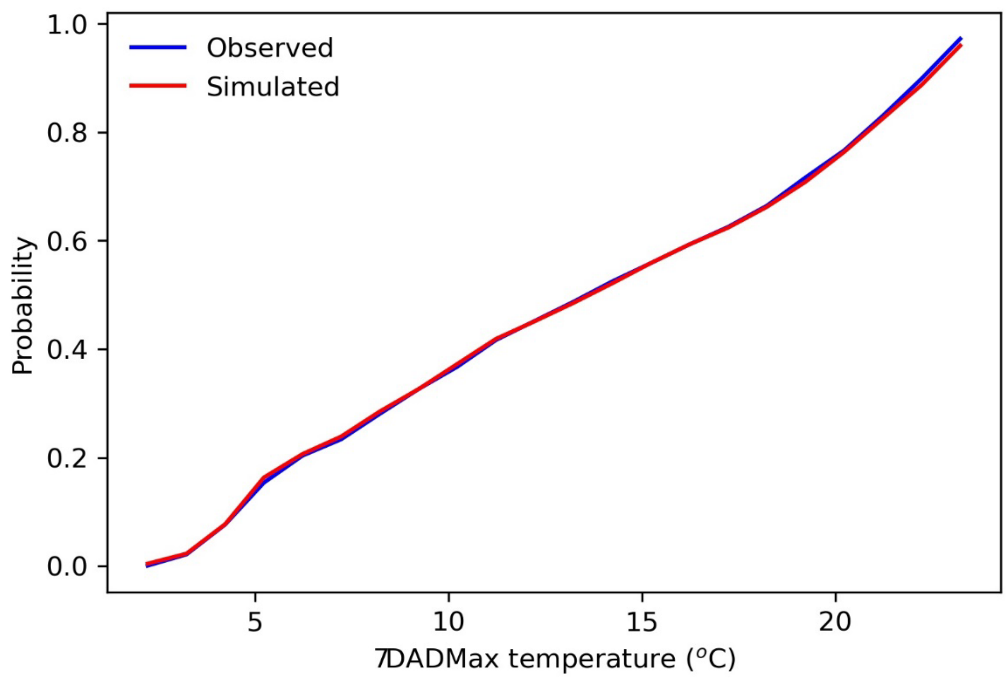


Figure 158. W2 simulated water temperatures versus observations at Sheep Creek RM 230, ECD graph.

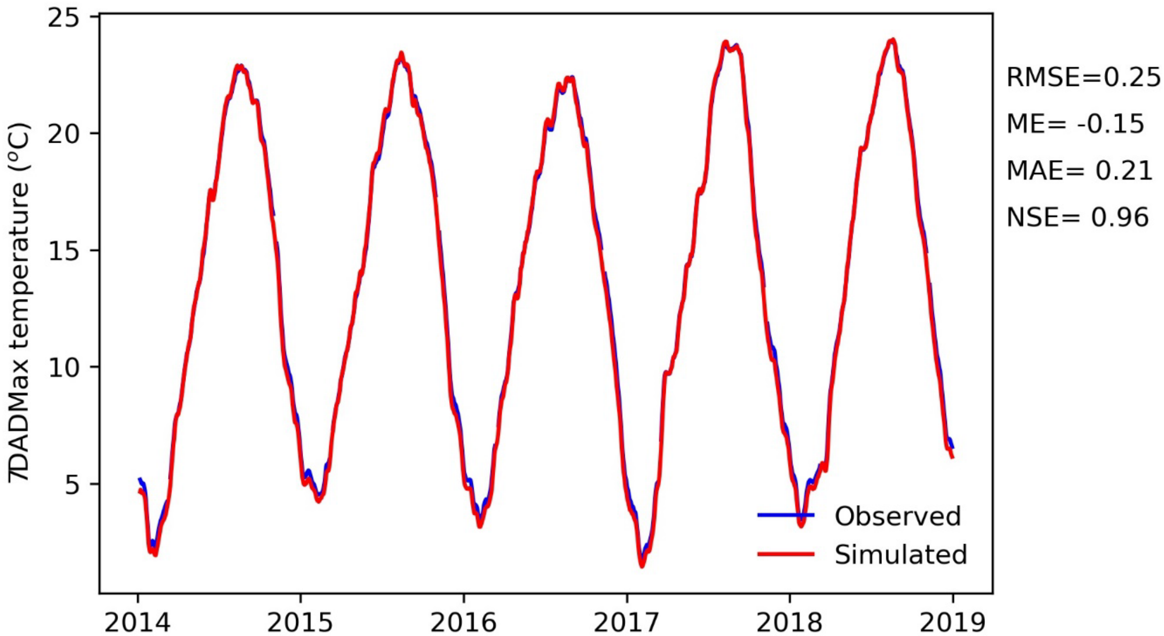


Figure 159. 7DADMax temperature Snake River near Pittsburg Landing at RM 216.

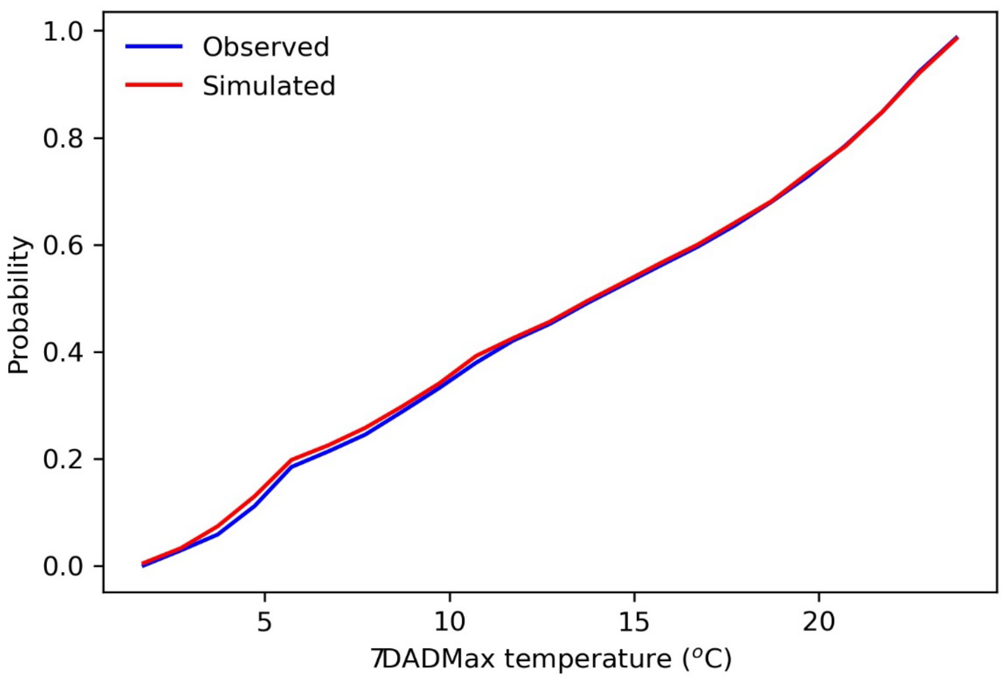


Figure 160. W2 simulated water temperatures versus observations near Pittsburg Landing at RM 216, ECD graph.

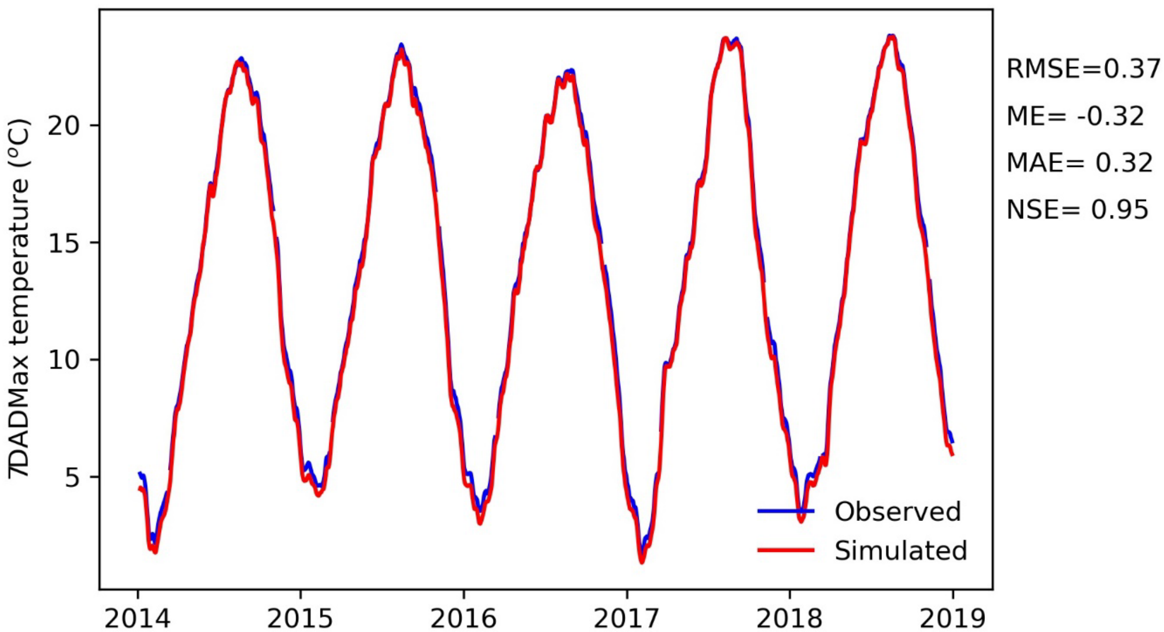


Figure 161. 7DADMax temperature Snake River near Dry Creek at RM 202.

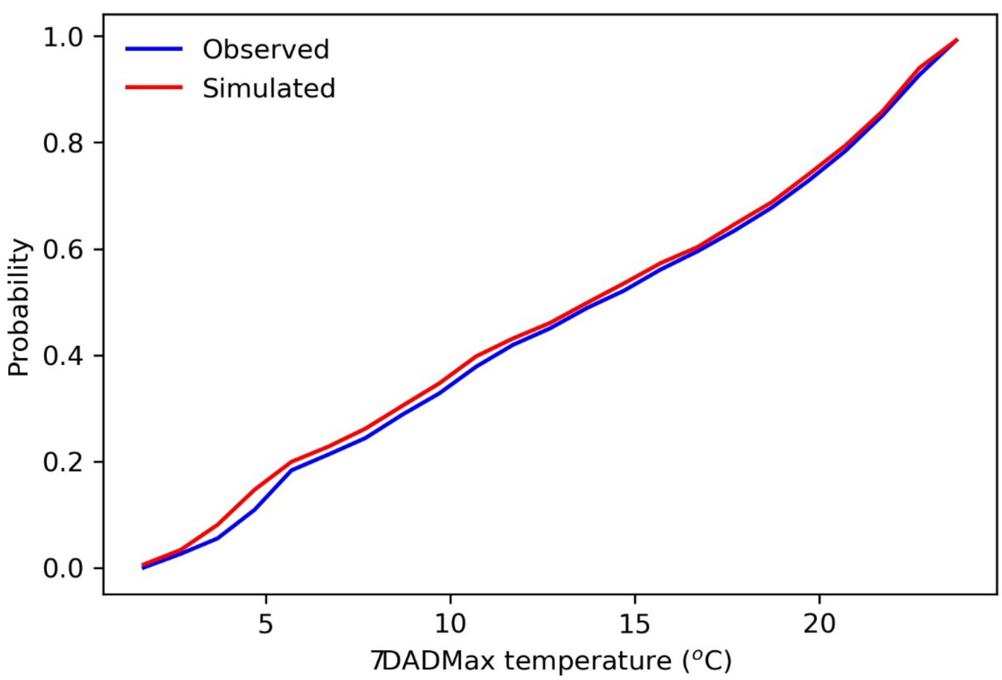


Figure 162. W2 simulated water temperatures versus observations near Dry Creek at RM 202, ECD graph.

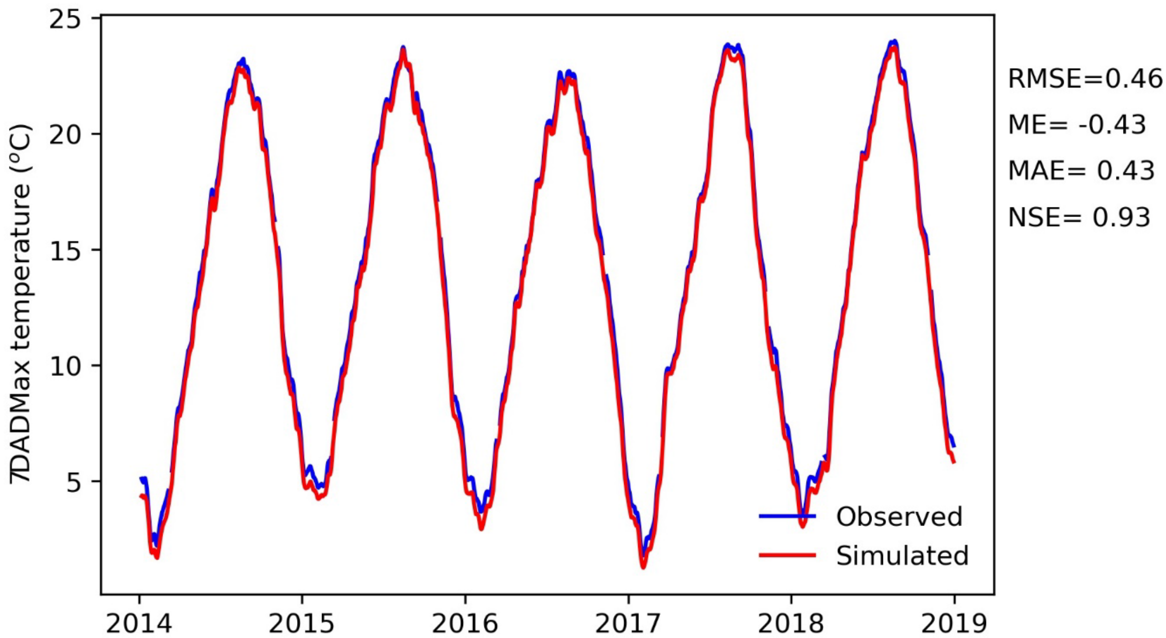


Figure 163. 7DADMax temperature Snake River above Salmon River at RM 189.

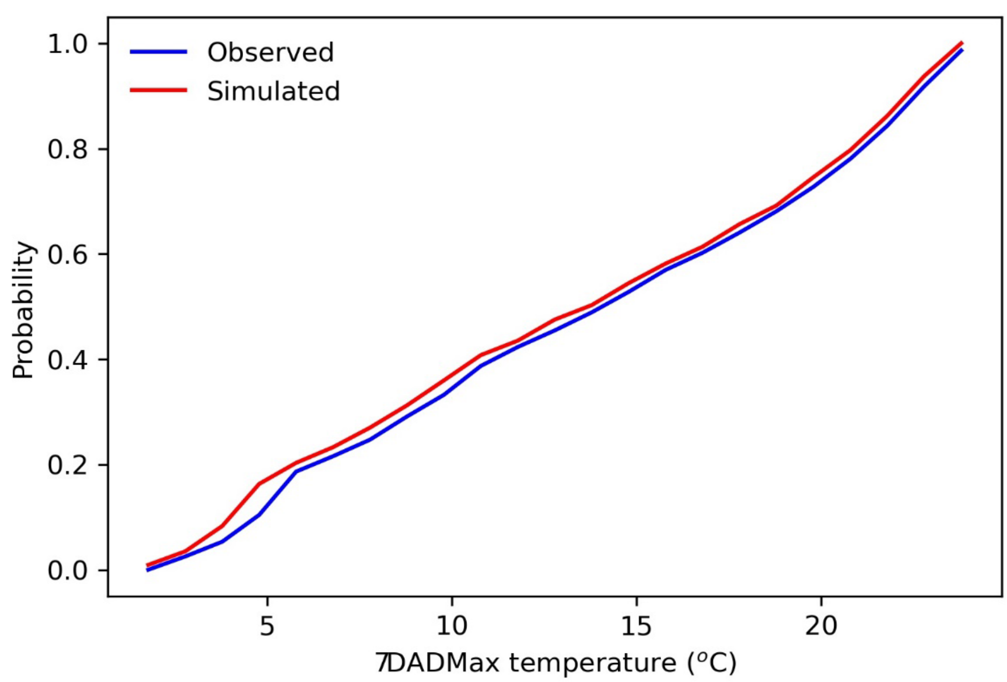


Figure 164. W2 simulated water temperatures versus observations above Salmon River at RM 189, ECD graph.

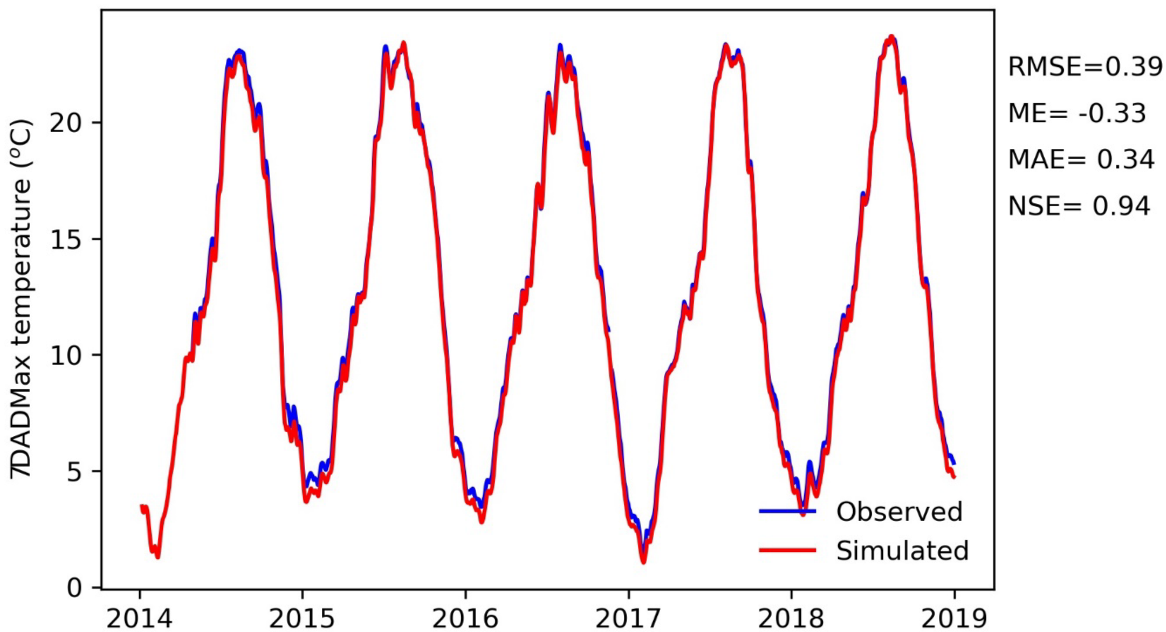


Figure 165. 7DADMax temperature Snake River near triple border at RM 176.

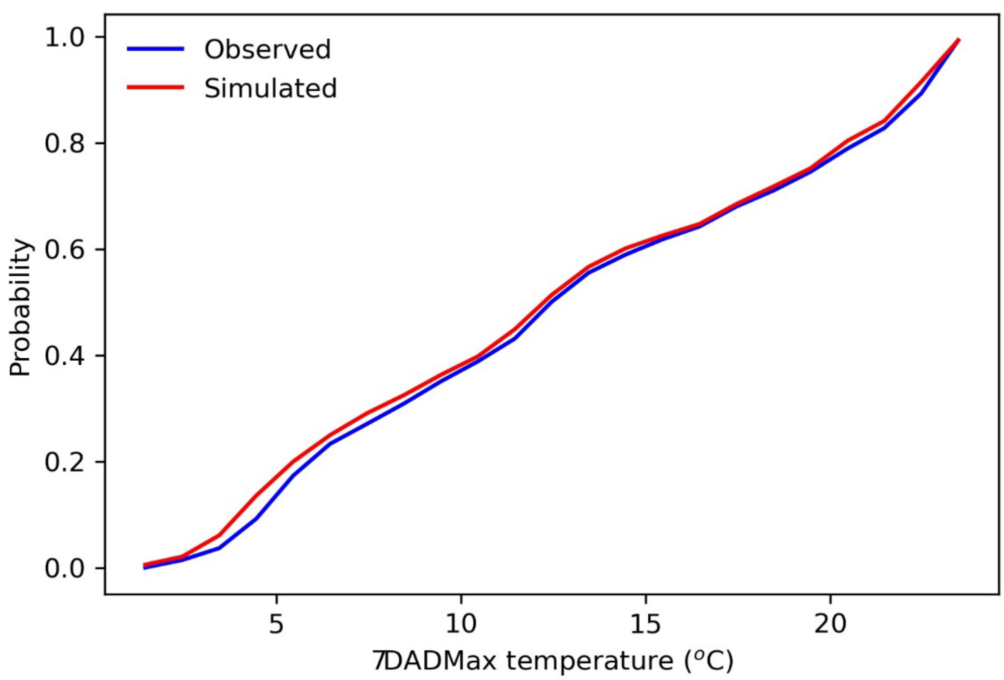


Figure 166. W2 simulated water temperatures versus observations near triple border at RM 176, ECD graph.

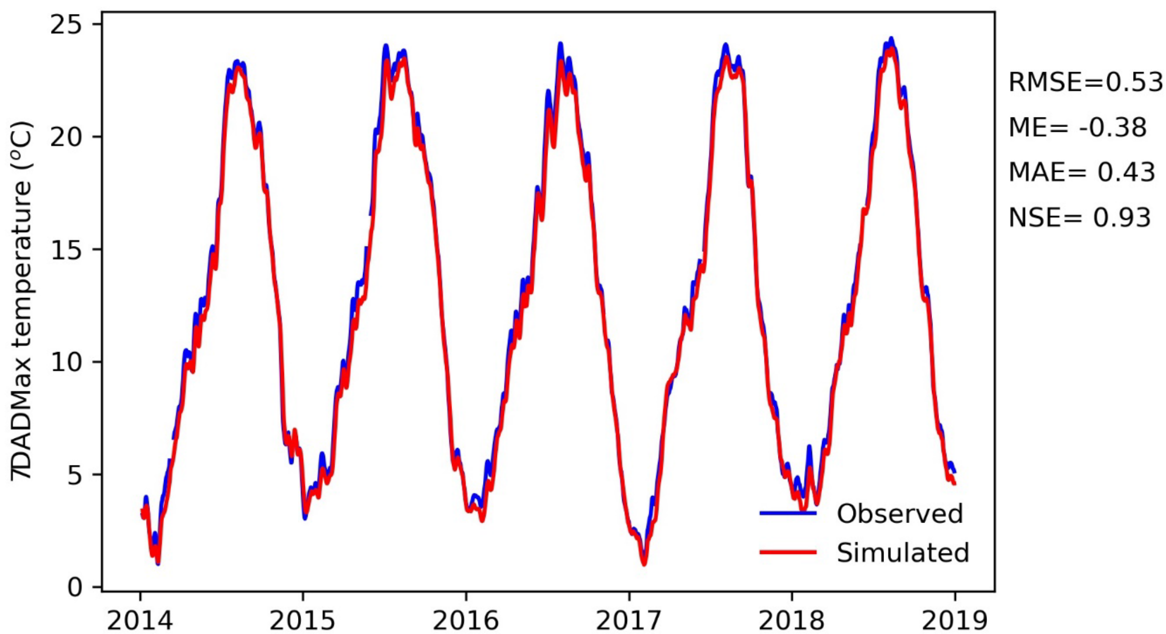


Figure 167. 7DADMax temperature Snake River near Anatone at RM 168.

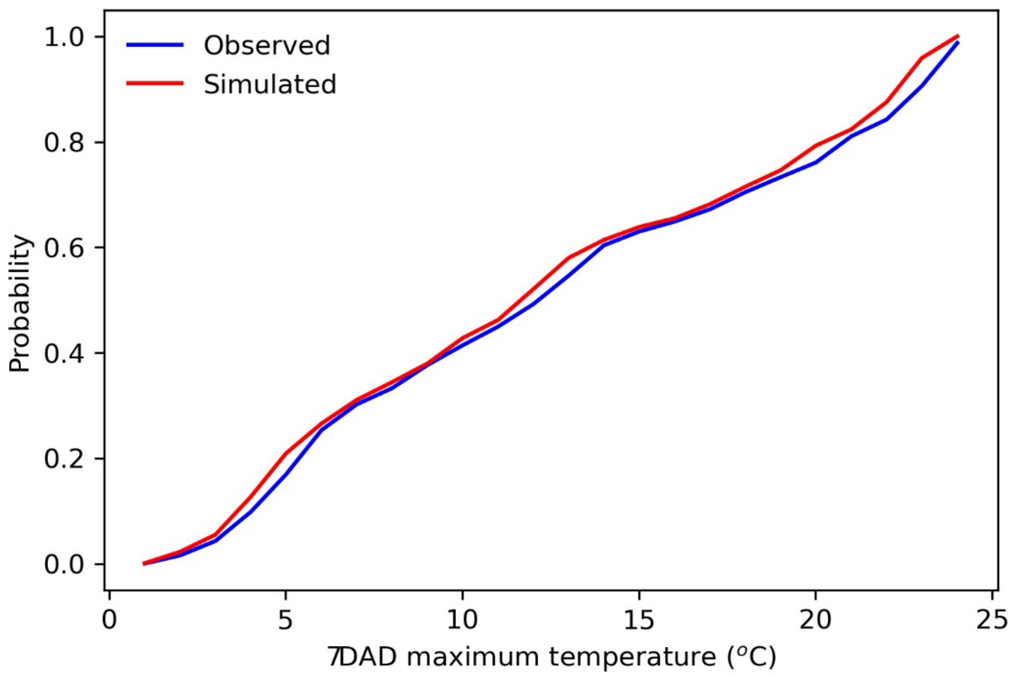


Figure 168. W2 simulated water temperatures versus observations near Anatone at RM 168, ECD graph.