Columbia Riverkeeper et al.

The attached public comments and three exhibits are submitted in response to Ecology's public notice on 401 certification for nine federal dams. The comment letter and exhibits are submitted on behalf of American Rivers, Columbia Riverkeeper, NRDC, the Northwest Sportfishing Industry Association, the Pacific Rivers Council, Save Our Wild Salmon, Snake River Waterkeeper, Spokane Riverkeeper, Washington Chapter Sierra Club, and the Washington Environmental Council.

American Rivers • Columbia Riverkeeper • Natural Resources Defense Council • Northwest Sportfishing Industry Association • Pacific Rivers Council • Save Our Wild Salmon • Snake River Waterkeeper • Spokane Riverkeeper • Washington Chapter Sierra Club • Washington Environmental Council

February 19, 2019

Washington Department of Ecology
Water Quality Program
Eleanor Ott, PE
PO Box 47600
Olympia, WA 98504

Via Online Comment Portal & Email

RE: Public Comments on 401 Certifications for Nine Federal Columbia and Snake River Dams

Washington Department of Ecology:

We write on behalf of American Rivers, Columbia Riverkeeper, the Natural Resources Defense Council, the Northwest Sportfishing Industry Association, Pacific Rivers Council, Save Our Wild Salmon, Snake River Waterkeeper, Spokane Riverkeeper, Washington Chapter Sierra Club, and the Washington Environmental Council with respect to Clean Water Act (CWA) 401 certifications for nine federal dams on the Columbia and Snake rivers. Washington state has an historic opportunity to protect water quality and fish in the Columbia and Snake rivers. The state can—for the first time ever—require that federal dams—Bonneville, The Dalles, John Day, McNary, Grand Coulee, on the Columbia River and Ice Harbor, Lower Monumental, Little Goose and Lower Granite on the Snake River—meet Washington's water quality standards pursuant to CWA section 401. The nine federal dams have operated for decades without federal licenses or pollution discharge permits. The state now has a critical opportunity to address many well-documented impacts to water quality and designated uses caused and exacerbated by the dams.

Our organizations urge the Washington Department of Ecology (Ecology) to exercise its authority under section 401 to hold the federal dam operators accountable for the significant and well-documented impacts of federal dams to water quality and designated uses in the Columbia and Snake rivers.

I. Background

The U.S. Environmental Protection Agency (EPA) requested Ecology section 401 certification on December 19, 2018,[1] for the following draft National Pollutant Discharge Elimination System (NPDES) permits:

- Ice Harbor Lock and Dam, NPDES Permit No. WA 0026816
- Lower Monumental Lock and Dam, NPDES Permit No. WA0026808
- Little Goose Lock and Dam, NPDES Permit No. WA0026786
- Lower Granite Lock and Dam, NPDES Permit No. WA0026794
- Bonneville Project, NPDES Permit No. WA 0026778
- The Dalles Lock and Dam, NPDES Permit No. WA 0026701
- John Day Project, NPDES Permit No. WA0026832
- McNary Lock and Dam, NPDES Permit No. WA 0026824
- Grand Coulee Dam, NPDES Permit No. WA0026867

The nine NPDES permits would authorize discharges from cooling water, equipment, floor drains, sumps, facility maintenance water, and other miscellaneous discharges. The U.S. Army Corps of Engineers (Corps) applied for NPDES permits for eight dams (the four lower Columbia and four lower Snake) in 2015 and the U.S. Bureau of Reclamation applied for a NPDES permit for Grand Coulee Dam in 2017.

On February 1, 2019, EPA abruptly withdrew the agency's request for 401 certifications. EPA provided no explanation for its decision. Notably, EPA's decision to withdraw the requests for 401 certification came one day after *The Seattle Times* ran a front-page story describing the temperature crisis on the Columbia and Snake rivers and Ecology's 401 certification authority for the nine federal dams.[2]

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[1] EPA initially requested preliminary certifications for federal dams in letters to Ecology dated September 19 and 20, 2018, and October 4, 2018. Ecology's current comment period requests comments on EPA's December 19, 2018, request.

[2] Mapes, Lynda, "Washington state to regulate federal dams on Columbia, Snake to cool hot water, aid salmon," *The Seattle Times* (Jan. 31, 2019); *See also* Mapes, Lynda, "EPA ices Washington state's effort to regulate hot water in Columbia, Snake rivers," *The Seattle Times* (Feb. 6, 2019).

II. Clean Water Act Section 401

Congress enacted section 401 to allow states to protect their waterways from the impacts of federally permitted activities, like dams, that discharge into state waters.[3] Before any federal agency can issue a permit for any activity that involves a discharge into a navigable water, the federal agency must obtain a state 401 certification.[2] The state's 401 certification can contain any conditions necessary to ensure that the applicant for the federal permit will not violate the state's water quality standards, and those conditions "shall become" part of the resulting federal license.[3]

In the landmark case *PUD No. 1 of Jefferson County v. Washington Dept. of Ecology*, Washington established that its section 401 certification authority reached *all* water quality impacts of federally permitted dams.[4] The United States Supreme Court agreed with Washington that, under section 401, the existence of any discharge at a federally permitted dam gives Washington the authority to address *all* of that dam's impacts to water quality. This includes temperature in the reservoirs, spill over the dams, total dissolved gas, and salmon migration.

III. Specific Comments on 401 Certifications for the Federal Dams

The decline of Columbia Basin salmon runs contributes to the starvation of Southern Resident orcas and recently forced Washington to close the Columbia River to fall salmon fishing.[5] Washington should use its authority under the Clean Water Act to do what the Trump administration and federal agencies cannot or will not do: protect and restore salmon, Pacific lamprey, sturgeon and other species threatened with extinction.

As demonstrated by empirical evidence and EPA modeling, the presence and operation of individual and multiple dams combines to warm the Columbia and Snake Rivers to unsafe levels for beneficial uses.[6] Temperatures are also increasing over

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[3] *S.D. Warren Co. v. Maine Bd. Of Envtl. Prot.*, 547 U.S. 370, 386 (2006).

[4] 511 U.S. 700, 707–08 (1994) (explaining that states may regulate the impacts of a project as a whole under Section 401, so long as a discharge is involved). The fact that the § 401 certifications at issue were triggered by federal NPDES permits, rather than FERC licenses, has no bearing on the scope of Ecology's authority under § 401. *Cf. Or. Nat. Desert Ass'n v. Dombeck*, 172 F.3d 1092, 1097–98 (9th Cir. 1998) (explaining that § 401 certifications can impose far-reaching protections for water quality, provided a discharge triggers the state's § 401 authority).

[5] WDFW, *News Release: Most of the Columbia River closing to salmon and steelhead fishing* (Sept. 11, 2018).

[6] EPA Region 10. RBM-10 Columbia River Temperature TMDL-Preliminary Technical Information. Presentation to Columbia River Tribes. August 14, 2018. Spokane, WA; River Management Joint

historical levels due to the impacts of climate change.[7] During the summer, the rivers are frequently so warm that salmon are unable to migrate upriver to spawn.[8] When river temperatures exceed 20℃ for several days at a time—as happens with increasing frequency due to climate change[9]—salmon have difficulty migrating upstream and begin succumbing to stress and disease.[10] According to the Fish Passage Center, "[U]nder a climate change scenario, the long-recognized and largely unaddressed problem of high water temperatures in the [Columbia and Snake rivers] becomes an ever-increasing threat to the survival of salmon."[11]

In the early 2000s, EPA completed a draft Columbia and Snake River Temperature Total Maximum Daily Load (TMDL). The temperature TMDL is a pollution budget designed to protect salmon from hot water in the Columbia and Snake rivers. EPA concluded, "The majority of the temperature increases (as much as 6 °C) are caused by the larger dams[.]"[12]

Despite decades of litigation, federal agencies have not complied with the Endangered Species Act, CWA, or recovered the Columbia Basin's once-mighty salmon runs.[13] EPA has not issued a final temperature TMDL. Notably, EPA's own modeling analyses clearly indicate the effects of the dams and climate change on elevated temperatures that violate water quality standards. Nonprofit organizations challenged the EPA's failure to finalize the temperature TMDL and, in October 2018, Hon. Ricardo Martinez, Chief District Judge for the Western District of Washington, ruled in plaintiffs favor. The court ordered EPA to issue a TMDL within 60 days. EPA appealed the district court's order to complete the temperature TMDL. Even if the court of appeals upholds

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Operating Committee (RMJOC II). 2018. Climate and hydrology datasets for RMJOC Long-term Planning Studies. Second Edition. Part I: Hydroclimate Projections and Analyses. Bonneville Power Administration, U.S. Army Corps of Engineers and U.S. Bureau of Reclamation. Portland, Oregon; Fish Passage Center, *Review of April 2016 Draft of NOAA Fisheries Report*, p. 1 (May 4, 2016).

[7] USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. DOI: 10.7930/NCA4.2018.

[8] Fish Passage Center, *Requested data summaries and actions regarding sockeye adult fish passage and water temperature issues in the Columbia and Snake rivers* (Oct. 28, 2015).

[9] John Yearsley, *A semi-Lagrangian water temperature model for advection-dominated river systems*, 45 Water Resources Research, pp. 15–16 (2009).

[10] National Marine Fisheries Service, *2015 Adult Sockeye Salmon Passage Report*, pp. 20–22 (2016).

[11] Fish Passage Center, *Review of April 2016 Draft of NOAA Fisheries report* 2015 Sockeye Salmon Passage Report, p. 1 (May 4, 2016).

[12] U.S. EPA, *Preliminary Draft Columbia/Snake Temperature TMDL*, p. 39 (July 2003).

[13] *See NWF v. NMFS*, 184 F. Supp. 3d 861 (D. Or. 2016); *Columbia Riverkeeper v. Pruitt*, No. 17-00289 (W.D. Wash. 2018).

the district court's order (and EPA does not appeal that decision), the earliest Washington can expect EPA will issue the TMDL is in about two years. Washington listed the Columbia River as impaired by high temperatures in 1994, and Washington and Oregon asked EPA for a temperature TMDL over 20 years ago.[14]

The state should not wait for EPA to act because that action is years away and highly uncertain. Section 401 provides Washington the critical legal tool to require the federal dam operators to address temperature impacts from federal dams now—a tool Washington has already used for federally licensed private dams on the river. In fact, even after EPA issues a final TMDL, the provisions in that TMDL are not self-executing. The state will need to incorporate those requirements into 401 certifications to turn them into binding measures.[15]

EPA may take the position that Washington's review and CWA certification is constrained to oil pollution, cooling water, and other pollutants discharged through point sources at the dams. Under section 401, Washington is not limited to regulating pollution discharged by point sources. The state must ensure that the applicant's activities—here, the dams and reservoirs—meet Washington water quality standards. Washington regularly issues comprehensive 401 certifications for other federally permitted dams in Washington—including the Columbia River dams operated by public utility districts. We groups urge Ecology to expediently pursue comprehensive 401 certifications for the nine federal dams.

Specifically, many large- and small-scale modifications to the structure and operation of the dams and reservoirs could improve water quality and salmon and native fish survival. Ecology should use the 401 certification process to require the federal agencies to model and identify mitigation actions including modifying adult and juvenile fishways, selectively drawing down certain reservoirs, increasing spring and summer flows, dam removal, and other measures that could reduce temperature and enhance fish survival. Ecology's section 401 certifications for other, non-federal dams on the Columbia River address similar conditions to promote achievement of temperature standards for beneficial uses

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[14] *NWF v. U.S. Army Corps of Eng'rs,* 132 F. Supp. 2d 876 (D. Or. 2001).

[15] U.S. EPA, *Preliminary Draft Columbia/Snake Temperature TMDL*, p. 49 (explaining that hydroelectric dams are considered "nonpoint sources" under the Clean Water Act and therefore the TMDL assigns load allocations that are not implemented through NPDES permits); *see also id.* at viii (explaining "TMDLs are not self-implementing. Nor do they impose any binding legal requirements under federal law."); *id.* at vii (stating "the TMDL is implemented through the NPDES Permit Program, State Water Quality Standards Certification Program, States Non-point Source Management Program and other appropriate mechanisms.").

We recommend that Ecology consider the following draft conditions and comments to ensure compliance with numeric and narrative water quality standards, protect designated uses, and comply with the state's antidegradation policy.

A. Temperature

We recommend that Ecology consider the following draft conditions to address designated use protection and compliance with narrative and numeric water quality standards.

- When EPA issues a final temperature TMDL for the Columbia River, the load allocations and any implementation plans of that TMDL shall become conditions of the certification.
- Pursuant to Washington Administrative Code (WAC) 173-201A-510(5), the U.S. Army Corps and U.S. Bureau of Reclamation (collectively "the federal agencies") must, within two years, develop and submit to Ecology a water quality attainment plan (WQAP) that provides a detailed strategy for achieving compliance with temperature standards in the face of climate change in the reservoir, fish passage facilities, and tailwaters, including:
    - Identify and describe in detail all measures, and combinations of measures, that could meet temperature standards, including, but not limited to, the following:
        - Seasonal reservoir drawdown to various pool levels, including drawdown to the spillway crest and to the maximum extent achievable under the dam's current configuration;
        - Releasing water stored pursuant to the US-Canada Columbia River Treaty to enhance spring and early summer flows for fish migrations and habitat.
        - Altering the dam structure and fishways to allow seasonal reservoir drawdowns below the levels achievable under the dam's current configuration;
        - Increasing attraction flows to fishways to reduce adult migration times over dams.
        - Dam removal;
        - Altering fish ladders and intakes to achieve water quality standards within the fish ladders and to reduce or eliminate temperature differences between the tailwater and the water exiting the fish ladders;

        - Pumping cool water into fish ladders from the coldest part of the reservoir, the tailwater, or artificially cooling the water that feeds the fish ladders.
    - Model and engage in other technical work to define the expected impacts of those identified measures, and combinations of measures, on water temperatures in the reservoir, forebays and tailraces fish ladders, and downstream free flowing river sections for individual dams and the system as a whole.
    - Seek operational and structural measures to selectively access cool water in Lake Roosevelt for downstream releases, including changes to the location of pumping facilities from Lake Roosevelt to Banks Lake.

- If Ecology determines, pursuant to WAC 173-201A-510(5)(c) and (d), that the WQAP submitted by the federal agencies does not ensure compliance with all applicable water quality criteria or provide a reasonable assurance that the dam will not cause or contribute to a violation of the water quality standards, Ecology shall retain the right to revoke or reopen the certification.

- If Ecology determines that the WQAP submitted by the federal agencies would ensure compliance with the temperature water quality criteria the federal dam operators must implement the measures in the WQAP as soon as possible, but in no case later than five years after Ecology makes the determination required by this section.

B. Total Dissolved Gas

We recommend that Ecology consider the following draft conditions to address designated use protection and compliance with narrative and numeric water quality standards.

- Except during involuntary spill events, dam operations—including spill to enhance fish passage—should not cause or contribute to exceedances of the applicable total dissolved gas (TDG) water quality criteria or any short-term modification thereto authorized under Washington or Oregon law.

- During the fish-spill season, the federal agencies must cause, at least, the maximum volume of water to flow over the spillways that will not result in violations of applicable TDG water quality criteria, or any short-term modification thereto authorized under Washington or Oregon law.

- The federal agencies must conduct field monitoring for gas bubble trauma in salmonids and other forms of vertebrate and invertebrate aquatic life throughout the fish spill season, including when TDG levels exceed the water quality criteria during flood or involuntary spill events. The federal agencies must report the results of such field monitoring to Ecology once a year. *NOTE: If Ecology or the Oregon Department of Environmental Quality (DEQ) amend or temporarily change TDG WQS, any associated monitoring requirements should complement rather than duplicate the monitoring requirements in the 401 Certification.*

C. Monitoring

We recommend that Ecology include conditions that require routine monitoring and evaluation of water quality parameters impacted by the presence and operation of federal dams. For example, Ecology should require that the federal agencies conduct, and submit to Ecology on a regular basis, water quality monitoring sufficient to document: (1) baseline environmental conditions; (2) compliance with the conditions of the certification; and (3) progress toward meeting water quality standards in the reservoirs and fishways.

D. Existing and Designated Use Studies

We recommend that Ecology include conditions to address existing and designated use protection. In particular, Ecology could include conditions, such as the examples provided below, to inform revised and future 401 certifications. Examples include:

- Within one year of permit issuance, the federal agencies shall complete and submit to Ecology within one year a report/study containing:
  - Existing and designated beneficial uses impacted by the dams;
  - Historic impacts of the project on the existing and designated beneficial uses;
  - Anticipated future impacts, in particular climate change of the dams on the existing and designated beneficial uses.

The report/study should examine not only uses that do not currently exist, but also uses that would be available without the project impacts.

- The federal agencies shall coordinate with Columbia River tribes regarding anadromous fish passage at Grand Coulee Dam and evaluate alternative fish passage scenarios.

E. General Conditions

We recommend that Ecology include general conditions similar to those the agency includes in 401 certifications on Federal Energy Regulatory Commission (FERC) licenses. For example, Ecology should include a condition that states: “Notwithstanding any other language in the certification, any violation of water quality standards is prohibited.” Ecology should also state that conditions are subject to changes based on new state or federal laws that reflect better understanding of how to protect beneficial uses. In addition, Ecology should include reopener language to provide flexibility in the event the agency needs to review the certifications based on new information to meet water quality standards, TMDLs, and other applicable requirements of state law.

F. Oil, Grease, and Cooling Water

EPA’s draft NPDES permits regulate point source discharges, including oil, grease, and cooling water.[16] We recommend that Ecology include conditions to ensure that oil, grease, cooling water, and other point source discharges comply with state water quality standards, protect designated uses, and comply with the state’s antidegradation policy. As part of Ecology’s evaluation, the agency should evaluate EPA’s proposed approach to requiring that the dams transition to environmentally acceptable lubricants (EALs). In the draft permits, EPA proposes to require the use of EALs for all equipment with oil to water grease interfaces, unless technically infeasible. Ecology should evaluate conditions to ensure the state retains authority to review and approve the federal agencies’ determinations on whether EALs are “technically infeasible.”

G. Other Potential Conditions

We also recommend that Ecology evaluate potential conditions to address:

- Flow for habitat and recreation;
- pH, dissolved oxygen, turbidity, and toxics; and
- Pacific Lamprey passage

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[16] To date, EPA has not posted the draft permits for public review, which undermines the public’s ability to comment on 401 certification for the draft permits.

IV. Conclusion

Ecology and Washington state led the nation in achieving water quality regulation of FERC-licensed dams. Now there is an unprecedented opportunity to require the federal dam operators to do their part to help improve water quality in the Columbia Basin by setting appropriate conditions for federal dams. A cleaner Columbia and Snake river will protect endangered salmon, help feed the starving Southern Resident orcas, and support all the communities in and outside the Basin that depend on a clean water and healthy salmon.

In particular, we urge Ecology to exercise its section 401 authority broadly to address the dams' significant impacts to water quality and designated uses that have, to date, gone unaddressed under alternative regulatory pathways. Ecology should require the federal agencies to address oil, temperature, and other pollution caused by the nine dams. Taking this action is in line with Washington's leadership on climate change.

As our region becomes hotter, our rivers and the species and communities that depend on them are suffering the consequences. If Washington is going to achieve a resilient Columbia Basin that can withstand climate change, the state must exercise its authority to address the significant impacts from federal dams.

Sincerely,

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Enc.

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

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December 2018

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1.0 INTRODUCTION

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

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

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

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

1.1 Phase I –RBM10 model Development and Code Modifications

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

1.2 Phase II –RBM10 model Recalibration and Alternative Model Setups

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

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

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

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

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

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

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

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

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

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

This phase of the project also included a review of an earlier draft of this report by technical staff from the three federal agencies that operate the hydroelectric dams along the Columbia and Snake rivers (USACE, BOR, and BPA). This review led to a number of improvements and clarifications in this document.

With the update and refinement of the RBM10 model completed, the next phase of work in the TMDL project is to apply the RBM10 model to evaluate impacts on mainstem river temperatures.

1.3 Columbia River Watershed Description

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

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

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

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

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

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

1.4 RBM10 model Description

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

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

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

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

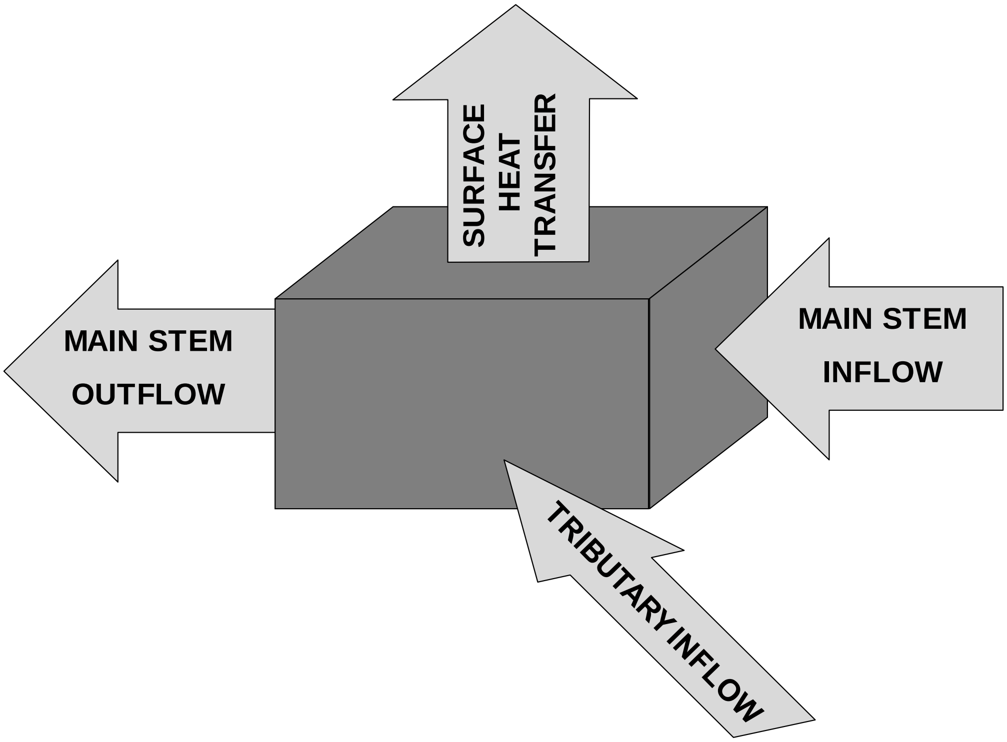

Figure 1-1 Conceptual representation of model segment in one-dimensional temperature model

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

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

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

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

2.0 2018 RBM10 model Structure and Data Inputs

2.1 Temporal Resolution

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

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

2.2 Spatial Representation

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

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

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

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

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

2.3 Hydrodynamics

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

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

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

where

U = river velocity, feet/second

Q = river flow, cfs

W_x = river width, feet

D = river depth, feet

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

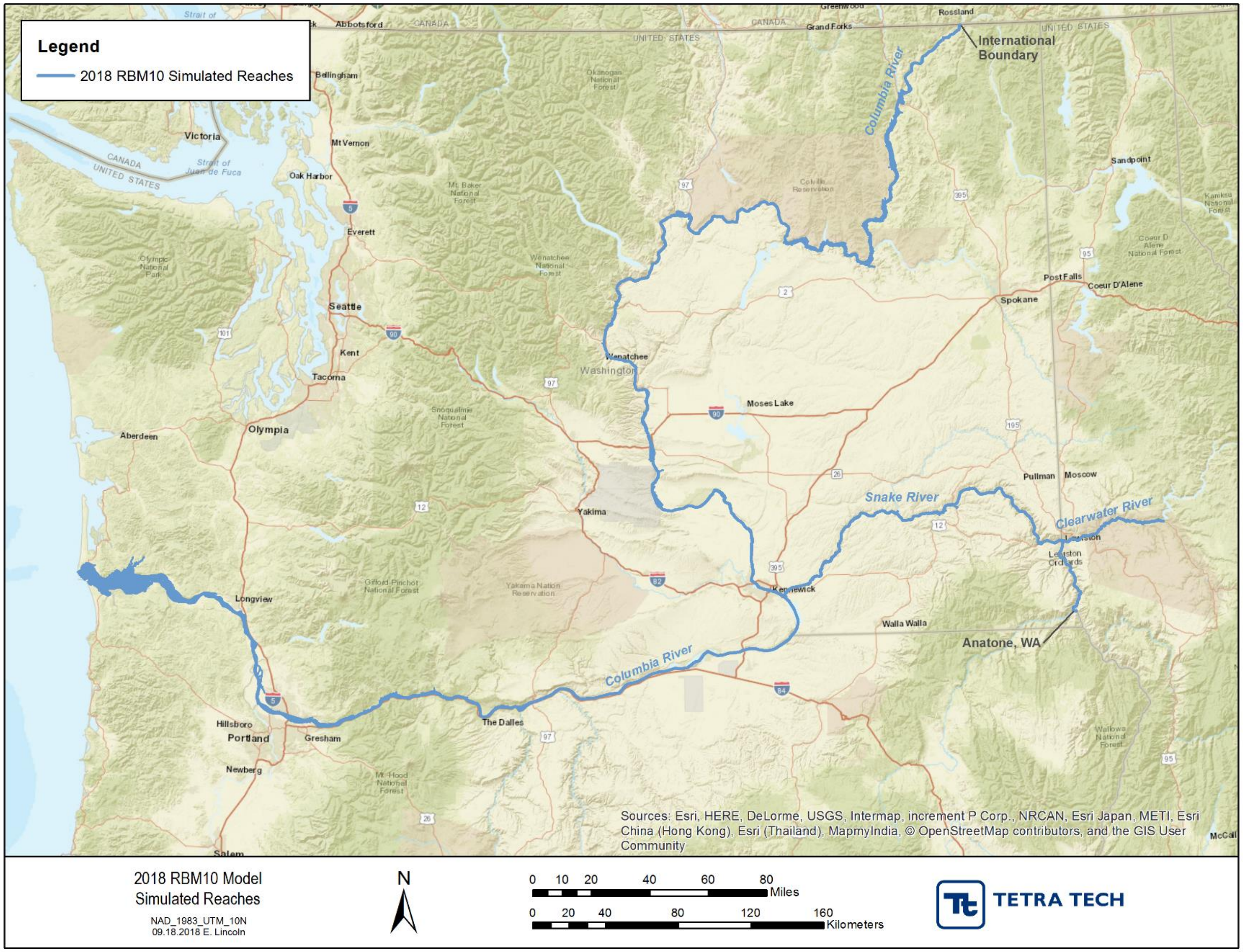

Figure 2-1 RBM10 model domain: Columbia River and Snake River mainstems

2.4 Upstream Boundary and Tributary Inputs

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

2.5 Data retrieval and QA/QC procedure

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

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

Table 2-2 Tributaries included in the 2018 RBM10 model

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

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

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

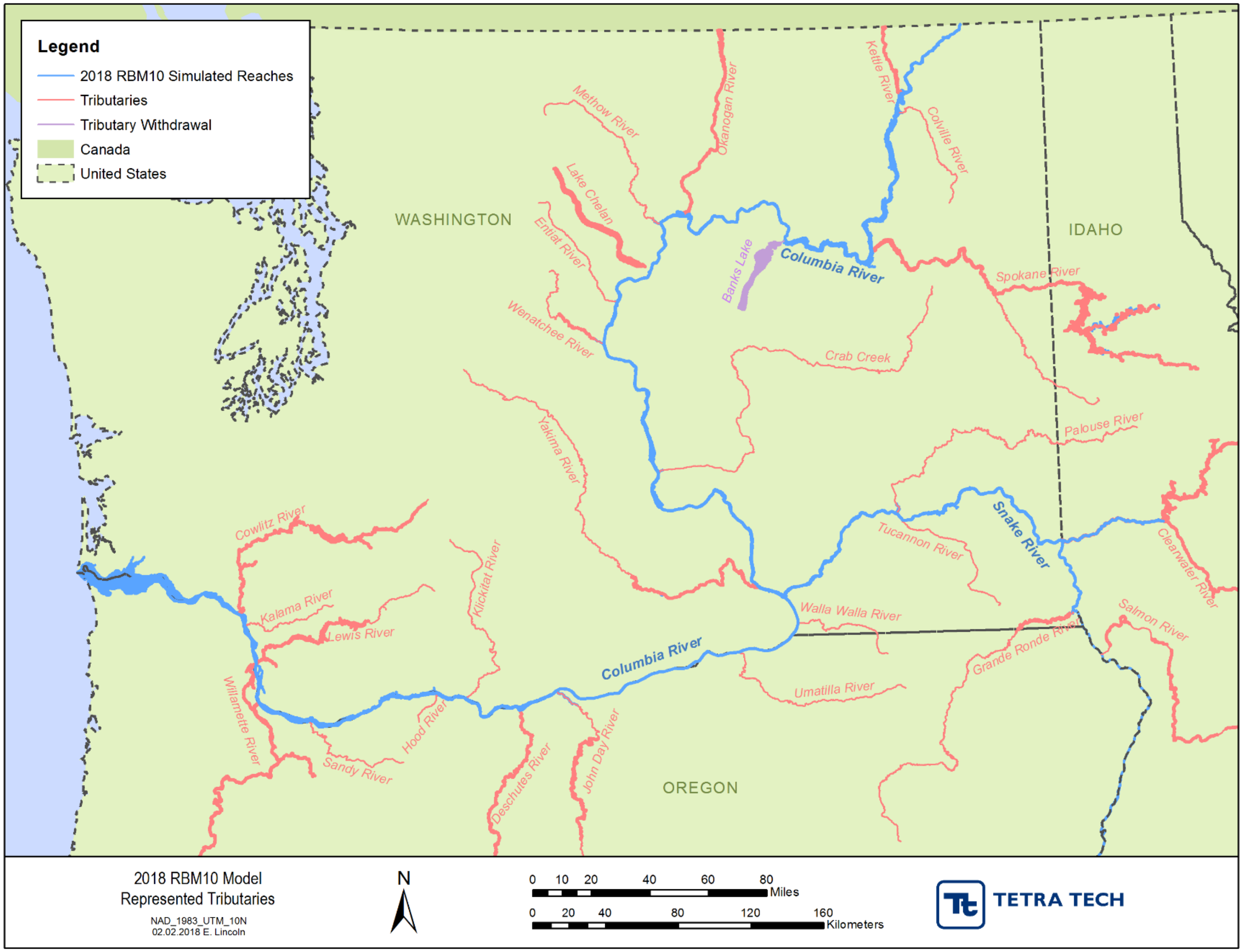

Figure 2-2 Columbia and Snake River tributaries represented in the 2018 RBM10 model

2.5.1 Flow Inputs

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

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

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

* Banks Lake - Banks Lake Pump Storage Project

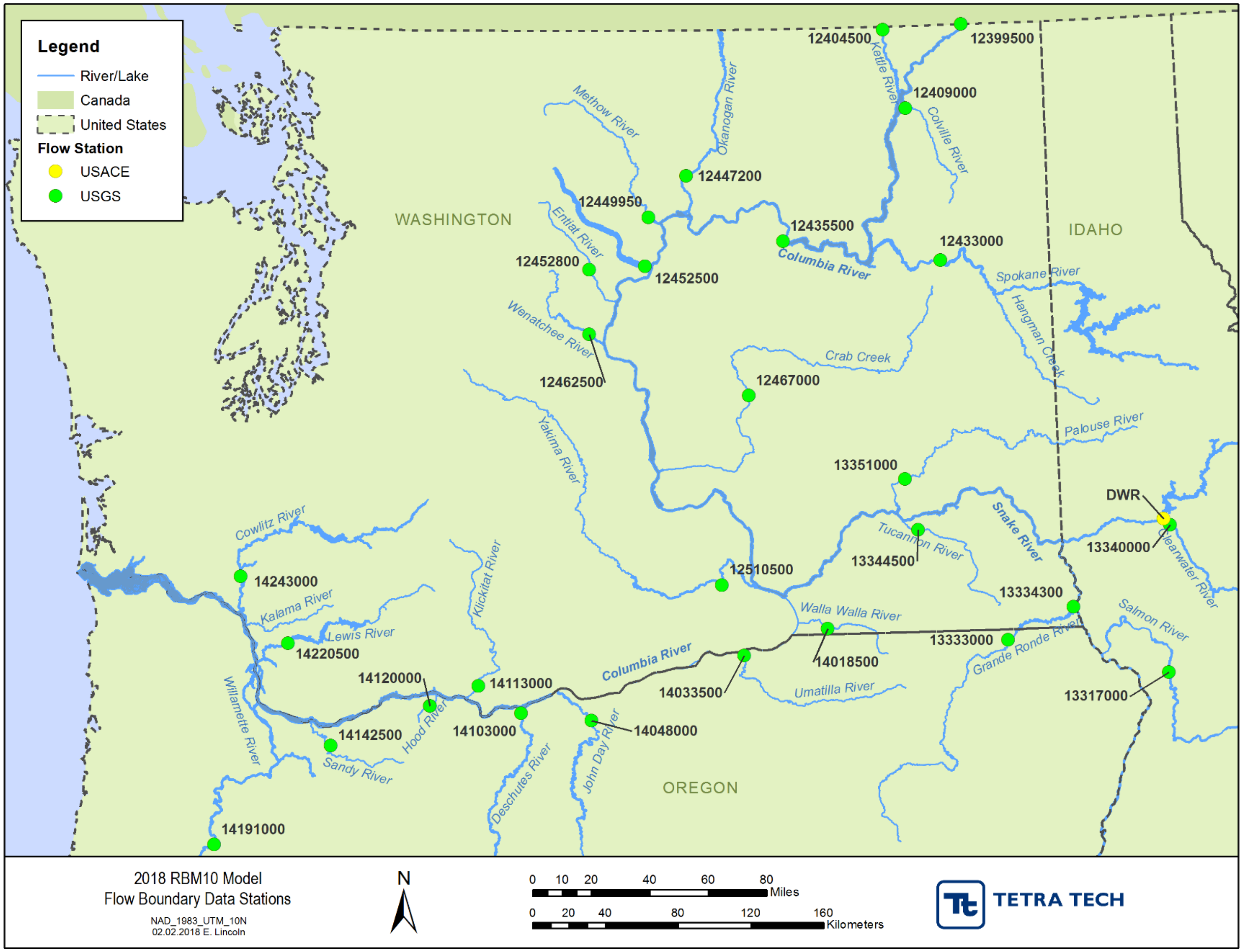

Figure 2-3 Stations used to generate flow boundary conditions for the Columbia and Snake Rivers

2.5.2 Temperature Inputs

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

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

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

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

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

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

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

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

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

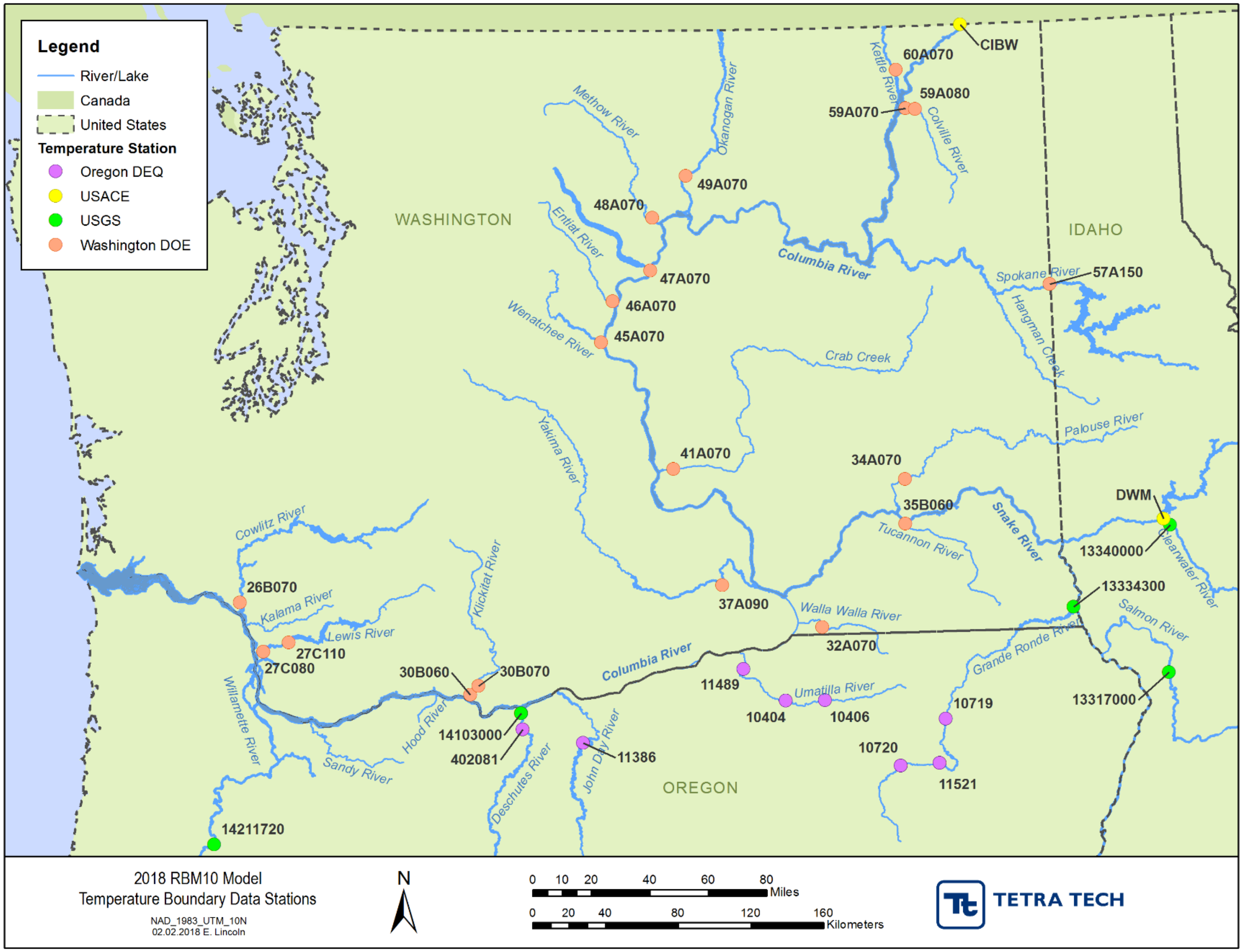

Figure 2-4 Stations used to generate temperature boundary conditions for the Columbia and Snake Rivers

2.6 Surface Heat Exchange and Meteorological Inputs

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

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

where

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

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

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

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

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

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

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

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

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

Shortwave (Solar) Radiation

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

where

Φ = the latitude of the site

δ = the declination of the sun at the site

D_y = the day of the year

Longwave (Atmospheric) Radiation

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

where

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

C = cloud cover, decimal fraction

T_{DB} = dry bulb temperature, ^{o}C

Evaporative Heat Flux

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

where

ρ = water density, kg/meter^3

λ = latent heat of vaporization, kcal/kg

E_v = empirical constant, mb^{-1}

W = wind speed, meters/second

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

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

Conductive Heat Flux

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

where

R_B = an empirical constant, 0.66

p_a = atmospheric pressure, mb

Black Body (Water Surface) Radiation

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

where

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

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

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

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

Table 2-6 WBAN stations used in 2018 RBM10 model

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

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

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

Table 2-7 GHCND stations used in 2018 RBM10 model

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

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

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

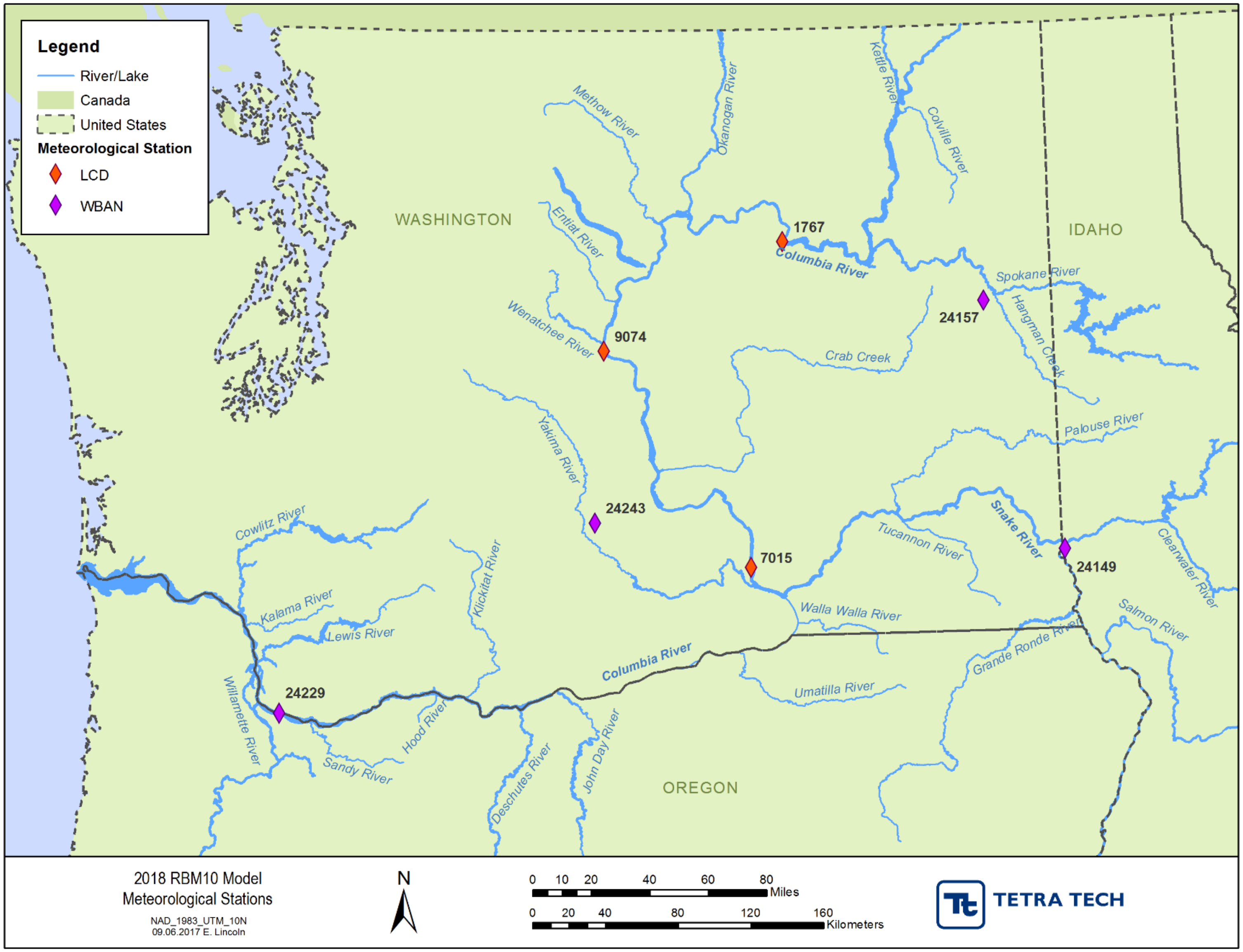

Figure 2-5 Meteorological stations within the simulated area

3.0 Model Calibration Process and Results

3.1 Calibration Approach

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.2 Data retrieval and QA/QC procedure

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

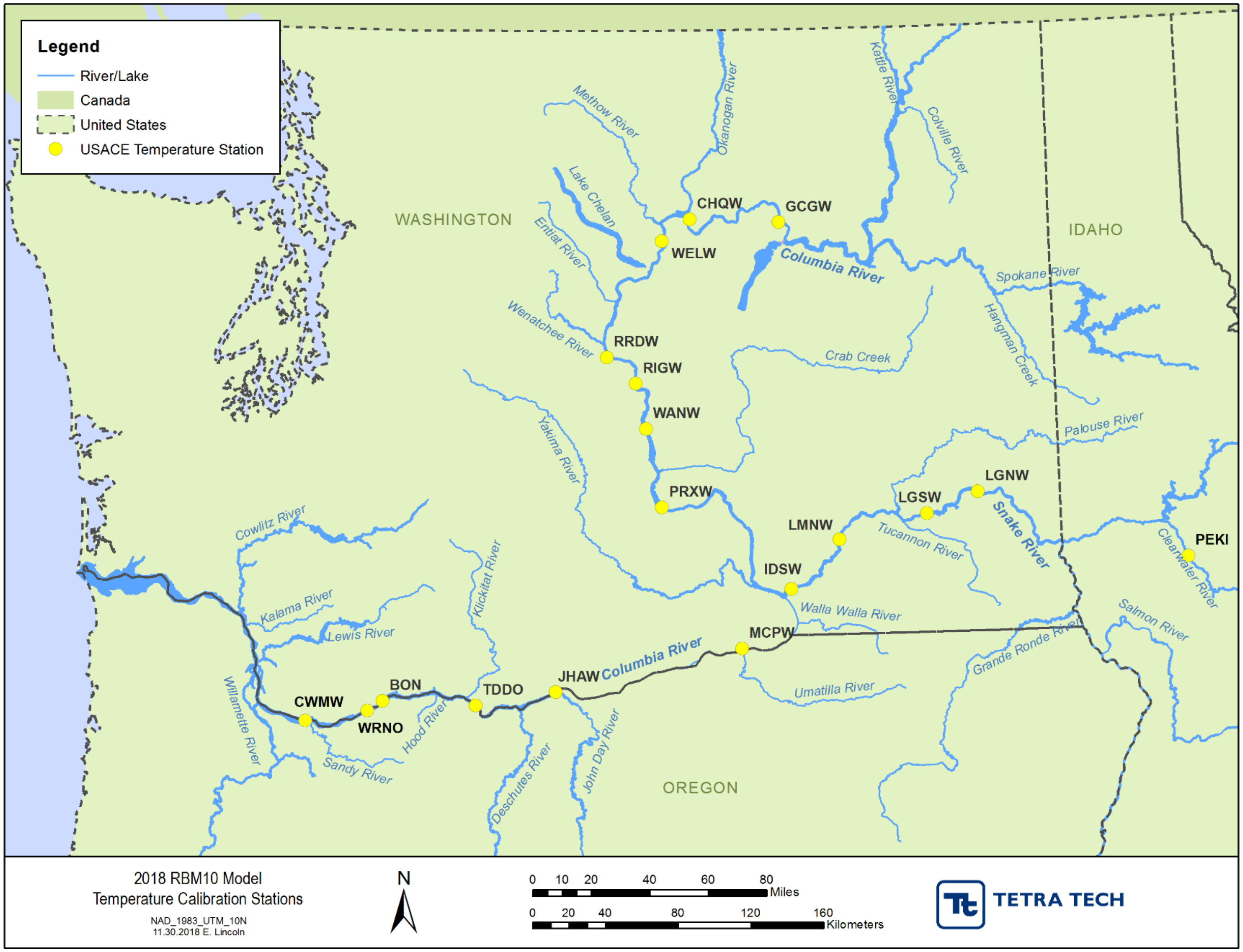

Figure 3-1 Temperature calibration stations for the RBM10 model

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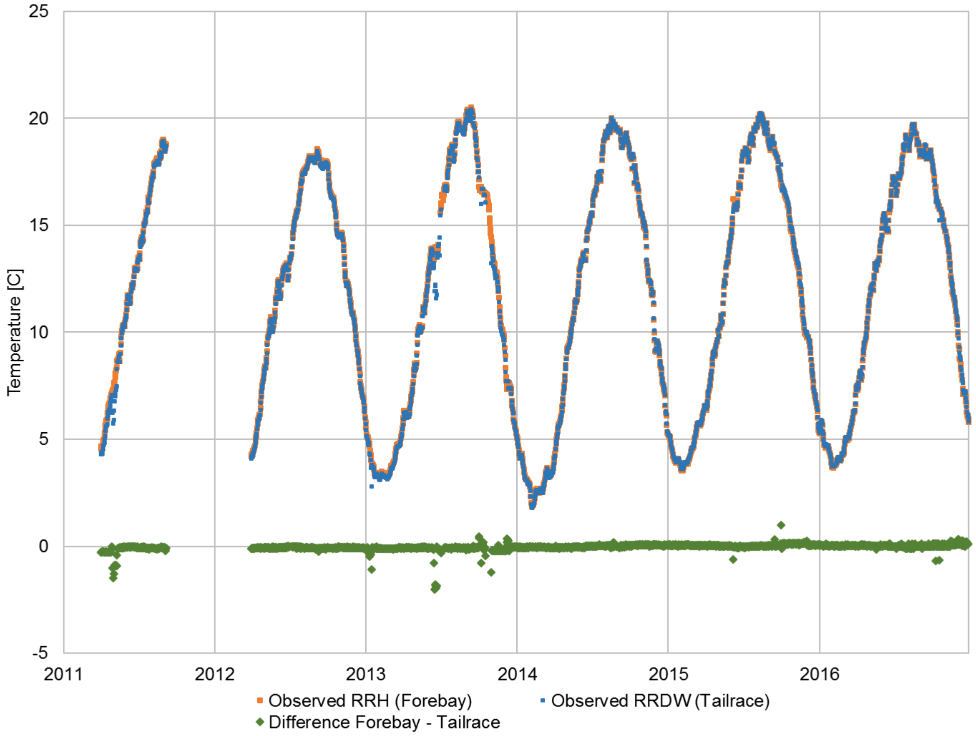

Figure 3-2 Comparison between forebay and tailrace water temperatures at the Rocky Reach Dam

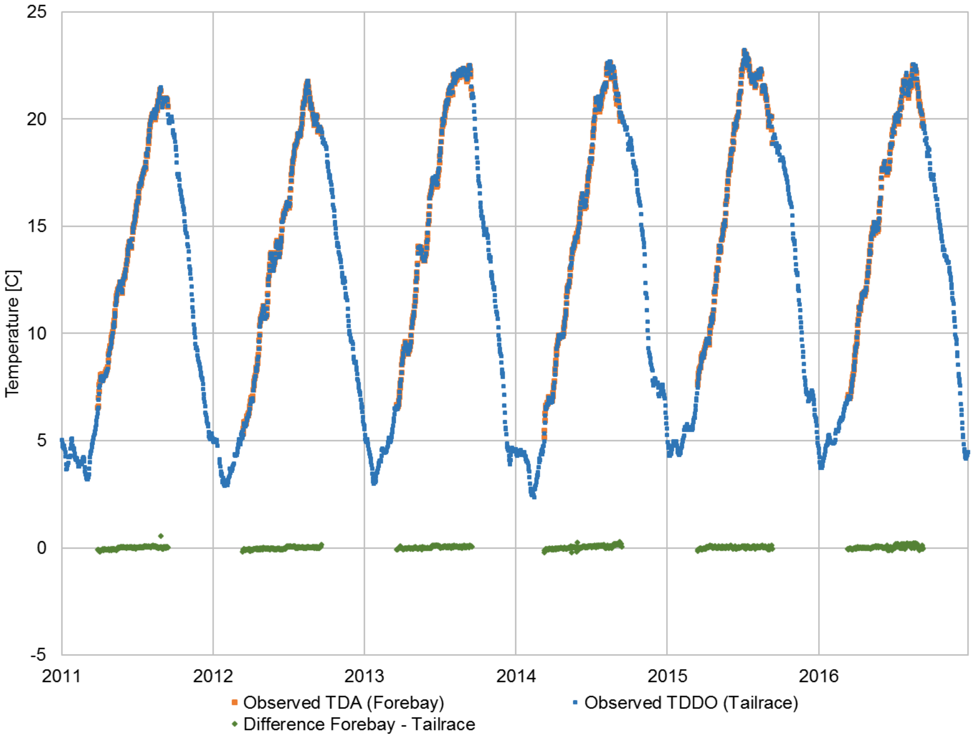

Figure 3-3 Comparison between forebay and tailrace water temperatures at The Dalles Dam

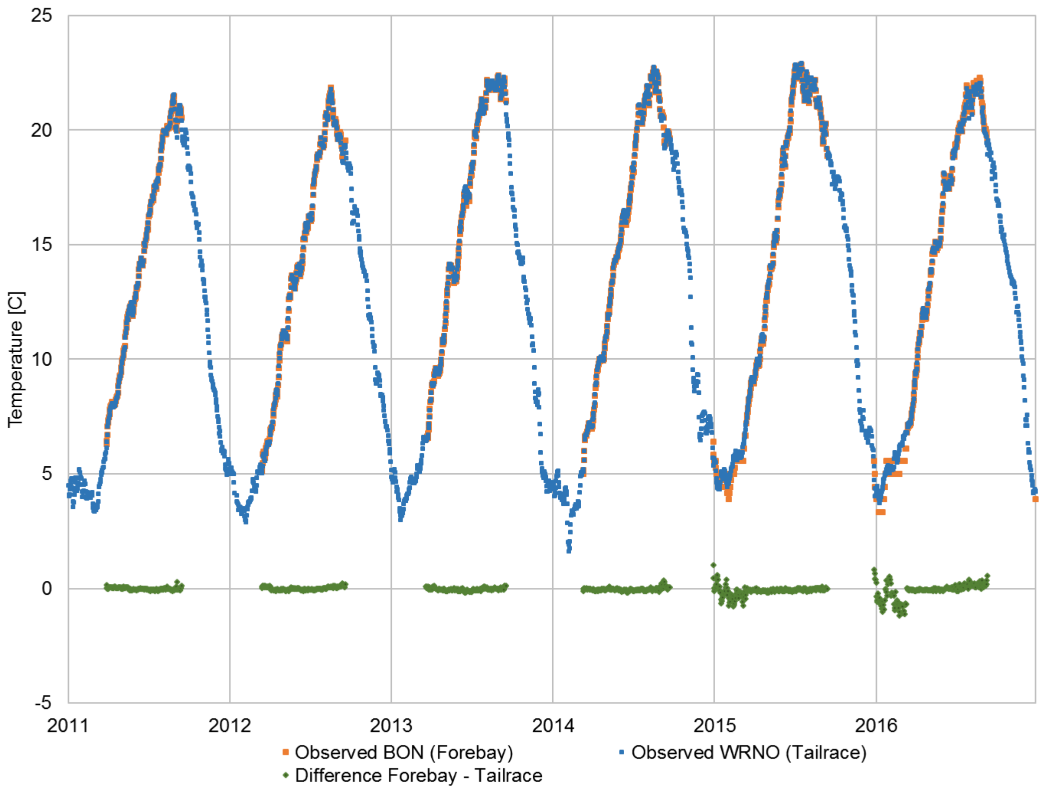

Figure 3-4 Comparison between forebay and tailrace water temperatures at the Bonneville Dam

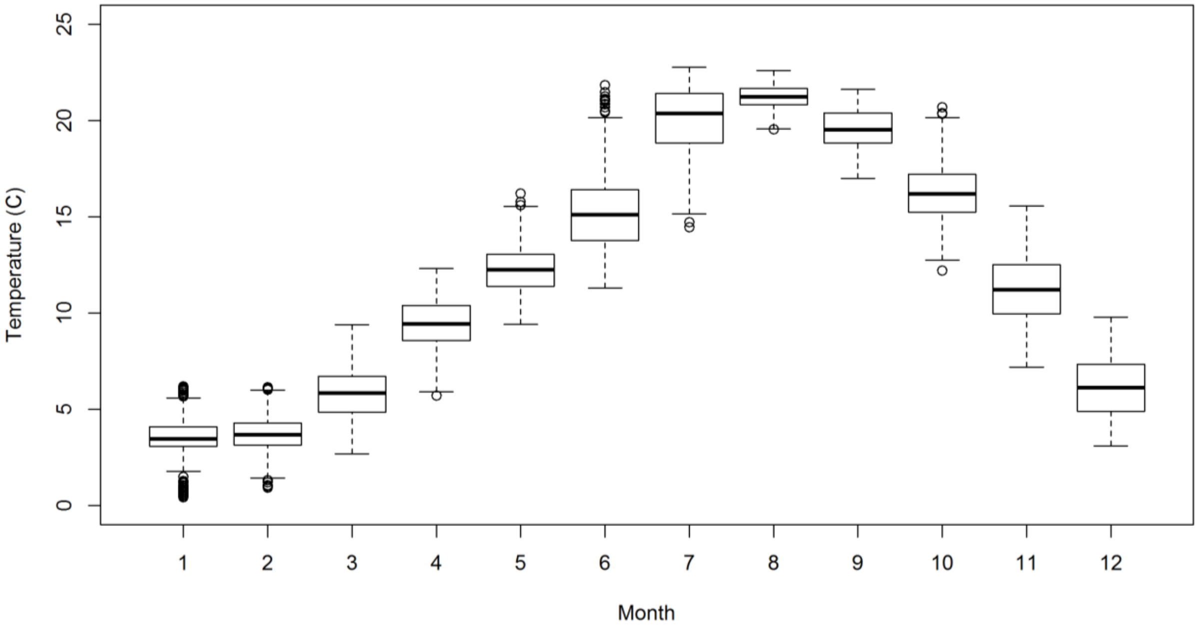

Figure 3-5 Monthly Box and Whisker plots of water temperature at Ice Harbor Dam tailrace with temperature outliers shown in circles

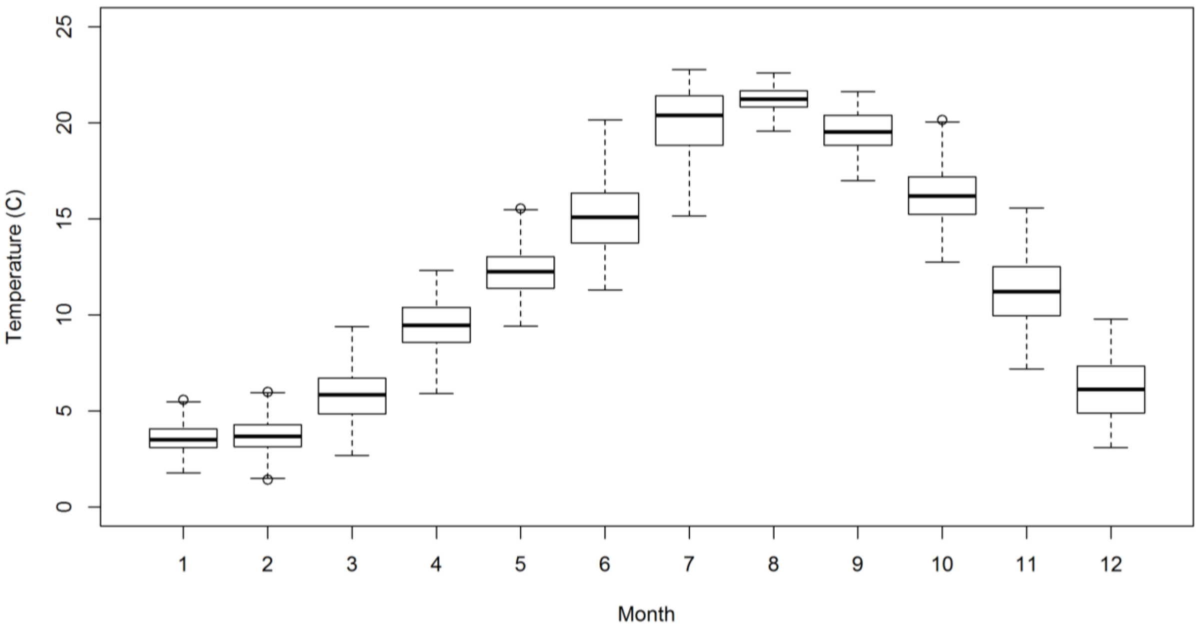

Figure 3-6 Monthly Box and Whisker plots of water temperature at Ice Harbor Dam tailrace with temperature outliers flagged as errors removed from the dataset

3.3 Model Performance Statistics

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.4 Model Calibration Plots

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

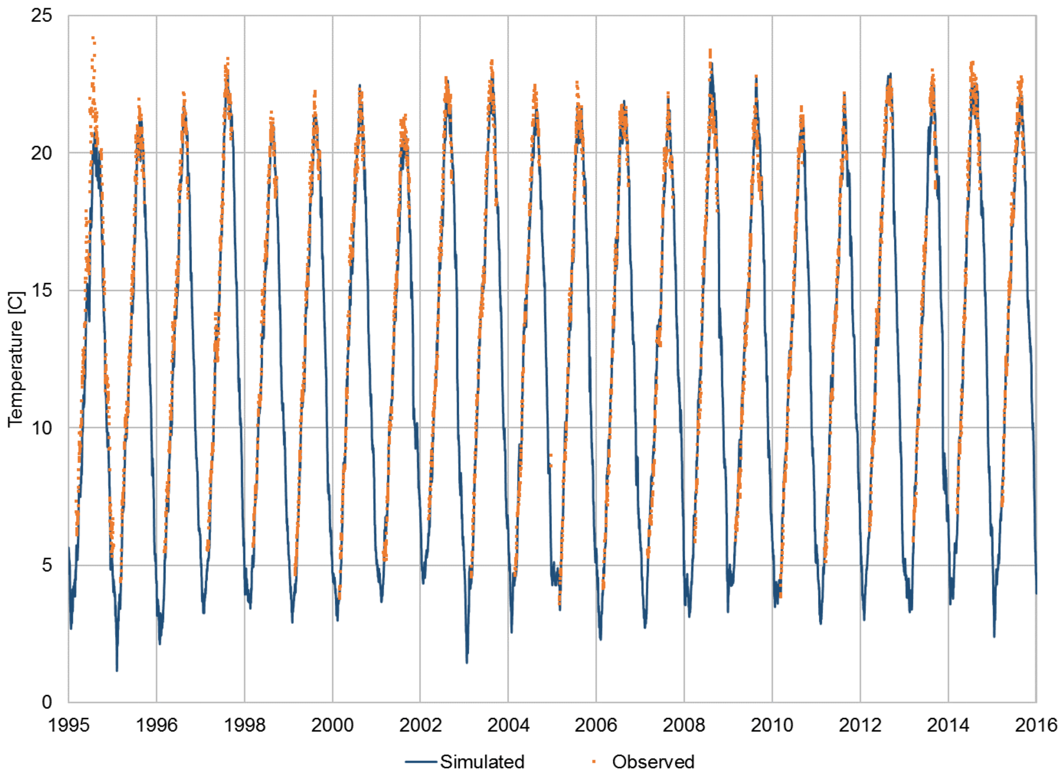

Figure 3-7 Simulated versus observed temperature at CWMW, Columbia River RM 119

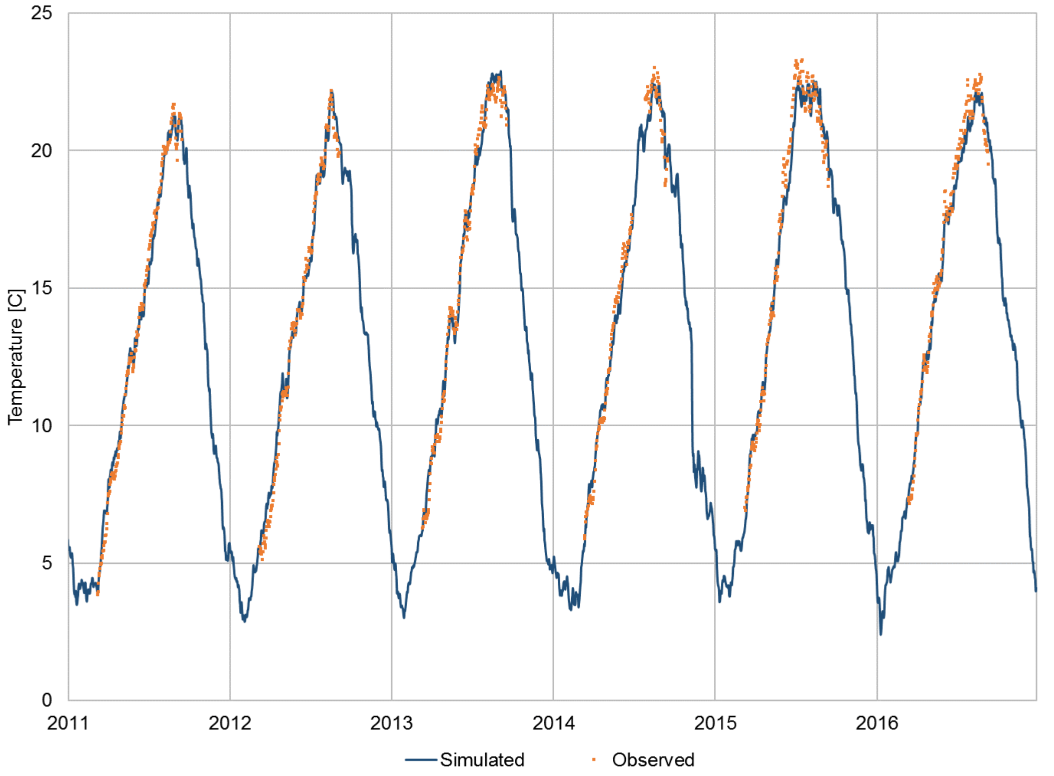

Figure 3-8 Simulated versus observed temperature at CWMW, period 2011 – 2016

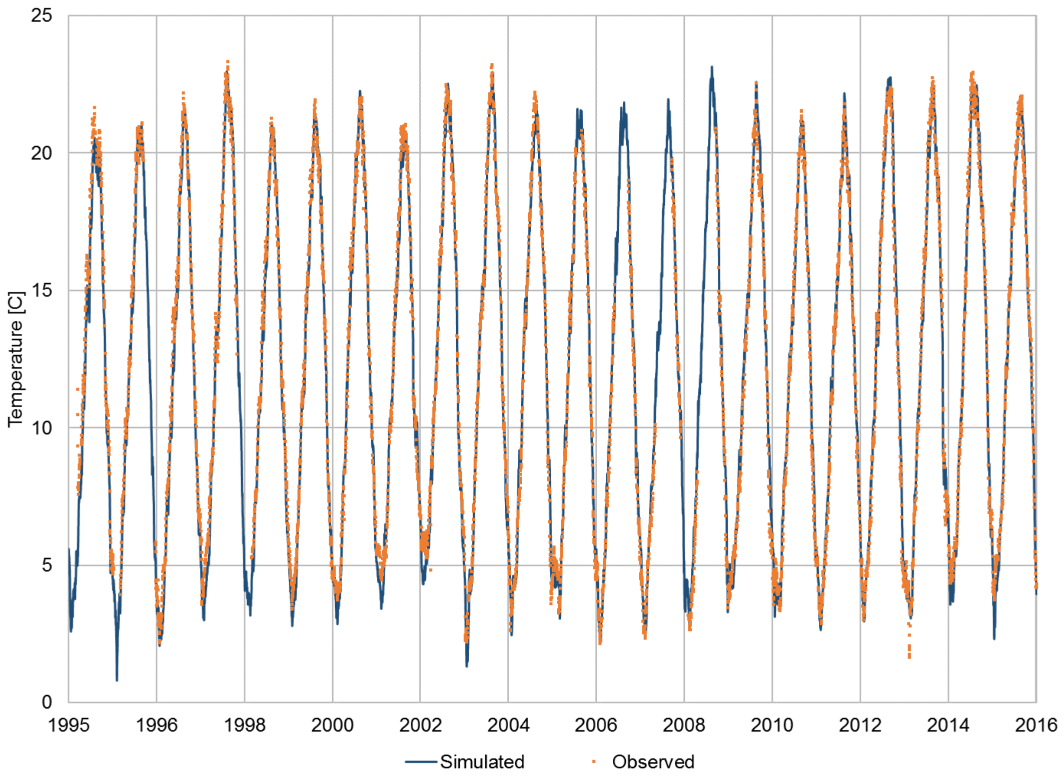

Figure 3-9 Simulated versus observed temperature at WRNO, Columbia River RM 140

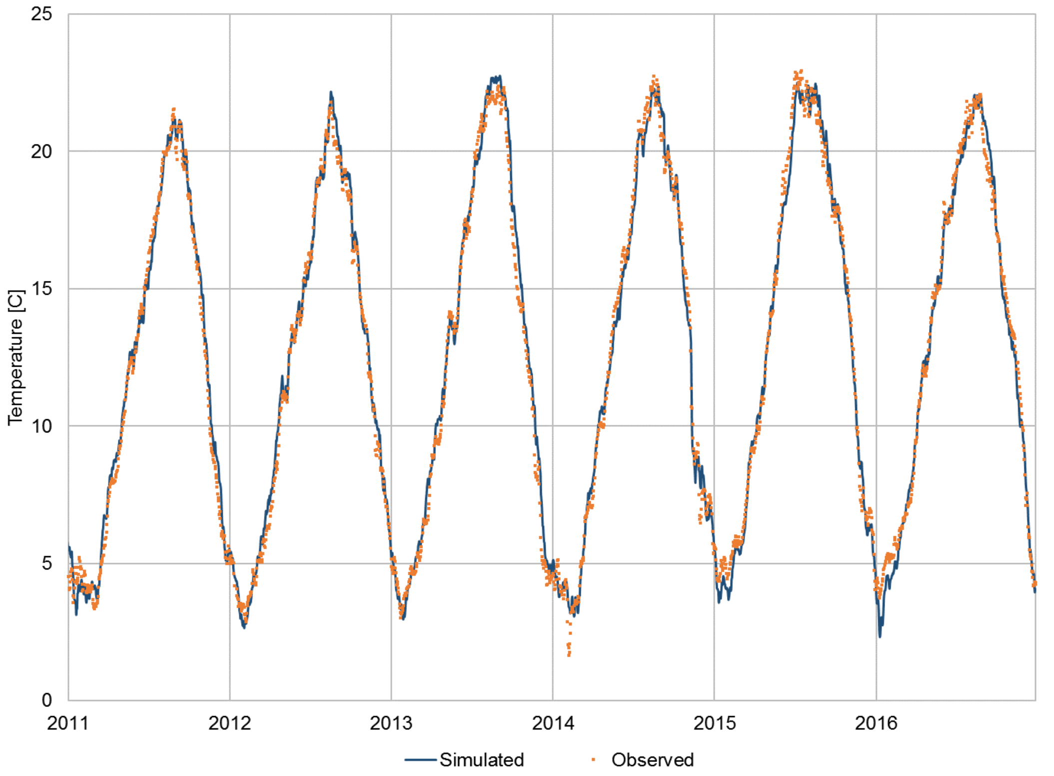

Figure 3-10 Simulated versus observed temperature at WRNO, period 2011 – 2016

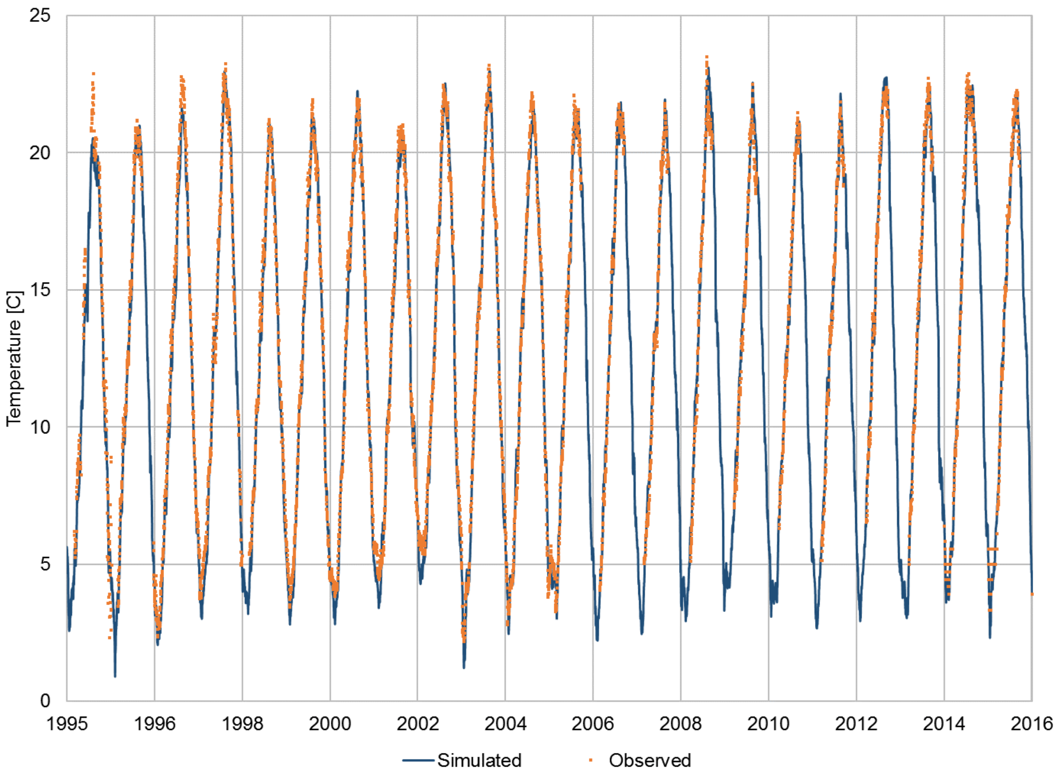

Figure 3-11 Simulated versus observed temperature at BON, Columbia River RM 146

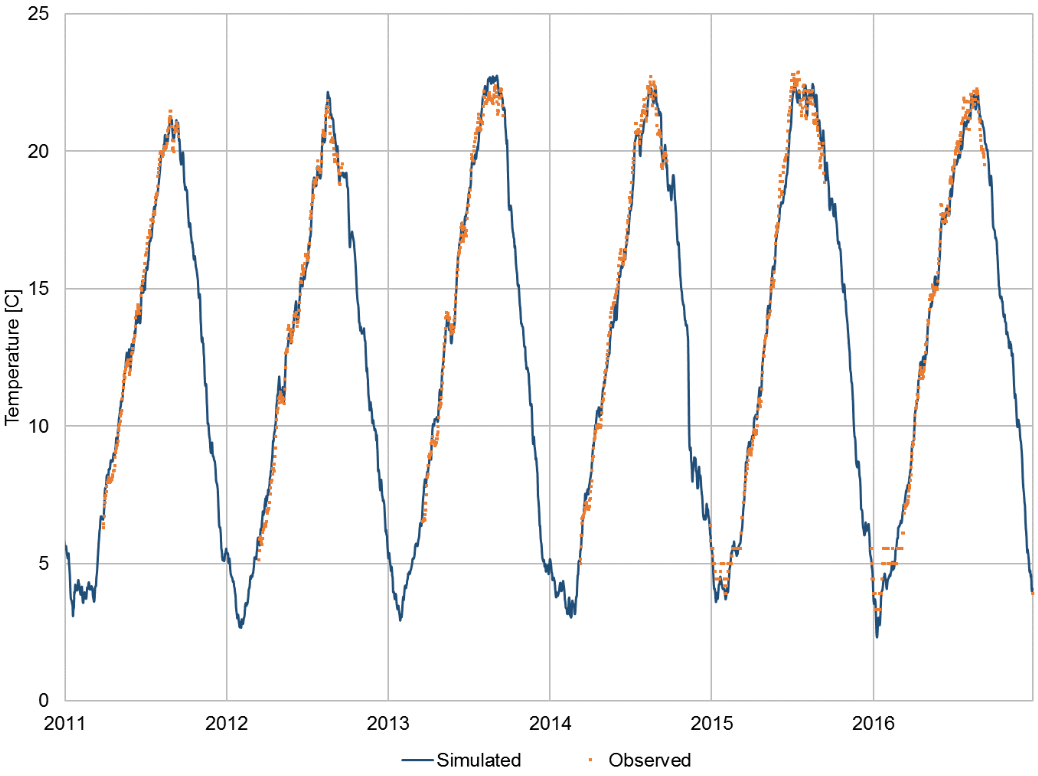

Figure 3-12 Simulated versus observed temperature at BON, period 2011 – 2016

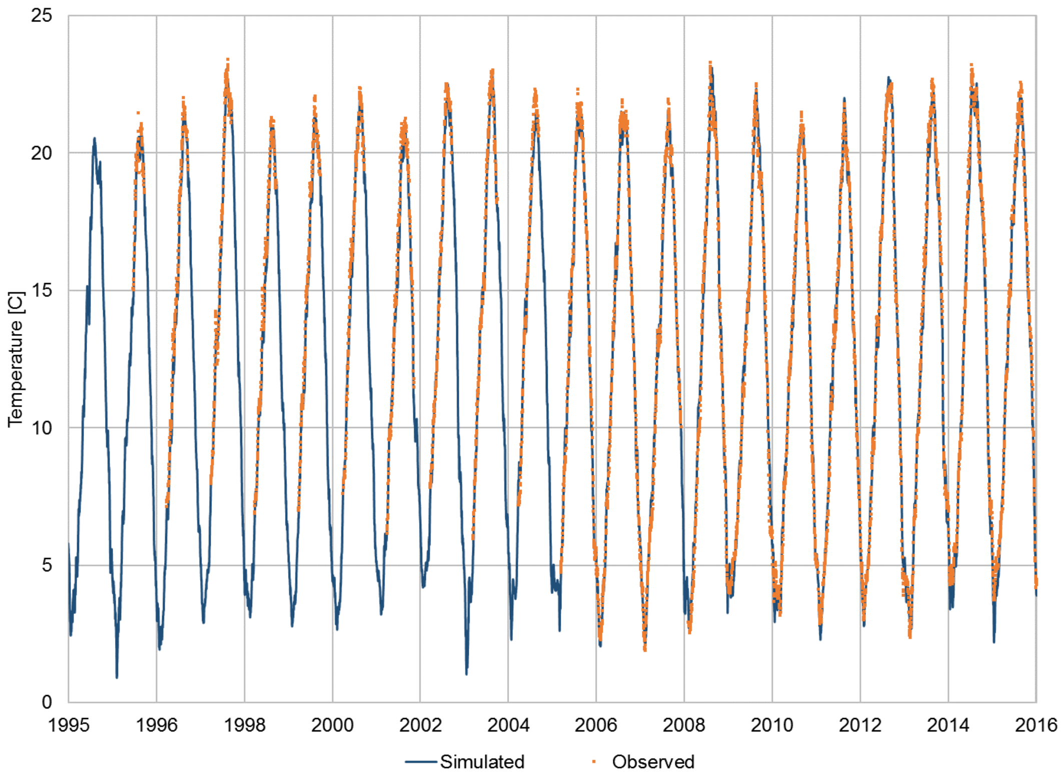

Figure 3-13 Simulated versus observed temperature at TDDO, Columbia River RM 190

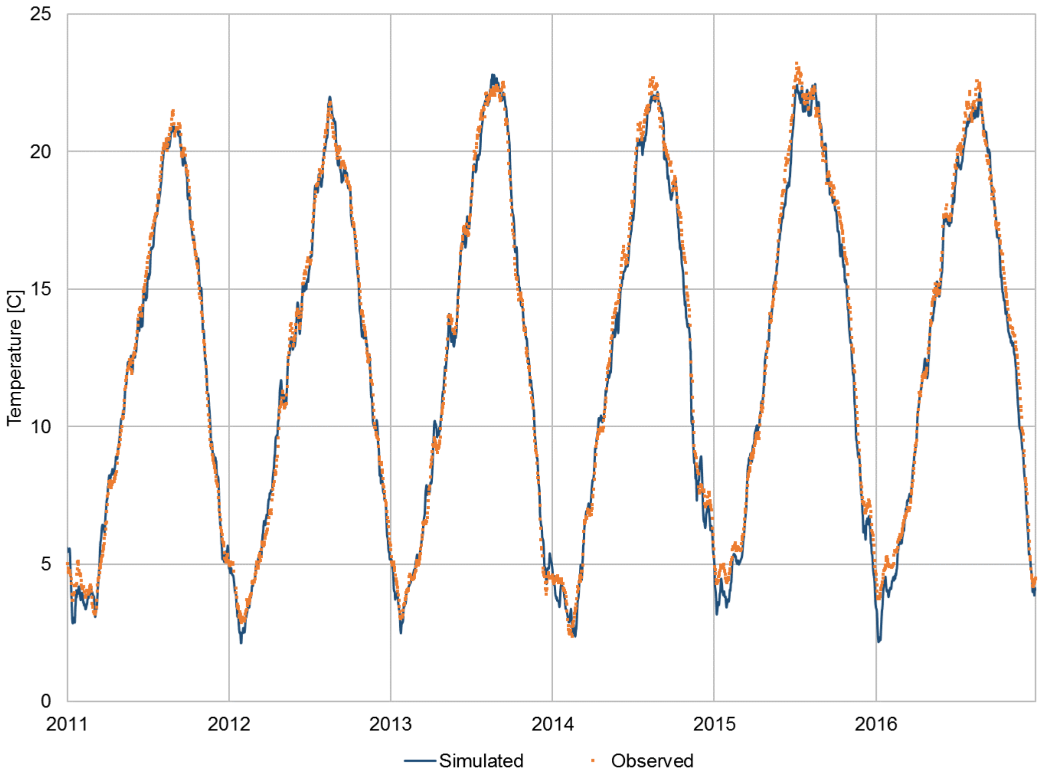

Figure 3-14 Simulated versus observed temperature at TDDO, period 2011 – 2016

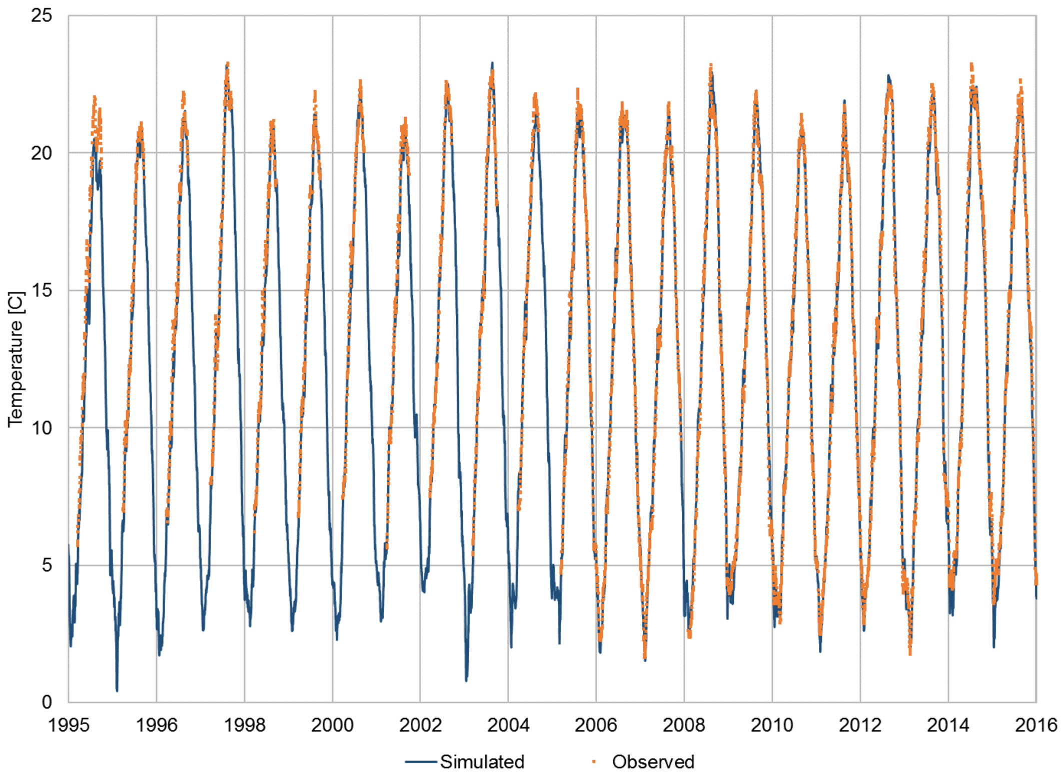

Figure 3-15 Simulated versus observed temperature at JHAW, Columbia River RM 215

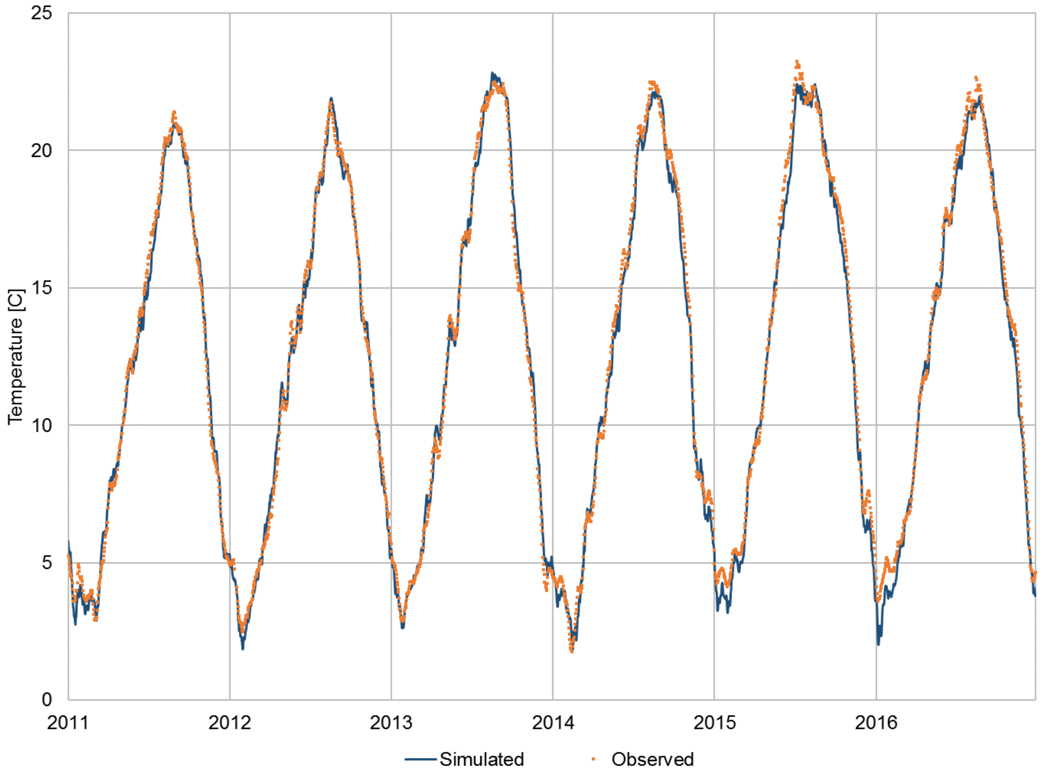

Figure 3-16 Simulated versus observed temperature at JHAW, period 2011 – 2016

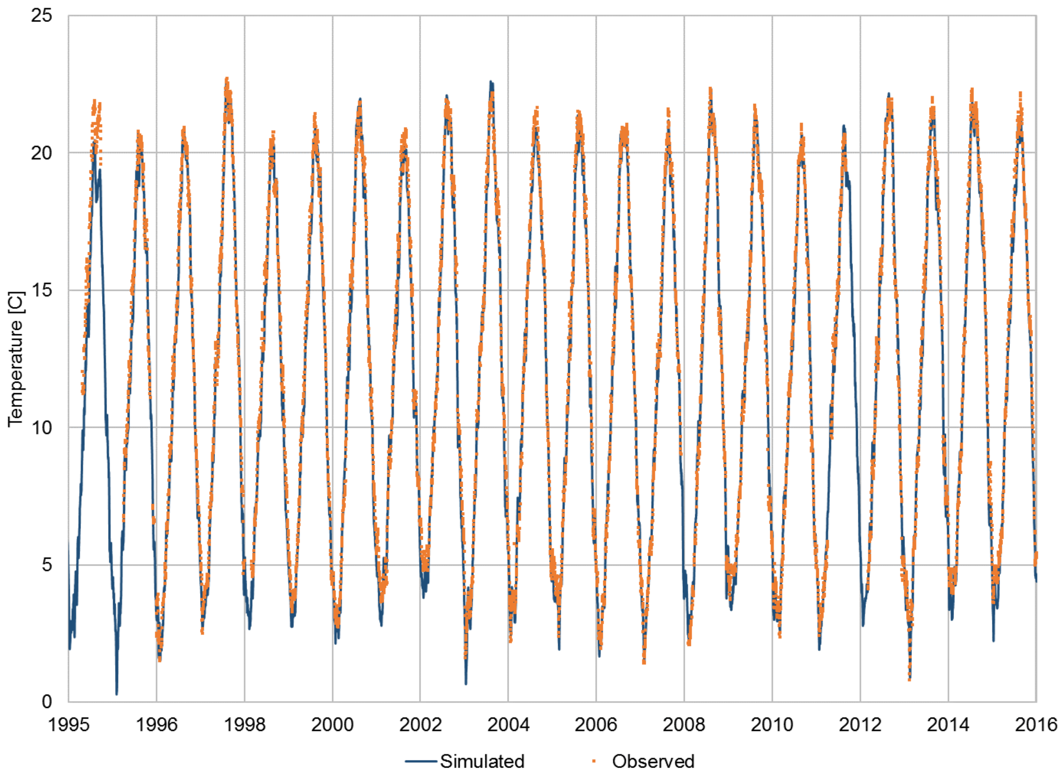

Figure 3-17 Simulated versus observed temperature at MCPW, Columbia River RM 291

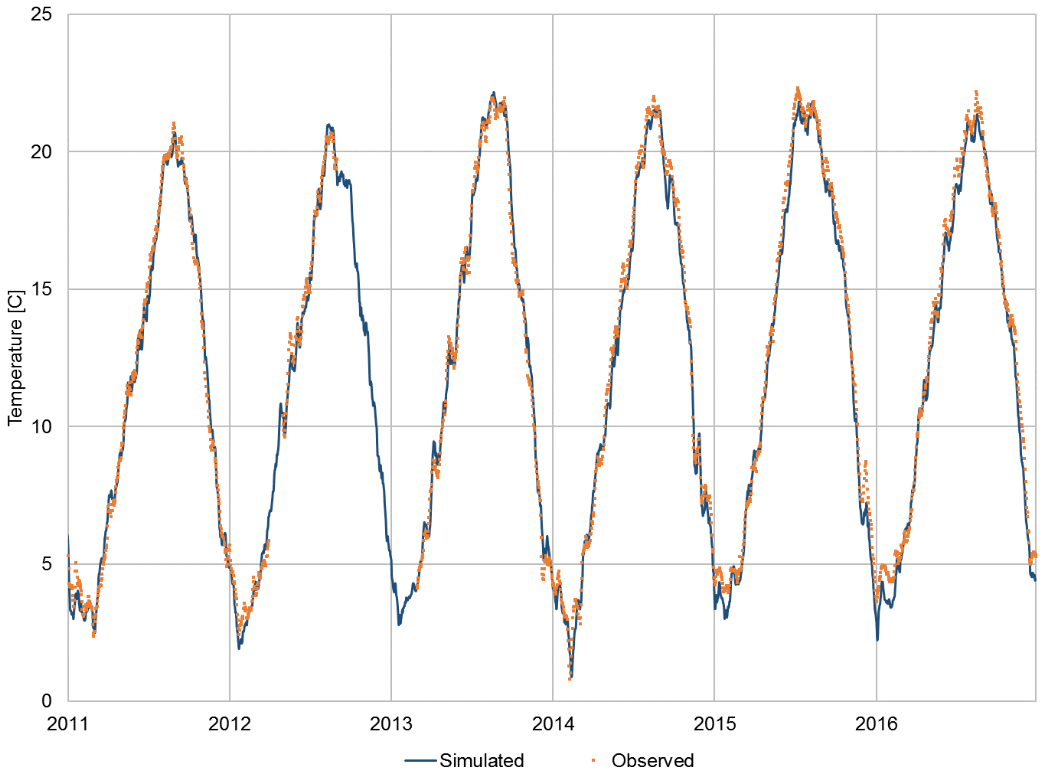

Figure 3-18 Simulated versus observed temperature at MCPW, period 2011 – 2016

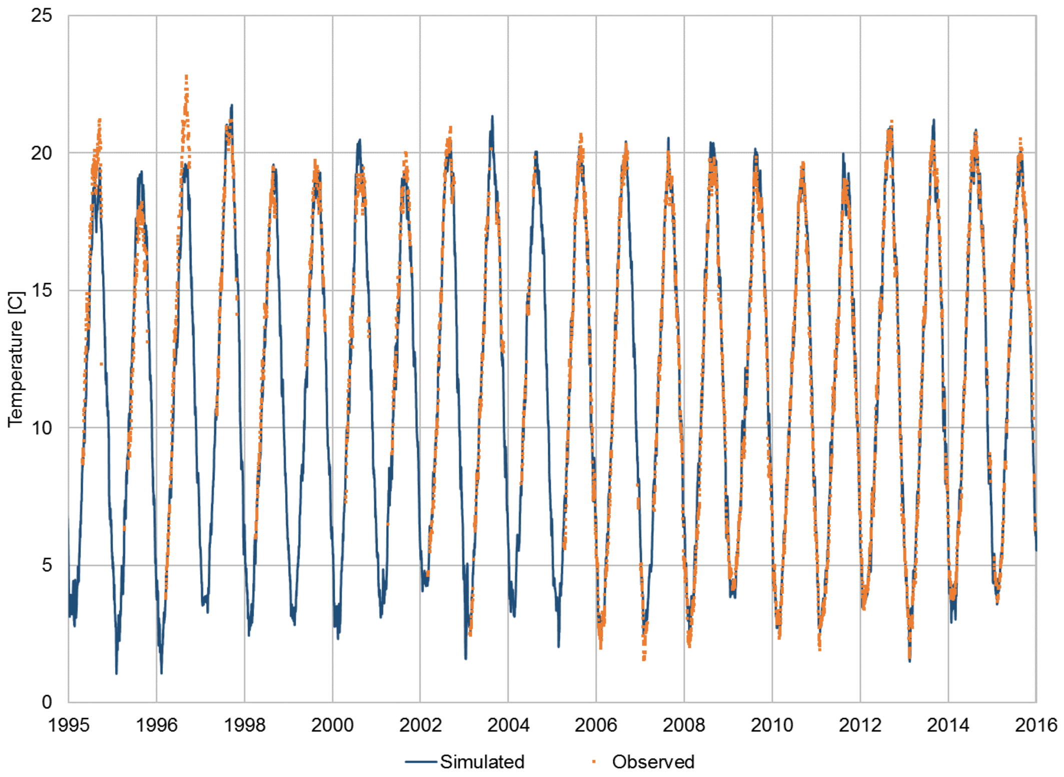

Figure 3-19 Simulated versus observed temperature at PRXW, Columbia River RM 396

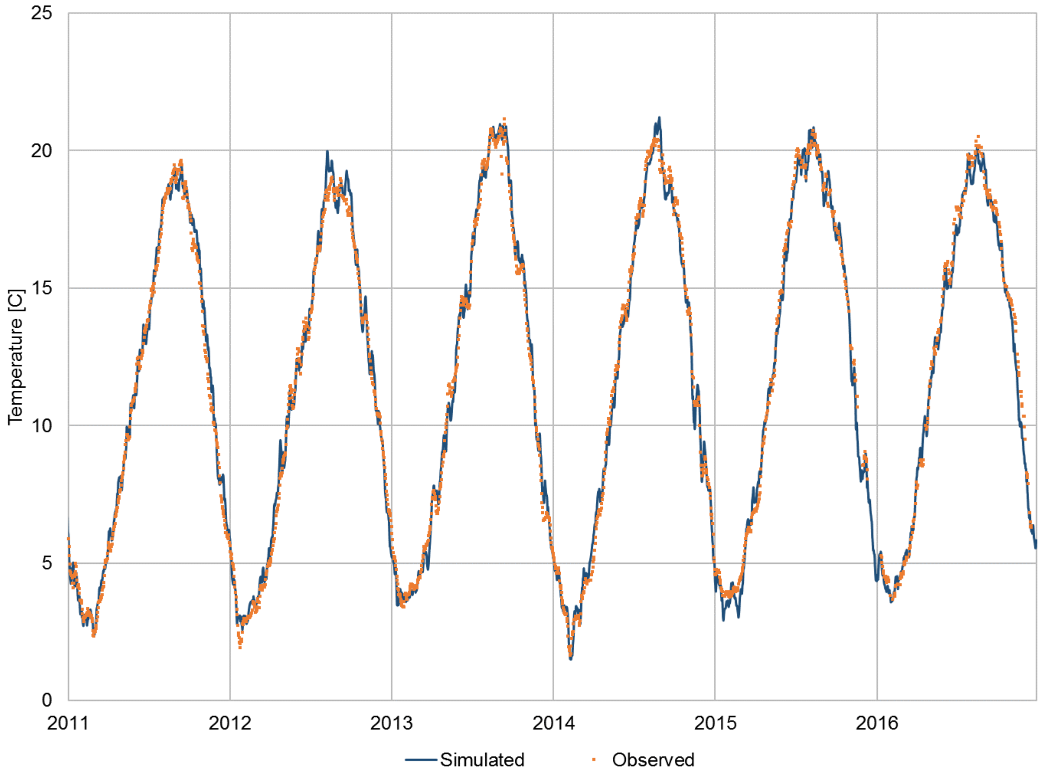

Figure 3-20 Simulated versus observed temperature at PRXW, period 2011 – 2016

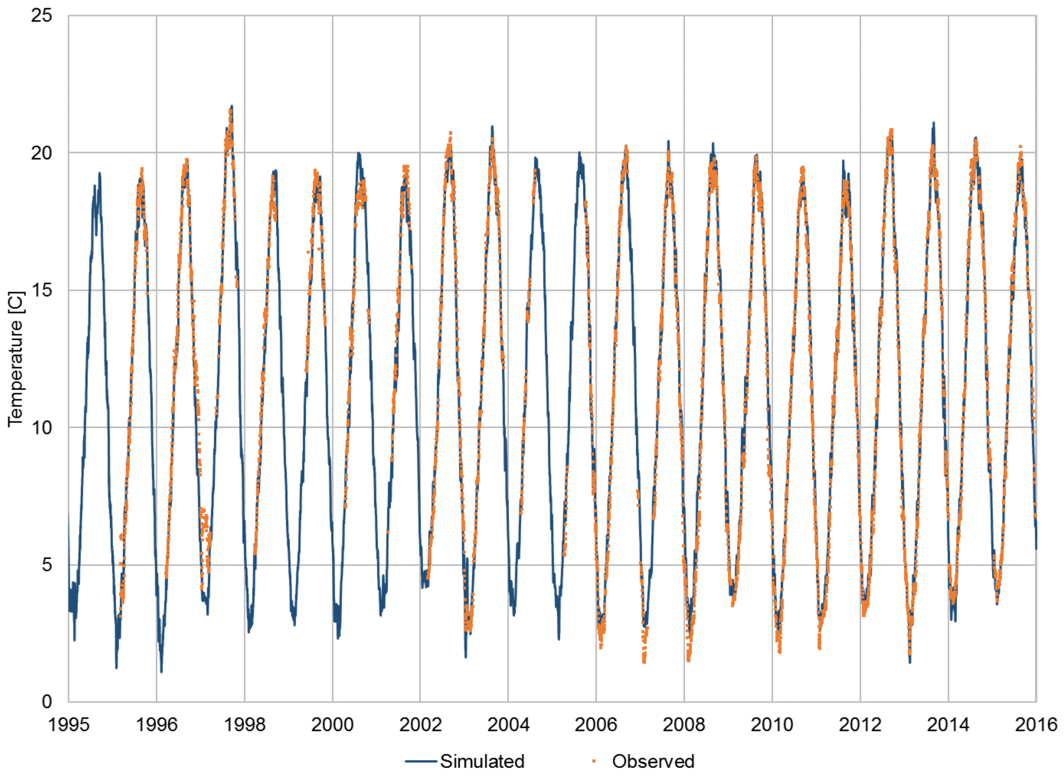

Figure 3-21 Simulated versus observed temperature at WANW, Columbia River RM 415

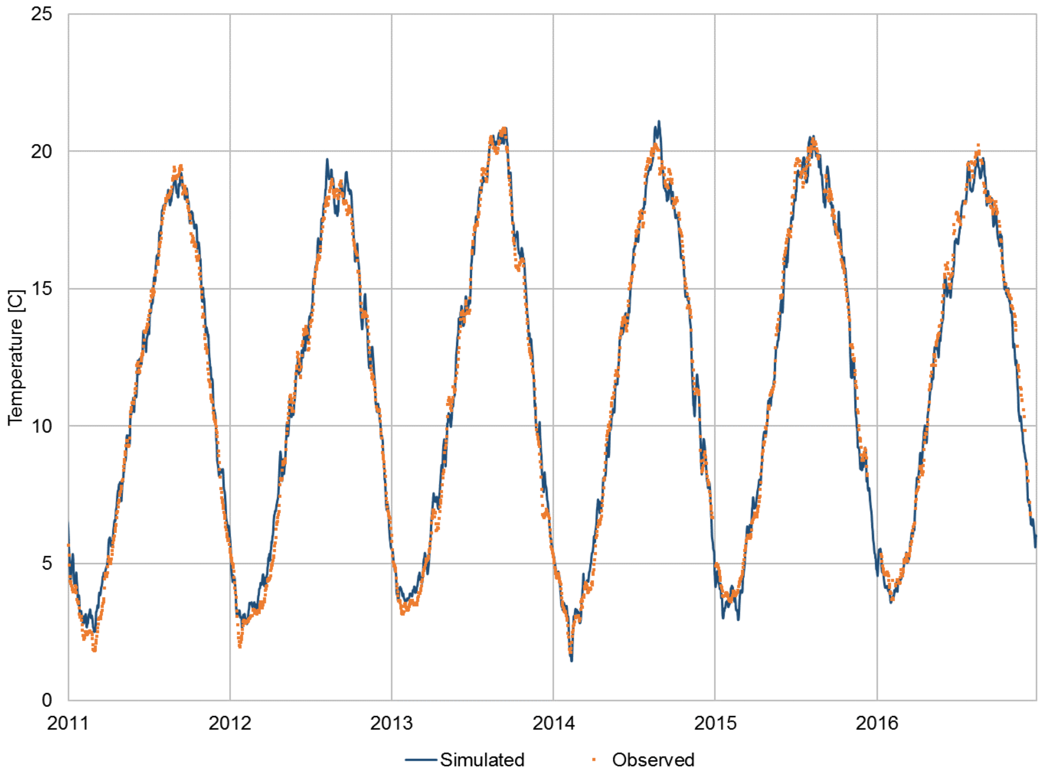

Figure 3-22 Simulated versus observed temperature at WANW, period 2011 – 2016

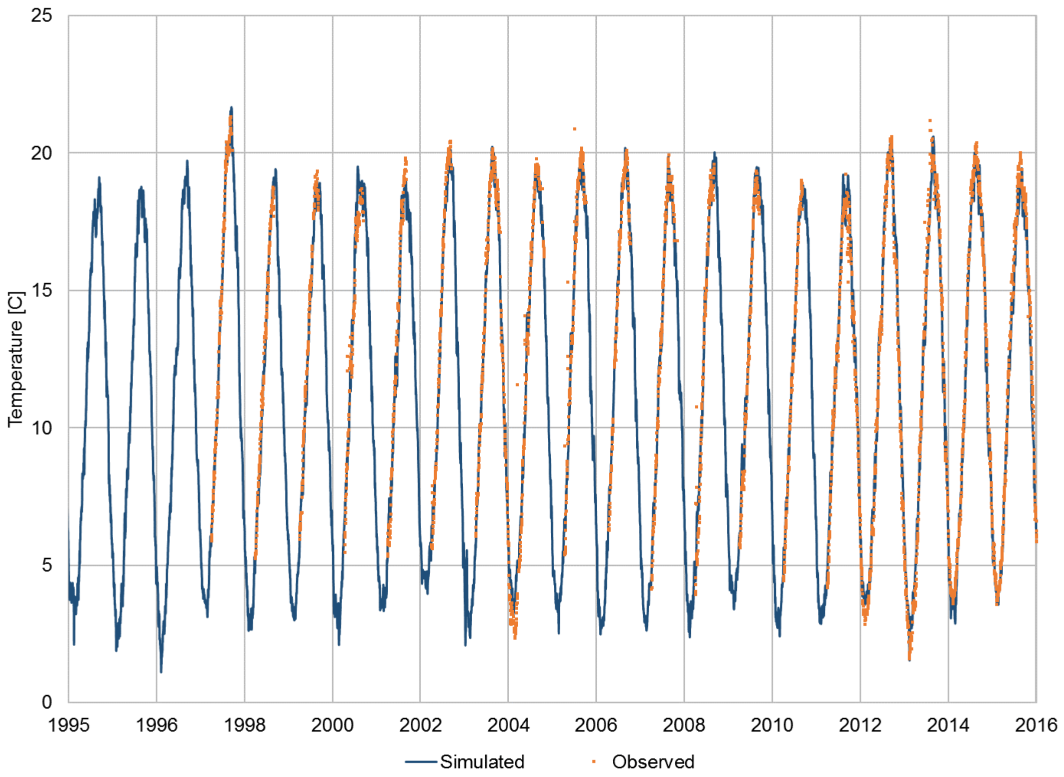

Figure 3-23 Simulated versus observed temperature at RIGW, Columbia River RM 452

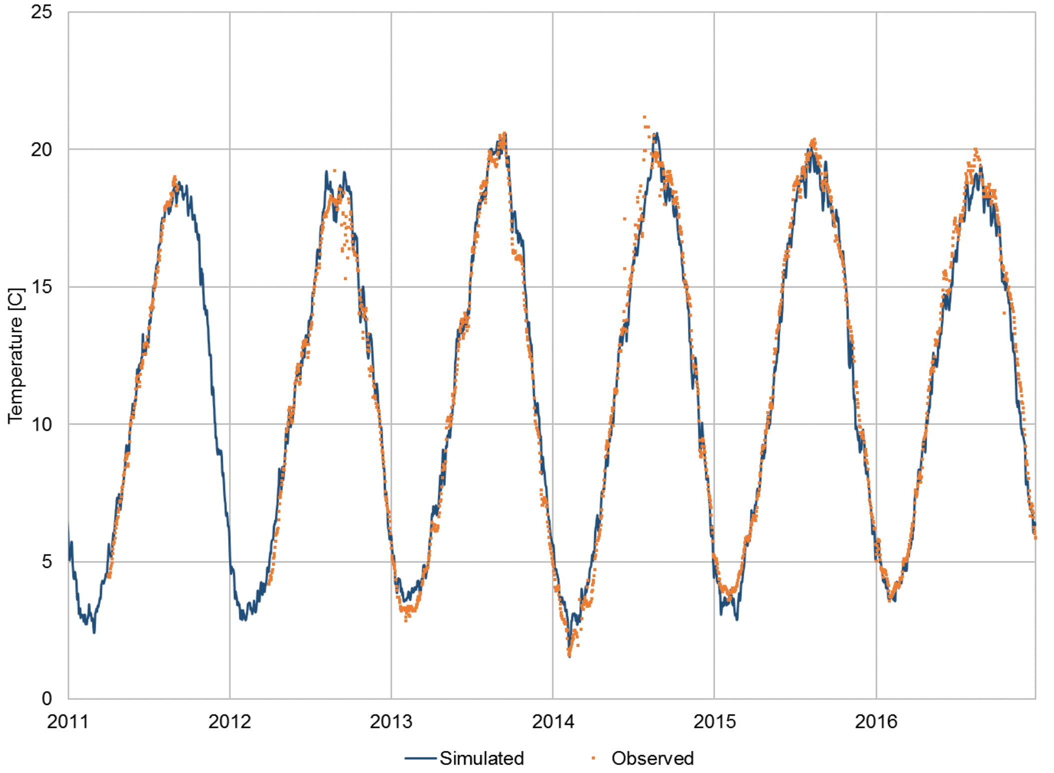

Figure 3-24 Simulated versus observed temperature at RIGW, period 2011 – 2016

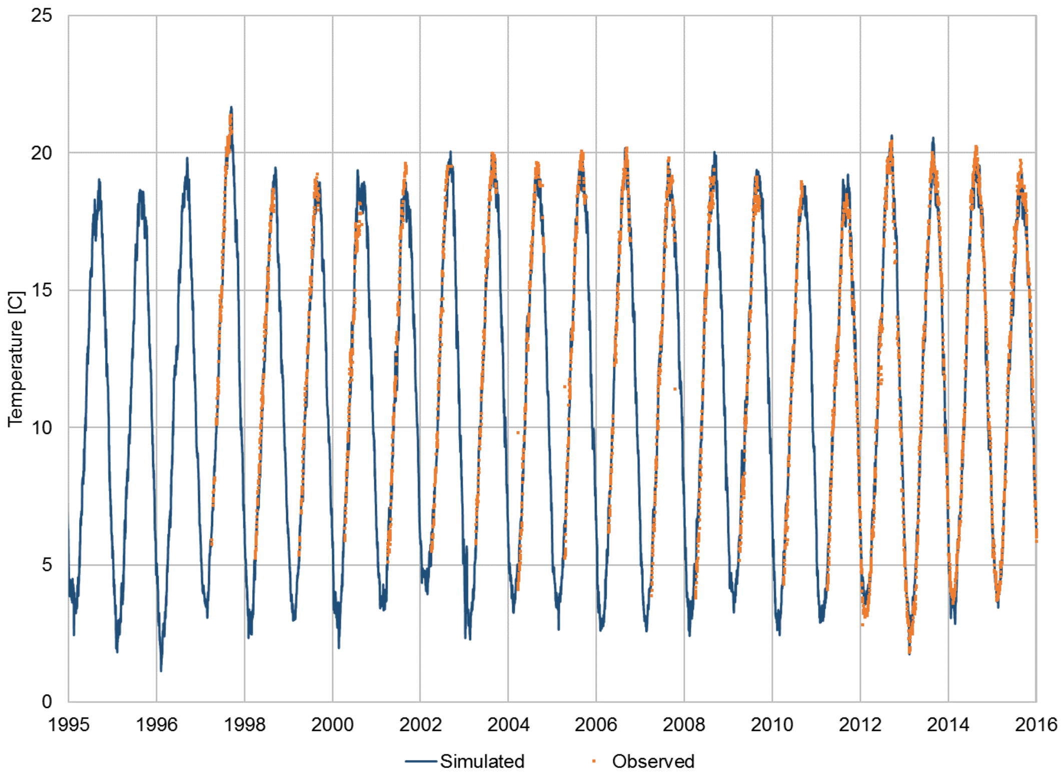

Figure 3-25 Simulated versus observed temperature at RRDW, Columbia River RM 472

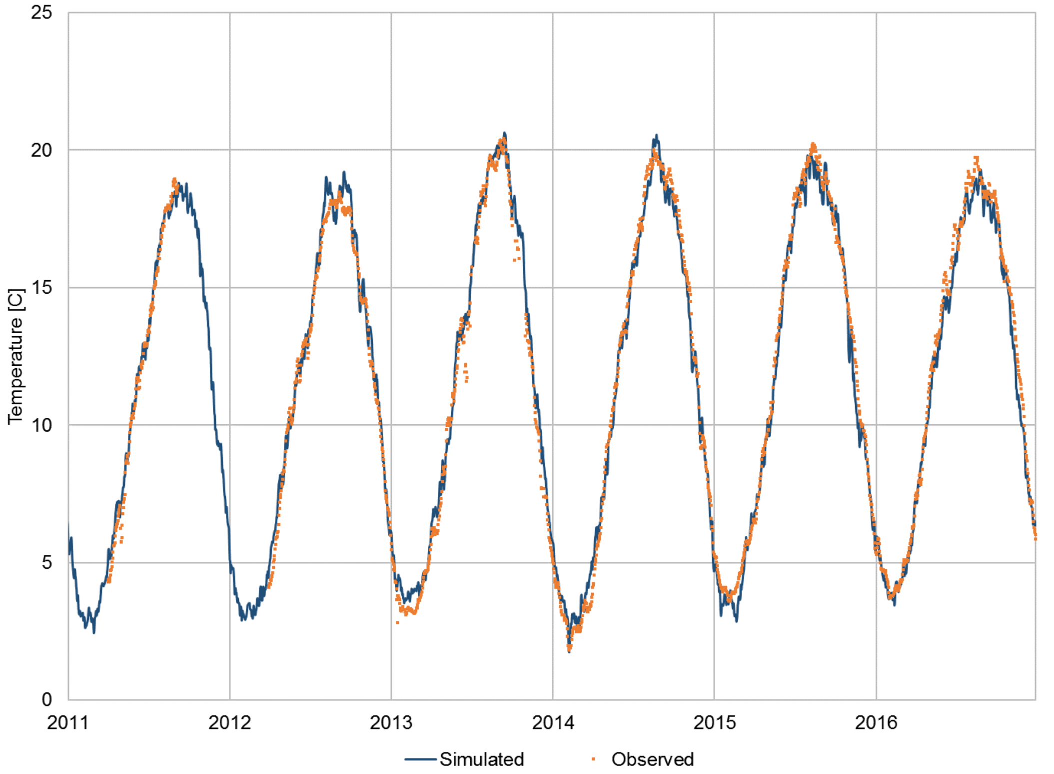

Figure 3-26 Simulated versus observed temperature at RRDW, period 2011 – 2016

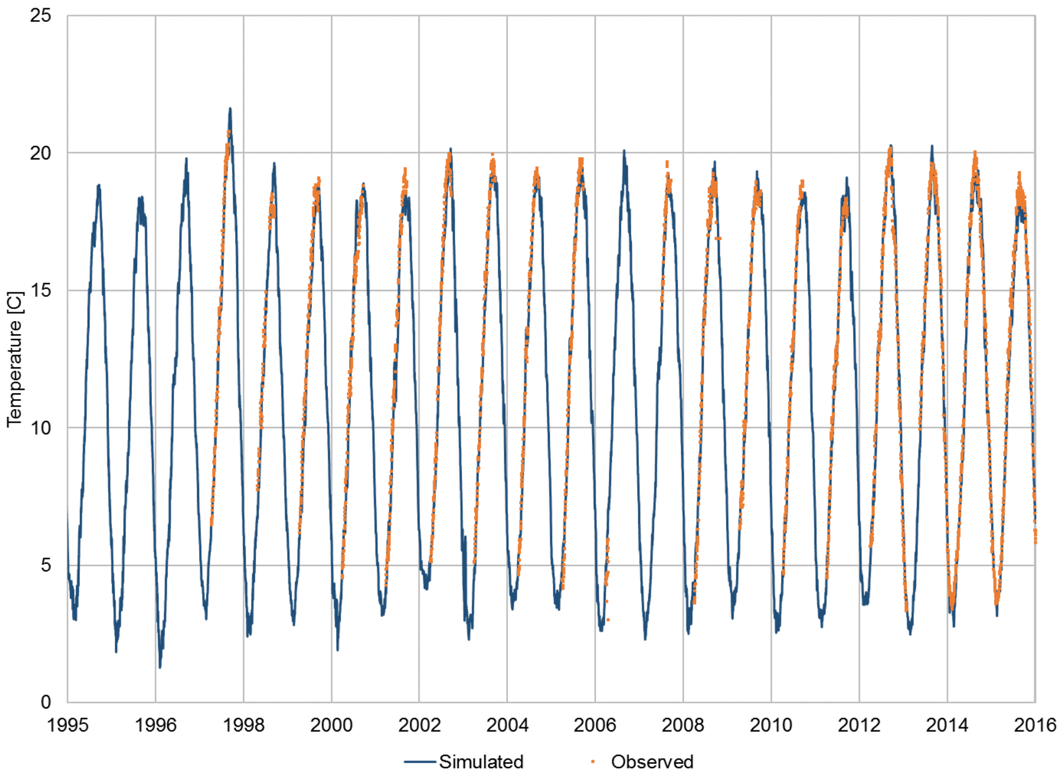

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Figure 3-27 Simulated versus observed temperature at WELW, Columbia River RM 514

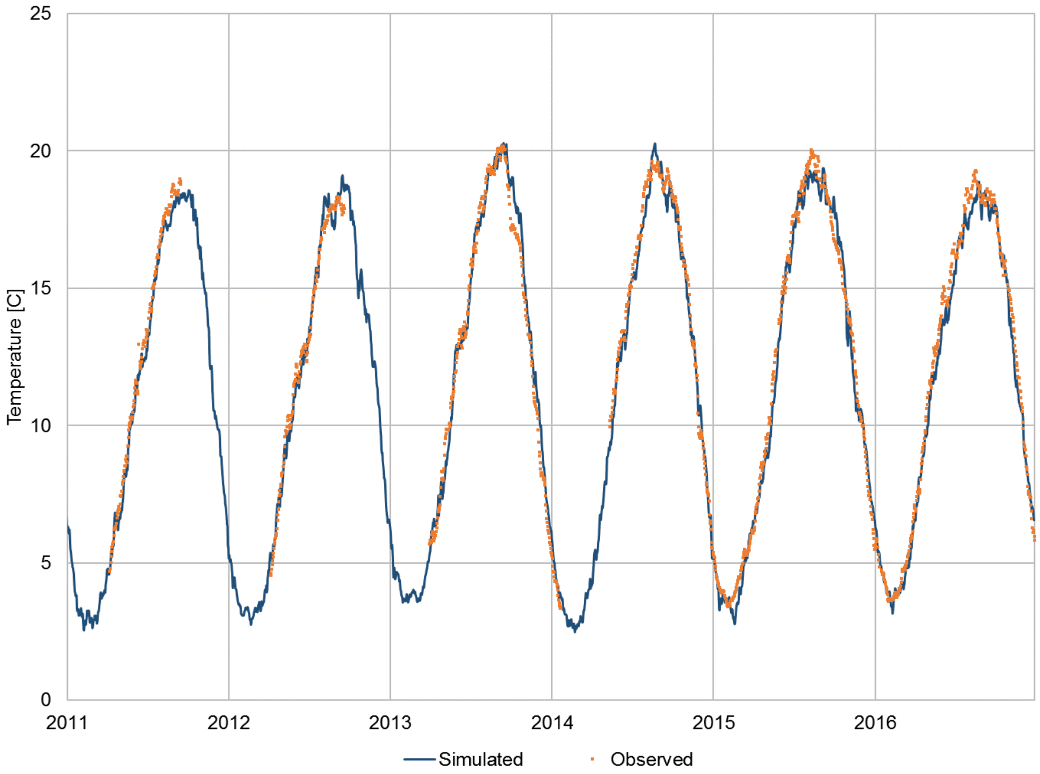

Figure 3-28 Simulated versus observed temperature at WELW, period 2011 – 2016

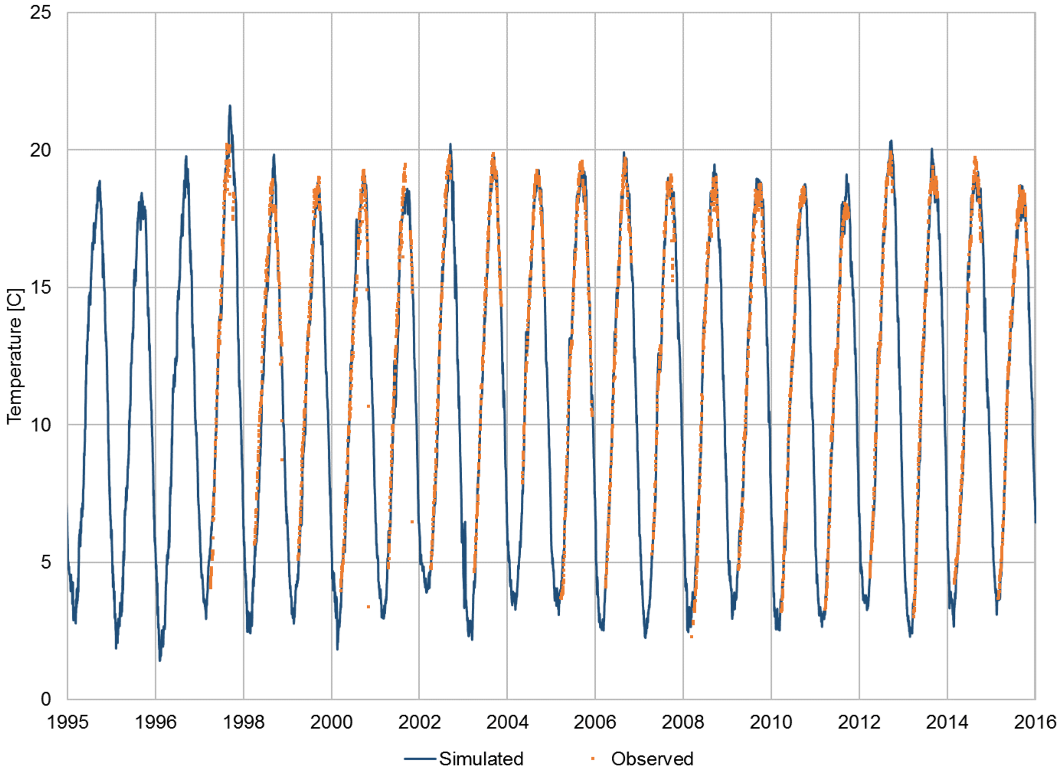

Figure 3-29 Simulated versus observed temperature at CHQW, Columbia River RM 545

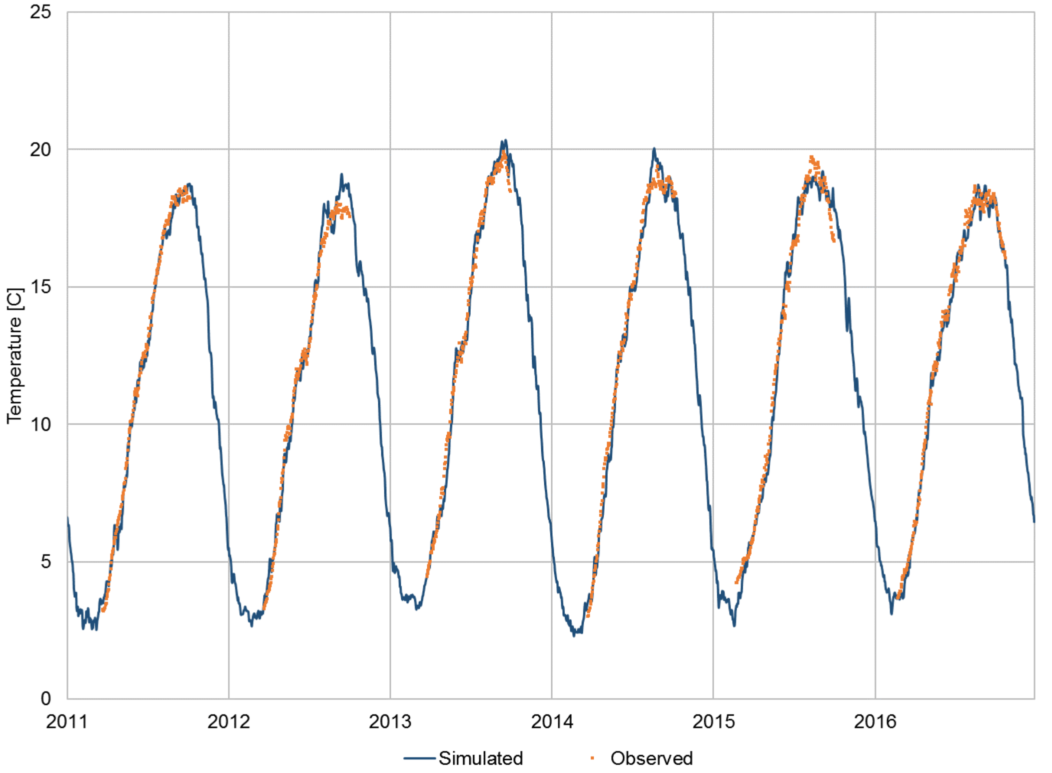

Figure 3-30 Simulated versus observed temperature at CHQW, period 2011 – 2016

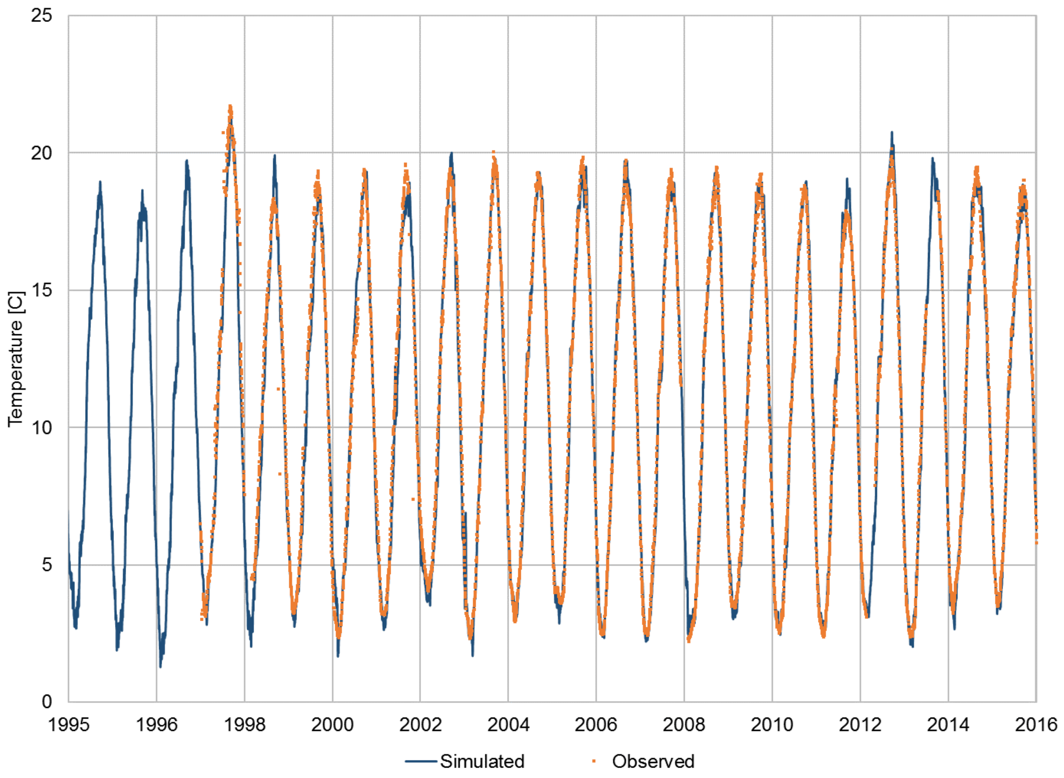

Figure 3-31 Simulated versus observed temperature at GCGW, Columbia River RM 590

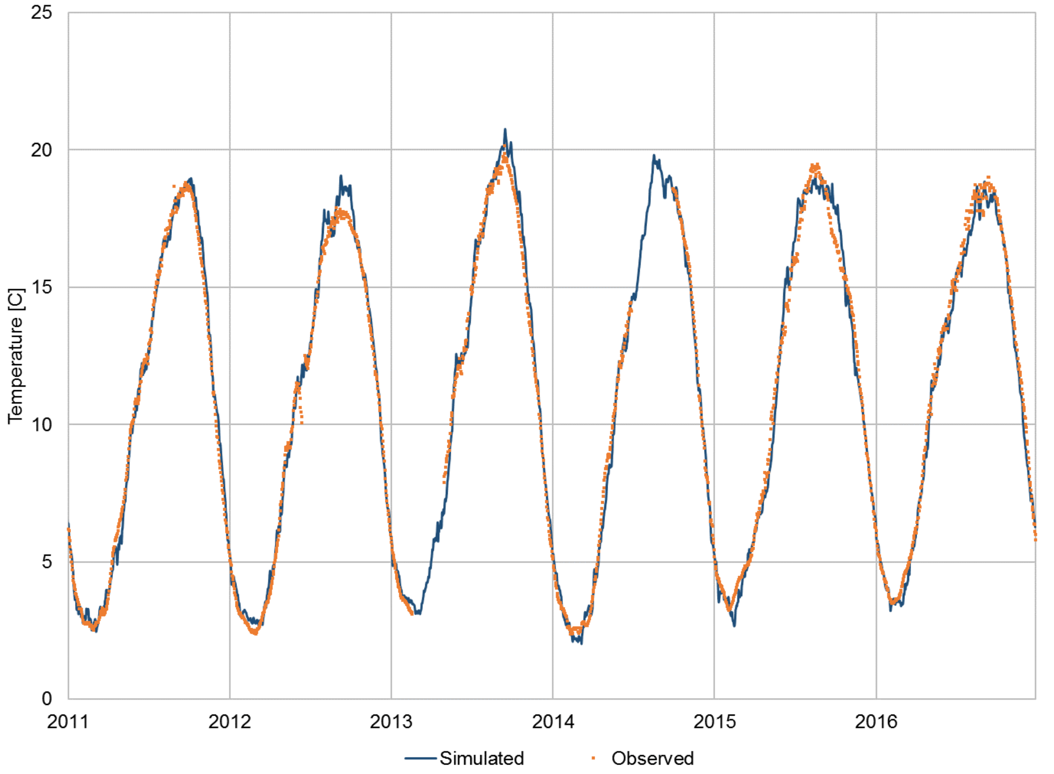

Figure 3-32 Simulated versus observed temperature at GCGW, period 2011 – 2016

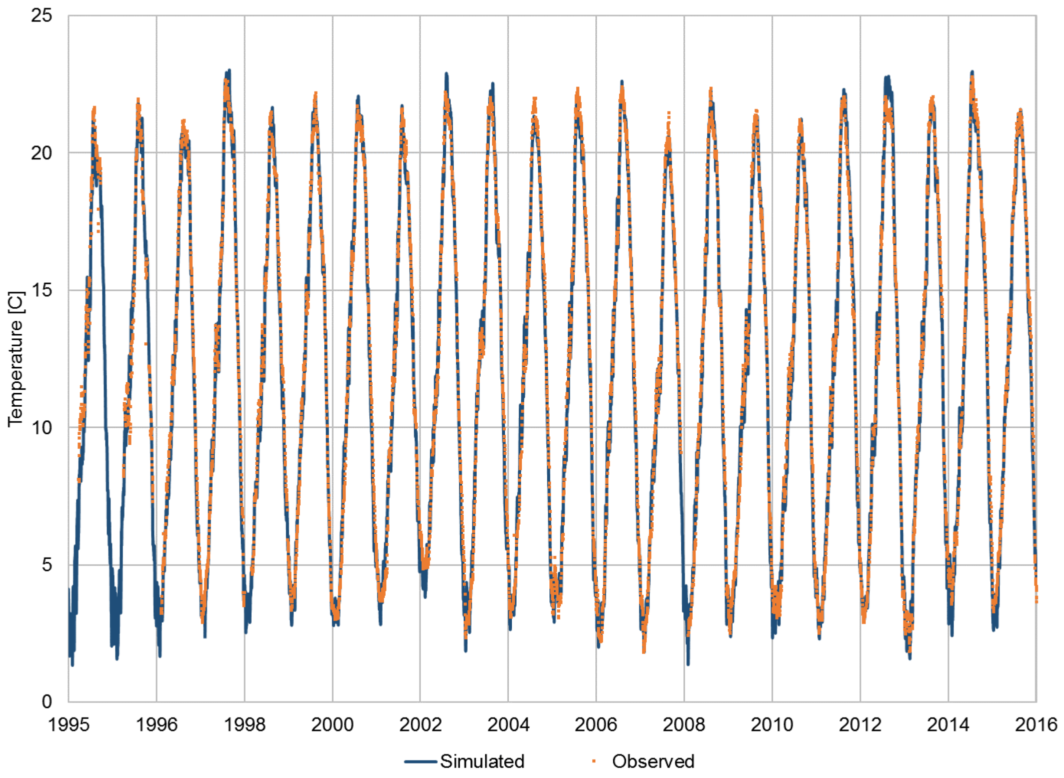

Figure 3-33 Simulated versus observed temperature at IDSW, Snake River RM 6.8

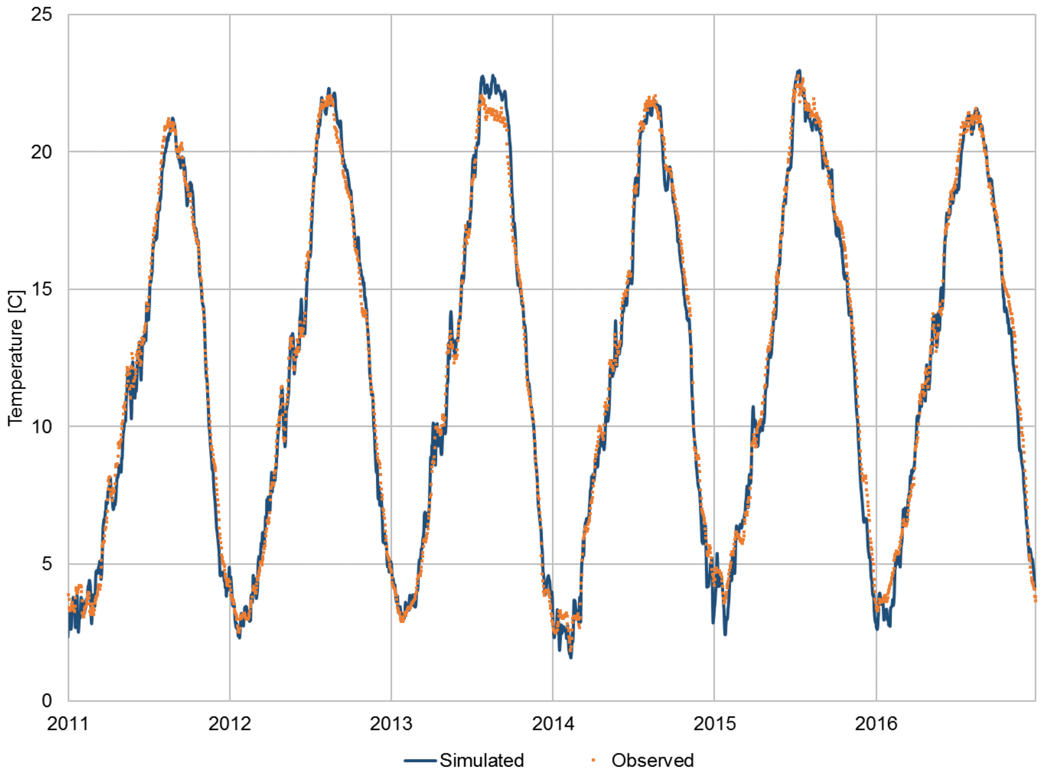

Figure 3-34 Simulated versus observed temperature at IDSW, period 2011 – 2016

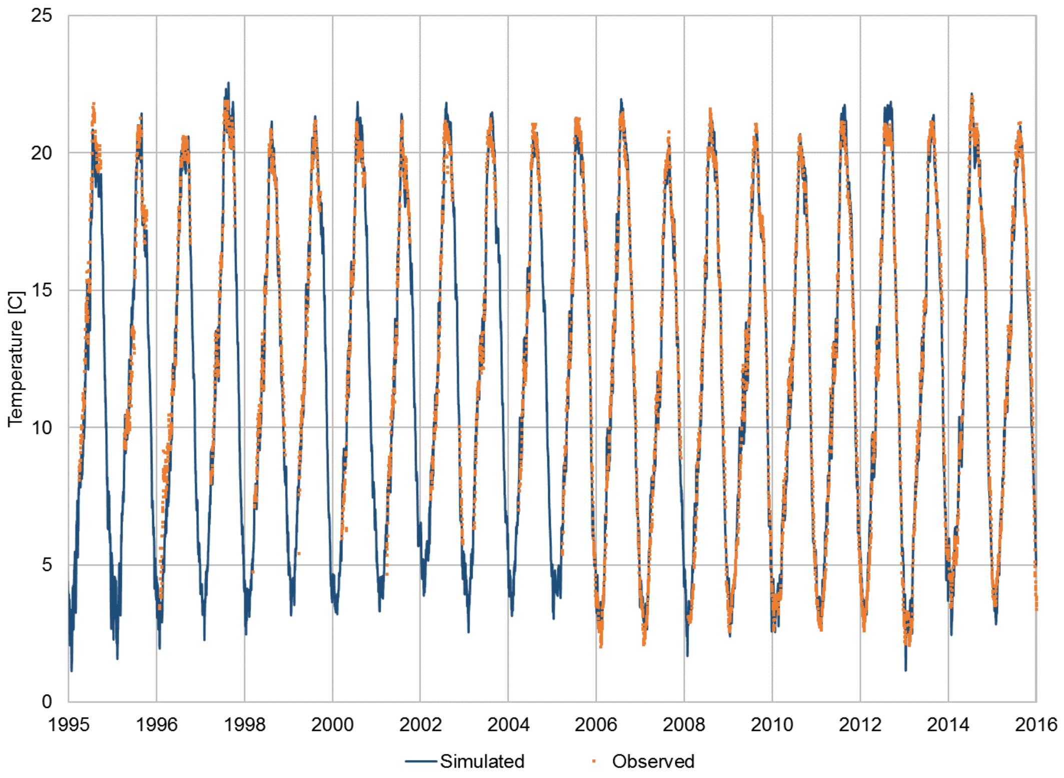

Figure 3-35 Simulated versus observed temperature at LMNW, Snake River RM 40.8

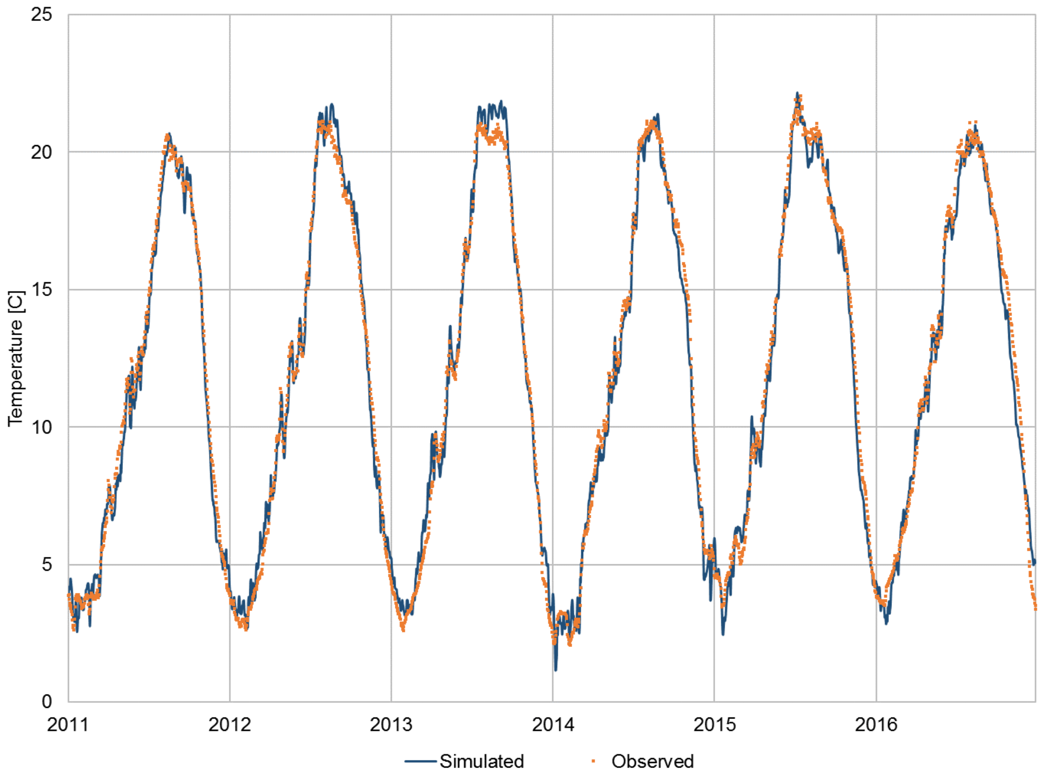

Figure 3-36 Simulated versus observed temperature at LMNW, period 2011 – 2016

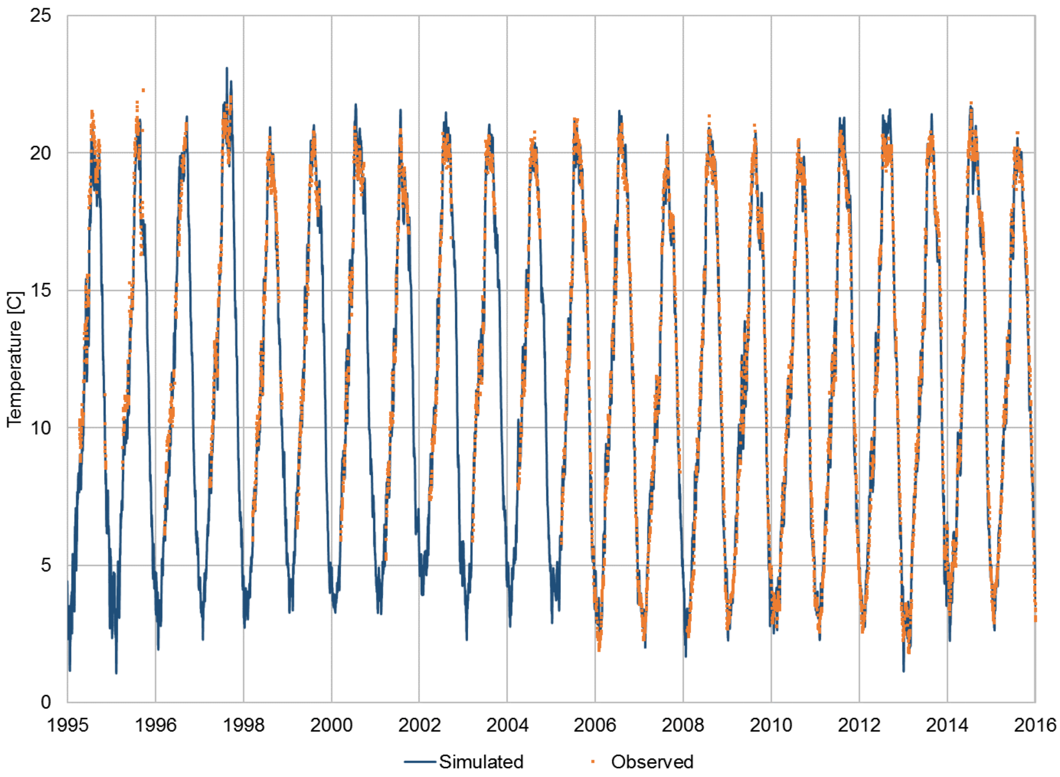

Figure 3-37 Simulated versus observed temperature at LGSW, Snake River RM 69.5

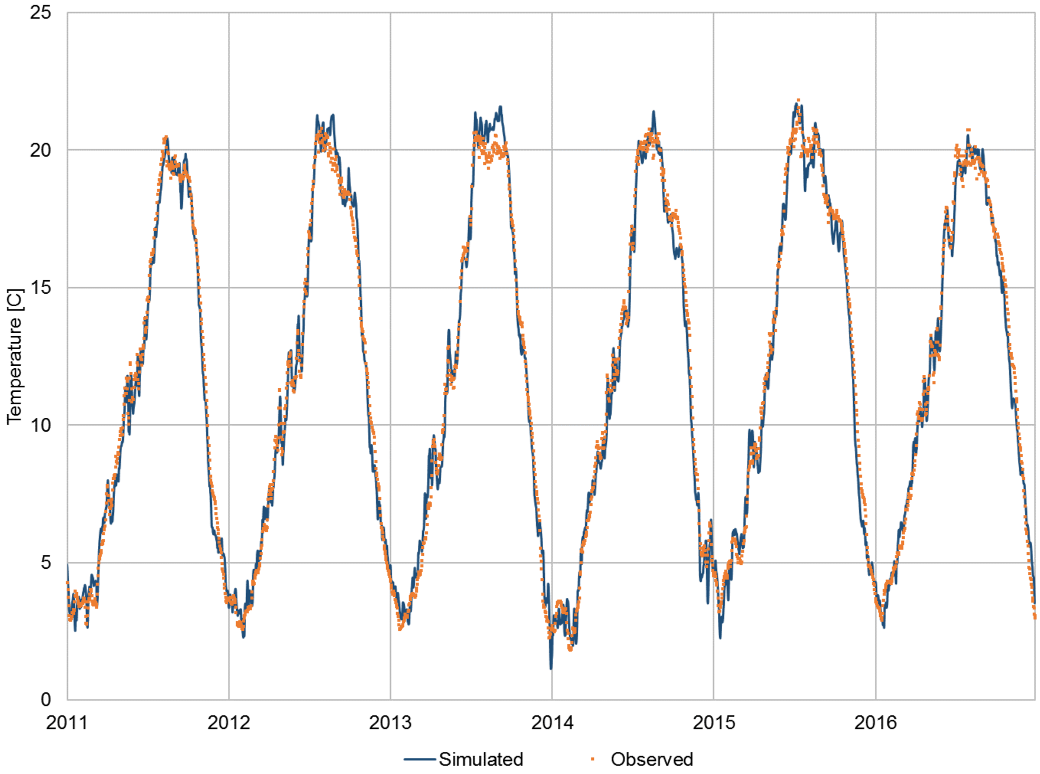

Figure 3-38 Simulated versus observed temperature at LGSW, period 2011 – 2016

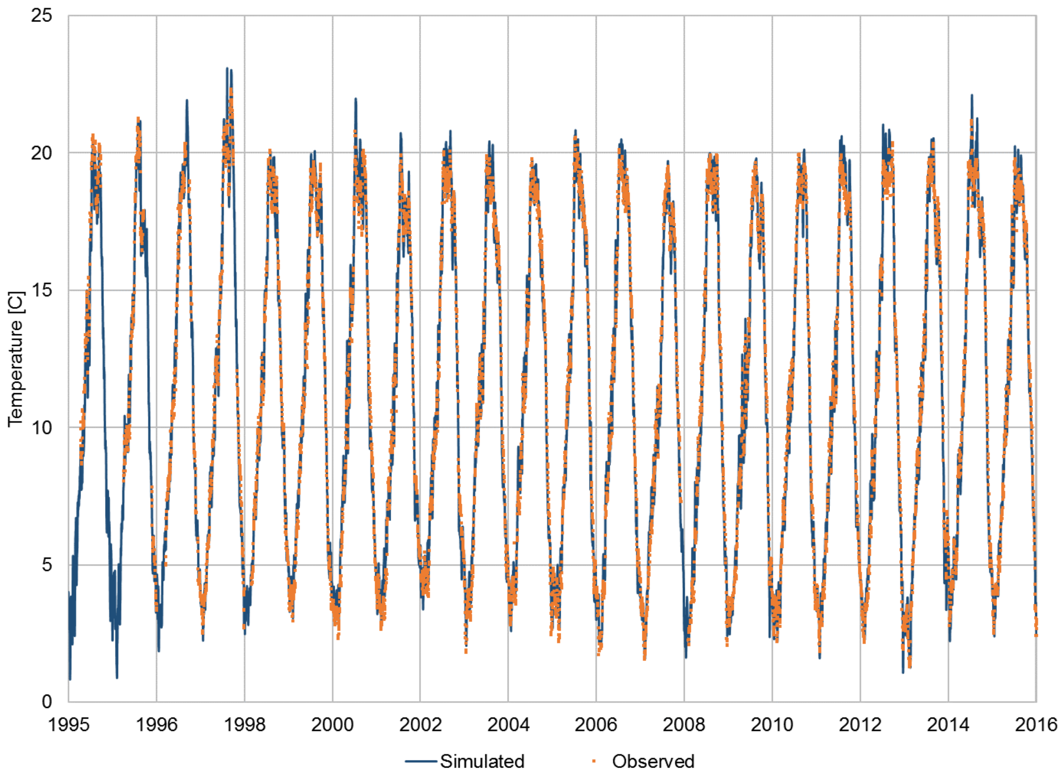

Figure 3-39 Simulated versus observed temperature at LGNW, Snake River RM 106.8

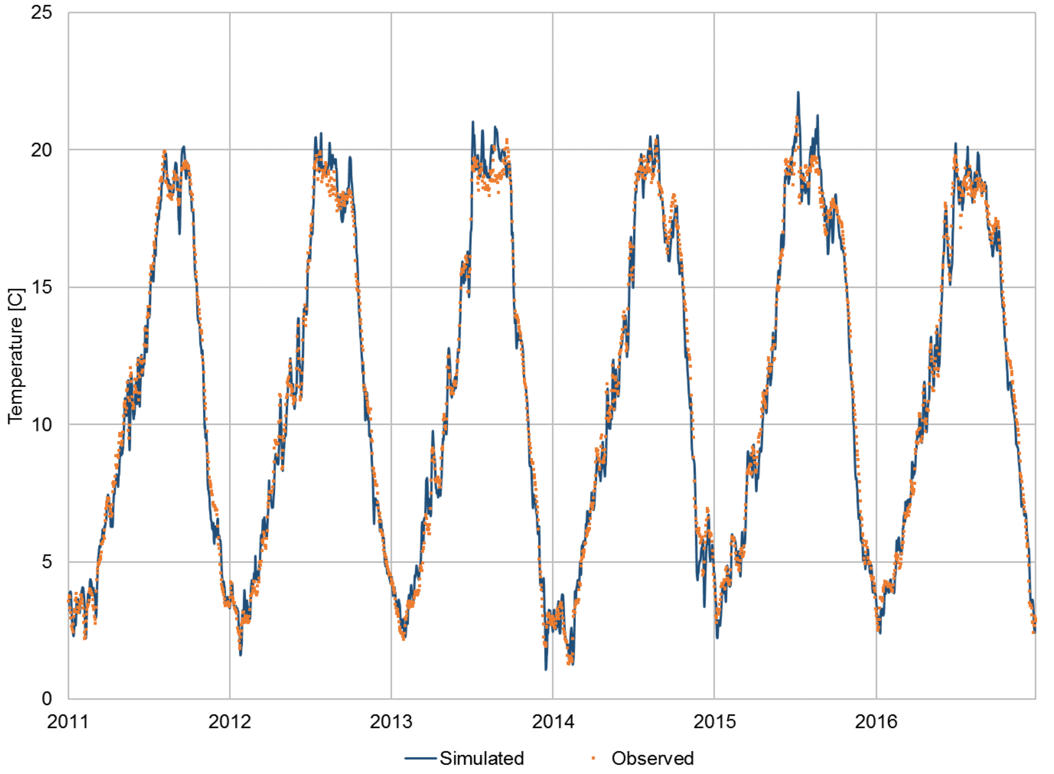

Figure 3-40 Simulated versus observed temperature at LGNW, period 2011 – 2016

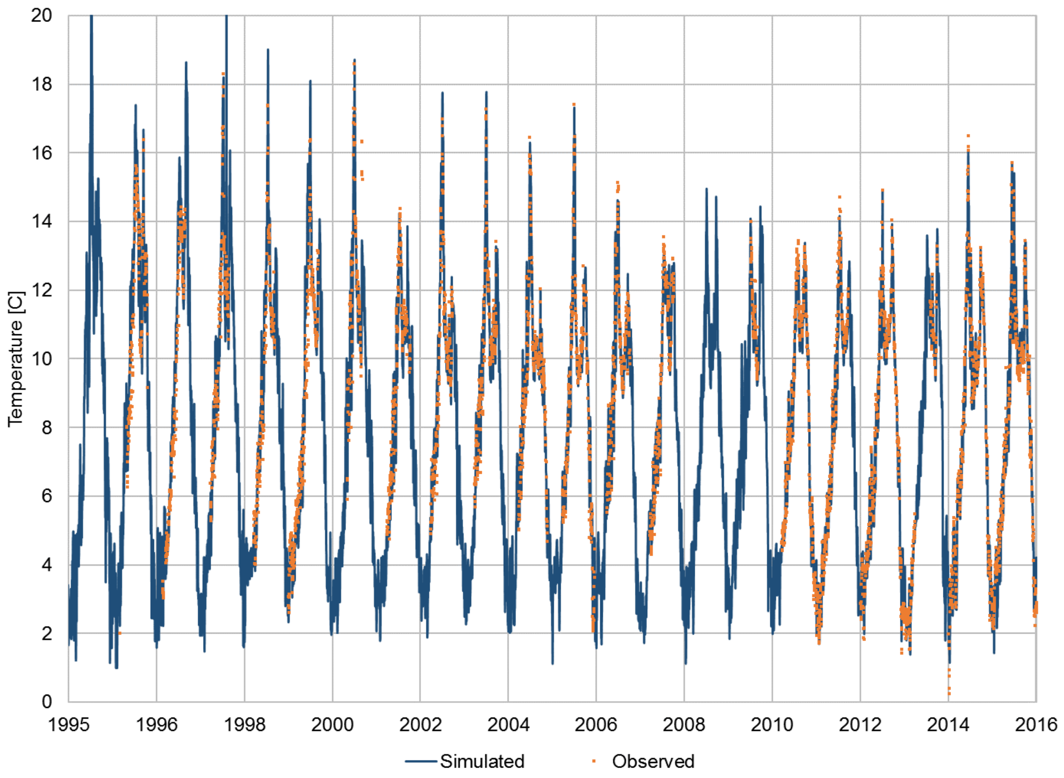

Figure 3-41 Simulated versus observed temperature at PEKI, Clearwater River RM 33

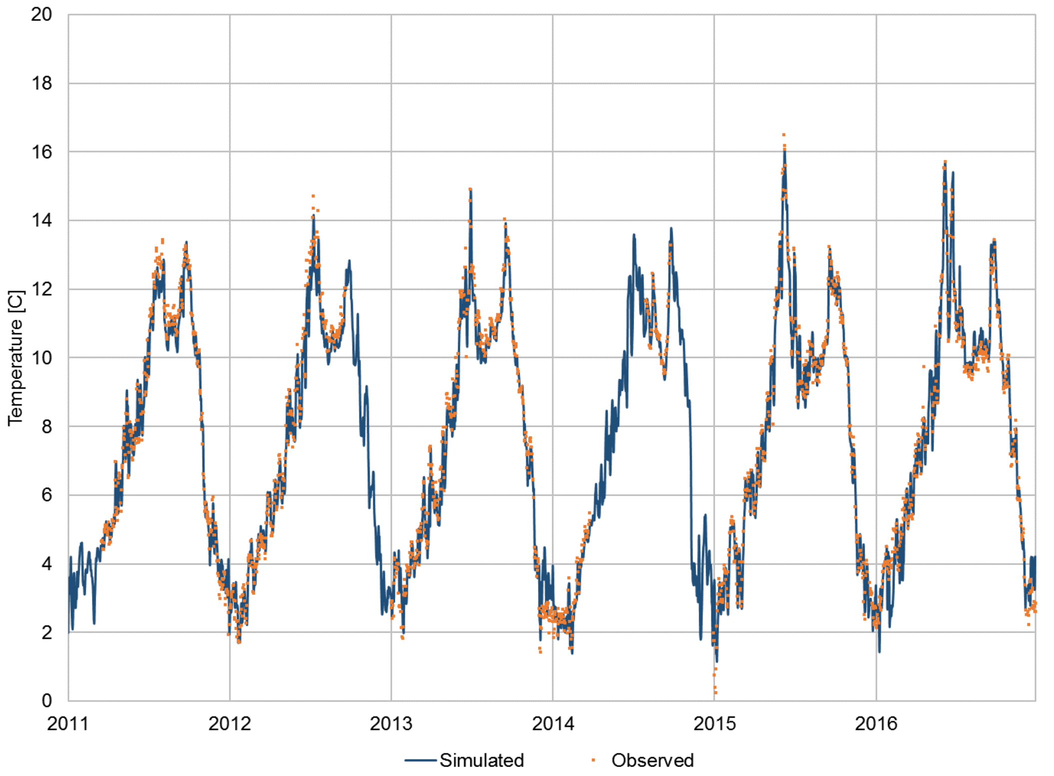

Figure 3-42 Simulated versus observed temperature at PEKI, period 2011 – 2016

3.5 10-Year Daily Average Temperature Comparisons

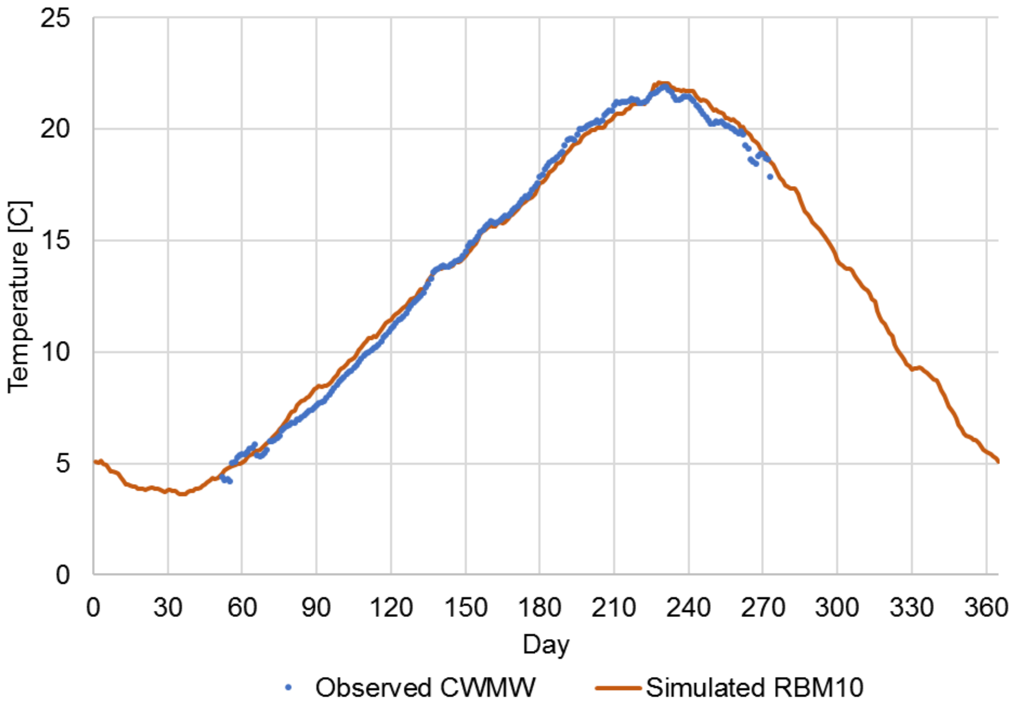

Figure 3-43 10-year daily average temperature comparison at CWMW

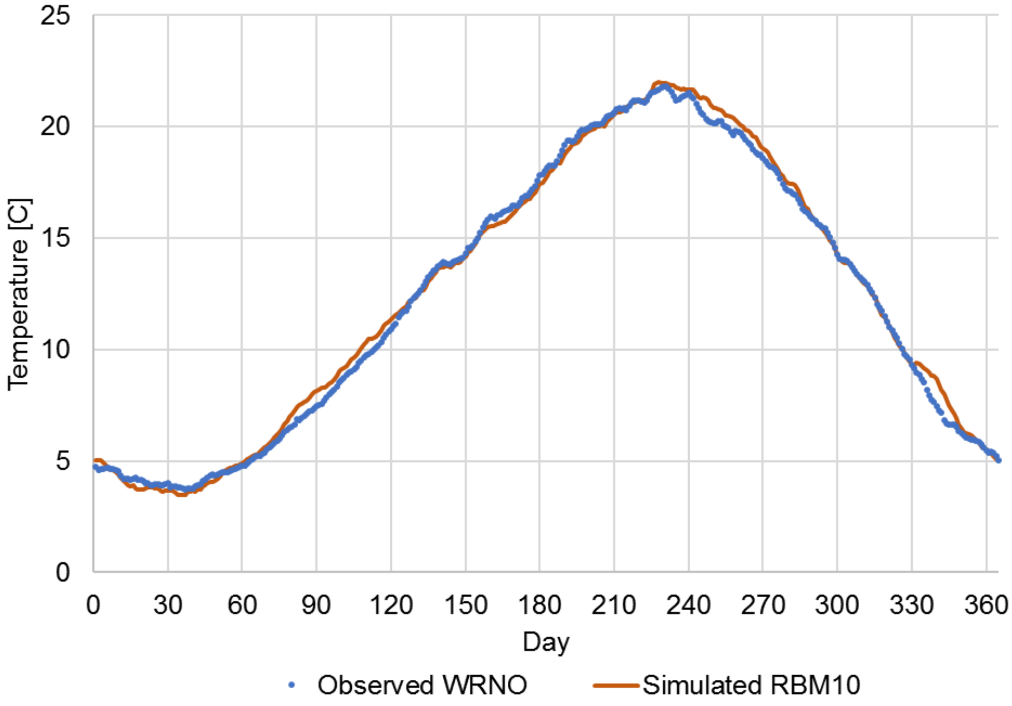

Figure 3-44 10-year daily average temperature comparison at WRNO

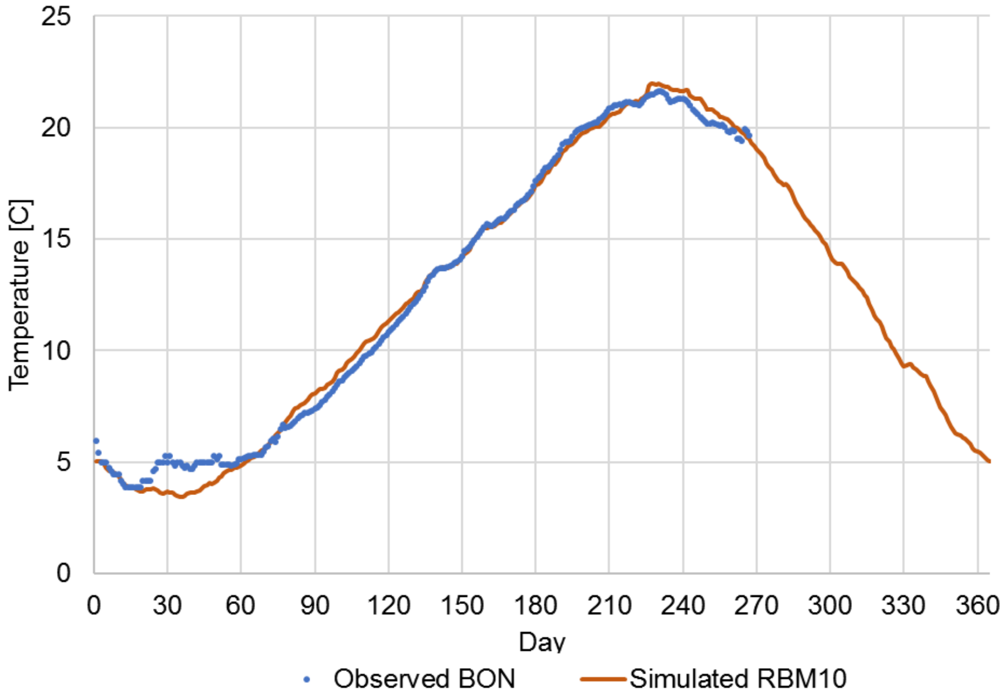

Figure 3-45 10-year daily average temperature comparison at BON

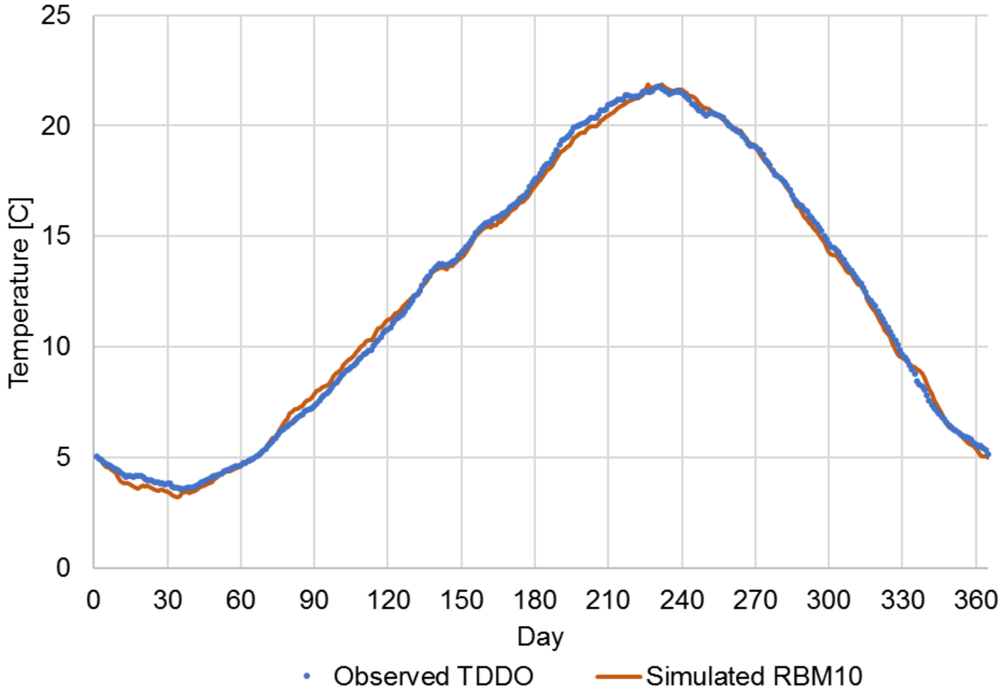

Figure 3-46 10-year daily average temperature comparison at TDDO

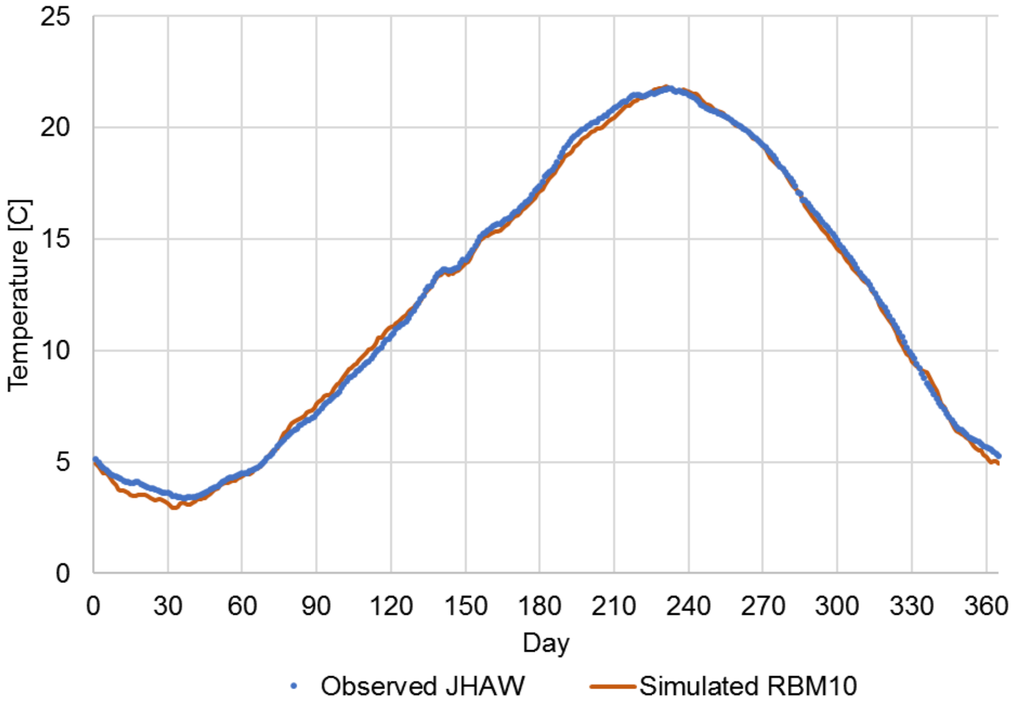

Figure 3-47 10-year daily average temperature comparison at JHAW

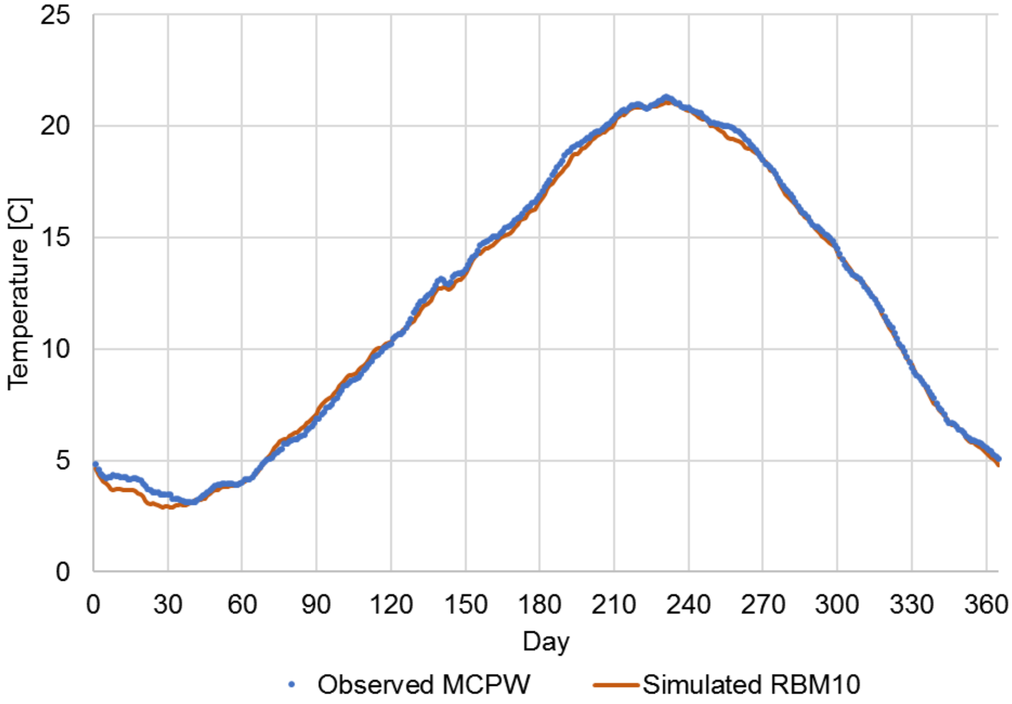

Figure 3-48 10-year daily average temperature comparison at MCPW

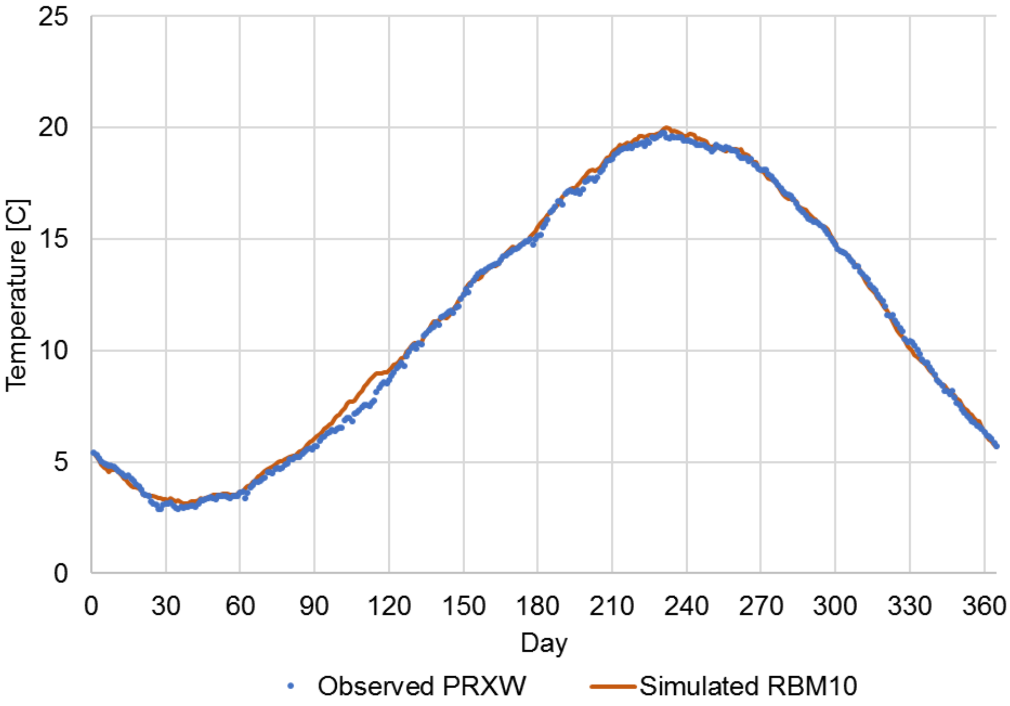

Figure 3-49 10-year daily average temperature comparison at PRXW

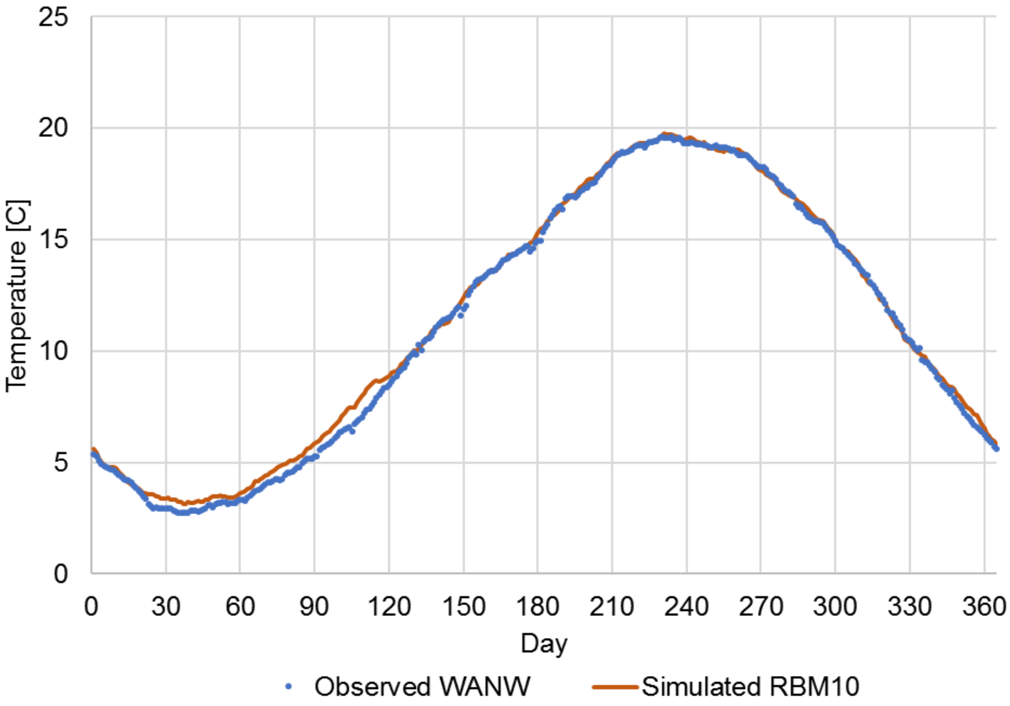

Figure 3-50 10-year daily average temperature comparison at WANW

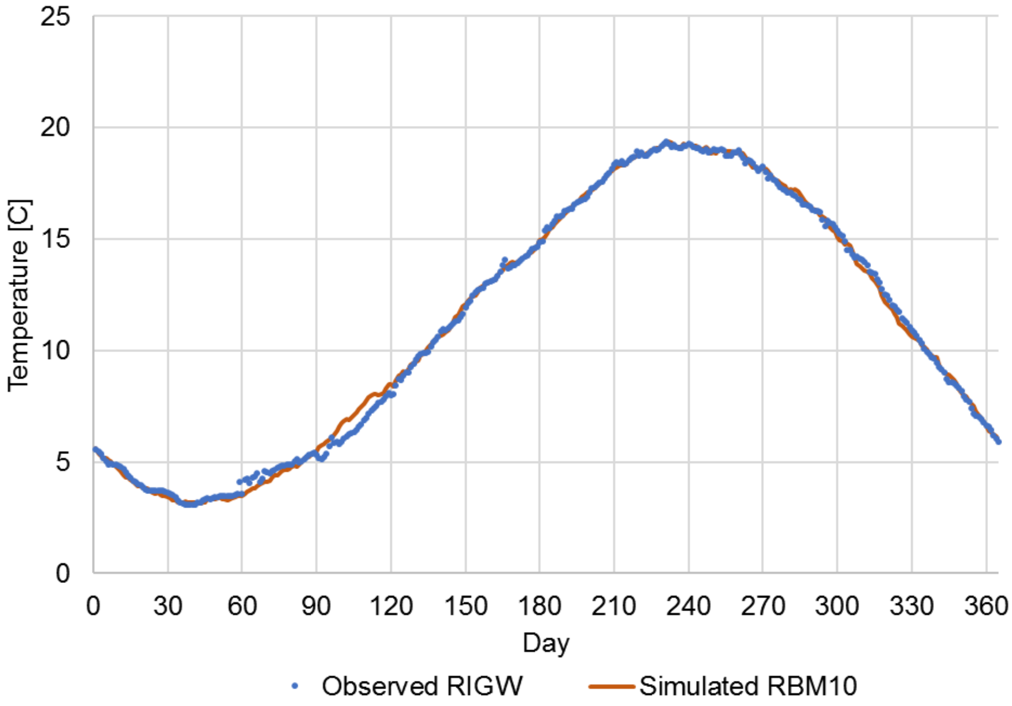

Figure 3-51 10-year daily average temperature comparison at RIGW

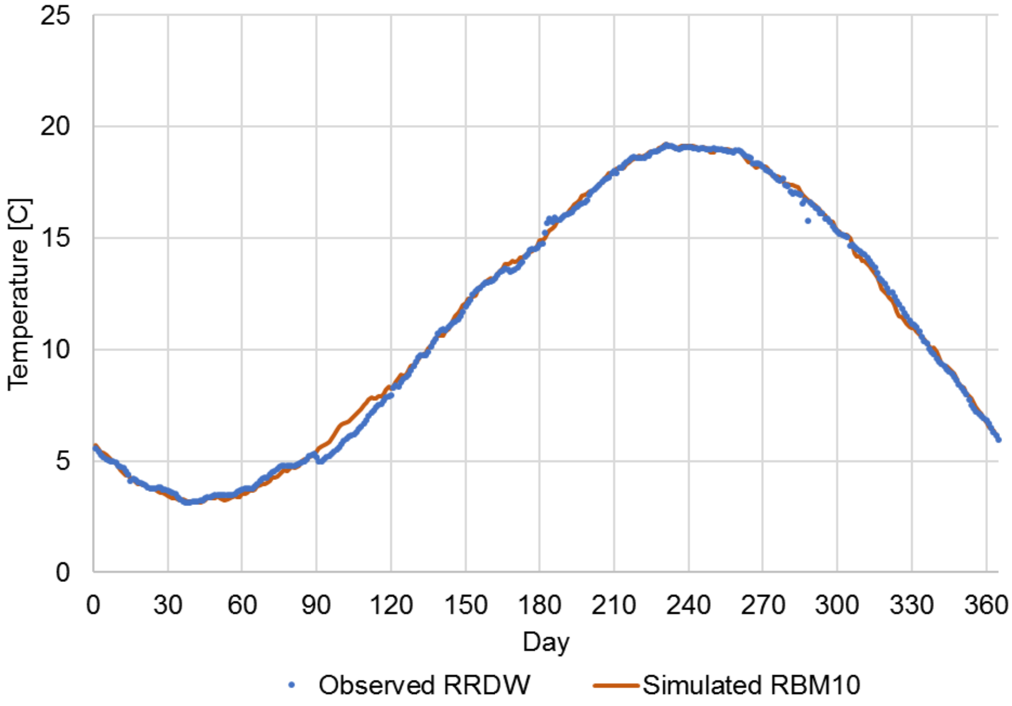

Figure 3-52 10-year daily average temperature comparison at RRDW

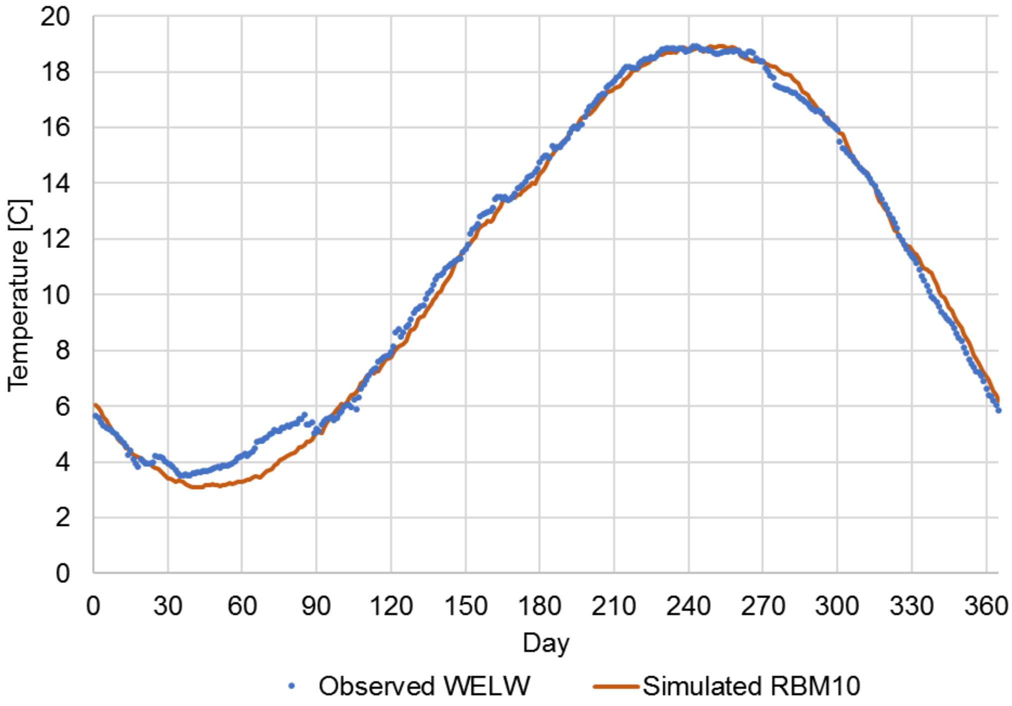

Figure 3-53 10-year daily average temperature comparison at WELW

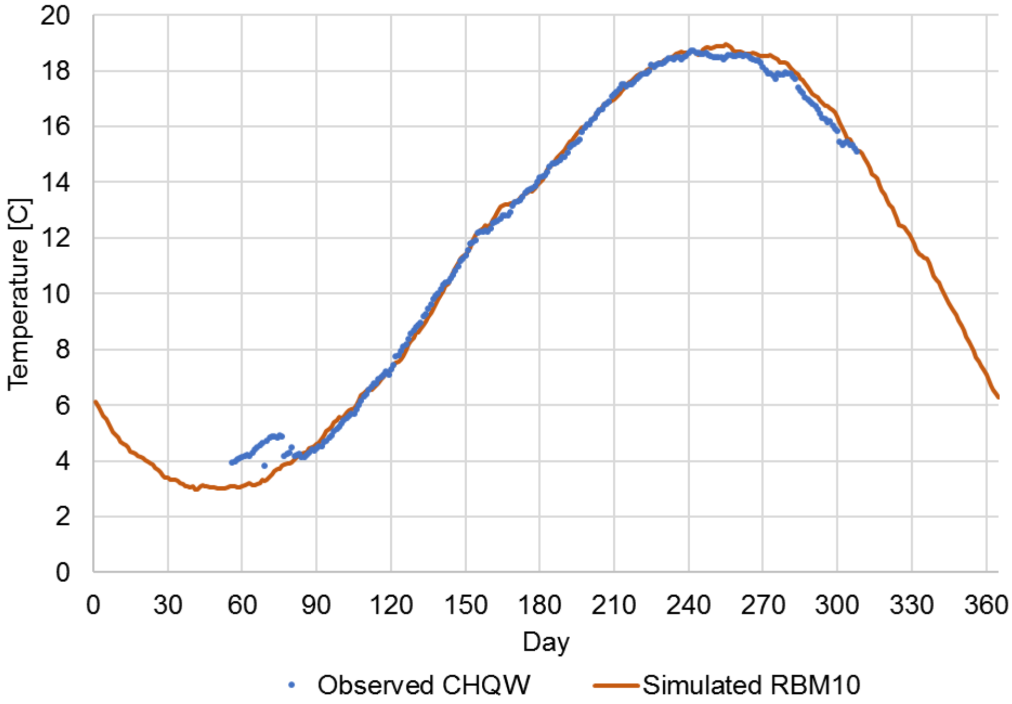

Figure 3-54 10-year daily average temperature comparison at CHQW

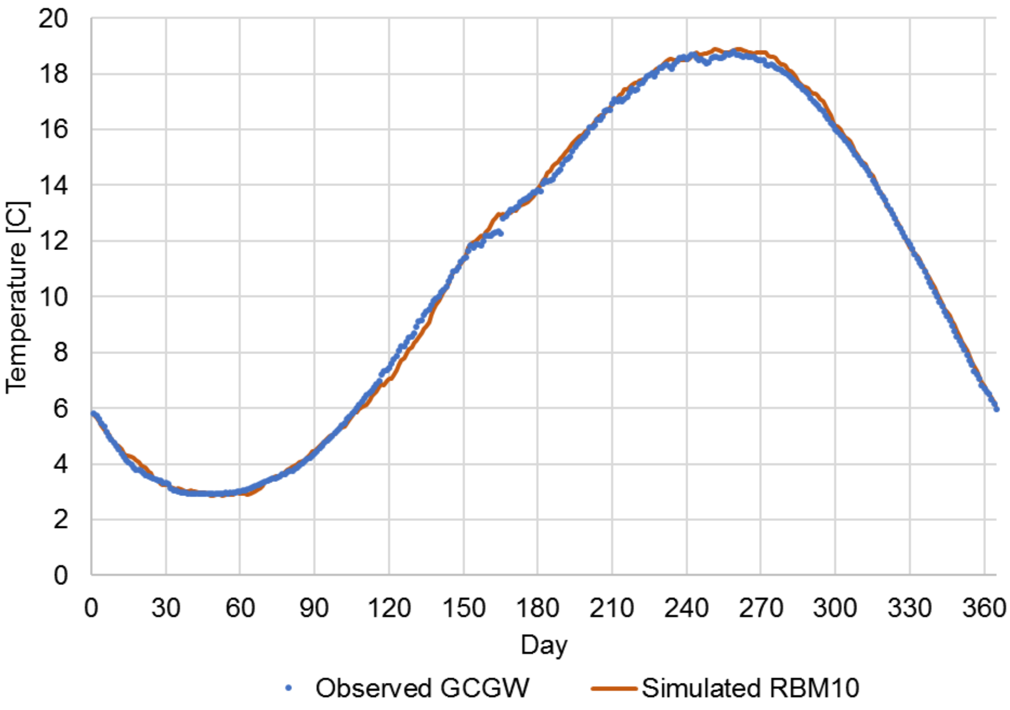

Figure 3-55 10-year daily average temperature comparison at GCGW

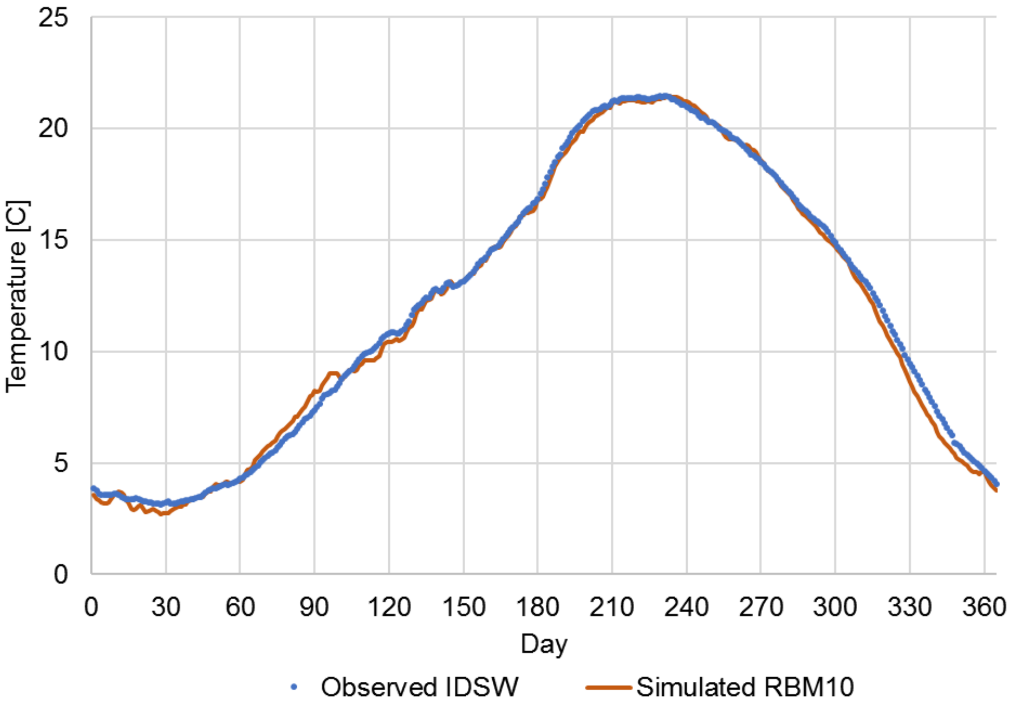

Figure 3-56 10-year daily average temperature comparison at IDSW

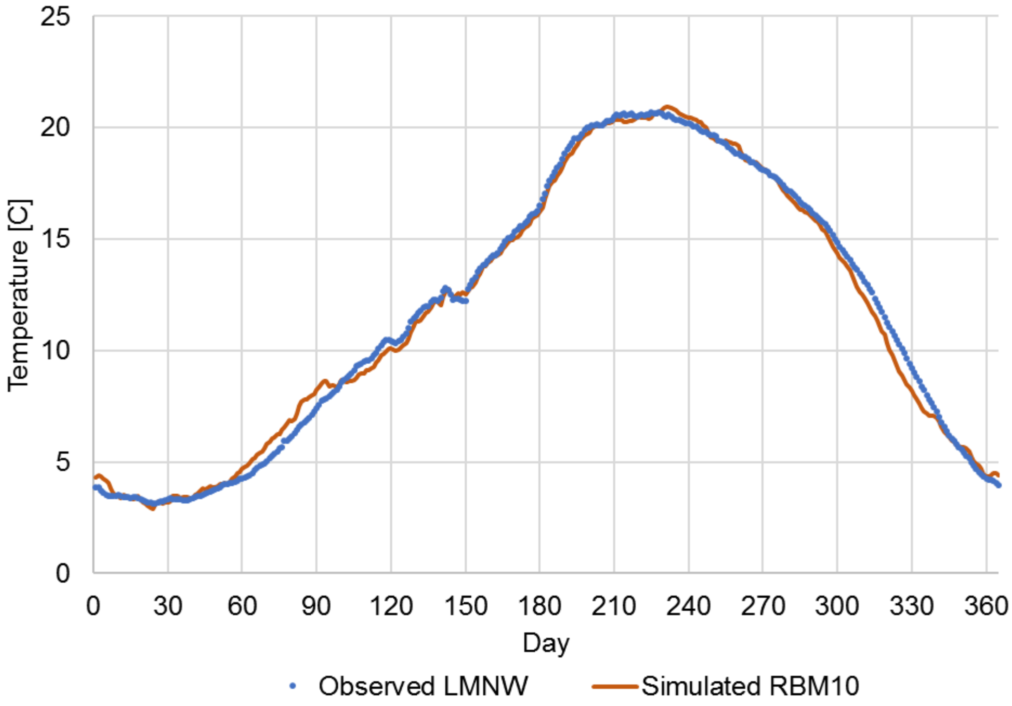

Figure 3-57 10-year daily average temperature comparison at LMNW

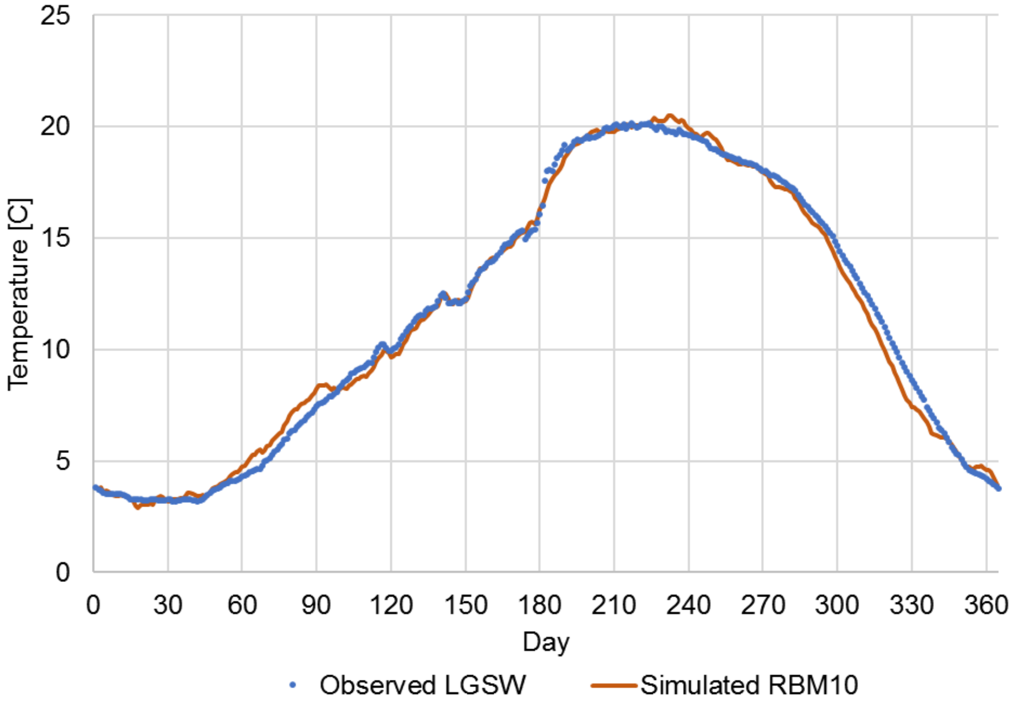

Figure 3-58 10-year daily average temperature comparison at LGSW

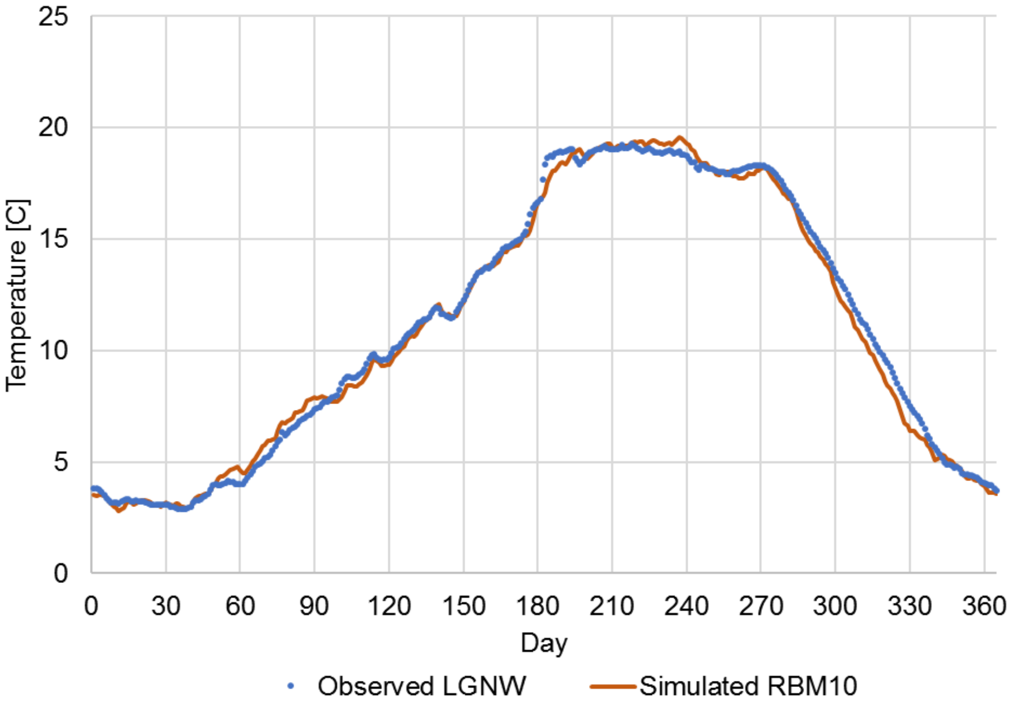

Figure 3-59 10-year daily average temperature comparison at LGNW

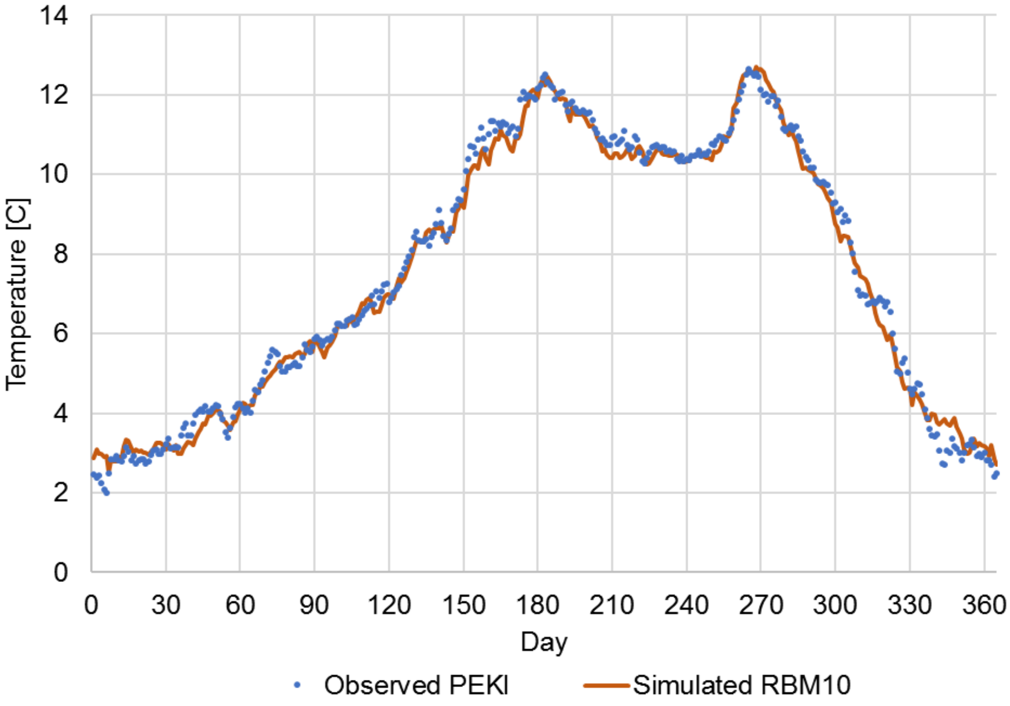

Figure 3-60 10-year daily average temperature comparison at PEKI

4.0 Alternative Columbia River Boundaries

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

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

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

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

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

5.0 Sensitivity Analysis

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

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

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

5.1 Sensitivity Scenarios

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

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

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

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

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

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

Table 5-1 Sensitivity analysis scenarios

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

6.0 Conclusions

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

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

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

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

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

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

7.0 References

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Appendix A Atmospheric, Flow, and Temperature Inputs

A.1 Atmospheric Inputs

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

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

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

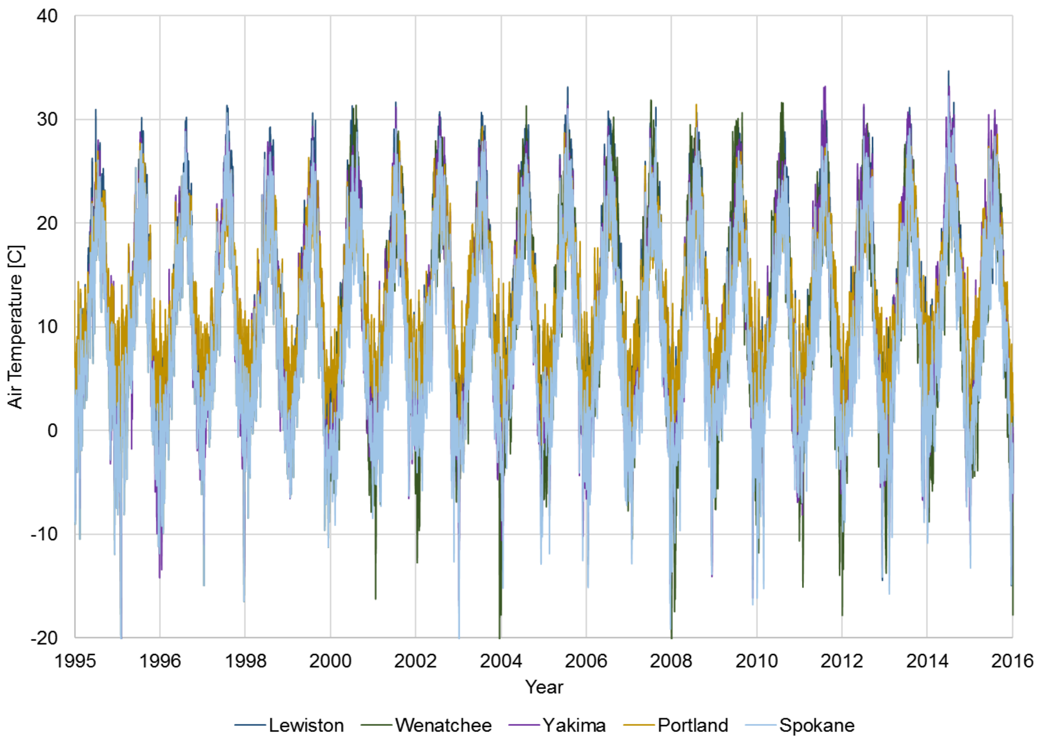


Figure A.1-1 RBM10 air temperature inputs 1995 – 2016 period

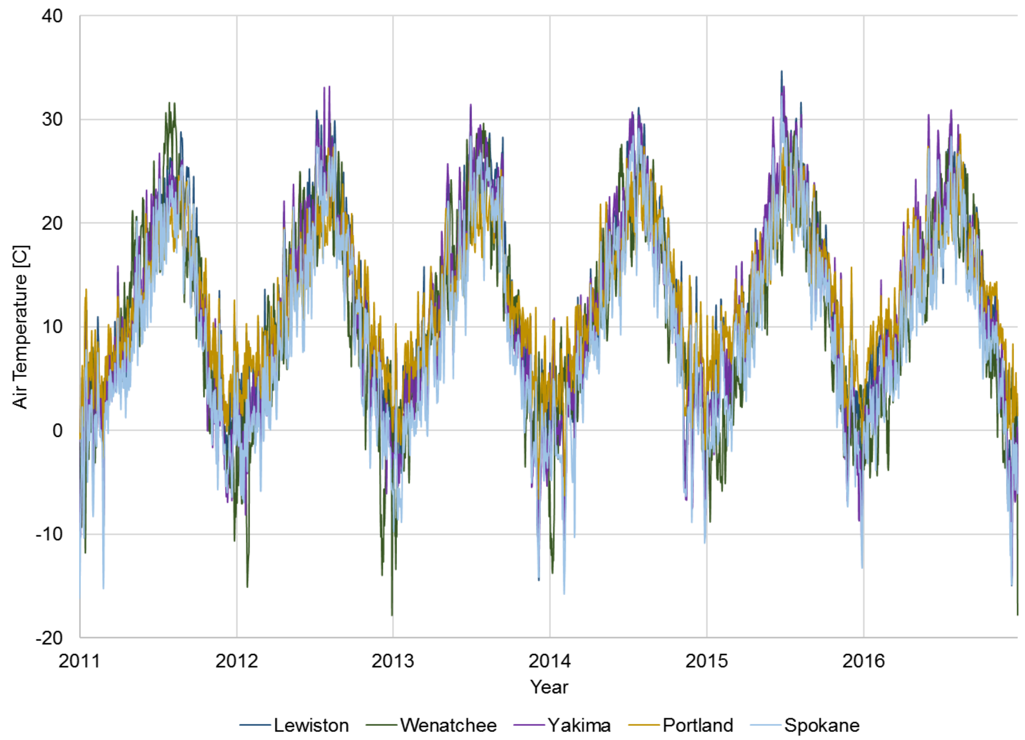


Figure A.1-2 RBM10 air temperature inputs 2011 – 2016 period

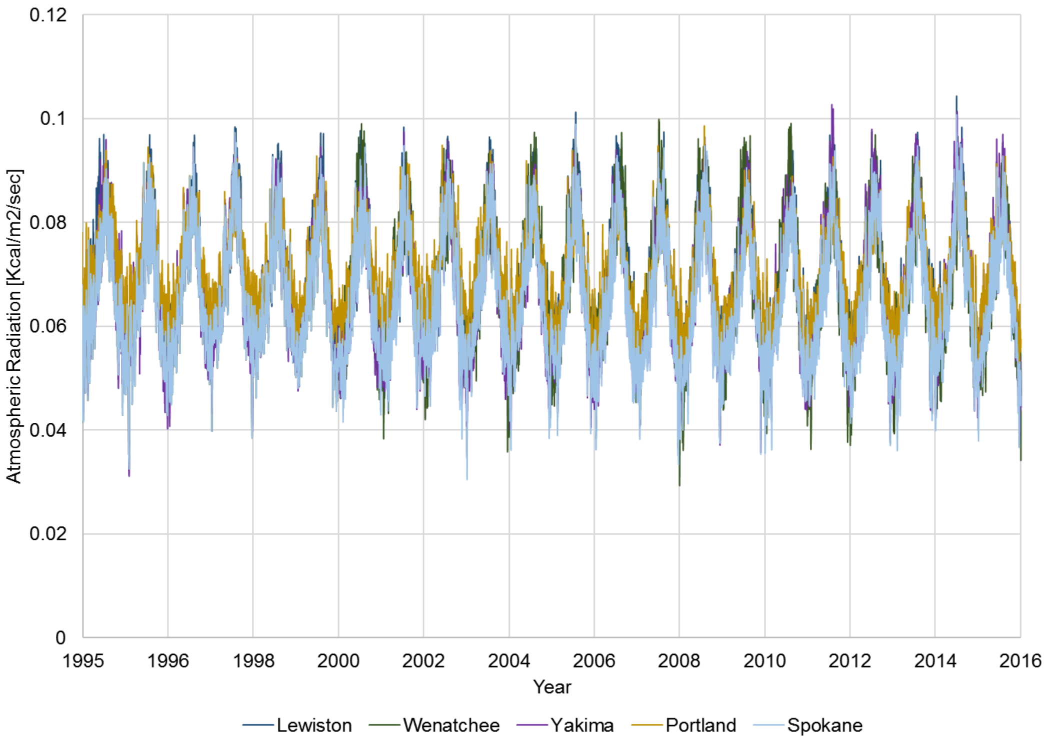


Figure A.1-3 RBM10 atmospheric radiation inputs 1995 – 2016 period

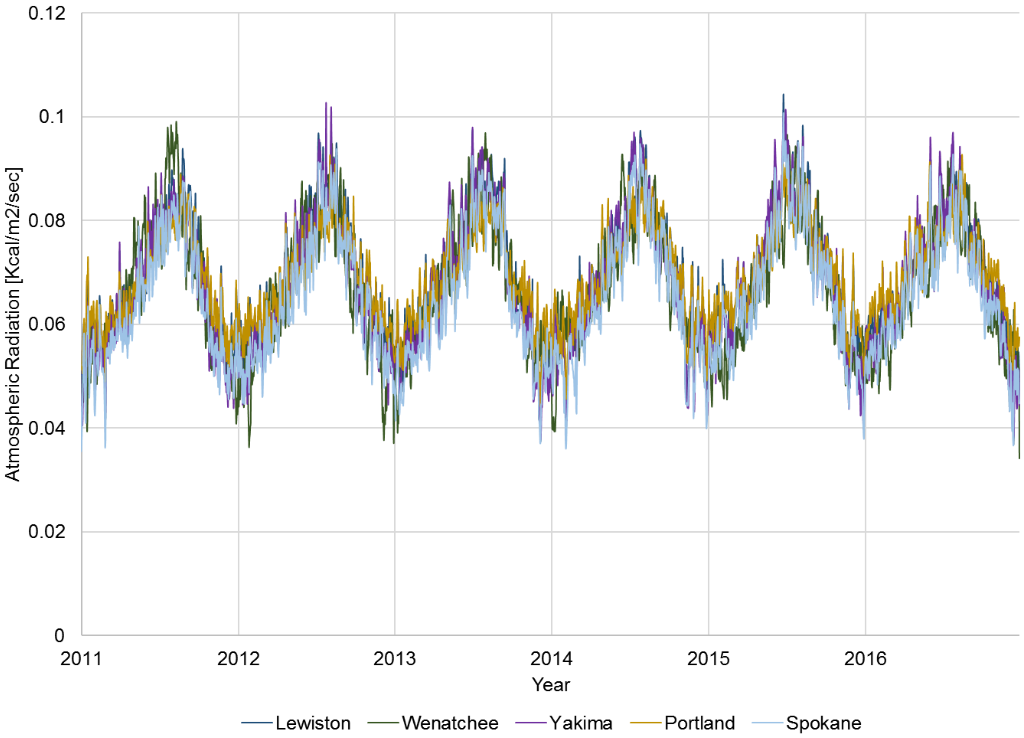


Figure A.1-4 RBM10 atmospheric radiation inputs 2011 – 2016 period

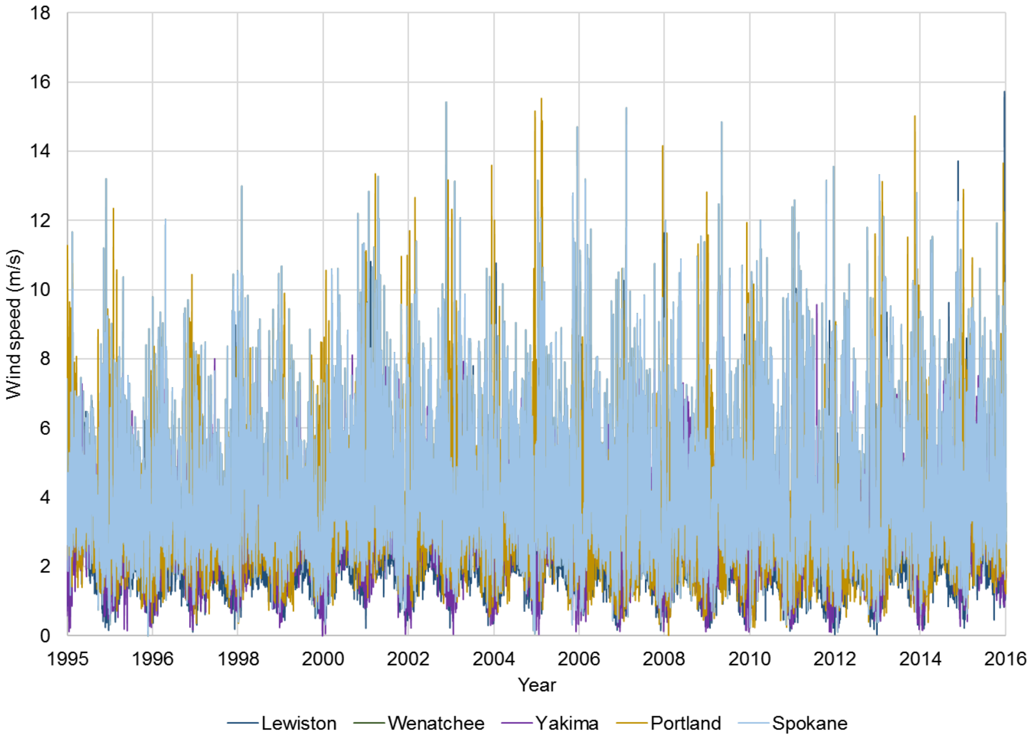


Figure A.1-5 RBM10 wind speed inputs 1995 – 2016 period

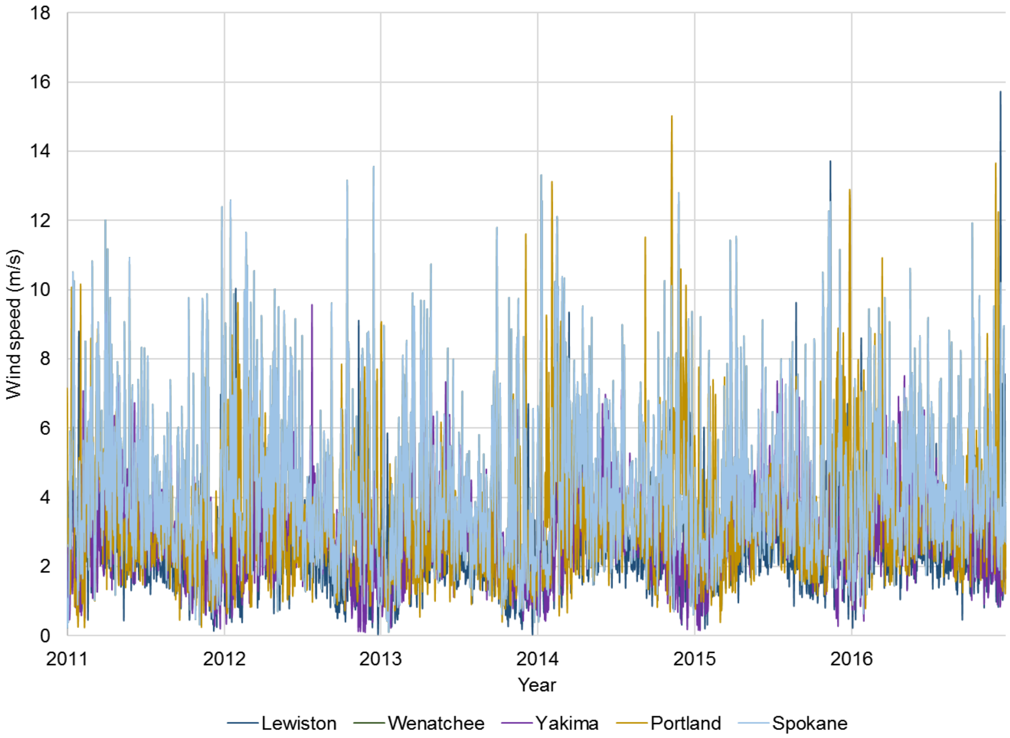


Figure A.1-6 RBM10 wind speed inputs 2011 – 2016 period

A.2 Headwater Flow Boundary Inputs

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

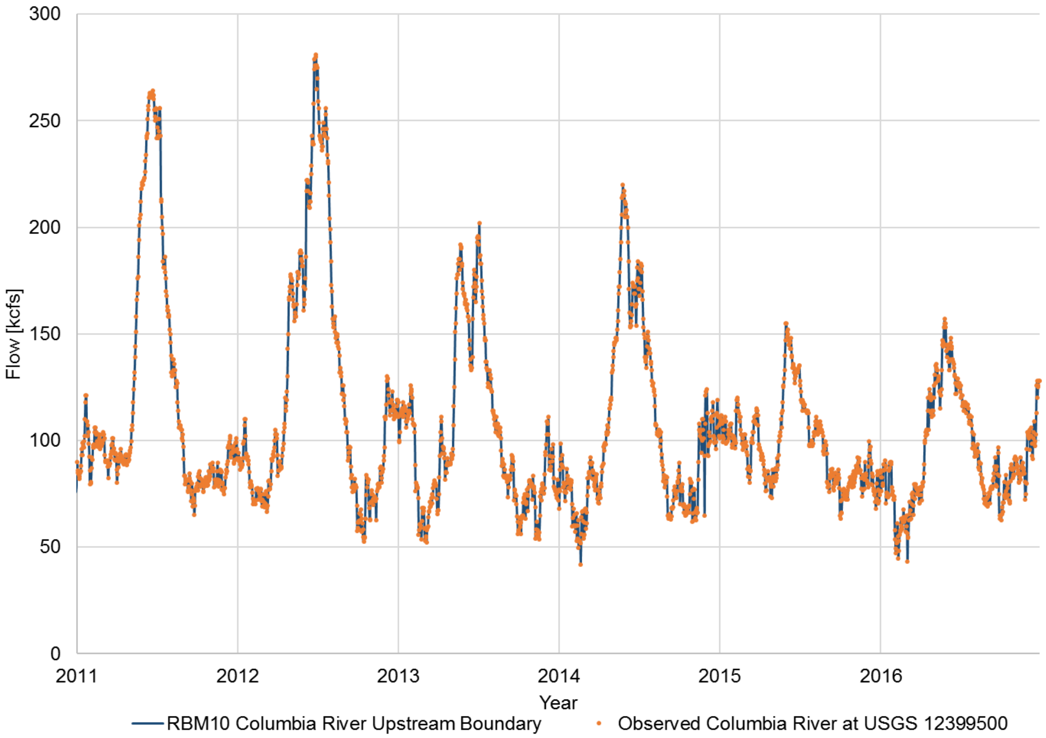


Figure A.2-1 Columbia River upstream boundary flow inputs

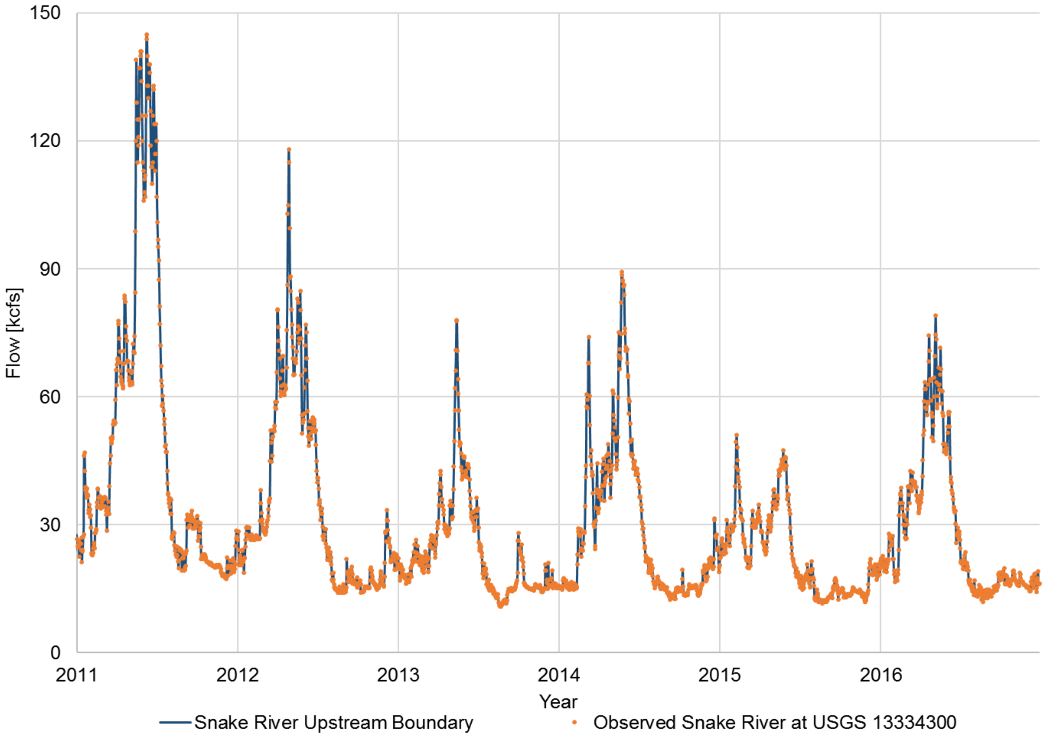


Figure A.2-2 Snake River upstream boundary flow inputs

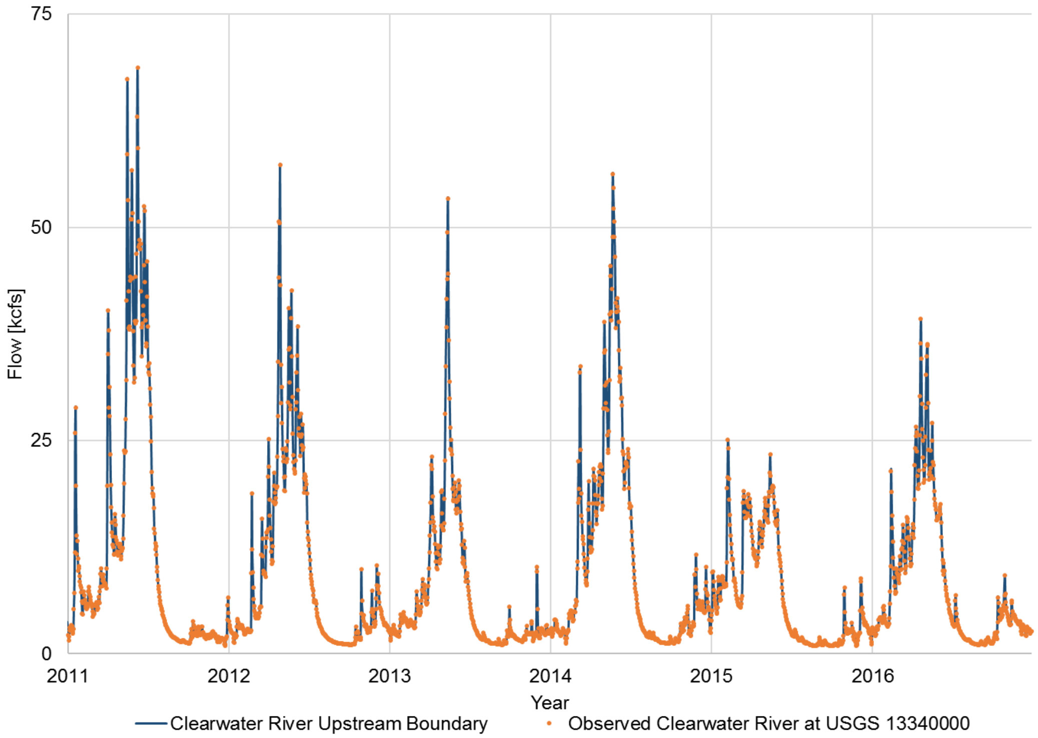


Figure A.2-3 Clearwater River upstream boundary flow inputs

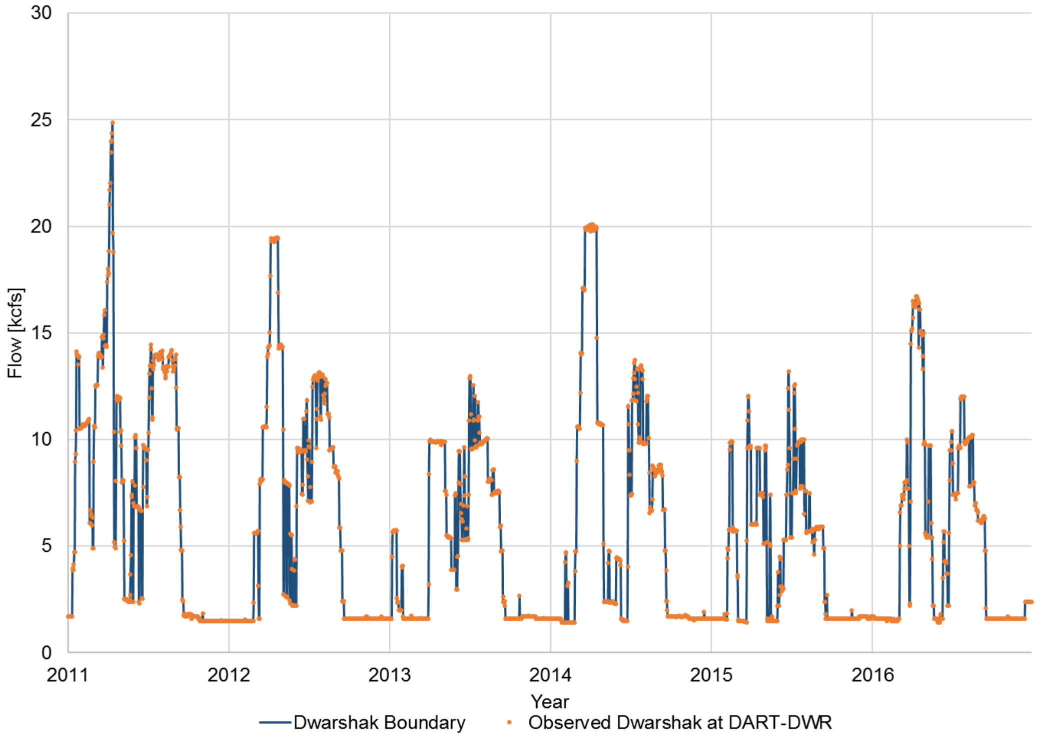


Figure A.2-4 Dworshak Dam boundary flow inputs

A.3 Temperature Boundary Inputs

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

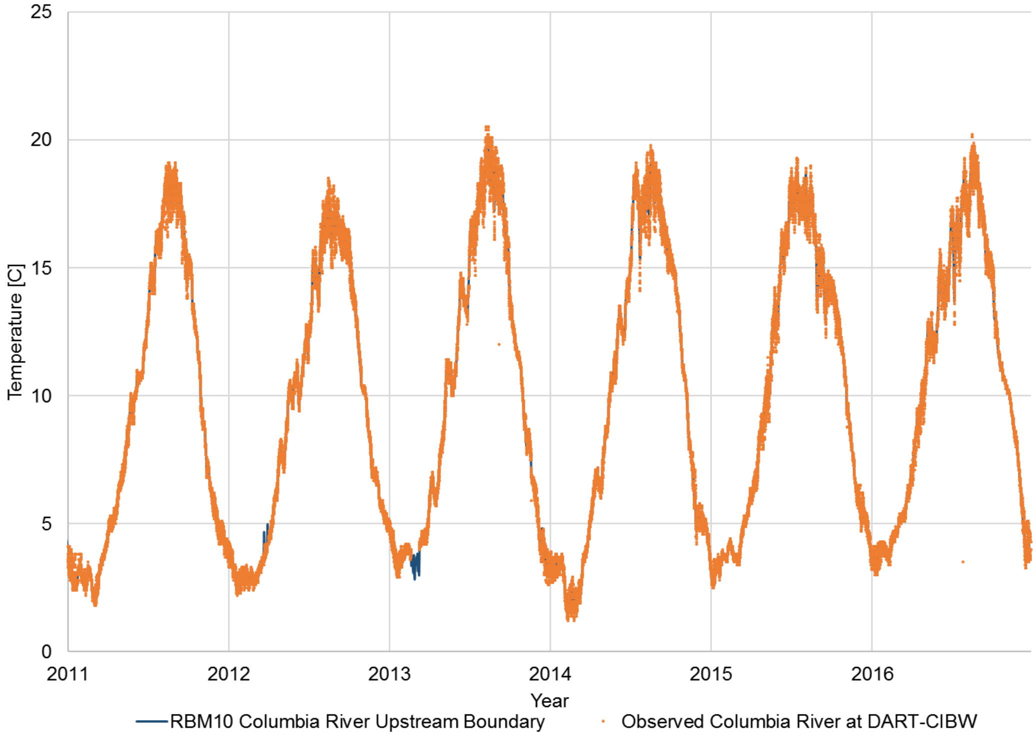


Figure A.3-1 Columbia River upstream boundary temperature inputs

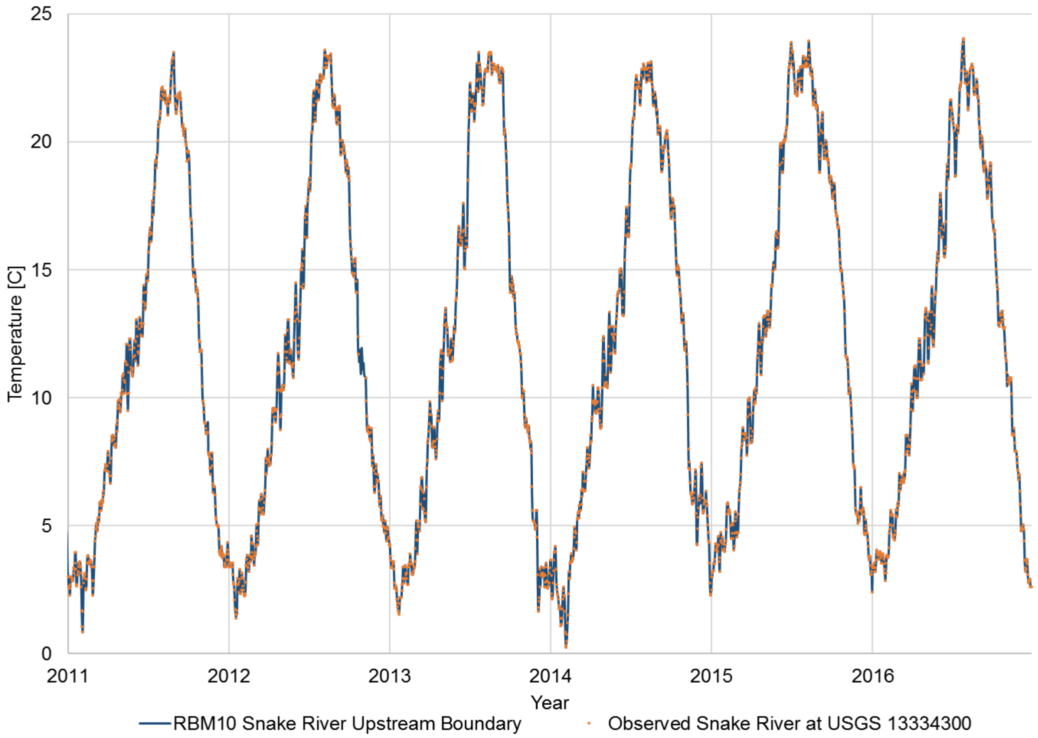


Figure A.3-2 Snake River upstream boundary temperature inputs

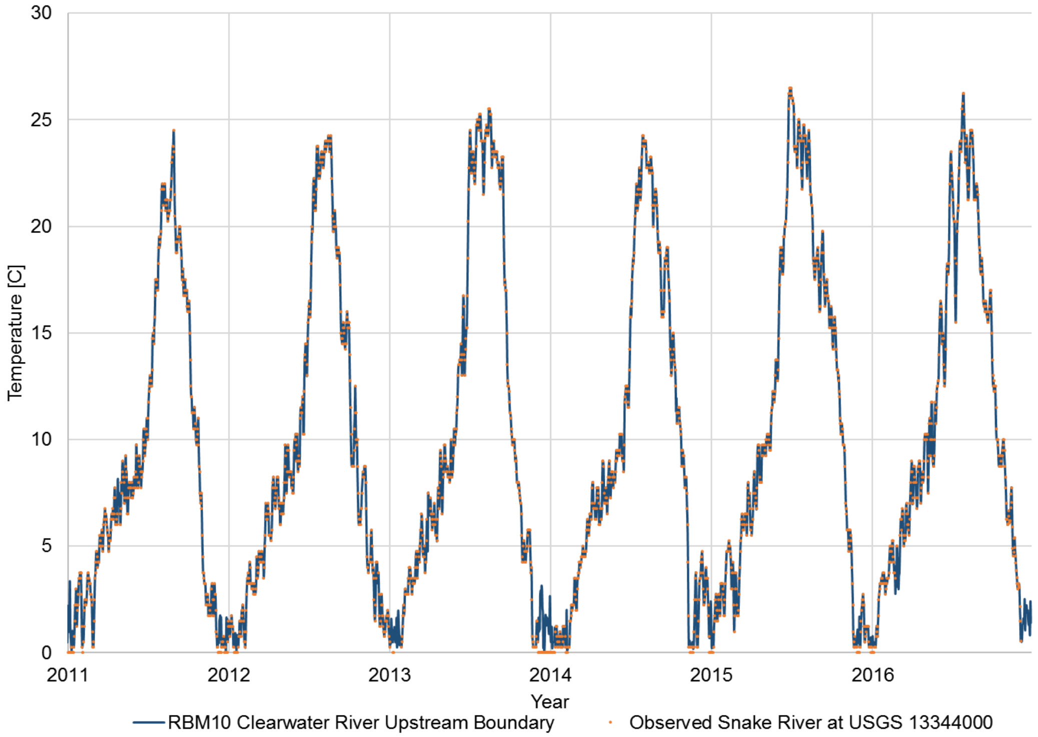


Figure A.3-3 Clearwater River upstream boundary temperature inputs

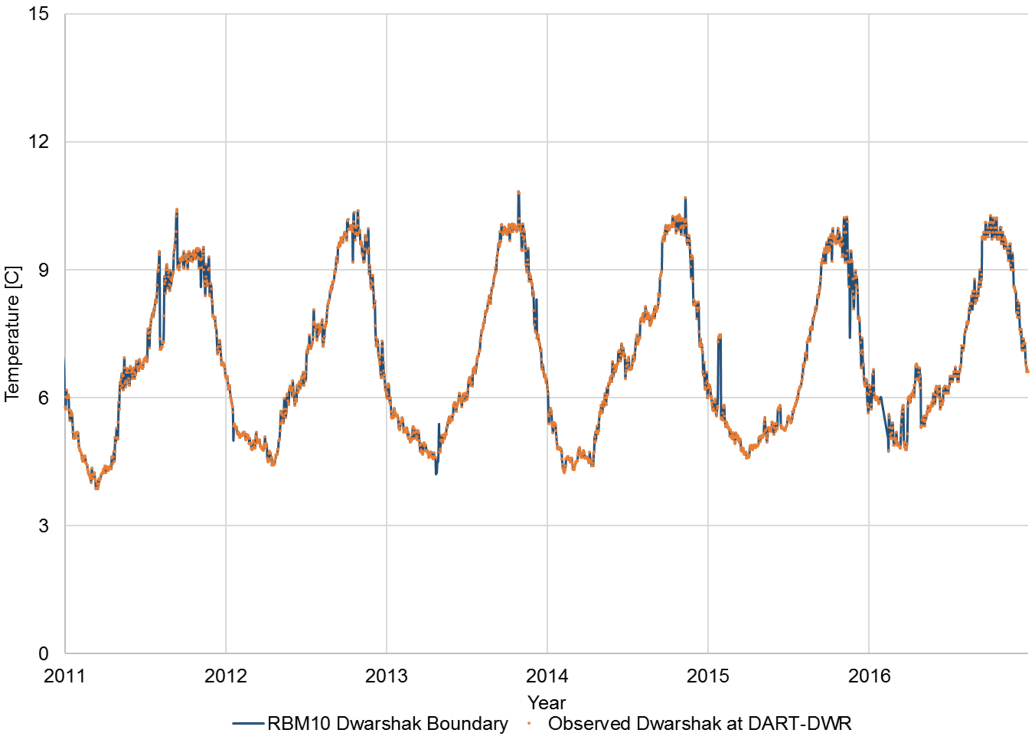


Figure A.3-4 Dworshak Dam boundary temperature inputs

A.4 Data Gap Filling Procedure for Water Temperature Inputs

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

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

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

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

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

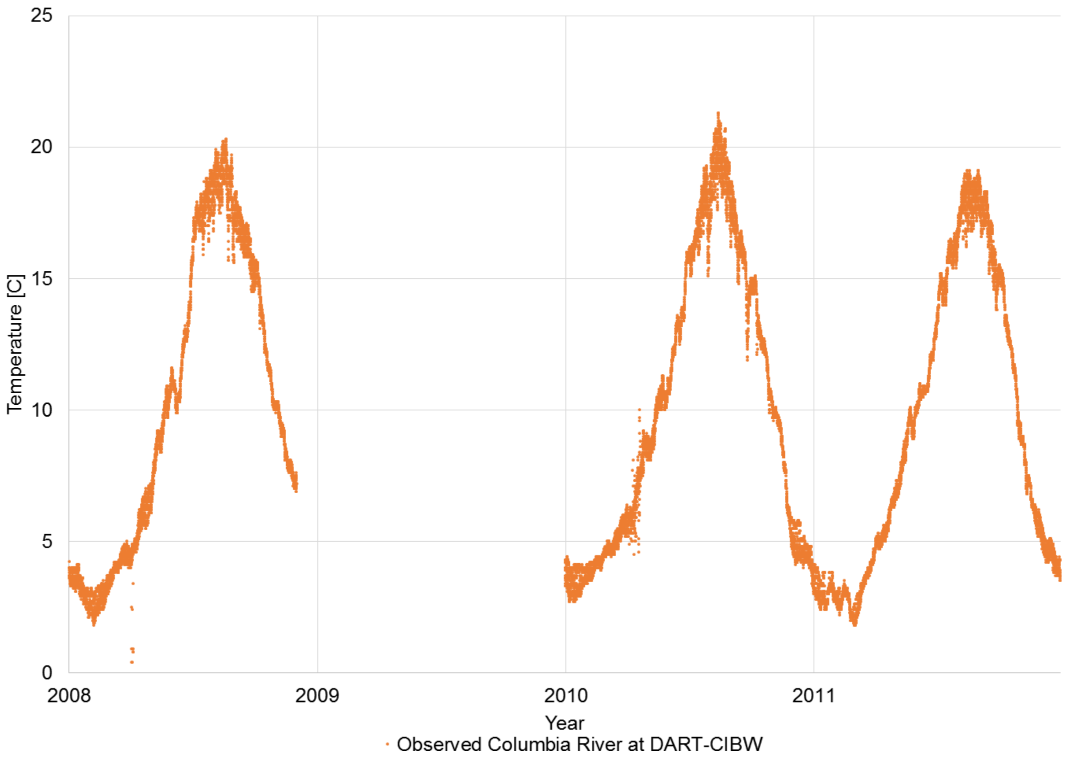


Figure A.4-1 Available water temperature observations at DART-CIBW station (2008 – 2011)

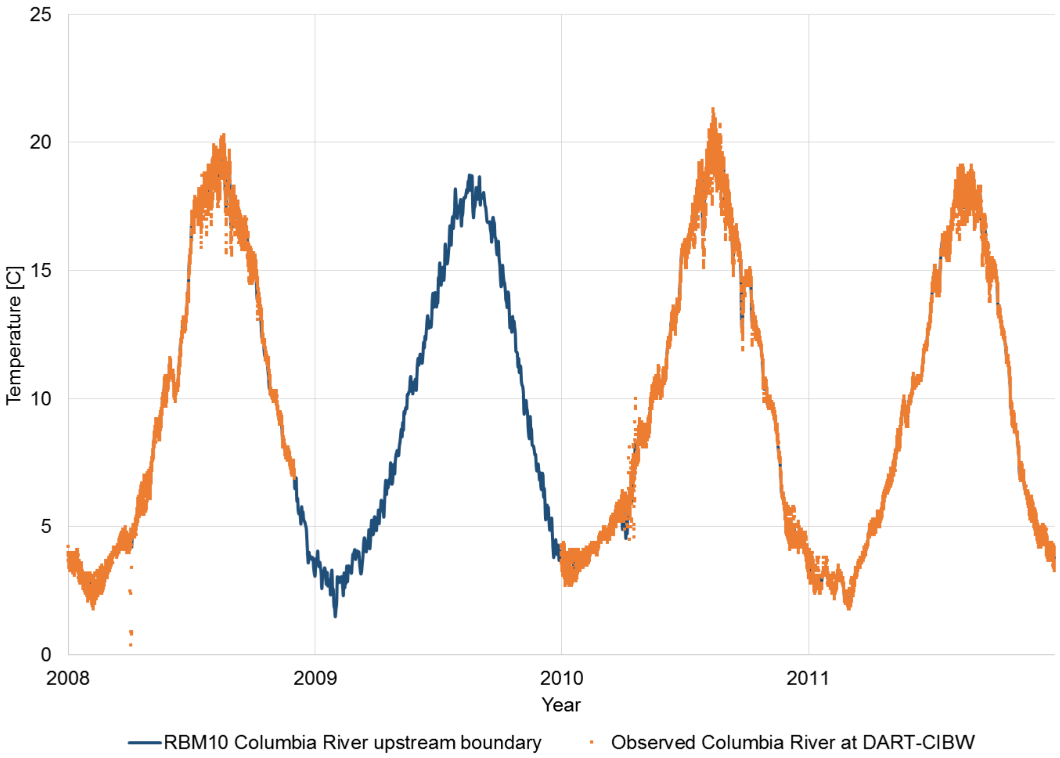


Figure A.4-2 Water temperature boundary conditions at the Columbia River upstream boundary (blue line) from observations available at DART-CIBW station (2008 – 2011)

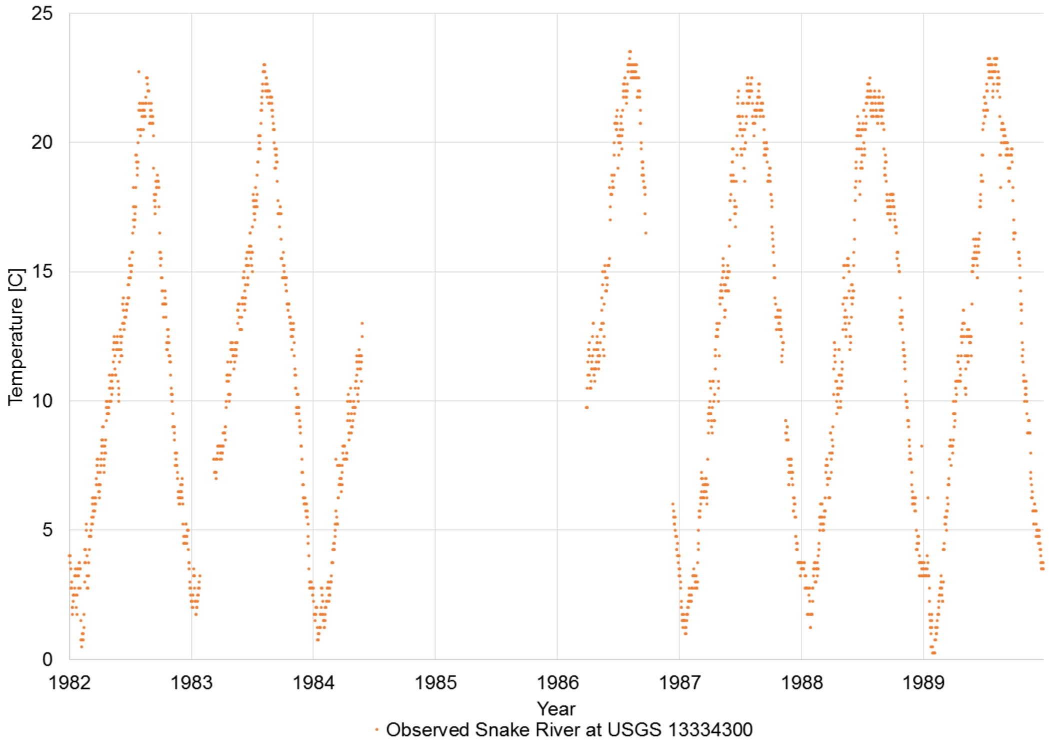


Figure A.4-3 Available water temperature observations at USGS 13334300 (1982 – 1990)

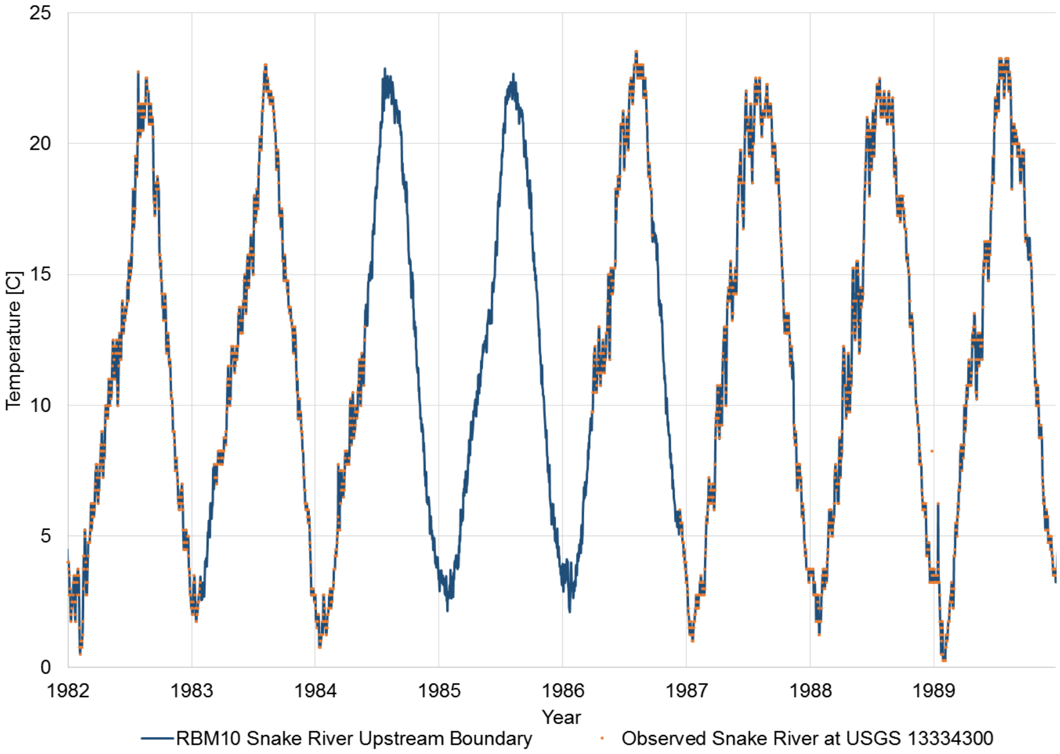


Figure A.4-4 Water temperature boundary conditions at the Snake River upstream boundary (blue line) from observations available at USGS 13334300 (1982 – 1990)

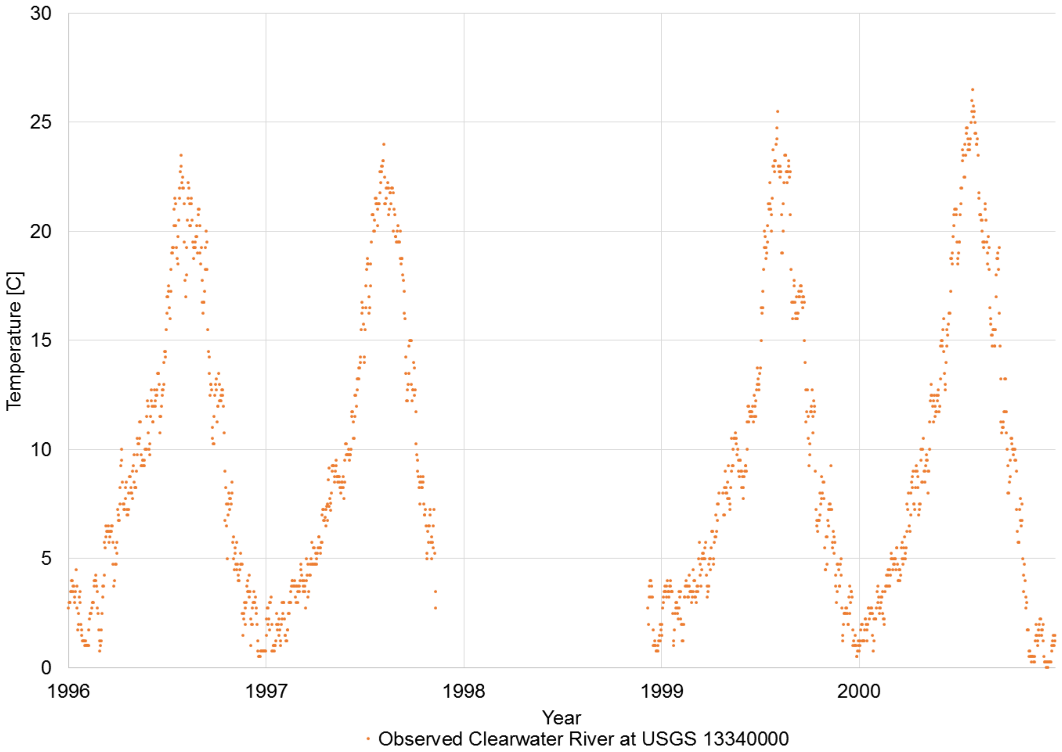


Figure A.4-5 Available water temperature observations at USGS 13344000 (1996 – 2001)

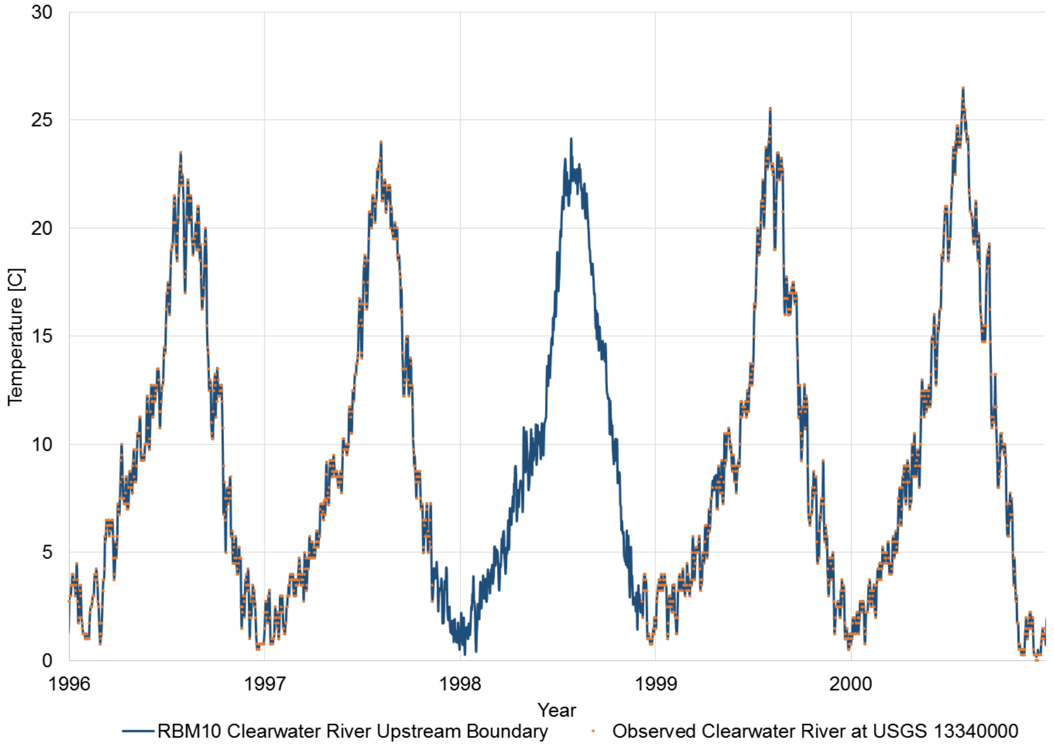


Figure A.4-6 Water temperature boundary conditions at the Clearwater River upstream boundary (blue line) from observations available at USGS 13340000 (1996 – 2001)

Appendix B Flow and Velocity Simulation Results

B.1 Flow Simulation

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

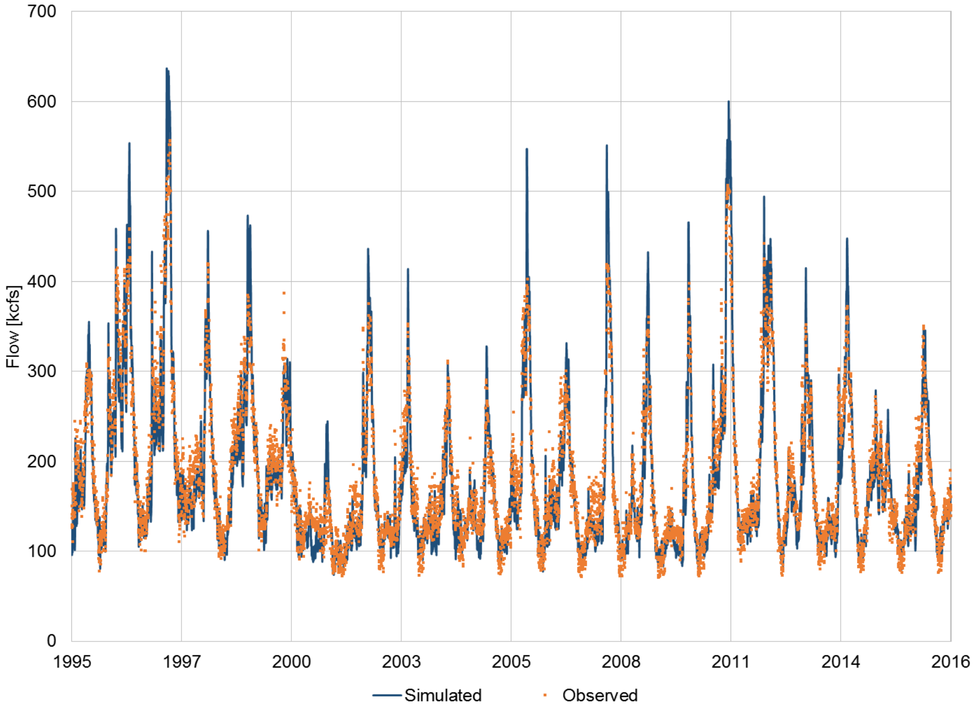


Figure B.1-1 Simulated versus observed flow at BON, Columbia River RM 146

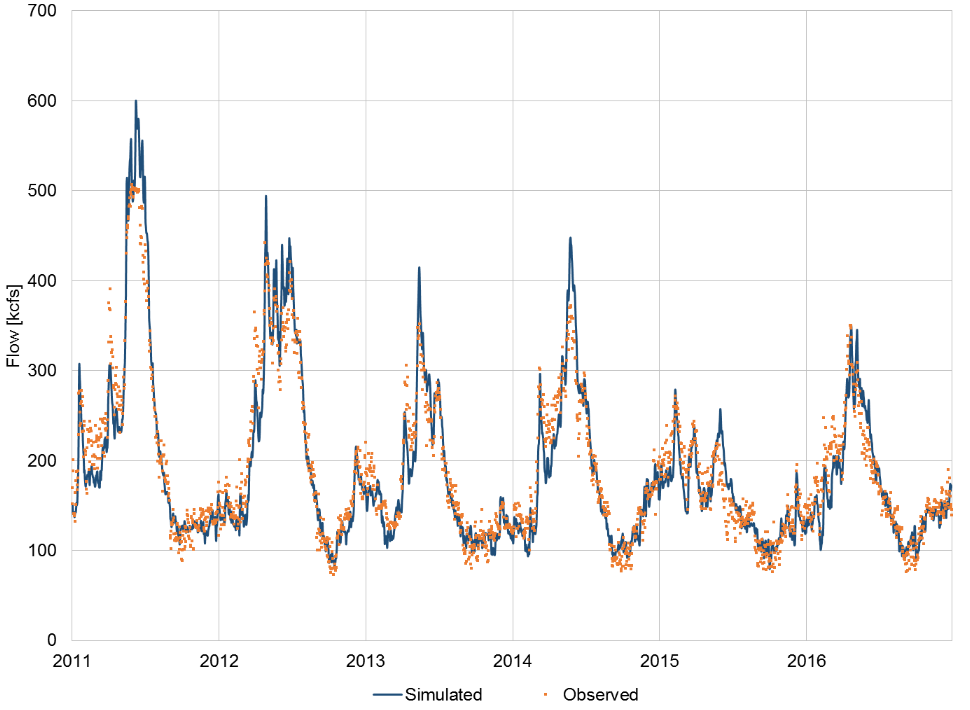


Figure B.1-2 Simulated versus observed flow at BON, period 2011 – 2016

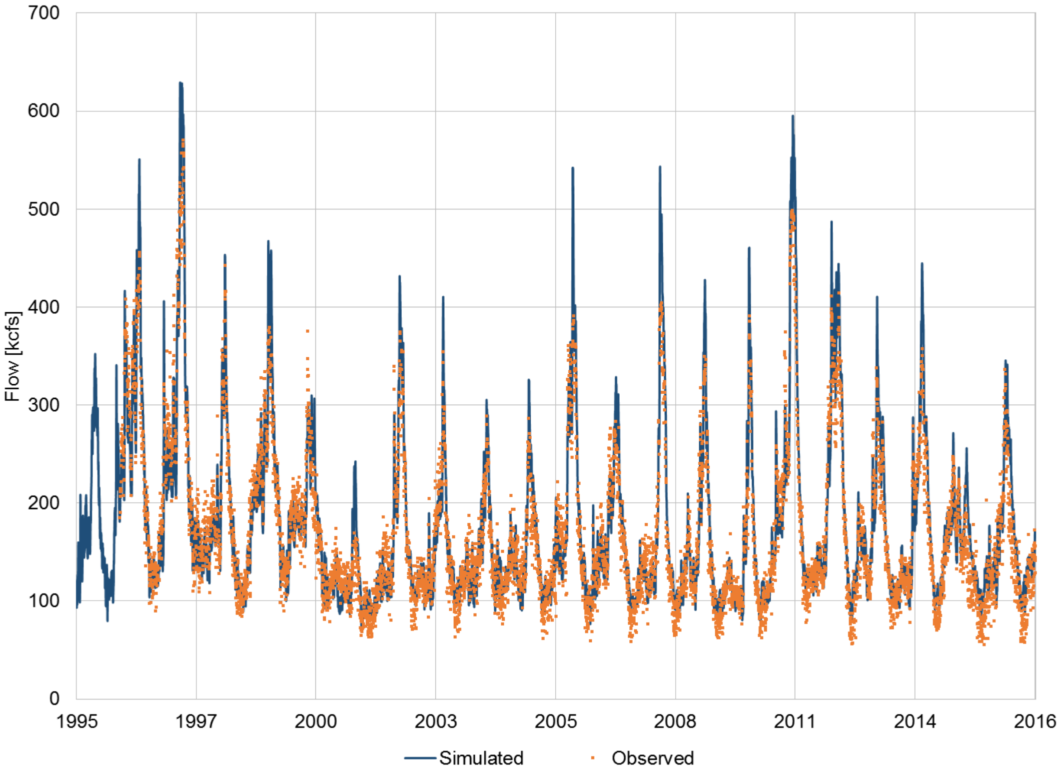


Figure B.1-3 Simulated versus observed flow at TDDO, Columbia River RM 190

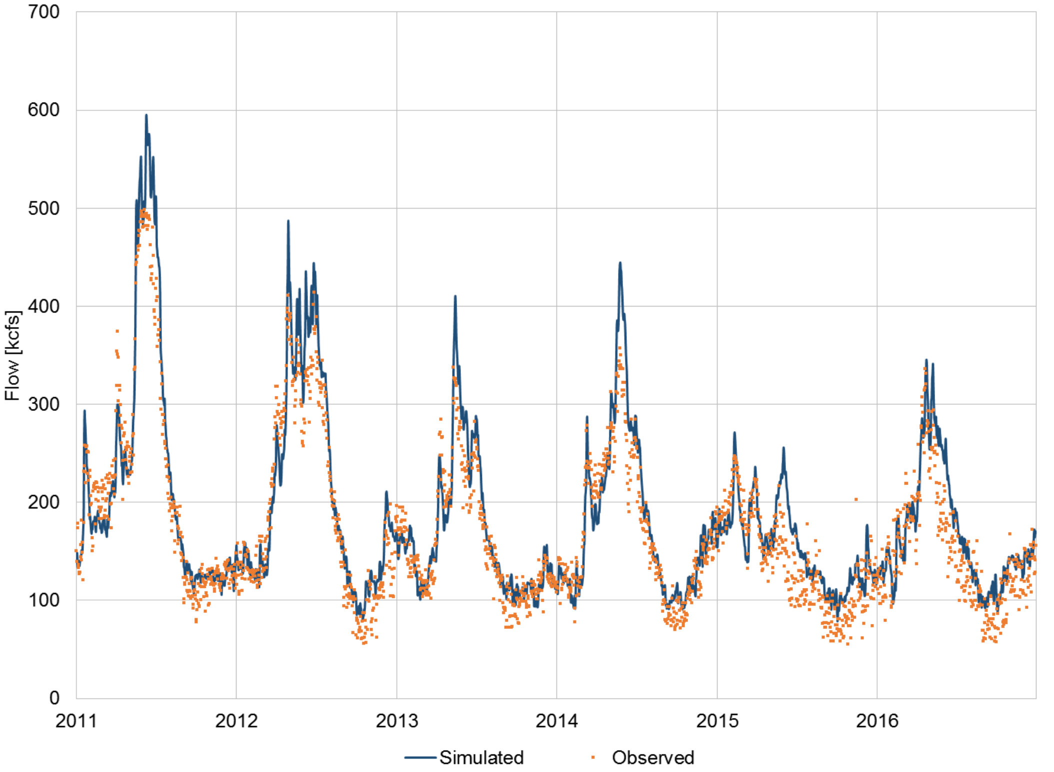


Figure B.1-4 Simulated versus observed flow at TDDO, period 2011 – 2016

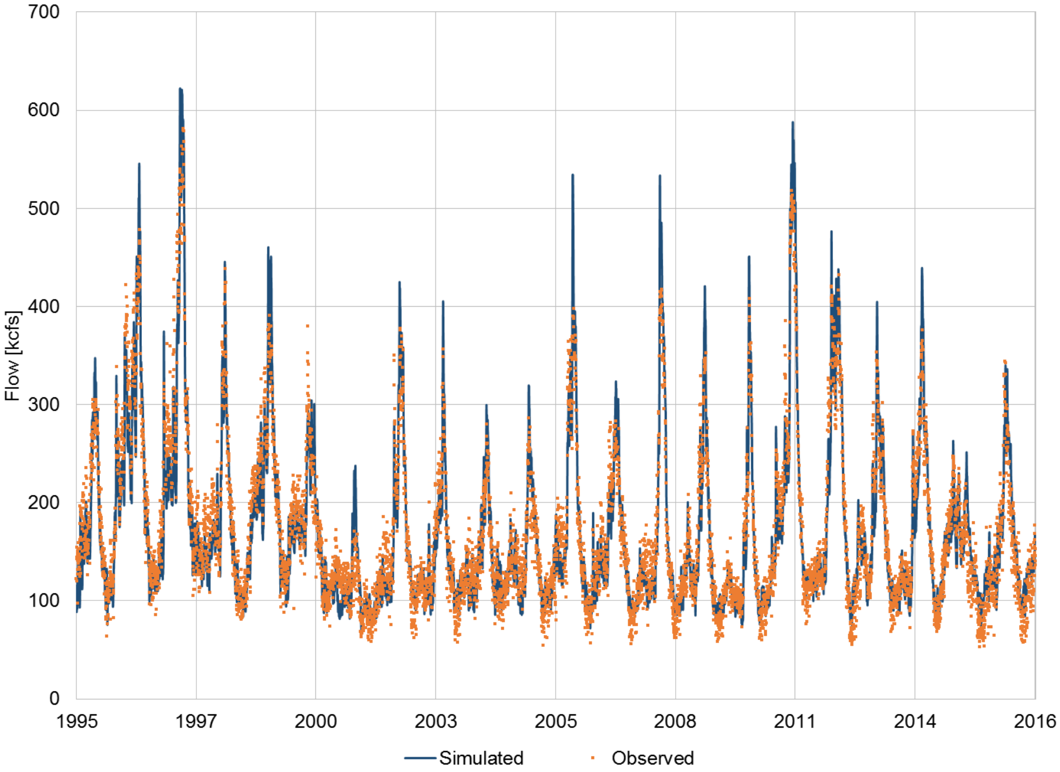


Figure B.1-5 Simulated versus observed flow at JHAW, Columbia River RM 215

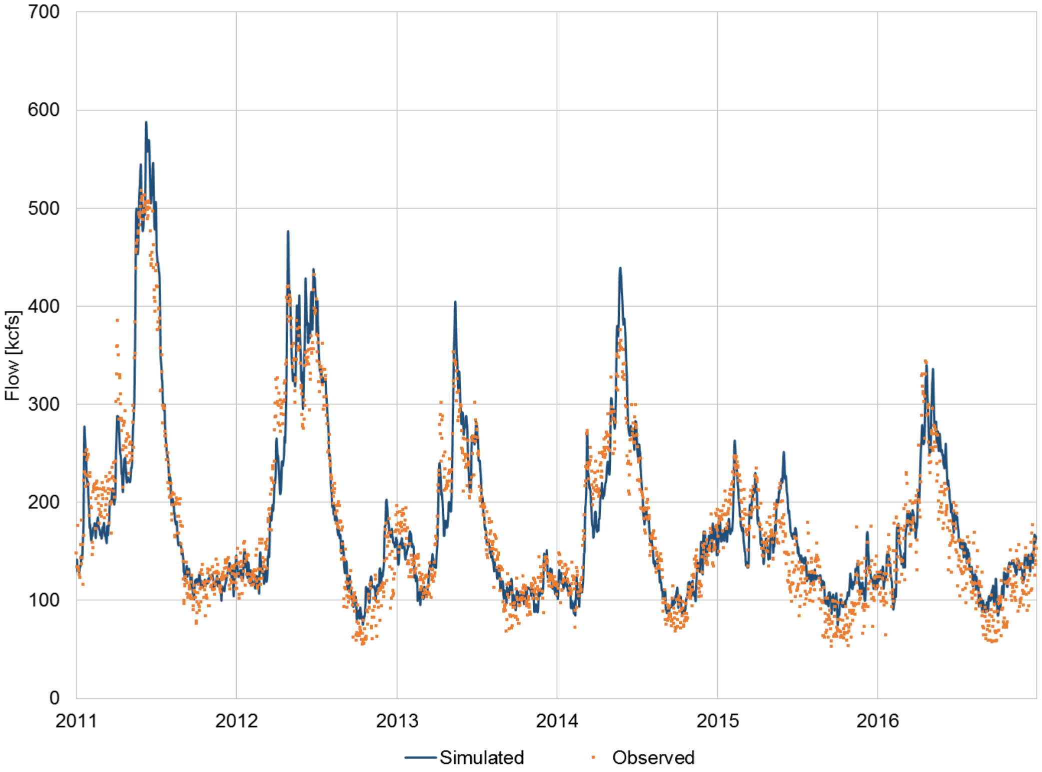


Figure B.1-6 Simulated versus observed flow at JHAW, period 2011 – 2016

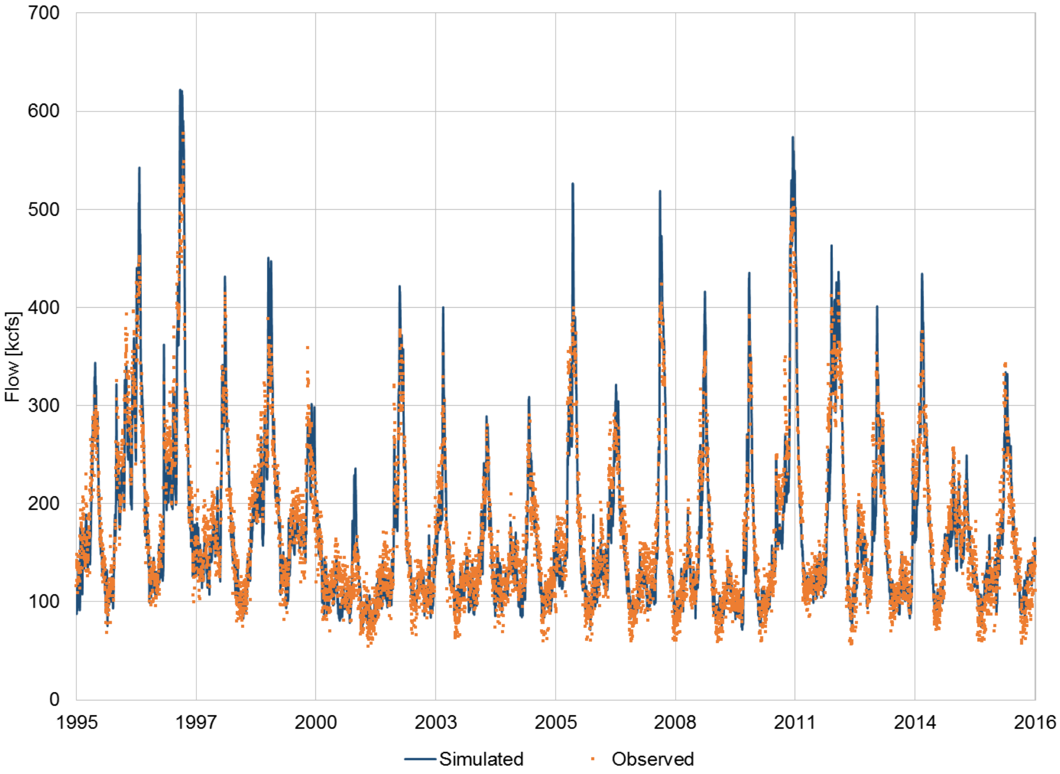


Figure B.1-7 Simulated versus observed flow at MCPW, Columbia River RM 291

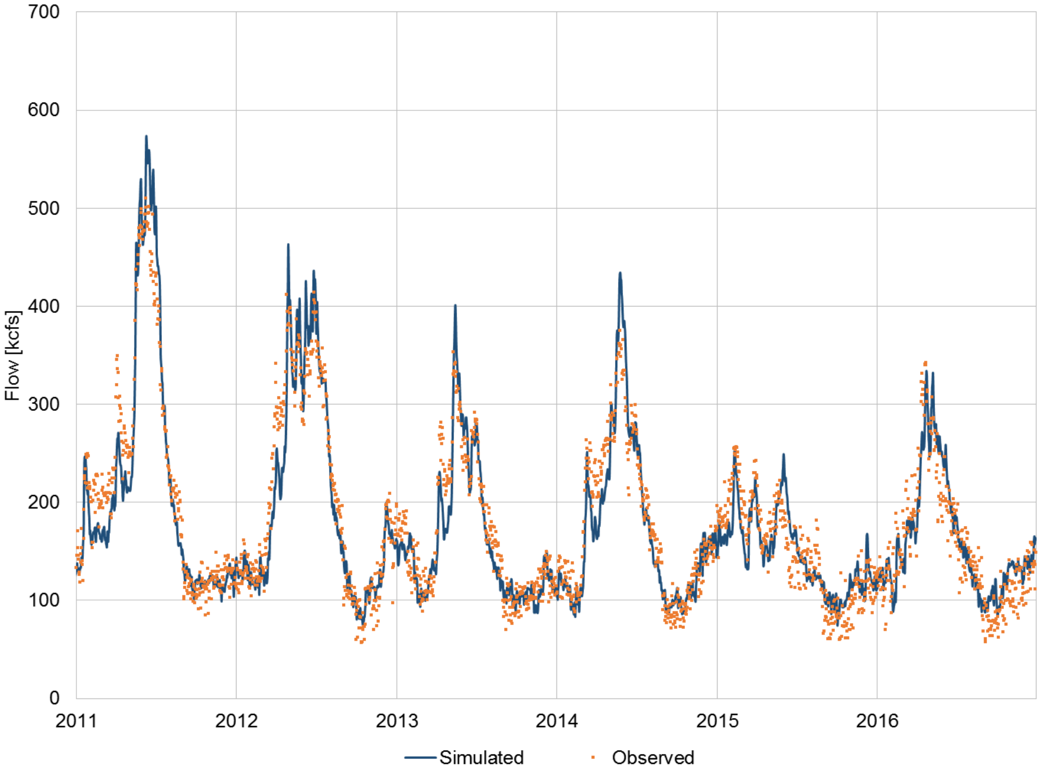


Figure B.1-8 Simulated versus observed flow at MCPW, period 2011 – 2016

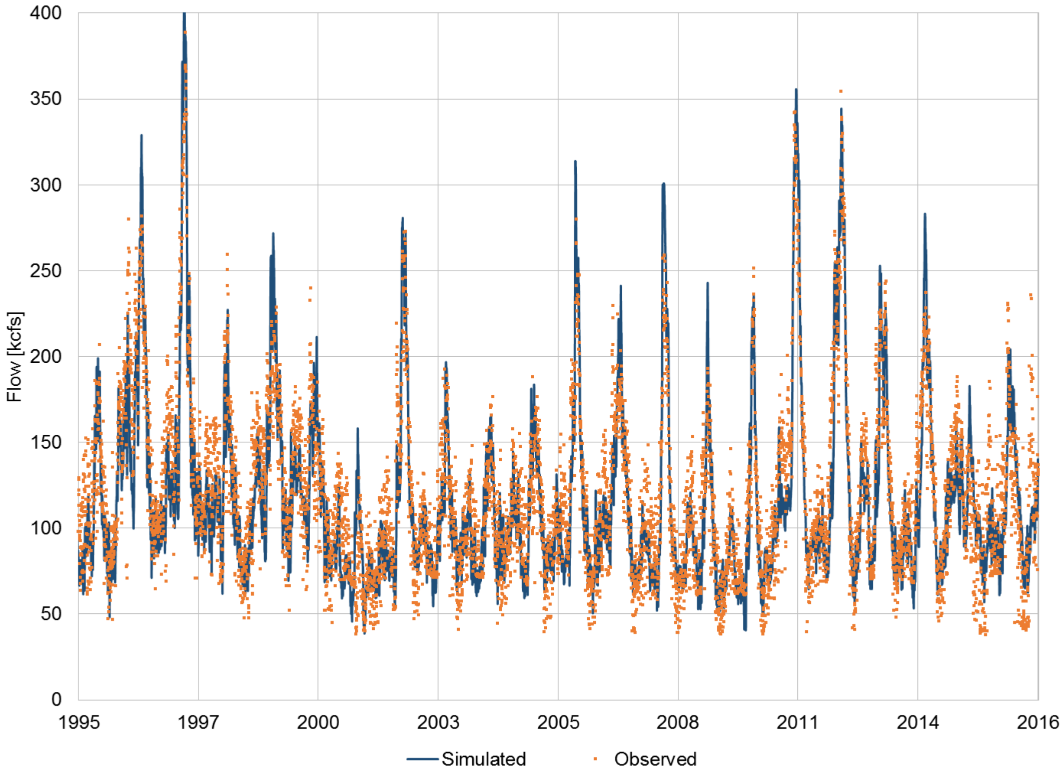


Figure B.1-9 Simulated versus observed flow at PRXW, Columbia River RM 396

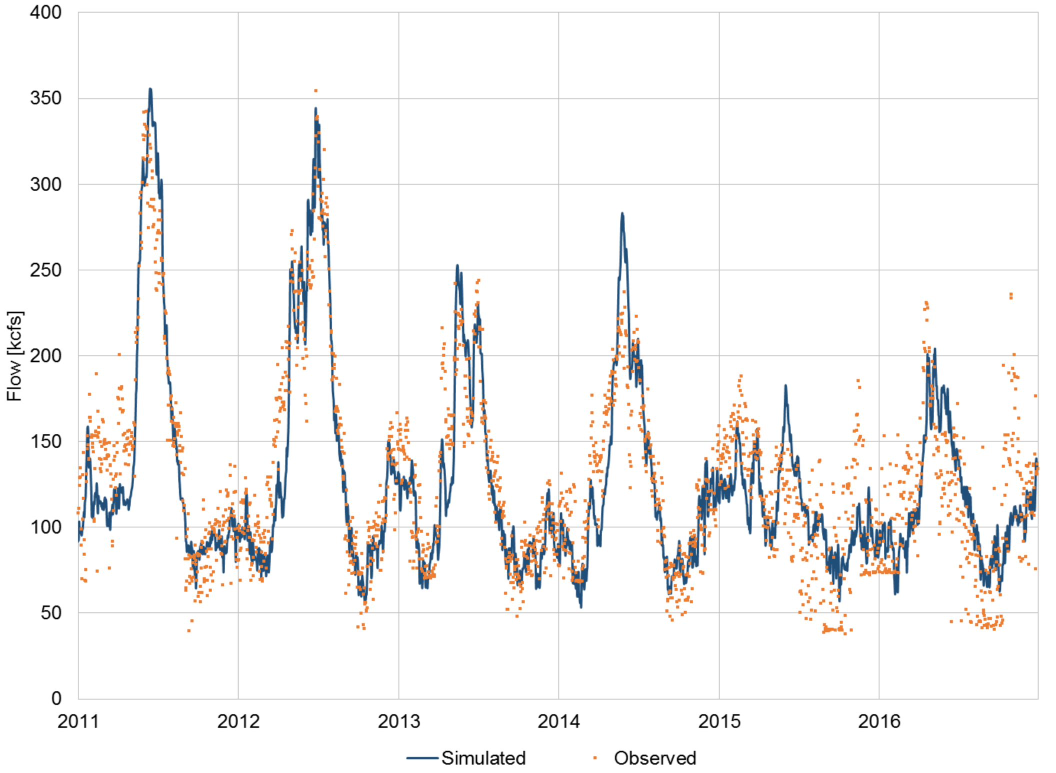


Figure B.1-10 Simulated versus observed flow at PRXW, period 2011 – 2016

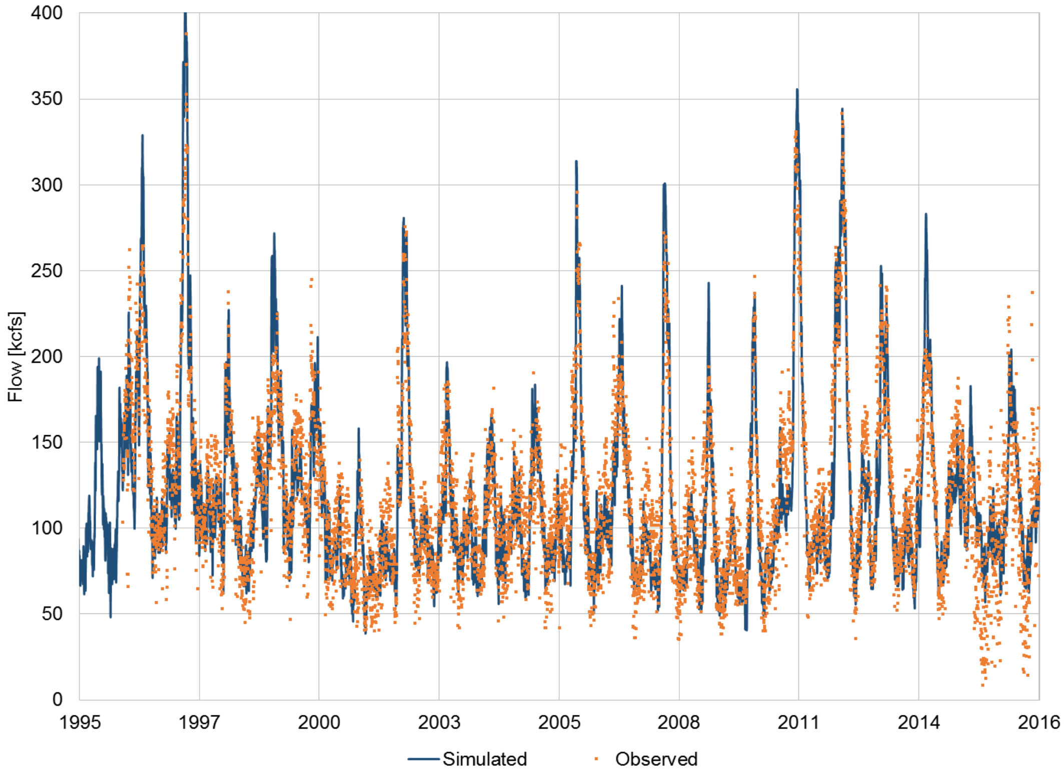


Figure B.1-11 Simulated versus observed flow at WANW, Columbia River RM 415

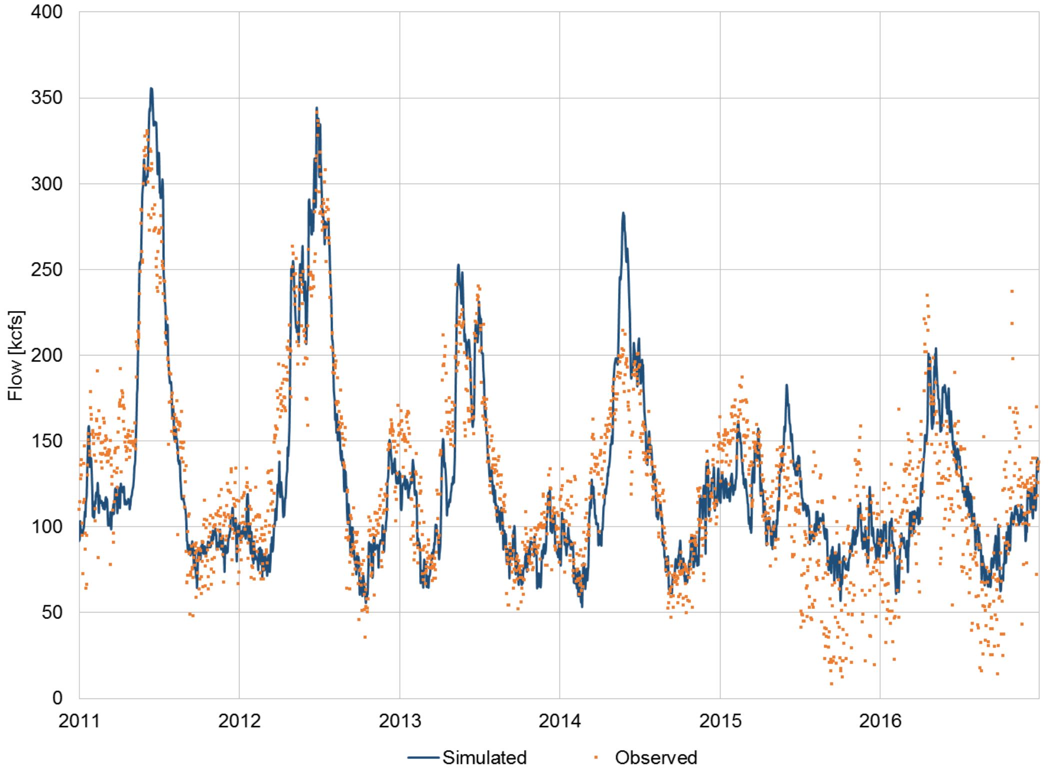


Figure B.1-12 Simulated versus observed flow at WANW, period 2011 – 2016

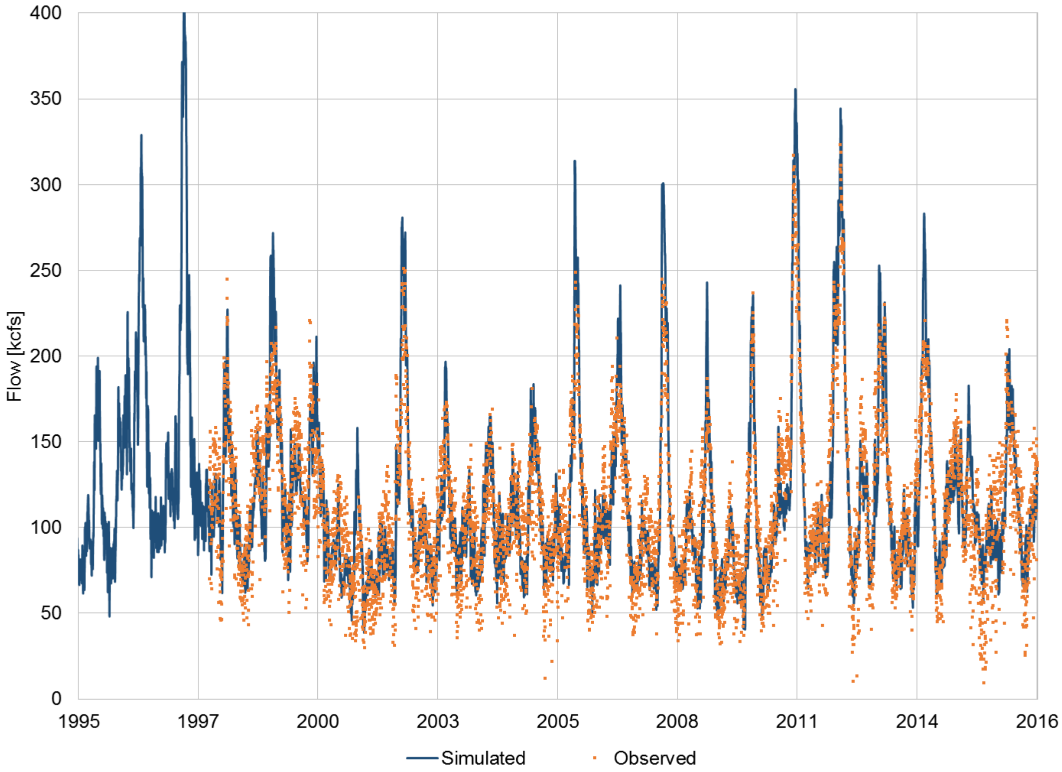


Figure B.1-13 Simulated versus observed flow at RIGW, Columbia River RM 452

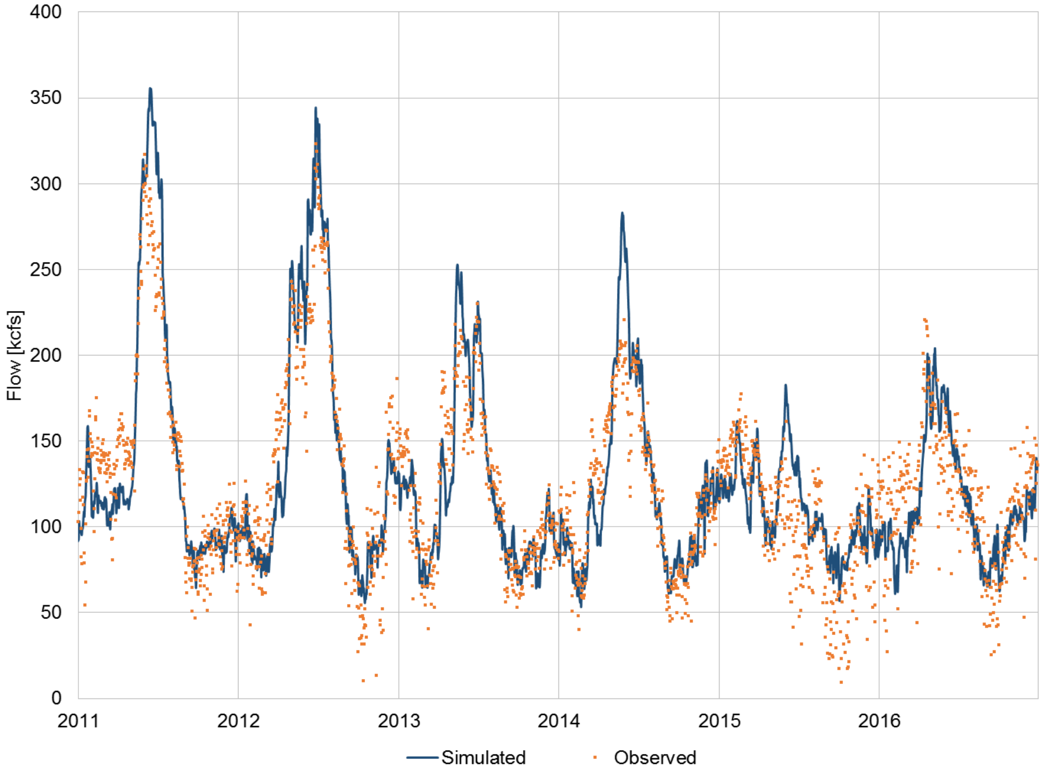


Figure B.1-14 Simulated versus observed flow at RIGW, period 2011 – 2016

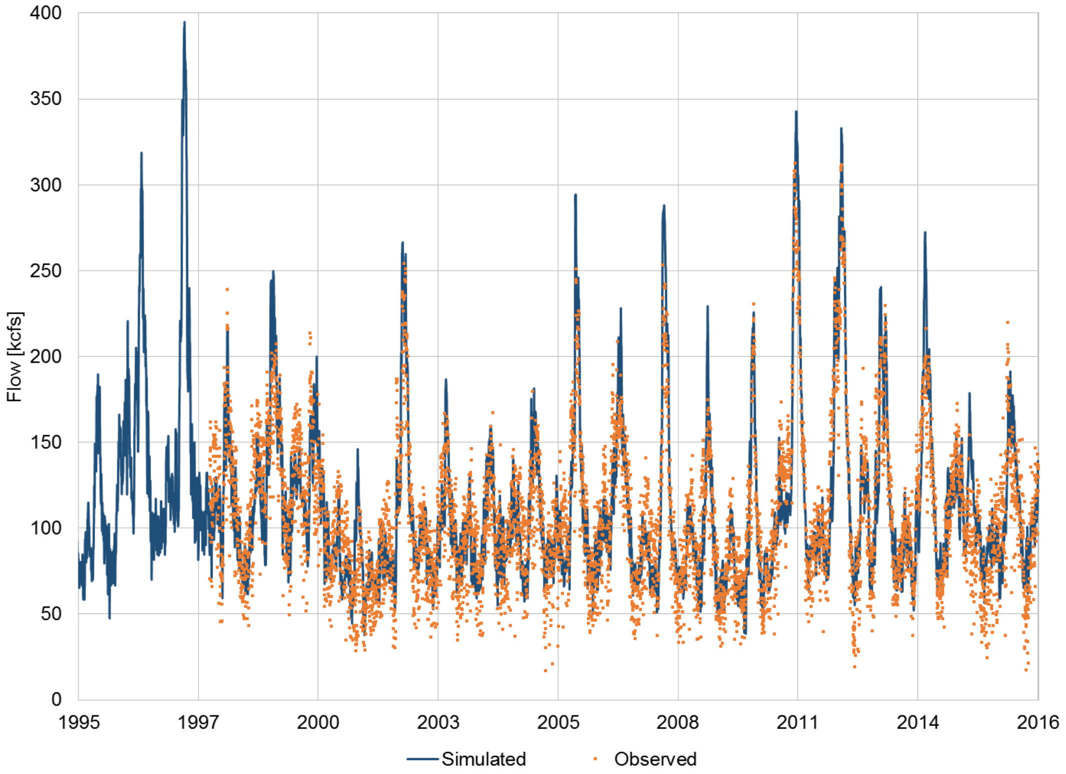


Figure B.1-15 Simulated versus observed flow at RRDW, Columbia River RM 472

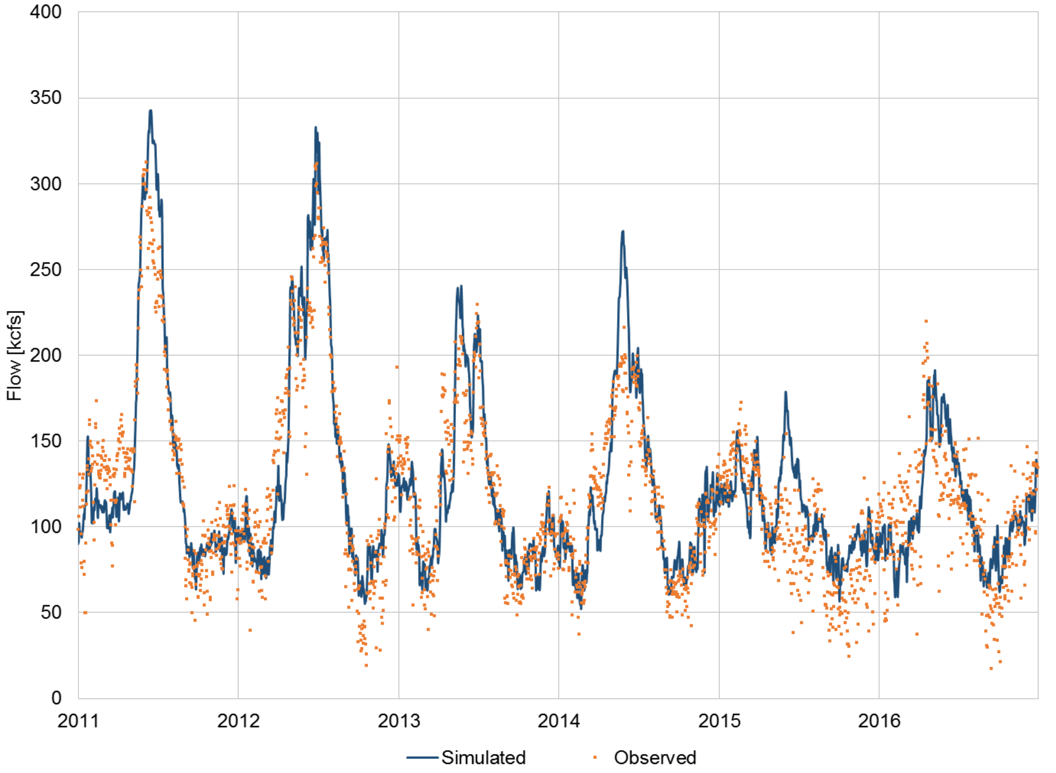


Figure B.1-16 Simulated versus observed flow at RRDW, period 2011 – 2016

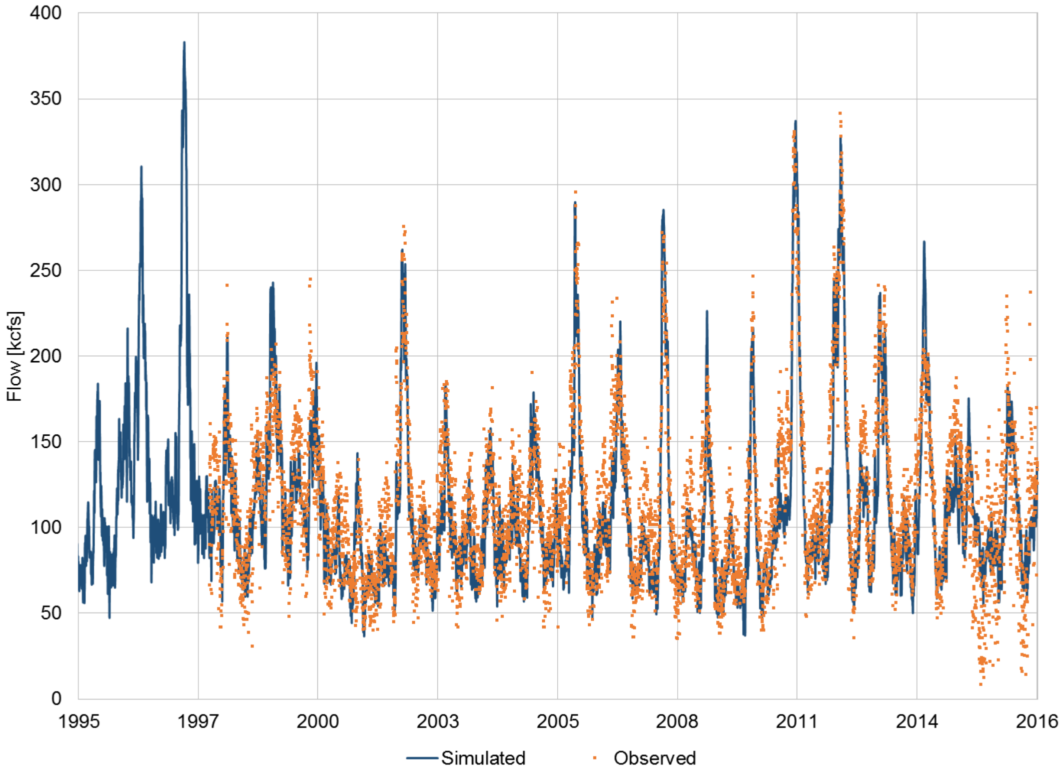


Figure B.1-17 Simulated versus observed flow at WELW, Columbia River RM 514

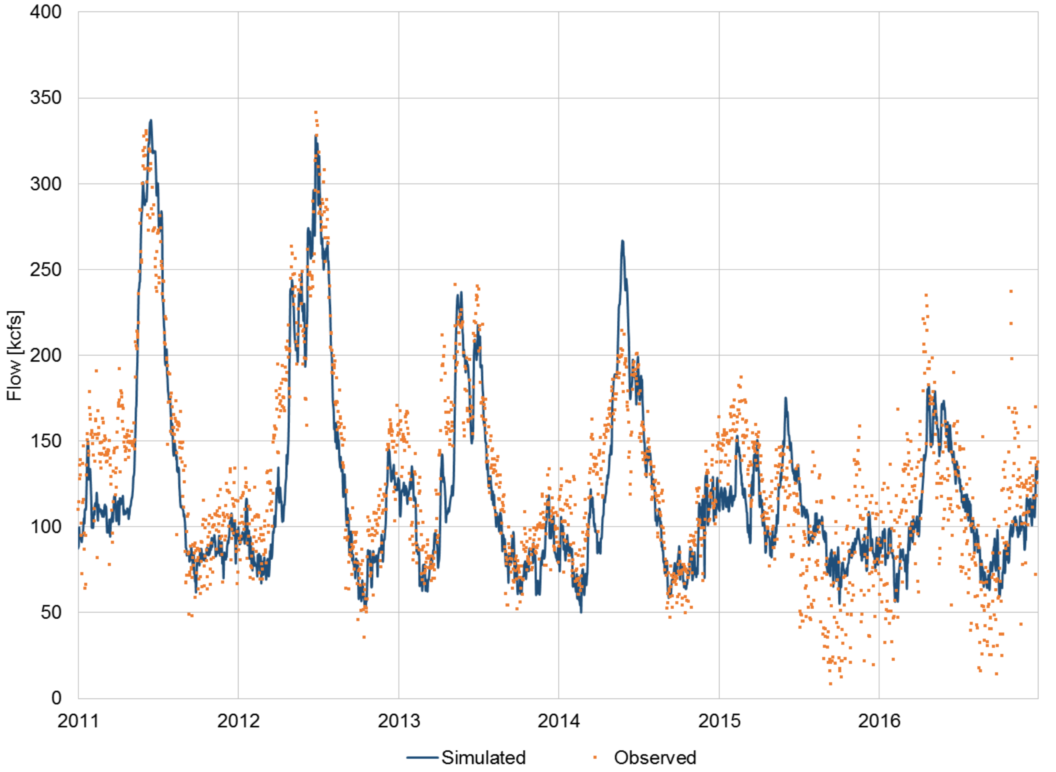


Figure B.1-18 Simulated versus observed flow at WELW, period 2011 – 2016

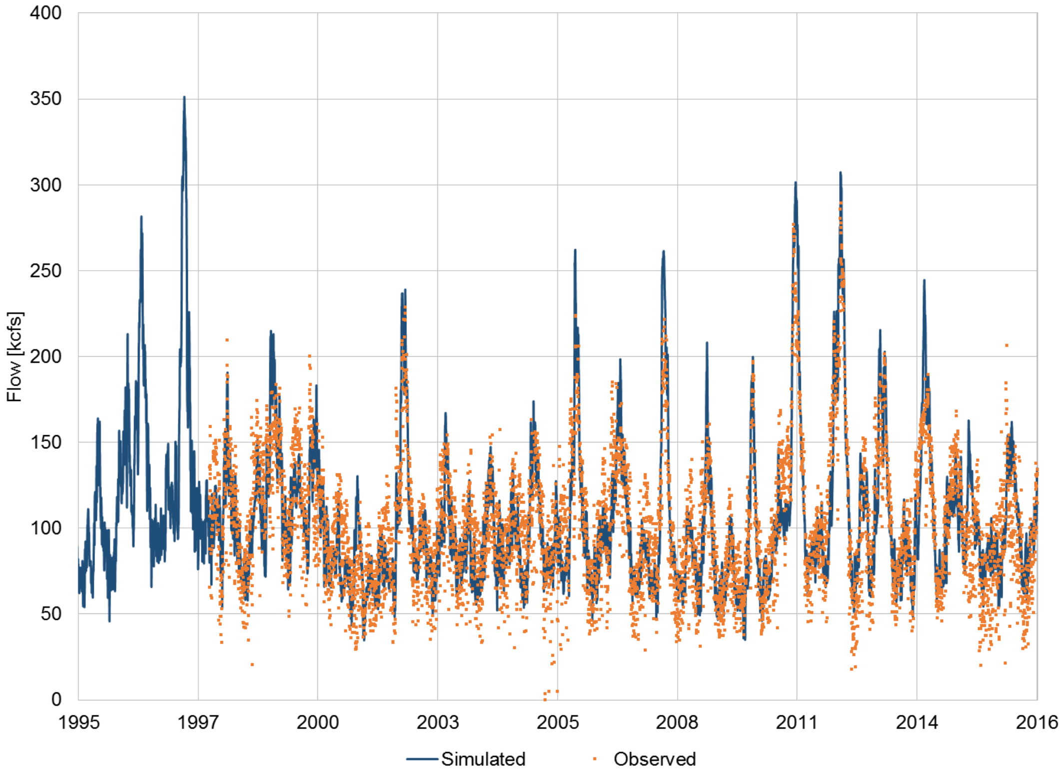


Figure B.1-19 Simulated versus observed flow at CHQW, Columbia River RM 545

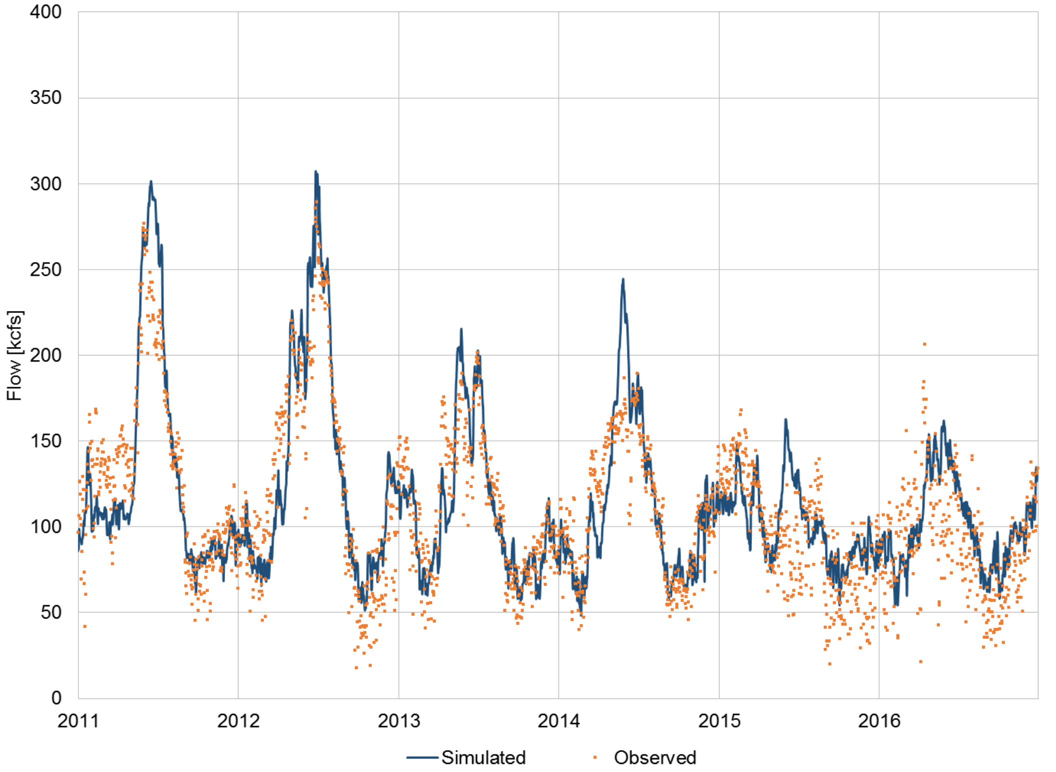


Figure B.1-20 Simulated versus observed flow at CHQW, period 2011 – 2016

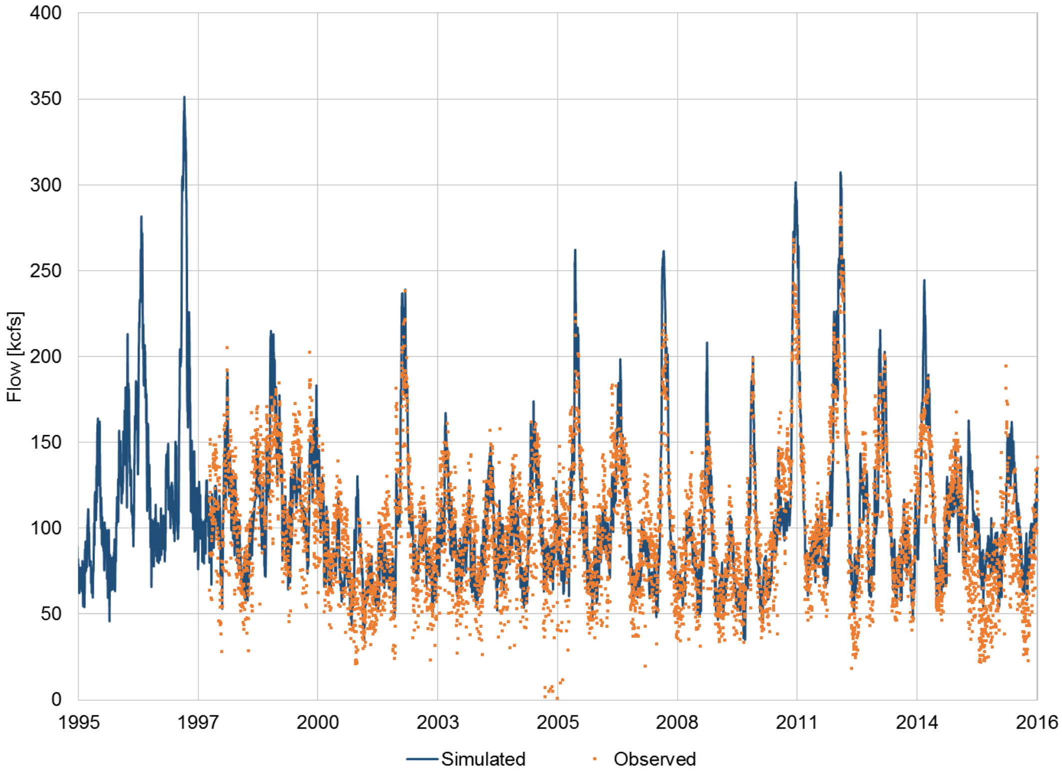


Figure B.1-21 Simulated versus observed flow at GCGW, Columbia River RM 590

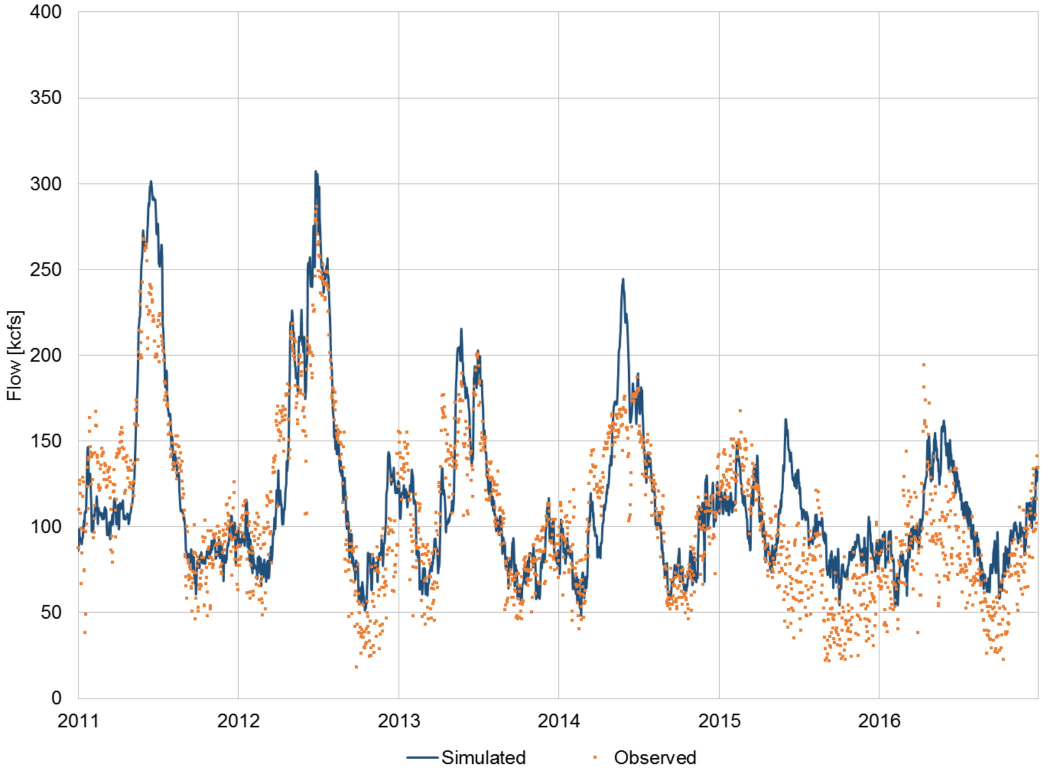


Figure B.1-22 Simulated versus observed flow at GCGW, period 2011 – 2016

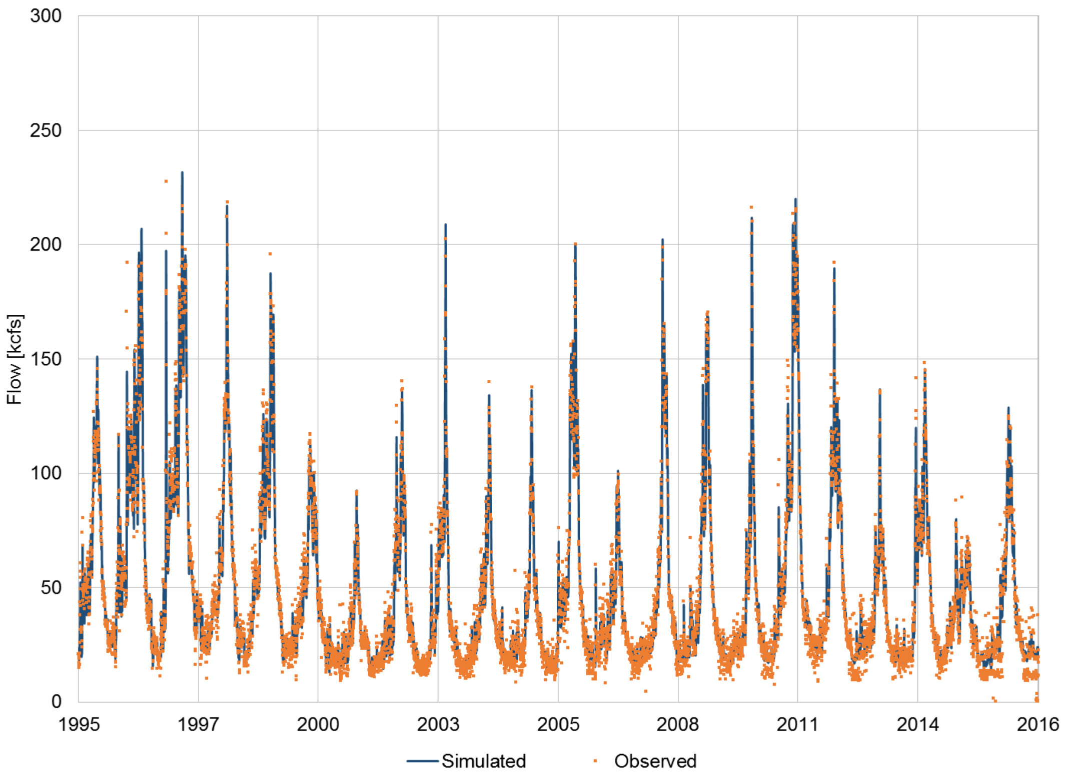


Figure B.1-23 Simulated versus observed flow at IDSW, Snake River RM 6.8

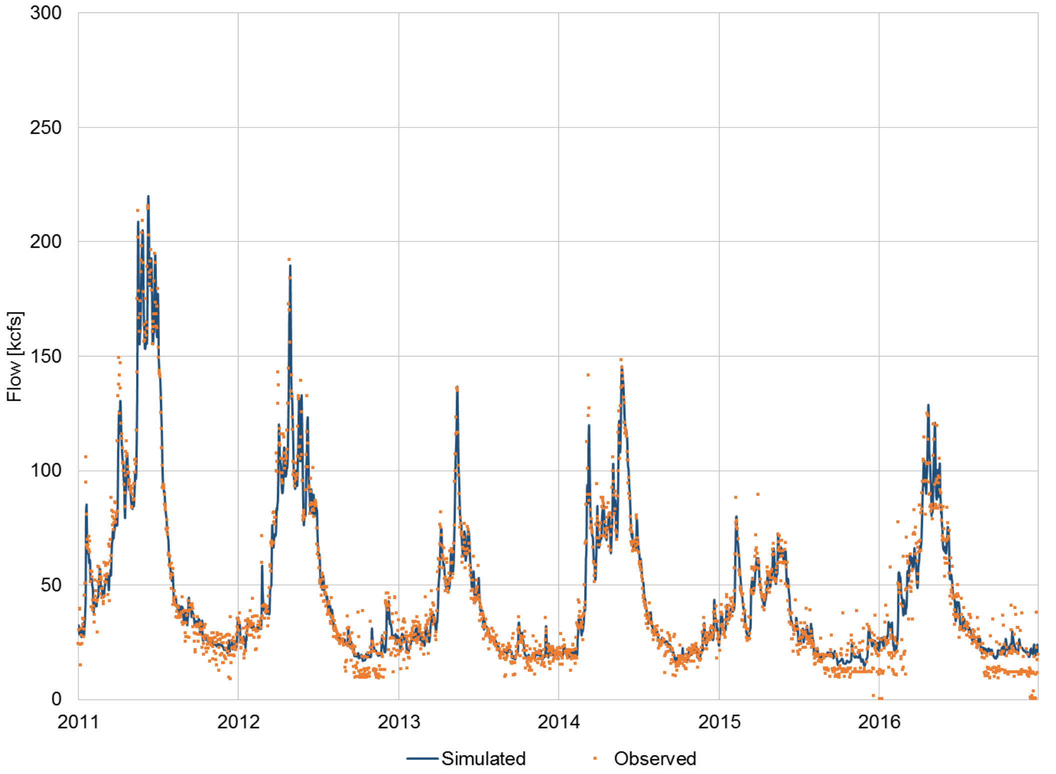


Figure B.1-24 Simulated versus observed flow at IDSW, period 2011 – 2016

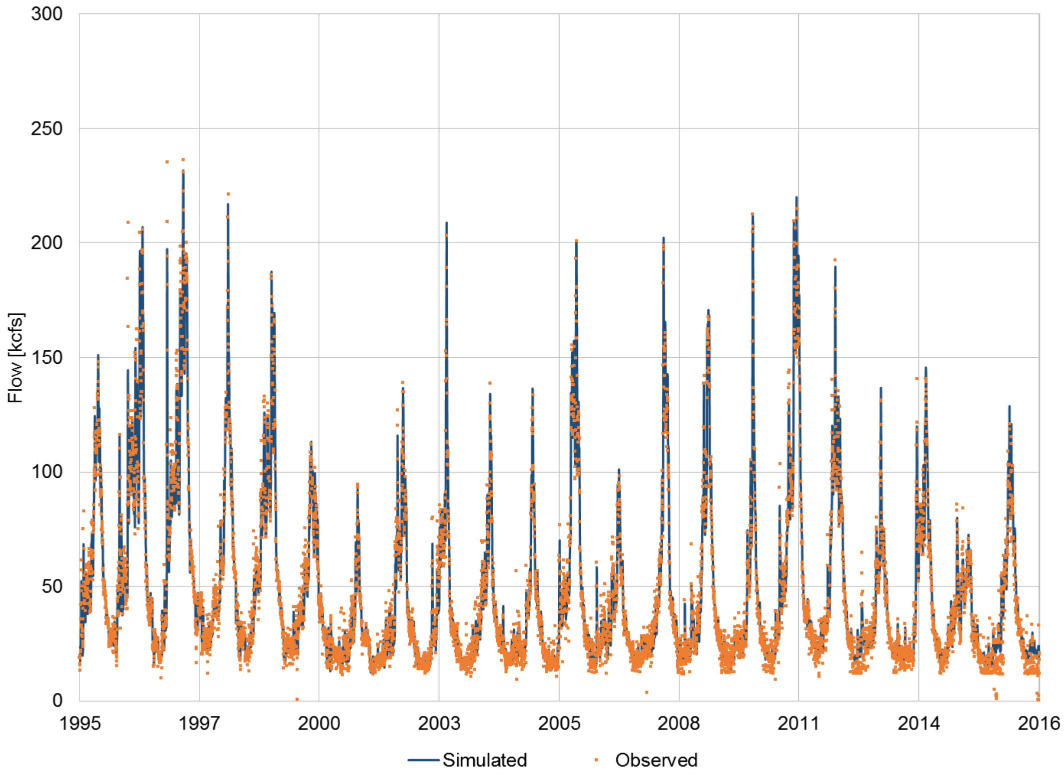


Figure B.1-25 Simulated versus observed flow at LMNW, Snake River RM 40.8

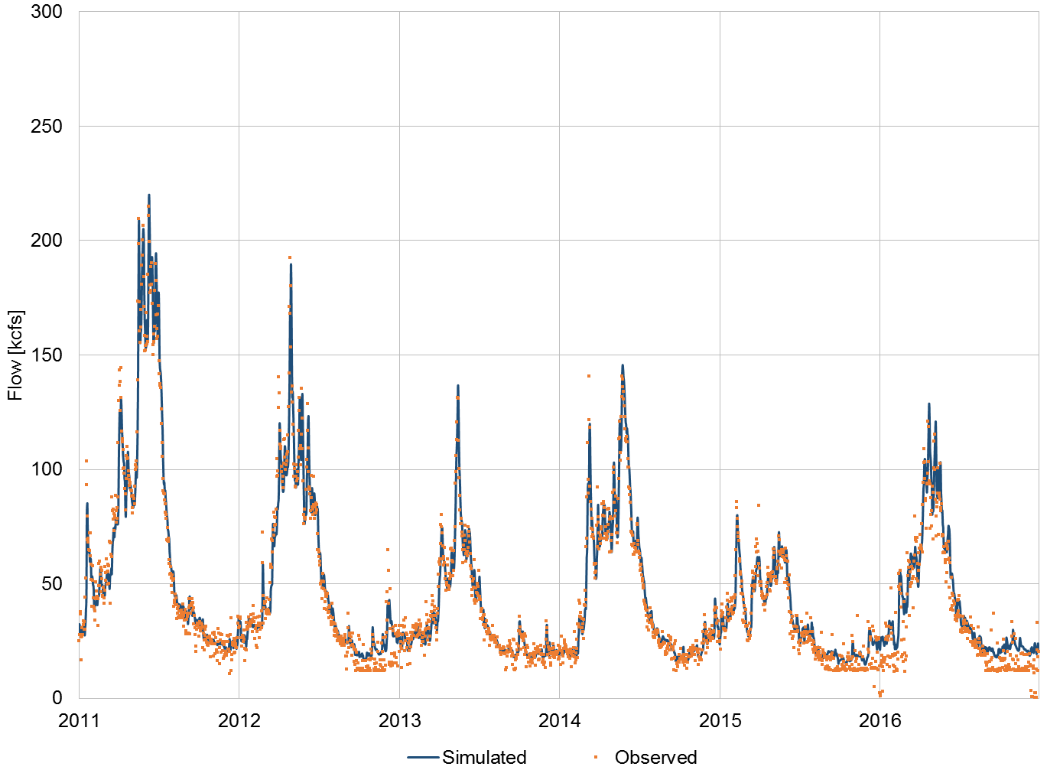


Figure B.1-26 Simulated versus observed flow at LMNW, period 2011 – 2016

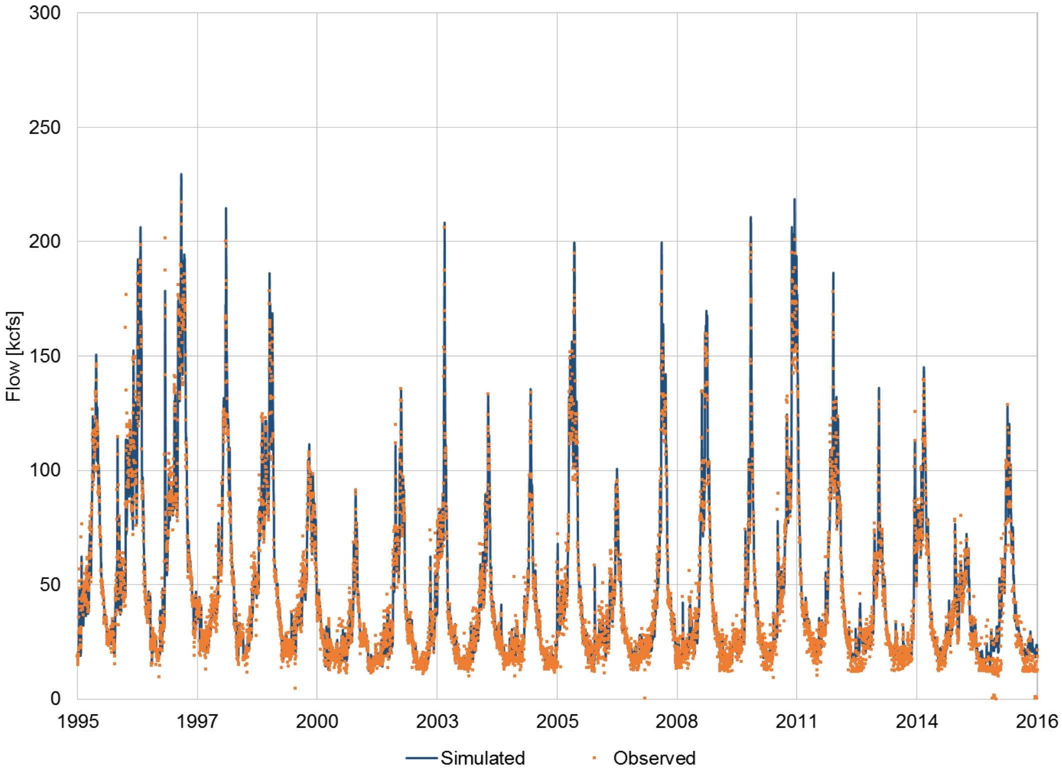


Figure B.1-27 Simulated versus observed flow at LGSW, Snake River RM 69.5

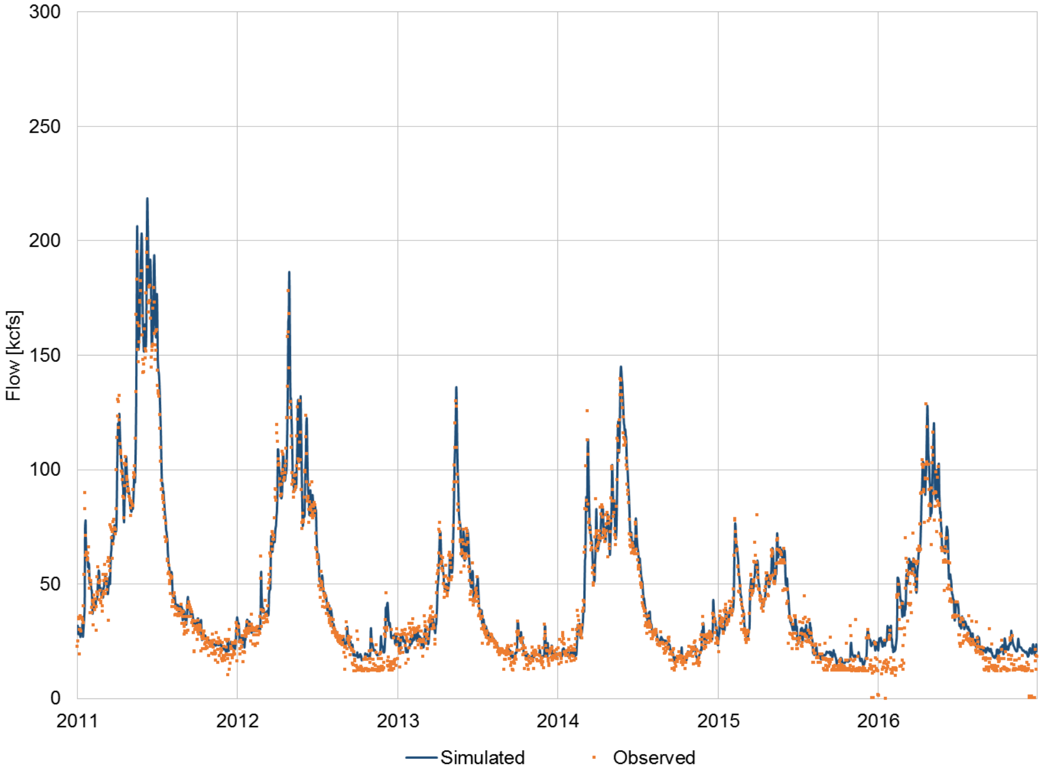


Figure B.1-28 Simulated versus observed flow at LGSW, period 2011 – 2016

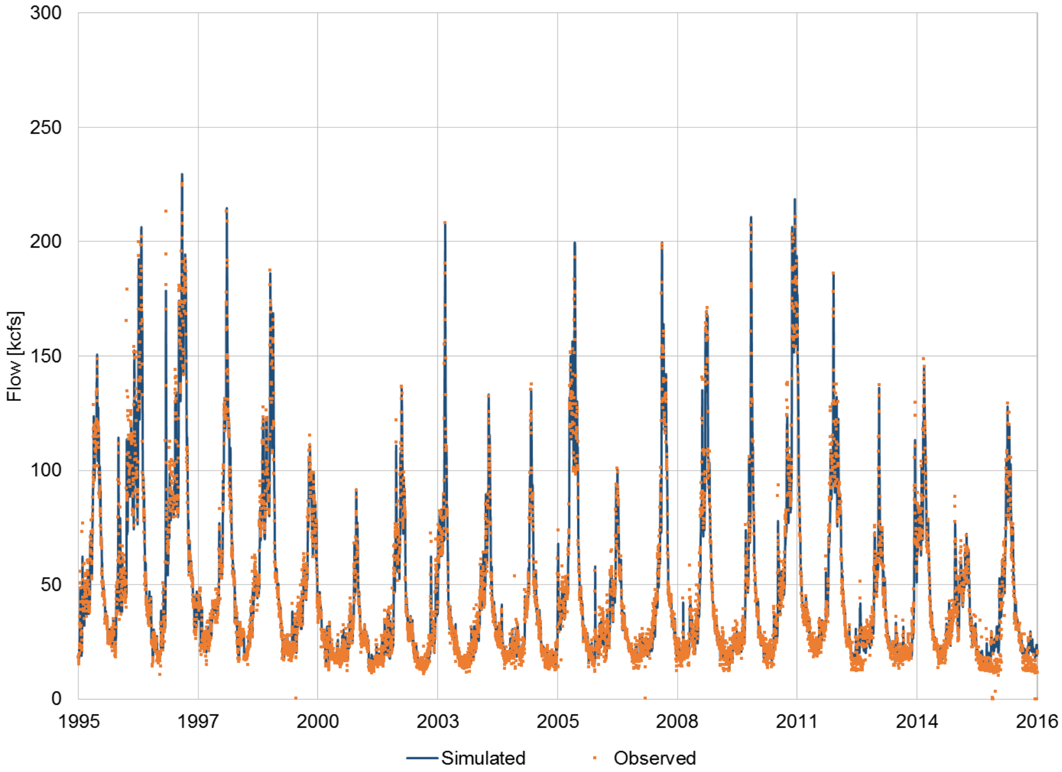


Figure B.1-29 Simulated versus observed flow at LGNW, Snake River RM 106.8

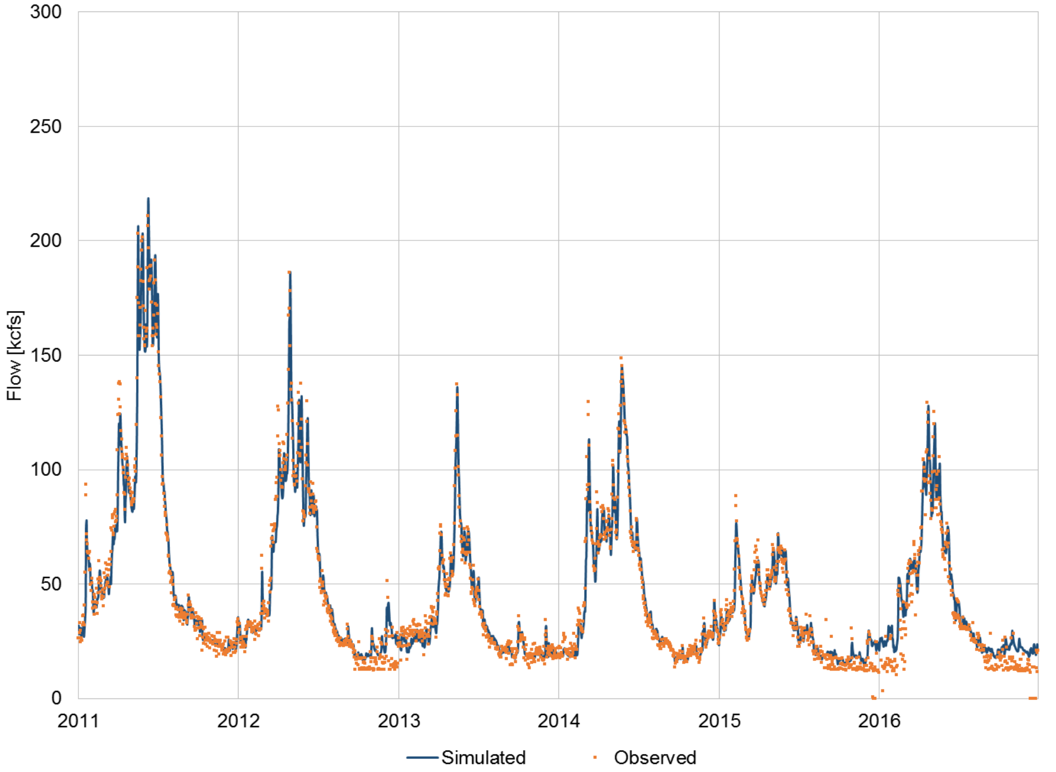


Figure B.1-30 Simulated versus observed flow at LGNW, period 2011 – 2016

B.2 Velocity Results

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

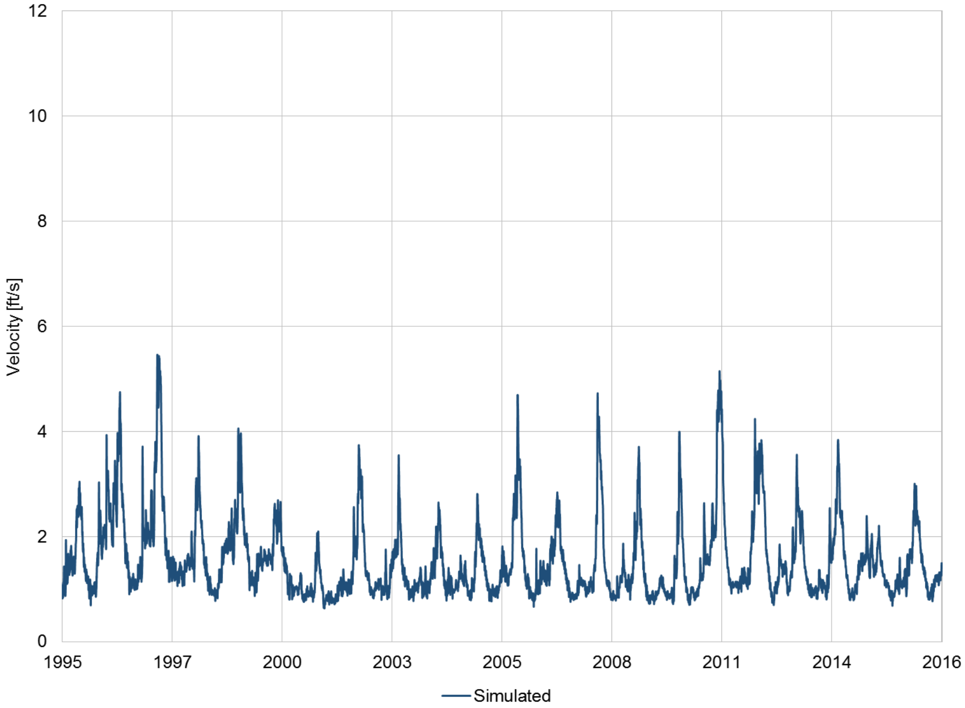


Figure B.2-1 Simulated velocity at BON, Columbia River RM 146

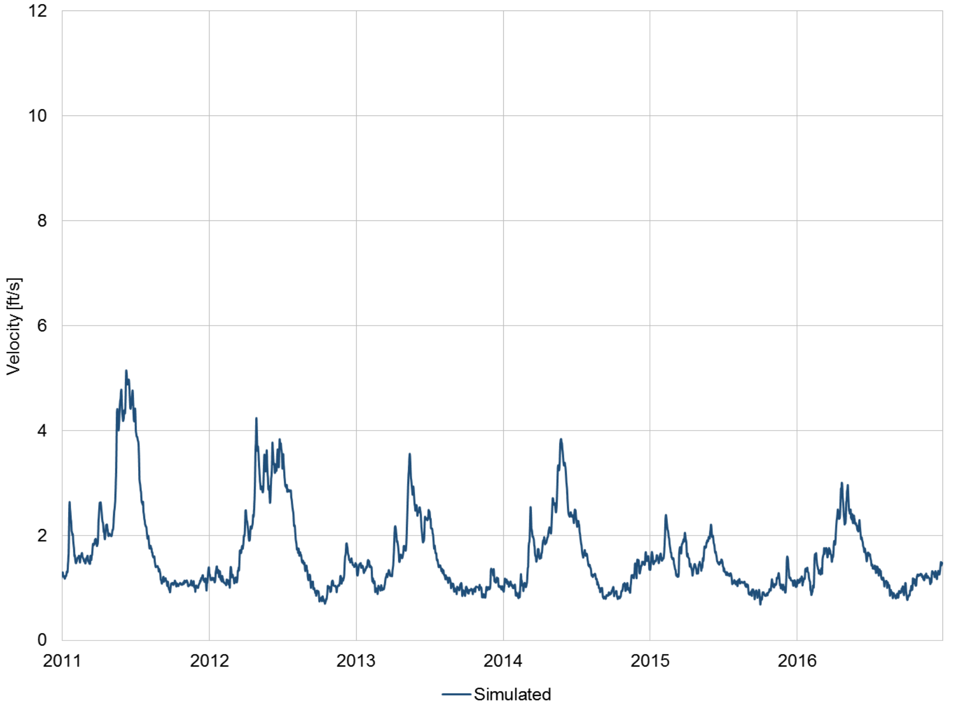


Figure B.2-2 Simulated velocity at BON, period 2011 – 2016

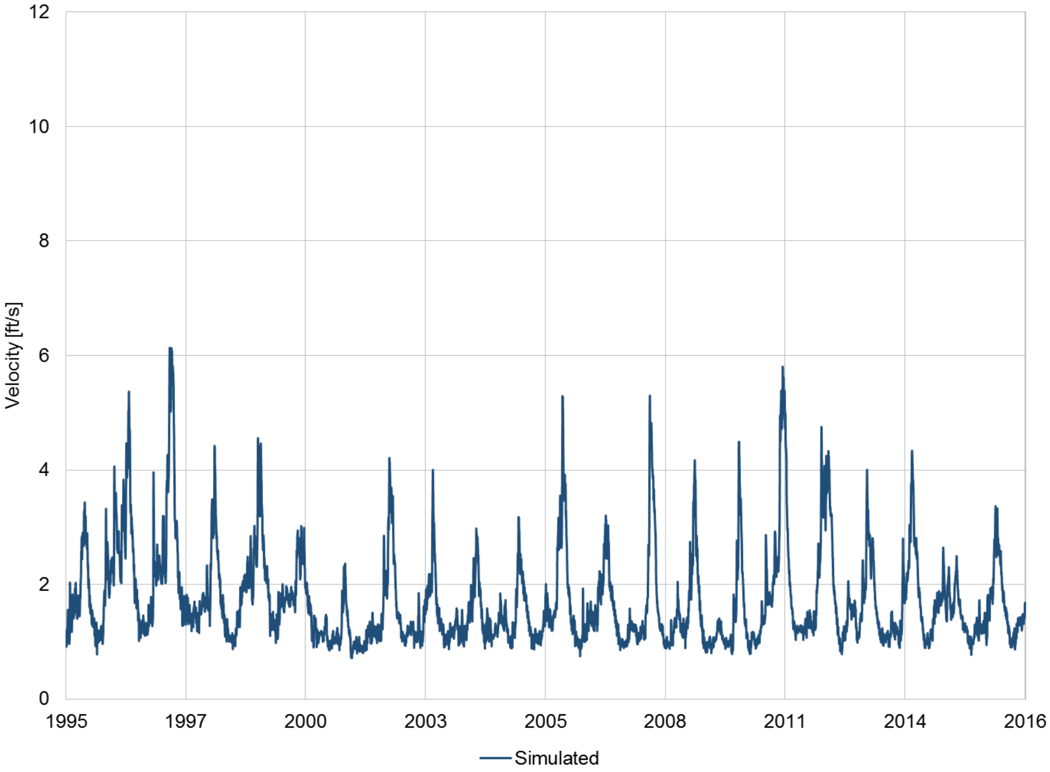


Figure B.2-3 Simulated velocity at TDDO, Columbia River RM 190

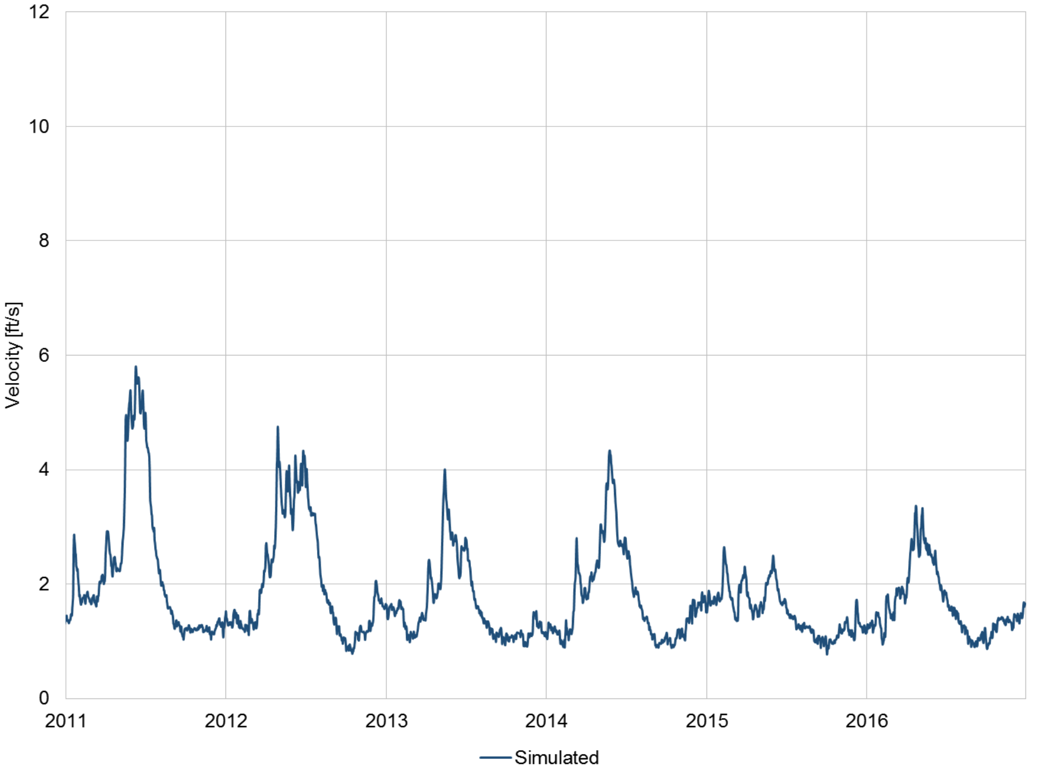


Figure B.2-4 Simulated velocity at TDDO, period 2011 – 2016

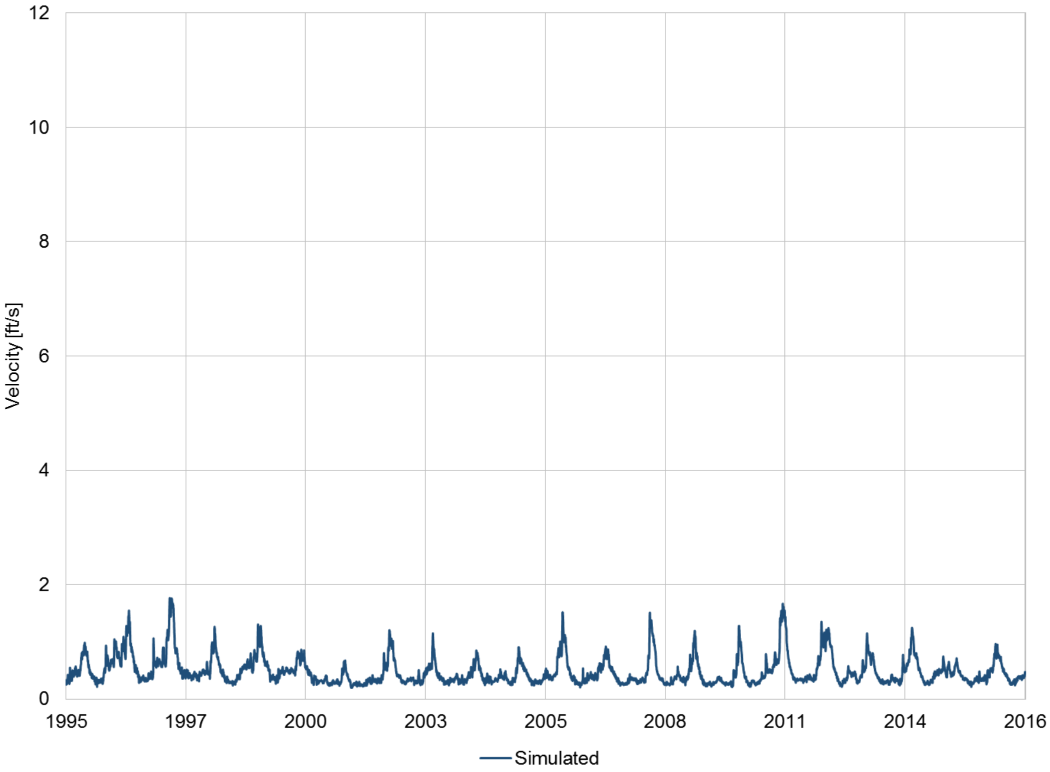


Figure B.2-5 Simulated velocity at JHAW, Columbia River RM 215

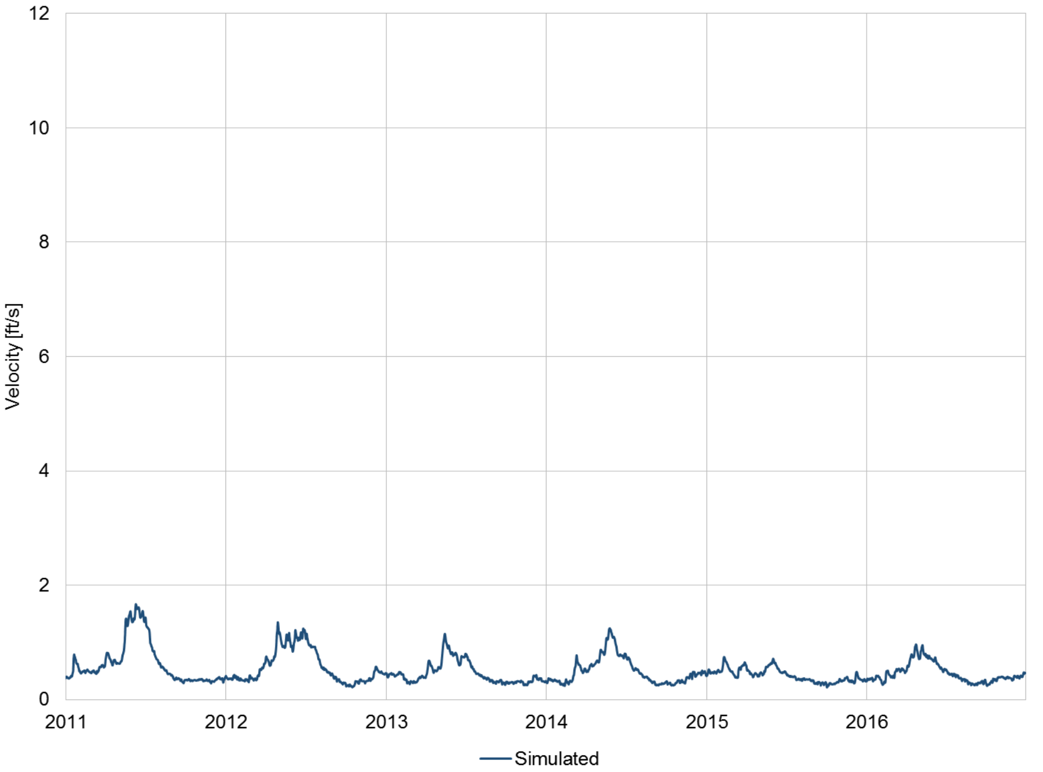


Figure B.2-6 Simulated velocity at JHAW, period 2011 – 2016

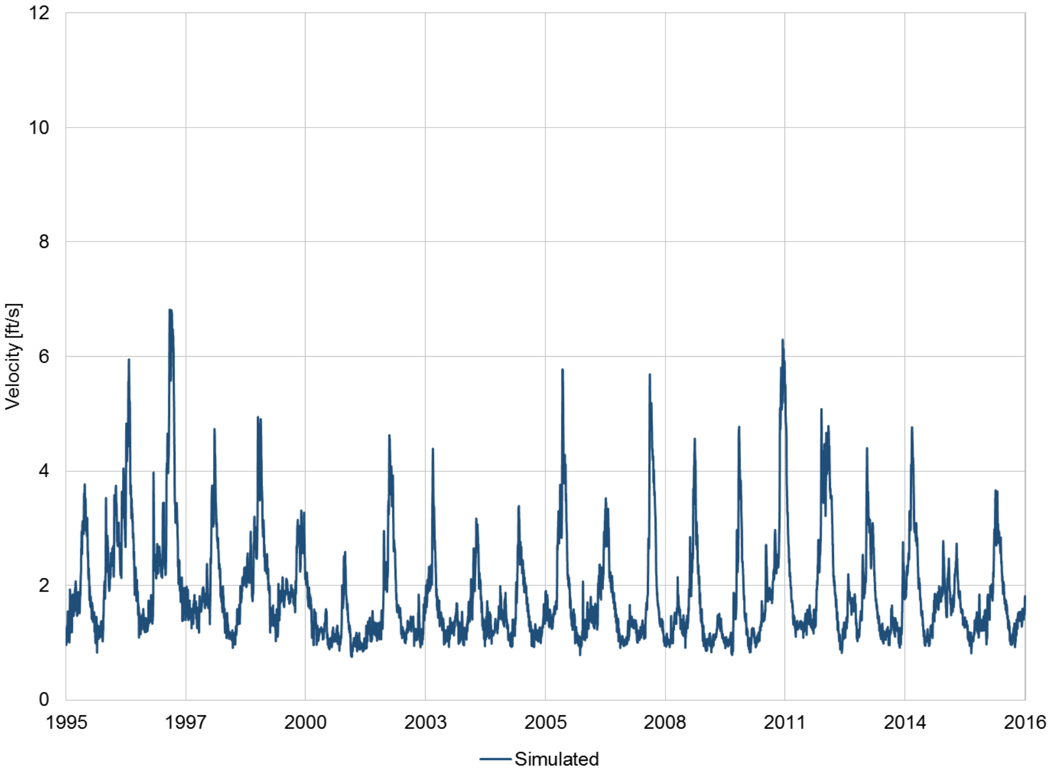


Figure B.2-7 Simulated velocity at MCPW, Columbia River RM 291

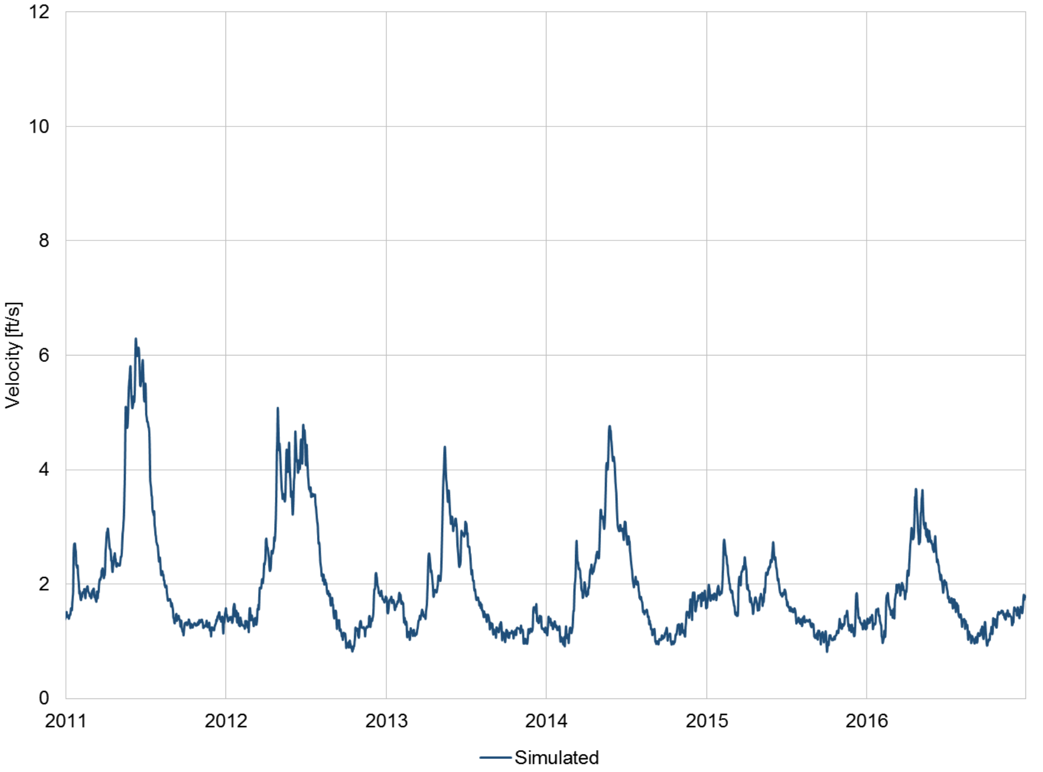


Figure B.2-8 Simulated velocity at MCPW, period 2011 – 2016

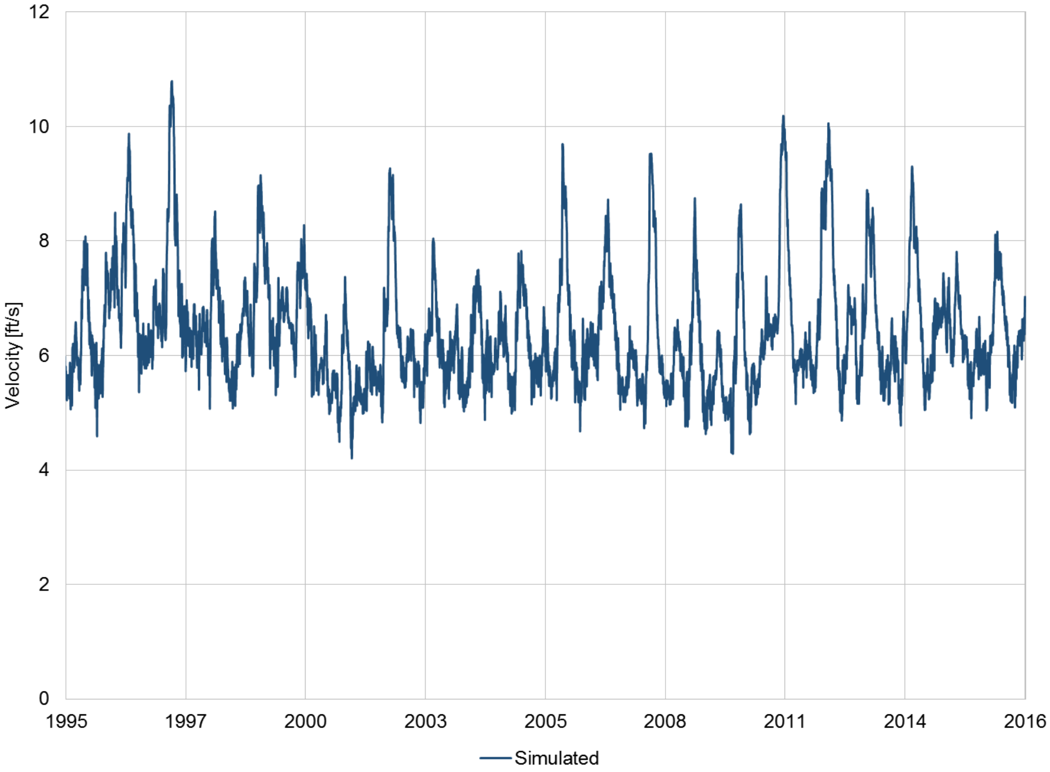


Figure B.2-9 Simulated velocity at PRXW, Columbia River RM 396

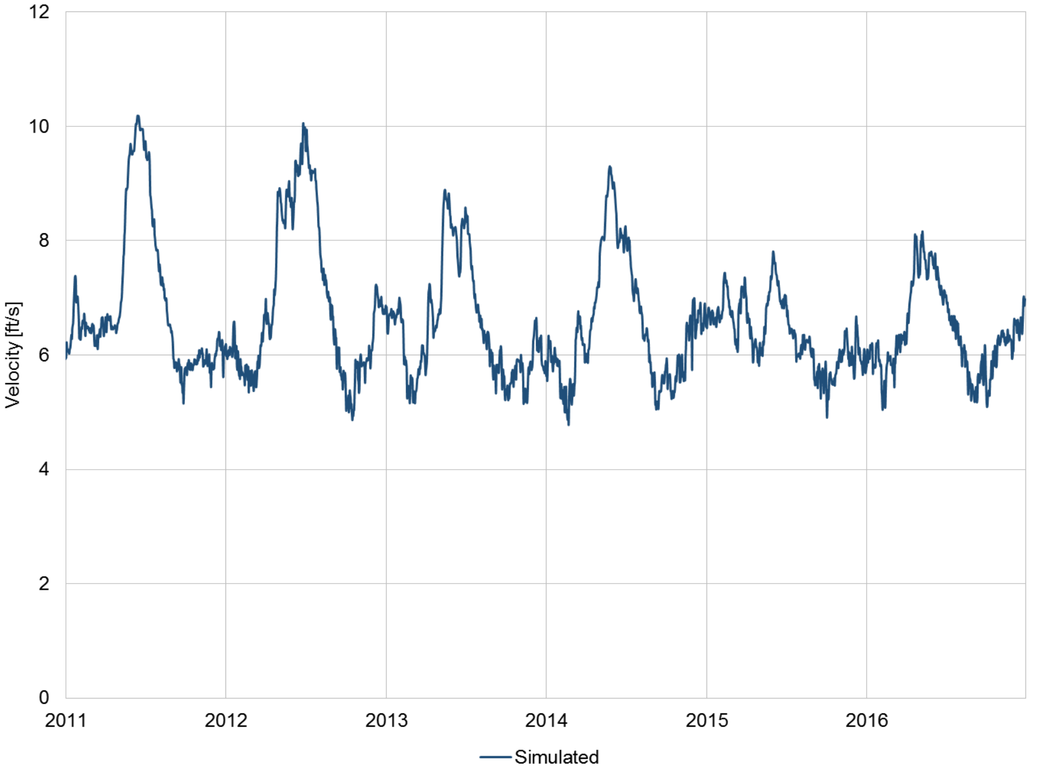


Figure B.2-10 Simulated velocity at PRXW, period 2011 – 2016

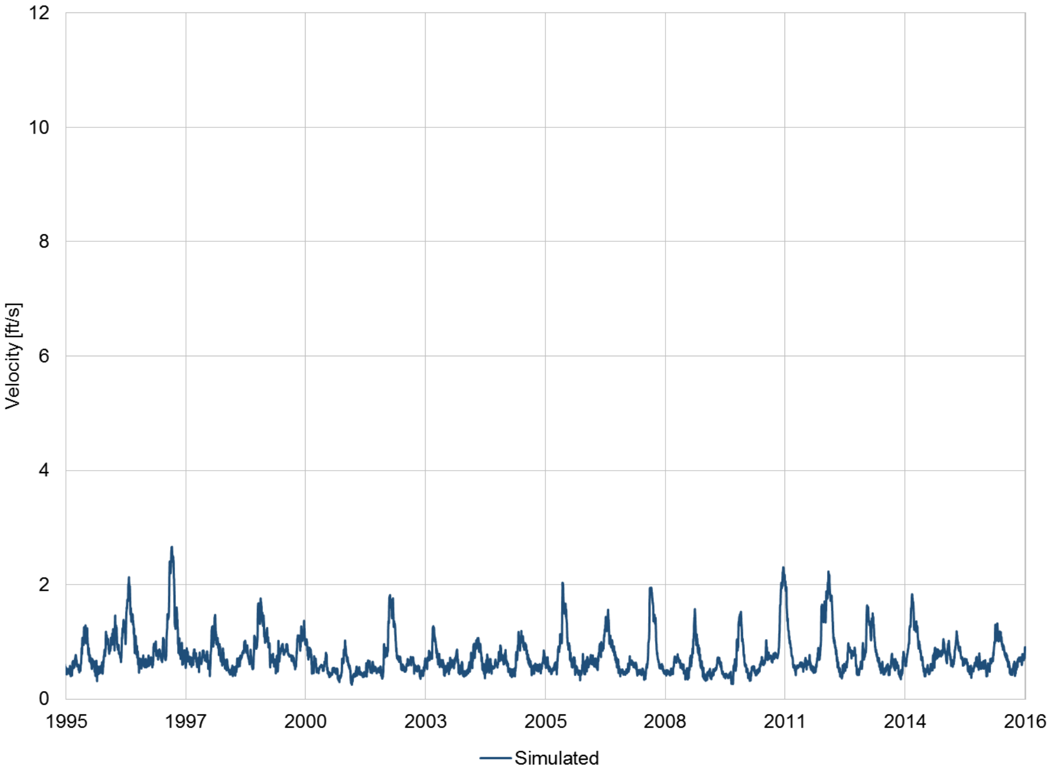


Figure B.2-11 Simulated velocity at WANW, Columbia River RM 415

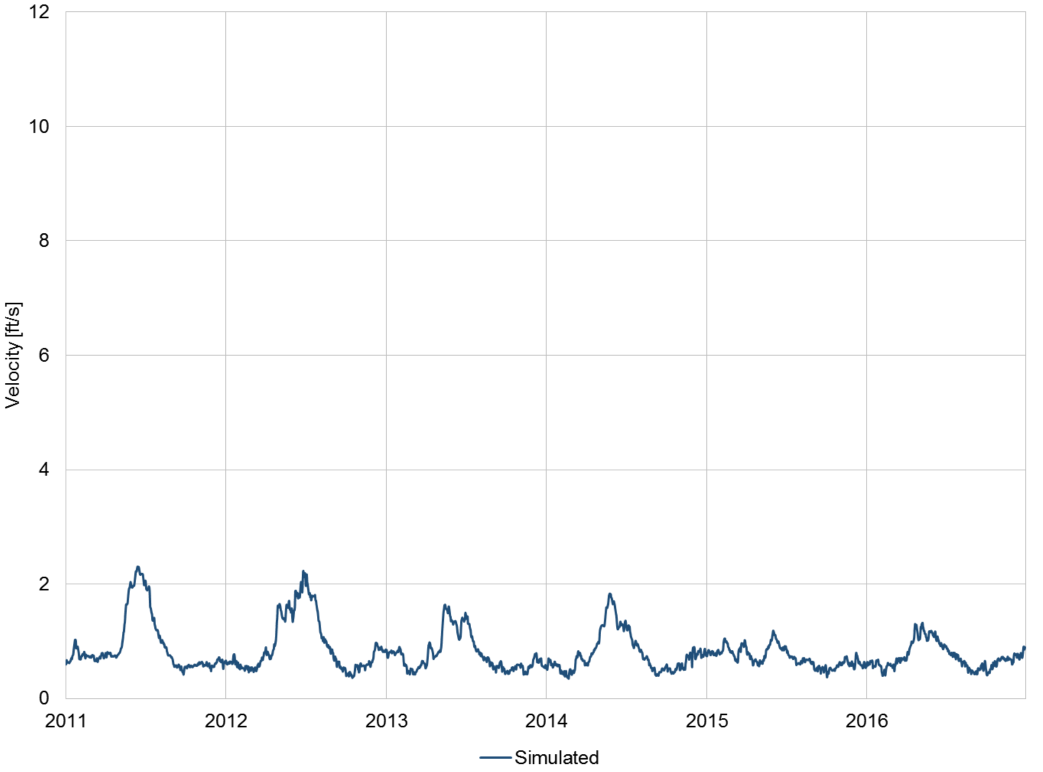


Figure B.2-12 Simulated velocity at WANW, period 2011 – 2016

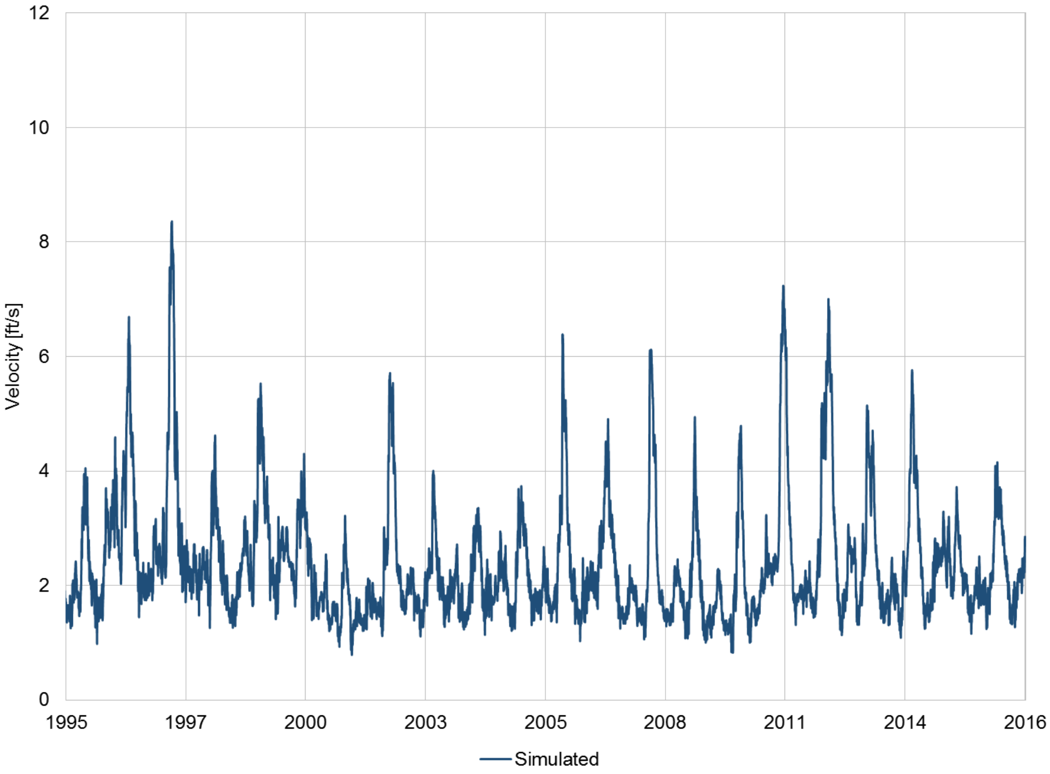


Figure B.2-13 Simulated velocity at RIGW, Columbia River RM 452

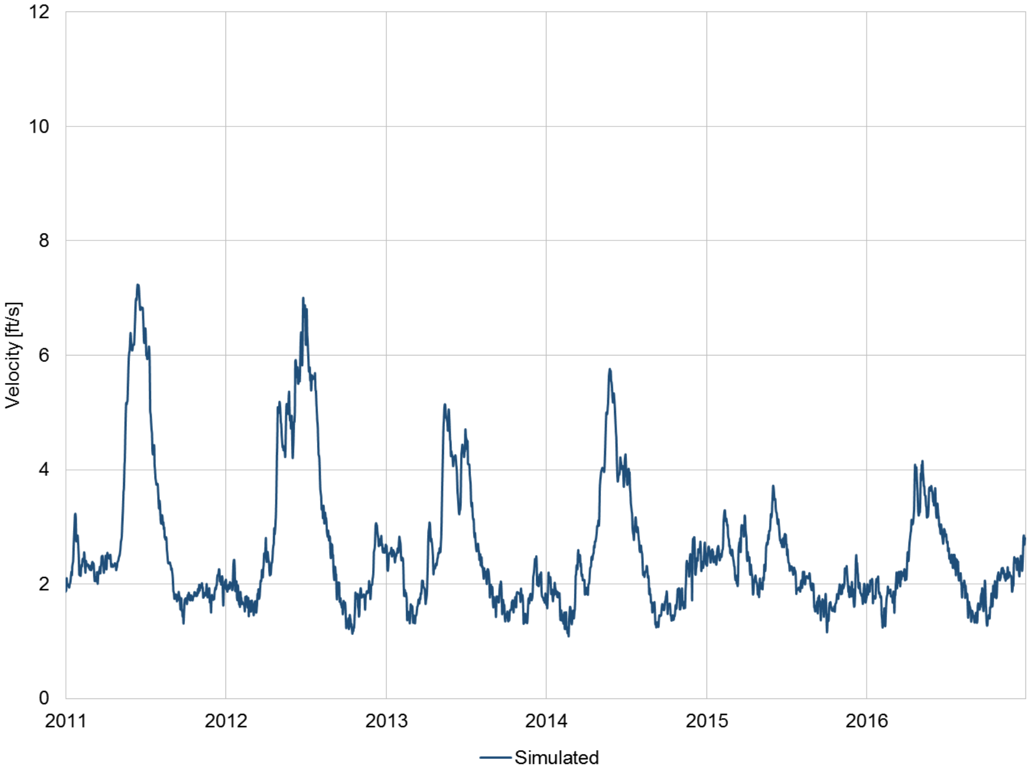


Figure B.2-14 Simulated velocity at RIGW, period 2011 – 2016

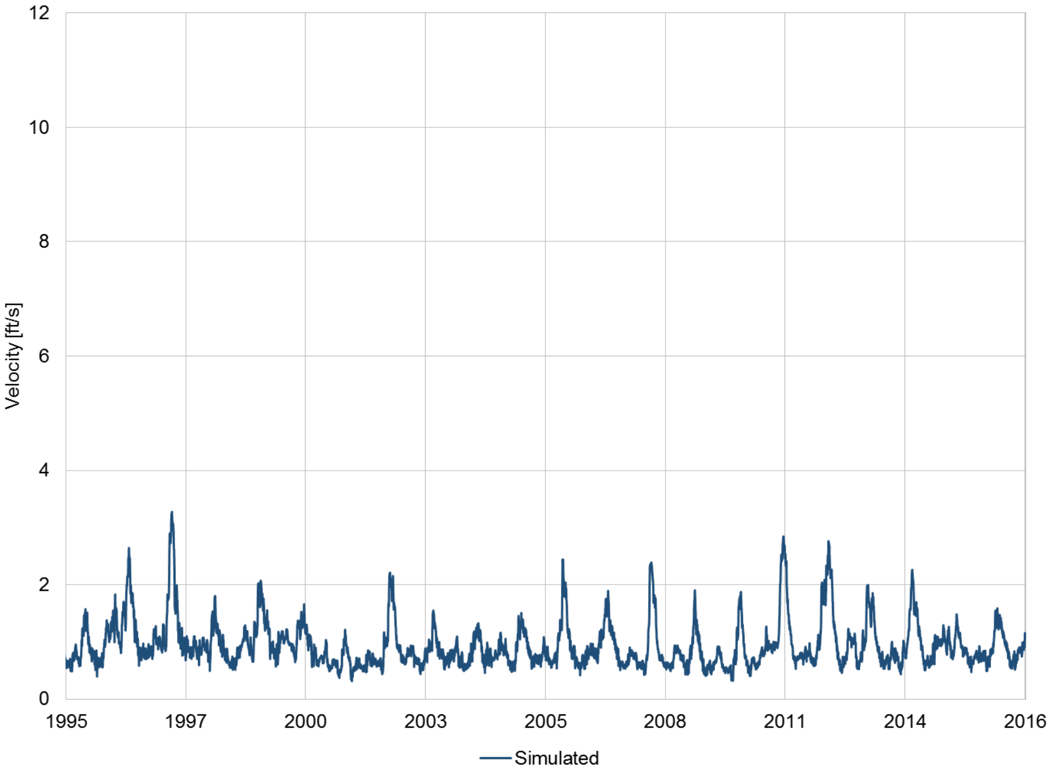


Figure B.2-15 Simulated velocity at RRDW, Columbia River RM 472

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

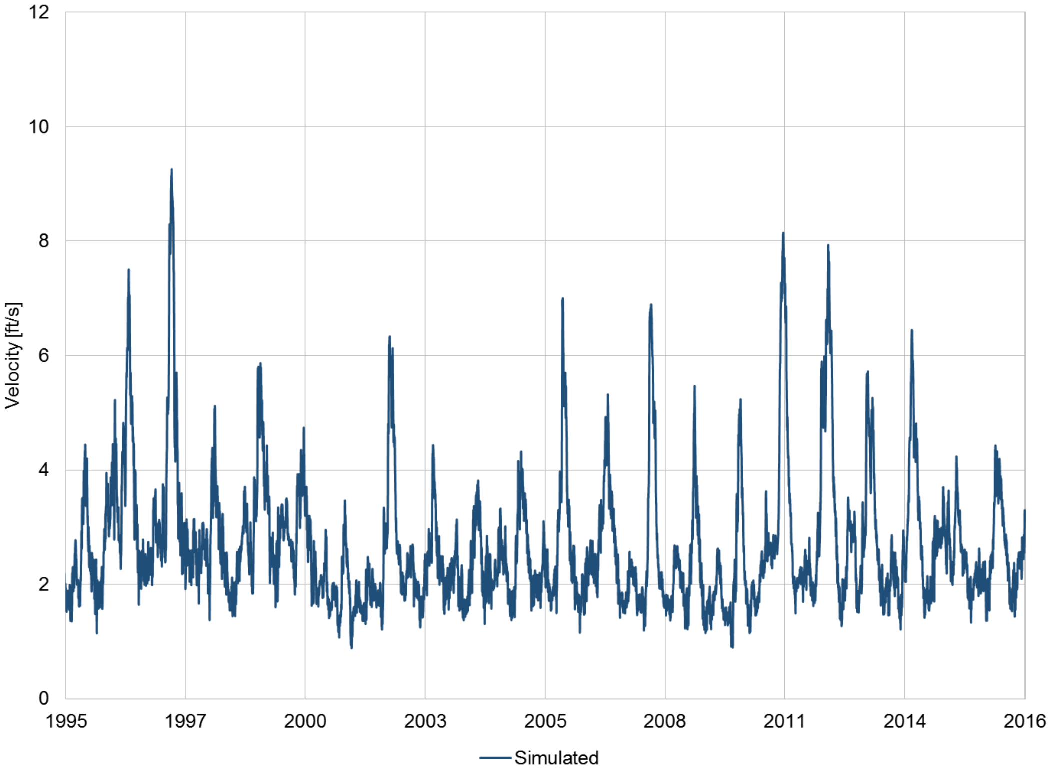


Figure B.2-17 Simulated velocity at WELW, Columbia River RM 514

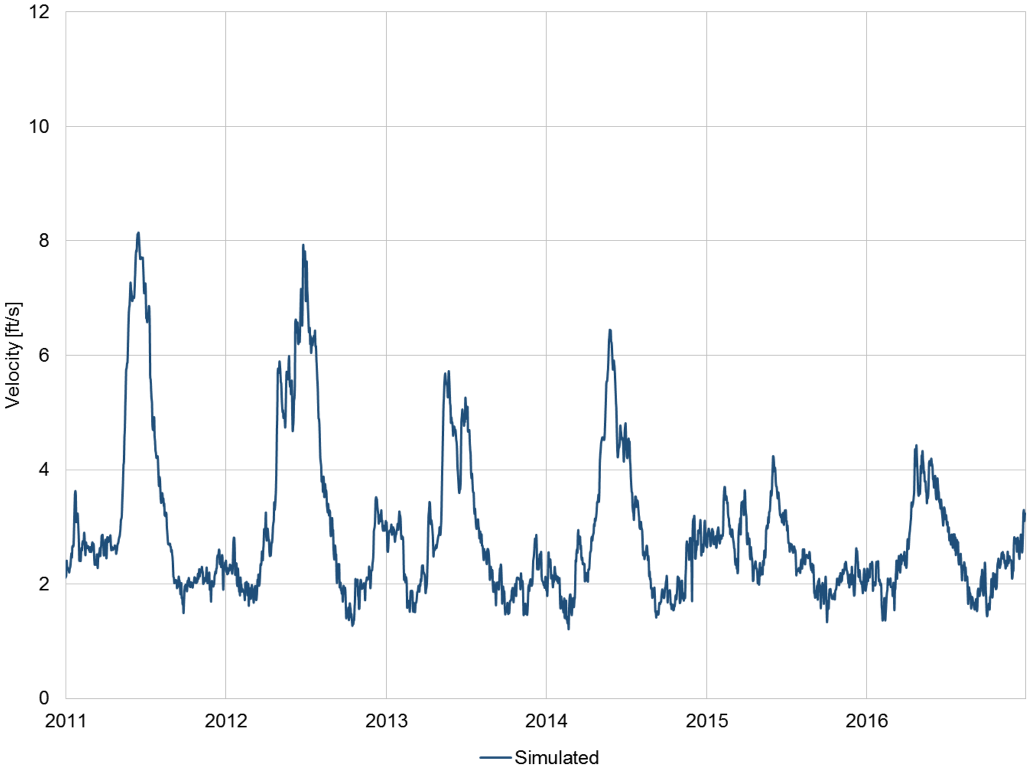


Figure B.2-18 Simulated velocity at WELW, period 2011 – 2016

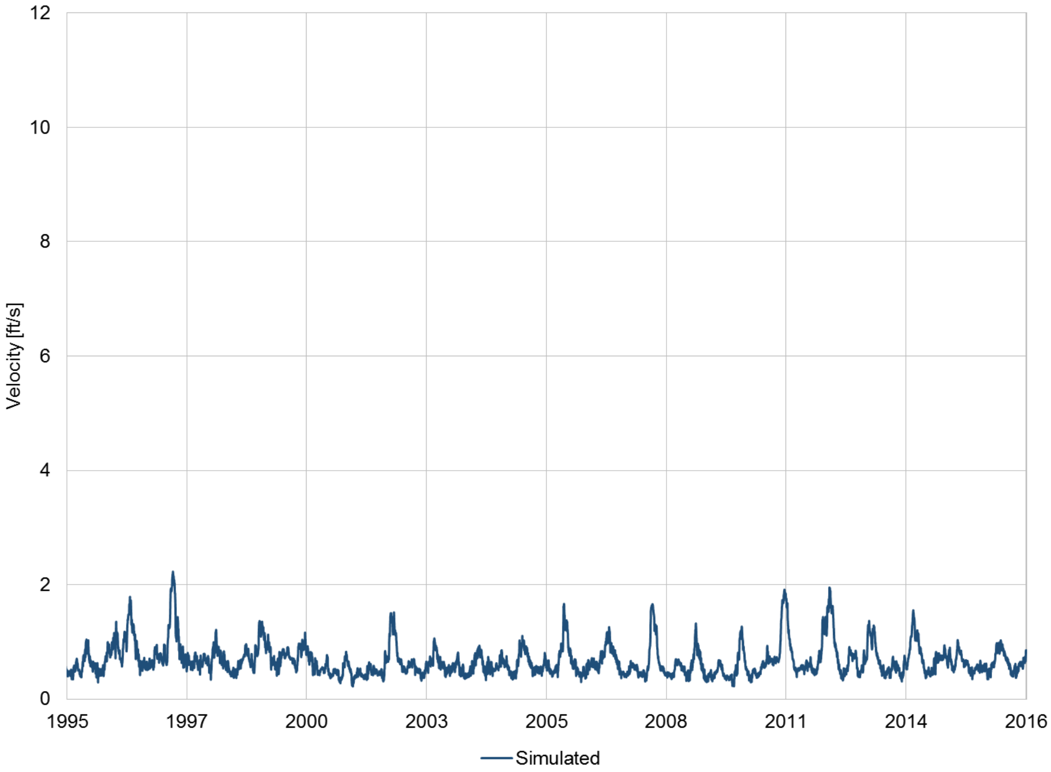


Figure B.2-19 Simulated velocity at CHQW, Columbia River RM 545

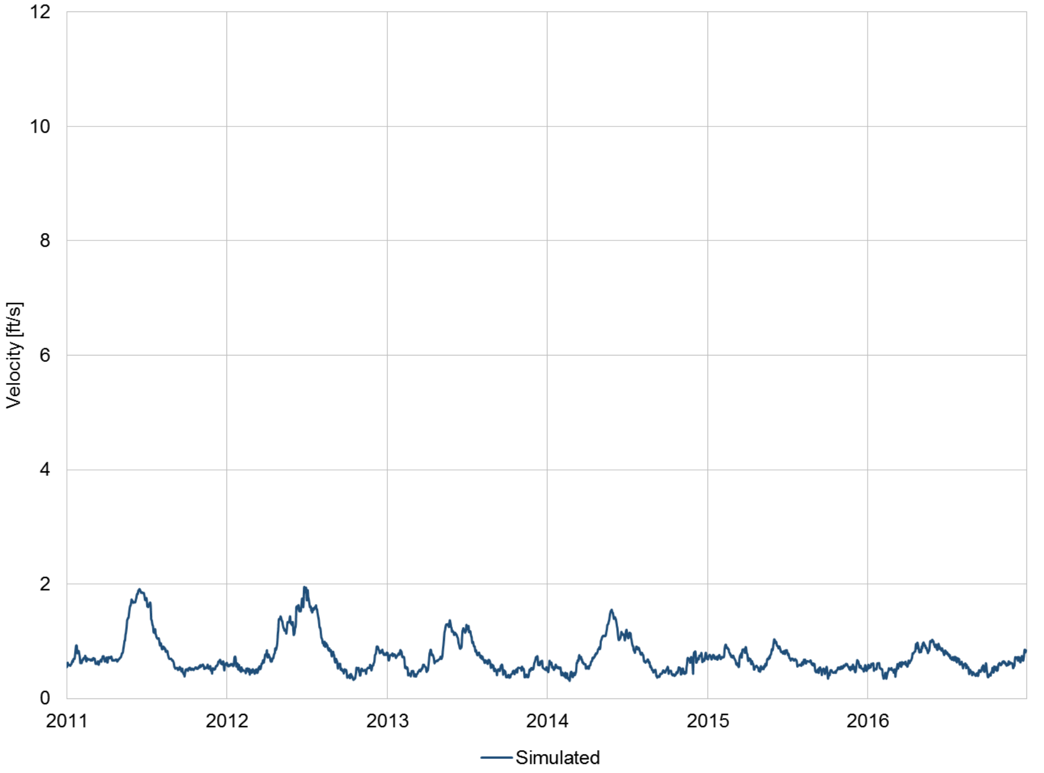


Figure B.2-20 Simulated velocity at CHQW, period 2011 – 2016

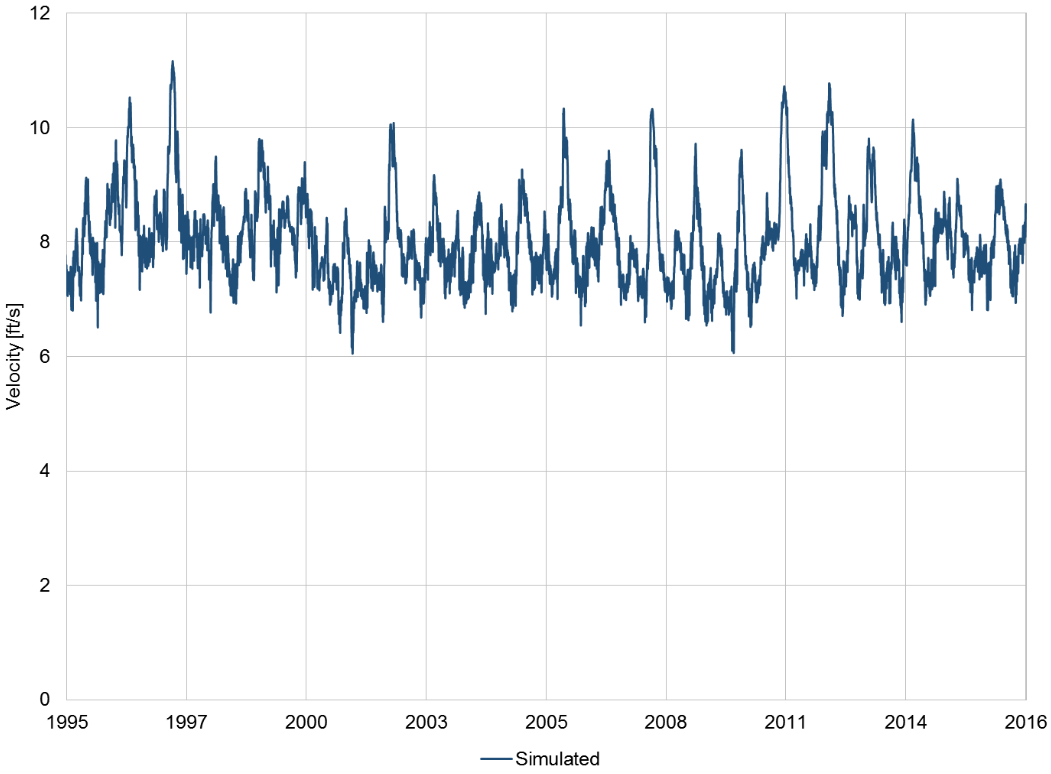


Figure B.2-21 Simulated velocity at GCGW, Columbia River RM 590

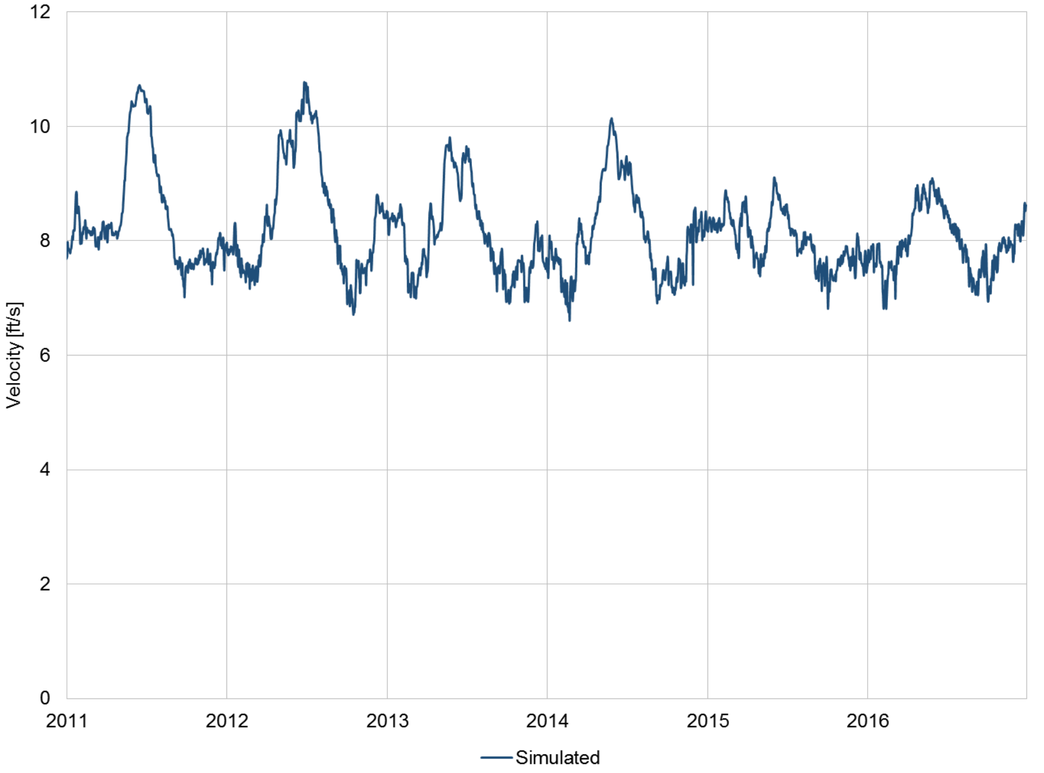


Figure B.2-22 Simulated velocity at GCGW, period 2011 – 2016

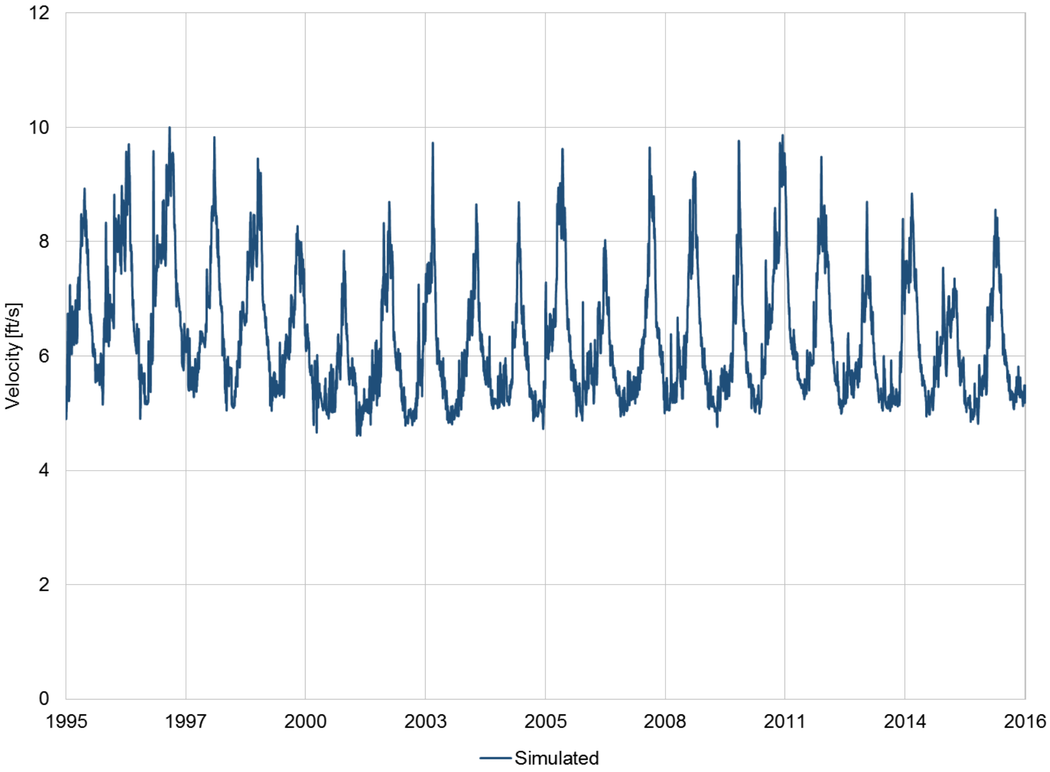


Figure B.2-23 Simulated velocity at IDSW, Snake River RM 6.8

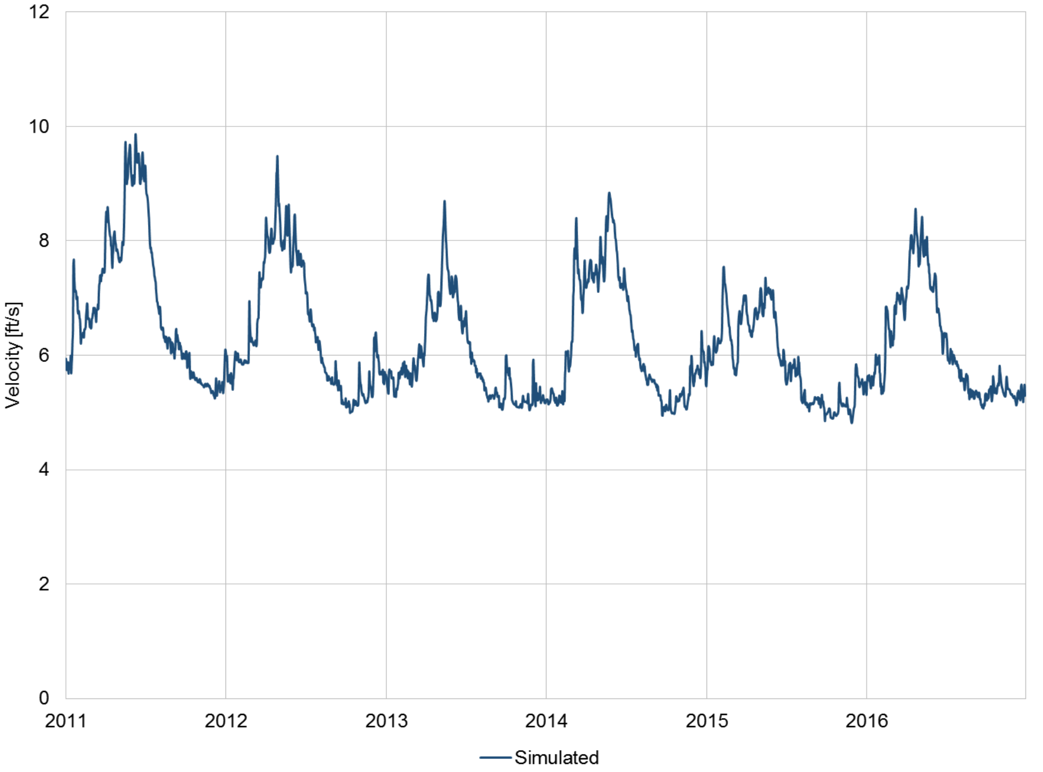


Figure B.2-24 Simulated velocity at IDSW, period 2011 – 2016

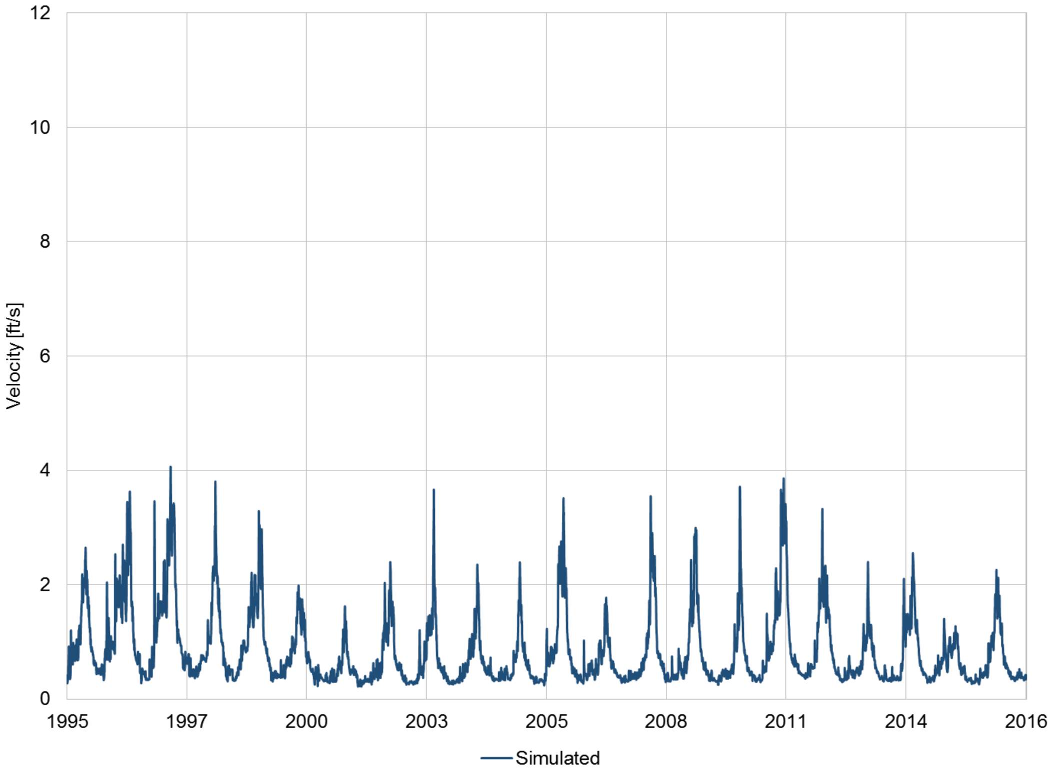


Figure B.2-25 Simulated velocity at LMNW, Snake River RM 40.8

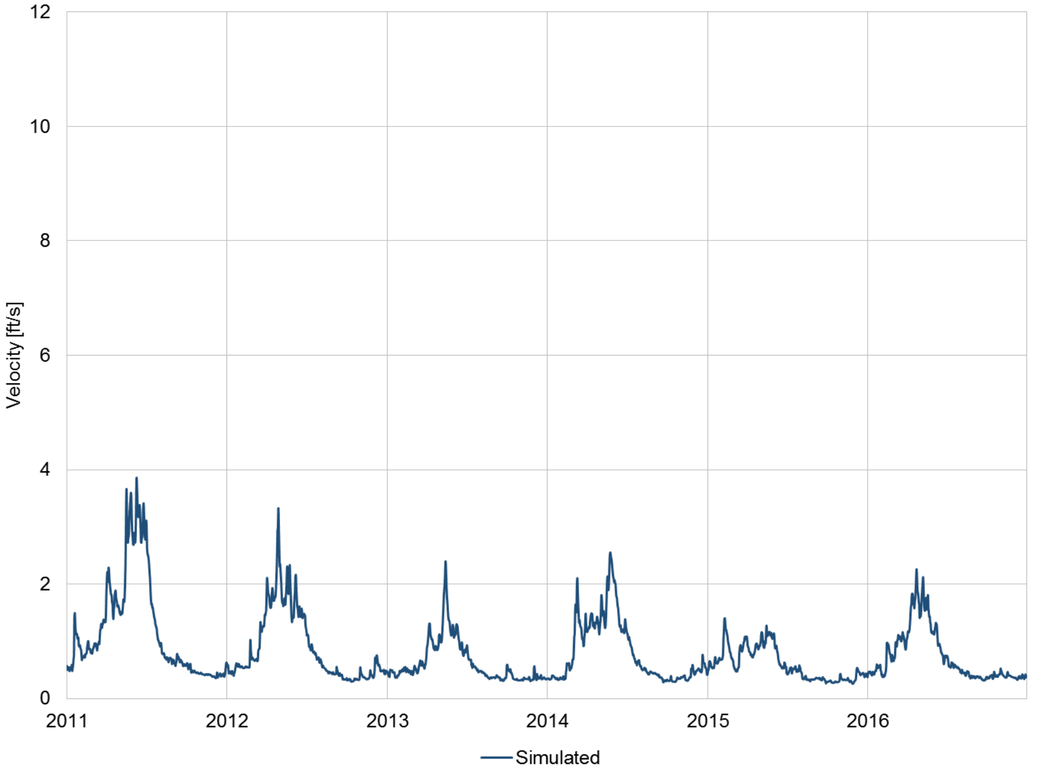


Figure B.2-26 Simulated velocity at LMNW, period 2011 – 2016

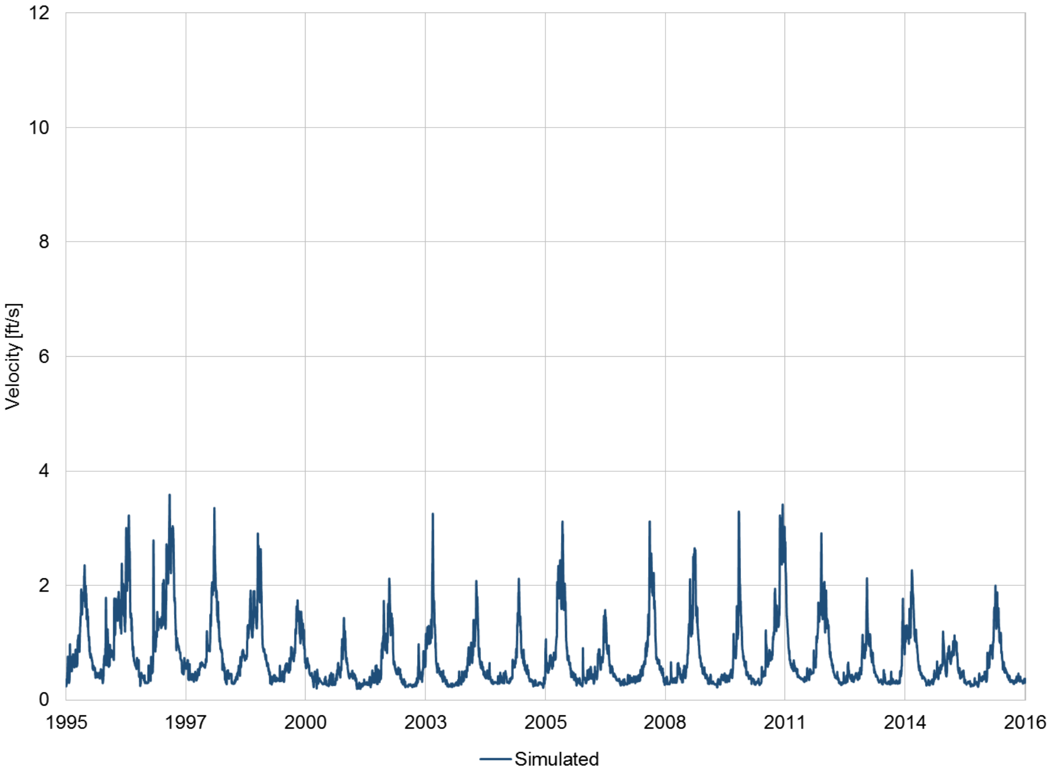


Figure B.2-27 Simulated velocity at LGSW, Snake River RM 69.5

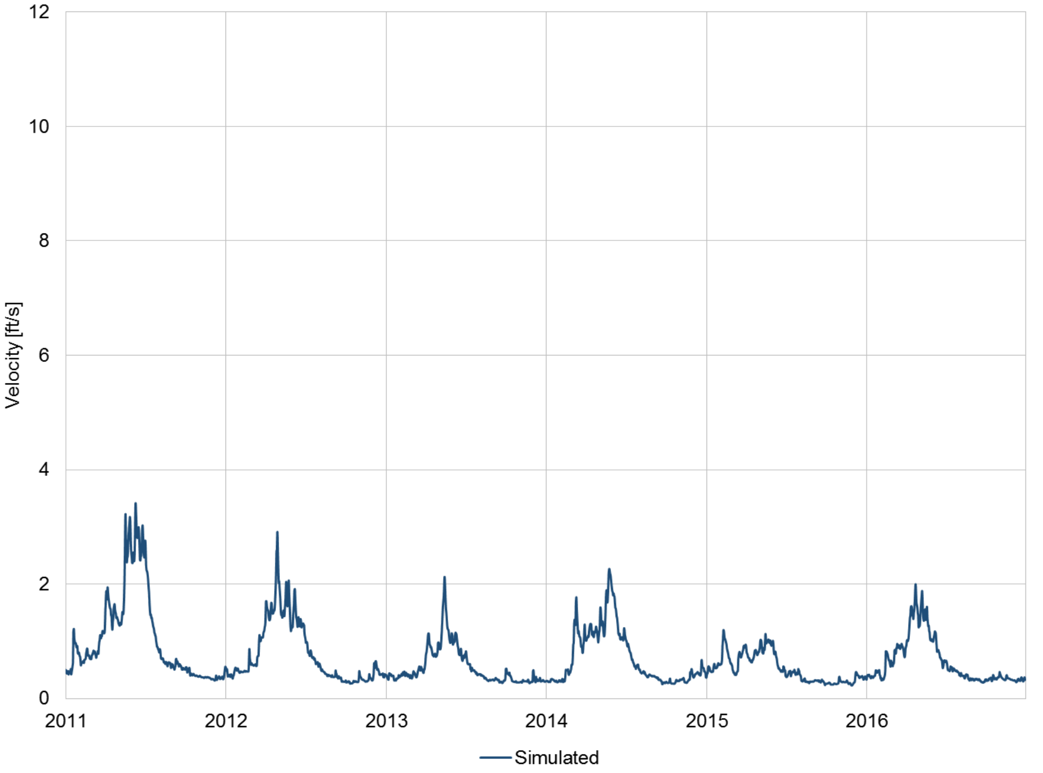


Figure B.2-28 Simulated velocity at LGSW, period 2011 – 2016

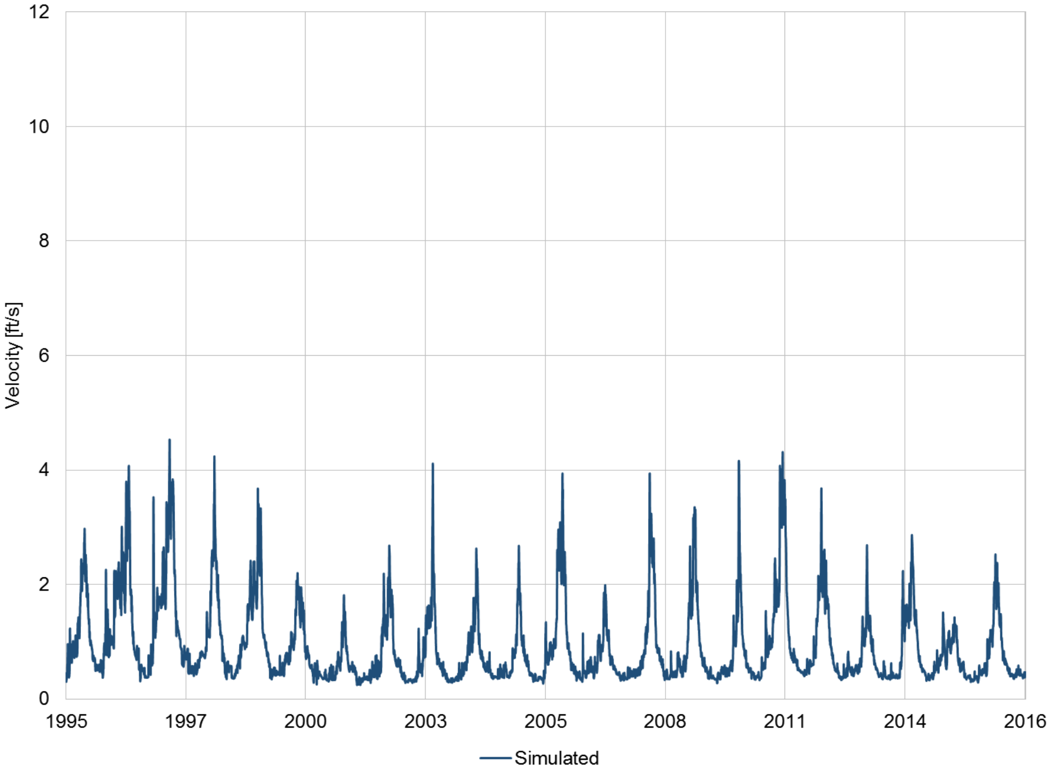


Figure B.2-29 Simulated velocity at LGNW, Snake River RM 106.8

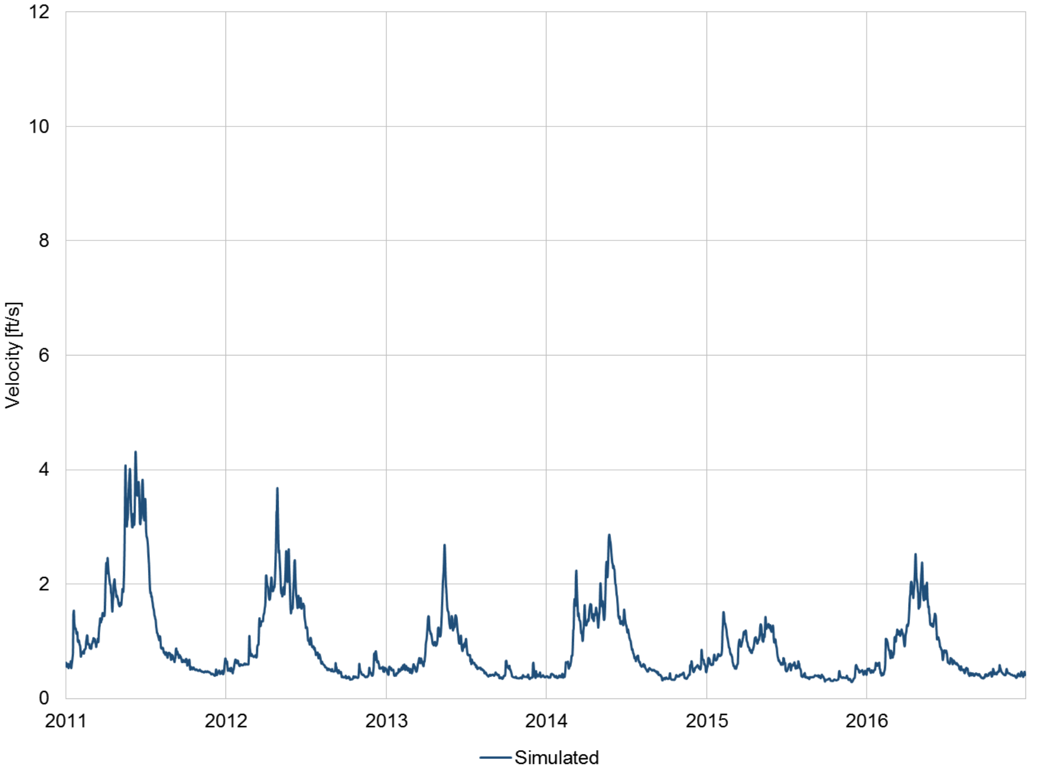


Figure B.2-30 Simulated velocity at LGNW, period 2011 – 2016

Appendix C 2018 RBM10B Model Setup

C.1 Introduction

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

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

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

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

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

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

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

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

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

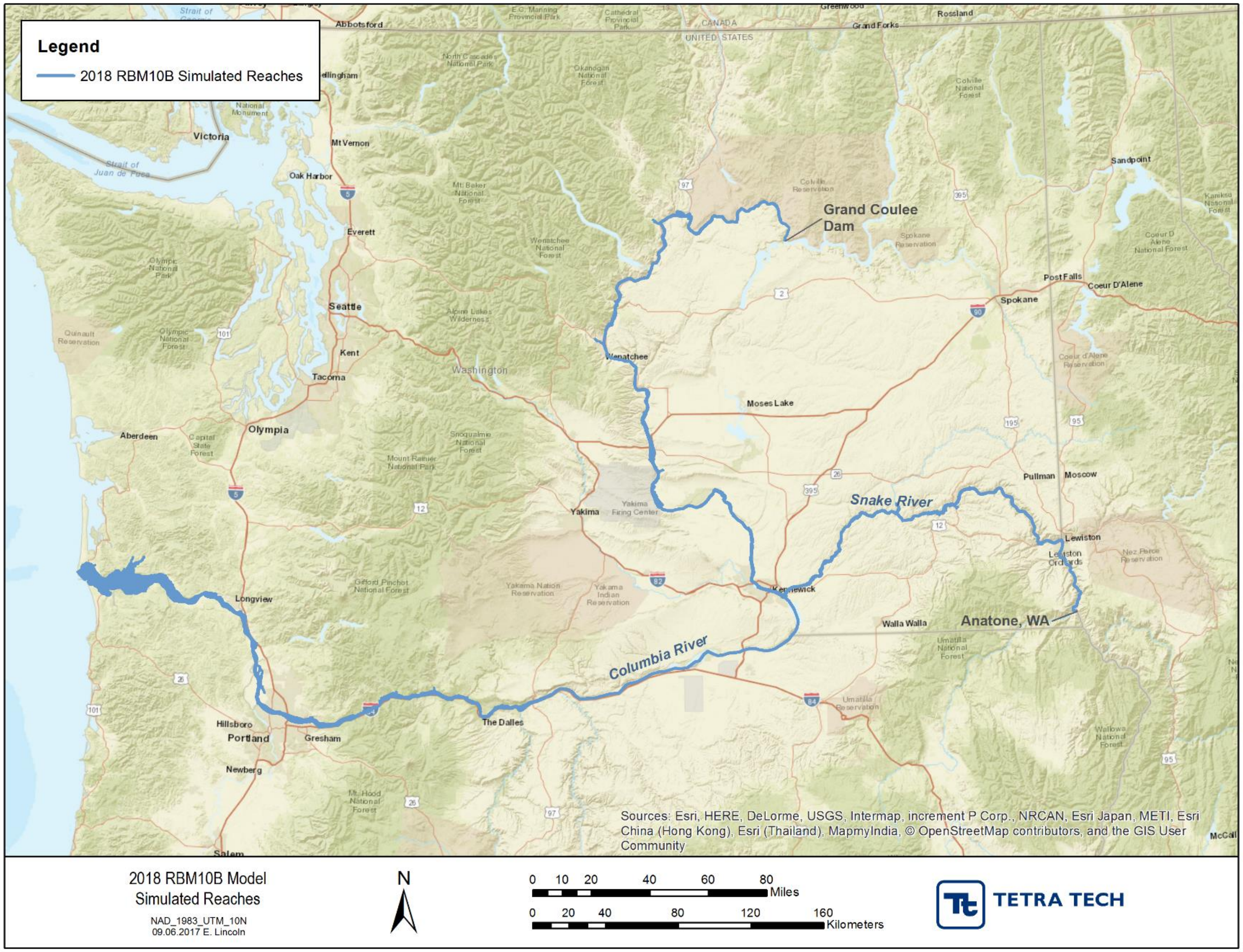


Figure C.1-1 2018 RBM10B spatial model representation of the Columbia and Snake Rivers

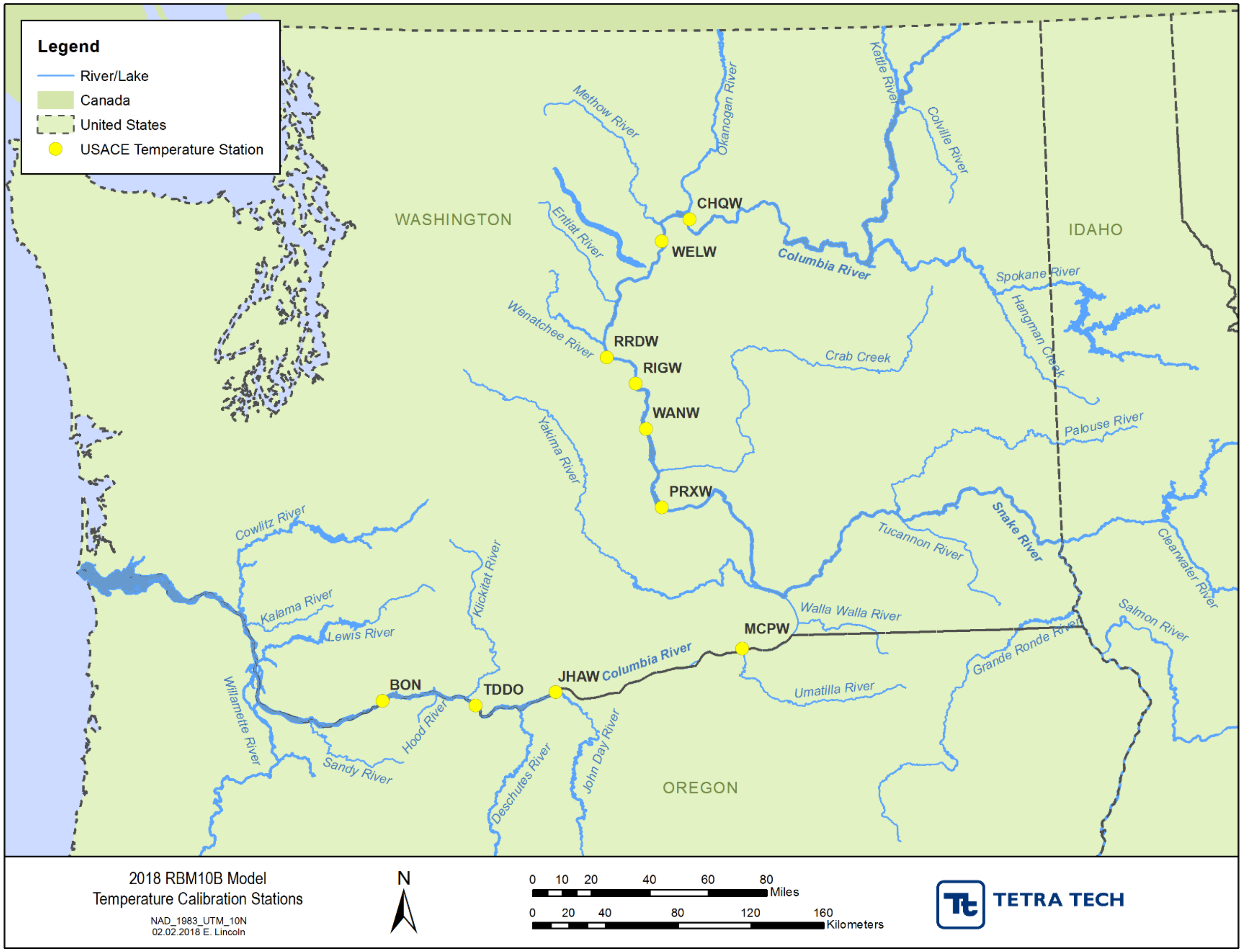


Figure C.1-2 2018 RBM10B Columbia and Snake Rivers temperature calibration stations

C.2 Water Temperature Model Performance Statistics

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

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

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

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

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

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

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

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

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

C.3 Temperature Model Results

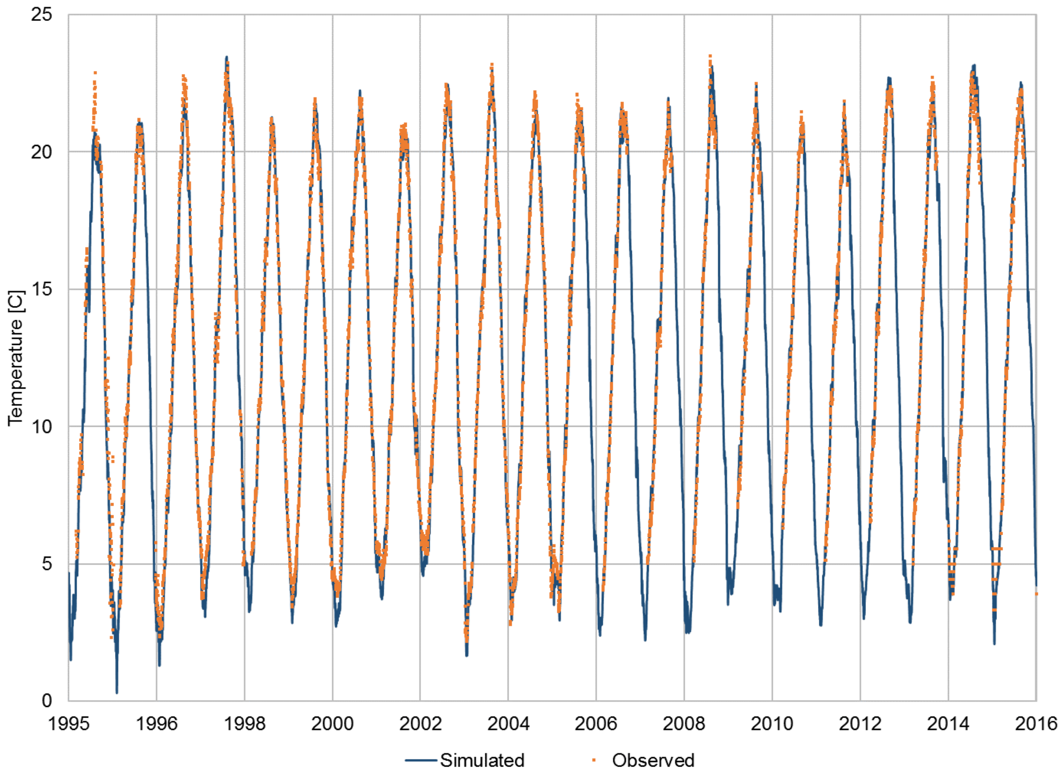


Figure C.3-1 Simulated versus observed temperature at BON, Columbia River RM 146

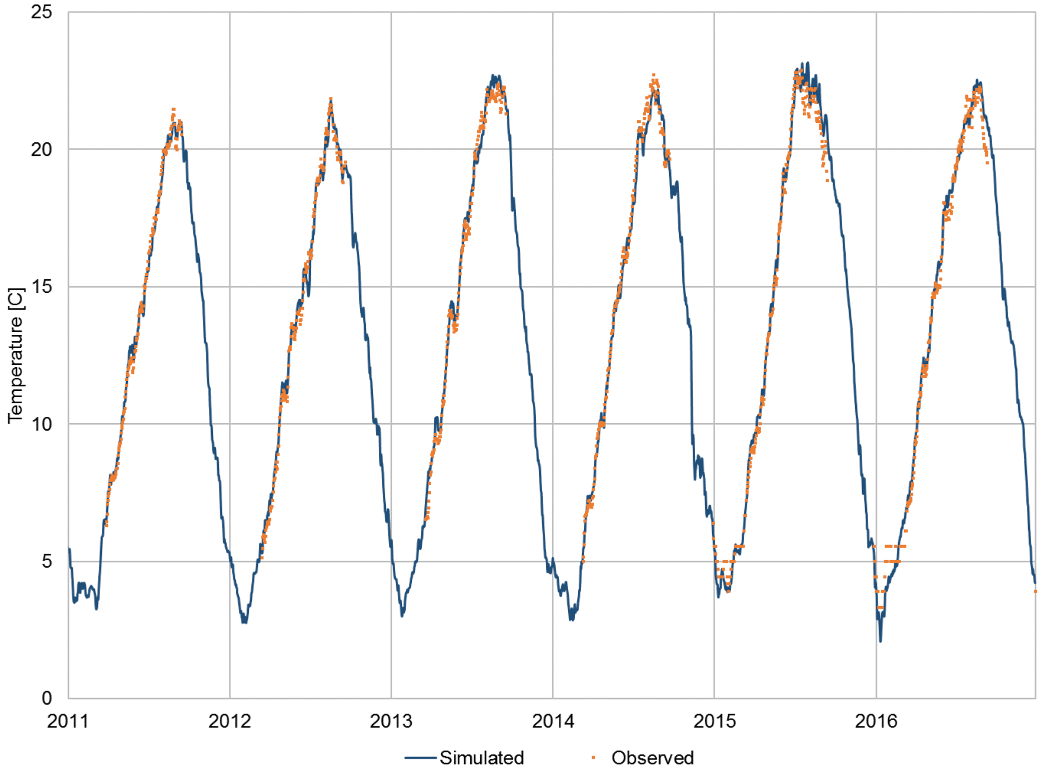


Figure C.3-2 Simulated versus observed temperature at BON, period 2011 – 2016

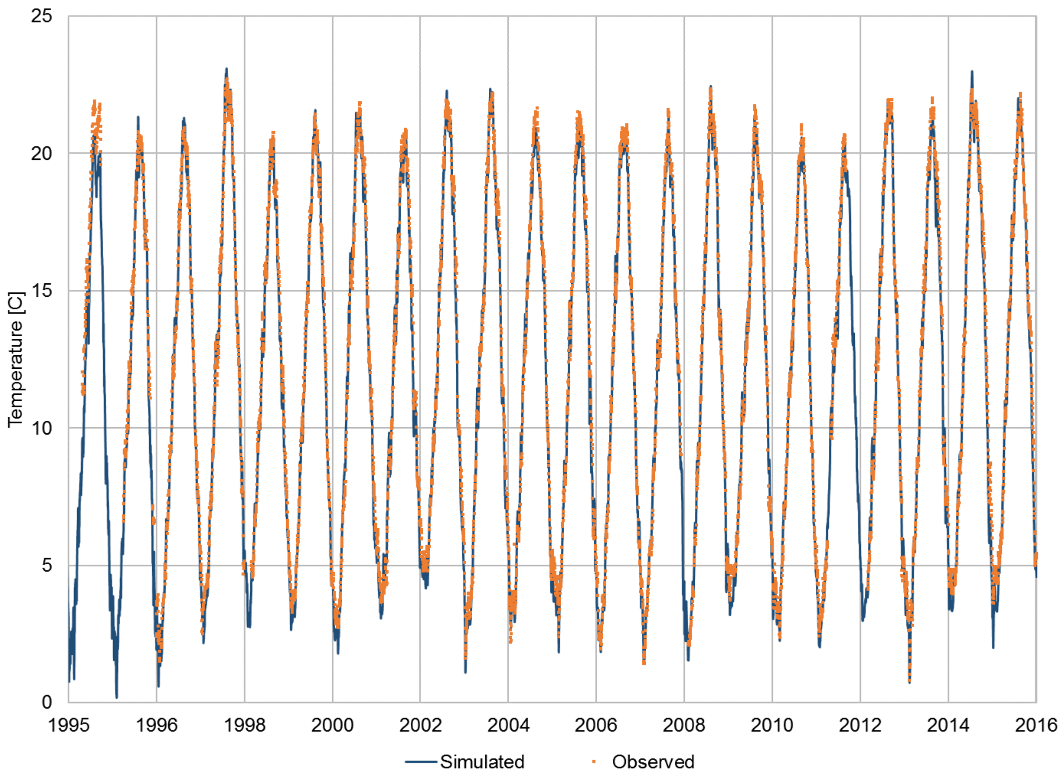


Figure C.3-3 Simulated versus observed temperature at MCPW, Columbia River RM 291

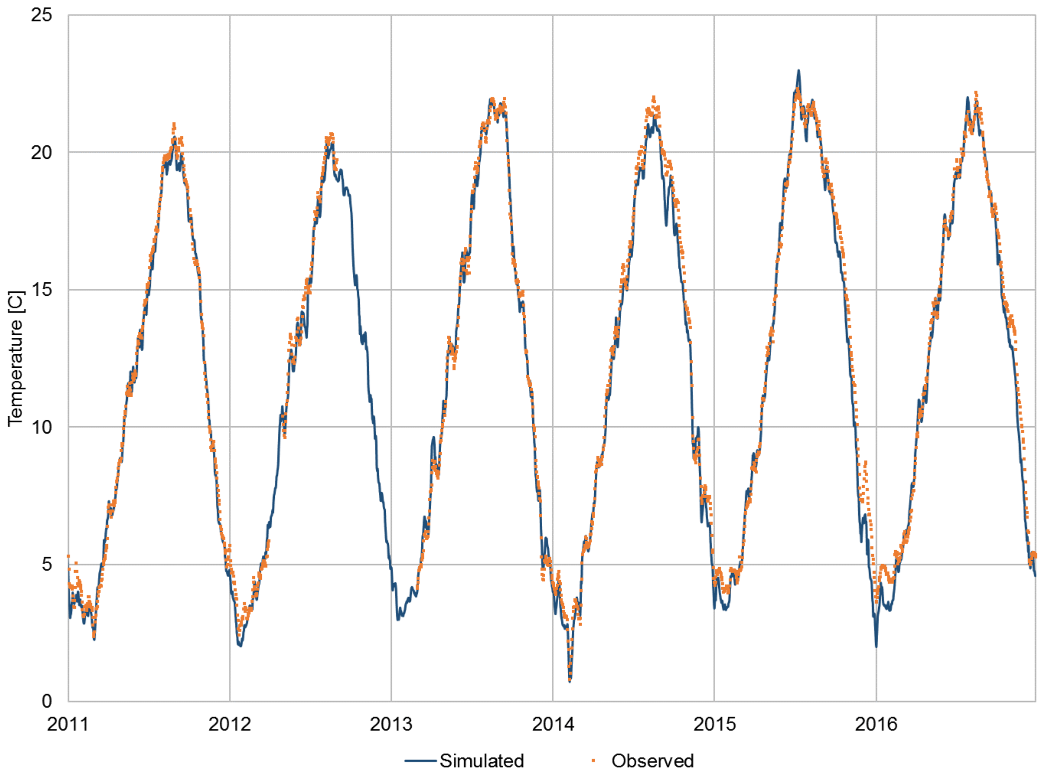


Figure C.3-4 Simulated versus observed temperature at MCPW, period 2011 – 2016

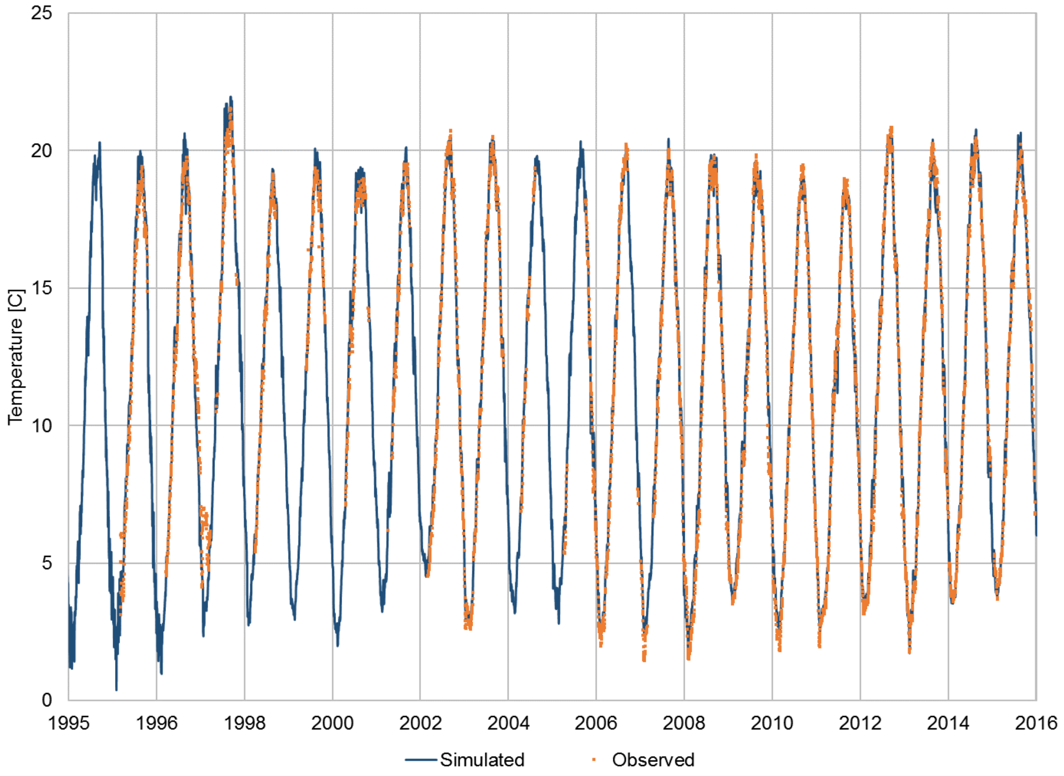


Figure C.3-5 Simulated versus observed temperature at WANW, Columbia River RM 415

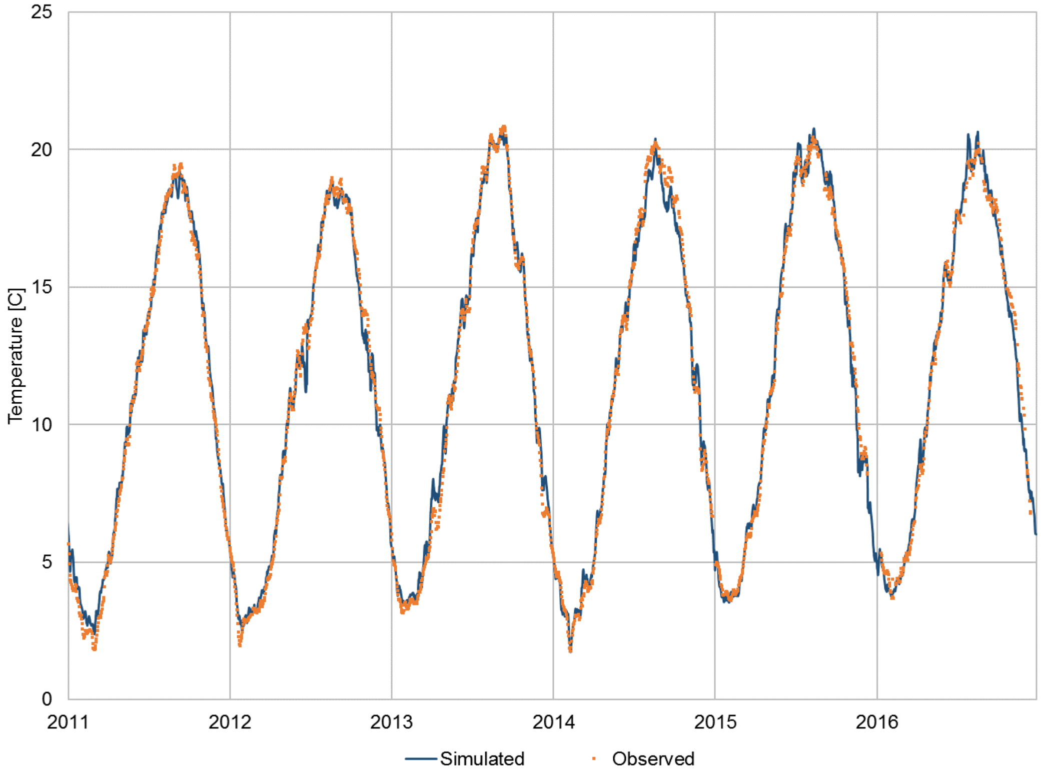


Figure C.3-6 Simulated versus observed temperature at WANW, period 2011 – 2016

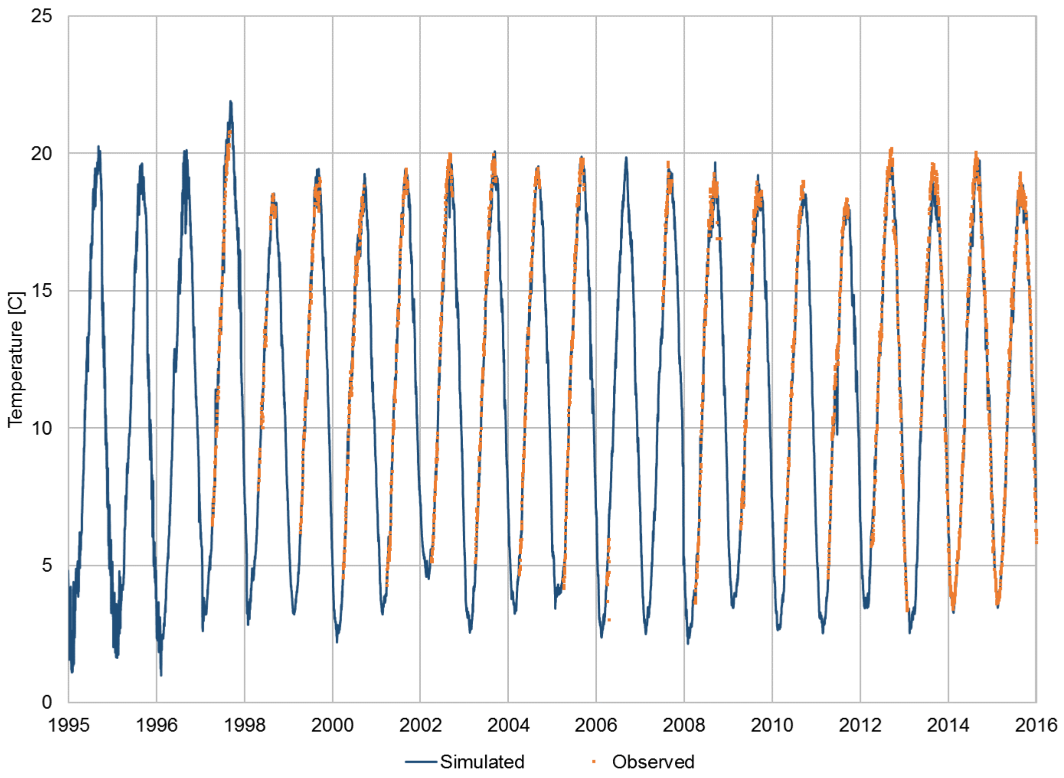


Figure C.3-7 Simulated versus observed temperature at WELW, Columbia River RM 514

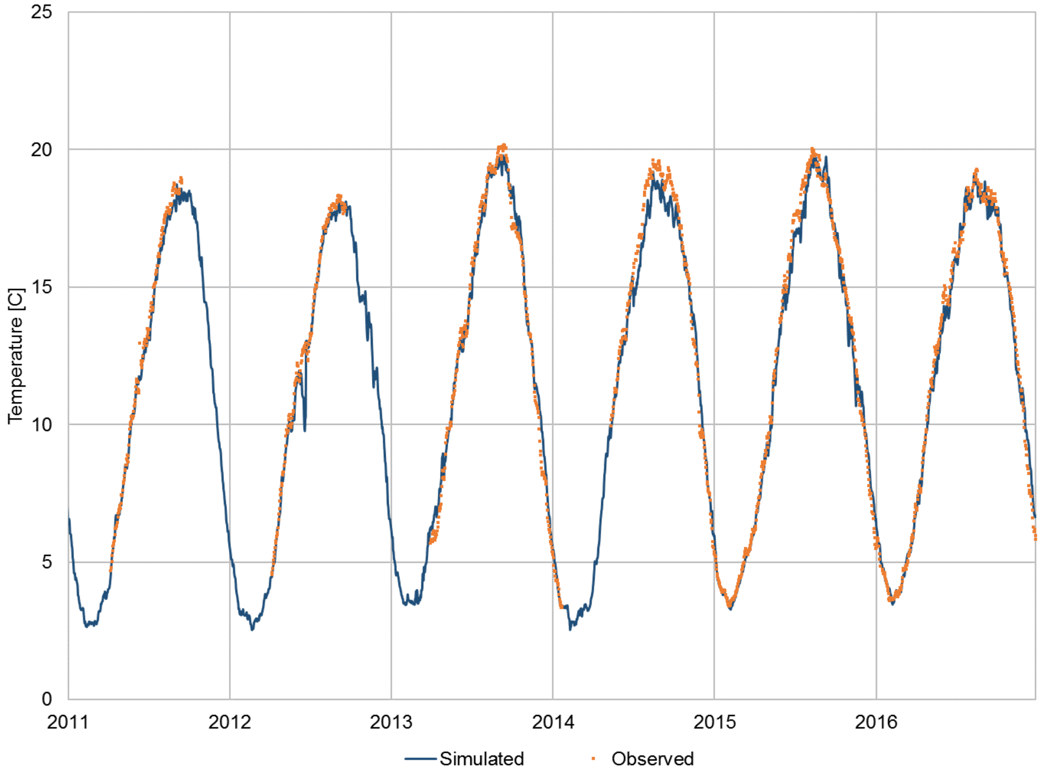


Figure C.3-8 Simulated versus observed temperature at WELW, period 2011 – 2016

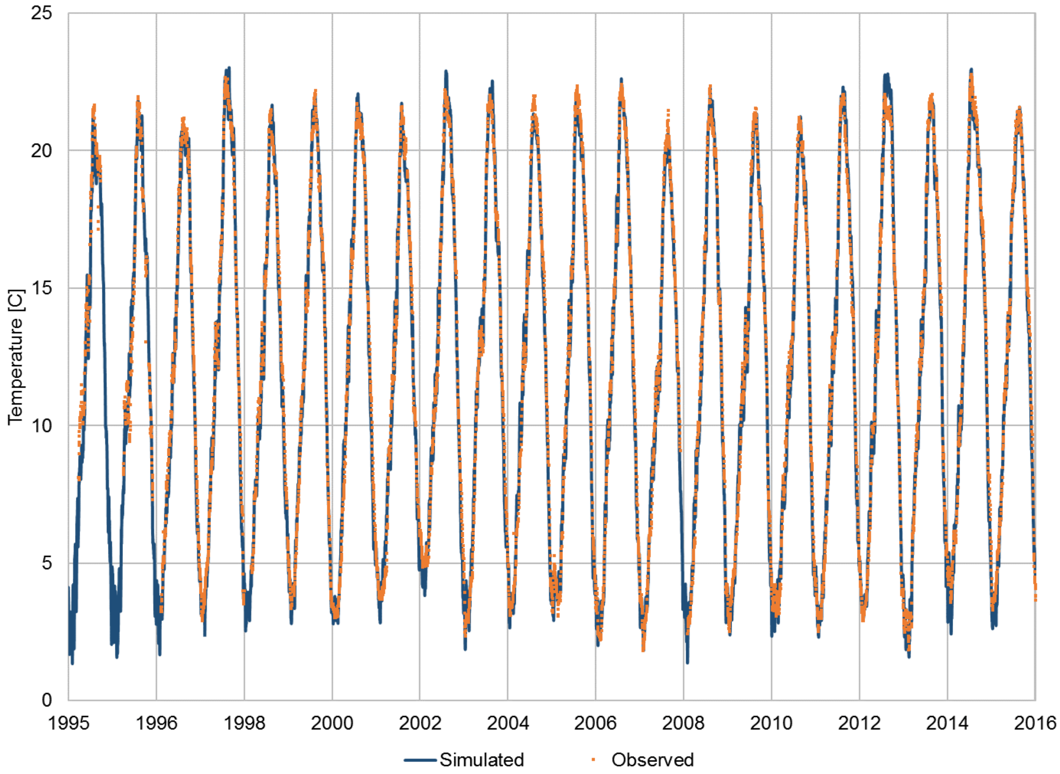


Figure C.3-9 Simulated versus observed temperature at IDSW, Snake River RM 6.8

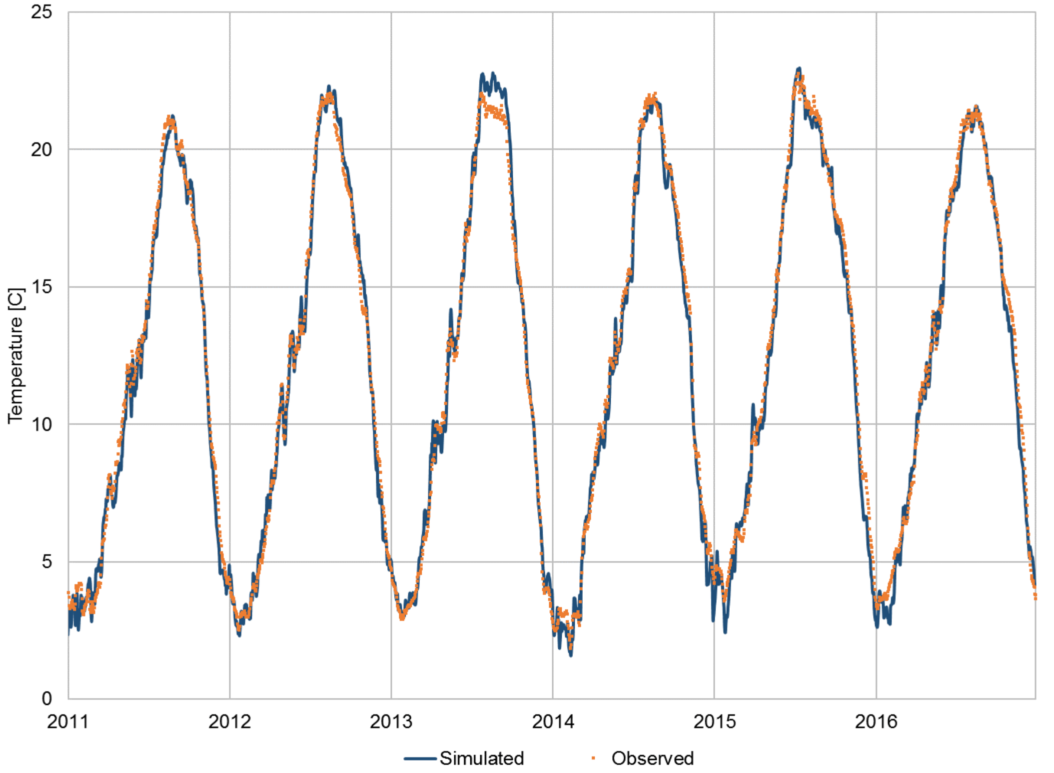


Figure C.3-10 Simulated versus observed temperature at IDSW, period 2011 – 2016

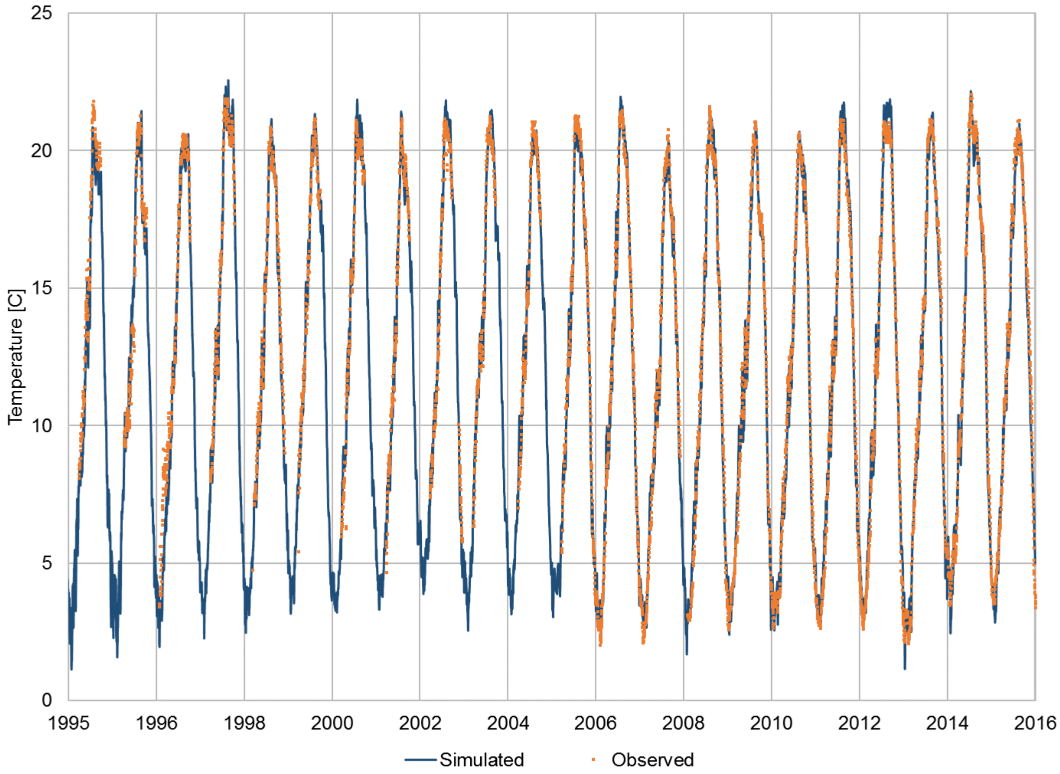


Figure C.3-11 Simulated versus observed temperature at LMNW, Snake River RM 40.8

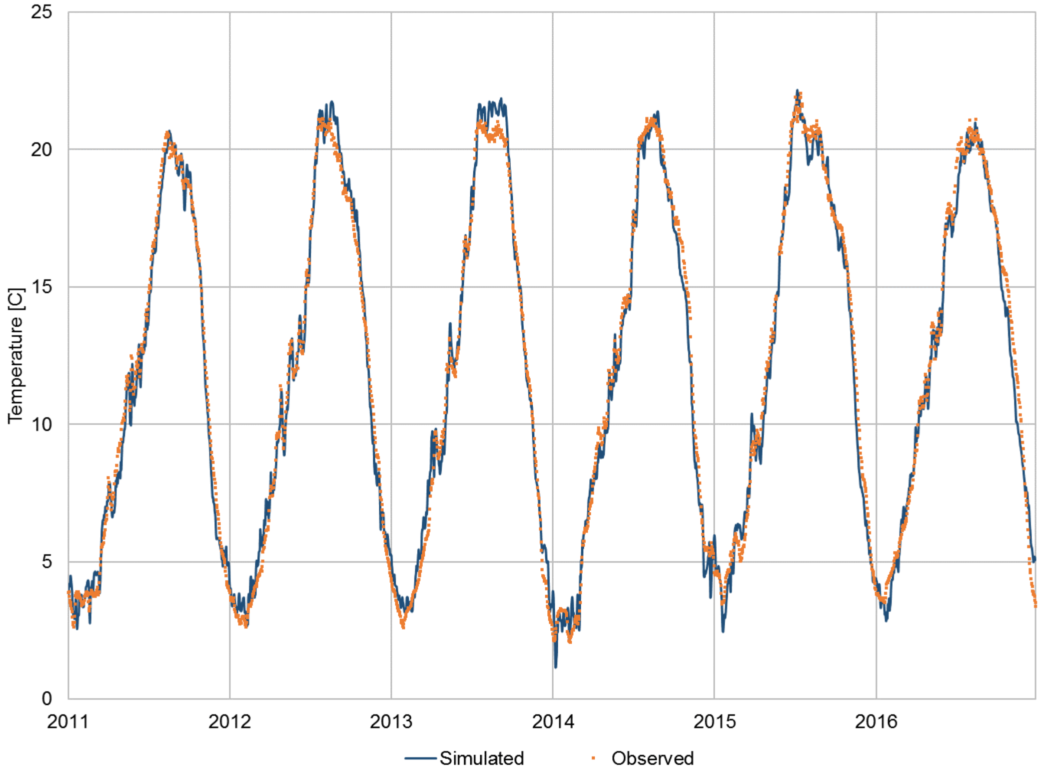


Figure C.3-12 Simulated versus observed temperature at LMNW, period 2011 – 2016

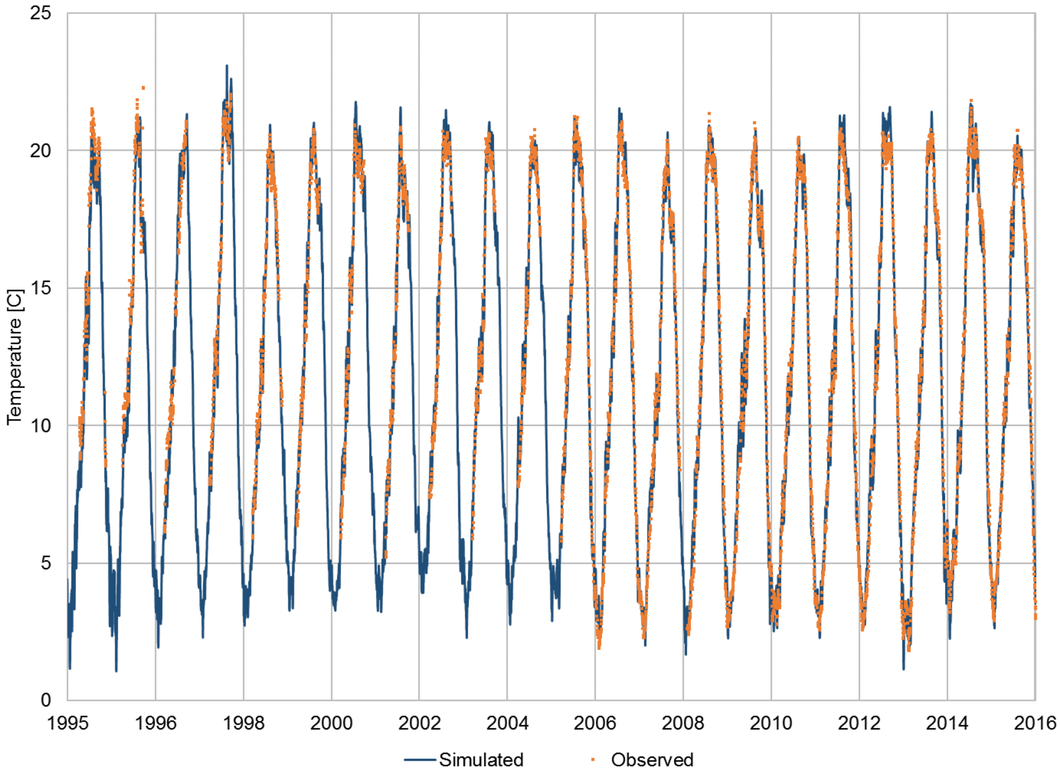


Figure C.3-13 Simulated versus observed temperature at LGSW, Snake River RM 69.5

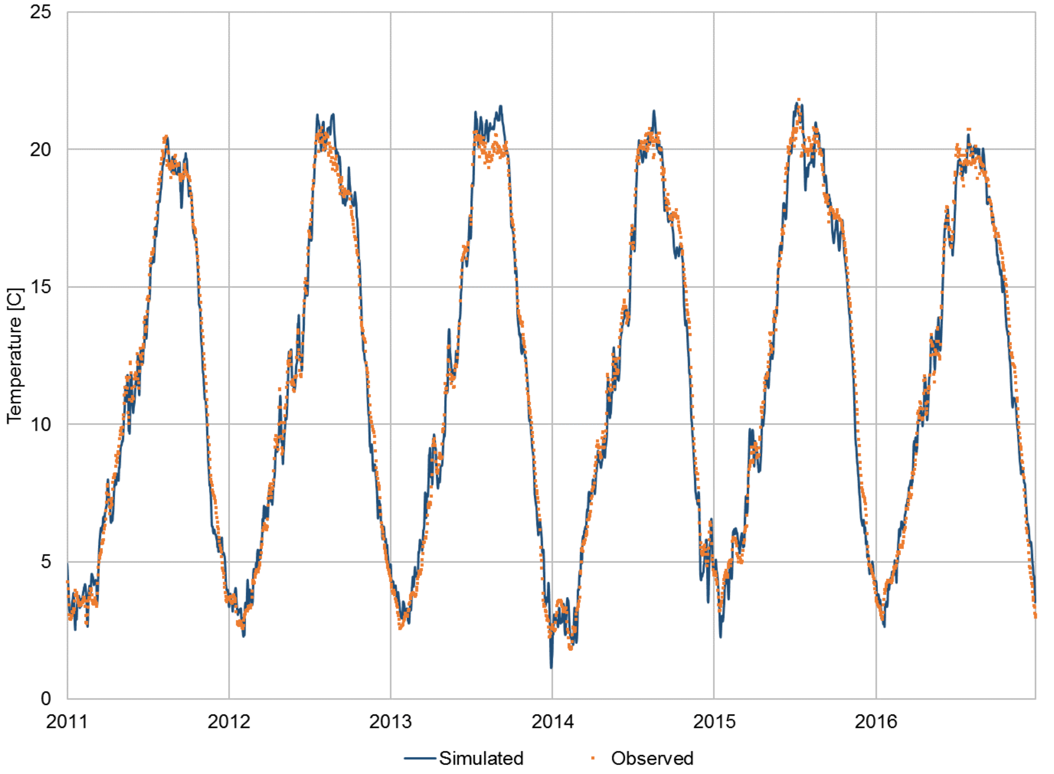


Figure C.3-14 Simulated versus observed temperature at LGSW, period 2011 – 2016

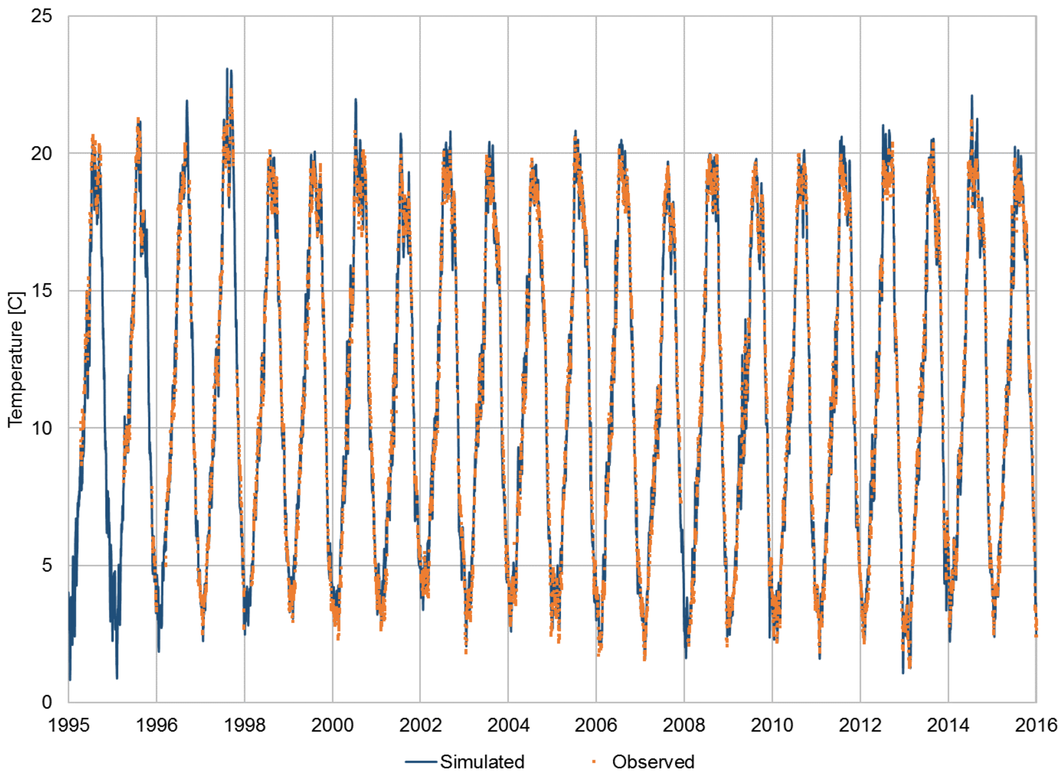


Figure C.3-15 Simulated versus observed temperature at LGNW, Snake River RM 106.8

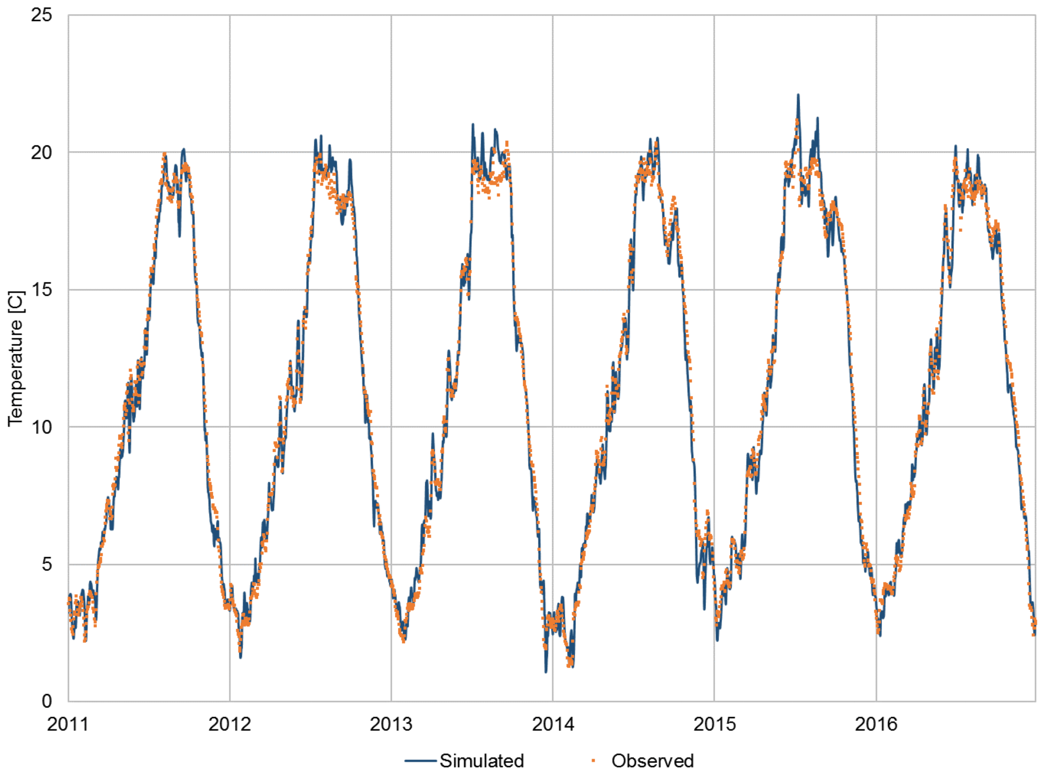


Figure C.3-16 Simulated versus observed temperature at LGNW, period 2011 – 2016

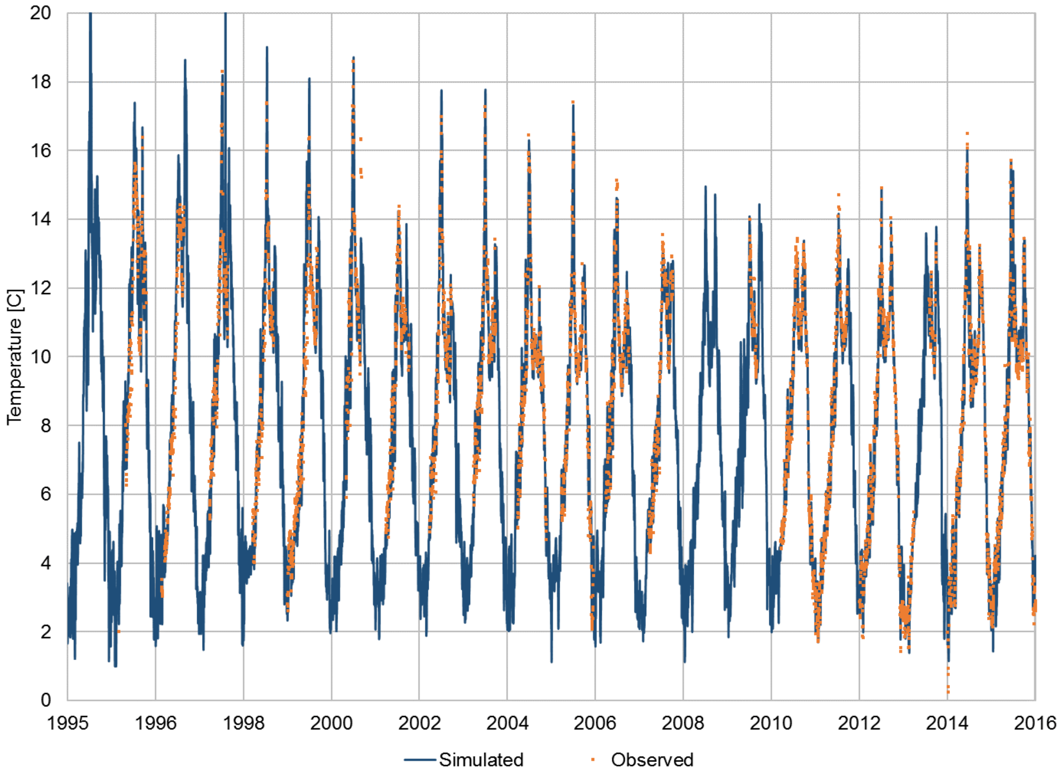


Figure C.3-17 Simulated versus observed temperature at PEKI, Clearwater River RM 33

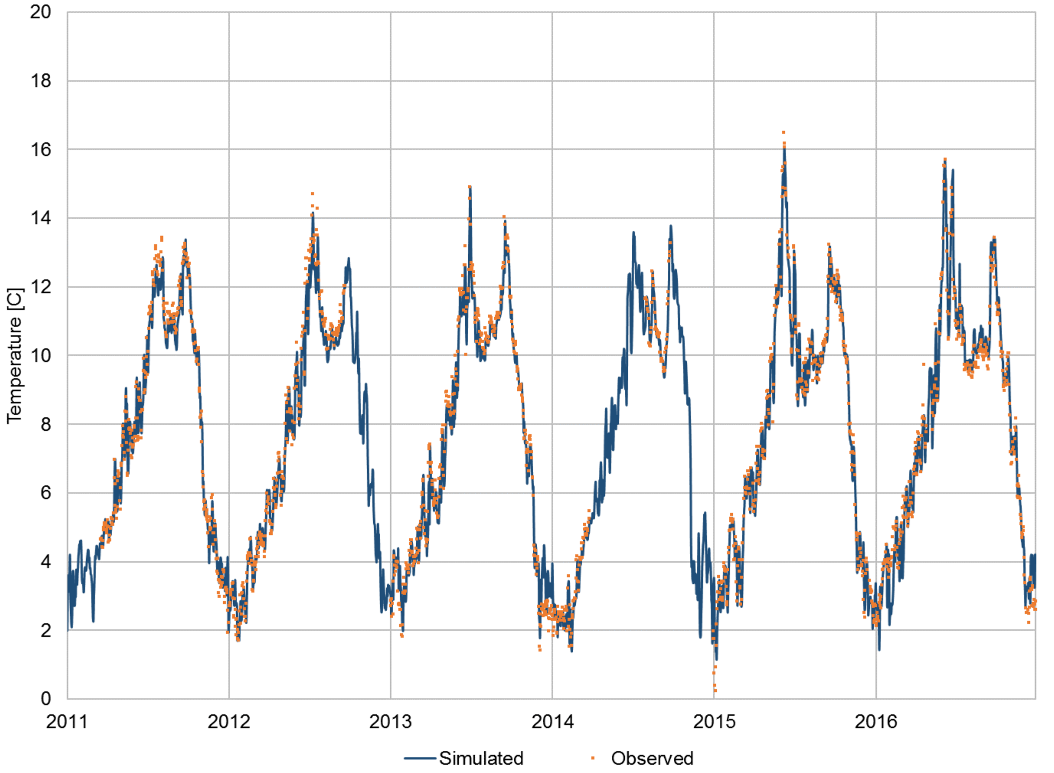


Figure C.3-18 Simulated versus observed temperature at PEKI, period 2011 – 2016

C.4 10-year Daily Average Temperature Comparisons

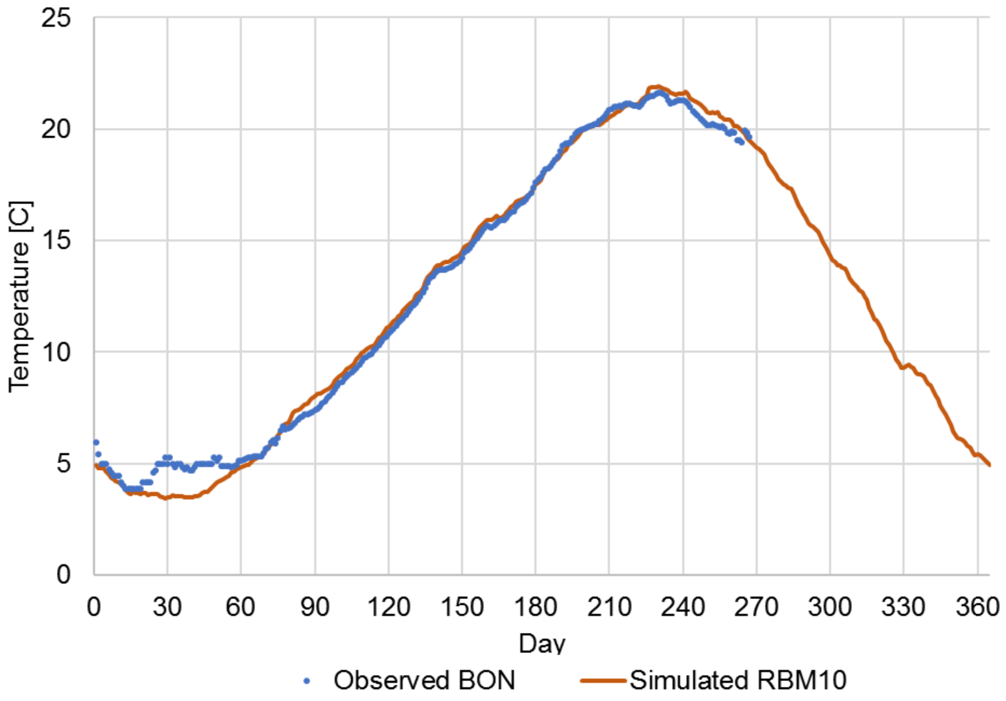


Figure C.4-1 10-year daily average temperature comparison at BON

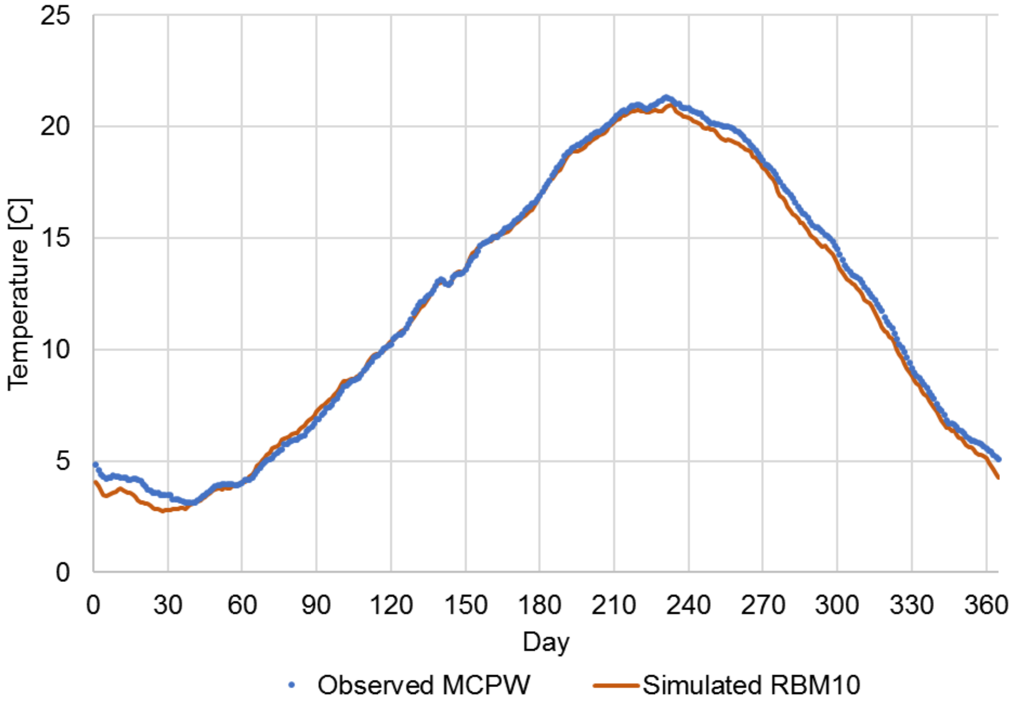


Figure C.4-2 10-year daily average temperature comparison at MCPW

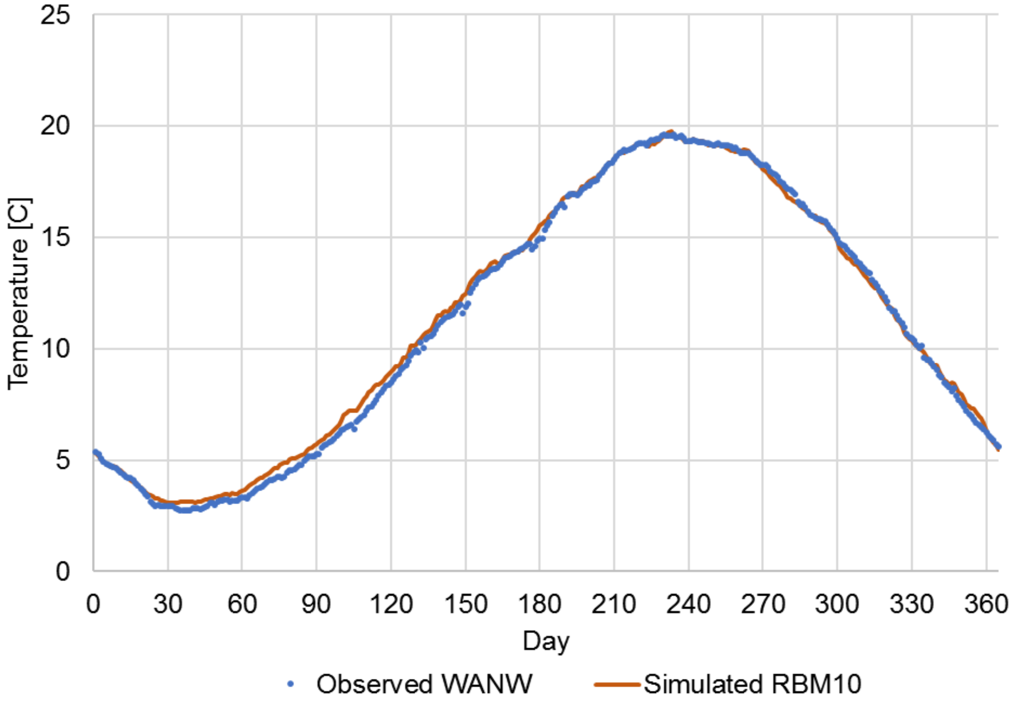


Figure C.4-3 10-year daily average temperature comparison at WANW

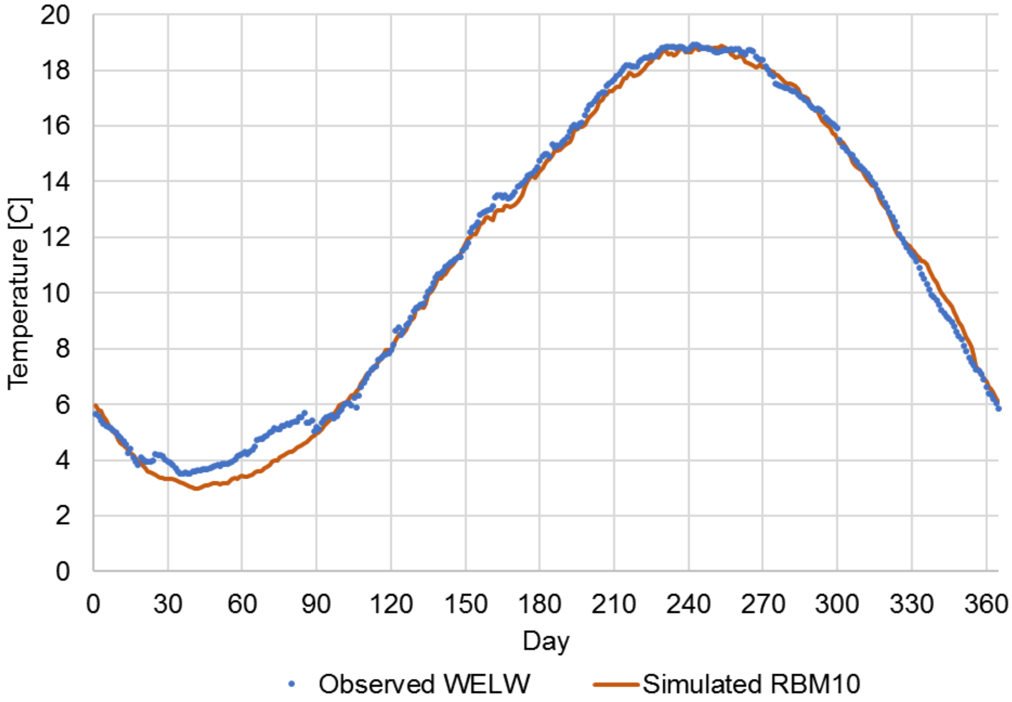


Figure C.4-4 10-year daily average temperature comparison at WELW

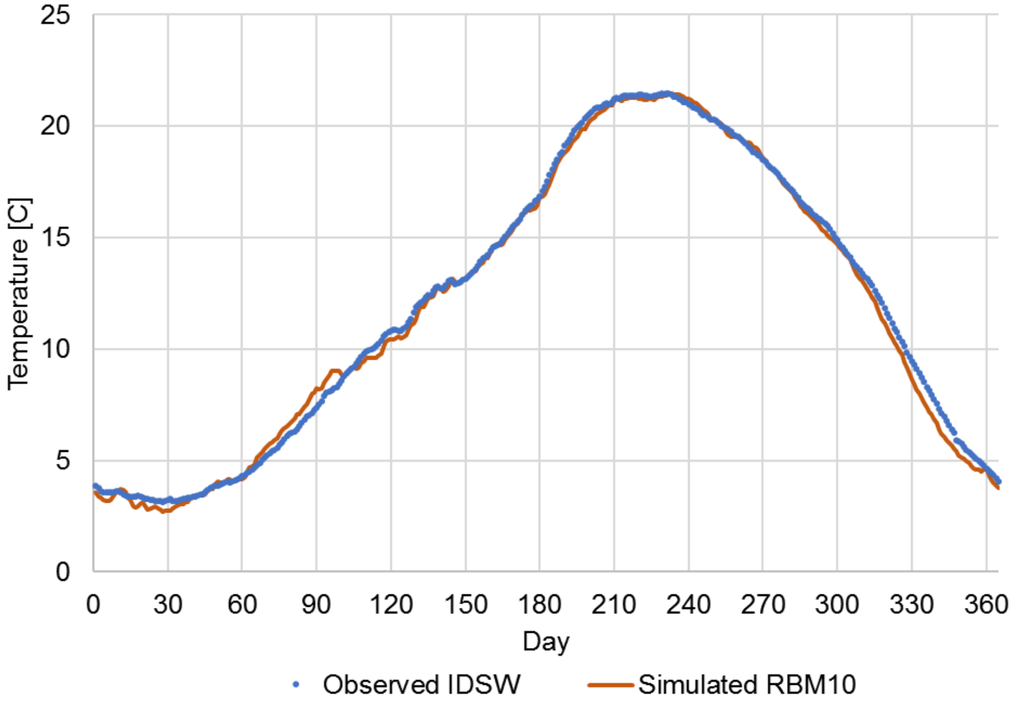


Figure C.4-5 10-year daily average temperature comparison at IDSW

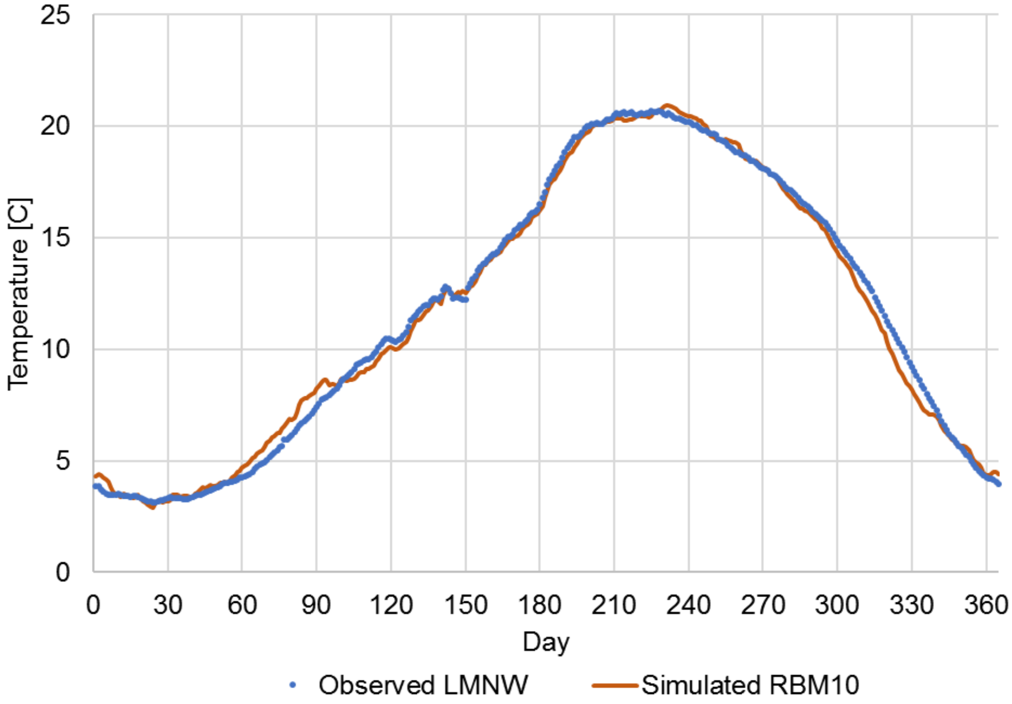


Figure C.4-6 10-year daily average temperature comparison at LMNW

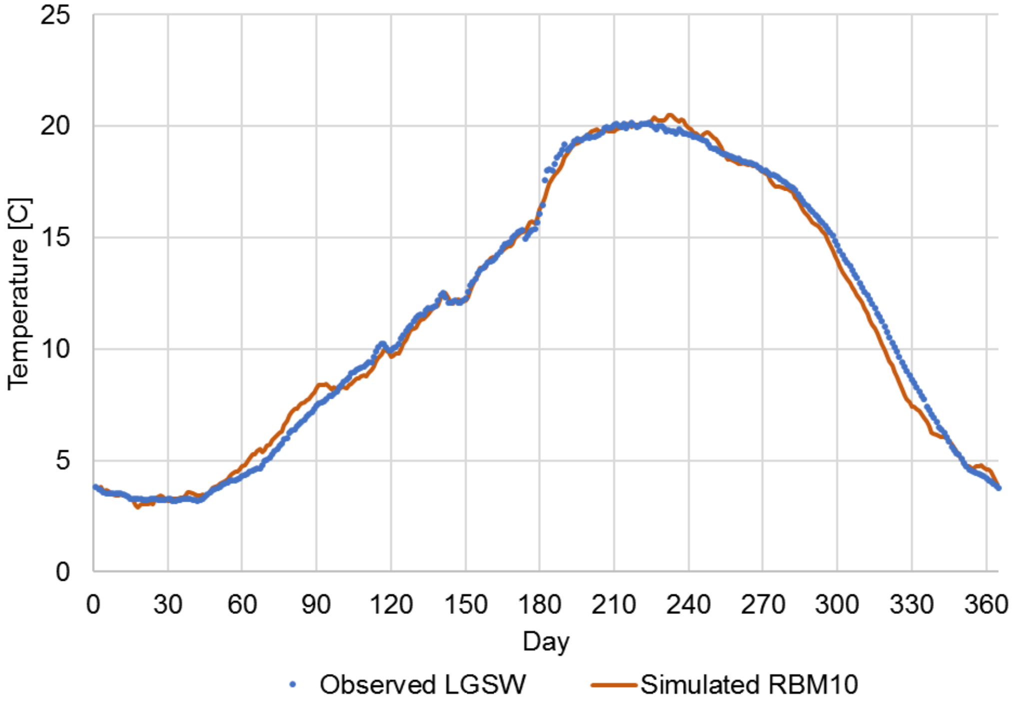


Figure C.4-7 10-year daily average temperature comparison at LGSW

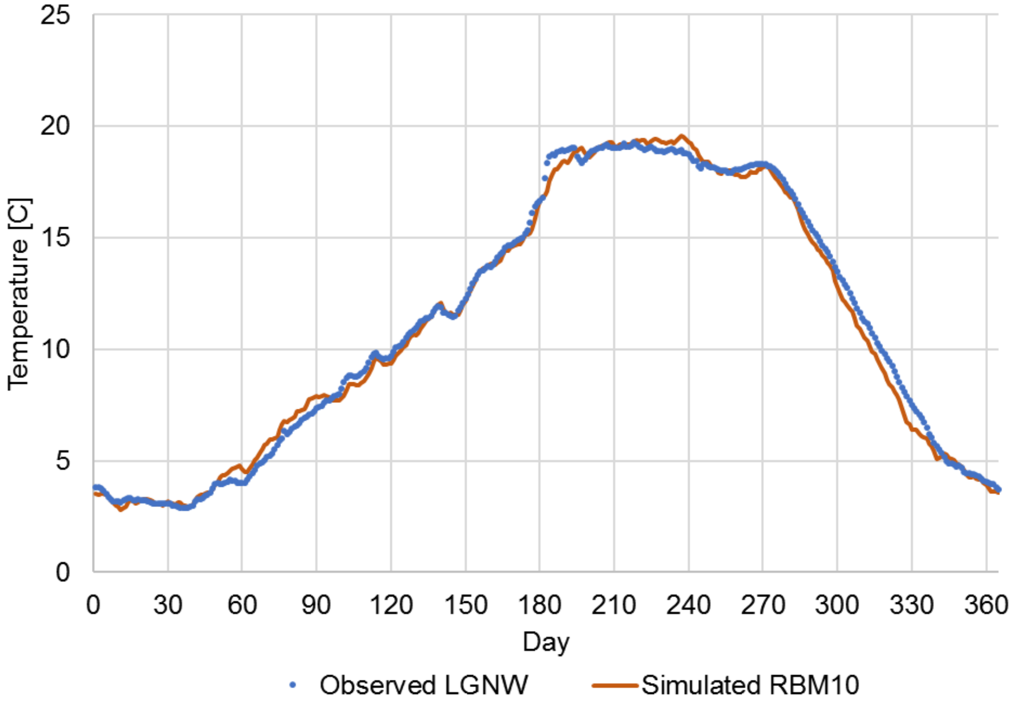


Figure C.4-8 10-year daily average temperature comparison at LGNW

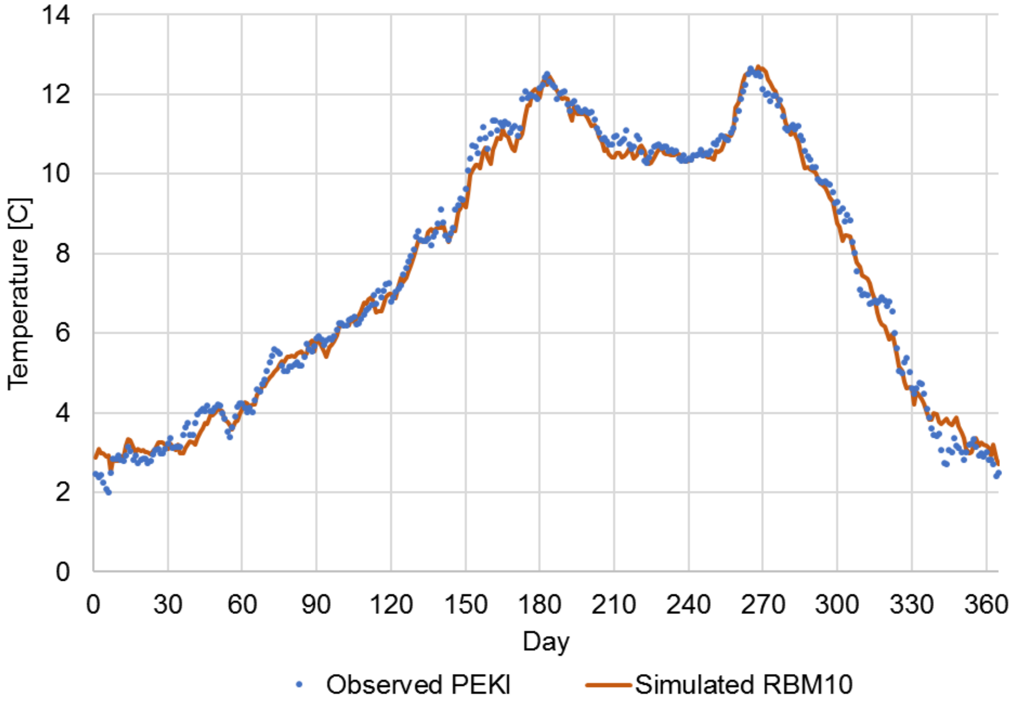


Figure C.4-9 10-year daily average temperature comparison at PEKI

C.5 Flow Discharge Model Results

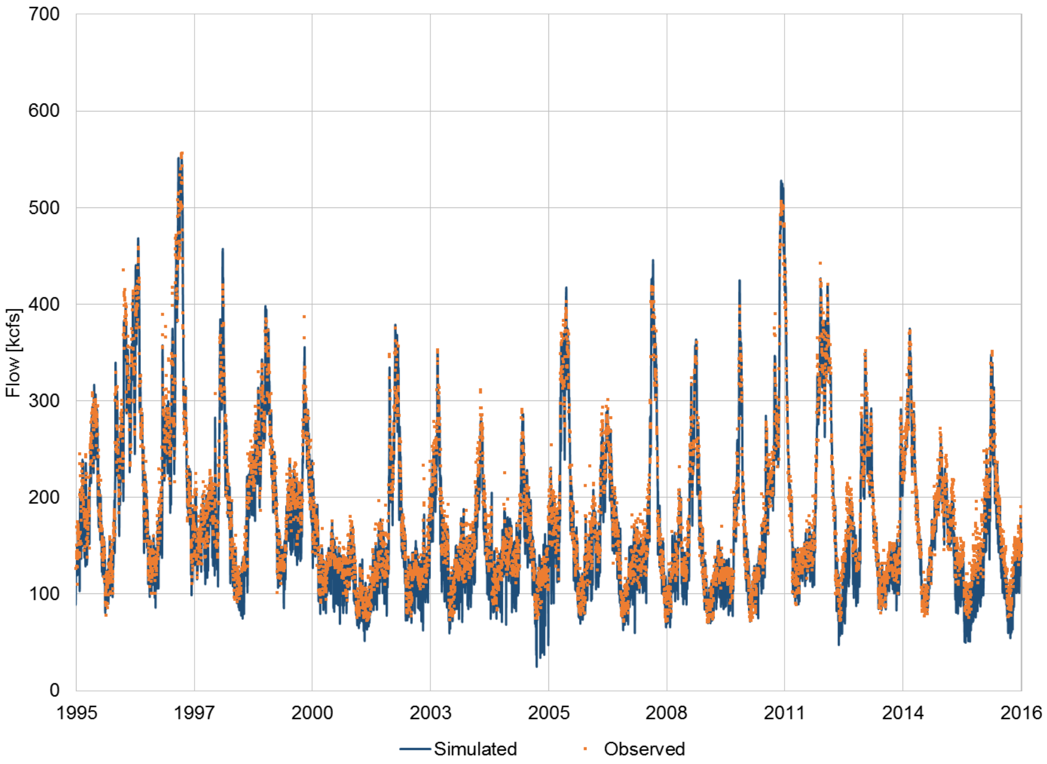


Figure C.5-1 Simulated versus observed flow at BON, Columbia River RM 146

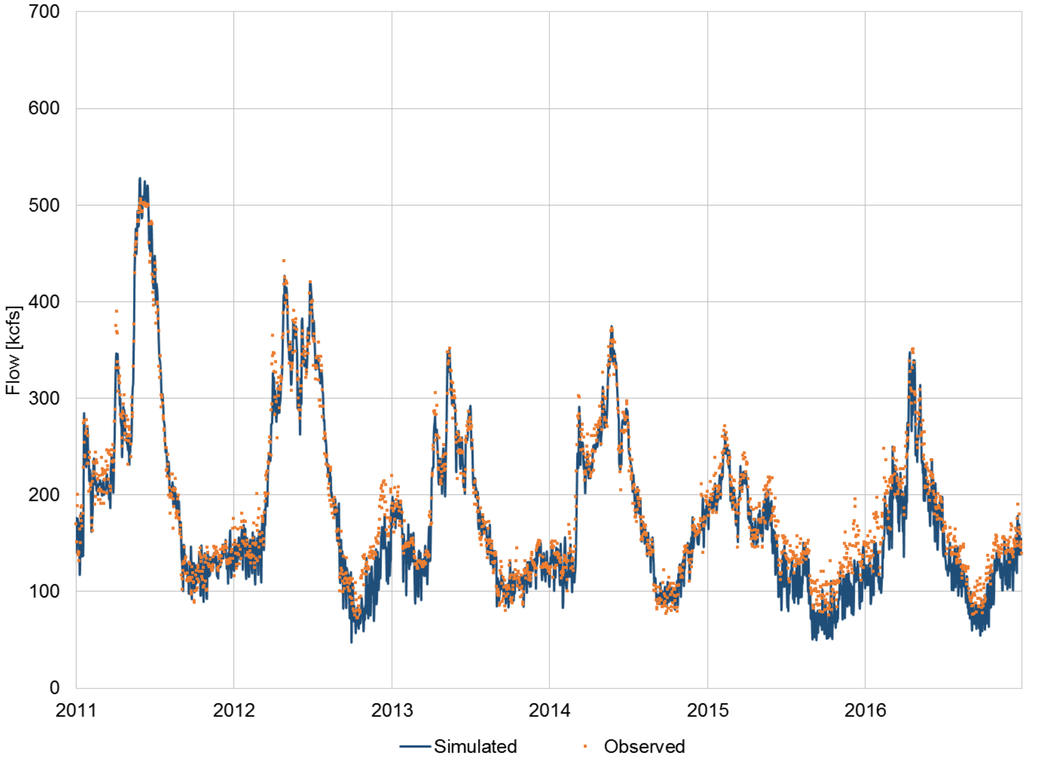


Figure C.5-2 Simulated versus observed flow at BON, period 2011 – 2016

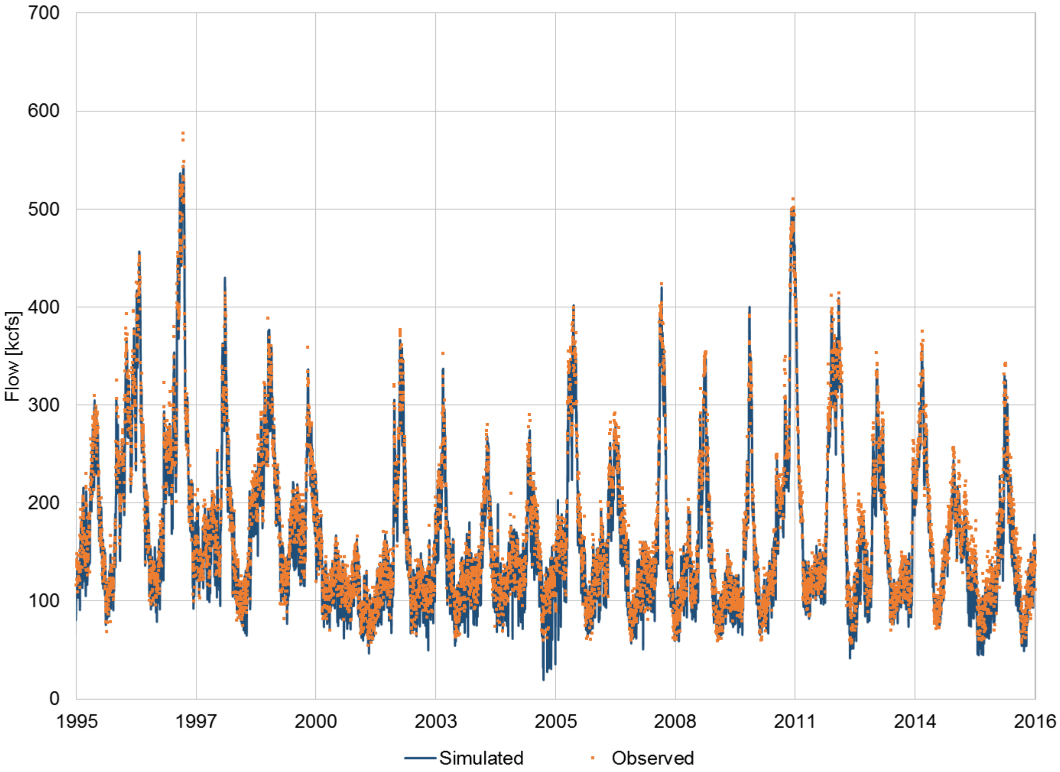


Figure C.5-3 Simulated versus observed flow at MCPW, Columbia River RM 291

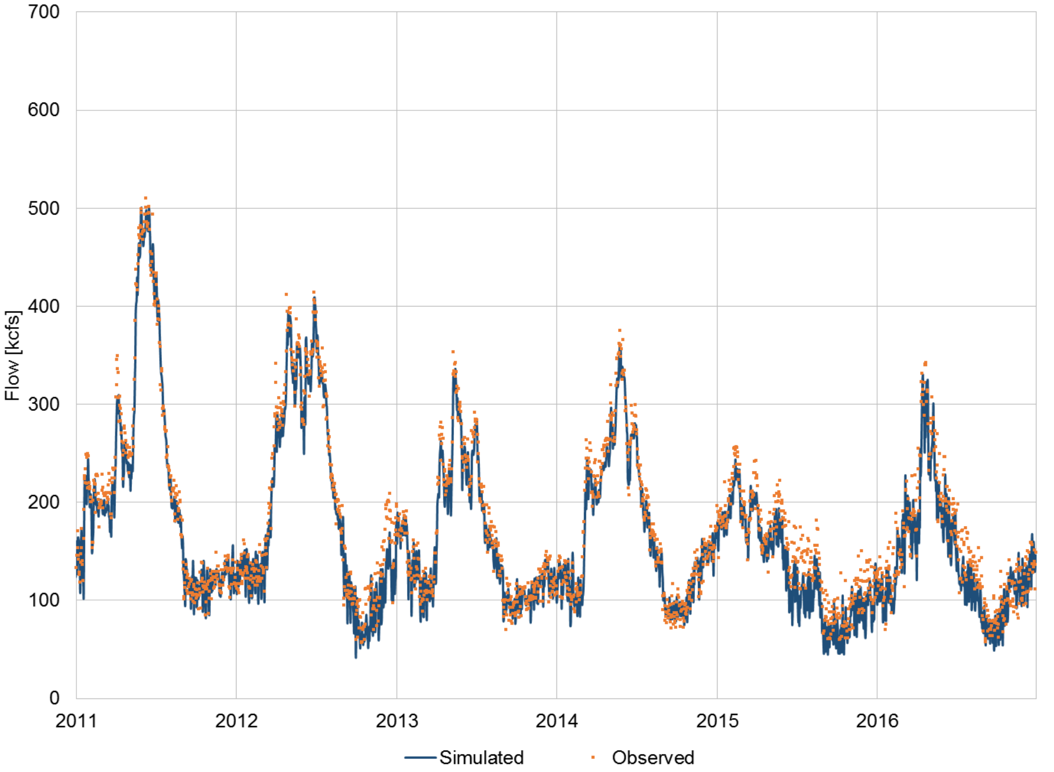


Figure C.5-4 Simulated versus observed flow at MCPW, period 2011 – 2016

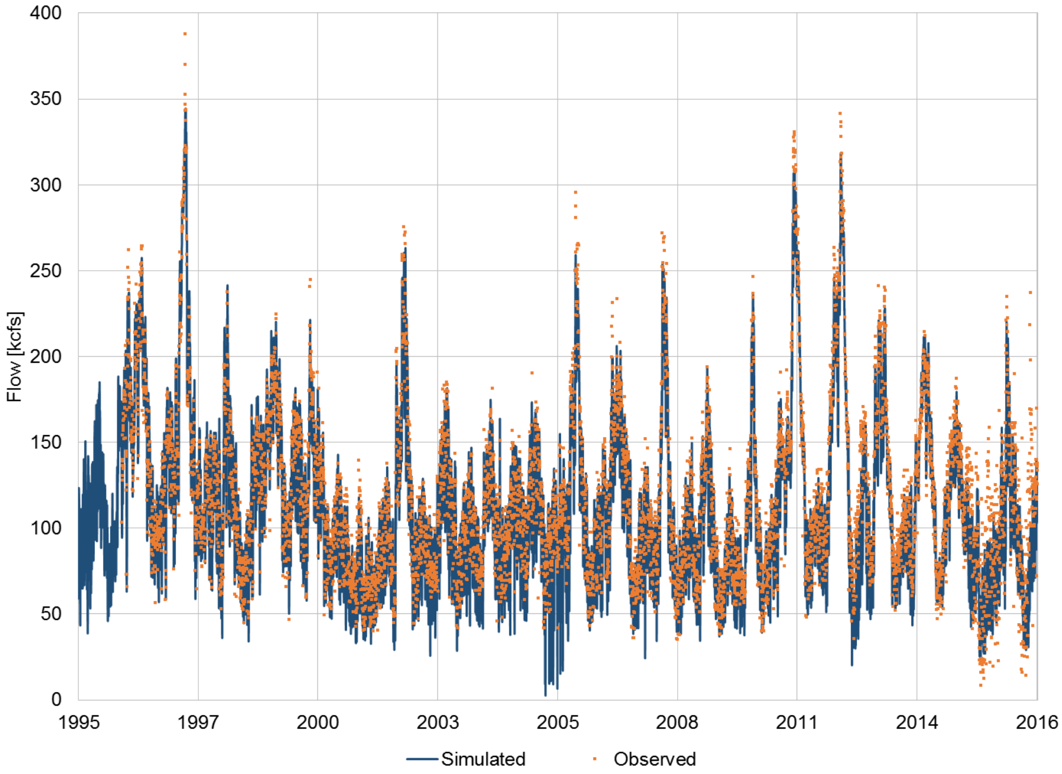


Figure C.5-5 Simulated versus observed flow at WANW, Columbia River RM 415

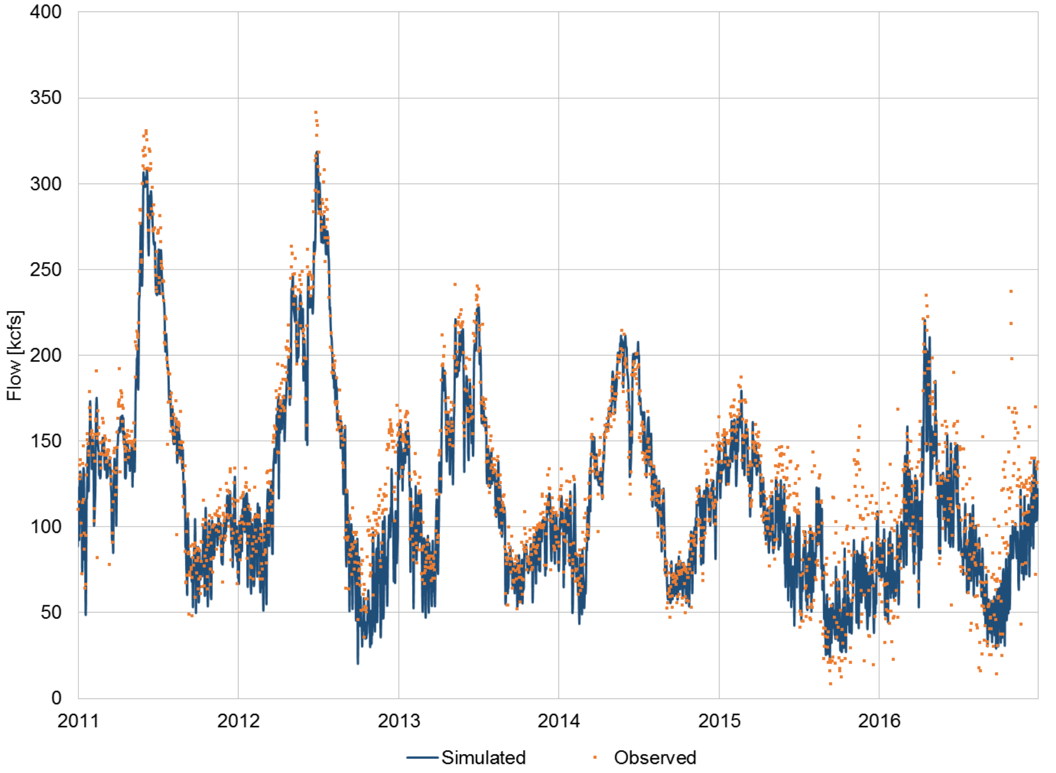


Figure C.5-6 Simulated versus observed flow at WANW, period 2011 – 2016

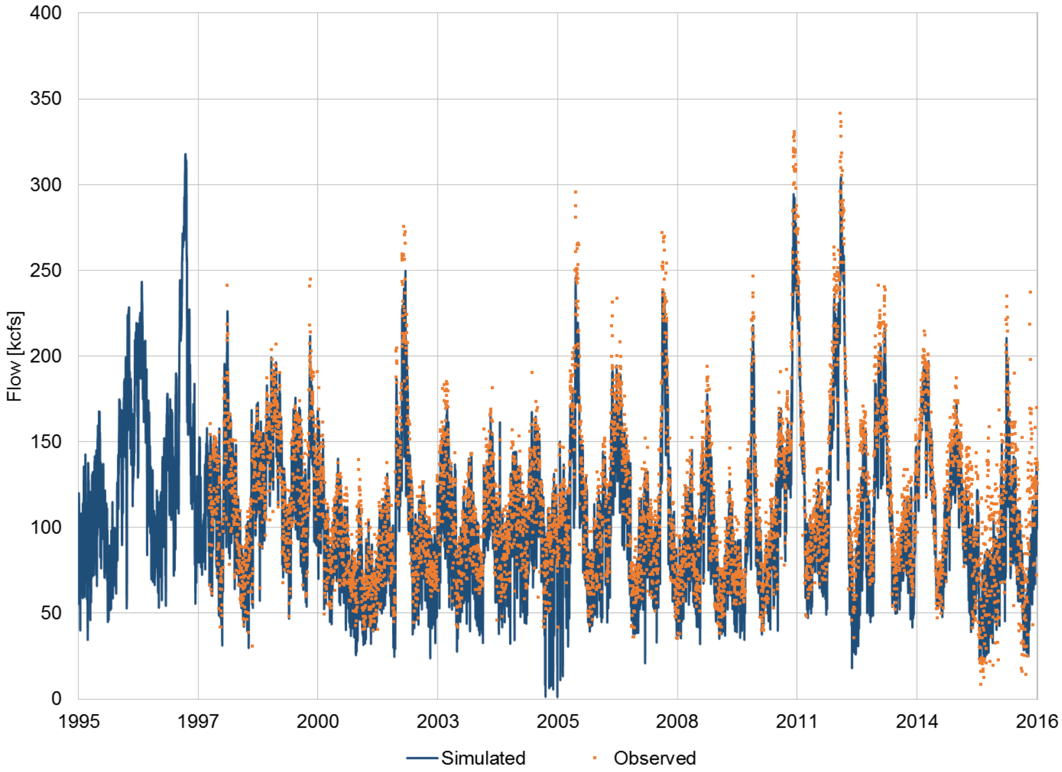


Figure C.5-7 Simulated versus observed flow at WELW, Columbia River RM 514

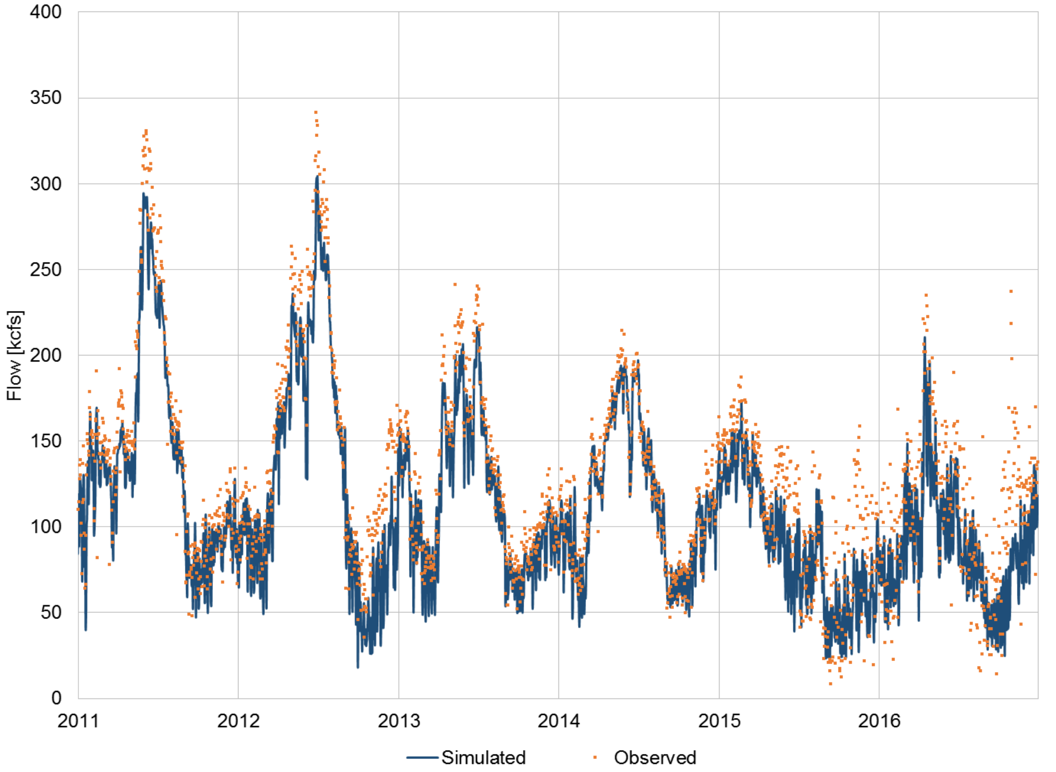


Figure C.5-8 Simulated versus observed flow at WELW, period 2011 – 2016

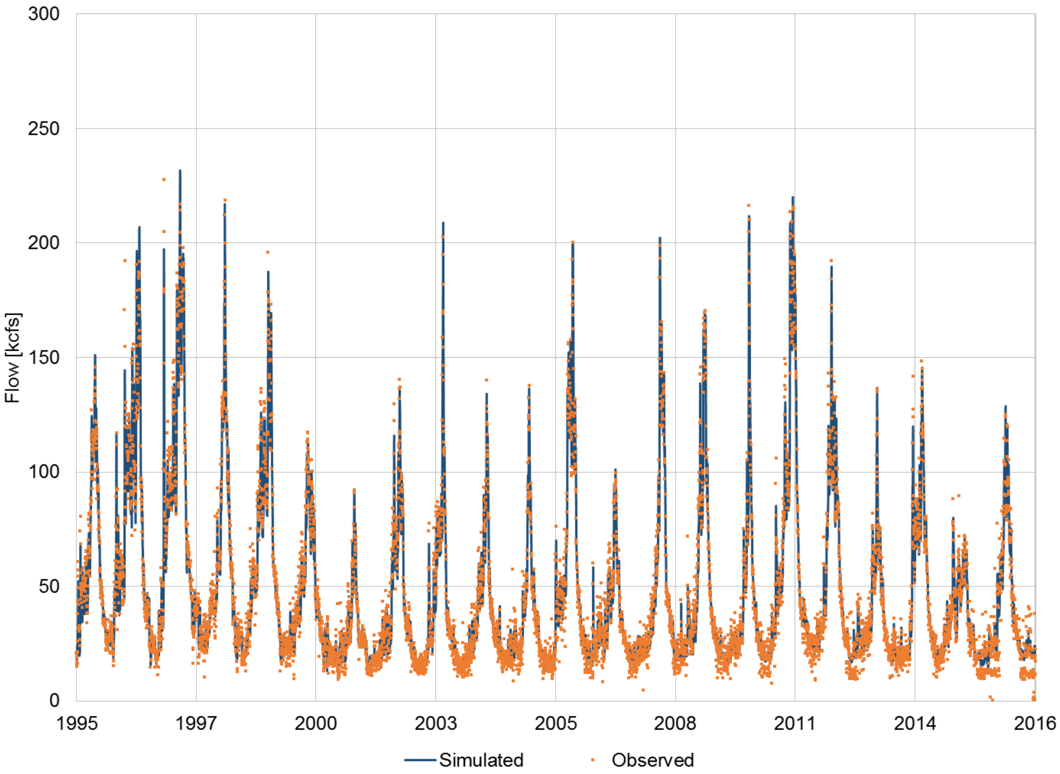


Figure C.5-9 Simulated versus observed flow at IDSW, Snake River RM 6.8

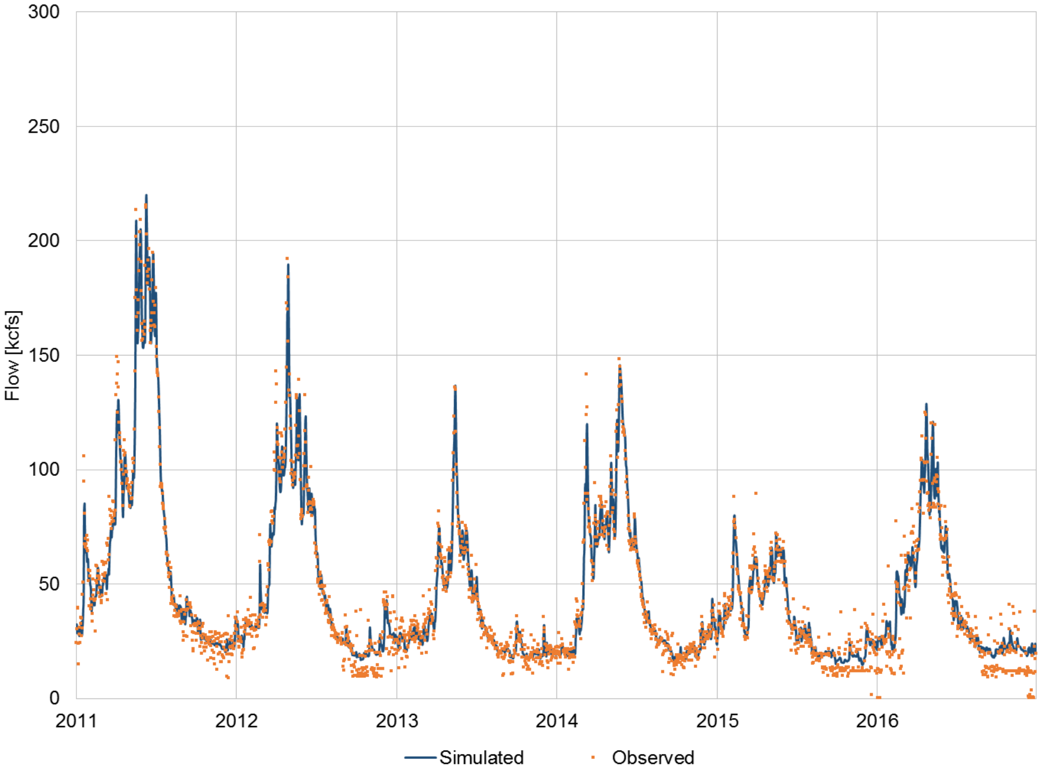


Figure C.5-10 Simulated versus observed flow at IDSW, period 2011 – 2016

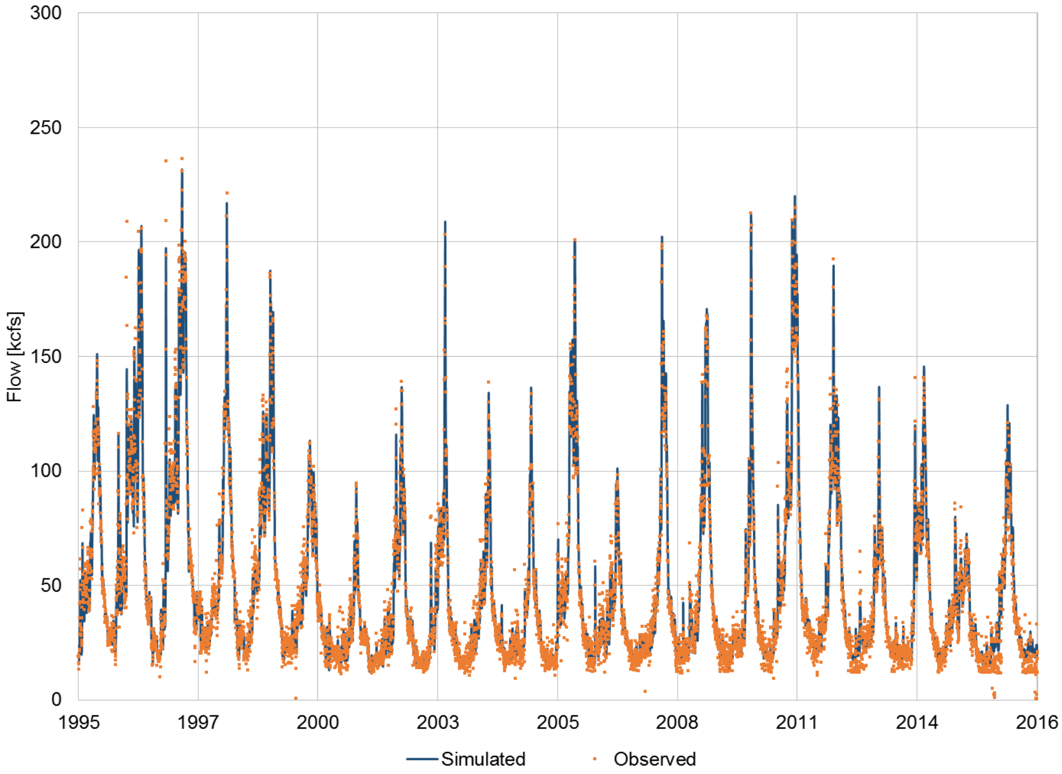


Figure C.5-11 Simulated versus observed flow at LMNW, Snake River RM 40.8

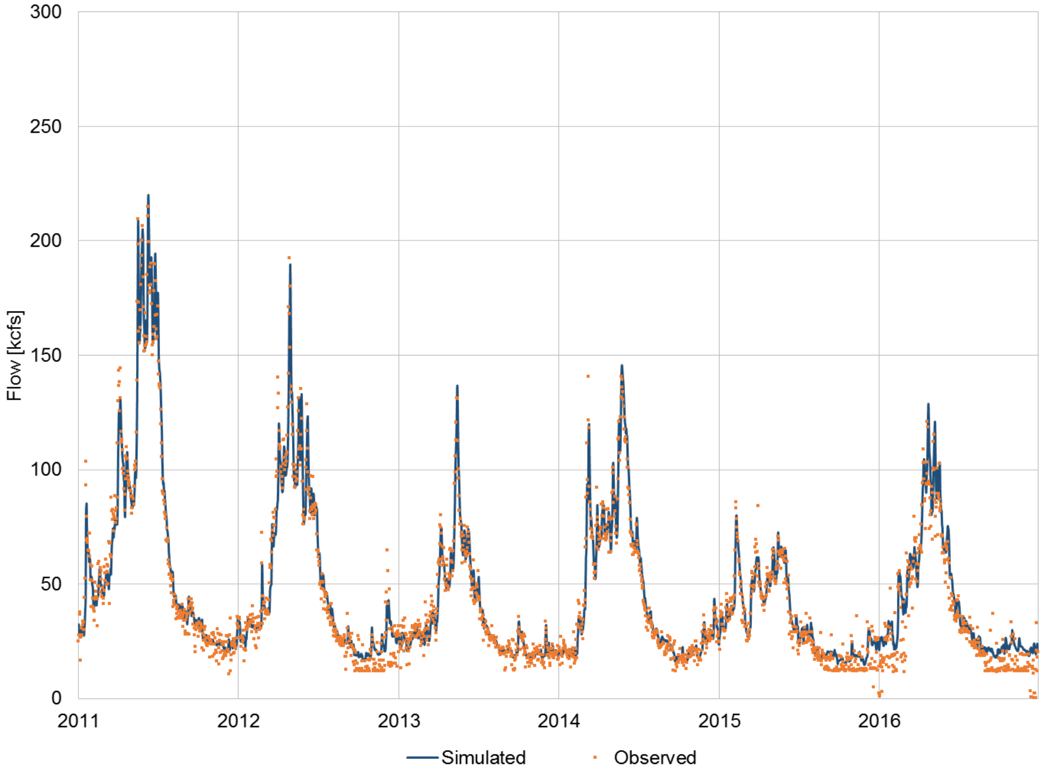


Figure C.5-12 Simulated versus observed flow at LMNW, period 2011 – 2016

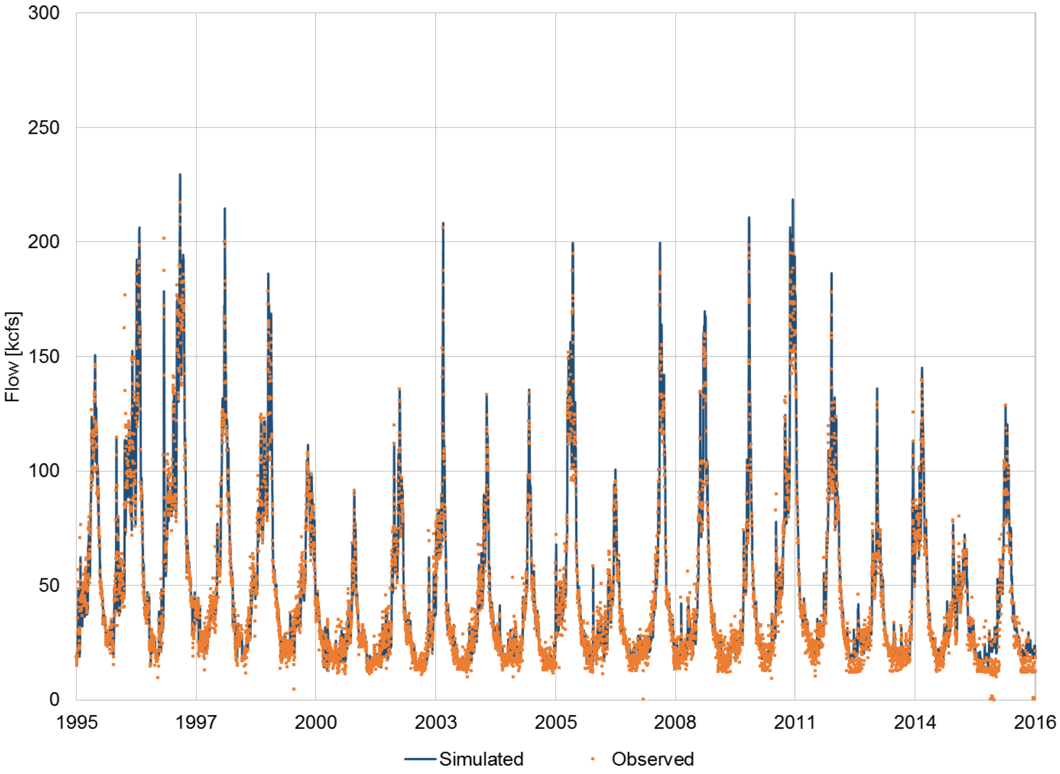


Figure C.5-13 Simulated versus observed flow at LGSW, Snake River RM 69.5

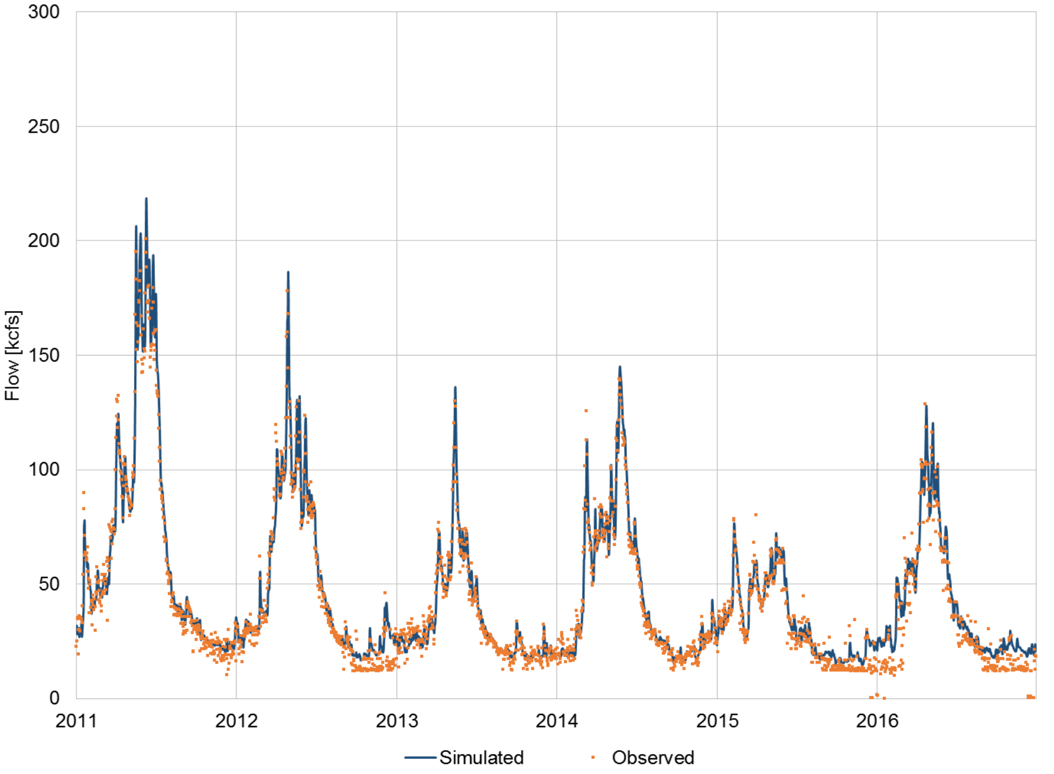


Figure C.5-14 Simulated versus observed flow at LGSW, period 2011 – 2016

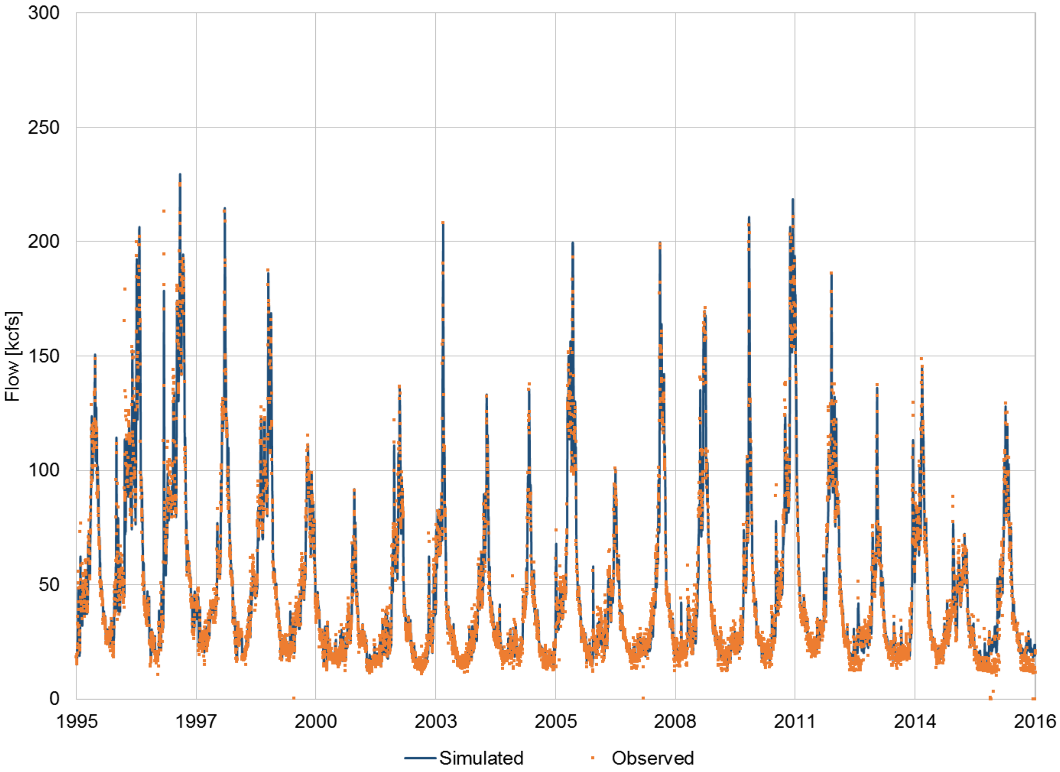


Figure C.5-15 Simulated versus observed flow at LGNW, Snake River RM 106.8

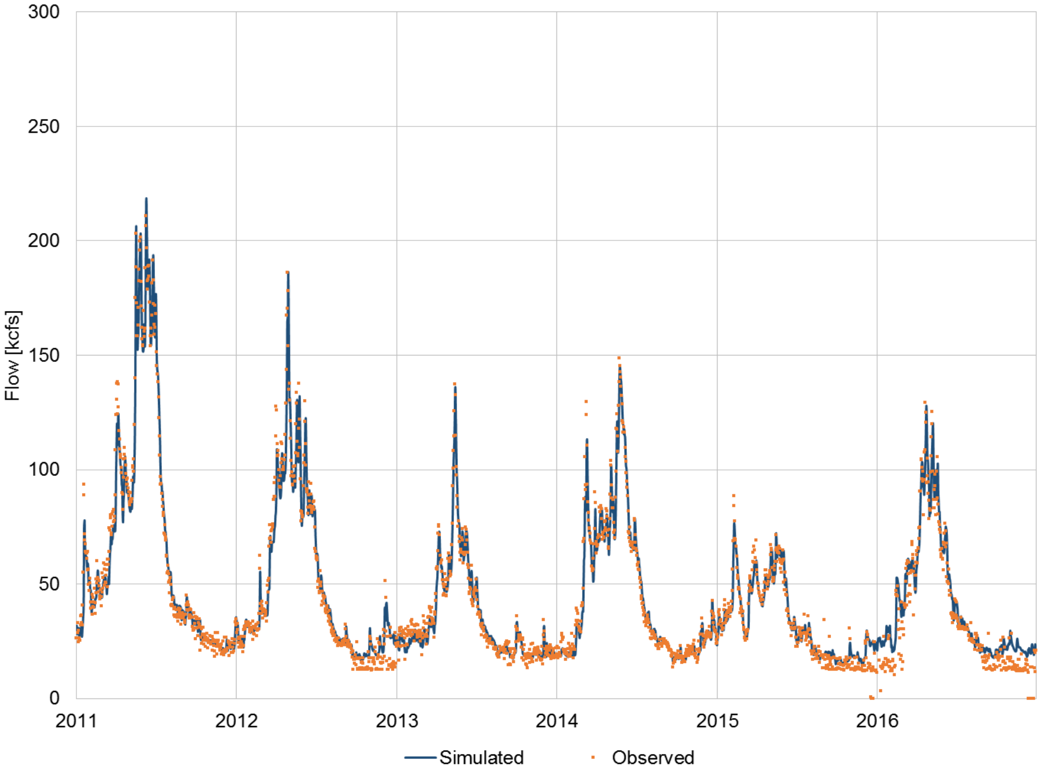


Figure C.5-16 Simulated versus observed flow at LGNW, period 2011 – 2016

Appendix D 2018 RBM10C Model Setup

D.1 Introduction

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

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

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

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

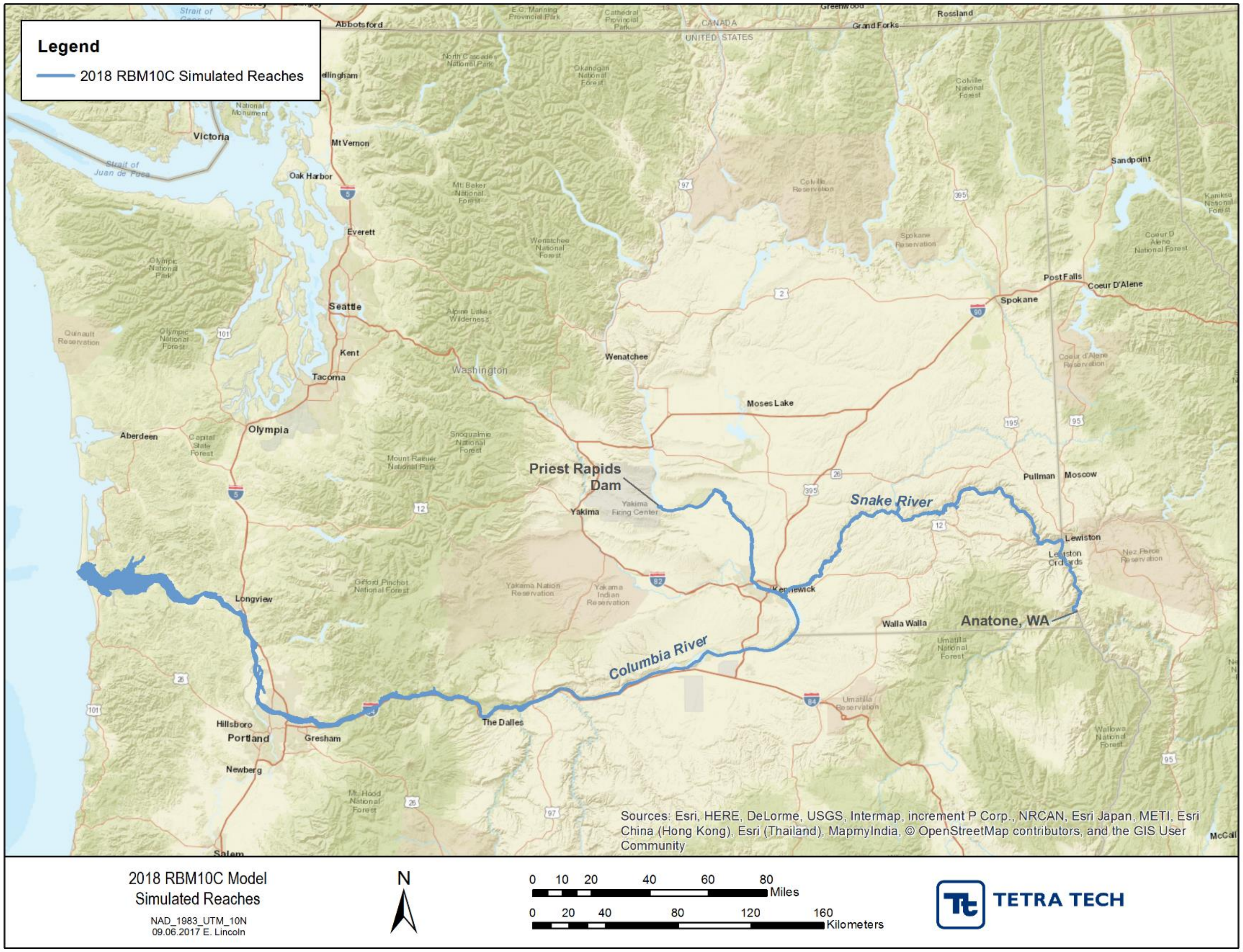
Station	Station ID	Station Description
Ice Harbor Dam tailwater	**IDSW**	Snake RM 6.8: Right bank 15,400 feet d/s of dam
Lower Monumental Dam tailwater	**LMNW**	Snake RM 40.8:Left bank 4,300 feet d/s of dam
Little Goose Dam tailwater	**LGSW**	Snake RM 69.5:Right bank 3,900 feet d/s of dam
Lower Granite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

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

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

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

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



Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

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

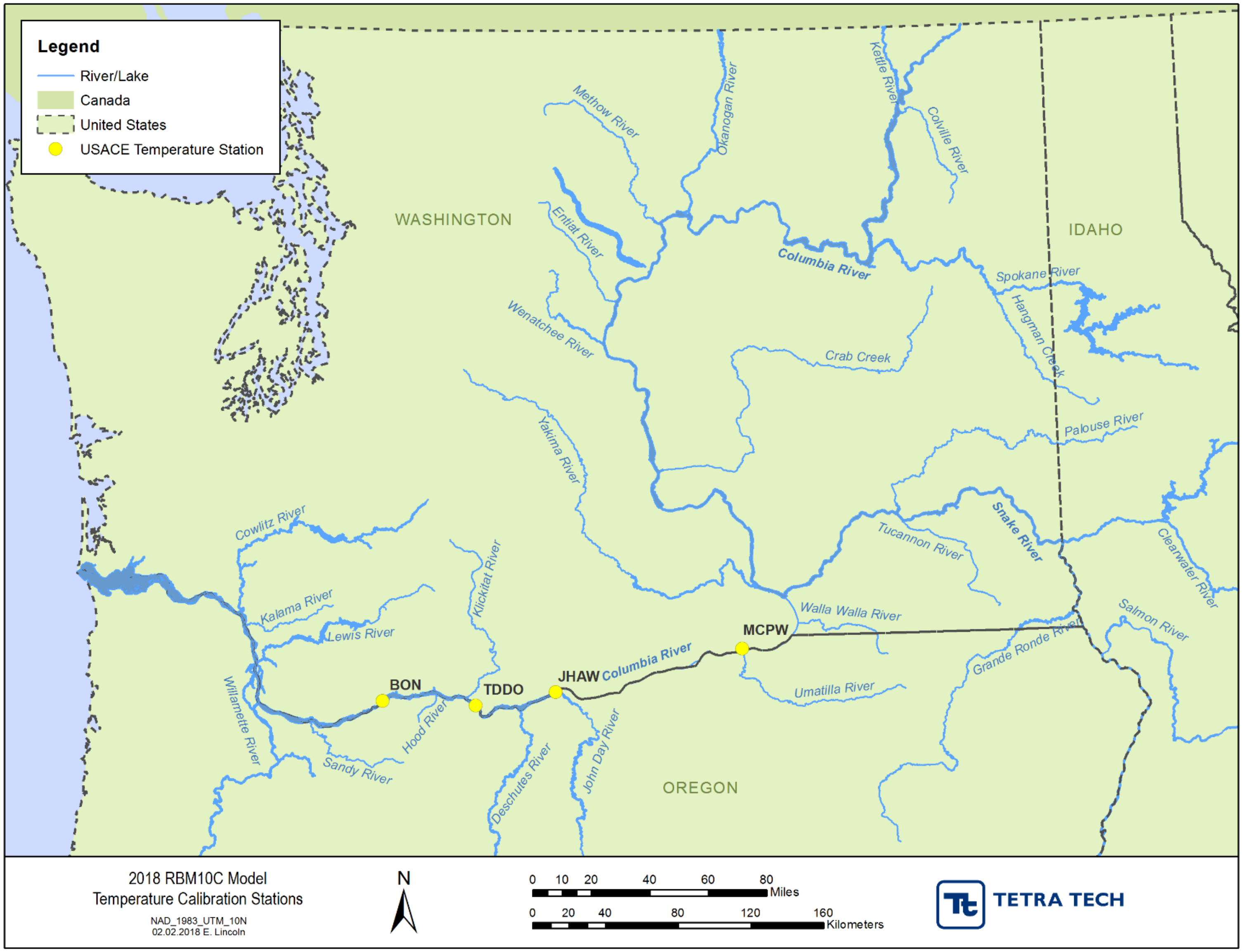


Figure D.1-2 2018 RBM10C Columbia and Snake Rivers temperature calibration stations

D.2 Water Temperature Model Performance Statistics

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

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

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

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

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

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

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

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

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

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

D.3 Temperature Model Results

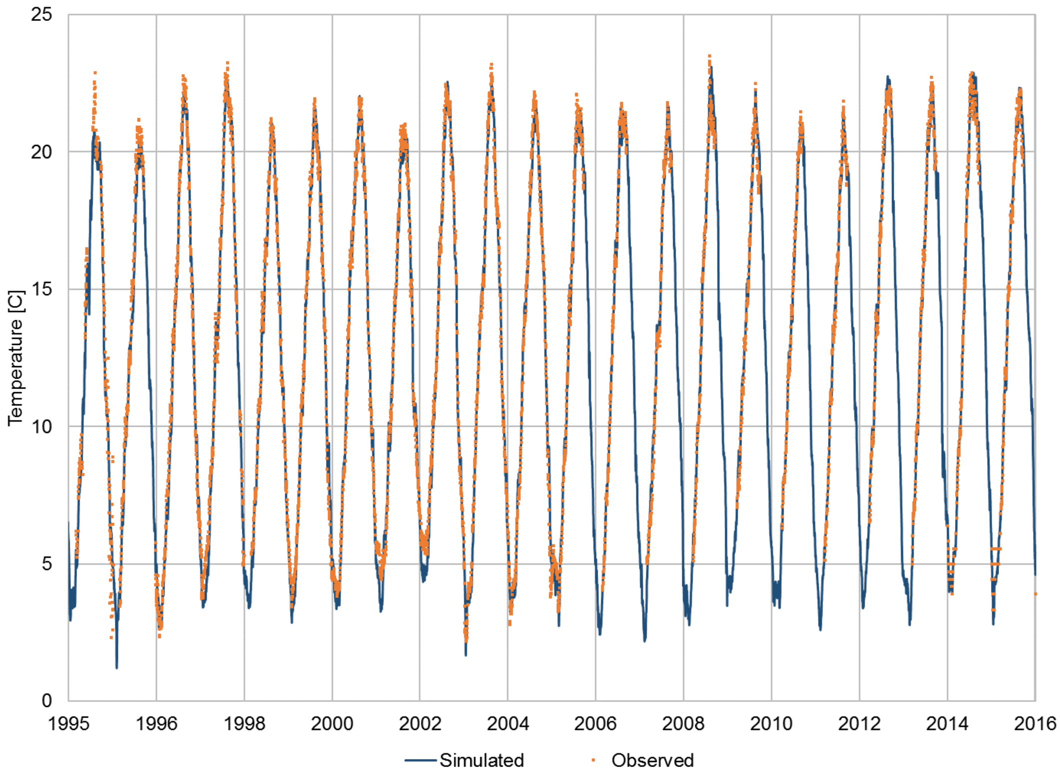


Figure D.3-1 Simulated versus observed temperature at BON, Columbia River RM 146

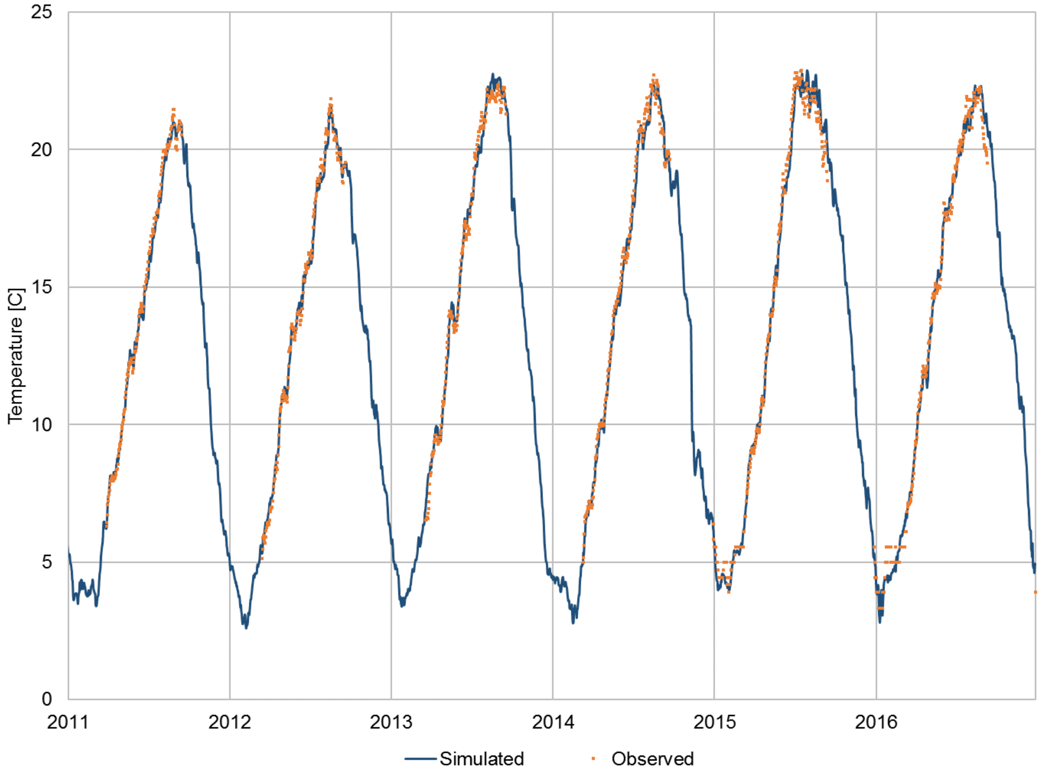


Figure D.3-2 Simulated versus observed temperature at BON, period 2011 – 2016

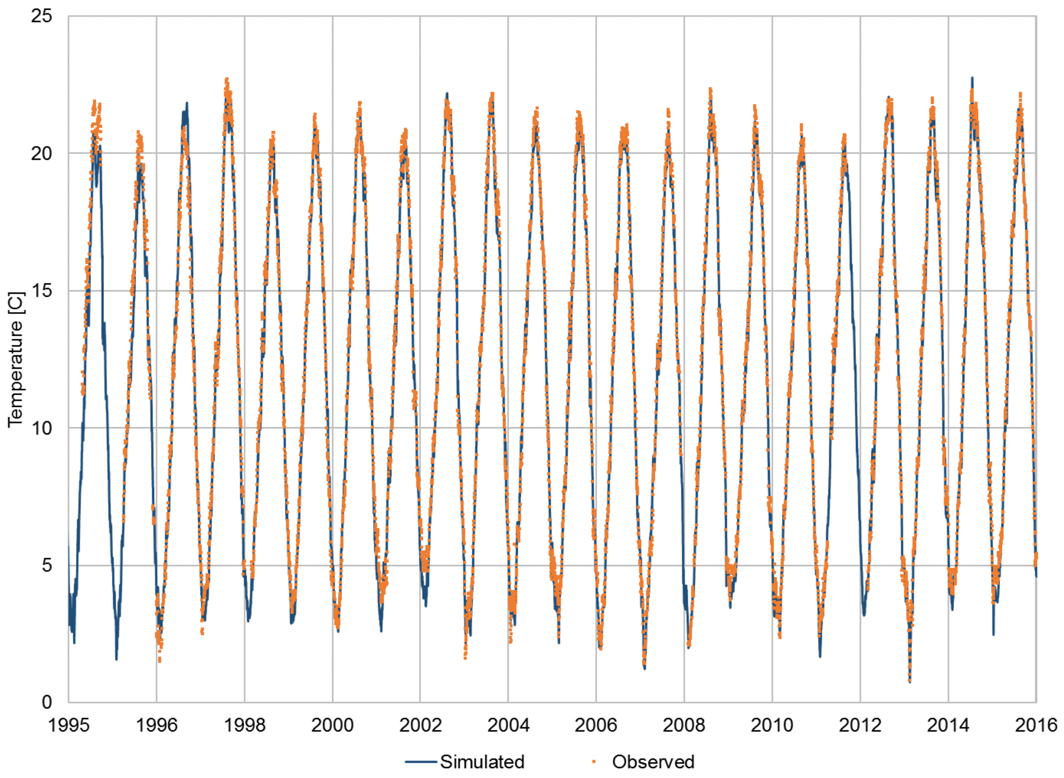


Figure D.3-3 Simulated versus observed temperature at MCPW, Columbia River RM 291

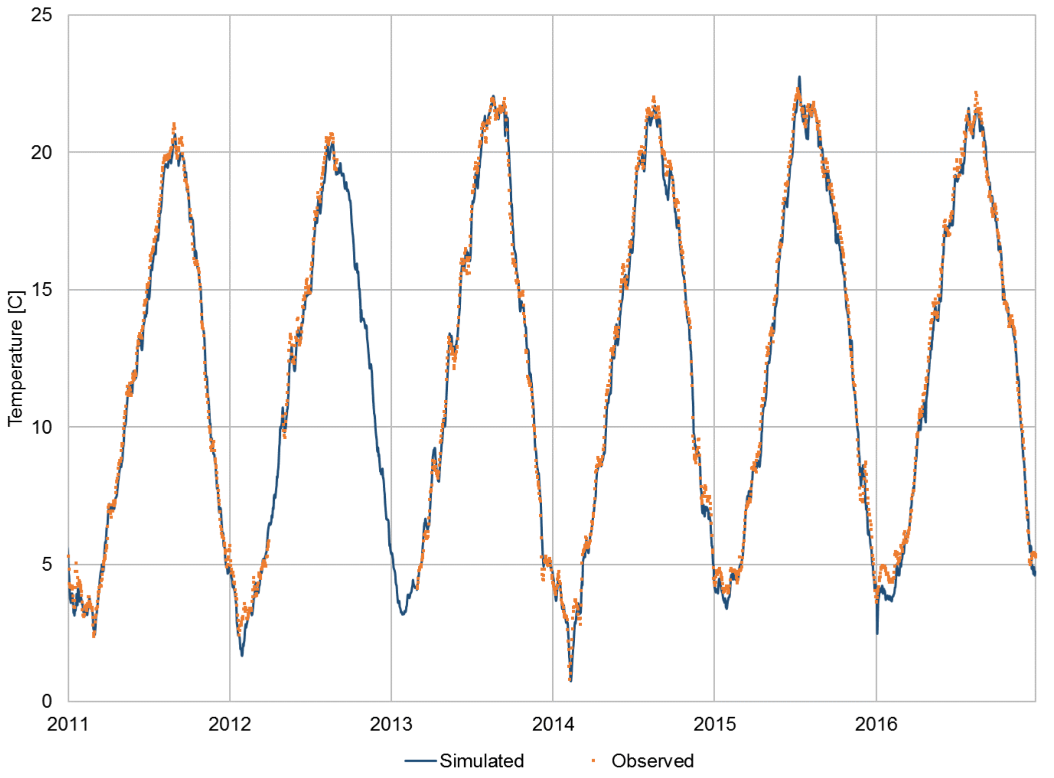


Figure D.3-4 Simulated versus observed temperature at MCPW, period 2011 – 2016

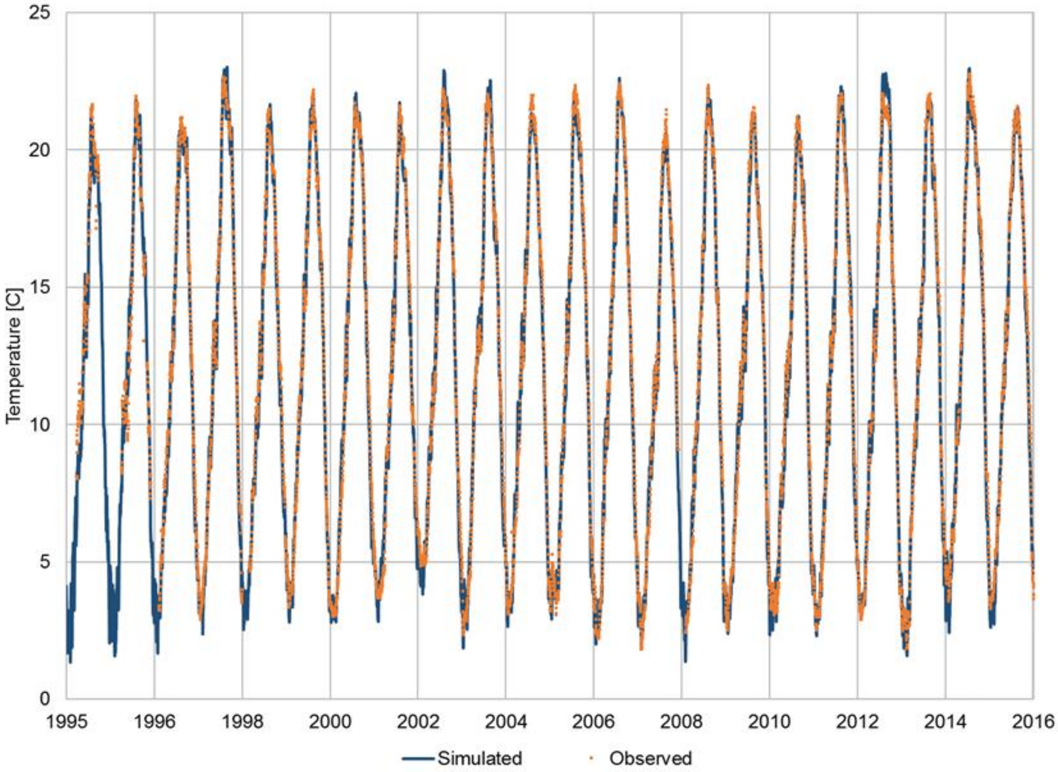


Figure D.3-5 Simulated versus observed temperature at IDSW, Snake River RM 6.8

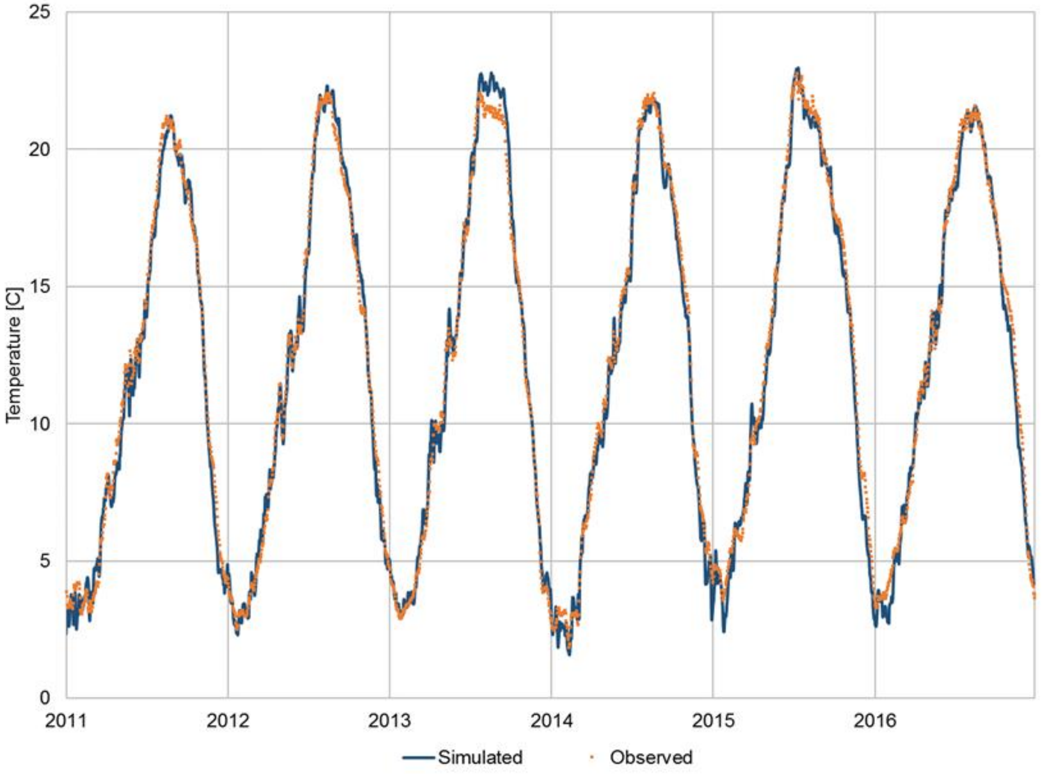


Figure D.3-6 Simulated versus observed temperature at IDSW, period 2011 – 2016

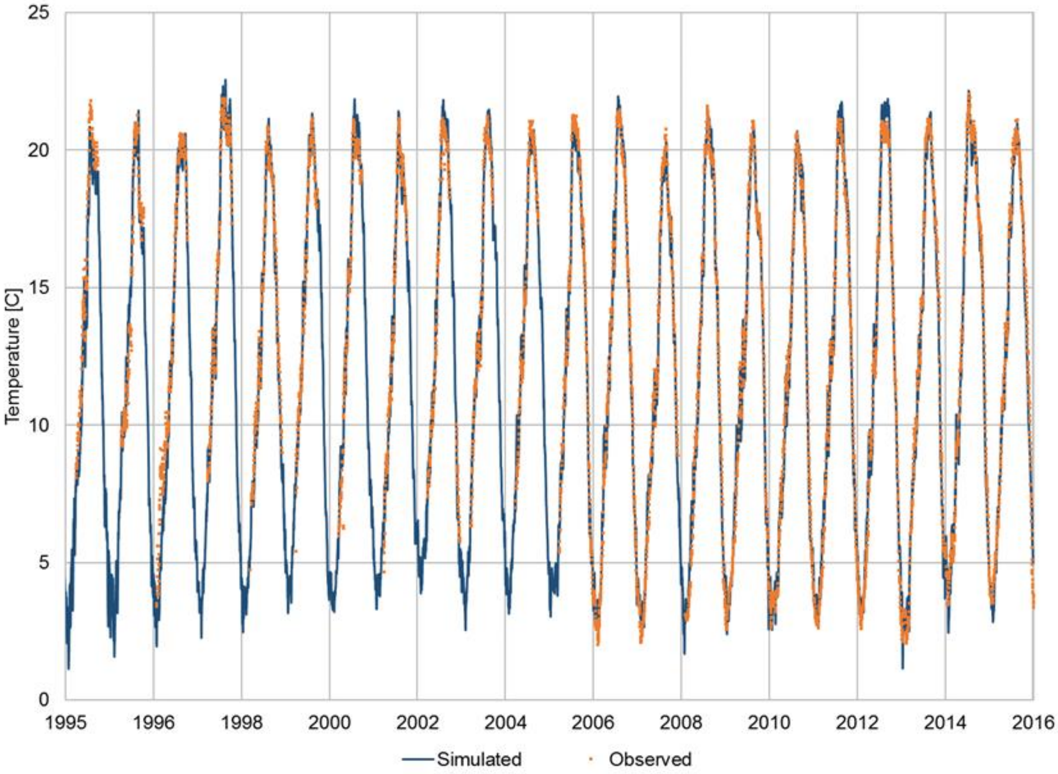


Figure D.3-7 Simulated versus observed temperature at LMNW, Snake River RM 40.8

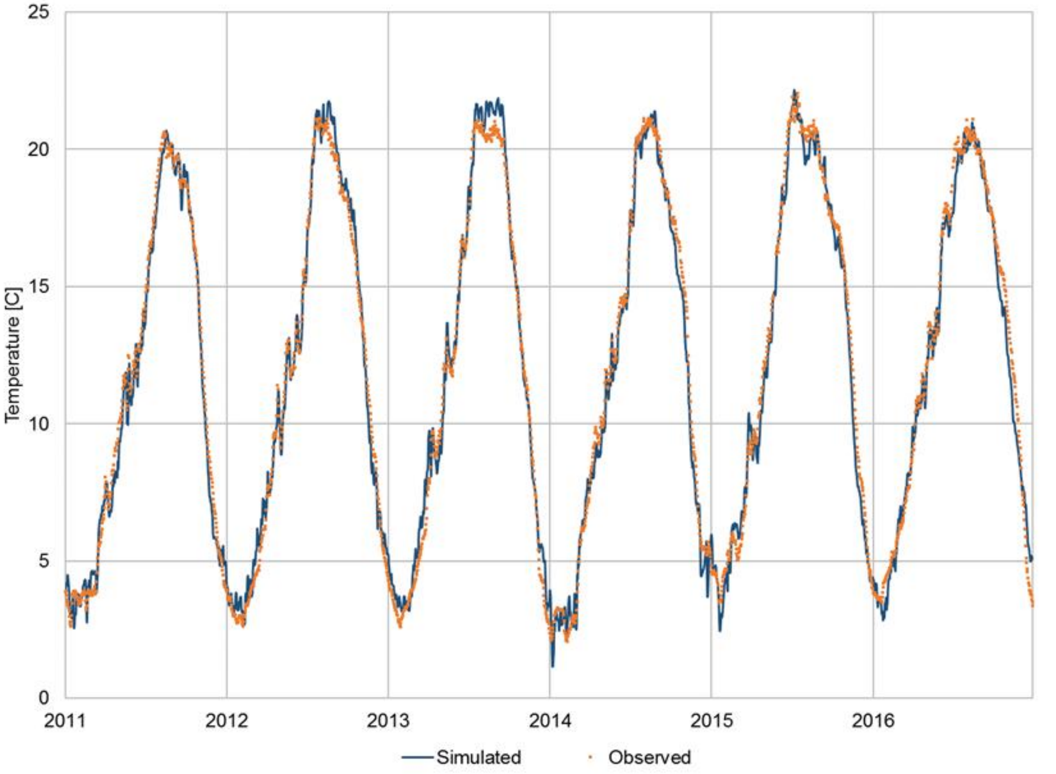


Figure D.3-8 Simulated versus observed temperature at LMNW, period 2011 – 2016

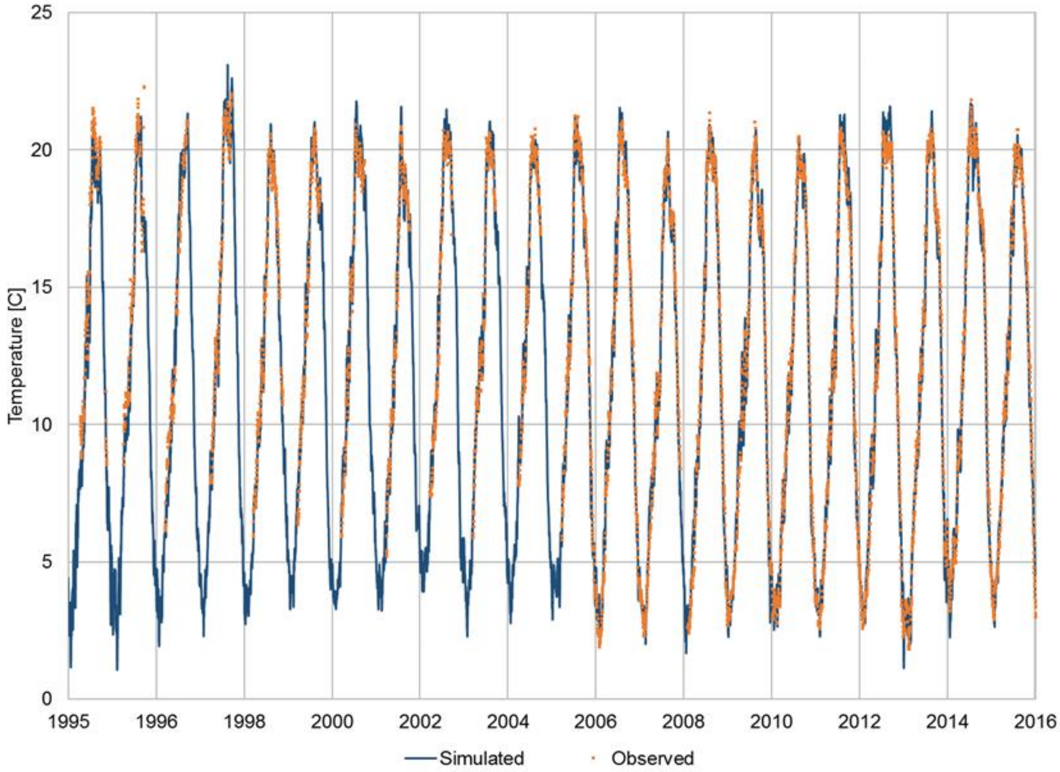


Figure D.3-9 Simulated versus observed temperature at LGSW, Snake River RM 69.5

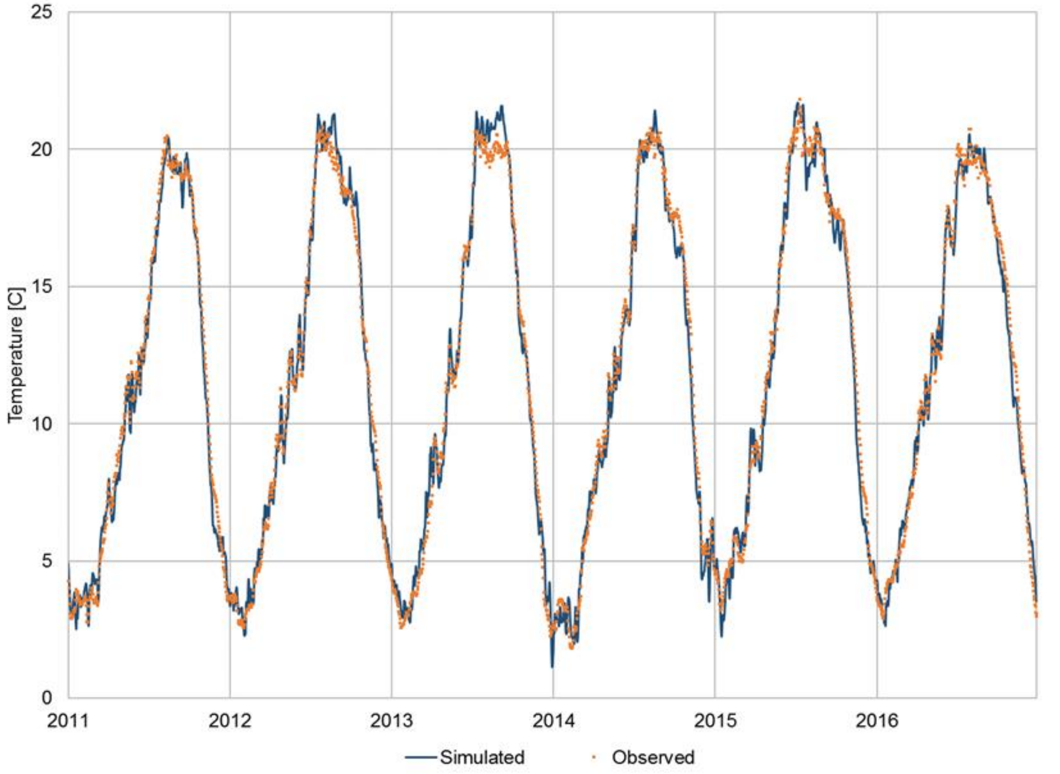


Figure D.3-10 Simulated versus observed temperature at LGSW, period 2011 – 2016

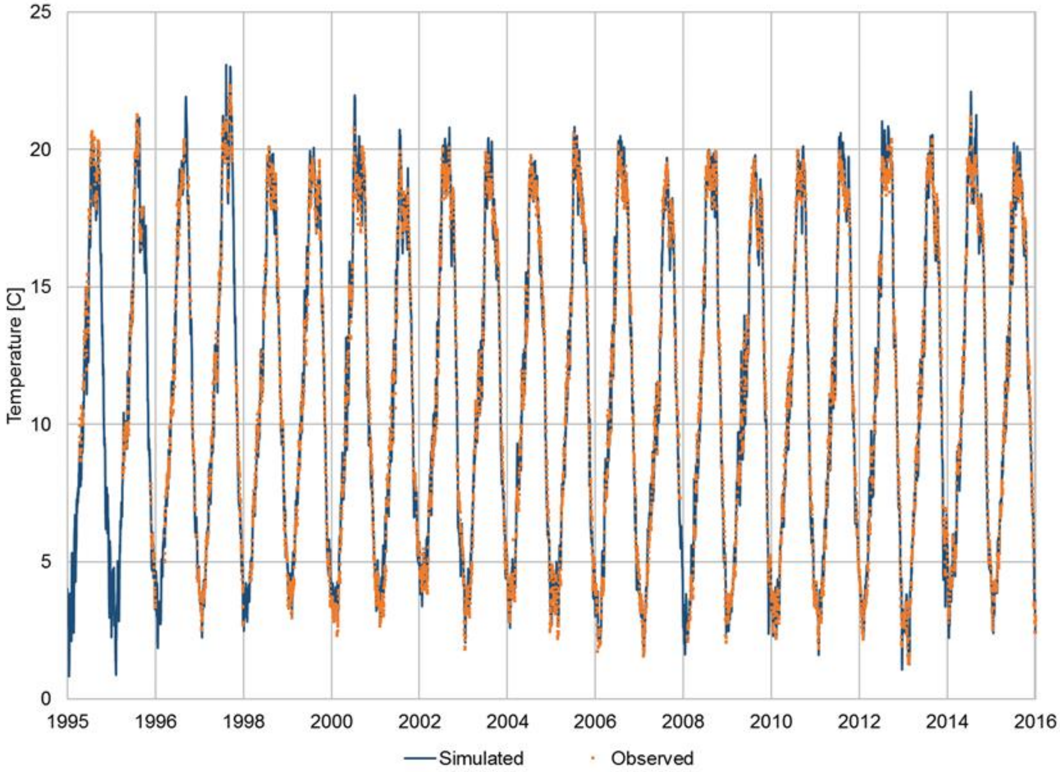


Figure D.3-11 Simulated versus observed temperature at LGNW, Snake River RM 106.8

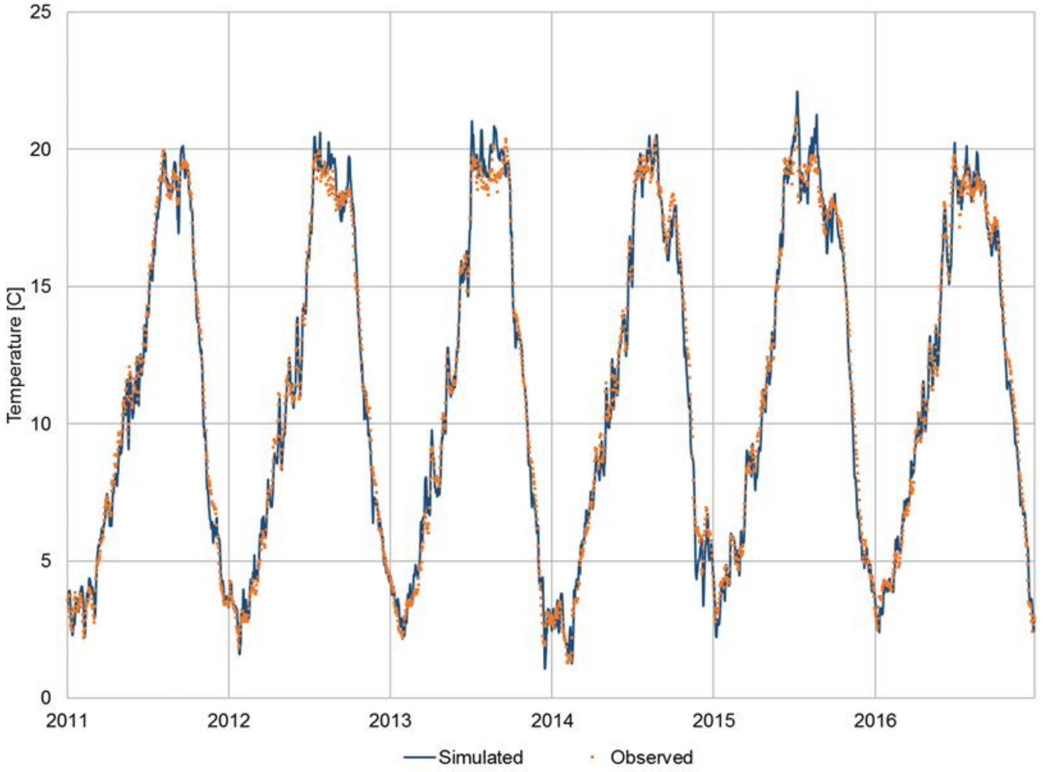


Figure D.3-12 Simulated versus observed temperature at LGNW, period 2011 – 2016

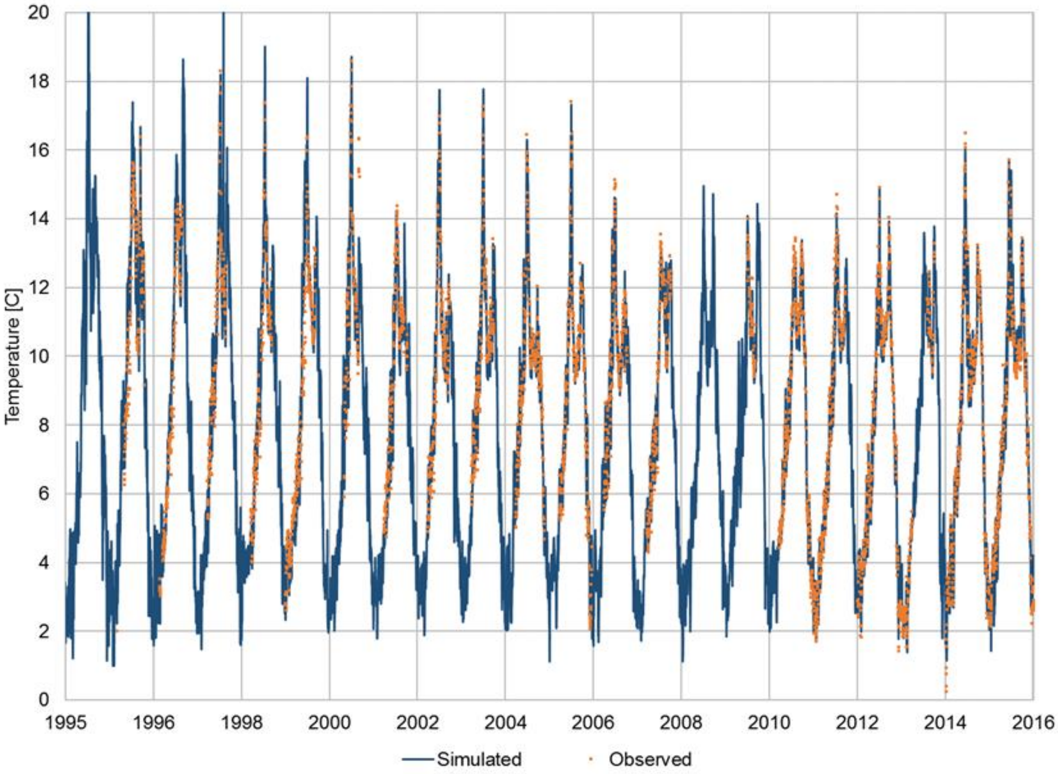


Figure D.3-13 Simulated versus observed temperature at PEKI, Clearwater River RM 33

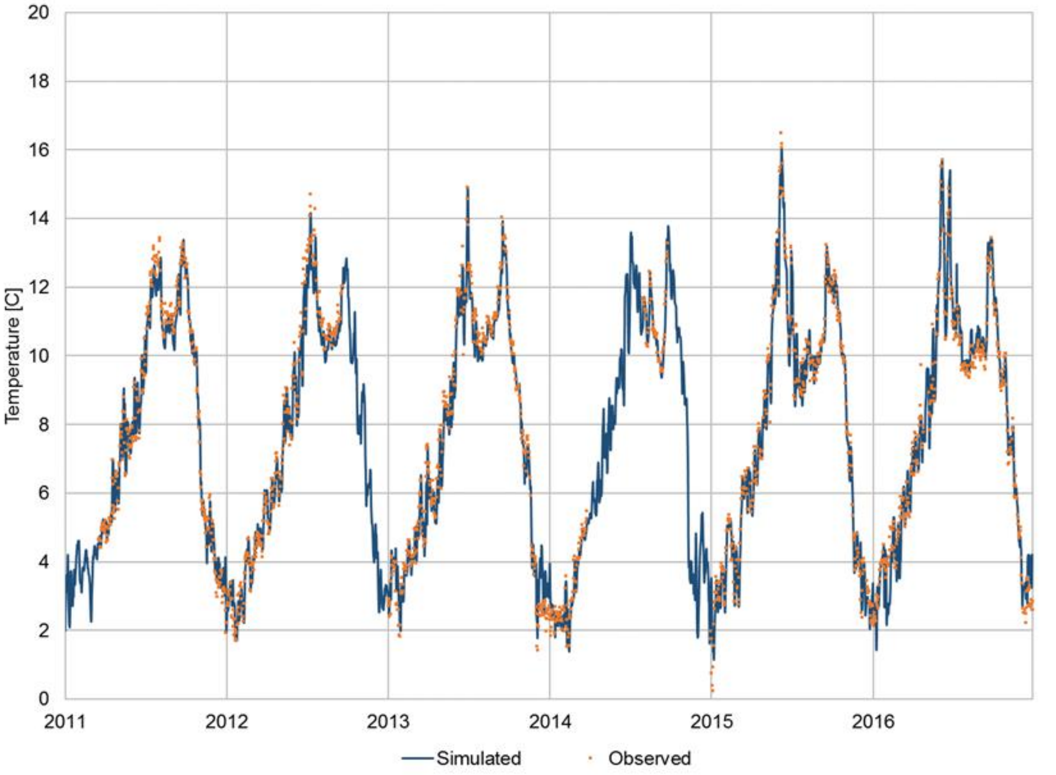


Figure D.3-14 Simulated versus observed temperature at LGNW, period 2011 – 2016

D.4 10-year Daily Average Temperature Comparisons

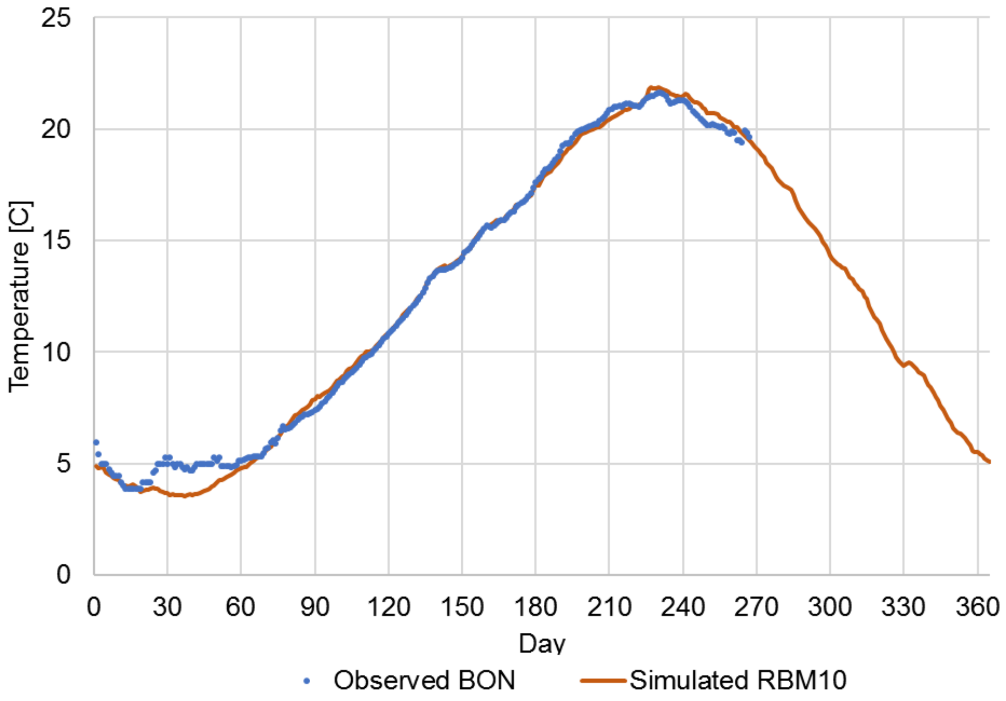


Figure D.4-1 10-year daily average temperature comparison at BON

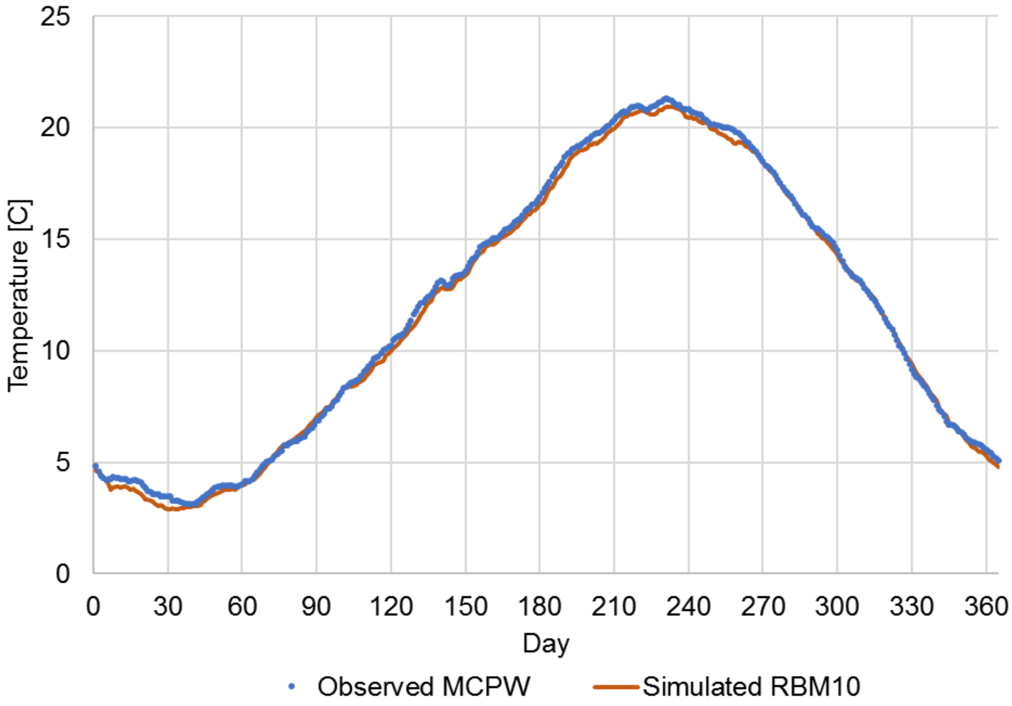


Figure D.4-2 10-year daily average temperature comparison at MCPW

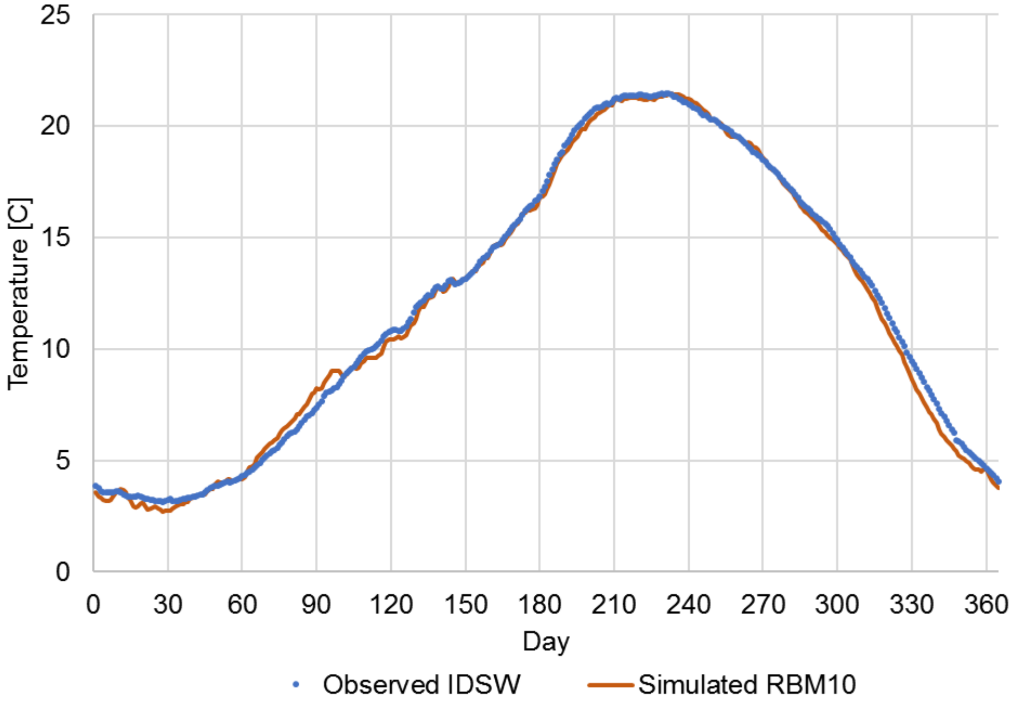


Figure D.4-3 10-year daily average temperature comparison at IDSW

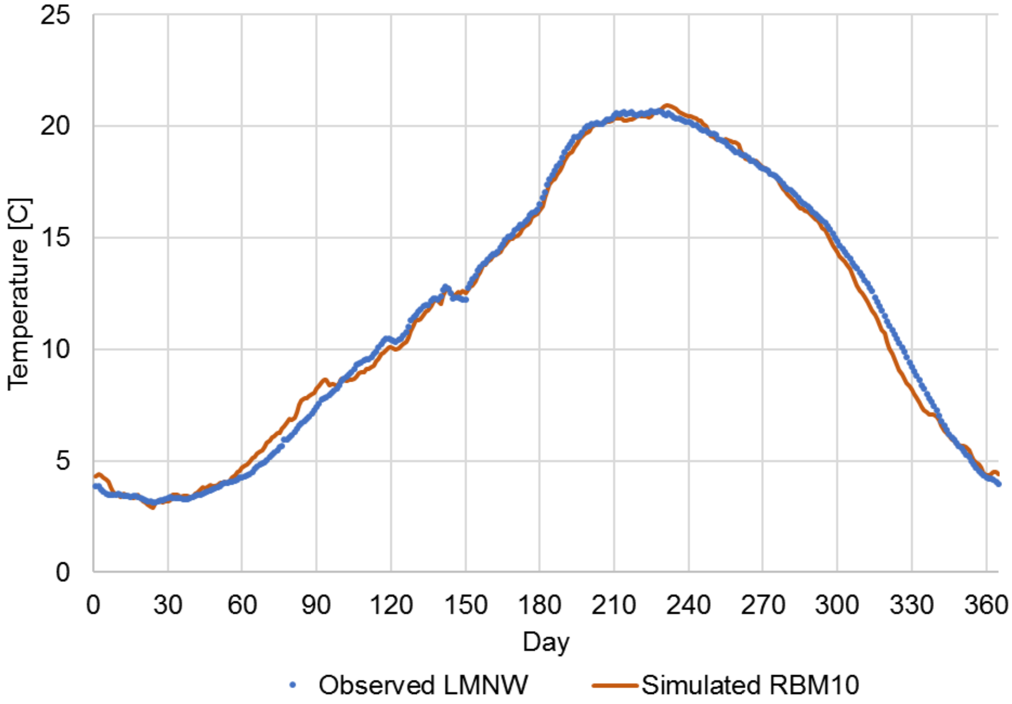


Figure D.4-4 10-year daily average temperature comparison at LMNW

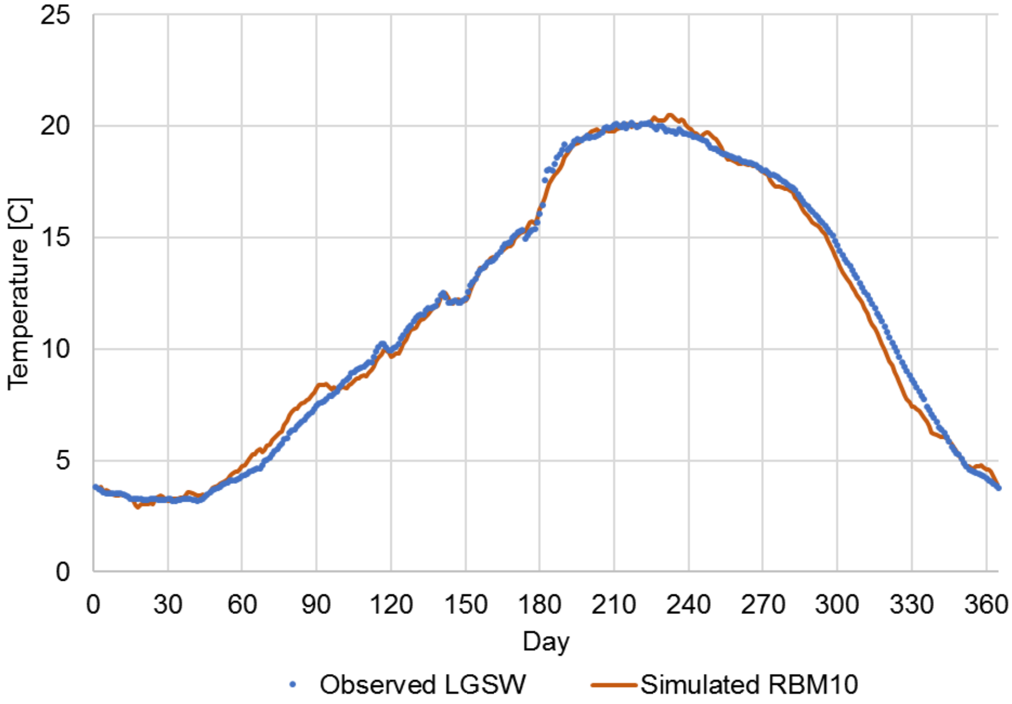


Figure D.4-5 10-year daily average temperature comparison at LGSW

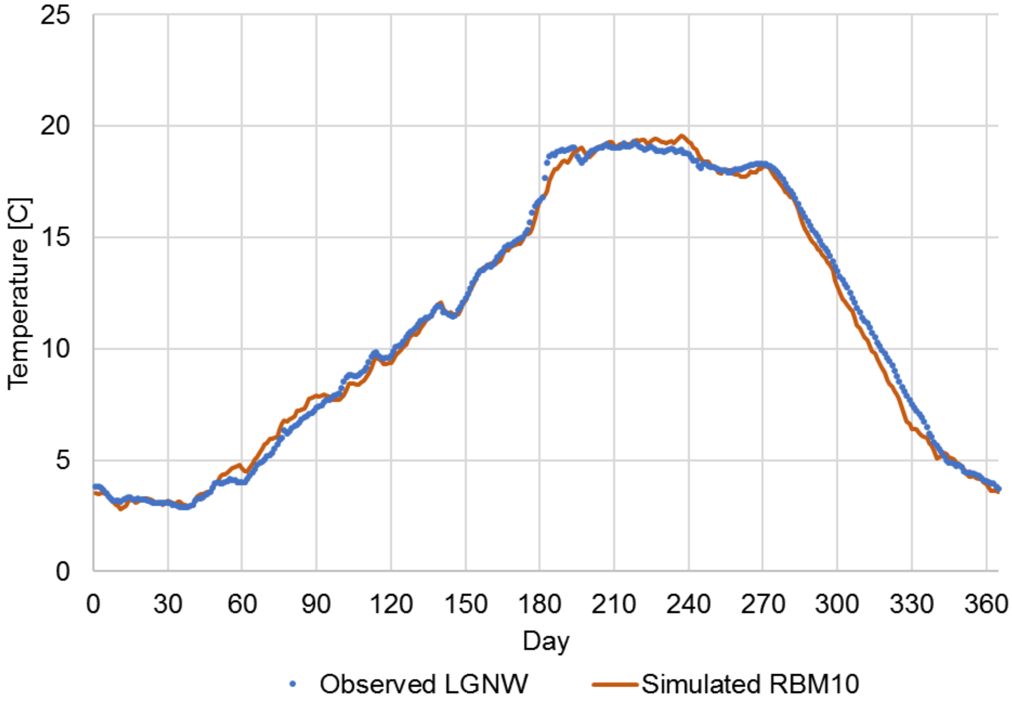


Figure D.4-6 10-year daily average temperature comparison at LGNW

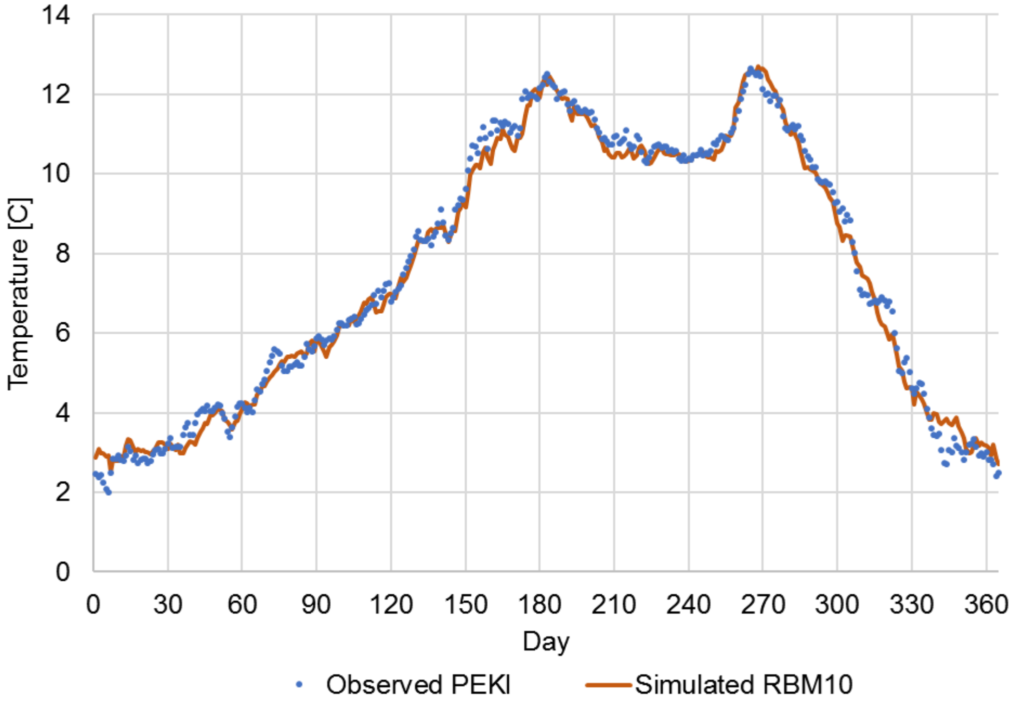


Figure D.4-7 10-year daily average temperature comparison at PEKI

D.5 Flow Discharge Model Results

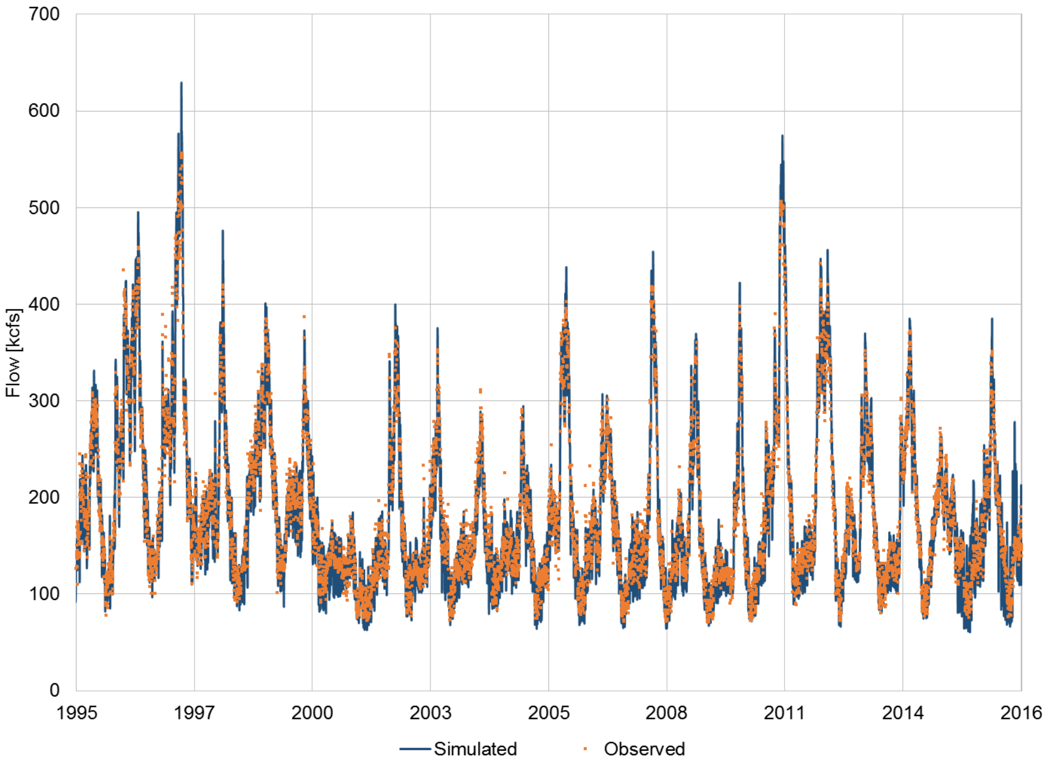


Figure D.5-1 Simulated versus observed flow at BON, Columbia River RM 146

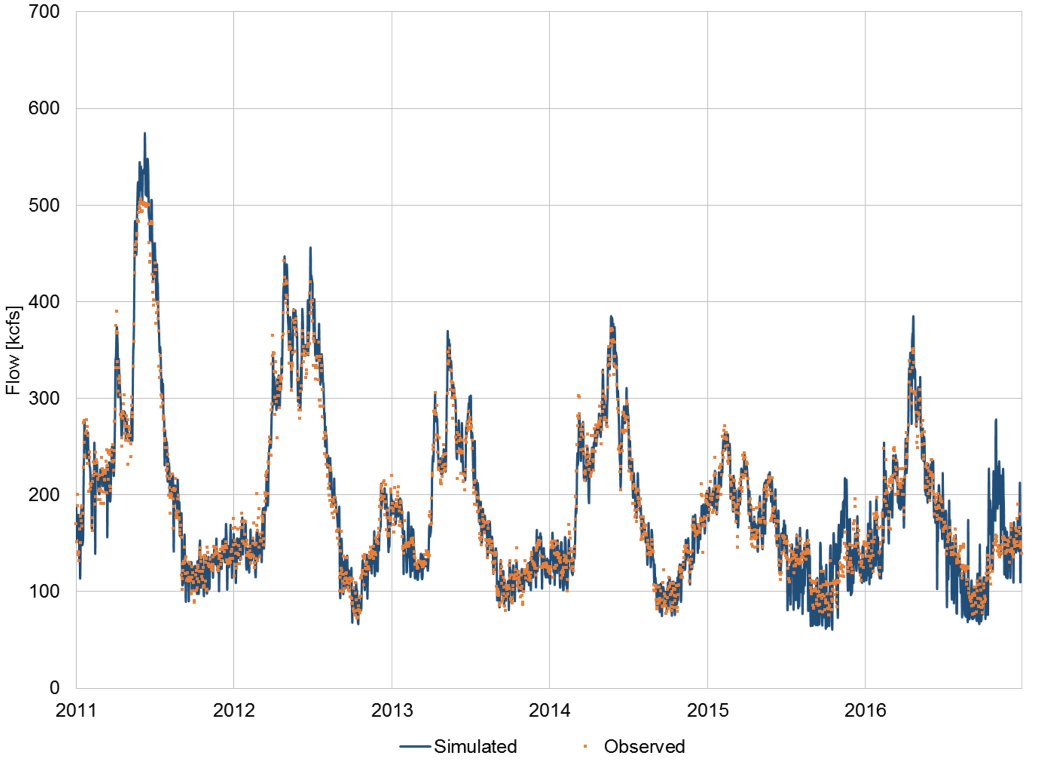


Figure D.5-2 Simulated versus observed flow at BON, period 2011 – 2016

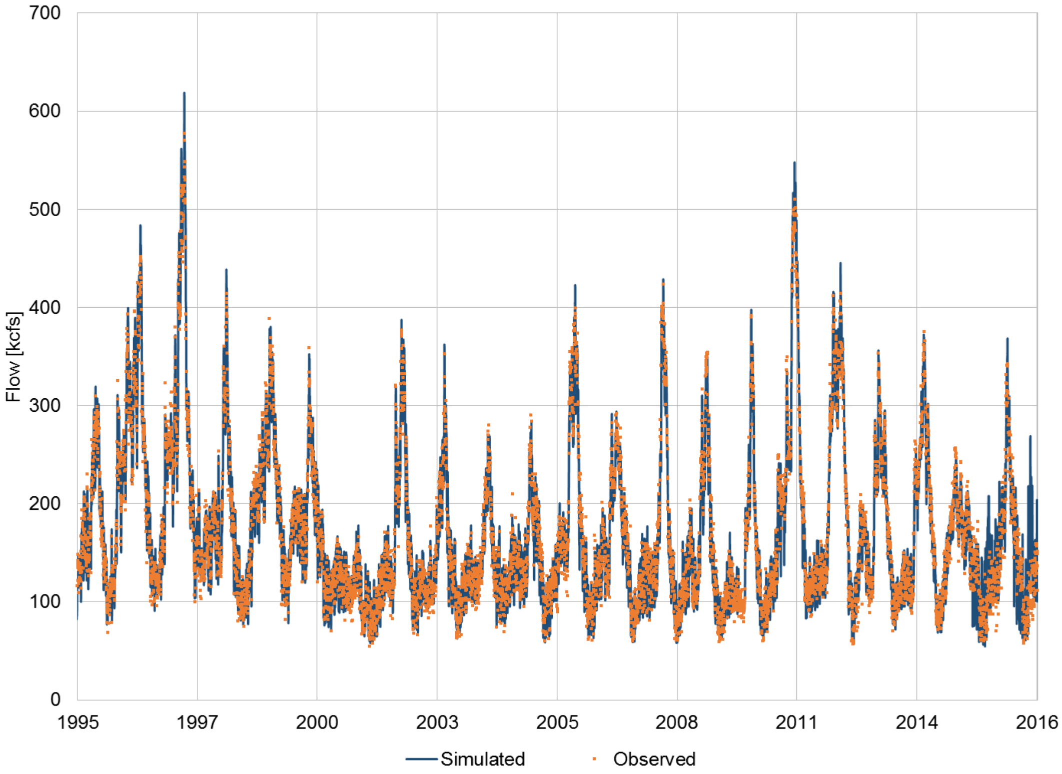


Figure D.5-3 Simulated versus observed flow at MCPW, Columbia River RM 291

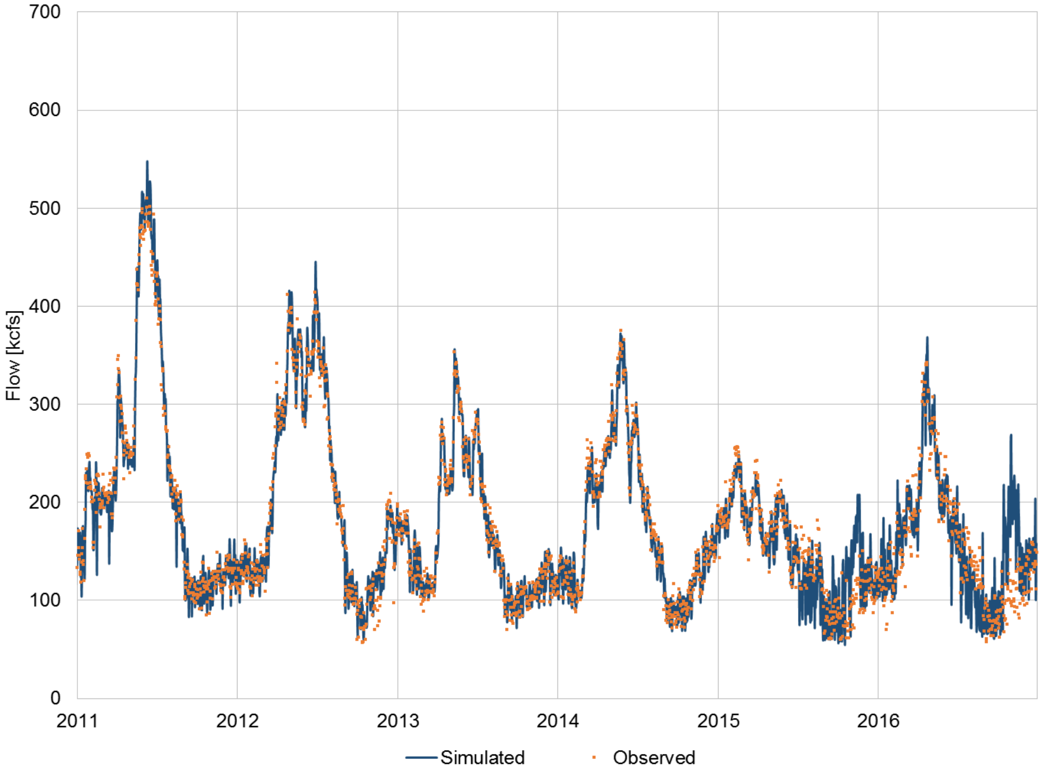


Figure D.5-4 Simulated versus observed flow at MCPW, period 2011 – 2016

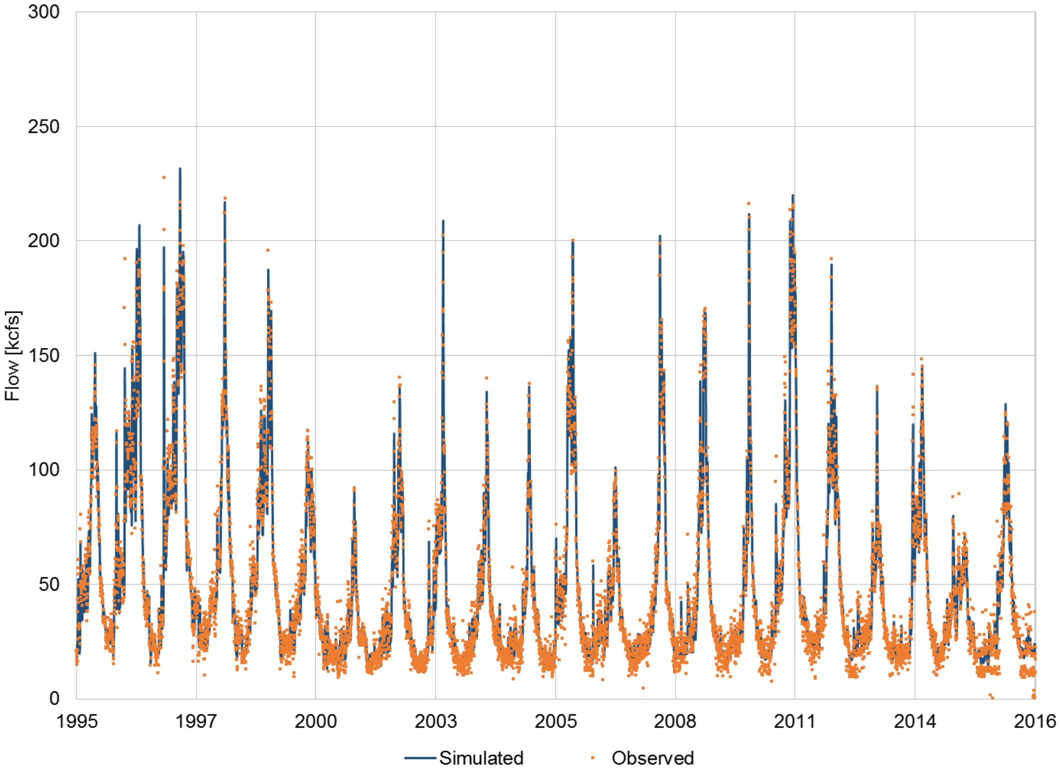


Figure D.5-5 Simulated versus observed flow at IDSW, Snake River RM 6.8

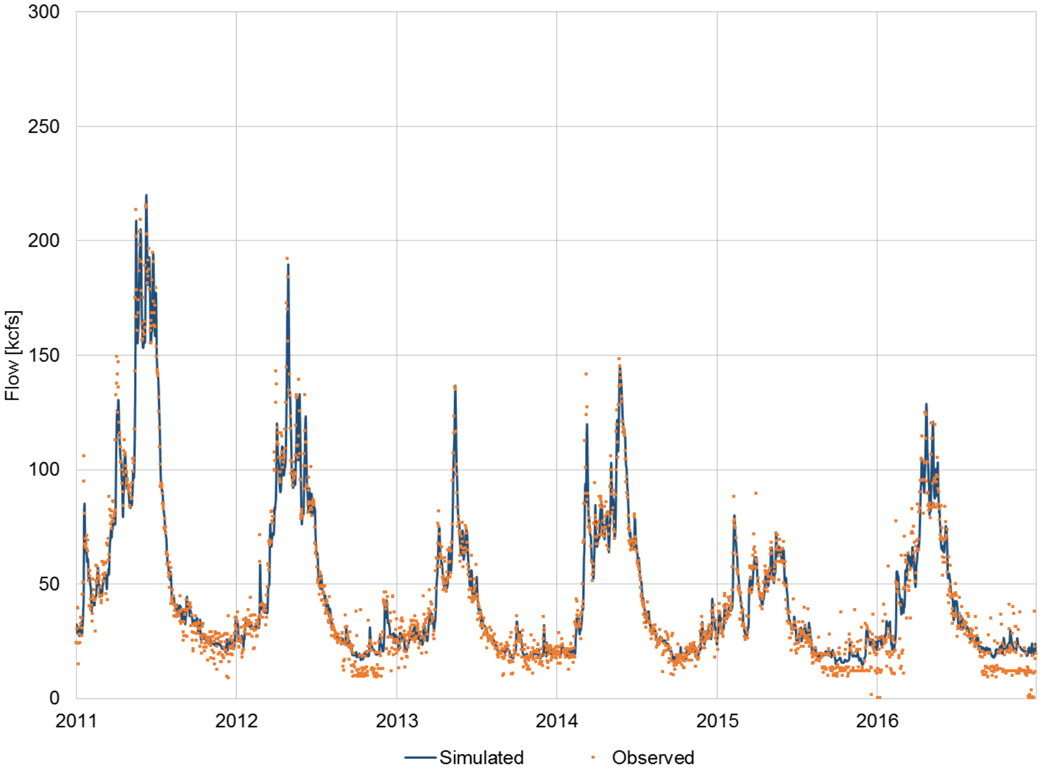


Figure D.5-6 Simulated versus observed flow at IDSW, period 2011 – 2016

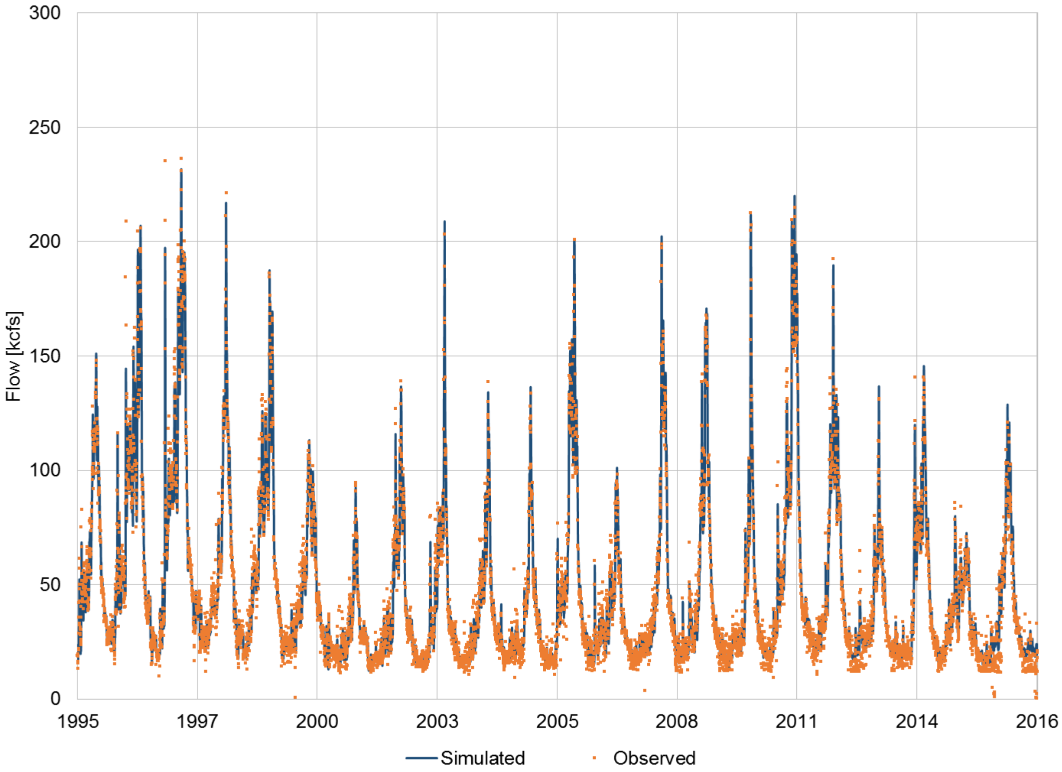


Figure D.5-7 Simulated versus observed flow at LMNW, Snake River RM 40.8

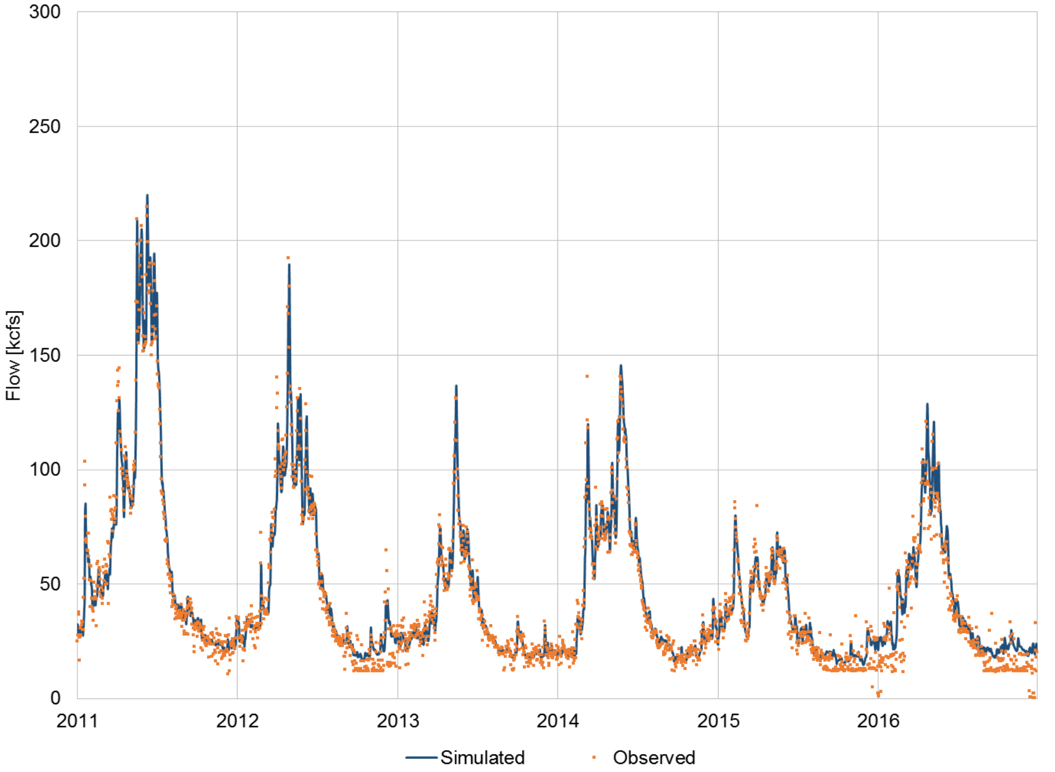


Figure D.5-8 Simulated versus observed flow at LMNW, period 2011 – 2016

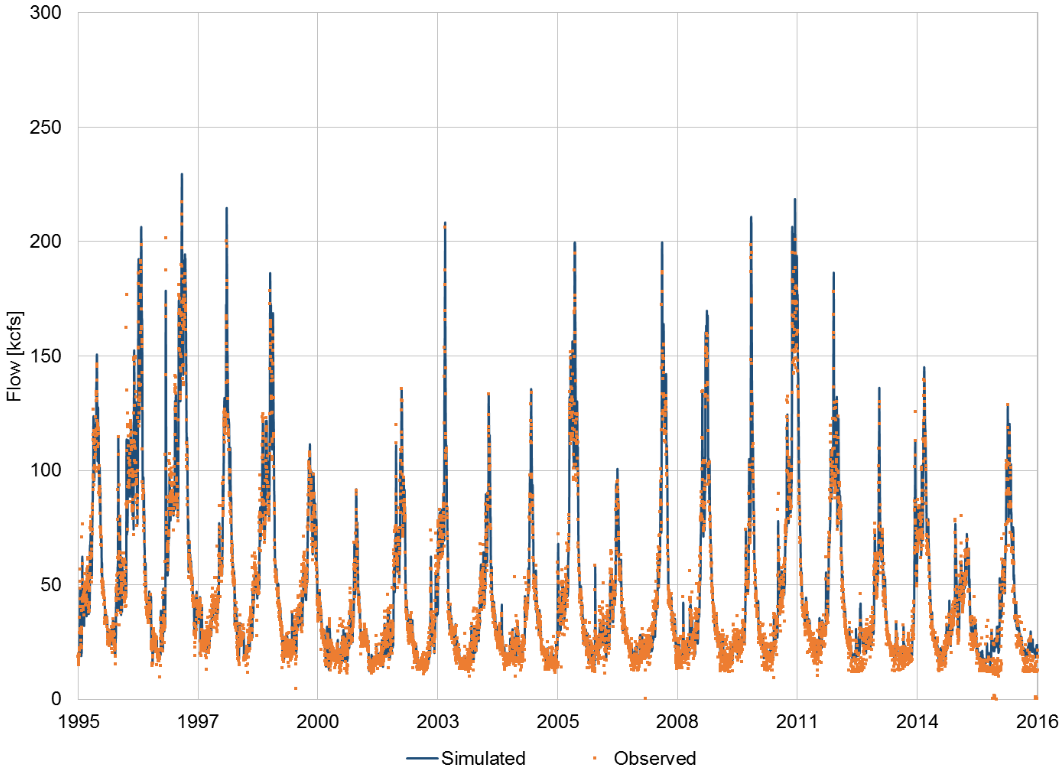


Figure D.5-9 Simulated versus observed flow at LGSW, Snake River RM 69.5

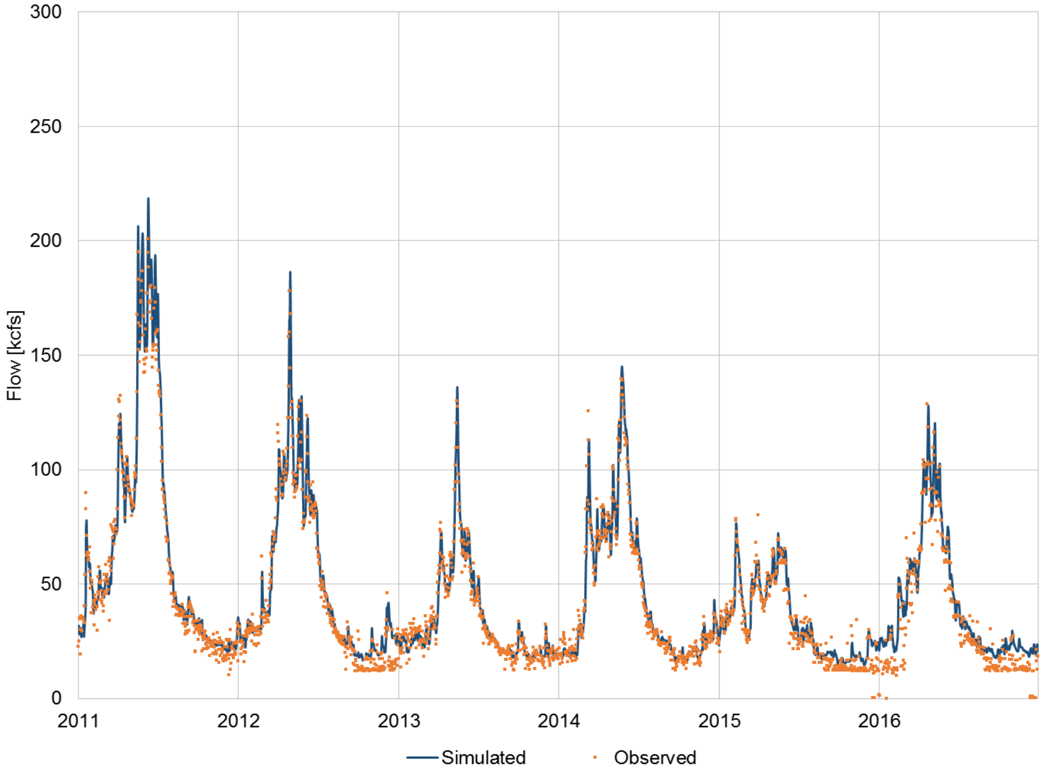


Figure D.5-10 Simulated versus observed flow at LGSW, period 2011 – 2016

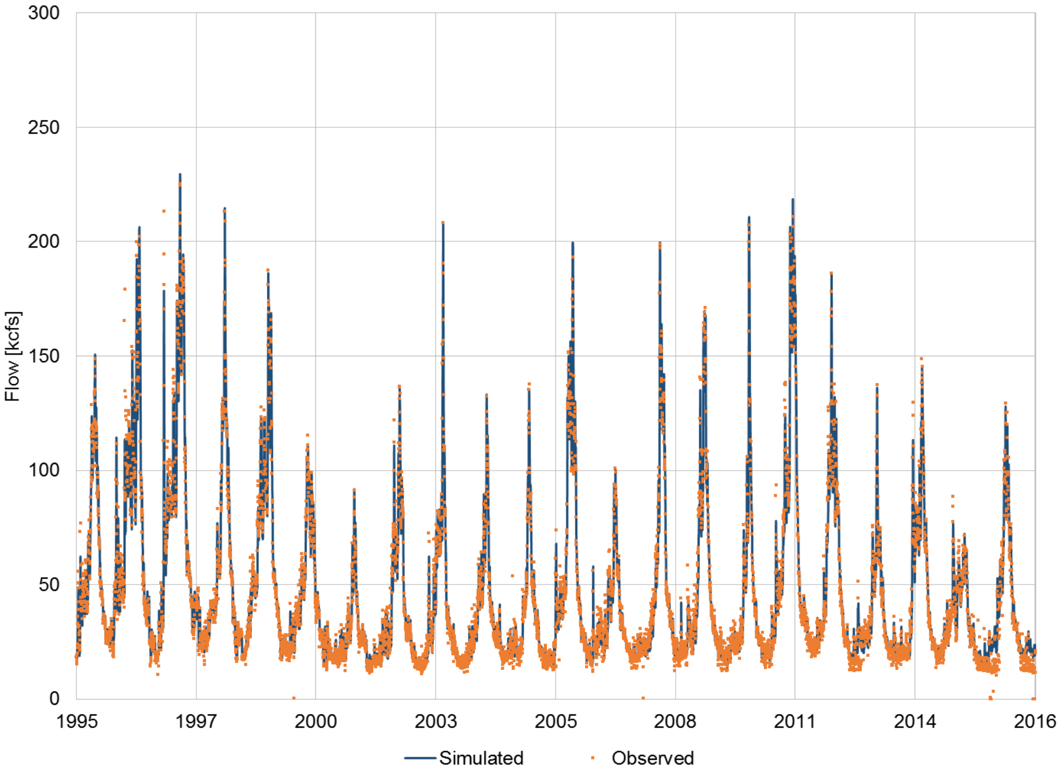


Figure D.5-11 Simulated versus observed flow at LGNW, Snake River RM 106.8

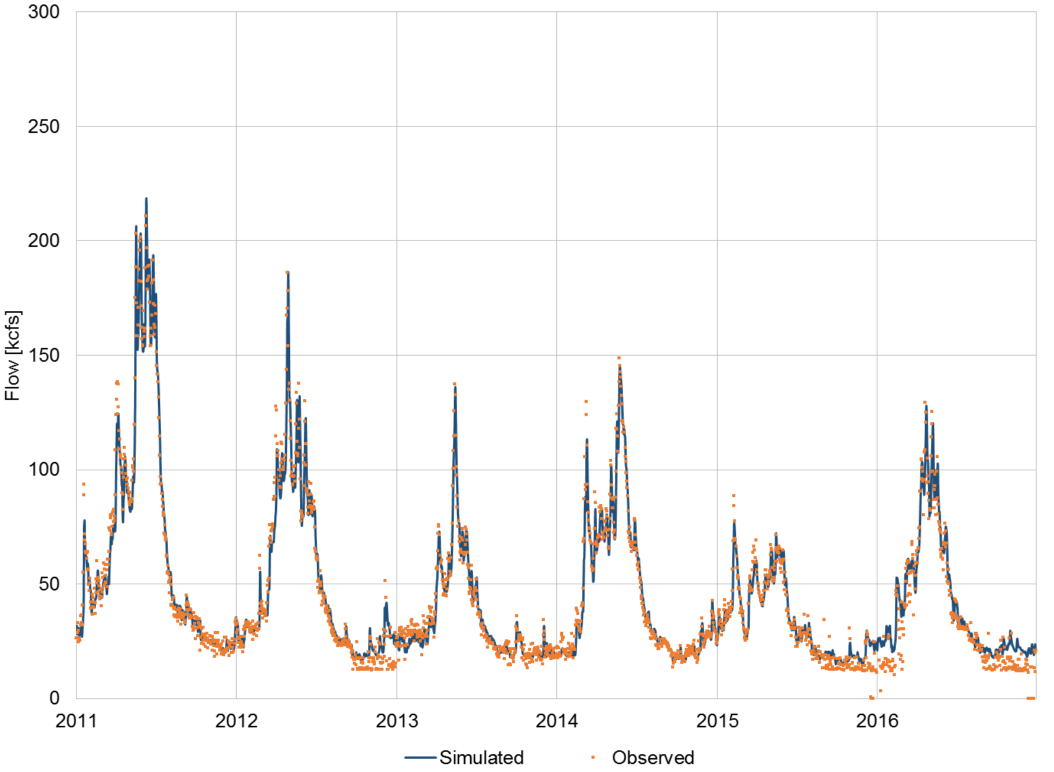


Figure D.5-12 Simulated versus observed flow at LGNW, period 2011 – 2016

Appendix E Geometric Properties of the Columbia and Snake River Reaches

E.1 Geometry of Channels and Reservoirs – Existing Conditions

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

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

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

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

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

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

E.2 Geometry of Channels and Reservoirs – Dams Removed

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

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

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

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

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

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

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

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

Appendix F Sensitivity Analysis

F.1 Columbia River Sensitivity Analysis Results

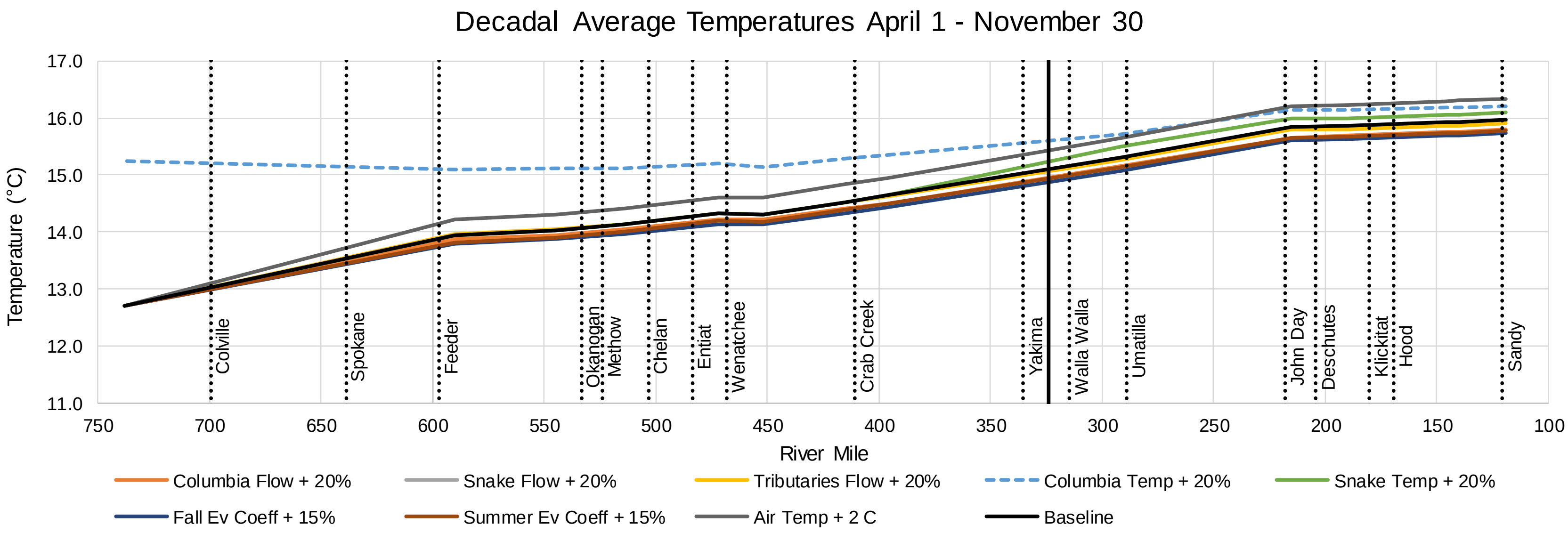


Figure F.1-1 Longitudinal changes in 10-year (April - November) average Columbia River water temperatures for each scenario evaluated

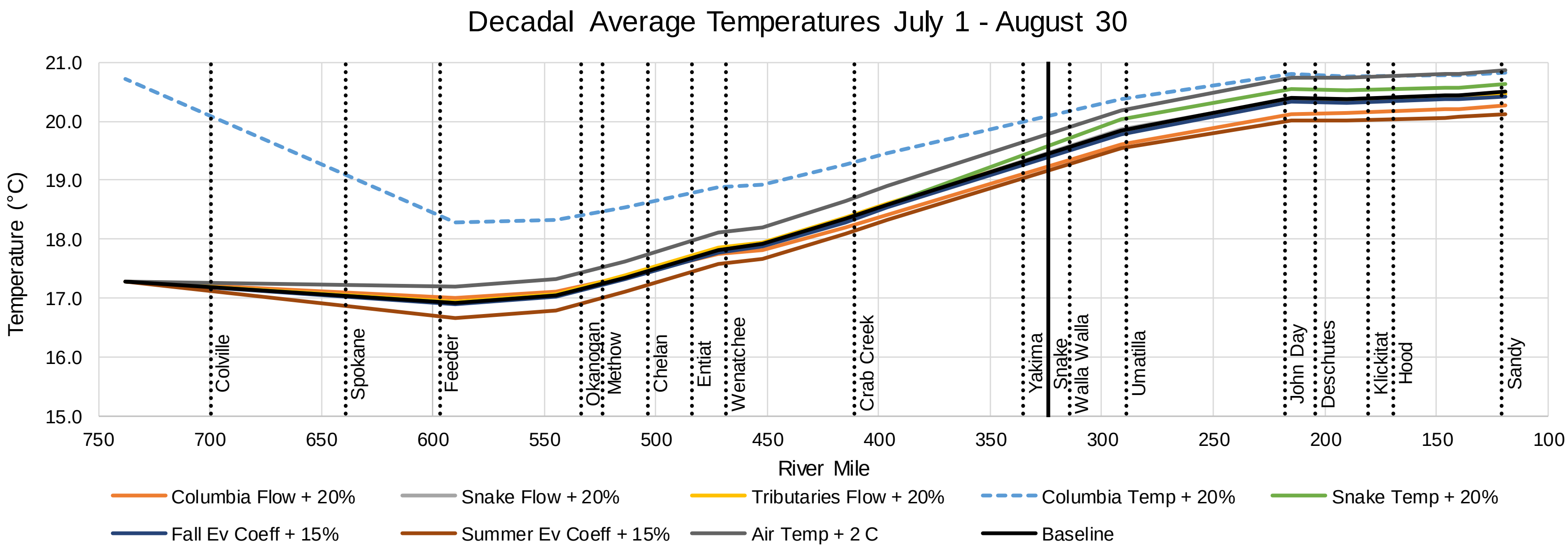


Figure F.1-2 Longitudinal changes in 10-year (July - August) average Columbia River water temperatures for each scenario evaluated

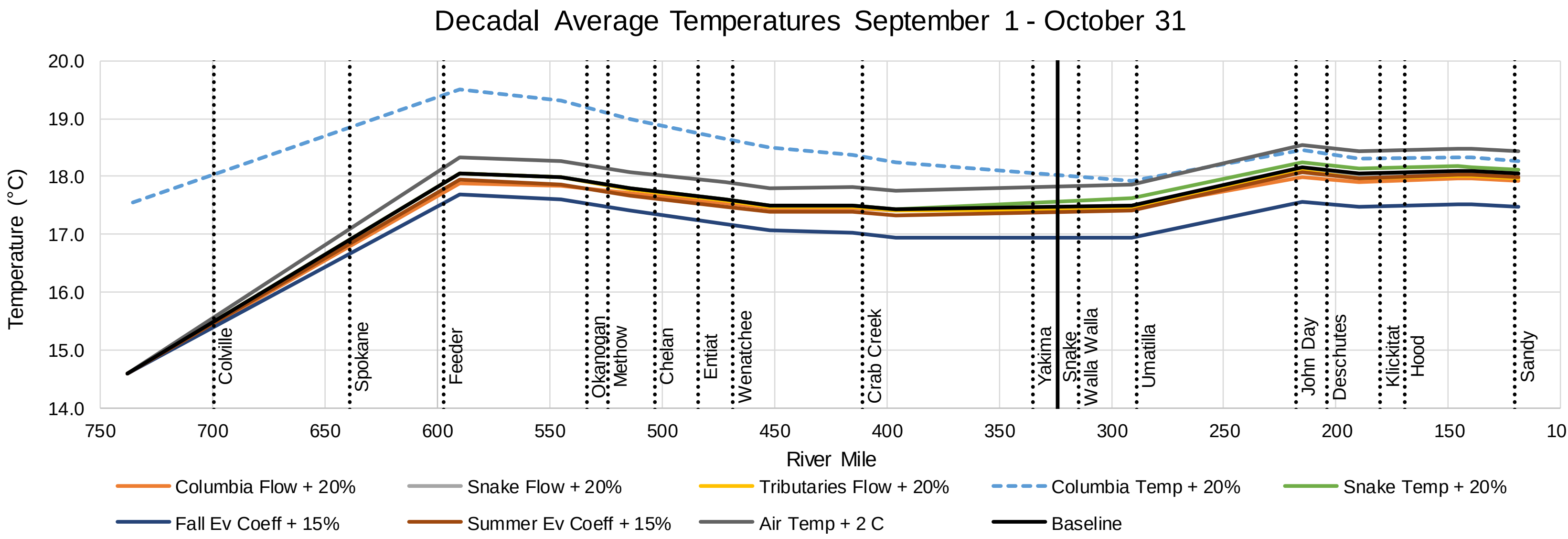


Figure F.1-3 Longitudinal changes in 10-year (September - October) average Columbia River water temperatures for each scenario evaluated

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

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

* Station location shown in Figure 3-1

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

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

* Station location shown in Figure 3-1

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

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

* Station location shown in Figure 3-1

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

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

* Station location shown in Figure 3-1

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

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

* Station location shown in Figure 3-1

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

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

* Station location shown in Figure 3-1

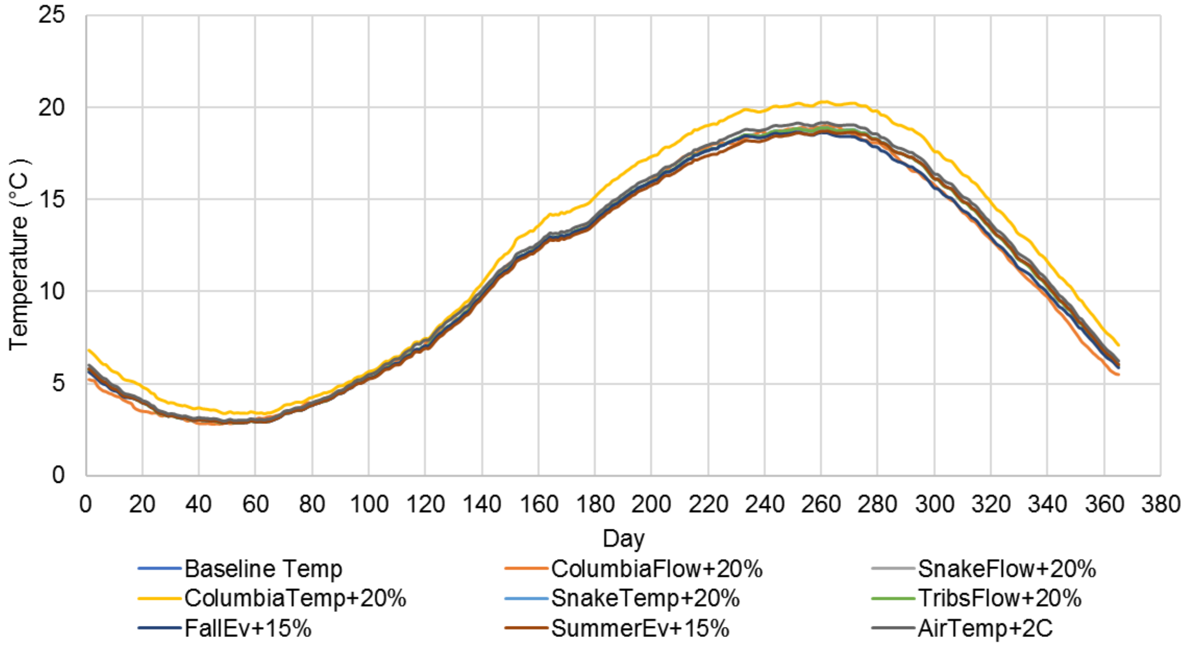


Figure F.1-4 Sensitivity of 10-year daily average temperatures at GCGW

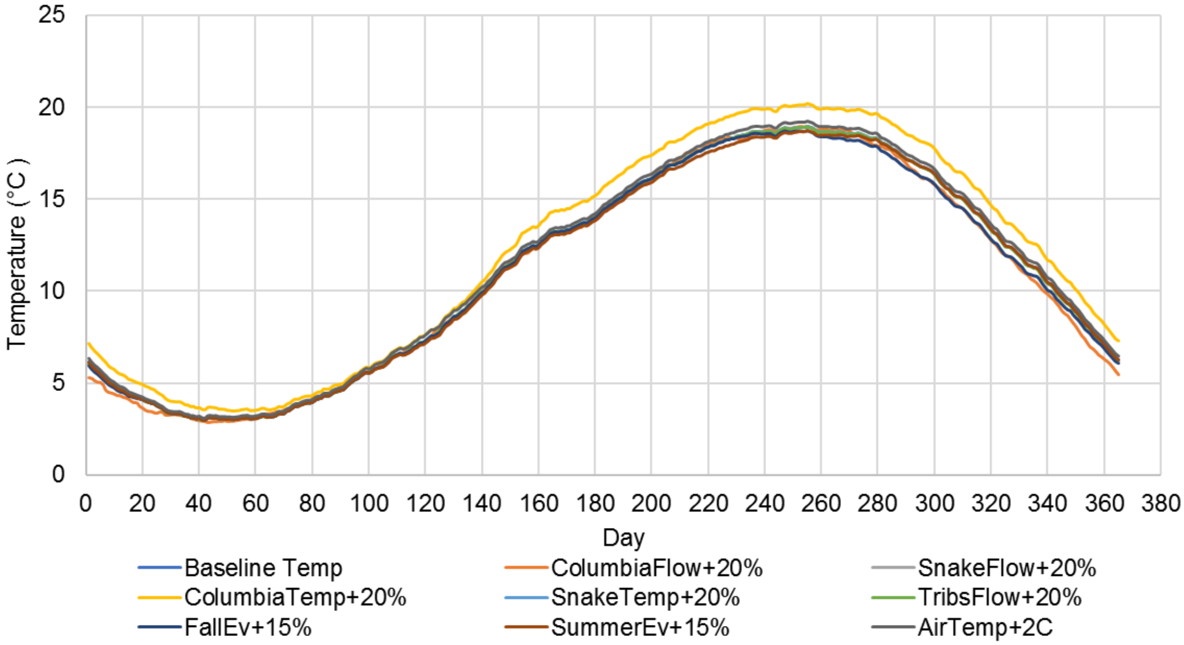


Figure F.1-5 Sensitivity of 10-year daily average temperatures at CHQW

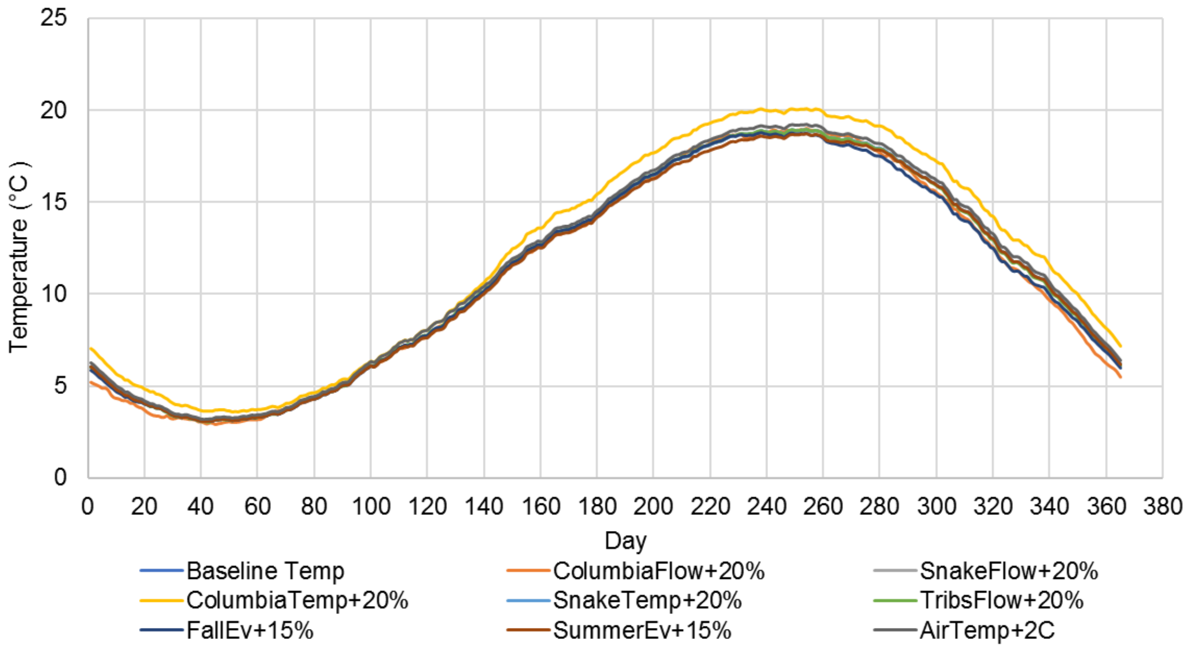


Figure F.1-6 Sensitivity of 10-year daily average temperatures at WELW

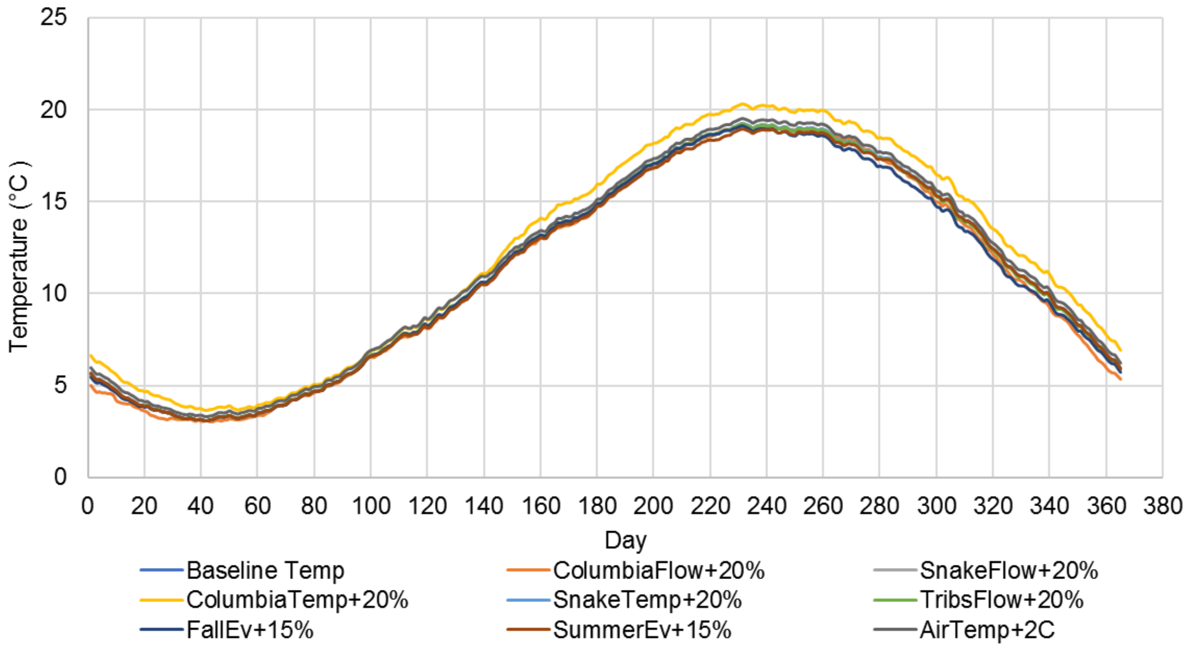


Figure F.1-7 Sensitivity of 10-year daily average temperatures at RRDW

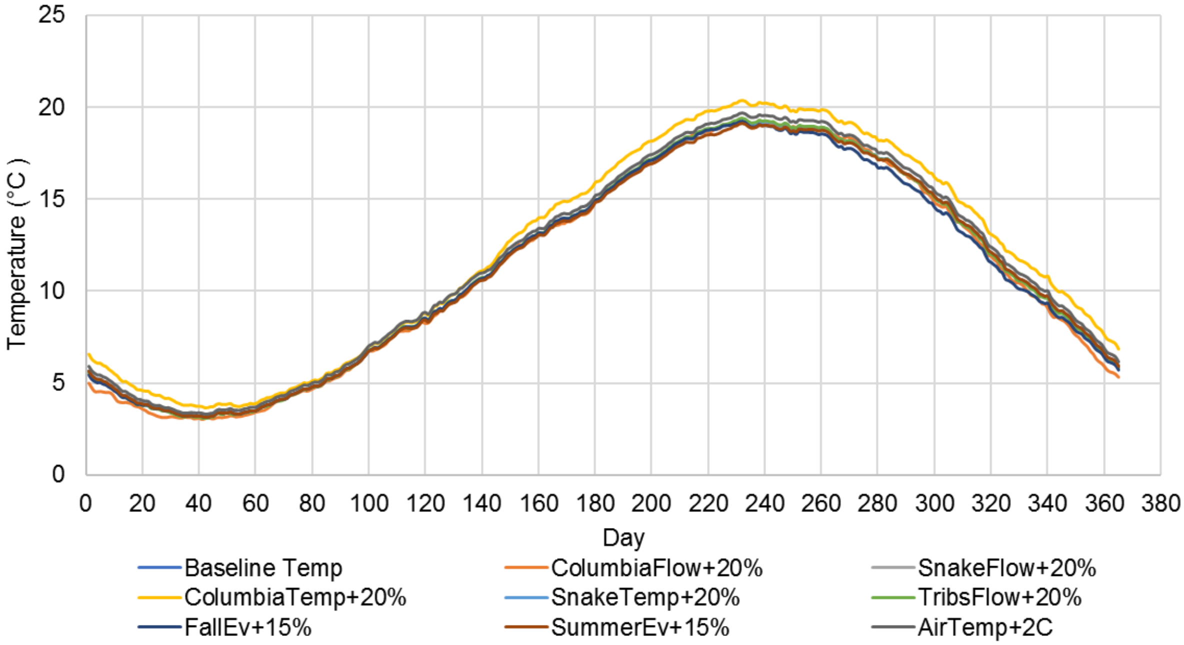


Figure F.1-8 Sensitivity of 10-year daily average temperatures at RIGW

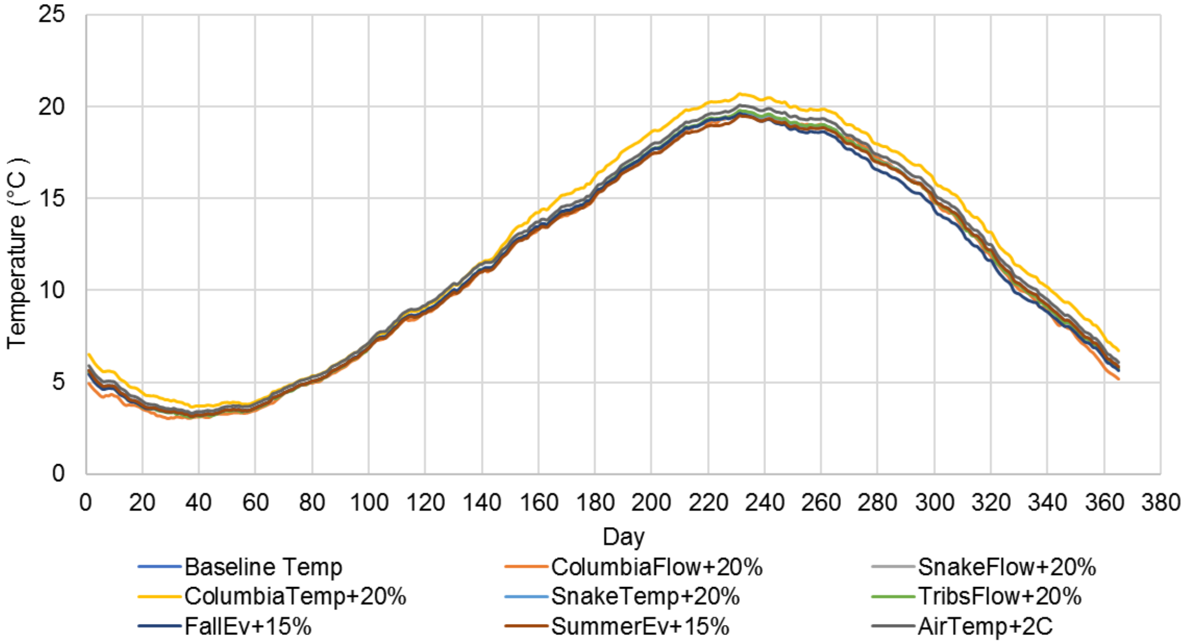


Figure F.1-9 Sensitivity of 10-year daily average temperatures at WANW

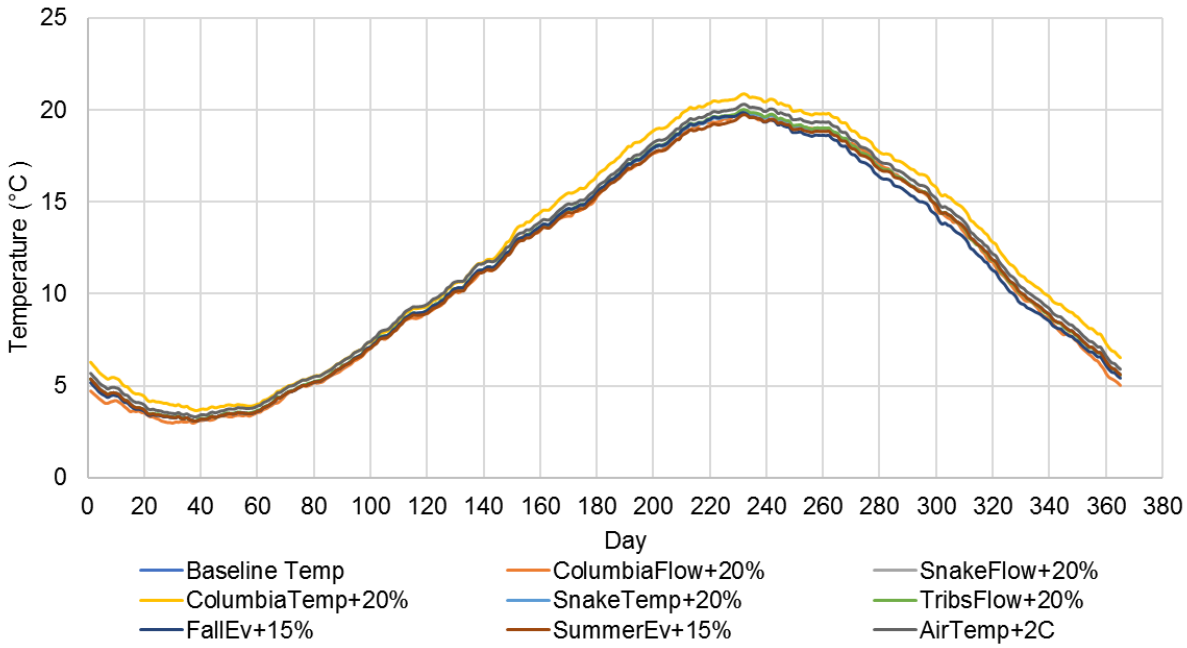


Figure F.1-10 Sensitivity of 10-year daily average temperatures at PRXW

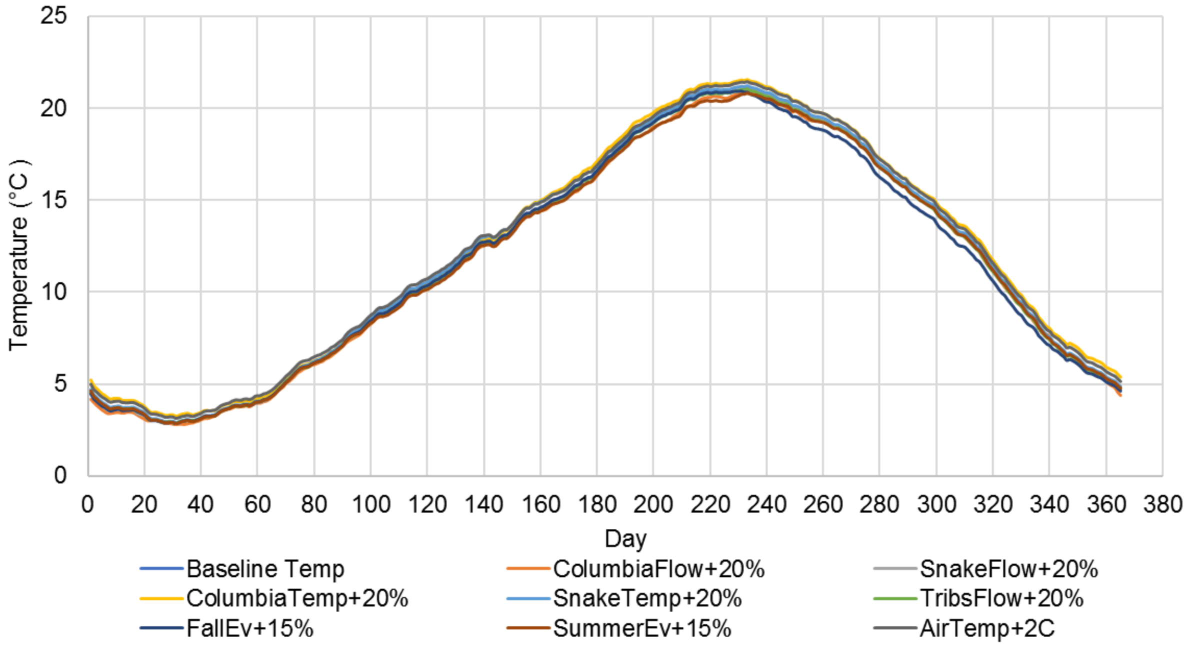


Figure F.1-11 Sensitivity of 10-year daily average temperatures at MCPW

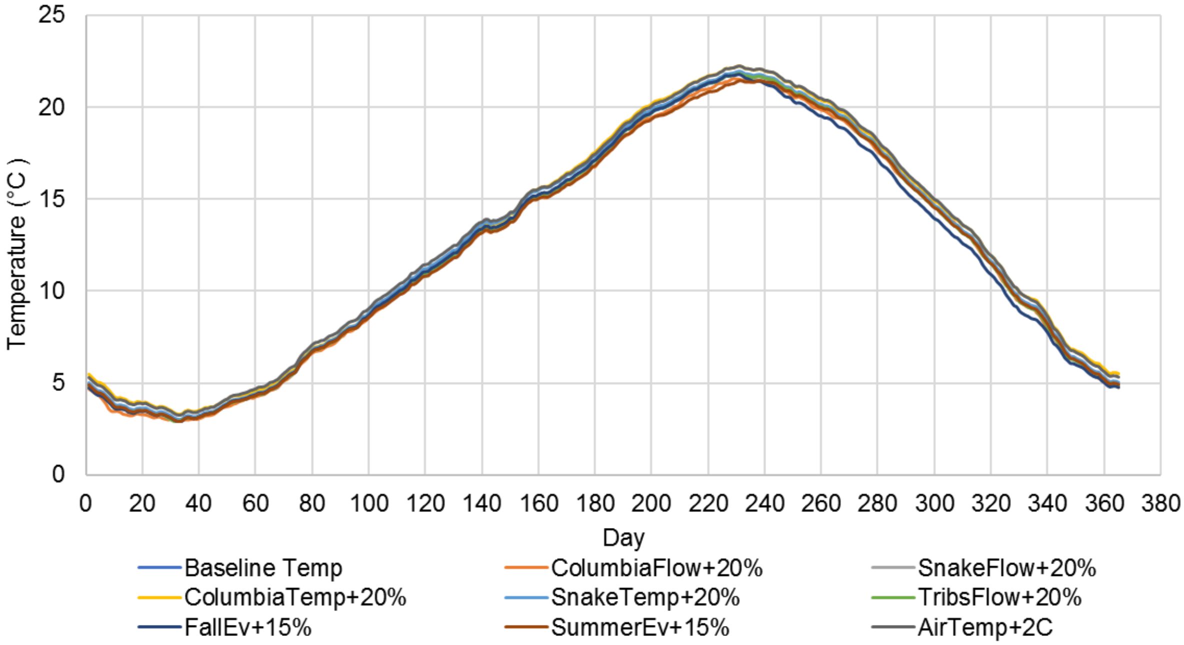


Figure F.1-12 Sensitivity of 10-year daily average temperatures at JHAW

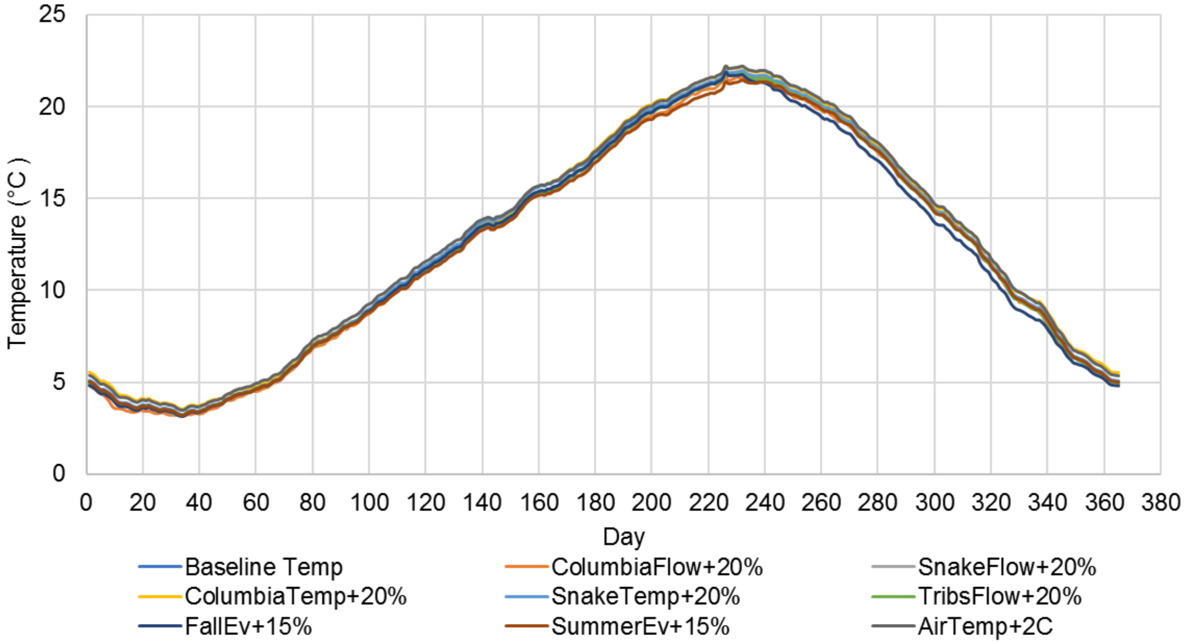


Figure F.1-13 Sensitivity of 10-year daily average temperatures at TDDO

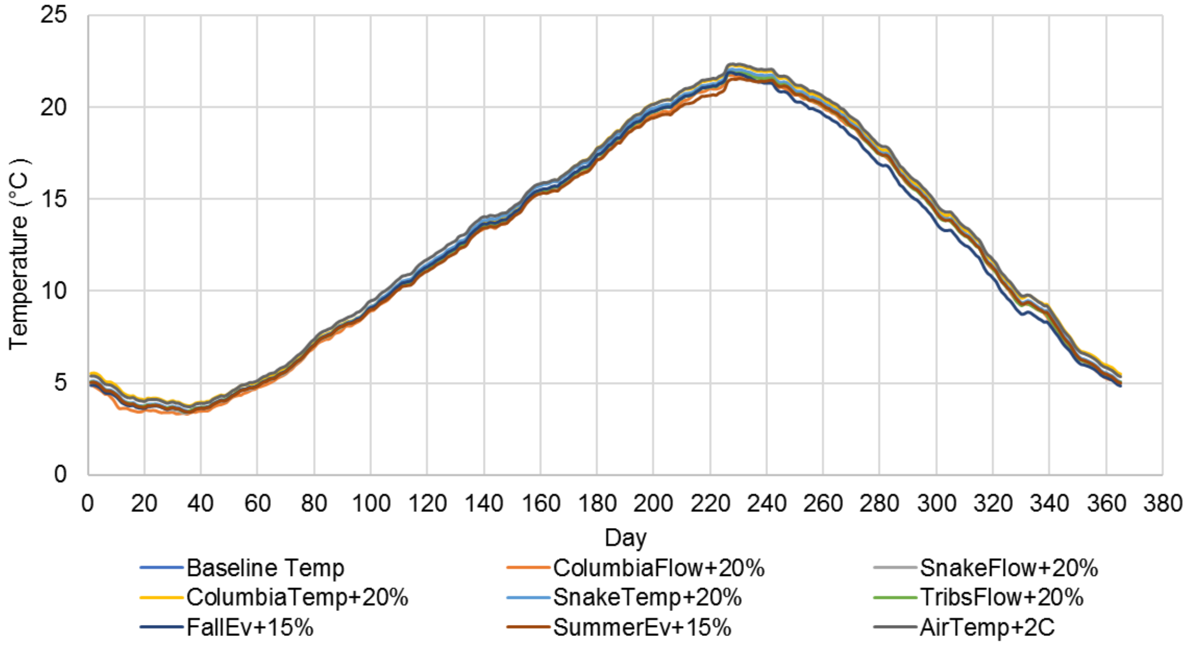


Figure F.1-14 Sensitivity of 10-year daily average temperatures at BON

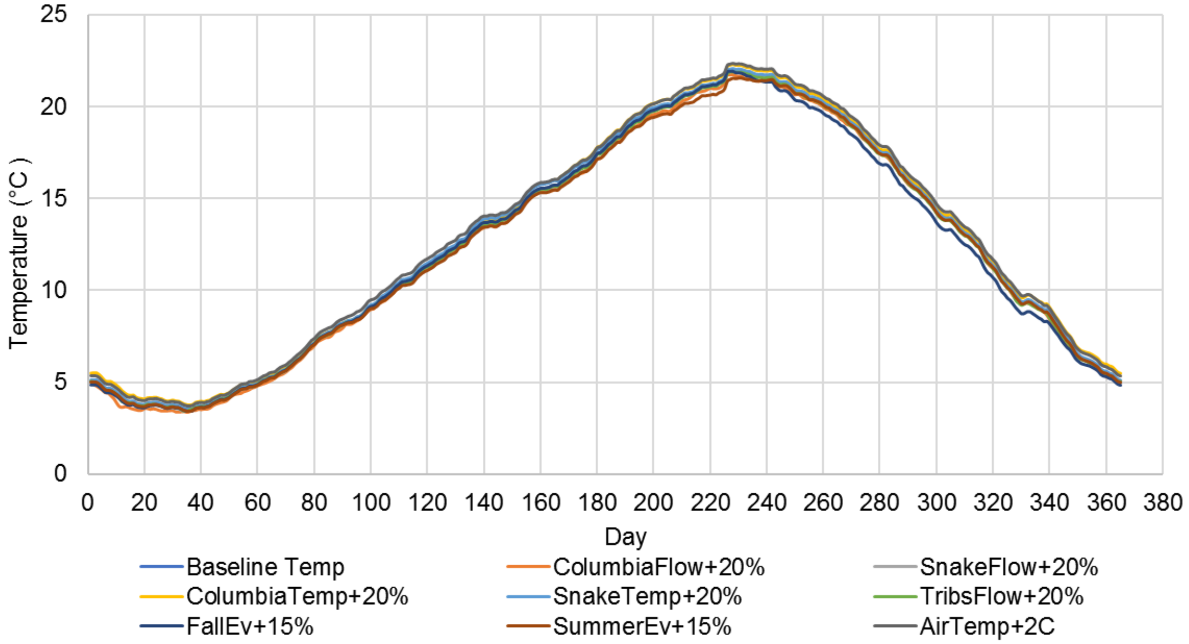


Figure F.1-15 Sensitivity of 10-year daily average temperatures at WRNO

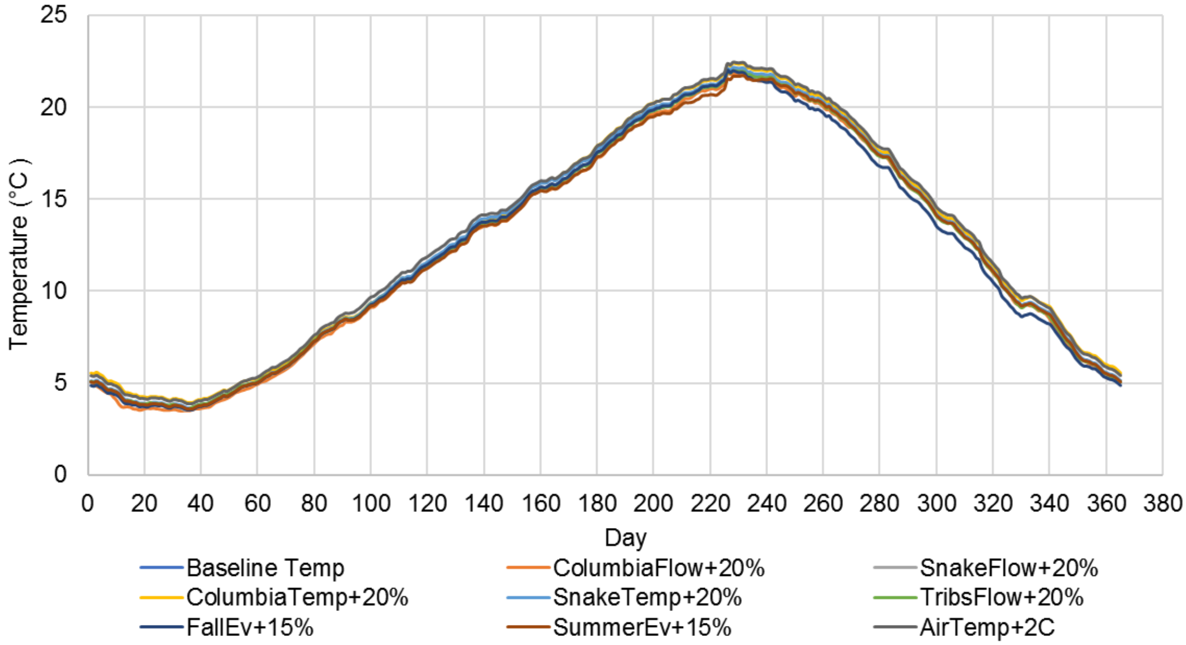


Figure F.1-16 Sensitivity of 10-year daily average temperatures at CMWN

F.2 Snake River Sensitivity Analysis Results

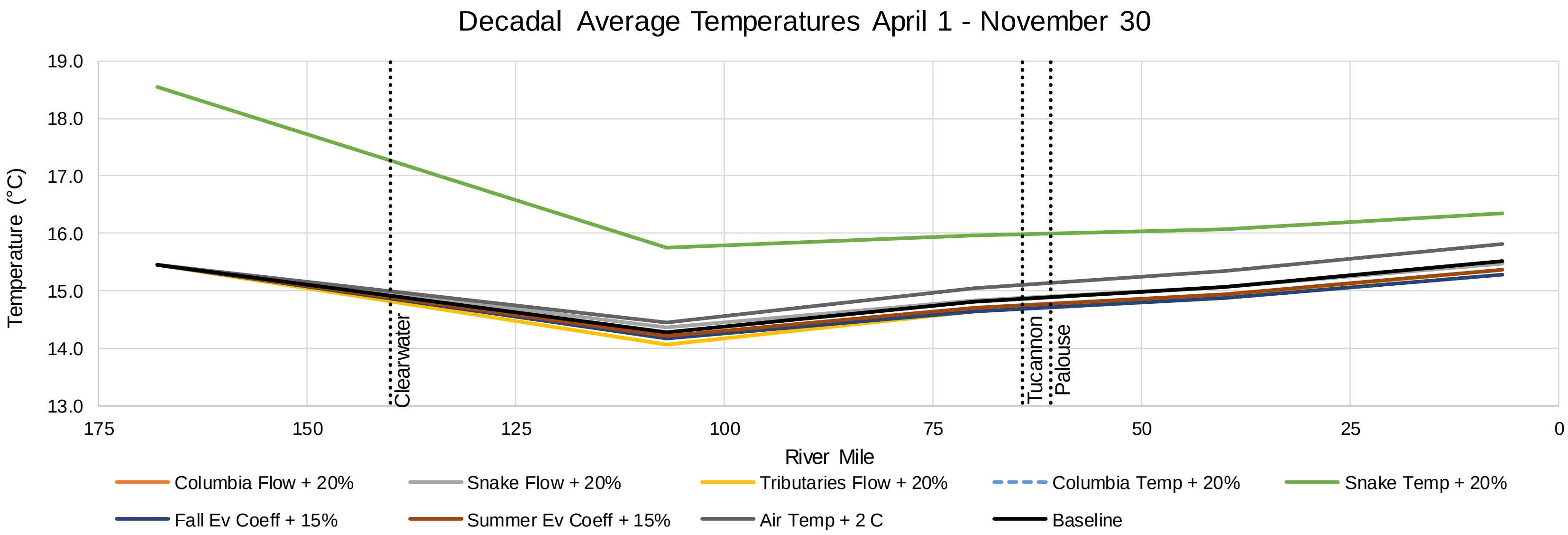


Figure F.2-1 Longitudinal changes in 10-year (April - November) average Snake River water temperatures for each scenario evaluated

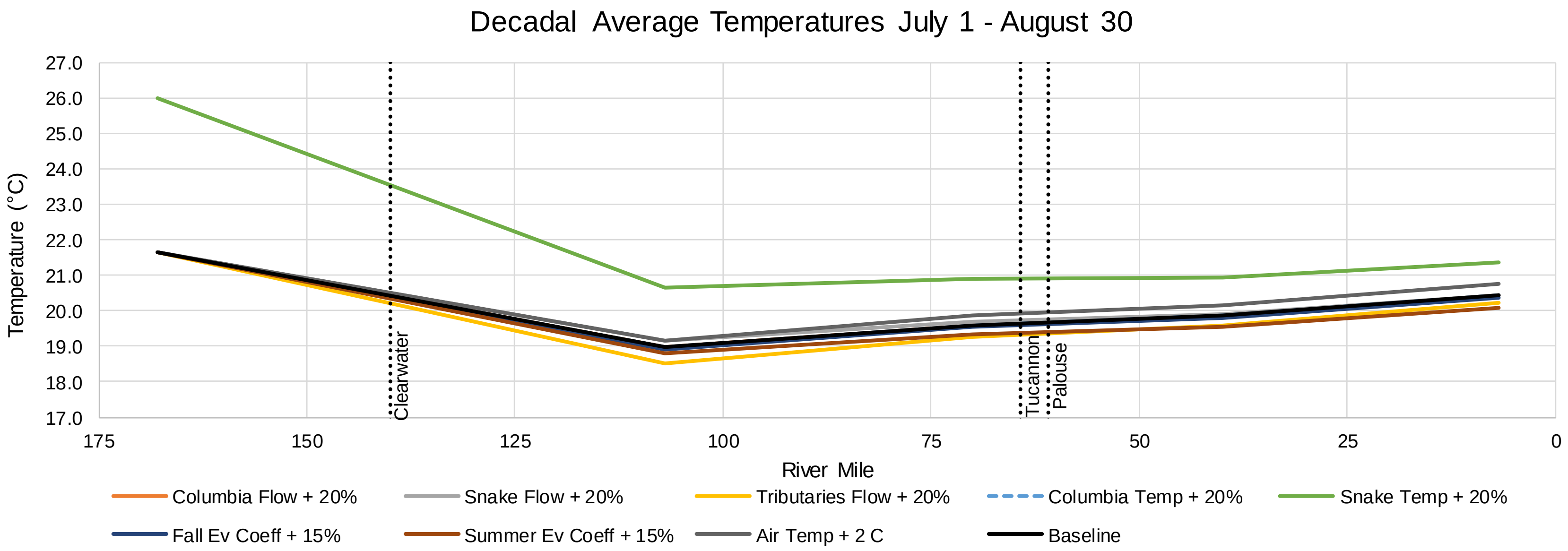


Figure F.2-2 Longitudinal changes in 10-year (July - August) average Snake River water temperatures for each scenario evaluated

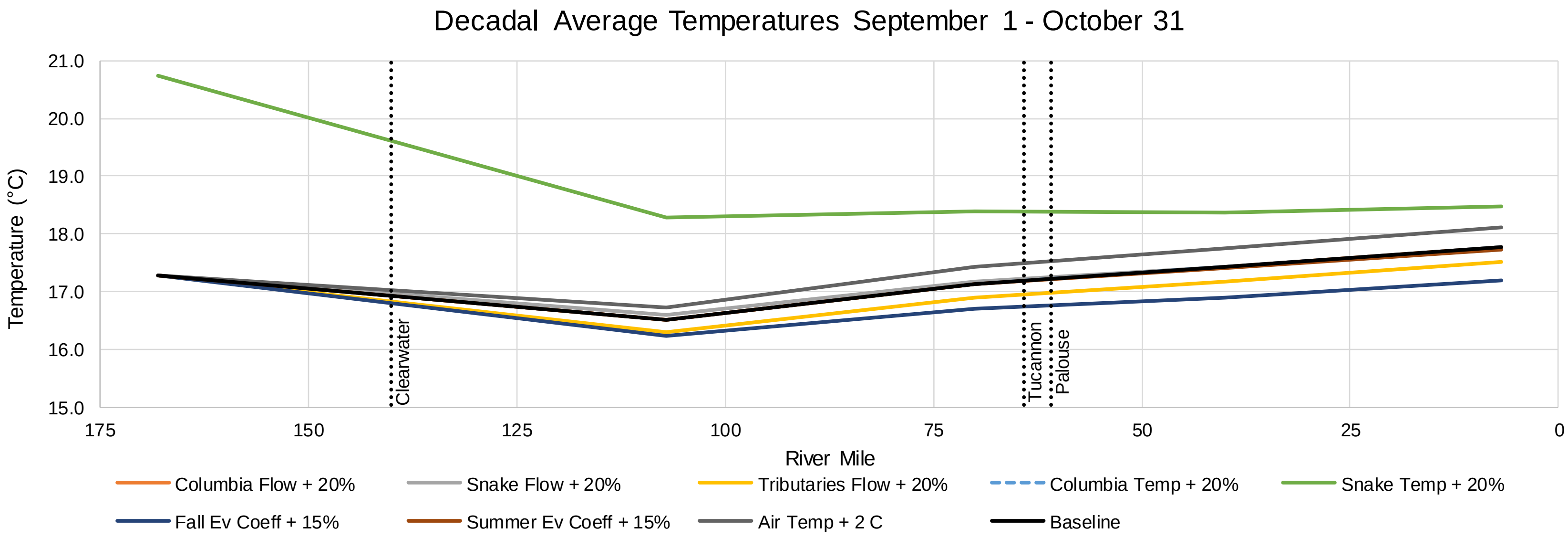


Figure F.2-3 Longitudinal changes in 10-year (September - October) average Snake River water temperatures for each scenario evaluated

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

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

* Station location shown in Figure 3-1

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

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

* Station location shown in Figure 3-1

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

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

* Station location shown in Figure 3-1

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

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

* Station location shown in Figure 3-1

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

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

* Station location shown in Figure 3-1

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

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

* Station location shown in Figure 3-1

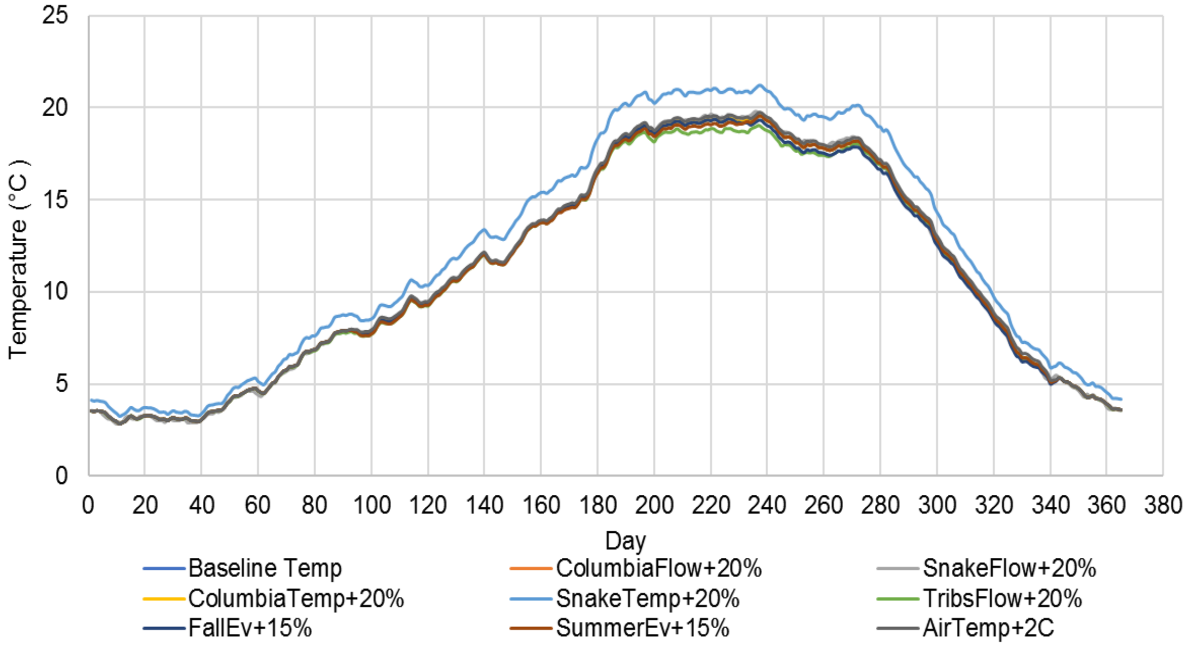


Figure F.2-4 Sensitivity of 10-year daily average temperatures at LGNW

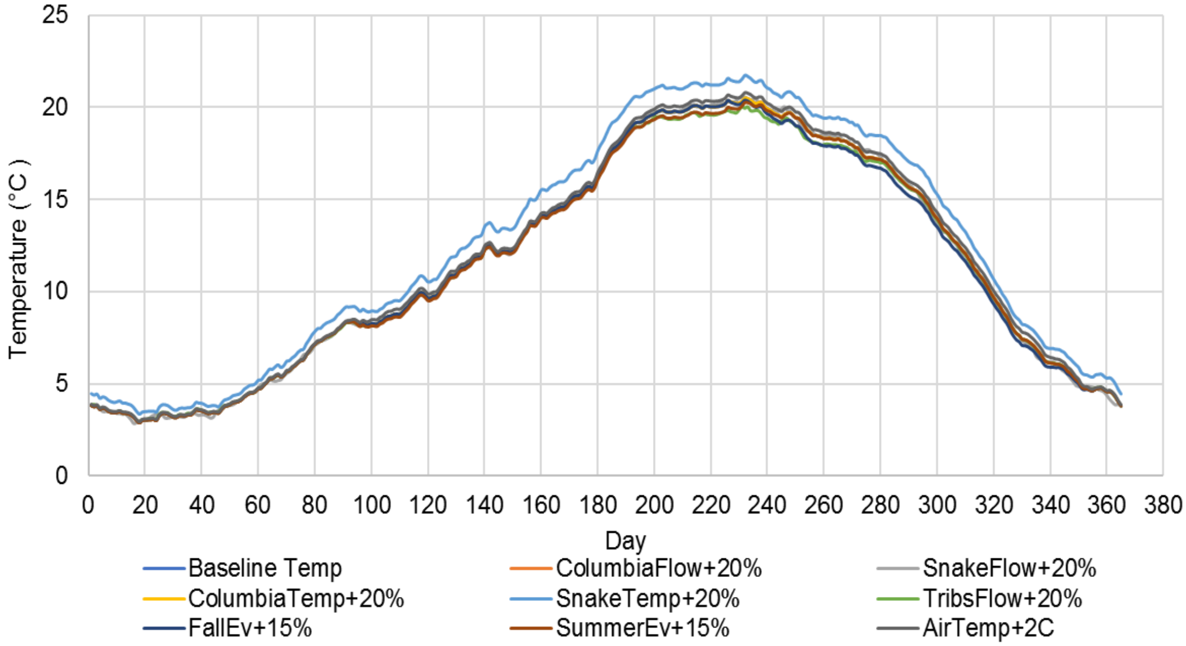


Figure F.2-5 Sensitivity of 10-year daily average temperatures at LGSW

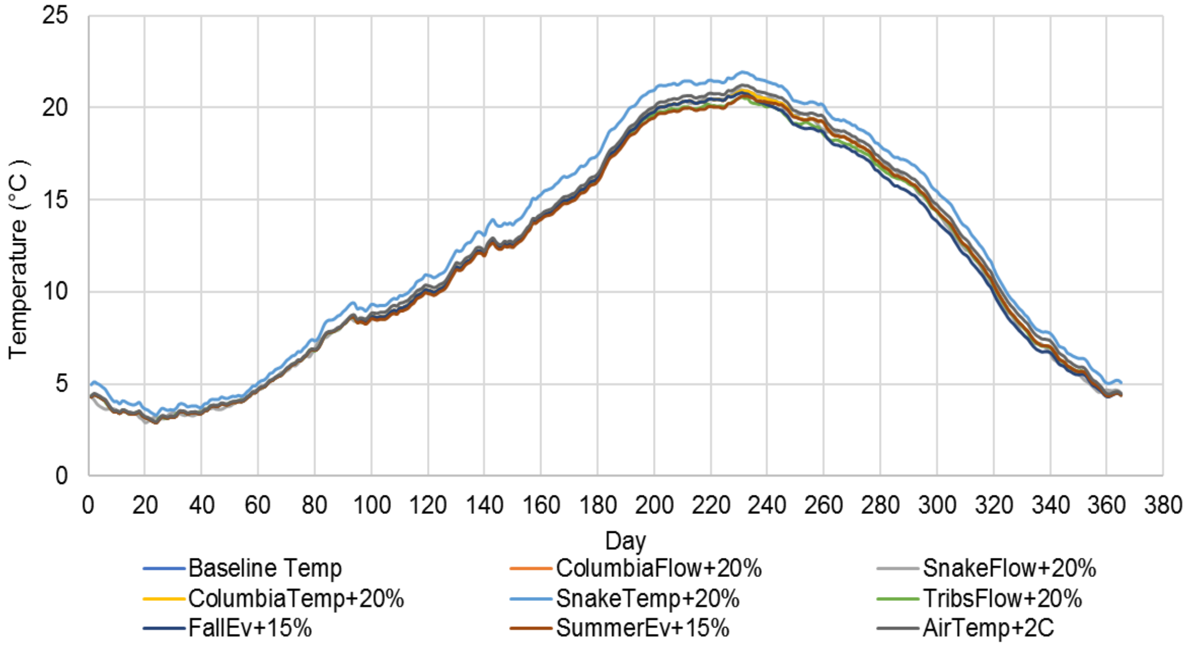


Figure F.2-6 Sensitivity of 10-year daily average temperatures at LMNW

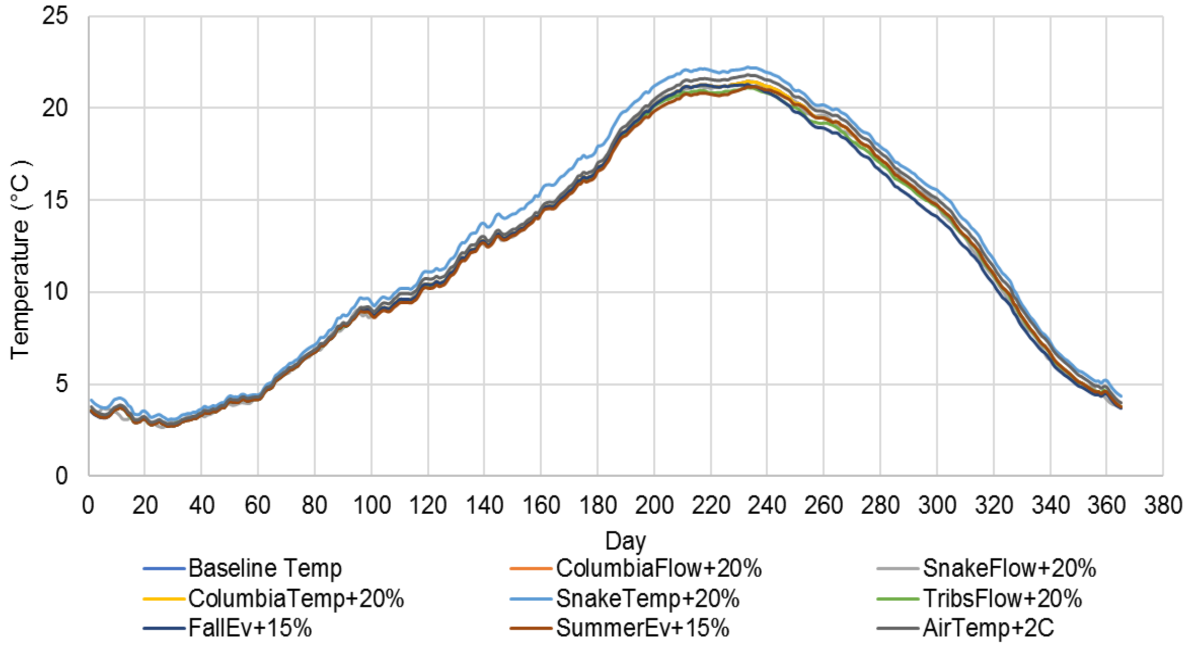


Figure F.2-7 Sensitivity of 10-year daily average temperatures at IDSW

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MEMORANDUM

TO: Charles Morrill, WDFW
Erick VanDyke, ODFW
Steven Hawley, citizen

Michele DeHart

FROM: Michele DeHart

DATE: October 28, 2015

RE: Requested data summaries and actions regarding sockeye adult fish passage and water temperature issues in the Columbia and Snake rivers.

The Fish Passage Center (FPC) staff received two similar requests for summaries of water temperature data, management actions, and adult sockeye passage in 2015. One request was submitted by Oregon Department of Fish and Wildlife and Washington Department of Fish and Wildlife technical staff, and one was a citizen request precipitated by a Seattle Times Article on adult sockeye passage, water temperatures, and management discussions and actions (http://www.seattletimes.com/seattle-news/environment/snowpack-drought-has-salmon-dying-in-overheated-rivers/). Because these requests were similar, we developed the following single response to both requests. Our response is divided into the following sections:

- Historical Context, Analyses and Water Temperature Standards;
- Recent Research Findings, Water Temperature and Effects on Adult Salmon;
- 2015 Flow and Water Temperature Data with Comparisons to Past Years;
- Documentation of Historical Water Temperature Problems in the Federal Columbia River Power System (FCRPS) Affecting Fish Passage; and,
- Analyses of 2015 PIT-tag Adult Sockeye Passage, Travel Time, and Survival with Comparisons to Past Years.

As a result of this review, **our overall conclusion is that elevated water temperatures in the Columbia and Snake rivers, including adult fishways, is a long-recognized problem that to date remains largely unmitigated.** Significant long-term actions to address these temperature issues are necessary for the continued survival of salmon populations, particularly sockeye.

The FPC staff participates in Fish Passage Advisory Committee (FPAC) meetings, Fish Passage Operations and Maintenance Committee (FPOM) meetings, and Technical Management Team (TMT) meetings as technical support staff. The FPC does not represent any state, federal or tribal fishery management agency. To that end, we have relied on actual operations data, adult fish passage count data, water temperature data, and PIT-tag recapture data and analyses in developing this summary. We have relied on notes from FPAC meetings, FPOM meetings, and TMT meetings. Following are the conclusions from each of the sections that were outlined above.

- Historical Context, Analyses and Water Temperature Standards.
    - Hydrosystem development has had a significant effect on temperature in the mainstem Columbia and Snake rivers. By slowing water flow and increasing surface area for solar radiation, dams caused increased water temperatures in the reservoirs.
    - The inability to meet water quality standards with respect to temperature was initially identified as an issue beginning with the 1995 Biological Opinion (BiOp).
    - Efforts were underway by the EPA to develop TMDL for the mainstem Snake and Columbia rivers, resulting in a draft Temperature Total Maximum Daily Load (TMDL) in 2003.
    - The melding of the two processes (TMDL Development and BiOp Water Quality Plans) resulted in the termination of the temperature TMDL process in favor of the water quality approach outlined in the BiOp. The 2003 Draft TMDL was never finalized and a maximum load allocation was never established for temperature.
    - Despite continued development of Water Quality Plans (WQPs) over the years, the BiOp process has fallen short of ever really making an impact on water temperature beyond the actions initially identified in the 1990s. Over thirty measures were considered to address temperature, but due to identified issues were dropped from the WQP.

- Recent Research Findings, Water Temperature and Effects on Adult Salmon.
    - Higher water temperatures have a number of negative effects on adult sockeye migration, including migration delays and reduced survival.
    - These negative effects on migration have been observed at temperatures less than the 20°C (68°F) water quality standard.
    - Adult ladders often exhibit temperature gradients because the water sources differ throughout the ladder. At temperature gradients greater than 1°C, Chinook and steelhead adults have a higher likelihood of significantly delayed migration to spawning grounds, increased total thermal exposure, depletion of energetic resources, and decreased migration success.
    - Cumulative temperature exposure time is critical to adult salmon survival.

- 2015 Flow and Water Temperature Data with Comparisons to Past Years.
    - The 2015 water year produced the second lowest spring flows at both Lower Granite (LGR) and McNary (MCN) dams since the 1995 BiOp.
    - The 2015 summer flows at LGR were the second lowest since 1995 and fifth lowest at MCN.

  - Drum gate maintenance at Grand Coulee dam exacerbated the low flow conditions on the Columbia during the spring of 2015.
  - The summer low flow situation in the Columbia was somewhat alleviated by the Columbia River Treaty provision of the proportional draft of reservoirs under low flow conditions, providing approximately 5 million acre feet of water from Canadian Reservoirs in 2015.
  - In 2015, temperatures at Middle Columbia, Snake River, and Upper Columbia projects were higher, earlier in the season, than the previous ten years
  - In 2015, temperatures at nearly all FCRPS projects exceeded the 20°C (68°F) standard for 35%–46% of the passage season (April–August). The one exception was LGR, which is due to the temperature augmentation water that is provided from Dworshak Reservoir.
  - Over the previous ten years (2005–2014), temperatures exceeded the 20°C (68°F) standard for 20%–30% of the passage season (April–August) at FCRPS projects, except at LGR.
  - Overall, exceedances of the 20°C (68°F) standard in the Upper Columbia are less common. However, 2015 had the highest proportion of days exceeding the 20°C (68°F) standard at many of these sites, when compared to the previous ten years.

- Documentation of Historical Water Temperature Problems in the FCRPS Affecting Fish Passage.
  - The need to address elevated temperatures in the adult ladders was identified as early as the 1994 BiOp.
  - In the present adult fishway configuration, there appears to be some potential for improving ladder water temperatures at LGR and LGS using axillary pumps. However, sockeye adult survival observed in 2015 would not have been mitigated by these measures at LGR and LGS since most mortality occurred prior to adults reaching LGS.

- Analyses of 2015 PIT-tag Adult Sockeye passage, Travel Time, and Survival with Comparisons to Past Years.
  - In 2015, Snake River sockeye adult survival (BON-LGR) was 0.04, which was much lower than previous years (2009 to 2014), ranging from 0.44 and 0.77.
  - Snake River sockeye adults that were transported as juveniles had lower adult survival rates through the FCRPS than did adults that migrated in-river as juveniles.
  - Upper Columbia adult sockeye survival (BON-RIS) in 2015 was 0.46, the lowest among the years analyzed (2009–2015).
  - Based on PIT-tag detections, arrival timing at BON is generally earlier for Upper Columbia sockeye than for Snake River sockeye.
  - Snake River adult sockeye that migrated in-river as juveniles and Upper Columbia River adult sockeye had similar adult fallback rates at BON. However, Snake River adult sockeye that were transported as juveniles exhibited much higher fallback rates than both of the Snake River and Upper Columbia River non-transported groups.

- Snake River sockeye adults took longer to pass through the ladders at BON than Upper Columbia adults, especially in 2015. Much of this difference was attributed to Snake River adults that were transported as juveniles.
- The higher water temperatures, earlier in the year, contributed to the poor adult survivals in 2015 for both Snake River and Upper Columbia sockeye.
- The combination of the earlier high water temperatures and later arrival timing for Snake River sockeye adults resulted in longer exposure to temperatures in excess of 20°C (68°F).
- In 2015, both Snake River and Upper Columbia sockeye showed a decline in adult survival and migration speed (BON-MCN) as temperatures increased.
- At similar temperatures, Snake River sockeye that were transported as smolts had a much lower migration speed (BON-MCN) than did non-transported individuals from both the Snake and Upper Columbia rivers.
- Accounting for smolt transportation and adult arrival timing at BON helps to explain some of the observed differences in BON-MCN adult survival between Snake and Upper Columbia sockeye

Historical Context, Analyses and Water Temperature Standards

Hydrosystem development has had a significant effect on temperature in the mainstem Columbia and Snake rivers. This impact goes beyond the effect caused by naturally high temperatures that may have historically occurred in the mainstem and the tributaries (Note: while naturally high temperatures are often cited to have occurred, there is little consistent water temperature data available to document pre-development river temperatures). By slowing water flow and increasing surface area for solar radiation, dams increase water temperatures in the reservoirs created. The major impact on the daily-average, cross-section water temperature is due to the increase in width and depth resulting from the construction and operation of the impoundments (Yearsley et al., 2001).

In 1995, the National Marine Fisheries Service (NMFS) issued a BiOp concluding that modifications to FCRPS operations were needed to ensure long-term survival of salmon stocks in the Snake River that were protected by the Endangered Species Act (ESA) (NMFS, 1995). The inability to meet water quality standards with respect to temperature was identified as an issue. A temperature of 20°C (68°F) was established as a reference temperature, considered the upper incipient lethal limit for salmon. Focus was on the prioritization of cool water releases from Dworshak and Brownlee dams for juveniles, evaluation and improvement of water prediction temperature models, the development of surface passage routes to decrease forebay delay, and the provision of water temperature control in fish ladders. At that time the Corps of Engineers (COE) agreed to coordinate with the Environmental Protection Agency (EPA) regarding their concerns on water temperature.

The net effect of hydro development in the Columbia and Snake hydrosystem was described by EPA. In October 2000, the states of Oregon, Washington and Idaho signed a Memorandum of Understanding with the U.S. Environmental Protection Agency Region 10 that established EPA as the lead agency for the development of a Columbia/Snake TMDL. TMDL development is usually a state responsibility, but considering the interstate and international nature of the waters, EPA's technical expertise in the modeling effort, and EPA's Tribal Trust responsibilities, EPA agreed to take responsibility for the technical development of this TMDL.

EPA conducted a series of modeling exercises (Yearsley, 2003) designed to develop the TMDL. In the analysis the impact of the presence of each dam was assessed, relative to the background that would naturally occur. These modeling exercises also assessed the relative importance of point source pollutants and tributary inputs. The modeling exercises discounted point source pollutants as having any effect on mainstem water temperatures, and identified only the major tributaries as having any impact on mainstem temperatures. Only the Spokane, Snake and Willamette rivers were deemed large enough to potentially alter the temperature of the Columbia River by a measurable amount (0.14°C). And, only the Salmon, Grande Ronde and Clearwater rivers are large enough to potentially alter the temperature of the Snake River by a measurable amount (0.14°C). The modeling exercises also identified the impacts on temperatures of each hydroproject and the maximum impact ranges from negligible to large, depending on the dam. Based on the modeling, the impact of Grand Coulee alone could be as great as 6.23°C, and the Snake River dams collectively can have a maximum impact as large as 6.8°C (EPA, 2003).

Based on the estimated impact that the Lower Snake River impoundments alone could collectively contribute to an increase in river temperature that could exceed 6°F (EPA 2003), it was expected that this could be demonstrated with actual data. To determine if there was an observable trend in temperature pre- and post-Snake River impoundment we compared the maximum scroll case temperature at Bonneville Dam (BON) for the period 1950 to 2015. It can be noted that there was an increase in temperature that began around 1977, which coincided with the completion of the four Snake River dams (Figure 1).

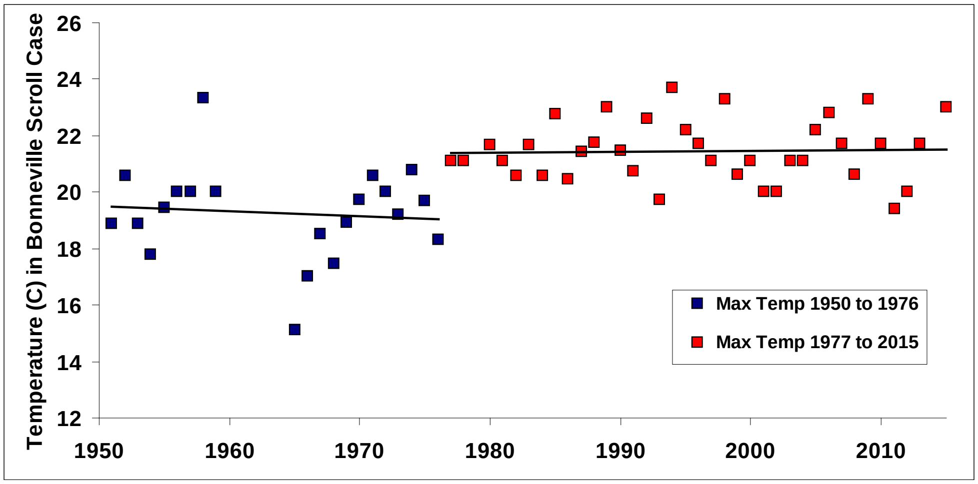

Figure 1. Maximum scroll case temperatures at Bonneville Dam in June and July for the years 1950 to 2015, with a break point at 1977 showing increased temperature coincident with the completion of the four Lower Snake River dams. Data source: Columbia River DART.

With the development of the call for the WQP in the 2000 BiOp (NMFS, 2000), a concurrent process was set to address both temperature and total dissolved gas. With time, the two processes merged and the Temperature TMDL process was no longer pursued in favor of the water quality approach outlined in BiOp. The 2003 Preliminary Draft TMDL (EPA, 2003) was never finalized and a maximum load allocation was never established for temperature.

Between the 2000 BiOp and 2004 BiOp, a Water Quality Team was established consisting of senior policy analysts supported by technical staff from the federal and state agencies, the tribal governments, and non-federal entities. The Water Quality Team developed the first WQP to incorporate the traditional TMDL development and implementation process with the new effort to improve water quality standards on the mainstem Columbia River.

Although initially supportive of developing the TMDL and also addressing adult ladder temperatures, the COE moderated their stance regarding the role of the hydrosystem in temperature occurrences above the States' criteria, or the 20°C (68°F) salmon reference temperature. The COE's official position (NMFS, 2004) was included as an appendix to the WQP that was part of the proposed Actions of the 2004 BiOp remand. The COE's position asserted that high mainstem temperatures occurred both pre- and post-impoundment and that, while the hydrosystem development and operation bore some responsibility for increasing mainstem water temperatures, they also wanted to recognize upstream influences (including the construction and operation of upstream dams, point source returns, agriculture practices, forestry practices and urban development) as well as climate change.

Despite continued development of WQPs over the years, the BiOp process has fallen short of ever really making an impact on water temperature beyond the actions initially identified in the 1990s. WQPs were developed in 2003, 2004, 2006, 2009 and 2014. The 2009 WQP included over thirty measures that could be considered to address temperature and identified issues, feasibility and timelines for implementation. By the 2014 WQP most actions were dropped and the WQP included only four actions for addressing temperature: Dworshak cool water releases; temperature modeling; temperature monitoring; and studies to identify thermal refugia. A more complete chronology of the process associated with temperature is included in Appendix A.

Recent Research Findings, Water Temperature and Effects on Adult Salmon

The 1995 BiOp included a river temperature upper limit of 20°C (68°F) (NMFS, 1995). This limit was set as the lethal limit for adult salmonids in the Columbia Basin. Temperatures have risen above this limit on many occasions since then, and negative impacts of high temperature on sockeye have been observed both above and below the BiOp standard.

Adult Sockeye Water Temperature Tolerances

The effects of high temperature on adult sockeye migration most obviously include direct mortality and migration delay, but can also include the depletion of energy resources for spawning (through delay and increased respiration), reduced gamete viability, and increased rates of disease (McCullough et al., 2001). Local adaptation for various source populations has created wide variations in thermal limits. Fraser River sockeye populations encounter river temperatures from 9°C (48°F) to 22°C (72°F), depending on the timing of migration (Eliason et al., 2011). Weaver Creek sockeye, a population that migrates in the cooler fall temperatures, has an optimal migration temperature of 14.5°C (58°F) (Eliason et al., 2011), with a significant decrease in survival at temperatures above 18°C (64°F) and no successful migrations at temperatures above 20.4°C (69°F) (Farrell et al., 2008). In contrast, summer migrating populations in the Fraser River have an optimal migration temperature of 17.2°C (63°F) (Eliason et al., 2011) with a 20% reduction in swimming ability at temperatures over 21°C (70°F) (McCullough et al., 2001).

Observations of thermal limits for sockeye are often observations of migration behavior at dams. In the Okanogan River, migration past the Zosel Dam stopped when temperatures were above 21.1°C (70°F) (Major and Mighell, 1967) or above 23°C (73°F) (Johnson et al., 2007). Migration appears to resume when temperatures decrease. High temperatures can also cause mortality in addition to a pause in migration. Weaver Creek sockeye (Fraser River) had reduced survival of 50% after being held in tanks at 18°C (64°F) when compared to 10°C (50°F) (Crossin et al., 2008). In the Columbia River, reduced survival was observed at temperatures exceeding 20°C (68°F) (Naughton et al., 2005). Crozier et al. (2014) observed reduced sockeye survivals at temperatures above 18°C (64°F), and Keefer et al. (2008) observed 100% mortality at 22°C (72°F).

Rather than observations of the effects of peak temperatures, a cumulative measure of thermal exposure may be the most appropriate measure of the effects of high water temperatures on sockeye migration and survival. From 2008 through 2013, Crozier et al. (2014) found that the cumulative thermal exposure can have more effect on adult survival than single point estimates of temperature through the migration period. However, uncertainty around thermal exposure measurements means the full impact is difficult to establish. Further studies with finer thermal resolution may clarify the impact of cumulative exposure to high temperatures rather than the peak temperatures experienced during migration.

Ladder Temperatures and Upstream Salmon Migration

Fish ladders often expose migrating adults to the highest temperatures and thermal stress encountered in the hydrosystem, due to warm surface water used for ladder flow (Keefer and Caudill, 2015). These high temperatures cause thermoregulatory behavior, such as exiting the ladder into the tailrace repeatedly. Additionally, ladders that use warm surface waters that flow into a cooler tailrace have a high thermal gradient, which also affects migration through the ladders. At temperature gradients of greater than 1^{o}C, Chinook and steelhead have a higher likelihood of entering the ladder multiple times followed by exits back into the tailrace (Caudill et al., 2013). This “in-and-out” movement in the ladder will significantly delay migration to spawning grounds, increase total thermal exposure, consume energetic resources, and decrease migration success (Caudill et al., 2013; Keefer and Caudill, 2015). The potential synergistic effects of high ladder temperatures combined with a high thermal gradient have not been studied.

2015 Flow and Water Temperature Data with Comparisons to Past Years

Biological Opinion Flow Targets in 2015

The 2015 water year produced the second lowest spring flows at both Lower Granite (LGR) and McNary (MCN) dams since the 1995 BiOp. The 2015 summer flows at LGR were the second lowest since 1995 and at MCN were the fifth lowest.

The spring low flow conditions at MCN were exacerbated by the need to draft Grand Coulee reservoir below its April 10th BiOp elevation of 1,283 feet to 1,255 feet in order to conduct drum gate maintenance at the project. This caused spring inflow to be diverted to refilling an additional 30 feet, rather than passing inflows downstream to the lower river. BiOp spring flow objectives were not met at either LGR or MCN.

The BOP (Best Operational Point) summer flow objectives were also not met at either LGR or MCN. The 2015 flows are shown in comparison to the BiOp flow objectives in Figure 2. However, while summer average flow at MCN averaged only 142.6 Kcfs, it could have been much lower. The Columbia River Treaty between the United States and Canada provides for the proportional summer draft of Canadian Reservoirs during dry periods to maintain power reliability for customers in the United States. Treaty operations/flows into the U.S. are established based upon the Treaty Storage Regulation Study (TSR) as modified by any supplemental operating agreements in effect. In 2015, based on the TSR, over 5 million acre feet of water was released from Canadian reservoirs during the summer period aiding the low summer flows in the Columbia River.

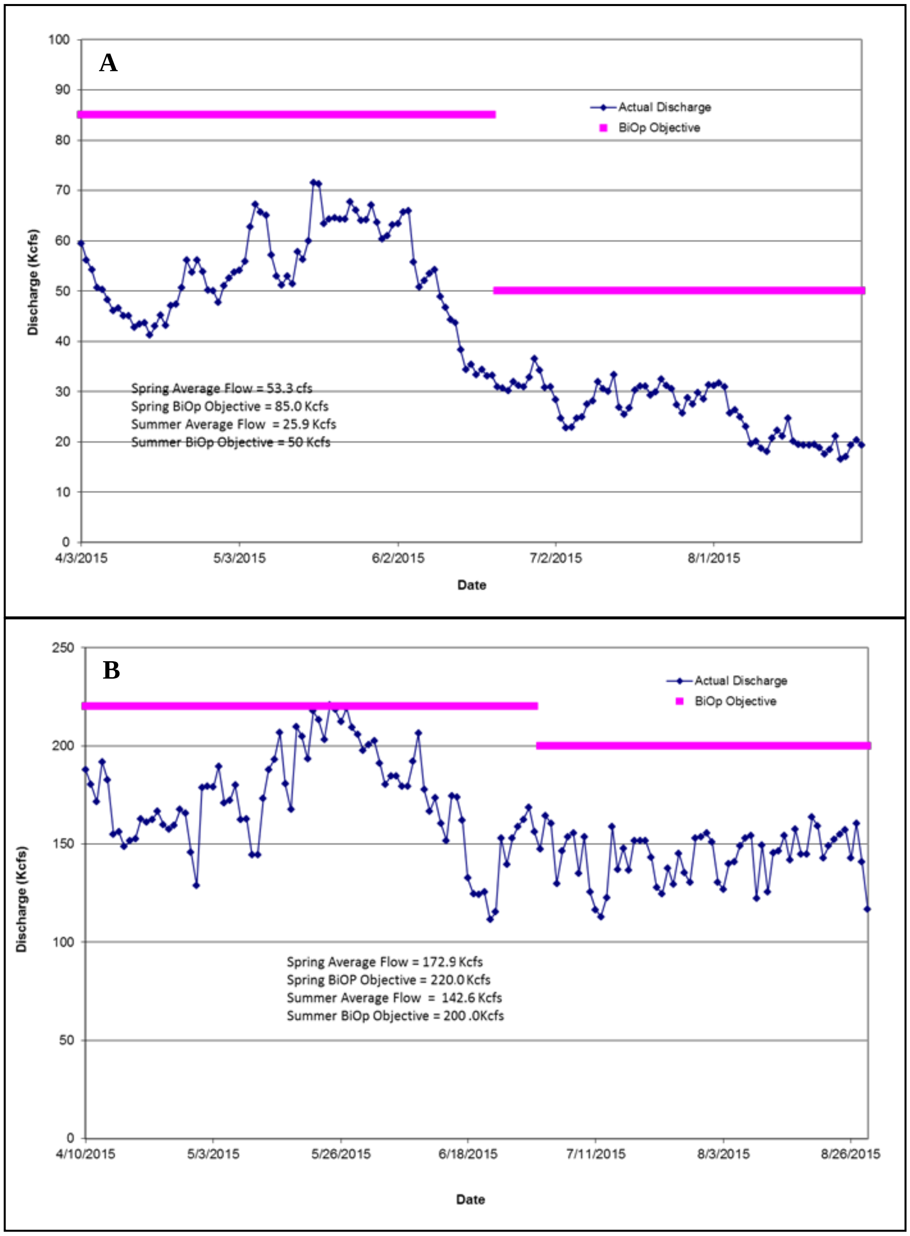

Figure 2. 2015 spring and summer flows at Lower Granite (A) and McNary (B) dams, in comparison to the 2014 Biological Opinion flow objectives.

2015 and Historical Water Temperatures

To put 2015 temperatures into context relative to the 20°C (68°F) water temperature criteria, temperature data from each of the eight FCRPS projects on the Middle Columbia and Snake rivers and the five Public Utility District (PUD) and two Bureau of Reclamation (BOR) projects on the Upper Columbia over the last eleven years (2005–2015) are presented below. The temperature data presented below are from the water quality monitors that are located both in the forebay and tailrace at each project, for the passage period of April 1st through August 31st. Below is a brief summary of the findings from this review.

In 2015, temperatures at Middle Columbia, Snake River, and Upper Columbia projects were higher, earlier in the season, than the previous ten years. Figures 3–5 are provided below to illustrate this pattern at three projects, one for each of the Middle Columbia, Snake, and Upper Columbia rivers (Appendix B provides figures for all projects reviewed).

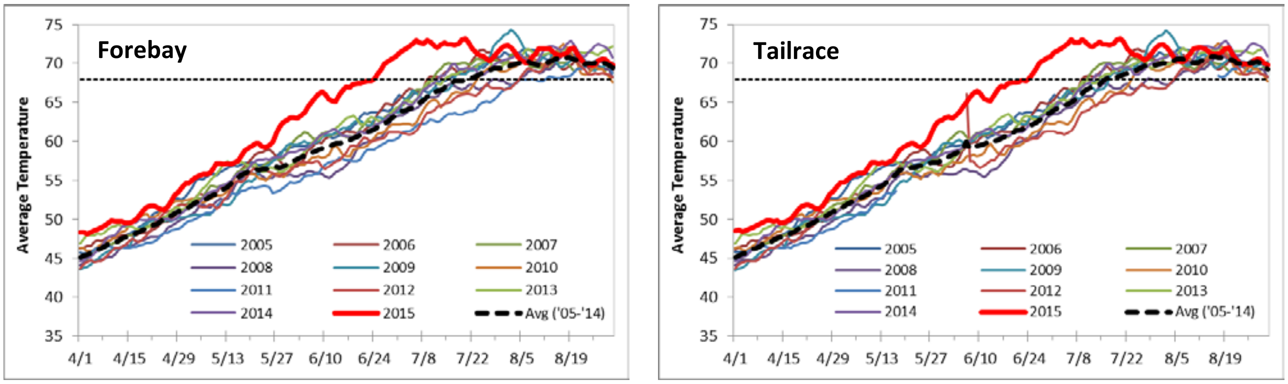

Figure 3. Daily average temperature (°F) at the Bonneville Dam water quality monitors in the forebay and tailrace (at Cascade Island) (B), April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard.

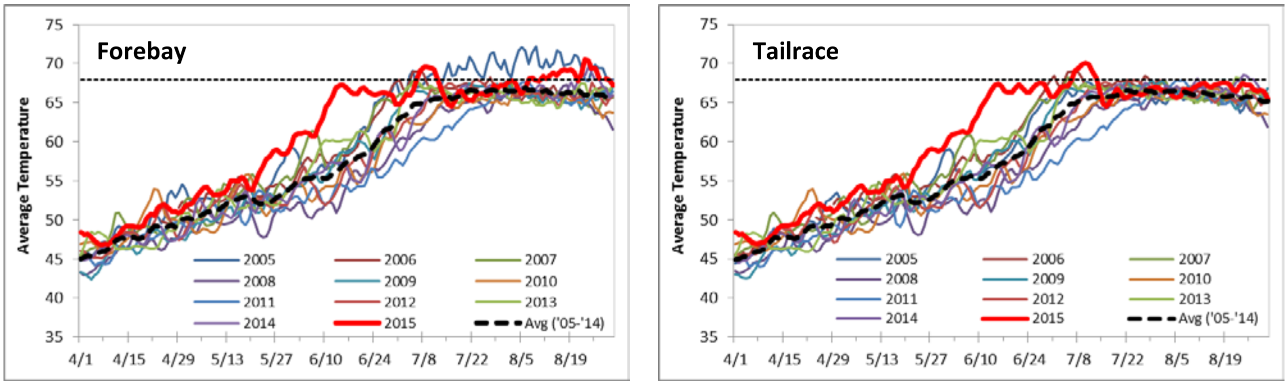

Figure 4. Daily average temperature (°F) at the Lower Granite Dam water quality monitors in the forebay and tailrace, April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard.

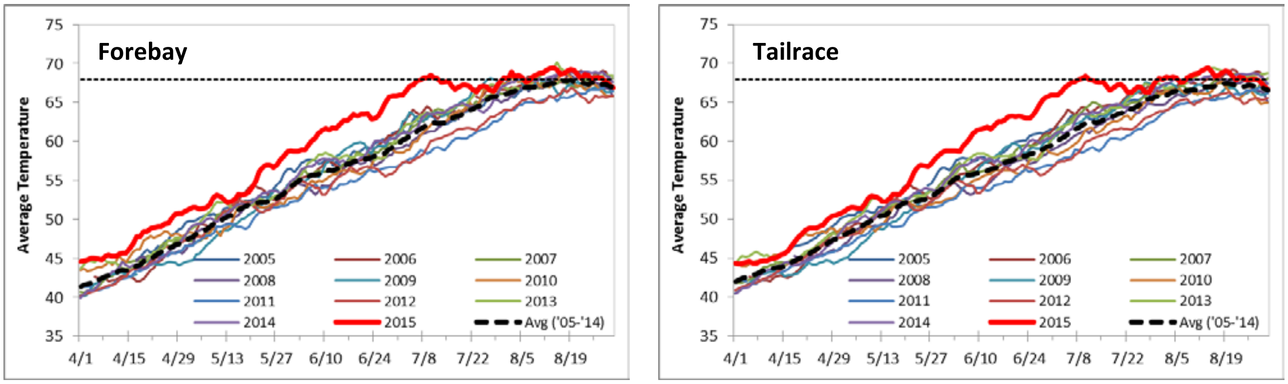

Figure 5. Daily average temperature (°F) at the Priest Rapids Dam water quality monitors in the forebay and tailrace, April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard.

In 2015 (April–August), temperatures exceeded the 20°C (68°F) standard at the Middle Columbia sites 43%–46% of the passage season (Tables B.1–B.4). While 2015 had the highest proportion of days exceeding the 20°C (68°F) standard, Middle Columbia sites commonly exceeded the 20°C (68°F) standard for 20%–30% of the passage season over the previous ten years (Figures B.1–B.4). These exceedances typically begin in mid-July or August whereas in 2015 exceedances began in late June.

In 2015 (April–August), temperatures exceeded the 20°C (68°F) standard 35%–45% of the season at Ice Harbor (IHR), Lower Monumental (LMN), and Little Goose (LGS) dams, but only 16% of the passage season in the forebay and 5% in the tailrace at Lower Granite Dam (LGR) (Tables B.5–B.8). The discrepancy in temperature standard exceedances between LGR and the other Snake River sites is due to the temperature augmentation water that is provided from Dworshak Reservoir (DWR). The effectiveness of temperature augmentation water from DWR is measured at the LGR tailrace. As with the Middle Columbia sites, it was common for LGS, LMN, and IHR to exceed the 20°C (68°F) standard for 20%–30% of the passage season (Figures B.5–B.7).

Overall, exceedances of the 20°C (68°F) standard in the Upper Columbia were much less common than what was observed at the Middle Columbia and Snake river sites (Tables B.9–B.15, Figures B.9–B.15). However, 2015 had the highest proportion of days exceeding 20°C (68°F) at many of the Upper Columbia sites, when compared to the previous ten years. In fact, at Priest Rapids (PRD) and Wanapum (WAN) dams, approximately 10%–20% of the days in 2015 exceeded the 20°C (68°F) standard.

Documentation of Historical Water Temperature Problems in the FCRPS Affecting Fish Passage

Historically, elevated temperatures in adult ladders have been documented as a significant issue for adult migration success. The 1992 Northwest Power Planning Council (NPPC) Strategy for Salmon (NPPC, 1992), Adult Salmon Measures #7 states:

> *Evaluate potential methods for decreasing water temperature in mainstem fish ladders and apply where appropriate.*

The 1994 and 1995 FCRPS BiOps that cover the 1994–1998 period recognized and included several references pertaining to high temperatures in the adult ladders. The following paragraph from these opinions (NMFS, 1994: pages 35, 37, and 39; NMFS, 1995: pages 54, 55, and 56) state:

> *High adult fish ladder temperatures at the Snake River projects during low water conditions may cause increases in adult salmon mortality. Reductions in ladder water temperatures as a result of ladder improvements are projected to begin in 1998. However, because no specific ladder modifications have been proposed, it is not possible to quantify the benefit to adult salmon passage.*

Furthermore, in Section IX (Conservation Recommendations) of the 1994 BiOp (NMFS 1994, pg. 76), NOAA directs the COE to address high water temperatures in adult fishways on an expedited basis with the following:

> *The COEs should develop and evaluate potential modifications for decreasing summer water temperatures in main stem Snake River project fish ladders. Effective modifications should be implemented on an expedited basis. This recommendation coincides with measures identified in NPPC Strategy for Salmon.*

Appendix A provides extensive detail regarding the transition from specific ladder water temperature criteria to an overall water quality/water temperature approach undertaken by the federal agencies.

More recently, in 2011, the COE issued a report (USACE, 2011) that outlines several alternatives to aid in reducing ladder temperatures at LGR. However, no action was taken to address the elevated ladder temperature at LGR until summer 2013 when adult passage at LGR was impeded by excessive temperatures in the ladder. The upper fishway at LGR reported water temperatures between 22°C (72°F) and 24°C (76°F), while the tailrace at the dam was reporting temperatures below 20°C (68ºF). The thermal gradient within the ladder restricted adult passage for all species. Of particular importance were the very low daily passage numbers for sockeye and the discrepancy between the counts of sockeye reported at LGS as compared to those reported at LGR.

In response to these concerns, three TMT calls were initiated between July 22, 2013, and July 24, 2013. After the initial call on July 22nd, the Action Agencies implemented an operation that prioritized Unit #1, effectively moving more water through the powerhouse and less water over the spillway, with all spilled water moving over the Removable Spillway Weir (RSW). Adult fish counts did not show a response to this operation.

On July 23, 2013, FPAC submitted SOR 2013-4 which asked the Action Agencies to immediately take actions that may increase adult passage and decrease the water temperature in the adult ladder. The proposed actions included: (1) cycling the navigation locks, (2) reducing the contribution of warm water from Diffuser #14, (3) utilizing additional pumps to provide cooler water to the ladder, (4) extending the intake to Diffuser #14 to draw cooler water to the ladder, and (5) modifying operations to facilitate adult passage during daytime hours and to provide juvenile protections during nighttime hours. These alternatives were consistent with the 1994 and 1995 BiOp Conservation Recommendations (NMFS, 1994; NMFS, 1995). In response, the COE agreed to implement the modified project operations outlined in the last bullet of SOR 2014-4 for a period of two days. The COE also agreed to investigate upper ladder options that would potentially aid in the reduction of warmest water contributions to the ladder. Subsequently, the COE utilized the emergency pumping system to draw cooler water from deeper in the forebay in an effort to reduce the temperature gradient in the ladder. Adults passing through the ladder did respond to the initiation of the emergency pumps.

A change to the Fish Passage Plan (FPP) was submitted by NOAA Fisheries in 2014 concerning temperatures and adult delay at LGR. This change form was not approved. However, in early August 2014, a combination of emergency pumps and rental pumps were utilized at LGR to facilitate the operation of the adult trap.

In 2015, sockeye passage throughout the Columbia and Snake rivers was impaired by high water temperatures and the only site with alternatives to address these high temperatures was LGR. Therefore, measures to address water temperature concerns and adult passage were primarily focused on LGR. Later, operations at LGS were modified to attempt to address adult passage delay. A full discussion on the actions considered at LGR and LGS to address elevated temperatures and adult passage issues at LGR and adult passage issues at LGS in 2015 are provided in Appendix C.

Analyses of 2015 PIT-tag Adult Sockeye Passage, Travel time, and Survival with Comparisons to Past Years

Methods

Currently, the COE collects ladder water temperatures at all FCRPS projects. However, there is no publically available database of these ladder water temperatures. Although requested, historical ladder temperatures were not provided for all projects and all years. In order to conduct the analyses of sockeye adult survival and effects of temperature, the relationship between forebay temperature and ladder temperature was investigated using the limited ladder temperature datasets we were able to obtain. Ladder temperatures were highly correlated with forebay temperatures (Figure 6). Therefore, forebay temperatures were utilized for these analyses. However, the use of forebay temperatures does not address high temperature spikes that were observed in the limited ladder temperature data provided by the COE, which would affect adult passage.

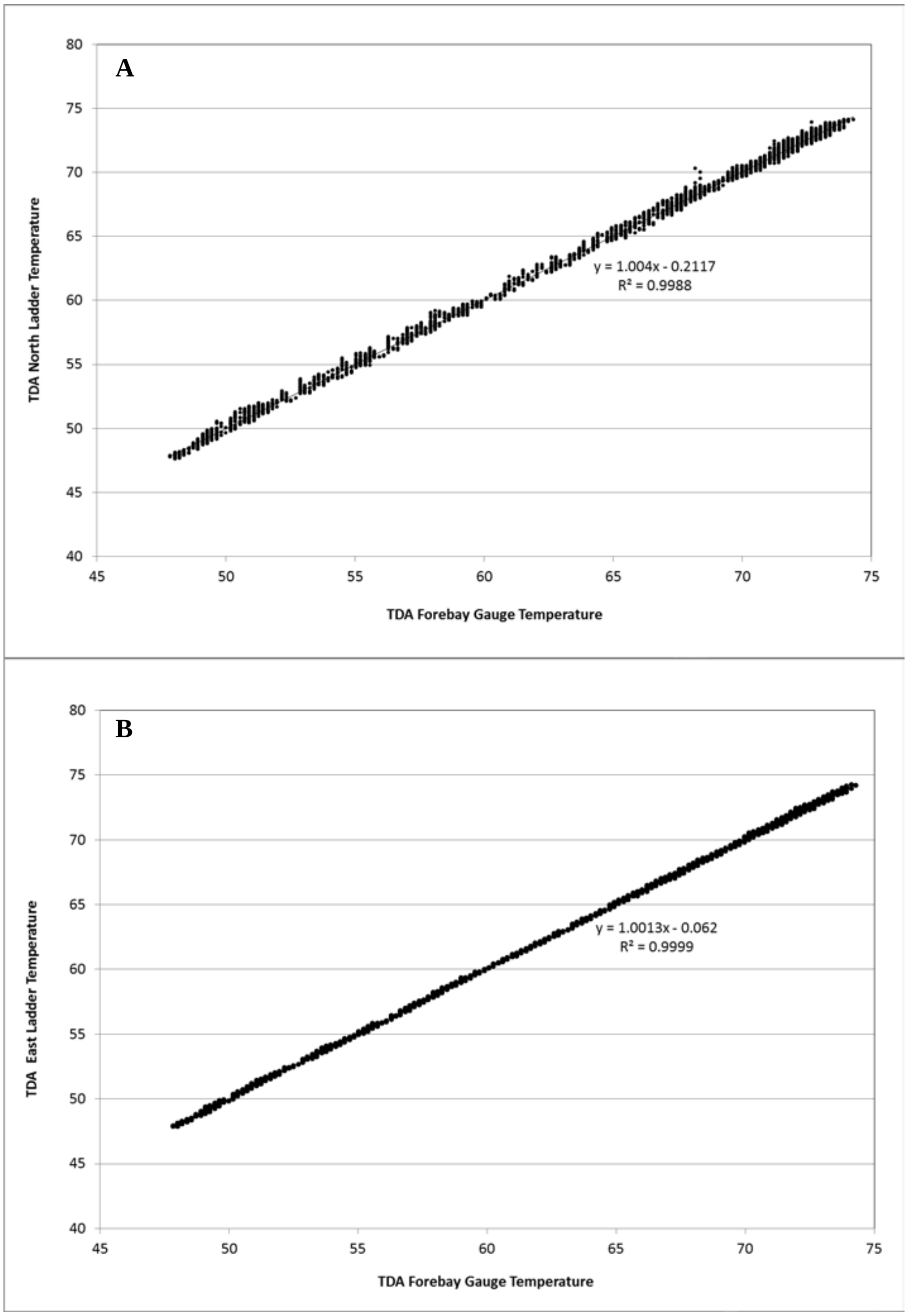

Figure 6. Relationship between forebay temperature and ladder temperatures in the North (A) and East (B) ladders at The Dalles Dam, 2015.

In this section, summaries of survival, migration and ladder travel times based on returning adult sockeye PIT-tagged as juvenile are presented. PIT-tag data from adults tagged at the BON adult fish facility are not included because summaries rely on previous juvenile migration history and ESU-origin which can only be determined from individuals PIT-tagged as juveniles.

Snake River Sockeye Adult Survival Estimates

Cormack-Jolly-Seber (CJS) estimates of adult survival from PIT-tagged sockeye are available starting in 2009. Prior to 2015, Snake River origin adult survival estimates from BON-LGR ranged from 0.44 (95% CI: 0.36–0.51) in 2013 to 0.77 (0.64–0.91) in 2010 (Table 1). In 2015, BON-LGR survival was 0.04 (0.02–0.05). Most of these returning adults never made it to MCN. In 2015, BON-MCN survival was 0.15 (0.12–0.18) and MCN-LGR survival was 0.25 (0.15–0.33). When standardizing for distance (i.e., survival per 100 river miles), the survival rate was nearly the same in the BON-MCN and MCN-LGR reaches, at 0.27 (0.23–0.31) and 0.24 (0.14–0.32), respectively.

Adult sockeye survival estimates above LGR are available only back to 2009. From 2009 to 2014, these estimates ranged from 0.32 (0.22–0.43) in 2013 to 0.77 (0.60–0.89) in 2010. In 2015, adult survival above LGR was 0.26 (0.06–0.46). The wider confidence interval for this estimate is due to very few PIT-tagged individuals (seven total) detected in the Sawtooth Valley in 2015. This resulted in an overall survival of 0.01 (0.00–0.02) from Bonneville Dam to the Sawtooth Valley in 2015. This extremely low estimate is also reflected by the extremely low returns of sockeye adults to the Sawtooth Valley (45 total PIT-tagged and non-PIT-tagged) (http://fishandgame.idaho.gov/public/fish/?getPage=29).

Table 1. Reach survival estimates with 95% confidence intervals in parenthesis of returning PIT-tagged Snake River sockeye salmon.

	Bonneville to McNary Dam	McNary to Lower Granite Dam	Lower Granite to Sawtooth Valley†	Bonneville to Lower Granite Dam	Bonneville Dam to Sawtooth Valley†
2009	0.74 (0.53-0.88)	1.00 (1.00-1.00)	0.65 (0.40-0.83)	0.74 (0.56-0.92)	0.48 (0.27-0.68)
2010	0.85 (0.70-0.93)	0.91 (0.80-1.02)	0.77 (0.60-0.89)	0.77 (0.64-0.91)	0.60 (0.44-0.76)
2011	0.67 (0.63-0.71)	0.97 (0.95-0.99)	0.74 (0.69-0.79)	0.65 (0.61-0.70)	0.48 (0.44-0.53)
2012	0.58 (0.49-0.67)	0.91 (0.83-0.99)	0.60 (0.48-0.72)	0.53 (0.44-0.62)	0.32 (0.24-0.40)
2013	0.68 (0.62-0.74)	0.65 (0.56-0.74)	0.32 (0.22-0.43)	0.44 (0.36-0.51)	0.14 (0.09-0.19)
2014	0.64 (0.59-0.69)	0.89 (0.85-0.93)	0.60 (0.53-0.68)	0.57 (0.51-0.62)	0.34 (0.29-0.39)
2015	0.15 (0.12-0.18)	0.27 (0.18-0.35)	0.29 (0.07-0.51)	0.04 (0.02-0.05)	0.01 (0.00-0.02)

† Survival estimates to Sawtooth Valley are based on detections of PIT-tagged sockeye adults in the Sawtooth Valley and does not include individuals that were collected for broodstock at LGR.

In recent adult return years (2013–2015), a seasonal survival effect has been evident, wherein the later arriving cohorts of the run survive much worse than those arriving earlier (Figure 7). This pattern was not evident from 2011–2012, and there were insufficient numbers of PIT-tagged returning adults to divide the run into quartiles in 2009 and 2010. In 2015, survival decreased from the first to third quartile of the run and remained flat thereafter, whereas in 2013 and 2014 there was no distinguishable trend in survival during the first three quartiles of the run followed by decline in survival in the fourth quartile of the run.

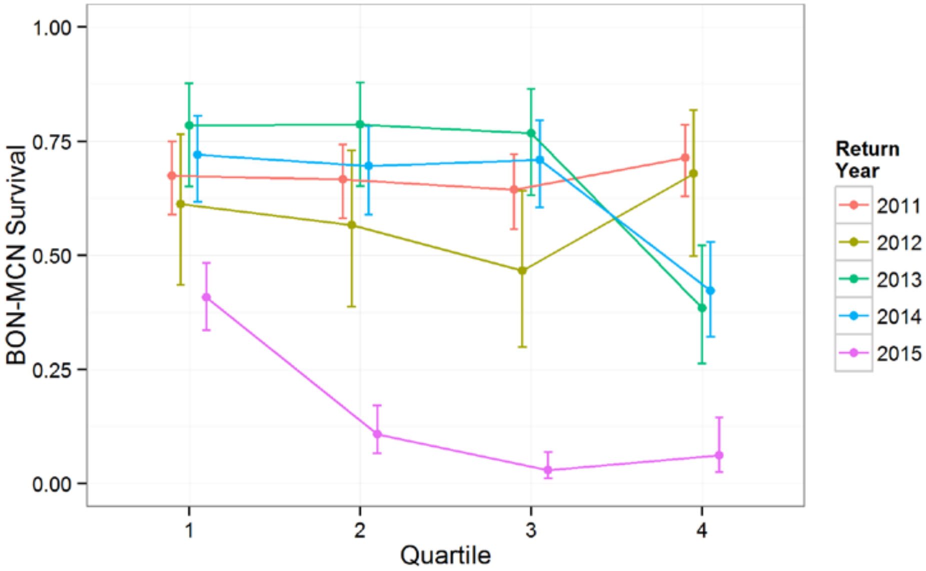

Figure 7. Survival from Bonneville to McNary Dam by run grouping determined by quartiles (i.e., first 25% of the run (1), 26%–50% of the run (2), etc.).

As documented in other studies (Keefer et al., 2008; Crozier et al., 2014), Snake River sockeye adults that were transported as juveniles did not survive as well, when compared to juveniles that migrated in-river (Figure 8). Return year 2011 was the one exception to this pattern, as differences in survival for transported and non-transported groups were indistinguishable in this year. As evidenced by non-overlapping confidence intervals, Snake River sockeye transported as juveniles had significantly lower survival than the non-transported groups in the BON-MCN reach in 2013, 2014 and 2015. This effect was also observed in the MCN-LGR reach in 2013 and 2015. Survival from MCN-LGR for sockeye that were transported as juveniles was 0.00 in 2015. This is based on the fact that eighteen sockeye adults that were transported as juveniles were detected at MCN in 2015 and none of these adults were detected at LGR. However, generating this survival estimate was still possible by assuming that non-transported and transported individuals have the same detection probability at and above Lower Granite Dam. There were insufficient numbers of PIT-tagged returning adult sockeye to estimate survival by juvenile migration history before 2011.

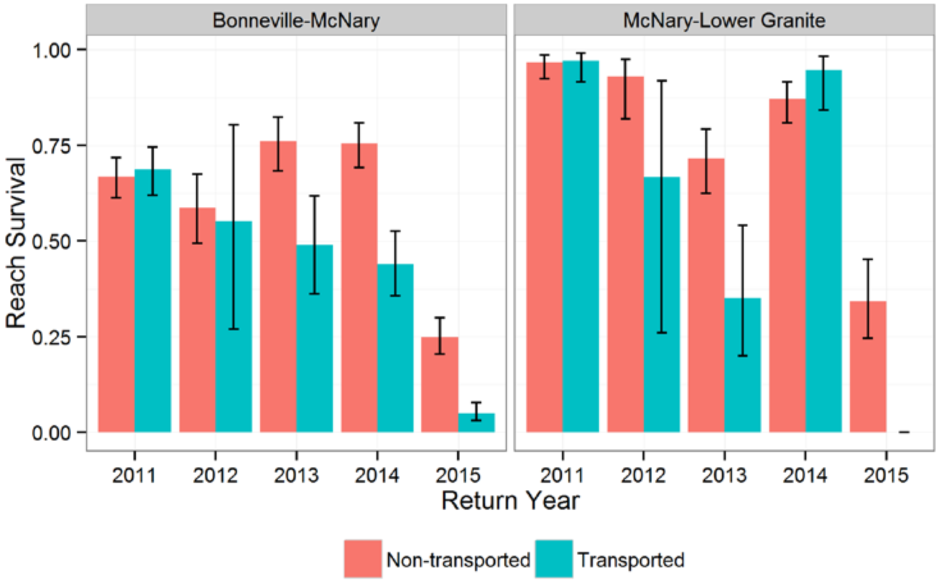

Figure 8. Snake River sockeye adult survival (95% confidence interval), from Bonneville to McNary, and McNary to Lower Granite Dam by return year and migration history.

Upper Columbia Sockeye Adult Survival Estimates

Adult sockeye survival in 2015 for Upper Columbia origin fish was also the smallest on record since 2009 (Table 2). Survival from BON-MCN was 0.61 (0.56–0.66) in 2015, where previous estimates ranged from 0.69 (0.65–0.72) in 2011 to 0.87 (0.83–0.91) in 2014. Survival from McNary to Rock Island Dam (RIS) in 2015 was 0.76 (0.71–0.81, which was also the lowest among the years analyzed.

Table 2. Reach survival estimates with 95% confidence intervals in parenthesis of returning PIT-tagged Upper Columbia sockeye salmon.

	Bonneville to McNary Dam	McNary to Rock Island Dam	Bonneville to Rock Island Dam
2009	0.80 (0.75-0.84)	0.94 (0.91-0.98)	0.75 (0.71-0.80)
2010	0.82 (0.79-0.84)	0.95 (0.93-0.96)	0.77 (0.75-0.80)
2011	0.69 (0.65-0.72)	0.86 (0.83-0.90)	0.59 (0.55-0.63)
2012	0.72 (0.68-0.75)	0.93 (0.91-0.96)	0.67 (0.63-0.71)
2013	0.79 (0.72-0.85)	0.89 (0.83-0.94)	0.70 (0.63-0.77)
2014	0.87 (0.83-0.91)	0.91 (0.86-0.96)	0.80 (0.74-0.85)
2015	0.61 (0.56-0.66)	0.76 (0.71-0.81)	0.46 (0.41-0.51)

A seasonal variation pattern in adult survival for Upper Columbia sockeye was evident in 2015, but this effect was not observed in previous return years (Figure 9). From 2011 to 2014, there was no distinguishable trend in adult survival from BON-MCN. In 2015, BON-MCN survivals steadily declined starting from the 2nd quartile of the run. There were insufficient numbers of PIT-tagged returning adults in 2009 and 2010 to divide the run into quartiles.

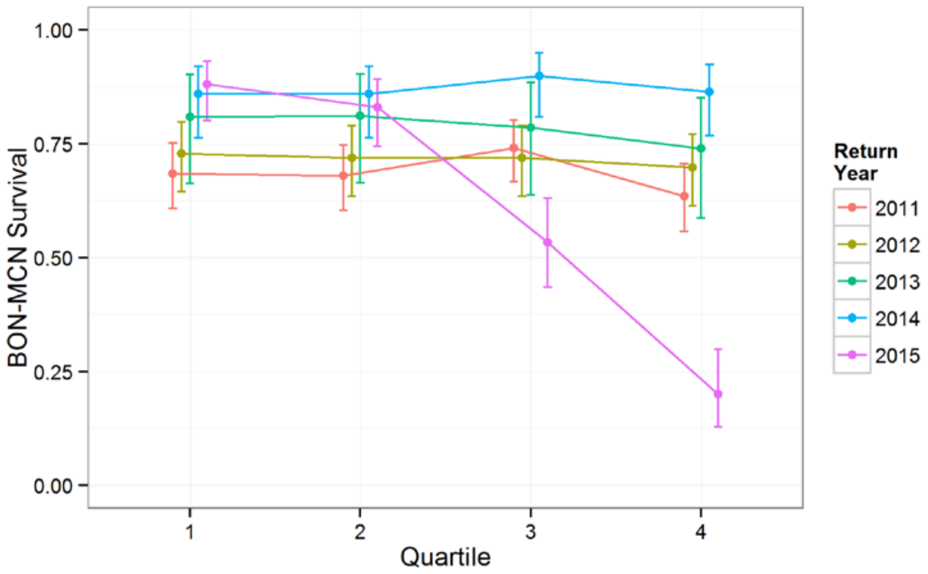

Figure 9. Survival from Bonneville to McNary Dam by run grouping determined by quartiles (i.e., first 25% of the run, 26%–50% of the run, etc.).

Snake River and Upper Columbia River Comparisons

In this section, summaries of timing, ladder delay and temperature are presented side-by-side for Snake River and Upper Columbia adult sockeye. These summaries are intended to help identify potential differences in survival for these two ESUs. It should be recognized, however, that there are many other important factors (see Crozier et al., 2014) that aren't considered here.

Arrival Timing

Snake River adult sockeye on average arrive at Bonneville Dam later than Upper Columbia sockeye (Figure 10). Among the years examined, the minimum difference in median arrival timing between Snake (both transported and non-transported) and Upper Columbia sockeye was three days in 2014. The maximum difference in median arrival timing was in 2012, where the median arrival dates for Snake River sockeye that were transported as juveniles versus migrated in-river were seven and 12 days later, respectively, than the median arrival date for Upper Columbia sockeye. In 2015, the median arrival dates for transported and non-transported Snake River sockeye were approximately 8 and 9 days later than that for Upper Columba Sockeye, respectively. Except for in 2012, there is no indication of a systematic difference in arrival timing between Snake River sockeye that were transported as juveniles versus those that migrated in-river. In all other return years, differences in median arrival timing for these two groups were within a day.

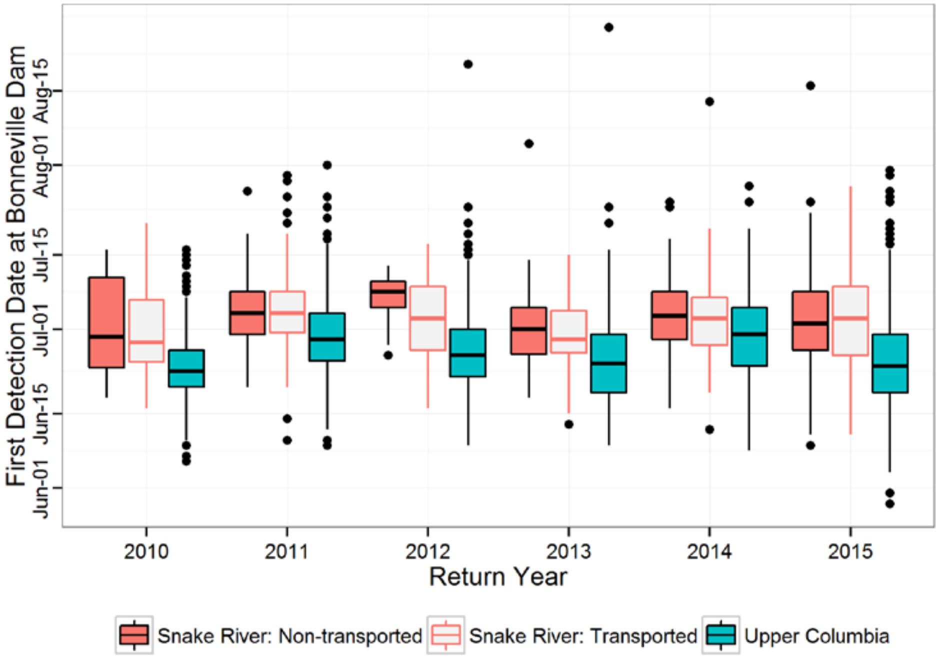

Figure 10. Boxplots of arrival timing at Bonneville Dam based first detection date for transported and non-transported Snake River and Upper Columbia sockeye adults.

<u>Ladder Delay and Fallback</u>

A comparison of adult fallback rates (i.e., re-ascensions through the ladder) at BON showed that Snake River sockeye fell back and re-ascended ladders at a higher rate than Upper Columbia sockeye during the same years (Figure 11). The differences in the percentage of adults that re-ascended between the Snake River and Upper Columbia stocks appeared mostly to do with the relatively high rate of re-detections of PIT-tagged Snake River sockeye adults that were transported as juvenile migrants. Fallback and re-ascension exposes fish to additional high temperatures in the ladders as well as increasing overall migration time.

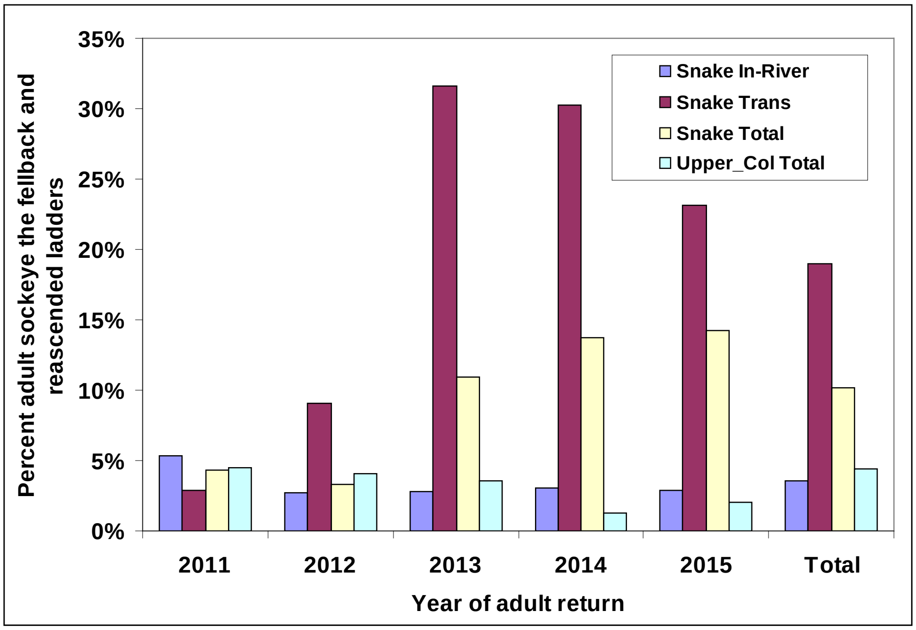

Figure 11. Adult sockeye fallback and re-ascension rates at Bonneville Dam in the years 2011 to 2015.

It appears that PIT-tagged Snake River origin sockeye adults took longer to pass through the ladders at BON than Upper Columbia River sockeye adults, when comparing the same ladders during the same year (Figure 12). Times represent that portion of the ladder between lower and upper PIT-tag coils and do not reflect total time spent in ladders. Increased travel time in ladders has been associated with large temperature differences between ladder entrance and ladder exit (Caudill et al., 2013). Longer ladder transit times result in longer exposure to high ladder temperatures.

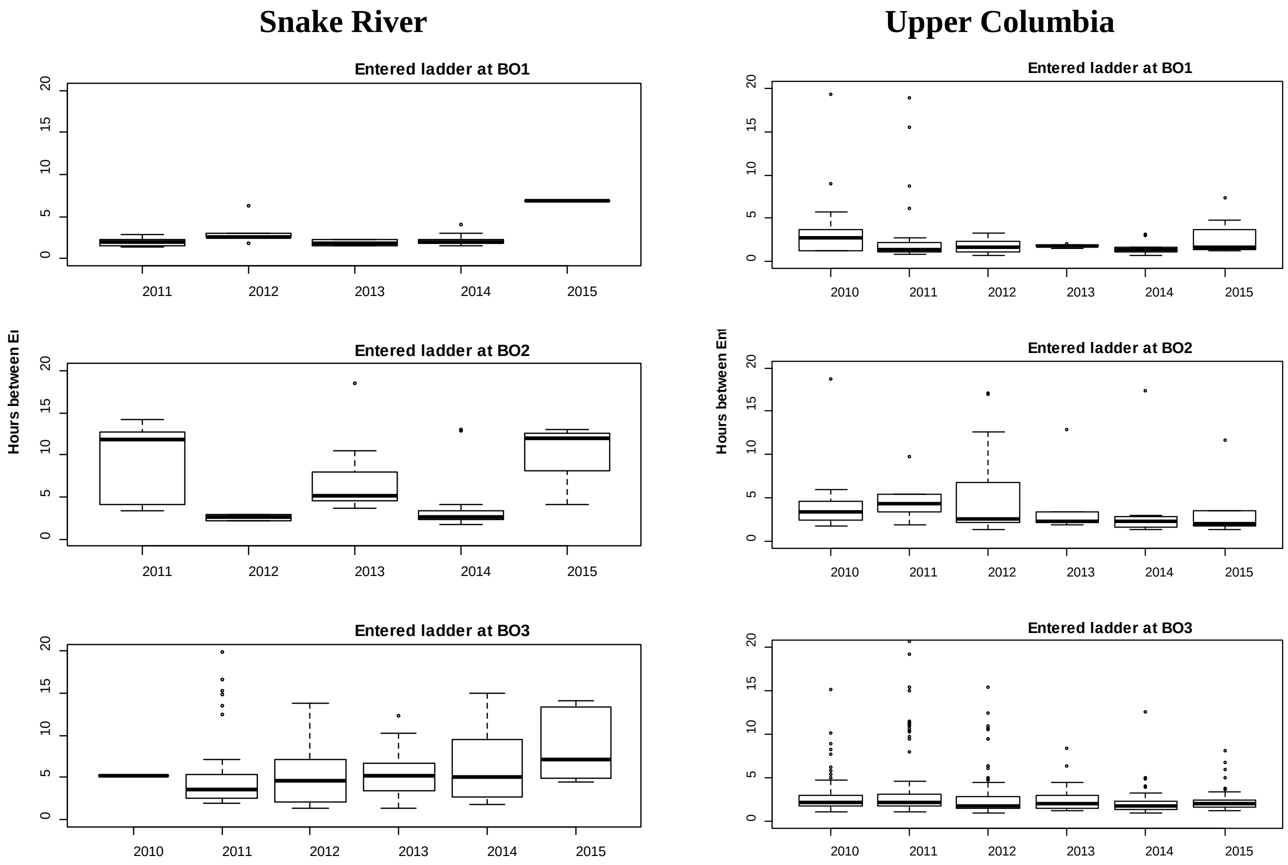

Figure 12. Box plots comparing relative time to pass through the adult ladders at Bonneville Dam for Snake River origin sockeye adults and Upper Columbia River sockeye adults. Passage times were restricted to those PIT-tagged adults that were detected at entrance coils and exit coils in the respective ladders.

Migration Temperatures

Since Snake River sockeye tend to arrive later than Upper Columbia sockeye, these fish should be exposed to higher temperatures at the start of their migration through Middle Columbia reservoirs, under the assumption that temperatures increase over the span of time when sockeye are present. This effect is shown in Figure 13, which displays BON forebay temperatures at the time an individual exited the BON adult ladder (i.e., last detection date). Return years 2014 and 2015 were the most extreme wherein the effect of entering BON reservoir later (characterized by the peak and right tail of the last detection date distribution) resulted in exposures near or above the 20°C (68°F) water temperature criteria.

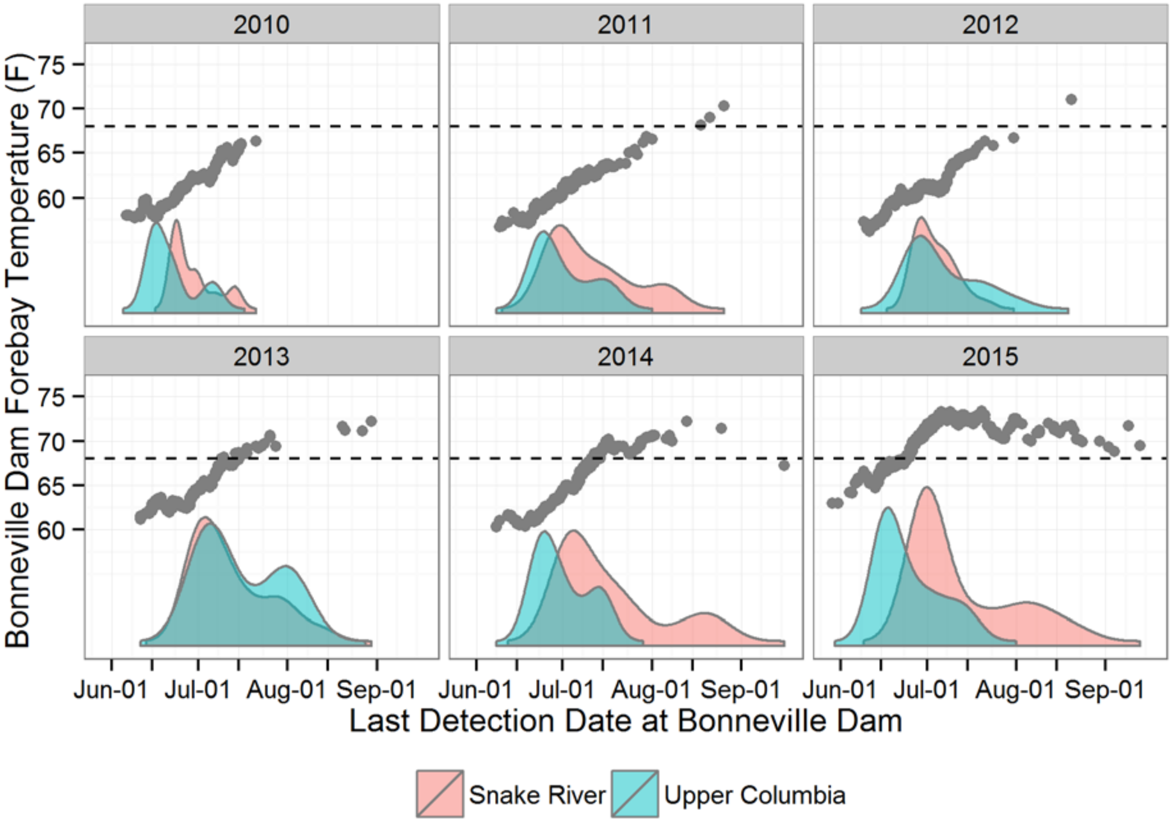

Figure 13. Observed Bonneville Dam forebay temperature upon Bonneville Dam ladder exit (i.e., last detect) (dots). Density plots of the distribution of exit dates for Snake and Upper Columbia River are shown below the scatterplot.

Temperature Exposure

Temperature exposure has been shown to be an important variable affecting adult sockeye survival (Crozier et al., 2014). Figure 14 shows boxplots of temperature exposure for Snake and Upper Columbia river stocks throughout the entire BON-MCN reach. Temperature exposure was calculated similarly as described in Crozier et al. (2014) by multiplying the reach travel time and the average of the downstream forebay and upstream tailrace temperature corresponding to the times forming the travel time estimate. Median temperature exposures were always higher in The Dalles Dam (TDA) to McNary Dam reaches from 2013–2015 for Snake compared to Upper Columbia river sockeye. Median temperature exposures from BON-MCN were also higher in return years 2013–2015 for Snake River sockeye compared to those from the Upper Columbia.

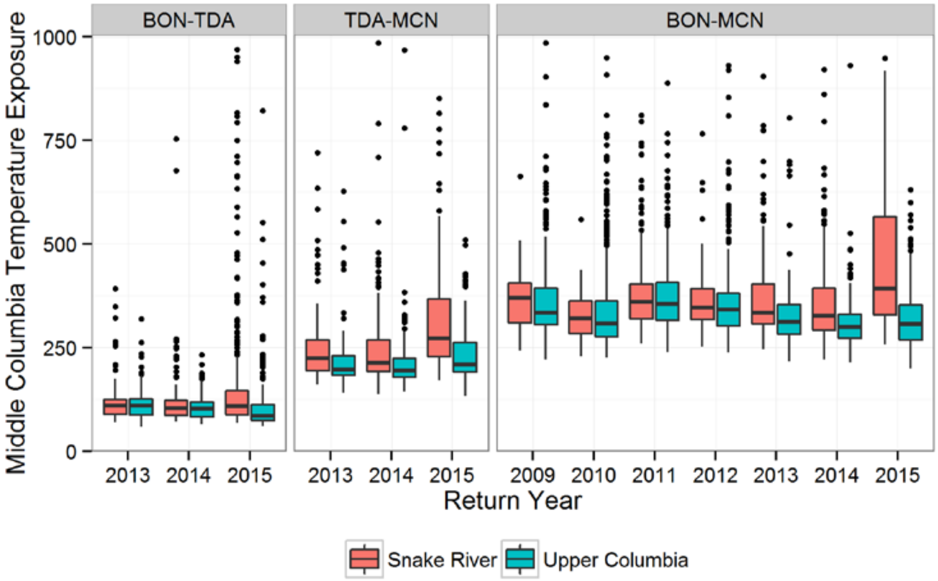

Figure 14. Temperature exposure from Bonneville to The Dalles, The Dalles to McNary, and Bonneville to McNary Dam by return year and origin. The y-axis was truncated at 1,000 for clarity.

<u>Temperature and Survival Relationship</u>

The relationship between temperature and BON-MCN survival for Upper Columbia and Snake River sockeye is shown in Figure 15. The temperature in the BON forebay associated with the last detection time at BON was used in order to examine this relationship. This temperature metric was chosen because it can be assigned to every PIT-tagged individual in this data set. The survival relationship was estimated from a CJS model with individual covariates. Return years 2014 and 2015 provided the greatest contrast between Snake River and Upper Columbia stocks (determined by visually examining non-overlapping confidence intervals). Upper Columbia sockeye survival did not change with increasing temperatures in 2014, whereas Snake River sockeye survival declined with increasing temperature. In the 2015 return year, both Snake River and Upper Columbia sockeye survival precipitately decreased with increasing BON forebay temperatures.

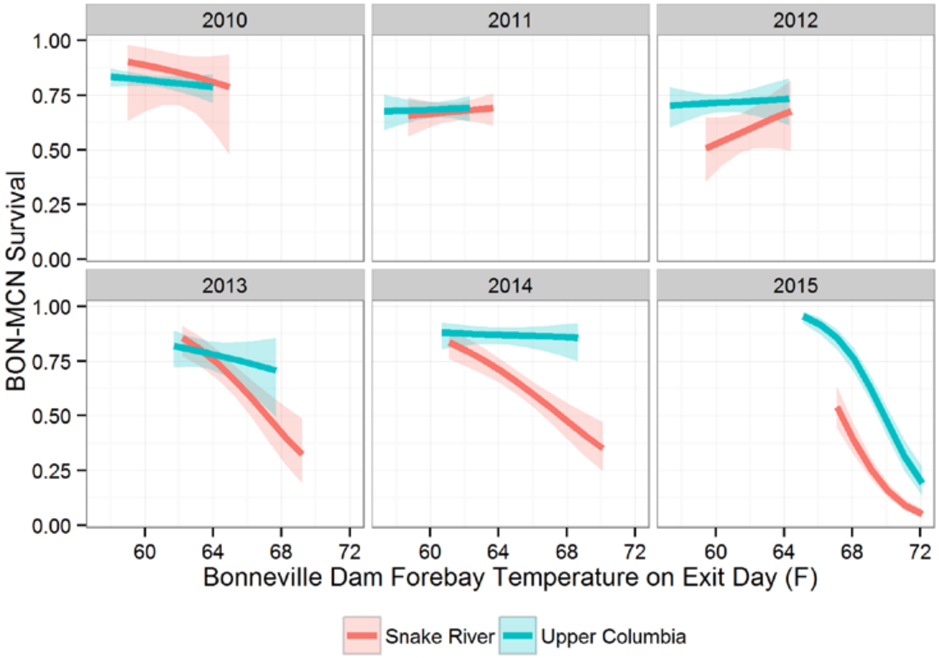

Figure 15. Estimated relationship between Bonneville Dam forebay temperature and Bonneville to McNary Dam survival by return year for Snake and Upper Columbia River adult sockeye. The shaded portion of the curves indicates 95% confidence intervals. All available data are used for the fitted relationship, but only the 2.5th to the 97.5th percentiles of observed temperatures in each return year are shown.

Temperature and Migration Speed Relationship

Previous analyses (Salinger and Anderson, 2006) showed that the swim speed of Chinook salmon increased with temperature below an optimal temperature, and decreased with temperature above the optimum. The relationship between temperature and migration speed for Snake River and Upper Columbia sockeye in 2015 is shown in Figure 16, where a quadratic relationship is fit to the observed MCN tailrace temperature (upon entrance) versus BON-MCN migration speed (miles per day). Only the 2015 return year was examined because this year provided the necessary contrast to examine a quadratic effect. With increasing temperatures beyond some optimum temperature, migration speeds decreased for both Snake River and Upper Columbia stocks. Furthermore, at similar temperatures, Snake River sockeye that were transported as smolts had a much lower migration speed than did non-transported individuals. This observation is consistent with previous observations showing that transported Snake River sockeye spend more time in the ladders than do non-transported Snake River sockeye and Upper Columbia sockeye.

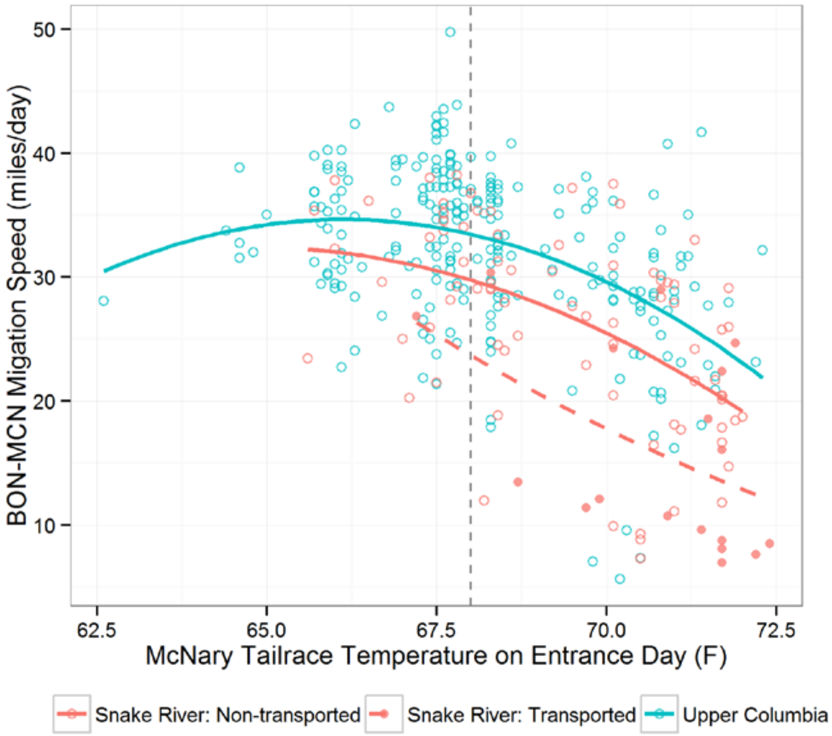

Figure 16. Estimated relationship between temperature and migration speed for PIT-tagged non-transported Snake River and Upper Columbia fish (solid lines and unfilled circles) and transported Snake River fish (dotted lines and filled circles) during the 2015 return year.

Weekly Comparisons

As presented above, Snake River sockeye adults that were transported as juveniles do not survive as well as those who were not transported as juveniles. In addition, Snake River sockeye tend to arrive later than Upper Columbia sockeye and are consequently exposed to higher temperatures. If transportation, later arrival, and exposure to higher temperatures are the primary mechanisms leading to reduced survival of Snake River adults compared to Upper Columbia River adults, then removing these effects should result in roughly equal survival for these two groups. In order to make this comparison, non-transported Snake River sockeye weekly and daily survival is compared to Upper Columbia sockeye survival. Temporal comparisons standardize for arrival effects and ensure that the two groups are exposed to the same environmental conditions upon arrival at BON.

Figure 17 shows weekly survival from BON-MCN of cohorts of 20 or more individuals exiting the BON adult ladder. Since not all return weeks have 20 or more individuals, a CJS model that used BON exit day as an individual covariate was also fit (Figure 18). This model assumes a linear relationship between the logit survival and BON exit day, whereas weekly survival estimates are allowed to vary freely. Results from these analyses indicate that accounting for smolt transportation and adult arrival timing at BON largely helps to explain much of the observed differences in BON-MCN adult survival between Snake and Upper

Columbia sockeye. However, there still may be other unexplained factors that contributed to the observed differences in survival between these two stocks, particularly in 2014 and 2015.

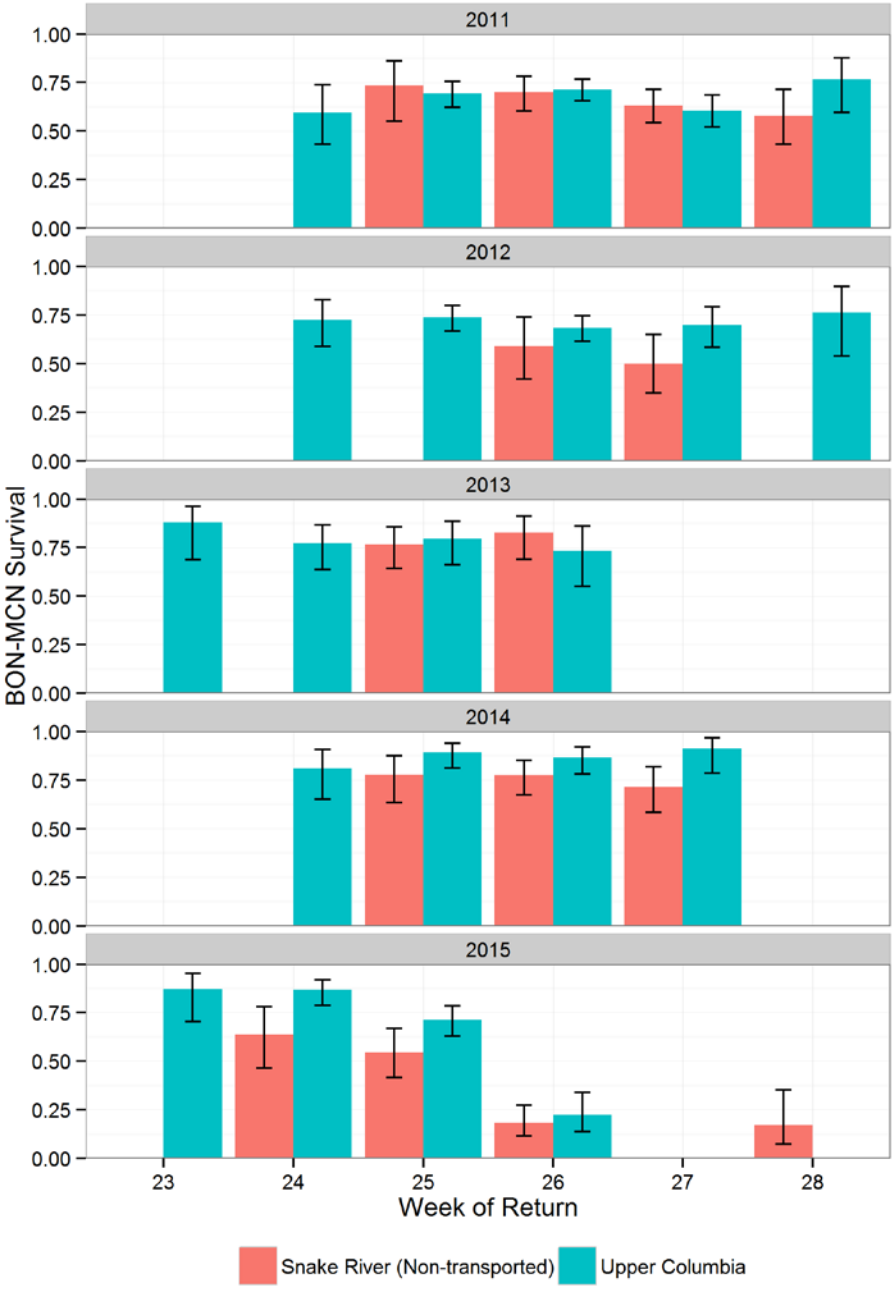

Figure 17. Survival (Bonneville to McNary) (95% confidence intervals) of non-transported Snake River and Upper Columbia sockeye adults by return week. Only return weeks with at least 20 individuals are displayed.

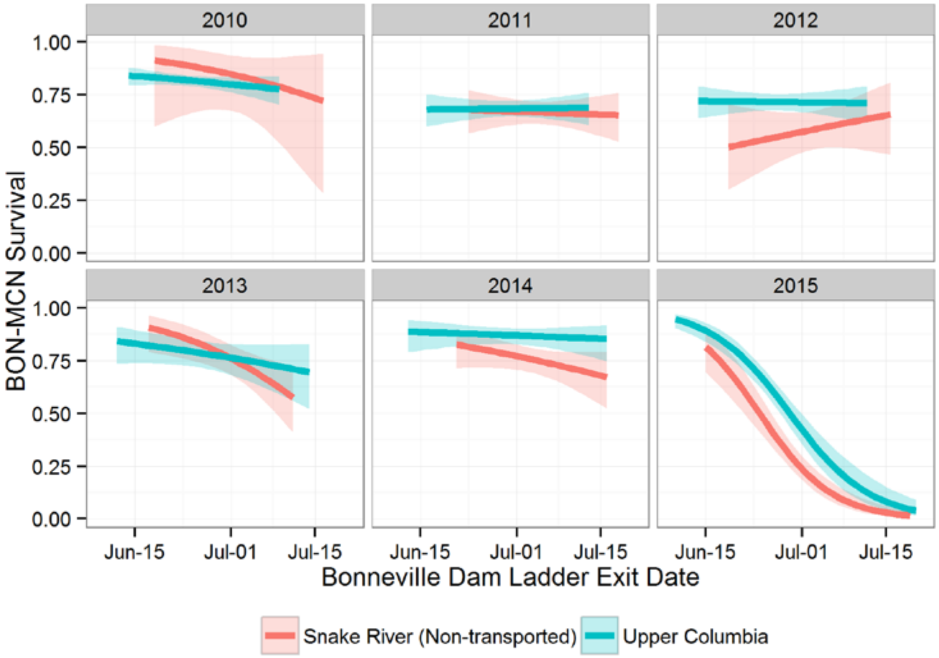

Figure 18. Estimated relationship between Bonneville Dam ladder exit date and Bonneville to McNary Dam survival by return year for non-transported Snake River and Upper Columbia adult sockeye. The shaded portion of the curves indicates 95% confidence intervals. All available data are used for the fitted relationship, but only the 2.5th to the 97.5th percentiles of exit dates in each return year are shown.

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Appendix A

The Historical Recognition of the Effect of FCRPS development and Operation on Water Temperatures

The issue of increased temperatures and the potential impacts to salmonid survival have long been recognized in the Columbia River hydrosystem. An early workshop occurred in 1963 recognizing the issues and the potential impacts that might occur from further hydrosystem expansion (Eldridge, 1963[1]). This review is intended to show the evolution of actions that were taken relative to temperature in the Snake and Columbia rivers under the implementation of the Clean Water Act (CWA) and the Endangered Species Act (ESA). The documents are voluminous and there are many. Consequently, some topics may have been overlooked. This appendix represents our best compilation of the various documents describing the process that occurred over the time span from the mid-1990s to the present.

1995–1999

In 1995, the National Marine Fisheries Service (NMFS) issued a Biological Opinion (BiOp) concluding that modifications to Federal Columbia River Power System (FCRPS) operations were needed to ensure long-term survival of salmon stocks in the Snake River that were protected by the ESA. The recommendations of the 1995 NMFS BiOp were adopted by the U. S. Army Corps of Engineers (COE) in a 1995 Record of Decision (ROD). In 1998, NMFS issued a supplemental BiOp for steelhead recommending further actions to the COE. The COE adopted these recommendations in a 1998 ROD. The 1998 ROD includes discussion of new information on continuing unresolved issues. They identify water quality standards with respect to total dissolved gas and temperature as one of these issues and, relative to temperature, offer: the prioritization of cool water releases from Dworshak for juveniles, the development of surface passage routes to decrease forebay delay, and to investigate adult ladder water temperature by collecting more information and evaluating engineering fixes. The COE states that they will coordinate with EPA regarding their concerns on water temperature.

In March of 1999, the National Wildlife Federation (NWF) filed a lawsuit with the district court contending that the COE's 1995 and 1998 RODs were arbitrary and capricious and contrary to law, since they did not address the COE's obligation to comply with state water quality requirements for temperature under the CWA. The plaintiffs contended that the documents failed to assure that the operation of the dams will comply with State water quality standards. The district court issued an opinion on February 16, 2001, stating that the COE had not addressed adequately in the 1995 and 1998 RODs the issue of the COE's obligation to comply with the CWA. The district court remanded the CWA issue to the COE for further consideration.

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[1] Eldridge, Edward F., ed. Proceedings: Water temperature: influences, effects and control. US Dept. of Health, Education, and Welfare, Public Health Service, Pacific Northwest Water Laboratory, 1963.

In the late 1990s the EPA began studying the impacts of dams on the mainstem Snake and Columbia rivers temperature. They stated, "The presence of hydroelectric dams has modified natural temperature regimes in the mainstem Columbia River. Snake River basin reservoirs are known to affect water temperatures in the river (Yearsley 1999) by extending water residence times and by altering the heat exchange characteristics of affected river reaches."

2000–2004

2000 Biological Opinion

The 2000 BiOp recognized the effect of water quality, both total dissolved gas (TDG) and temperature, on federally listed anadromous fish. The BiOp lays out a path for the federal agencies (EPA, NMFS, USFWS, COE, BOR and BPA) to undertake efforts to address listed species under ESA, and create a tie to the water quality improvements under the CWA. Under the CWA, the Total Maximum Daily Loads (TMDLs) were being developed. The 2000 BiOp called for the development of a Water Quality Plan that incorporates the actions for achieving the standards outlined in the TMDL.

The 2000 BiOp states that:

> NMFS, in coordination with EPA, USFS, and the Action Agencies (the COE, BOR and BPA), has considered the respective ecological objectives of the ESA and the CWA. In many instances, actions implemented for the conservation of ESA listed species will also move toward attainment of water quality standards (e.g., reducing TDG and temperature). The overlap of statutory purpose is extensive; however, there are additional actions that are appropriate in a water quality plan, but are nonessential for the survival and recovery of the listed species. Thus, such actions are not required components of the ESA RPA. Further the water quality plan is likely to require lengthy study and implementation exceeding the duration of this biological opinion.

The 2000 BiOp calls for the federal agencies to address both TDG and water temperature. Most actions outlined to address TDG are not considered here. The following actions relate to the proposed actions for water temperature. The BiOp states that the federal agencies are committing to the establishment of a new Water Quality Team (senior policy level) and to the development of a Water Quality Plan (WQP) that is part of the annual planning process for the mainstem Columbia and Snake rivers. At the same time, it was recognized that the EPA and the states of ID, WA and OR, in coordination with the Columbia River tribes, are developing a Columbia and Snake river TMDL under court order. The water quality plan was to be integrated and consistent with TMDL limits and ongoing TMDL activities. The WQP was expected to include the following actions with respect to temperature:

- Make operational and capital investments;
- Reach consensus on offsite mitigation to attain water temp standards;
- Identify adequate physical and biological temperature monitoring;
- Implement and model to better assess and act on thermal problems;

- Develop emergency measures to address immediate and acute water temperature problems.

The WQP was also expected to consider specific reservoir operations for temperature regulation including Dworshak Reservoir cool water releases; Brownlee Reservoir cool water releases established through FERC relicensing; and McNary Dam operation and configuration to address thermal issues in the forebay and juvenile fish impacts. The WQP was also to address, among other things, improvements in long-term temperature monitoring and modeling, an evaluation of fish ladder temps, an evaluation of temperature effects on juvenile passage behavior and survival, and to identify adult passage losses

However, the 2000 BiOp specifically states that the development of neither a Draft TMDL, nor providing funding to develop tributary TMDLs, are included as 2000 BiOp Reasonable and Prudent Alternative (RPA) actions.

2001

In May of 2001, the COE issued the 2001 Record of Consultation and Statement of Decision (ROD). In the document the COE acknowledges that “the construction and existence of the dams may contribute to a shift in the temperature regime of the Snake River.” The COE said it would take additional steps, consistent with the recommendations in the NMFS 2000 BiOp, to improve its operations for compliance with state water quality standards stating:

> The Corps has implemented several actions to help alleviate adverse water temperature conditions in the Columbia River Basin. Selective withdrawal systems to release water from one or more specific depths are present at Libby and Dworshak dams. Operation of Dworshak dam for flow augmentation for juvenile fish in the summer months has also aided in reducing water temperatures in the lower Snake River.

Other than the steps mentioned above, however, the COE said that it did not have reliable information that structural modification would reduce water temperature in the reservoirs or have a significant effect on temperature water quality standard exceedances. The COE concluded that the operation of the mainstem COE dams on the Snake and Columbia rivers has no significant impact on water temperatures.

The National Wildlife Federation (NWF) filed an amended complaint on August 24, 2001, challenging the 2001 ROD. In its amended complaint, the NWF contended that the 2001 ROD violated the Administrative Procedures Act since it failed to address adequately the issue of exceedances of state water temperature standards. The district court concluded that the 2001 ROD implemented “each of the specific operational actions prescribed in the NMFS 2000 BiOp intended to reduce water temperatures and that the 2001 ROD evaluated properly the COE's obligation to comply with state water quality standards as required by the CWA,” and that “[t]here [was] no evidence in the record that the measures adopted in the [2001] ROD to reduce water temperatures in order to comply with the Endangered Species Act [were] not consistent with the COE's obligations under the Clean Water Act to mitigate temperature exceedances." The district court concluded that the 2001 ROD did not violate the Administrative Procedures Act. Both the NWF and the Nez Perce Tribe appealed the decision. The court however concluded that "the COE was not arbitrary and capricious and did not act contrary to law in concluding that there were no further steps it could take to reduce temperature exceedances in the lower Snake River."

2003 July Draft Temperature Total Maximum Daily Load

In October 2000, the States of Oregon, Washington and Idaho signed a Memorandum of Understanding with the U.S. Environmental Protection Agency-Region 10 (EPA) that established EPA as the lead agency for the development of a Columbia/Snake Mainstem Temperature TMDL. TMDL development is usually a state responsibility, but considering the interstate and international nature of the waters, EPA's technical expertise in the modeling effort, and EPA's Tribal Trust responsibilities, EPA agreed to take responsibility for the technical development of this TMDL. Once the EPA developed the TMDL, it was to be up to the states to develop a plan to implement the TMDL.

The EPA modeled the Columbia system using RBM10 (a peer reviewed, one dimensional energy budget model (Yearsley et al., 2001)) and assessed the impacts on natural water temperature (no human caused pollution or alterations) of point sources, tributary inputs and dams. They determined that:

1. The effect of existing point sources is very small and do not lead to water quality exceedances when averaged in with the total river flow;
2. Most of the tributaries have a negligible effect on the cross sectional average temperatures, with exception of the Spokane, Snake and Willamette, which are large enough to affect the temperature of the Columbia River and only the Grande Ronde, Salmon and Clearwater are large enough to potentially alter the Snake River. The magnitude of the effect is a function of temperature differential and flow volume.
3. Dams do have an effect on temperature in the mainstem. The maximum impact ranges from negligible to large, depending on the dam. Based on the modeling, the impact of Grand Coulee alone could be as great as 6.23°C, and the Snake River dams together can have a maximum impact as large as 6.8°C.

The TMDL was to provide a total increase within each reach within target sites to develop waste load allocations. However, the draft TMDL was never finalized and all activity on the TMDL ceased at this time. According to the WA Department of Ecology website (http://www.ecy.wa.gov/programs/wq/tmdl/TMDLsbyWria/tmdlColumbiaRvr.html), the status of the TMDL is **"Delayed to allow necessary discussions and information exchange."**

2004 Biological Opinion

The development of a WQP was initiated by the 2000 BiOp. Work on that Plan occurred between 2000 and 2004, when the Plan was incorporated into the 2004 BiOp as Appendix A.

The WQP addresses both total dissolved gas and temperature. The mainstem Snake and Columbia river water temperature was composed of five categories:

1. The background of water temperature issues in the Columbia and Snake rivers, the goal of the NMFS 2000 FCRPS BiOp and the TMDL process,
2. The monitoring of water temperature in the area covered by the plan,
3. A brief discussion addressing the RPAs in the BiOp that address water temperature and the long-term non BiOp (Clean Water Act) strategy to get temperature levels below 20°C.
4. A description of operational, structural and other changes that have been proposed that may have potential to lower water temperature levels or provide a better understanding of water temperature impacts to aquatic species.
5. A final summary and appendix.

The background section discusses the overlap of ESA and CWA and the responsibilities of the federal agencies. It also lays out the standards for temperatures for each of the states and the tribes. There is also a disclaimer from the COE stating that the historic temperatures exceeded 20°C (68°F) prior to the dams and hydropower can't be characterized as the only issue, citing climate change and upstream influences. A separate appendix (Appendix F) is also included in the BiOp that addresses the COE's perspective. The COE believes that water temperatures in the Snake and Columbia mainstem rivers are warmer today than they were historically. However, the Corps also believes that hydropower is not solely responsible for the change and implicates climate change and upstream influences for responsibility.

2005 to Present

2008 Biological Opinion

In the 2008 BiOp, the Action Agencies proposed to continue to operate the FCRPS to reduce water temperatures during periods of juvenile and adult fish migration, particularly in the lower Snake River, and to minimize the harmful effects of elevated levels of spill-generated TDG on anadromous and resident fish.

The BiOp continued the operation of Dworshak Dam to regulate outflow temperatures to attempt to maintain water temperatures at Lower Granite tailwater at or below the water quality standard of 20°C (68°F). Also, under RPA 1515 the Action Agencies agreed to continue to update the WQP for TDG and water temperature in the Mainstem Columbia and Snake rivers and implement water quality measures to enhance ESA-listed juvenile and adult fish survival, and mainstem spawning and rearing habitat. The WQP was to contain water quality measures needed to meet both ESA and CWA responsibilities. For purposes of the 2004 RPA that addressed the WQP, the WQP was to include the following measures to address water temperature to meet ESA responsibilities:

- Continued development of the CE-QUAL-W2 model for estimating river temperatures from Dworshak Dam on the Clearwater and Upper Snake River near the confluence with the Grand Ronde River (USGS Anatone gauge) through the lower Snake River (all four COE lower Snake River projects) to assist in real-time decision making for Dworshak Dam operations;

- Expansion of water temperature modeling capabilities to include the Columbia River from Grand Coulee to Bonneville dams to better assess the effect of operations or flow depletions on summer temperatures;
- Investigation of alternatives to reduce total mass loading of TDG at Bonneville Dam while maintaining juvenile survival performance, and
- Continued operation of lower Snake River projects at MOP (Minimum Operational Pool).

In the 2008 BiOp only the Lower Granite Dam ladder is addressed regarding the issue of increased temperatures and potential impacts to salmonid survival. RPA 28 calls for the modification of the Lower Granite fishway to improve upstream adult passage conditions impaired by temperature differential. A prototype was expected to be in place by 2011.

Water Quality Plan (WQP)

The WQP has been revised every few years. Despite continued development of WQPs over the years, the BiOp process has fallen short of ever really making any significant progress on actions to address water temperature beyond the actions initially identified in the 1990s. WQPs were developed in 2003, 2004, 2006, 2009 and 2014. The 2009 WQP included over thirty measures that could be considered to address temperature, and identified issues, feasibility and timelines for implementation. By the 2014 WQP most actions were dropped and the WQP only includes four actions for addressing temperature: Dworshak cool water releases; temperature modeling; temperature monitoring; and studies to identify thermal refugia.

2014 Biological Opinion

In this BiOp, water temperature is consistently identified as a limiting factor for salmonid survival. The BiOp acknowledges temperatures have increased, but seems to place more emphasis on the climate change rather than on the impact of dams. While climate change is undoubtedly a contributing measure, the impacts of the dams will only further exacerbate those effects.

The 2014 BiOp specifically discusses the issues that were observed in 2013 regarding passage at Lower Granite Dam. The emphasis is on Lower Granite ladder and developing a longer-term engineering fix beyond the presently implemented (since 2013) pump system. No other ladders appear to be discussed. It is interesting to note, however, the language shifts blame to co-managers for ranking other projects higher than fixing the ladder at LGR, stating “Since 2008, the co-managing agencies (including NOAA Fisheries) have generally ranked other activities higher than the Lower Granite adult ladder (called for in RPA Action 28) in the Corps' annual prioritization process.”

Appendix B

Historical Water Temperatures at Middle Columbia, Lower Snake, and Upper Columbia Projects

Table B.1 – Summary of temperature data at Bonneville Dam collected at water quality monitors in the forebay and tailrace (Cascade Island). Data are summarized for the April 1–August 31 period, 2005–2015. Fill colors indicate magnitude of Proportion of Days Exceeding 68°F water quality standard (white = lowest values, yellow = 50th percentile, red = highest values).

Year	Bonneville Forebay Monitors					Bonneville Tailrace Monitors				
	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F
2005	153	47	0.31	71.9	16-Jul	153	47	0.31	72.0	16-Jul
2006	153	53	0.35	71.8	10-Jul	153	53	0.35	71.9	10-Jul
2007	153	52	0.34	71.2	11-Jul	153	52	0.34	71.1	11-Jul
2008	153	27	0.18	71.2	5-Aug	153	28	0.18	71.3	28-Jul
2009	153	46	0.30	74.3	17-Jul	153	46	0.30	74.2	17-Jul
2010	153	38	0.25	72.5	24-Jul	153	38	0.25	72.6	24-Jul
2011	153	19	0.12	70.7	13-Aug	61[A]	14	0.23	70.6	17-Aug
2012	153	27	0.18	71.3	5-Aug	113[B]	27	0.24	71.4	5-Aug
2013	153	48	0.31	72.2	15-Jul	151	47	0.31	72.0	14-Jul
2014	153	50	0.33	72.9	13-Jul	153	50	0.33	72.9	13-Jul
2015	153	69	0.45	73.2	24-Jun	153	69	0.45	73.2	24-Jun

[A] Due to high flows, the Bonneville tailrace monitor (at Cascade Island) was out of commission from May 18–August 17.

[B] Due to high flows, the Bonneville tailrace monitor (at Cascade Island) was out of commission from April 27–June 5.

Table B.2 – Summary of temperature data at The Dalles Dam collected at water quality monitors in the forebay and tailrace. Data are summarized for the April 1–August 31 period, 2005–2015. Fill colors indicate magnitude of Proportion of Days Exceeding 68°F water quality standard (white = lowest values, yellow = 50th percentile, red = highest values).

Year	The Dalles Forebay Monitors					The Dalles Tailrace Monitors				
	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F
2005	153	48	0.31	72.0	15-Jul	153	48	0.31	72.2	15-Jul
2006	153	54	0.35	72.2	9-Jul	151	54	0.36	72.1	9-Jul
2007	153	53	0.35	71.6	10-Jul	153	53	0.35	71.5	10-Jul
2008	153	31	0.20	71.3	26-Jul	153	32	0.21	71.5	27-Jul
2009	153	46	0.30	73.7	17-Jul	153	47	0.31	73.9	16-Jul
2010	153	39	0.25	72.4	22-Jul	153	39	0.25	72.5	22-Jul
2011	153	25	0.16	70.5	6-Aug	153	27	0.18	70.6	5-Aug
2012	153	27	0.18	71.2	5-Aug	153	28	0.18	71.2	4-Aug
2013	152	49	0.32	72.2	14-Jul	153	49	0.32	72.4	14-Jul
2014	152	50	0.33	72.7	13-Jul	153	51	0.33	72.8	12-Jul
2015	153	71	0.46	73.7	22-Jun	153	71	0.46	73.8	22-Jun

Table B.3 – Summary of temperature data at John Day Dam collected at water quality monitors in the forebay and tailrace. Data are summarized for the April 1–August 31 period, 2005–2015. Fill colors indicate magnitude of Proportion of Days Exceeding 68°F water quality standard (white = lowest values, yellow = 50th percentile, red = highest values).

	John Day Forebay Monitors					John Day Tailrace Monitors				
Year	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F
2005	153	47	0.31	72.0	16-Jul	153	48	0.31	71.9	15-Jul
2006	153	53	0.35	72.2	9-Jul	153	52	0.34	72.1	11-Jul
2007	151	53	0.35	71.4	10-Jul	153	53	0.35	71.3	10-Jul
2008	153	30	0.20	72.3	25-Jul	153	31	0.20	71.2	26-Jul
2009	153	45	0.29	74.7	17-Jul	153	44	0.29	73.8	19-Jul
2010	153	39	0.25	72.2	24-Jul	153	39	0.25	72.0	24-Jul
2011	153	26	0.17	70.7	6-Aug	153	27	0.18	70.5	5-Aug
2012	153	28	0.18	71.1	4-Aug	153	28	0.18	71.2	4-Aug
2013	153	49	0.32	72.7	14-Jul	153	49	0.32	72.5	14-Jul
2014	153	51	0.33	72.7	12-Jul	153	51	0.33	72.5	12-Jul
2015	153	69	0.45	74.3	24-Jun	153	69	0.45	73.8	24-Jun

Table B.4 – Summary of temperature data at McNary Dam collected at water quality monitors in the forebay and tailrace. Data are summarized for the April 1–August 31 period, 2005–2015. Fill colors indicate magnitude of Proportion of Days Exceeding 68°F water quality standard (white = lowest values, yellow = 50th percentile, red = highest values).

	McNary Forebay Monitors					McNary Tailrace Monitors				
Year	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F
2005	153	42	0.27	70.8	21-Jul	153	42	0.27	71.0	21-Jul
2006	153	45	0.29	70.5	17-Jul	153	48	0.31	70.8	12-Jul
2007	153	45	0.29	69.9	12-Jul	153	48	0.31	69.7	11-Jul
2008	153	26	0.17	70.9	5-Aug	153	28	0.18	70.9	4-Aug
2009	153	43	0.28	72.0	20-Jul	153	45	0.29	72.3	18-Jul
2010	152	34	0.22	71.0	27-Jul	153	37	0.24	71.1	24-Jul
2011	153	14	0.09	69.8	18-Aug	153	13	0.08	69.9	19-Aug
2012	153	19	0.12	69.2	6-Aug	153	18	0.12	69.2	6-Aug
2013	153	43	0.28	71.7	20-Jul	153	43	0.28	71.5	20-Jul
2014	153	35	0.23	71.8	22-Jul	153	35	0.23	71.6	22-Jul
2015	153	66	0.43	71.9	27-Jun	153	67	0.44	72.1	26-Jun

Table B.5 – Summary of temperature data at Ice Harbor Dam collected at water quality monitors in the forebay and tailrace. Data are summarized for the April 1–August 31 period, 2005–2015. Fill colors indicate magnitude of Proportion of Days Exceeding 68°F water quality standard (white = lowest values, yellow = 50th percentile, red = highest values).

	Ice Harbor Forebay Monitors					**Ice Harbor Tailrace Monitors**				
Year	**Num. Days**	**Days Exceeding 68°F**	**Prop. Days Exceeding 68°F**	**Max. Temp. (°F)**	**First Day Exceeding 68°F**	**Num. Days**	**Days Exceeding 68°F**	**Prop. Days Exceeding 68°F**	**Max. Temp. (°F)**	**First Day Exceeding 68°F**
2005	153	49	0.32	71.7	14-Jul	151	52	0.34	71.8	11-Jul
2006	151	57	0.38	71.7	6-Jul	151	58	0.38	72.2	5-Jul
2007	153	54	0.35	72	9-Jul	153	54	0.35	72.4	9-Jul
2008	153	30	0.20	70.9	28-Jul	153	35	0.23	70.6	27-Jul
2009	153	50	0.33	71.9	13-Jul	153	51	0.33	72.3	12-Jul
2010	153	40	0.26	70.8	23-Jul	153	40	0.26	70.8	23-Jul
2011	153	28	0.18	70.0	4-Aug	153	30	0.20	70.2	2-Aug
2012	153	48	0.31	71.2	15-Jul	153	49	0.32	71.7	14-Jul
2013	153	50	0.33	71.2	13-Jul	153	51	0.33	71.6	12-Jul
2014	153	46	0.30	71.6	17-Jul	153	47	0.31	71.6	16-Jul
2015	153	68	0.44	72.8	25-Jun	153	69	0.45	73.0	24-Jun

Table B.6 – Summary of temperature data at Lower Monumental Dam collected at water quality monitors in the forebay and tailrace. Data are summarized for the April 1–August 31 period, 2005–2015. Fill colors indicate magnitude of Proportion of Days Exceeding 68°F water quality standard (white = lowest values, yellow = 50th percentile, red = highest values).

	Lower Monumental Forebay Monitors					**Lower Monumental Tailrace Monitors**				
Year	**Num. Days**	**Days Exceeding 68°F**	**Prop. Days Exceeding 68°F**	**Max. Temp. (°F)**	**First Day Exceeding 68°F**	**Num. Days**	**Days Exceeding 68°F**	**Prop. Days Exceeding 68°F**	**Max. Temp. (°F)**	**First Day Exceeding 68°F**
2005	153	40	0.26	70.0	14-Jul	153	44	0.29	69.9	14-Jul
2006	148	57	0.39	70.8	5-Jul	151	57	0.38	70.3	5-Jul
2007	153	45	0.29	70.9	10-Jul	153	46	0.30	70.6	9-Jul
2008	153	13	0.08	69.5	15-Aug	153	14	0.09	69.4	14-Aug
2009	153	32	0.21	70.9	13-Jul	152	31	0.20	70.9	15-Jul
2010	153	30	0.20	70.2	28-Jul	153	32	0.21	69.9	24-Jul
2011	153	17	0.11	69.4	6-Aug	153	15	0.10	69.1	7-Aug
2012	153	44	0.29	69.9	16-Jul	152	44	0.29	70.0	16-Jul
2013	153	53	0.35	70.1	10-Jul	152	50	0.33	69.9	12-Jul
2014	153	45	0.29	70.0	18-Jul	153	47	0.31	70.0	16-Jul
2015	153	69	0.45	71.8	24-Jun	153	69	0.45	71.7	24-Jun

Table B.7 – Summary of temperature data at Little Goose Dam collected at water quality monitors in the forebay and tailrace. Data are summarized for the April 1–August 31 period, 2005–2015. Fill colors indicate magnitude of Proportion of Days Exceeding 68°F water quality standard (white = lowest values, yellow = 50th percentile, red = highest values).

	Little Goose Forebay Monitors					Little Goose Tailrace Monitors				
Year	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F
2005	153	19	0.12	69.8	14-Jul	153	19	0.12	69.3	14-Jul
2006	151	51	0.34	70.8	3-Jul	151	45	0.30	70.2	3-Jul
2007	153	35	0.23	70.9	9-Jul	153	34	0.22	69.8	9-Jul
2008	153	7	0.05	69.6	15-Aug	153	6	0.04	68.6	15-Aug
2009	153	23	0.15	70.2	11-Jul	153	18	0.12	70.4	25-Jul
2010	153	12	0.08	71.0	2-Aug	153	11	0.07	69.8	9-Aug
2011	153	11	0.07	69.3	4-Aug	153	7	0.05	68.9	7-Aug
2012	153	32	0.21	69.8	16-Jul	153	30	0.20	69.4	16-Jul
2013	153	33	0.22	69.5	7-Jul	153	30	0.20	69.2	9-Jul
2014	153	40	0.26	69.9	19-Jul	153	39	0.25	69.4	19-Jul
2015	153	56	0.37	71.9	20-Jun	153	54	0.35	71.2	21-Jun

Table B.8 – Summary of temperature data at Lower Granite Dam collected at water quality monitors in the forebay and tailrace. Data are summarized for the April 1–August 31 period, 2005–2015. Fill colors indicate magnitude of Proportion of Days Exceeding 68°F water quality standard (white = lowest values, yellow = 50th percentile, red = highest values).

	Lower Granite Forebay Monitors					Lower Granite Tailrace Monitors				
Year	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F
2005	153	50	0.33	72.2	4-Jul	150	0	0.00	67.6	N/A
2006	151	5	0.03	69.2	5-Jul	151	8	0.05	69.0	1-Jul
2007	153	0	0.00	67.9	N/A	153	1	0.01	68.2	5-Jul
2008	153	0	0.00	67.3	N/A	153	0	0.00	67.1	N/A
2009	153	0	0.00	67.6	N/A	153	0	0.00	67.9	N/A
2010	153	0	0.00	66.8	N/A	153	0	0.00	67.4	N/A
2011	153	0	0.00	67.6	N/A	153	0	0.00	67.9	N/A
2012	153	0	0.00	68.0	N/A	153	0	0.00	67.9	N/A
2013	153	0	0.00	67.5	N/A	153	2	0.01	68.2	22-Aug
2014	153	5	0.03	69.6	22-Aug	153	3	0.02	68.6	24-Aug
2015	152	25	0.16	70.5	7-Jul	153	7	0.05	70.1	7-Jul

Table B.9 – Summary of temperature data at Grand Coulee Dam collected at water quality monitors in the forebay and tailrace. Data are summarized for the April 1–August 31 period, 2005–2015. Fill colors indicate magnitude of Proportion of Days Exceeding 68°F water quality standard (white = lowest values, yellow = 50th percentile, red = highest values).

Year	Grand Coulee Forebay Monitors					Grand Coulee Tailrace Monitors				
	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F
2005	153	18	0.12	70.8	13-Aug	153	0	0.00	66.7	N/A
2006	153	22	0.14	69.7	6-Aug	153	0	0.00	67.5	N/A
2007	153	17	0.11	69.1	7-Aug	153	0	0.00	67.5	N/A
2008	153	1	0.01	70.0	24-Aug	153	0	0.00	66.3	N/A
2009	153	14	0.09	71.2	18-Aug	153	0	0.00	65.7	N/A
2010	153	14	0.09	71.4	16-Aug	153	0	0.00	65.9	N/A
2011	153	0	0.00	66.7	N/A	151	0	0.00	65.7	N/A
2012	153	0	0.00	66.3	N/A	149	0	0.00	64.1	N/A
2013	145	8	0.06	70.8	24-Aug	145	0	0.00	66.7	N/A
2014	153	5	0.03	70.1	24-Aug	153	0	0.00	66.6	N/A
2015	149	3	0.02	69.3	24-Aug	153	0	0.00	67.1	N/A

Table B.10 – Summary of temperature data at Chief Joseph Dam collected at water quality monitors in the forebay and tailrace. Data are summarized for the April 1–August 31 period, 2005–2015. Fill colors indicate magnitude of Proportion of Days Exceeding 68°F water quality standard (white = lowest values, yellow = 50th percentile, red = highest values).

Year	Chief Joseph Forebay Monitors					Chief Joseph Tailrace Monitors				
	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F
2005	152	0	0.00	67.0	N/A	153	0	0.00	66.7	N/A
2006	150	0	0.00	67.3	N/A	153	0	0.00	67.2	N/A
2007	153	0	0.00	67.4	N/A	153	0	0.00	67.2	N/A
2008	134	0	0.00	66.4	N/A	143	0	0.00	65.8	N/A
2009	152	0	0.00	66.1	N/A	153	0	0.00	65.3	N/A
2010	153	0	0.00	66.1	N/A	153	0	0.00	65.3	N/A
2011	152	0	0.00	65.1	N/A	153	0	0.00	64.9	N/A
2012	153	0	0.00	64.3	N/A	153	0	0.00	64.2	N/A
2013	152	0	0.00	67.4	N/A	152	0	0.00	67.1	N/A
2014	153	0	0.00	67.2	N/A	153	0	0.00	66.9	N/A
2015	151	0	0.00	67.5	N/A	152	0	0.00	67.5	N/A

Table B.11 – Summary of temperature data at Wells Dam collected at water quality monitors in the forebay and tailrace. Data are summarized for the April 1–August 31 period, 2005–2015. Fill colors indicate magnitude of Proportion of Days Exceeding 68°F water quality standard (white = lowest values, yellow = 50th percentile, red = highest values).

Year	Wells Forebay Monitors					Wells Tailrace Monitors				
	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F
2005	149	0	0.00	66.9	N/A	149	0	0.00	66.8	N/A
2006	153	0	0.00	67.8	N/A	153	0	0.00	67.6	N/A
2007	148	0	0.00	67.5	N/A	13	0	0.00	42.6	N/A
2008	140	0	0.00	67.4	N/A	61	0	0.00	67.4	N/A
2009	153	0	0.00	66.4	N/A	153	0	0.00	66.3	N/A
2010	135	0	0.00	66.4	N/A	141	0	0.00	66.1	N/A
2011	147	0	0.00	65.8	N/A	145	0	0.00	65.8	N/A
2012	148	0	0.00	64.7	N/A	148	0	0.00	64.6	N/A
2013	152	0	0.00	67.9	N/A	152	0	0.00	67.7	N/A
2014	139	0	0.00	67.2	N/A	109	0	0.00	67.3	N/A
2015	146	0	0.00	67.9	N/A	146	1	0.01	68.1	14-Aug

Table B.12 – Summary of temperature data at Rocky Reach Dam collected at water quality monitors in the forebay and tailrace. Data are summarized for the April 1–August 31 period, 2005–2015. Fill colors indicate magnitude of Proportion of Days Exceeding 68°F water quality standard (white = lowest values, yellow = 50th percentile, red = highest values).

Year	Rocky Reach Forebay Monitors					Rocky Reach Tailrace Monitors				
	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F
2005	153	0	0.00	67.4	N/A	153	0	0.00	67.3	N/A
2006	143	1	0.01	68.1	28-Aug	141	1	0.01	68.1	28-Aug
2007	132	0	0.00	67.7	N/A	132	0	0.00	67.7	N/A
2008	153	0	0.00	67.8	N/A	153	0	0.00	67.7	N/A
2009	153	0	0.00	66.5	N/A	153	0	0.00	66.4	N/A
2010	153	0	0.00	66.5	N/A	153	0	0.00	66.5	N/A
2011	153	0	0.00	66.3	N/A	153	0	0.00	66.1	N/A
2012	153	0	0.00	64.8	N/A	153	0	0.00	64.7	N/A
2013	153	0	0.00	67.7	N/A	143	0	0.00	67.6	N/A
2014	153	0	0.00	68.0	N/A	153	0	0.00	68.0	N/A
2015	153	6	0.04	68.4	13-Aug	153	7	0.05	68.4	13-Aug

Table B.13 – Summary of temperature data at Rock Island Dam collected at water quality monitors in the forebay and tailrace. Data are summarized for the April 1–August 31 period, 2005–2015. Fill colors indicate magnitude of Proportion of Days Exceeding 68°F water quality standard (white = lowest values, yellow = 50th percentile, red = highest values).

Year	Rock Island Forebay Monitors					Rock Island Tailrace Monitors				
	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F
2005	151	0	0.00	67.6	N/A	153	0	0.00	67.6	N/A
2006	143	1	0.01	68.2	28-Aug	143	2	0.01	69.6	28-Aug
2007	143	2	0.01	68.6	30-Aug	132	0	0.00	68.0	N/A
2008	152	0	0.00	67.6	N/A	153	0	0.00	67.9	N/A
2009	153	0	0.00	66.7	N/A	153	0	0.00	66.9	N/A
2010	151	1	0.01	68.8	8-Aug	153	0	0.00	66.8	N/A
2011	153	0	0.00	66.2	N/A	153	0	0.00	66.2	N/A
2012	153	0	0.00	65.0	N/A	153	0	0.00	66.6	N/A
2013	153	0	0.00	67.9	N/A	153	0	0.00	67.9	N/A
2014[A]	152	2	0.01	68.3	19-Aug					
2015	153	11	0.07	68.7	10-Aug	153	12	0.08	68.6	10-Aug

[A] Tailrace temperatures not available due to Wanapum drawdown—gauge was often out of water. Not able to assess exactly when this occurred.

Table B.14 – Summary of temperature data at Wanapum Dam collected at water quality monitors in the forebay and tailrace. Data are summarized for the April 1–August 31 period, 2005–2015. Fill colors indicate magnitude of Proportion of Days Exceeding 68°F water quality standard (white = lowest values, yellow = 50th percentile, red = highest values).

Year	Wanapum Forebay Monitors					Wanapum Tailrace Monitors				
	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F	Num. Days	Days Exceeding 68°F	Prop. Days Exceeding 68°F	Max. Temp. (°F)	First Day Exceeding 68°F
2005	111	2	0.02	68.3	3-Aug	111	0	0.00	66.9	N/A
2006	149	17	0.11	70.9	5-Aug	148	8	0.05	68.7	18-Aug
2007	150	7	0.05	68.8	14-Aug	153	1	0.01	68.1	31-Aug
2008	135	10	0.07	69.4	14-Aug	135	1	0.01	68.1	20-Aug
2009	153	15	0.10	70.6	25-Jul	153	0	0.00	67.3	N/A
2010	153	6	0.04	69.4	2-Aug	153	0	0.00	67.7	N/A
2011	151	1	0.01	68.1	28-Aug	151	0	0.00	67.0	N/A
2012	153	0	0.00	67.3	N/A	153	0	0.00	66.1	N/A
2013	151	25	0.17	70.7	7-Aug	151	17	0.11	69.0	11-Aug
2014	153	18	0.12	68.8	12-Aug	153	14	0.09	68.5	14-Aug
2015	153	32	0.21	69.9	8-Jul	149	14	0.09	69.0	3-Aug

Table B.15 – Summary of temperature data at Priest Rapids Dam collected at water quality monitors in the forebay and tailrace. Data are summarized for the April 1–August 31 period, 2005–2015. Fill colors indicate magnitude of Proportion of Days Exceeding 68°F water quality standard (white = lowest values, yellow = 50th percentile, red = highest values).

	Priest Rapids Forebay Monitors					Priest Rapids Tailrace Monitors				
Year	**Num. Days**	**Days Exceeding 68°F**	**Prop. Days Exceeding 68°F**	**Max. Temp. (°F)**	**First Day Exceeding 68°F**	**Num. Days**	**Days Exceeding 68°F**	**Prop. Days Exceeding 68°F**	**Max. Temp. (°F)**	**First Day Exceeding 68°F**
2005	111	0	0.00	67.3	N/A	109	0	0.00	67.7	N/A
2006	148	13	0.09	69.1	7-Aug	149	11	0.07	69.2	14-Aug
2007	153	1	0.01	68.2	31-Aug	153	1	0.01	68.1	31-Aug
2008	135	11	0.08	68.7	15-Aug	134	0	0.00	68.0	16-Aug
2009	151	4	0.03	68.6	27-Jul	153	0	0.00	67.6	27-Jul
2010	153	5	0.03	68.6	2-Aug	153	0	0.00	67.7	16-Aug
2011	151	0	0.00	67.2	N/A	151	0	0.00	67.0	N/A
2012	153	0	0.00	66.9	N/A	153	0	0.00	66.3	N/A
2013	151	22	0.15	70.1	10-Aug	151	22	0.15	69.4	10-Aug
2014	153	22	0.14	68.9	4-Aug	153	18	0.12	68.8	13-Aug
2015	153	31	0.20	69.4	8-Jul	153	23	0.15	69.4	9-Jul

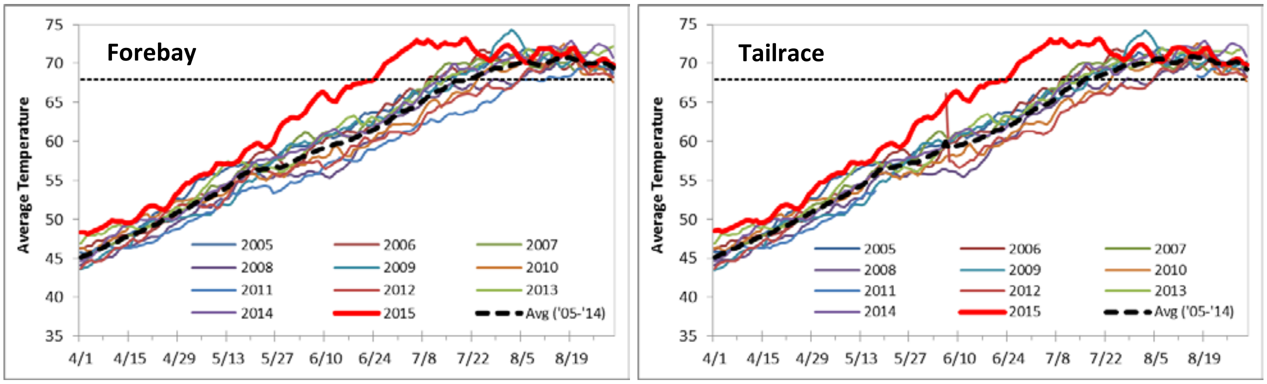

Figure B.1 – Daily average temperature (°F) at the Bonneville Dam water quality monitors in the forebay and tailrace (at Cascade Island), April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard.

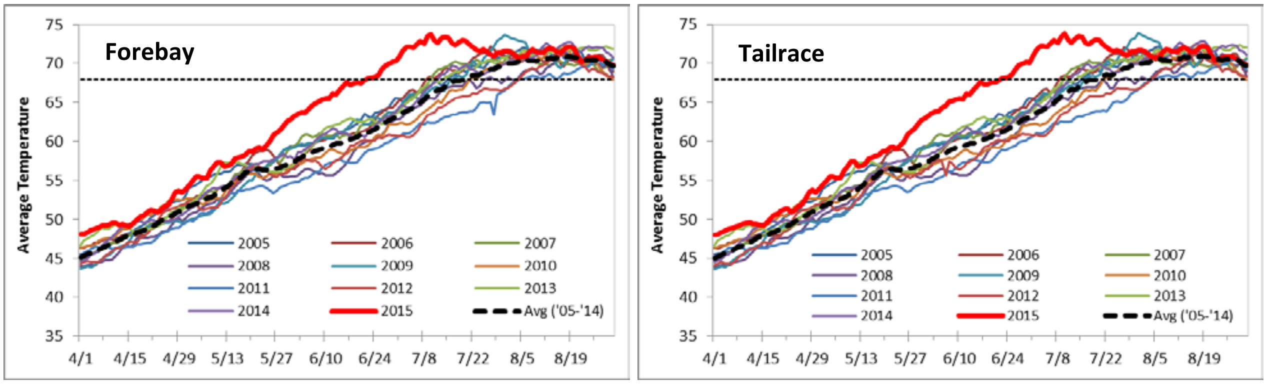

Figure B.2 – Daily average temperature (°F) at The Dalles Dam water quality monitors in the forebay and tailrace, April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard.

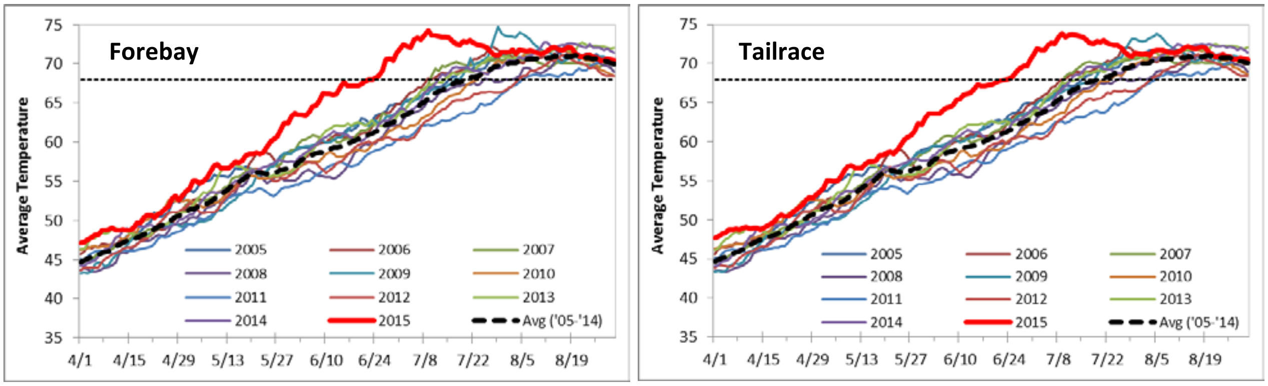

Figure B.3 – Daily average temperature (°F) at the John Day Dam water quality monitors in the forebay and tailrace, April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard.

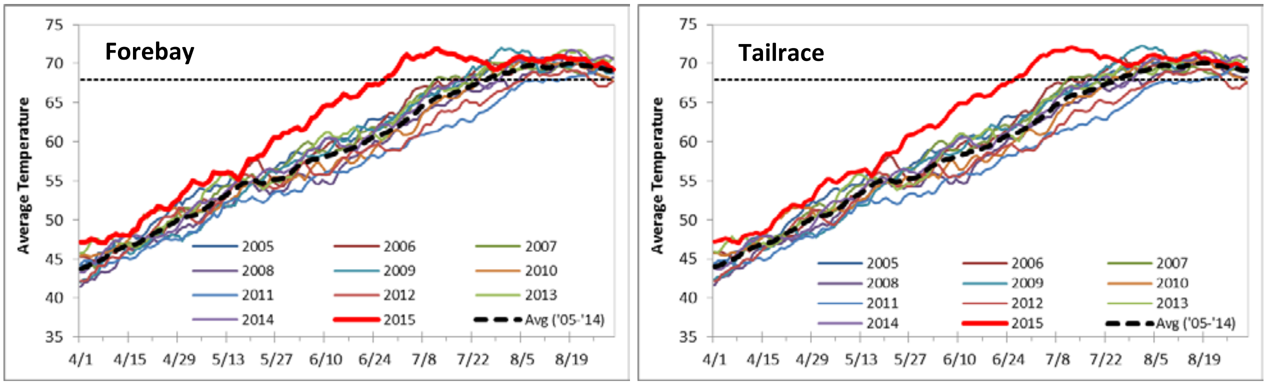

Figure B.4 – Daily average temperature (°F) at the McNary Dam water quality monitors in the forebay and tailrace, April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard.

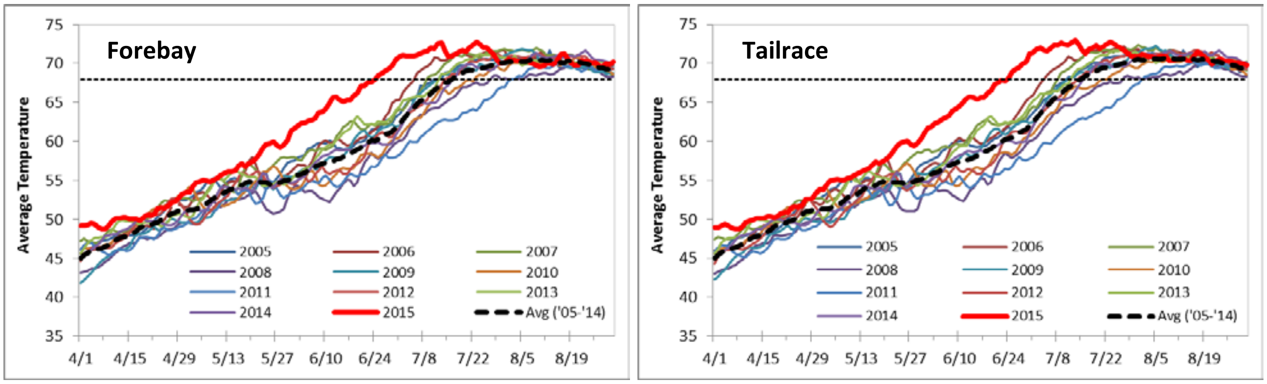

Figure B.5 – Daily average temperature (°F) at the Ice Harbor Dam water quality monitors in the forebay and tailrace, April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard.

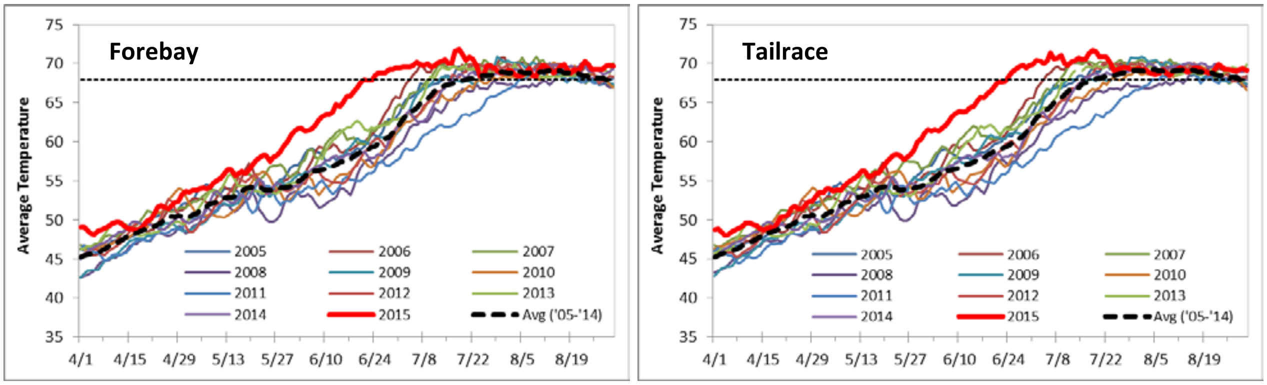

Figure B.6 – Daily average temperature (°F) at the Lower Monumental Dam water quality monitors in the forebay and tailrace, April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard.

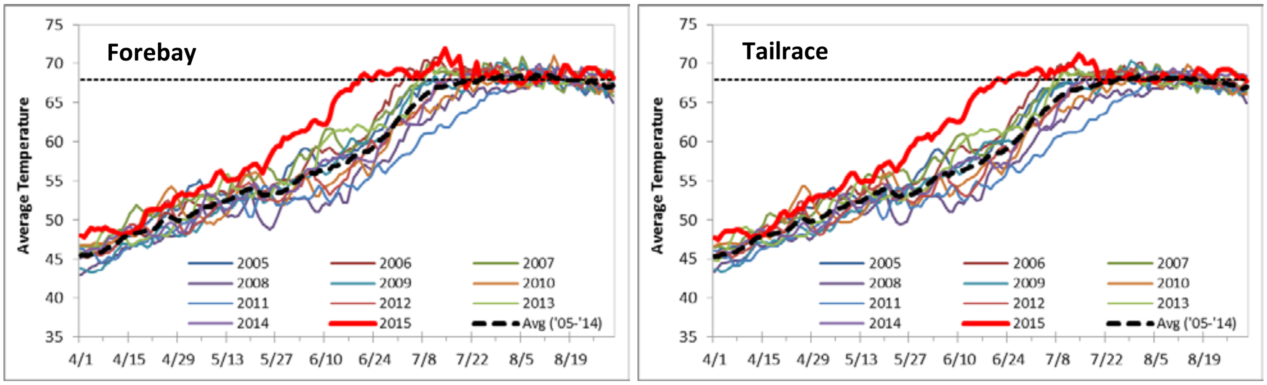

Figure B.7 – Daily average temperature (°F) at the Little Goose Dam water quality monitors in the forebay and tailrace, April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard.

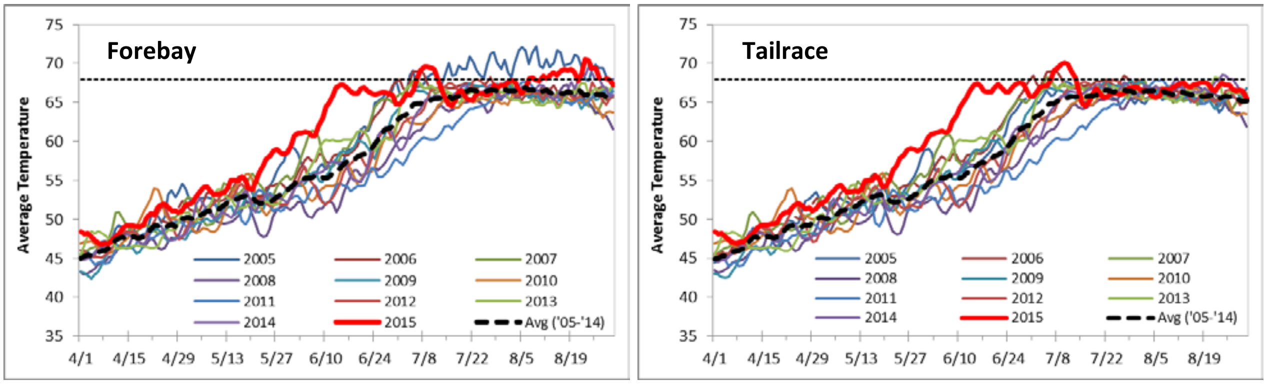

Figure B.8 – Daily average temperature (°F) at the Lower Granite Dam water quality monitors in the forebay and tailrace, April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard.

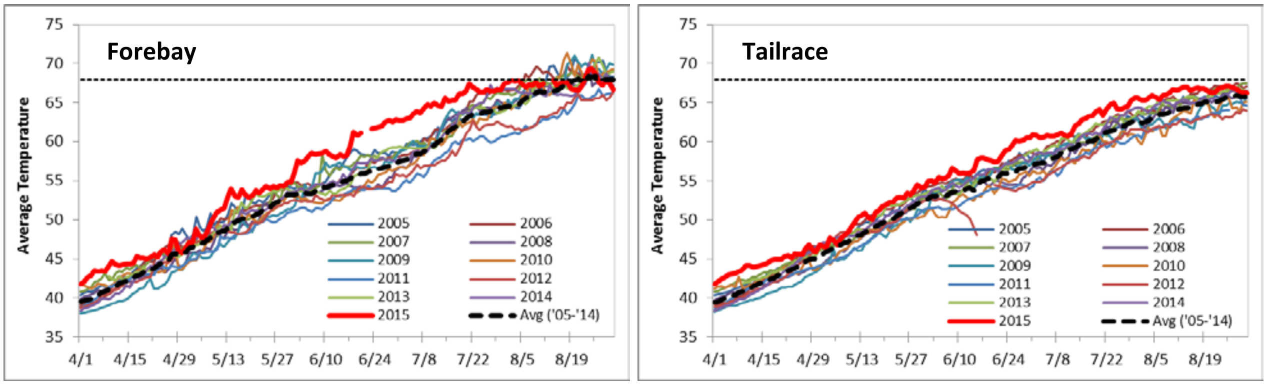

Figure B.9 – Daily average temperature (°F) at the Grand Coulee Dam water quality monitors in the forebay and tailrace, April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard.

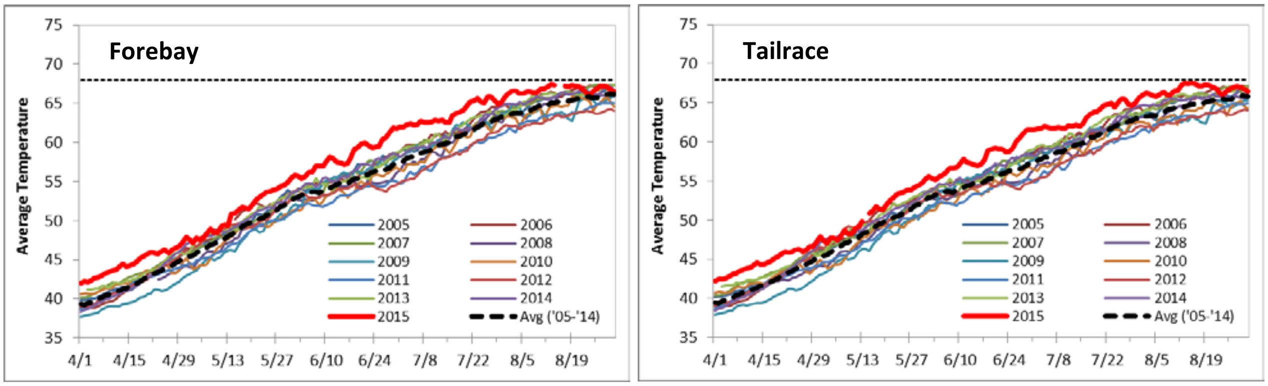

Figure B.10 – Daily average temperature (°F) at the Chief Joseph Dam water quality monitors in the forebay and tailrace, April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard.

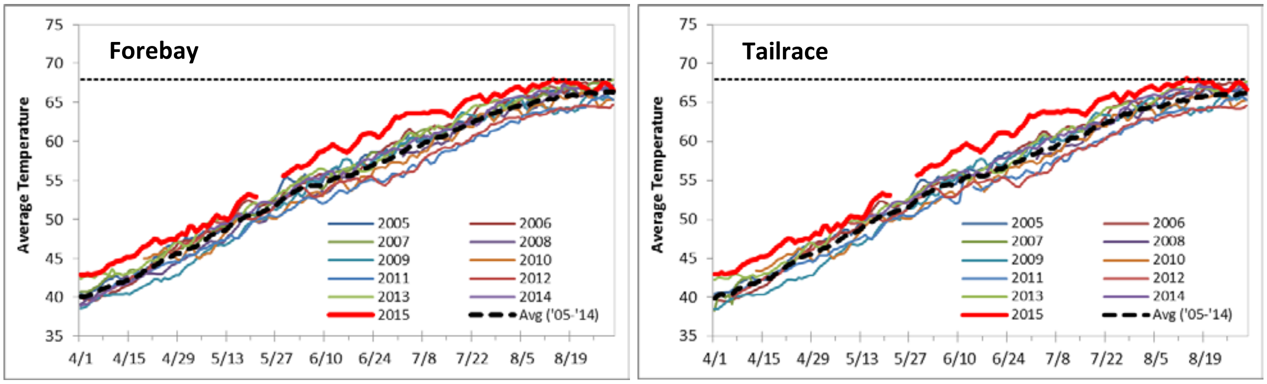

Figure B.11 – Daily average temperature at the Wells Dam water quality monitors in the forebay and tailrace, April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard.

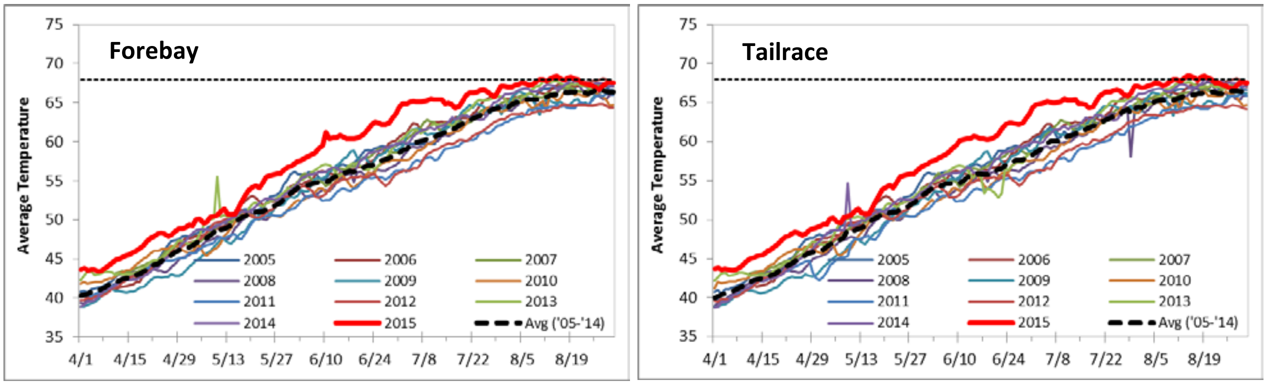

Figure B.12 – Daily average temperature (°F) at the Rocky Reach Dam water quality monitors in the forebay and tailrace, April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard.

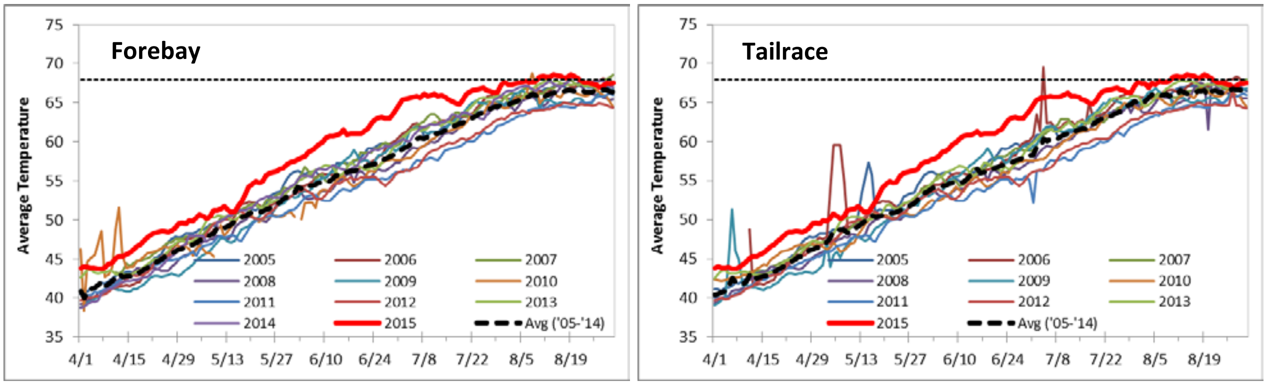

Figure B.13 – Daily average temperature (°F) at the Rock Island Dam water quality monitors in the forebay and tailrace, April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard. ***Wanapum drawdown operations in 2014 caused the tailrace monitor to be in and out of the water. Therefore, 2014 data for this monitor are not provided.***

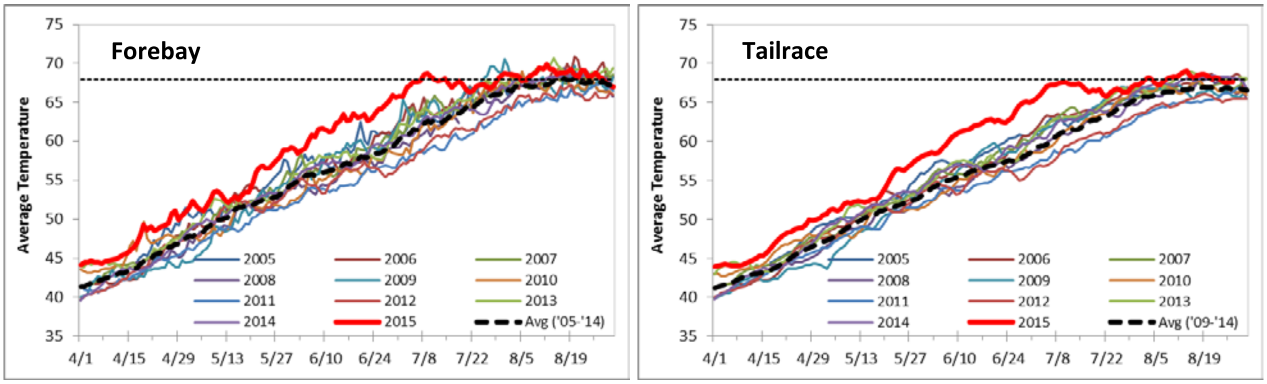

Figure B.14 – Daily average temperature (°F) at the Wanapum Dam water quality monitors in the forebay and tailrace, April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard.

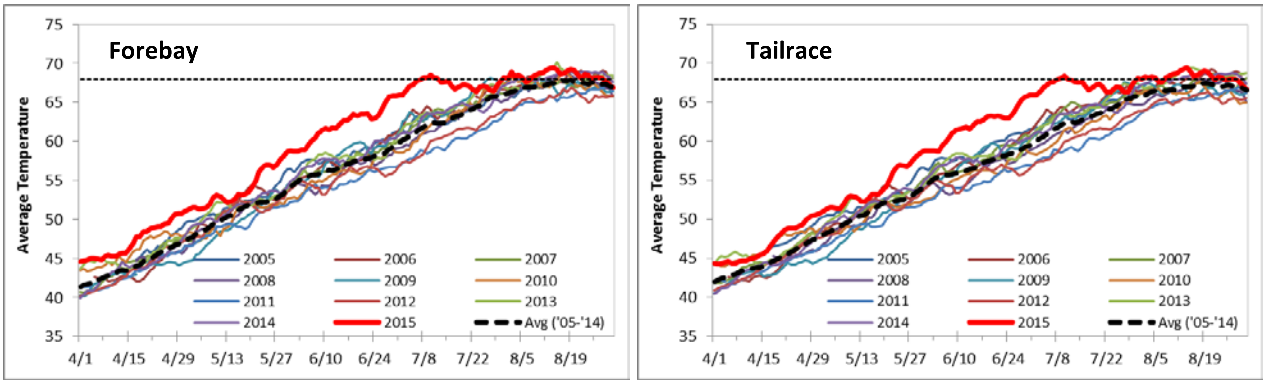

Figure B.15 – Daily average temperature (°F) at the Priest Rapids Dam water quality monitors in the forebay and tailrace, April 1–August 31, 2005–2015. Dashed line represents the 10-year average (2005–2014). Horizontal dashed line is provided at 68°F for perspective relative to the water quality standard.

Appendix C

2015 Chronology of Events Associated with Adult Sockeye

The temperature issues at the Snake River projects began in late June as local temperatures became increasingly hotter. There are few actual tools that can be implemented to address temperature issues. One is the release of cool water from a limited volume in Dworshak Reservoir to ameliorate temperature at Lower Granite Dam tailrace. The second is the implementation of additional fish pumps (at Lower Granite Dam only) to draw deeper, cooler water from the forebay reservoir to decrease adult fish ladder temperatures. These two tools were fully implemented in 2015 and the passage issues and mortality of sockeye continued. This lack of viable alternatives led to the consideration of actions that had an associated cost in juvenile and adult mortality including: emergency trapping and hauling at high water temperatures and changing spill operations that decreased juvenile passage protection. The cost to juvenile and adult survival and the lack of a plan for evaluation of operations led to differences in recommendations among the salmon managers.

Following is a brief summary put together by the Fish Passage staff of the sequence of events regarding the development of alternative operations during what became a declared fish emergency. It is the FPC staff's recollection of the important aspects of each of the conversations that had taken place, and, unintentionally, may not include all points discussed. Not all meetings are recorded and the re-creation is based on staff memory. Additional information can be obtained through the Fish Passage Advisory Committee notes and audio recordings (http://www.fpc.org/documents/fpac_minutes/fpac_minutes_currentyear.html) and the Corps of Engineers (COE) Technical Management notes (http://www.nwd-wc.usace.army.mil/tmt/agendas/2015/). Notes for the COE's Fish Passage Operations and Maintenance meetings that occur outside of the scheduled monthly meeting are not publicly available.

July 1 - Technical Management Team Meeting

Prior to July 1st, the usual Dworshak operations are for the project to be filling over June to its "full" elevation (1,600 feet) by or about June 30th. A portion of that water (to elevation 1,535 feet by August 31st or 1,520 feet by mid-September) is then available for flow augmentation and temperature regulation. At the July 1st meeting the COE reported that on June 27th DWR discharge was increased to 12.5 Kcfs based on predicted "soaring temps." However, these temperatures did not materialize and DWR was decreased on June 29th to full powerhouse discharge.

Based on their model results the COE predicted that discharges of 5.3 Kcfs were good enough to maintain Lower Granite temperatures below 68°F through the July 4th weekend. At this meeting there was some concern expressed by the Salmon Managers regarding sockeye conversion through the Snake River and advised they were monitoring the passage numbers.

July 8 - Technical Management Team Meeting

On July 7th DWR discharge increased to 7.5 Kcfs to address the fact that Lower Granite temperatures increased considerably over the July 4th weekend with the decreased outflow from Dworshak. Conditions did not occur as COE had expected on July 1st (i.e., weather hotter and no storms as predicted).

July 8 - Fish Passage Operations and Maintenance Conference Call

Concern had been expressed regarding sockeye passage. The RSW was said to be causing the formation of an eddy near the ladder entrance that may be impeding passage. The recommendation was made to implement an operation with the RSW off and the provision of uniform spill pattern through the conventional spill bays. This spill was to be implemented through Monday July 13th. This was not opposed by the parties. ***On July 8th at 1:00 PM, the COE closed the Lower Granite RSW based on TMT and FPOM coordination. The project operated with spill in a uniform pattern with no RSW.***

July 10 - Fish Passage Operations and Maintenance Conference Call

Visual counts at LGR appeared to increase (July 1st to July 7th counts ranged from 2 to 25 and the July 8th and 9th counts were 12 and 17). However, at this point, concern was expressed by the Nez Perce Tribe, USFWS and ODFW that they were uncertain whether this was a natural variability observed in the dam counts or a response of the LGR operational change (Unit 2, RSW off).

IDFG mentioned normal adult conversion BON-LGR is 70%; 2015 so far was 25%. IDFG believed warm temperatures were stalling fish and, therefore, declared an adult emergency. Due to the declared fish emergency, the trap at Lower Granite Dam could be operated at temperatures that are above the operational limit if permitted by NOAA. IDFG initiated a trap and haul operation at LGR on July 13th to collect adult sockeye and transport them to Eagle Hatchery as captive broodstock (trapping to occur 5 days/week for four hours during the cooler morning period). They intended to collect 400 fish and were working with NOAA on the permit.

At this meeting a discussion occurred regarding the use of the Ice Harbor Dam trap, and the COE agreed to look into its operation. All parties agreed to continue Unit 2, with no RSW operation until after an FPOM discussion that was scheduled for Monday, July 13th.

July 13 - Fish Passage Operations and Maintenance Conference Call

IDFG announced that they had looked into operating the trap at IHR, but because of personnel and transport vehicle limitations had decided they would not pursue this operation further. At this meeting NOAA recommended that in addition to the RSW change, they would like to switch the priority unit operation from Unit 2 to Unit 1. After the counts during the first two days of 12 and 17, the next three days had counts of 8, 5 and 6. NOAA and the COE expressed concern that operating Unit 2 causes an eddy to form near the adult ladder entrance that may be impeding passage. They verbally presented information they said showed that Unit 1 operation in 2013 had much higher passage than Unit 2 operation. IDFG researchers believed that any change in operation causes a change in ladder counts and were supportive of this operation. The Nez Perce and ODFW did not support the change. Unit 1 is a fixed blade unit that operates at a higher hydraulic capacity and, therefore, decreases spill and juvenile passage protection when flows are low. The FPC requested an explanation of what criteria would be used to determine the success of an operation. The COE responded that they did not have a criterion, but would be able to determine if a change was positive after they saw the adult ladder counts.

In spite of the lack of consensus, since NOAA recommended the change, the COE agreed to make the change. ***On July 13th at 4:00 PM, the project switched to Unit 1 priority**. **The project operated with more flow through the powerhouse and decreased spill in a uniform pattern, with no RSW.***

July 17 - Fish Passage Operations and Maintenance Conference Call

This call was held to check on the operation at Lower Granite Dam. The adult sockeye counts for the past four days were 13, 17, 19 and 25. There was claim of successfully increasing adult sockeye passage under the Unit 1 operation. However, there was caution expressed regarding the fact that at the same time the ambient temperatures cooled and it was likely that ladder temperatures also cooled, leading to the increase in adult passage. The COE was asked to supply the ladder temperatures. They claimed they would have to see because there were limited resources and they may not be able to collect the data. The COE continued operation of Unit 1 with the RSW off and uniform spill.

Note: A formal request was made by the FPC via e-mail to COE for the ladder temperature data at all the ladders for this year and any historic data as well.

July 20 - Fish Passage Operations and Maintenance Conference Call

Prior to the meeting FPC had distributed a short memo to FPAC outlining the results of the Unit 1 operation and ending with a recommendation to return to Unit 2 operation. The adult sockeye counts for the previous three days were 13, 2 and 2. In addition to a discussion regarding whether Unit 1 operation was successful, or whether we were just observing changes in ladder temperatures, NOAA initiated a discussion of switching to full powerhouse/no spill at LGR, instead of Unit 1/Spill rest.

The operation was left unchanged based on NOAA's recommendation. The same parties (ODFW, NPT, WDFW and USFWS) did not agree with this operation. At this point, while agencies did not agree, they did not announce that they would formally object to the operation and initiate a policy-level review.

July 21 - Fish Passage Advisory Committee Meeting

IDFG made a proposal to change to Unit 2 at LGR for two days plus deep spill. At LGS they proposed a no spill operation for 24 hours alternating with two day blocks of FOP operations. CRITFC/Umatilla suggested modifying the LGS operations to no spill during daylight hours and spill everything in excess of one unit during nighttime hours. The Nez Perce, ODFW and USFWS supported change to Unit 2 at LGR, but they were waiting for ladder temperatures before making any decision at LGS.

July 21 – Fish Passage Operations and Maintenance Conference Call

A special FPOM conference call was requested after the FPAC meeting. At the meeting IDFG presented their modified proposal. The USFWS discussed an analysis that they had just conducted on the temperature data that had been released an hour before the meeting. USFWS pointed out that there is a relation between the ladder exit temperature and adult counts. After the discussion, the COE stated they were continuing Unit 1 at LGR as per the NOAA recommendation and agreed to the LGS test. USFWS, ODFW and Nez Pierce objected to the LGS operations. WDFW did not agree, but would not object. At this point Walla Walla was going to proceed with LGR, but not LGS due to disagreement, but the COE RCC (Reservoir control center) asked if people were objecting, but not elevating to RIOG. It was made clear that the objecting parties would be discussing with their policy staff to determine if the issue would be elevated.

Later that afternoon the COE sent an e-mail (see below) saying they were not going to implement the operations.

July 21 - COE e-mail 5:48 p.m.

TMT Members and Alternates,

Upon further coordination with Corps Legal and Policy Staff and NOAA Fisheries the Corps will not be implementing The Little Goose Dam operation discussed during today's unscheduled FPOM Emergency Call (daytime no spill and nighttime one unit minimum generation spill the remainder of inflow). The Corps will provide additional coordination with Regional Salmon Managers regarding potential operations to improve sockeye passage in the Snake River.

Regarding operations at Lower Granite Dam we are continuing with the current operation with unit 1 as the priority unit and spilling a uniform pattern without operation of the RSW until further notice. The Corps will provide an update on this operation during the TMT meeting scheduled for tomorrow at 9am. Conference call information for the TMT meeting may be found on the following website:

http://www.nwd-wc.usace.army.mil/tmt/agendas/2015/0722_Agenda.html

Regards,
Doug
Doug Baus
US Army Corps of Engineers
Northwestern Division
Fisheries Biologist

July 22 – Technical Management Team Meeting and Subsequent e-mail Conversations

The proposed operations were discussed. Prior to the meeting USFWS distributed to FPAC a memo describing the analysis conducted between ladder temperatures and LGS passage. This analysis was discussed at the meeting. The following poll was taken and recorded at the TMT meeting regarding the proposed operations:

- Idaho – Support.
- Montana – Support.
- NOAA – Support.
- Washington – Does not support; no objection.
- Colville – Does not support; no objection.
- Nez Perce – Object.
- USFWS – Object.
- Oregon – Object.
- Umatilla – Object.
- BPA [not polled at TMT, however, supports the Corps decision].
- Corps [not polled at TMT, support].
- Bureau of Reclamation [not polled at TMT]

After the poll the COE summarized their intent to maintain Unit 1 priority at Lower Granite with uniform spill and the RSW shut off:

> In accordance with NOAA's request, the COE will consider operating Little Goose for daytime generation only, with no spill from 4 am-8 pm, and one unit at minimum generation at night, spilling the remainder of outflow from 8 pm-4 am. Based on TMT's feedback today, the COE will consult with legal and policy staff on this operation and email TMT its decision this afternoon.

Later that day (July 22^{nd}) the following e-mail was sent, implementing the operations.

July 22 - COE e-mail at 9:49 p.m.
TMT Members, Alternates, and Interested Parties,

Regarding experimental emergency operations discussed today at TMT to increase adult Snake River Sockeye passage at Little Goose (LGS) and Lower Granite (LWG) dams, the Corps will implement NOAA Fisheries recommended experimental emergency operation at LGS. This operation will include a period of no spill during the daylight hours of 4am to 8pm and a period of a single unit operation at minimum generation while spilling the remainder of outflow during the nighttime hours of 8pm to 4am. The experimental emergency LGS operation will occur for 2 days beginning on Thursday, July 23, at 4am and will continue through Saturday, July 25 at 4am. LGS will resume operations that were underway prior to this experimental operation on Saturday, July 25 at 4am. Regarding LWG operations, the Corps will continue to implement NOAA Fisheries recommended operation to maintain unit 1 priority and deep spill (no spillway weir). The Corps has scheduled a TMT meeting for Monday, July 27, at 9 am and will provide

the TMT with information about current conditions; and will be prepared to discuss this experimental emergency operation and recommendations for continuation of this operation or alternatives with TMT representatives. In addition the Corps will provide an update on this operation during the FPOM conference call on Friday, July 24.
Regards,
Doug
Doug Baus
US Army Corps of Engineers
Northwestern Division
Phone: (503) 808-3995
Douglas.M.Baus@usace.army.mil

The next morning (July 23rd), ODFW sent an official request raising the issue to RIOG.

July 23 - ODFW e-mail at 8:33 a.m.
Given Oregon and others earlier objection to this planned operational change at Little Goose Dam and the solidification of a similarly premised special operation that did not clearly demonstration an association between the operational changes at Lower Granite Dam and adult sockeye passage over Lower Granite Dam, we feel it necessary to elevate this discussion to the Regional Implementation Oversight Group process.

Since the original elevation process has been altered by what has been described as the last elevation to RIOG, it is my understanding that TMT direct link to this elevation process is not being followed for this this request. Further, It is my understanding the expected process will require that Oregon's RIOG representative deliver the formal request to the RIOG chair. I will provide that information to the Oregon's representative and expect he will deliver an additional formal request to elevate this discussion as soon as possible. Given Oregon's and others objection to the plan below and our intent to elevate this discussion, we anticipate that no action will be taken to implement the operation described below until the RIOG process is completed.

Erick Van Dyke
Oregon Department of Fish and Wildlife
17330 SE Evelyn Street
Clackamas, Oregon 97015

COE distributed an e-mail recognizing that the issue was being raised to RIOG. The e-mail included two attached documents from NOAA as justification for their decision: (1) A NOAA letter which advised implementation based on their technical review of the impact on juveniles and (2) NOAA's technical review. See below for COE's e-mail.

July 23 - COE e-mail 3:19 p.m.
TMT Members, Alternates, FPOM Lower Granite Dam Special Operations Team, and Interested Parties,

After consideration of the information provided by sovereign representatives at TMT (and in previous discussions with FPOM), consideration of technical analyses provided by NOAA Fisheries (see attachments), and the need to make a timely decision given the immediate need to address endangered adult sockeye passage, the Corps initiated the 2-day experimental emergency operation at LGS as outlined in my email below.

The attached NOAA Fisheries memos were considered by the Corps to inform our decision to implement the 2-day emergency experimental operation. The Corps is providing these memos for your consideration, and to assist upcoming discussions at FPOM (July 24) and TMT (July 27) on proposals and actions to address the emergency conditions impacting ESA listed adult sockeye (and other adult migrants), and support other ongoing activities, such as NOAAs trapping of adult sockeye at LWG and IDFGs transport efforts. Some TMT members have objected to the 2-day emergency operation at LGS, and have expressed an intent to elevate this emergency action to the RIOG, so additional coordination may be necessary.
Regards,
Doug
Doug Baus
US Army Corps of Engineers
Northwestern Division
Fisheries Biologist

July 24 – Fish Passage Advisory Committee Meeting

The meeting was called to prepare for FPOM later that day. Three documents were shared — (1) USFWS provided an update to their ladder counts and adult passage analysis, (2) NOAA, on the Thursday afternoon prior to the meeting, after official request, sent a document with two pictures of tailrace conditions in 2013, and (3) the increased passage analysis that was conducted on the 2013 passage data, which was NOAA’s justification for operating Unit 1 at LGR.

FPC provided a graph of LGR project operations under the three recently implemented configurations; discussed the discrepancies between projects in annual counts and suggested using caution when using counts to assess sizes of populations stalling; and provided recommendations of some additional changes that might be considered for implementation to improve sockeye passage at projects without decreasing juvenile passage protection by decreasing spill, including:

1. Cycling locks at the projects to allow adult sockeye an alternate route of passage upstream.
2. Securing additional pumps to allow adding cooler water drawn from deeper depths in the forebay to decrease ladder temperatures at Little Goose Dam.

NOAA also distributed an Excel file that provided 2015 conversion rates at the Snake River projects based on PIT-tagged fish. In addition, NOAA distributed a graph of individual PIT-tagged adults showing that early in the season most adult sockeye converted to LGR, in the middle of the Bonneville run many fish did not convert well from Bonneville, and recently no fish converted from the lower Columbia to the Snake.

July 24 – Fish Passage Operations and Maintenance Conference Call

This meeting was held after only one day of the no spill operation at LGS. Concern was expressed that the NOAA proposal was for the test to continue without considering the outcome of the first 2-day block. It was clarified that the first 2-day block would be considered on July 27th before going forward. At this meeting the Nez Perce told the group that, in discussion with the manager from Lyons Ferry Fish Hatchery the previous day, sockeye adults were observed jumping at the ladder entrance to the hatchery where cooler spring water is used. IDFG wanted to immediately look into the feasibility of trapping at the facility. COE noted that they had been made aware of this observation earlier in the week, but did not think it was feasible due to hatchery construction work and, therefore, had not pursued it. The Nez Perce representative believed it would be fine based on her conversation with the hatchery manager.

USFWS suggested some additional changes be considered to improve sockeye passage at projects without decreasing juvenile passage protection by decreasing spill, including:

1. Cycling locks at the projects to allow adult sockeye an alternate route of passage upstream.
2. Securing additional pumps to allow adding cooler water drawn from deeper depths in the forebay to decrease ladder temperatures at Little Goose Dam.

COE responded that maintenance issues at LGS precluded their cycling the lock, and contractual and monetary issues precluded pursuing additional pumps, although they agreed to look into this further.

July 27 – Technical Management Team Conference Call

The operations were reviewed at the meeting. Many believed the information was inconclusive and no decisions were made pending discussion at the FPOM meeting and pending the outcome of the RIOG meeting planned for Tuesday morning (July 28th). COE stated that the LGS operation had clear effect on decreasing temperature in LMN forebay. Other TMT members did not agree with this observation.

July 27 – Fish Passage Operations and Maintenance Conference Call

Trap operations were updated. The decision on LGS operations was still on hold until after RIOG on Tuesday (July 28th). COE reiterated that they do not understand why trapping operations are not being extended, particularly given current ladder temperatures.

An update was given on the Lyons Ferry Hatchery: The adult ladder has been opened and so far only adult Chinook and steelhead (no sockeye) have been seen.

NOAA seems to believe that LGS operation was more successful than not, and would like to collect another "data point" by repeating the test. NOAA seemed to have shifted the measure of success as getting fish to LGR trap and that is how they will measure success of these operations. ODFW suggested that low counts at the end of the run, as currently being seen, makes it difficult to assess success of operational changes. ODFW suggested that NOAA should look at variability in 2015 counts for the last portion of run compared to other years. Is variability in 2015 different from other years?

July 27 - COE e-mail at 6:40 p.m.
TMT Members, Alternates, FPOM Lower Granite Dam Special Operations Team, and Interested Parties,

The Corps received a recommendation from NOAA Fisheries today, July 27, 2015 at 5:51 pm to initiate the second 2-day experimental emergency operation at Little Goose Dam (LGS) beginning tomorrow, July 28 at 4am, and continuing through Thursday, July 30 at 4am. The Corps has reviewed NOAA's recommendation and the accompanying rationale, as well as considered the discussions and information provided by sovereign representatives at the recent TMT and FPOM meetings (July 22, 24, and 27), and reviewed the available data on adult sockeye passage and water temperature from the first experimental emergency 2-day operation. Based on our review and consideration of the above, and in light of current moderate weather conditions and forecasted resumption of very warm conditions, along with prospective Hells Canyon releases later this week, the Corps decided to begin implementation of the NOAA recommended operation for the next 2 days. Consistent with the first experimental emergency 2-day operation (see email below), this operation will include a period of no spill during the daylight hours of 4am to 8pm and a period of a single unit operation at minimum generation while spilling the remainder of outflow during the nighttime hours of 8pm to 4am. LGS will resume operations that were underway prior to this experimental operation on Thursday, July 30 at 4am.

The Corps acknowledges there are regional sovereigns that support this experimental 2-day operation and others that oppose; however, a timely decision was necessary given the immediate need to attempt to improve passage conditions for the endangered adult sockeye passage. If you have new information that has not yet been shared, please send to me as soon as possible. Additionally, if you have new proposals to address adult sockeye passage (and other adult migrants) for the Corps' consideration or have other information regarding this 2-day experimental operation, please send to me and we will discuss at our next TMT meeting on Wednesday, July 29 at 9am.

Regards,
Doug
Doug Baus
US Army Corps of Engineers
Northwestern Division
Phone: (503) 808-3995
Douglas.M.Baus@usace.army.mil

July 28 – Fish Passage Advisory Committee

Concern was expressed that decisions are being made outside of the process and agreed upon time lines. Although FPAC members understood that no decision was to be made until after the RIOG meeting on Tuesday, July 28th, NOAA recommended that the COE implement the experimental blocks this morning (see above e-mail from COE on July 27th) in an attempt to assist upriver migration as soon as possible with the hope that adults passing LGS during this operation would arrive at LGR prior to the weekend and, therefore, would have higher likelihood of being captured at LGR during trap and haul operation.

USFWS provided graphs of forebay temperatures at LGR, LGS, and LMN. They pointed out that the graphs demonstrated that LMN forebay temperatures did not appear to be as obviously correlated with LGS operational changes as the COE had claimed during the TMT and FPOM calls on Monday (July 27th), since both Lower Granite and Little Goose showed similar decreases in temperature.

At the meeting it was asked if NOAA had any more recommendations that may "surprise" FPAC members, and they said they were considering halting the operation of the RSW at LMN—but at this point no decisions have been made.

IDFG determined that collecting sockeye at Lyons Ferry Hatchery was not feasible.

July 29 – Technical Management Team Meeting

In response to the COE's July 27th meeting, the FPC distributed the ladder temperature analysis from USFWS and requested that the COE discuss the implementation of additional actions that may be taken, such as securing pumps at Little Goose Dam. The COE said that they did not find the temperature information "compelling." They said that cycling the locks at Little Goose Dam was not possible because of damage to the lock that presently needed to be addressed. They did not discuss cycling the locks at the other projects. With regard to the pumps they stated it was not feasible due to: (1) funding, (2) contracting issues, and (3) work orders (such as wiring) that would be necessary at the project. The Nez Perce brought up the fact that discussion of this was in the sense of an "emergency" and yet maybe actions weren't being taken in the sense of an "emergency."

The first day of the second LGS test produced adult counts of 1.

A TMT was called for the following day to discuss operations going forward.

July 30 – Technical Management Team Conference Call

NOAA proposed no additional testing at Little Goose Dam.

IDFG proposed two options to discontinue emergency trapping at LGR.

1. Trapping will end at noon on July 31, 2015.

2. Researchers continue to press that when there are any changes made to operations they observe an initial increase in adult passage. Therefore, commence operation of Unit 2 on Monday morning and collect fish until Wednesday at noon.

There was agreement to implement the second option. Operations will return to Unit 2 priority at Lower Granite Dam and will continue in that configuration unless further operational changes are recommended later in the month. All flow in excess of that needed to operate Unit 2 will be spilled in a uniform pattern and the RSW will not be operated.

NOAA FISHERIES

2015 Adult Sockeye Salmon Passage Report

NOAA Fisheries in Collaboration with
The U.S. Army Corps of Engineers and Idaho Department of Fish and Game

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2015 ADULT SOCKEYE SALMON PASSAGE REPORT

1. Introduction

In 2015, low snow pack, coupled with extremely high air temperatures throughout the interior Columbia basin resulted in warm water in the major tributaries to the lower Snake and Columbia rivers. Temperatures in the mainstem Columbia River were the highest recorded from roughly mid-June to mid-July. Adult sockeye salmon, which normally migrate during this period, sustained heavy losses in the Columbia River and tributaries. ESA-listed Snake River sockeye salmon were especially affected in the mainstem migration corridor, with losses exceeding 95% between Bonneville and Lower Granite dams.[1] The purpose of this paper is to document the conditions that occurred throughout the Columbia River basin in 2015 and to describe and assess the actions that were taken to minimize these impacts by the federal hydrosystem operators (the U.S. Army Corps of Engineers (USACE), Bonneville Power Administration (BPA), and U.S. Bureau of Reclamation (Reclamation); the Idaho Department of Fish and Game; and the National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NOAA Fisheries) to reduce adult mortality. These efforts were coordinated with other state, tribal, and federal agencies through existing regional processes such as the Technical Management Team (TMT) for the hydropower system. We conclude this paper by recommending monitoring, structural, and process improvements that would enhance the ability of the federal hydrosystem operators and state and tribal fish and wildlife agencies to minimize the effects of a similar event if these conditions re-occur. Technical staff from NOAA Fisheries, USACE, and the Idaho Department of Fish and Game (IDFG) collaborated in the development of this paper. Literature reviewed in the preparation of this report included Fish Passage Center (2015).

1.1 Snake River Sockeye Salmon

Historically, anadromous sockeye salmon (*Oncorhynchus nerka*) were abundant throughout Idaho's upper Snake and Salmon River watersheds. The majority of these populations were extirpated and only the Redfish Lake population in the Sawtooth Valley (Figure 1) supported anadromy in the last part of the 20th century.[2] According to records kept by IDFG, University of Idaho, and NOAA Fisheries' predecessor, the U. S. Bureau of Commercial Fisheries, the escapement of adult sockeye salmon to this location ranged from a high of 4,361 (1955) to a low of 11 (1961) during 1954 through 1966. After a lapse of almost two decades, IDFG reinitiated the monitoring program in 1985. They estimated that only 61 anadromous adults returned to Redfish Lake through 1989, with zero adults returning in 1990. NOAA Fisheries listed hydropower development, water withdrawal and diversions, water storage, harvest, predation,

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[1] Other species of salmon and steelhead typically migrate outside of this time period both as juvenile and adults and were not substantially impacted.

[2] Functional spawning aggregations of resident *Oncorhynchus nerka* persisted in the Sawtooth Valley even when the anadromous form was functionally extirpated (Waples et al. 2011).

and inadequate regulatory mechanisms as factors contributing to the decline of Snake River sockeye salmon (NMFS 1991).

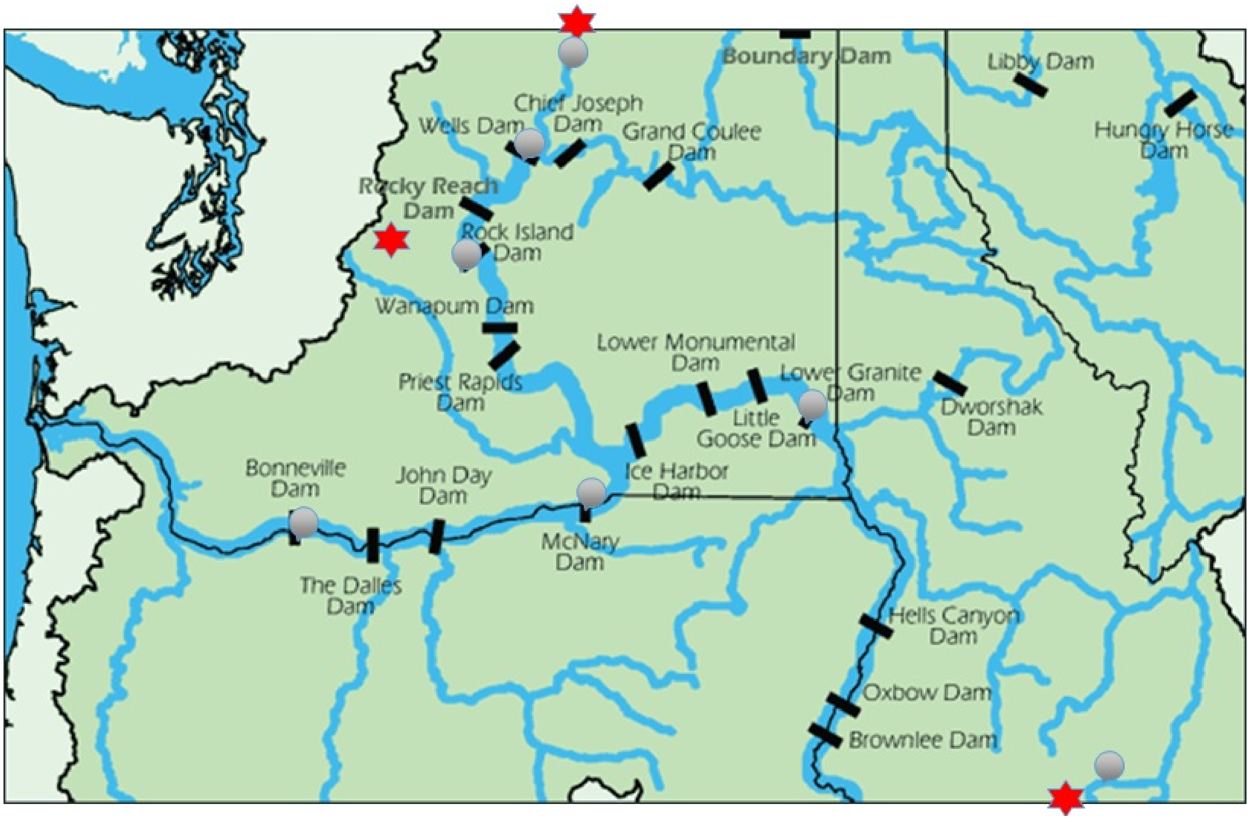

Figure 1. Map of the Columbia River Basin showing large hydroelectric projects, PIT tag detectors used in this report to estimate adult sockeye salmon survival rates (grey circles), and the location of sockeye salmon spawning populations (red stars).

Along with program cooperators, the IDFG initiated the Snake River sockeye salmon captive broodstock program in May, 1991, in response to the decline of anadromous returns to central Idaho. The goal of the program was to use captive broodstock technology to avoid extinction while conserving the species’ remaining genetic diversity. Twenty-five years later, these goals have been met. Current goals include using the captive broodstock program to increase the number of individuals in the population, creating a viable ESU that can provide sustained opportunities for sport and treaty harvest. Efforts are therefore underway to expand and amplify the hatchery program to increase the number of anadromous adults returning to the Sawtooth Valley. However, temperature-related passage issues for Snake River sockeye salmon could impede the success of this strategy. During low flow summers, we have observed temperatures that exceed lethal levels for salmonids in the lower Snake River, including the reach above the confluence of the Clearwater River, and in the Salmon River. Because of this concern, the 2008 FCRPS Biological Opinion (BiOp) included a provision for initiating an emergency adult trap-and-haul operation from Lower Granite Dam (LGR). These activities were more explicitly considered (i.e., with permits for handling increased numbers of fish) in the 2010 Supplemental

FCRPS BiOp and NOAA Fisheries retained the emergency trap and haul provisions in the 2014 Supplemental FCRPS BiOp.

1.2 Lake Wenatchee and Okanogan River Sockeye Salmon

In addition to the ESA-listed Snake River sockeye salmon ESU that spawns in Idaho's Sawtooth Valley, there are two unlisted ESUs that spawn in the upper Columbia basin in Washington State and British Columbia (Gustafson 1997). Okanogan River sockeye salmon spawn in areas upstream from Lake Osoyoos, in Lake Osoyoos, and in a downstream tributary to the Okanogan, the Similkameen River (below Enloe Dam near Oroville, Washington). Although the principal spawning and main rearing area for this ESU is in British Columbia, the migration corridor for both juveniles and adults from all the spawning areas used by Okanogan sockeye salmon is through the Columbia River in Washington and Oregon. Lake Wenatchee sockeye salmon spawn above or in Lake Wenatchee and rear in Lake Wenatchee and also migrate through the Columbia River. Both spawning areas are at relatively low elevations (Lake Osoyoos is at 278 m in the Okanogan basin and Lake Wenatchee is at 572 m) compared to Redfish Lake in Idaho's Sawtooth Valley, used by Snake River sockeye salmon (1,996 m above sea level; Appendix Table B-1 in Gustafson 1997). The juvenile and adult migration corridors for both of the Washington ESUs (986 and 842 km, for Okanogan River and Lake Wenatchee fish, respectively) are much shorter than for Snake River sockeye salmon (1,448 km). In addition to these two ESUs, the Yakama Nation started a program to reintroduce sockeye salmon into Lake Cle Elum in 2009, using adult sockeye captured at Priest Rapids Dam for broodstock.

Based on escapements above 10,000 (1992-1996), which were probably a substantial fraction of each ESU's historical abundance, NOAA Fisheries Biological Review Team (BRT) concluded that neither the Okanogan River or Lake Wenatchee sockeye salmon ESU was in danger of extinction, nor likely to become endangered in the foreseeable future (Gustafson 1997). However, the BRT noted that very low returns in the three most recent years suggested that the status of each ESU should be reconsidered if abundance remained low. More recently, sockeye salmon in the upper Columbia basin rebounded to modern day records: over 645,100 adult sockeye returned to the Columbia River in 2014, the largest sockeye run counted since the construction of Bonneville Dam in 1938 (WDFW 2016). The final adult sockeye salmon count at Bonneville Dam in 2015 was 510,706 fish. Based on PIT tag detection data, NOAA Fisheries estimates that 7.2% of PIT tagged Upper Columbia sockeye salmon were fallbacks that reascended the ladder and were counted at least twice. Using this rate to correct ladder counts, we estimate that about 476,405 Upper Columbia River sockeye salmon ascended Bonneville Dam. Using juvenile PIT tagging rates and adult PIT tag detections, IDFG estimates that 4,069 adult Snake River sockeye salmon passed Bonneville Dam in 2015.[3] Therefore, more than 470,000 of the sockeye salmon that returned to Bonneville Dam were bound for the upper Columbia basin.

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[3] We derived this estimate by expanding the PIT tag detections at Bonneville Dam by the ratios of tagged to untagged smolts for specific release groups.

Adult returns to the spawning basins have been high during the period 2005-2014, averaging 93,300 to Zosel Dam, (also near Oroville, Washington, at the outlet to Lake Osoyoos) and 51,500 at Tumwater Canyon Dam (on the Wenatchee River near Leavenworth, Washington) (Columbia River DART 2016a, b). Only 37,624 sockeye salmon passed the underwater video camera at Zosel Dam (Schaller 2016) and about 30,000 fish returned to Tumwater Dam in 2015 (Columbia River DART 2016b), reflecting losses in the lower Columbia as described in this report and through the mid-Columbia reach.

2. Environmental Conditions

In the following sections, we review the environmental conditions that caused the salmon managers concern during the 2015 sockeye migration season.

2.1 Flow and Temperature Conditions

During 2015, winter through summer (January–July) and spring and summer (April–August) runoff volumes at The Dalles and Lower Granite ranked near the lowest observed in a 56-year water record (Table 1).

Table 1. Runoff volume for the Snake and Columbia Rivers during 2015 by location, period, rank out of 56 years, volume, and percent of the previous 30-year average. Source: Norris (2015).

Location	Period	Rank (out of 56 years)	Runoff volume (kaf)	Percent (of 30-year avg)
Columbia River at The Dalles	January – July	46	82,951	83
Columbia River at The Dalles	April – August	54	58,407	67
Snake River at Lower Granite	January – July	53	12,397	56
Snake River at Lower Granite	April – August	53	11,466	54

The low spring runoff volume was the result of two factors: above average winter air temperatures (Table 2) and below average precipitation during April–August (Table 3). Air temperatures throughout the basin during key snow accumulation months of January through March were 5.1-7.6°F[4] above average and much of the precipitation fell as rain instead of snow. The combination of low snow levels in the interior basin and low spring precipitation resulted in below average tributary and mainstem flows. These were combined with June air temperatures that were 5.4-7.6°F degrees above average, resulting in unseasonably high water temperatures in both the tributaries and mainstem rivers. Flows and water temperatures in the Columbia River during the month of June, 2015, resembled conditions that we normally see during late-July and August.

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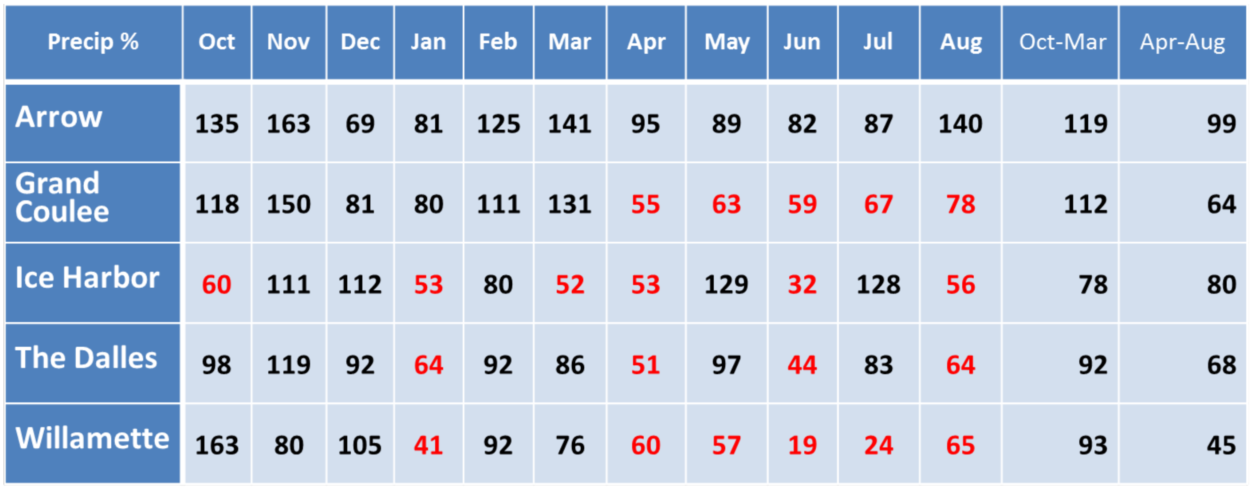
[4] To convert a difference in degrees Fahrenheit to degrees Celsius, divide degrees Fahrenheit by 1.8.

Table 2. Differences in monthly air temperatures at Columbia basin sites in 2015 compared to the 1981-2010 average (monthly temperatures more than 5 degrees above the 1981-2010 average are shown in red). Source: NOAA/NWS NWRFC

Temperature Departure °F	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Avg °F
Arrow	3.8	-1.8	3.4	5.9	6.3	3.9	0.1	3.0	4.9	2.4	0.0	**2.9**
Grand Coulee	4.4	-2.2	3.2	5.5	6.2	4.6	0.2	2.7	6.4	2.4	1.5	**3.2**
Ice Harbor	4.3	-1.1	4.7	5.6	7.6	6.0	0.5	2.3	7.4	0.2	1.6	**3.6**
The Dalles	4.6	-1.4	4.0	5.9	7.0	5.6	0.4	2.9	7.4	1.9	1.9	**3.7**
Willamette	3.9	-0.1	2.8	5.1	5.0	4.6	-0.3	2.2	5.4	3.3	1.7	**3.1**

Table 3. Differences in monthly percent of average precipitation at Columbia basin sites compared to the 1981-2010 average (red text indicates values less than 80% of the 1981-2010 average). Source: NOAA/NWS NWRFC



Precip %	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Oct-Mar	Apr-Aug
Arrow	**135**	**163**	**69**	**81**	**125**	**141**	**95**	**89**	**82**	**87**	**140**	**119**	**99**
Grand Coulee	**118**	**150**	**81**	**80**	**111**	**131**	**55**	**63**	**59**	**67**	**78**	**112**	**64**
Ice Harbor	**60**	**111**	**112**	**53**	**80**	**52**	**53**	**129**	**32**	**128**	**56**	**78**	**80**
The Dalles	**98**	**119**	**92**	**64**	**92**	**86**	**51**	**97**	**44**	**83**	**64**	**92**	**68**
Willamette	**163**	**80**	**105**	**41**	**92**	**76**	**60**	**57**	**19**	**24**	**65**	**93**	**45**

Both of the unlisted upper Columbia (Lake Wenatchee and Lake Osoyoos) spawning populations and listed Snake River sockeye salmon use the Columbia River as a migration corridor. The temperatures they experienced at Bonneville and McNary dams during their June – July, 2015, upstream migration period were up to 4°C warmer than the recent 10-year average (Figure 2). [5] Upper Columbia River sockeye headed for Lake Osoyoos migrate through the Okanogan River, which reached a temperature of 28°C at the Malott, Washington gage in early July (Figure 3a). Snake River sockeye experienced temperatures up to 25°C at the White Bird gage on the Salmon

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[5] Temperatures can be converted to degrees Fahrenheit using the following formula:

$$Degrees\ Fahrenheit = \left(Degrees\ Celsius * \frac{9}{5}\right) + 32.$$

River during the same period (Figure 3b). We describe the biological significance of these elevated temperatures in Section 2.3, below.

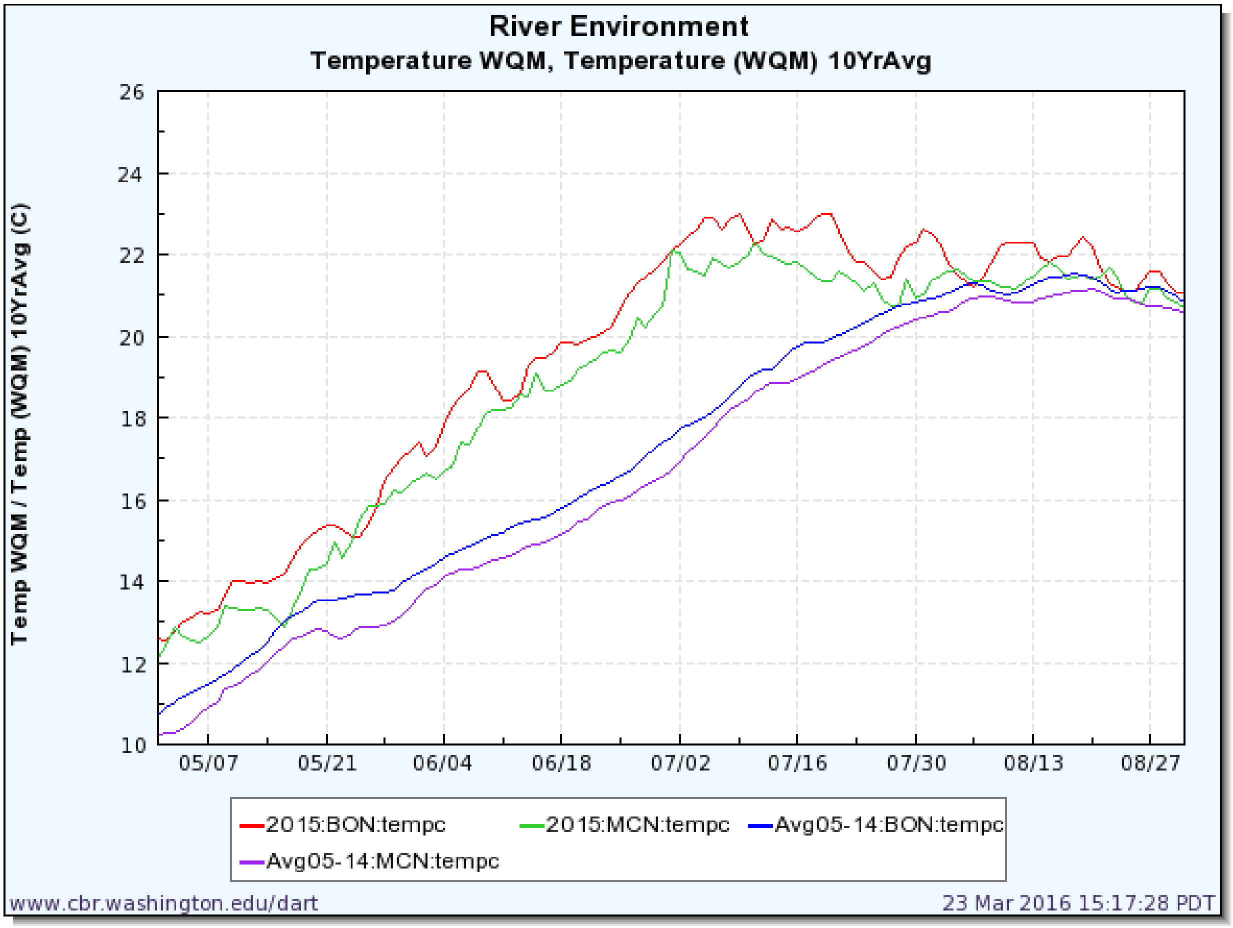
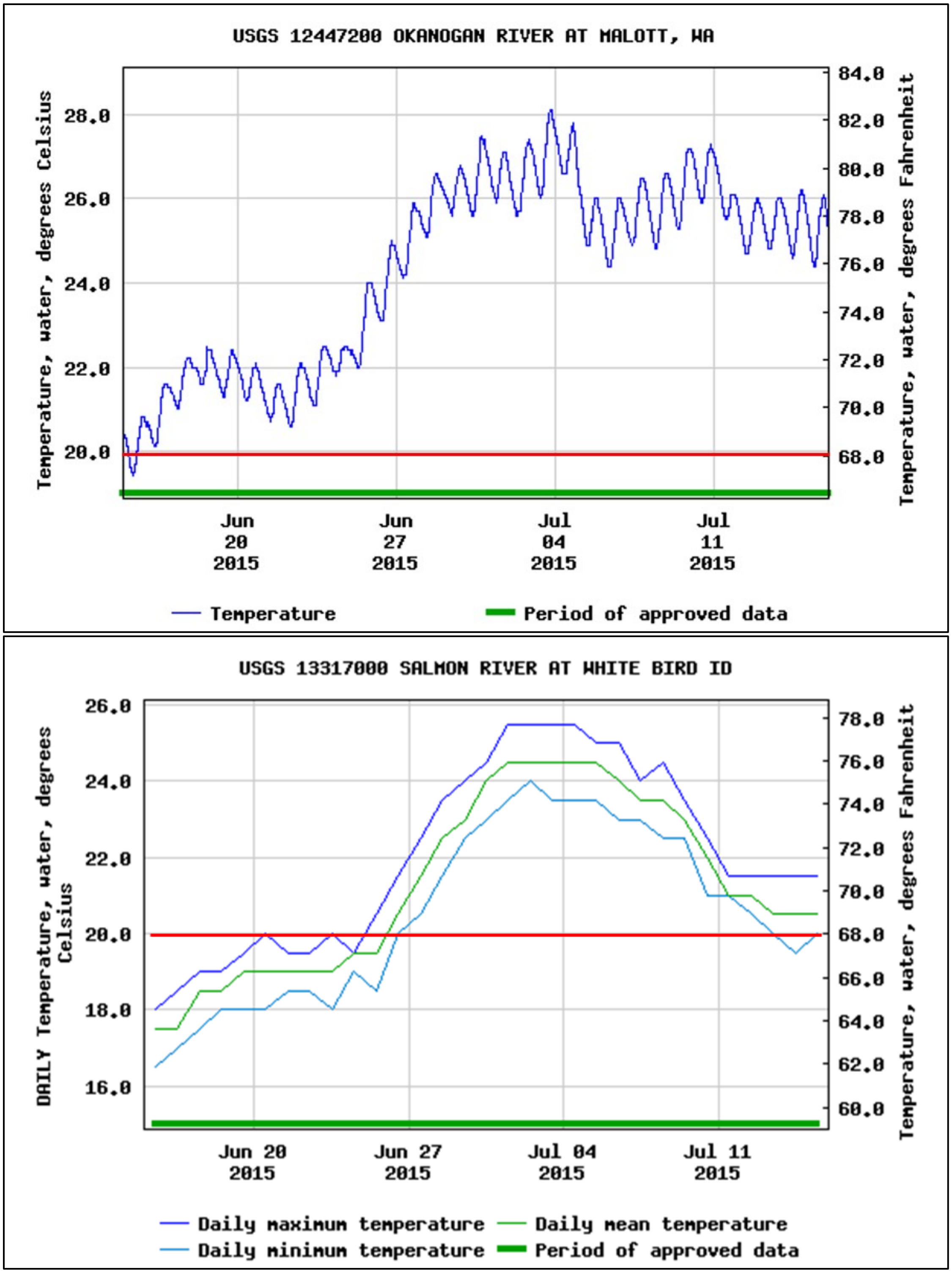


Figure 2. Columbia River temperature at Bonneville Dam and McNary Dam (forebays) in 2015 relative to the prior 10-year average.



Figures 3a and 3b. Temperatures in the Okanogan (a) and Salmon (b) rivers during 2015. “Approved data” were subjected to quality assurance review before publication. Source: USGS

2.2 Mainstem Reservoir Environment and Thermal Stratification

The following sections describe the general effects of reservoirs and flow augmentation in the lower Snake and Columbia rivers on temperatures including thermal stratification and the potential to create temperature gradients in adult fish ladders. Specific operations for adult sockeye salmon migration during 2015 are discussed in Section 4.

2.2.1 Thermal Effects of Upstream Storage Reservoirs

Little information is available on historical temperatures in the lower Snake River basin. Peery and Bjornn (2002) provided temperature information near the mouth of the Snake River from 1955 to 1958, prior to the construction of the lower Snake River dams or the Hells Canyon Complex, showing that temperatures in the free-flowing lower Snake River often exceeded 20°C in July and August during this period and occasionally exceeded 25°C (Figure 4).

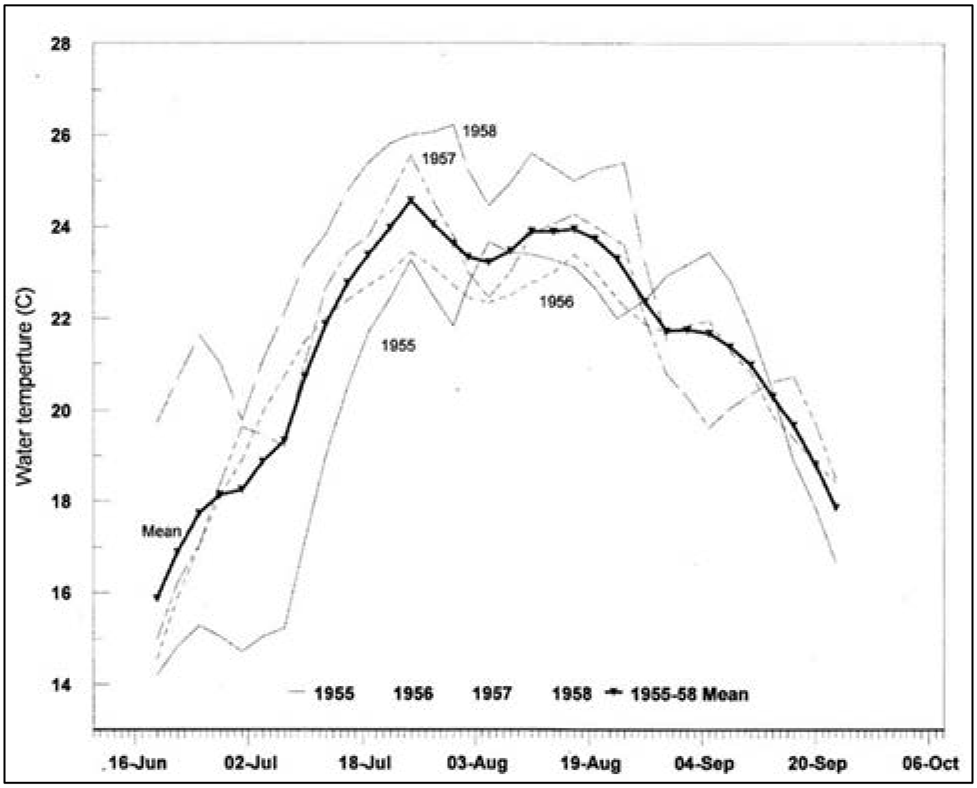


Figure 4. Water temperatures recorded at the mouth of the Snake River (Sacajawea, WA) during 1955-58, and mean water temperatures for the four years. Source: Eldridge (1963) and Peery and Bjorn 2002.

Idaho Power Company began to operate the Hells Canyon project in 1959 and Reclamation began to operate the Grand Coulee project in the upper Columbia in 1942. One might expect that the greater surface area and low velocity of water in the large storage reservoirs would result in more solar exposure and heat gain, and thus higher downstream water temperatures than in a river without dams. However, Moore (1969, cited in EPA 2002), found that both projects released water that was cooler than inflow during spring through mid-August (Figures 5a and 5b) and warmer than inflow during fall and winter. This is possible because these reservoirs become thermally stratified and the cooler water released from depth buffers peak summer temperatures in downstream river segments. Thus, water management at the large storage reservoirs in the Hells Canyon reach and upper Columbia basin likely did not contribute substantially to the warm water conditions that adult sockeye salmon experienced during the June-July, 2015, migration.[6]

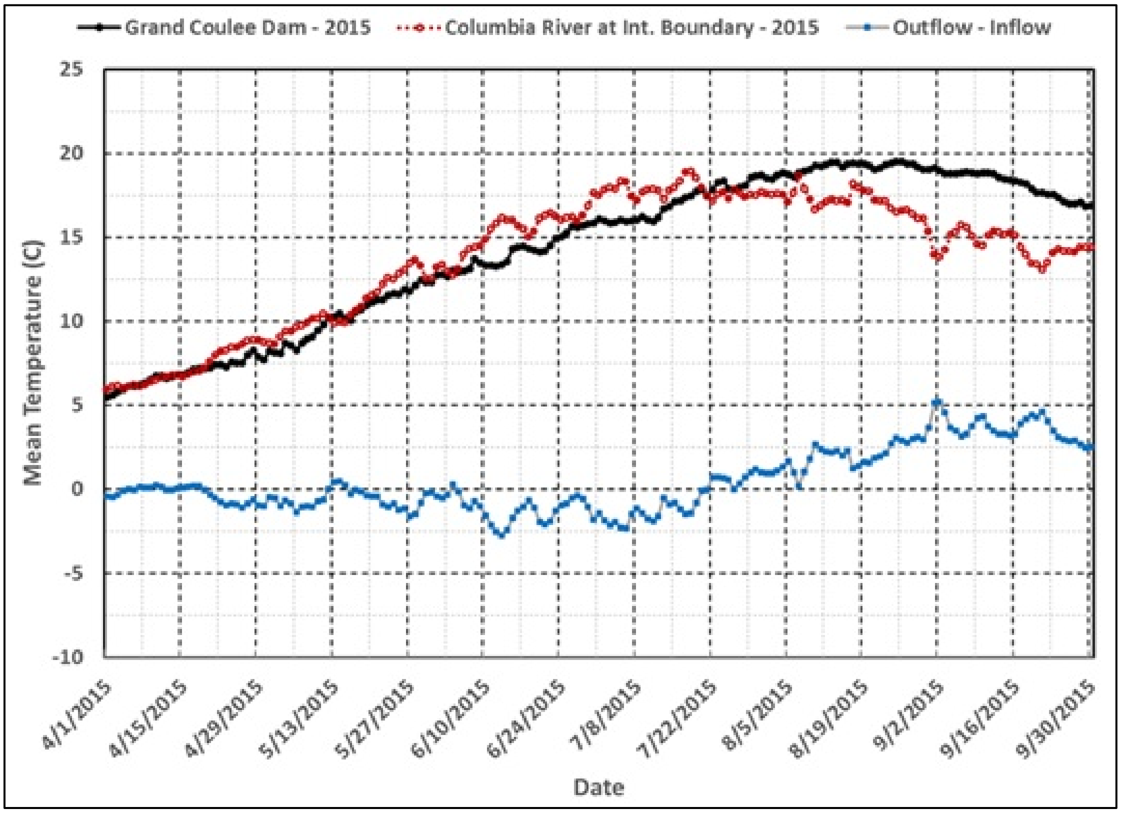


Figure 5a. Outflow temperatures at Grand Coulee Dam compared to upstream Columbia River temperatures at the international boundary. Blue line indicates the difference (inflow – outflow) in temperature. Source: USBR Hydromet Data.

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[6] Moore (1969) had similar findings for Grand Coulee Dam in the upper Columbia basin where the large mass of cold water at depth in Lake Roosevelt dampens the effect of elevated inflow temperatures. Outflow during late spring and early summer 2015, when most adult sockeye salmon from the Okanogan and Lake Wenatchee populations were in the mainstem, was cooler than inflow. This effect dissipated in the mid-Columbia reach, which is affected by the privately-owned hydropower projects.

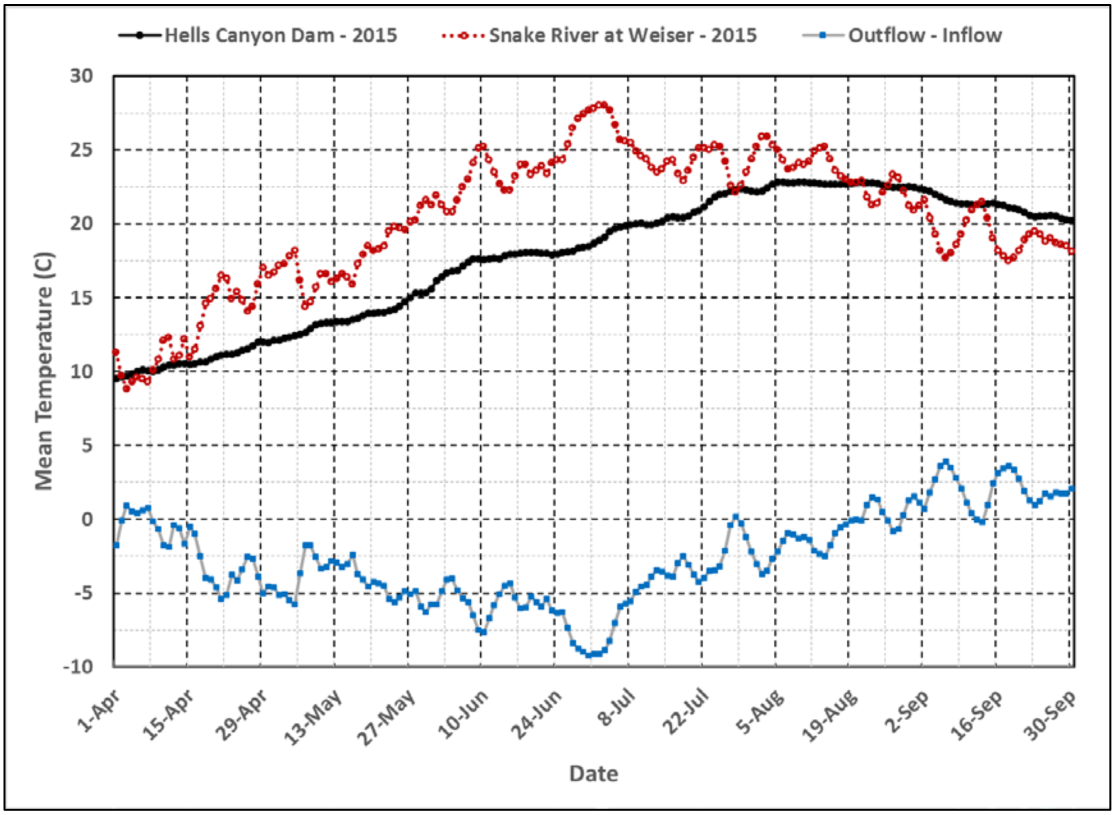

Figure 5b. Outflow temperatures at Hells Canyon Dam compared to upstream Snake River temperatures near Weiser, Idaho. Blue line indicates the difference (inflow – outflow) in temperatures. Sources: Idaho Power Company and USGS data.

2.2.2 Reservoir Environment in the Lower Snake River

Increased water residence times and solar heating, along with inflow from interior basin tributary systems, contribute to warming in the lower Snake River reservoirs. In an effort to moderate this effect, the USACE releases cold water from the hypolimnion of Dworshak Reservoir on the North Fork Clearwater River, Idaho. Temperatures from the Clearwater River are typically 10°C or more cooler than those in the lower Snake during July and August and the colder and denser water from the Clearwater plunges beneath the flow in the lower Snake (Cook et al. 2006). The layering phenomenon is reinforced by the prevailing upstream summer winds, which further slowing the movement of the surface water mass (Caudill et al. 2013).[7] Among the four lower Snake projects, the strongest stratification is observed in the forebay of Lower Granite Dam during summer, where surface waters are often several degrees warmer than in the tailrace. The warmer surface layer feeds into the top of the fish ladder at Lower Granite Dam, 48 km downstream. In comparison, the water in the tailrace is a combination of warm water from the ladder and surface passage weir plus cold water discharged from the turbines (from deeper in the reservoir) and intermediate temperature water discharged from the regular spill gates (from an

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[7] According to Cook et al. (2006), wind forcing can hold water in the upper layer in place or even move it slightly upstream.

intermediate depth).[8] Turbulence in the tailrace mixes these sources together and the pattern repeats at the dams farther downstream although with smaller thermal gradients between each forebay and tailrace as the effect of colder water from Dworshak Reservoir diminishes.

The difference in temperature between the warmer water at the top of the ladder (fishway exit) and the cooler water at the bottom (entrance) can block the movement of migrating fish. This was especially true in 2015 when water flowing into the reservoir from the Snake River was much warmer than that released from Dworshak Dam. Water from the tailrace of Lower Granite Dam became thermally stratified once again as it sank to depth in Little Goose Reservoir (although to a lesser degree than in Lower Granite pool), creating the same type of ladder exit and entrance temperature differential at this project.

2.2.3 Water Temperature Control Operations at the Lower Snake River Projects

As described above, the release of cold water from behind Dworshak provides river managers with the ability to influence temperature in the lower Snake River.[9] Dworshak is operated to reach its full elevation (1,600 feet above Mean Sea Level) by the end of June and then drafted to its lower limit (1,520 feet) by mid-September, an operation that releases a total volume of 1.2 million acre-feet. The USACE uses a water quality and hydrodynamic model (CEQUALW2) to assess the volume that should be released each week so that temperatures do not exceed 20°C in the Lower Granite tailrace. Inputs to the model include the anticipated volumes of water flowing into Lower Granite Reservoir from the Snake and Clearwater rivers, water temperatures in the Snake and Clearwater rivers, water temperature and discharge volume from Dworshak Reservoir, wind, forecasted air temperature, and an index of solar radiation. The regional Technical Management Team reviews these results on a weekly basis throughout the summer months to ensure that the 1.2 million acre-feet of water is released from Dworshak Reservoir as efficiently as possible to meet the temperature objective. Dworshak operations and outflow temperatures in 2015 are summarized in Figure 6.

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[8] When the removable spillway weir (RSW) is in operation, it releases warmer water taken from the surface of the reservoir.

[9] The ability to moderate mainstem temperatures dissipates below Little Goose Dam (USACE 2013).

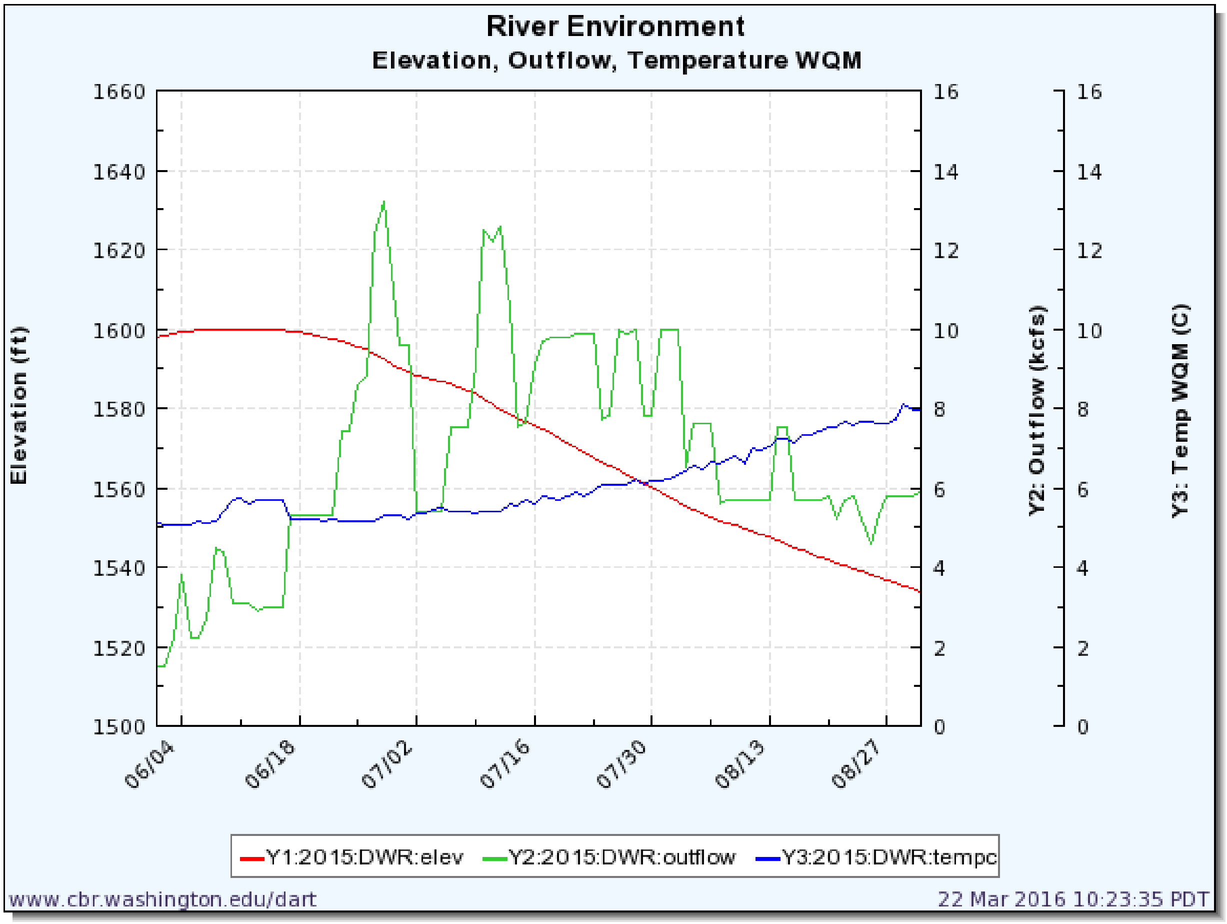

Figure 6. Dworshak Dam reservoir elevations, outflows, and water temperature releases, June 1 to August 31, 2015.

In addition, the USACE (2002) examined the potential to reduce heat gain and thus mainstem temperatures by breaching mainstem dams for its Lower Snake River Juvenile Salmon Migration Feasibility Report and Environmental Impact Statement. The study used EPA's RBM-10 model, which had been developed to support a total maximum daily load (TMDL) for temperature as required under Section 303(d) of the Clean Water Act (Yearsley 1999, as cited in USACE 2002). The EPA provided their temperature modeling expertise and resources to assist the USACE in evaluating the effects of the dams and impoundments on lower Snake River temperature. The USACE found that the RBM-10 model was an effective tool for modeling temperature effects and relied primarily on the RBM-10 modeling results in the temperature analysis for its Lower Snake River Juvenile Salmon Migration Feasibility Report/Environmental Impact Statement. When the RBM-10 simulations assumed Dworshak flow augmentation in average flow years, average temperatures at Snake RM 107 exceeded 20°C for 64 days with dams in place compared to 59 days for the near-natural condition (USACE 2002). Historical data showed that the 20°C benchmark has been exceeded less frequently in years with flow augmentation from Dworshak, confirming these modeling results.

However, RBM 10 is a one-dimensional model that assumes the reservoirs are well mixed, not stratified or layered. Thus, although the RBM 10 results were useful for examining the likely effects of dam breaching on average temperatures in the lower Snake River, they do not address the current problem of the effects of the stratified reservoir on ladder temperatures and adult migration. The stratified reservoirs in the lower Snake River created a problem in 2015, when the surface water feeding the adult ladder exit was much warmer than that at the entrance, but the existence of colder water at depth that can be pumped into the top of the ladder provided an opportunity to reduce the thermal gradient (Caudill et al. 2013; see also Section 4).

2.2.4 Reservoir Environment in the Lower Columbia River

As discussed earlier, the federal operators took many actions (especially cool water releases from upstream storage reservoirs and additional summer flows from U.S. and Canadian storage projects) to reduce temperatures in the mainstem upper Columbia and lower Snake rivers in an otherwise warm, low runoff year. However, that cooling effect did not prevent the lower Columbia River from becoming substantially warmer in 2015 compared to the previous 10 years (see Figure 2, page 13). Between mid-June and mid-July when most sockeye salmon were passing Bonneville Dam, temperatures were often 4 or 5°C warmer than average, exceeding 20°C five or more weeks earlier than under average conditions. The heat gain within the McNary to Bonneville reach was about 1°C, similar to the recent 10-year average.

The ability to influence temperatures even in the upper reaches of the mainstem Columbia River using water released from Grand Coulee Dam is limited. Grand Coulee Dam has three powerhouses; the older left and right powerhouses draw water from about 60 m in Lake Roosevelt and a newer power plant that draws water from around 27 m. Selective water withdrawals for temperature control are limited to the amount of water that can be passed through the older powerhouses (90,000 cfs), which is below the amount needed to meet the fisheries flow objectives. As a result, the newer powerhouse must also be operated, reducing the efficiency of this operation for temperature management. Furthermore, the effect attenuates with distance downstream and does not moderate temperatures in the lower Columbia reach.

2.3 Effects of Elevated Temperatures on the Survival of Adult Salmon

Elevated temperatures in the mainstem migration corridor have the potential to reduce the survival and productivity of adult salmon, including sockeye. These effects occur via several mechanisms: direct lethality to adults and smolts under high temperature conditions; delay in migration and spawning; depletion of energy stores through heightened respiration; deformation of eggs and decreased viability of gametes; and increased incidence of disease (McCullough et al. 2001). Each of these effects is briefly discussed in the following sections.

1. Direct Lethality
Survival rates based on the amount of time exposed and temperature of exposure in laboratory studies are described in the scientific literature. The standard index for effects reporting is the “upper incipient lethal temperature,” which represents the exposure temperature (given previous acclimation at a constant temperature) that 50% of the experimental fish can tolerate for 7 days

(Elliott 1981, cited in McCullough et al. 2001). Upper incipient lethal temperatures for adult salmonids range from 21-22°C for fish acclimated at 19°C before testing.

2. Delay in Migration and Spawning

Adult sockeye can continue to migrate when water temperatures exceed 20°C, but a sustained exposure to higher temperatures will slow migration (McCullough et al. 2001). Swimming speed and migration rates can be impaired if oxygen concentrations are also low; fish may refuse to migrate, migrate back downstream, or seek shelter in tributaries or other cold-water refuges if these are available (Keefer et al. 2008). Under these conditions, net upstream movement may be reduced or delayed.

During periods of high water temperatures, flow from the forebay of a mainstem dam into the fish ladder can expose migrating adults to high temperatures and thermal stress. In addition, ladders fed by warm surface waters, but with the fish entrance in a cooler tailrace will have a thermal gradient or differential. At temperature differentials of greater than 1°C, Chinook and steelhead have a higher likelihood of entering the ladder multiple times followed by exits back into the tailrace. This movement in the ladder can significantly delay migration, increase thermal exposure, consume energy, and decrease migration success (Keefer and Caudill 2015).

3. Depletion of Energy Stores through Heightened Respiration

An organism expends more energy on metabolic processes such as respiration near the upper end of its thermal tolerance, reducing its capacity to carry out activities such as swimming. Prolonged exposure to elevated temperatures during migration has been related to prespawning mortality. Increased metabolic costs can deplete energy reserves before adults reach their spawning grounds, reducing the size and number of viable eggs even in fish that survive the journey (Sauter et al. 2001). Farrell et al. (2009) describe a potential “death spiral” due to cardiac insufficiency when individuals are exposed to water temperatures above optimal (15-20°C) for sustained periods (Farrell et al. 2008; Eliason et al. 2013).

4. Deformation of Eggs and Decreased Viability of Gametes

Hatchery managers have long known that highest survival of Chinook adults occurs when fish are held at water temperatures less than 14°C and that when adults hold in higher temperature water, egg survival declines (McCullough et al. 2001). Laboratory and field studies show that when adult fish are exposed to constant or average temperatures above 13-15.6°C during the final part of their upstream migration or during holding prior to spawning, the size, number, and/or fertility of eggs are reduced.

5. Increased Incidence of Disease

The bacterial infection *columnaris* has been observed throughout the mainstem Columbia River and in numerous tributaries: the Okanogan, Wenatchee, John Day, Umatilla, Yakima, Snake, and Similkameen rivers. It is carried by all species of Pacific salmon and also by carp, sucker, chub, bass, northern pikeminnow, chiselmouth, and catfish (Colgrove and Wood 1966, as cited in

Materna 2001). Ordal and Pacha (1963; as cited in Materna 2001) considered temperature-induced *columnaris* a major factor responsible for declines of Columbia River Chinook salmon. Other diseases associated with warm water also can produce significant mortalities. *Aeromonas salmonicida* and *A. hydrophila* are common bacterial pathogens linked to high water temperatures (Groberg et al. 1978). These organisms are the infective agent for *furunculosis*, a pathogen affecting all Pacific salmon. Resistance to this disease varies with fish strain, but expression of the disease is also related to water temperature. There also are variations in resistance to *Ceratomyxa shasta*, with the effects of the parasite enhanced by warm water.

6. Summary: Effects of Elevated Temperatures

There are a number of pathways by which warm temperatures can influence the survival and productivity of upstream migrating salmon including Snake River sockeye. In addition to the specific mechanisms discussed above, several of these can interact to reduce survival to the spawning grounds (Keefer et al. 2008). For example, fish that encountered a thermal gradient in the ladders at the lower Snake River dams could already have been weakened by disease. Or the increased metabolic demand for respiration in warm water could have made them less likely to press on past a thermal gradient. Although the actual mechanism of loss is unknown for most of the fish that did not return to spawning area in the Sawtooth Valley, Lake Wenatchee or Okanogan River, there is sufficient evidence that the problem was exacerbated, if not caused, by elevated mainstem temperatures.

3. Adult Sockeye Salmon Migration Timing and Survival in 2015

The migration timing of adult Columbia Basin sockeye salmon at Bonneville Dam in 2015 was consistent with the pattern seen during the previous 10-year period. Fish began to arrive at Bonneville in early June and passage peaked near the last week of June, ending in July (Figure 7). However, unlike the previous years, water temperatures at Bonneville Dam were as much as 4°C warmer during June and July 2015 (see Figure 2, page 13). These high temperatures appear to have taken a toll on adult sockeye survival[10] as described below.

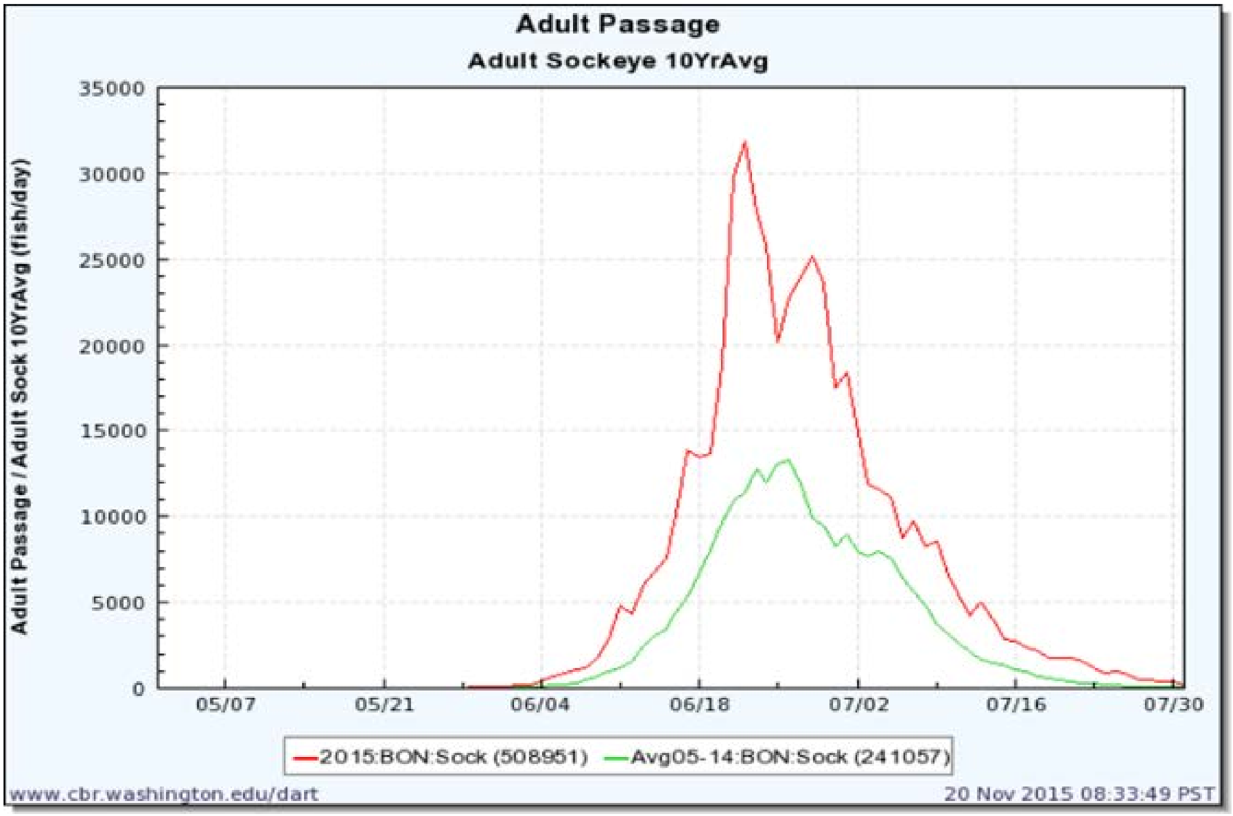

Figure 7. Adult sockeye salmon ladder counts at Bonneville Dam in 2015 compared to the 2005-2014 average.

3.1 Survival Rates in the Bonneville to McNary Reach

Weekly survival estimates for Upper Columbia River (UCR) stocks of sockeye and Snake River sockeye that were either migrated inriver or were transported as juveniles are shown in Figure 8.

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[10] In this report, we estimate survival using data obtained from PIT tags and dam counts. PIT tags provide the most accurate measure of fish passage and survival through the system, allowing us to calculate fallback and reascension rates, to partition mortality between specific river reaches, and to estimate rates of straying into non-native spawning areas. Because PIT tags allow fish of known geographic origin to be tracked through the hydrosystem, we can estimate survival for specific populations. A total of 679 PIT-tagged Snake River sockeye salmon were detected passing Bonneville Dam in 2015, compared to a much smaller number (425) of sockeye from the Upper Columbia population (i.e., because far fewer were PIT-tagged). Dam counts are also an important indicator of passage success in a mainstem reach, but lack the detail provided by PIT-tagged fish and by themselves cannot account for adult fallback and reascension or straying rates.

Survival of Snake River Sockeye through the Bonneville to McNary reach was extremely low in 2015. This coincided with a period of unseasonably warm water temperatures in the lower Columbia River. Whereas temperatures are usually about 14°C in early June and increase to 20°C by late July, they reached nearly 18°C in early June and increased to almost 23°C by early July, 2015 (see Figure 2, page 13). Fish that passed Bonneville Dam early in the season when water temperatures were still less than 18°C had the highest survival, approaching 90% for upper Columbia sockeye and 70% for Snake River fish. Survival rates of adult sockeye salmon passing Bonneville declined substantially once water temperatures exceeded 20°C.

Based on PIT-tag detections,[11] the relatively low upstream survival of Snake River sockeye salmon that were transported as juveniles appears to have contributed to the low overall return rate of adults from this ESU (Figure 8). Transported fish have higher straying, wandering, and fallback rates as adults than those that are not transported (Keefer and Caudill 2012). Fish that exhibited any of these behaviors moved upstream more slowly and therefore were more likely to experience mainstem temperatures above 20°C during 2015.

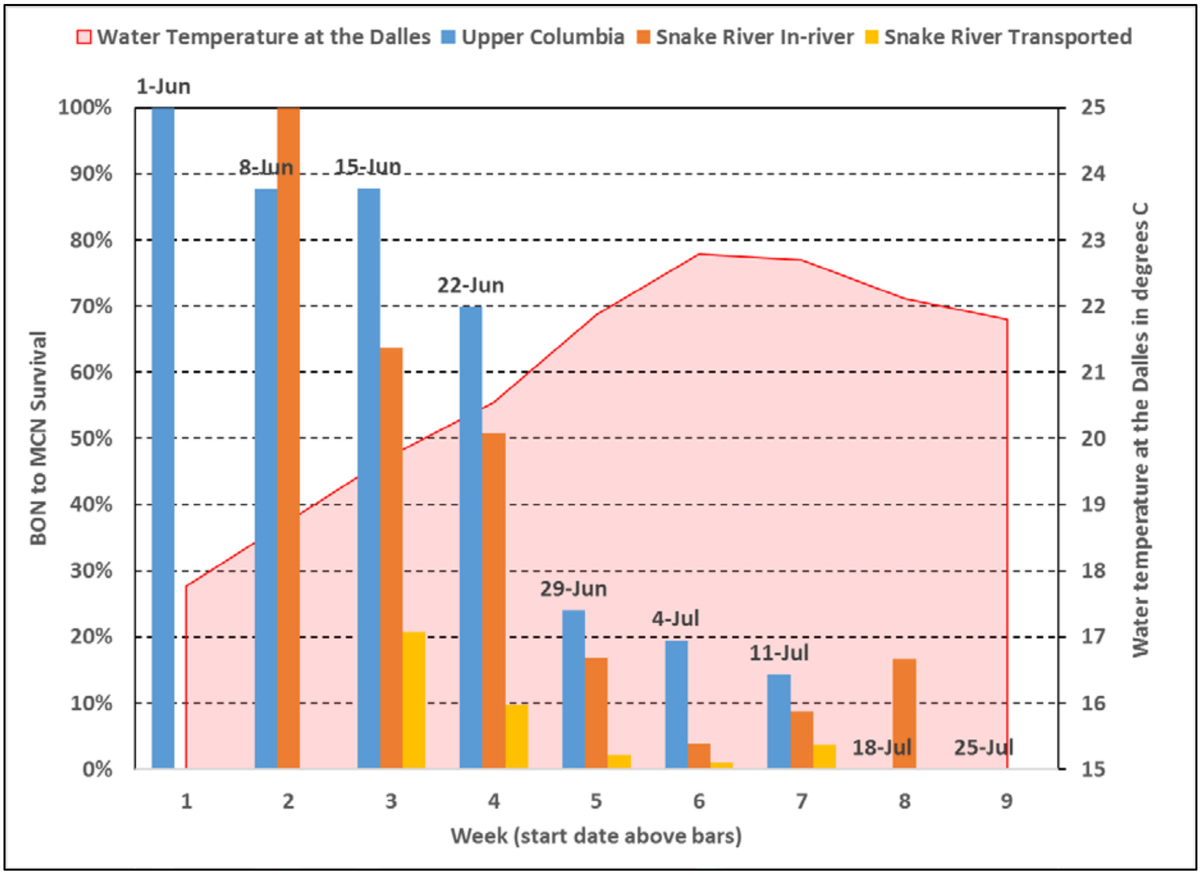

Figure 8. Weekly adult sockeye survival estimates from Bonneville to McNary dam in 2015 for Upper Columbia River sockeye salmon (blue bars), Snake River sockeye salmon that migrated inriver as juveniles (orange bars), and Snake River sockeye that were transported as juveniles (yellow-orange bars) with water temperatures (red line) at The Dalles Dam. Source: PITAGIS data and Columbia River DART.

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[11] Idaho Fish and Game estimates that 16.7% of adult Snake River Sockeye returning in 2015 were PIT tagged.

One example of the effects of the delayed sockeye run was captured in a video clip made in the vicinity of Drano Lake, near the confluence of the Little White Salmon and Columbia rivers, in July, 2015 (Figure 9). Adult salmon are attracted to this area because it is often cooler than the mainstem Columbia River, but symptoms of disease were clearly visible on many of the fish observed in this video.

Figure 9. Video capture of an adult sockeye near Drano Lake during mid-July, 2015. The white areas on the surface of the fish appear to be a fungus, possibly *Saprolegnia* sp., which is known to affect fish subjected to thermal stress (Roberts 2012).

Annual estimates of survival (2010-2015) from Bonneville to McNary dams for upper Columbia River (UCR) stocks and Snake River sockeye that migrated inriver as juveniles or were transported are shown in Figure 10. Beginning in 2012, survival rates of UCR sockeye salmon have been substantially higher than estimates for Snake River sockeye salmon. During 2013-2015, the survival rates for adults that migrated inriver as juveniles were significantly higher than for adults that had been transported. Tailrace temperatures at The Dalles Dam during June and July were highest in 2015, followed by 2013-14 (Figure 11).

The survival differences between UCR and Snake River sockeye salmon are consistent with their respective passage timing at Bonneville Dam. In general, based on PIT tag detections of known origin fish, adult Snake River sockeye begin passing Bonneville about a week later than the UCR stocks. Thus, Snake River fish are exposed to higher (cumulative) temperatures than UCR sockeye stocks, which was likely responsible, either directly or indirectly (or both), for their lower survival rates in 2013-15. There was no difference in migration timing at Bonneville Dam between adult sockeye that had been transported or migrated inriver as juveniles. However, it appears that Snake River sockeye salmon that had been transported as juveniles had an impaired homing ability, which delayed their upstream progress and increased their exposure to elevated mainstem temperatures.

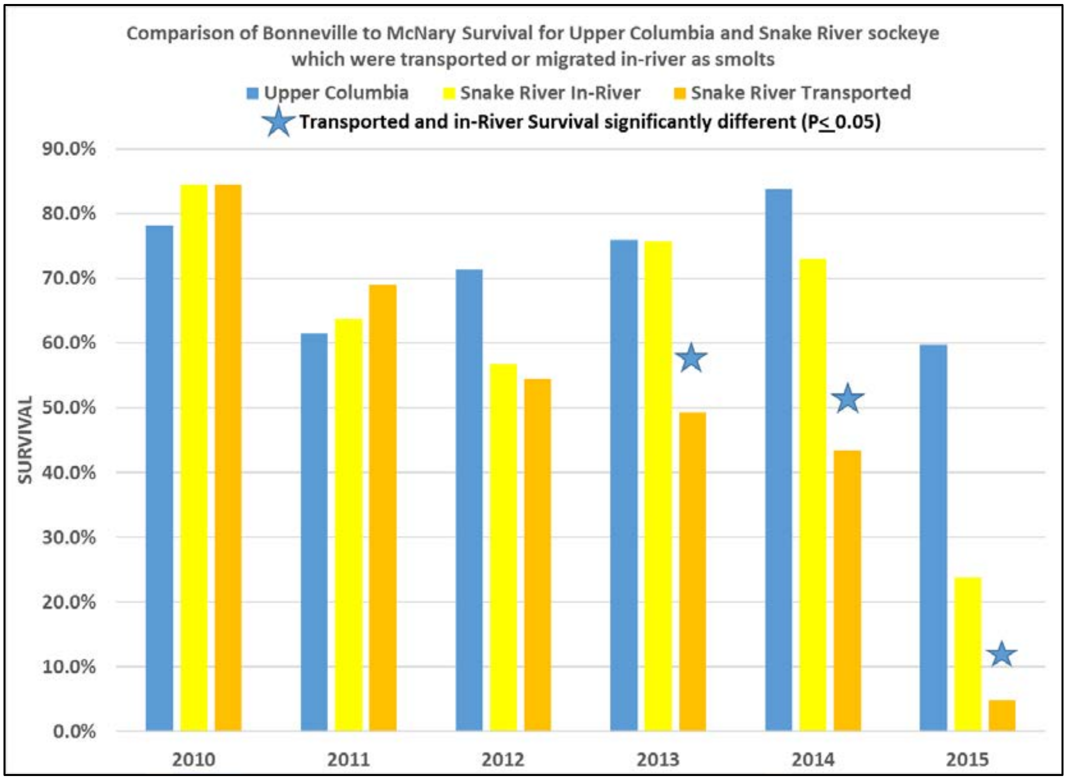

Figure 10. Annual adult survival estimates from Bonneville to McNary dams for upper Columbia River sockeye stocks (blue bars) and Snake River sockeye salmon that migrated inriver (yellow bars) or were transported as juveniles (orange bars). Source: PTAGIS data

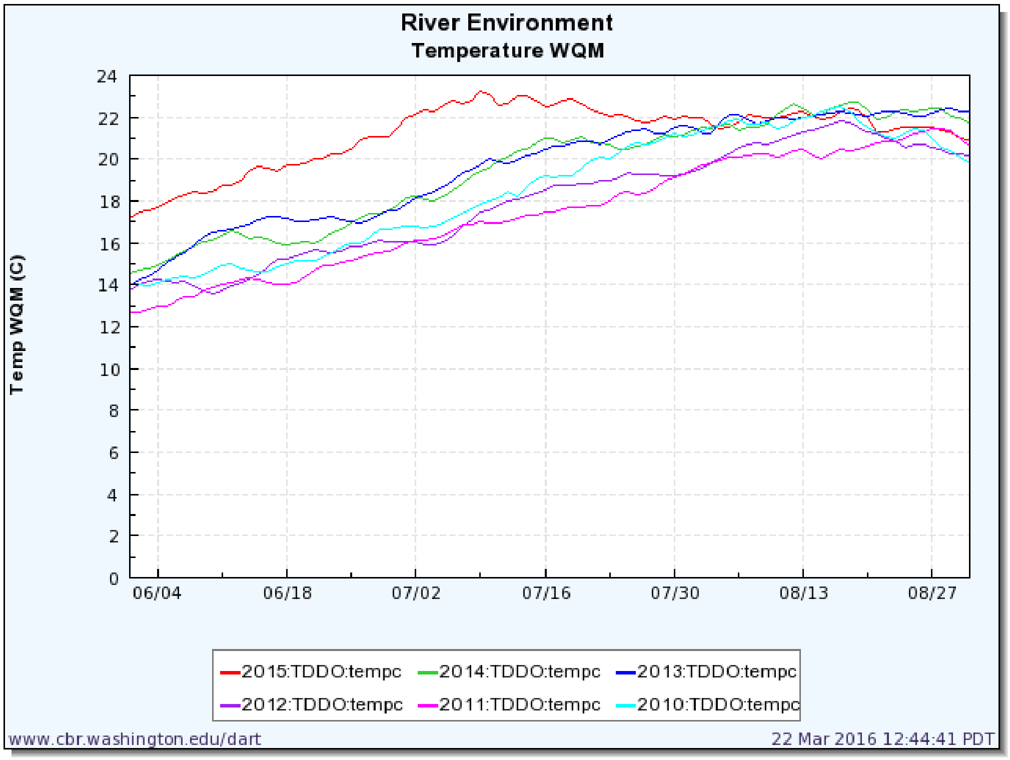

Figure 11. Tailrace temperatures at The Dalles Dam from June 1 to August 31 (2010-2015).

3.2 Survival Rates in the McNary to Rock Island / Wells Reach and the Okanogan River

Although adult survival from Bonneville to McNary Dam was higher for upper Columbia than Snake River sockeye salmon during 2015, survival to the spawning grounds was poor for both groups. About 47% of the adults bound for the upper Columbia basin survived passage from Bonneville to Wells Dam, but only 6% passed Zosel Dam on the Okanagan River and about 2% ultimately survived to Lake Osoyoos, just upstream (Fryer 2016). A total of 37,624 sockeye passed upstream through the underwater video at Zosel in 2015 (Schaller 2016). These are total observed counts (upstream minus downstream) and have not been adjusted for fallback. An unknown percent of those fish successfully spawned. This was far below survival observed during the past 5 years, during which survival rates ranged from about 25-50% from Bonneville Dam to spawning (Fryer 2016).

3.3 Survival Rates in the McNary to Lower Granite Reach and the Mainstem Salmon River

Only 14% of the PIT-tagged population that passed Bonneville Dam in 2015 were detected at McNary, 9% at Ice Harbor, and 4% at Lower Granite. One percent of the Snake River sockeye salmon detected at Bonneville reached Idaho's Sawtooth Valley, and another 0.5% were collected at Lower Granite Dam and transported directly to Eagle Fish Hatchery (Figure 12).[12] Of the 8% detected at Ice Harbor Dam, less than about 44% were detected at Lower Granite Dam, compared to an average of 90.6% between Ice Harbor and Lower Granite Dam during the preceding five years (range = 70.6% to 97.4% from 2010 to 2014). Though ameliorated by releases of stored water from Dworshak Dam and reduced temperatures (relative to inflow) from the Hells Canyon Complex, adult sockeye salmon were still exposed to unusually high June and July water temperatures in the lower Snake (Figure 13) in addition to their exposure in the lower Columbia River during 2015. As described in Section II.A (Flow and Temperature Conditions), temperatures in the Salmon River reached 25°C during early July. Of the 27 detected PIT-tagged adult sockeye at Lower Granite Dam, three were collected and transported directly to Eagle Fish Hatchery. Of the remaining 24 migrating in-river, less than one third (seven) were detected in the Sawtooth Valley.

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[12] Of the 98 adult Snake River Sockeye salmon that were detected at McNary Dam, nine strayed up the Columbia River (were detected at or above Priest Rapids Dam). Six of these fish were transported as juveniles, three migrated inriver as juveniles (one of which fell back at Ice Harbor Dam before migrating up the Columbia River. All nine of these fish that strayed survived to pass Rock Island Dam, seven were detected at Wells Dam, but none of these fish were detected at Zosel Dam in the Okanogan River.

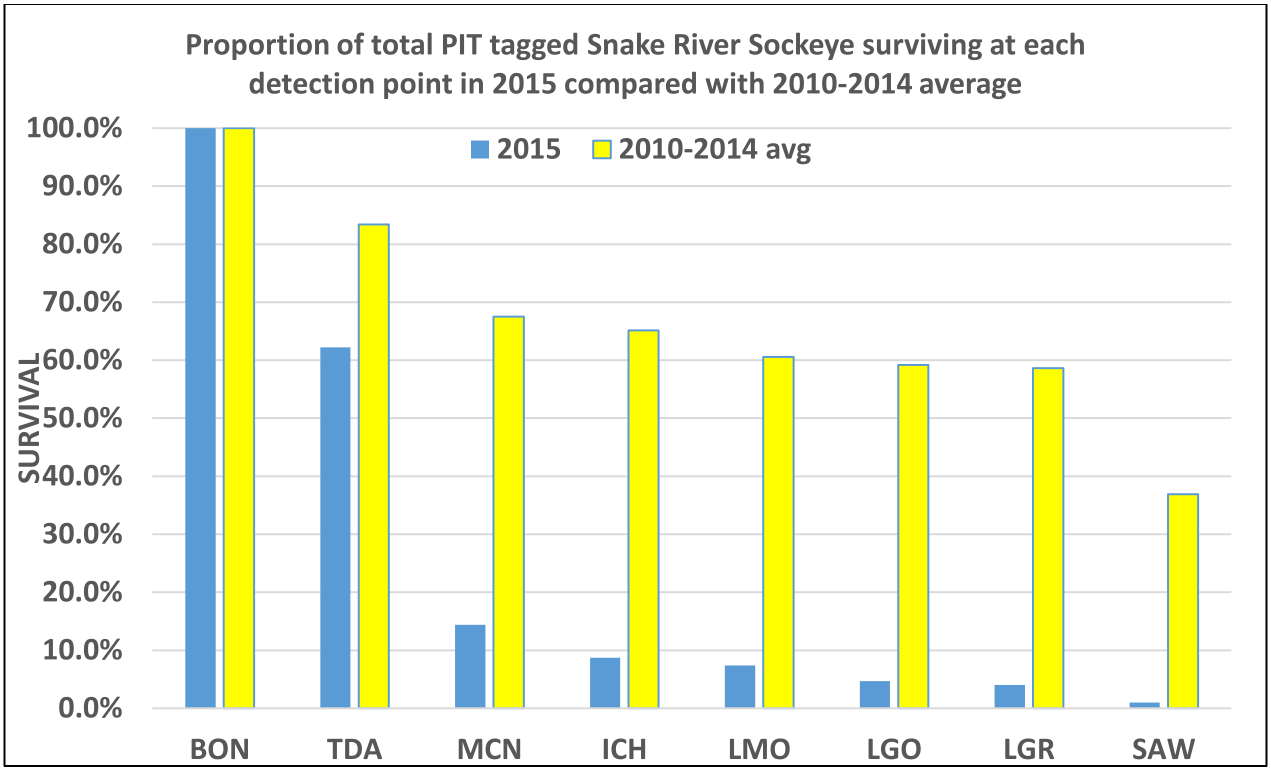

Figure 12. Proportion of total PIT-tagged Snake River sockeye salmon detected at Bonneville Dam that survived to each subsequent detection point (The Dalles, McNary, Ice Harbor, Lower Monumental, Little Goose, and Lower Granite dams and the Sawtooth Hatchery weir) in 2015 compared to average for 2010-2014. Source: PTAGIS data

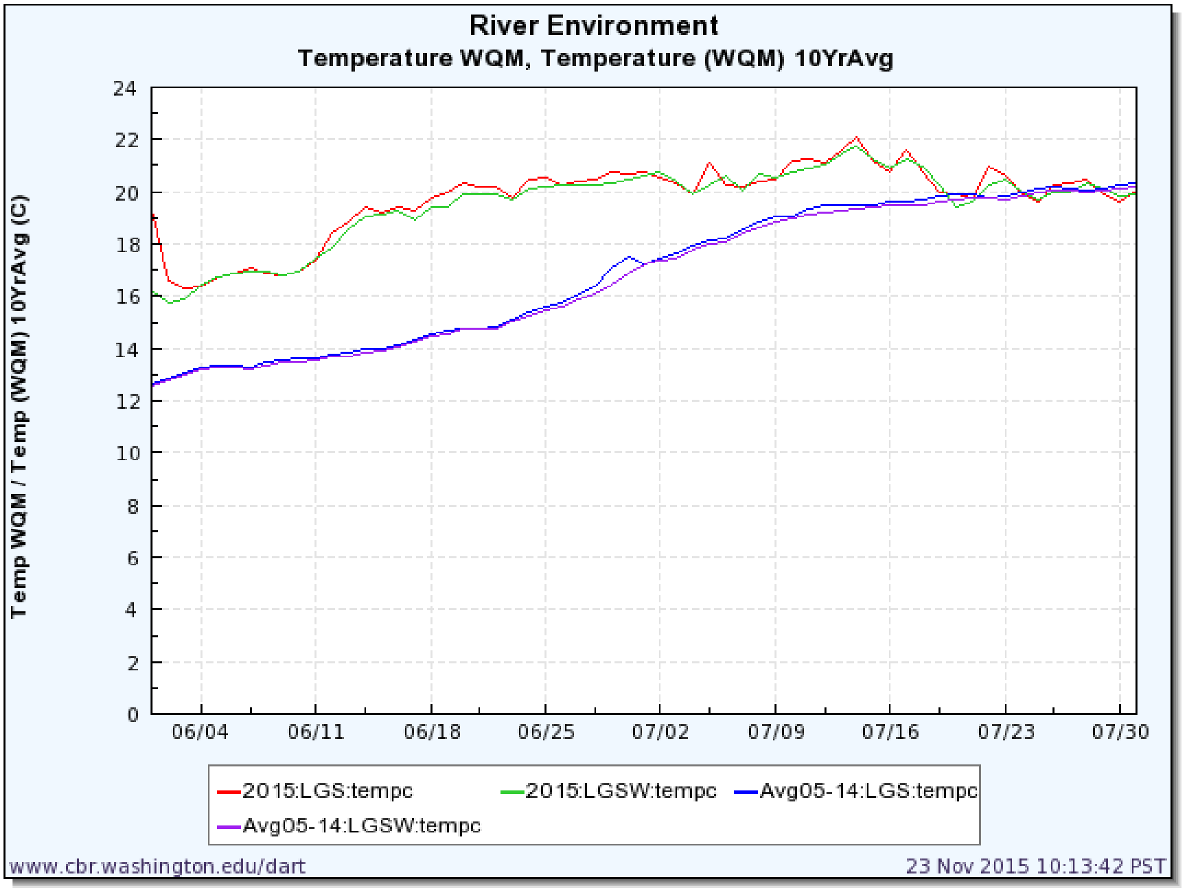

Figure 13. Water temperatures measured in the forebay (red line) and tailrace (green line) at Little Goose Dam during June and July, 2015, and 10-year average temperatures at these locations (blue and purple lines), respectively.

3.4 Summary of Mainstem and Tributary Survival and Detection Histories

Survival rates of Snake River and upper Columbia River sockeye salmon in key reaches of the adult migration corridor are shown in Tables 4 and 5, respectively.

Table 4. Estimated annual survival rates of adult Snake River sockeye salmon by adult migration year and juvenile migration history from Bonneville Dam to the Sawtooth Valley (yellow shaded cells) indicate statistically significant differences, P<0.05. Source: PTAGIS data

Adult Migration Year	Juvenile Migration History	# at BON	Survival Estimates (%)			
			BON to MCN	MCN to LGR	BON to LGR*	LGR to Sawtooth Valley
2010	Inriver	32	84	96	**81**	77
	Transported	8	88	74	**63**	80
2011	Inriver	307	64	97	**62**	75
	Transported	209	69	95	**66**	77
2012	Inriver	111	57	94	**53**	64
	Transported	11	55	67	**36**	50
2013	Inriver	136	76	76	**57**	33
	Transported	69	49	38	**19**	31
2014	Inriver	216	71	93	**66**	56
	Transported	129	43	95	**41**	55
2015	Inriver	320	26	33	**8**	29^
	Transported	357	5	0	**0**	0

* The survival estimate for the BON to LGR reach is the product of survival from (BON to MCN) x (MCN to LGR). For example, (0.84) x (0.96) = 0.81 or 81%.

^ There were 27 detections of PIT tagged adults at Lower Granite Dam in 2015 (transported and inriver juvenile migrants combined). Three of the 27 were transported to the hatchery for spawning and 24 migrated instream. Of these 24, only seven (i.e., 29%) were detected in the Sawtooth Valley.

Table 5. Estimated annual survival rates of adult upper Columbia River sockeye salmon by migration year from Bonneville Dam to Rock Island Dam (both UCR ESUs) and Rock Island to Zosel Dam (Okanogan River sockeye salmon only). Source: CRITFC.

Adult Migration Year	Juvenile Migration History	# at BON	Survival Estimates (%)			
			BON to MCN	MCN to RIS	RIS to WEL (Okanogan River Only)	WEL to Zosel (Okanogan River Only)^
2010	Inriver	957	82	95	88	77
2011	Inriver	651	69	86	78	75
2012	Inriver	572	74	91	63	39
2013	Inriver	157	77	88	85	70
2014	Inriver	323	88	88	80	69
2015*	Inriver	425	60	78	100	12

* Estimated escapement of Wenatchee River and Okanogan River sockeye in 2015 was 10-15% and 3-4.5%, respectively.

^ Prior to 2014, >5% of PIT tagged fish were detected at Zosel Dam. Beginning in 2014, additional detectors were deployed and as a result, detection probabilities have greatly improved.

Detection histories of adult sockeye migrating through the mainstem dams (to Rock Island Dam for UCR stocks of sockeye salmon and to LGR for Snake River sockeye salmon) in 2015 are depicted in Figure 14. Several conclusions can be drawn from this figure about the behavior of adult sockeye groups discussed in this paper:

- UCR sockeye adult salmon passed Bonneville Dam earlier than Snake River inriver adults, which resulted in differential exposures to increasing temperatures in June and July.
- Early migrating adults (those that passed Bonneville Dam before temperatures exceeded 20°C) migrated quickly (similar to past years) and survived through the mainstem migration corridor at relatively high rates.
- Few adults from any group that migrated past Bonneville Dam after temperatures reached about 22°C at The Dalles ultimately survived to the uppermost dams.
- Later arriving PIT tagged fish from all groups were detected in the mouth of the Deschutes River – a known thermal refuge – and there is visual evidence of adults resting near Drano Lake (see Figure 2, page 13), a known thermal refuge in Bonneville pool.
- Later arriving fish exposed to temperatures in excess of 21 or 22°C were far more likely to “fall back” at The Dalles Dam. Some of the Snake River inriver migrants subsequently fell back at Bonneville Dam before moving upstream again. A much larger number (and proportion) of transported Snake River sockeye salmon which were exposed to the

highest temperatures engaged in these behaviors (falling back at The Dalles and Bonneville Dams and being detected at the mouth of The Deschutes River).

- Some Snake River sockeye were apparently able to survive for several months in the Little Goose reservoir – a thermal refugia resulting from Dworshak water releases – migrating past Lower Granite Dam in late September or October. However, none of these fish are known to have survived to the Sawtooth Valley.
- Adult Snake River sockeye salmon that were transported as juveniles appeared to have an impaired homing ability compared to those that migrated inriver. This resulted in delays in upstream passage and increased exposure to elevated temperatures. This likely contributed to the large disparity in estimated survival between Bonneville and Lower Granite dams for smolts that were transported (0% survival) and those that migrated inriver as juveniles (8%).

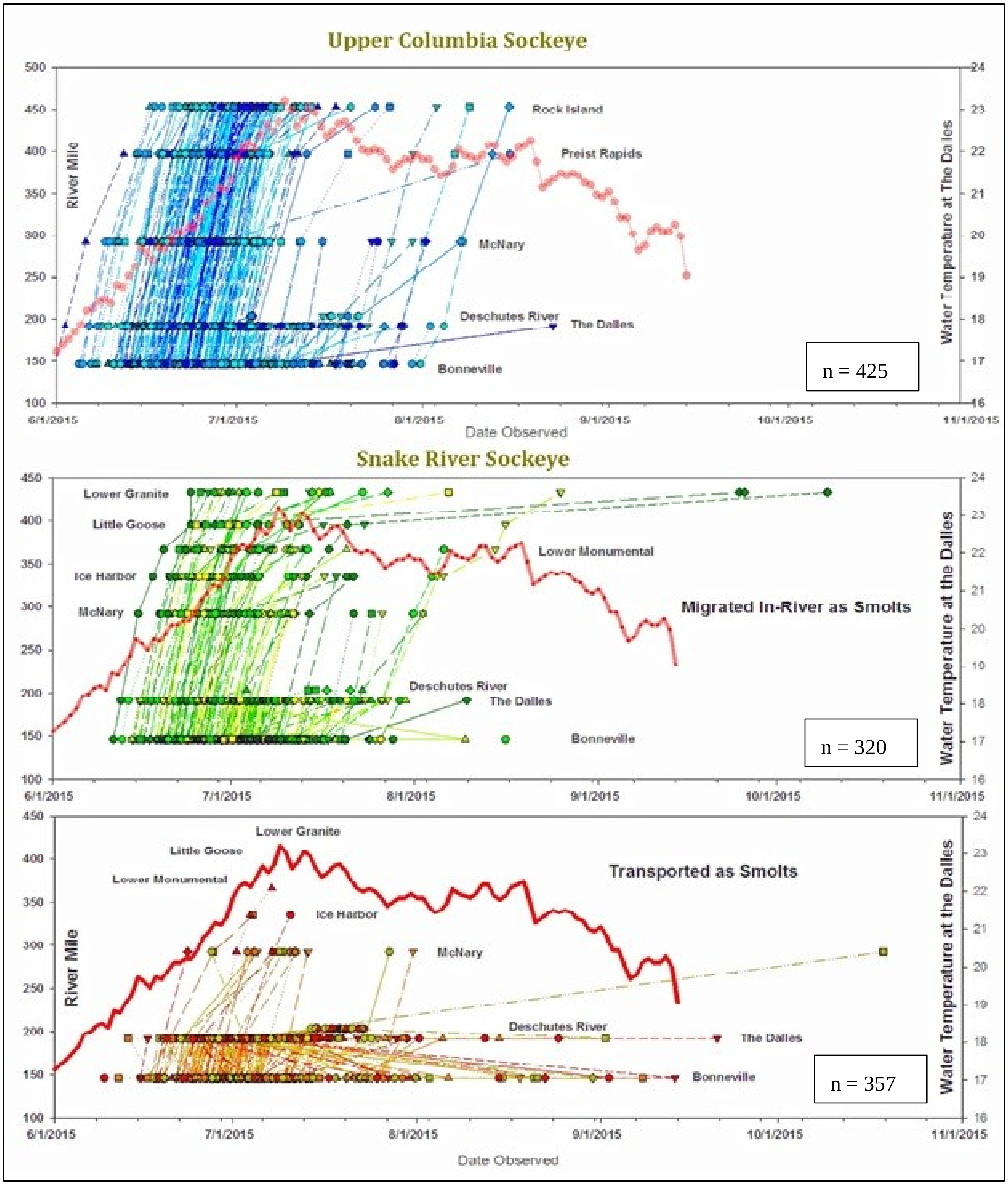

Figure 14. 2015 PIT tag detection histories for adult UCR sockeye salmon stocks (upper panel – with temperatures at The Dalles Dam) and Snake River sockeye salmon that migrated inriver (middle panel) or were transported as juveniles (lower panel). Source: PTAGIS data.

4. In-Season Management Decisions and Actions

Based on in-season observations of dam counts and PIT-tag conversion rates[13] it was evident to regional salmon managers by early July that the sockeye run was not performing well. In 2015, the salmon managers focused their attention on management actions in the lower Snake River where there were some ability to manage temperatures by releasing cold water from Dworshak Dam,[14] some of the facilities needed for a successful trap-and-haul operation were present at Lower Granite Dam, and there was some potential to draw cooler water from the project forebays. In contrast, few in-season actions could be taken to improve conditions on the lower Columbia River because there are no large storage reservoirs that can be used to regulate temperature in that reach and the run-of-the-river reservoirs are not well stratified (i.e., no cooler layer at depth that can be pumped up to cool the fish ladders).

The salmon managers set a target temperature of 19.2°C in the tailrace of Lower Granite Dam to provide some assurance that 20°C was not exceeded during the sockeye migration period. However, two of the solar radiation monitoring sensors near Lewiston Idaho, malfunctioned just before the July 4th weekend so that incorrect data were used in the USACE's water quality model. Based on flawed modeling results, the Technical Management Team (TMT)[15] agreed to reduce discharge from Dworshak Dam while temperatures in the lower Snake River were increasing rapidly, exceeding 21°C in the tailrace of Lower Granite for several days during the peak of the sockeye migration. Temperatures as high as 22°C were observed in the tailrace at Little Goose Dam by mid-July, the next project downstream (see Figure 13, page 30). Temperatures as high as 25°C were measured near the surface in the forebay.

Passage of sockeye at the Little Goose project slowed dramatically during mid-July when temperatures reached these levels, but the reason was not clear to the fisheries managers at the time. The three reasons postulated as likely for the passage delay were:

- Adults were exhausted from stress and disease due to prolonged exposure to the high temperatures they had already encountered in the lower Columbia and Snake rivers
- The ladder was drawing water, at times exceeding 25°C, from a shallow depth in the forebay, creating a temperature differential that adults perceived as a passage barrier
- Adults had difficulty finding the entrance to the fish ladder at this project because back eddies in the tailrace interfered with attraction flows.

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[13] Conversion rates measure the minimum survival of adult fish passing from one dam to the next upstream dam of interest. This number can be adjusted (upwards) to account for harvest and background stray rates.
[14] Cold water released from Dworkshak Dam on the north fork of the Clearwater River exerts the greatest control on temperature at Lower Granite Dam; the quantity of water released from Dworshak is generally regulated to target a 20°C temperature in the Lower Granite Dam (LWG) tailrace after mixing first with warmer waters of the mainstem Clearwater River and later, the Snake River. Its effect decreases downstream as it mixes with water in the lower Snake River to the point where there it has little effect on temperature (below Ice Harbor Dam).
[15] The Technical Management Team, composed of federal, state, and tribal agency representatives, is a forum for advising federal operators on adaptively managing inseason operations of the Federal Columbia River Power System in accordance with the 2008 FCRPS BiOp (as amended in 2010 and 2014).

It is likely that all of these factors were responsible to some degree. Following discovery of the malfunctioning solar radiation monitoring stations, Dworshak releases were increased to achieve the Lower Granite tailrace target. The remaining management choices were primarily focused on project operations at the each of the lower Snake River dams.

4.1 Project-Specific Operations

NOAA Fisheries declared a passage emergency on July 13, 2015, which allowed USACE to operate the adult trap at Lower Granite Dam outside the range of previously established maximum temperatures (which were developed to provide safe conditions for fish handled in the trapping facility). The Idaho Department of Fish and Game (IDFG) hauled trapped adults to Eagle Hatchery in insulated trucks, circumventing a 400-mile migration in unusually warm water (see Section IV.B, Adult Sockeye Salmon Transportation). The TMT also discussed changing spill and turbine operations at Lower Granite and Little Goose dams to improve hydraulic tailrace conditions and make the fish ladders more attractive to adults. NOAA Fisheries proposed operating only Unit 1 at Lower Granite Dam and spilling the remaining volume of water. Turbine Unit 1 is a “fixed blade unit,” which requires a greater volume of water to operate than Unit 2. That is, a lesser volume of water would be available to spill, an important consideration during the 2015 low runoff year when the volume of water spilled at Lower Granite was already below the planned BiOp level of 18 kcfs. The fisheries managers made a similar decision to operate Unit 1 during the summer of 2013 (another warmer than average year) and this appeared to result in higher hourly adult ladder counts of fall Chinook salmon (Table 6).[16] Also, USACE had reported that hydraulic conditions in the tailrace of Lower Granite appeared much better (visual observations) under Unit 1 operation (Figure 15).

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[16] Modified operations were conducted in 2013 at Lower Granite Dam when high temperatures and confusing tailrace hydraulics had established during both the sockeye and fall Chinook passage seasons. Based on tailrace observations and count data, the operation of the fixed blade Unit 1 at a higher unit flow reversed the tailrace eddy (Figure 15) and increased fall Chinook salmon counts over the Fish Passage Plan operation (Table 6). Temporary alterations to operations outside of the Fish Passage Plan are infrequent, but may be warranted when an adult passage issue outweighs the risk to juvenile salmonids, especially if very few juveniles are passing at a particular project during low flow and high temperature conditions. In-season alterations to project operations may range from spill pattern changes, removing spillway weirs, change in priority units, or changes in spill pattern or volume to temporarily improve attraction for adults during emergency situations.

Table 6. Adult Chinook counts in the ladders at Lower Granite Dam during July 25–August 10, 2013, when emergency pumps were in operation and Turbine Unit 1 alternated with Unit 2. The operation was designed to enhance tailrace conditions while spilling water up to the Total Dissolved Gas cap (120% of saturation) as measured in the tailrace at each project. Source: USACE data

Number of Adults	Unit 2	Unit 1
Ascending Ladder	260	2,021
Descending Ladder	232	1,337
Net Ascending	28	684
Hours Operated	88	239
Net Ascending / Hour	0.3	2.9

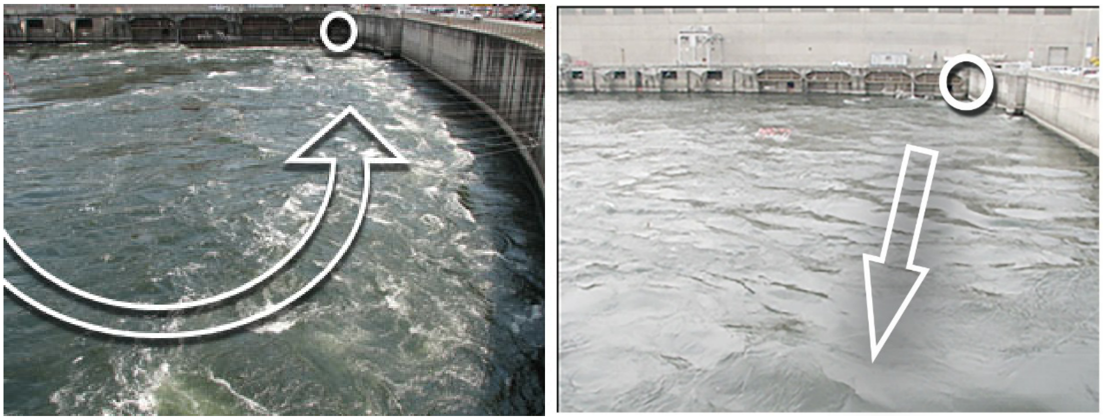

Figure 15. Tailrace conditions at Lower Granite Dam in July 2013 showing the reverse eddies with Turbine Unit 2 operating (left) and improved downstream flow with Unit 1 operating (right). Circles show ladder entrances. Arrow on the left shows the direction of the back eddies, which can confuse adults trying to orient into the current to move upstream. Arrows on the right show the direction of flow (away from the ladder entrance) without the reverse eddies. Photo courtesy of Darren Ogden (Northwest Fisheries Science Center).

4.1.1 Operations at Lower Granite Dam

Since 2013, USACE has used auxiliary and emergency pumps to draw deep, cool forebay water at Lower Granite Dam to cool and reduce the thermal temperature gradient within the fish ladder. In 2015, rented emergency pumps were operated from June 25 - Sept 30, 2015 to reduce temperatures in the upper exit section of the ladder. The auxiliary pump was operated from June 23 - Sept 30 to cool the middle section of the ladder. Even with these actions, substantial differences in temperature were observed between the entrance (bottom) and exit (top) of the adult fish ladder (Figure 16).

Sockeye counts at Lower Granite Dam were increasing at the beginning of July with ladder exit temperatures remaining under 21.1°C (Figure 16). After July 3rd, ladder exit temperatures increased beyond 21.7°C as a warming trend began in the lower Snake River. Counts declined with only two adult sockeye counted on July 7th. Twelve sockeye were counted on July 8th, after the USACE closed the removable spillway weir and implemented a uniform spill pattern, even though the daily ladder exit temperature averaged 23.3°C. The daily count again increased slightly (to 17 fish) on the 9th (ladder exit temperature averaging 23.4°C). The temperature increased slightly to 23.6°C on the 10th and sockeye passage declined. On the 13th, the turbine unit priority was switched to Unit 1 with a uniform spill pattern (Figure 16). Counts increased steadily for four days after the change in priority, which corresponded with a brief decrease in ladder exit temperatures. Passage rates dropped rapidly to two fish per day on the 18th and 19th as ladder exit temperatures again increased to above 21.7°C. Passage remained minimal until exit temperatures fell below 21.1°C on the 21st and the remaining sockeye exited the ladder in a pattern that is characteristic of counts at the tail end of a fish run.

The return to Turbine Unit 2 operation on the afternoon of July 31st did not correspond with an observable passage response, although it did coincide with the tail end of the run and ladder exit temperatures above 21.1°C. However, this behavior is typical: fish counts at Lower Granite Dam have consistently shown a stronger initial response to a change to Unit 1 operations than a change to Unit 2 operations. As a side note, none of the fish that passed Lower Granite after July 16th are known to have survived migration to the Sawtooth Valley.

In summary, it appears that the emergency operations at Lower Granite Dam did not have a detrimental impact and may have benefited adult passage through improved adult attraction conditions. The poor condition of the fish by the time they reached Lower Granite and the elevated ladder temperatures were likely the main drivers of the low passage counts in 2015. The day-to-day variability in ladder counts may have been related to the ladder exit temperatures and/or the turbine unit priority/spill operations, but the data sets are too small and variable for statistical comparisons.

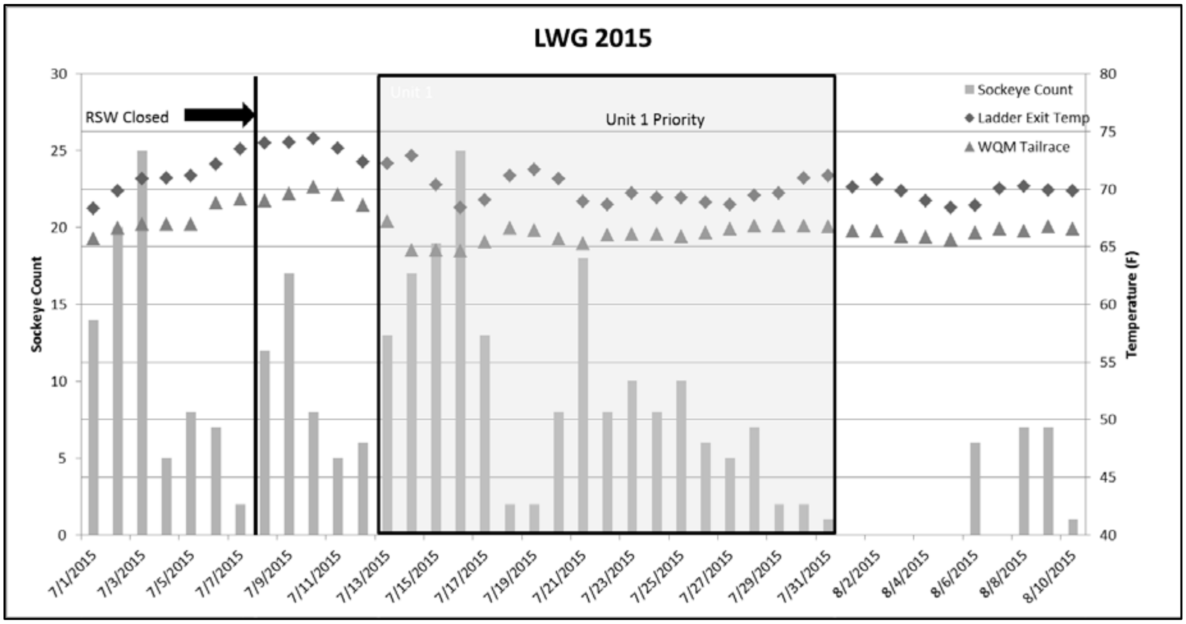

Figure 16. Sockeye salmon ladder counts, ladder exit pool temperature, and tailrace temperature (WQM Tailrace) at Lower Granite Dam during 2015. Source: USACE data

4.1.2 Operations at Little Goose Dam

Figure 17 summarizes adult sockeye ladder counts and ladder exit temperatures at Little Goose Dam during summer 2015. Passage was clearly affected on at least two occasions when temperatures exceeded about 23°C (June 27-28 and July 8-9).

The USACE removed the temporary spillway weir for the season on June 18, 2015. As counts and conversion rates through Little Goose Dam remained low, NOAA Fisheries proposed that USACE pass all water through the turbines during daytime (i.e., provide no spill) at this project. This action was expected to reduce the potential for eddies to form, making it easier for adults to locate the fish ladder, and reducing temperatures in the tailrace. The temperature at 30 m in the Little Goose forebay, where the turbine intakes are located, was approximately 19°C, several degrees cooler than at 20 m where the spillways draw water. Therefore, operating only the turbines had the potential to provide cooler water to adults holding below the project.

The TMT did not reach consensus on implementing these operations when they were discussed on July 22nd. The State of Oregon and the Nez Perce Tribe objected, citing more confidence that they would reduce the survival of migrating Snake River fall Chinook salmon smolts than that they would provide any benefit to adult sockeye salmon. Taking the co-managers’ comments into account, NOAA Fisheries recommended a block design schedule for spill operations at Little Goose Dam (i.e., blocks of two days each with spill off, on, and off). NOAA Fisheries analyzed the potential negative effect on the juvenile fall Chinook population prior to implementation, and identified little or no negative effect (Appendix A).

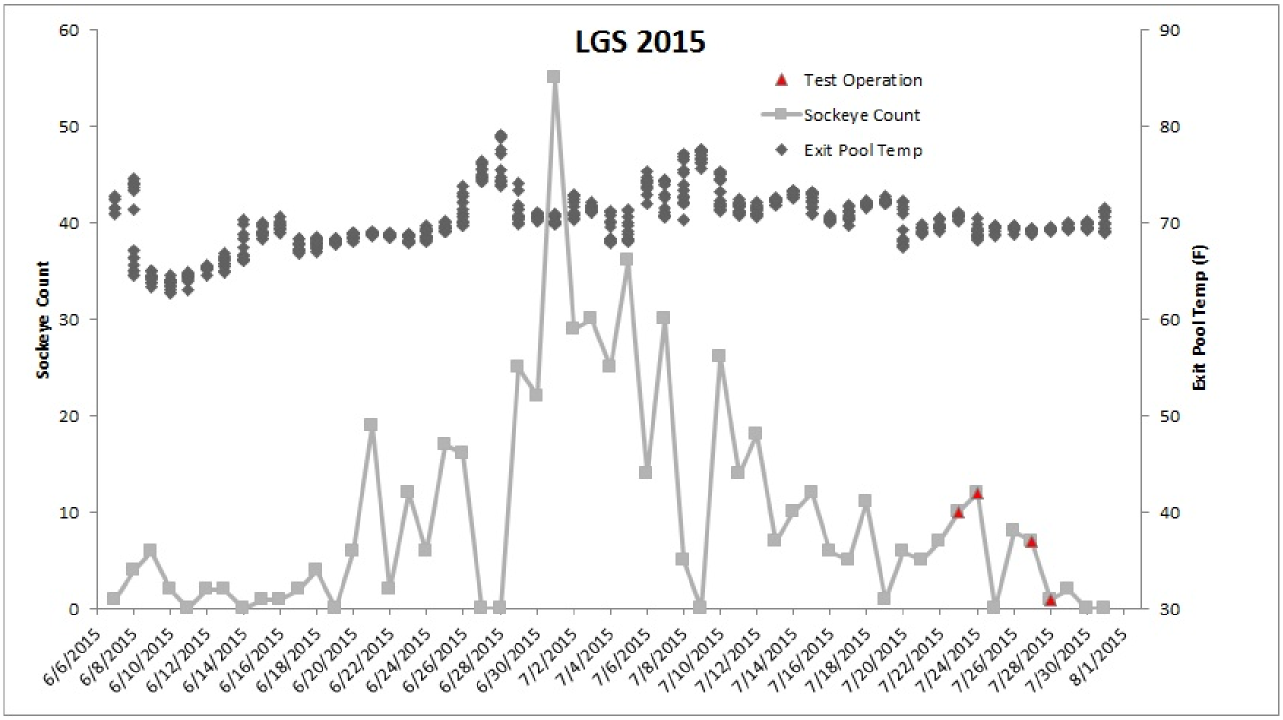

Figure 17. Adult sockeye passage counts and hourly ladder exit temperatures at Little Goose Dam in 2015 (red triangles denote counts during days when spill was turned off in an effort to provide better hydraulic conditions at the Little Goose ladder entrance). Source: USACE data

The 6-day blocked spill operation began at Little Goose on July 23rd with agreement that any additional days without spill would be contingent on the results. Initially, adult passage increased at Little Goose (Table 7), but the adult count was also similar on one of the no-spill days. And the second block of two days, with spill, produced similar results as the preceding block of no-spill days.

A best case result would have been an increase in adult passage of several hundred fish, the cumulative difference between the ladder counts at Lower Monumental and Little Goose dams. However, only 40 fish passed the Little Goose ladder after July 23rd. Therefore, no additional no-spill days were proposed after July 28th.

Table 7. Adult sockeye salmon passage at Lower Monumental and Little Goose dams during the blocked spill operations at Little Goose Dam. Daytime spill was not provided on days marked "Test." Source: USACE data

Date	Test Days	Adults Ascending Lower Monumental[a]	Adults Ascending Little Goose
7/20/2015		12	6
7/21/2015		3	5
7/22/2015		1	7
7/23/2015	x	0	10
7/24/2015	x	9	12
7/25/2015		0	0
7/26/2015		4	8
7/27/2015	x	3	7
7/28/2015	x	1	1
7/29/2015		1	2
7/30/2015		0	0
7/31/2015		0	0

[a] The numbers of adult sockeye ascending Lower Monumental Dam are shown in this table as a gage of the numbers available to ascend the ladders at Little Goose Dam. However, the cumulative adult count at Lower Monumental was several hundred fish greater than at Little Goose Dam, indicating several hundred fish may have been lost between Lower Monumental Dam and Little Goose Dam.

The fate of the fish that did not pass Little Goose Dam is unknown. Most likely, these fish either died in Lower Monumental Reservoir (water temperatures in the tailrace of Little Goose Dam, at the upper end of Lower Monumental Reservoir, approached 22°C, see Figure 13, page 30) or fell back past Lower Monumental and Ice Harbor dams and ascended the upper Columbia River. Similar to what was observed in Drano Lake and the Deschutes River in the lower Columbia River, compromised fish may have held and died in the cool water outflow from Lyon's Ferry Hatchery, which is located midway between Lower Monumental and Little Goose dams. Support for the latter possibility is based on the observation that about 30% of the adult sockeye that were trapped at Lower Granite Dam originated in the upper Columbia basin. If the proportion of out-of-basin fish was also this high (or higher) at Little Goose, and if many of these fish fell back, it would account for most of the ladder count differential. The relative influence of each factor (mortality due to high temperature exposure versus fallback) is unknown.

On July 23, 2013, the regional Fish Passage Advisory Committee submitted System Operation Request 2013-4 to the USACE, suggesting measures with the potential to increase adult passage. These included cycling (opening and closing) the navigation locks as often as practical. This suggestion was also proposed during a Fish Passage Operations and Maintenance (FPOM) conference call on July 24th, where the USFWS also requested cycling of the locks as an alternate route of passage upstream (Fish Passage Center 2015). The parties debated the question of how effective more frequent lock operation would be in passing adults with little consensus on the benefits. The following review of the available information indicates that some additional fish could be passed through the locks if they were operated more frequently, but the benefit is likely to be small and there is little information to evaluate the potential for negative effects.

Based on PIT tag detections and migration studies, adult salmonids do use the navigation locks at the lower Columbia and Snake River dams for upstream passage, but the frequency of use is very low. More than 99% of the PIT-tagged adults known to pass Snake River dams had migrated through and were detected in the fish ladders (PSMFC 2014). The rest of the undetected adults (<1%) could have passed through the locks or have passed through the adult ladder undetected due to tag “collisions” (interference). Keefer et al. (2004) found that adult salmonids “only occasionally pass navigation locks.” Bjornn and Peery (1992) reported that 0.86% of sockeye salmon, 1.1% steelhead, and 1.3% of Chinook salmon passed through the Bonneville Lock during the 1969 season. Only 7 out of 801 (0.8%) radio tagged Chinook salmon passed through the locks at Bonneville Dam in 1996 (Keefer et al. 1996). Less than 2% of adults with radio-telemetry tags migrated through the locks at John Day and The Dalles dams (Boggs et al. 2004).

This information indicates that under current operations, small numbers of adults pass through the navigation locks. Although the locks should not be considered a primary passage route, more frequent operation could be considered as a strategy to pass a small number of additional fish during low flow, high temperature conditions. If implemented, the fate of these fish should be monitored to determine whether there are negative effects associated with this passage route. However, other alternatives aimed at improving conditions within the adult fishways during periods of high temperatures appear to be more promising and effective (see Section 5).

4.2 Adult Sockeye Salmon Transportation

In this section, we describe the “trap-and-haul” operation for adult sockeye at Lower Granite Dam during 2015. In June, the Idaho Department of Fish and Game (IDFG) and NOAA Fisheries became increasingly concerned that environmental conditions (extremely low flows, above average water temperatures, and the projected forecast for continued sunny and very hot temperatures) could lead to major problems for migrating adult salmon in the Columbia River, especially endangered Snake River sockeye salmon. They closely monitored and reported water temperatures and conversion rates through the FCRPS on a weekly basis as PIT-tagged fish began to arrive at Bonneville Dam. By July 6th the monitoring showed: 1) water temperatures continuing to increase into the lethal range for salmonids, 2) significant declines in adult sockeye conversion rates between dams and increasing fallback rates, and 3) large numbers of adult sockeye found dead or dying in cool water refuges throughout the lower Columbia (e.g., near Drano Lake, as described above). They therefore agreed to declare an adult Snake River sockeye salmon passage emergency and to implement trap and haul at Lower Granite Dam beginning July 13, 2015. Plans were made to trap adult sockeye from the ladder and transport them to the Eagle Fish Hatchery (EFH) for holding until their final disposition could be determined (e.g., spawned in the hatchery or released into the natal lakes in the Sawtooth Valley for natural spawning). NOAA Fisheries permitted this activity as direct take under the IDFG’s Endangered

Species Act Section 10(a)(1)(a) 1454 permit and as incidental take under the 2014 FCRPS Supplemental Biological Opinion.[17]

1. Trap and Haul Operations

Staff from USACE, NOAA Fisheries, and IDFG trapped adult sockeye for transport to the Eagle Fish Hatchery between July 13 and August 5, 2015.[18] The trap was operated from about 7:00 am to 11:30 am each day, before temperatures rose to potentially lethal levels. Occasionally, the period of operation would be extended (e.g., to capture an adult sockeye observed passing the viewing window). On other days, operations did not begin until sockeye were observed in the viewing window, reducing the likelihood of handling other species of salmon and steelhead. The duration of trapping was extended until 2:00 pm on July 28th to increase captures of sockeye while water temperatures in the ladder were cooler. Staff from the Nez Pierce Tribe's Department of Fisheries Resources Management provided additional help beginning on July 28th so that the emergency trap and haul operation could be extended. Trapping hours were based on transport logistics and reducing fish stress, but PIT-tag and window count data also indicated that sockeye salmon were actively moving in the ladder between the hours of 7 and 11 am. Prior PIT-tag data indicated a probability of capturing about 30% of the run during this 4-hr time frame (Figure 18). The fisheries agencies began emergency trapping when water temperatures in the fish ladder exceeded 21°C. They discontinued the effort to trap sockeye salmon on August 5, 2015, when fewer than five fish were observed in the counting window and few or no adults were likely to enter the trap. However, four more fish were captured and transported to Eagle Fish Hatchery between August 5–13, 2015, during routine biosampling (fork length, weight, sex, hatchery marks, tag numbers, and fish condition) for Chinook salmon and steelhead.

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[17] NOAA Fisheries authorized additional incidental take of adult sockeye salmon, Chinook salmon and steelhead to support the sockeye transportation effort, beyond that originally anticipated in the 2008 FCRPS Biological Opinion (as amended in 2010 and 2014), on July 10, 2015. The permit included up to 10% mortality of Snake River sockeye salmon, handling of about 1,000 Chinook salmon and 3,800 steelhead, and the incidental mortality of up to 38 listed Chinook salmon and 33 steelhead. (See Appendix B)

[18] In addition, some of the adult sockeye falling back over the dam were collected from the juvenile fish separator (Table 8).

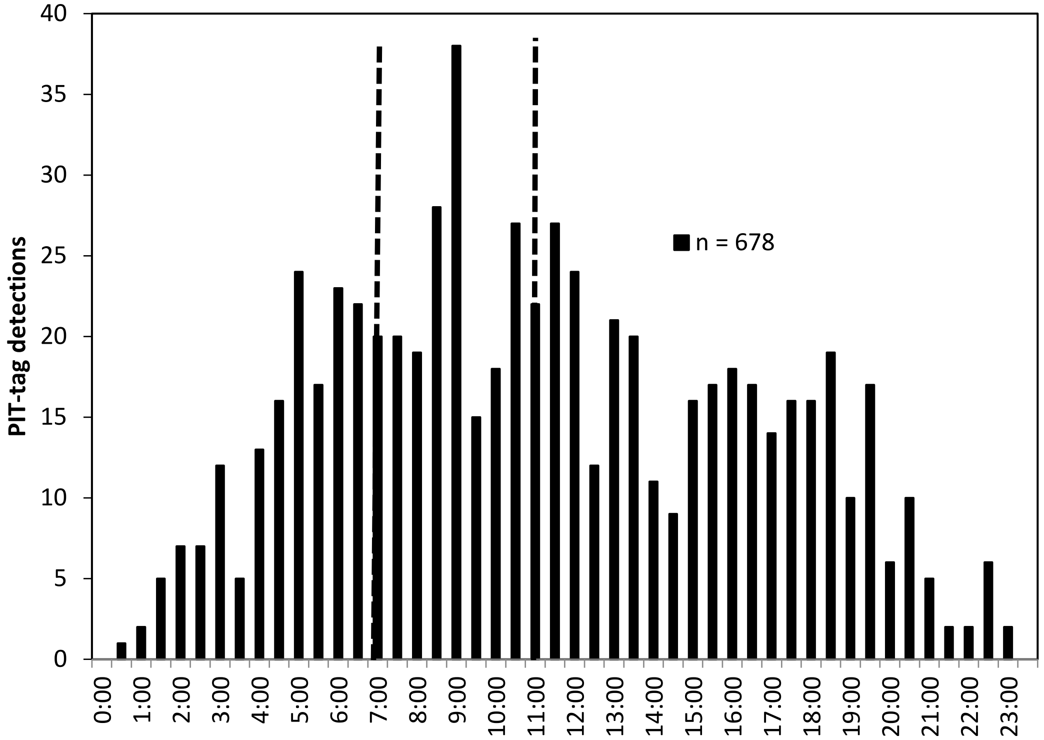

Figure 18. Cumulative number of PIT tag detections per hour near the counting window in the fish ladder at Lower Granite Dam during 2011-2014. Trapping at Lower Granite Dam occurred from 7–11 am to avoid additional temperature stress during the afternoon period. Source: PTAGIS data

Initially, all fish were transported to Eagle Fish Hatchery the day they were trapped.[19] Later in the season, fish were held up to 26 hours before transport. The transport vehicle was a truck fitted with two 250-gallon insulated fiberglass tanks with continuous oxygen delivery (45 to 50 psi in a flow adjusted to 1.0 to 1.5 ppm).[20] Transport times from Lower Granite Dam to the hatchery averaged 8.3 hours (range = 7.8 to 8.9 hours) and fish were visually monitored about every two hours for signs of stress or unusual activity during transport.[21]

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[19] Sockeye collected at the juvenile separator or collected during bio-sampling activities for Chinook salmon or steelhead were held in the steelhead kelt tank at Lower Granite Dam for one night before being transported to Eagle Fish Hatchery.

[20] Each transport tank was fitted with one recirculating water pump and “air scoops” (aerators) to help with gas exchange. The tanks were filled with 13.3°C water at the hatchery, but the water gradually warmed during transit to Lower Granite Dam. By the time the fish were loaded into the tanks, temperatures averaged 17°C, ranging from 16-17.8°C. Sockeye were held in the transport tanks from a few minutes to 3.5 hours before the vehicle left for the hatchery and during this time, the oxygen systems and aerators were in operation and fish were monitored closely for signs of stress. Fifty pounds of cubed ice was added to each tank about three hours into the trip to begin tempering the water to match the hatchery’s water temperature of 13°C.

[21] After arrival at Eagle Fish Hatchery, water in the transport tanks was further tempered to within 2.2°C of the temperatures in hatchery’s holding tanks 13.3ºC. Due to arrival late in the day at Eagle Fish Hatchery, the adults were transferred from the transport tanks to 3-m circular holding tanks. The next morning fish were examined and the following metrics were recorded: fork length, weight, sex. Marks, tag number, and fish condition were also noted. Genetic samples were taken from all of the fish and scale samples were collected from the unmarked returns. Fish were injected with the antibiotic Erythromycin and treated with formalin.

A total of 51 sockeye salmon were collected at Lower Granite Dam during the 2015 fish passage emergency (Figure 19). Of these, 19 were unmarked, indicating they had emigrated from a natural spawning area (although their parents could have been hatchery-origin fish that were outplanted to spawn). Another 32 were marked, indicating they were raised in a hatchery facility. The number of fish collected each day at Lower Granite ranged from zero to six. A total of five were collected from the juvenile separator (Table 8). There were no mortalities during trapping or transport.

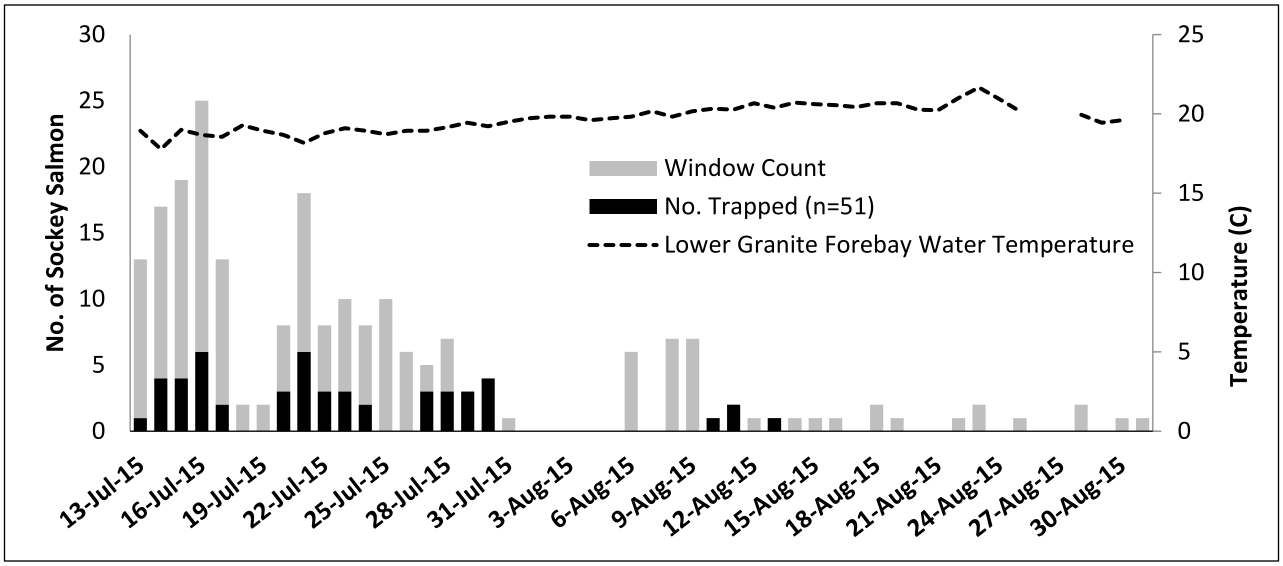

Figure 19. Number of adult sockeye salmon trapped and transported from Lower Granite Dam to Eagle Fish Hatchery (black bars) and the daily window counts (grey bars). Water temperatures in the Lower Granite forebay are also plotted (broken line). Source: IDFG data

2. Genetic Analysis and Identification of Out-of-Basin Sockeye Salmon

The IDFG takes fin clips from all anadromous and captive sockeye salmon each year and based on a suite of 13-16 microsatellite markers, determines relatedness in the population. This allows them to prioritize fish to be used for spawning at the hatchery and for release into natural spawning areas. The initial genetic analyses indicated that some of the adults trapped at Lower Granite had alleles not present in the captive broodstock; thus IDFG performed a genetic assignment test using the program GeneClass2 (Piry et al. 2004) to ascertain population membership. The IDFG maintains a baseline for microsatellite data for the Sawtooth Valley basin, but a larger baseline was needed to ascertain out-of-basin membership. Geneticists from the Columbia River Intertribal Fish Commission (CRITFC) provided a baseline for *O. nerka* throughout the Columbia River Basin. The fish collected at Lower Granite Dam were then screened with 96 Single Nucletoide Polymorphisms (SNPS) to compare to this larger baseline. Of the 51 adults collected at Lower Granite Dam, 35 (69%) were assigned to the Snake River sockeye salmon genetic stock group and of these, three were natural origin fish. The remaining 16 (31%) were determined to be from the Lake Wenatchee or Lake Osoyoos (Okanogan) genetic stocks and were subsequently culled from the potential broodstock. Of the fish identified as out-of-basin, as many as three could have been collected from the juvenile bypass system and if so, may have been trying to fall back downstream.[22] We observed no discernable difference in run timing distribution at Lower Granite Dam between the Snake River and out-of-basin adults (Figure 20).

Table 8. Date of collection, total number of fish collected (N), number of fish collected on the juvenile bypass separator (N_{SEP}) and in the adult trap (N_{TRAP}) at Lower Granite Dam in 2015, number of fish genetically assigned to the Snake River sockeye broodstock (N_{SRS}), and number of fish assigned to an out-of-basin genetic stock and culled (N_{CULLED}). Source: IDFG data

Collection Date	N	N_{SEP}	N_{TRAP}	N_{SRS}	N_{CULLED}
7/13/2015	1	0	1	1	0
7/14/2015	4	0	4	3	1
7/15/2015	4	0	4	3	1
7/16/2015	6	1	5	6	0
7/17/2015	2	1	1	1	1
7/20/2015	3	0	3	1	2
7/21/2015	6	0	6	3	3
7/22/2015	3	1	2	2	1
7/23/2015	3	0	3	2	1
7/24/2015	2	1	1	2	0
7/27/2015	3	0	3	3	0
7/28/2015	3	0	3	3	0
7/29/2015	3	0	3	3	0
7/30/2015	2	1	1	0	2
7/31/2015	2	0	2	0	2
8/10/2015	1	0	1	1	0
8/11/2015	2	0	2	1	1
8/13/2015	1	0	1	0	1
	51	5	46	35	16

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[22] The fish collected in the juvenile separator were not differentially marked from those collected in the trap so geneticists could not determine if these adults were more likely to have originated outside of the Snake River basin.

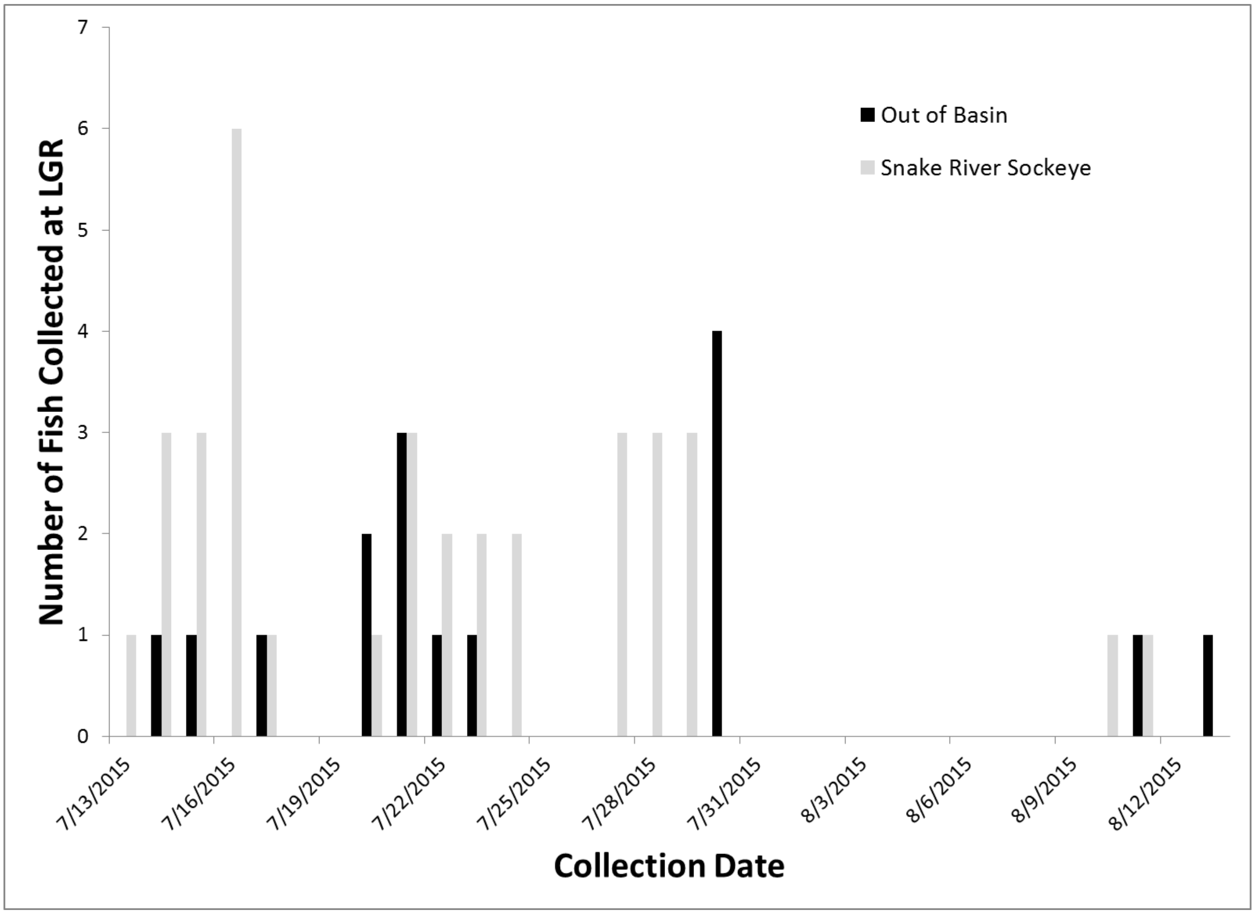

Figure 20. Run timing of Snake River sockeye salmon and fish assigned to an out-of-basin genetic stock collected at Lower Granite Dam from July 13, 2015, to August 13, 2015. Source: IDFG data

3. Hatchery Spawning

Of the 35 Snake River sockeye salmon that were trapped at Lower Granite and transported to Eagle Fish Hatchery for incorporation into the captive broodstock program, only one died during holding period at the hatchery. The remaining 34 (17 females and 17 males) were spawned. One of the females was non-productive, leaving 16 females from the trap and haul program that contributed to brood year 2015 production (Table 9). Fish collected at the Redfish Lake Creek weir (25 females, 25 males) were also prioritized for spawning at Eagle Fish Hatchery whereas the fish collected at the Sawtooth Hatchery weir (4 females, 1 male) were released into Pettit Lake for volitional spawning along with some of the captive broodstock adults. The anadromous fish had experienced high temperatures during their migration and it was presumed that they would contribute more fitness benefits to the population by being spawned in the hatchery rather than released for natural spawning. The IDFG was also concerned that the egg quality/viability of these fish had been compromised due to the stress that these fish had undergone during their migration. Given the uncertainty of the egg quality of the anadromous adults, production targets were instead based upon the number of maturing fish in the captive broodstock. The eggs from the anadromous spawners could be used to bring production levels above target. Anadromous fish were spawned with other anadromous or captive broodstock adults.

After spawning, female fecundity, egg quality, and spawn timing were compared for adults collected from the Lower Granite trap with those trapped at Red Fish Lake Creek. The survival of eggs from the “green” to “eyed” stage was significantly higher for fish collected at Lower Granite (84%) compared to those from the Red Fish Lake Creek trap (67%; t = 2.1, *df* = 35, P = 0.04; Table 9), indicating a loss of egg viability for those that migrated in-river from Lower Granite to the Sawtooth Valley. In terms of spawn timing, the median spawning date for the females trapped at Lower Granite was November 3, 2015, compared to October 16, 2015, for the females trapped at Redfish Lake Creek (Figure 21). These differences could have been mediated by temperature: the fish collected at Lower Granite were placed on cooler water when they arrived at Eagle Fish Hatchery, which may have delayed spawn timing compared to fish exposed to warm water for their entire migration.

Table 9. Spawning results for females collected at Lower Granite Dam (LGR) and transported to Eagle Fish Hatchery (EFH) and for females collected at the Redfish Lake Creek (RFLC) trap. Source: IDFG data

	LGR Trap and Haul	*Returning to RFLC trap*
Number of Females	16*	21*
First Spawn Date	9 October	22 September
Last Spawn Date	12 November	12 November
Total Eggs (green)	33,288	55,596
Average Fecundity	2,081	2,647
Total Eyed Eggs	28,074	38,843
Survival to Eyed Stage	84%	67%
Average Eggs per gram	15 (larger eggs)	21 (smaller eggs)

*****One of the females collected at Lower Granite Dam and four of the females collected at Red Fish Lake Creek were non-productive.

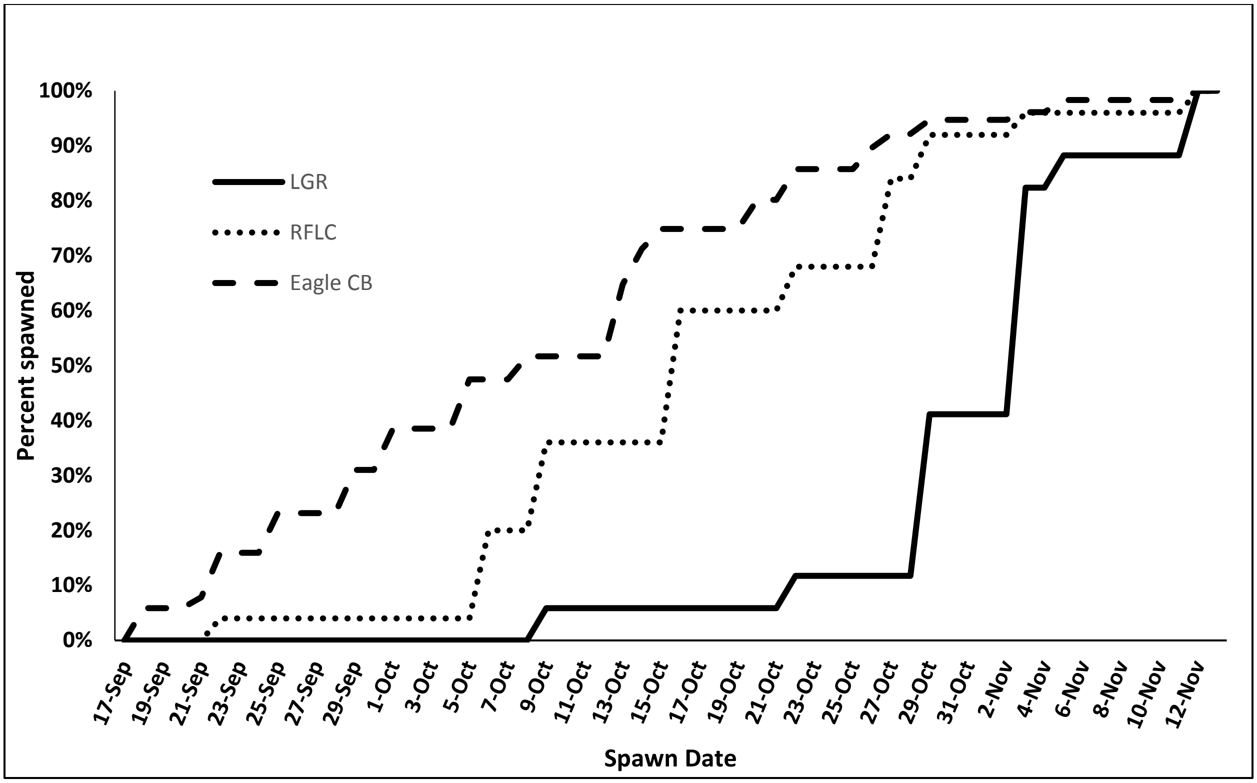

Figure 21. Spawn timing for female sockeye salmon collected at Lower Granite Dam and transported to Eagle Fish Hatchery, females collected at the Red Fish Lake Creek trap and transported to the hatchery, and captive broodstock females reared at the hatchery. Source: IDFG data

4. Outcomes

A total of 56 adults (30 females, 26 males) successfully migrated back to the basin in-river and seven of these fish had PIT tags. The total included 11 natural-origin and 45 hatchery-origin adults. PIT-tag data informed migration timing and survival from Lower Granite to the basin for in-river migrants (Figure 22). Migration from Lower Granite to the basin averaged 46 days (range = 38-58 days). Of the 27 PIT-tagged fish detected at Lower Granite Dam, three were collected and transported to the Eagle Fish Hatchery.

The Snake River fish collected at Lower Granite accounted for 38% of the overall return and almost doubled the number of sockeye collected in the Snake River basin in 2015. The lack of an accurate assessment of population sizes at Lower Granite and limited numbers of PIT-tagged fish present a significant challenge when estimating the relative benefit of the trap-and-haul effort. For example, based on PIT-tag detections, survival estimates from Lower Granite to the basin was about 29% (see Table 4). Survival estimates using window count data were significantly lower (about 15%).[23] Regardless of which method is used to estimate the survival benefits,

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[23] Window counts may also be used to estimate conversion rates. However, there is some uncertainty in the number of adults passing over Lower Granite given that some fish fallback over the dam and may be counted multiple times, and this uncertainty is compounded by an unknown proportion of fish from out-of-basin genetic stock groups that were enumerated in the counting window this year. The 2015 fallback estimate at Lower Granite was 7.7% and the proportion of out-of-basin fish collected during this operation was 31%, so it is likely that the window count was

without the trap-and-haul operation it is likely that none of the Snake River sockeye salmon adults that passed over Lower Granite after July 16th would have survived their migration to the Sawtooth Valley. This emergency action provided a mechanism to include a larger and more representative sample of adults with anadromous experience (and the likely fitness benefit of that experience) in the genetic resources of the captive broodstock program.

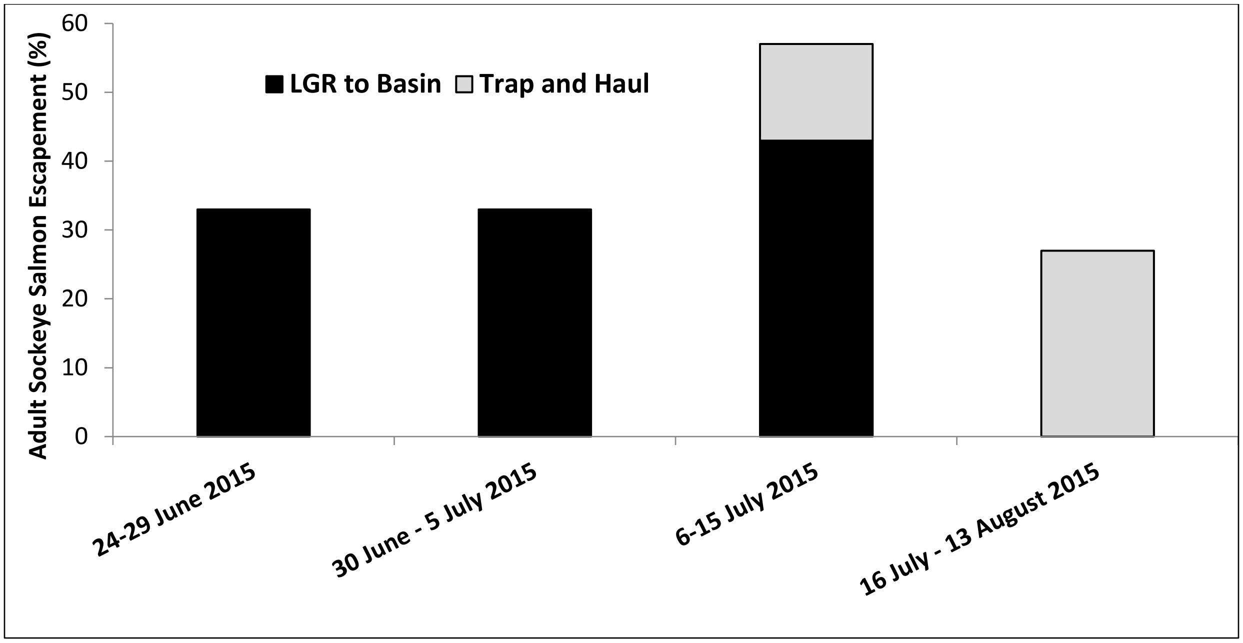

Figure 22. Adult sockeye salmon survival from Lower Granite to the Sawtooth Valley by time period and in-river migration versus transport strategy based on PIT-tag data. Source: IDFG data

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high and led to an underestimate of the survival rate from Lower Granite to the basin. Therefore, the in-river survival and trap-and-haul benefits estimates based upon PIT-tag data are likely more accurate.

5. Discussion

The June and July 2015 temperatures experienced in the mainstem and tributaries of the Columbia River basin were unprecedented. Although this condition has not been observed in the recent historical record (i.e., temperature data from Bonneville Dam and McNary dams are available since 1949 and 1956, respectively) it is reasonable to expect that similar events could occur more often in the future. Rare events are unlikely to have large or lasting impacts to sockeye salmon populations because their complex life histories provide resiliency against cataclysmic events. However, if this type of event occurs more frequently, the impact on sockeye salmon populations in the Columbia River basin could be substantial.

Sockeye losses and aberrant behaviors indicative of stress appear to have begun in the lower Columbia River when temperatures at The Dalles Dam exceeded 21 or 22°C. UCR sockeye salmon stocks were least affected, probably because a higher proportion of these stocks passed Bonneville Dam prior to these conditions. There was no difference in passage timing at Bonneville Dam of adult Snake River sockeye salmon that migrated inriver or that were transported as juveniles. However, far fewer adults that had been transported as juveniles survived to McNary Dam and none survived to Lower Granite Dam. It is unclear why this difference was so large in 2015 but it was likely due to an interaction between high temperatures and altered behavior (e.g., homing ability) that increased the exposure of adults from the transport group.[24] The high sockeye mortalities in 2015 warrant a review of actions that have been taken and consideration of additional actions that might avoid or lessen some of these effects in the future.

5.1 System Operations

Tributary river temperatures were abnormally high throughout the Columba River basin. Outflows from large water storage facilities (Brownlee Dam, Grand Coulee Dam, and Dworshak Dam) are cooler in June and July than project inflows. However, even temperature reductions in the range of 5°C as observed through the Hells Canyon Complex, though beneficial, were insufficient to counteract inflows from tributaries and heating throughout the downstream reaches. Releases of cool water from Dworshak Dam were effective at reducing temperatures in the lower Clearwater River and lower Snake River, though the effect dampened at each successive downstream project. However, inaccurate information from key temperature gages fostered management decisions that allowed temperatures to exceed targets for a short time before it was discovered and corrective operations were taken. Releases of stored water from the upstream projects (which accounted for up to 30% of river flows at The Dalles Dam in July) to increase flows also likely benefited adult migrants by preventing temperatures from increasing as much as they might have otherwise. Although temperatures in the lower Columbia River were

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[24] Although adult survival has not previously varied with juvenile migration history except in the McNary to Ice Harbor reach, during 2013, adult migrants that had been transported as juveniles were twice as likely to fall back over Bonneville, The Dalles, or McNary Dam as those that were inriver juvenile migrants (Crozier et al. 2014).

warm, the heat gain in the reach between Bonneville and McNary dams was about 1°C in 2015, similar to the previous 10-year average.

5.2 Lower Granite Dam Operations

During 2014, the USACE installed temporary pumps to draw 25-50 cfs of cooler water from a depth of 60 feet in the forebay for discharge into the top of the adult fishway. This cooler water mixes with 25 cfs from a depth of 30 feet that is provided by the existing pumps. This action appears to have been successful as temperatures measured at the adult fish trap were generally kept below 21°C and fish continued to ascend the ladder throughout the migration season. A permanent structure was completed in 2016, which enhances the USACE's ability to provide better temperature conditions in the upper section of the adult fishway and the adult trap.

Prioritizing turbine unit 1 (over turbine unit 2) and taking the removable spillway weir out of service during periods of low flow appear to have also contributed to improved hydraulic conditions and likely assisted adult migrants attempting to find the ladder entrance.[25] There is still uncertainty regarding the effect of surface and intermediate depth spill on forebay and downstream temperatures at Lower Granite Dam and this uncertainty is likely to persist until enhanced models are developed or physical tests are conducted. In August, 2016, the Regional System Configuration Team assigned a high priority for the USACE to develop a model that more accurately predicts temperature effects in project forebays and tailraces with changes in spill and turbine operations.

5.3 Little Goose Dam Operations

On July 23-24 and July 27-28, spillways were turned off during the daytime, when adult fish predominantly pass through the ladders, to assess whether this action could improve hydraulic conditions near the fishway entrance and entice fish to pass upstream where they could reside in somewhat cooler waters in Little Goose Reservoir. If passage were successful, these fish would also potentially move upstream and pass Lower Granite Dam where they would be available for capture and transportation which was ongoing. Although adult ladder counts did increase at Little Goose Dam on July 23-24, too few fish (only 40 adults passed through the Little Goose ladder after July 23) were counted on subsequent days to prove definitively the efficacy of this action. It seems clear that this action did not negatively affect adult passage (counts at Little Goose did increase independently of Lower Monumental Dam counts). Also, given the relative strength of threatened Snake River fall Chinook salmon (and the relatively few migrating smolts in the Snake River reservoirs at this time) compared to the value of endangered adult Snake

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[25] Use of the Removable Spillway Weir (RSW) causes more turbulence in the tailrace near the adult ladder entrance relative to a deeper spill gate operation with a more uniform pattern. The use of the RSW can also pass warmer water downstream. Some individuals contend that this warm water release is beneficial because it can decrease temperature conditions in the Lower Granite forebay. Others that that operating the RSW has little effect on forebay temperatures at Lower Granite, but should be avoided to keep the water in the downstream reservoir as cool as possible.

River sockeye salmon and the circumstances faced by managers in 2015, erring on the side of adult sockeye salmon passage in the midst of uncertainty seemed warranted and prudent.

5.4 Adult Sockeye Transportation

A total of 56 adult Snake River sockeye salmon (30 females and 26 males) returned to the Sawtooth Valley in 2015. IDFG, in cooperation with the Nez Perce Tribe, NOAA Fisheries, and USACE successfully trapped and transported 51 adult sockeye salmon from Lower Granite Dam to the Eagle Fish Hatchery. No mortalities occurred as a result of these activities. Of these fish, 35 (69%) were Snake River sockeye salmon (17 females and 17 males – one died during holding at the hatchery) and 16 (31%) were from the unlisted Lake Wenatchee or Okanogan River populations. This high proportion of strays was unexpected and the implications will need to be carefully considered in the future. The fecundity of the transported females compared favorably to those that migrated to the Redfish Lake Creek Trap: they had larger eggs and the eggs had a higher survival rate to the eyed stage. The trap and transport efforts increased the number of spawners in 2015 by about 38%, indicating that it is an effective, if limited, tool for increasing the survival of these valuable fish during periods of extreme temperatures.

5.5 New Actions at Lower Granite Dam

Permanent intake structures and pumps were installed at Lower Granite Dam in February 2016. These are being used in the summer months to draw water up from a 60-foot depth in the forebay to cool the exit section of the adult ladder. These structures should provide a permanent solution for the differential temperatures that have been observed in the adult ladder at Lower Granite Dam, especially in 2015.

Turbine Unit 1 is being rebuilt as a fully functional Kaplan unit with the same operational range as Unit 2. This refurbishment is scheduled for completion by April 2017. Turbine Unit 1 was used in 2013 and 2015 as a potential means of increasing adult sockeye passage (see previous discussion). A controversy arose because Unit 1 (with blades fixed) requires a greater volume of flow to operate than Unit 2, and consequently less flow goes over the spillway. Returning Unit 1 to its status as fully functional Kaplan unit will allow it the same operating range as Unit 2.

6. Recommendations

This report has described numerous effects of the high temperatures experienced by adult sockeye salmon returning to their natal lakes in 2015. It has also described several actions that were taken by federal hydropower operators and co-managers, to minimize or reduce these impacts in some fashion. Based on our consideration of information summarized in this report, NOAA Fisheries recommends that the following measures (by federal operators, other hydro and water storage facility operators, and regional co-managers) as means of improving management decision making and reducing, to the extent practicable, the negative impacts of high summer temperatures on adult sockeye salmon. NOAA Fisheries expects that some of these actions will take several years to accomplish and that others will continue indefinitely. Although these actions focus on the impounded reaches of the Snake and Columbia River, NOAA Fisheries recommends that agencies with land management, water management, or Clean Water Act authorities (or other governmental or private organizations involved in the preservation, conservation, or restoration of habitat) prioritize actions that would reduce summer temperatures in tributaries and reservoirs throughout the interior Columbia River Basin.

1. **Improve monitoring and reporting of all mainstem fish ladder temperatures and identify ladders with substantial temperature differentials (>1.0°C).**
    - Monitor temperatures in adult ladders near the entrances and exits (downstream of diffusers) at each mainstem dam. Also monitor temperatures in the forebay (using temperature strings) and tailrace adjacent to the fishway entrances and exits of each mainstem dam. This data should be made accessible online and in near real time. (NOTE: some dams already have sensor strings that might serve this purpose.)
    - Rationale: Both excessive river temperatures and ladder temperature differentials appeared to contribute to adult sockeye passage issues in 2015. Timely knowledge of real time temperature conditions would help identify a looming potential problem and help inform the effectiveness of management actions targeted to address ladder and reservoir temperature issues.

2. **NOAA Fisheries, co-managers, and federal operators will develop triggers to indicate when summer temperatures are likely to exceed critical thresholds**.
    - The trigger should consider some probability that river or ladder temperatures would likely exceed an agreed upon critical threshold (e.g., ladder differential, tailrace temperature, flow, and thermal exposure) that would alert hydro operators and co-managers as early as possible, that measures should be taken to minimize the impacts of high temperatures on migrating adult salmon and steelhead. Specifically, a triggering event would:

      1) cause the TMT to meet the following day to discuss and recommend actions; and
      2) cause USACE and BPA to ready and implement actions.

- Rationale: Cumulative thermal exposure has been highly correlated with adult sockeye migration success through the FCRPS and should be considered in the development of management triggers (Crozier et al. 2014). Developing triggers indicative of likely high temperatures weeks in advance would allow more time to consider alternative measures and enhance the region's ability to ready and implement proactive measures to maintain, to the extent practicable, passage through adult fish ladders.

3. **NOAA Fisheries, co-managers, and federal operators should develop a trap and transport contingency plan for Snake River sockeye salmon.**
    - The Plan should consider temperature and tailrace conditions in the lower Columbia River as well as the Snake and Salmon rivers and the likelihood that adult Snake River sockeye salmon will survive to the targeted fish trap. IDFG and other co-managers involved in further development of sockeye salmon recovery planning should develop goals and objectives for trap and transport operations.
    - Rationale: The trap and transport contingency plan should allow managers to act quickly, and in concert, to implement necessary measures to attain objectives. Quicker implementation of pre-planned actions should increase the likelihood that targeted adults will be trapped successfully and used to complement and further recovery goals and objectives.

4. **Evaluate, and install if feasible and effective, pumps in the Little Goose Dam forebay to bring cool water from depth into the adult ladder.**
    - Evaluate the feasibility of, and install permanent pumps to bring deeper water up into the ladder exit at Little Goose Dam, if likely to be effective at reducing temperature differentials in the single fish ladder at Little Goose Dam.
    - Rationale: Temporary (rental) pumps have been used at Little Goose Dam during 2016 and thus far have been effective in reducing ladder temperatures and the potential for a temperature gradient. If this operation proves successful as temperatures warm through late summer, the Plan should consider installing permanent pumps at this project, as well.

5. **Investigate methods to reduce maximum temperatures and temperature differentials in adult fish ladders at mainstem lower Snake and Columbia dams identified (either through reviews of existing data or through monitoring – see #1 above) as having these problems, and implement if feasible.**
    - Operational and structural means of reducing differential temperatures (ideally, to <1.0°C if feasible) in mainstem dam fish ladders should be investigated. These methods might include altered spill levels or spill patterns, altered turbine priorities (and restoring Kaplan status to Unit 1 at Lower Granite Dam), as well as the use of inducers, cooling pumps, and deeper intakes to feed cooler water to the fishway exits.
    - Rationale: Impaired adult passage through mainstem fishways due to high summer temperatures can contribute to substantial adult losses (particularly of migrating sockeye and summer Chinook salmon). Investigating, and implementing if feasible, operational or structural methods to reduce these effects will likely be increasingly important in the future given observed and predicted warming trends in the Columbia basin.

6. **The federal operators should prepare an alternatives study assessing the potential to trap and haul adult sockeye salmon[26]at lower Snake River projects to meet the goal and objectives of a contingency plan developed by NOAA and the Co-managers (see #3 above).**
    - The alternatives study should assess technical and biological issues associated with developing a facility to trap and haul adult salmon and steelhead. The federal operators should coordinate with IDFG, Nez Perce Tribe, Shoshone-Bannock Tribe, and NOAA Fisheries, in the development of this study.
    - Rationale: Trapping adult salmon, though not ideal (see discussion in previous sections), ultimately proved to be a safe and effective means of collecting a portion of the Snake River sockeye salmon migrants and transporting them to the Eagle Hatchery. Trapping adults at locations downstream of Lower Granite Dam has the potential to collect a larger number of adults from this ESU (and potentially Snake River summer Chinook salmon and steelhead) for transport to safe locations during periods of high summer temperatures.

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[26] Potential effects (either negative or positive) to other species (e.g., summer Chinook salmon, steelhead, or lamprey) that could be caught incidentally in a fish trap should also be considered.

7. **Develop water temperature models, or similar tools, to assess the effect of alternative project operations at Lower Granite and Little Goose dams on ladder and tailrace temperatures or implement a study to empirically assess the effect of proposed operations.**
    - As noted earlier in this document, there remains uncertainty and disagreement regarding the relative effect of turbine and spill operations on forebay and tailrace temperatures at Lower Granite and Little Goose dams. A modeling tool should be designed to reasonably predict the temperature response in the forebay and tailrace of Lower Granite and Little Goose dams. Alternatively, empirical studies could be developed and implemented to test alternative hypotheses regarding these actions. Update: In May of 2016, the System Configuration Team (SCT) requested the USACE prioritize and develop a model to more accurately predict the temperature effects in lower Snake River projects forebays and tailraces with changes in spill and turbine operations.
    - Rationale: Disagreement regarding the effects of operations on forebay and tailrace temperatures hampered regional discussions and delayed implementation of potentially beneficial actions in 2015. The existing models are not able to evaluate the likely near-field (ladder, tailrace, and downstream reservoir thermal layering) effects of alternative operations (e.g., surface route spill compared to conventional spill or no spill) at Lower Granite and Little Goose dams. Empirical tests of these actions could provide enough information to address regional concerns. Lacking this capability, the regional managers are likely to continue to disagree over the best course of action to take in these circumstances.

8. **NOAA Fisheries and Co-managers and federal and other hydro operators should develop and prioritize locations where additional PIT tag detections could substantially improve our understanding of adult behavior and survival during high temperature events, and cooperate in the development and installation of these detection systems, if practicable.**
    - PIT tag detections at mainstem fish ladders, river mouths (e.g., the Deschutes River), and other detection systems in tributary habitat near the spawning grounds provided valuable information for assessing the behavior and survival of adult sockeye salmon exposed to high temperatures in 2015. However, many gaps remain. For example, many PIT tagged adult sockeye were not detected again after passing The Dalles Dam. These fish could have moved past John Day Dam, fallen back at the Dalles Dam or found and moved into thermal refuges (e.g., Drano Lake).
    - Rationale: Broadly supported, prioritized recommendations of additional detection locations would be valuable for future regional discussions in many planning forums. Unlike active tag studies, once PIT tag detectors are installed, data are available annually and can therefore be relied upon for assessing fish behavior during

unexpected environmental conditions. Knowing the behavior and fate of these fish could lead to additional measures to enhance survival in future years.

9. **NOAA Fisheries, hydro operators, and co-managers should continue to evaluate the relative migration success of adult Snake River sockeye salmon that migrated inriver or were transported from lower Snake River collector projects as juveniles and consider this information when developing future transport strategies at the Snake River collector projects.**
    - Substantial effort has gone into developing transport strategies that consider seasonal and annual patterns in the returns of inriver migrating and transported Snake River steelhead and spring/summer Chinook. Only recently have returns of PIT tagged hatchery Snake River sockeye salmon been sufficient for similar evaluations. NOAA Fisheries should evaluate the potential to make annual assessments for hatchery and naturally produced Snake River sockeye salmon.
    - Rationale: This report documents behavioral differences between adult sockeye salmon that were transported as juveniles compared to those that migrated in river. Specifically, losses of fish in the lower Columbia River that were transported as juveniles far exceed losses of fish that were not transported and none of the transported group survived the upstream migration to Lower Granite Dam in 2015. Similar, though less substantial survival differences have occurred in some, but not all previous years. Consistent monitoring and additional analyses of transported and inriver sockeye salmon smolts returning as adults will need to be considered, along with updated information on spring/summer Chinook and steelhead that migrate at the same time, in developing future transportation strategies at the Snake River collector projects. Although findings that altered transportation operations as a result of this effort would not necessarily be responsive to high temperature events, they would contribute to a broader strategy for increasing the returns of adult Snake River sockeye salmon given observed ranges of environmental conditions.

10. **Evaluate the Dworshak cold water release program to maintain temperatures in the lower Snake River below 18°C during June and most of July to reduce adult sockeye salmon mortality in the lower Snake River.**
    - The volume of water needed to maintain temperatures at or below 18°C as well as the volume needed to reduce water temperatures when the target is exceeded should be evaluated and compared to the current water temperature management target of 20°C. Coolwater releases from Dworshak should be used efficiently to substantially benefit multiple salmon and steelhead species. This process should include NOAA Fisheries, other regional fisheries managers, particularly the Nez Perce Tribe, and the State of Idaho.

- Rationale: Sockeye passage generally peaks in early July at Ice Harbor Dam. Maintaining temperatures below 18°C during this time would benefit migrating adult sockeye salmon. However, managing to this target is not without risk as less cool water would be available in August and early September to benefit adult migrants of other species (and rearing juvenile fall Chinook salmon). An evaluation of the trade-offs between species of alternative temperature targets would assist managers to most efficiently use Dworshak Dam cool water releases to benefit multiple anadromous species.

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Appendices

Appendix A – Analysis of Emergency Sockeye Operation at Little Goose Dam

Appendix B – NMFS Take Determination Letter

Appendix A: Analysis of Emergency Sockeye Operation at Little Goose Dam

FILE MEMORANDUM

DATE: 7/22/2015

FROM: Trevor Conder NOAA Fisheries

TO: Ritchie Graves

SUBJECT: Analysis of Emergency Sockeye Operation at Little Goose Dam

This analysis investigates the direct survival impact to migrating subyearling Chinook salmon as a result of a temporary change from a 30% spill operation to a test 0% spill operation at Little Goose Dam (LGO) in an attempt to increase adult sockeye passage. This memo uses regionally available survival and smolt monitoring data to estimate the impacts of this test operation. Based on this analysis, we expect the impacts of this two day full powerhouse operation will likely result in the direct mortality of an additional 29 juvenile migrants, which equates to .01% of the subyearlings passing the project.

Based on smolt monitoring information provided at the Fish passage Center website, the passage index for subyearling Chinook salmon at LGO has been declining over the last five days (7-18-7/22) averaging 1321 and ranging from 1015 to 1802 (Table. 1).

Site	SampleDate	Species	RearDisp	Riverflow	Collcount	Sampcount	PassIndex
LGS	7/18/2015	CH0	Combined	29.11	1197	51	1802
LGS	7/19/2015	CH0	Combined	32.52	882	58	1345
LGS	7/20/2015	CH0	Combined	28.51	772	77	1277
LGS	7/21/2015	CH0	Combined	28.46	706	205	1168
LGS	7/22/2015	CH0	Combined	27.51	617	123	1015

Table 1. Subyearling Smolt Monitoring Data Acquired 7/22 from Fish Passage Center Data site at http://www.fpc.org/smolt/smoltqueries/smpdailydata2015v1.aspPassage

Using this information, we estimate a two day 48 hour operation will potentially affect 2642 subyearling Chinook assuming the passage index is an accurate estimate of juvenile salmonid passage at LGO, and this average passage index will continue. Passage index of STH and Yearling Chinook indicate a declining trend and is less than 100 fish per day for both species at LGO.

In 2007, prior to the installation of the LGO TSW, data from (Beeman et al. 2008) indicates that 4.4% of subyearling Chinook used turbines, 25.8% used the bypass route, and 69.8% used a deep spillway route.

Based on this information, and considering the 2007 operation is the most similar to the current operation, we use this past information to assume for this analysis that 4.4% of subyearling Chinook are currently passing through turbines at LGO and 69.8% are using deep spill under the current no TSW operation. If there is a switch to full powerhouse operation as planned, all downstream migrants will be navigating through the LGO powerhouse and we expect the proportion of fish using turbines will increase as a function of FGE observed in recent years.

		Route			
Year	Measure	Deep Spill	Spillway Weir	Turbine	Juvenile Bypass System
2012	Proportion	0.2484	0.4765	0.0493	0.2258
	Survival	0.9421	0.9623	0.8128	0.9807
2013	Proportion	0.1213	0.6470	0.0502	0.1816
	Survival	0.9106	0.9143	0.8402	0.8978

Table 2. Passage proportion and survival probability by route for subyearling Chinook salmon at Little Goose Dam (Harnish et al. 2015).

In 2012 and 2013, the screen system at LGO guided approximately 80% of fish migrating through the powerhouse into the JBS system with 17.9% and 21.7% of powerhouse migrants using turbine routes (Table 2). Using an average of the two years (19.8%) the number of fish expected to arrive during a two day operation based on the two day passage index average of 2642 (.198*2642) equates to 523 fish going through turbine units. This is compared to 116 fish passing turbines that we can expect under the current deep spill scenario. This is a difference of 407 fish that may experience a lower turbine survival probability. Considering that under a 30% operation these fish would use the spillway, 2013 deep spill survival data to these 407 fish produces an estimated 371 survivors (.9106 * 407). Under the test operation, these fish will likely migrate through turbines so applying the same low turbine survival data to these 407 fish produces an estimated 342 survivors (.8402 * 407). This is a difference of an additional 29 subyearlings lost to mortality due to this proposed two day operation. Given the high guidance at LGO, the rest of the fish will likely be bypassed to transport barges and are not further considered in this direct survival evaluation.

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Appendix B: NMFS Determination Take Letter

UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL MARINE FISHERIES SERVICE
West Coast Region
1201 NE Lloyd Boulevard, Suite 1100
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July 10, 2015

Ann Setter
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RE: Emergency trapping and transport of Snake River Sockeye Salmon at Lower Granite

Dear Mr Hassmer:

National Marine Fisheries Service (NMFS) Interior Columbia Basin Office's Columbia Hydropower branch has determined that take associated with your request to initiate a trap and hall operation for Snake River Sockeye as part of an emergency action due to high temperatures in the Snake River Basin is permitted in 2015 under the IDFG Section 10(a)(1)(a) permit for the Snake River Sockeye Salmon Hatchery Program and the 2014 FCRPS Supplemental Biological Opinion (2014 Opinion). The estimated numbers of listed salmonids needed to conduct this activity in 2015 are given in Table 3 below.

Project Justification, Description, and Methods

The State of Idaho plans to transport Snake River Sockeye collected at Lower Granite Dam (LGD) and transport them to the Eagle Fish Hatchery for broodstock collection or release into Redfish Lake. This action is being taken as an emergency measure due to the extreme temperature conditions being experienced throughout the lower Snake River, extending upstream through the Salmon River Basin. During the first week of July temperatures in the forebay of LGD have exceeded 25^0 C at a 3 meter depth, temperature at the Anatone gauge located upstream of Lower Granite Reservoir have exceeded 24^0C, and temperature at the Whitebird gauge on the Salmon River has exceeded 25^0C. These temperatures are extremely stressful to sockeye and are approaching lethal levels if the fish are exposed to these temperatures for an extended duration. Collection and transport of these fish from the Lower Snake River projects to Sawtooth Valley lakes or artificial propagation facilities is deemed essential to increase the survival rate of individuals from this endangered population. Collection and transport from LGD will facilitate recovery actions described in the Snake River Sockeye Salmon Recovery Plan.

The collection and transport of sockeye is consistent with provisions of NMFS's 2014 Supplemental Biological Opinion (2014 BiOp) on the Federal Columbia River Power System (FCRPS) and the Endangered Species Act (ESA) Section 10(a)(1)(A) permit to Idaho Department of Fish and Game (IDFG) for the Snake River Sockeye salmon hatchery program. The Section 10(a)(1)(A) permit specifically authorizes removal of sockeye salmon from the Lower Granite Dam trap when low-flow or temperature conditions are expected to limit adult survival to the hatchery and the spawning grounds. Allowable mortality was not to exceed 10% of the fish handled during trapping and transport. Due to the extreme temperature conditions this year, IDFG has requested additional take coverage for incidental mortality to Sockeye salmon from 10% to 20%.

NMFS' 2014 BiOp supplemented the actions of the 2008 and 2010 FCRPS BiOps. Reasonable Prudent Alternative (RPA) Action 42 of these opinions addressed the need to investigate the collection and transport of adult sockeye from LGD to Sawtooth Valley lakes or the artificial propagation facilities. NMFS included an effects analysis in section 2.5.1.5 of the 2010 BiOp for operating the LGD trap to collect sockeye for transport. This analysis recognized that some Chinook and steelhead would also be collected and would incur some mortality incidental to the process of collecting and sorting adult sockeye. IDFG has requested an additional, incidental, potential lethal take of 38 Chinook salmon and 33 steelhead as a result of this action. Due to high temperatures in the Snake and Columbia rivers, and at the site of the adult trap at Lower Granite Dam (>70^{0}F) this July, about 2.7^{0}F warmer than in the poor sockeye survival year of 2013 (Crozier et al. 2014), the incidental take of sockeye, Chinook, and steelhead is likely to be higher than NMFS anticipated in 2010.

The trap at LGD is normally not operated when water temperature exceeds 70^{0}F. This criterion will be exceeded. The Corps has tried to cool the temperature of the trap by installing pumps that draw cooler water from a depth of 45 feet in the dam's forebay, but has been unable to achieve the 70^{0}F criterion. Operation of this trap outside of the 70^{0}F temperature criterion is consistent with RPA Action 9, Fish Emergencies, of NMFS's 2014 BiOp, which allows operation of fish facilities outside of criteria during emergency events. NMFS deems the current temperature conditions in the Salmon and lower Snake Rivers to constitute an emergency, and action is needed to reduce its impact on these returning Snake River sockeye salmon adults. The LGD trap will only be operated for a four hour period in morning hours (6:00 am to 12:00 pm) to limit the stress to collected fish. Trapping is also being considered at the Ice Harbor project. The same restriction would be applied at this location i.e. Trapping will be limited to a 4 hour period within the hours 6:00 am to 12:00 pm.

Operational Reporting & Notification Requirements

The following additional measures will be taken to document the condition of all species handled during adult trapping for evaluation and preparation of an adaptive management plan for use in future years if these environmental conditions continue or worsen:
Daily Trap operation records will include:

1. Trap and fish ladder water temperatures
2. Trap operation rate
3. Number of fish trapped and handled by species, and their final disposition (transported, released, etc.)
4. Number of mortalities or injuries by species
5. Relevant observations on fish condition

A daily report will be emailed to NOAA Fisheries with a summary of these items.
Fish transportation records (for sockeye salmon only) will include:

1. Numbers of fish transported each day
2. Time fish were held before transport
3. Transport time to the Sawtooth Valley and temperature at which the fish were transported.
4. Mortalities incurred during transport
5. Survival to spawning at the hatchery of transported fish.

Within 2 months of the completion of sockeye spawning, IDFG will send a report documenting these records and presenting a summary and analysis of the procedures to NOAA Fisheries.

Take Estimates

At present, IDFG Section 10(a)(1)(a) permit for the Snake River Sockeye Salmon Hatchery Program allows a 10% mortality rate and IDFG has requested a 20% rate. Neither this permit, nor the 2014 Supplemental FCRPS BiOp has a mechanism for allowing such an increase. However, we request that you assess the cause of mortality when such occurs. Mortalities resulting from infectious diseases due to the high water temperatures necessitating this action should not count against your take authorization because these individuals would have otherwise died prior to spawning in the migration corridor upstream of the FCRPS. Thus, you are still authorized a 10% incidental mortality rate through the hatchery program permit.

IDFG estimated the number of fish that will be handled during the trapping process are 1,000 listed Chinook and 3,800 steelhead passing during the prosed emergency trapping period (July 13 – July 3, the 19-day estimated period of this operation). NMFS believes these are reasonable estimates. The adult trap will be operated during a four hour period within the hours of 6:00 AM – 12:00 PM.

IDFG has estimated the adult sockeye trapping activity may result in 38 listed Chinook salmon and 33 steelhead incidental mortalities. Table 8-5 of the 2014 Supplemental FCRPS BiOp summarizes estimates of take resulting from all RM&E activities given average abundance during the 2008-2012 migration years (including operation of the adult traps for routine purposes). NMFS finds that the incidental take requested to implement the sockeye emergency transportation should not exceed the overall take allotted in the 2014 BiOp. Additionally, given the relatively large return of Snake River spring/summer Chinook salmon in 2015, the proportional impacts will likely be smaller than estimated.

Please notify Paul Wagner (503)231-2316, paul.wagner@noaa.gov as soon as possible of any deviation from the terms and conditions in this determination.

Sincerely

Ritchie J. Graves, Chief
Columbia Hydropower Branch
Interior Columbia Basin Office
NOAA Fisheries, West Coast Region

Cc: Rock Peters
Russ Kiefer
Darren Ogden
Bill Hevlin
Paul Wagner

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