Assessment of Impacts to Columbia and Snake River Temperatures using the RBM10 Model

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***** DRAFT *****

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ACRONYMS/ABBREVIATIONS

Acronyms/Abbreviations	Definition
°C	Degrees Celsius
BOR	U.S. Bureau of Reclamation
BPA	Bonneville Power Administration
CRSO	Columbia River Systems Operation
DART	(Columbia River) Data Access in Real Time
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
MAE	Mean absolute error
NPDES	National Pollutant Discharge Elimination System
PUD	Public Utility District
R^2	Correlation coefficient
RM	River mile
RMSE	Root mean square error
TMDL	Total Maximum Daily Load
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WQC	Water quality criteria

1.0 INTRODUCTION

This report documents the application of the RBM10 model to assess the impact of human activities that alter Columbia and Snake river temperatures. The primary purpose of this work is the planned development of a Total Maximum Daily Load (TMDL) for temperature in the Columbia and Snake Rivers.

The RBM10 model used for this assessment is an updated version of the model code and database used for a 2003 draft TMDL (EPA, 2003). This update was conducted in 2017 and 2018 by Tetra Tech, Inc., under contract to the U.S. Environmental Protection Agency (EPA). A model update report documents all aspects of the update (Tetra Tech 2018). Topics include a description of the model update process, model structure and limitations, data inputs, model calibration, and evaluation of model performance. In addition to updating and re-calibrating the model, Tetra Tech also developed a number of tools and analyses to support this impact assessment, including river geometry characteristics for free-flowing model scenarios, trend analysis of simulated temperatures, point source inputs, and software utilities to support boundary condition and tributary scenarios.

This project 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), the Bonneville Power Administration (BPA), and the U.S. Bureau of Reclamation (BOR) are developing one- and two-dimensional models to assess temperature in the Columbia and Snake Rivers. EPA is collaborating with the above federal agencies, particularly in circumstances where model scenarios for the TMDL are similar to CRSO EIS model scenarios.

Assessment of human-caused temperature impacts to rivers presents several technical challenges. The thermal regime of a river is continually changing in response to atmospheric heat inputs as well as watershed influences such as headwater temperatures and tributary inputs. To identify source impacts, the effect of source inputs must be separated from the natural variation in the system. Furthermore, temperature impacts dissipate over time and space as river temperatures continually rise or fall toward equilibrium with atmospheric conditions. This presents a challenge for cumulative impact analysis.

Mathematical models are useful tools to address challenges of this kind, and they are commonly used in TMDL analysis. By tracking the time-varying factors influencing river temperature, models can be used to assess the thermal loading capacity and source impacts across time and space. EPA has extensively evaluated and tested the RBM10 temperature model, ensuring that the model is capable of performing this source assessment.

For the Columbia River TMDL, the scale of modeling and analysis is unusually large, with a study area spanning almost 900 river miles. Even so, the study area does not include a significant fraction of the overall Columbia River basin watershed in Canada, Idaho, Oregon, and Wyoming (headwaters of the Snake River). It is not practical to build a model of the entire Columbia Basin watershed, so the watershed area upstream of the model domain is treated as a boundary condition that delivers water of known flow and temperature into the modeled reaches.

The TMDL source assessment presents some unique technical features and challenges. The assessment must address the cumulative impacts from 15 hydroelectric dams (11 on the Columbia River and 4 on the Snake River) and incorporate the impact of cold water releases from Dworshak Dam via the Clearwater River to the Snake River.

In addition, a growing body of research is producing evidence that climate change has caused a substantial increase in Columbia and Snake Rivers temperatures. This RBM10 modeling assessment includes analysis of the warming trend using long term simulations. This analysis is part of a broader effort in the TMDL project to review and synthesize available estimates of warming to date as well as projected future trends.

2.0 RBM10 MODEL

2.1 MODEL DEVELOPMENT

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 times and simplicity of the model setup afford the opportunity to simulate long time periods. The long simulation periods can be utilized to 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 EPA and continued to develop and apply the model at the University of Washington. The model theory and test applications were published in the peer-reviewed journal Water Resources Research in 2009 (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).

Under contract with EPA, Tetra Tech completed an update of the RBM10 model system in 2017 and 2018. This project updated the model database, simulation period, and calibration of the RBM10 model while retaining all of the core mathematical structure of the model, which was originally developed by EPA Region 10. This update and all relevant information about the 2018 RBM10 model is documented in the RBM10 model report (Tetra Tech 2018). Additional details on the model structure are 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. In Phase I of the project, Tetra Tech updated the FORTRAN code of the RBM10 model and preprocessing utilities (Tetra Tech 2017), and the model simulation period was extended through 2016 for a full simulation period of 1970 – 2016. In Phase II of the update, input and calibration data quality issues and potential sources of error were investigated and resolved, and the model was recalibrated to improve the model performance.

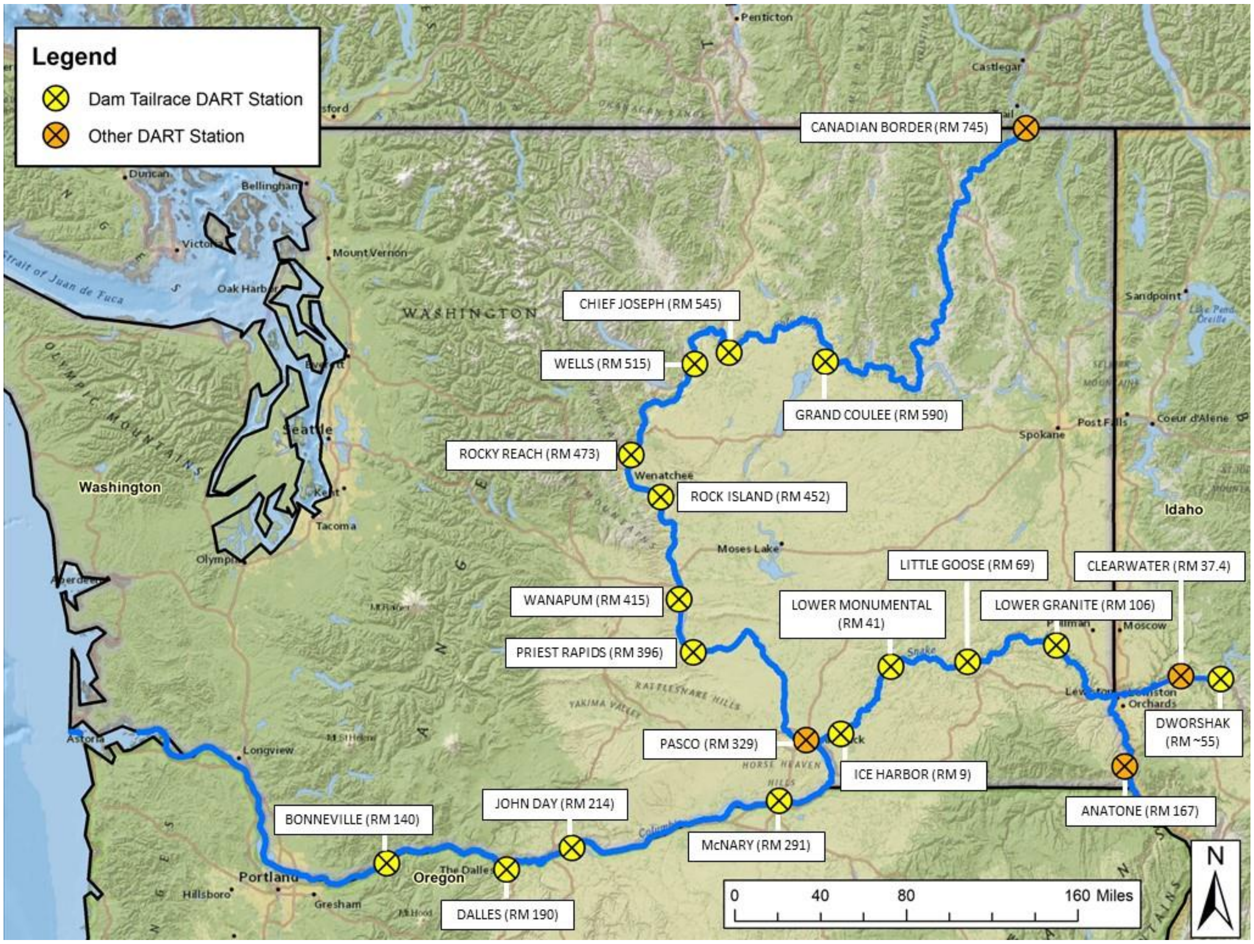
The RBM10 model of the Columbia and Snake Rivers simulates the following inputs and processes: upstream boundary inputs (flow, temperature), hydrodynamics within each model segment (flow, velocity, channel geometry), surface heat exchange within each model segment, and heat inputs from tributaries.

The following processes are not simulated because they have 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.

2.2 MODEL CHARACTERISTICS

2.2.1 Spatial Representation

The 2018 RBM10 model simulates the Columbia River from the Canadian border (Columbia river mile [RM] 745.0) to the mouth at Astoria, Oregon; the Snake River from Anatone, Washington (Snake RM 168) to its confluence with the Columbia River near Pasco, Washington; and the Clearwater River from Orofino, Idaho (Clearwater RM 44.6) to its confluence with the Snake River near Lewiston, Idaho (Snake RM 139.3) (***Figure 2-1***). 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.



Source: Washington Department of Ecology Large Dams and River Miles datasets

Figure 2-1 The Columbia and Snake Rivers in Washington and Oregon.

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 relatively uniform and can be assumed constant for modeling purposes. The length of the reaches in the RBM10 model usually varies between one mile and ten miles. Reaches are then divided into segments which are the computational units of the model, meaning that a unique temperature is simulated in each segment. The typical length of a segment in the RBM10 model is one mile.

The RBM10 model domain includes the existing hydroelectric projects on the Columbia and Snake Rivers (***Figure 2-1***). Except for 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 modeling purposes.

Table 2-1 Mainstem Columbia and lower Snake River dams in RBM10 Model Domain

Name	RM	Operator	Type	Year(s) Completed*	Generating Capacity (MW)
Columbia River					
Grand Coulee Dam	597	BOR	Storage	1973	525
Chief Joseph Dam	545	USACE	Run of River	1961/1973	2,069
Wells Dam	516	Douglas County Public Utility District No. 1	Run of River	1967	774
Rocky Reach Dam	474	Chelan County Public Utility District No. 1	Run of river	1961/1971	1,280
Rock Island Dam	453	Chelan County Public Utility District No. 1	Run of River	1932/1953/ 1979	624
Wanapum Dam	416	Grant County Public Utility District No. 2	Run of River	1964	1,038
Priest Rapids Dam	397	Grant County Public Utility District No. 2	Run of River	1961	956
McNary Dam	292	USACE	Run of River	1957	980
John Day Dam	216	USACE	Run of River	1971	2,160
The Dalles Dam	192	USACE	Run of River	1960/1973	1,780
Bonneville Dam	146	USACE	Run of River	1938/1982	1,050
Snake River					
Lower Granite Dam	108	USACE	Run of River	1975/1978	810
Little Goose Dam	70	USACE	Run of River	1970/1978	810
Lower Monumental Dam	42	USACE	Run of River	1970/1978	810
Ice Harbor Dam	10	USACE	Run of River	1962/1976	603

*Multiple years indicate initial completion year and subsequent installation of additional hydroelectric turbine year(s)

The reservoir behind Grand Coulee Dam (Lake Roosevelt) is used for flood control purposes and, in consequence, the fluctuations in water elevations can be significant and reservoir volumes must be estimated each day. The RBM10 model uses the water surface elevation as an input to calculate the changes in velocity and residence time of the water moving throughout the reservoir.

2.2.2 Temporal Resolution

The 2018 RBM10 model simulates daily average temperatures in the Columbia and Snake Rivers from 1970 through 2016. The simulation period was constrained by the timeframe of the completion of the hydroelectric system and the availability of publicly available data necessary to setup and run the model. The last hydroelectric project, Lower Granite Dam, was completed in 1975.

The use of one-dimensional, daily average simulations carries benefits. This modeling approach allows for an efficient, long-term simulation (47 years) that captures extreme high and low daily average temperatures in the historic record. This approach and the underlying input database incorporates the overall range of variation better than most models used for TMDL development.

2.2.3 System Variability

Seasonal variation in river temperature is substantial in the Columbia and Snake Rivers. An example of seasonal and annual variability is illustrated in ***Figure 2-2***, which shows the range of average daily temperatures estimated for a free-flowing river over a 47-year model simulation at Priest Rapids Dam.

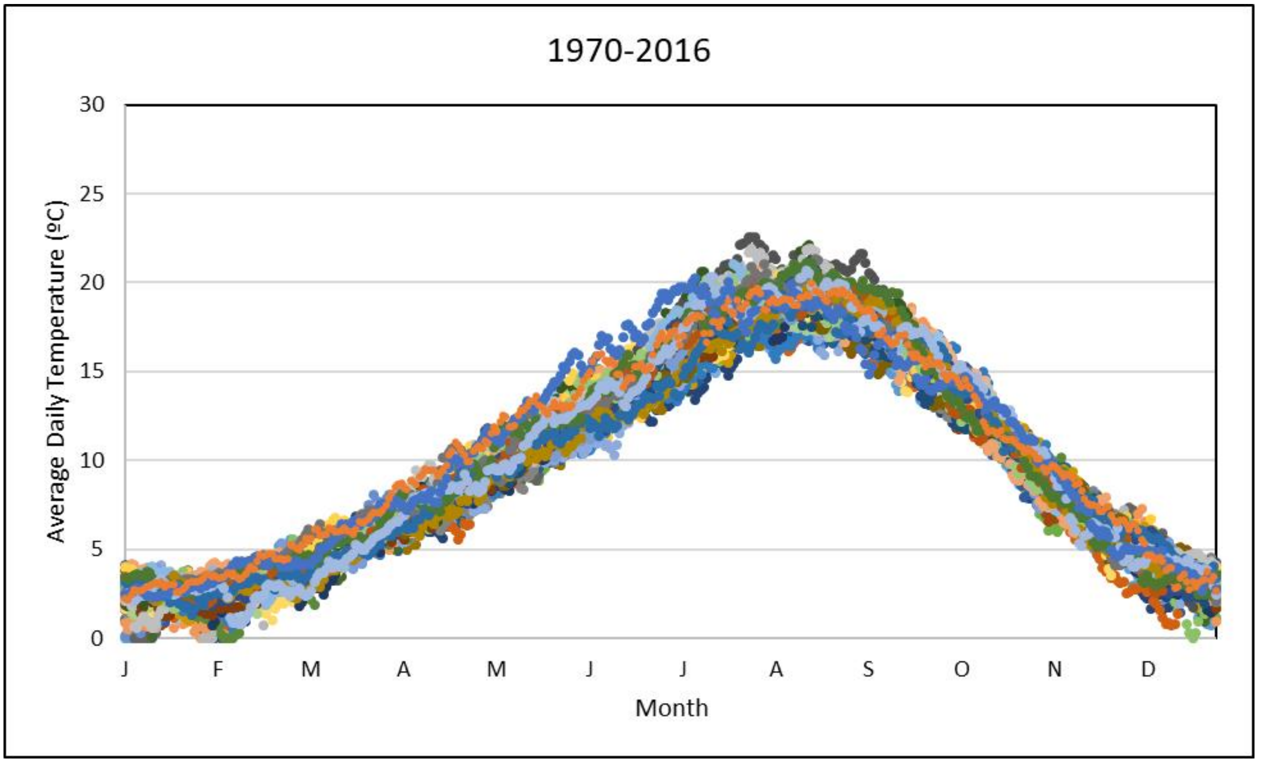


Figure 2-2 RBM10 simulation of free-flowing river temperatures at Priest Rapids Dam on the Columbia River (all years: 1970 – 2016)

A recognition of system variability and inherent model uncertainty influences how model scenarios are run and outputs are post-processed in this report. EPA's goal is to capture central tendencies in the multi-year simulations (e.g. long-term mean conditions) while also capturing seasonal variation and critical conditions. In addition, conservative assumptions are needed to ensure that impacts are not underestimated. EPA achieved these goals through the following actions:

- Present-day conditions in model simulations are represented by the aggregated results for 2011 – 2016 to provide a multi-year average.

- Model results are aggregated by month (approximately 30-day periods) to address seasonal variation and provide long-term averages that are not influenced by outlier days/weeks.
- Impacts are estimated as mean values and not extreme values in most cases to maximize confidence in the impact estimates. This helps quantify impacts when the changes are relatively small compared to the range of variation.
- Impacts of point sources are evaluated at the mean and 90^{th} percentile level because of the regulatory implications of point source impact estimates and the need for a conservative approach (i.e., margin of safety).
- Model outputs are processed at all dam tailrace sites, major tributary confluences, and a location with substantial point source inputs (Columbia RM 42) to ensure that worst-case locations of impact are identified.

This assessment focuses on source impacts from July through mid-November, when EPA's data assessment indicates that temperatures exceed numeric criteria in state water quality standards in certain locations and time frames (Merz et al. 2018).

2.2.4 Model Calibration and Performance

The 2018 RBM10 model update and calibration 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 (temperature warming rates), duration and magnitude of peak temperatures during the summer season, and negative slope of the temperatures during the fall season (temperature cooling rates).

The following example plots are comparisons of simulated and measured temperatures at the tailrace monitoring location at John Day Dam on the lower Columbia River. The first plot shows daily temperatures over the period 2011 – 2016. The second plot is a composite of 10-year average temperatures for each day of the year. Temporal plots were reviewed in conjunction with the error statistics to evaluate model performance and identify potential areas of concern in the model setup and/or data inputs. The complete set of plots and error statistics used to evaluate model quality are included in the model update report (Tetra Tech 2018).

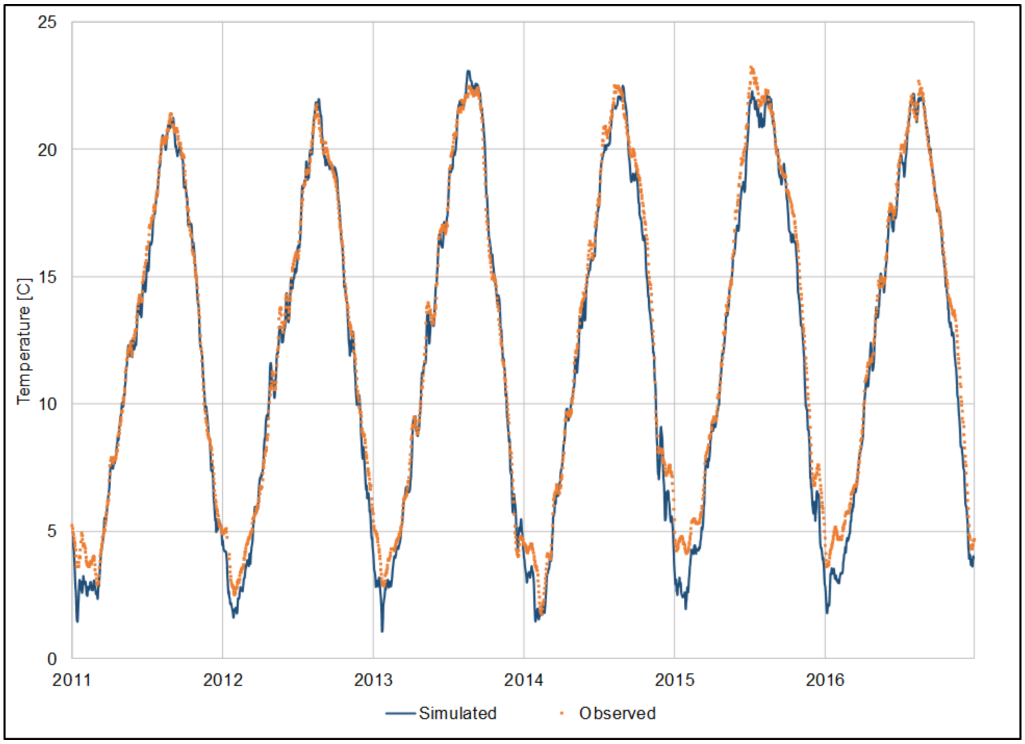


Figure 2-3 Simulated and observed daily average temperatures at John Day Dam (2011 – 2016)

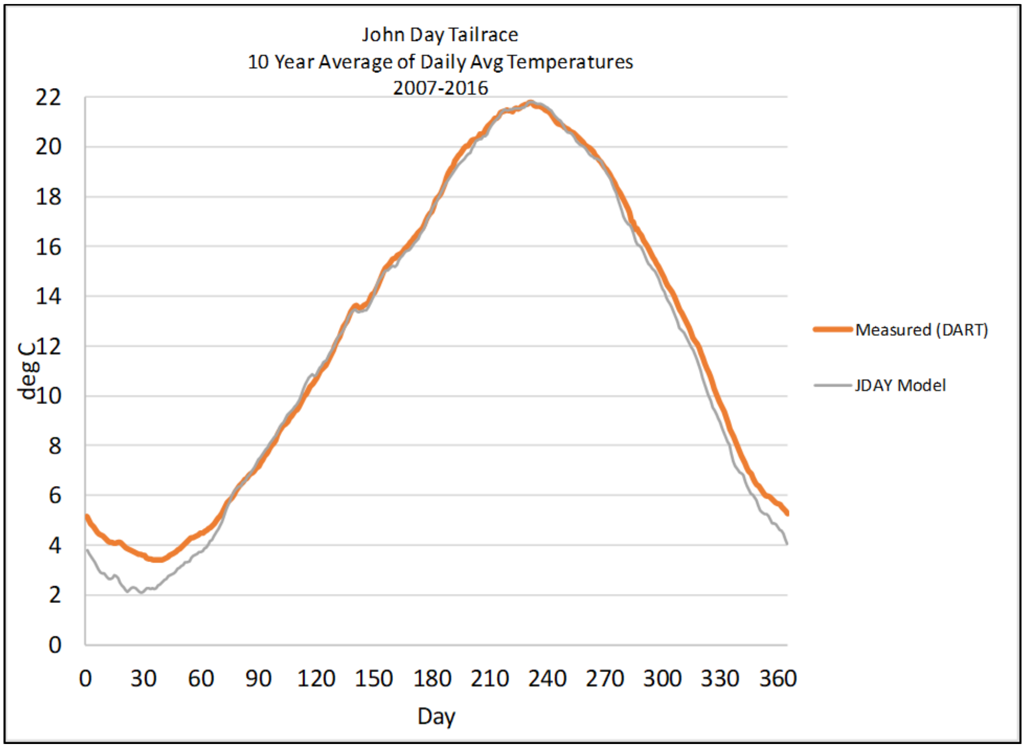


Figure 2-4 Simulated and observed 10-year average daily temperatures at John Day Dam

The ability of the model to capture these temperature variations was determined 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 minimize the differences between the simulated and observed temperatures.

Examples of statistical results obtained at each station in the Columbia and Snakes Rivers are presented in ***Table 2-2*** and ***Table 2-3***. The tables present the statistical analyses resulting from the comparison of the model simulations against all available observations within the period 2007 – 2016.

Overall, the statistics of model performance 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 mean absolute errors (MAEs) of 0.4°C – 0.5°C, and average root mean square errors (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 (R^2) between the observations and model simulations in the Columbia and Snake Rivers is 0.99.

Table 2-2 Model performance statistics (July – August)

Columbia River					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R^2**
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					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R^2**
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					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R^2**
PEKI	1337	0.174	0.377	0.500	0.918
	Average	**0.174**	**0.377**	**0.500**	**0.918**

Table 2-3 Model performance statistics (September – October)

Columbia River					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R^2**
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					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R^2**
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					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R^2**
PEKI	768	0.057	0.271	0.357	0.962
	Average	**0.057**	**0.271**	**0.357**	**0.962**

As part of the model update, EPA conducted a sensitivity analysis of the RBM10 model. This analysis examined the mainstem temperature responses to generic changes in key model inputs (e.g., boundary conditions and model parameters). This information provides useful background for the scenario results, because it describes the relative influence of different model inputs on mainstem temperatures. The sensitivity results are provided in an appendix of the model development report (Tetra Tech 2018).

3.0 SCENARIOS AND RESULTS

3.1 CONCEPTUAL APPROACH OF SOURCE ASSESSMENT USING MODELS

The conceptual approach in modeling to assess source impacts begins by using the calibrated model results (e.g., current conditions) as the baseline for source scenario comparisons. To develop the source scenarios, the calibrated model is modified to remove a given source (or set of sources), leaving all other aspects of the model unchanged. The scenario model is run with the source removed, and results from this model run are compared to the existing condition baseline. Any changes in the simulated temperature are the result of the source removed from the model setup for the scenario run.

3.2 SOURCES EVALUATED IN THIS ASSESSMENT

This report includes assessment of the following activities that impact the temperature of the Columbia and Snake Rivers:

- Dam impoundments
- Dworshak cold water releases
- Climate change
- Tributaries
- Boundary conditions
- Point sources
- Banks Lake water diversion

The model is set up and results are post-processed in a variety of ways to assess these activities. This report is organized by source type. For each source, a brief description of the scenario methodology and assumptions is provided. The scenarios are organized as shown in ***Table 3-1***.

Table 3-1 RBM10 modeling assessment scenarios and analyses

Name	Analysis Type	Focus/Purpose	Model Output Time Frame	Description
Current	Baseline	Excess temperature/loading; compared to other scenarios in source assessment work	1970 – 2016	Calibrated model simulation of existing conditions.
Free-Flowing	Source Assessment – Dams	Impact of sources in TMDL study area	1970 – 2016	Free-flowing river geometry and velocity. Otherwise identical to “Current,” including current flow and temperature conditions at upstream boundaries, tributaries, Banks Lake pump storage, and DWR dam releases.
PS1	Source Assessment – Point Sources	Point source impact	2011 – 2016	“Current” with addition of major point sources and aggregated heat load for minor point sources and future growth. Compared to “Current” to estimate impact.
TR1	Source Assessment – Tributaries	Tributary impact	2011 – 2016	“Current” except for tributary temperature adjustment – reducing all tributary temperatures by 0.5 °C.
WD1	Source Assessment – Banks Lake Pump Storage	Effect of Banks Lake pump storage operations at Grand Coulee	2011 – 2016	Model simulation with “Current” setup except without the diversion/return flow. Compared to “Current” to estimate impact.
BC1	Boundary Impact	Current boundary condition impact	2011 – 2016	Set upstream Columbia and Snake Rivers boundary temperatures to colder temperatures. All other assumptions equal to “Current” scenario.
BC2	Boundary Impact	Boundary condition impact on free-flowing river	2011 – 2016	Set upstream Columbia and Snake Rivers boundary temperatures to colder temperatures. All other assumptions equal to “Free-Flowing” scenario.
(note 1)	Trend Analysis	Estimate of warming since 1970s with dams in place	1970 – 2016	Analysis of trends in output with “Current” model setup.
(note 1)	Trend Analysis	Estimate of warming since 1970s in free-flowing river	1970 – 2016	Analysis of trends in output with “Free-Flowing” model setup. Compared to “Current” to evaluate effect of dams on climate change trend.
DWR1	Boundary Impact	Dworshak Dam cold water release benefits with Snake River dams in place	2011 – 2016	Dworshak Dam releases replaced by flow and temperature for the North Fork Clearwater River above Dworshak reservoir. All other assumptions equal to “Current” scenario.
DWR2	Boundary Impact	Dworshak Dam cold water release benefits in free-flowing Snake River	2011 – 2016	Dworshak Dam releases replaced by flow and temperature for the North Fork Clearwater River above Dworshak reservoir. All other assumptions equal to “Free-Flowing” scenario.

[1] Climate change analysis evaluates trends in output of Current and Free-Flowing scenarios.

3.3 DAM IMPOUNDMENTS (FREE-FLOWING SCENARIO)

To estimate the impact of dams on Columbia and Snake River temperatures, the 2018 RBM10 model setup was altered to represent a free-flowing river instead of a series of reservoirs. The calibrated model already simulated free-flowing reaches such as the Hanford reach, Snake River above Lewiston, and Clearwater River. The methodology used to vary river geometry in free-flowing reaches is described in the model development report (Tetra Tech, 2018). For the "Free-Flowing" scenario, this methodology was applied across the entire model domain.

3.3.1 Methodology and Assumptions

The USACE Hydrologic Engineering Center and called the River Analysis System (HEC-RAS) model results were processed to determine the free-flowing reach geometry for the scenario. The HEC-RAS models were used to simulate channel hydraulics for flow conditions across the range of observed flows in the Columbia River and Snake River. Measured 2010 river bed bathymetry is used as the information base for the HEC-RAS models. Since this data represents current river bottom conditions, it does not account for the change in the river bed that would be expected with dam removal (e.g., erosion of sediments near dams after dam removal).

The flow and associated channel-width and cross-sectional area estimated in HEC-RAS were captured in regression equations. These equations were then built into RBM10, and the model adjusted the free-flowing river geometry each day based on the simulated daily instream flow.

All values presented in plots and tables are daily average, cross-sectional average river temperature. Current conditions are used for all boundary inputs in both "Current" (i.e., impounded) and "Free-Flowing" scenarios, including Dworshak Dam cold water release operations for 2011 – 2016. In the "Current" scenario, upstream flow is passed through each dam in RBM10, including Grand Coulee (the elevation of Lake Roosevelt is variable and based on observations). This means the estimated impacts from the "Free-Flowing" scenario represent only the change in river geometry, not flow management operations at Grand Coulee Dam and other dams as flows are not changed between the two scenarios.

3.3.2 Characteristics of Dam Impacts

The impoundment of a river behind a dam commonly causes a temporal shift in the seasonal temperature regime. ***Figure 3-1*** shows measured and simulated daily average temperatures for each day of the year, averaged over a 10-year period (2007 – 2016), at the Canadian border and Grand Coulee Dam tailrace. The measurements and model estimates are consistent, and both show a substantial temporal shift in temperatures at the dam location. This is a commonly observed characteristic of dam impacts, where late summer/fall temperatures downstream of a dam are warmer than a free-flowing river due to the thermal inertia of the impoundment created by the dam. The same thermal inertia delays warming in the early summer, so the dam releases slightly colder water than the free-flowing river in this time frame.

One option for estimating the impact of Grand Coulee Dam is to calculate the difference in measured temperatures at the border and at the dam over a selected timeframe. For Grand Coulee Dam, the plot indicates that this measurement-based estimate would be similar to the impact simulated by the model, because the simulated temperatures under free-flowing conditions change very little between the border and Grand Coulee Dam.

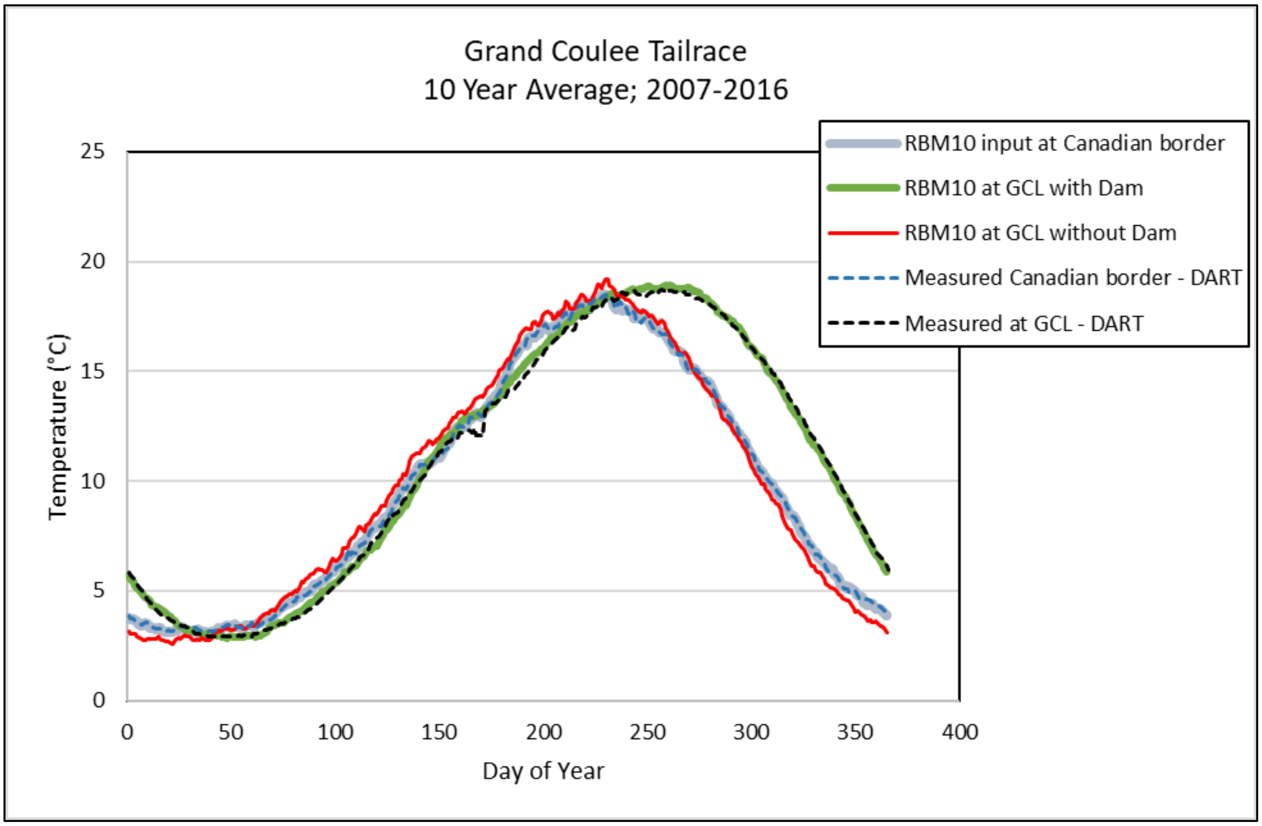


Figure 3-1 Simulated and observed 10-year average temperatures at the Canadian border and Grand Coulee Dam

Figure 3-2 shows a comparison of "Free-Flowing" and "Current" conditions at John Day Dam. Since the entire river upstream of this location has no dams in the "Free-Flowing" scenario, this plot is showing the cumulative impact of the 12 dams upstream of John Day Dam, including dams on both the Columbia and Snake Rivers. This is the location with the highest cumulative impact from dams in the summer months (see ***Table 3-2*** through ***Table 3-4*** below). The plot shows the same characteristic impact as the Grand Coulee plot, where fall temperatures are warmer than a free-flowing river due to the thermal inertia of impoundments. In addition, for this location, summer temperatures are sustained at higher temperatures, for a longer period of time, than the free-flowing condition.

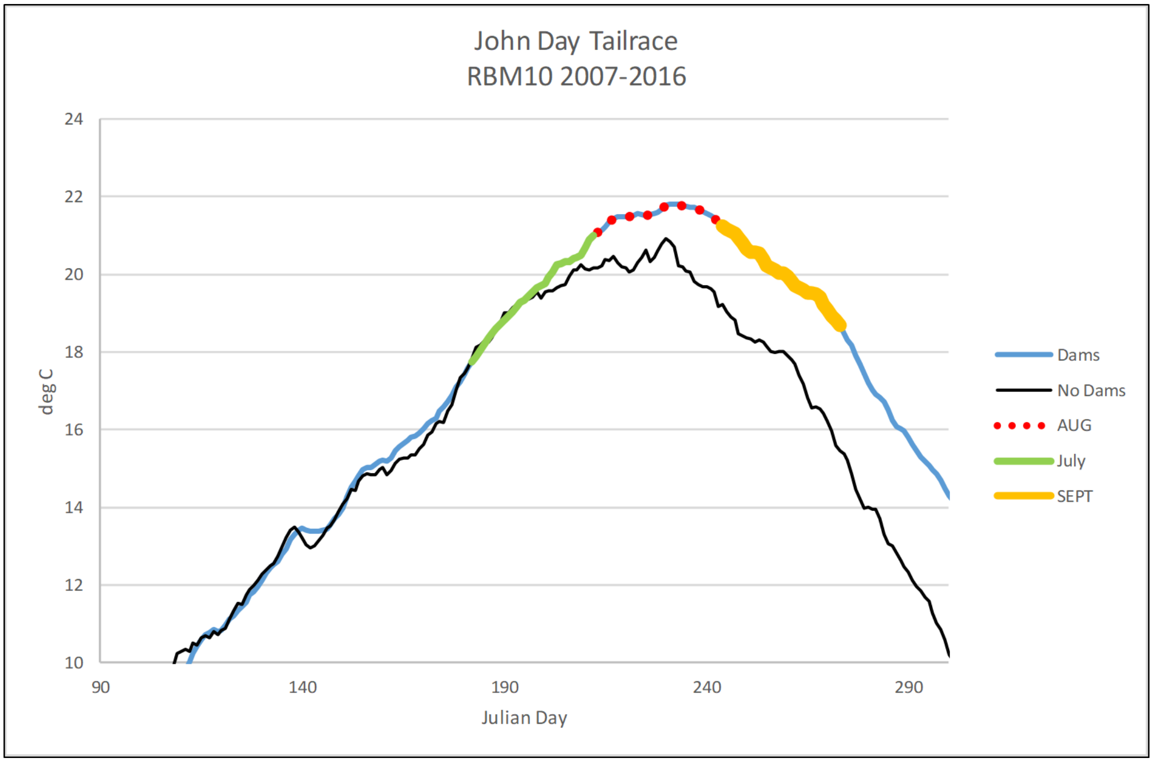


Figure 3-2 Simulated daily average temperatures for free-flowing and current scenarios at John Day Dam

3.3.3 Cumulative Impacts

To evaluate dam impacts, the model is run in "Free-Flowing" and "Current" conditions, and simulated temperatures were output at each dam tailrace location. In order to characterize current impacts, model outputs for 2011 – 2016 were analyzed. The results are provided as monthly average values in plots and tables. The Columbia River results include the 30-day period from October 15 through November 15, because a fall spawning criterion applies at a location near Bonneville Dam in that timeframe. The following interpretation is provided on the results:

- Dam impacts vary substantially by month and by river location.
- Mid-Columbia River locations are highly influenced by Grand Coulee Dam. Grand Coulee Dam releases water temperatures that are cooler or warmer than the "Free-Flowing" conditions depending on the month. The warming effect increases from August through mid-November.
- The hottest temperatures and highest cumulative impacts generally occur at John Day Dam. Downstream of this location, the river temperatures are steady in the "Current" conditions and continue to increase in the "Free-Flowing" conditions. This results in a cooling impact for the dams downstream of John Day Dam.
- The Snake River generally has a warming effect on the mainstem Columbia River.

The following figures (***Figure 3-3*** through ***Figure 3-10***) show the mean monthly temperatures for the entire model domain from a longitudinal perspective. The river flows from right to left from the model boundary at the right-hand side of each plot. RM 0 for the Columbia River is the mouth at the Pacific Ocean, while RM 0 for the Snake River is the confluence with the Columbia River. Model results are output at each dam tailrace. In addition, model results immediately upstream and downstream of the Snake River confluence are provided in the Columbia River plots, and the temperature at the Clearwater River confluence with the Snake River is shown in the Snake River plots.

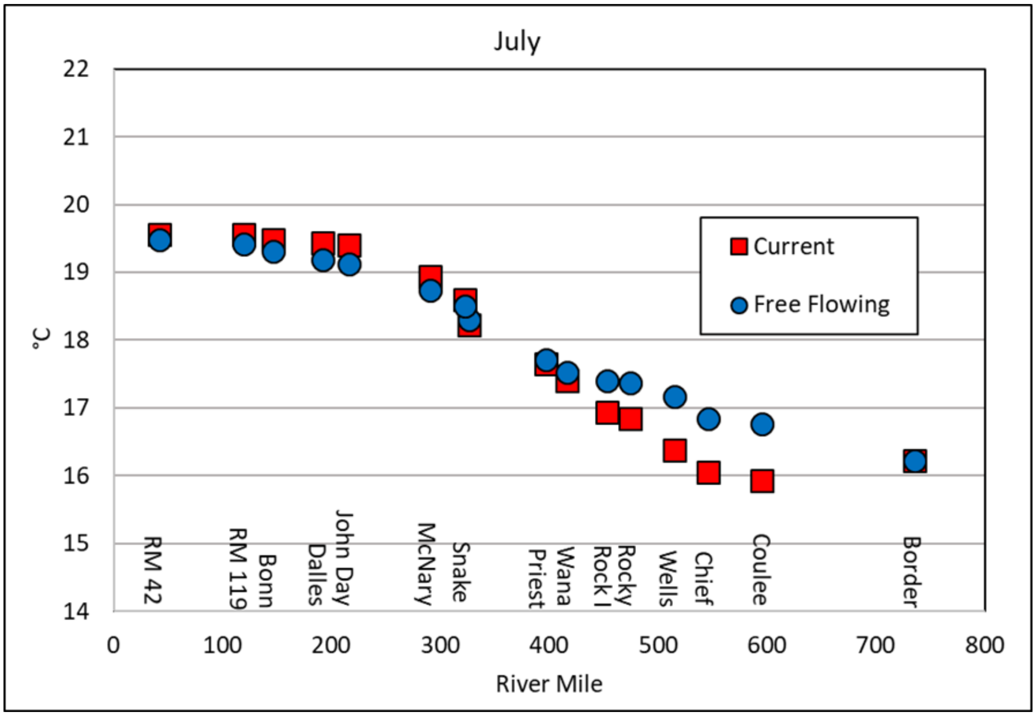


Figure 3-3 Simulated temperature of free-flowing and current Columbia River; July

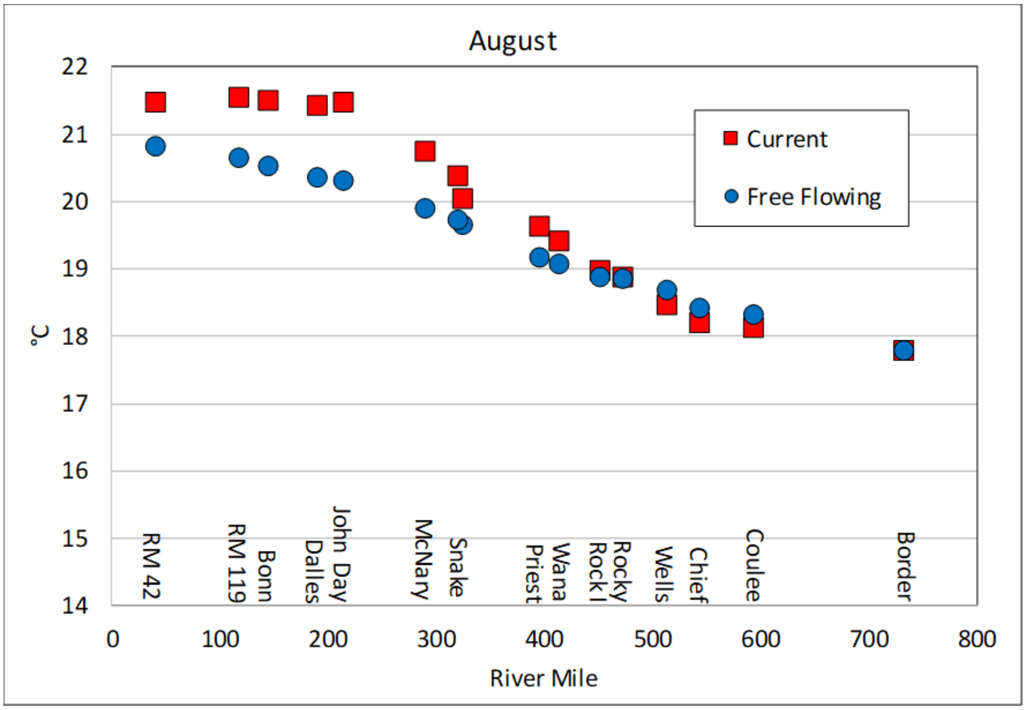


Figure 3-4 Simulated temperature of free-flowing and current Columbia River; August

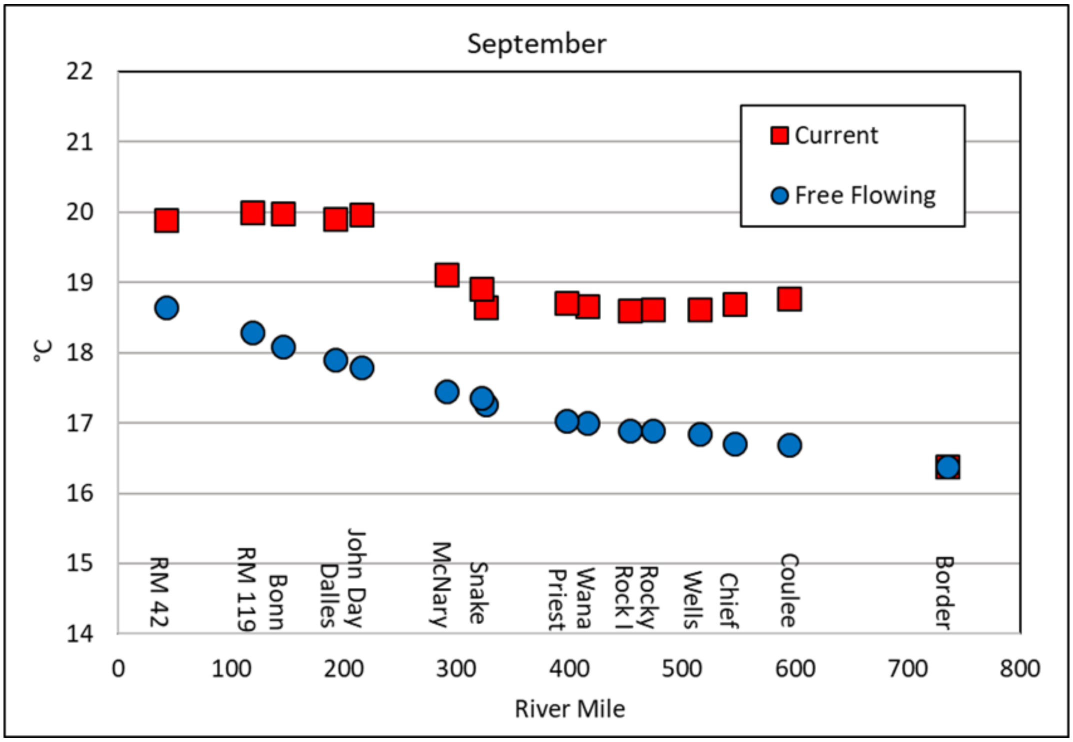


Figure 3-5 Simulated temperatures of free-flowing and current Columbia River; Sept

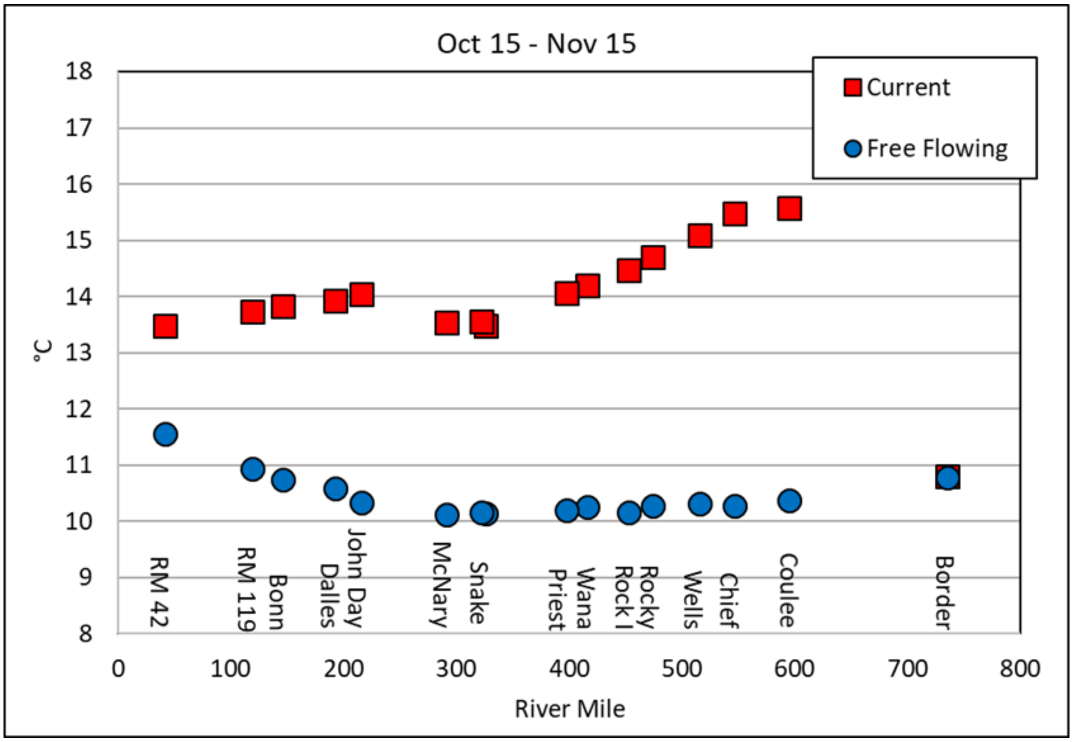


Figure 3-6 Simulated temperature of free-flowing and current Columbia River; October 15 to November 15

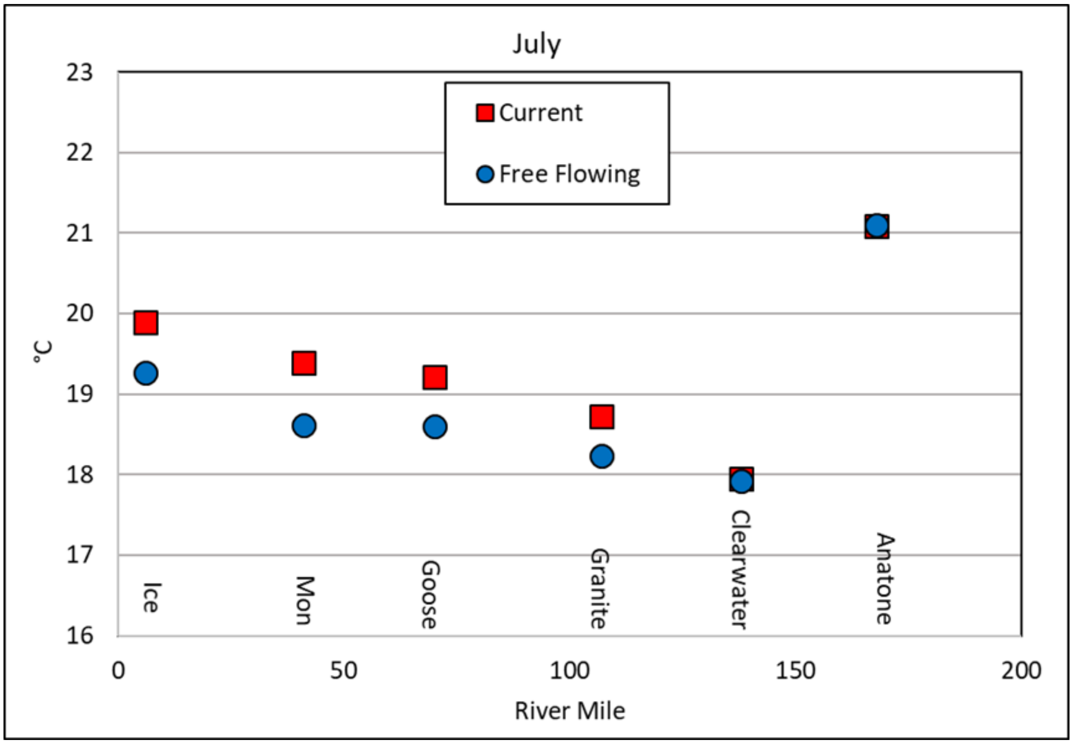


Figure 3-7 Simulated temperature of free-flowing and current Snake River; July

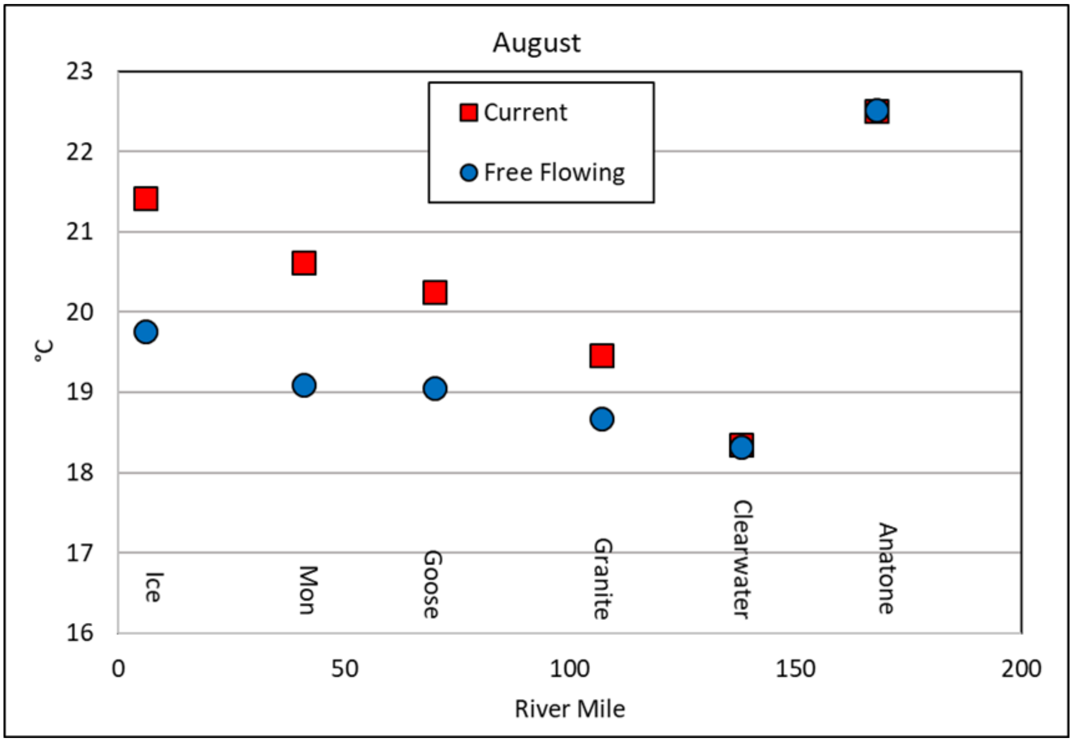


Figure 3-8 Simulated temperature of free-flowing and current Snake River; August

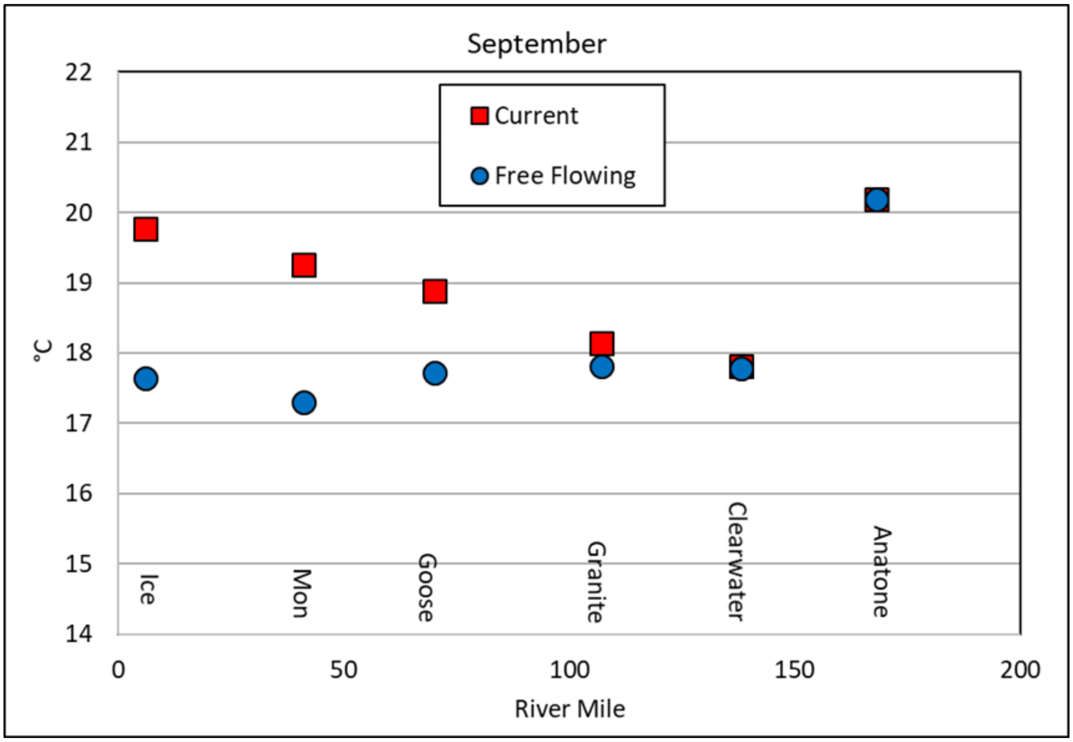


Figure 3-9 Simulated temperature of free-flowing and current Snake River; Sept

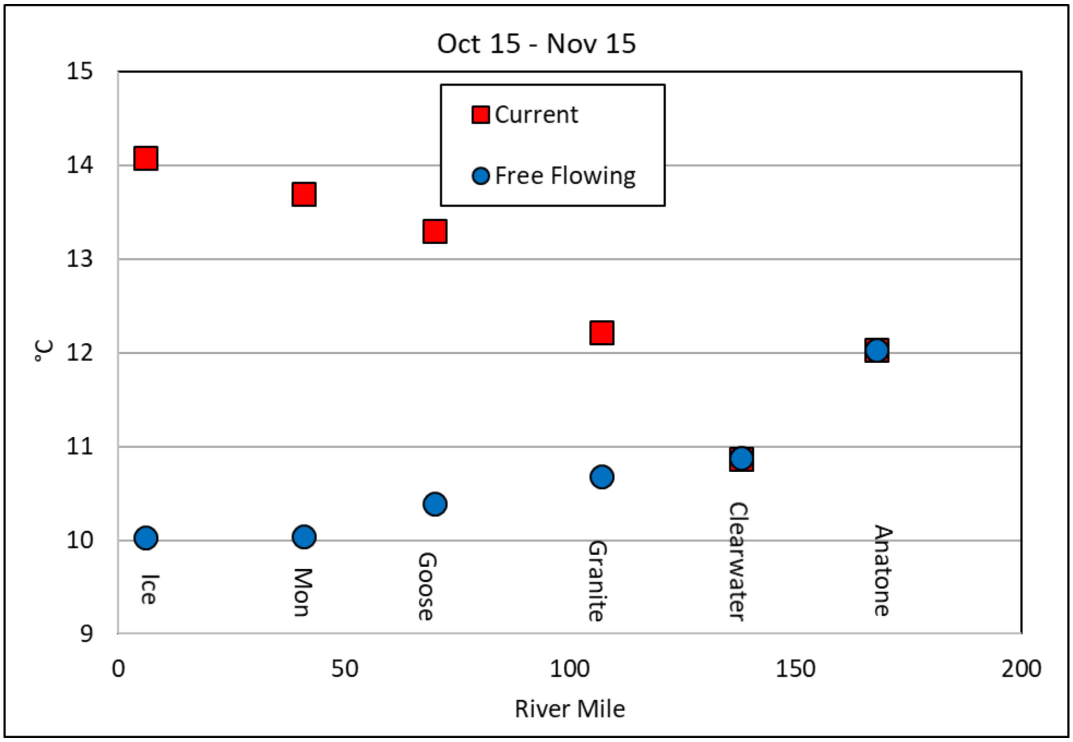


Figure 3-10 Simulated temperature of free-flowing and current Snake River; October 15 to November 15

The numeric values for temperature differences shown in the figures above are provided in ***Table 3-2*** through ***Table 3-5*** below. The cumulative impact is the difference between the current and free-flowing temperature at a given location. The reach impact is the difference between the simulated temperature change in the reach immediately above the assessment location under current conditions versus free-flowing conditions.

Table 3-2 Estimated Mean Monthly Impact of Dam Impoundments on Columbia and Snake River Temperatures (July; 2011-2016)

Location	River Mile	RBM10 Current	RBM10 Free Flowing	Individual Reach Impact	Cumulative Impact
COLUMBIA RIVER					
Canadian Border	735	16.22	16.23	NA	NA
Grand Coulee	595	15.92	16.77	-0.8	-0.9
Chief Joseph	546	16.04	16.86	0.0	-0.8
Wells	515	16.38	17.18	0.0	-0.8
Rocky Reach	474	16.85	17.37	0.3	-0.5
Rock Island	453	16.93	17.41	0.0	-0.5
Wanapum	416	17.40	17.54	0.3	-0.1
Priest Rapids	397	17.64	17.73	0.1	-0.1
Hanford Reach	326	18.22	18.32	0.0	-0.1
Snake Confluence	322	18.59	18.49	0.2	0.1
McNary	291	18.94	18.73	0.1	0.2
John Day	216	19.40	19.10	0.1	0.3
Dalles	192	19.43	19.18	0.0	0.3
Bonneville	146	19.48	19.29	-0.1	0.2
SNAKE RIVER					
Anatone	168	21.09	21.09	NA	NA
Clearwater Confluence	138	17.94	17.92	NA	NA
Lower Granite	107	18.73	18.24	0.5	0.5
Little Goose	70	19.21	18.60	0.1	0.6
Lower Monumental	41	19.39	18.62	0.2	0.8
Ice Harbor	6	19.89	19.23	-0.1	0.7

Table 3-3 Estimated Mean Monthly Impact of Dam Impoundments on Columbia River Temperatures (August; 2011-2016)

Location	River Mile	RBM10 Current	RBM10 Free Flowing	Individual Reach Impact	Cumulative Impact
COLUMBIA RIVER					
Canadian Border	735	17.77	17.78	NA	NA
Grand Coulee	595	18.11	18.30	-0.2	-0.2
Chief Joseph	546	18.19	18.39	0.0	-0.2
Wells	515	18.44	18.67	0.0	-0.2
Rocky Reach	474	18.85	18.83	0.2	0.0
Rock Island	453	18.96	18.86	0.1	0.1
Wanapum	416	19.39	19.05	0.2	0.3
Priest Rapids	397	19.62	19.15	0.1	0.5
Hanford Reach	326	20.02	19.64	-0.1	0.4
Snake Confluence	322	20.36	19.68	0.3	0.7
McNary	291	20.72	19.86	0.2	0.9
John Day	216	21.44	20.28	0.3	1.2
Dalles	192	21.41	20.32	-0.1	1.1
Bonneville	146	21.48	20.50	-0.1	1.0
SNAKE RIVER					
Anatone	168	22.51	22.51	NA	NA
Clearwater Confluence	138	18.35	18.32	NA	NA
Lower Granite	107	19.47	18.68	0.8	0.8
Little Goose	70	20.24	19.06	0.4	1.2
Lower Monumental	41	20.62	19.10	0.3	1.5
Ice Harbor	6	21.42	19.71	0.2	1.7

Table 3-4 Estimated Mean Monthly Impact of Dam Impoundments on Columbia and Snake River Temperatures (September; 2011-2016)

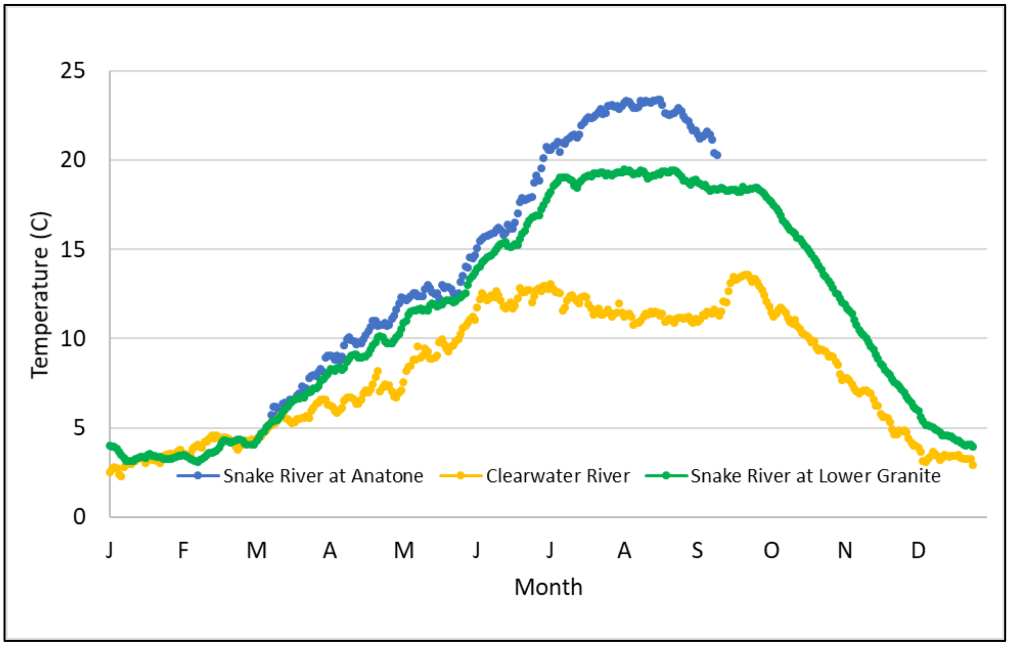
Location	River Mile	RBM10 Current	RBM10 Free Flowing	Individual Reach Impact	Cumulative Impact
COLUMBIA RIVER					
Canadian Border	735	16.38	16.38	NA	NA
Grand Coulee	595	18.78	16.68	2.1	2.1
Chief Joseph	546	18.70	16.70	-0.1	2.0
Wells	515	18.61	16.84	-0.2	1.8
Rocky Reach	474	18.61	16.89	0.0	1.7
Rock Island	453	18.60	16.89	0.0	1.7
Wanapum	416	18.67	17.00	0.0	1.7
Priest Rapids	397	18.72	17.02	0.0	1.7
Hanford Reach	326	18.65	17.26	-0.3	1.4
Snake Confluence	322	18.91	17.35	0.2	1.6
McNary	291	19.12	17.44	0.1	1.7
John Day	216	19.97	17.78	0.5	2.2
Dalles	192	19.90	17.90	-0.2	2.0
Bonneville	146	19.98	18.09	-0.1	1.9
SNAKE RIVER					
Anatone	168	20.19	20.19	NA	NA
Clearwater Confluence	138	17.81	17.80	NA	NA
Lower Granite	107	18.14	17.82	0.3	0.3
Little Goose	70	18.88	17.73	0.8	1.2
Lower Monumental	41	19.26	17.30	0.8	2.0
Ice Harbor	6	19.77	17.63	0.2	2.1

Table 3-5 Estimated Mean Monthly Impact of Dam Impoundments on Columbia and Snake River Temperatures (October; 2011-2016)

Location	River Mile	RBM10 Current	RBM10 Free Flowing	Individual Reach Impact	Cumulative Impact
COLUMBIA RIVER					
Canadian Border	735	10.80	10.79	NA	NA
Grand Coulee	595	15.57	10.37	5.2	5.2
Chief Joseph	546	15.47	10.28	0.0	5.2
Wells	515	15.10	10.29	-0.4	4.8
Rocky Reach	474	14.71	10.27	-0.4	4.4
Rock Island	453	14.47	10.15	-0.1	4.3
Wanapum	416	14.19	10.25	-0.4	3.9
Priest Rapids	397	14.06	10.20	-0.1	3.9
Hanford Reach	326	13.47	10.14	-0.5	3.3
Snake Confluence	322	13.56	10.16	0.1	3.4
McNary	291	13.55	10.12	0.0	3.4
John Day	216	14.04	10.33	0.3	3.7
Dalles	192	13.92	10.58	-0.4	3.3
Bonneville	146	13.84	10.74	-0.2	3.1
SNAKE RIVER					
Anatone	168	12.03	12.03	NA	NA
Clearwater Confluence	138	10.87	10.88	NA	NA
Lower Granite	107	12.22	10.68	1.6	1.5
Little Goose	70	13.30	10.39	1.4	2.9
Lower Monumental	41	13.70	10.04	0.8	3.7
Ice Harbor	6	14.07	10.03	0.4	4.0

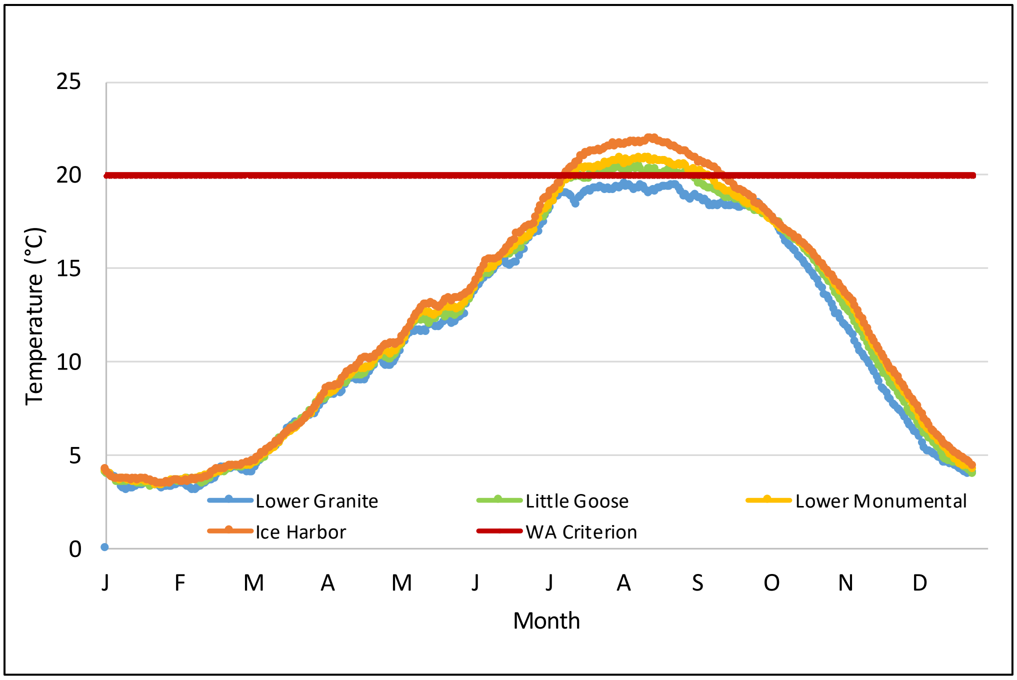
3.4 DWORSHAK DAM COLD WATER RELEASES (DWR1 AND DWR2 SCENARIOS)

From early July to mid-September, Dworshak Dam in Idaho releases substantial volumes of cold water into the Clearwater River, which has a significant cooling effect on the lower Snake River. The dam is operated by USACE with a goal of achieving the Washington 20°C water quality criterion at Lower Granite Dam downstream of the Clearwater River confluence. As seen in ***Figure 3-11***, these operations are very successful in achieving the goal at Lower Granite Dam. However, this cooling benefit steadily dissipates at each successive downstream dam site (***Figure 3-12***).



Source: Merz et al. 2018; mean of daily maxima, 2011-2016

Figure 3-11 Measured temperatures in the Snake River upstream and downstream of the Clearwater River, and in the Clearwater River.



Source: Merz et al. 2018; mean of daily maxima, 2011-2016

Figure 3-12 Measured temperatures at the four Snake River dams in the TMDL study area

3.4.1 Methodology and Assumptions

The beneficial impact of Dworshak Dam operations on current temperature conditions were evaluated in two ways. First, a qualitative comparison was made of long term simulation results for periods before and after Dworshak Dam cold water release operations. Second, a model scenario that simulates conditions without Dworshak Dam operations (DWR1) was run and compared to the current condition scenario over the same period (2011-2016). The DWR1 scenario was constructed by substituting the flow and temperature of the North Fork Clearwater upstream of Dworshak reservoir as the assumed inflow to the Clearwater River at the North Fork Clearwater confluence, rather than the actual flow and temperature released by Dworshak Dam over this period. The flow and temperature data used as DWR1 inputs are shown in ***Figure 3-13*** and ***Figure 3-14***.

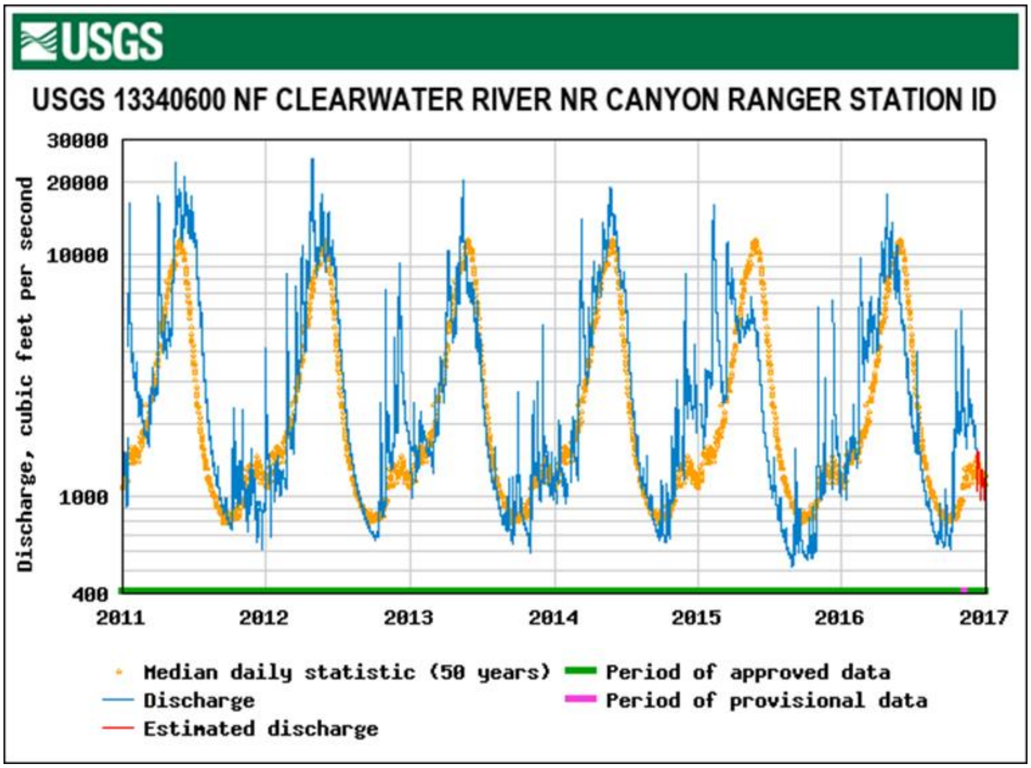
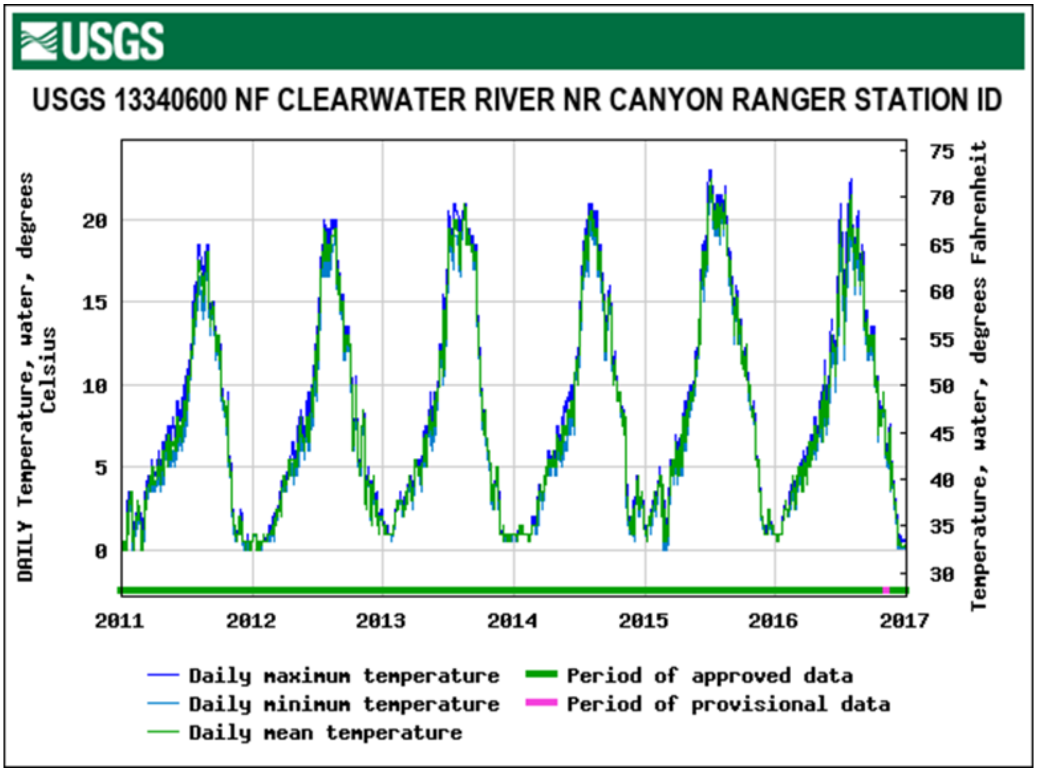


Figure 3-13 Flow of Nork Fork Clearwater River upstream of Dworshak Reservoir.



Source: USGS NWIS website; 2011 – 2016

Figure 3-14 Temperature of Nork Fork Clearwater River upstream of Dworshak Reservoir.

USGS also monitored the Clearwater River near the mouth at Ahsakha, Idaho before Dworshak Dam was constructed (1957 – 1970). While this is a different time period than the RBM10 simulation period (1970 – 2016), the long term average conditions for the two datasets can be compared as a quality assurance check on the RBM10 estimation of conditions without Dworshak operations. This comparison is shown in ***Figure 3-15***.

A significant outlier occurs in the middle of the summer in the RBM10 simulation (see circled value in ***Figure 3-15***). This spike occurs on the same day of the year throughout the simulation for the scenario run with no Dworshak releases (Day 225). This day is when the evaporation coefficients in the RBM10 model change from values representing spring and early summer conditions to values representing late summer and fall conditions. This Day 225 change in coefficient values is an inherent part of the calibrated model structure that underlies all current conditions simulations and scenario simulations. This is the only case in this assessment where an outlier has been observed, and it occurs in this scenario because the river flow is substantially lower than normal conditions simulated using RBM10. After the model overestimates the temperature on Day 225, the simulated temperatures return to normal the following day. Because this outlier cannot be removed without altering the calibrated model, it was left in place for the Dworshak assessment. Since Dworshak benefit estimates are aggregated by month, this outlier results in a small over-estimation of benefits in August.

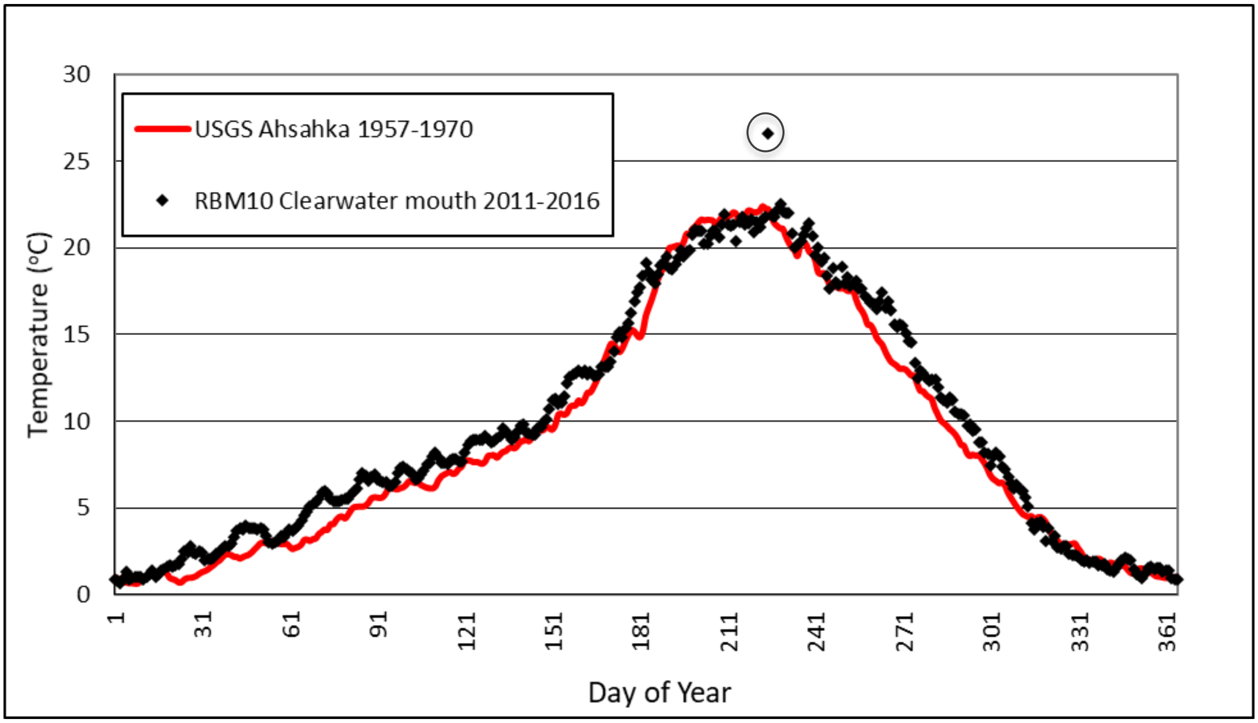


Figure 3-15 Mean daily temperature of Clearwater River at mouth measured in 1957-1970 and simulated for 2011-2016.

3.4.2 Results

The first evaluation of Dworshak Dam impacts was a qualitative examination of long term model output. The 47-year simulation period for RBM10 includes a significant period when Dworshak Dam operations were not used to cool downstream waters as they are today, and different time periods can be plotted to see the impact of Dworshak Dam operations on Snake River temperatures. Two locations are plotted in ***Figure 3-16*** and ***Figure 3-17***: Lower Granite Dam and Ice Harbor Dam. The Lower Granite Dam plot shows that cold water releases have reduced temperatures in recent decades. The Ice Harbor Dam plot illustrates how this cooling effect is difficult to discern by the time waters reach this location approximately 100 miles downstream of Lower Granite Dam.

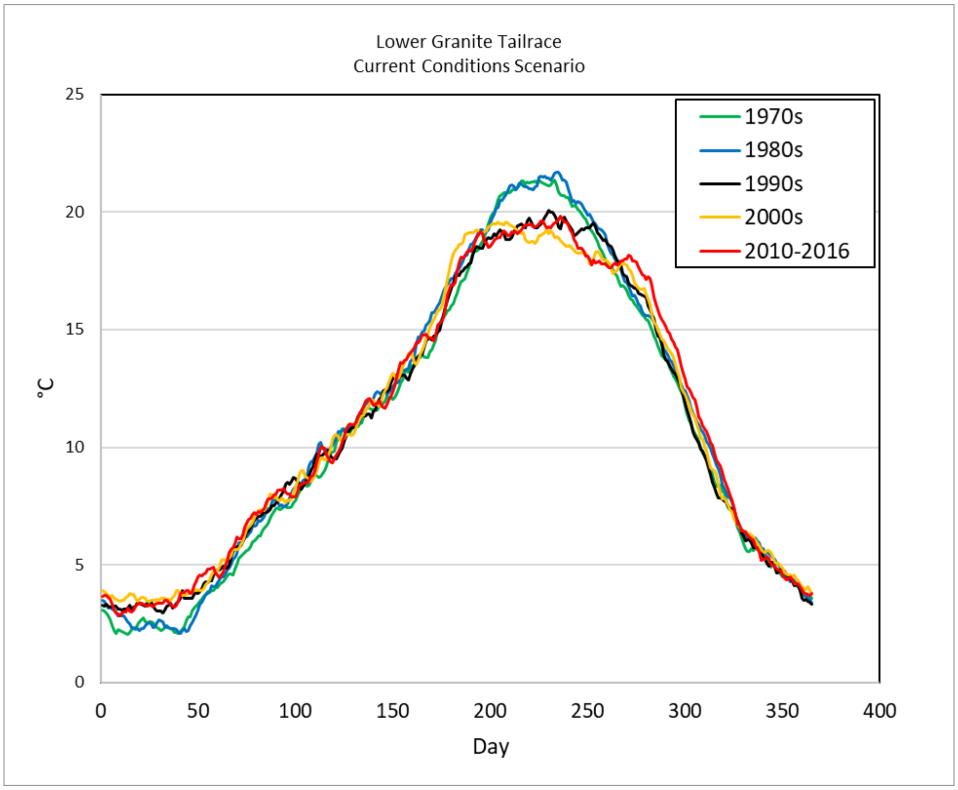


Figure 3-16 Simulated decadal average temperatures at Lower Granite Dam

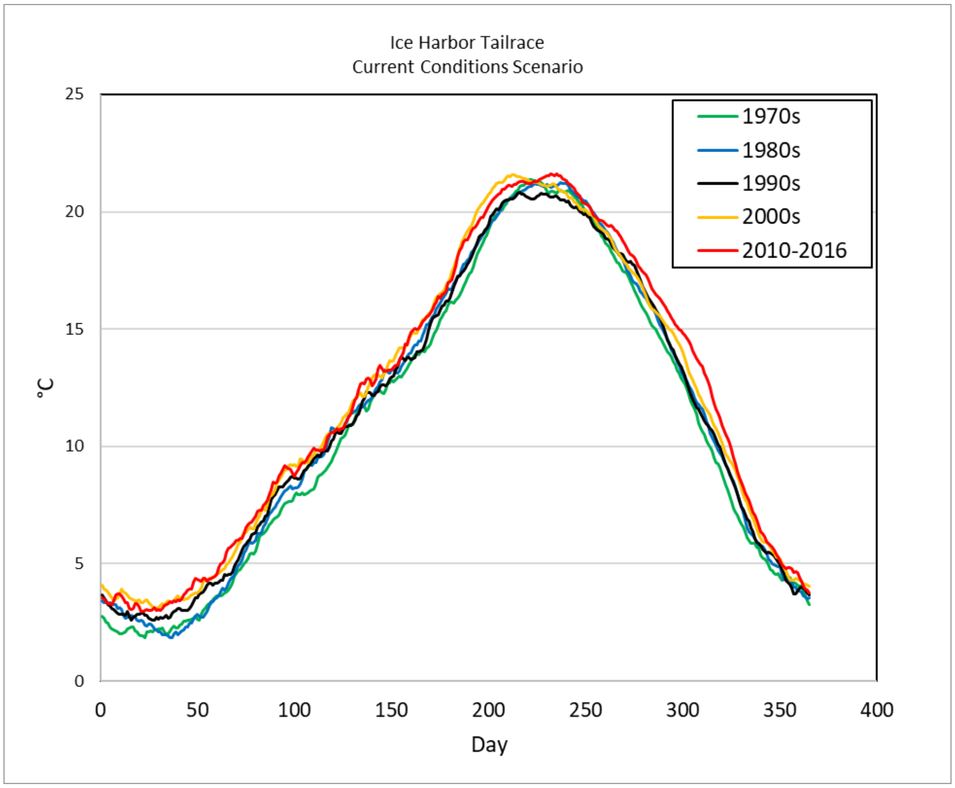


Figure 3-17 Simulated decadal average temperatures at Ice Harbor Dam

The Dworshak Dam benefits analysis used information from a comparison between the "Current" and "DWR1" model simulations for the 2011 – 2016 period. In this case, the "Current" conditions are simulated and then compared to the results when cold water releases into the Clearwater River from Dworshak Dam are removed ("DWR1" scenario) by substituting monitored flows and temperatures from the Canyon Ranger station monitoring site upstream of Dworshak reservoir.

The estimated impact of Dworshak Dam releases is shown in ***Figure 3-18*** through ***Figure 3-20***. The temperature differences in these plots are then summarized ***Table 3-6***.

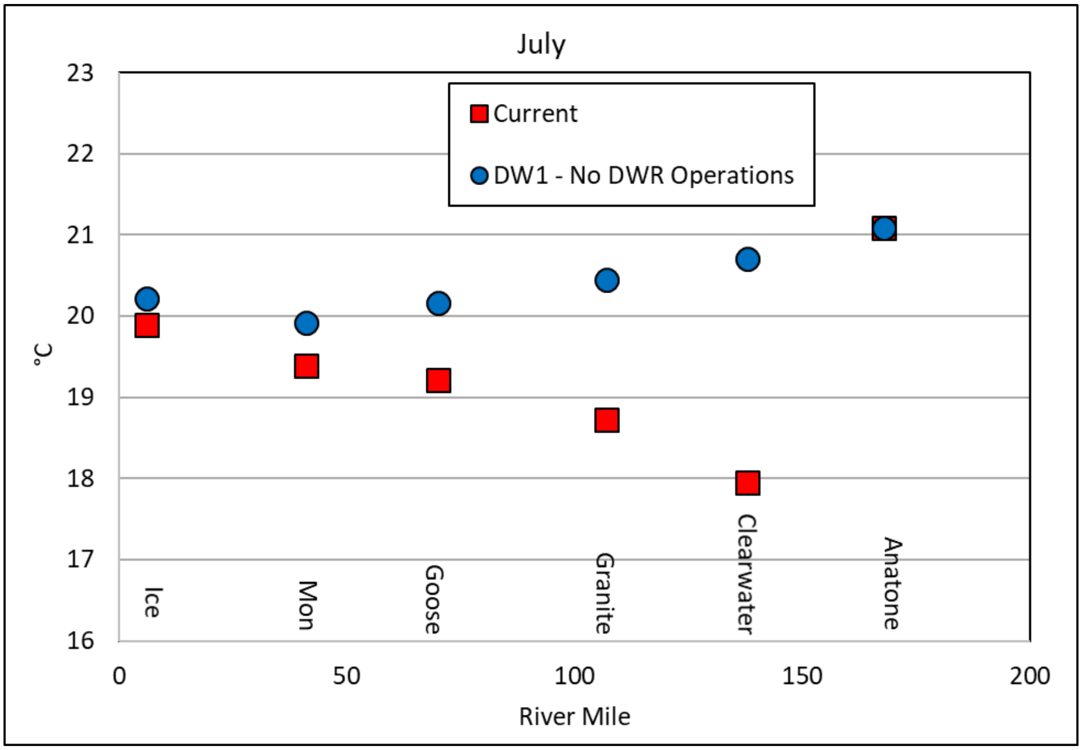


Figure 3-18 Estimated impact of Dworshak Dam operations (2011 – 2016; July)

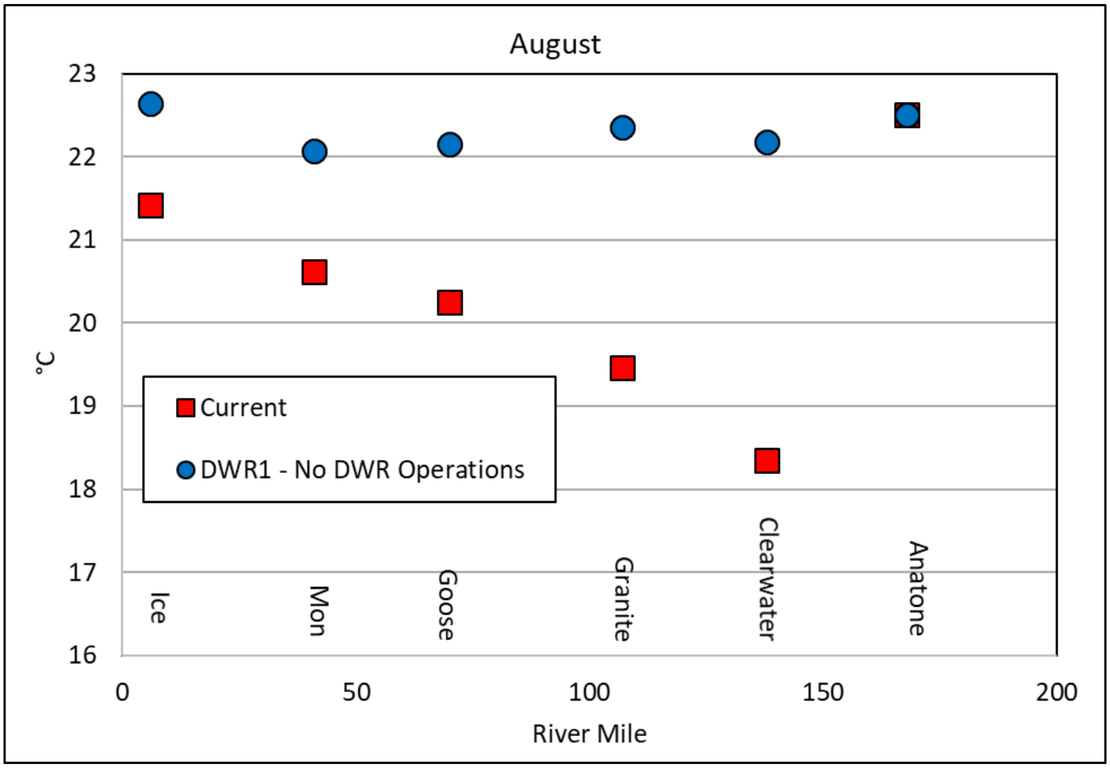


Figure 3-19 Estimated impact of Dworshak Dam operations (2011 – 2016; August)

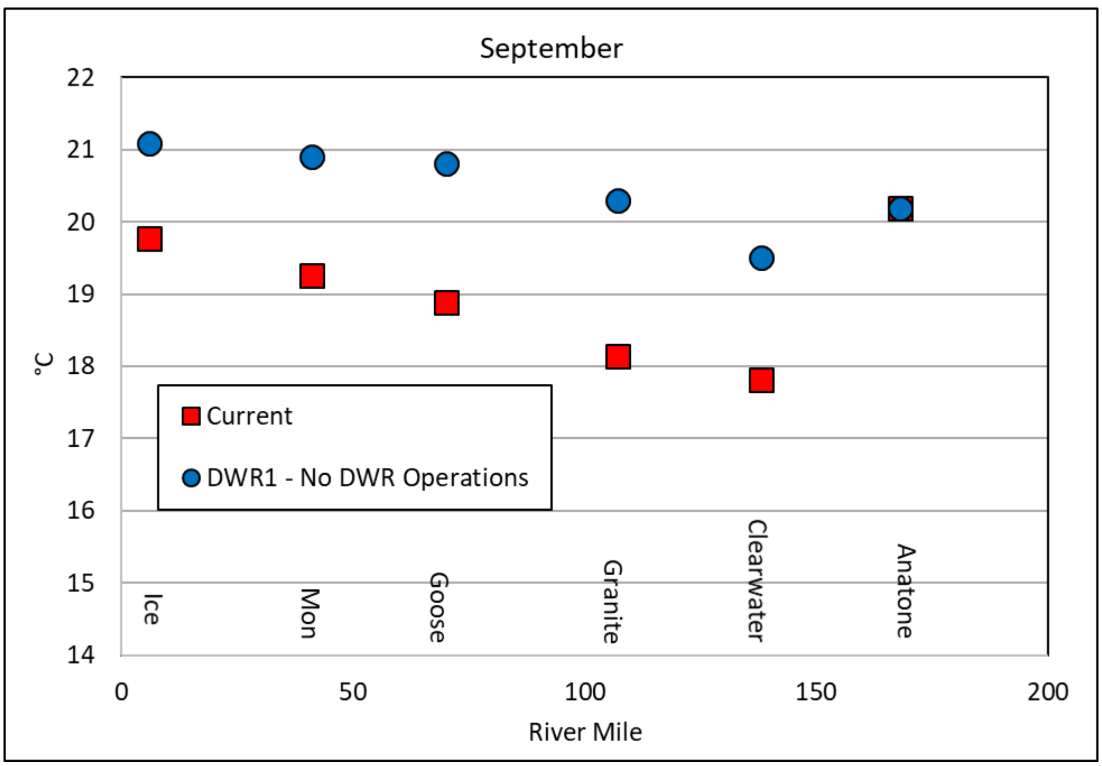


Figure 3-20 Estimated impact of Dworshak Dam operations (2011 – 2016; September)

Table 3-6 Estimated beneficial temperature impact of Dworshak Dam operations on current river temperatures

Location	RM	RBM10 Current (°C)			RBM10 Current without Dworshak Operations (°C)			Estimated Benefit (∆°C)		
		July	Aug	Sept	July	Aug	Sept	July	Aug	Sept
Snake River										
Clearwater	138	17.9	18.4	17.8	20.7	22.2	19.5	-2.8	-3.8	-1.7
Lower Granite	107	18.7	19.5	18.1	20.5	22.4	20.3	-1.7	-2.9	-2.2
Little Goose	70	19.2	20.2	18.9	20.2	22.1	20.8	-0.9	-1.9	-1.9
Lower Mon	41	19.4	20.6	19.3	19.9	22.1	20.9	-0.5	-1.4	-1.6
Ice Harbor	6	19.9	21.4	19.8	20.2	22.6	21.1	-0.3	-1.2	-1.3
Columbia River										
Below Snake Confluence	322	18.6	20.4	18.9	18.6	20.5	19.1	0.0	-0.1	-0.2

Dworshak Dam Impact on Free-Flowing Snake River

In addition to the “Current” and “Free-Flowing” scenarios that include Dworshak Dam cold water releases and the “DWR1” scenario that excludes them, the “DWR2” scenario represents the free-flowing Snake River in the absence of cold water releases. The results of all four scenarios are plotted together to provide a qualitative comparison of river temperatures in both the impounded and free-flowing lower Snake River, with and without cold water releases from Dworshak Dam (***Figure 3-21*** through ***Figure 3-23***).

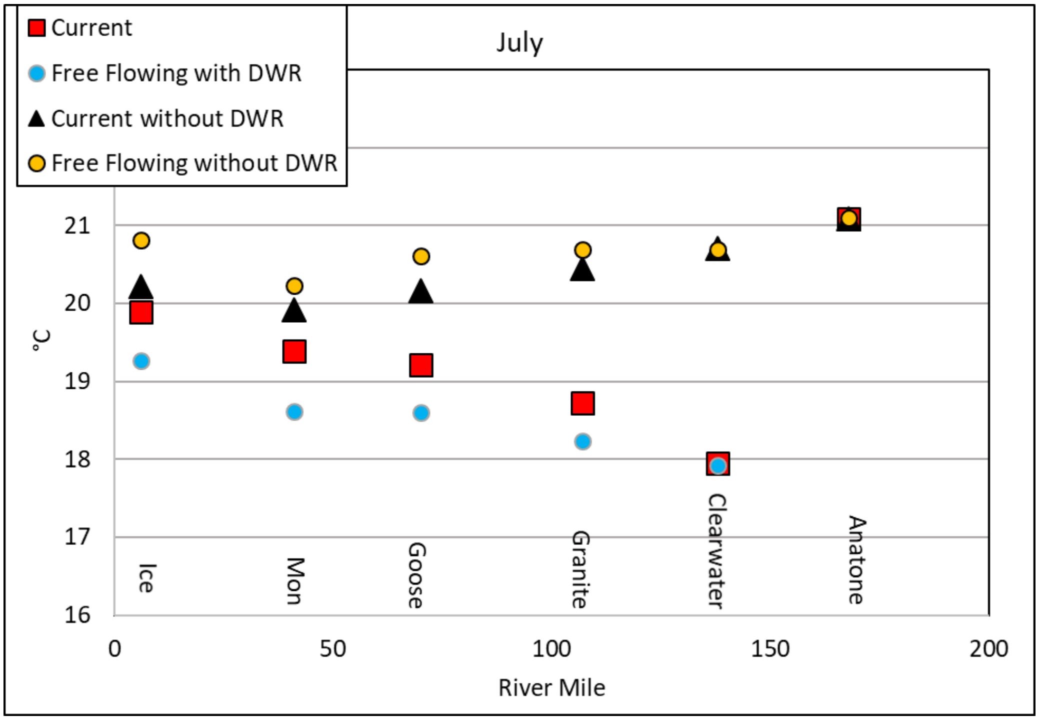


Figure 3-21 Comparison of Dworshak Dam impact scenarios (2011 – 2016; July)

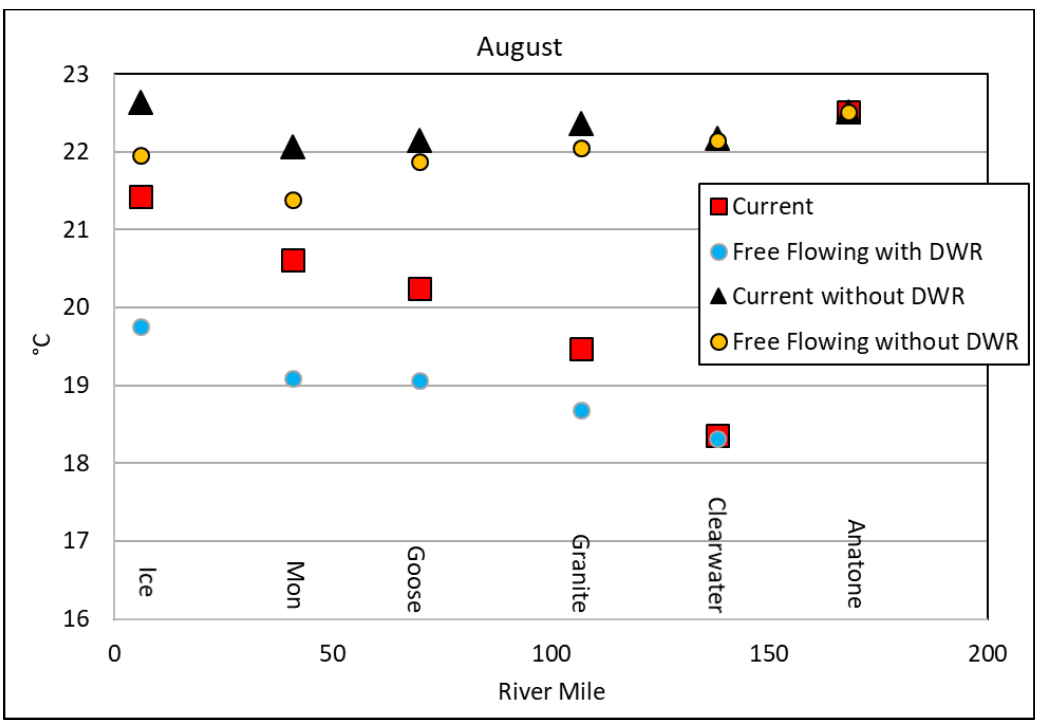


Figure 3-22 Comparison of Dworshak Dam impact scenarios (2011 – 2016; August)

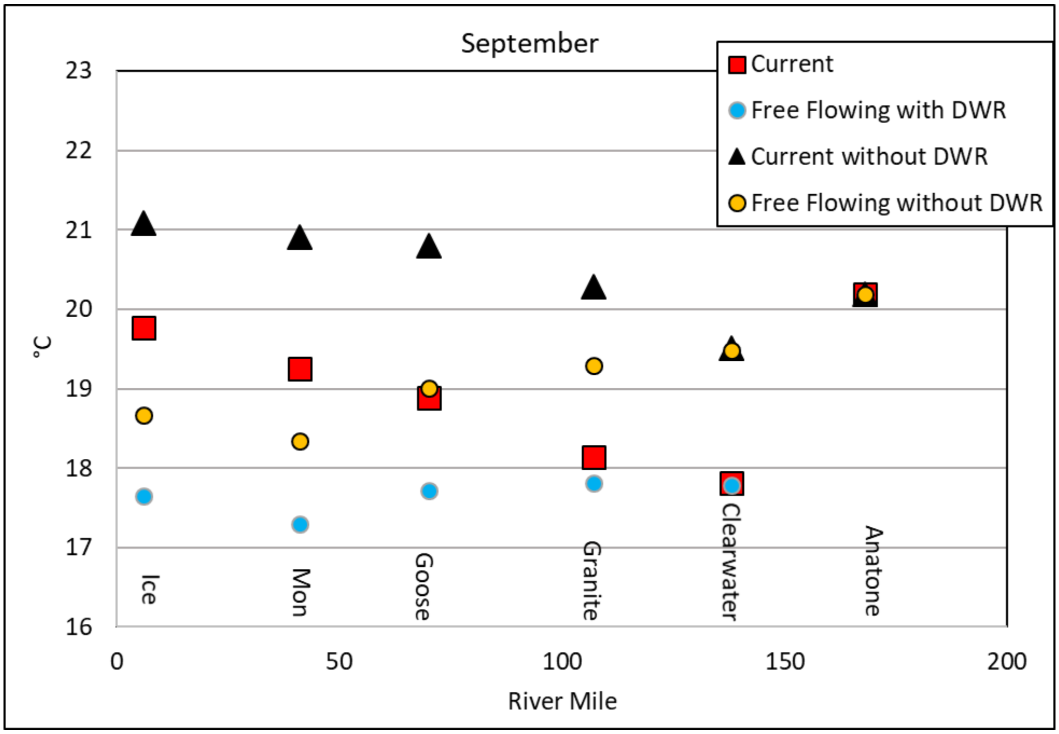


Figure 3-23 Comparison of Dworshak Dam impact scenarios (2011 – 2016; September)

3.5 CLIMATE CHANGE

The 47-year simulation period of the RBM10 model of the Columbia and Snake Rivers affords a unique opportunity to evaluate climate change over the 1970 – 2016 period. This chapter provides a variety of analyses conducted using the model, including air temperature trends in the model inputs, trends in model-predicted temperatures for the current impounded condition as well as the free-flowing condition, comparison of model results to historic measured conditions, and qualitative information relating to the combined effects of dams and climate change.

3.5.1 Methodology and Assumptions

An analysis of air temperature trends at select RBM10 model weather stations was conducted to evaluate how temperature inputs changed over time. Annual average air temperature was calculated for the period spanning 1970 – 2016, and a linear regression performed to estimate magnitude.

In addition, trend analyses were performed on RBM10 simulated water temperatures to identify long term trends for July, August, September and October. The analysis focused on monthly average and monthly 90th percentile temperatures from 1970 to 2016. The analyses were performed based on water temperature simulations from the "Current" and "Free-Flowing" scenarios.

The analysis was conducted for the Columbia River at Bonneville Dam tailwater (BON), Priest Rapids tailwater (PRXW), Wells Dam tailwater (WELW), and for the Snake River at Ice Harbor

Dam tailwater (IDSW). Monthly average temperature and monthly 90th percentile monthly temperatures were calculated for each year for the months of July, August, September, and October. The non-parametric Mann-Kendall test for trend (Mann 1945; Kendall 1975) forms the basis of the method that was used for the trend analyses – the Seasonal Kendall Test. The method was developed and popularized by USGS researchers throughout the 1980s (Hirsch et al. 1991), and USGS published computer code supporting its use. The null hypothesis H_O is there is no trend, while the alternative hypothesis H_A is either an upward or downward trend (a two-tailed test). A rate of change or trend slope was calculated based on Sen's non-parametric slope estimator (Sen 1968). This method estimates a series of slopes between values from the same season. The seasonal Kendall slope is the median of this series of slopes. A confidence interval (p value) was also estimated.

EPA has produced additional information that bolsters the trend findings based on historical (1964 – 1969) temperature data for the Columbia River at the Priest Rapids Dam (Leinenbach 2018). These data were compared graphically to recent Columbia River temperature conditions at the same location as well as RBM10 model simulations for the earliest decade (1970s) and current conditions.

Finally, RBM10 simulation output was structured to show a graphical portrayal of the combined effects of climate change and dam impacts.

3.5.2 Air Temperature Trends

Air temperature trends were analyzed at select locations that are used as weather inputs for the RBM10 model. Annual average air temperature was calculated for the period spanning 1970 – 2016, and a linear regression performed to estimate magnitude. Trends are shown for Lewiston (***Figure 3-24***), Yakima (***Figure 3-25***), and Portland (***Figure 3-26***). The decadal changes estimated from the regression slopes are:

- Lewiston: 0.22°C per decade.
- Yakima: 0.25°C per decade.
- Portland: 0.21°C per decade.

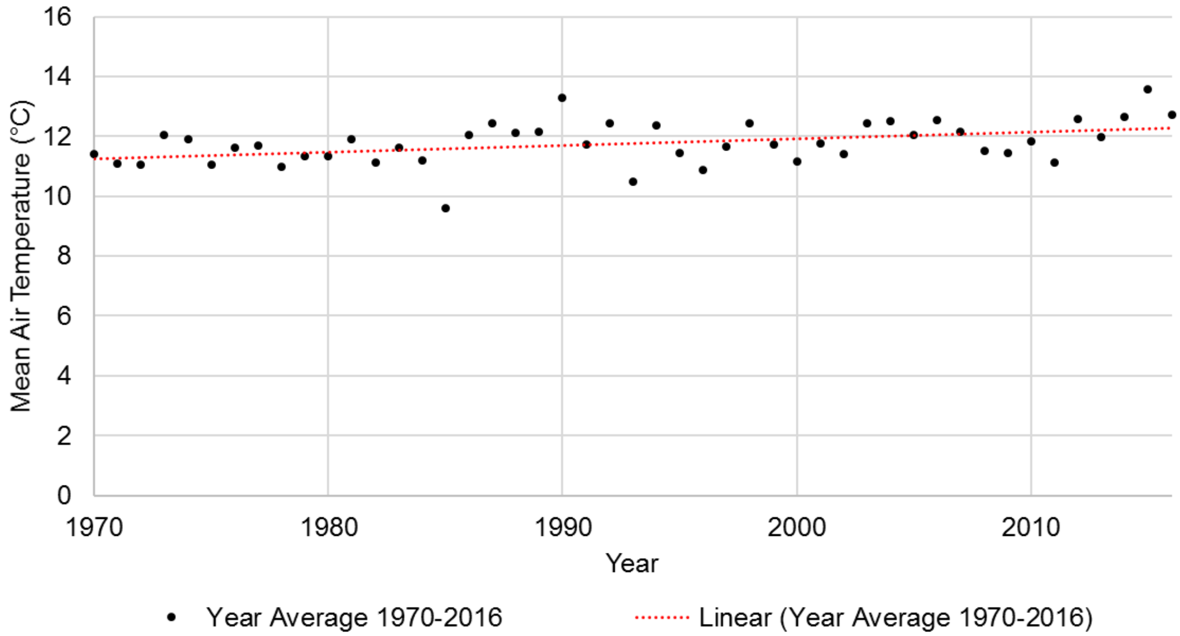


Figure 3-24 Trend for annual average air temperature at Lewiston, Idaho

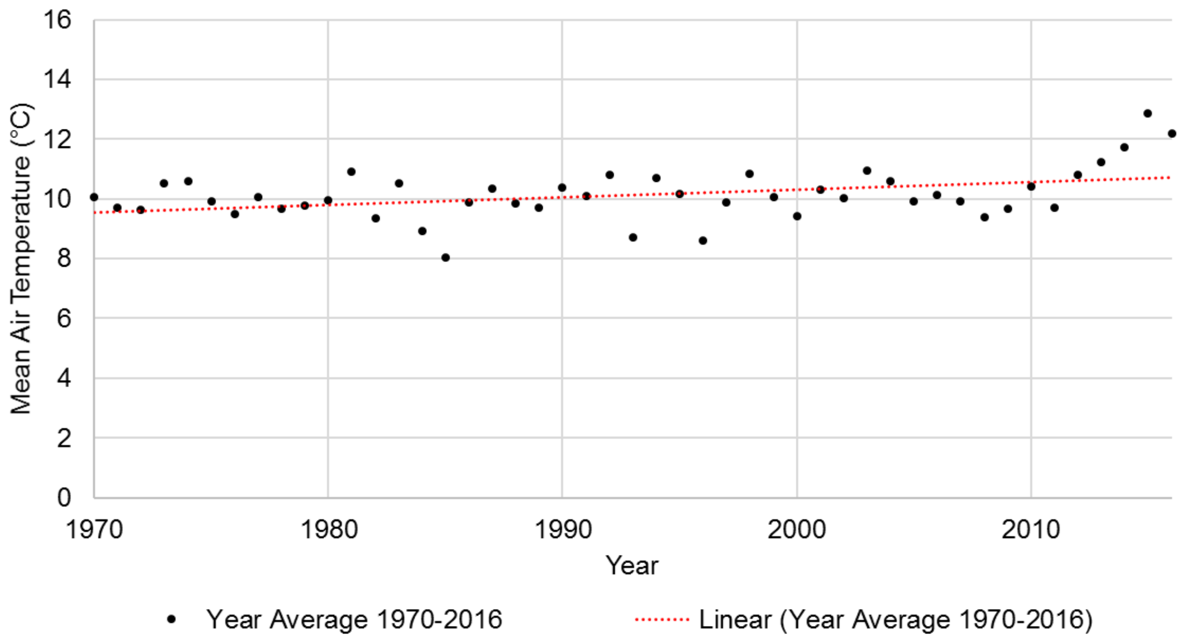


Figure 3-25 Trend for annual average air temperature at Yakima, Oregon

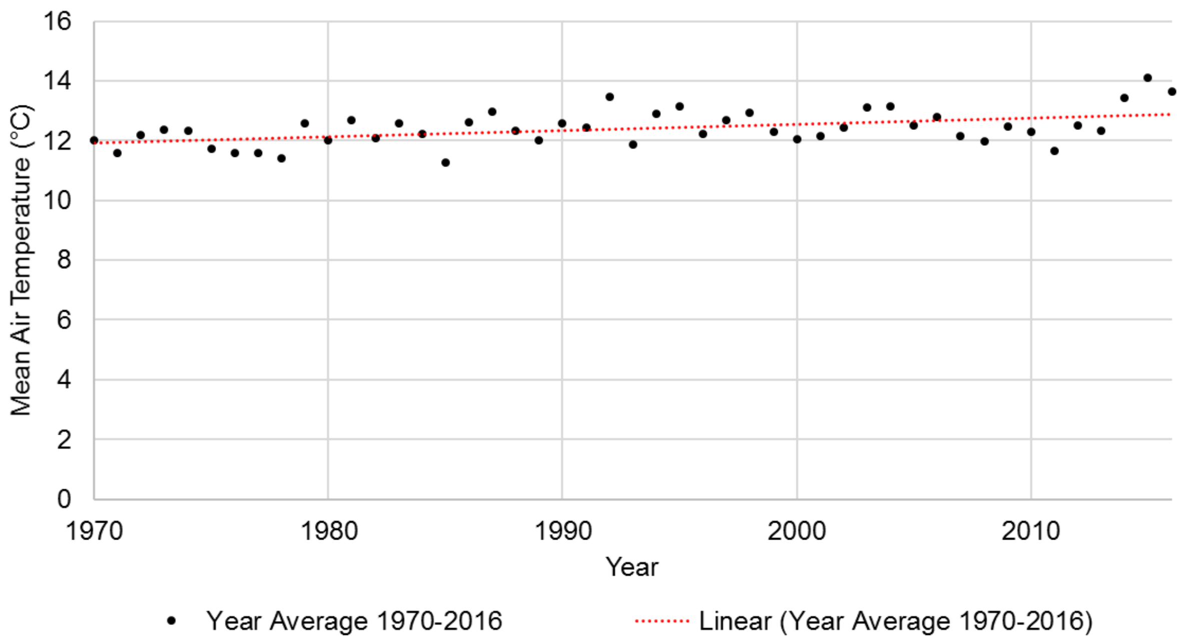


Figure 3-26 Trend for annual average air temperature at Portland, Oregon

3.5.3 Water Temperature Trends

Water temperature trends are analyzed using RBM10 model simulated temperatures for "Current" conditions (with dams in place) and "Free-Flowing" conditions. Both scenarios simulate the period 1970-2016. Graphical and tabular results include July, August, September and October monthly average and monthly 90th percentile temperatures. The analysis was conducted for the Columbia River at Bonneville Dam tailwater (BON), Priest Rapids tailwater (PRXW), Wells Dam tailwater (WELW), and for the Snake River at Ice Harbor Dam tailwater (IDSW).

The summary results for all locations and timeframes for "Current" conditions are shown in ***Table 3-7***. All the trends were considered significant at a p-value of 0.05, with the exception of mean temperatures in August and September at Ice Harbor Dam. Changes per decade are highest at Bonneville Dam and lowest at Ice Harbor Dam. There is less relative variation between months, with the highest changes occurring in July.

Table 3-7 Mean monthly water temperatures and decadal changes predicted from trend analysis of RBM10 model output

Location	Month	Warming Trend °C per Decade
Wells Dam	July	0.38
Wells Dam	August	0.36
Wells Dam	September	0.33
Wells Dam	October	0.29
Priest Rapids Dam	July	0.41
Priest Rapids Dam	August	0.42
Priest Rapids Dam	September	0.40
Priest Rapids Dam	October	0.37
Bonneville Dam	July	0.46
Bonneville Dam	August	0.40
Bonneville Dam	September	0.42
Bonneville Dam	October	0.43
Ice Harbor Dam	July	0.41
Ice Harbor Dam	August	0.06
Ice Harbor Dam	September	0.09
Ice Harbor Dam	October	0.39

A comparison of trends under “Current” and “Free-Flowing” scenarios indicates a higher warming trend in the free-flowing river than the impounded river in the month of July. However, results indicate a smaller warming trend in August, September, and October in a free-flowing river (***Table 3-8***). Snake River warming trends in the summer are substantially lower than the Columbia River trends due to Dworshak Dam releases in the latter part of the record. However, in October, when Dworshak cold water operations have ceased, the trend under free-flowing conditions is lower than the trend under current conditions.

Table 3-8 Comparison of trend for mean monthly temperature increase for current and free-flowing model scenarios using RBM10

Location	RBM10 1970-2016 **Δ°C per decade**							
	July		August		September		October	
	Current	Free Flowing	Current	Free Flowing	Current	Free Flowing	Current	Free Flowing
Columbia River								
Wells Dam	0.38	0.44	0.36	0.26	0.33	0.16	0.29	0.05
Priest Rapids	0.41	0.46	0.42	0.28	0.40	0.21	0.37	0.10
Bonneville Dam	0.46	0.47	0.40	0.26	0.42	0.32	0.43	0.25
Snake River								
Ice Harbor Dam	.41	.05	.06	-.32	.09	.18	.39	.23

Detailed trend information by location, scenario, and time frame is provided below in **Figure 3-27** through **Figure 3-42** and **Table 3-9** through **Table 3-16**.

<u>Trend Analysis at Bonneville Dam</u>

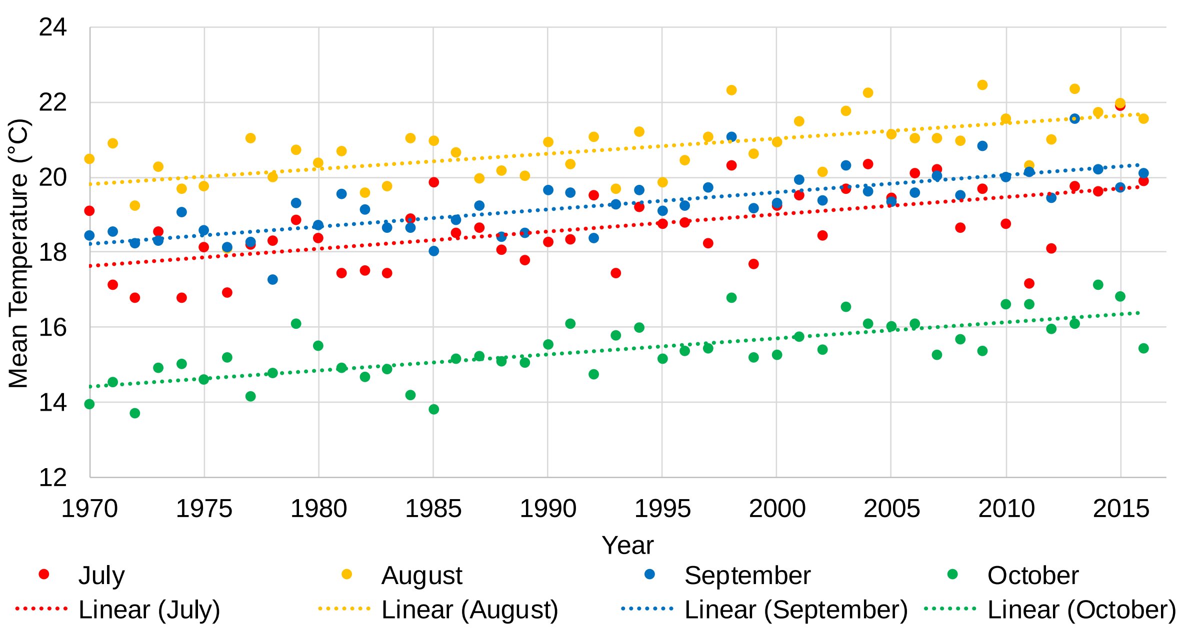


Figure 3-27 Simulated monthly mean temperatures at Bonneville Dam (Current)

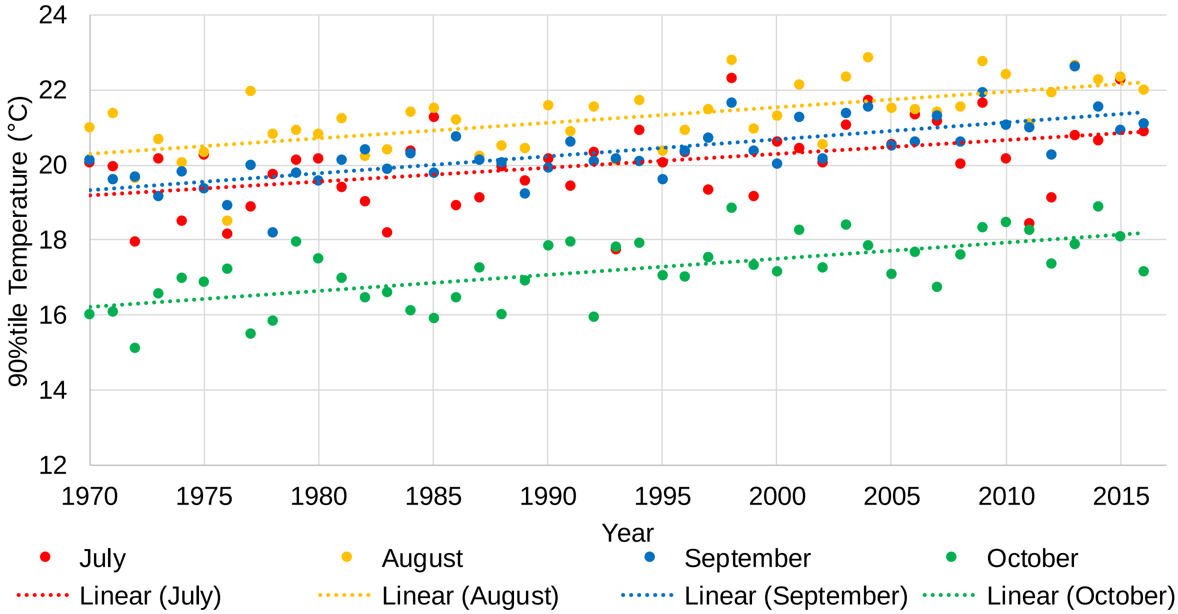


Figure 3-28 Simulated monthly 90th percentile temperatures at Bonneville Dam (Current)

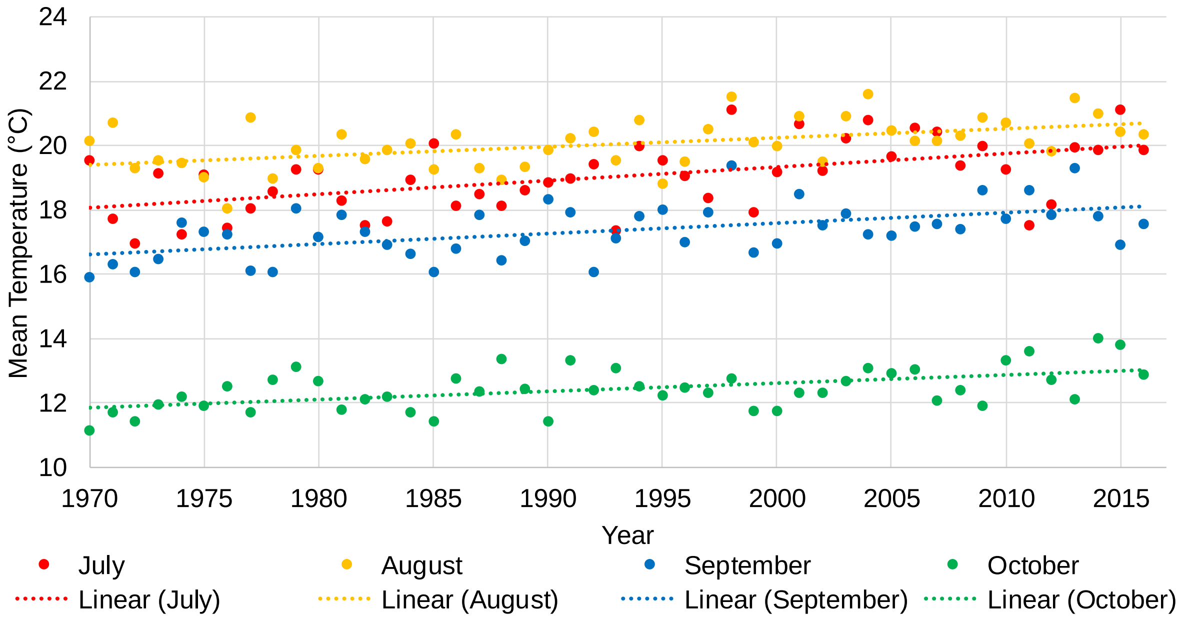


Figure 3-29 Simulated monthly mean temperatures at Bonneville Dam (Free-Flowing)

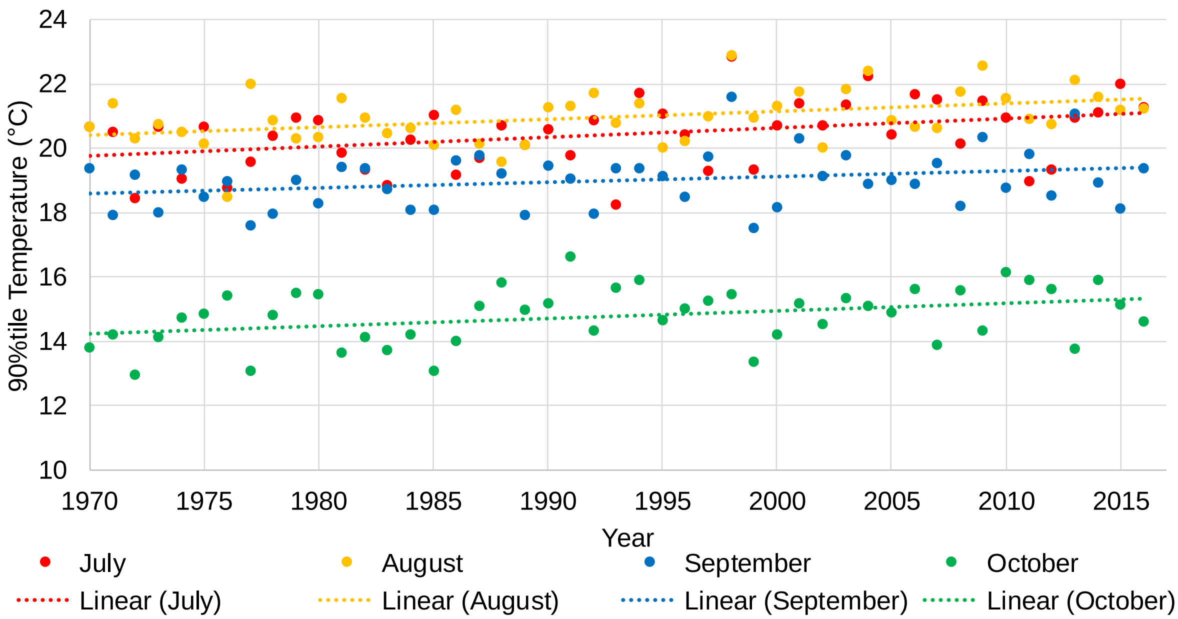


Figure 3-30 Simulated monthly 90th percentile temperatures at Bonneville Dam (Free-Flowing)

Table 3-9 Current run seasonal Kendall test slopes and p values at Bonneville Dam

Month	Mean		90th percentile	
	Slope	p value	Slope	p value
July	0.0461	<0.0000	0.0374	0.0005
August	0.0395	<0.0000	0.0414	<0.0000
September	0.0417	<0.0000	0.0413	<0.0000
October	0.0429	<0.0000	0.0433	<0.0000

Table 3-10 Free-Flowing run seasonal Kendall test slopes and p values at Bonneville Dam

Month	Mean		90th percentile	
	Slope	p value	Slope	p value
July	0.0465	0.0002	0.0307	0.0031
August	0.0260	0.0008	0.0225	0.0089
September	0.0320	0.0009	0.0131	0.1045
October	0.0252	0.0007	0.0247	0.0080

Trend Analysis at Priest Rapids Dam

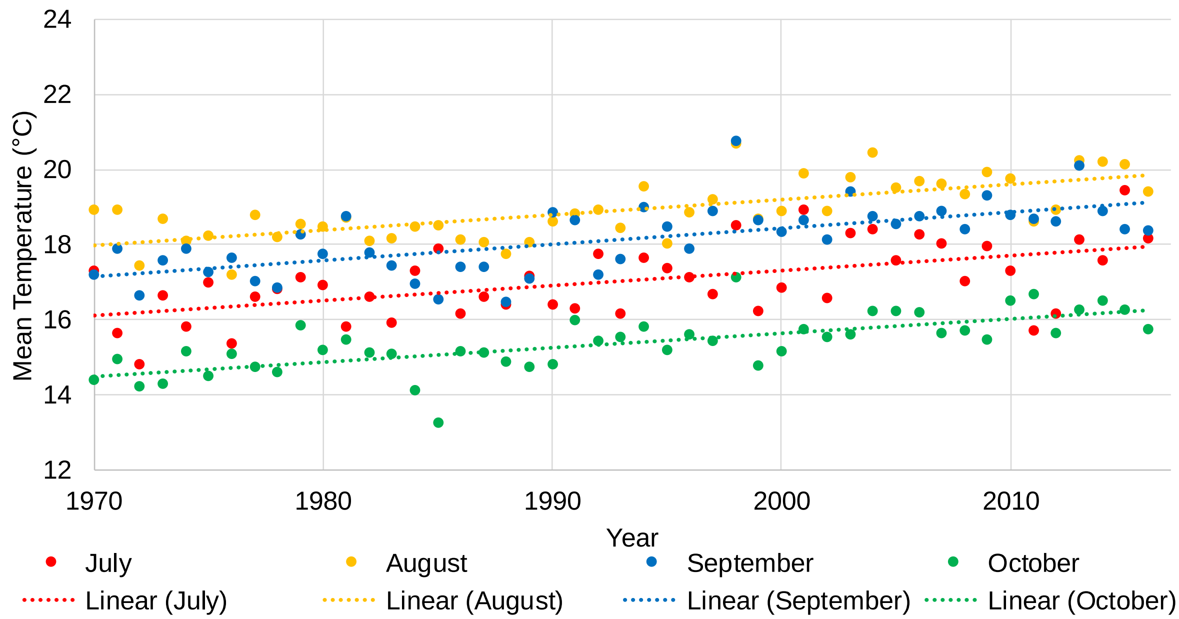


Figure 3-31 Simulated monthly mean temperatures at Priest Rapids (Current)

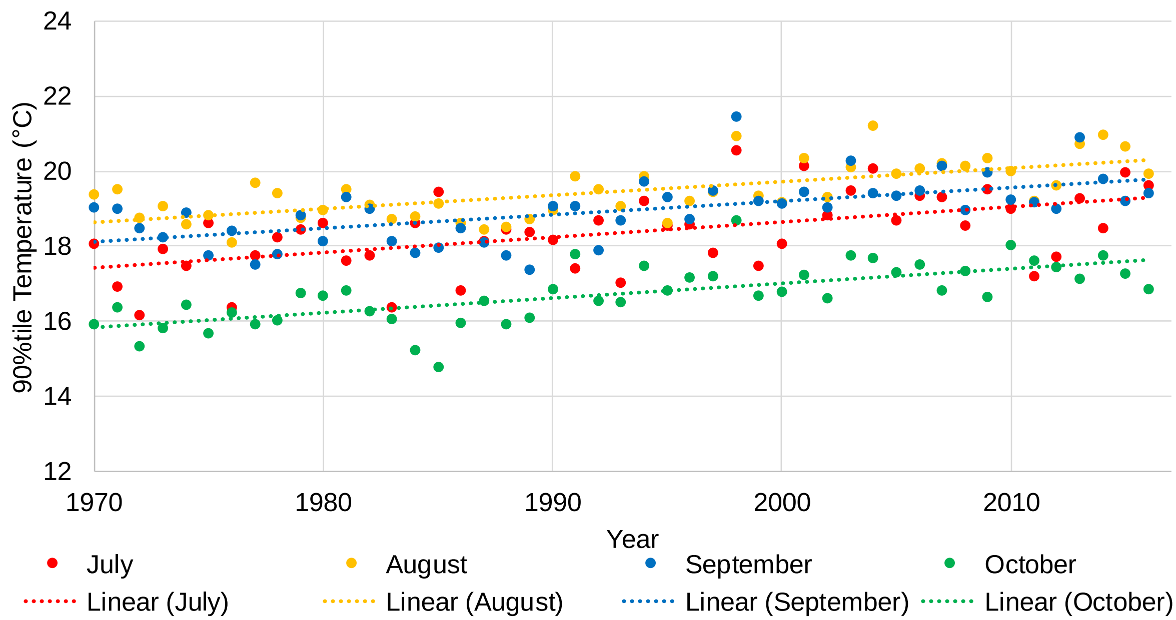


Figure 3-32 Simulated monthly 90th percentile temperatures at Priest Rapids (Current)

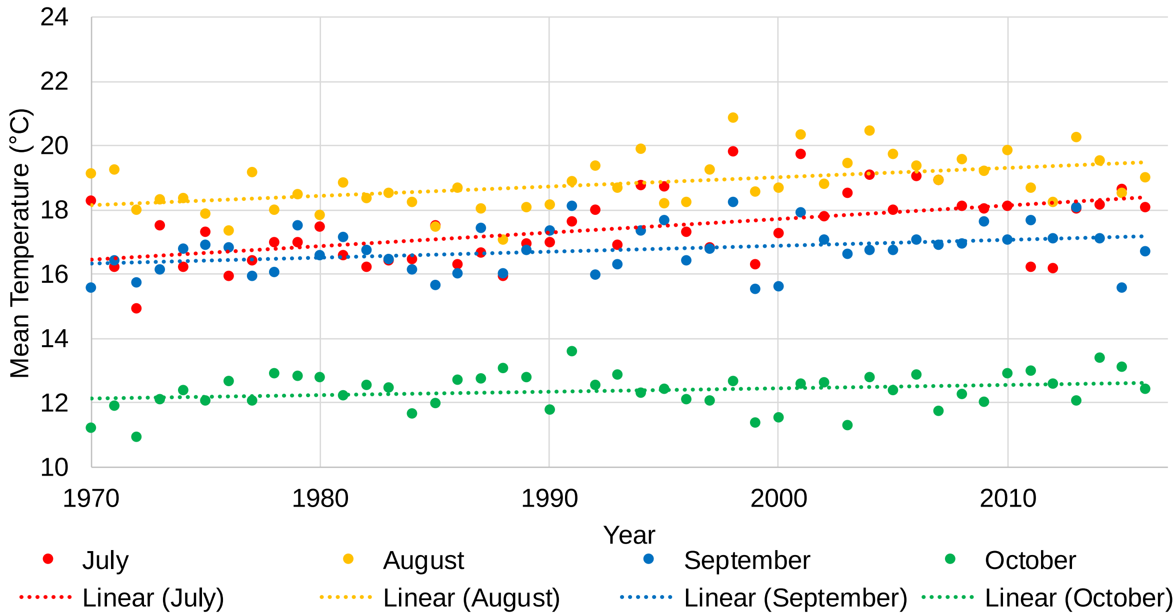


Figure 3-33 Simulated monthly mean temperatures at Priest Rapids (Free-Flowing)

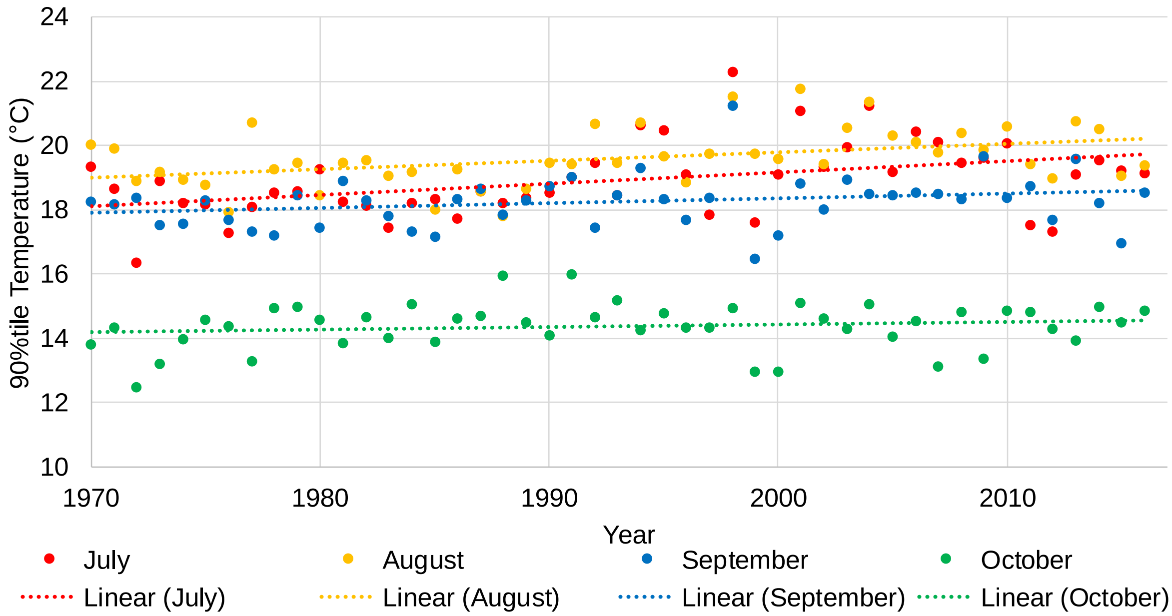


Figure 3-34 Simulated monthly 90th percentile temperatures at Priest Rapids (Free-Flowing)

Table 3-11 Current run seasonal Kendall test slopes and p values at Priest Rapids

Month	Mean		90th percentile	
	Slope	p value	Slope	p value
July	0.0412	0.0004	0.0405	0.0002
August	0.0424	<0.0000	0.0356	<0.0000
September	0.0395	<0.0000	0.0332	<0.0000
October	0.0367	<0.0000	0.0374	<0.0000

Table 3-12 Free-Flowing run seasonal Kendall test slopes and p values at Priest Rapids

Month	Mean		90th percentile	
	Slope	p value	Slope	p value
July	0.0458	0.0004	0.0331	0.0026
August	0.0282	0.0005	0.0261	0.0072
September	0.0211	0.0140	0.0133	0.0349
October	0.0100	0.1233	0.0096	0.1660

Trend Analysis at Wells Dam

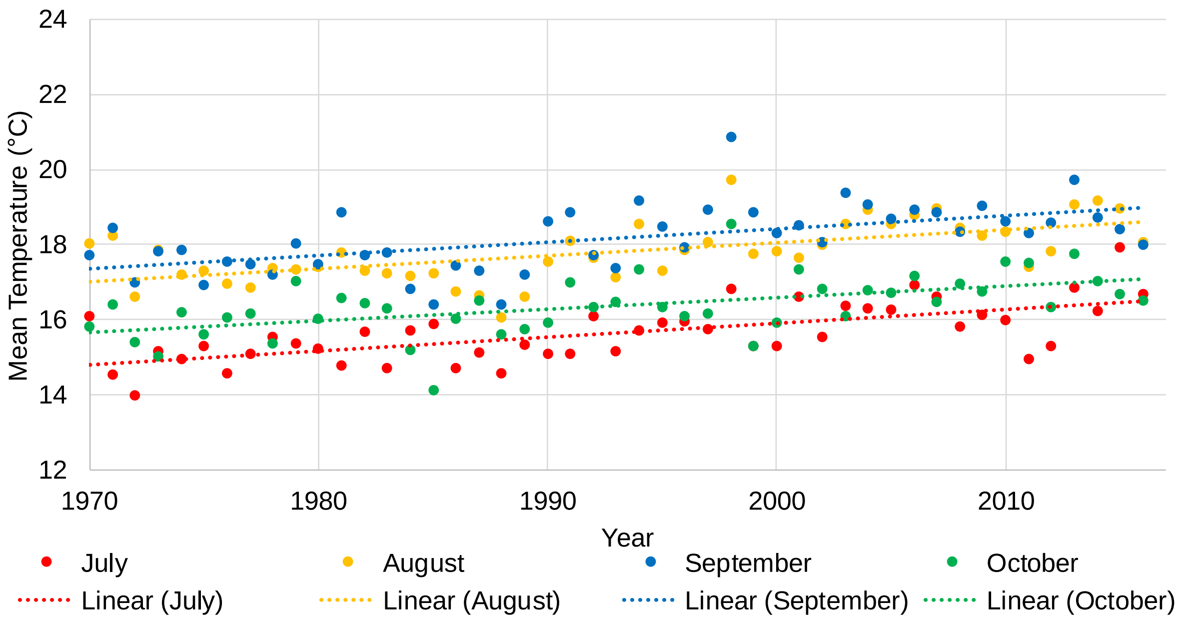


Figure 3-35 Simulated monthly mean temperatures at Wells Dam (Current)

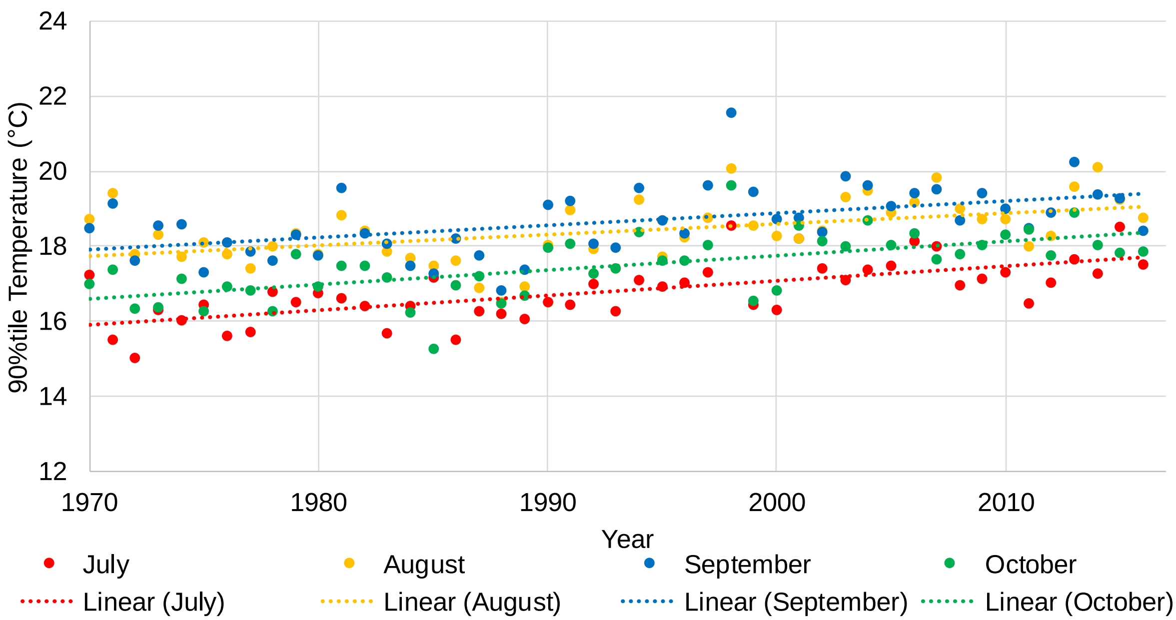


Figure 3-36 Simulated monthly 90th percentile temperatures at Wells Dam (Current)

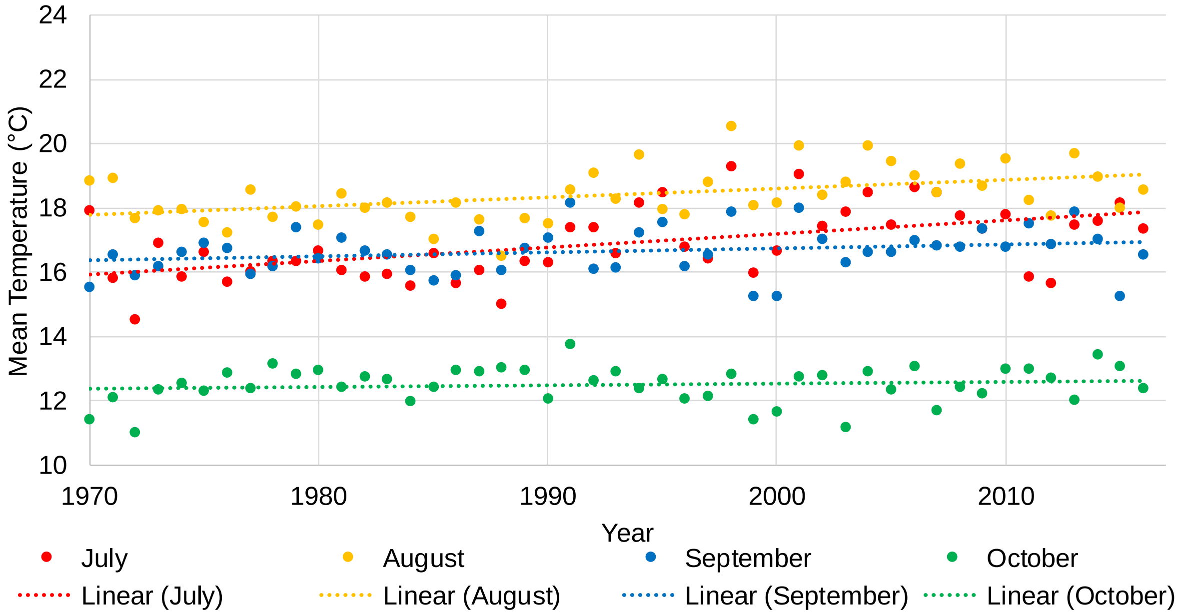


Figure 3-37 Simulated monthly mean temperatures at Wells Dam (Free-Flowing)

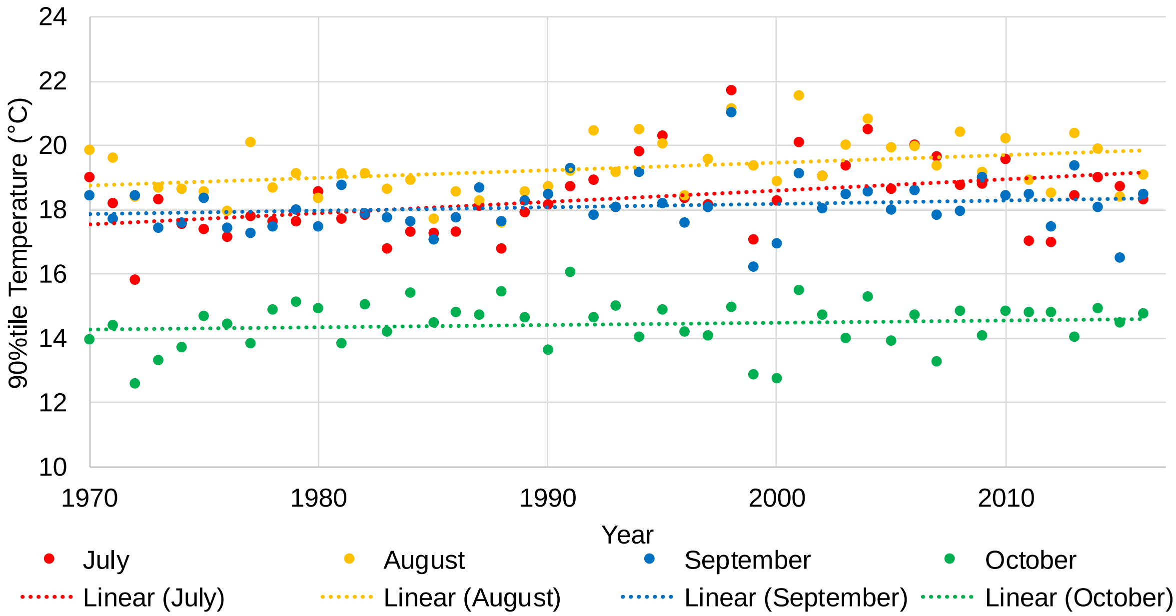


Figure 3-38 Simulated monthly 90th percentile temperatures at Wells Dam (Free-Flowing)

Table 3-13 Current run seasonal Kendall test and p values at Wells Dam

Month	Mean		90th percentile	
	Slope	p value	Slope	p value
July	0.0379	<0.0000	0.0383	<0.0000
August	0.0359	<0.0000	0.0277	0.0015
September	0.0327	0.0003	0.0322	0.0008
October	0.0288	0.0001	0.0369	<0.0000

Table 3-14 Free-Flowing run seasonal Kendall test and p values at Wells Dam

Month	Mean		90th percentile	
	Slope	p value	Slope	p value
July	0.0439	0.0005	0.0350	0.0024
August	0.0258	0.0020	0.0236	0.0271
September	0.0157	0.0373	0.0136	0.0694
October	0.0050	0.3448	0.0064	0.3737

Trend Analysis at Ice Harbor Dam

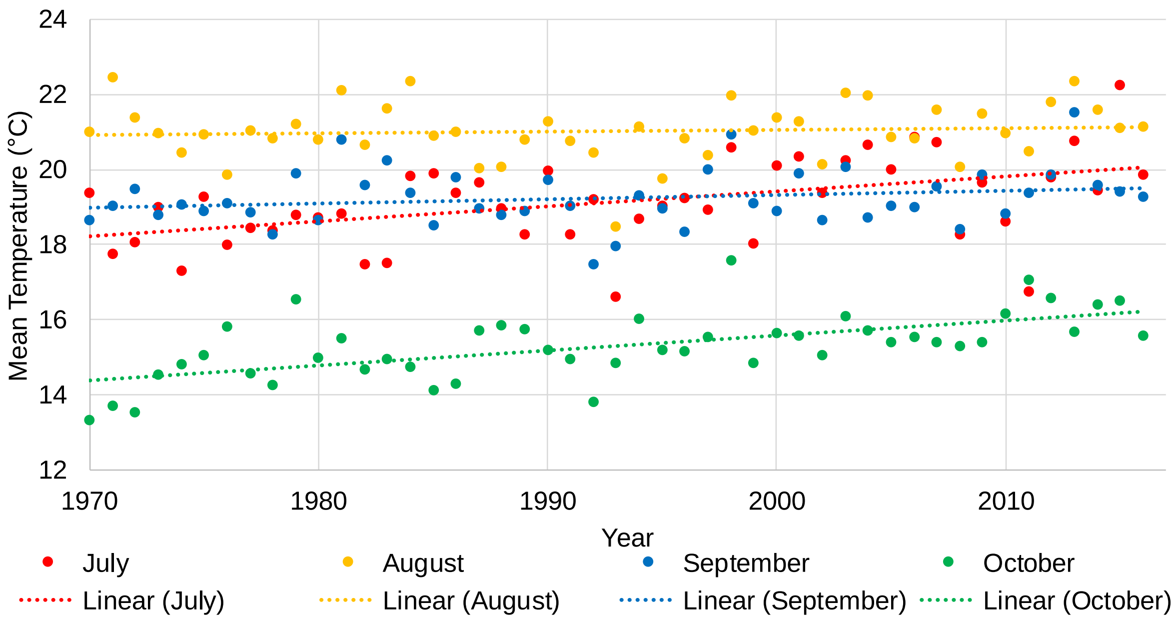


Figure 3-39 Simulated monthly mean temperatures at Ice Harbor Dam (Current)

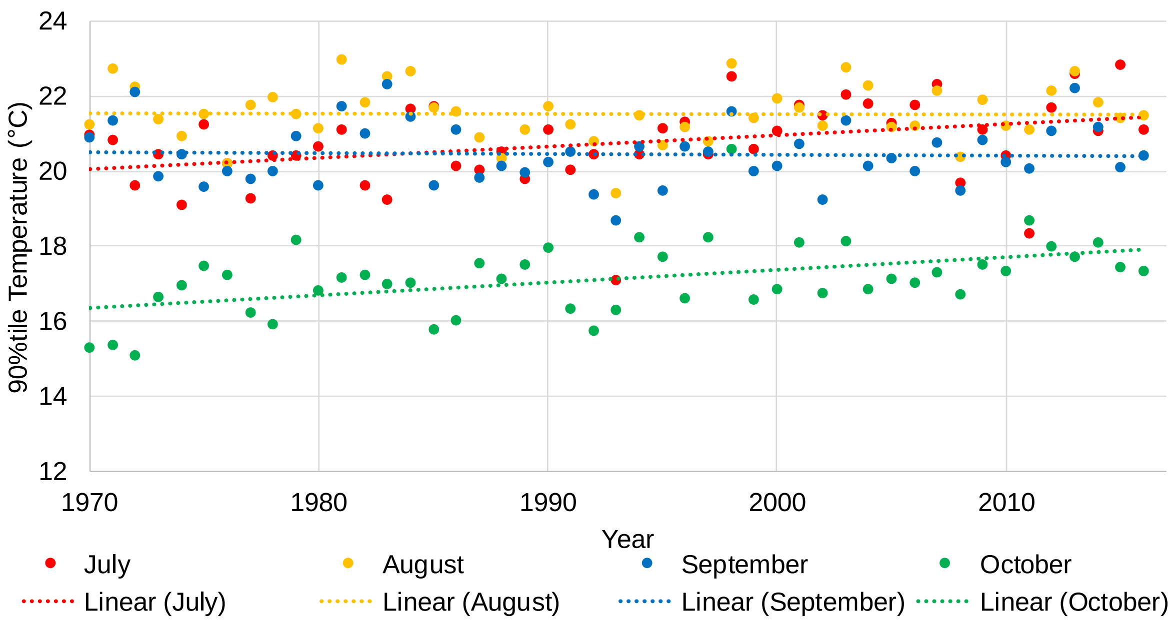


Figure 3-40 Simulated monthly 90th percentile temperatures at Ice Harbor Dam (Current)

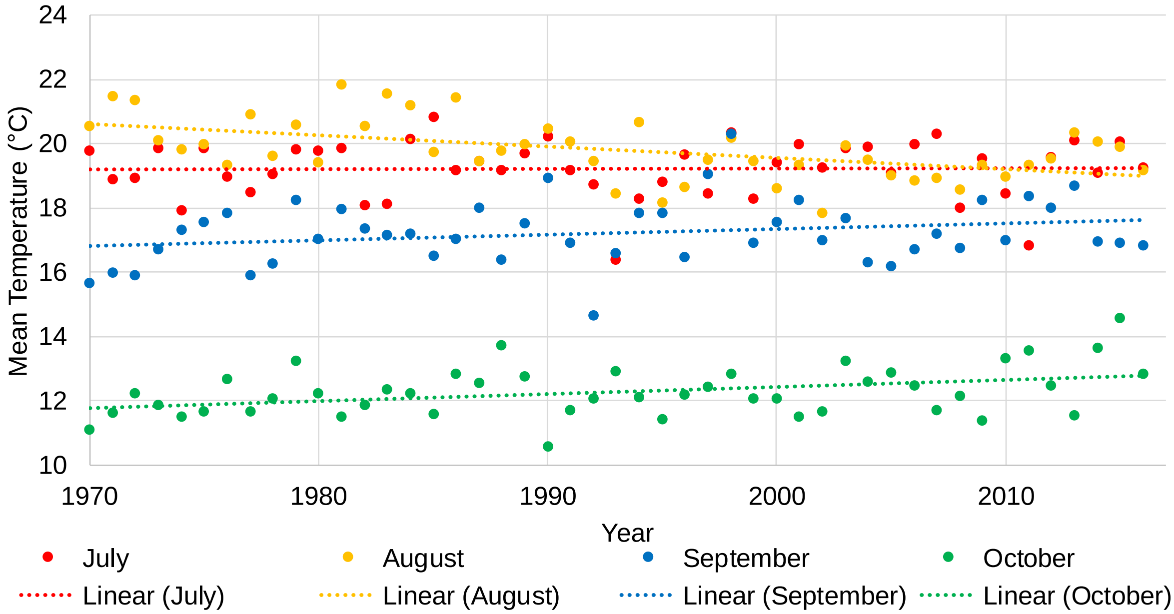


Figure 3-41 Simulated monthly mean temperatures at Ice Harbor Dam (Free-Flowing)

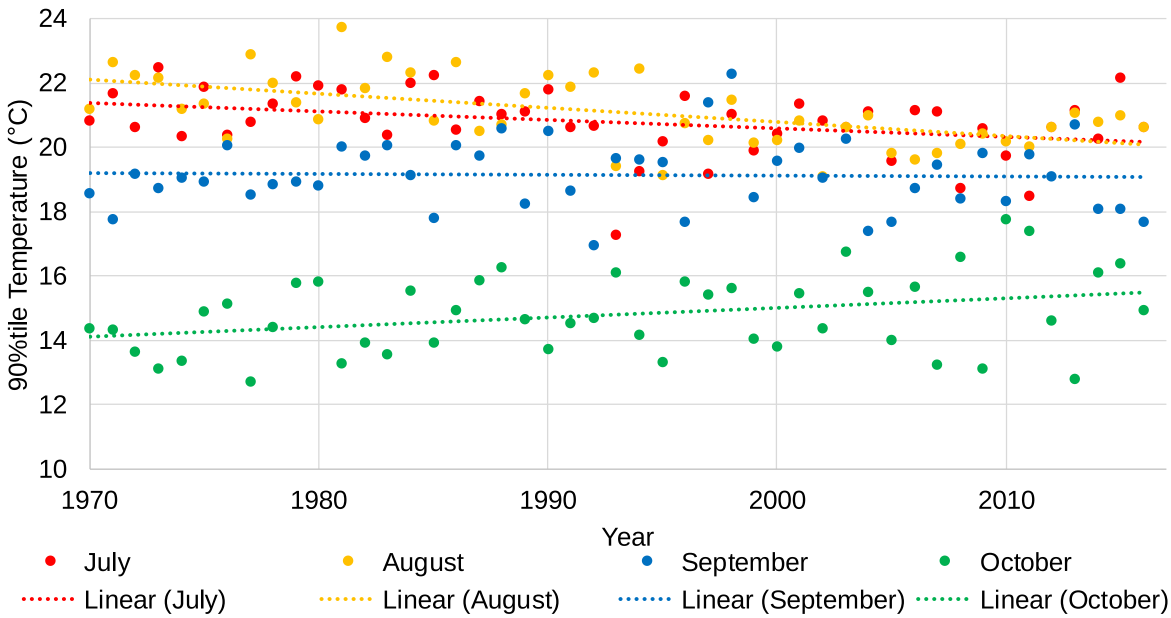


Figure 3-42 Simulated monthly 90th percentile temperatures at Ice Harbor Dam (Free-Flowing)

Table 3-15 Current run seasonal Kendall test and p values at Ice Harbor Dam

Month	Mean		90th percentile	
	Slope	p value	Slope	p value
July	0.0413	0.0004	0.0359	0.0017
August	0.0057	0.441	0.0000	0.9854
September	0.0092	0.1897	0.0025	0.8258
October	0.0393	<0.0000	0.0363	0.0008

Table 3-16 Free-Flowing run seasonal Kendall test and p values at Ice Harbor Dam

Month	Mean		90th percentile	
	Slope	p value	Slope	p value
July	0.0050	0.5149	-0.0256	0.0290
August	-0.0323	0.0006	-0.0408	0.0003
September	0.0176	0.1126	-0.0042	0.7482
October	0.0226	0.0151	0.0313	0.0334

Comparison to 1960s Data at Priest Rapids Dam

EPA has also compared RBM10 results to historical (1964 – 1969) temperature data for the Columbia River at the Priest Rapids Dam (Leinenbach 2018). The river temperature data were obtained from a Battelle report (Jaske et al., 1970), and recent Columbia River temperature conditions at the Priest Rapids Dam tailrace were obtained from the Columbia River Data Access in Real Time (DART) website. Water temperature measurements at the Priest Rapids Dam show that recent temperatures are warmer than previously observed conditions (***Figure 3-43***).

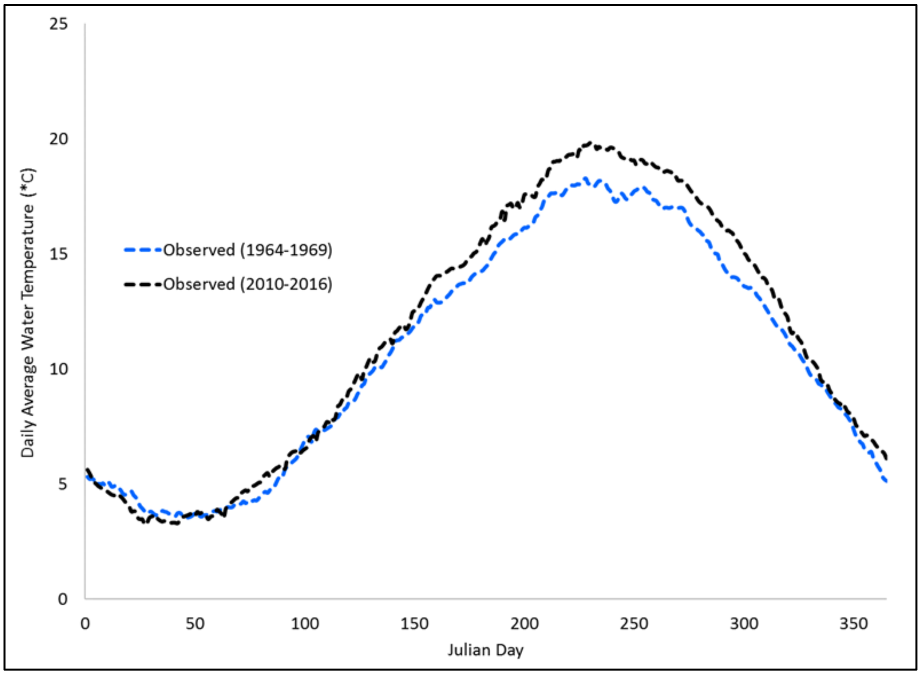


Figure 3-43 Measured Columbia River temperature trends at the Priest Rapids Dam in the 1964 – 1970 and the 2010 – 2016 periods.

RBM10 temperature predictions for the Columbia River at the tail race of the Priest Rapids Dam showed a similar temperature trend of water temperature increases during recent periods (***Figure 3-44*** through ***Figure 3-46***).

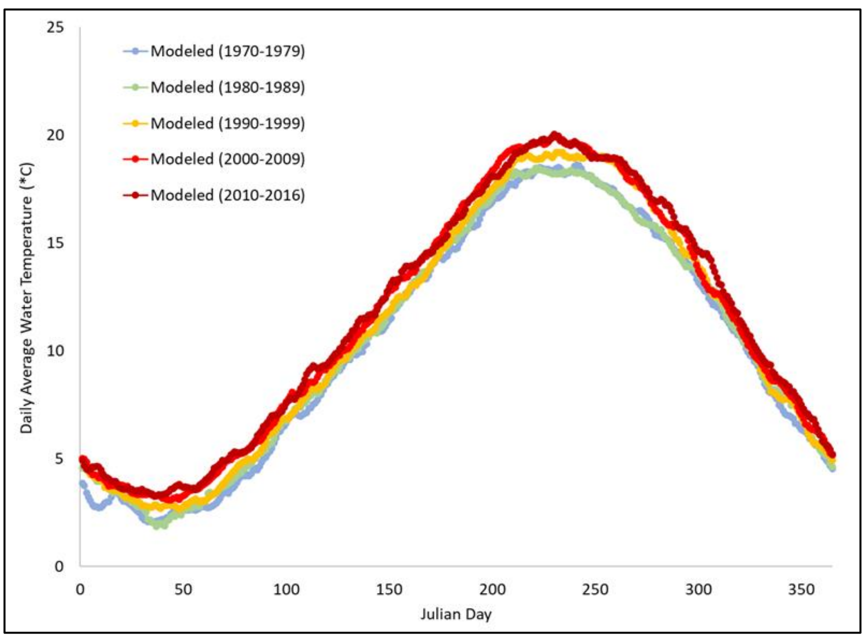


Figure 3-44 RBM10 simulated trends at the Priest Rapids Dam.

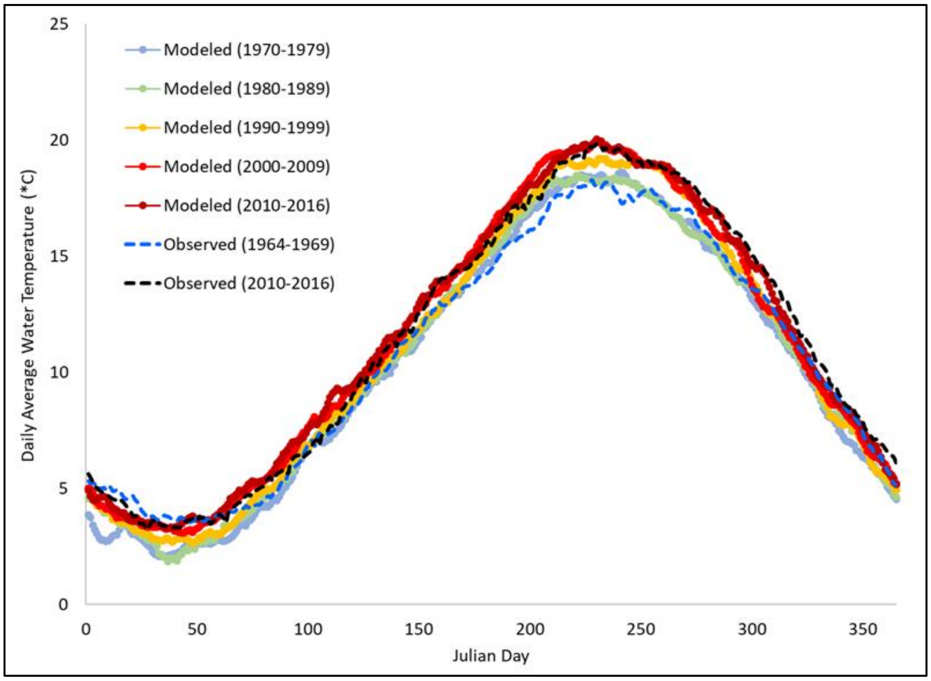


Figure 3-45 Comparison between simulated and measured trends at the Priest Rapids Dam.

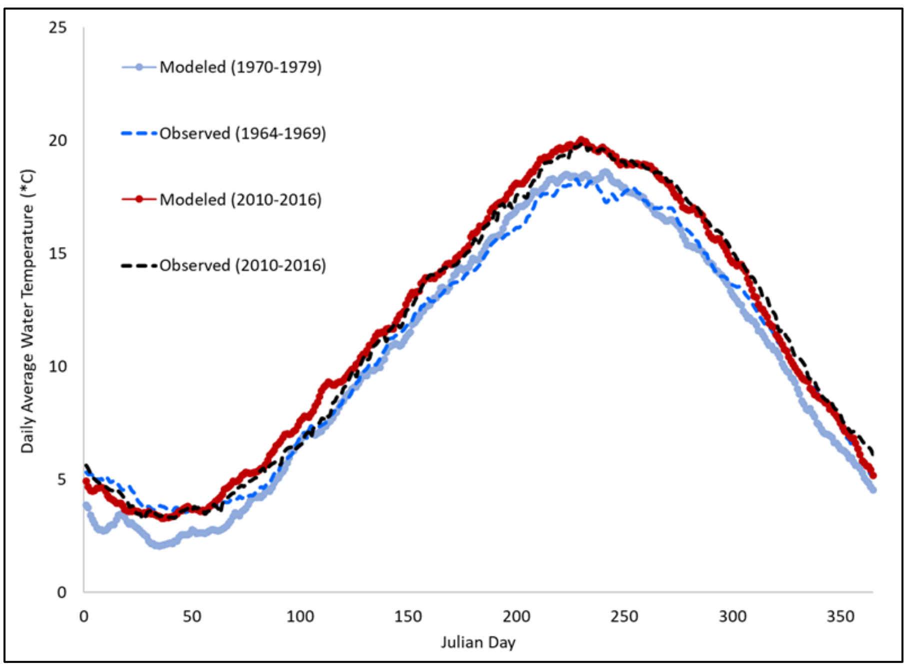
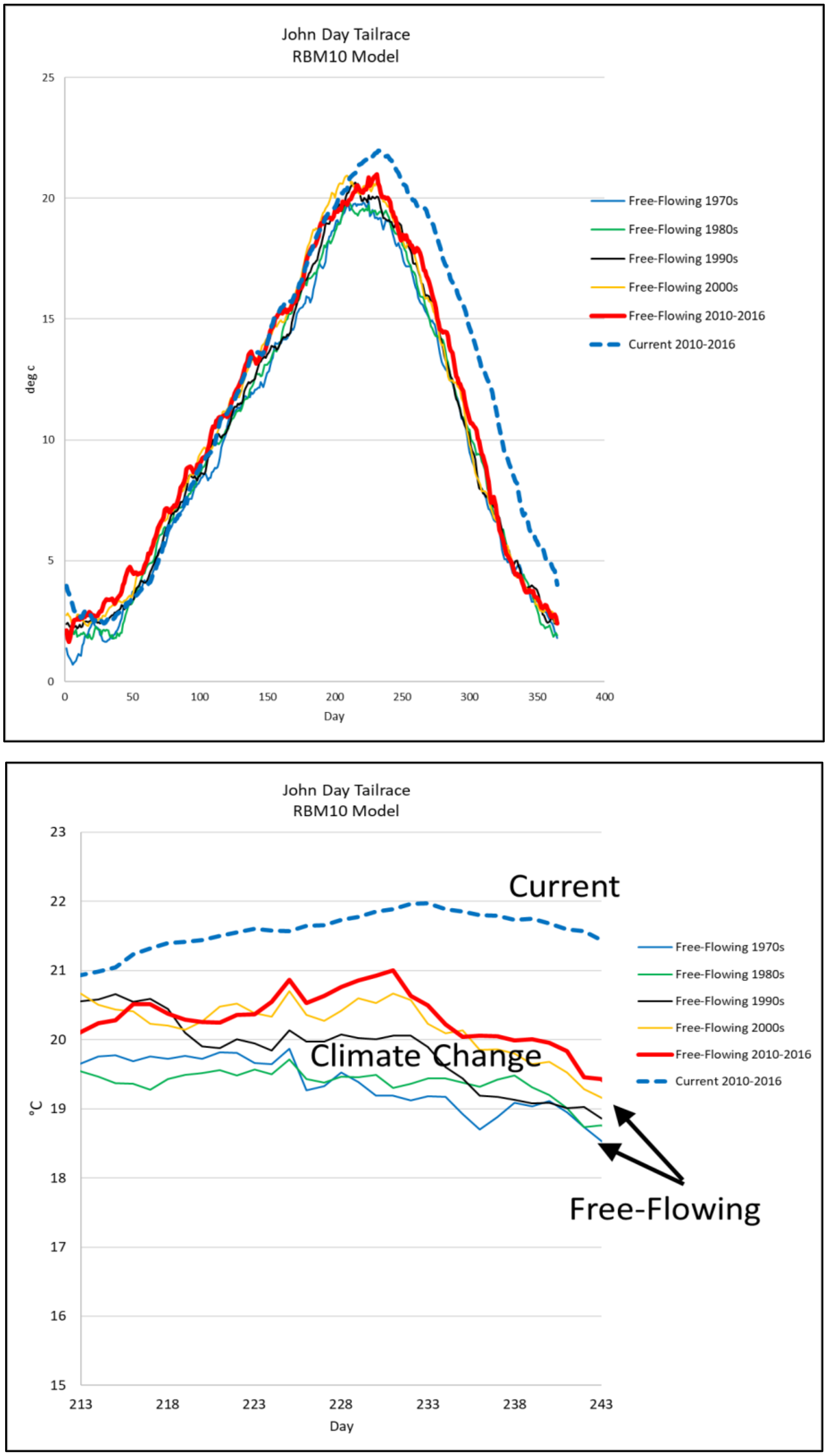


Figure 3-46 Comparison between simulated and measured trends at the Priest Rapids Dam for periods 2010-2016 and 1960-1979.

Comparison of Climate Change and Dam Impacts

In order to qualitatively evaluate the combined impact of climate change and dams, the model output from the “Free-Flowing” and “Current” scenarios is combined in ***Figure 3-47***. Climate and dam impacts can be distinguished by first running the model from 1970-2016 with “Free-Flowing” geometry to isolate climate change impacts on the river absent the dams. Then the “Current” condition from the most recent partial decade (2010-2016) is superimposed on the plot and visually compared to the “Free-Flowing” temperatures from the same period. This plot suggests that climate impacts to date may be similar in magnitude to dam impacts.



Lower panel zooms to a close-up of August conditions.

Figure 3-47 Simulated decadal average temperatures for free-flowing river (1970-2016) compared to the current impounded conditions (2010-2016).

3.6 TRIBUTARIES (TR1 SCENARIO)

The RBM10 model incorporates the 25 largest tributaries contributing flow to the Columbia and Snake Rivers. Past assessment for the 2003 draft TMDL and experience with the updated 2018 RBM10 model indicate that changes to tributary temperatures have a relatively small impact on Columbia and Snake Rivers temperatures with the exception of the Clearwater River impact on the Snake River (due to Dworshak Dam operations) and the Snake River impact on the Columbia River. Both tributary impacts are incorporated into the model assessment as simulated reaches. The remaining 23 tributaries are boundary inputs of flow and temperature to the mainstems (***Table 3-17***).

Table 3-17 Major 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
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

3.6.1 Methodology and Assumptions

The combined inflows at the model boundaries and 23 major tributary confluences provide all of the primary flow inputs to the mainstem Columbia and Snake Rivers. This is demonstrated in the agreement between simulated and measured flow in shown in the model development report (Tetra Tech 2018).

The RBM10 model includes tributaries as inputs of flow and temperature to the Columbia and Snake Rivers, so detailed analysis of current human-caused impacts to the tributaries is not feasible with RBM10. A separate regional assessment of potential restoration potential in Columbia River tributaries indicates that there are riparian impacts to many of the tributaries, and an average reduction of 0.5°C in summer/fall tributaries may be feasible (Fuller et al., 2018). This finding forms the basis for the TR1 model scenario, wherein the summer/falls temperatures of all major tributaries are reduced by 0.5°C below current temperatures. When the results of this scenario are compared with the "Current" conditions simulation, the difference in mainstem temperatures represents the current impact of tributaries (assuming each is uniformly impacted by 0.5°C).

3.6.2 Results

The maximum temperature impact of the tributary change based on the TR1 model simulation is 0.1°C and occurs in the Columbia River at John Day Dam and McNary Dam. Plots for the month of August are provided in ***Figure 3-48*** and ***Figure 3-49***. The impact of tributaries is generally higher on the Columbia River than the Snake River because it has larger tributaries.

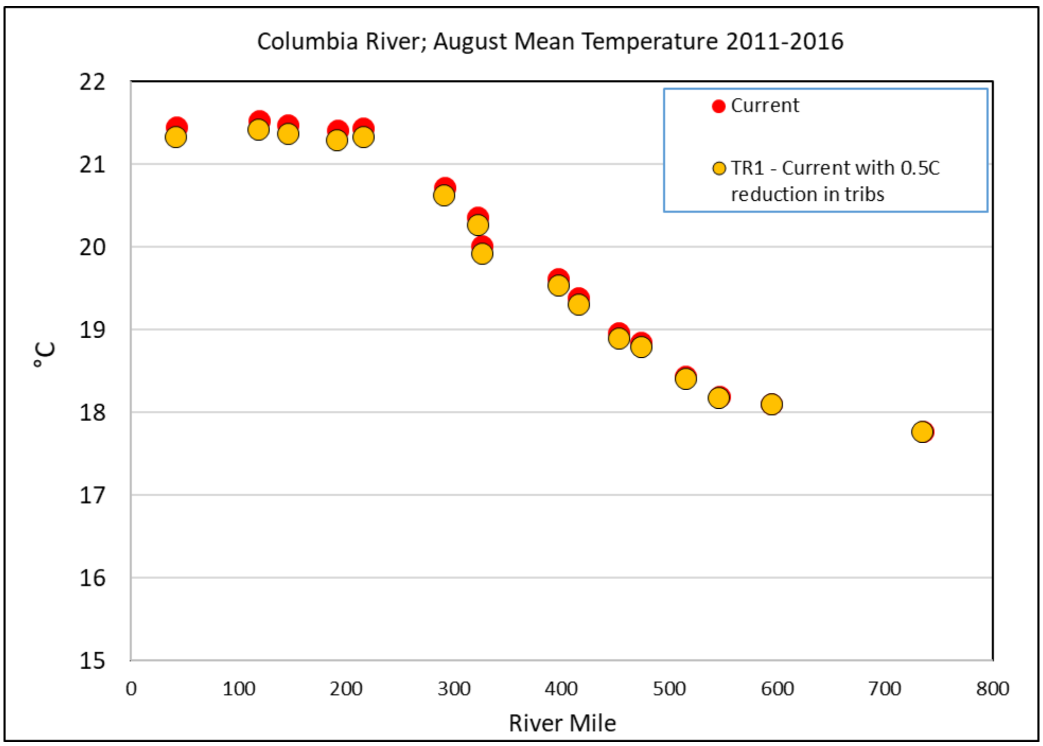


Figure 3-48 Simulated temperatures for Columbia River with 0.5°C tributary temperature reduction – August

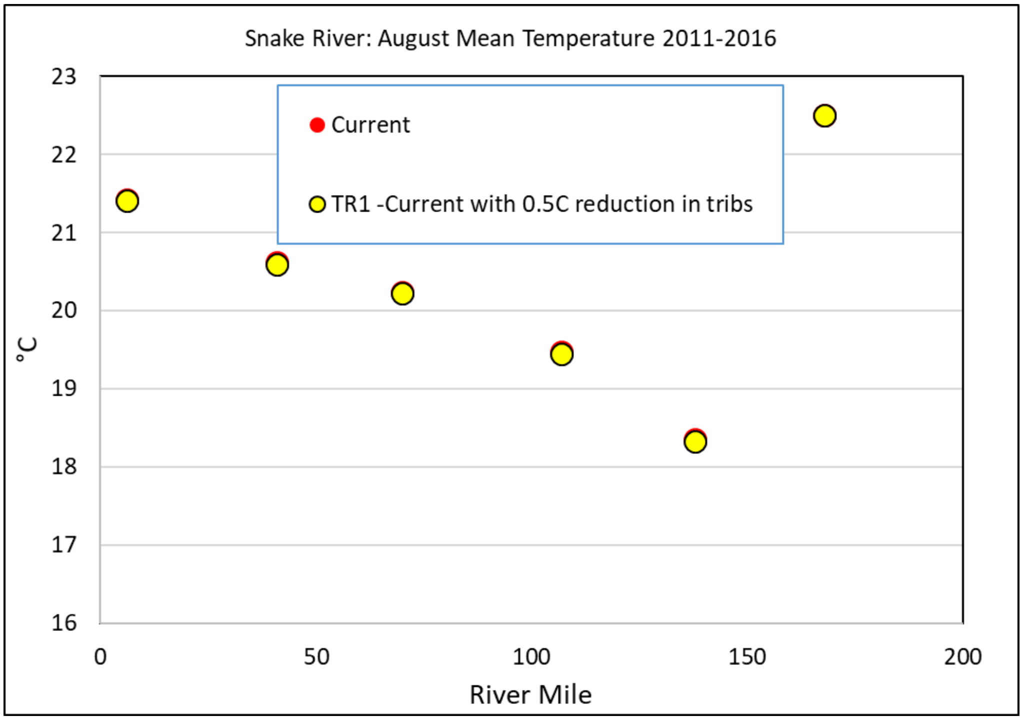


Figure 3-49 Simulated temperatures for Snake River with 0.5°C tributary temperature reduction – August

3.7 BOUNDARY CONDITIONS (BC1 AND BC2 SCENARIOS)

Summer water temperatures at the upstream boundaries of the TMDL study area are higher than Washington water quality criteria. This part of the modeling assessment evaluates the impact of reduced boundary temperatures on downstream temperatures and impacts. The model is run with reduced boundary temperatures at "Current" impounded conditions (scenario "BC1") and "Free-Flowing" conditions (scenario "BC2").

3.7.1 Methodology and Assumptions

In scenarios "BC1" and "BC2", Columbia and Snake Rivers model boundary daily average temperature is capped at the applicable temperature criterion value:

- Columbia River at Canadian border = 16°C.
- Snake River at Anatone = 20°C.

The caps are implemented by limiting the time series boundary inputs when current temperatures exceed the cap for the entire summer/fall period of the assessment (July – November 15).

3.7.2 Results

Monthly mean temperatures for scenarios "BC1" and "BC2" are plotted alongside the "Current" and "Free-Flowing" conditions in ***Figure 3-50*** through ***Figure 3-55***.

In the Columbia River, under the "Current" scenario, the Grand Coulee impoundment impact almost negates the effect of colder July/August temperatures at the border. Colder border temperatures cause a more sustained cooling in the "Free-Flowing" river downstream from the border. The net effect is a minor improvement in "Current" temperatures, and dam impacts increase because of colder "Free-Flowing" temperatures.

Snake River patterns are similar to the Columbia River, but the border temperature influence is higher in the upper reaches. The effect of border temperature gradually diminishes in the "Current" scenario at each successive dam.

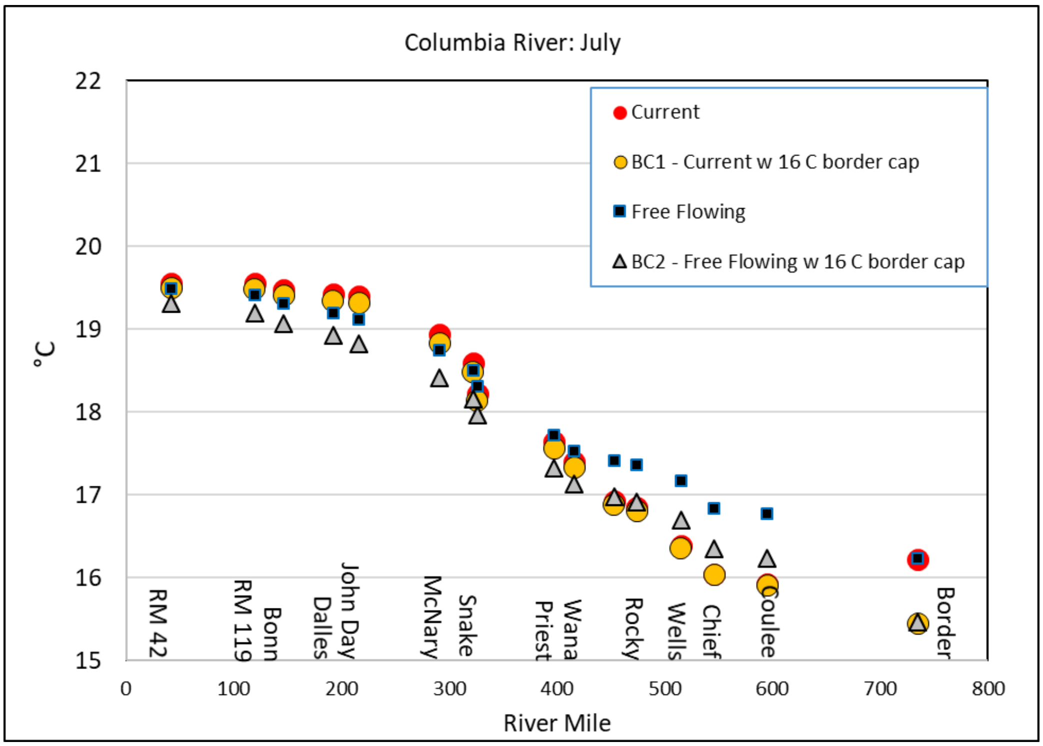


Figure 3-50 Simulated temperatures for Columbia River with reduced upstream boundary temperature – July

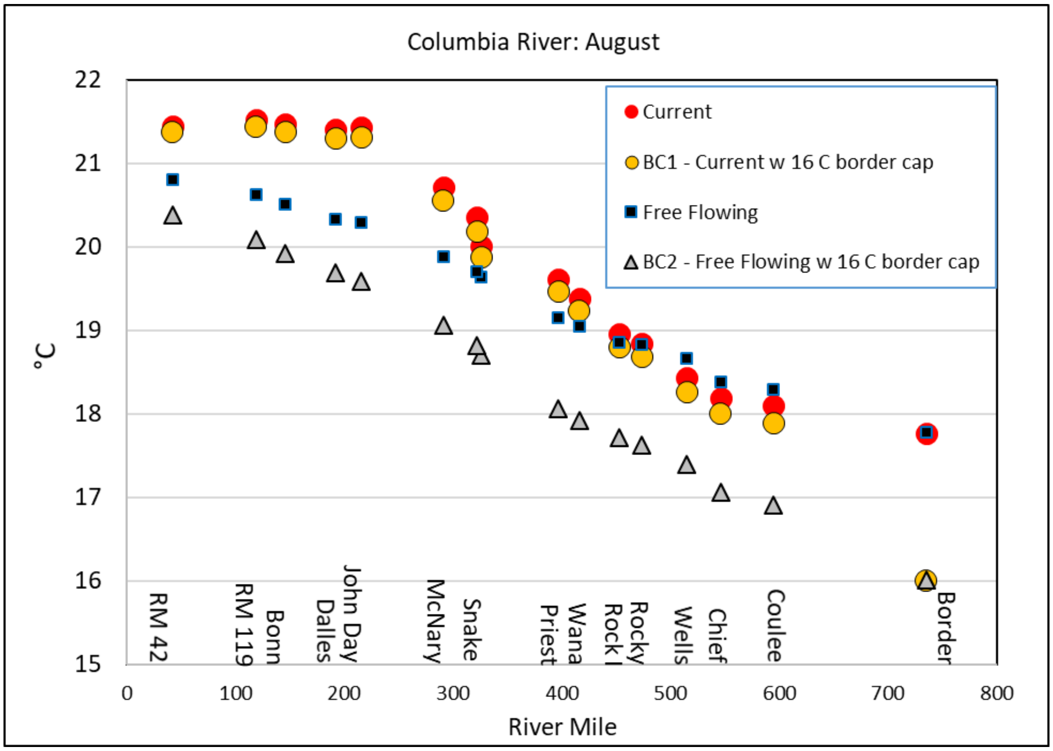


Figure 3-51 Simulated temperatures for Columbia River with reduced upstream boundary temperature – August

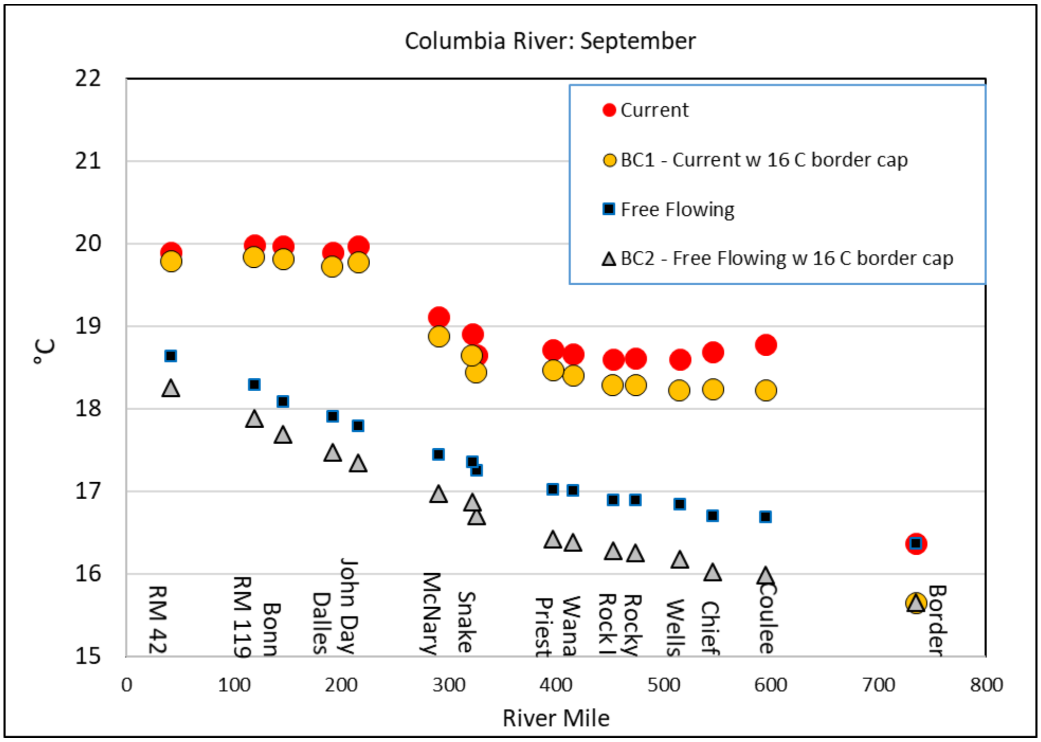


Figure 3-52 Simulated temperatures for Columbia River with reduced upstream boundary temperature – September

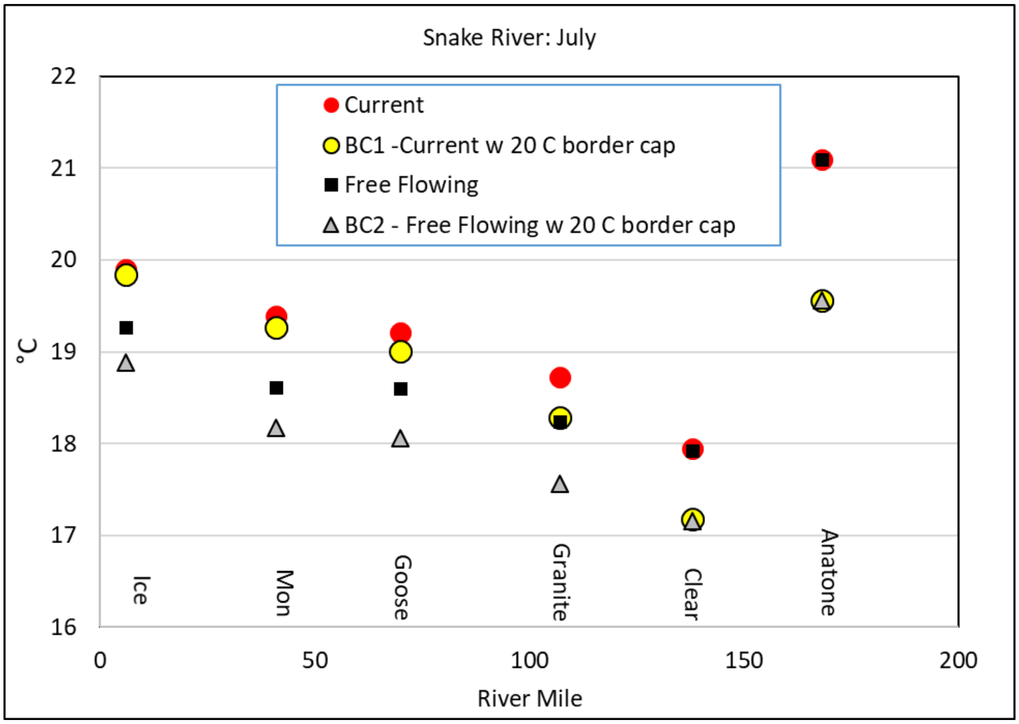


Figure 3-53 Simulated temperatures for Snake River with reduced upstream boundary temperature – July

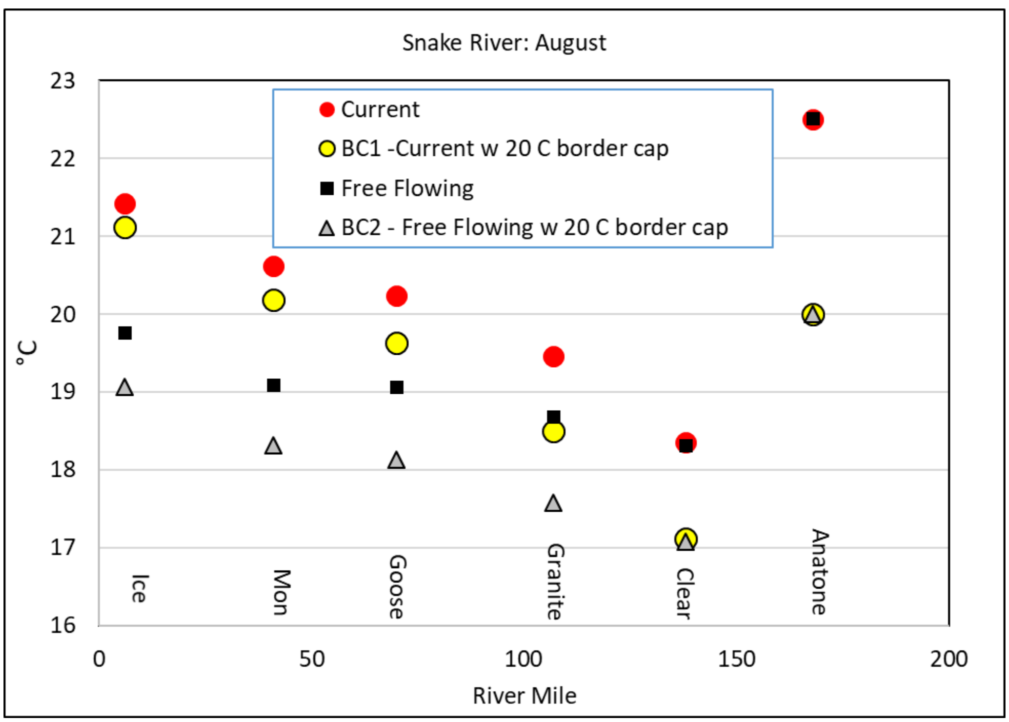


Figure 3-54 Simulated temperatures for Snake River with reduced upstream boundary temperature – August

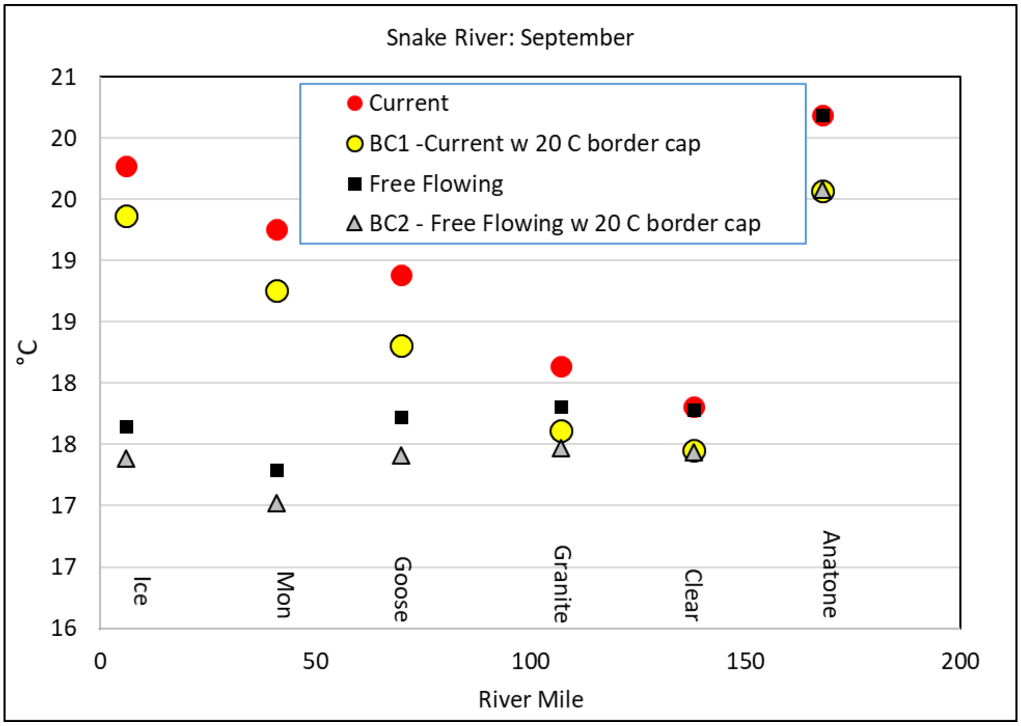


Figure 3-55 Simulated temperatures for Snake River with reduced upstream boundary temperature – September

3.8 POINT SOURCES (PS1 SCENARIO)

The impact of National Pollutant Discharge Elimination System (NPDES) permitted facilities has been assessed by running RBM10 with and without point source inflows. Because of the number of facilities, it is necessary to group sources into aggregated model inputs. Municipal and industrial facilities designated as major facilities in the NPDES program are included as individual inputs in the model at the river mile of their discharge, while minor facilities are grouped into a single gross input of heat at the midpoint of the TMDL reach into which they discharge. EPA's formula for defining the major and minor designation for municipal treatment works permits is based on flow, whereas the formula for industrial permits is based on a variety of factors unrelated to heat loading. For this reason, some minor industrial permittees may discharge higher heat loads than some of the major industrial facilities.

3.8.1 Methodology and Assumptions

There are 28 major point sources included as individual model inputs of flow and temperature, with 26 sources on the Columbia River and two on Snake River (***Table 3-18***). The facilities incorporated into the modeling analysis are listed in the tables below. The heat loads input into the model for all discharges are based on the design flow and maximum discharge temperature. In some cases, alternate metrics are used when design flow and maximum temperature are not available in permitting and compliance databases. There are 58 minor point sources included on the Columbia River and 2 minor point sources on the Snake River that were included in the modeling (***Table 3-19*** and ***Table 3-20***).

Table 3-18 Major point sources on the Columbia River

Facility Name	Permit Number	Location RM	Flow (MGD)	Temp (°C)
E Wenatchee STP	WA0020621	465.7	3.80	26.2
Alcoa Wenatchee	WA0000680	455.2	3.60	25.6
Columbia Generating Sta / Energy Northwest	WA0025151	351.8	9.40	32.0
Richland STP	WA0020419	337.1	11.39	29.4
Kennewick POTW	WA0044784	328.0	12.20	27.0
Pasco	WA0044962	327.6	7.20	27.4
Boise Cascade Walulla / Boise White Paper LLC	WA0003697	316.0	28.20	36.9
The Dalles STP	OR0020885	186.5	4.15	27.0
Hydro Extrusion USA, LLC	OR0001708	186.0	3.40	36.4
Hood River OR STP	OR0020788	165.0	2.00	25.7
Georgia Pacific / GP Consumer Operations LLC	WA0000256	120.0	37.60	37.7
Gresham OR WWTP	OR0026131	117.5	15.00	23.9
Marine Park / Vancouver Marine Park Reclamation Facility	WA0024368	109.5	16.09	25.1
Vancouver Westside STP	WA0024350	105.0	28.31	26.0
Clark County PUD	WA0023639	103.2	14.95	23.3

Facility Name	Permit Number	Location RM	Flow (MGD)	Temp (°C)
Portland STP OR	OR0026905	102.5	100.00	19.7
Boise/St Helens OR STP	OR0020834	86.0	1.91	28.5
Dyno Nobel Inc.	OR0001635	82.0	24.64	34.0
Noveon Kalama, Inc/ Emerald Kalama Chemical	WA0000281	74.0	14.70	34.7
Steelscape, Inc.	WA0040851	72.2	0.15	35.0
Longview Fibre	WA0000078	67.4	57.00	39.4
Three Rivers Regional	WA0037788	66.0	26.00	30.0
Weyerhauser Longview	WA0000124	64.0	79.20	45.6
Port of St. Helens	OR0034231	53.0	0.95	22.9
GP Wauna OR Mill	OR0000795	42.0	46.30	30.9
Astoria OR STP	OR0027561	18.0	4.20	25.0

Table 3-19 Minor point sources located on the Columbia River

Facility Name	Permit Number	Location RM	Flow (MGD)	Temp (°C)
Avista – Kettle Falls	WA0045217	702.4	0.23	30.5
Grand Coulee Dam (WA)	Permit appl.	596	178	16.8
Grand Coulee WWTP	WA0044857	596.6	0.30	24.1
City of Coulee Dam	WA0020281	596.0	0.50	25.4
Colville Confederated Tribes	WAG130016	580.0	4.86	25.4
CTCR	WAG130025	580.0	25.38	25.4
Bridgeport STP	WA0024066	543.7	0.36	24.2
Brewster	WA0021008	529.8	0.61	26.0
Patteros STP	WA0020559	524.1	0.10	24.0
Chelan POTW	WA0020605	503.5	2.64	25.0
Entiat STP	WA0051276	485.0	0.15	26.0
Tree Top Inc Wenatchee	WA0051527	470.8	0.70	26.6
Naumes Processing / Keyes Fibre Corp	WA0051811	470.5	4.15	25.4
KB Alloys/ AMG Al North Amer.	WA0002976	458.5	0.30	40.0
Specialty Chemical	WA0002861	456.3	0.35	16.1
Vantage STP	WA0050474	420.6	0.09	26.1
Twin City Foods Kennewick	WA0021768	328.3	0.01	24.4
Agrium Bowles Road	WA0003671	322.6	15.00	30.8
Agrium Game Farm Road	WA0003727	321.0	14.10	27.2

Facility Name	Permit Number	Location RM	Flow (MGD)	Temp (°C)
Sanvik Metals	WA0003701	321.0	0.24	37.8
McNary Dam (WA)	Permit appl.	291	0.9	19.7
McNary Dam (OR)	Permit appl.	291	15.9	22
Umatilla STP	OR0022306	285.0	0.80	25.4
Arlington STP	OR0020192	238.0	0.13	25.0
Goldendale	WA0021121	216.7	2.40	23.3
John Day Dam (WA)	Permit appl.	214	52	19.3
John Day Dam (OR)	Permit appl.	214	100	22.6
Biggs OR WWTP	OR0041246	205.5	0.0385	26.1
The Dalles Dam (WA)	Permit appl.	190	56.0	20.0
Dalles/Oregon Cherry OR	OR0000736	189.5	0.50	25.0
Mosier OR	OR0028045	174.5	0.09	25.6
SDS Lumber	WA0051152	170.2	25.00	29.4
Bingen STP	WA0022373	170.2	2.40	24.0
Spring Crk Natl Fish Hatchery	WAG130006	165.0	5.11	25.4
Cascade Locks OR STP	OR0041271	148.2	0.49	28.0
Stevenson STP	WA0020672	150.0	0.45	27.0
Tanner Creek Wastewater Treatment Plant - USACE	OR0022624	146.1	0.10	22.0
North Bonneville STP	WA0023388	144.0	0.13	25.4
Bonneville Dam (OR)	OR0034355	141.5	4.14	23.6
Bonneville Lock & Dam-USACE	OR0034355	141.5	4.14	23.6
Multnomah Falls OR Lodge STP	OR0040410	135.9	0.50	31.6
Exterior Wood, Inc. / Taiga Building Products USA	WA0040711	123.8	0.50	25.4
Washougal STP	WA0037427	123.5	2.24	24.1
Camas STP	WA0020249	121.2	6.10	32.7
Toyo Tanso USA OR	OR0034916	118.1	104.95	25.3
Port of Portland	OR0000060	116.9	2.11	24.8
Knife River Corporation - NW	OR0044652	116.7	9.00	25.0
Sundial Marine Construction & Repair, Inc.	OR0044601	116.7	0.02	25.4
Portland Water Bureau	OR0031135	115.0	4.15	20.0
Vancouver Ice & Fuel Oil	WA0039918	106.0	0.04	25.4
Northwest Packing Co.	WAR001129	105.2	4.15	25.4
Salmon Creek STP	WA0023639	95.5	14.95	23.3
Columbia River Carbonates	WA0039721	83.5	0.31	14.1

Facility Name	Permit Number	Location RM	Flow (MGD)	Temp (°C)
Kalama STP	WA0020320	75.0	0.80	25.4
Port of Kalama	WA0040843	72.2	0.02	25.4
Riverwood OR Mobile Home Park / Magar E Mager	OR0031143	70.6	0.01	24.0
Rainier OR STP	OR0020389	67.0	0.99	25.0
Stella STP	WA0039152	56.4	0.00	25.4
PGE Beaver OR	OR0027430	53.0	1.44	35.0
Cathlamet STP	WA0022667	32.0	0.14	25.4
Bio-Oregon Protein	OR0000612	10.8	0.43	25.4
Pacific Surimi Co., Inc.	OR0034657	10.0	0.38	25.4
Point Adams Packing Co. / California Shellfish Co.	OR0000868	6.6	0.68	12.8
Bell Buoy Crab Co. (Now South Bend Products LLC)	WA0000159	6.0	0.20	18.4
Ilwaco STP	WA0023159	2.0	1.01	23.0
Jessies Ilwaco Fish Co.	WA0000361	2.0	0.75	18.3

Table 3-20 Minor point sources located on the Snake River

Facility Name	Permit Number	Location RM	Flow (MGD)	Temp (°C)
Clarkston STP	WA0021113	138.0	2.20	26.9
Lower Granite Dam (WA)	Permit appl.	106	29.0	20.2
Little Goose Dam (WA)	Permit appl.	69	40.1	19.4
Lyon's Ferry (hatchery)	WAG137006	59.1	91.90	25.4
Lower Monumental Dam (WA)	Permit appl.	41	27.8	17.1
Ice Harbor Dam (WA)	Permit appl.	9	39.8	21.4

In addition to current discharges, a heat load representing a potential future growth allowance was included as a model input at the midpoint of each TMDL reach. The heat load is equal in each reach and was calculated as follows:

- All facility loads throughout study area were summed, and 5% of this total loading was calculated as a future growth allocation.
- The total growth allocation above was divided by the number of reaches to achieve an equal load per reach.
- The resulting future growth load for a given reach, equal to 5×10^8 kcal/day, was inserted as a discharge load into the midpoint of each reach. This loading is roughly equivalent to the heat load discharged by a municipal treatment works for a city of the size of Astoria, Oregon.

The impact of this future growth allocation was evaluated alongside the current major and minor NPDES facilities.

3.8.2 Results

Based on a comparison of simulated river temperatures with and without point source discharges, the cumulative impact of the point sources is a 90th percentile temperature increase of 0.09°C, and this impact occurs in October at River Mile 42 of the Columbia River. The maximum impact on the Snake River is a 90th percentile impact of 0.06°C and it occurs in October at Lower Granite Dam. ***Table 3-21*** and ***Table 3-22*** show the mean and 90th percentile impacts at each location and time frame.

Table 3-21 Estimated impacts of point sources and future growth loading to Columbia River (2011 – 2016)

	Estimated Increase in Temperature (°C)							
	Mean				90th Percentile			
Location	**July**	**Aug**	**Sept**	**Oct**	**July**	**Aug**	**Sept**	**Oct**
RM 42	0.03	0.04	0.06	0.08	0.04	0.05	0.07	0.09
Camas	0.01	0.01	0.02	0.02	0.01	0.02	0.02	0.03
Warrenton	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02
Bonneville	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02
Dalles	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02
John Day	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.02
McNary	0.01	0.01	0.02	0.02	0.01	0.01	0.02	0.03
Priest R.	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01
Wanapum	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01
Rock I.	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01
Rocky R.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wells	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Chief Jos.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G. Coulee	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 3-22 Estimated impacts of point sources and future growth loading to Snake River (2011 – 2016)

	Estimated Increase in Temperature (°C)							
	Mean				90th Percentile			
Location	**July**	**Aug**	**Sept**	**Oct**	**July**	**Aug**	**Sept**	**Oct**
Ice Harbor	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.03
Lower Mon	0.01	0.02	0.02	0.03	0.02	0.02	0.03	0.03
Little Goose	0.02	0.02	0.03	0.03	0.02	0.03	0.03	0.04
L Granite	0.02	0.03	0.04	0.05	0.03	0.04	0.05	0.06

3.9 BANKS LAKE WATER DIVERSION (WD1 SCENARIO)

The Banks Lake pump storage project operates a large water agricultural withdrawal and pump storage system at Grand Coulee Dam. Inflows and outflows of the project compared to the Columbia River flows upstream at the Canadian border are shown in ***Figure 3-56***. The magnitude of inflows and outflows from the project ranges from approximately -20% to +5% of mainstem inflows at Canadian border in 2011 – 2016.

3.9.1 Methodology and Assumptions

The model is run for “Current” conditions that include Banks Lake project flows, and then the model is run with those flows set to zero. A comparison of simulated temperatures for the two scenarios provides the estimated impact of the operations. Note that Lake Roosevelt surface water elevations are unchanged from “Current” conditions to isolate the impact of Banks Lake project inflows and outflows.

3.9.2 Results

The results for 2011-2016 show a maximum impact to mean monthly temperatures of 0.1°C at McNary Dam Tailrace in July and a similar impact at John Day Dam tailrace in August. The impact is slightly positive (reduces temperatures) in October. Tabulated impacts by location and month are provided in ***Table 3-23***.

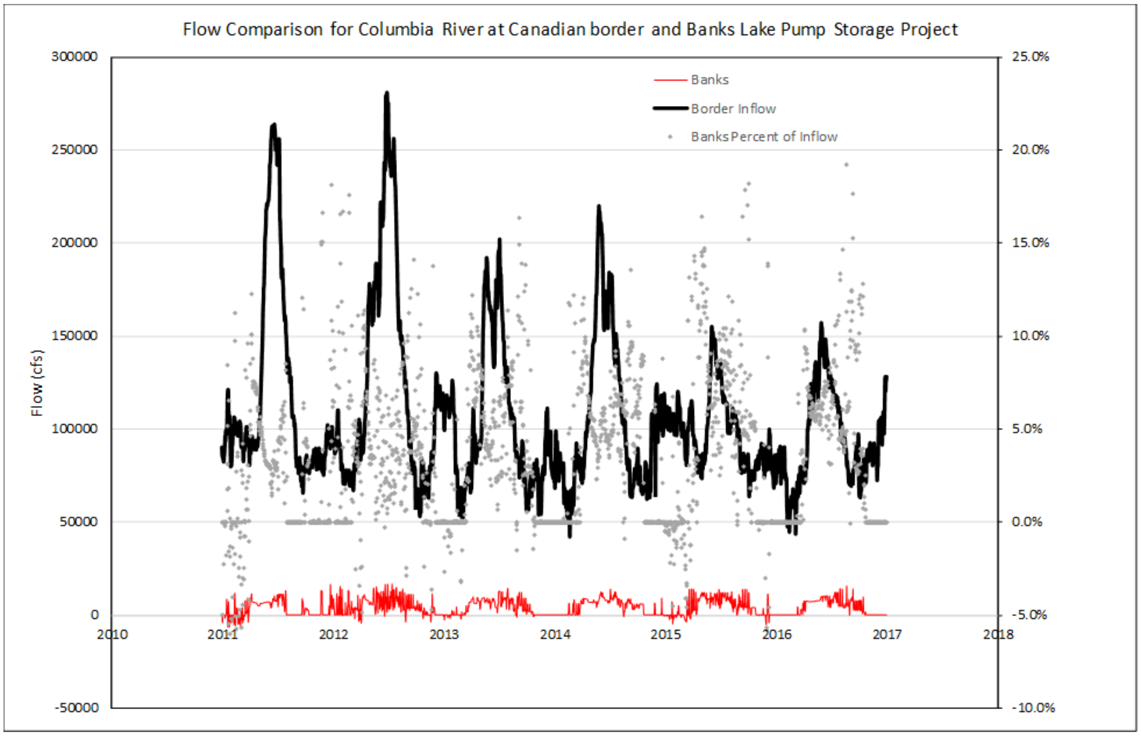


Figure 3-56 Comparison of Banks Lake project flows and Columbia River flows for 2001 – 2016

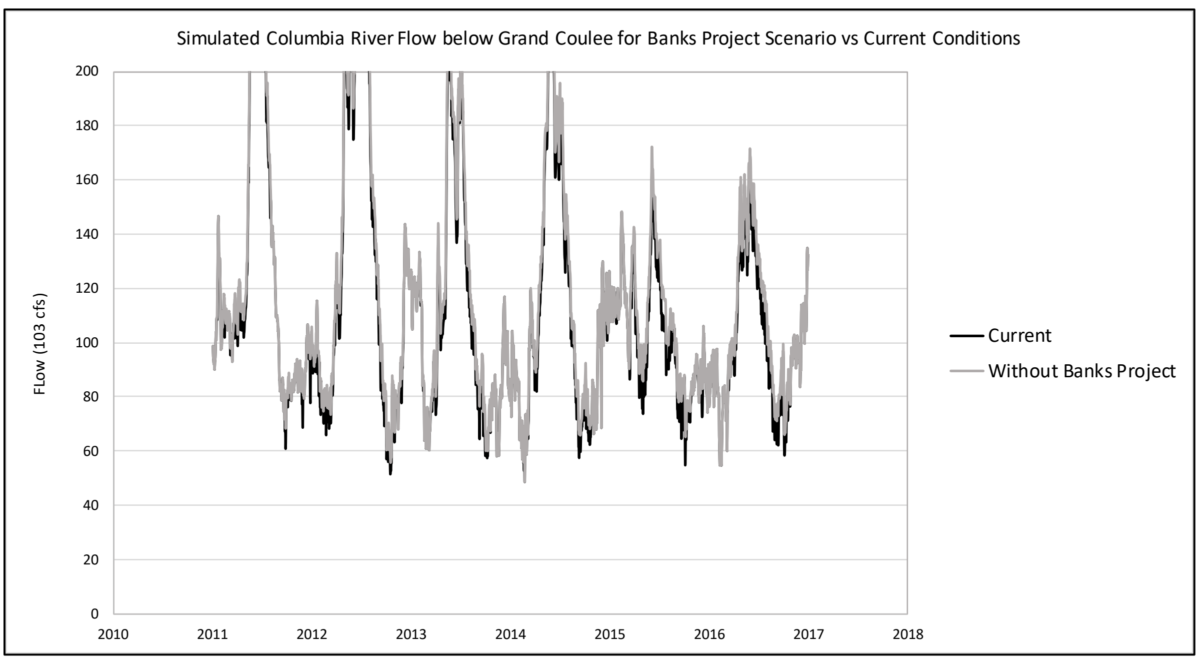


Figure 3-57 Simulated Columbia River flow downstream of Grand Coulee

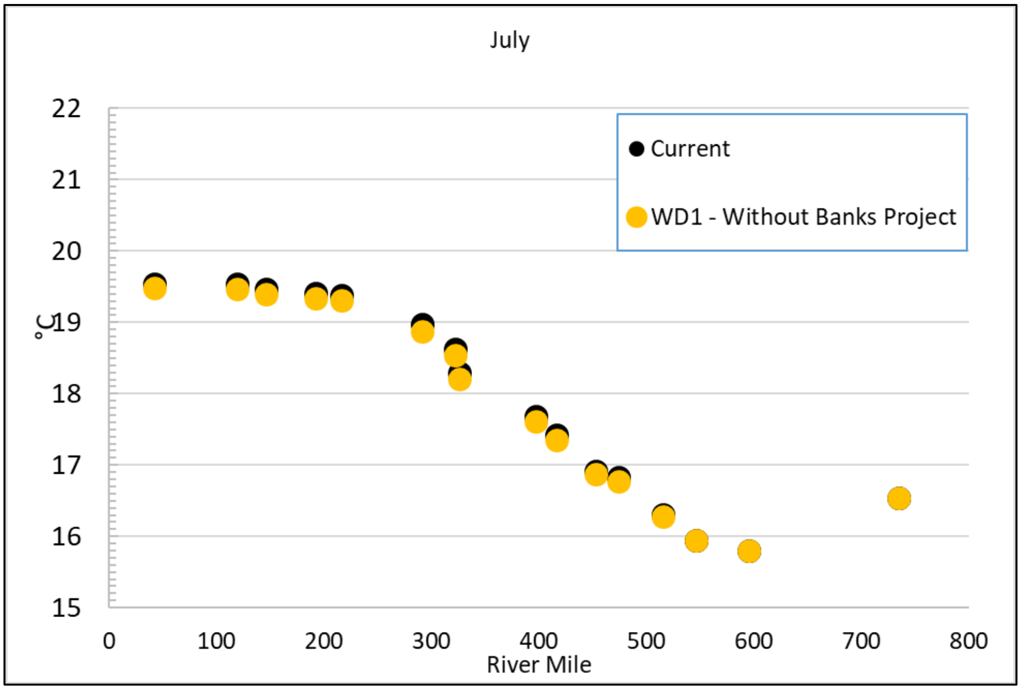


Figure 3-58 Simulated temperatures with and without Banks Lake project flows – July

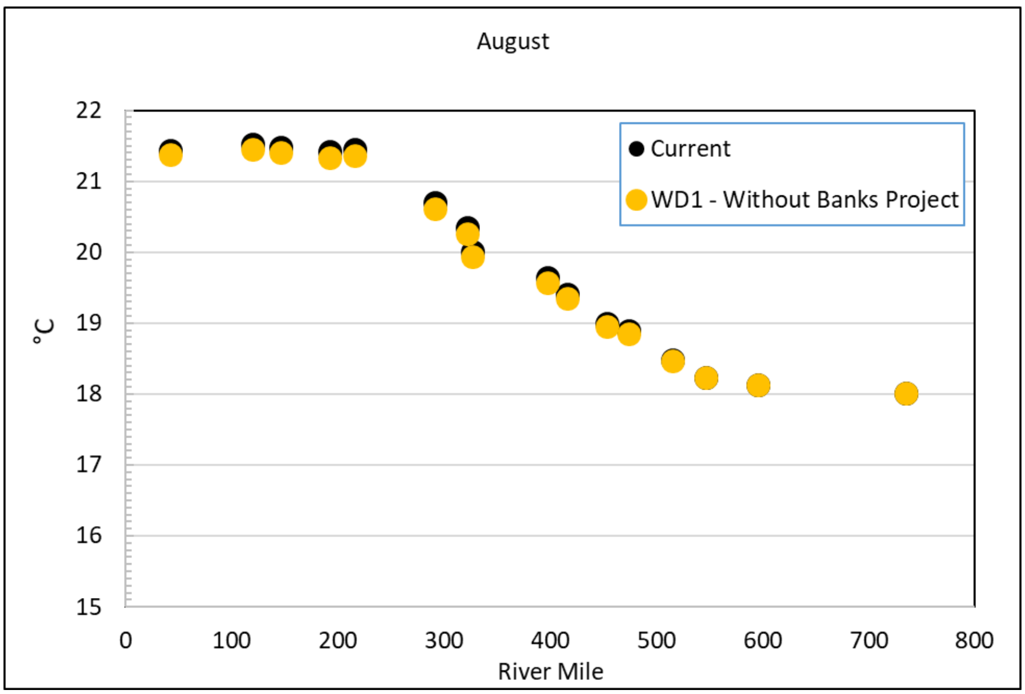


Figure 3-59 Simulated temperatures with and without Banks Lake project flows – August

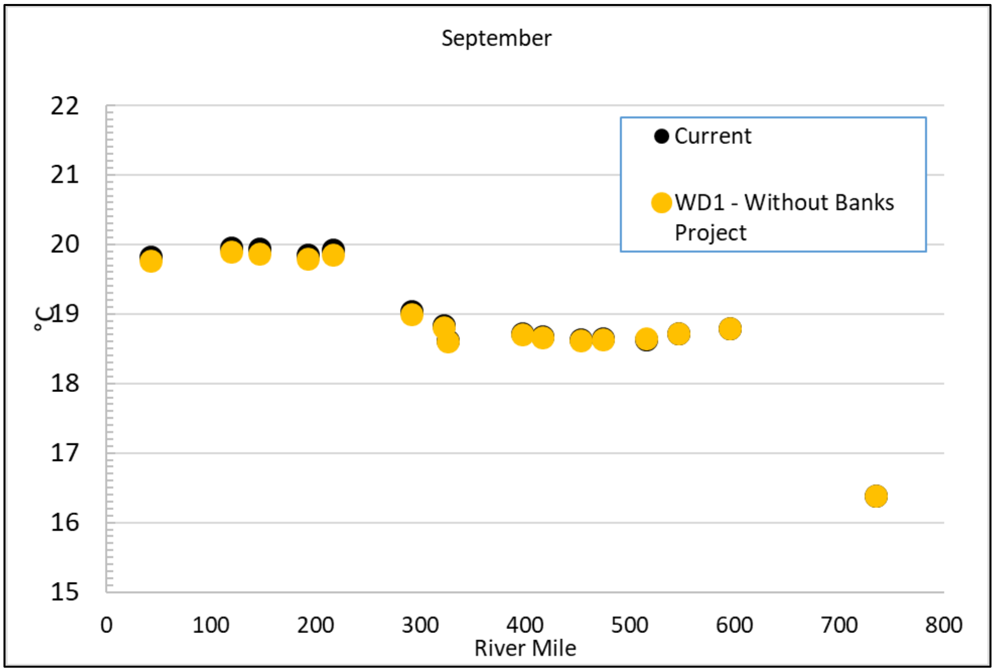


Figure 3-60 Simulated temperatures with and without Banks Lake project flows – September

Table 3-23 Temperature Impact of Banks Lake Project on Columbia River Temperature

River Mile	July	August	September	Oct 15-Nov 15
595	0.00	0.00	0.00	0.00
546	0.01	0.01	0.00	0.00
515	0.03	0.02	0.00	-0.01
474	0.05	0.04	0.01	-0.01
453	0.05	0.04	0.01	-0.01
416	0.07	0.06	0.01	-0.02
397	0.08	0.07	0.02	-0.02
326	0.09	0.08	0.01	-0.02
322	0.09	0.08	0.02	-0.02
291	0.10	0.08	0.04	-0.02
216	0.08	0.10	0.07	-0.01
192	0.08	0.08	0.06	-0.01
146	0.07	0.08	0.07	-0.01
119	0.07	0.07	0.06	0.00
42	0.06	0.06	0.05	0.00

4.0 SUMMARY

This RBM10 model assessment considered temperature impacts to the Columbia and Snake Rivers from point sources, tributaries, dams, climate change, and an agricultural water withdrawal. The assessment results indicate that climate change and dam impacts are the dominant sources impacting river temperatures, with impacts that are an order-of-magnitude higher than point sources, agricultural withdrawals (Banks Lake project), and tributaries.

Long term RBM10 simulations (1970 – 2016) provide one line-of-evidence of a warming trend in Columbia and Snake River temperatures in July – October due to climate change. At three locations evaluated on the Columbia River (Wells, Priest Rapids, and Bonneville), the estimated summer trend generally ranged from 0.3°C to 0.4°C warming per decade. At Ice Harbor Dam on the Snake River, July and October trends were similar to the Columbia River, but the trend in August and September is less than 0.1°C per decade due the influence of Dworshak Dam operations in recent years.

Results indicate a smaller warming trend in August, September, and October in a free-flowing Columbia River. Similarly, in October, when Dworshak Dam cold water operations have ceased, the warming trend in the Snake River under free-flowing conditions has a lower slope than the trend under current conditions.

Dams constructed between 1932 and 1975 on the Columbia and lower Snake Rivers have a cumulative warming impact on the mainstem rivers in the summer period. For the Columbia River, the cumulative dam impact ranges from a 0.8°C cooling at Grand Coulee Dam in July to 2.2°C warming at John Day Dam in August. For the Snake River, the cumulative dam impact ranges from 0.3°C warming at Lower Granite Dam in September to 2.1°C warming at Ice Harbor Dam in September.

Dworshak Dam provides significant cooling to the upper portion of the lower Snake River in the summer. In August, mean temperatures are estimated to be a minimum of 3.8°C colder in the Snake River at the Clearwater River confluence than they would be without Dworshak Dam releases. However, this cooling benefit diminishes toward the mouth of the Snake River, with an estimated benefit at Ice Harbor Dam of 1.2°C in August.

A generalized summary of the range of cumulative impacts from each source category across all model output locations is provided in ***Table 4-1***. The climate change estimate is the estimated change to date in the baseline temperature regime. Point sources, tributaries, and the Banks Lake project impacts are an order-of-magnitude lower than the impacts from dams and climate change.

Table 4-1 Estimated range of source impacts in summer on Columbia and Snake Rivers (July–September; 2011-2016)

River	Point Sources (∆°C)	Tributaries (∆°C)	Banks Lake Project (∆°C)	Dworshak Dam Cooling (∆°C)	Dams (∆°C)	Climate Change (°C increase per decade)[1]
Columbia River	0.0 - 0.1	0.0 - 0.1	0.0 - 0.1	0.0 - (-0.2)	(-0.8) - 2.2	0.3 – 0.4 per decade
Snake River	0.0 - 0.1	0.0 - 0.1	NA	(-0.1) - (-3.8)	0.3 - 2.1	<0.1[2] – 0.4 per decade

[1]Trend in simulated temperatures for 1970-2016
[2]Lower trend for August and September

5.0 UNCERTAINTY

Uncertainty is always a part of regulatory environmental assessment, and uncertainty is inherent to not only model-based assessment but also measurement-based assessment. Models and measurements ("data") are complementary information sources to assess the condition of the environment. Models are often developed and used to address gaps and limitations in our measurement systems because we cannot measure every location at every time across a large-scale watershed. In turn, measurement data are critical as inputs for model development, and gaps and/or imprecision in data will affect the accuracy of a model.

This modeling and climate change assessment are intended to provide the best available estimates of the temperature impacts to the Columbia and Snake Rivers. The 2018 RBM10 model is well-calibrated and provides an appropriate tool to evaluate impacts from a variety of sources. Nevertheless, the analysis is limited and influenced by the following sources of uncertainty:

- Measurement gaps and errors: Monitoring is not seamless, and gaps must be filled. Quality assurance checks cannot identify all measurement and recording errors.
- Model uncertainty: Models are simplifications of the natural system, and predictions do not perfectly match the observations. Several model reports for RBM10 document the simplifications and assumptions of the model as well as the differences between simulated and measured temperatures (Yearsley et al. 2001, Yearsely 2009, Tetra Tech 2018).
- System variability: Assessments must identify source impacts in a variable environment.

As with any scientific endeavor, the results in this assessment may be reviewed and reevaluated over time as new information and analyses about this topic are produced by EPA and/or other organizations.

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