APPENDIX D RBM10 MODEL SCENARIO REPORT

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

Scenario Report

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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
ME	Mean error
MAE	Mean absolute error
NPDES	National Pollutant Discharge Elimination System
PUD	Public Utility District
R^2	Correlation coefficient
RBM10	River Basin Model-10
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
WLA	Waste load allocation
WQC	Water quality criteria
WQS	Water quality standards

1.0 INTRODUCTION

This report documents the application of the River Basin Model-10 (RBM10) 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 (EPA 2019a). 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. Agency discussions on these models have involved a team of individuals from the EPA and each of the Co-Lead agencies who were involved in the development, use, and application of the agencies' respective models. The participants from each agency identified and evaluated similarities and differences in the modeling assessments and concluded that both temperature model predictions provide useful and technically appropriate analyses of the Columbia and lower Snake River water temperatures. As such, the EPA believes that the CE-QUAL W2 and HEC RAS models are appropriate to use in developing the Draft EIS and that the RBM10 model is appropriate to use in developing the TMDL.

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). 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 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 2019 RBM10 model are documented in the RBM10 model report (EPA 2019a). 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.

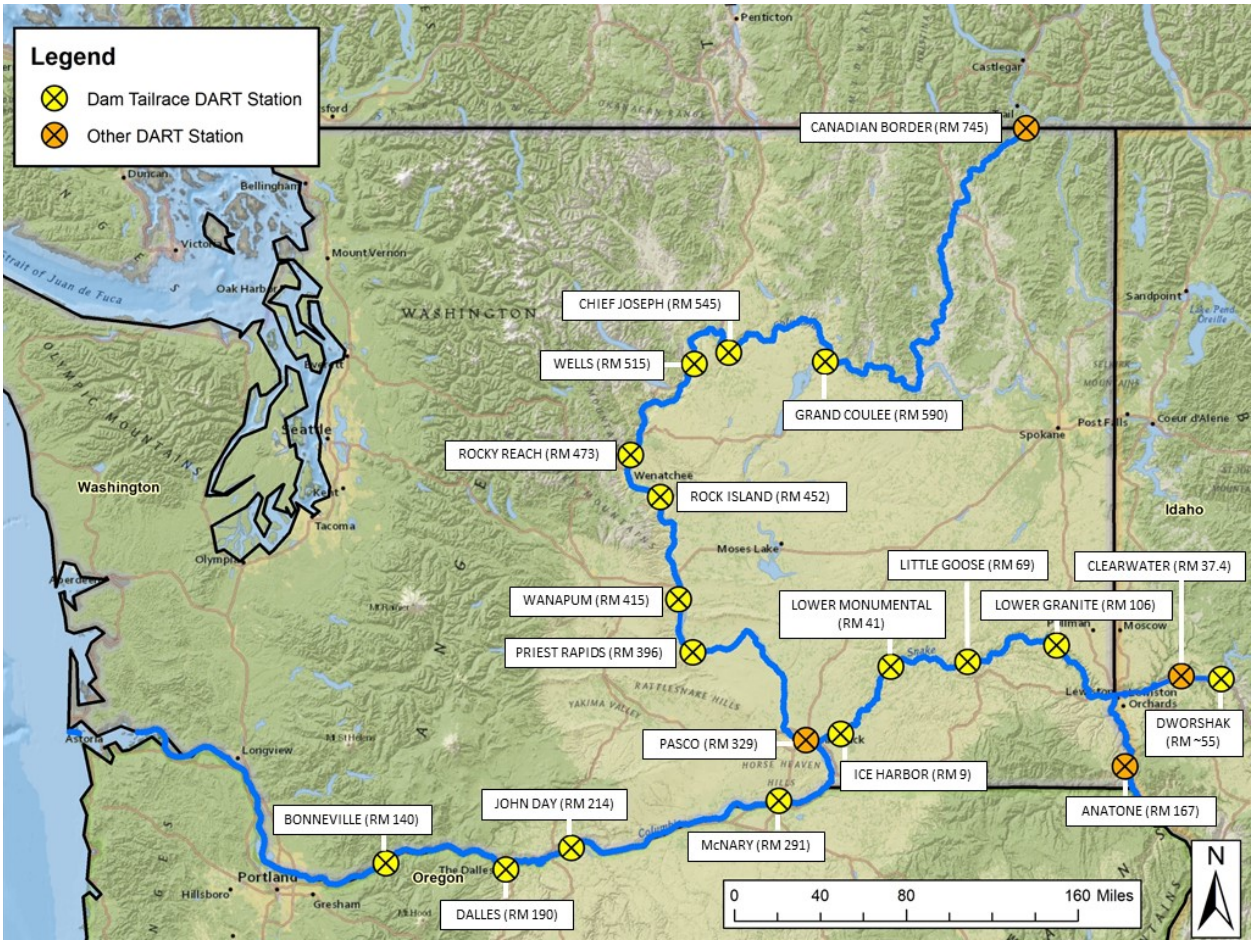
The following processes are not simulated because they have relatively minor influences on the cross-sectional average temperature of these large mainstem rivers: groundwater and

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 2019 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 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

Dam Name	RM	Operator	Type	Year(s) Completed*	Generating Capacity (MW)
Columbia River					
Grand Coulee	597	BOR	Storage	1973	6,465
Chief Joseph	545	USACE	Run of River	1961/1973	2,158
Wells	516	Douglas County Public Utility District No. 1	Run of River	1967	774
Rocky Reach	474	Chelan County Public Utility District No. 1	Run of River	1961/1971	1,280
Rock Island	453	Chelan County Public Utility District No. 1	Run of River	1932/1953/ 1979	624
Wanapum	416	Grant County Public Utility District No. 2	Run of River	1964	1,038
Priest Rapid	397	Grant County Public Utility District No. 2	Run of River	1961	956
McNary	292	USACE	Run of River	1957	980
John Day	216	USACE	Run of River	1971	2,160
The Dalles	192	USACE	Run of River	1960/1973	1,780
Bonneville	146	USACE	Run of River	1938/1982	1,050
Snake River					
Lower Granite	108	USACE	Run of River	1975/1978	810
Little Goose	70	USACE	Run of River	1970/1978	810
Lower Monumental	42	USACE	Run of River	1970/1978	810
Ice Harbor	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 operated for multiple purposes including flood control, hydropower generation, recreation and irrigation. 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 2019 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.

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 on the Columbia River. Each dot in the graph is a simulated daily average water temperature using a different color for each year. The range of variability exhibited by the daily average water temperatures within the period 1970 - 2016 is approximately ±3°C from the mean.

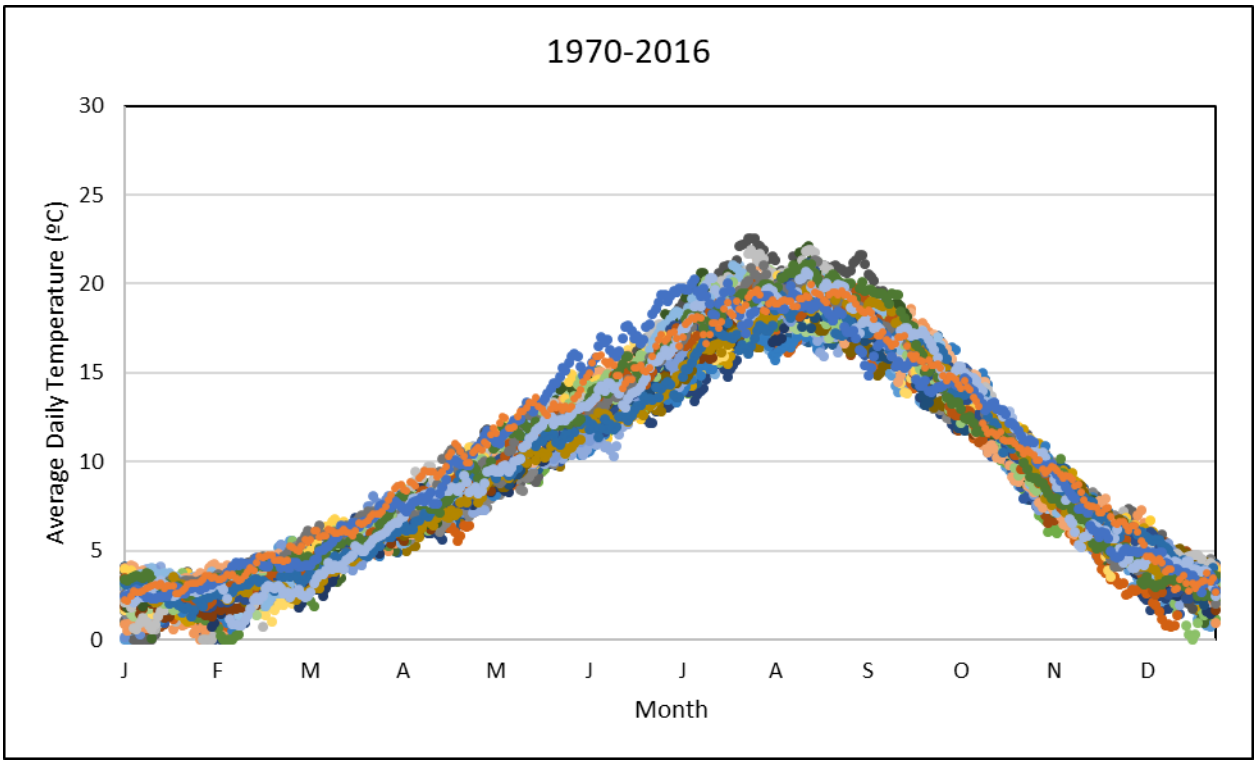


Figure 2-2 Annual variability of daily average water temperatures simulated by RBM10 under free-flowing conditions at Priest Rapids Dam on the Columbia River.

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 90th 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 October, when EPA's data assessment indicates that temperatures exceed water quality criteria (WQC) in state water quality standards (WQS) in certain locations and time frames (Merz et al. 2018).

2.2.4 Model Calibration and Performance

The 2019 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).

Figure 2-3 and ***Figure 2-4*** are example plots comparing simulated and measured temperatures at the tailrace monitoring location at John Day Dam on the lower Columbia River. ***Figure 2-3*** shows daily temperatures over the period 2011 – 2016. ***Figure 2-4*** 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 RBM10 model update report (EPA 2019a).

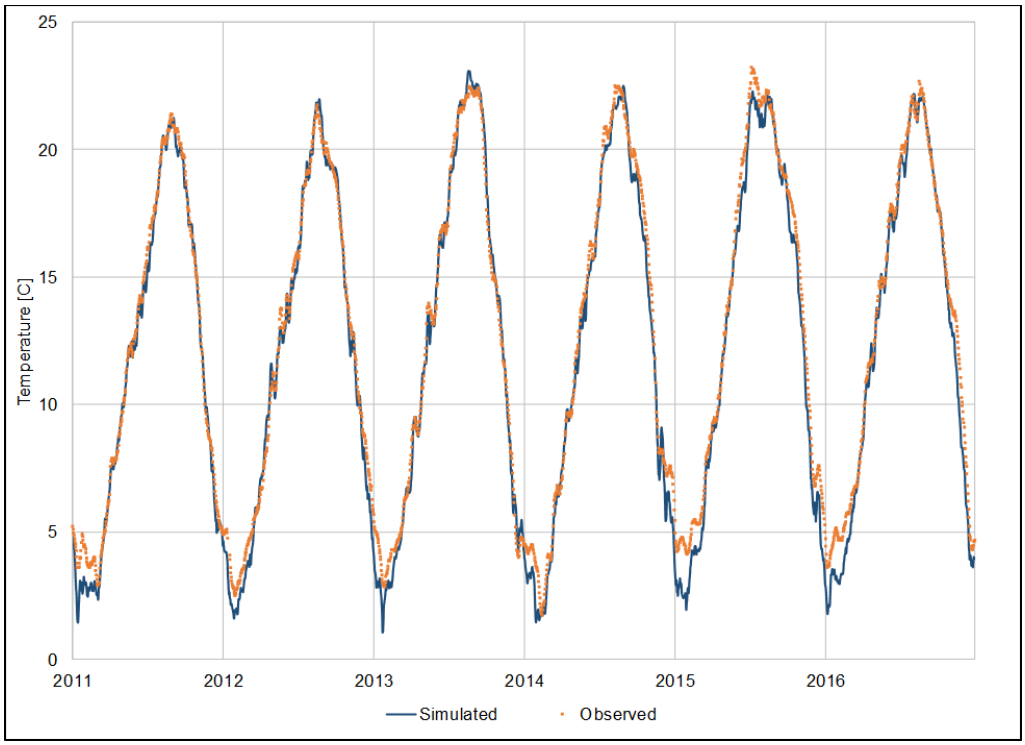


Figure 2-3 Simulated and observed daily average temperatures at John Day Dam (2011 – 2016)

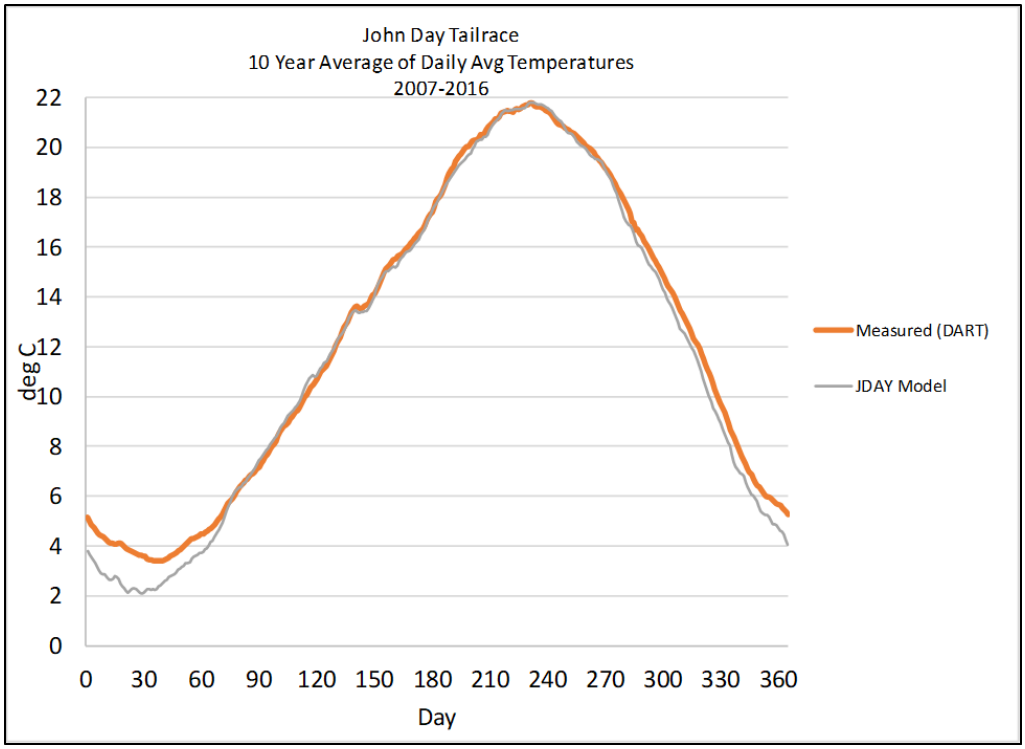


Figure 2-4 Simulated and observed 10-year average daily temperatures at John Day Dam

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.

Overall, the statistics of model performance are similar and, in most cases, improved compared to those reported by Yearsley (2003). Statistical results for the critical period (July – August and September – October) are presented in ***Table 2-2*** and ***Table 2-3***. The tables summarize the comparisons of the model simulations against all available observations within the period 2007 – 2016. The performance statistics indicate that the 2019 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. Additional model performance statistics are provided in the model update report (EPA 2019a).

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

Columbia River					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R^2**
CWMW	1376	0.046	0.430	0.548	0.947
WRNO	1383	-0.073	0.371	0.463	0.965
BON	1792	-0.096	0.388	0.501	0.958
TDDO	1284	0.094	0.345	0.431	0.969
JHAW	1355	0.103	0.328	0.406	0.976
MCPW	1356	0.130	0.307	0.376	0.977
PRXW	1249	-0.236	0.397	0.495	0.961
WANW	1118	-0.107	0.367	0.458	0.961
RIGW	1154	-0.017	0.430	0.558	0.937
RRDW	1158	-0.082	0.409	0.493	0.946
WELW	1065	0.163	0.417	0.504	0.950
CHQW	1170	-0.041	0.387	0.484	0.952
GCGW	1081	-0.068	0.423	0.539	0.944
	Average	**-0.014**	**0.384**	**0.481**	**0.957**
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**
LEWI	1115	-0.125	0.348	0.467	0.897
PEKI	1337	0.174	0.377	0.500	0.918
	Average	**0.025**	**0.363**	**0.484**	**0.908**

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

Columbia River					
Station	**Observations**	**ME**	**MAE**	**RMSE**	**R^2**
CWMW	500	-0.641	0.673	0.814	0.877
WRNO	1370	-0.428	0.592	0.752	0.967
BON	1200	-0.554	0.615	0.778	0.805
TDDO	901	-0.047	0.435	0.557	0.972
JHAW	892	-0.031	0.430	0.545	0.973
MCPW	1243	0.127	0.410	0.506	0.976
PRXW	1032	-0.008	0.406	0.502	0.958
WANW	973	-0.037	0.393	0.480	0.958
RIGW	632	0.076	0.583	0.746	0.886
RRDW	547	0.116	0.514	0.670	0.898
WELW	518	-0.085	0.503	0.638	0.857
CHQW	821	-0.288	0.498	0.659	0.736
GCGW	1083	-0.218	0.493	0.612	0.863
	Average	**-0.155**	**0.503**	**0.635**	**0.902**
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**
LEWI	344	0.105	0.374	0.495	0.942
PEKI	768	0.057	0.271	0.357	0.962
	Average	**0.081**	**0.323**	**0.426**	**0.952**

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 update report (EPA 2019a).

A single-day outlier was observed during this assessment in the RBM10 simulations for the lower Clearwater River. An example is shown for scenarios related to Dworshak operations in ***Figure 2-5*** (see section 3.4 for full information about Dworshak scenarios). A spike in simulated temperatures occurs on one day of the year in the scenario simulations (Day 225 - August 13). This day is the transition point 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 scenario simulations. To eliminate any influence of the outlier for this day on the scenario results in the TMDL study area, the model output for all Snake River locations and all scenarios is post-processed to replace Day 225 predictions with interpolated values between the predicted temperatures for Day 224 and Day 226.

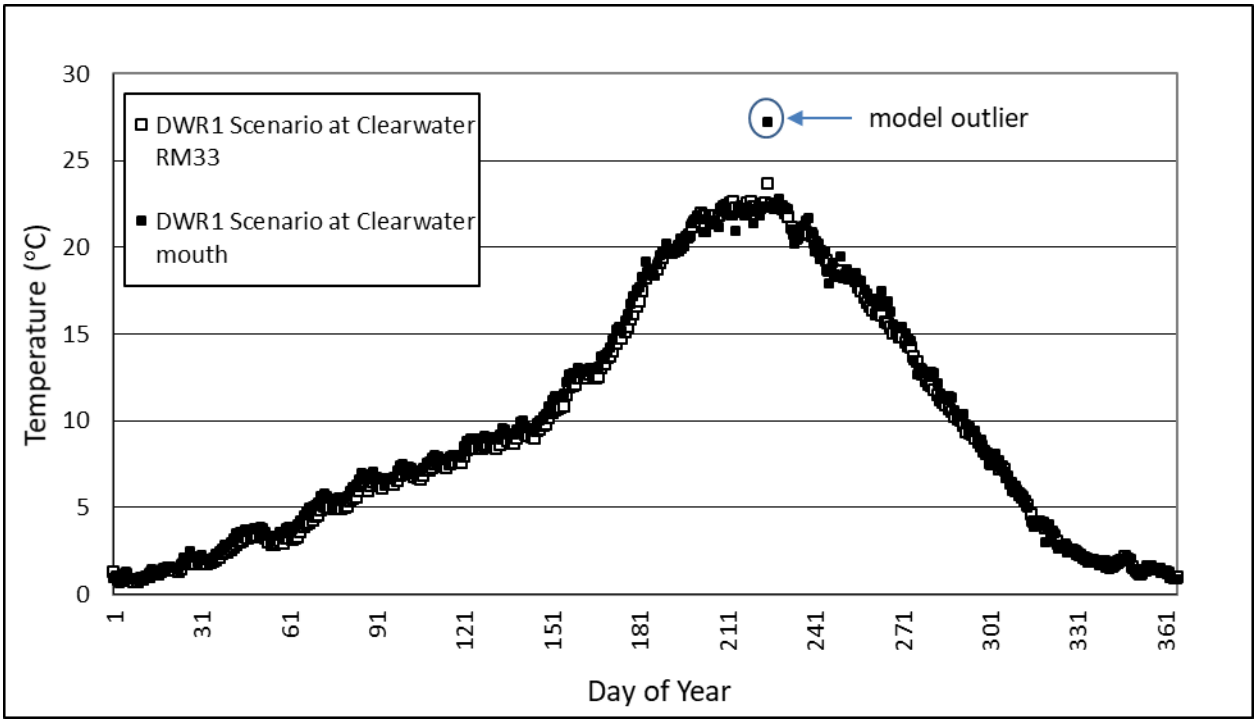


Figure 2-5 RBM10 simulation results for scenario DWR1 (No Dworshak Dam) at Clearwater River Mile 33 and mouth (2011-2016).

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 results from the current conditions model. 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 Dam (DWR) 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	Temperature impact/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 flow and temperature conditions at upstream boundaries, tributaries, Banks Lake pump storage, and DWR dam release.
Snake1934	Source Assessment – Dams	Effect of long-term bathymetry changes in Snake River	2011 – 2016	Free-flowing river geometry and velocity using 1934 bathymetry. Otherwise identical to "Current," including current flow and temperature conditions at upstream boundaries, tributaries, 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.
TR1	Source Assessment – Tributaries	Tributary impact	2011 – 2016	"Current" except for tributary temperature adjustment – reducing all tributary temperatures by 0.5 °C.
TR2	Source Assessment – Tributaries	Tributary impact	2011 – 2016	"Current" except for tributary temperature adjustment – capping tributary temperatures to the water quality criterion temperature.
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.
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.
N/A[1]	Trend Analysis	Estimate of warming since 1970s with dams in place	1970 – 2016	Analysis of trends in output with "Current" model setup.
N/A[1]	Trend Analysis	Estimate of warming since 1970s in free-flowing river to evaluate effect of dams on climate change trend	1970 – 2016	Analysis of trends in output with "Free-Flowing" model setup.
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 2019 RBM10 model setup was altered to represent a free-flowing river without the existing series of reservoirs. For the purposes of this report, the term “free-flowing” model is used to denote that all rivers are free flowing within the modeled area.

The strategy to develop the “Free-Flowing” model consisted of replacing the impounded reaches and dams in the 2019 RBM10 model with free-flowing channels. This was achieved by replacing the geometry of the impounded reaches in the 2019 RBM10 model with the geometry of free-flowing channel reaches obtained from available no-dams USACE Hydrologic Engineering Center - River Analysis System (HEC-RAS) models of the Columbia and Snake Rivers. The 2019 RBM10 model already simulated some free-flowing reaches such as the Hanford reach, Snake River above Lewiston, and Clearwater River. Therefore, only the geometry of the reaches subject to dam impoundments in the 2019 RBM10 model were changed in the Free-Flowing model.

The methodology used to vary river geometry in free-flowing reaches is described in the model development report (EPA 2019a). For the “Free-Flowing” scenario, this methodology was applied across the entire model domain.

3.3.1 Methodology and Assumptions

To develop the geometry of the Free-Flowing RBM10 model, first, available “Free Flowing” (without dams) HEC-RAS models of the Columbia and Snake Rivers were used to simulate channel hydraulics for flow conditions across the range of observed flows in the Columbia River and Snake River. The HEC-RAS models were used to simulate flow conditions between 20,000 cubic feet per second (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, HEC-RAS provided simulation outputs of cross-section area (Ax) and channel width (Wx) at different locations along the Columbia River and Snake River channels. These model outputs were used in a nonlinear regression analysis to calculate power curve coefficients (Aa, Ba, Aw, Bw) used by RBM10 to simulate cross-section area ($Ax=Aa*Q^{Ba}$) and width ($Wx=Aw*Q^{Bw}$) in unimpounded reaches (see EPA 2019a). The RBM10 model used these power curves to simulate the free-flowing river geometry each day based on the simulated daily instream flow.

The Free-Flowing model was finally obtained by replacing the geometry of impounded reaches in the 2019 RBM10 model with the geometric power curves estimated with the results of the HEC-RAS models.

The assumptions for the Free-Flowing scenario include:

- Model comparisons, including all values presented in plots and tables are daily average, cross-sectional average river temperatures.
- In the Free-Flowing scenario, all modeled reaches are free flowing.
- Current conditions boundary inputs are used in the Free-Flowing model, including Dworshak Dam cold water release operations for 2011 – 2016. This means that flow operations upstream of the model boundaries are assumed to be the same in both scenarios and are implicitly accounted for in the flow boundary conditions.

- In the Current conditions scenario, flow operations at Grand Coulee are simulated in RBM10 by prescribing observed tailrace flows immediately below the dam. In the Free-Flowing scenario, flow operations at Grand Coulee are removed from the model so flows freely move from upstream to downstream (***Figure 3-1***). Flows increase or decrease depending on the presence of tributaries or withdrawals.
- The results from the Free-Flowing model reflect the impacts of removing the dams located in the modeled area.

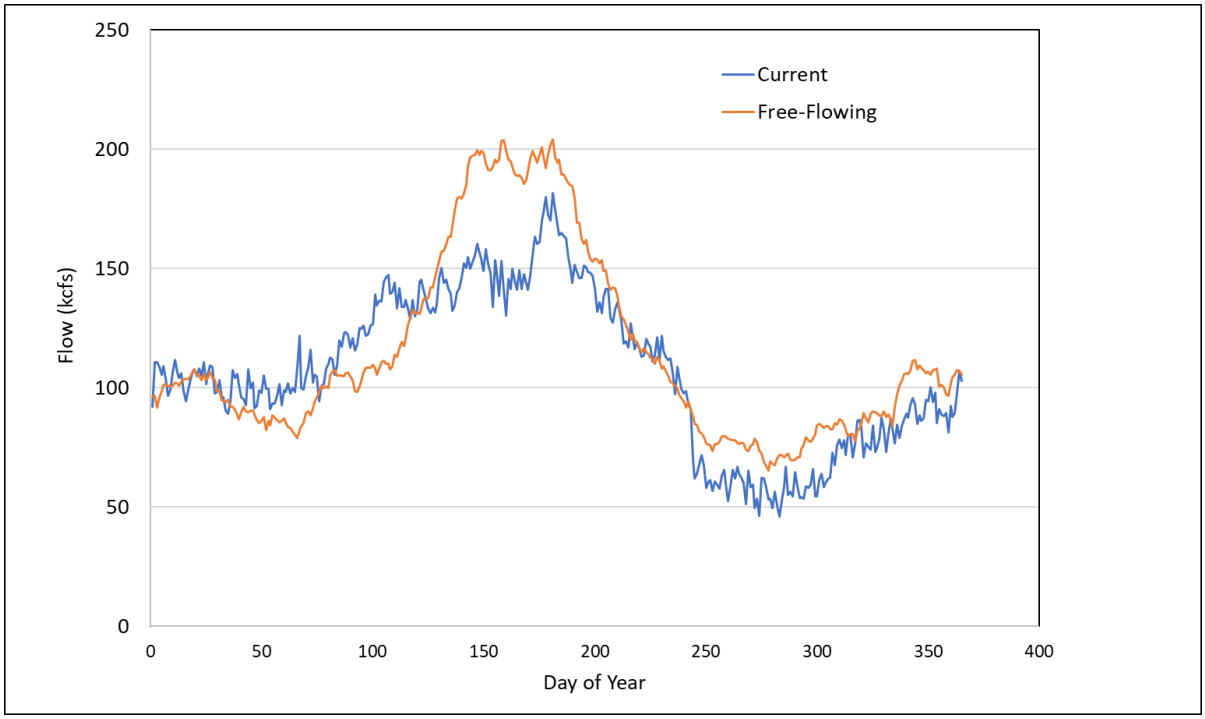


Figure 3-1 RBM10 daily average river flow for current conditions and free-flowing conditions in the Columbia River at the tailrace of Grand Coulee Dam (2011-2016).

Measured 2010 river bed bathymetry was used as the information base for the "Free-Flowing" HEC-RAS models. Since the 2010 bathymetry data represents river bottom conditions with dams in place, 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). To evaluate potential effects of bathymetry changes on free-flowing river temperature estimates, EPA obtained 1934 bathymetry information for the Snake River from USACE. Using the same methodology as was used to develop the Free-Flowing scenario using the HEC-RAS 2010 riverbed bathymetry, EPA developed an RBM10 model setup representing the 1934 Snake River hydraulics. This is called the "Snake1934" scenario, and results of this scenario were compared to the Free-Flowing scenario to assess the sensitivity of free-flowing river temperatures to changes in the river channel bathymetry.

3.3.2 Characteristics of Dam Impacts

Dams have several impacts on river hydraulics. Some of the major impacts include changes in travel times, channel volumes, and cross section channel widths. Travel times increase in the presence of dams because these structures are physical obstructions to the free movement of flow from upstream to downstream areas. Dams create a backwater effect that extends upstream, slowing the flow and causing a large impoundment of water behind the dam. As a result of this impoundment of water, depths and channel widths increase behind dams.

To evaluate the impacts of dams on travel times and channel widths on the Columbia River and Snake River, the average travel times and channel widths were calculated from July through October at selected locations using the Current and Free-Flowing models. The simulation results are summarized in ***Table 3-2*** and ***Table 3-3*** respectively. The results showed that travel times from the upstream boundary to the selected locations on the Columbia River were approximately 7 to 15 times larger under Current conditions than under Free-Flowing conditions. On the Snake River and under Current conditions, the travel times were approximately 8 to 13 time larger than those under Free-Flowing conditions. In both models and within the July – October period, July was the month with the shortest travel times and October the month with the largest travel times. The monthly changes in travel times can be correlated with the annual flow regimes in the Columbia and Snake Rivers.

The impacts of dams on channel widths on the Columbia and Snake Rivers are shown in ***Table 3-3***. On the Columbia River and under Current conditions, channel widths were approximately 1.4 to 2.8 times larger than those calculated under Free-Flowing conditions. On the Snake River and under Current conditions, channel widths were 1.7 to 1.9 times larger than those calculated under Free-Flowing conditions.

Table 3-2 Modeled monthly average travel times from upstream boundary to selected locations on the Columbia and Snake Rivers

Border to Priest Rapids – Travel Time (days)					
Model	**RM**	**July**	**Aug**	**Sept**	**Oct**
Current	397	43.6	62.2	77.5	85.1
Free-Flowing	397	4.2	5.0	5.6	5.7
Border to Bonneville – Travel Time (days)					
Model	**RM**	**July**	**Aug**	**Sept**	**Oct**
Current	146	56.8	79.9	104.1	112.2
Free-Flowing	146	8.0	9.7	10.9	11.1
Anatone to Ice Harbor – Travel Time (days)					
Model	**RM**	**July**	**Aug**	**Sept**	**Oct**
Current	7	20.1	30.6	37.9	42.5
Free-Flowing	7	2.4	2.8	3.1	3.2

Table 3-3 Modeled monthly average channel width at selected reaches on the Columbia and Snake Rivers

	Priest Rapids Reach – Width (ft)					
Model	**From (RM)**	**To (RM)**	**July**	**Aug**	**Sept**	**Oct**
Current	415	397	3,094	3,094	3,094	3,094
Free-Flowing	415	397	1,534	1,254	1,115	1,108
	Bonneville Reach – Width (ft)					
Model	**From (RM)**	**To (RM)**	**July**	**Aug**	**Sept**	**Oct**
Current	165	146	3,705	3,705	3,705	3,705
Free-Flowing	165	146	2,635	2,318	2,165	2,152
	Ice Harbor Reach – Width (ft)					
Model	**From (RM)**	**To (RM)**	**July**	**Aug**	**Sept**	**Oct**
Current	10	5	2,255	2,255	2,255	2,255
Free-Flowing	10	5	1,317	1,251	1,216	1,213

With regards to temperature, the impoundment of a river behind a dam commonly causes a temporal shift in the seasonal temperature regime. ***Figure 3-2*** 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.

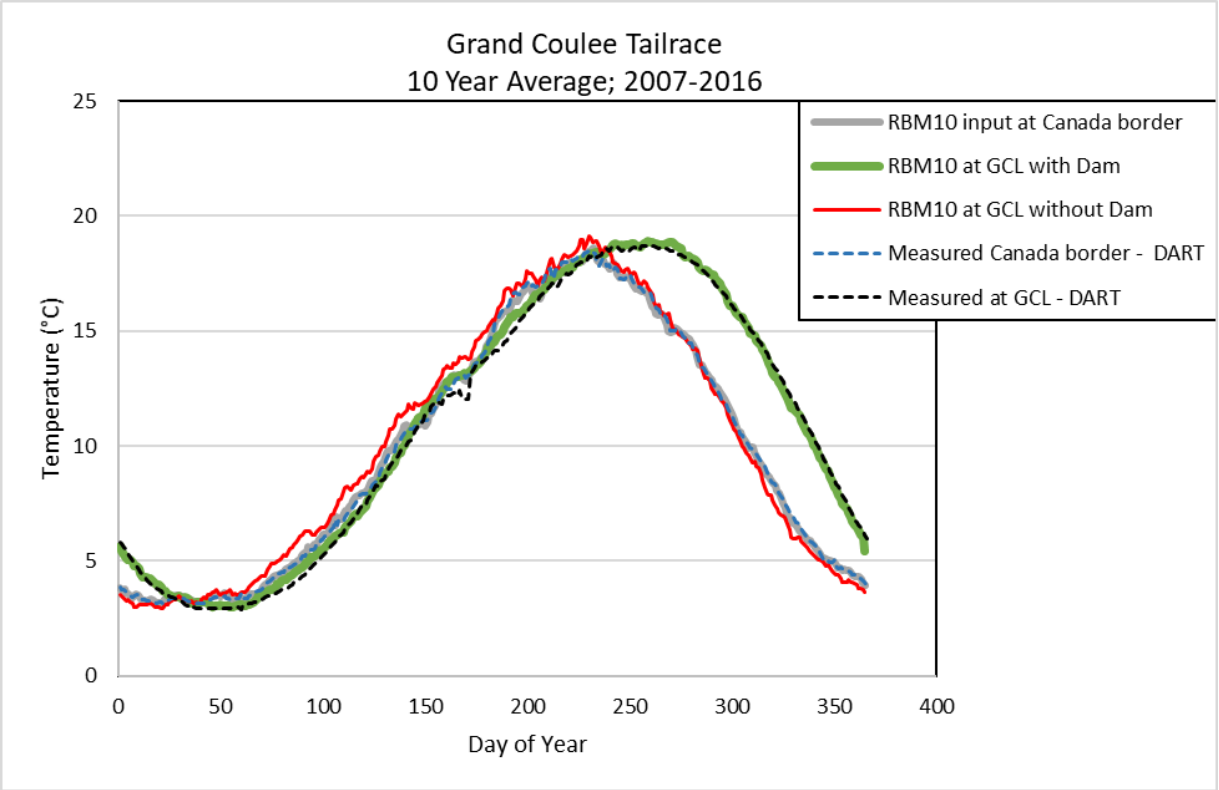


Figure 3-2 Simulated and observed 10-year average temperatures at the Canadian border and Grand Coulee Dam

Figure 3-3 shows a comparison of Free-Flowing and Current conditions at John Day Dam for the period 2011-2016. 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 3-4*** through ***Table 3-6*** 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.

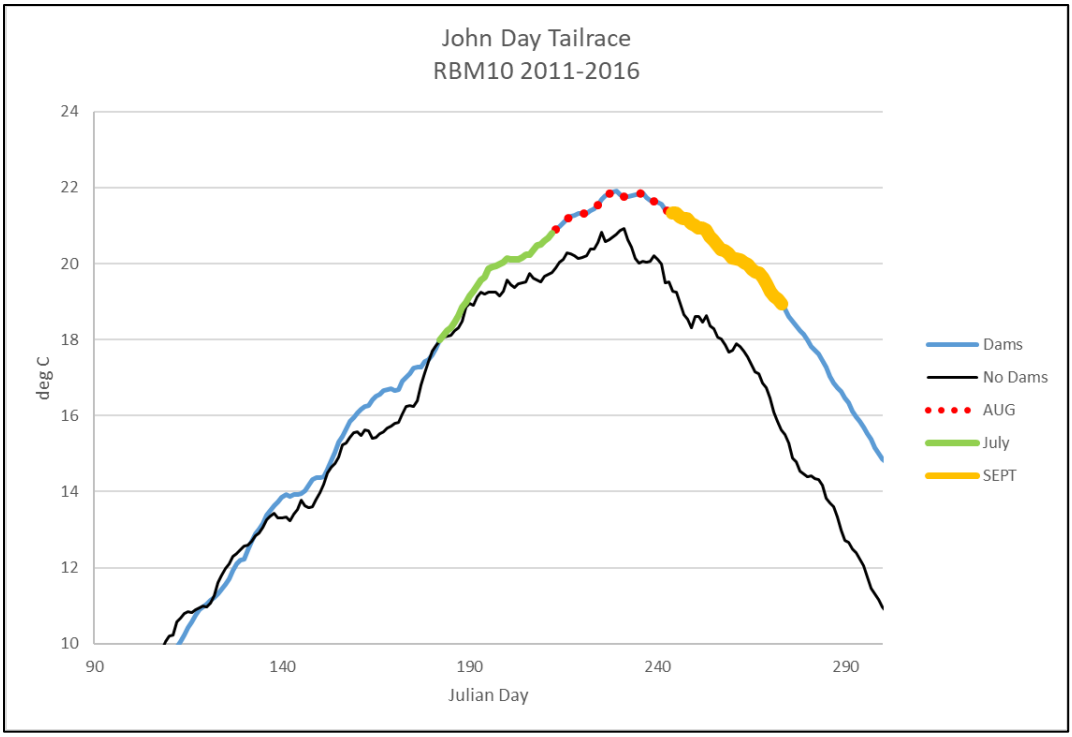


Figure 3-3 Simulated daily average temperatures for Free-Flowing and Current scenarios at John Day Dam

3.3.3 Cumulative Impacts

To evaluate dam impacts, the model is run in Free-Flowing and Current conditions, and simulated temperatures for 2011 – 2016 were output at each dam tailrace location. The results are provided as monthly average values in plots and tables. The following interpretation of the results is provided:

- Dam impacts on water temperature 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 October.
- 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 reduced cumulative impact at the dam locations downstream of John Day Dam.
- The Snake River generally has a warming effect on the mainstem Columbia River.

The following figures (***Figure 3-4*** through ***Figure 3-11***) 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.

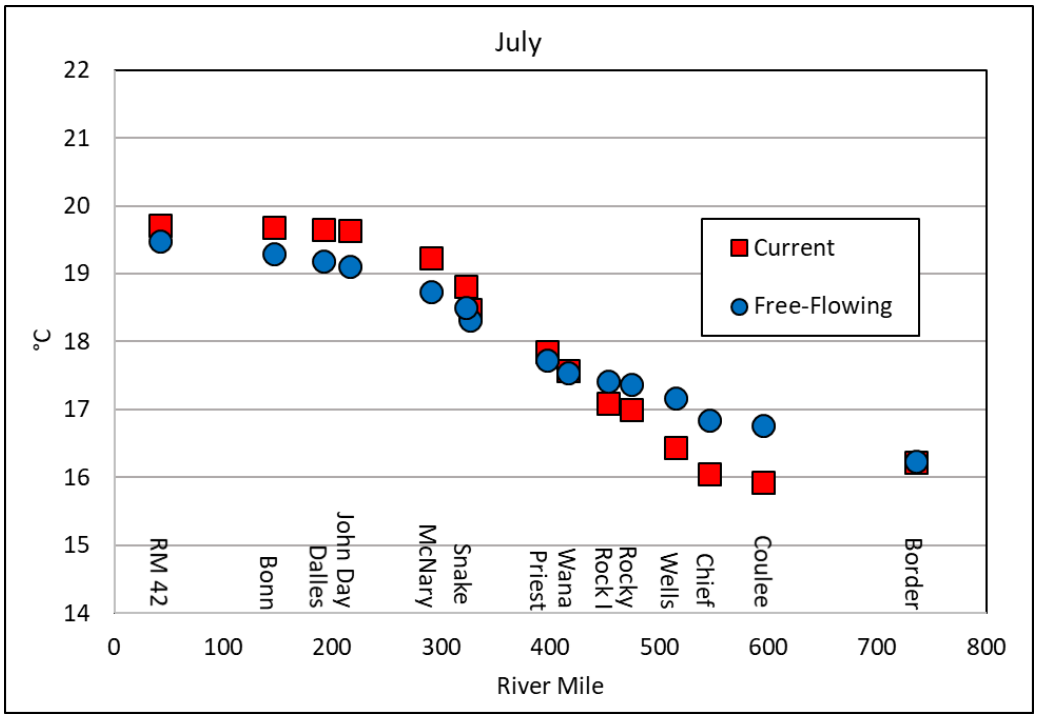


Figure 3-4 Simulated temperature of free-flowing and current Columbia River; July

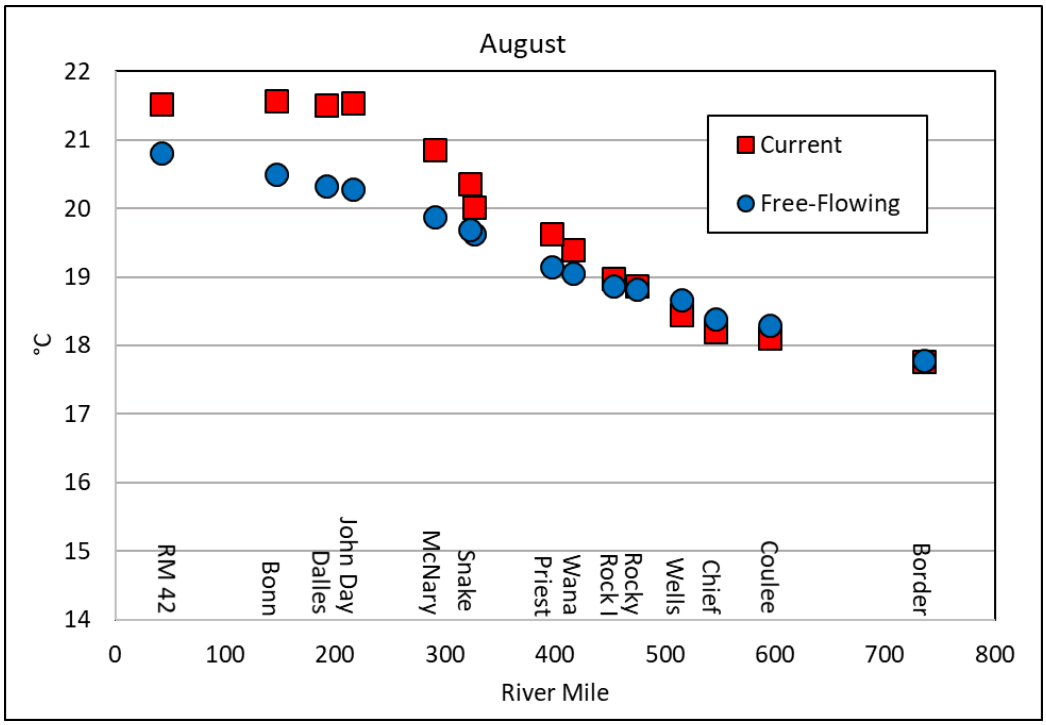


Figure 3-5 Simulated temperature of free-flowing and current Columbia River; August

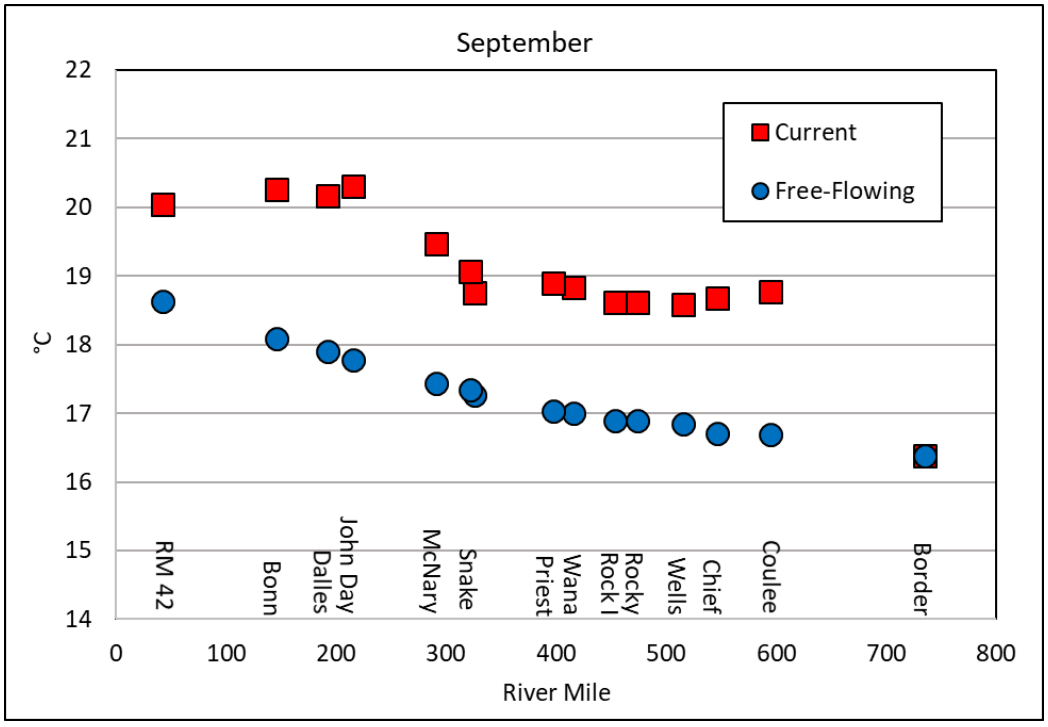


Figure 3-6 Simulated temperatures of free-flowing and current Columbia River; September

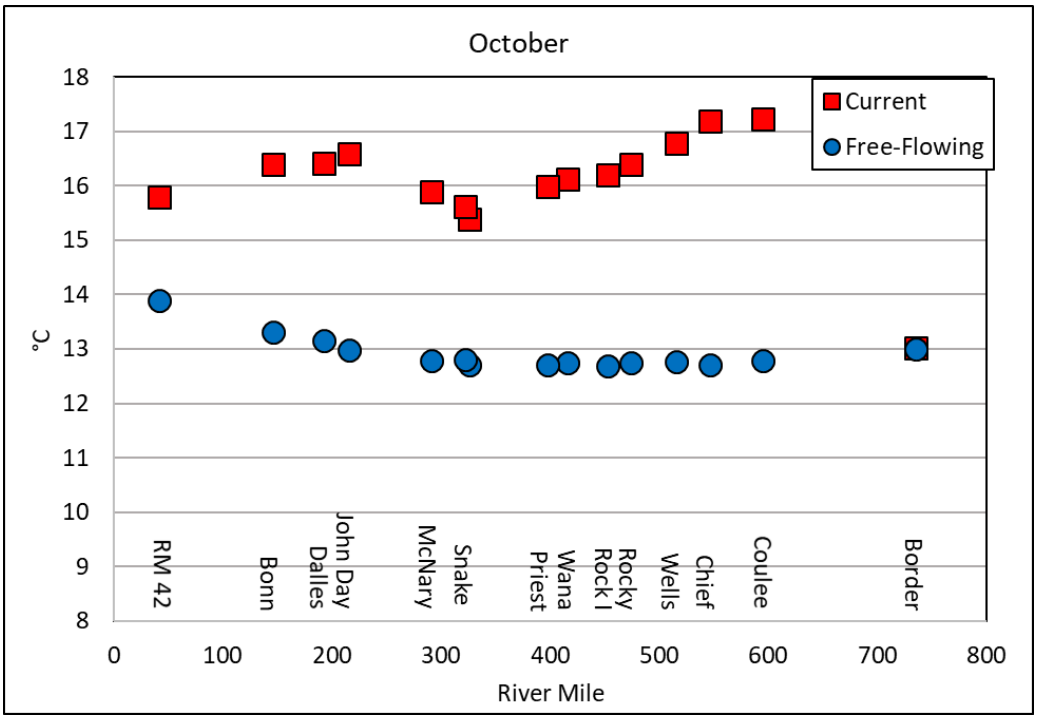


Figure 3-7 Simulated temperature of free-flowing and current Columbia River; October

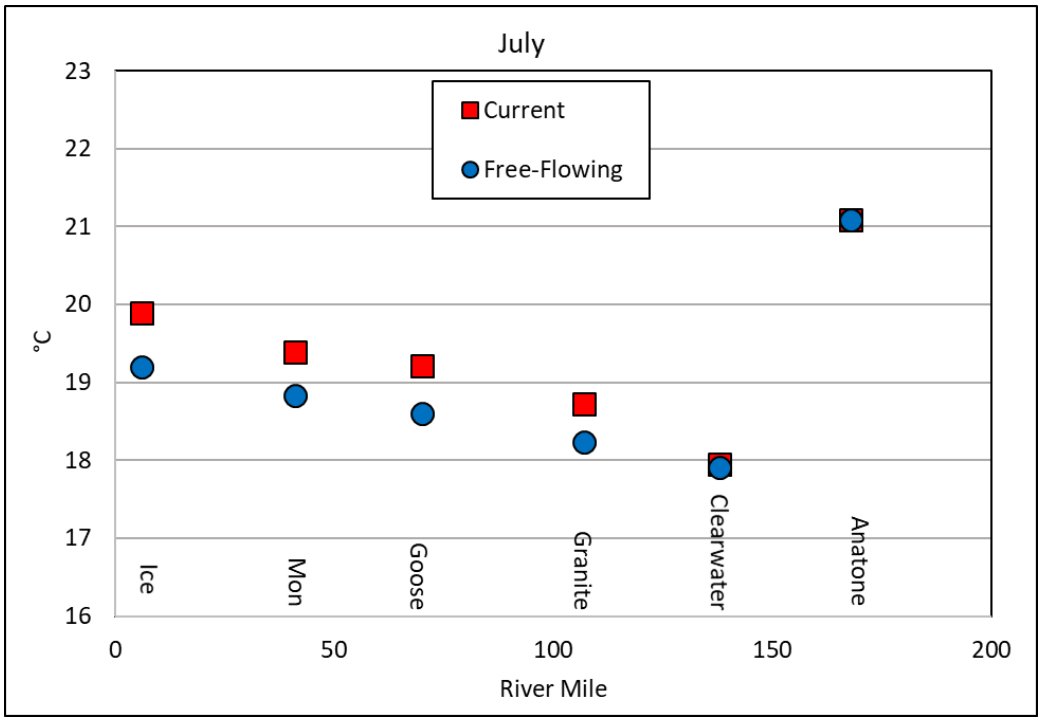


Figure 3-8 Simulated temperature of free-flowing and current Snake River; July

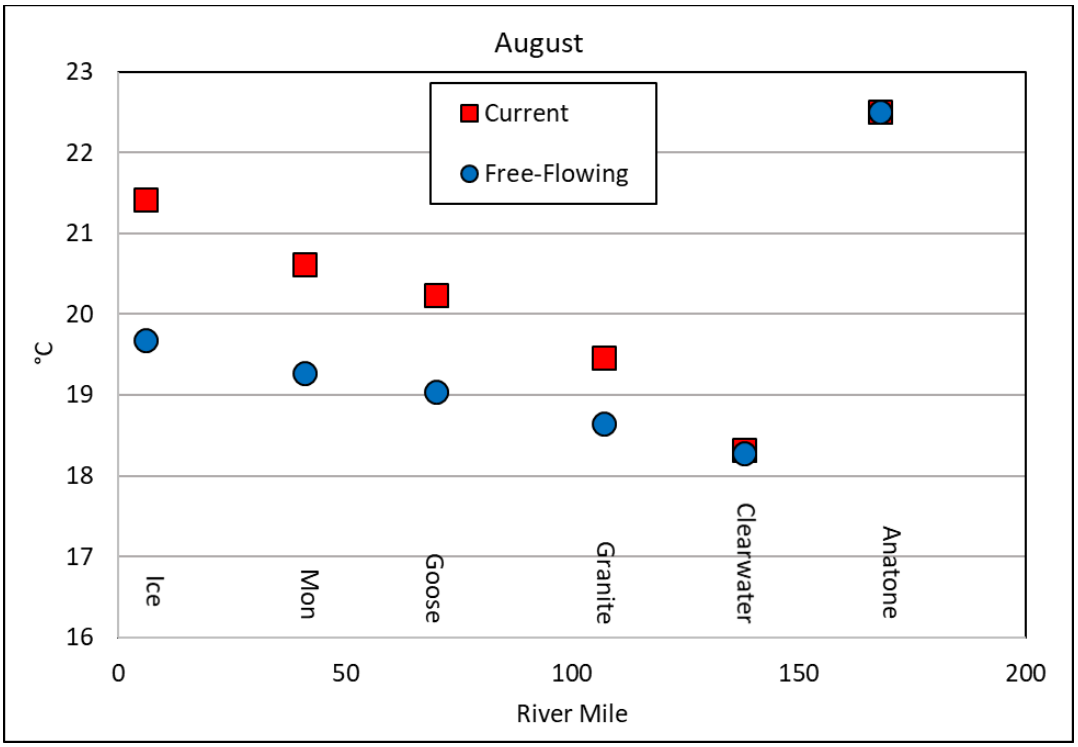


Figure 3-9 Simulated temperature of free-flowing and current Snake River; August

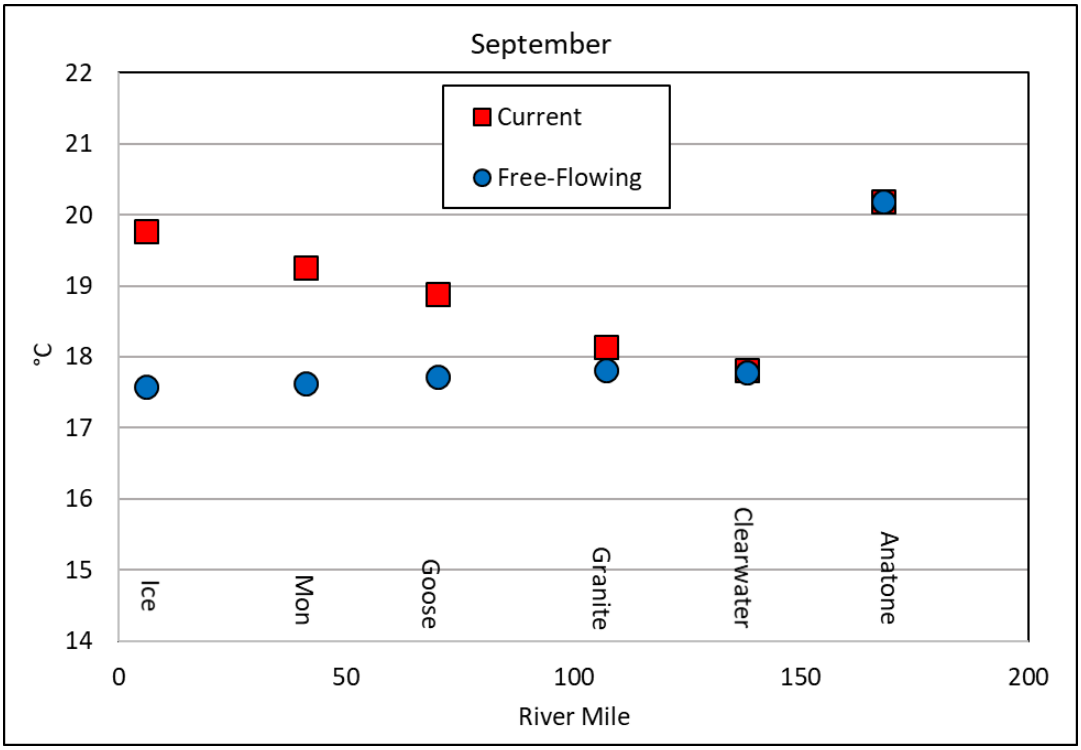


Figure 3-10 Simulated temperature of free-flowing and current Snake River; September

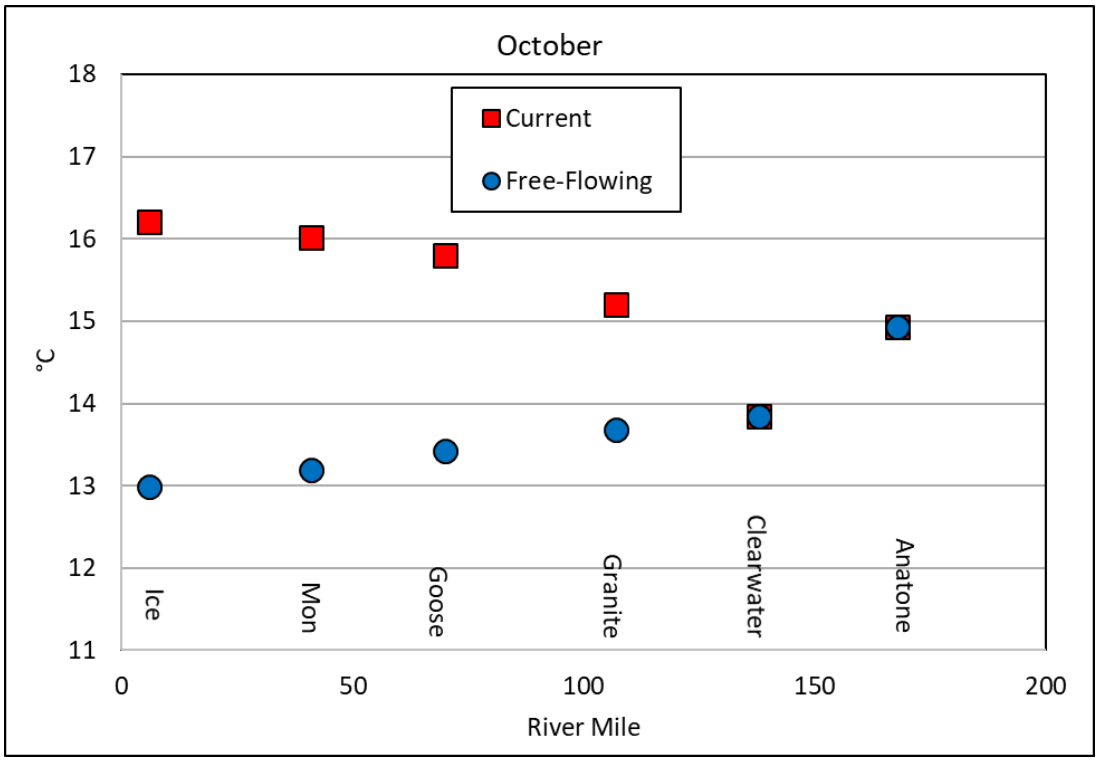


Figure 3-11 Simulated temperature of free-flowing and current Snake River; October

The numeric values for temperature differences shown in the figures above are provided in ***Table 3-4*** through ***Table 3-7*** 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 3-4 Estimated Mean Monthly Impact of Dam Impoundments on Columbia and Snake River Temperatures (July; 2011-2016)

Location	River Mile	RBM10 Current (°C)	RBM10 Free Flowing (°C)	Individual Reach Impact[1] (°C)	Cumulative Impact[2] (°C)
Columbia River					
Canadian Border	735	16.22	16.23	NA	NA
Grand Coulee	595	15.92	16.77	-0.8	-0.8
Chief Joseph	546	16.06	16.84	0.1	-0.8
Wells	515	16.43	17.17	0.0	-0.7
Rocky Reach	474	17.00	17.37	0.4	-0.4
Rock Island	453	17.09	17.41	0.0	-0.3
Wanapum	416	17.57	17.53	0.4	0.0
Priest Rapids	397	17.85	17.72	0.1	0.1
Hanford Reach	326	18.48	18.31	0.0	0.2
Snake Confluence	322	18.81	18.50	0.1	0.3
McNary	291	19.23	18.73	0.2	0.5
John Day	216	19.64	19.11	0.0	0.5
Dalles	192	19.66	19.18	-0.1	0.5
Bonneville	146	19.68	19.30	-0.1	0.4
Snake River					
Anatone	168	21.09	21.09	NA	NA
Clearwater Confluence	138	17.94	17.91	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	18.84	-0.1	0.6
Ice Harbor	6	19.89	19.20	0.1	0.7

[1] Individual reach impact is the difference between the simulated temperature change in the reach immediately upstream of the assessment location under current conditions versus free-flowing conditions.

[2] Cumulative impact is the difference between the current and free-flowing temperature at a given location.

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

Location	River Mile	RBM10 Current (°C)	RBM10 Free Flowing (°C)	Individual Reach Impact[1] (°C)	Cumulative Impact[2] (°C)
Columbia River					
Canadian Border	735	17.77	17.78	NA	NA
Grand Coulee	595	18.11	18.29	-0.2	-0.2
Chief Joseph	546	18.20	18.39	0.0	-0.2
Wells	515	18.45	18.66	0.0	-0.2
Rocky Reach	474	18.87	18.83	0.2	0.0
Rock Island	453	18.98	18.86	0.1	0.1
Wanapum	416	19.40	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	19.69	0.3	0.7
McNary	291	20.86	19.87	0.3	1.0
John Day	216	21.54	20.29	0.3	1.3
Dalles	192	21.50	20.32	-0.1	1.2
Bonneville	146	21.57	20.51	-0.1	1.1
Snake River					
Anatone	168	22.50	22.50	NA	NA
Clearwater Confluence	138	18.32	18.28	NA	NA
Lower Granite	107	19.47	18.64	0.8	0.8
Little Goose	70	20.24	19.05	0.4	1.2
Lower Monumental	41	20.62	19.27	0.2	1.3
Ice Harbor	6	21.42	19.68	0.4	1.7

[1] Individual reach impact is the difference between the simulated temperature change in the reach immediately upstream of the assessment location under current conditions versus free-flowing conditions.

[2] Cumulative impact is the difference between the current and free-flowing temperature at a given location.

Table 3-6 Estimated Mean Monthly Impact of Dam Impoundments on Columbia and Snake River Temperatures (September; 2011-2016)

Location	River Mile	RBM10 Current (°C)	RBM10 Free Flowing (°C)	Individual Reach Impact[1] (°C)	Cumulative Impact[2] (°C)
Columbia River					
Canadian Border	735	16.38	16.38	NA	NA
Grand Coulee	595	18.78	16.69	2.1	2.1
Chief Joseph	546	18.67	16.70	-0.1	2.0
Wells	515	18.58	16.85	-0.2	1.7
Rocky Reach	474	18.61	16.89	0.0	1.7
Rock Island	453	18.62	16.90	0.0	1.7
Wanapum	416	18.84	17.01	0.1	1.8
Priest Rapids	397	18.89	17.03	0.0	1.9
Hanford Reach	326	18.76	17.26	-0.4	1.5
Snake Confluence	322	19.06	17.34	0.2	1.7
McNary	291	19.47	17.44	0.3	2.0
John Day	216	20.31	17.78	0.5	2.5
Dalles	192	20.17	17.90	-0.3	2.3
Bonneville	146	20.26	18.09	-0.1	2.2
Snake River					
Anatone	168	20.19	20.19	NA	NA
Clearwater Confluence	138	17.81	17.79	NA	NA
Lower Granite	107	18.14	17.81	0.3	0.3
Little Goose	70	18.88	17.72	0.8	1.2
Lower Monumental	41	19.26	17.63	0.5	1.6
Ice Harbor	6	19.77	17.58	0.6	2.2

[1] Individual reach impact is the difference between the simulated temperature change in the reach immediately upstream of the assessment location under current conditions versus free-flowing conditions.

[2] Cumulative impact is the difference between the current and free-flowing temperature at a given location.

Table 3-7 Estimated Mean Monthly Impact of Dam Impoundments on Columbia and Snake River Temperatures (October; 2011-2016)

Location	River Mile	RBM10 Current (°C)	RBM10 Free Flowing (°C)	Individual Reach Impact[1] (°C)	Cumulative Impact[2] (°C)
Columbia River					
Canadian Border	735	13.01	13.01	NA	NA
Grand Coulee	595	17.22	12.78	4.4	4.4
Chief Joseph	546	17.19	12.72	0.0	4.5
Wells	515	16.78	12.76	-0.5	4.0
Rocky Reach	474	16.39	12.75	-0.4	3.6
Rock Island	453	16.20	12.69	-0.1	3.5
Wanapum	416	16.13	12.75	-0.1	3.4
Priest Rapids	397	15.99	12.72	-0.1	3.3
Hanford Reach	326	15.39	12.71	-0.6	2.7
Snake Confluence	322	15.61	12.80	0.1	2.8
McNary	291	15.89	12.79	0.3	3.1
John Day	216	16.58	12.98	0.5	3.6
Dalles	192	16.41	13.16	-0.4	3.3
Bonneville	146	16.39	13.31	-0.2	3.1
Snake River					
Anatone	168	14.93	14.93	NA	NA
Clearwater Confluence	138	13.85	13.84	NA	NA
Lower Granite	107	15.20	13.68	1.5	1.5
Little Goose	70	15.81	13.43	0.9	2.4
Lower Monumental	41	16.02	13.19	0.4	2.8
Ice Harbor	6	16.21	12.98	0.4	3.2

[1] Individual reach impact is the difference between the simulated temperature change in the reach immediately upstream of the assessment location under current conditions versus free-flowing conditions.

[2] Cumulative impact is the difference between the current and free-flowing temperature at a given location.

3.3.4 Bathymetry Scenario for Free-Flowing Snake River (Snake1934 Scenario)

The impact estimates above are based on the Free-Flowing scenario which is based on measured 2010 river bed bathymetry. The 2010 river bed has been altered by decades of impoundment and associated settling of suspended solids. EPA obtained 1934 bathymetry information for the Snake River from USACE, and used the same HEC-RAS and regression methodology as the Free-Flowing scenario setup to develop an RBM10 model setup for the Snake River with 1934 hydraulics. This is called the “Snake1934” scenario, and results of this

scenario were compared to the Free-Flowing scenario to assess the sensitivity of free-flowing river temperatures to changes in the river bed bathymetry. ***Figure 3-12*** shows this comparison for July, August, and September. The results indicate that the effect of bathymetry changes is relatively small with a mean absolute difference of 0.1°C. Temperatures are slightly colder with 1934 bathymetry at three dam locations, but they are slightly warmer at the fourth (Lower Monumental Dam ("Mon" in plot below).

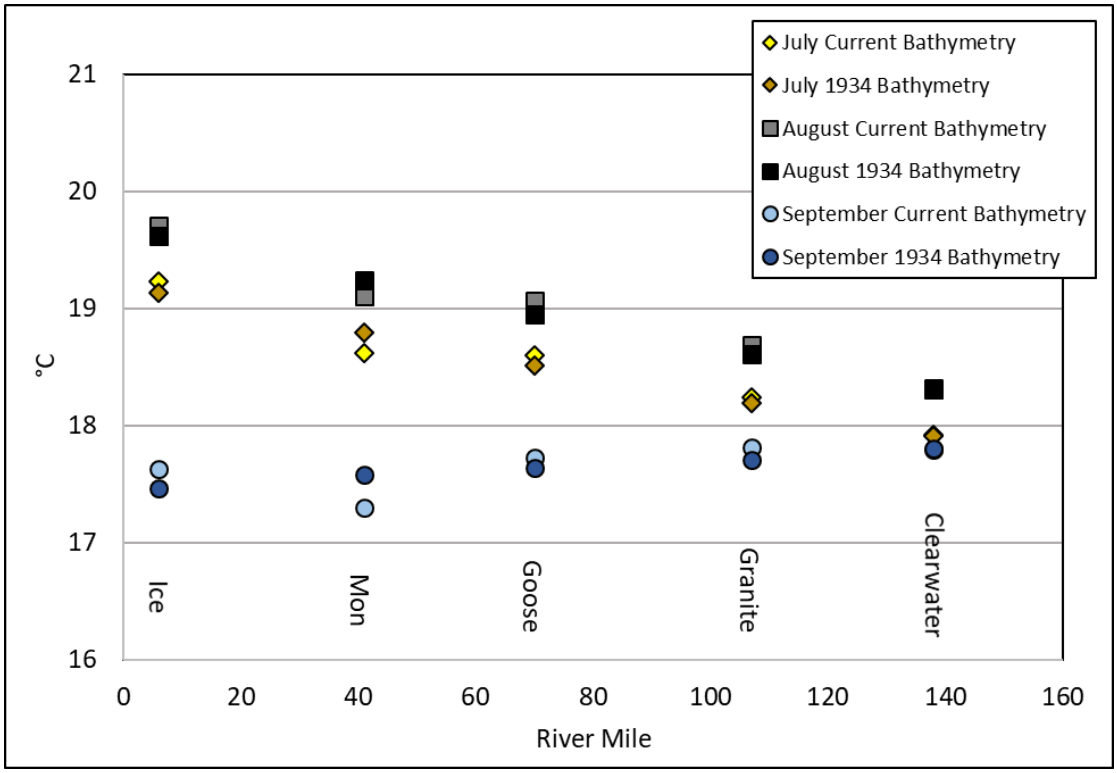
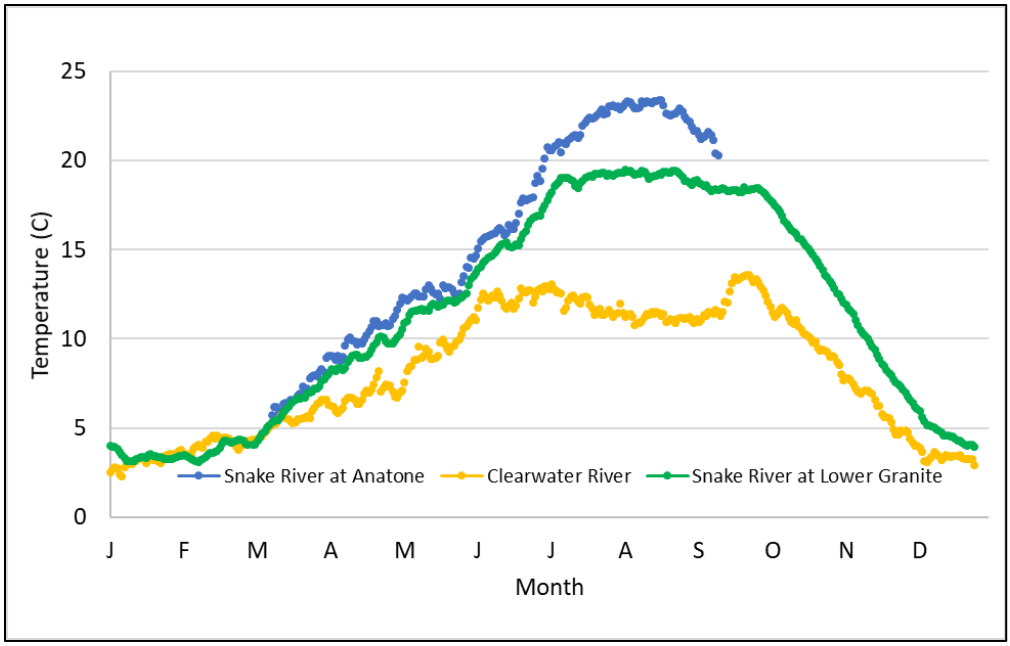


Figure 3-12 Simulated daily average temperature (2011-2016) in free-flowing Snake River using 2010 and 1934 bathymetry data

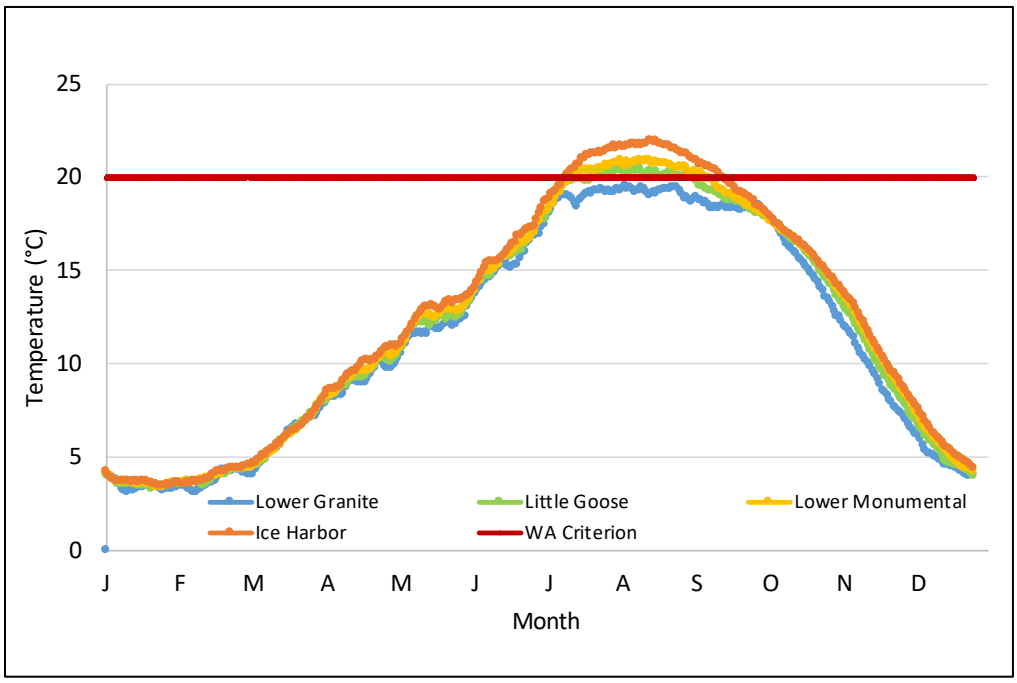
3.4 DWORSHAK DAM COLD WATER RELEASES (DWR1 AND DWR2 SCENARIOS)

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 WQC at Lower Granite Dam downstream of the Clearwater River confluence. As seen in ***Figure 3-13***, 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 3-14***).



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

Figure 3-13 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 3-14 Measured temperatures at the four Snake River dams in the TMDL study area and 20°C WQC

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). After assessing Dworshak impacts on current river conditions, another scenario (DWR2) was developed to assess the impact of Dworshak operations on a free-flowing Snake River using the same boundary inputs as scenario DWR1.

The DWR1 and DWR2 scenarios were constructed by substituting estimated flows and temperatures of the North Fork Clearwater without Dworshak Dam for the actual flow and temperature released by Dworshak Dam over this period (used for the Current Conditions simulation). The estimated flows are based on flows measured at the USGS gauge near Canyon ranger station, located upstream of Dworshak reservoir (USGS 13340600). This location does not capture all of the flow in the watershed, and EPA obtained model-estimated flows for the entire watershed from USACE (Turner 2018, pers. comm.). This information had some gaps and inconsistencies with the Canyon ranger station data, so EPA compared it to the Canyon station to estimate a scale factor. A multiplier of 1.3 was applied to the Canyon data to estimate the total flow from the watershed. The resulting estimated daily flow used as DWR1 and DWR2 input is shown in ***Figure 3-15***.

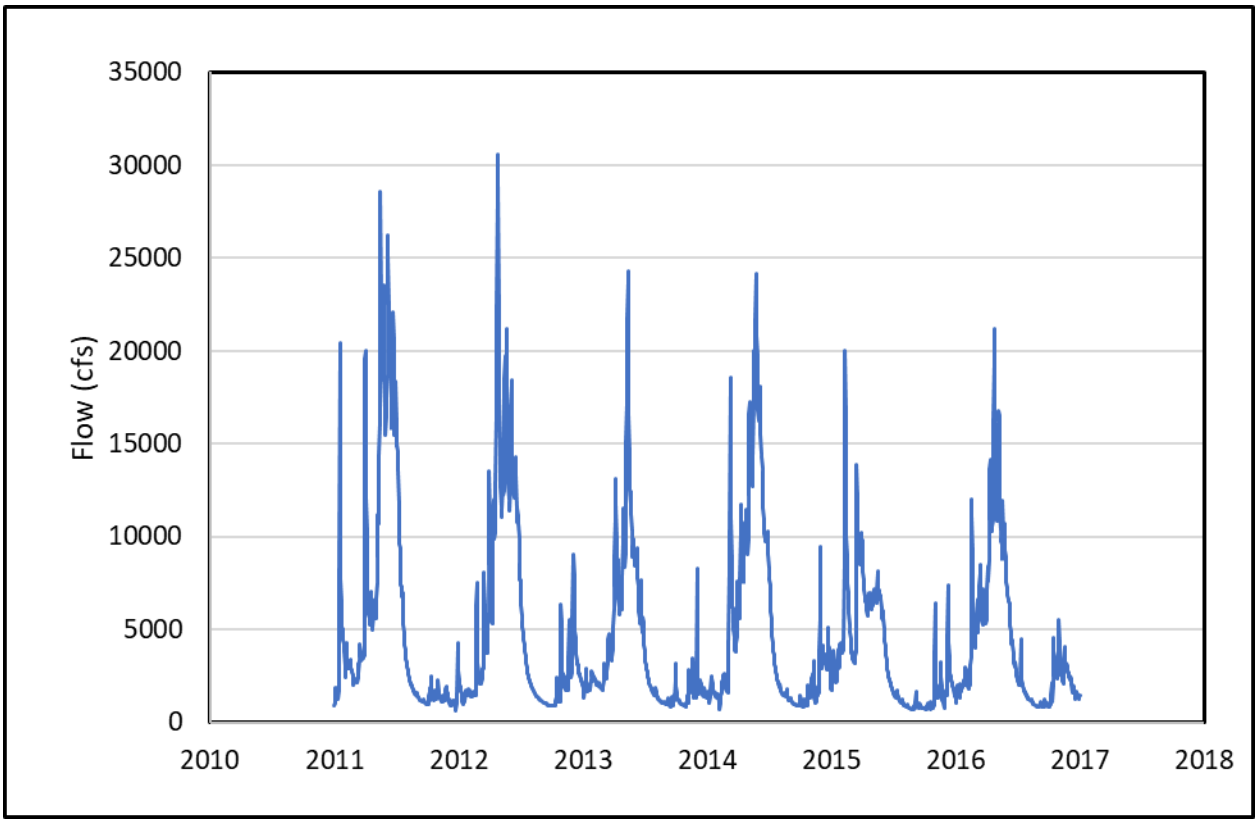


Figure 3-15 Estimated flow of Nork Fork Clearwater River at mouth without Dworshak Dam used as boundary inputs for RBM10 scenarios DWR1 and DWR2

For estimating temperature of the North Fork in the absence of Dworshak Dam, EPA used USGS monitoring data from the North Fork Clearwater River near the mouth at Ahsakha, Idaho before Dworshak Dam was constructed (1957 – 1970). This data was also provided by USACE (Turner pers. comm. 2018). The daily average for the Ahsakha location is shown in ***Figure 3-16*** alongside recently measured temperatures higher in the watershed above Dworshak reservoir at the Canyon ranger station. While the time frame of the Canyon station data aligns with the simulation years for this assessment (2011-2016), the temperatures are substantially colder than the Ahsakha temperatures and therefore unrepresentative of temperatures at the mouth in the absence of Dworshak Dam. The Ahsakha temperatures were looped for each year in the 2011-2016 model for the DWR1 and DWR2 scenarios.

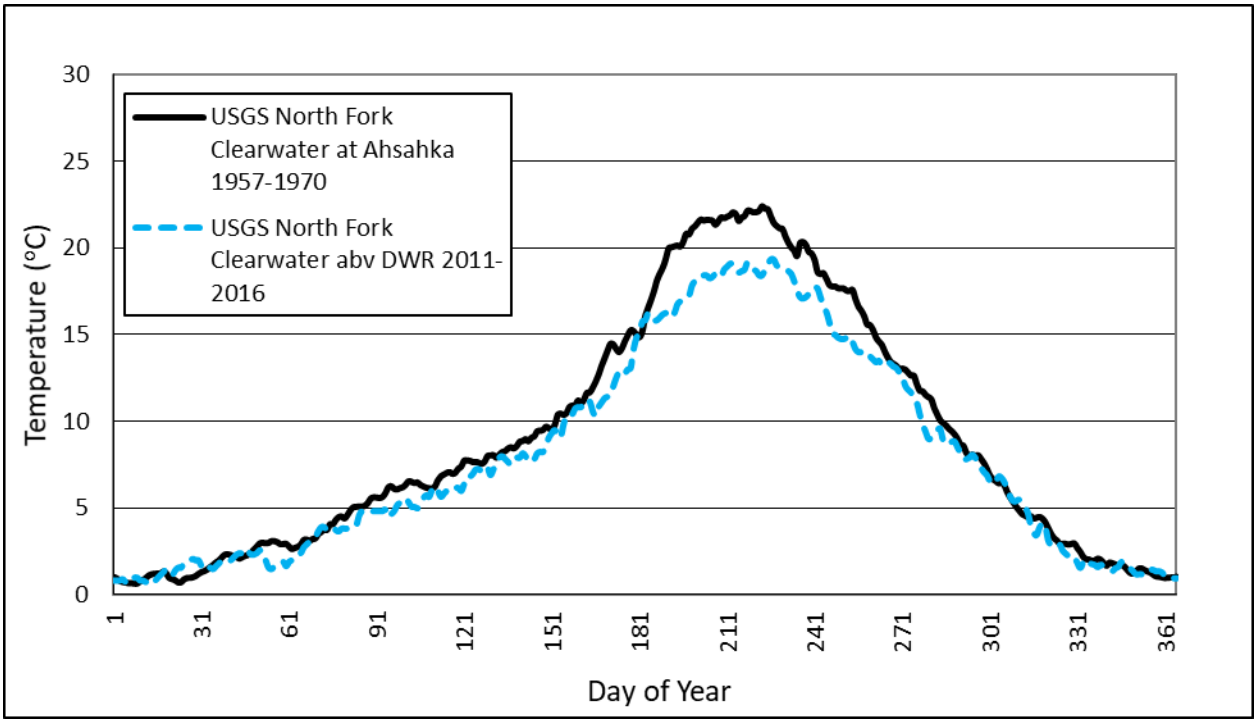


Figure 3-16 Daily mean temperature of North Fork Clearwater River measured at Ahsahka, Idaho in 1957-1970 (used in DWR1 and DWR2 scenarios) and above Dworshak reservoir in 2011-2016.

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 the Current Conditions model 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 3-17*** and ***Figure 3-18***: 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.

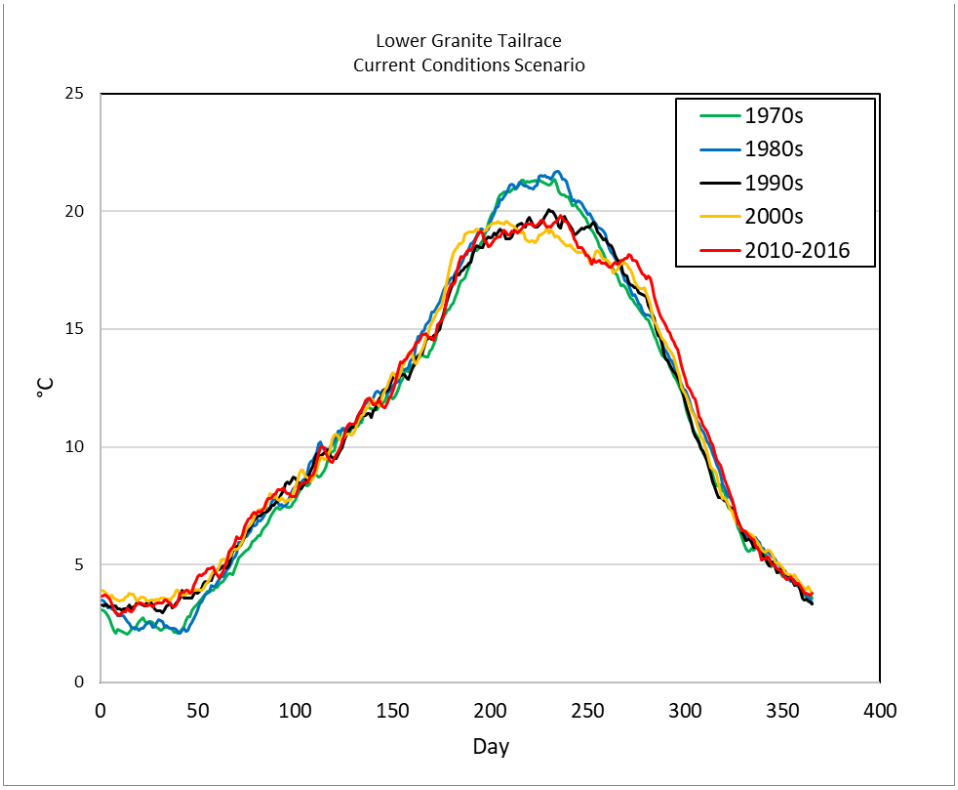


Figure 3-17 Simulated decadal average temperatures at Lower Granite Dam

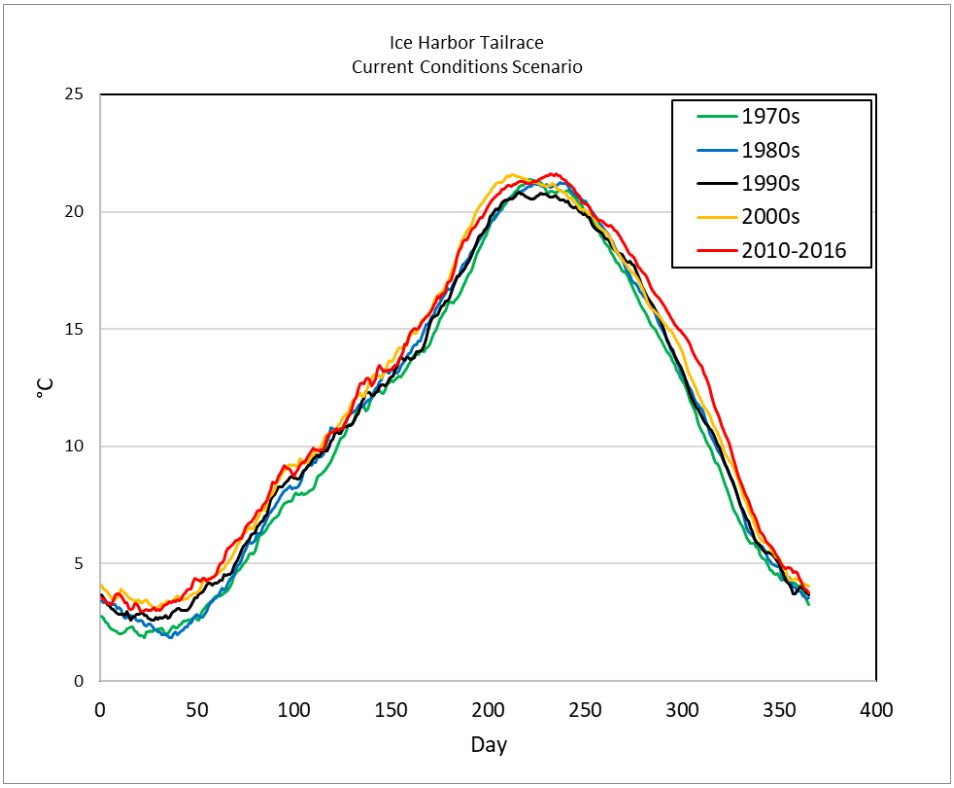


Figure 3-18 Simulated decadal average temperatures at Ice Harbor Dam

The second evaluation of 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 mathematically removed (DWR1 scenario) by changing the model inputs for the North Fork Clearwater River to reflect estimated conditions in the absence of the dam. The results of this evaluation are shown in ***Figure 3-19*** through ***Figure 3-21***. The temperature differences in these plots are then summarized in ***Table 3-8***.

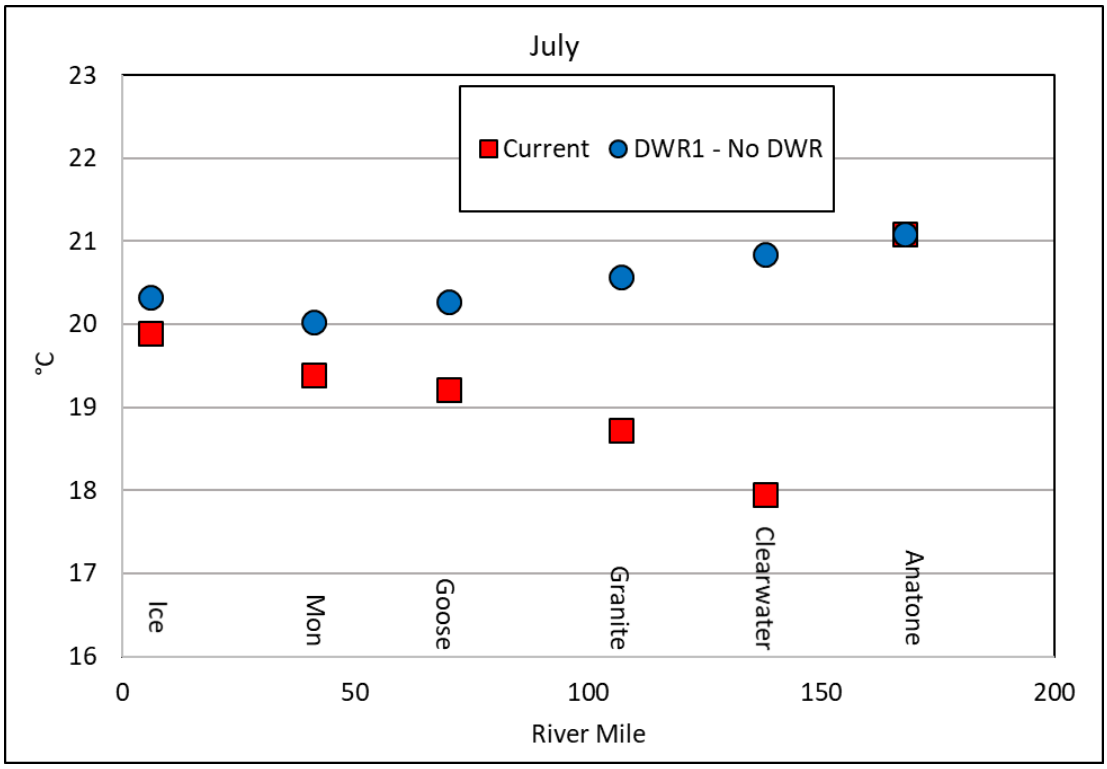


Figure 3-19 Estimated impact of Dworshak Dam operations (2011 – 2016; July)

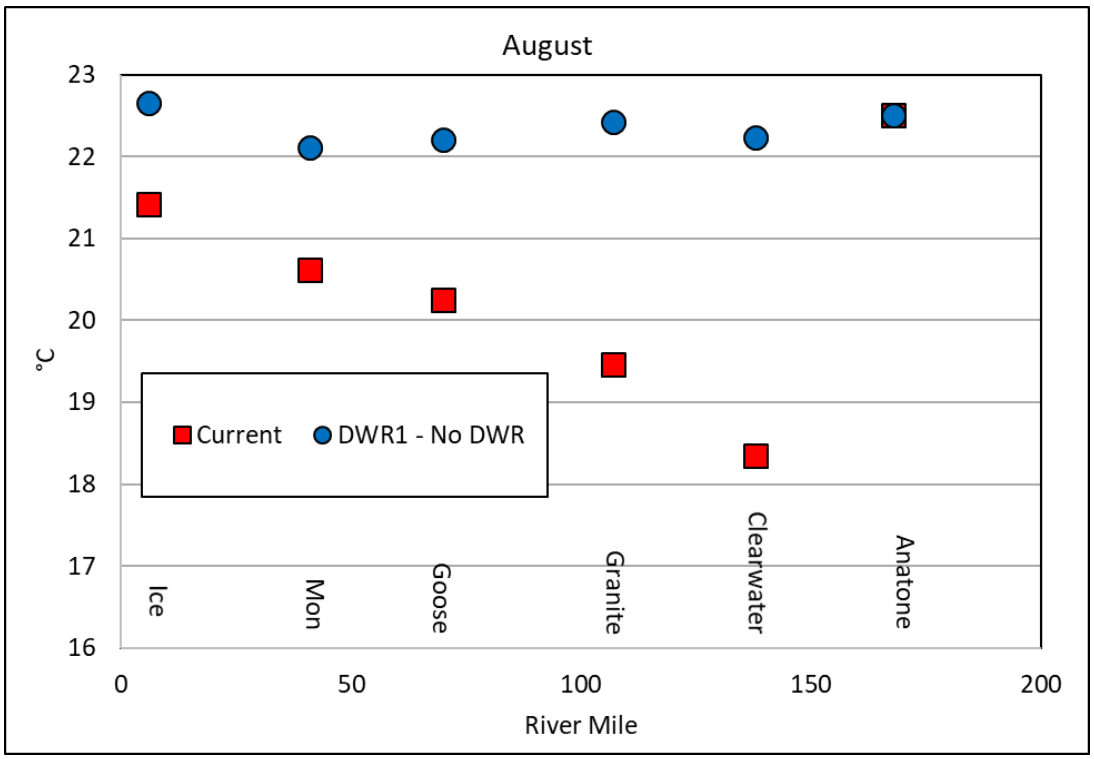


Figure 3-20 Estimated impact of Dworshak Dam operations (2011 – 2016; August)

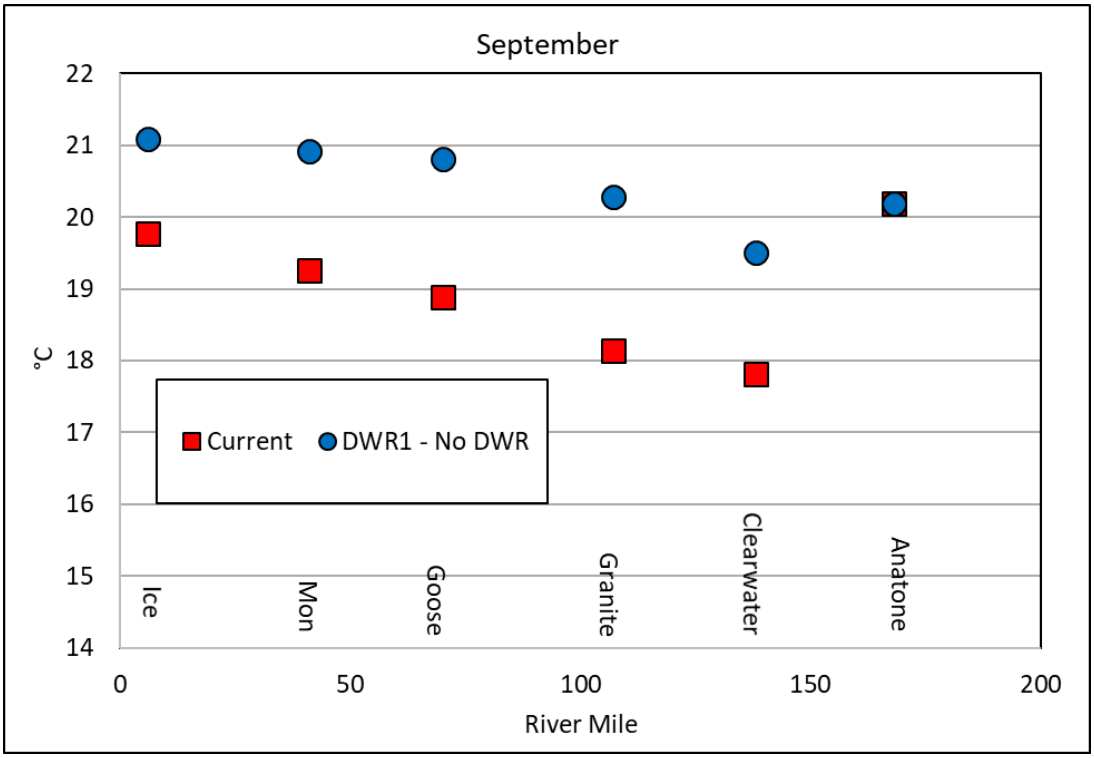


Figure 3-21 Estimated impact of Dworshak Dam operations (2011 – 2016; September)

Table 3-8 Estimated beneficial temperature impact of Dworshak Dam operations on current river temperatures

Location	RM	Current (°C)			DWR1 Scenario[1] (°C)			Estimated Benefit (Δ°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	18.8	20.4	19.1	18.8	20.5	19.3	0.0	-0.1	-0.2

[1] DWR1 Scenario - cold water releases into the Clearwater River from Dworshak Dam are mathematically removed by changing the model inputs for the North Fork Clearwater River to reflect estimated conditions in the absence of the dam.

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 3-22*** through ***Figure 3-24***).

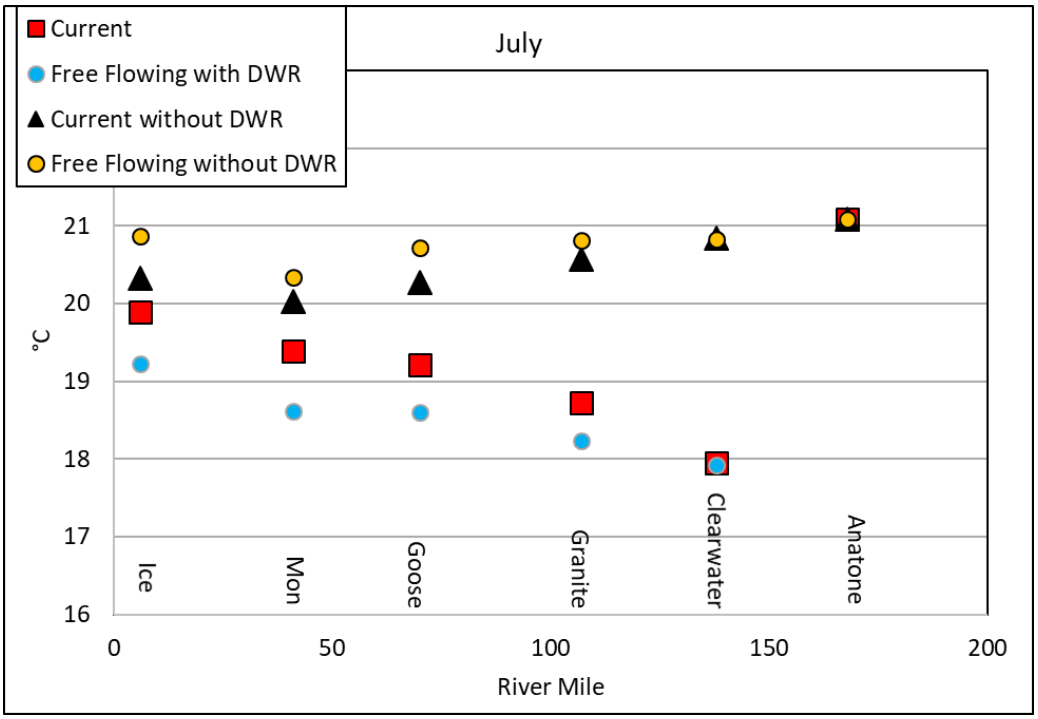


Figure 3-22 Comparison of Dworshak Dam impact scenarios (2011 – 2016; July)

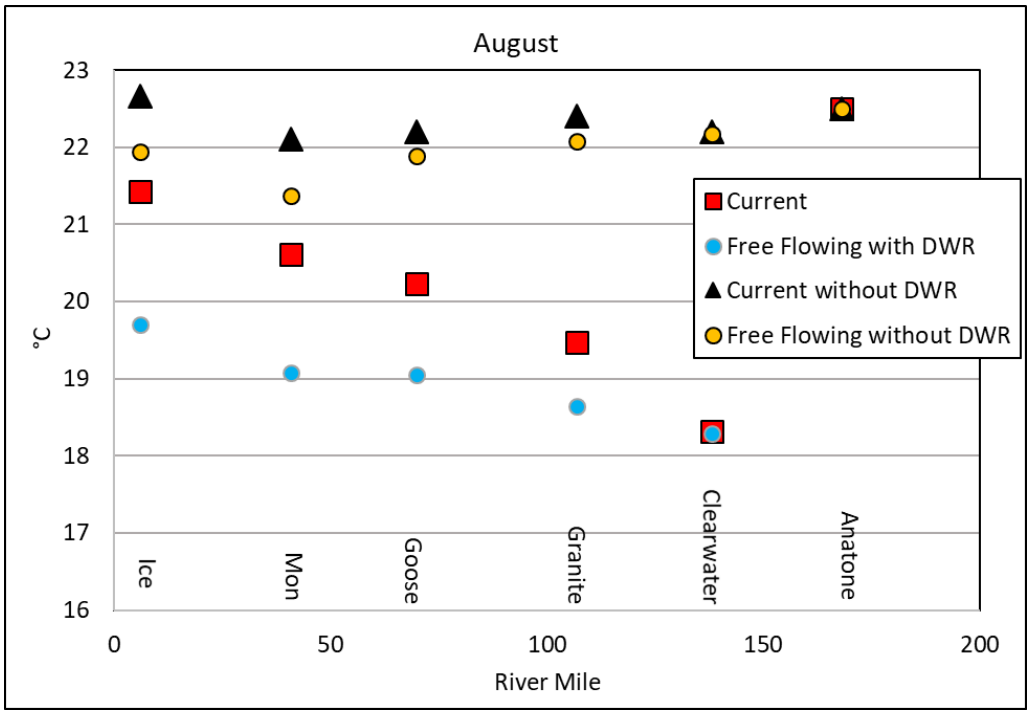


Figure 3-23 Comparison of Dworshak Dam impact scenarios (2011 – 2016; August)

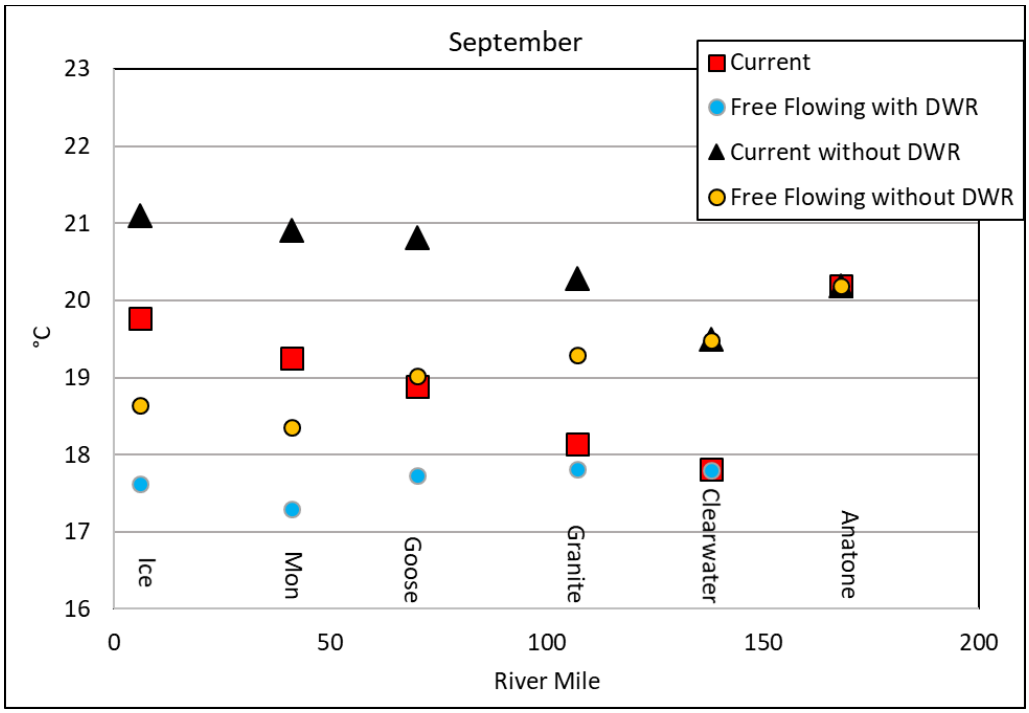


Figure 3-24 Comparison of Dworshak Dam impact scenarios (2011 – 2016; September)

3.5 CLIMATE CHANGE (TREND ANALYSIS)

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 flows, trends in model-predicted water temperatures for the Current 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.

The trend analyses performed on air temperatures and water temperatures are used as a first line of evidence of a warming climate in the modeled area. The trend analyses do not include strategies to decouple or filter temperature trends from known atmospheric oscillations such as the El Niño–Southern Oscillation (ENSO) or the Pacific Decadal Oscillation (PDO), nor explicitly assess potential impacts of flow regulations and impacts of land use changes on water temperatures. These limitations are expected to be offset by the use of a relatively large dataset of records and model outputs of 47 years (1970 – 2016) assuming that the variability in atmospheric oscillations should not introduce a long-term trend in climate observations.

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 and monthly (July, August, September and October) average air temperatures were calculated for the period spanning 1970 – 2016, and a linear regression performed to estimate magnitude.

In addition, trend analyses were performed on Current Conditions 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. P-values were calculated as a test of significance on the trend slopes to accept or reject the null hypothesis. The interpretation of the p-values is as follows:

- If the p-values are less than 0.05 (p-value≤0.05), the probability that the null hypothesis is true is less than or equal to 5%. The null hypothesis or no trend in the data is therefore rejected. The calculated slope explains the trend in the data.
- If the p-values are greater than 0.05 (p-value>0.05), the probability that the null hypothesis is true is greater than 5%. The null hypothesis or no trend in the data is therefore accepted as there is a weak statistical evidence that the calculated slope explains the trend in the data.

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 Current Conditions model simulations for the earliest decade (1970s). 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

Annual and monthly (July, August, September and October) average air temperature trends were analyzed at Lewiston, Yakima, and Portland. These selected stations are used as weather inputs for the RBM10 model. To estimate annual trend magnitudes, a linear regression was performed on the annual average air temperatures for the period spanning 1970 – 2016. To estimate monthly trends, linear regressions were performed on the monthly average air temperatures for the months of July, August, September and October for the period spanning 1970 – 2016. The results of the annual and monthly trend analyses are summarized in ***Table 3-9*** and shown from ***Figure 3-25*** through ***Figure 3-30***.

Table 3-9 Summary of air temperature trend analyses

Station	Decadal ΔT (°C)				
	Annual	July	Aug	Sept	Oct
Lewiston	0.22	0.37	0.20	0.48	0.23
Yakima	0.25	0.52	0.29	0.41	0.22
Portland	0.21	0.24	0.29	0.30	0.25
Average	**0.23**	**0.38**	**0.26**	**0.40**	**0.23**

At a monthly basis, September and July had the largest decadal increases in monthly average air temperatures. From the regression slopes, September temperatures increased between 0.30°C to 0.48°C by decade, and July temperatures increased between 0.24°C and 0.37°C by decade.

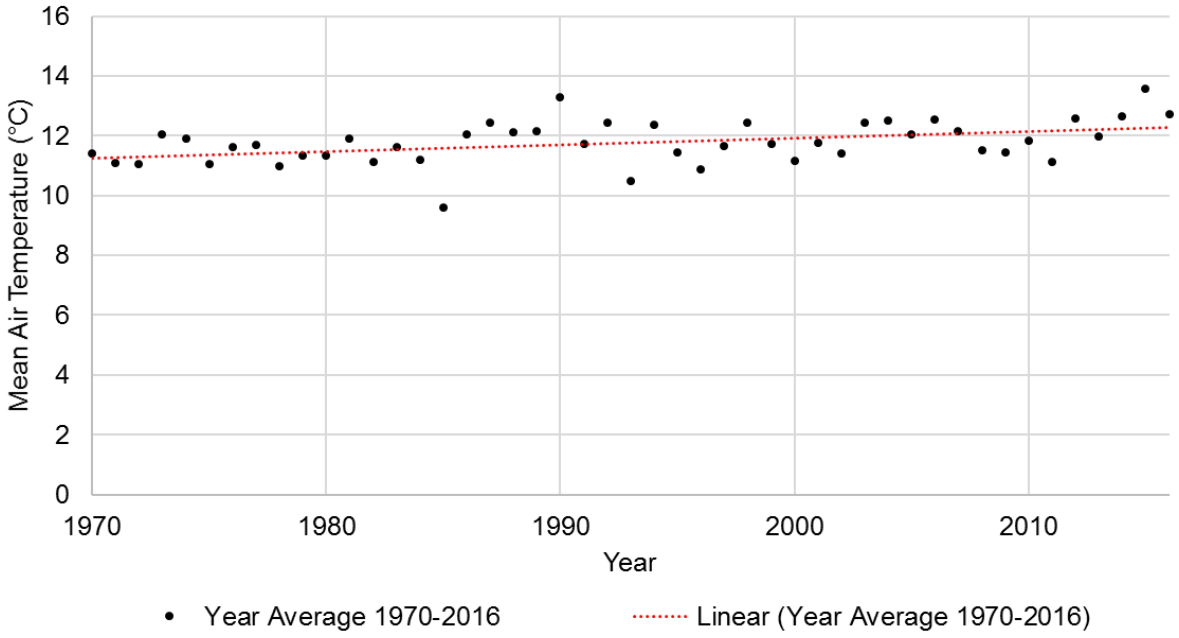


Figure 3-25 Trend for annual average air temperature at Lewiston, Idaho

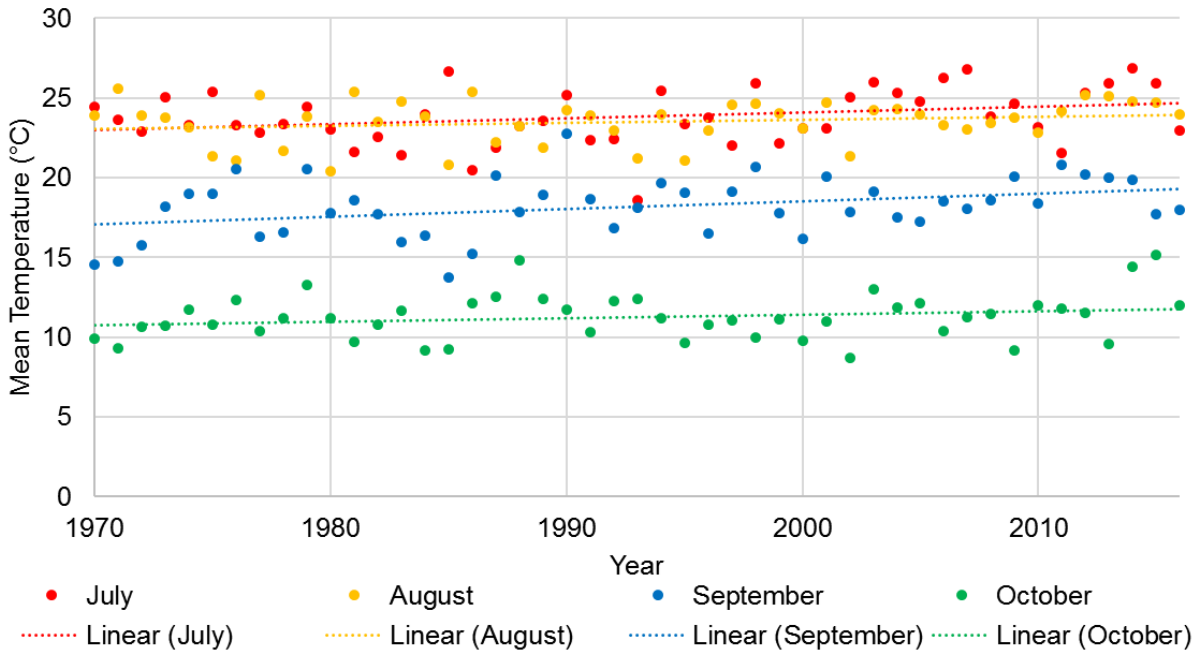


Figure 3-26 Trend for monthly average air temperature at Lewiston, Idaho

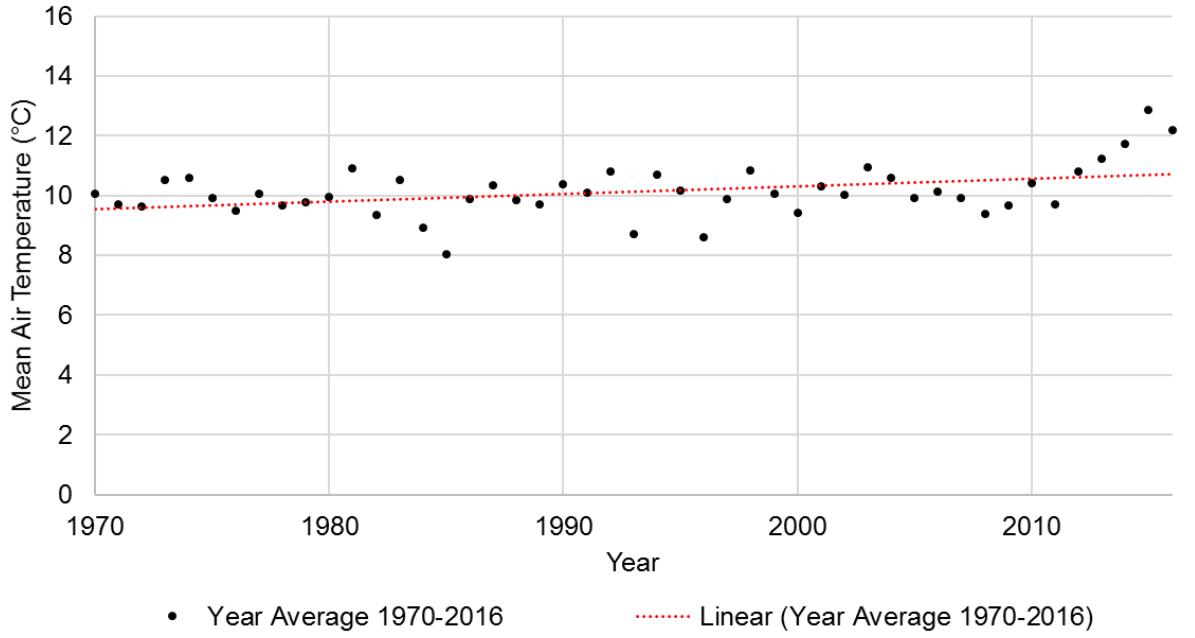


Figure 3-27 Trend for annual average air temperature at Yakima, Oregon

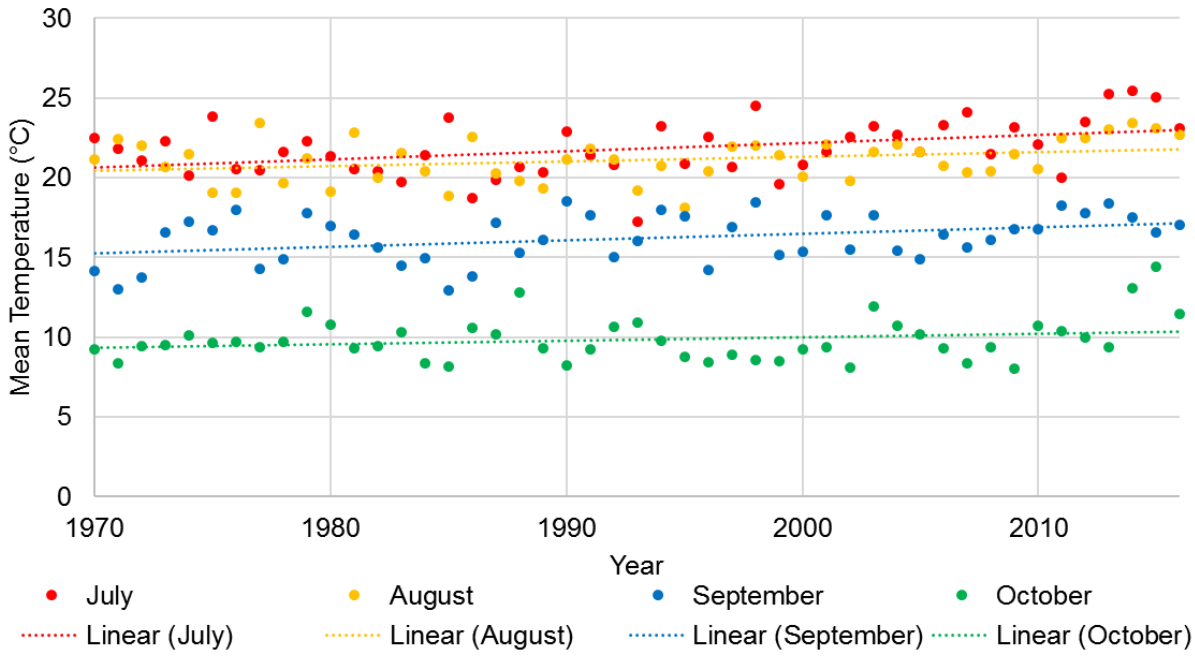


Figure 3-28 Trend for monthly average air temperature at Yakima, Oregon

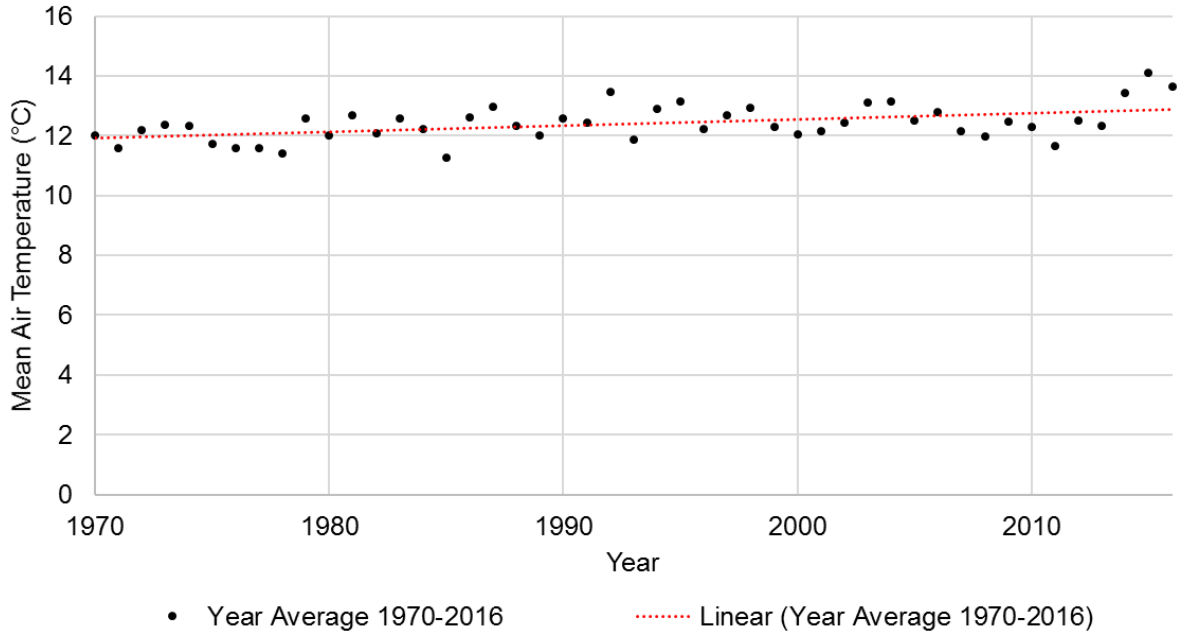


Figure 3-29 Trend for annual average air temperature at Portland, Oregon

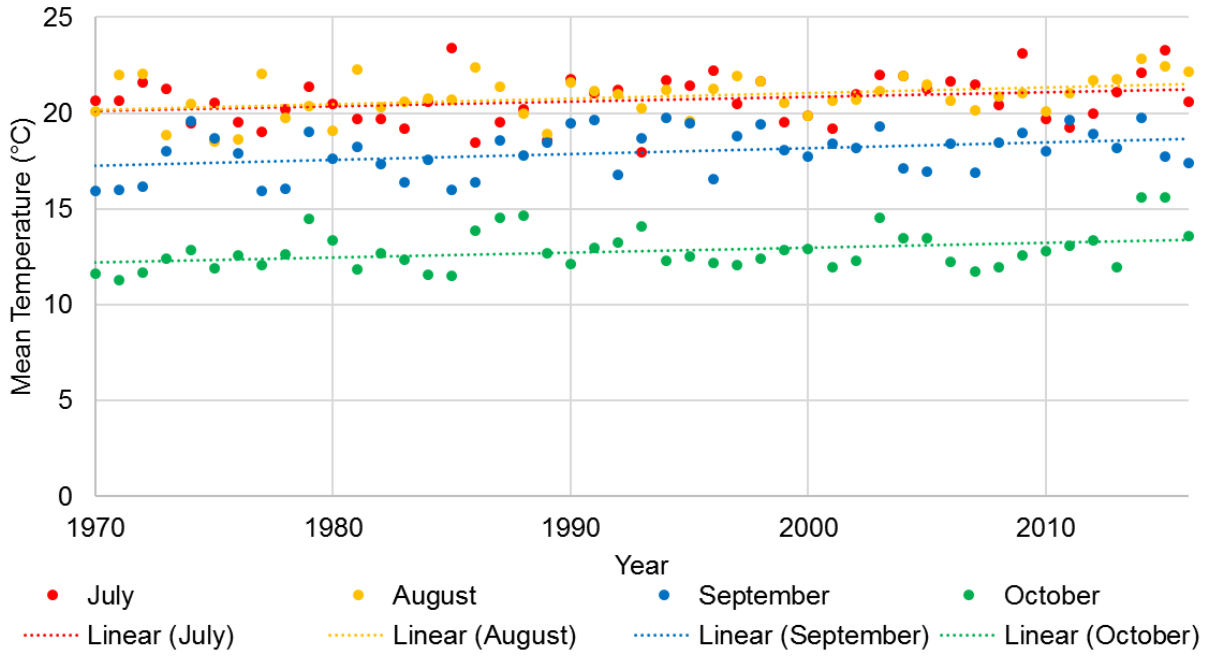


Figure 3-30 Trend for monthly average air temperature at Portland, Oregon

3.5.3 Flow Trends

Annual and monthly (July, August, September and October) average flow trends were analyzed at Bonneville Dam tailrace (BON) and Ice Harbor Dam tailrace (IDSW). To estimate annual trend magnitudes, a linear regression was performed on the annual average flows for the period spanning 1970 – 2016. To estimate monthly trends, linear regressions were performed on the monthly average flows for the months of July, August, September and October for the period spanning 1970 – 2016. The results of the annual and monthly trend analyses are summarized in ***Table 3-10*** and shown from ***Figure 3-31*** through ***Figure 3-34***

The trend analyses in general showed slight flow reductions from 1970 through 2016. The decadal trends of annual average flows at Bonneville Dam tailrace and Ice Harbor tailrace were -52.9 Kcfs/decade and -30.8 Kcfs/decade respectively. At a monthly basis, July, September and October were the months with the largest negative trends varying from -35.6 Kcfs/decade to -76.7 Kcfs/decade at Bonneville Dam tailrace, and from -16.8 Kcfs/decade to -22.4 Kcfs/decade at Ice Harbor Dam tailrace. Meanwhile, August flows showed the lowest decadal changes. Average August flows decreased by -14.8 Kcfs/decade at Bonneville Dam tailrace and increased by 14.0 Kcfs/decade at Ice Harbor Dam tailrace.

Table 3-10 Summary of flow trends at Bonneville Dam tailrace and Ice Harbor Dam tailrace

Station	Decadal ΔQ (Kcfs)				
	Annual	July	Aug	Sept	Oct
BON	-52.9	-35.6	-14.8	-76.7	-66.8
IDSW	-30.8	-16.8	14.0	-14.6	-22.4

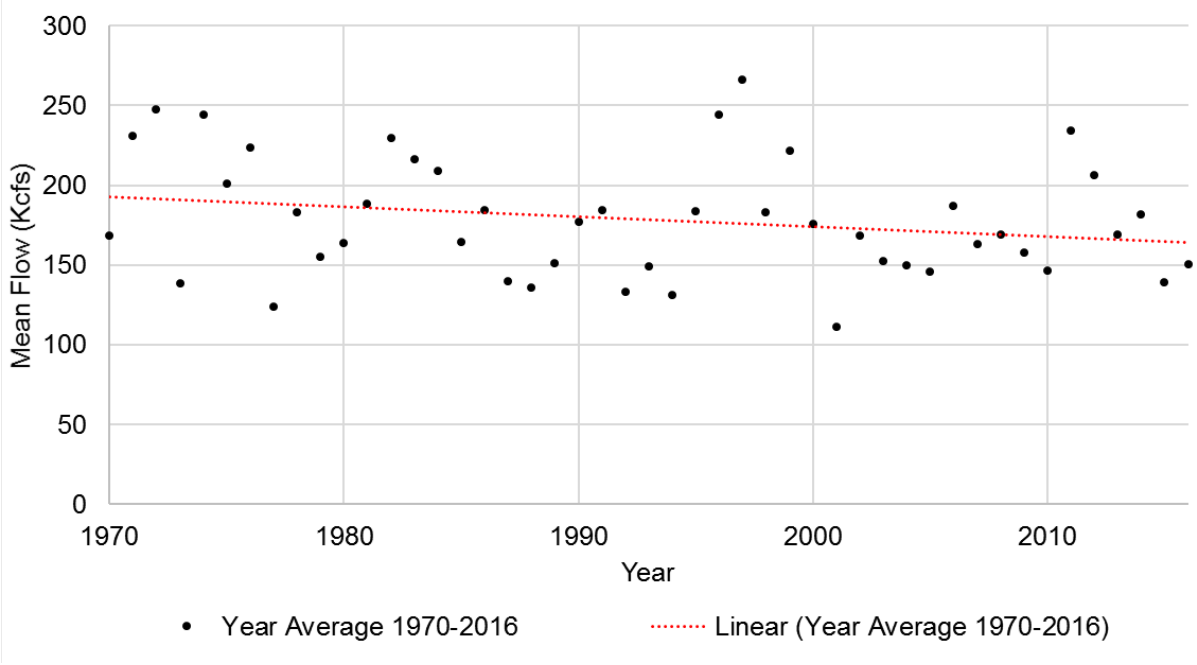


Figure 3-31 Trend for annual average flow at Bonneville Dam

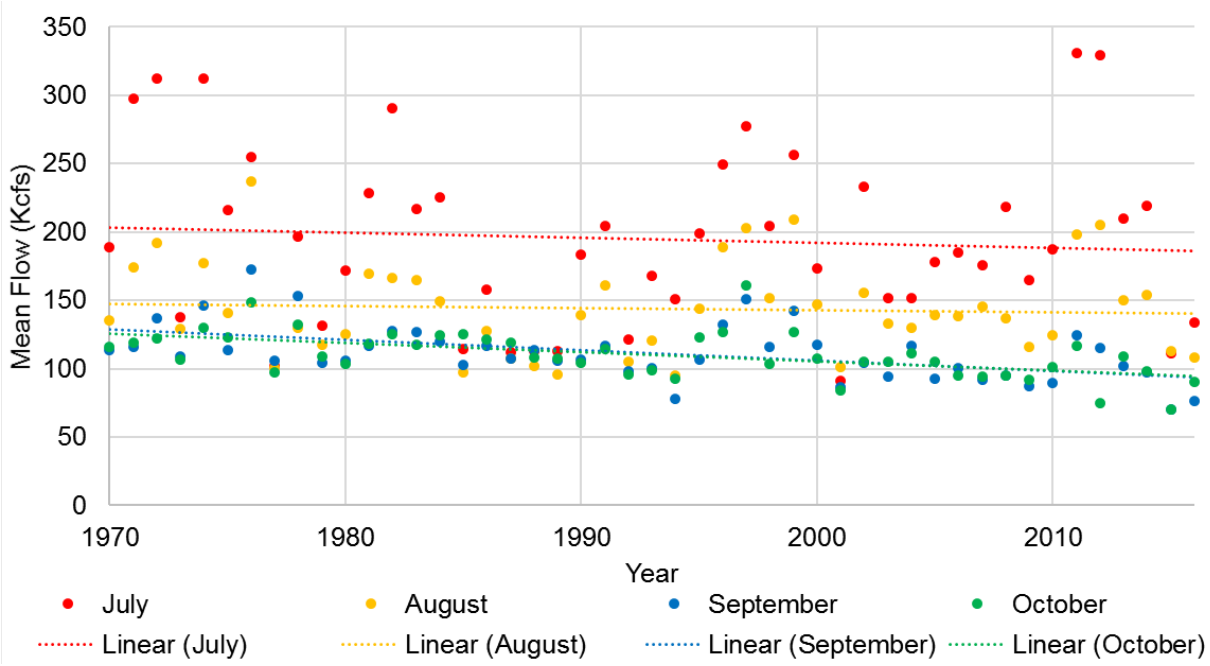


Figure 3-32 Trend for monthly average flow at Bonneville Dam

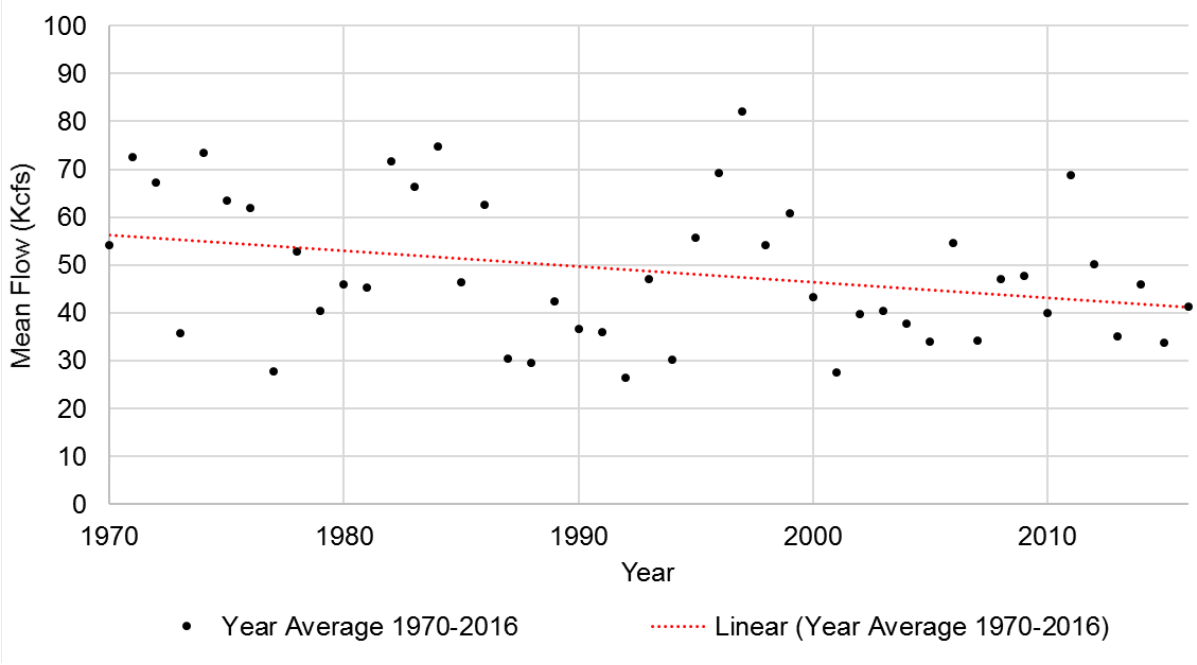


Figure 3-33 Trend for annual average flow at Ice Harbor Dam tailrace

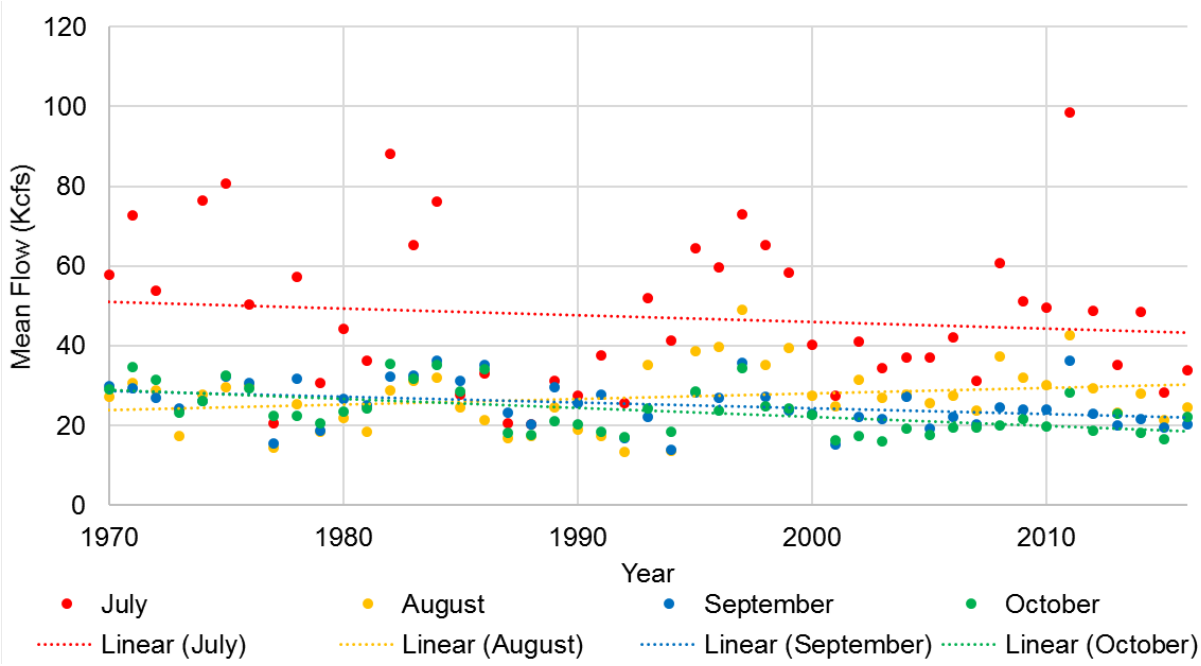


Figure 3-34 Trend for monthly average flow at Ice Harbor Dam tailrace

3.5.4 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 trend 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 3-11***. All the trends were considered significant with p-values less than 0.05, with the exception of mean temperatures in August and September at Ice Harbor Dam. Average changes per decade are highest at Bonneville Dam and lowest at Ice Harbor Dam. For the Columbia River, there is less relative variation between months, with the highest changes occurring in July.

Table 3-11 Mean monthly water temperatures for 1970, 2016 and decadal changes predicted from trend analysis of RBM10 Current conditions model output

Location	Month	Water Temperature (°C)		
		1970	2016	Change per Decade
Wells Dam	July	14.3	16.4	0.38
Wells Dam	August	16.6	18.5	0.35
Wells Dam	September	17.0	18.9	0.33
Wells Dam	October	15.5	17.1	0.27
Priest Rapids Dam	July	15.7	18.0	0.41
Priest Rapids Dam	August	17.7	19.9	0.40
Priest Rapids Dam	September	16.7	19.2	0.41
Priest Rapids Dam	October	14.2	16.2	0.34
Bonneville Dam	July	17.3	19.9	0.48
Bonneville Dam	August	19.4	21.7	0.40
Bonneville Dam	September	17.6	20.3	0.45
Bonneville Dam	October	13.9	16.5	0.45
Ice Harbor Dam	July	17.8	20.1	0.41
Ice Harbor Dam	August	20.8	21.1	0.06
Ice Harbor Dam	September	18.8	19.3	0.09
Ice Harbor Dam	October	14.1	16.3	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. In contrast, results indicate a smaller warming trend in August, September, and October in a free-flowing river (***Table 3-12***). 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 3-12 Comparison of trend for mean monthly temperature increase for Current and Free-Flowing model scenarios using RBM10

Location	RBM10 1970-2016 ∆°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	0.35	0.26	0.33	0.16	0.27	0.05
Priest Rapids	0.41	0.46	0.40	0.28	0.41	0.21	0.34	0.10
Bonneville Dam	0.48	0.47	0.40	0.26	0.45	0.32	0.45	0.25
Snake River								
Ice Harbor Dam	0.41	0.05	0.06	-0.32	0.09	0.18	0.39	0.23

Detailed trend information by location, scenario, and time frame is provided below in **Figure 3-35** through **Figure 3-50** and **Table 3-13** through **Table 3-20**.

Trend Analysis at Bonneville Dam

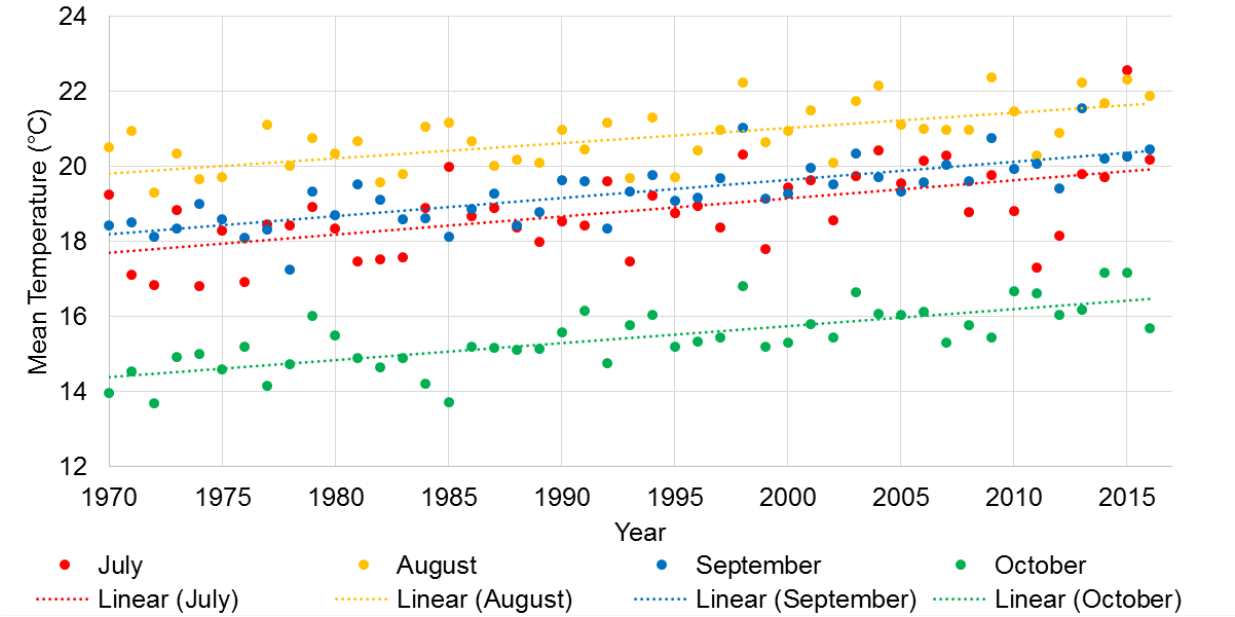


Figure 3-35 Simulated monthly mean temperatures at Bonneville Dam (Current)

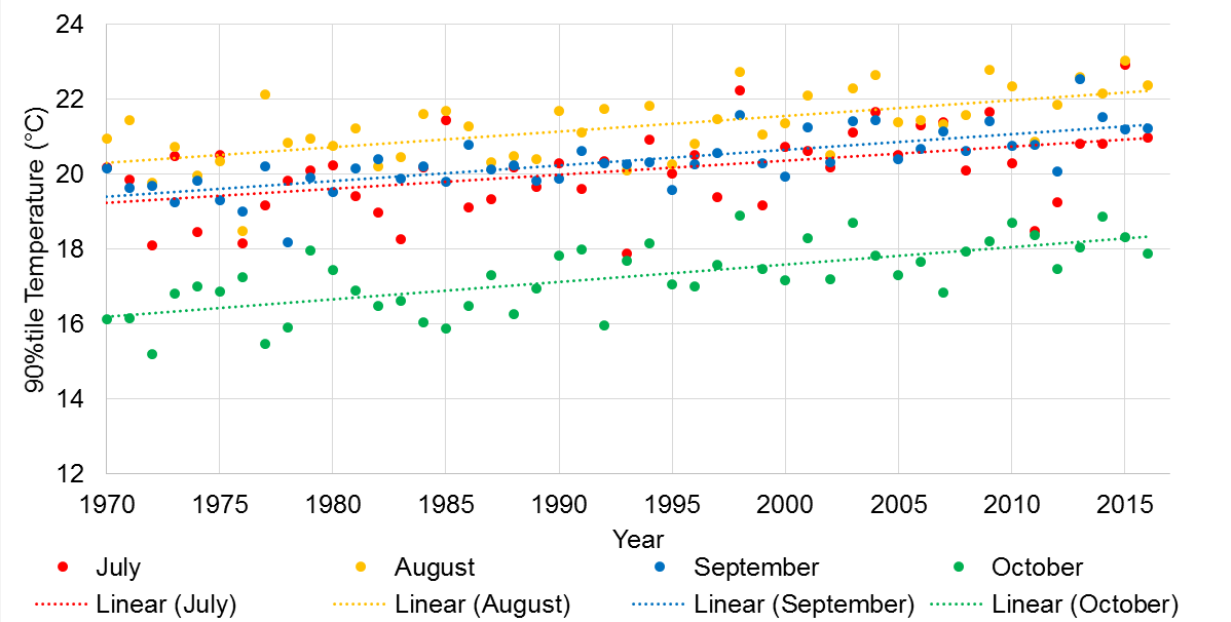


Figure 3-36 Simulated monthly 90th percentile temperatures at Bonneville Dam (Current)

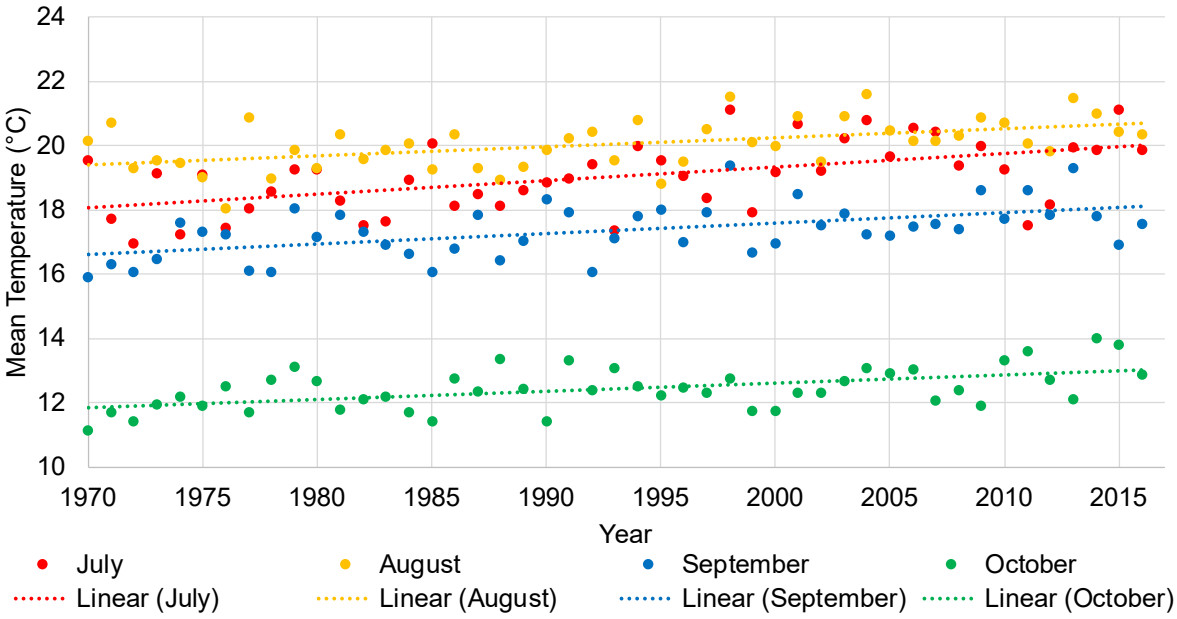


Figure 3-37 Simulated monthly mean temperatures at Bonneville Dam (Free-Flowing)

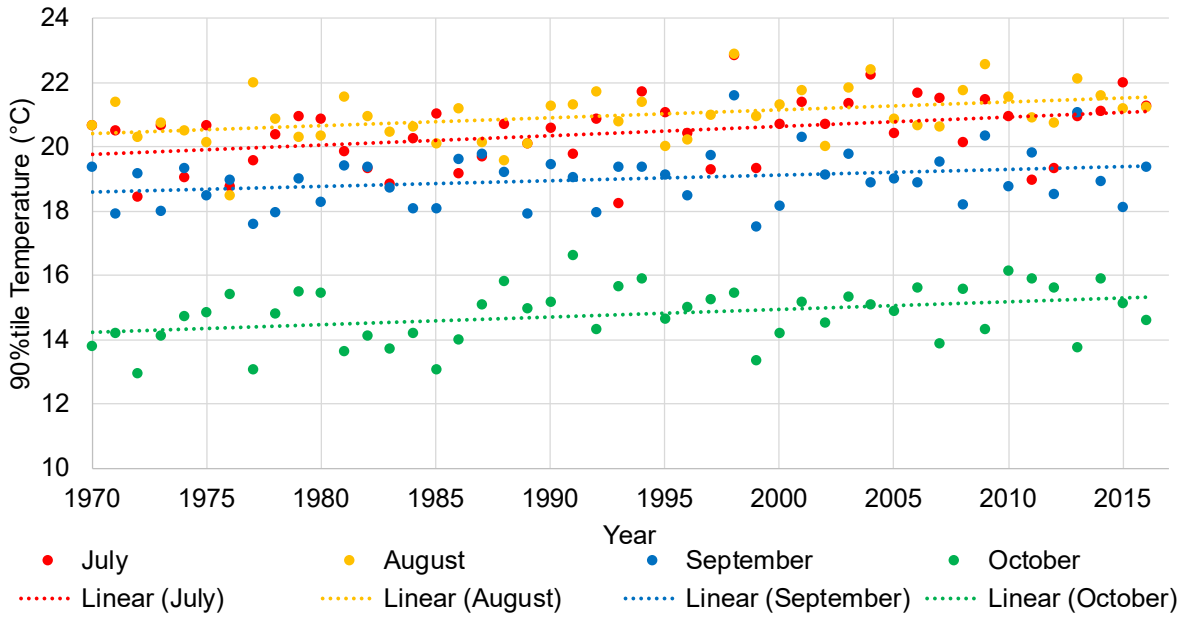


Figure 3-38 Simulated monthly 90th percentile temperatures at Bonneville Dam (Free-Flowing)

Table 3-13 Current conditions seasonal Kendall test slopes and p values at Bonneville Dam

Month	Mean		90th percentile	
	Slope	p value	Slope	p value
July	0.0475	0.0001	0.03923	0.0006
August	0.0402	<0.0000	0.04273	<0.0000
September	0.0450	<0.0000	0.03793	<0.0000
October	0.0450	<0.0000	0.04618	<0.0000

Table 3-14 Free-Flowing scenario 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

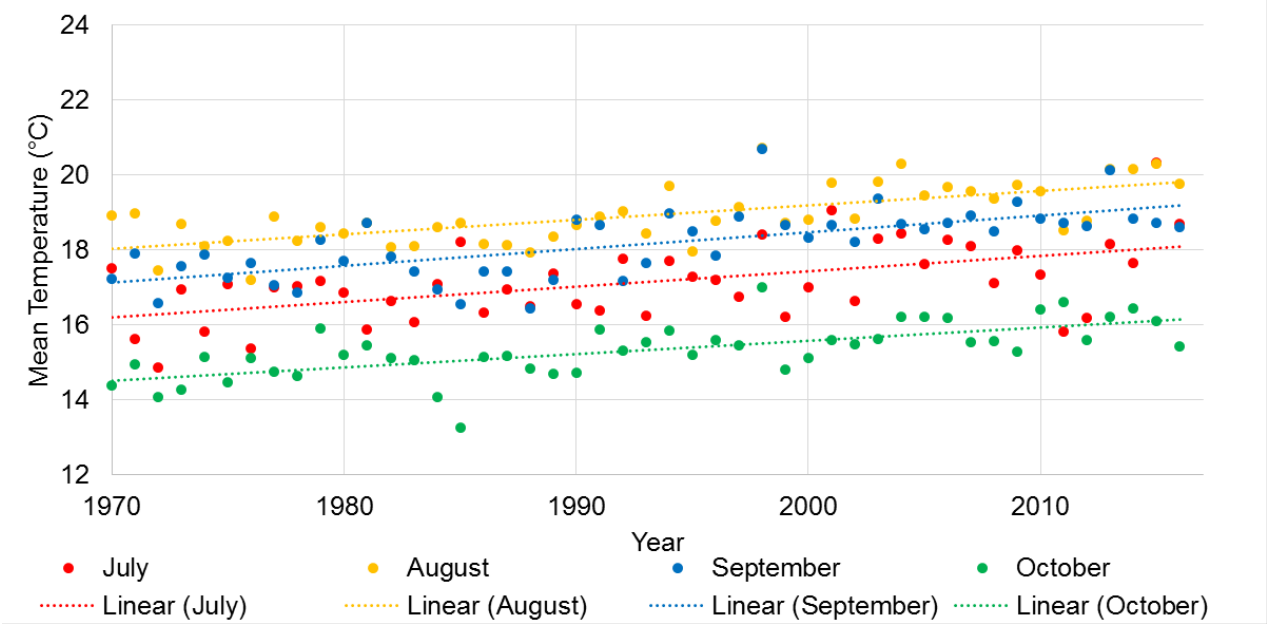


Figure 3-39 Simulated monthly mean temperatures at Priest Rapids (Current)

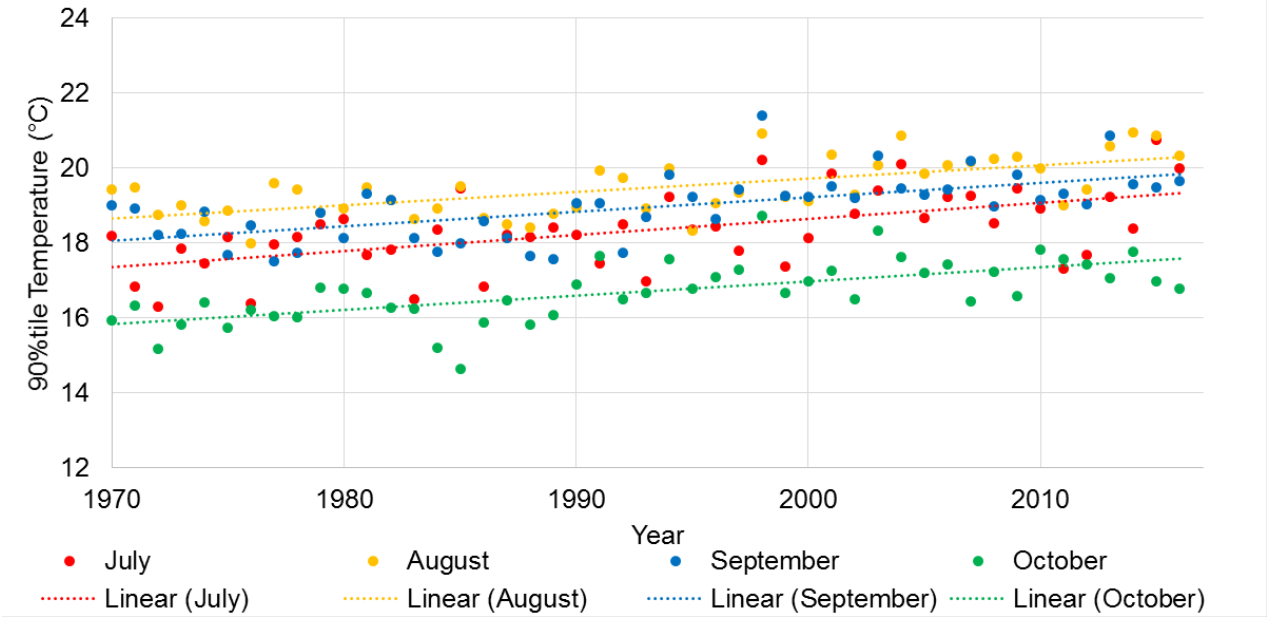


Figure 3-40 Simulated monthly 90th percentile temperatures at Priest Rapids (Current)

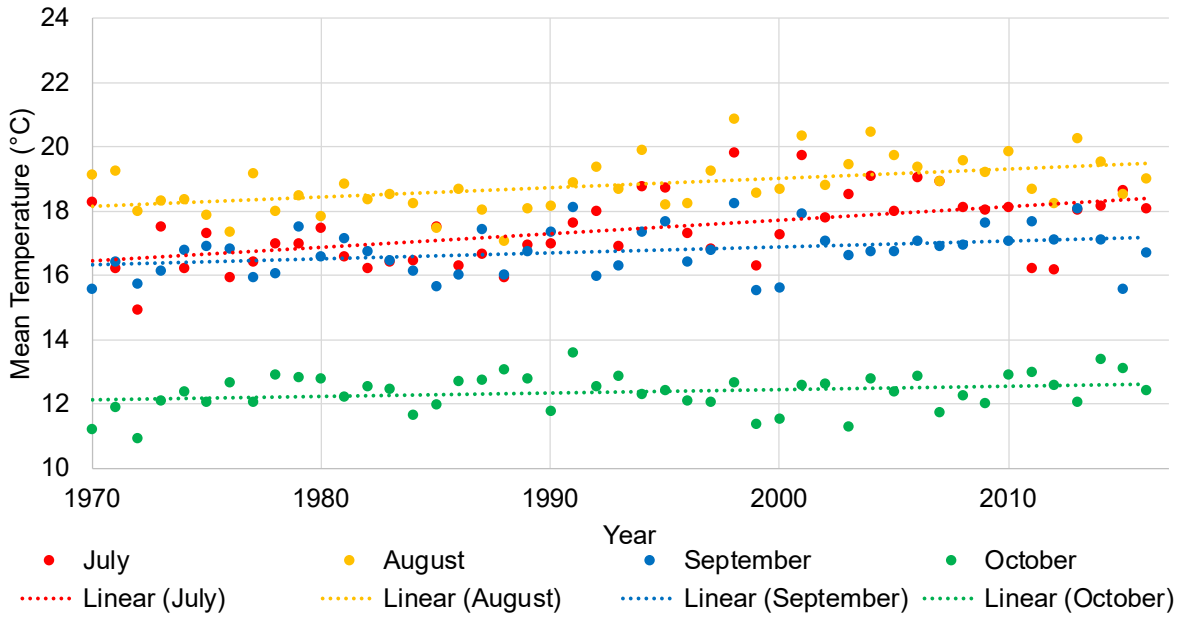


Figure 3-41 Simulated monthly mean temperatures at Priest Rapids (Free-Flowing)

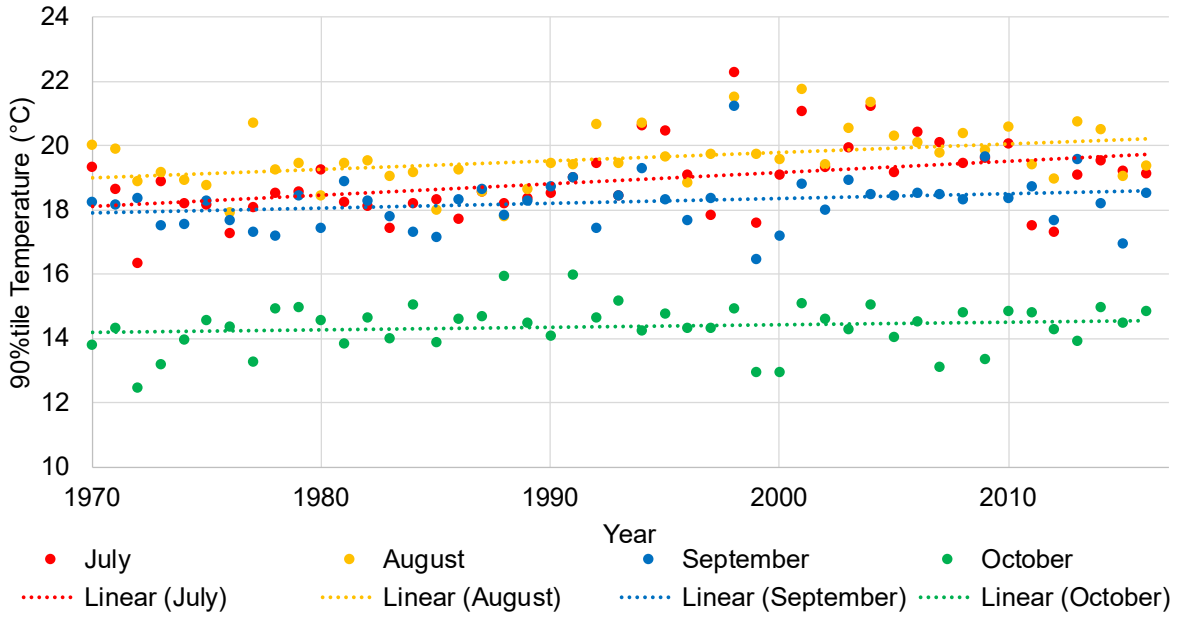


Figure 3-42 Simulated monthly 90th percentile temperatures at Priest Rapids (Free-Flowing)

Table 3-15 Current conditions seasonal Kendall test slopes and p values at Priest Rapids

Month	Mean		90th percentile	
	Slope	p value	Slope	p value
July	0.0407	0.0006	0.0406	0.0001
August	0.0400	<0.0000	0.0341	<0.0000
September	0.0410	<0.0000	0.0354	<0.0000
October	0.0342	<0.0000	0.0363	<0.0000

Table 3-16 Free-Flowing scenario 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[1]	0.0100	0.1233	0.0096	0.1660

[1] Month without trend (p-value>0.05).

Trend Analysis at Wells Dam

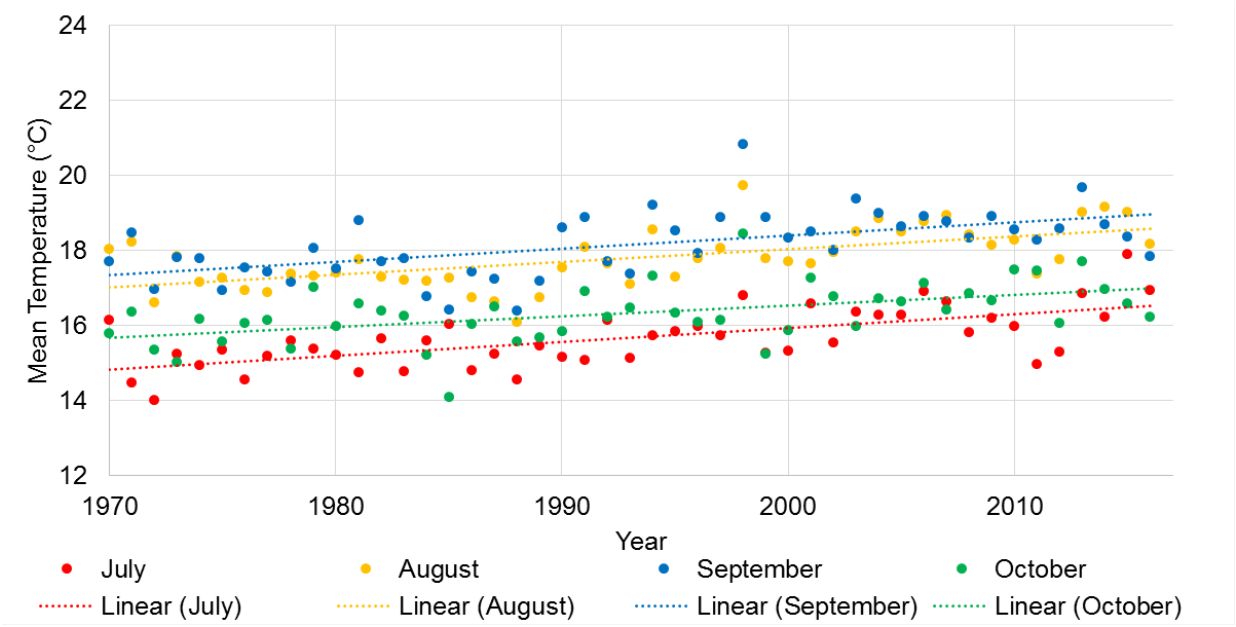


Figure 3-43 Simulated monthly mean temperatures at Wells Dam (Current)

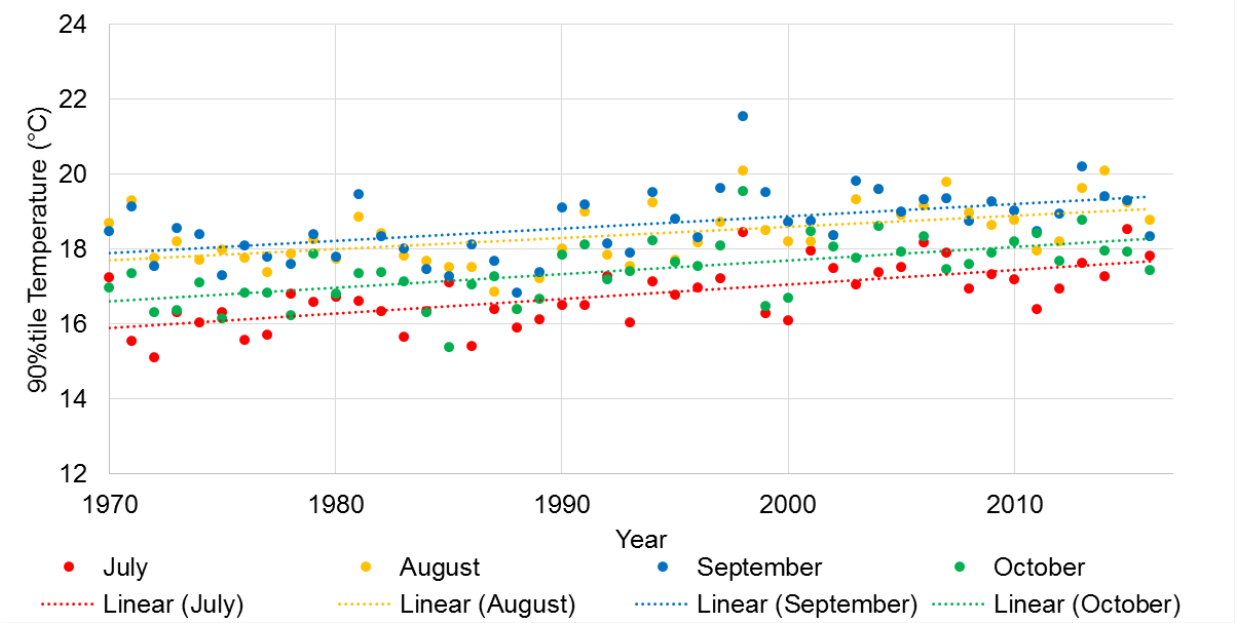


Figure 3-44 Simulated monthly 90th percentile temperatures at Wells Dam (Current)

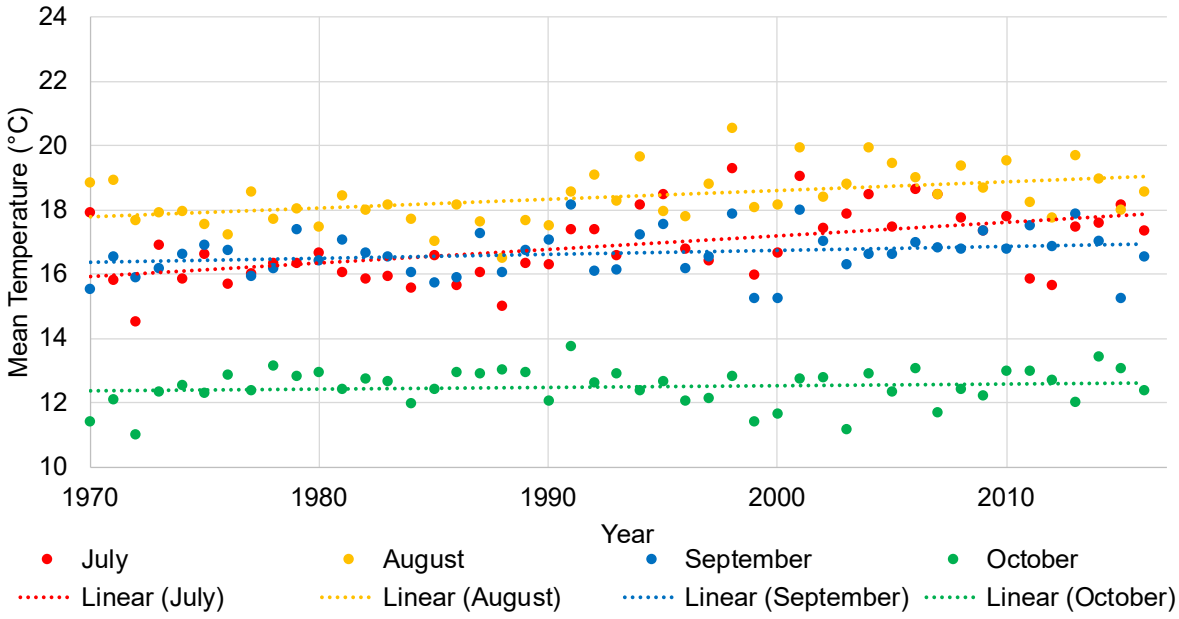


Figure 3-45 Simulated monthly mean temperatures at Wells Dam (Free-Flowing)

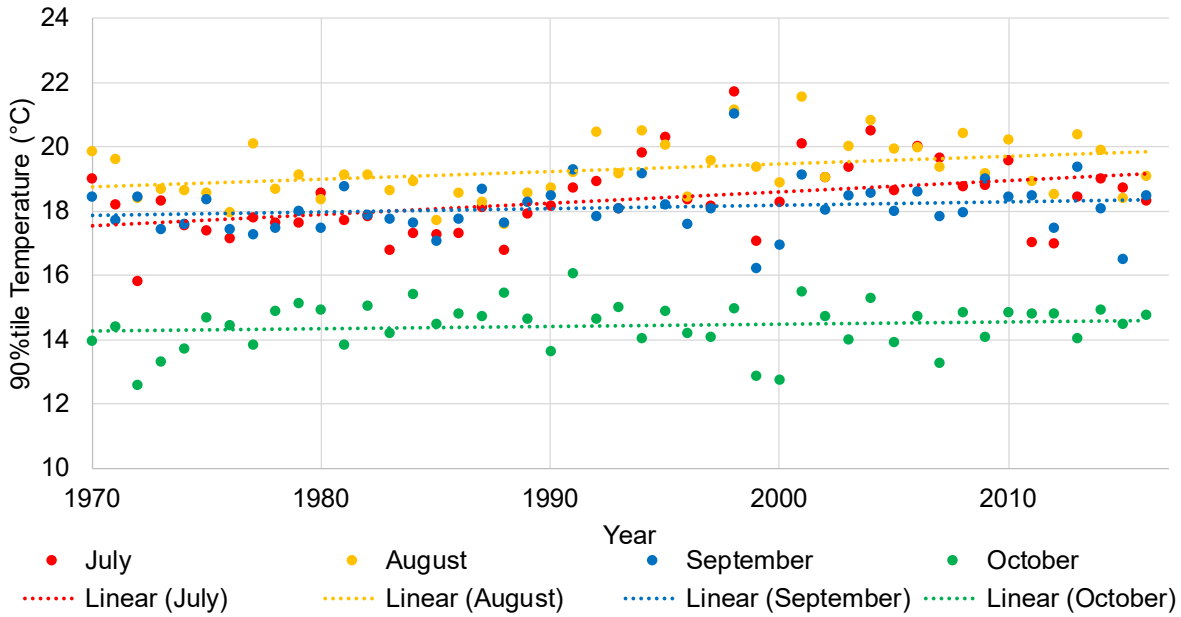


Figure 3-46 Simulated monthly 90th percentile temperatures at Wells Dam (Free-Flowing)

Table 3-17 Current conditions seasonal Kendall test and p values at Wells Dam

Month	Mean		90th percentile	
	Slope	p value	Slope	p value
July	0.0377	<0.0000	0.0400	<0.0000
August	0.0350	<0.0000	0.0290	0.0010
September	0.0325	0.0003	0.0322	0.0008
October	0.0269	0.0003	0.0350	<0.0000

Table 3-18 Free-Flowing scenario 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
Octobe[r1]	0.0050	0.3448	0.0064	0.3737

[1] Month without trend (p-value>0.05).

Trend Analysis at Ice Harbor Dam

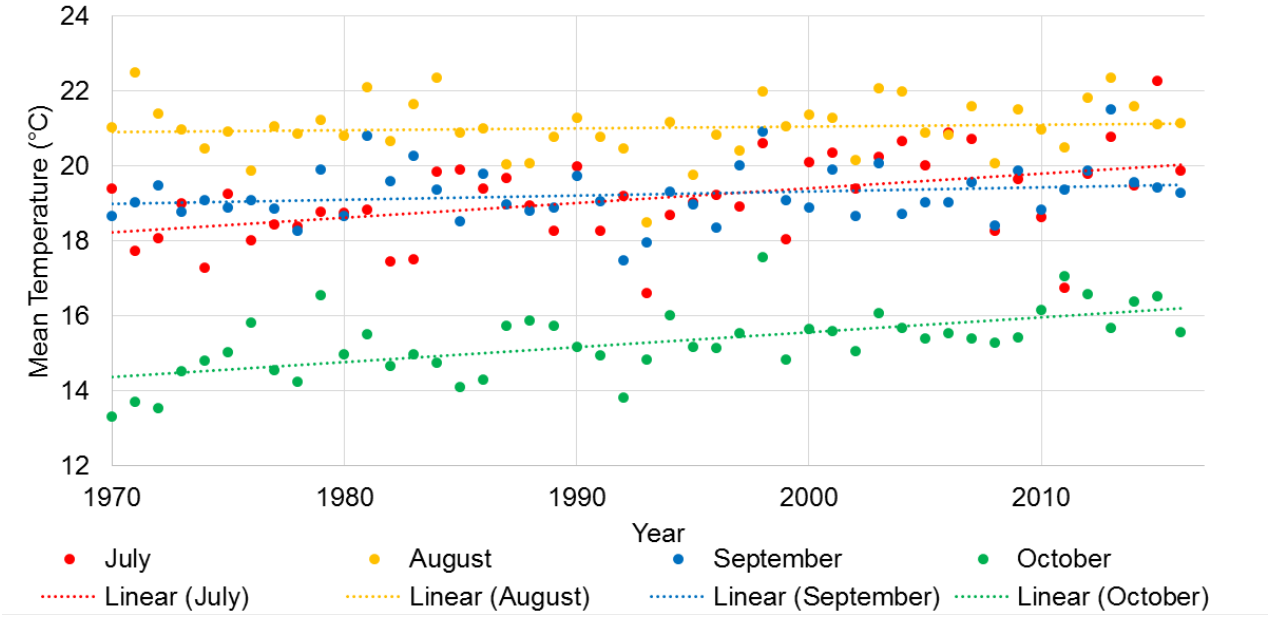


Figure 3-47 Simulated monthly mean temperatures at Ice Harbor Dam (Current)

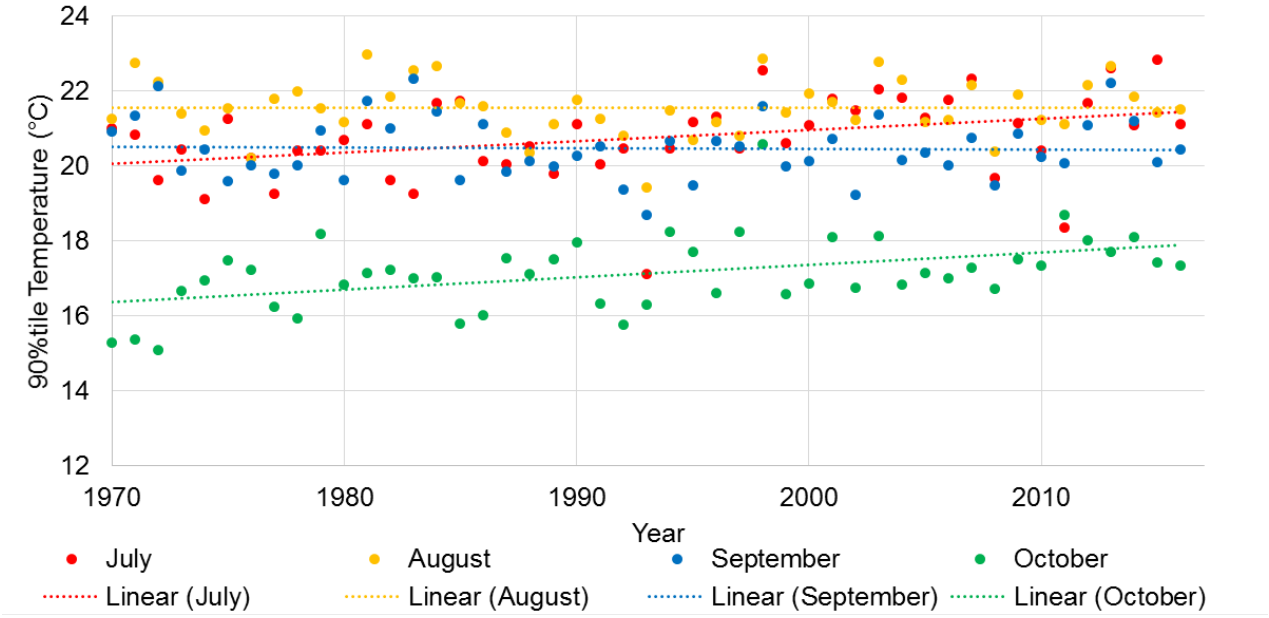


Figure 3-48 Simulated monthly 90th percentile temperatures at Ice Harbor Dam (Current)

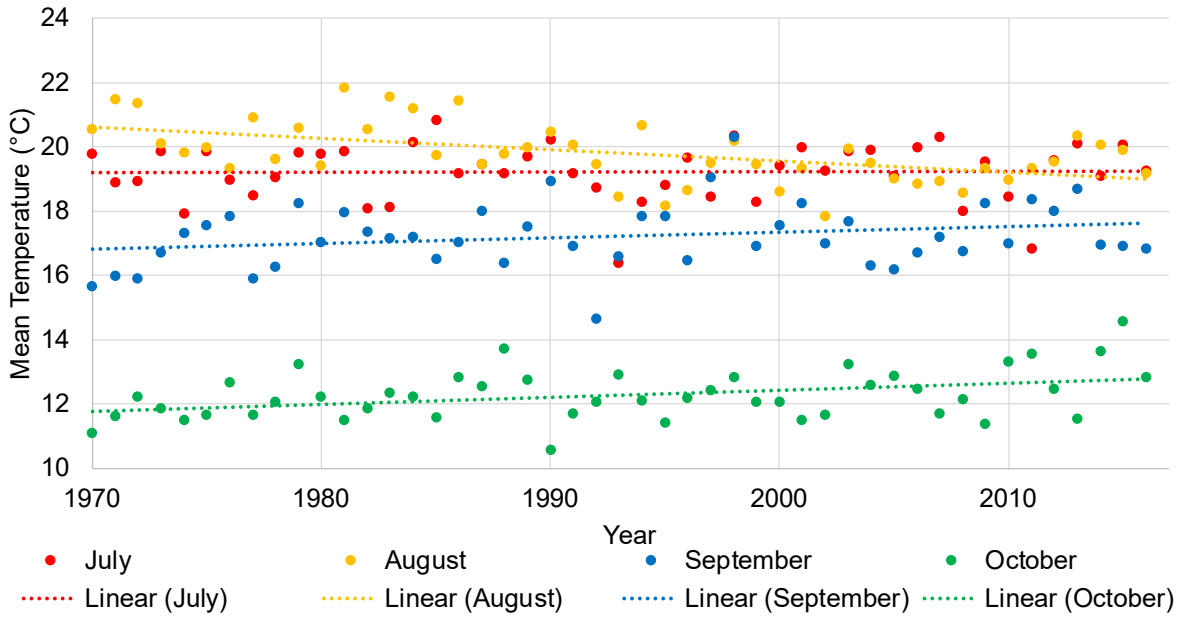


Figure 3-49 Simulated monthly mean temperatures at Ice Harbor Dam (Free-Flowing)

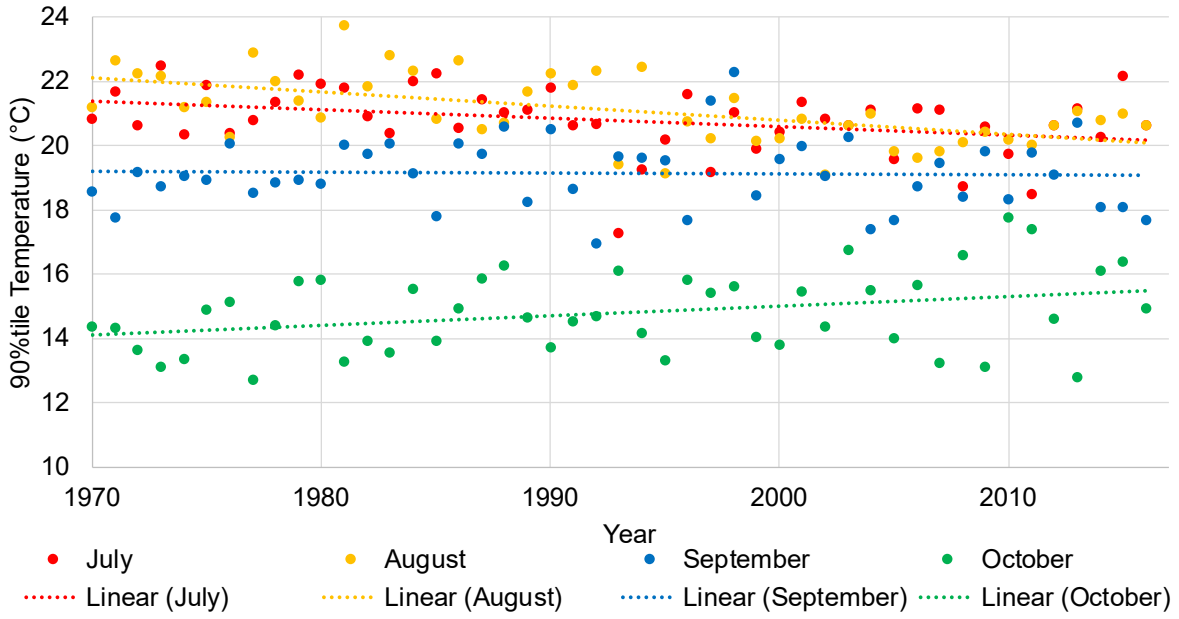


Figure 3-50 Simulated monthly 90th percentile temperatures at Ice Harbor Dam (Free-Flowing)

Table 3-19 Current conditions 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[1]	0.0057	0.441	0.0000	0.9854
September[1]	0.0092	0.1897	0.0025	0.8258
October	0.0393	<0.0000	0.0363	0.0008

[1] Month without trend (p-value>0.05).

Table 3-20 Free-Flowing scenario 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[1]	0.0176	0.1126	-0.0042	0.7482
October	0.0226	0.0151	0.0313	0.0334

[1] Month without trend (p-value>0.05).

Comparison to 1960s Data at Priest Rapids Dam

EPA has also compared recent daily averaged temperature data to historical (1964 – 1969) daily average temperature data on the Columbia River at the Priest Rapids Dam (Leinenbach 2018). EPA took advantage of a unique opportunity to compare relatively high quality historic temperature data from the early 1960s to recent temperatures. The data from the 1960s is important because this decade corresponds to the decade when significant anthropogenic influence on climate is estimated to have begun (EPA 2019b). The historical (1964 – 1969) river temperature data were obtained from a Battelle report (Jaske et al. 1970), and the recent Columbia River temperature 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 (***Figure 3-51***) which is consistent with the temperature trends obtained from the RBM10 model outputs, both in direction and magnitude (See Section 3.5.4).

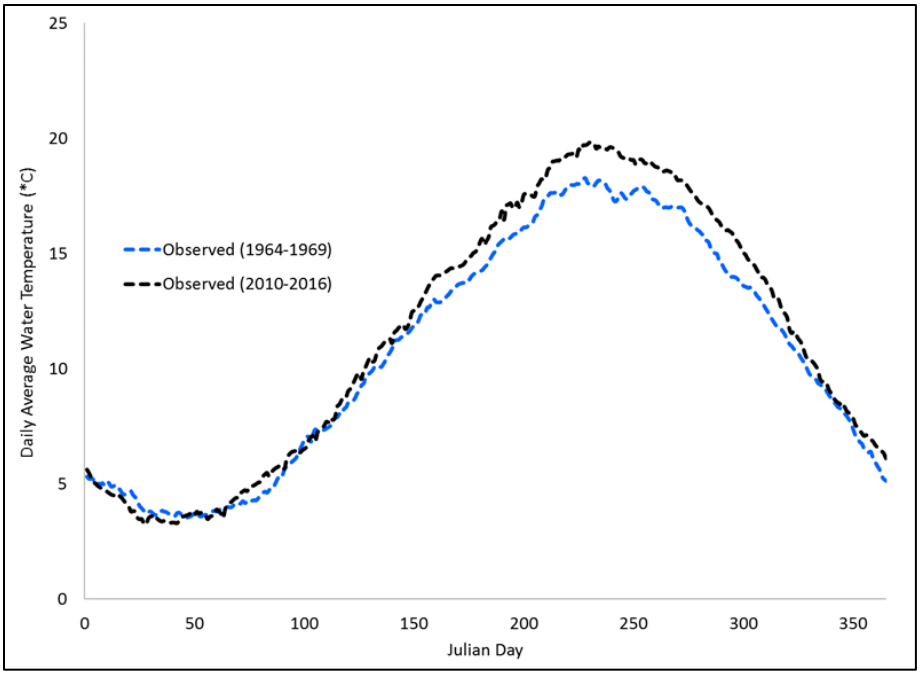


Figure 3-51 Measured Columbia River temperature trends at the Priest Rapids Dam in the 1964 – 1970 and the 2010 – 2016 periods.

RBM10 Current condition 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 3-52*** through ***Figure 3-54***).

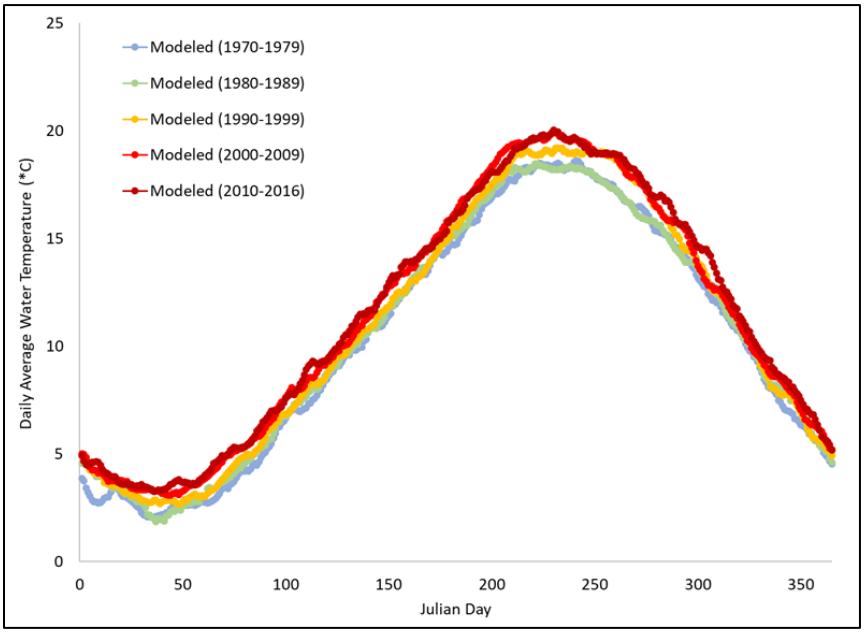


Figure 3-52 RBM10 simulated trends at the Priest Rapids Dam.

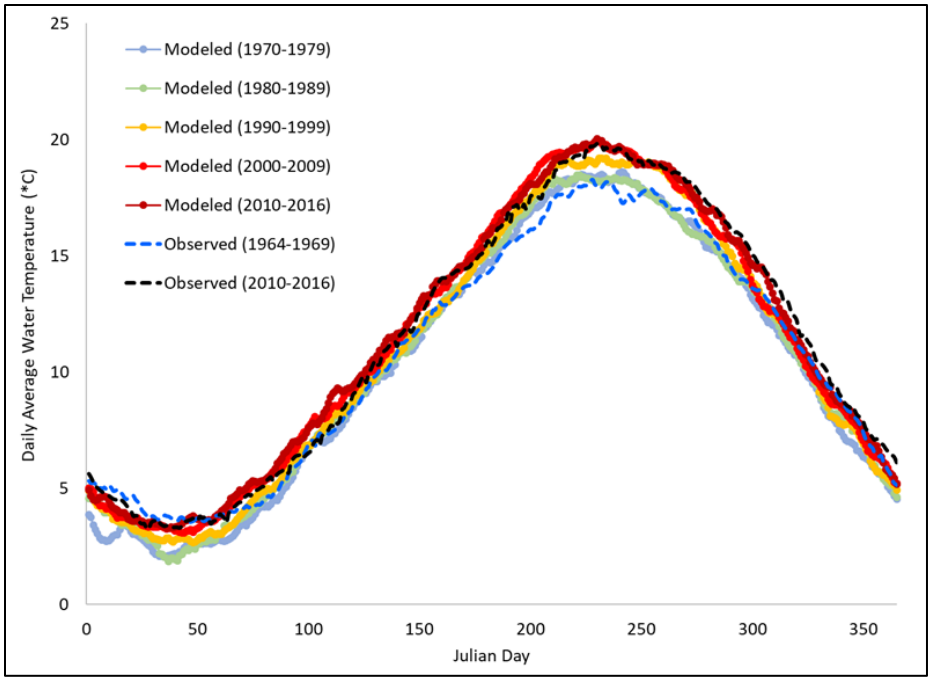


Figure 3-53 Comparison between Current condition simulated and measured trends at the Priest Rapids Dam.

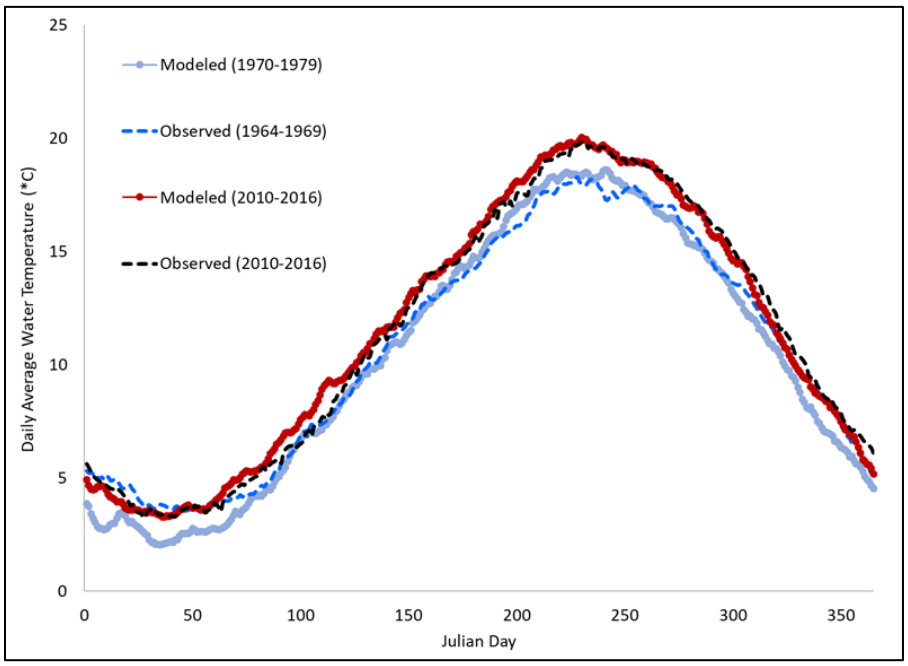
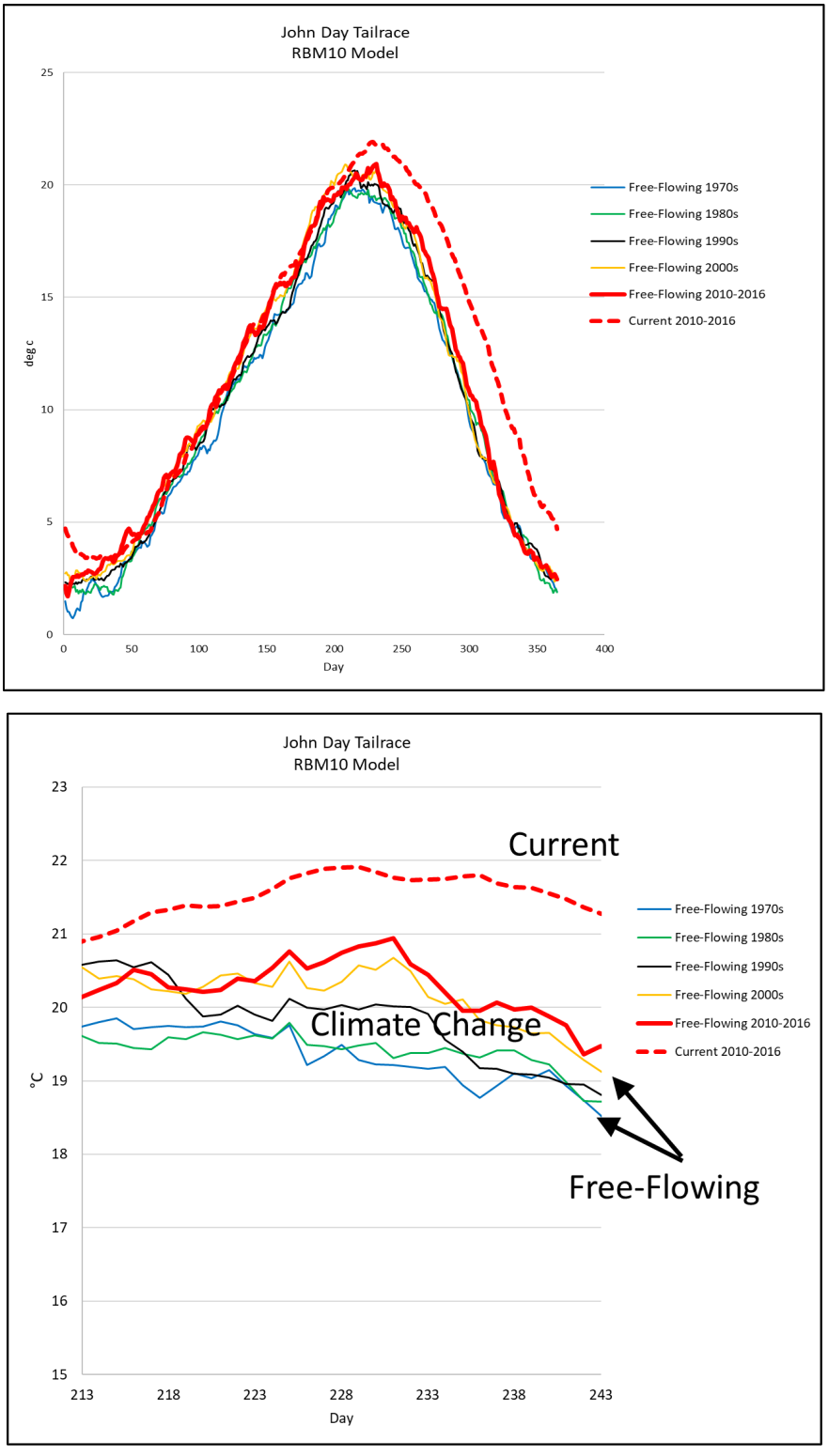


Figure 3-54 Comparison between Current condition simulated and measured trends at the Priest Rapids Dam for periods 2010-2016 and 1960-1979.

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 3-55***. 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 3-55 Simulated decadal average temperatures for free-flowing river (1970-2016) compared to the current impounded conditions (2010-2016).

3.6 TRIBUTARIES (TR1 AND TR2 SCENARIOS)

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 2019 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 3-21***). The table also includes the WQC for the Columbia and Snake river tributaries within the TMDL project area.

Table 3-21 Major tributaries included in the 2019 RBM10 model

Tributary Source	Receiving Waterbody	Water Quality Criterion (°C)
Dworshak Dam[1]	Clearwater River (RM 40)	NA[2]
Clearwater River	Snake River (RM 140)	NA[2]
Tucannon River	Snake River (RM 64)	17.5
Palouse River	Snake River (RM 61)	17.5
Kettle River	Columbia River (RM 706)	16.0
Colville River	Columbia River (RM 699)	17.5
Spokane River	Columbia River (RM 639)	17.5
Okanogan River	Columbia River (RM 533)	17.5
Methow River	Columbia River (RM 524)	17.5
Chelan River	Columbia River (RM 503)	17.5
Entiat River	Columbia River (RM 484)	17.5
Wenatchee River	Columbia River (RM 468)	17.5
Crab Creek	Columbia River (RM 411)	17.5
Yakima River	Columbia River (RM 335)	17.5
Walla Walla River	Columbia River (RM 314)	17.5
Umatilla River	Columbia River (RM 289)	18.0
John Day River	Columbia River (RM 218)	20.0
Deschutes River	Columbia River (RM 204)	18.0
Klickitat River	Columbia River (RM 180)	16.0
Hood River	Columbia River (RM 169)	16.0
Sandy River	Columbia River (RM 121)	18.0
Willamette River	Columbia River (RM 101)	20.0
Lewis River	Columbia River (RM 87)	17.5
Kalama River	Columbia River (RM 73)	17.5
Cowlitz River	Columbia River (RM 68)	17.5

[1] Dworshak Dam is on the North Fork Clearwater River near its confluence with the Clearwater
[2] Tributary outside TMDL project area

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 shown in the model development report (EPA 2019a).

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. The TR1 model scenario uniformly reduces summer/fall temperatures of all major tributaries by 0.5°C below current temperatures to evaluate the cumulative impact of changes in tributary temperatures on the mainstem temperature. The TR2 model scenario caps temperatures of each tributary at its applicable WQC to evaluate the impact related to tributary temperatures exceeding WQC. The temperatures are capped at the values in ***Table 3-21***.

3.6.2 Results

The maximum temperature impact of the 0.5°C tributary change based on the TR1 model simulation is 0.08°C in the Columbia River at River Mile 42 below the confluence with the Cowlitz River in September. For scenario TR2, the maximum improvement when temperatures are capped at the tributary temperature WQC is 0.21°C at River Mile 42 in August. Plots for the TR2 scenario for the month of August are provided in ***Figure 3-56*** and ***Figure 3-57***. The impact of tributaries is higher on the Columbia River than the Snake River because it has larger tributaries.

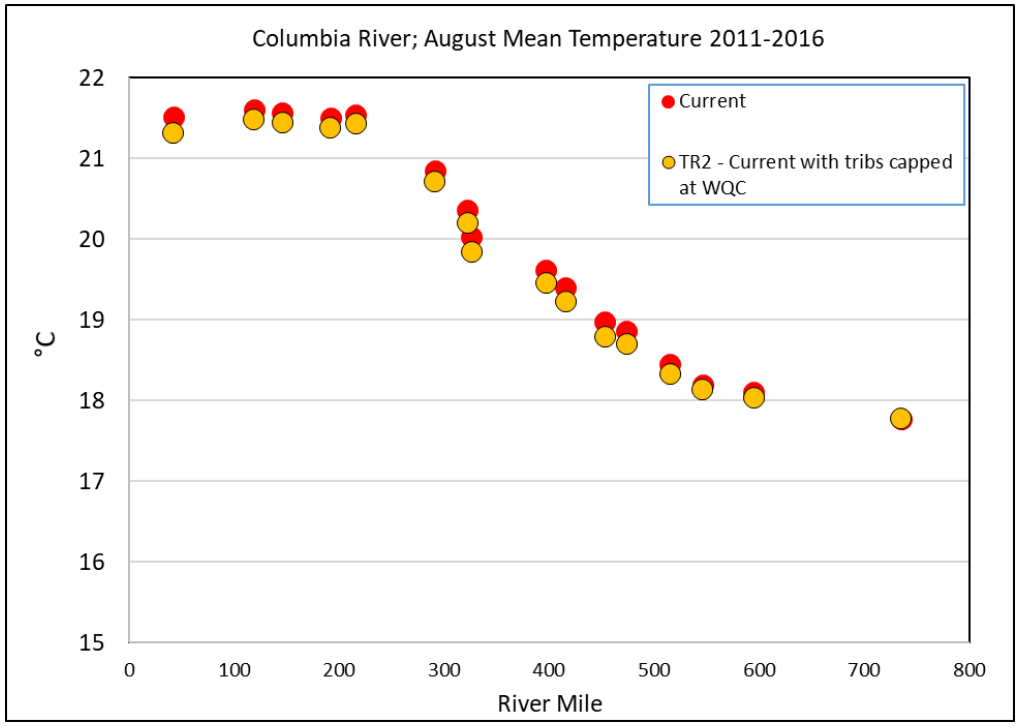


Figure 3-56 Simulated temperatures for Columbia River for TR2 Scenario – August

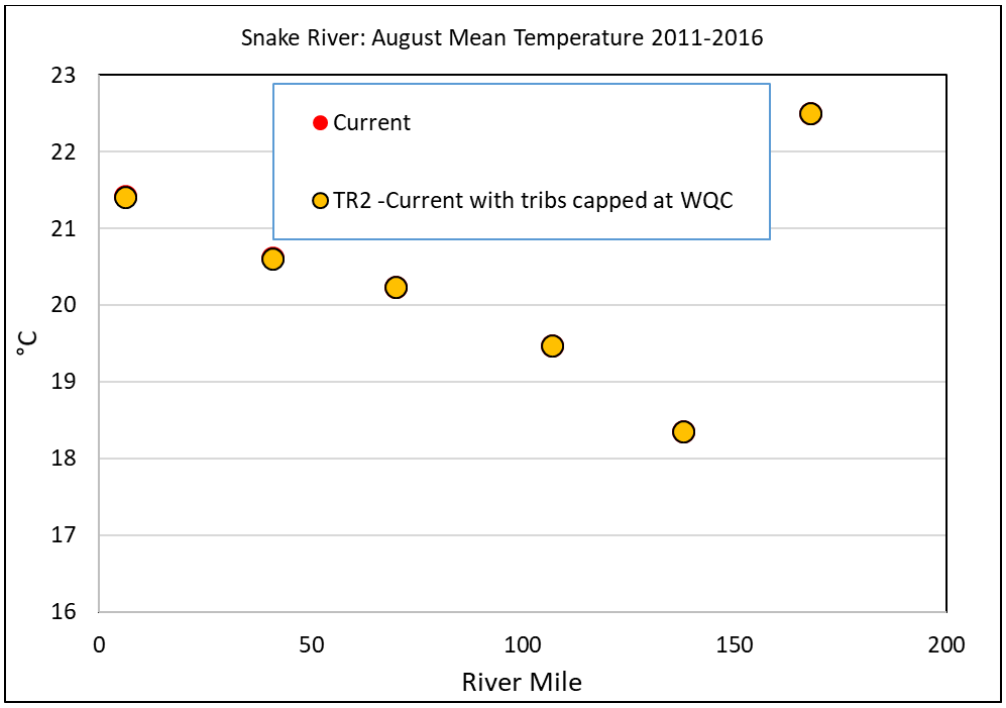


Figure 3-57 Simulated temperatures for Snake River for TR2 Scenario – August

3.7 BOUNDARY CONDITIONS (BC1 AND BC2 SCENARIOS)

Summer water temperatures at the upstream boundaries of the TMDL study area are higher than Washington WQC. 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 – October).

3.7.2 Results

Monthly mean temperatures for scenarios BC1 and BC2 are plotted alongside the Current and Free-Flowing conditions in ***Figure 3-58*** through ***Figure 3-63***. Under the BC1 scenario, ***Figure 3-58*** through ***Figure 3-60*** illustrate that the benefits of cooler temperatures at the Canadian border are short-lived and have largely dissipated when the Columbia River flows past Grand

Coulee tailrace; the tailrace temperatures are similar to Current conditions. In the BC2 scenario, 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 temperatures compared to the Current condition model, 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 simulated BC1 and Current temperatures are closer together at each dam moving downstream.

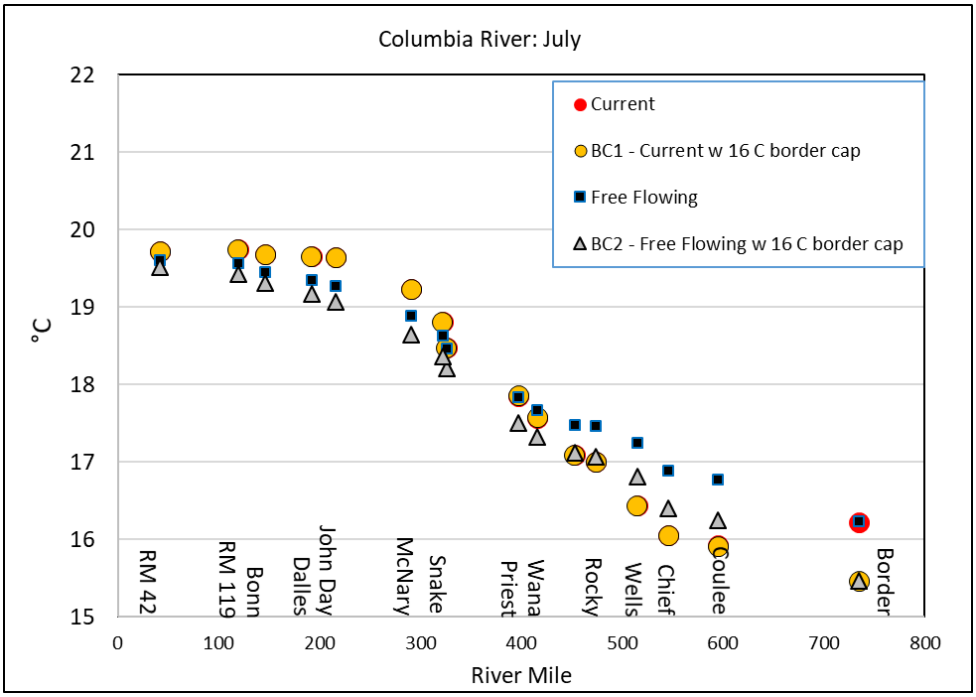


Figure 3-58 Simulated temperatures for Columbia River with reduced upstream boundary temperature – July

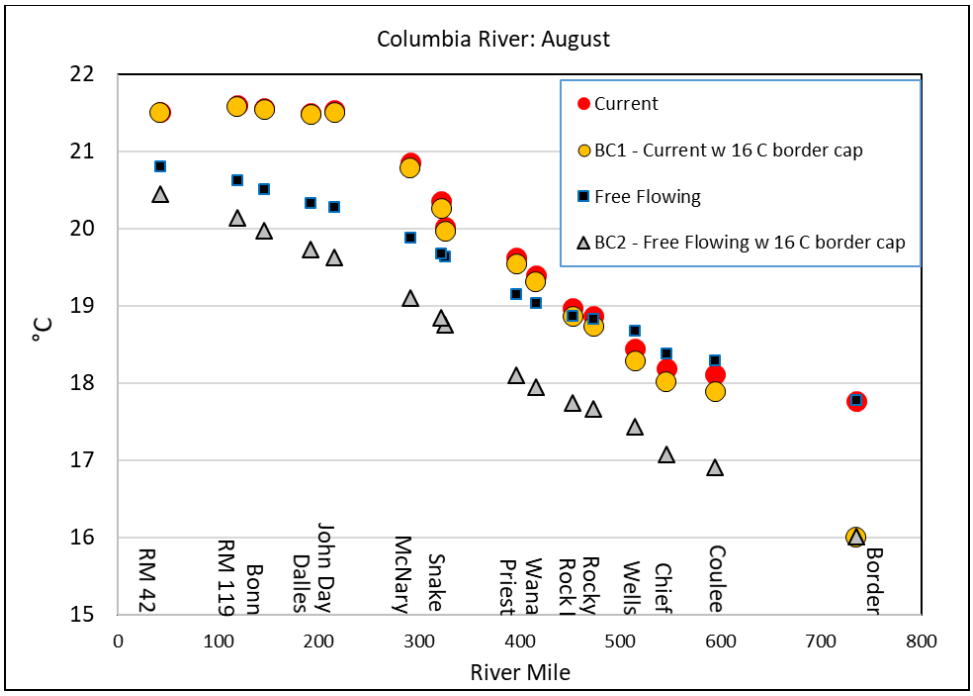


Figure 3-59 Simulated temperatures for Columbia River with reduced upstream boundary temperature – August

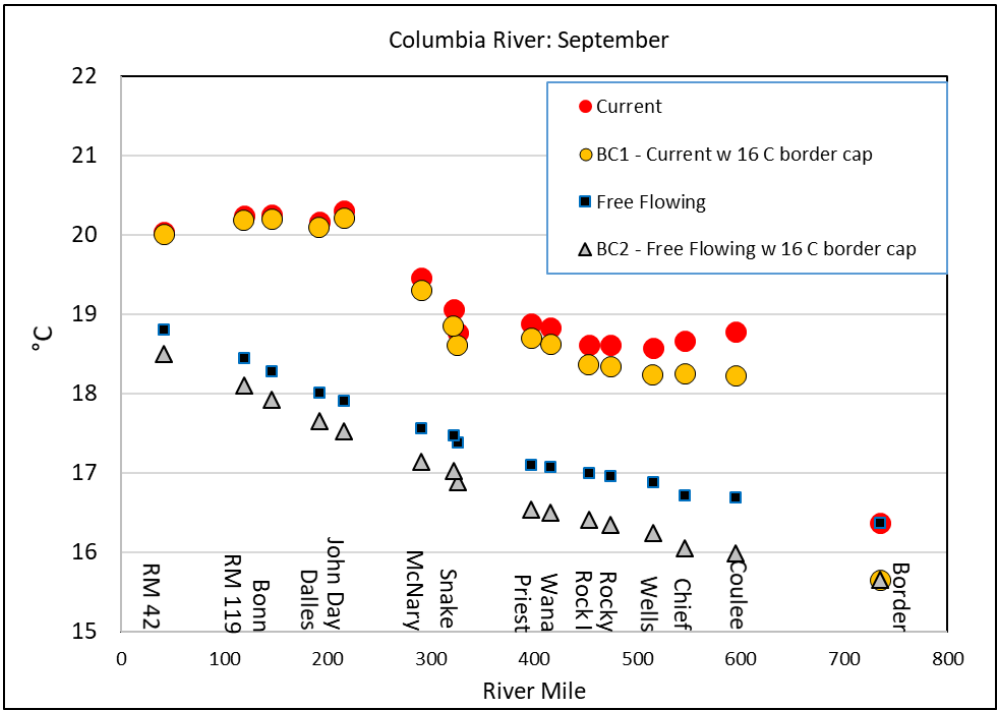


Figure 3-60 Simulated temperatures for Columbia River with reduced upstream boundary temperature – September

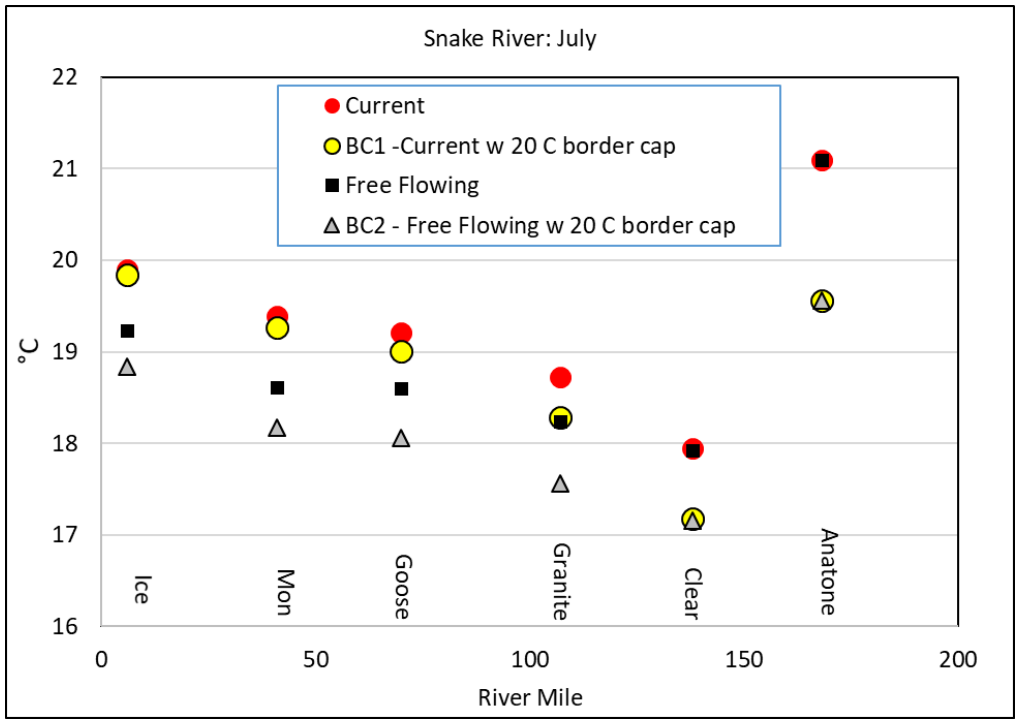


Figure 3-61 Simulated temperatures for Snake River with reduced upstream boundary temperature – July

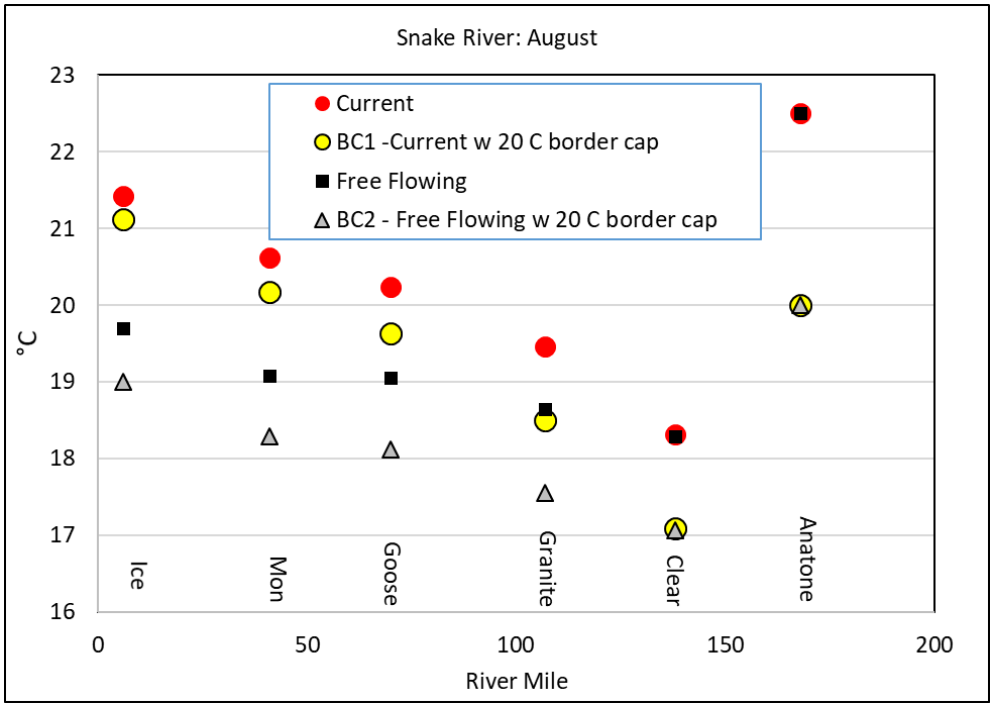


Figure 3-62 Simulated temperatures for Snake River with reduced upstream boundary temperature – August

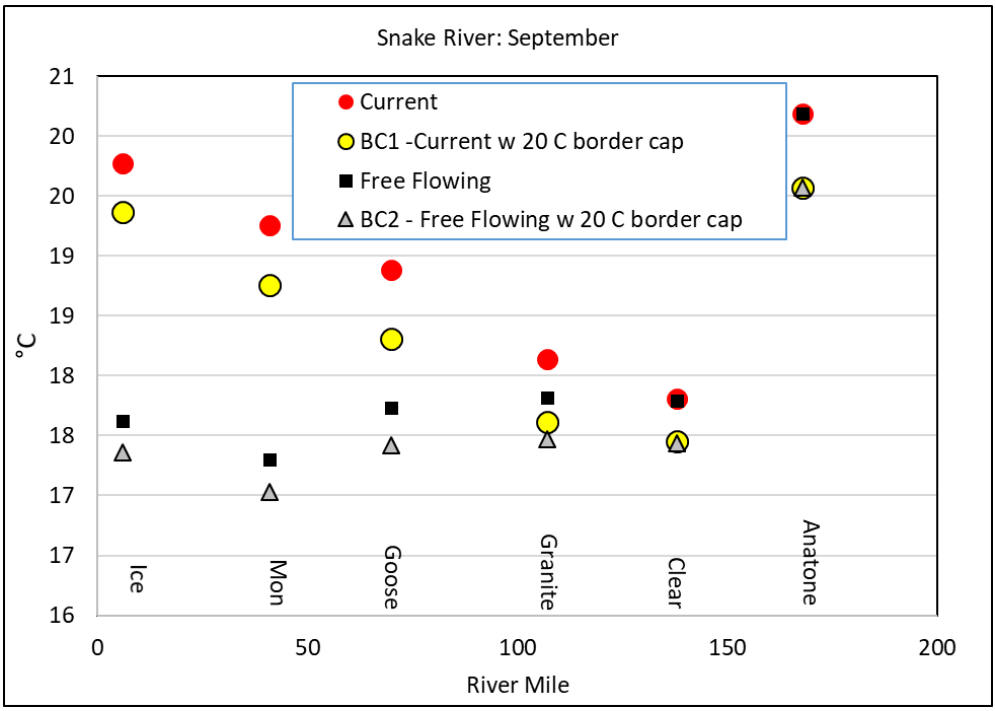


Figure 3-63 Simulated temperatures for Snake River with reduced upstream boundary temperature – September

3.8 NPDES 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 discharges. 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. Because of the large number of minor NPDES facilities, it is necessary to aggregate these sources into a single gross input of heat at the midpoint of the TMDL reach into which they discharge. It is noted that 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 major industrial facilities.

The potential impact of stormwater is assessed separately through screening calculations described at the end of this section.

3.8.1 Methodology and Assumptions

There are 31 major point sources included as individual model inputs of flow and temperature, with 29 sources on the Columbia River and two on Snake River (***Table 3-22***). There are 89 minor point sources included on the Columbia River and 6 minor point sources on the Snake River that were included in the modeling. 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. For facilities lacking effluent temperature data, EPA used temperatures representative of the industry sector to estimate heat loads (***Table 3-23*** and ***Table 3-24***).

Table 3-22 Major facility point sources located on the Columbia River

Facility Name	Permit Number	Location (RM)	Flow (MGD)	Temp (°C)	Heat Load (kcal/day)
Wenatchee	WA0023949	466.6	5.5	26.2	5.44E+08
E Wenatchee Sewage Treatment Plant (STP)	WA0020621	465.7	3.0	26.2	2.97E+08
Alcoa Wenatchee	WA0000680	455.2	5.5	25.6	5.31E+08
Columbia Generating Sta / Energy Northwest	WA0025151	351.8	9.4	35.9	1.27E+09
Richland STP	WA0020419	337.1	11.4	29.4	1.27E+09
Kennewick Publicly-Owned Treatment Plant (POTW)	WA0044784	328.0	12.2	27.0	1.24E+09
Pasco	WA0044962	327.6	10.8	27.3	1.11E+09
Agrium Hedges	WA0003699	323.3	0.03	17.2	1.95E+06
Agrium Kennewick	WA0003671	322.6	22.6	23.1	1.97E+09
Agrium Finley	WA0003727	321.5	14.0	27.2	1.44E+09
Packaging Corporation of America	WA0003697	316.0	28.2	37.1	3.95E+09
The Dalles STP	OR0020885	186.5	4.2	27.0	4.23E+08
Hydro Extrusion USA, LLC	OR0001708	186.0	6.0	34.0	7.70E+08
Hood River OR STP	OR0020788	165.0	2.0	25.7	1.94E+08
Georgia Pacific / GP Consumer Operations LLC	WA0000256	120.0	76.0	37.7	1.08E+10
Gresham OR Waste Water Treatment Plant (WWTP)	OR0026131	117.5	15.0	23.9	1.35E+09
Marine Park / Vancouver Marine Park Reclamation Facility	WA0024368	109.5	16.1	25.1	1.53E+09
Vancouver Westside STP	WA0024350	105.0	28.3	26.0	2.78E+09
Salmon Creek STP	WA0023639	103.2	17.0	23.3	1.50E+09
Portland STP OR	OR0026905	102.5	130.0	24.9	1.22E+10
Boise/St Helens OR STP	OR0020834	86.0	12.7	28.5	1.37E+09
Dyno Nobel Inc.	OR0001635	82.0	24.6	34.0	3.16E+09
Emerald Kalama Chemical	WA0000281	74.0	15.0	34.7	1.97E+09
Steelscape, Inc.	WA0040851	72.2	0.2	35.0	2.38E+07
Westrock Longview	WA0000078	67.4	57.0	38.4	8.28E+09
Three Rivers Regional	WA0037788	66.0	26.0	32.5	3.19E+09
Nippon Dynawave Packaging Corporation	WA0000124	64.0	79.6	45.0	1.35E+10
Millenium Bulk Terminals	WA0000086	63.0	6.6	28.9	7.25E+08
Port of St. Helens	OR0034231	53.0	3.3	32.0	3.99E+08
GP Wauna OR Mill	OR0000795	42.0	39.6	35.4	5.29E+09
Astoria OR STP	OR0027561	18.0	6.2	25.0	5.85E+08

Table 3-23 Minor facility point sources located on the Columbia River

Facility Name	Permit Number	Location (RM)	Flow (MGD)	Temp (°C)	Heat Load (kcal/day)
Avista – Kettle Falls	WA0045217	702.4	0.34	32.2	4.12E+07
Coulee Dam Electric Facility (WA)	WA0026867	596	178.0	16.8	1.13E+10
Grand Coulee WWTP	WA0044857	596.6	0.3	24.1	2.73E+07
City of Coulee Dam	WA0020281	596.0	0.5	23.9	4.51E+07
Interior, Reclamation	WA0024163	596.0	0.018	24.7	1.68E+06
Colville Confederated Tribes	WAG130016	580.0	4.86	25.4	4.65E+08
Confederated Tribes of the Colville Reservation	WAG130025	580.0	25.4	25.4	2.43E+09
Chief Joseph Dam	EPA	545	92.5	18.2	6.36E+09
Chelan Fruit Cooperative Pateros South Plant	WAG435265	--	0.2	18.8	1.42E+07
Well Fish Hatchery	WAG135009	--	36.2	17.7	2.42E+09
Bridgeport STP	WA0024066	543.7	0.36	24.2	3.33E+07
Brewster	WA0021008	529.8	0.61	26.0	5.99E+07
Pateros STP	WA0020559	524.1	0.10	24.0	8.91E+06
Wells Dam	WA0991031	515.5	28.5	35.4	3.81E+09
Chelan Fruit Cooperative Beebe Plant	WAG435270	--	0.2	23.7	1.79E+07
Chelan POTW	WA0020605	503.5	2.6	25.0	2.49E+08
Entiat STP	WA0051276	485.0	0.15	26.0	1.47E+07
Rocky Reach Dam	WA0991033	473.5	17.6	21.3	1.42E+09
Stemlit Growers Euclid	WAG435172	--	0.1	26.1	9.87E+06
Stemlit Growers Olds Station 2	WAG435157	--	0.1	21.3	8.05E+06
Eastbank Hatchery	WAG135011	--	27.1	16.8	1.78E+09
Chelan Hatchery	WAG135006	--	6.7	16.8	4.25E+08
Tree Top Inc Wenatchee	WA0051527	470.8	0.18	26.6	7.03E+07
Naumes Processing / Keyes Fibre Corp	WA0051811	470.5	1.4	24.7	1.32E+08
Lineage Logistics	WA0052400	466.8	1.9	24.7	1.74E+08
KB Alloys/ AMG Al North Amer.	WA0002976	458.5	0.3	40.0	4.53E+07
Specialty Chemical	WA0002861	456.3	0.35	16.1	2.13E+07
Rock Island Dam	WA0501487	455.9	0.34	20.5	2.62E+07
Rock Island Dam	WA0991032	453.5	14.1	22.8	1.21E+09
Crescent Bart WWTP	WA0991013	440	0.16	23.9	1.48E+07
Vantage STP	WA0050474	420.6	0.09	26.1	8.57E+06
Wanapum Dam	WA0991028	416	17.8	18.1	1.22E+09
Priest Rapids Dam	WA0991029	397	15.9	20.5	1.23E+09
Twin City Foods Kennewick	WA0021768	328.3	0.01	24.4	7.37E+05
Agrium Bowles Road	WA0003671	322.6	15.0	30.8	1.74E+09
Agrium Game Farm Road	WA0003727	321.0	14.1	27.2	1.45E+09

Facility Name	Permit Number	Location (RM)	Flow (MGD)	Temp (°C)	Heat Load (kcal/day)
Sanvik Metals	WA0003701	321.0	0.24	37.8	3.45E+07
McNary Lock and Dam (WA)	WA0026824	291	0.9	19.7	6.70E+07
McNary Dam (OR)	ODEQ	291	15.9	22.0	1.32E+09
Richland Water Treatment Plant	WAG645000	--	0.8	23.9	7.23E+07
Umatilla STP	OR0022306	285.0	1.1	26.1	1.08E+08
Oregon Fish and Wildlife	ORG137011	275	7.1	17.5	4.71E+08
Oregon Fish and Wildlife	ORG137017	275	18.1	16.6	1.13E+09
Arlington STP	OR0020192	238.0	0.13	25.0	1.18E+07
Goldendale	WA0021121	216.7	2.4	23.3	2.11E+08
John Day Project (WA)	WA0026832	214	52.0	19.3	3.79E+09
John Day Dam (OR)	ODEQ	214	100.0	22.6	8.53E+09
Biggs OR WWTP	OR0041246	205.5	0.039	26.1	3.79E+06
Wishram POTW	WA0051292	200.9	0.10	23.9	8.75E+06
The Dalles Dam (WA)	WA0026701	190	56.0	20.0	4.23E+09
Underwood Fruit & Warehouse	WAG435043	--	0.0014	12.7	6.72E+04
Dalles/Oregon Cherry OR	OR0000736	189.5	0.74	23.0	6.43E+07
Lyle POTW	WA0050482	183.2	0.098	23.9	8.84E+06
Mosier OR	OR0028045	174.5	0.085	25.6	8.22E+06
SDS Lumber	WA0051152	170.2	25.0	29.4	2.78E+09
Bingen STP	WA0022373	170.2	0.8	24.0	7.25E+07
Spring Crk Natl Fish Hatchery	WAG130006	165.0	5.1	16.8	3.25E+08
Cascade Locks OR STP	OR0041271	148.2	0.49	28.0	5.21E+07
Stevenson STP	WA0020672	150.0	0.45	27.4	4.66E+07
Oregon Fish and Wildlife	ORG130001	143	32.0	15.5	1.87E+09
Tanner Cr Wastewater Treatment Plant – USACE	OR0022624	146.1	0.1	22.0	8.31E+06
North Bonneville STP	WA0023388	144.0	0.25	20.1	1.90E+07
Bonneville Dam (OR)	OR0034355	141.5	0.86	23.6	7.70E+07
Bonneville Project (WA)	WA0026778	141.5	26.0	21.1	2.07E+09
Multnomah Falls OR Lodge STP	OR0040410	135.9	0.5	31.6	5.97E+07
Exterior Wood, Inc. / Taiga Building Products USA	WA0040711	123.8	0.5	24.7	4.66E+07
Washougal STP	WA0037427	123.5	2.2	24.1	2.04E+08
Camas STP	WA0020249	121.2	6.1	25.5	5.87E+08
Toyo Tanso USA OR	OR0034916	118.1	0.2	25.3	1.91E+07
Port of Portland	OR0000060	116.9	3.0	20.0	2.27E+08
Knife River Corporation - NW	OR0044652	116.7	9.0	25.0	8.50E+08
Sundial Marine Construction & Repair, Inc.	OR0044601	116.7	0.022	24.7	2.01E+06
Portland Water Bureau	OR0031135	115.0	4.2	20.0	3.13E+08

Facility Name	Permit Number	Location (RM)	Flow (MGD)	Temp (°C)	Heat Load (kcal/day)
River Road Generating Plant	WA0040932	105	0.7	38.5	9.45E+07
Columbia River Carbonates	WA0039721	83.5	0.31	14.1	1.67E+07
Kalama STP	WA0020320	75.0	0.8	23.9	7.22E+07
Port of Kalama	WA0040843	72.2	0.02	24.7	1.86E+06
Riverwood OR Mobile Home Park / Magar E Mager	OR0031143	70.6	0.013	24.0	1.18E+06
Rainier OR STP	OR0020389	67.0	1.0	25.0	9.35E+07
Stella STP	WA0039152	56.4	0.0035	23.9	3.16E+05
PGE Beaver OR	OR0027430	53.0	1.4	35.0	1.90E+08
Cathlamet STP	WA0022667	32.0	0.38	24.0	3.47E+07
Bio-Oregon Protein	OR0000612	10.8	0.52	28.0	5.50E+07
Pacific Surimi Co., Inc.	OR0034657	10.0	0.38	24.7	3.54E+07
Fort Columbia State Park	WA0038709	10.0	0.005	20.5	3.87E+05
Point Adams Packing Co. / California Shellfish Co.	OR0000868	6.6	0.68	12.8	3.31E+07
Bell Buoy Crab Co. (Now South Bend Products)	WA0000159	6.0	0.2	18.4	1.39E+07
Ilwaco STP	WA0023159	2.0	1.0	23.0	8.77E+07
Jessies Ilwaco Fish Co.	WA0000361	2.0	0.75	18.3	5.18E+07

Table 3-24 Minor facility point sources located on the lower Snake River

Facility Name	Permit Number	Location (RM)	Flow (MGD)	Temp (°C)	Heat Load (kcal/day)
Clarkston STP	WA0021113	138.0	2.2	27.4	2.28E+08
Lower Granite Dam and Locks (WA)	WA0026794	106	29.0	20.2	2.21E+09
Little Goose Lock and Dam (WA)	WA0026786	69	40.1	19.4	2.94E+09
Lyon's Ferry (hatchery)	WAG137006	59.1	91.9	16.8	5.84E+09
Lower Monumental Lock and Dam (WA)	WA0026808	41	27.8	17.1	1.80E+09
Ice Harbor Lock and Dam (WA)	WA0026816	9	39.8	21.4	3.22E+09

There are no major NPDES facilities on the lower Snake River within the TMDL study area. Two major facilities are located just upstream of the TMDL study area: Clearwater Paper and the City of Lewiston. One minor facility, the City of Asotin, is also located upstream. For estimating point source impacts, loading assumptions for these facilities are included in the PS1 model scenario (***Table 3-25***).

Table 3-25 Modeled point sources located outside TMDL study area

Facility Name	Permit Number	Location RM	Flow (MGD)	Temp (°C)
Clearwater Paper	ID0001163	139.3	44.7	33.0
City of Lewiston	ID0022055	140.1	5.7	23.6
City of Asotin	WA0020818	145.0	0.16	23.8

The initial model scenario for the existing NPDES facilities estimated a maximum temperature impact of approximately 0.09°C at the critical location (RM 42). EPA estimated a reserve loading to bring the impact to 0.1°C. To calculate the reserve loading, EPA inserted a heat load in the model at the midpoint of each TMDL reach in addition to the heat loads from all existing NPDES facilities. EPA then ran the model iteratively, increasing the reserve heat load until the maximum impact equaled 0.1°C. The resulting reserve load for each reach is 4.4×10^9 kcal/day. This loading is similar to the heat load discharged by the largest individual point sources in the study area.

3.8.2 Results

The cumulative impact of the point sources and the reserve loading in the summer is a 90th percentile temperature increase of 0.1°C, and this impact occurs in September at RM 42 of the Columbia River. The maximum impact on the Snake River is a 90th percentile impact of 0.09°C and it occurs in September at Lower Monumental Dam. ***Table 3-26*** and ***Table 3-27*** show the mean and 90th percentile impacts at each location and time frame. October results are provided for the Columbia River (Bonneville location) where a fall spawning WQC is applicable.

Table 3-26 Estimated impacts of point sources and reserve loading to Columbia River (2011 – 2016)

		Estimated Increase in Temperature (°C)							
		Mean				90th Percentile			
Location	RM	July	Aug	Sept	Oct	July	Aug	Sept	Oct
G. Coulee	595	0.00	0.00	0.00	NA	0.01	0.00	0.01	NA
Chief Jos.	546	0.01	0.01	0.01	NA	0.02	0.01	0.02	NA
Wells	515	0.02	0.01	0.02	NA	0.03	0.02	0.04	NA
Rocky R.	474	0.02	0.02	0.03	NA	0.03	0.03	0.04	NA
Rock I.	453	0.02	0.03	0.03	NA	0.04	0.04	0.06	NA
Wanapum	416	0.03	0.03	0.04	NA	0.04	0.04	0.06	NA
Priest R.	397	0.03	0.03	0.05	NA	0.04	0.04	0.06	NA
McNary	291	0.04	0.04	0.06	NA	0.05	0.05	0.07	NA
John Day	216	0.04	0.03	0.04	NA	0.04	0.04	0.05	NA
Dalles	192	0.04	0.03	0.04	NA	0.04	0.04	0.05	NA
Bonneville	146	0.04	0.03	0.04	0.06	0.04	0.04	0.05	0.07
RM 42	42	0.06	0.06	0.08	NA	0.07	0.07	0.10	NA

Table 3-27 Estimated impacts of point sources and reserve loading to Snake River (2011 – 2016)

		Estimated Increase in Temperature (°C)					
		Mean			90th Percentile		
Location	RM	July	Aug	Sept	July	Aug	Sept
L. Granite	107	0.03	0.05	0.06	0.05	0.06	0.08
Little Goose	70	0.04	0.05	0.06	0.05	0.06	0.08
Lower Mon	41	0.04	0.05	0.07	0.06	0.06	0.09
Ice Harbor	6	0.05	0.05	0.07	0.06	0.06	0.08

3.8.3 Stormwater Assessment

It was not feasible to use RBM10 to estimate the potential impacts of stormwater discharges, because minimal data is available on flow or temperature of stormwater discharges. EPA designed the stormwater temperature impact analysis on a 1999 study that modeled the thermal enrichment of streams due to stormwater runoff in Ontario, Canada (James & Xie, 1999), where estimated runoff flow (Q_{RO}) and temperature (T_{RO}) are dependent on depth of rainfall (P), area of runoff (A), and air temperature (T_A). James and Xie (1999) estimated a linear relationship between (wet) pavement temperature (T_P) and runoff temperature.

$$T_{RO} = 3.26 + 0.828T_P$$

Through field measurements, they also showed that pavement temperatures are consistently 8 to 9°C higher than air temperatures during both rainy and dry periods. To be conservative, EPA assumed a 9°C difference and used this equation to estimate runoff temperature based on air temperature:

$$T_{RO} = 3.26+0.828(T_A+9)$$

The degree to which Columbia and Snake river temperature may be affected by stormwater runoff depends on the flow (Q_R) and temperature of the river (T_R) at the point where runoff enters the river. EPA assumed all runoff within a given river reach (between dams and major confluences) enters the river as a single point source at the beginning of the reach.

Based on the results of James and Xie, EPA derived the following equation to calculate the change in river temperature (ΔT_R):

$$\Delta T_R = \frac{Q_{RO}}{Q_R}(T_{RO} - T_R) = \frac{\sum_{i=1}^{n} A_i P}{Q_R}\Big(\big(3.26 + 0.828(T_A + 9)\big) - T_R\Big),$$

where n is equal to the number of stormwater discharges into the Columbia and A is the area from which each discharge originates. Estimated temperature increases in each reach based on this method are shown in ***Table 3-28***. EPA completed a supplemental analysis on the two reaches that are the most urbanized: Bonneville Dam to Coast (river mile 140 – 0), and Priest Rapids Dam to Snake River Confluence (river mile 396 – 325). For these reaches, EPA used GIS land cover and hydrologic data to refine the area covered by municipal permits, considering only the effective impervious area that drains directly into the Columbia River. EPA recognizes that some MS4 permitted areas fall outside of city boundaries; for this estimation, however, EPA assumed that permit coverage falls within city boundaries. In both cases, refining the area from which each discharge originates resulted in a smaller temperature impact.

Table 3-28 Estimated maximum temperature impacts of stormwater

		Temperature Increase (°C)	
Reach	**River**	**July**	**August**
Canada to Grand Coulee	Columbia	8.44E-6	7.03E-6
Grand Coulee to Chief Joseph	Columbia	3.70E-5	2.56E-5
Chief Joseph to Wells	Columbia	0	0
Wells to Rocky Reach	Columbia	3.32E-5	5.83E-6
Rocky Reach to Rock Island	Columbia	3.31E-3	2.30E-3
Rock Island to Wanapum	Columbia	0	0
Wanapum to Priest Rapids	Columbia	0	0
Priest Rapids to Snake River	Columbia	2.30E-2 / 6.63E-3[1]	1.56E-2 / 4.49E-3[1]
Snake River to McNary	Columbia	1.92E-5	1.39E-5
McNary to John Day	Columbia	7.95E-5	5.15E-5
John Day to The Dalles	Columbia	8.88E-6	6.46E-6
The Dalles to Bonneville	Columbia	2.06E-4	2.52E-4
Bonneville to Coast	Columbia	4.40E-2 / 9.54E-3[1]	5.41E-2 / 1.17E-2[1]
Clearwater River to Lower Granite	Snake	1.59E-3	1.54E-3
Lower Granite to Little Goose	Snake	2.61E-5	2.53E-5
Little Goose to Lower Monumental	Snake	0	0
Lower Monumental to Ice Harbor	Snake	0	0
Ice Harbor to Columbia River	Snake	2.26E-5	1.81E-5

[1] For two reaches (Priest Rapids to Snake River & Bonneville to Coast), EPA completed a supplemental temperature impact analysis and obtained this result.

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 3-64***. 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 (WD1 scenario). Flow comparisons are shown in ***Figure 3-64*** and ***Figure 3-65***. 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 (***Figure***

3-66 through ***Figure 3-68***). The impact is slightly positive (reduces temperatures) in October. Tabulated impacts by location and month are provided in ***Table 3-29***.

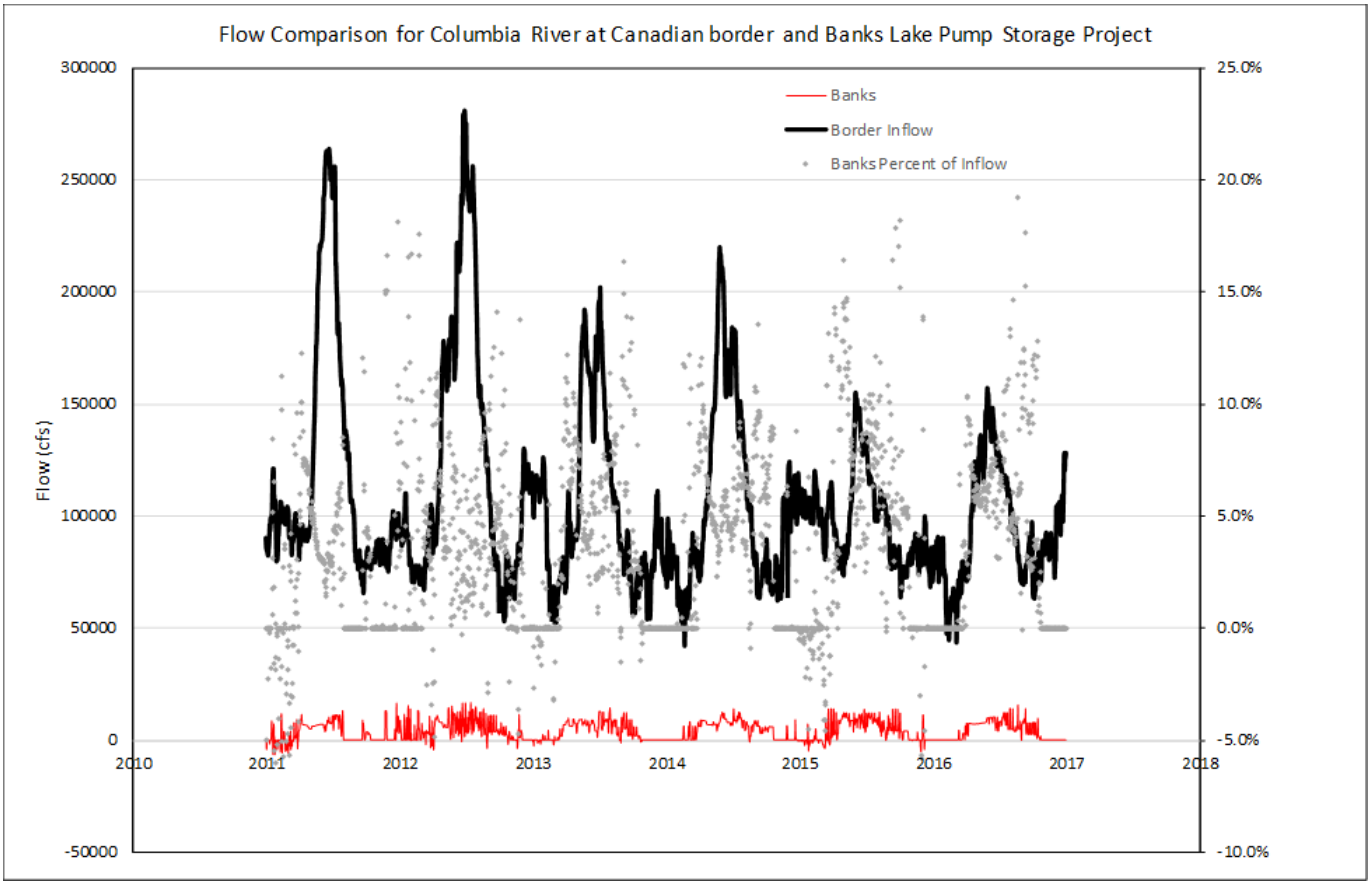


Figure 3-64 Comparison of Banks Lake project flows and Columbia River flows for 2001 – 2016

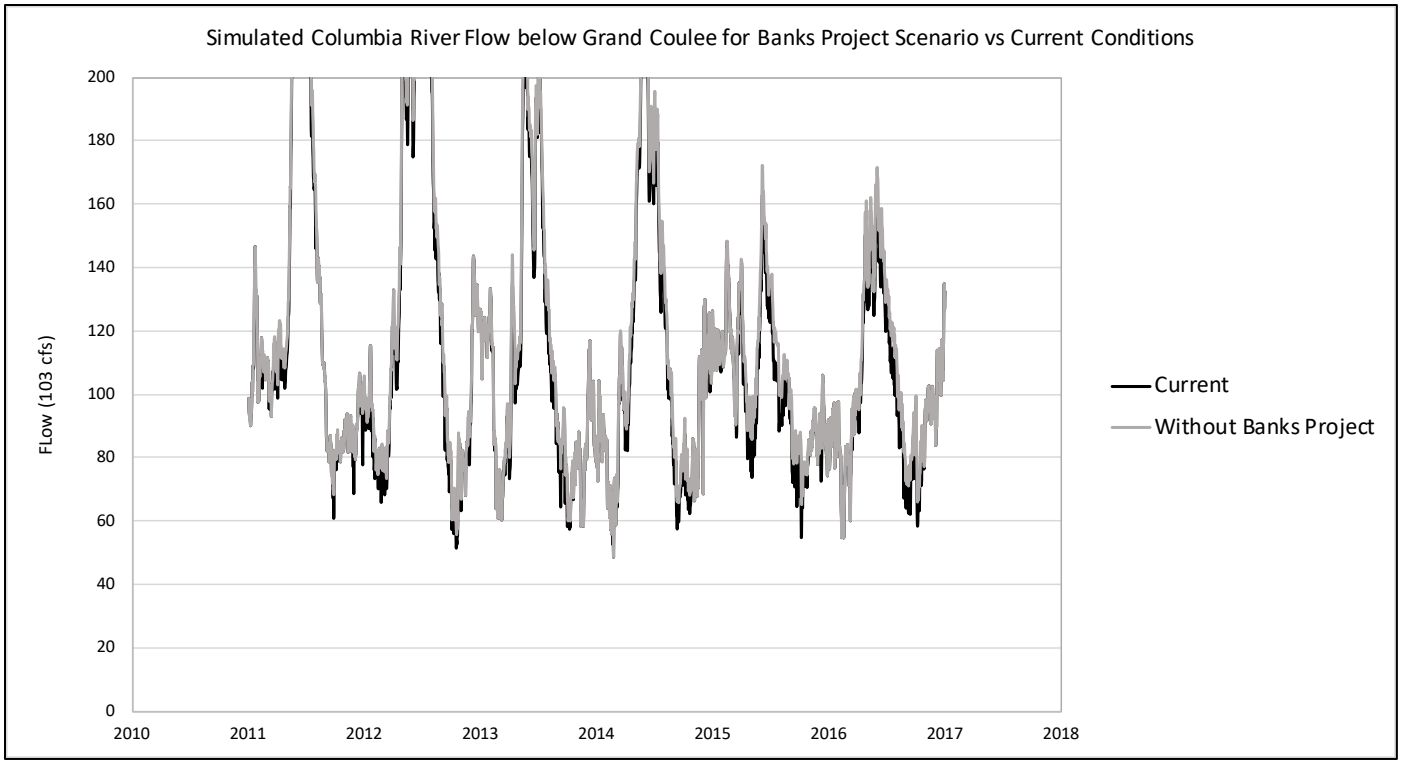


Figure 3-65 Simulated Columbia River flow downstream of Grand Coulee

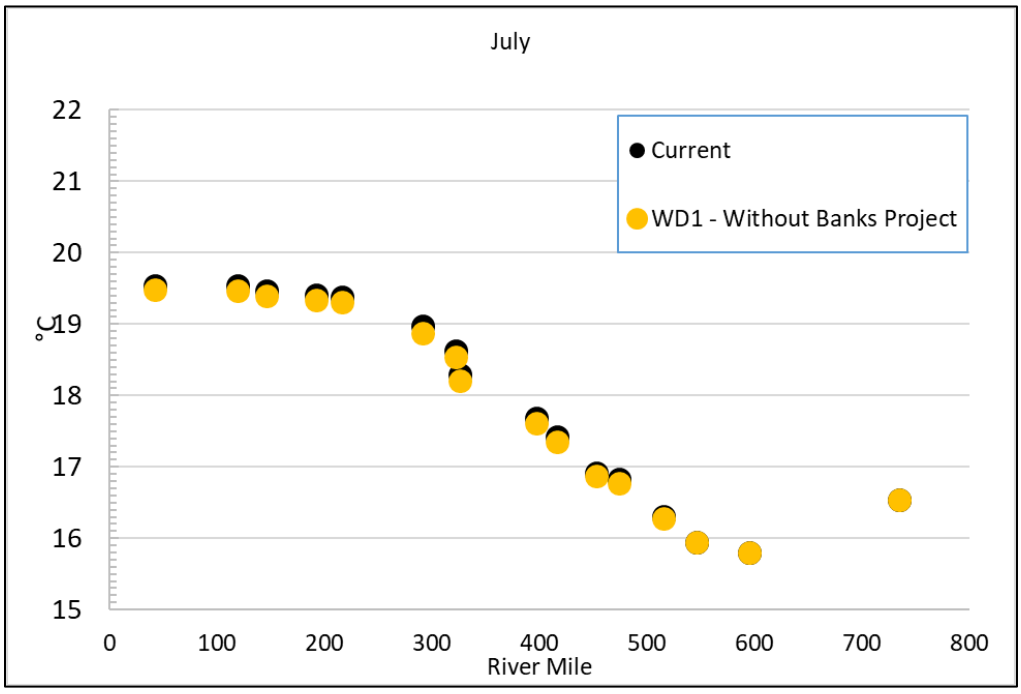


Figure 3-66 Simulated temperatures with and without Banks Lake project flows – July

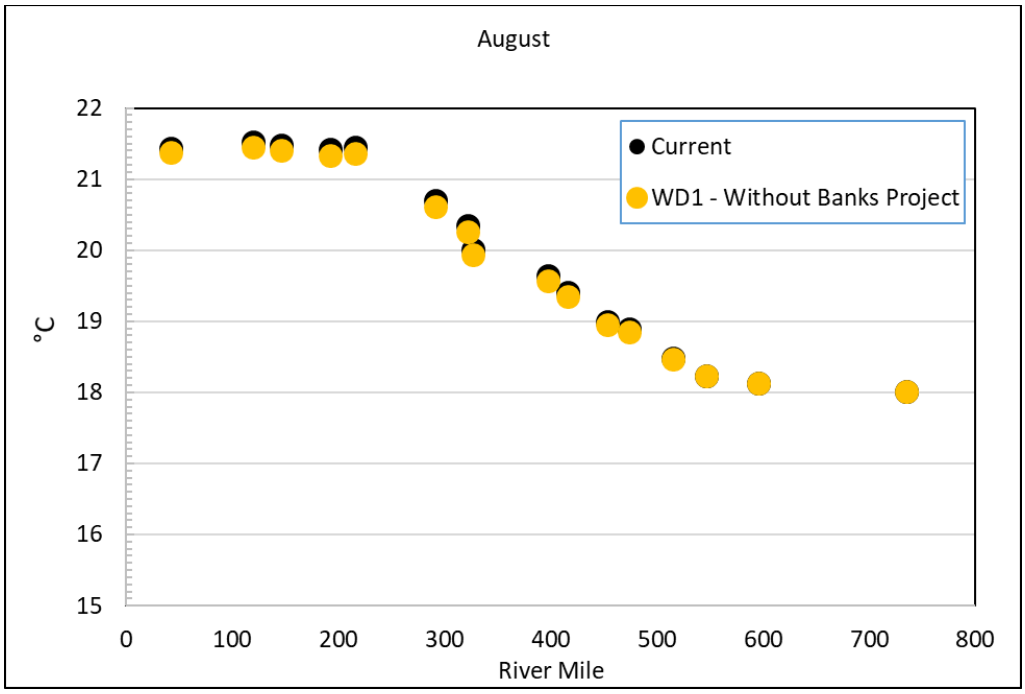


Figure 3-67 Simulated temperatures with and without Banks Lake project flows – August

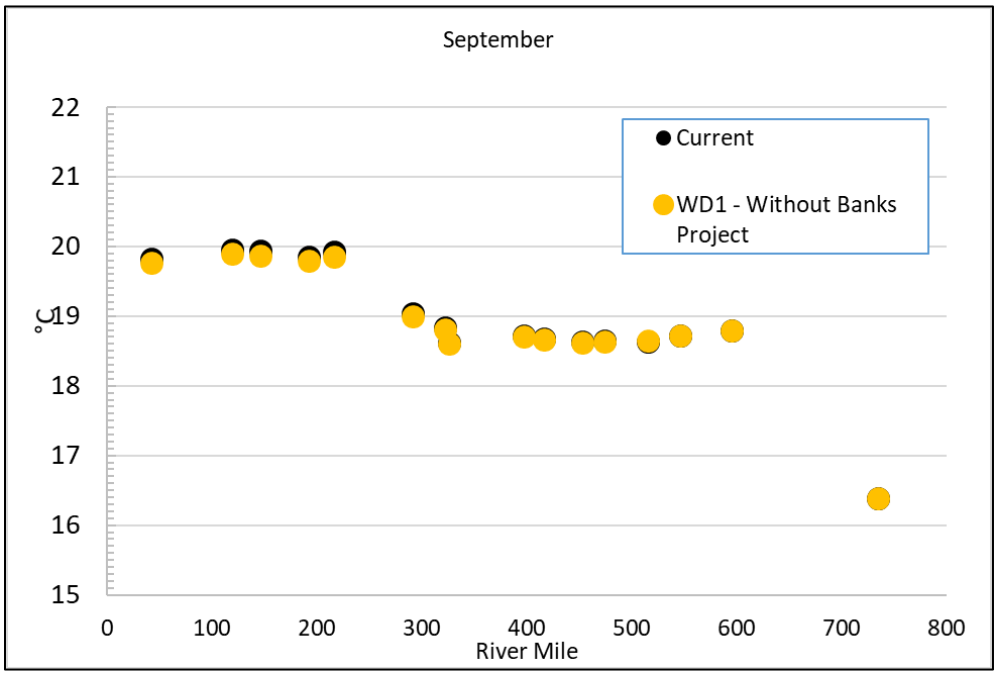


Figure 3-68 Simulated temperatures with and without Banks Lake project flows – September

Table 3-29 Temperature Impact of Banks Lake Project on Columbia River Temperature

RM	July	August	September	October
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	-0.02
474	0.07	0.04	0.01	-0.04
453	0.06	0.04	0.02	-0.04
416	0.09	0.06	0.03	-0.03
397	0.10	0.07	0.04	-0.03
326	0.11	0.08	0.02	-0.04
322	0.10	0.07	0.04	-0.02
291	0.10	0.09	0.05	0.00
216	0.08	0.10	0.08	0.05
192	0.07	0.09	0.07	0.04
146	0.07	0.08	0.07	0.03
119	0.07	0.08	0.06	0.03
42	0.05	0.06	0.04	0.02

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 0.9°C cooling at Grand Coulee Dam in July to 2.4°C warming at John Day Dam in September. 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. Dam impacts increase in the fall, with warming of 4.5°C at Chief Joseph Dam on the Columbia River and 3.2°C at Ice Harbor Dam on the Snake River in October.

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 across RBM10 model domain (July–October; 2011-2016)

River	Point Sources (∆°C)	Tributaries (∆°C)	Banks Lake Project (∆°C)	Dworshak Dam Cooling (∆°C)	Dams (∆°C)	Climate Change[1] (∆°C)
Columbia R.	**0.0 - 0.1**	**0.0 - 0.1**	**0.0 - 0.1**	**(-0.2) - 0.0**	**(-0.9) – 4.5**	**1.0 - 2.0**
Snake River	**0.0 - 0.1**	**0.0 - 0.1**	**NA**	**(-3.8) - 0.0**	**0.3 – 3.2**	**1.0 - 2.0[2]**

[1]Trend in simulated temperatures for 1970-2016
[2]July trend. Lower trend for August and September due to Dworshak operations

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 2019 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, EPA 2019a).
- 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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