APPENDIX G CLIMATE CHANGE

Assessment and Synthesis of the Literature on Climate Change Impacts on Temperatures of the Columbia and Snake Rivers

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Acronyms/Abbreviations

Acronyms/Abbreviations	Definition
°C	Degrees Celsius
AR	Assessment reports
BOR	U.S. Bureau of Reclamation
BPA	Bonneville Power Administration
CMIP	Coupled Model Intercomparison Project
CRSO	Columbia River System Operations
CWA	Clean Water Act
DART	(Columbia River) Data Access in Real Time
DM	Daily maximum
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act
FCRPS	Federal Columbia River Power System
kcfs	Kilo cubic feet per second
MAE	Mean absolute error
MOA	Memorandum of Agreement
NHD	National Hydrography Database
NOAA	National Oceanic and Atmospheric Administration
PUD	Public Utility District
R^2	Correlation coefficient
RCP	Representative concentration pathways
RM	River mile
RMSE	Root mean square error
USACE	U.S. Army Corps of Engineers
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
VIC	Variable infiltration capacity

1.0 INTRODUCTION

Across the Pacific Northwest, changing environmental dynamics including weather patterns and air temperatures, river flow timing, flow source (snowpack or rainfed) and magnitude, and wildfire prevalence are impacting river temperatures. As these trends continue into the future, changing conditions are expected to have even more pronounced influences on water temperature (May et al. 2018). These changes in river temperatures are expected to affect the health, behavior, and survival of cold water fish at both the individual and population scale (Crozier et al. 2008a). Where increased river temperatures result in exposure to temperatures above the optimal range for Columbia River salmon, impacts can include increased heat stress and migration delays, among other direct and indirect effects (Crozier et al. 2008b). In downstream mainstem waters where large areas of contiguous cold water are absent, cold water refuges may play an increasingly important role in mitigating the effects of exposure to temperatures that exceed fish thermal tolerance thresholds. Because of the importance of cold water availability to commercially, culturally, and recreationally important species, it is important to evaluate where and when such deleterious increases in river temperature are expected to occur across the Pacific Northwest and in the Columbia River basin.

Emerging research on climate change effects has shown regional variation in impacts on water temperature (Kaushal et al. 2010; USEPA 2013; Johnson et al. 2015). The Pacific Northwest and the Columbia River have a unique set of responses to climate factors (Beechie et al. 2013; Mantua et al. 2010; Crozier et al. 2011; Isaak et al. 2018). In addition to climate change, water temperatures are also affected by local watershed hydroclimatic and physiographic settings, land use, water management infrastructure, and other factors (Webb et al. 2008; Kaushal et al. 2010; Isaak et al. 2012). This review presents a synthesis of available information on the warming trend in stream temperatures across the Pacific Northwest, with a focus on the Columbia and Snake Rivers, as well as information on projected future changes.

Water temperature reflects the balance between energy inputs, storage, and loss from a waterbody. Weather conditions, which include air temperature, precipitation, solar (short-wave) radiation, long-wave radiation, evaporation, convection, and wind are primarily responsible for the heat exchange process at the air–water interface. Hydrologic processes that change the volume of water, and thus the response to heat inputs, or the movement and mixing of water of different heat contents can affect water temperature. These hydrologic processes, which include snowmelt timing, streamflow, tributary flow, groundwater flow, and hyporheic flows among others, are sensitive to climate changes (where climate represents long-term averages of weather) that affect precipitation and evapotranspiration (i.e. water balance). For example, one of the causes of increased summer water temperatures throughout the Norwest region has been summer flow declines due to earlier snowmelt. Research shows that increases in cool season temperatures (October through March) throughout the Northwest over the past 40-70 years can been linked to earlier snowmelt and a historical decline in summer flows (Karl et al. 2009). Karl et al. (2009) indicate that the April 1 snowpack in the Cascade Mountains, a key indicator of natural storage in the Northwest, has decreased by approximately 25% over the past 40-70 years primarily due to an increase of 2.5 °F in cool season temperatures during that period. And summer flows are expected to further decline as April 1 snowpack in the Cascade Mountains are projected to decline by as much as 40% by 2040 (Payne et al. 2004).

Water temperature is influenced not only by climatic factors directly affecting heat flux and hydrologic processes but also by channel characteristics, shading by riparian vegetation, and thermal density stratification in large rivers and lakes (Poole and Berman 2001; Caissie 2006; Webb et al. 2008; Hannah and Garner 2015).

To characterize the potential effects of climate change, it is a common practice to consider system response, or sensitivity, to either historical climate variability or numerical model simulations of system response to a range of plausible future climate change scenarios. Assessment of the water temperature response to climate change can help identify the range of potential impacts, identify vulnerabilities, and inform the development of adaptation strategies to ameliorate current impacts and reduce future risks.

Due to current limits of knowledge, randomness of nature, and the uncertainty in future human actions, exact forecasts of changes in streamflow and water quality endpoints decades into the future are not possible. However, it is possible to project with some confidence a range of possible future outcomes based on our current understanding of the earth-climate system and use that information to put bounds on the science and policy questions related to future changes in water quality. This document summarizes the estimated impacts of climate change on river temperatures to-present as well as the future projected changes to river temperatures available for the Pacific Northwest, including Columbia and Snake River temperatures.

Research in the Pacific Northwest shows that water temperatures are primarily driven by, and can be modeled as a function of, air temperatures (Mantua et al. 2010, Mohseni et al. 1998). Therefore, the analyses presented in Section 2.0 and Section 3.0 emphasize the historical and projected impacts of increasing air temperatures on water temperatures on the Columbia River and Snake River. Increased water temperatures, however, cannot be ascribed solely to increased air temperatures due to climate change. Other processes such as dam impoundment, flow regulation, land use changes, snowmelt, short term natural variability, and other factors can also influence the historical and projected variability of water temperatures. These factors are not explicitly evaluated in this study. Rather, the primary goal of this document is to identify long term trends and future projections for air and water temperatures.

2.0 CURRENT IMPACT ASSESSMENT

Studies of system responses to historical climatic variability typically focus on trends and the correlation between water temperature and climatic variables. In this context, *climatic variability* refers to the inherent heterogeneity of observed data over time (e.g., temperature, precipitation, environmental factors) (EPA 2011). Despite the presence of climate variability, numerous research studies indicate warming trends in air temperature and water temperature in the Pacific Northwest. Air temperature increases are especially important drivers of water temperature increases, due to the physical linkage of increasing downwelling longwave radiation and warmer groundwater (Isaak et al. 2018). The Columbia and Snake mainstem water temperatures are strongly linked to air temperature as well, as shown by a sensitivity analysis conducted with the RBM10 model (EPA 2019) and statistical regression (Isaak et al. 2017).

2.1 AIR TEMPERATURE TRENDS

The U.S. Global Change Research Program (2017) performed an air temperature trend analysis comparing the period of 1901 – 1960 with 1986 – 2016. This study reported that annual mean Northwest air temperatures have increased by 0.86°C, with maximum air temperatures increasing by 0.84°C, and minimum air temperatures increasing by 0.87°C. Isaak et al. (2018) reported that across Pacific Northwest rivers, mean annual air temperatures increased at a rate of 0.27°C per decade during the 40-year period of 1976 – 2015 (with a comparable rate of increase over the last two decades of 0.23°C per decade between 1996 and 2015). The study evaluated air temperature data collected at 168 sites in the Washington, Oregon, Idaho, eastern Montana and Wyoming, and northeastern California. The highest monthly temperature increases during the 1976 – 2015 period occurred in January (0.61°C), July (0.56°C), August (0.38°C), and September (0.41°C) (Isaak et al. 2018).

To provide an additional line of evidence for air temperature trends in the Columbia basin, EPA conducted an analysis of air temperature at select locations used for the RBM10 model of the Columbia and Snake rivers (EPA 2019). Annual average air temperature was calculated for the period spanning 1970 – 2016, and a linear regression performed to estimate magnitude. Trends are shown for Lewiston, Idaho (***Figure 2-1***), Yakima, Washington (***Figure 2-2***), and Portland, Oregon (***Figure 2-3***). The decadal changes estimated from the regression slopes are:

- Lewiston, Idaho: 0.22°C per decade.
- Yakima, Washington: 0.25°C per decade.
- Portland, Oregon: 0.21°C per decade.

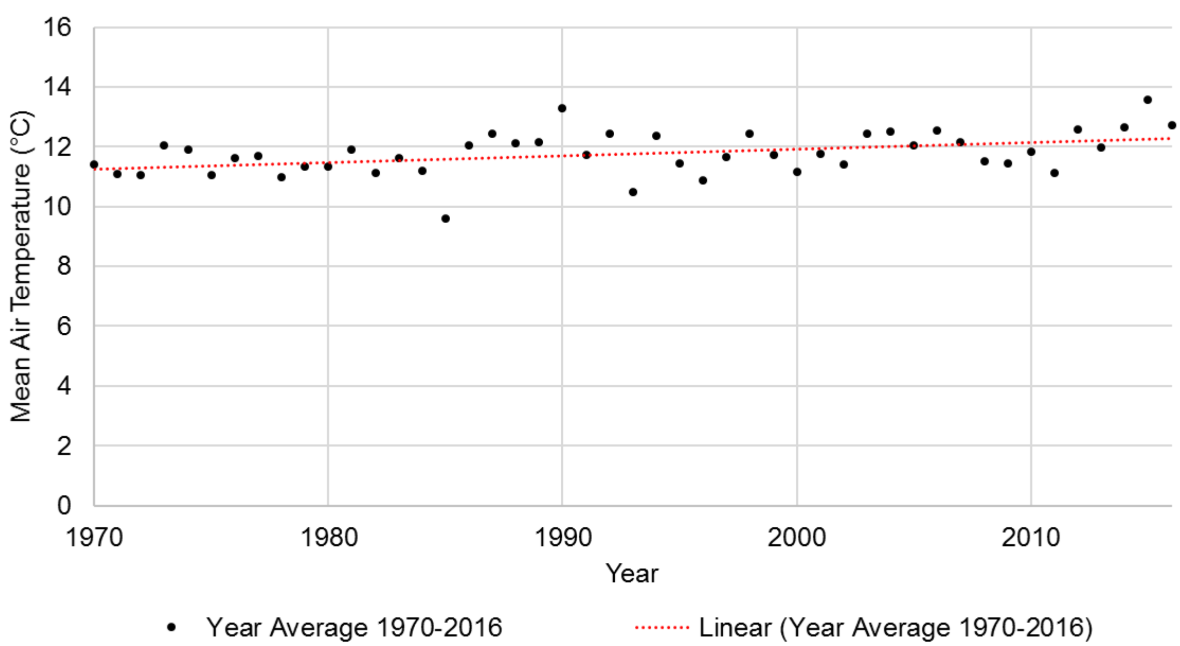

Figure 2-1 Trend for annual average air temperature at Lewiston, Idaho

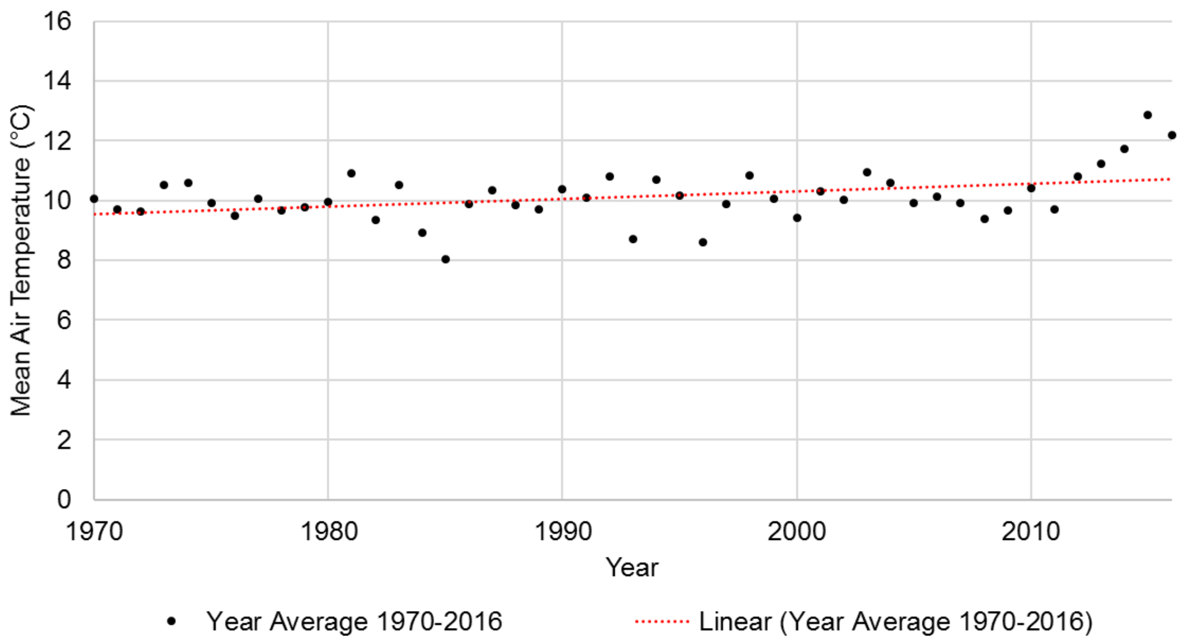

Figure 2-2 Trend for annual average air temperature at Yakima, Washington

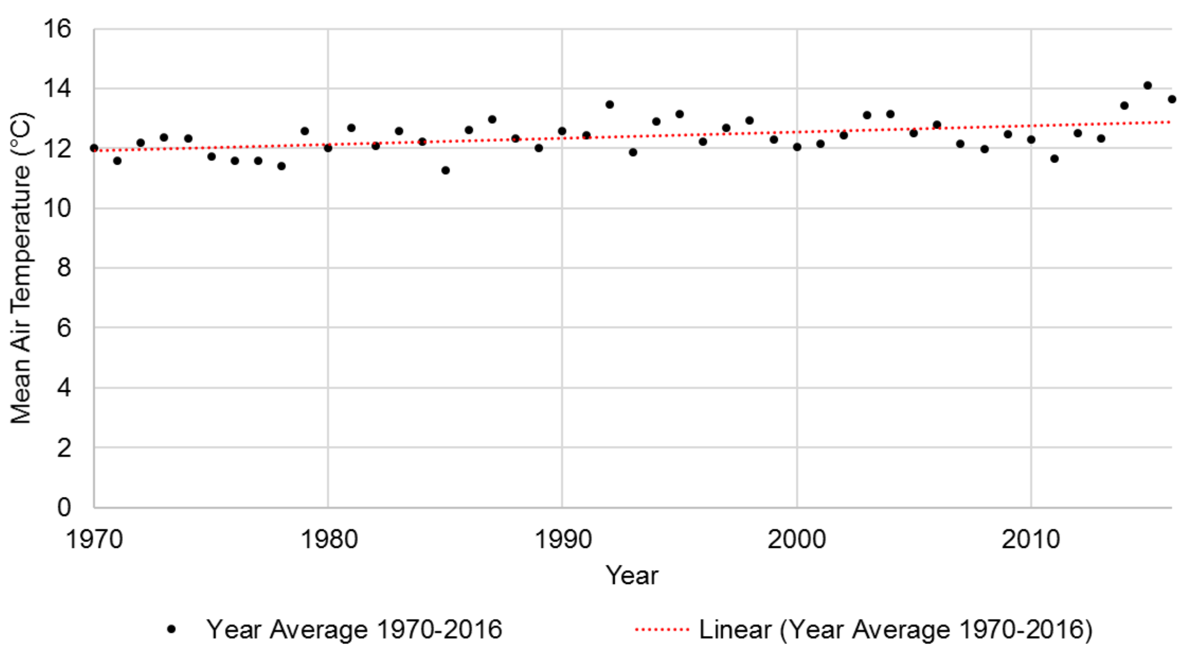

Figure 2-3 Trend for annual average air temperature at Portland, Oregon

2.2 WATER TEMPERATURE TRENDS BASED ON OBSERVATIONS

The most comprehensive historical water temperature records come from USGS stream gage locations, hydroelectric facilities on larger rivers, or drinking water treatment plant source water intakes (Kaushal et al. 2010; Isaak et al. 2011). Many of these locations are influenced by local thermal alteration from urbanization, power plant cooling, or dams and reservoirs (Webb et al. 2008; Kaushal et al. 2010; Isaak et al. 2011). This can make it difficult to identify climate-related effects. However, there are several studies from various locations throughout the Pacific Northwest characterizing water temperature trends from observed data. These studies are discussed below and summarized in ***Table 2-1***.

In a national-scale study, Kaushal et al. (2010) analyzed temperature trends from 1978 to 2007 in streams and rivers at 40 long-term river monitoring sites in the contiguous United States. Nine of the sites were in Oregon watersheds with varying levels of human disturbance. Average annual water temperature increased at eight sites, with rates ranging from 0.009°C to 0.030°C per year (0.09°C to 0.30°C per decade). Increasing trends at five sites were statistically significant. Water temperatures at one site, the Blue River, decreased at a rate of 0.038°C per year (0.38°C per decade). The Blue River site is located downstream of a dam, and the dam operating procedures may have influenced this temperature trend (Kaushal et al. 2010).

Isaak et al. (2012) conducted a regional-scale study (Pacific Northwest and Montana) to assess stream temperature trends in unregulated (free-flowing) and regulated streams from 1980 – 2009. Seven sites located on unregulated rivers and streams with reconstructed temperature trends averaged across the sites show statistically significant increasing trends in daily average temperatures during the summer (+0.22°C per decade), fall (+0.09°C per decade), and winter seasons (+0.04 °C per decade), as well as annually (+0.11°C per decade). Decreasing trends were observed at these same sites during the spring (-0.07°C per decade). Seasonal and annual stream temperature trends at unregulated sites were positively correlated with air temperature and were associated with summer streamflow volumes.

In an assessment of stream temperature data using the NorWest statistical stream network model from more than 20,000 sites in the western U.S., Isaak et al. (2017) found that Pacific Northwest river and stream August mean temperatures have increased by an average of 0.17°C per decade (standard deviation = 0.067°C per decade) from the reconstructed trend spanning 40 years, from 1976 – 2015. For larger northwestern U.S. rivers, including Pacific Northwest rivers, estimated trends from time series at 391 sites revealed that warming trends are ubiquitous in the summer and fall months, with July – September mean river temperature increases of 0.18°C – 0.35°C per decade during 1996 – 2015 and 0.14°C – 0.27°C per decade during 1976 – 2015 (Isaak et al. 2018). The average regional increase was linked to air temperature increases; however, at a local to sub-regional scale, other drivers, such as changes in flow, can be influential.

In the mid-Columbia River, results from the NorWest model show that August mean river and stream temperatures have increased by approximately 0.20°C per decade from the reconstructed trend over 40 years, from 1976 – 2015 (Isaak et al. 2017). At the Bonneville Dam monitoring site, with the longest continuous river temperature record (since 1939), the increase in river temperatures is most pronounced in summer. There is no complete time series that reaches back to before dam construction on the Columbia River. From 1949 – 2010, mean July water temperatures at Bonneville Dam increased by 2.6°C (Crozier et al. 2011). In the mid-Columbia River basin, the increase in summer water temperatures is largely driven by air temperature increases rather than flow variation, based on the statistical underpinning of the NorWest model (Isaak et al. 2017).

In addition to the chronic effects of increasing baseline river temperatures, acute exceedances of thermal tolerance maxima occurred more frequently in recent years and are projected to be of increasing magnitude and frequency (Isaak et al. 2018). One recent example of extreme Columbia River basin temperatures occurred in 2015, when temperatures in early June reached in excess of 21°C weeks earlier than is typical and remained 2°C – 4°C above monthly average temperatures for several weeks, contributing to a mass die-off of sockeye salmon in the Columbia and Snake Rivers (Isaak et al. 2018, NMFS 2016). Approximately 14% of the sockeye salmon that passed through the Bonneville Dam were detected upstream at McNary dam on the Columbia River, while on average 68% were detected the previous five years (NMFS 2016). In general, the first and last dates in each calendar year on which water temperatures exceed 20°C at Bonneville Dam are occurring earlier and later than they have historically (National Research Council 2004).

Water temperature records spanning several decades are also available for the Columbia River at the Data Access in Real Time (DART) website. These data were explored for trends, but numerous issues were found with the data quality. Prior to 1984, measurements of water temperature in the Columbia and Snake Rivers consisted of manual observations of temperature from thermometers placed in the cooling water stream of dam turbines. These observations, generally described as scroll case measurements, were made daily by dam operations personnel. There were quality assurance issues in the instruments, location of the instruments, and protocols for collecting and reporting data. Many of these deficiencies appeared to be related to the original motivation for installing the thermometers, which was for purposes of monitoring the operation of turbines rather than for analyzing temperature effects on Pacific salmon. Temperature monitoring associated with the total dissolved gas program was initiated in 1984 at many of the dams. In contrast to the scroll case temperature monitoring program, the purpose of the total dissolved gas monitoring is to guide spill and discharge management to minimize the production of excess dissolved gas. The resulting data reported on the Columba River DART website show limited attention to temperature data quality control. DART data from the mid-1990s to present tend to have fewer gaps and discrepancies, but analysis of these data still requires quality assurance work to remove spurious data (Merz et al. 2018). As a result of the data quality issues before the 1990s, EPA has not conducted any independent trend analyses with the DART data.

Table 2-1 Observed trends in annual average stream temperature in the Northwest

Waterbody	Location	Record of observation	Temperature Change (°C/decade)	P value	Source
Fir Creek	Brightwood, OR	1978 – 2007	+0.21	< 0.05*	Kaushal et al. 2010
North Santiam River	Niagara, OR	1979 – 2007	+0.21	< 0.05*	
Rogue River	McLeod, OR	1979 – 2007	+0.3	< 0.05*	
Bull Run River	Multnomah Falls, OR	1978 – 2007	+0.19	0.079	
North Fork Bull Run River	Multnomah Falls, OR	1979 – 2007	+0.09	0.34	
South Fork Bull Run River	Multnomah Falls, OR	1979 – 2007	+0.19	0.089	
Rogue River at Dodge Bridge	Eagle Point, OR	1979 – 2007	+0.21	< 0.05*	
Blue River	Blue River, OR	1979 – 2007	–0.38	< 0.05*	
South Santiam River	Foster, OR	1979 – 2007	0.000	0.977	

Waterbody	Location	Record of observation	Temperature Change (°C/decade)	P value	Source
7 sites on unregulated rivers and streams	Washington, Oregon, Idaho, Montana	1980 – 2009†	Spring: -0.07 Summer: +0.22 Fall: +0.09 Winter: +0.04 Annual: +0.11	<0.01*	Isaak et al. 2011
Multiple sites in the Pacific Northwest	Pacific Northwest	1976 – 2015	August: +0.17	-	Isaak et al. 2017
391 sites on larger rivers and streams	Northwestern U.S.	1976 – 2015	July: +0.27 August: +0.14 September: +0.15	-	Isaak et al. 2018
Columbia River	Bonneville Dam	1949 – 2010	July: +0.43	-	Crozier et al., 2011

* Denotes significance at $P < 0.05$.
† Rates of change are based on reconstructed trend (multiple regression models were used to overcome potential bias from missing years of observations and regional climate cycles).

2.3 DEVELOPMENT OF CLIMATE BASELINE TIMEFRAME

Analysis of the potential impacts of climate change on water temperatures requires definition of a baseline condition prior to the onset of climate change. Water temperatures in the Columbia and Snake River mainstems are strongly influenced by air temperature, with less influence from other factors such as shade and tributary inputs (Isaak et al. 2018; EPA 2019). Both rivers are wide, which minimizes the impact of shade on river temperatures, and many large impoundments are present on each river, which result in pooling and flow retention, allowing for enhanced heating due to atmospheric influences. Therefore, the baseline is first defined in terms of air temperature. The air temperature baseline is then extrapolated to a water temperature baseline for the same period.

It is important to note that the baseline temperature is not a single condition but rather a temperature regime characterized by a distribution of temperatures. Air and water temperatures in the Columbia River basin vary widely and are strongly influenced by decadal patterns in sea surface temperature anomalies, such as the El Niño – Southern Oscillation. This inherent variability makes it difficult to resolve a climate change signal. For example, some of the warmest summer temperatures on record in the basin occurred during the 1930s (Abatzoglou et al. 2014) and were attributed to coincident warming in both the Pacific and Atlantic Oceans (Markus et al. 2016). To account for natural variation, the baseline temperature can be characterized as a distribution with a mean and standard deviation.

To select a baseline timeframe for climate, it is important to parse the anthropogenic and natural factors that affect air temperature in the Pacific Northwest. Abatzoglou et al. (2014) provides a thorough analysis of the topic, allowing for discrimination of the anthropogenic influence from other factors. The authors analyzed long-term air temperature records in the Pacific Northwest dating back to the turn of the 20th century but focused on conditions since 1920 when the density of observing stations increased dramatically. Using multiple linear regression techniques, they attributed variation in the seasonal temperature records to the El Niño – Southern Oscillation/Pacific-North American pattern, solar variability, volcanic aerosols, and anthropogenic forcing (including climate change). ***Figure 2-4*** from Abatzoglou et al. (2014) provides the basis for selection of the baseline.

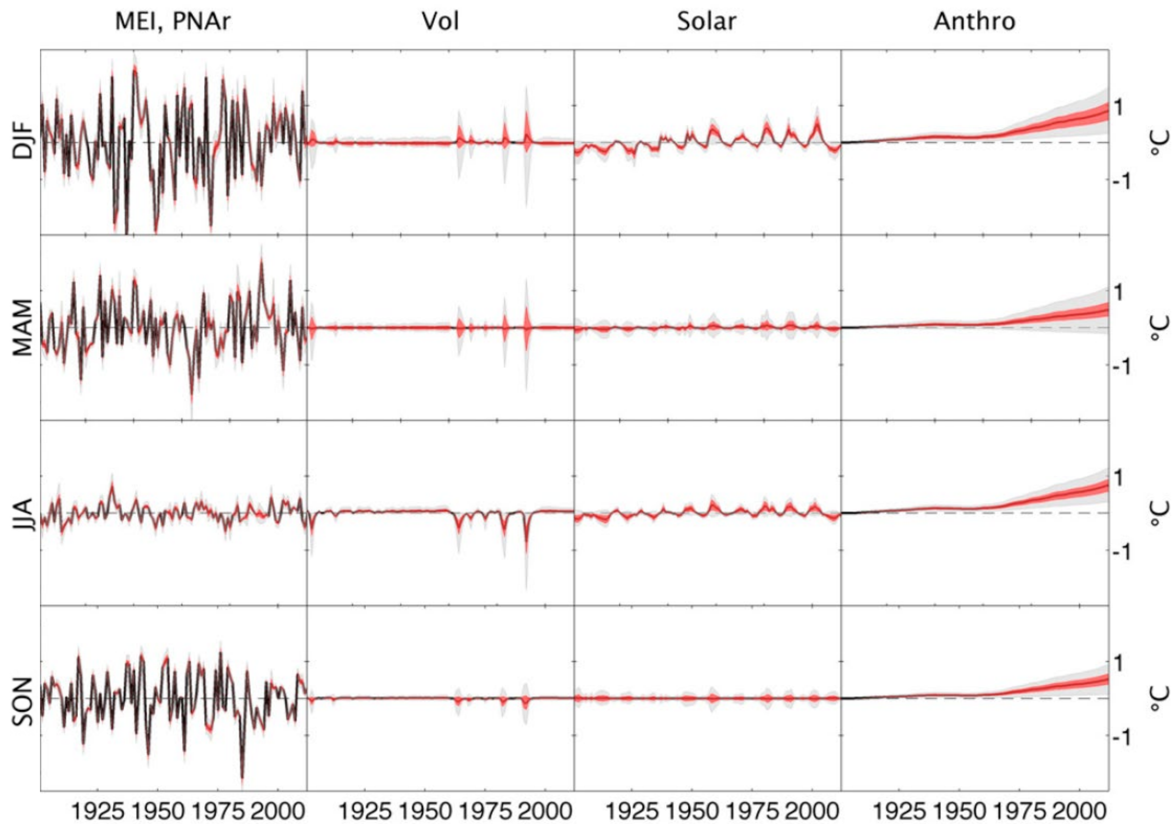

Figure 2-4 Factors influencing air temperature during the 20th century (from Abatzoglou et al. 2014)

The columns in the figure correspond to time series plots showing the influence of the factors affecting temperature: "MEI, PNAr" are the combined influence of the El Niño – Southern Oscillation and the Pacific-North American pattern, "Vol" represents the influence of volcanic aerosols, "Solar" represents effects of cyclical solar radiation (sunspot) variability, and "Anthro" represents anthropogenic influence. The rows represent seasons, with "JJA" corresponding to June, July, and August. A close examination of the "Anthro" plot for JJA shows a small upward trend in temperature between 1900 and 1960, and a more dramatic upward trend beginning in 1960. Based on this analysis, 1960 was selected as the year in which climate change begins to have a stronger effect on air temperature. Note that climate change does have a small effect prior to 1960, but the influence of climate change was minimal to that point. The air temperature baseline is therefore defined as the distribution of air temperatures prior to 1960. Given the interdecadal oscillations and other factors influencing air temperature, the mean should be taken from a relatively long monitoring period of record.

Given the linkage between air temperature and water temperature in the Columbia River, the air temperature baseline can be used to identify a water temperature baseline distribution. It is noted that some of the Columbia and Snake River dams were constructed after the 1960 baseline. Bonneville Dam and Grand Coulee Dam were completed and began operations in 1938 and 1942, respectively. Many of the other major dams in the Columbia River Basin were completed in the 1950s and 1960s, including McNary (1954), Chief Joseph (1955), The Dalles (1957), Ice Harbor (1961), Priest Rapids (1961), Wells (1967), and John Day (1968). In the

1970s, the current dam configuration was completed with the addition of Dworshak (on the North Fork Clearwater, 1974)), Lower Granite (1975), and an Ice Harbor expansion (1976).

Water temperature trends can be estimated using long-term air temperature records as inputs to statistical models and mechanistic models. For example, EPA's RBM10 model (EPA 2019) has an input database that allows for a simulation of daily temperatures from 1970-2016, which captures most of the period from the 1960 baseline to the present. The next section describes water temperature trend estimates from modeling assessments.

2.4 TRENDS ESTIMATED USING MODELS

A simple and direct approach to estimating the water temperature baseline is to use statistical models of water temperature developed by Mantua et al. (2010). Mantua et al. used a logistic regression approach developed by Mohseni et al. (1998) to predict weekly river temperatures for weeks 15 to 42 of the year (encompassing the warmer months) as:

$$T_S = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_a)}}$$

In this equation, T_S is the predicted weekly average stream water temperature in °C, T_a is the average weekly air temperature. The variables μ (minimum stream temperature), α (maximum stream temperature), γ (steepest slope of the function), and β (air temperature at the inflection point of the logistic curve) are all fitting parameters. Once the site-specific parameters are determined, the prediction depends solely upon air temperature.

Mantua et al. developed and calibrated these models for 124 stations throughout Washington state, 23 of which are along the Columbia River from the Canadian border to the mouth of the Columbia River. Historic air temperature data were obtained from eight National Climate Data Center monitoring sites and were supplemented using gridded 1/16° spatial resolution air temperature estimates spanning 1915 – 2006 developed from Elsner et al. (2010[1]). Weekly results of model application for historical air temperature conditions at each site, commencing in 1915 and running through 2006, have been made publicly available. Note that the water temperatures are estimates based on the regression from air temperatures, and do not necessarily reflect observed historical water temperatures, which would have been influenced by changing conditions as dams were installed at various dates. However, they do reflect a reasonable approximation of the response of water temperature to air temperature using the historical air temperature record. Using the Mantua et al. (2010) model results, EPA derived monthly baseline water temperature distributions for the period 1915 – 1959 for five locations (***Table 2-2***). Water temperatures in a given month vary across sites, with the warmest temperatures occurring at Bonneville Dam, and the coldest temperatures at Wells Dam.

[1] Elsner et al. (2010) developed the historic gridded estimates of air temperature from several sources of observed station data, primarily from the National Climate Data Center Cooperative Observer network and Environmental Canada daily data. Methods were used to account for varying periods of record, to interpolate point station data to the 1/16° grid, and to adjust the estimates for topographic influences.

Table 2-2 Estimated baseline monthly mean air and water temperatures (1915 – 1959) (based on Mantua et al., 2010)

Month	Mean Air Temp (°C)	Mean Water Temp (°C)	Standard Deviation Water Temp (°C)
Grand Coulee Dam tailrace, Columbia River			
July	22.1	18.1	0.43
August	20.9	17.9	0.53
September	17.0	16.4	1.46
Wells Dam tailrace, Columbia River			
July	21.3	16.8	0.96
August	20.4	16.5	1.06
September	15.8	13.2	2.60
Priest Rapids Dam forebay, Columbia River			
July	23.4	18.7	0.60
August	22.4	18.5	0.60
September	18.1	16.4	1.89
Bonneville Dam forebay, Columbia River			
July	18.1	19.5	1.14
August	17.9	19.4	1.02
September	15.5	17.5	2.05
Ice Harbor Dam tailrace, Snake River			
July	23.0	20.3	1.19
August	21.7	19.7	1.19
September	17.7	16.8	2.20

The Mantua et al. historical climate results were reported through 2006. EPA analyzed the last ten years of the Mantua et al. data (1997 – 2006) to derive the estimated water temperature change since 1960 (***Table 2-3***). The average change per decade was smallest in July at each site (mean 0.09°C) and largest in September (mean 0.17°C). There was also variability in the decadal changes between the sites, with the smallest changes at Grand Coulee Dam, and the largest changes at Ice Harbor Dam. The Mantua et al. (2010) monthly mean predictions of water temperature vary little between July and August across the sampled sites, while the analysis of observed water temperature data shows consistently higher water temperatures in August than July. This likely reflects a limitation of the Mantua et al. (2010) regression method.

Table 2-3 Comparison of baseline and current air and water temperatures (1915–1959; 1997-2006)
(based on Mantua et al., 2010)

Month	1915 - 1959 Mean Water Temp (°C)	1997 - 2006 Mean Water Temp (°C)	Change per Decade* (°C)
Grand Coulee Dam tailrace, Columbia River			
July	18.1	18.2	0.02
August	17.9	18.2	0.06
September	16.4	16.7	0.07
Wells Dam tailrace, Columbia River			
July	16.8	17.1	0.07
August	16.5	17.1	0.13
September	13.2	14.0	0.18
Priest Rapids Dam forebay, Columbia River			
July	18.7	19.0	0.07
August	18.5	18.9	0.10
September	16.4	17.2	0.18
Bonneville Dam forebay, Columbia River			
July	19.5	20.1	0.15
August	19.4	20.2	0.17
September	17.5	18.4	0.23
Ice Harbor Dam tailrace, Snake River			
July	20.3	21.0	0.16
August	19.7	20.7	0.25
September	16.8	17.8	0.23

* Ending date assumed to be 2002 (midway between 1997 and 2006)

Yearsley (2009) used the RBM model, an earlier version of the RBM10 model EPA is currently using for the Columbia and Snake Rivers (EPA 2019), to predict the cumulative increase in Columbia River mainstem daily average temperatures between a baseline condition (1951 – 1978) and an early century (2020) climate scenario. The climate scenarios are discussed in more detail in Section 3.0. The results showed a river temperature increase at Bonneville Dam of approximately 1°C during the summer months.

For this assessment, EPA has applied the RBM10 model to provide an additional line of evidence for decadal change since the 1960 baseline (EPA 2019). Model output for the simulation of current conditions along the Columbia and Snake Rivers from 1970 – 2016 was used. The hydroelectric system and dams were constructed prior to 1970 except for Lower Granite Dam (completed in 1975).

Trend analyses of the model outputs were conducted for the Columbia River at Bonneville Dam tailwater, Priest Rapids Dam tailwater, Wells Dam tailwater, and for the Snake River at Ice Harbor Dam tailwater. Monthly average river temperature and monthly 90th percentile temperatures were calculated for each year for the months of July, August, September, and October. Trends for both statistics were nearly identical; therefore, only monthly average river temperatures are provided here. 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 method was developed and popularized by USGS researchers throughout the 1980s (Hirsch et al.

1991), and USGS published computer code supporting its use. A non-parametric test is frequently used for trend analysis since time series data exhibit autocorrelation. 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). A confidence interval (p value) was also estimated. An example plot is provided in ***Figure 2-5***.

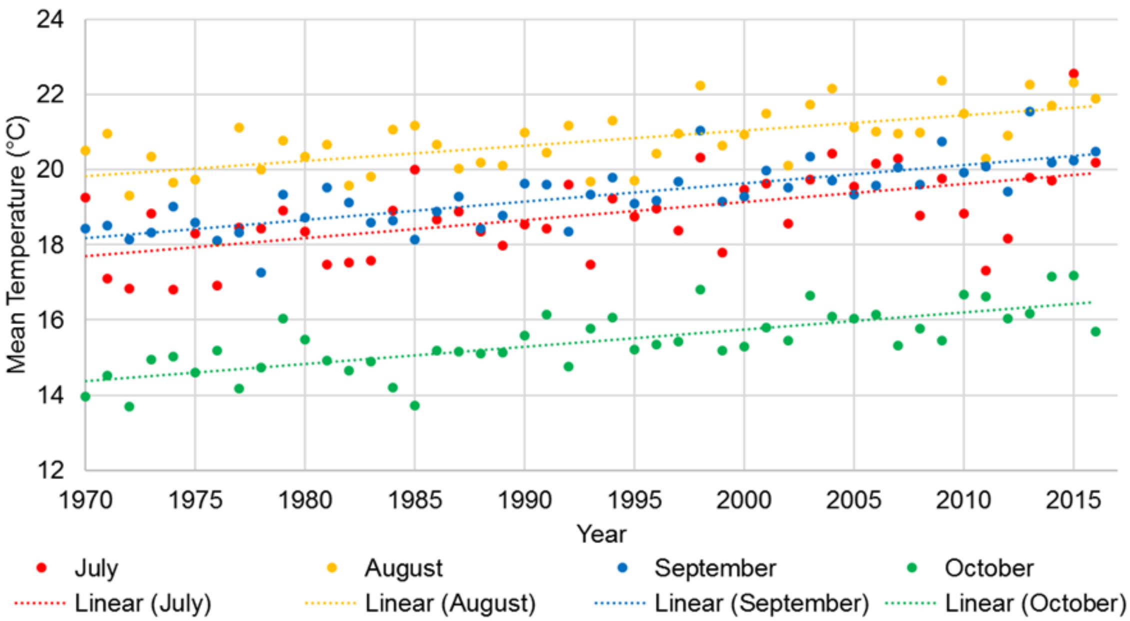

Figure 2-5 Trend in monthly mean temperatures at Bonneville Dam

The results for all locations and timeframes are shown in ***Table 2-4***. Estimated 1960 water temperatures are based on a backwards projection of the water temperature trend predicted by RBM10 for 1970 – 2016. All the trends were considered significant at a p-value of 0.05, with the exception of mean temperatures in August and September at Ice Harbor Dam. Changes per decade are highest at Bonneville Dam and lowest at Ice Harbor Dam. The lower trend at Ice Harbor Dam is likely due to the influence of cold water releases from the Dworshak Dam. Summer releases were increased beginning in the late 1990s to provide cooler water temperatures in the lower Snake River.

Table 2-4 Mean monthly water temperatures and decadal changes predicted from trend analysis of RBM10 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

The Mantua et al. (2010) analyses and RBM10 analyses (EPA 2019) show different warming rates per decade, with Mantua et al. (2010) reporting lower rates. During summer months such as August, the Mantua model does not have a clear increasing trend until the early 1980s at most locations, such as at the Bonneville Dam tailrace (***Figure 2-6***). The Mantua et al. (2010) model 10-year moving average shows an increase of 0.4°C per decade from 1980 to present, which is similar to the RBM10 model trend rate for 1970 – 2016 at Bonneville Dam. However, the reported trend rate from the Mantua et al. (2010) analysis based on the average of 1997 – 2006 vs. the average of 1915 – 1959, represented as a 43-year span (1960 – 2002) is only 0.17°C per decade at Bonneville Dam tailrace in August. The RBM10 analysis is a linear regression on results beginning in 1970, which is a period of fairly steady increases. Projecting the RBM10 linear increase after 1970 back to 1960 is a rough estimation approach, because there was not the same rate of consistent increase observed between 1960 and 1970.

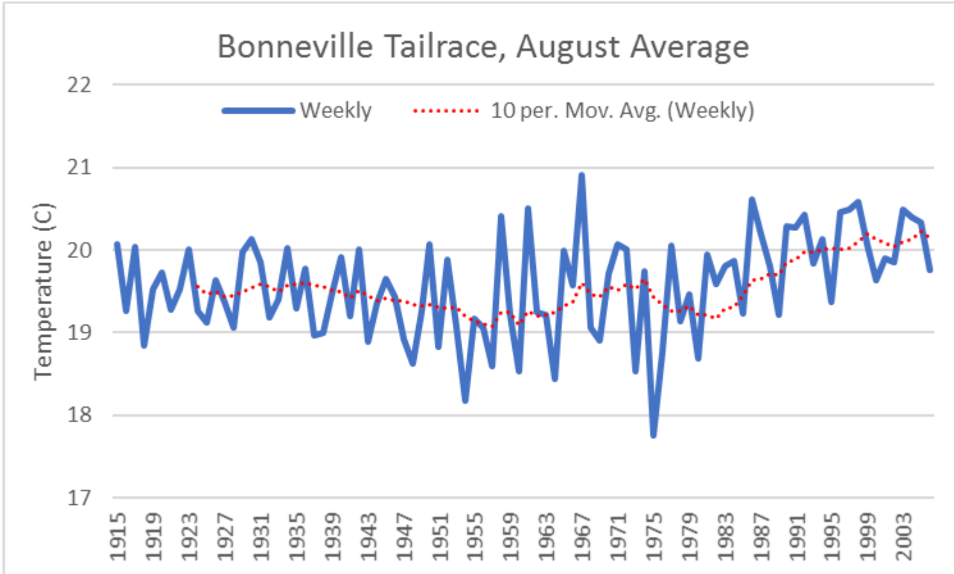

Figure 2-6 August average water temperature at Bonneville predicted by Mantua et al. 2010 regression model

EPA also evaluated the warming trend estimated by RBM10 assuming free-flowing conditions (all dams removed from simulation except Dworshak) and compared it to the same trend in the current conditions scenario. For the Columbia River, the results for mean monthly temperature show a slightly higher warming trend in the free-flowing river than the impounded river in the month of July. However, results indicate a smaller warming trend in August, September, and October in a free-flowing river (***Table 2-5***). Snake River warming trends in August and September are substantially lower than the Columbia River trends due to Dworshak Dam cold water releases in the latter part of the record. However, in October, when Dworshak cold water releases are not operating, the trend under free-flowing conditions is lower than the trend under current conditions.

Table 2-5 Comparison of trend for mean monthly temperature increase for current and free-flowing model scenarios using RBM10

Location	RBM10 1970-2016 **Δ°C per decade**							
	July		August		September		October	
	Current	Free Flowing	Current	Free Flowing	Current	Free Flowing	Current	Free Flowing
Columbia River								
Wells Dam	0.38	0.44	0.35	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

2.5 SUMMARY OF CURRENT IMPACTS

In summary, predicted trends in water temperatures (present compared to a baseline of 1960) vary between sites as shown by the analysis of the Mantua et al. (2010) historical data, and there is considerable variation at the sites themselves as indicated by the standard deviations (which is expected given the influence of the El Niño – Southern Oscillation and the Pacific-North American pattern). Amidst this variation, there is strong evidence of a warming trend in Pacific Northwest waters and in the Columbia River mainstem since 1960, as indicated by literature and the analyses conducted herein by EPA. Based on available information (***Table 2-1***), the estimated increase in river temperatures since the 1960 baseline ranges from 0.2°C to 0.4°C per decade, for a total temperature increase to date of 1.5°C ± 0.5°C. The trend analysis of the RBM10 model output shows decadal changes at the upper end of that range, while the analysis of historic Mantua et al. regression estimates of water temperature shows decadal changes at the lower end of the range. The RBM10 model results also indicate that Columbia River dam impoundments exacerbated the climate-related warming in mid-summer and early fall, compared to predicted trends in a free-flowing river (***Table 2-5***).

3.0 FUTURE IMPACT PROJECTIONS

Modeling studies use statistical or numerical simulation approaches to estimate water temperature responses to scenarios of potential future climate change. Scenarios typically include a range of potential futures based on different climate models, different assumptions about future greenhouse gas emissions, and different future time periods. Climate model output can be used as inputs to hydrologic and water quality models, providing a capability to evaluate a wide range of potential climate futures, including interactions with changes in land use and other factors affecting water quality. Simulated results are commonly presented as average (annual or seasonal) changes in water temperature (median or average) relative to a historical baseline period. The results of all modeling studies are directly conditional on the specific methods, models and climate change scenarios evaluated.

Studies of climate change in the Columbia River basin have used downscaled output from two rounds of the Coupled Model Intercomparison Project (CMIP) global climate modeling experiments conducted for the Intergovernmental Panel on Climate Change Assessment Reports (ARs): CMIP3, associated with AR4 (2005/2006); and CMIP5, associated with AR5 (released in 2012). CMIP5 included a variety of process improvements to global climate models, but simulated responses to a given degree of radiative forcing are generally similar between these two rounds. One significant way in which the two phases differ is that CMIP3 uses future scenarios from the Special Report on Emission Scenarios that are based on scenarios of future emissions that rely on various assumptions about economic growth and human responses[2].

[2] CMIP3 emissions scenarios referenced in this document include:

CMIP5 scenarios, termed Representative Concentration Pathways (RCPs) take a different approach in which explicit but highly uncertain socioeconomic projections are not made; rather, each RCP is based on an assumption of a specific level of radiative forcing at the end of the 21st century. For instance, RCP 8.5 is an upper-bound scenario that assumes radiative forcing increases to 8.5 W/m^2 by 2100. The middle-of-the-road Special Report on Emission Scenarios A1B scenario from CMIP3 is similar to the RCP 6 scenario from CMIP5 (radiative forcing increases to 6.0 W/m^2 by 2100), with both reaching an approximate CO_2 equivalent concentration of 850 ppm by 2100.

3.1 FUTURE PROJECTIONS OF METEOROLOGICAL CHANGES

Across the Pacific Northwest, an increase in average annual air temperatures of 1.8°C to 5.5°C is projected by the end of the century (compared to the period 1970 – 1999), depending on the scenario, with the greatest increases projected for the summer (Mote et al. 2014; Rupp et al. 2017). Rupp et al. (2017) estimates that air temperatures at the end of the century will increase by 3.0 and 5.5 °C above the 1970-1999 baseline average temperatures under the RCP 4.5 and RCP 8.5 scenarios respectively. The estimated temperature differences between the RCP 4.5 and RCP 8.5 projections are 0.5 °C by 2050, and 2.5 °C by 2099.

The River Management Joint Operating Committee authored a report characterizing projected climate change impacts in the Columbia River basin and other basins in western Oregon and Washington (2018). The focus is on projected temperature, precipitation, snowpack, and streamflow changes through the rest of the 21st Century. The study found that, on average, air temperatures have already increased by 0.8°C in the region since the 1970s, and projected future increases by 2070 range from 1.7°C to 3.3°C (based on CMIP5 RCP 4.5 emissions pathways). Changes in future precipitation are more uncertain, but are generally predicted to increase, notably during winter. Summers are expected to become drier. Winter snowpacks are expected to decline since more winter precipitation will fall as rain rather than snow. As a result, average summer flows are expected to be lower and/or there will be a longer period of low summer flows, which will likely cause a tighter coupling of water temperature to air temperature. Predicted seasonal flow changes between recent historic and 2030s conditions are shown graphically in ***Figure 3-1***. Flows are expected to increase during winter and spring and decrease during summer and fall.

A1B. This future climate emissions scenario assumes very rapid economic growth, a global population peaking mid-century followed by a decline, rapid development of new and more efficient technologies, and a balance between fossil intensive and non-fossil energy sources.

B1. This future climate emissions scenario assumes the same population pattern as A1B, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies.

A2. This future climate emissions scenario assumes a continuously increasing population, with per capita economic growth and technological change more fragmented and slower than other scenarios

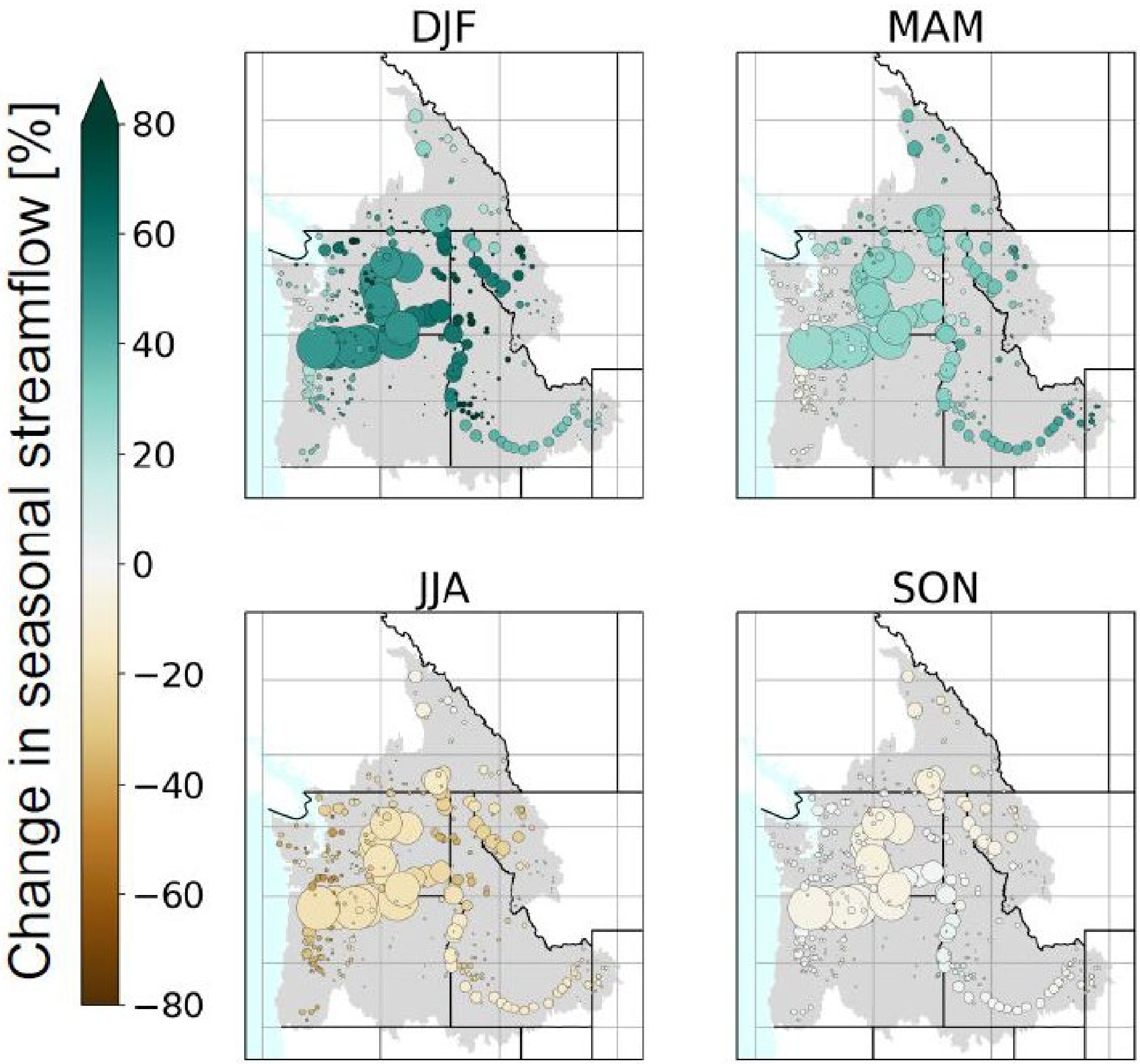

Figure 3-1 Predicted changes in seasonal streamflow between the period 1976-2005 and the 2030s
(from River Management Joint Operating Committee, 2018)

DJF = Dec-Feb; MAM = Mar-May; JJA = Jun-Aug; SON=Sep-Nov; Circle size denotes relative streamflow volume

3.2 FUTURE PROJECTIONS OF WATER TEMPERATURE INCREASES

Studies and analyses describing projected future water temperature increases are presented below in three sub-sections: regional assessments, Columbia River mainstem, and Columbia River tributaries. Results are summarized in ***Table 3-1***. The studies use different future time periods but can be generally classified into early century (approximately 2010 – 2030), mid-century (approximately 2030 – 2070), and late century (approximately 2070 – 2100).

3.2.1 Regional Assessments

In the Methow River near Winthrop, Washington, average annual stream temperatures are projected to increase by 0.4°C to 0.8°C (early century to late century, respectively) in response to moderate emissions (CMIP3 A1B) (Caldwell et al. 2013). Similar increases ranging from 0.6°C to 1.7°C (early century to late century, respectively) are projected in response to moderate emissions (A1B) for watersheds in Washington, Oregon, Idaho, western Montana, and portions of British Columbia (Wu et al. 2012). Simulations by Mantua et al. (2010) for over 100 sites predict increases in stream temperatures in Washington ranging from approximately 1°C to 2°C for early century, 1°C to 4°C for mid-century, and 1°C to 5°C for late century. Results varied across sites and by CMIP3 emission scenario (low [B1] to moderate emissions [A1B]).

Climate change could alter seasonal and shorter-duration summer maximum stream temperature, which is a critical period for aquatic ecosystems and could impact cold water biota (Ficke et al. 2007). Effects on water temperature are more evident in the snow-dominant watersheds, where reduced winter snowfall and earlier snowmelt is expected to result in lower summer stream flows and higher summer stream temperature. For example, Wu et al. (2012) predict streamflow decreases of about 19% to 30% in mid- and late century, respectively. Several modeling studies in Washington watersheds suggest the greatest increases in stream temperature will occur during the summer months (Caldwell et al. 2013; Wu et al. 2012; Cristea and Burges 2010; Mantua et al. 2010). Cristea and Burges (2010) projected increases in future average summer stream temperatures in Wenatchee, Icicle, and Nason Creeks in Washington. The magnitudes of projected changes in water temperatures in these waters are strongly influenced by riparian shading.

In the South Fork Nooksack River, Washington, late century water temperature increases ranging from 3.5°C to 6°C are projected during critical summer low-flow conditions (simulations based on moderate emissions, CMIP3 A1B) (Butcher et al. 2016). However, restoration of full system riparian shading was predicted to mitigate potential future water temperature increases by 30% to 60% during critical conditions. Maximum 7-day average stream water temperatures were projected to increase by 1.1°C to 3.6°C by late century even with system potential shade. Model simulations also suggested that critical condition water temperatures could exceed thermal tolerances for salmon in 60% to 94% of the Nooksack River by late century.

Using the CMIP3 A1B (medium emissions) scenario and the NorWest spatial statistical network model, the Pacific Northwest regional August mean river temperatures are projected to increase by 0.7°C in 2040 and 1.4°C in 2080, compared to a baseline period of 1993 – 2011 (Isaak et al. 2017).

Beechie et al. (2013) used a coupled model, called the dominant river tracing-based stream flow and temperature model, to estimate flow and stream temperature in the Columbia River basin for future climate conditions (CMIP3 A1B). They predicted an increase in the maximum weekly mean temperature across the watershed of 1°C to 4°C for 2030 – 2069 and 2°C to 6°C for 2070 – 2099. They also predict that the number of stations where water temperatures are projected to exceed 21°C for more than nine weeks per year will increase dramatically by the end of the century.

3.2.2 Columbia Mainstem

Isaak et al. (2017) estimate that August mean river temperatures across the mid-Columbia basin, calculated using the CMIP3 A1B (medium emissions) scenario and the NorWest spatial statistical network model, will increase by approximately 1.0°C by 2040 and 2.0°C by 2080, compared to a baseline period of 1993-2011.

Using the RBM model, Yearsley (2009) projected an increase in the daily average temperature in the Columbia and Snake River mainstems. At Bonneville, from 1951 – 1978 until 2040, the predicted increase was approximately 1°C during the summer months, with some variation over the year. The projected increase depended upon location, with higher maximum temperature increases predicted for certain times of year at Ice Harbor Dam, for example, compared to the Bonneville Dam. The predictions used the A1B scenario with a composite of four downscaled GCMs driving the VIC model for hydrology.

3.2.3 Columbia Tributaries

Simulations from a global-scale study by van Vliet et al. (2013) under CMIP3 A2 (high) and B1 (low) emissions scenarios suggest that average annual water temperatures in the Columbia River basin could increase by an average of 1.6°C by late century.

Using the NorWest statistical stream network model (Isaak et al. 2018), EPA analyzed estimates of current and future tributary temperatures (EPA 2018). Tributary temperatures are predicted to increase between 0.6°C and 0.7°C relative to Columbia River temperatures (***Figure 3-2***). In addition, many tributaries in the future, despite being relatively cooler than the Columbia River, could become warmer than water temperature thresholds for fish habitat and therefore would be less functional as cold water refuges. ***Figure 3-3*** and ***Figure 3-4*** show current conditions and 2080 projections, respectively.

EPA also conducted enhanced temperature modeling to assess Columbia River tributary riparian shade restoration potential under current (1993 – 2011) and projected future (2040s and 2080s) conditions (Fuller et al. 2018). The goal was to provide insight into potential changes in cold water refuge for Pacific Salmon. Like the analysis in EPA 2018, this project used geospatial representations of covariates that affect stream temperature and spatial stream network models (Isaak et al. 2018). Current and future climate scenarios were paired with three shade assumptions: no vegetation, current vegetation, and potential restored vegetation. Overall, for the tributaries analyzed, mean August temperatures across the tributaries in the basin decreased by 0.5°C when shade was restored (with a range of 0°C - 1.3°C). The improvement in temperature depended heavily on current extent of vegetation and stream width. Results indicated that with current vegetation, August monthly mean stream temperatures would increase on average by 1.1°C for the 2040s scenario and 2.0°C for the 2080s scenario. For the restored vegetation scenario, the relative August mean increases across all tributaries were about the same (1.0°C for 2040s and 2.0 for 2080s, compared to current restored conditions).

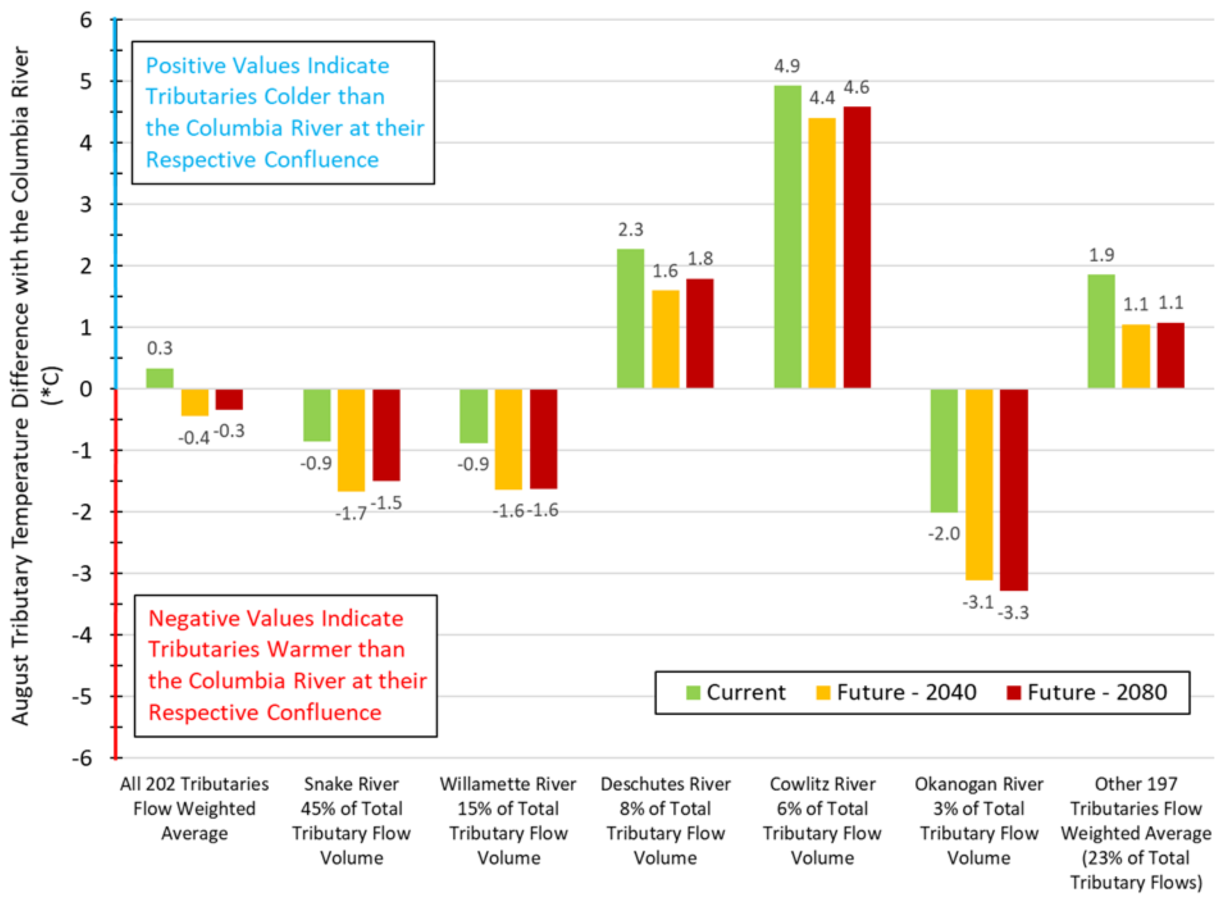

Figure 3-2 Difference in Columbia River tributary and mainstem August mean temperatures at confluences and future projections

(from EPA 2018)

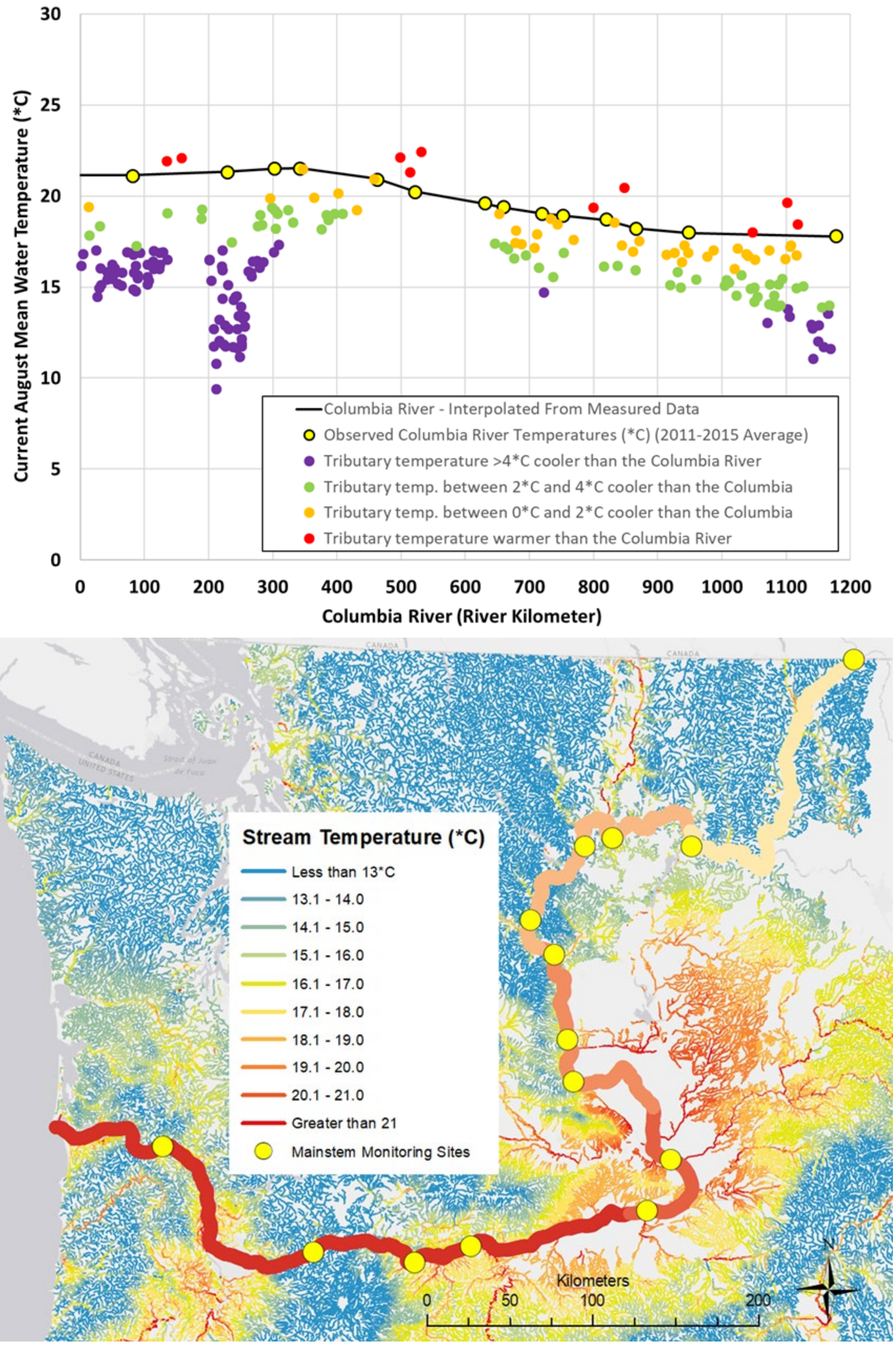

Figure 3-3 Estimated current August mean temperature in the Columbia River and tributaries

(from EPA 2018)

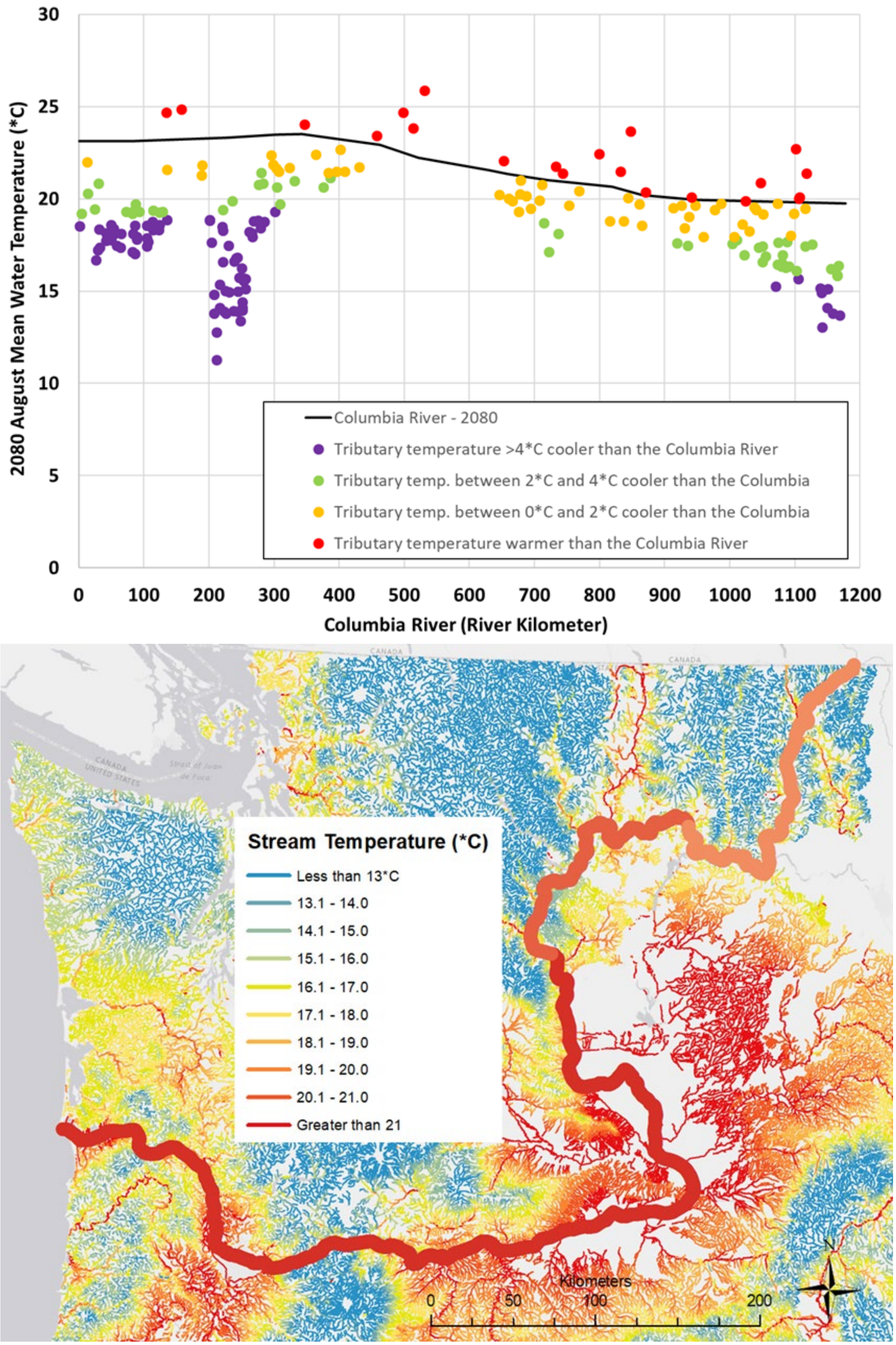

Figure 3-4 Estimated 2080 August Mean temperature in the Columbia River and tributaries (from EPA 2018)

Table 3-1 Projected stream temperature responses to future climate change scenarios in the Northwest

Watershed/ Region	Future Period	Water Model(s)	Scenario(s) Used to Drive Water Models [a/]	Projected Water Temp. Changes (°C)		Citation
				Annual (Range)	Seasonal (Range)	
Regional Assessments						
Methow River, WA	Early Century	Coupled GLM-VIC statistical modeling	**Climate** *Number*: 10 *Emissions*: A1B	+0.4 (±1.6)	*July:* +1.4	Caldwell et al. 2013
	Mid Century			+0.7 (±1.8)	*July:* +2.4	
	Late Century			+0.8 (±1.9)	*July:* +2.8	
Unspecified watersheds, OR/WA/ID/MT	Early Century	DRTT	**Climate** *Number*: 20 *Emissions*: A1B	+0.55 (+0.01 to +1.09)	*Summer*: +0.92 (-0.27 to +2.66)	Wu et al. 2012
	Mid Century			+0.93 (+0.03 to +1.80)	*Summer*: +1.37 (-0.47 to +4.08)	
	Late Century			+1.68 (+0.08 to +3.17)	*Summer*: +2.10 (-0.46 to +5.81)	
124 sites, WA	Early Century	Statistical modeling approach [d/]	**Climate** *Number*: 19 *Emissions*: A1B, B1	-	*Summer:* [c/] < +1 to +2	Mantua et al. 2010
	Mid Century				*Summer:* [c/] < +1 to +4	
	Late Century				*Summer:* [c/] < +1 to +5	
Wenatchee, Icicle and Nason Creeks, WA	Early Century	QUAL2Kw	**Climate** *Number*: 39 *Emissions*: A1B, B1	-	*Summer*: A1B: +0.61 to +1.30 B1: +0.53 to +1.09	Cristea and Burges 2010
	Mid Century				*Summer*: A1B: +0.95 to +2.08 B1: +0.74 to +1.66	
	Late Century				*Summer*: A1B: +1.35 to +2.86 B1: +1.05 to +2.30	
South Fork Nooksack River, WA	Early Century	VIC Qual2Kw	**Climate** *Number:* 3 *Emissions:* A1B	-	*7-day changes for 7Q10 streamflow:* +1.4 to +1.9	Butcher et al. 2016
	Mid Century				+2.2 to +3.1	
	Late Century				+2.9 to +5.1	
Pacific Northwest region	Mid Century	NorWest spatial statistical network model	**Climate** *Number:* 1 *Emissions:* A1B		*August:* +0.73	Isaak et al. 2017
	Late Century				*August:* +1.42	
Columbia River basin and coastal drainages of OR and WA	Mid Century	Dominant river-tracing streamflow model	**Climate** *Number:* 1 *Emissions:* A1B		*Max weekly mean:* +1 to +4	Beechie et al. 2013
	Late Century				*Max weekly mean:* +2 to +6	
Columbia River Mainstem						
Mid-Columbia River basin	Mid Century	NorWest spatial statistical network model	**Climate** *Number:* 1 *Emissions:* A1B		*August:* +1.0	Isaak et al. 2017
	Late Century				*August:* +2.0	

Watershed/ Region	Future Period	Water Model(s)	Scenario(s) Used to Drive Water Models [a/]	Projected Water Temp. Changes (°C)		Citation
				Annual (Range)	Seasonal (Range)	
Columbia River at Bonneville	Early Century	VIC	**Climate** *Number:* 4 *Emissions:* A1B		*Summer:* +1.0	Yearsley 2009
	Mid Century				*Summer:* +1.7	
Columbia River Tributaries						
Columbia River, WA/ OR/ID (258,000 km^2)	Late Century	VIC-RBM	**Climate** *Number:* 6 *Emissions:* A2, B1	+1.6°C (95th percentile: +2.6°C)	-	van Vliet et al. 2013
Columbia River tributaries	Mid Century	Spatial stream network models	**Climate** *Number:* 1 *Emissions:* A1B		*August mean:* +1.1	Fuller et al, 2018
	Late Century				*August mean:* +2.0	
Columbia River tributaries	Mid Century	NorWest spatial statistical network model	**Climate** *Number:* 1 *Emissions:* A1B		*August mean:* +0.8	EPA 2018
	Late Century				*August mean:* +2.0	

DRTT= Dominant river-tracing-based temperature model; GLM= Generalized linear model; VIC= Variable Infiltration Capacity model; QUAL2Kw= water quality model; VIC-RBM= Variable Infiltration Capacity model, combined with a one-dimensional stream-temperature model referred to as the RBM. Early Century: approximately 2010 – 2030; Mid Century: approximately 2030 – 2070; Late Century: approximately 2070 – 2100.

3.3 SUMMARY OF HISTORICAL AND FUTURE IMPACT PROJECTIONS

Climate change has already and is projected to continue to influence river temperatures across the Northwest, including the temperatures of the Columbia and Snake Rivers, and will influence multiple aspects of river hydrographs, including timing and magnitude of river flow. Based on the synthesis herein, climate change has increased temperatures in the Columbia and Snake River mainstems by 1.5°C ± 0.5°C since 1960. From the present-day baseline, the warming trend is expected to continue in the coming decades. The two studies that specifically analyzed the Columbia River (Isaak et al. 2018 and Yearsley 2009) predict an increase in summer mainstem river temperatures of 1.7°C to 2.0°C by the end of the century. Similar increases are projected for Columbia River tributaries. These estimates are provided in a context of regionwide projections of river temperature increases in summer generally ranging from 1°C to 5°C by the end of the century.

3.4 UNCERTAINTY IN FUTURE IMPACT PROJECTIONS

The available projections of future air and water temperatures in the Northwest region and the Columbia and Snake Rivers are uncertain, because these projections are developed using models that represent atmospheric, hydrologic and heat transfer processes based on our current scientific understanding of those complex processes. In addition, the datasets used as the basis for the future climate projections including historical climate information and future estimates of human activities are imperfect and based on assumptions that may not hold in the future. Despite the limitations and uncertainties, the scientific projections point towards a distinctly warmer climate at the end of the 21st century (Rupp et al. 2017). The available research is unanimous in projecting warmer temperatures, but there is uncertainty in the slope of the trend at different periods of the 21st century. For example, Rupp et al. (2017) estimated that air temperatures at the end of the century will increase by 3.0 and 5.5 °C above the 1970-

1999 baseline average under the RCP4.5 and RCP8.5 scenarios respectively. The estimated temperature differences between the RCP4.5 and RCP8.5 projections were 0.5 °C by 2050, and 2.5 °C by 2099. Future air and water temperature warming rates will ultimately be dictated by the actual levels of greenhouse gas emissions and the evolution of the complex global energy system (Isaak et al. 2018).

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