Total Maximum Daily Loads for the Willamette Subbasins

Technical Support Document

Appendix G: Climate Change and Stream Temperature in Oregon: A Literature Synthesis

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State of Oregon
DEQ Department of Environmental Quality

This document was prepared by:

Joel Achenbach, Jordan Palmeri, and Ryan Michie

Oregon Department of Environmental Quality
Water Quality Division

700 NE Multnomah Street, Suite 600
Portland Oregon, 97232
Contact: Steve Mrazik
Phone: 503-229-5983 x267
www.oregon.gov/deq

State of Oregon
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1 Introduction

The principal question this literature review attempts to answer is if climate change is a source of stream temperature warming and what the impact has been.

Stream temperatures throughout the state of Oregon have generally shown an increasing trend over, at least, the past half-century. There have been a variety of studies published over the years that explore these rising stream temperatures and the causes. These studies have been performed at various spatial scales, ranging from the entire western-states region to individual stream reaches. Some studies have attempted to quantify the rate of change to date, some have attempted to apportion these observed changes into potential causes, and others have focused on projecting future changes to stream temperatures based on changes to air temperature and precipitation patterns predicted by global climate models. In the ensuing discussion, we synthesize this body of literature in pursuit of estimates of the impact from climate change on stream temperatures in Oregon. This analysis draws upon EPA's synthesis approach used for the climate change analysis in the Lower Columbia and Snake River Temperature TMDL (EPA, 2021).

This review begins with an inventory of the observed air temperature, stream temperature, and stream discharge trends in the Pacific Northwest documented in scientific literature. We then summarize several studies that illustrate the heterogeneity and complexity of stream systems, and their stream heat budgets. These studies demonstrate that basin-specific analyses are necessary to accurately attribute changes in stream temperature to various drivers (e.g., climate change versus land use changes).

2 Observed climate change impacts at the regional scale

Much of the literature on Pacific Northwest stream temperature trends incorporates trend analyses on air temperature and stream discharge. Some authors performed attribution analyses with linear regression techniques and assigned responsibility for the changes in stream temperature between these two other variables (e.g., Isaak et al., 2012, 2018). For these reasons, it was useful to include a review of air temperature trends and discharge trends en route to an inventory of stream temperature trends.

2.1 Air temperature trends

Statewide historical climate time series provided by the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI) estimated that the Oregon statewide average annual air temperature has increased at a rate of 0.12°C/decade from 1900 to 2020. August mean air temperature has increased at a rate of 0.15°C/decade over the same period. For the period of 1960 to present, that trend increases to +0.18°C/decade for the annual mean and +0.29°C/decade for the August mean temperature (NOAA, 2022).

Abatzoglou et al. (2014) analyzed long-term air temperature records in the Pacific Northwest and found that the mean annual air temperature in the region increased by approximately 0.6-0.8°C from 1901 to 2012 (+0.07°C/decade). Between 1970 and 2012 they found that trend was +0.20°C/decade.

Historic air temperature trends in the region were also presented by Isaak et al. (2017). Specifically, historic August air temperatures were developed as an input parameter into the NorWeST stream temperature model. The NorWeST model divides the western U.S. into 23 different geographic processing units (PUs) in its trend reconstruction analysis. These PUs were delineated based on physiographic similarity, expected data density, and National Hydrography Dataset (NHD) unit boundaries. The Oregon stream network lies within four of the 23 PUs (see Figure 2-1). For this literature synthesis, we reported only the trends for those four PUs, noting that those trends are not based exclusively on Oregon stream segments data (i.e., these four PUs include data from streams in neighboring states). This study reported that August mean air temperature trends in the Oregon-related PUs range from +0.29°C to +0.53°C per decade between 1976-2015 (see **Table 2-1**).

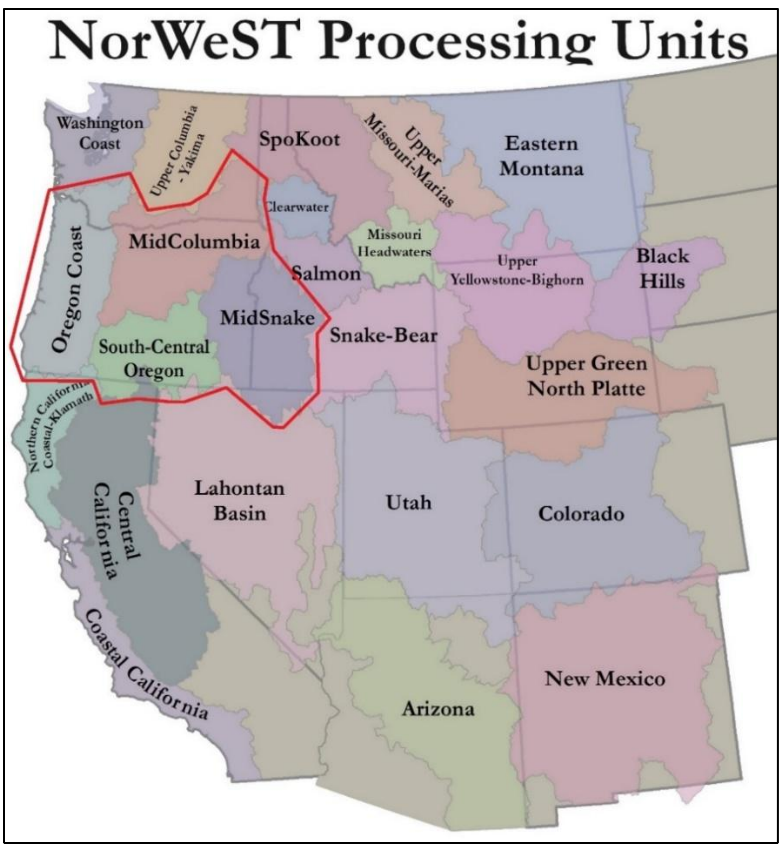

Figure 2-1: Map of NorWeST model area with Oregon-relevant processing units highlighted. Figure adapted from USFS (2022).

Table 2-1: Observed trends in average air temperature.

Location	Record of observation	Air temperature trend (°C/decade)	Source
Pacific Northwest (WA, OR, ID, & parts of MT)	1901-2012	JJA: +0.07 Annual: +0.07	Abatzoglou et al., 2014
	1970-2012	Annual: +0.20	
Oregon statewide	1900-2020	August: +0.15 Annual: +0.12	NCEI, 2022
	1960-2020	August: +0.29 Annual: +0.18	
Mid-Snake	1976-2015	August: +0.53	Isaak et al., 2017
Mid-Columbia		August: +0.45	
Oregon Coast		August: +0.29	
South-Central Oregon		August: +0.52	
Average of the 4 NorWeST Processing Units in Oregon		August: +0.45	
Notes: JJA = June, July, August; PU = processing unit.			

2.2 Stream discharge trends

When attempting to characterize historic stream temperature changes and attribute them to climate change vs. other factors, the role of stream discharge is an important consideration. Flow volume can mediate the effect of increased air temperature on river temperatures, as lower discharge volumes are associated with reduced thermal capacity and consequent increased sensitivity to air temperature (Isaak et al., 2018; Paul et al., 2019). This is especially relevant to temperature TMDLs, where the period of interest is the coincidence of summer low-flows and high air temperatures (Arismendi et al., 2013). Indeed, Isaak et al. (2012) showed that discharge accounted for approximately 50% of interannual stream temperature variability during summer months in northwest streams.

The Pacific Northwest is experiencing changes in both discharge timing and overall volumes. These changes are largely due to decreasing snowpack or earlier snowmelt, or both, which are in turn due to warmer winter and spring air temperatures (Dalton & Fleishman, 2021; Karl et al., 2009; Mote et al., 2018). Several studies have attempted to quantify this shift in discharge timing and the resulting declines in summertime streamflow magnitudes.

Stewart et al. (2005) analyzed streamflow time-series data from 1948 to 2002 for a network of 302 snowmelt-dominated gages in the western U.S. and found that regional streamflow timing, as measured by the dates of the spring pulse onset and the annual flow centroid, had shifted 10 to 30 days earlier over the 55-year study period. The authors also reported decreases in spring and early summer fractional flows across the snowmelt-dominated basins. Namely, between 1948 to 2002, the fraction of annual flow occurring between April and July decreased by 10% to 50%, and in June decreased by 5% to 25%. The authors used principal component analyses to conclude that these discharge trends were primarily attributable to increased air temperatures vs. precipitation changes.

Luce and Holden (2009) explored stream discharge trends from 43 stream gages in the Pacific Northwest over the period of 1948 to 2006. Six of those gages were in Oregon and three were just across the Oregon-Washington border. Of those nine relevant sites, seven showed statistically significant declines in the 25^{th} percentile annual flow, ranging in magnitude from a 20% to 40% decline (-3% to -7% per decade).

Isaak et al. (2017) also compiled historic stream discharge trends during the NorWeST stream temperature model development. As described in Section 2.1, we included in this literature synthesis only the trends for the four NorWeST PUs that overlap with Oregon (Figure 2-1). This study reported that mean August discharge trends in these PUs range from +0.2% to -8.5% per decade between 1976 to 2015.

Table 2-2: Observed trends in discharge in Oregon PUs.

Location	Record of observation	Stream discharge trend (%/decade)	Source
Western U.S.	1948-2002	Fraction of annual flow during spring/summer: -2 to -9	Stewart et al., 2005
7 stream gages in/near Oregon	1948-2006	Annual 25^{th} Percentile Flow: -3 to -7	Luce and Holden, 2009
Mid-Snake PU	1976-2015	August: -6.4	Isaak et al., 2017
Mid-Columbia PU		August: +0.2	
Oregon Coast PU		August: -3.9	
South-Central Oregon PU		August: -8.5	
Average of the 4 NorWeST PUs in Oregon		August: -4.7	
Notes: AMJJ = April, May, June, July PU = Processing Unit.			

The magnitude and character of streamflow regime changes depends on many geographic features (Chang and Jung, 2010), especially on whether the basin is rainfall-dominated, mixed rain and snow, or snow-dominated (Stewart et al., 2005). Many studies that explored Pacific Northwest hydrologic trends focused on snow-dominated systems. However, not all Oregon streams are snow-dominated, and therefore the regional trends discussed above and summarized in **Table 2-2** should be considered carefully when attempting to characterize a specific river system.

Three recent Oregon-based discharge trend studies used basin-specific analytical approaches vs. broad-scale regional approaches. These studies used global climate model projections as inputs to process-based hydrologic models to estimate potential future streamflow changes under different climate scenarios. The results of these studies general agreed with the historic trends summarized above. Burke and Ficklin (2017) applied a Soil and Water Assessment Tool (SWAT) model in the coastal Siletz watershed and compared mid-21^{st} century projections to a historic baseline of 1970 to 1999. Their results suggest that in the mid-21^{st} century Siletz River, the center timing of flow (CT) will shift roughly three days earlier, winter and early spring flows will increase by 5% to 10%, and summer low-flows will decrease slightly (<5%) vs. baseline. Yazzie & Chang (2017) used the Precipitation Runoff Modeling System (PRMS) to model flow changes in the snow-dominated upper Umatilla River in the mid-to-late 21^{st} century. Their results suggest that the CT will shift approximately 30 days earlier from the 1980s to the 2080s and mean summer flows may decrease by approximately 5% per decade. Chen & Chang (2021) used a SWAT model to project Clackamas River streamflow changes for the 2050s and

2080s. They found that the CT is expected to shift 2 to 3 weeks earlier and the 7 day low-flow is expected to decrease in most climate change and land use change scenarios.

3 Stream temperature trends

Three studies recently reported on observed trends in average stream temperature for unregulated streams and regulated streams in Oregon. The results are summarized in **Table 3-1** and **Table 3-2**.

In a national-scale study, Kaushal et al. (2010) analyzed stream and river temperature trends at 40 long-term river monitoring sites in the contiguous U.S. from 1978 to 2007. Nine sites were in Oregon watersheds; four of those were in minimally disturbed (“unregulated”) systems and five were in regulated systems. Average annual water temperature increased at rates from 0.09°C to 0.21°C per decade at unregulated sites, while (less consistent) temperature trends at regulated sites ranged from -0.38°C/decade (Blue River) to +0.30°C/decade (Rogue River). The Blue River monitoring site was downstream of a dam, and dam operations likely contributed to this anomalous trend (Kaushal et al., 2010).

Isaak et al. (2012) conducted a regional-scale study (Pacific Northwest and Montana) of stream temperature trends in both unregulated and regulated streams from 1980-2009. The analyzed sites included the same nine Oregon sites (four unregulated, five regulated) assessed by Kaushal et al. (2010). These two studies used different analytical methods and thus found slightly different trend estimates for the same sites, but the trend directions were consistent. Isaak et al. (2012) also calculated seasonal trends for each study site; the summer trends are reported in **Table 3-1** and **Table 3-2**.

Arismendi et al. (2013b) analyzed five long-term gage stations in minimally human-influenced (unregulated) forested western Oregon catchments. The authors evaluated trends in daily minimum, maximum, and mean stream temperatures for the period of 1979 to 2009. **Table 3-1** presents the annual average daily mean stream temperature trend for each gage; these trends follow closely with those reported in the other two studies.

Isaak et al. (2017) used a spatial stream network (SSN) statistical model (i.e., NorWeST) to evaluate historical stream temperature change trends for all streams (1:100k) in the western U.S (**Table 3-3**). This model was built from stream temperature data collected at over 20,000 sites from 1976 to 2015. This generalized linear mixed model included both random and fixed effects, including air temperature and stream discharge covariates, to predict temperature conditions. As explained in Section 2, the NorWeST model divides the model domain into 23 distinct PUs, four of which overlap with the state of Oregon. Reported modeled August stream temperature trends (**Table 3-3**) are comparable to observed field conditions (**Table 3-1** and **Table 3-2**).

The trends reported in **Table 3-1**, **Table 3-2**, and **Table 3-3** allow identification of a range of plausible historic climate change-driven stream temperature impacts across a variety of Oregon stream systems. As evident in the trends reported herein, stream warming rates are greatest in summer when flows are lowest and therefore most sensitive to air temperature increases (Isaak et al., 2018). Also, the trends in regulated systems are more variable, as upstream flow and temperature management can confound natural long-term warming trends in the data (Isaak et al., 2012).

Table 3-1: Observed trends in average stream temperature for unregulated streams.

Stream name	Gage ID	Location	Record of observation	Stream temperature trend (°C/decade)	P value	Source
Fir Creek	14138870	Brightwood, OR	1978-2007	Annual: +0.21	<0.05	Kaushal et al., 2010[1]
Bull Run River	14138850	Multnomah Falls, OR	1978-2007	Annual: +0.19	0.079	
NF Bull Run River	14138900	Multnomah Falls, OR	1979-2007	Annual: +0.09	0.340	
SF Bull Run River	14139800	Multnomah Falls, OR	1979-2007	Annual: +0.19	0.089	
Fir Creek	14138870	Brightwood, OR	1980-2009[2]	Annual: +0.11 JJA: +0.27	-	Isaak et al., 2012
Bull Run River	14138850	Multnomah Falls, OR		Annual: +0.12 JJA: +0.23		
NF Bull Run River	14138900	Multnomah Falls, OR		Annual: +0.09 JJA: +0.10		
SF Bull Run River	14138800	Multnomah Falls, OR		Annual: +0.11 JJA: +0.29		
Fir Creek	14138870	Brightwood, OR	1979-2009	Annual: +0.13	0.004	Arismendi et al., 2013b
SF Bull Run River	14139800	Multnomah Falls, OR		Annual: +0.07	0.207	
McRae Creek	TSMCRA	Linn County, OR		Annual: +0.22	<0.001	
Lookout Creek	TSLOOK	Lane County, OR		Annual: +0.26	<0.001	
Elk Creek	14338000	Jackson County, OR		Annual: +0.05	0.438	

Notes:

1) P-values for reported values with Kaushal et al., 2010 study represent values associated with reported annual estimates and decadal values were derived from these annual estimates.

2) 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).

Abbreviations: JJA = June, July, August; SF = South Fork; NF = North Fork

Table 3-2: Observed trends in average stream temperature for regulated streams.

Stream name	Gage ID	Location	Record of observation	Stream temperature trend (°C/decade)	P value	Source
Rogue River near McLeod	14337600	McLeod, OR	1979-2007	Annual: +0.30	<0.05	Kaushal et al., 2010 (see note 1)
Rogue River at Dodge Bridge	14339000	Eagle Point, OR		Annual: +0.21	<0.05	
North Santiam River	14181500	Niagara, OR		Annual: +0.21	<0.05	
South Santiam River	14187200	Foster, OR		Annual: 0.00	0.977	
Blue River	14162200	Blue River, OR		Annual: -0.38	<0.05	
Rogue River near McLeod	14337600	McLeod, OR	1980-2009	Annual: +0.25 JJA: +0.27	-	Isaak et al., 2012
Rogue River at Dodge Bridge	14339000	Eagle Point, OR		Annual: +0.17 JJA: +0.33		
North Santiam River	14181500	Niagara, OR		Annual: +0.16 JJA: +0.52		
South Santiam River	14187200	Foster, OR		Annual: -0.11 JJA: -0.33		
Blue River	14162200	Blue River, OR		Annual: -0.38 JJA: -0.48		

Notes:
1) P-values for reported values with Kaushal et al., 2010 study represent values associated with reported annual estimates and decadal values were derived from these annual estimates.
JJA = June, July, August

Table 3-3: Stream temperature trends for NorWeST Processing Units in Oregon.

Geographic region	Location	Record of observation	Stream temperature trend (°C/decade)	P value	Source
Mid-Snake PU	Southwest Idaho and Eastern Oregon	1976-2015	August: +0.24	-	Isaak et al., 2017
Mid-Columbia PU	North-Central Oregon & Southeast Washington		August: +0.19		
Oregon Coast PU	Coastal Oregon		August: +0.14		
South-Central Oregon PU	South-Central Oregon		August: +0.25		

NOTE: PU = Processing Unit

3.1 Air temperature baseline

Past studies that have quantified changes to climatologic variables in the Pacific Northwest have begun their change and trend analyses at approximately 1950 (Luce & Holden, 2009; Mote et al., 2018; Stewart et al., 2005). The authors of these studies generally justify the selection of ±1950 as the baseline using a few lines of evidence: (1) they note that there is a jump in the number of monitoring sites and the completeness of data records around this time; (2) they allude to analyses that show the most robust trends in the data begin around 1950; and (3) they cite even earlier peer-reviewed studies that also used 1950 as a baseline (Stewart et al., 2005).

A study by Abatzoglou et al. (2014) offers a further line of evidence for determining a climate baseline in the Pacific Northwest. This study used multiple linear regression (MLR) techniques to investigate the relative contributions of various climate drivers to the observed increases in air temperature from 1901 to 2012. The climate drivers they evaluated were solar variability, volcanic aerosols, internal climate variability (specifically, El Niño-Southern Oscillation and the Pacific North American pattern), and anthropogenic radiative forcing (representing the sum of radiative forcing by greenhouse gases, ozone, tropospheric aerosols, and land use and snow albedo changes). Importantly for the determination of a climate change baseline, the authors plotted the influence of each of these drivers with respect to time. These plots revealed a noticeable inflection point in the historic record at which anthropogenic forcing begins to show a greater (and steadily increasing) impact on air temperature. That inflection point is approximately the year 1960, as is clearly visible in **Figure 3-1**, under the heading “Anthro”.

Considering this analysis by Abatzoglou et al. and the established track record in peer-reviewed literature of using ±1950 as a baseline, we choose to define the air temperature baseline as the distribution of air temperatures prior to 1960.

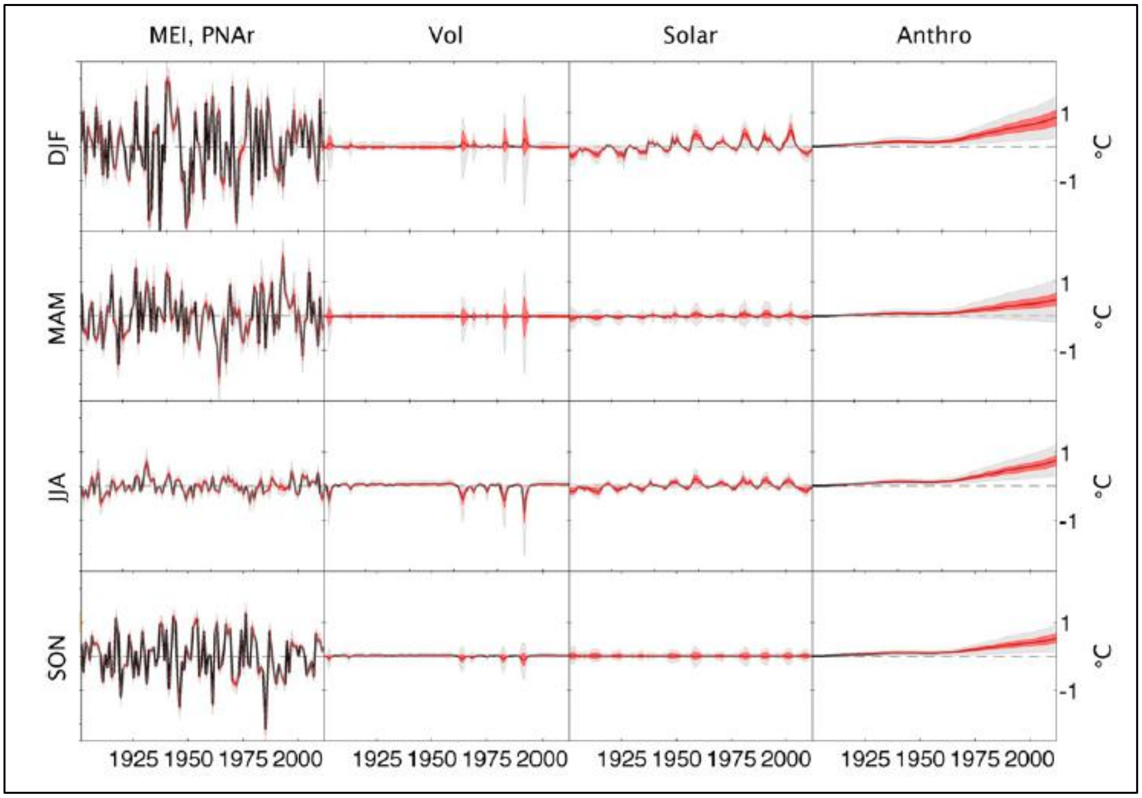

Figure 3-1: Drivers of air temperature in the Pacific Northwest during the 20th century. Taken from Abatzoglou et al., 2014.

3.2 Translating air temperature to stream temperature

The resiliency of river temperatures to changes in air temperature varies across the landscape. There can be a strong linkage between air temperature and water temperatures in some rivers, such as wide, low-gradient rivers with relatively long residence times and high river surface area exposure to solar radiation. For example, the Columbia and Lower Snake River Temperature TMDL (USEPA, 2020) included a successful translation of air temperatures to corresponding stream temperatures using an empirical conversion equation put forth by Mohseni et al. (1998) and applied to the Columbia River by Mantua et al. (2010). However, in smaller rivers, statistical models of stream temperature that are based solely on air temperature have been shown to perform poorly because they fail to capture the localized impacts of factors such as groundwater, flow regimes, riparian shading, latitude, and elevation (Arismendi et al., 2014). For many rivers, multivariate statistical models or mechanistic models at the basin scale are needed for detailed estimation of climate change impacts on river temperatures.

4 Analyzing climate change impacts at the basin level

Stream temperature is determined by different natural factors in a watershed, including, but not limited to, groundwater flux, stream discharge, solar radiation (riparian vegetation and/or topography), and air temperature (Webb & Nobilis, 2007). Anthropogenic factors, including groundwater and surface water diversions, deforestation, urbanization, thermal discharges, and hydromodification, also play a significant role (Kaushal et al., 2010; Nelson & Palmer, 2007). Each of these factors and their relative influence on stream temperature vary widely among stream systems in the state of Oregon, emphasizing the need for basin-scale analyses when trying to quantify the impacts of climate change in the context of a temperature TMDL.

4.1 Modeling approaches used in past studies

There are several studies in the Pacific Northwest that have used mechanistic or statistical models, or both to simulate changes in stream temperature that result from changes to climatic or geographic inputs.

As part of a synthesis of available climate change information, EPA's Columbia and Snake River TMDL assessment (2021) employed a multi-decade simulation of the RBM10 model to estimate temperature increases in the Columbia River. The overall synthesis of multiple studies supported an estimated historical increase in river temperatures since 1960 ranging from 0.2°C to 0.4°C per decade. The trend analysis of the RBM10 model output showed decadal changes at the upper end of that range, while air temperature regression estimates showed decadal changes at the lower end of the range. The RBM10 model results also indicated 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. A previous application of RBM10 Columbia River model was implemented in order to estimate the effects of future climate change, indicating that summer temperatures at Bonneville will increase by approximately 1°C above 1951 to 1978 baseline conditions at 2040 (Yearsley, 2009).

Diabet et al., (2012) and Wondzell et al., (2019) employed a Heat Source model for a 37-km section of the Middle Fork John Day River and evaluated the relative influence of three key variables on stream temperature (i.e., air temperature, discharge, and riparian vegetation) based on a range of future thermal regimes expected under a warming climate. Diabet et al., (2012) found the maximum 7-day moving average of the daily maximum (7DADM) river temperature increase in July resulting from a +4°C mean air temperature increase from the different scenarios evaluated ranged between 1.1°C and 1.9°C relative to the the 2002 baseline. The +4°C mean air temperature increase is based on the spatially and temporally downscaled 2080 mean air temperature increase from the B1 climate model (IPCC 2007) as calculated by Mantua et al (2010). Wondzell et al., (2019) found that riparian shading had the greatest influence on stream temperatures regardless of changes in air temperature or stream discharge. The authors also reported that changes of shade, air temperature, and stream discharge influenced the thermal regime in different ways, with changes of shade primarily impacting daily maximum water temperatures, air temperature changes uniformly impacting water temperatures throughout the 24-hour daily cycle, and stream discharge changes decreased the diurnal range of temperature conditions but had little impact on daily average temperatures. Additionally, they determined that incoming stream temperature in the upstream boundary had little effect on the maximum 7DADM at the downstream model boundary, as the 37-km reach was sufficiently long to dissipate this added heat by the bottom of the reach. Alternatively, the authors found that the downstream boundary temperature was sensitive to changes of tributary and groundwater inputs due to the numerous large tributary and groundwater sources located within this reach.

Butcher et al., (2016) used the mechanistic QUAL2Kw model to evaluate temperature response to climate change for the South Fork Nooksack River in western Washington. The QUAL2Kw model is the primary model utilized by Washington Ecology during temperature TMDL development. The authors reported that restoration of system potential vegetation shading would significantly mitigate expected impacts from increasing future air temperatures, along with the effects of the associated decreased stream flow conditions. However, the authors also determined that projected increases in heat inputs and lower summer flows may begin to overwhelm the mitigating impact of increased shading by the 2040s, with a high probability of exceeding cited lethal temperature thresholds under low flow critical conditions.

Similar results were reported in Yonce et al., (2021), which utilized a combination of hydrologic modeling, Soil and Water Assessment Tool (SWAT), and QUAL2K temperature modeling to evaluate the effectiveness of riparian buffers to reduce potential impacts of climate change on stream temperatures in Lookout Creek, Oregon. They determined that potentially warmer future climate conditions will not dramatically impact future summer base flow conditions in the Lookout Creek because this network is already a mixed snow and rain system and is expected to remain so with expected future climate changes. Accordingly, climate induced changes in hydrology were determined to not be a major factor causing future water temperature increases in the Lookout Creek. However, the QUAL2K modeling results showed that stream temperatures will increase between 17% and 38% under an existing riparian buffer condition by the late century due to effects of higher air temperature associated with climate change, and that riparian buffers cannot fully compensate or offset these expected water temperature increases.

The four examples above present mechanistic modeling efforts developed for only the mainstem reaches within each basin. Spatial stream network (SSN) statistical models have also been shown to accurately predict stream temperatures, while evaluating the effects of climate and land use changes (Fuller et al., 2022; Isaak et al., 2017). The SSN modeling approach incorporates random effects (i.e., spatial autocorrelation in stream flow associated with dendritic river network connectivity and branching) and localized fixed effect factors (i.e., riparian shading, air temperature, stream flow, groundwater, etc.) predictions of climate change effects on water temperature are accomplished through the manipulation of fixed effects. Finally, the SSN modeling approach estimates temperature conditions for all rivers within a basin, not only the mainstem reaches as is common in process-based modeling.

Isaak et al., (2017) developed an SSN model (i.e., NorWeST) to estimate historical stream temperature change trends for all streams (1:100k) in the western U.S. (**Table 3-3**). **Table 3-3** summarizes reported modeled historical August stream temperature trends for Oregon. Isaak et al., (2017) also found that future stream temperatures will continue to warm because of climate change, although variation of this future impact will likely occur within and among river networks due to local differences in climate forcing and stream responsiveness. The mean August stream temperature for the Oregon Coastal model processing unit which includes the Willamette, predicts an average increase of about 1.1 °C and 2.0 °C by 2040 and 2080, respectively. This increase is relative to the 1993-2011 baseline temperatures.

Fuller et al., (2022) developed an SSN statistical model to predict future climate change impacts for all Oregon tributary reaches of rivers that drain into the Columbia River. They reported that riparian restoration would result in large stream temperature reductions throughout the Columbia basin; however, climate change-driven air temperature increases, and flow decreases in the 2040s and 2080s would not be fully mitigated by riparian shade restoration alone. The authors reported a mean August temperature increase relative to the 2000s baseline with no change in vegetation is 0.97°C and 1.86°C by the 2040s and 2080s, respectively. The mean August temperature increase relative to the 2000s current condition baseline with rivers undergoing fully restored streamside vegetation is 0.1°C and 0.99°C by the 2040s and 2080s, respectively. These SSN statistical model results are similar to the trends reported above by other mechanistic modeling studies.

5 Oregon forests: contributions to carbon sequestration and emissions

In 2019, the Oregon Department of Forestry (ODF) and the U.S. Department of Agriculture Forest Service (USFS) Forest Inventory and Analysis Program published the *Forest Ecosystem Carbon Inventory Report (2001-2016)*, based on analysis of tree and other vegetation data from approximately 10,000 field plots distributed across Oregon's forests (Christensen et al., 2019). Each plot was visited once between 2001 and 2006 and once between 2011 and 2016 to estimate the total carbon mass in Oregon's forests and the carbon flux changes over the period. Measurements and models were used to estimate carbon flux through seven forest carbon pools (*i.e.,* live trees, standing dead trees, understory vegetation, down woody debris, forest floor, roots, and soils). Results indicated that approximately 70% of the carbon stored in Oregon forests was on public forest land with the National Forests comprising over half of forest-stored carbon (52%). Overall, just under half (49%) of forest-stored carbon was belowground in forest soils, and about a third (32%) was aboveground in the live tree pool. The remaining stored carbon was distributed among dead trees (2%), roots (7%), down wood (5%), forest floor (4%), and understory vegetation (1%).

Carbon flux across all assessed forest ownerships and ecoregions was approximately 30.9 ± 7.4 million metric tons CO_2-equivalents per year (MMT CO_2e/yr); in other words, carbon storage in Oregon's forests increased by approximately 31 MMT CO_2e/yr. The report highlighted those various ownerships stored additional carbon on the landscape at different rates. From 2001 to 2016, roughly 90% of total carbon flux (i.e., new storage) into forest ecosystems occurred on National Forests, where harvests declined after Northwest Forest Plan implementation in the 1990s (Krankina et al., 2012). Tree growth on corporate and State forests was greater than on non-corporate, USFS, and other ownerships. However, corporate and State forests also had the greatest carbon flux to harvested wood products (HWPs) from timber, which resulted in greater total annual flux estimate uncertainties. Results indicate that corporate and State ownerships may have removed carbon from the landscape faster than it was replenished through new tree growth, thus becoming net carbon emission sources.

When harvested timber leaves the forest, it enters the HWP pool. The revised *Oregon Harvested Wood Products Carbon Inventory 1906 to 2018* includes historical carbon storage and flux estimates for Oregon forest-derived HWPs (Morgan et al., 2022). As of 2017, of the cumulative estimated HWP carbon output since 1906 (2,986 MMT CO_2e), about 25% was in current-use products, 18% was in solid waste disposal sites, 19% had been emitted to the atmosphere by burning fuelwood for energy, and 38% had been emitted by decomposition or burning without energy capture.

From 2001 to 2016, carbon sequestration by Oregon forests exceeded emissions from timber harvest. During that period, the HWP carbon pool increased by approximately 8.4 MMT CO_2e/yr on average. The average net change in the combined forests and HWP carbon pools was approximately 39.4 MMT CO_2e/yr (31 MMT forests + 8.4 MMT HWP).

Major factors in this net carbon storage included reduced harvest and increased green tree retention on Federal lands following Northwest Forest Plan implementation (Krankina et al., 2012). This resulted in less total timber going to Oregon’s HWPs but a large increase in private forests’ proportional contributions to them. Corporate industrial forests’ annual carbon flux uncertainty was too large to determine if the net change was significantly different from zero; nonetheless, this sector contributed the most carbon to HWPs.

Research has shown that strategies including extended forest rotations, larger riparian buffers, and increased green tree retention can increase ecosystem-level carbon storage (Diaz et al., 2018; Griscom et al., 2017; Hudiburg et al., 2019; Law et al., 2018). Some such strategies have co-benefits for wildlife, water quality, and water temperature (Buotte et al., 2020). At the HWP level, longer rotations may also mean greater harvest volume (Anderson, 2022). Additional product-level strategies to increase carbon storage include material reuse and shifting from short-use HWPs (e.g., pulp and paper) to longer-use HWPs (e.g., residential and commercial construction products, engineered wood, wood fiber insulation).

When averaged from 2001 to 2016, Oregon’s forests were a net sink of atmospheric carbon. However, when USFS’s Forest Inventory and Analysis, inventory has assessed the full set of plot remeasurements, which include 2020 wildfire impacts, we may learn that Oregon’s forests can become a net source of atmospheric carbon. The ODF has completed comprehensive ecosystem and HWP carbon inventories under the forest carbon accounting framework, and is now developing capabilities to simulate carbon outcomes of alternative forest management scenarios to inform future management policies that integrate carbon mitigation and climate change effects.

6 Summary conclusion

The Pacific Northwest is showing an increase in stream temperatures due to the impacts of climate change, in part, from anthropogenic sources. There have been a variety of studies published over the years that explore these rising stream temperatures and the causes.

The publications reviewed report that since the late 1970s, climate change-driven stream temperature impacts have ranged from +0.05°C to +0.27°C per decade on unregulated streams and -0.48°C to + 0.52°C per decade on regulated streams. Stream temperature trends in regulated systems are more variable, as upstream flow and temperature management can confound natural long-term warming trends in the data (Isaak et al., 2012). The temperature impact in the summer months (June, July, and August) is greater relative to the annual average impact.

This review presented an inventory for some of the observed air temperature, stream temperature, discharge trends and contributions of carbon sequestration and emissions from forestry in the Pacific Northwest as documented in the scientific literature. Because stream systems and their heat budgets are heterogeneous and complex, rigorous site-specific estimates of climate change impacts require basin or river specific models. The models are increasingly showing evidence that increased riparian shading is the primary factor influencing stream temperatures and will subdue or mitigate the impact from air temperature or stream discharge changes over time. This literature report also revealed that in Washington state lower summer flows may begin to overwhelm the mitigating impact of increased shading by the 2040s with a high probability of exceeding cited lethal temperature thresholds under low flow critical conditions. This suggests riparian shading and minimizing water withdrawals during low flow periods are important management strategies to mitigate climate change-driven stream temperature impacts.

Oregon will benefit from ODF and USFS that are developing sustainable forest management plans for improving carbon sequestration and storage. A collaborative, multi-agency approach to lowering stream temperatures is critical. DEQ acknowledges the impacts of climate change on Oregon's waters and will continue to evaluate the results of models and the effects of potential mitigation strategies in TMDLs within the framework of meeting water quality standards.

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