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RESEARCH ARTICLE

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Warming of the lower Columbia River, 1853 to 2018

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Abstract

Water temperature is a critical ecological indicator; however, few studies have statistically modeled century-scale trends in riverine or estuarine water temperature, or their cause. Here, we recover, digitize, and analyze archival temperature measurements from the 1850s onward to investigate how and why water temperatures in the lower Columbia River are changing. To infill data gaps and explore changes, we develop regression models of daily historical Columbia River water temperature using time-lagged river flow and air temperature as the independent variables. Models were developed for three time periods (mid-19th, mid-20th, and early 21st century), using archival and modern measurements (1854–1876; 1938–present). Daily and monthly averaged root-mean-square errors overall are 0.89°C and 0.77°C, respectively for the 1938–2018 period. Results suggest that annual averaged water temperature increased by 2.2°C ± 0.2°C since the 1850s, a rate of 1.3°C ± 0.1°C/century. Increased water temperatures are seasonally dependent. An increase of approximately 2.0°C ± 0.2°C/century occurs in the July–Dec time-frame, while springtime trends are statistically insignificant. Rising temperatures change the probability of exceeding ecologically important thresholds; since the 1850s, the number of days with water temperatures over 20°C increased from ∼5 to 60 per year, while the number below 2°C decreased from ∼10 to 0 days/per year. Overall, the modern system is warmer, but exhibits less temperature variability. The reservoir system reduces sensitivity to short-term atmospheric forcing. Statistical experiments within our modeling framework suggest that increased water temperature is driven by warming air temperatures (∼29%), altered river flow (∼14%), and water resources management (∼57%).

KEYWORDS
climate change effects, estuary, river regulation effects, tidal river, water temperature

1 | INTRODUCTION

Increased air temperatures and extreme heatwaves are affecting ecosystem processes of the northeastern Pacific Ocean and the Pacific Northwest region of the United States and Canada, with consequences that are not yet fully understood, despite being widely acknowledged to have severe impacts on the biota (Brownlee, 2022; Crozier et al., 2019, 2020; McCullough et al., 2009). Both marine heatwaves occurring in oceanic and coastal waters, and terrestrial–aquatic heatwaves, have been attributed to anthropogenic climate change (Herring et al., 2018; Philip et al., 2022). A warming climate is predicted to increase water temperature in most streams of the

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Columbia River basin by 2°C–5°C by the 2080s, relative to the late 20th century (Ficklin et al., 2014; Mantua et al., 2010). Determining the cumulative effects of coastal watershed management in the context of such long-term environmental trends is a great challenge currently, which is extremely important for the purpose of informing future ecosystem management (National Academies of Science, Engineering and Medicine, 2022). The development and validation of approaches to resolve this challenge, particularly when endangered species are at risk, is an urgent task for interdisciplinary science today. This study develops a method to resolve and evaluate historical-to-present water temperature trends in regulated rivers, which affect aquatic life. In particular, the study area is home to the threatened and endangered, culturally and economically important, anadromous and resident fishes: Pacific salmon and trout (CEQ, 2022; Crozier et al., 2021; U.S. Department of the Interior, Bureau of Reclamation, 2016). Effects of thermal performance on physiological rates and in turn survival have been shown at all life stages of Pacific salmonids (FitzGerald & Martin, 2022).

The historical evolution and current trends in water temperature have profound implications for how large river systems, such as the Columbia River, are managed. In 1998, under the Clean Water Act, the states of Washington and Oregon listed parts of the Columbia and Snake Rivers as impaired waterbodies because the temperatures consistently exceeded the states' water quality standards of 20°C (Columbia Riverkeeper v. Pruitt, 337 F. Supp. 3d 989 (W.D. Wash., 2018)). Since then, temperatures have continued to surpass the threshold set by the states, especially in the summer. In 2015, an estimated 250,000 migrating sockeye salmon died because of dangerously warm temperatures in the Columbia and Snake Rivers (Columbia Riverkeeper v. Pruitt, 337 F. Supp. 3d 989 (W.D. Wash., 2018)). The U.S. Environmental Protection Agency (EPA) has determined that the modern reservoir system is a significant contributor to warming river temperatures, particularly in the late summer and early fall (U.S. EPA, 2003). Evaluating and quantifying other causes of increased water temperature has proven challenging, both due to the intermingled contributions of flow regulation, climate change, and land-use changes, and due to the lack of historical data prior to construction of dams (Bottom et al., 2011; Weitkamp, 1994). Within this context, water temperature models and data from the prereservoir period are important for defining a natural baseline against which to interpret modern patterns. Preliminary studies based on statistical models suggest substantial long-term changes; Bottom et al. (2011) estimated an increase of 1.8°C to 2.9°C from 1890 to 2002 at Bonneville Dam, located 235 km from the ocean at the upstream limit ("head") of tides. More than half of this increase (seasonally varying range of 0.8°C in summer to 2.0°C in autumn) was attributable to the reservoir system. Similar results were obtained by Overman (2017). However, these statistical approaches were based on monthly or biweekly averaged temperature, and therefore do not capture the effect of synoptic (5–7 day) weather patterns. These studies also did not compare hindcasts to prereservoir data.

In this study, we develop statistical models of daily water temperature back to 1853 at the head of tides in the Columbia River at Bonneville Dam, and compare model results against available measurements from 1854 to 1876 and the 1930s to the present. Widespread industrialization, flow regulation, navigational development, timber harvesting, agricultural irrigation, and other land-use practices have substantially changed the Columbia River basin over the past 150 years, particularly between 1900 and 1970 (Naik & Jay, 2005, 2011). Increasing air temperatures over the past century have caused a steep decline in the maximum snow water equivalent, leading to snow drought occurrences (Shrestha et al., 2021), and contributed to larger winter flows and a shift toward an earlier, smaller spring-melt freshet (U.S. Department of the Interior, Bureau of Reclamation, 2016; Mote, 2003; Stewart et al., 2005). The construction of 14 mainstem and more than 400 tributary dams between 1900 and 1970, but most prominently between 1953 and 1970, has deepened the system. For example, the depth of the Bonneville reservoir reach has changed from 3–15 m to 20–25 m, and altered residence time (U.S. Army, 1892, 1911; U.S. EPA, 2019). Additionally, at low water the pool just upstream of the John Day dam is up to 40 m greater today than historically (O'Connor et al., 2021). Compared to the 19th century, flow regulation has reduced average spring flows by >40% and increased winter flows by almost 60% (Jay & Naik, 2011; Naik & Jay, 2011; Talke et al., 2020). Annual mean flow has been reduced by about 15%–17%, equally attributable to climate change and irrigation diversion (Naik & Jay, 2011). Thus, measurements and model predictions before the 1880–1900 period represent a natural hydrological baseline. In this article, we examine two key questions. First, how have changes to river flow and climate affected daily fluctuations, seasonal patterns, and long-term trends in water temperature? Second, how different was the water temperature of the historical, 19th century system from the modern system? By using archival measurements and statistical modeling, we are able to obtain new insights into the causes of long-term water temperature changes, and attribute them among different system stressors.

2 | METHODS AND DATA

2.1 | Background: Columbia River hydrology

The Columbia River Basin (Figure 1) spans parts of seven states in the United States and the Canadian province of British Columbia, its 2000-km mainstem draining 668,000 km^2, and is the fourth largest river in the United States by average discharge at the mouth (Kammerer, 1990; Stanford et al., 2005). Originating in the Canadian Rocky Mountains, a variety of climates and ecosystems are found within the watershed, including desert, forest, shrubland, alpine, and riparian zones (National Research Council, 2004). Precipitation primarily falls as snow during the winter months, but as rain near the coast, while summers are dry. Prior to European settlement, snowmelt-driven peak flows usually occurred in May and June (Jay & Naik, 2011). There are currently 31 large dams along the Columbia River and its tributaries, which together make up the Federal Columbia River Power System. The first mainstem dams to come online

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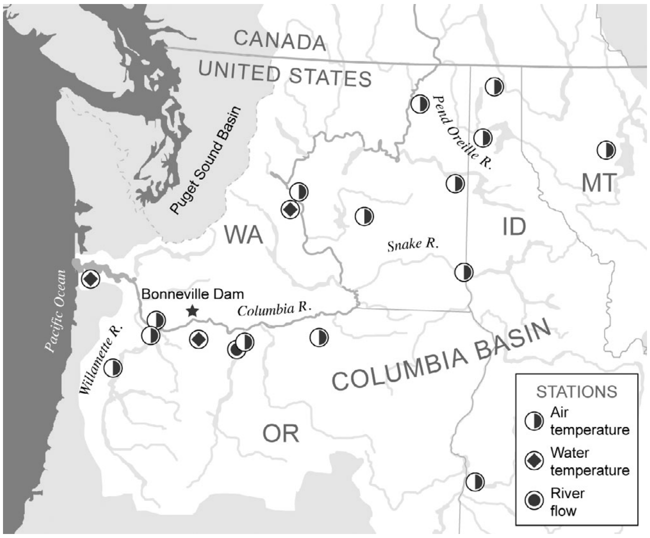

FIGURE 1 A map of the stations within the Columbia River Basin used in developing the statistical models.

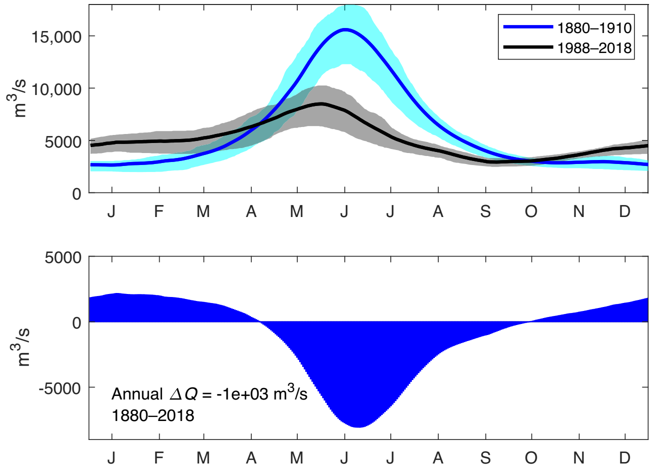

FIGURE 2 Annual hydrograph of the Lower Columbia River showing the change in river flow between the beginning and end of the 20th century. The data have been smoothed with a 30-day moving average. Data were obtained from the USGS gage at The Dalles. [Color figure can be viewed at wileyonlinelibrary.com]

were Rock Island Dam in 1933 and Bonneville Dam in 1938 (National Research Council, 2004; Petersen & Kitchell, 2001). The first major storage dam was the Grand Coulee dam (1942). Additional mainstem reservoirs continued to be built until 1984, though all but two were completed by 1970 (Bonneville Power Administration, 2001). Three of the four lower Snake River dams were completed by 1970, the last in 1975.

The timing and magnitude of river discharge in the Columbia River has greatly changed since the 19th century due to a combination of regulation, diversion, and climate change (Naik & Jay, 2011; Talke et al., 2020). The annually averaged discharge of the Columbia River at The Dalles (~River km 303) between water years 2001 and 2020 ranged from 3300 (2001) to 6750 m^3/s (2011), with a daily mean flow range between 1700 and 15,000 m^3/s (Figure 2). During the 1880–1910 period, average discharge was ~40% larger in the spring, but ~20% smaller during autumn and winter, than today (Figure 2; Naik & Jay, 2011; National Research Council, 2004). The causes and effects of altered hydrology are numerous. Irrigated agriculture has diverted water from the river, large-scale logging has altered the vegetation and landscape, and the hydroelectric power system has changed the volume and seasonality of river flow (Naik & Jay, 2005, 2011). Because of irrigation withdrawals, changes in climate, and deforestation, annual-average flows have decreased by about 15%–17% (Naik & Jay, 2011; Talke et al., 2020). The decrease in magnitude of the spring freshet is largely attributable to flow regulation; and the timing of peak flows has been affected by both human-caused and climate changes. European settlers first started bringing livestock and agricultural practices to the region in the 1820s–1840s (Gibson, 1985), while irrigation diversion began around 1840 (Simons, 1953). However, only after the beginning of the 20th century did these activities occur on a scale large enough to significantly impact the river system (Bottom et al., 2005; National Research Council, 2004; Sherwood et al., 1990). The timing of peak flows is thought to have been more influenced by climate prior to about 1920, while direct human activities more significantly modulated flows after about 1970 (Naik & Jay, 2011; Simenstad et al., 1992).

The factors that alter river hydrology also likely influence river water temperatures. Large-scale timber harvesting and grazing have reduced the vegetation and shading around tributary creeks and rivers and increased their widths, causing an increase in solar heating and water temperature (ISAB, 2011; National Research Council, 2004; White et al., 2017). Landscape changes, water diversions, and management practices associated with agriculture also likely affect water temperature (National Research Council, 2004). Storage reservoirs, by holding water in deep pools, increase the mean depth, heat storage capacity, and residence time of the system and influence temperature (Olden & Naiman, 2010; Webb & Nobilis, 1995). Finally, the Hanford nuclear reactor used water from the Columbia River to cool its reactors, particularly between 1955 and 1965. The resulting heating temporarily increased water temperatures by ~0.8°C to 1°C at Bonneville Dam, compared to the prereactor norm (Moore, 1968).

2.2 | Data

Three types of data, including air temperature, river flow, and water temperature, were used to construct and validate the statistical model described in section 2.3.

2.2.1 | Water temperature

The primary daily water temperature measurements were from Bonneville Dam, with additional data from Astoria (Oregon), Vancouver (Washington), and Rock Island Dam (Washington; Figure 1). For

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Bonneville Dam—located about 64 km upstream of Portland, Oregon, and Vancouver, Washington—the data came from two sources. Daily water temperature data from 1938 to 1990 were provided by the Northwest Power Planning Council (http://www.streamnet.org/files/407/StuTempData.html accessed August 1, 2018). See also Petersen and Kitchell (2001). For 1990–2018, data were provided by the United States Army Corps of Engineers (USACE http://www.nwd-wc.usace.army.mil/dd/common/dataquery/www/ accessed April 25, 2019). Up until 1993, measurements were recorded between 6:00 AM and 8:00 AM; thereafter, no timing information was available for measurements, which occurred either 0, 1, or 2 times a day. Comparisons with intermittent higher resolution data at hourly frequency (1992–2002) suggest that the uncertainty introduced by the lack of timing information is minor, and ranged from 0°C to 0.4°C. Therefore, a homogenous daily data set were produced by averaging data from days with two measurements.

Data quality and consistency were verified through comparison with nearby measurements. To verify historical data quality, we digitized and analyzed daily morning temperature measurements at Vancouver between 1941 and 1947. These archival measurements, made by the U.S. Weather Bureau, are available at the National Centers for Environmental Information (https://www.ncdc.noaa.gov/IPS/). Using daily and monthly averages, results show a root mean square error (RMSE) between Bonneville Dam and Vancouver of 0.85°C and 0.61°C, respectively. The Bonneville measurements were also compared with those taken by the USGS near Washougal, WA between 1997 and 2014, with a resulting daily RMSE of 0.8°C and mean bias of +0.09°C at Washougal. The RMSE for years between 2001 and 2004 was noticeably larger, and excluding these years lowered the daily RMSE to 0.54°C and shifted the bias to +0.1°C at Bonneville. Possible reasons for temperature variations include natural variability (in space and time) in a large water body, or instrumental and human errors. Nonetheless, this variability is fairly consistent over an extended duration. A monthly RMSE of ~0.6°C therefore approximates the inherent uncertainty, and represents a lower limit of accuracy against which to assess our statistical modeling (section 2.3).

Water temperature data from Astoria, Oregon (located ~25 km from the coast) are useful for investigating 19th and early 20th century conditions because they predate most hydrologic modifications. Daily measurements of surface water temperature were tabulated along with tidal measurements from 1854 to 1876, typically at 6:00 AM and 6:00 PM (Talke et al., 2020). All measurements were digitized and quality assured. Additionally, monthly averaged estimates of water temperature and density from the tide gauge station at Astoria-Tongue Point (29 km from the coast) are available from 1925 to 1955 (U.S. Department of Commerce. U.S. Coast and Geodetic Survey, 1954, 1956). Additionally, we digitized the daily measurement data upon which these averages are based for 1940–1942 (data in Moore, 1968) and obtained additional daily records from the National Oceanic and Atmospheric Administration (NOAA) for the years 1950–1995.

Modern, hourly measurements of water temperature are available from the NOAA tide station at Tongue Point from 1993 to the present (station 9439040). During low river discharge conditions (<3000 m^3/s) in the modern system, salinity intrusion reaches Tongue Point, particularly during neap tides (Chawla et al., 2008; Hudson et al., 2017). Therefore, modern measurements at Tongue Point are often affected by ocean water temperatures. Historically, this oceanic influence appears to have been less, or negligible, particularly in surface waters, because of lower salinity intrusion before channel deepening (e.g., Al-bahadily, 2020; Jay & Smith, 1990; Sherwood et al., 1990). Monthly averaged estimates of water temperature and density from the tide gauge station from 1925 to 1955 (U.S. Department of Commerce. U.S. Coast and Geodetic Survey, 1954, 1956) suggest that, historically, the location was primarily freshwater and only exceeded a monthly average of 3.26 practical salinity units (PSU) during periods of anomalously low discharge. A comparison against monthly averaged river stations made in 1940–1942 between Warrendale, OR (rkm 226) and Astoria, OR (rkm 28) suggests a seasonally varying bias of 0.3°C–1.8°C, with the largest bias (Warrendale higher) during low-flow periods. The low-flow bias may occur because of salinity intrusion, but also because during low Columbia River discharge, coastal tributaries downriver of Bonneville (with different water temperatures) become a larger proportion of the measured river signal in the tidal river and estuary (Jay et al., 2015, 2016). Overall, the observed Astoria water temperature from the monthly averaged river stations is biased slightly high relative to Bonneville in winter, and slightly low in summer. We addressed this possible bias in daily records by only using time periods where the salinity was ≤2 PSU at Tongue Point, based on a modeled historical relationship between discharge and salinity (Al-bahadily, 2020).

The Astoria data from 1854 to 1876, bias-corrected to reflect conditions at the location of Bonneville Dam, were used to develop a 19th century temperature model of the Columbia River (section 2.3; see Data S1 for more information). The monthly root-mean-squared error (RMSE) between the true Bonneville and estimated Bonneville measurements based on Astoria data from 1938 to 1947 is 0.6°C. This RMSE is comparable to the RMSE of 0.61°C measured between Vancouver and Bonneville 1941–1947, and suggests that bias-corrected Astoria data are a reasonable proxy for Bonneville Dam temperatures.

Lastly, to compare how temperature differences between Bonneville Dam and the upper basin changed over time, we analyzed water temperature data from Rock Island Dam, located at river kilometer 729 (source: USACE; http://www.nwdwc.usace.army.mil/dd/common/dataquery/www/). The Rock Island data span the period from 1933 to the present and are useful for ascertaining changes as additional dams were constructed along the river.

2.2.2 | Air temperature

Daily maximum air temperatures 1850–2018 were obtained from multiple sources and for 13 locations throughout the basin (Figure 1). Air temperature datasets from 1892 to the present were obtained from NOAA's National Centers for Environmental Information. Earlier

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records from 1849 to 1891 were obtained from the Midwestern Regional Climate Center (2000) (https://mrcc.purdue.edu/, see Table S1), based on tabulations from the U.S. Signal Service and individual observers. The longest, most complete datasets begin in the mid–late 1800s in Spokane, WA (1881), Vancouver, WA (1849), and Portland, OR (1875). An additional 10 stations span nearly all of the 20th century (Table S1).

Many of the air temperature measurements are occasionally affected by small changes in gauge location including elevation. Consequently, there are biases inherent in the raw data. Because it is challenging to precisely quantify and correct for these biases, we also used bias-corrected daily air temperature from Berkeley Earth's daily gridded datasets (http://berkeleyearth.org/data/, accessed August 25, 2019). Water temperature models based on the bias-corrected temperature records were subsequently compared to model results based on raw data, to assess possible systematic bias.

2.2.3 | River flow

Daily measurements of river discharge are available from The Dalles, Oregon from 1878 to the present (U.S. Geological Survey station 14105700). For 1854–1876, we used daily incremented, 30-day average discharge estimates based on an analysis of tide gauge records in Astoria (Talke et al., 2020). These discharge estimates include the effect of coastal tributaries, particularly during the rainy season (November–April) and are therefore slightly larger on average than measurements at The Dalles (~20%).

2.3 | Statistical model

We used a statistical modeling approach to estimate daily water temperatures at the site of Bonneville Dam for time periods for which no records are available, and to investigate reasons for secular trends. The statistical model is motivated by the one-dimensional (1D) advection–diffusion heat balance equation, but simplified to a linear regression approach following other studies (e.g., Benyahya et al., 2007; Talke et al., 2023; see Data S1). Such statistical models are advantageous because they are simple, require fewer computational resources, and can span much larger spatial and temporal time scales than deterministic models (Benyahya et al., 2007; Caldwell et al., 2013). A correlation between air temperature and water temperature is the driving mechanism behind most such models, though other inputs such as river flow are also often used (Benyahya et al., 2007; Bottom et al., 2011; Caldwell et al., 2013; Erickson et al., 2000; Gu, 1998; Moore, 1968; Neumann et al., 2003; Pohle et al., 2019; Stefan & Preud'homme, 1993; Webb et al., 2003).

Here, we modeled the stochastic variability of water temperature. In this approach, the climatological average was removed from the data and the remaining deviations from the mean, called the residuals, were used for model development (Benyahya et al., 2007; Caissie et al., 1998). By using the daily deviations from the mean, much of the seasonal autocorrelation inherent in environmental variables such as temperature is removed. Thus, the assumption of time-independence in the statistical regression analysis was satisfied. Additionally, many studies demonstrate that including air temperature from previous days as a regressor can improve model performance, particularly in deep rivers (Erickson et al., 2000; Stefan & Preud'homme, 1993; Webb et al., 2003). The observed decorrelation structure with time is directly related to system depth; deeper systems react to air temperature fluctuations more slowly than shallow systems (Stefan & Preud'homme, 1993). We therefore also included time-lagged air temperature in our model. Stefan and Preud'homme (1993) outlined a simple way to estimate the daily time lag (δ) based on the average river depth (h) and the thermal diffusivity coefficient (α):

$$\delta = \frac{h}{\alpha} \qquad (1)$$

where $\alpha = \frac{K}{\rho c_p}$, ρ and c_p are the density and specific heat of water, and K is the surface heating coefficient. A typical value for K is ~30 W/m$^{2\circ}$C for an average wind speed of 5 m/s and average water temperature of 15°C (Edinger et al., 1974).

Based on these considerations, we developed a regression model, which relates the daily water temperature anomaly, $T_w{}'$, to the corresponding air temperature anomaly $T_a{}'$ and the river discharge anomaly, $Q_p{}'$, (see also Talke et al., 2023)

$$T_w{}'(t) = a + \sum_1^n b_n * T_a{}'(t-n) + \sum_1^m c_m * Q_p{}'(t-m). \qquad (2a)$$

In Equation (2a), b_n represents the correlation coefficient between the river temperature anomaly at time t and the air temperature anomaly n days earlier. Similarly, c_m represents the correlation coefficient between the river temperature anomaly at time t and the river discharge anomaly centered m days earlier. Each anomaly $\varepsilon'(t)$ is defined by subtracting the climatological average for a specific yearday, $\bar{\varepsilon}(t)$, from the measured data $\varepsilon(t)$, i.e.,

$$\varepsilon'(t) = \varepsilon(t) - \bar{\varepsilon}(t), \qquad (2b)$$

where $\varepsilon(t)$ is either T_w, T_a, or Q_p. The averaging time is chosen to be long relative to interannual variability, but short relative to long-term trends (see section 2.3.1). A 30-day moving average is applied to each $\bar{\varepsilon}(t)$ to reduce noise. We calibrated models based on Historical (1855–1868), Pre-Dam (1938–1952), and Modern (2004–2018) data. Each period roughly represents a system state: the earliest beginning with the treaties of 1855 in the Columbia Basin, which had been made up of contiguous territories of Native villages and bands as recently as 1850 (Ray, 1936); early 20th century conditions, but still prior to the start of most Columbia River flow regulation; and modern conditions. In practice, data availability and the need to avoid the warming caused by the Hanford nuclear reactor limit the Historical (1855–1868) and Pre-Dam (1938–1952 calibration periods to 14 and 15 years, respectively. For example, the Historical calibration (1855–1876) was based

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on the availability of air temperature records at Vancouver (1849–1868) and water temperature at Astoria (July 1854–October 1876). For consistency, and to minimize the influences of any trends in the data, we defined the "Modern" statistical model based on data from 2004 to 2018. Although some reservoirs came online before 1953 (such as Bonneville Dam), large storage capacity reservoirs primarily came online after 1953; hence, we refer to the period from ~1900 to 1953 as "Pre-Dam." We note that any statistical regression approach cannot easily assess the contributions of individual factors such as changed snow-pack or shading to altered water temperature, and a physics-based modeling approach may be more appropriate for future projections (e.g., Caldwell et al., 2013; Ficklin et al., 2014; Mantua et al., 2010). Nonetheless, our approach was able to quickly assess, to first order, changes to the system that would be challenging within a modeling framework (e.g., the integrated effect of reservoirs and landscape changes over long time scales; see results). Further, the insights from our measurements and model results can be used to inform future numerical modeling efforts.

A robust least-squares regression approach was used to determine the coefficients in Equation (1). The total number of time lags, n and m, were determined through trial and error, and only coefficients statistically significant at the 95% confidence level were retained. The daily time lags simulate the effect of synoptic scale fluctuations (e.g., heat waves or cold snaps). For time lags n larger than ~2 weeks, a block average approach was required to obtain statistically significant correlations.

2.3.1 | Implementation of statistical model

Regression models for the Historical, Pre-Dam, and Modern periods were produced for each long-term meteorological station, a total of 13 locations (Table S1). Additionally, we developed "winter," "summer," and "annual" statistical models for each location and time period, for a total of 108 models. Both theory, results from other watersheds (e.g., Laizé et al., 2017), and our analysis of data suggest that the important terms in the heat balance shift seasonally; for example, the spatial gradient of water temperature (dT_w/dx) between Rock Island Dam and Bonneville Dam is typically lower during the winter than the summer months (~0.2 vs. 0.6°C per 100 km). For all three periods, the overall fit to the data (as measured by RMSE) improved by defining seasonal models for winter and summer, and using a model based on all data ("annual") for the remaining periods, as compared to using the annual model for the whole year. The months of the year used for the seasonal model were determined through experimentation (Table S2). Air temperature was more strongly correlated with water temperature as compared to river flow, and showed a consistently positive correlation. River flow was less correlated with water temperature, and displayed more variable correlation across seasons giving evidence to the complex relationship between the two parameters (Ficklin et al., 2014; Webb & Nobilis, 2007). Including river flow as an input improved the RMSE of each model, as much as 0.2°C depending on the season and time period; thus, river flow was included in the final versions of the models.

2.3.2 | Model validation

Examples of the composite model fits for the three different model periods are shown in Figure 3. Overall, the results show that the model captures seasonal and interannual variability well. The model also captures the timing of daily and weekly heating or cooling events (see e.g., Figure 3b), but appears to be overdamped. Hence, the model is successful at capturing overall patterns and the timing of extremes, but less able to capture the magnitude of short-term fluctuations.

The RMSE errors for each of the three models applied to each time period from Vancouver are shown in Table 1. Each model does significantly better than a model based solely on climatology, with daily RMSE values of 0.67 to 0.90°C compared to 1.01°C to 1.31°C for climatology. On a monthly averaged basis, the RMSE between composite model and measurements is 0.54°C to 0.75°C, only slightly larger than the ~0.6°C RMSE in monthly averaged water temperature observed between pairs of nearby instrumental measurements (see section 2.2). These considerations suggest that much of the modeled residual is attributable to measurement bias, uncertainty, and cross-

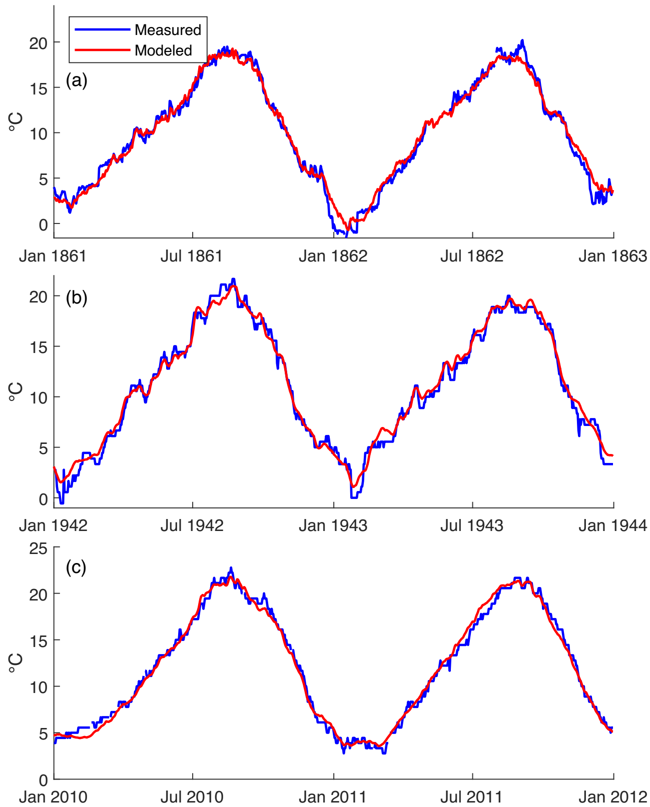

FIGURE 3 A comparison of the measured data and modeled results at Bonneville, for the years (a) 1861–1863, (b) 1942–1944, and (c) 2010–2012. The measured data in (a) is from Astoria, which was bias-corrected to reflect Bonneville conditions. [Color figure can be viewed at wileyonlinelibrary.com]

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TABLE 1 Comparison of RMSE values for the calibration periods of each model using Vancouver T_a.

RMSE	Historical (1855–1868)	Pre-dam (1938–1952)	Modern (2004–2018)
Daily, modeled	0.80°C	0.90°C	0.67°C
Daily, based on climatology	1.11°C	1.31°C	1.01°C
Monthly	0.56°C	0.75°C	0.54°C

sectional variability, though uncertainties in air temperature measurements and model coefficients also contribute. Expressed in terms of variance, ~60%–70% of the variance present in the measured temperature fluctuations $T_w{}'$ are represented in the model. Though there are likely some unmodeled processes (particularly on the synoptic time scale) and some unresolvable uncertainty, the overall agreement is good.

2.3.3 | Hindcast model

For each available meteorological station, we applied the statistical models from each time period and developed a composite data set for each meteorological station. First, the winter, annual, and summer model results from each time period were stitched together (Figure 1). The annual model estimates were used for any days not within the summer or winter models. The "Historical" model was used prior to 1880, the Pre-Dam model was applied for records between 1880 to 1969, and the "Modern" model was applied after 1970, the year commonly identified as the approximate beginning of modern reservoir management (Sherwood et al., 1990). The start of the Pre-Dam model was chosen as 1880 based on the observation that anthropogenic landscape and irrigation effects become noticeable around 1900 (Bottom et al., 2011), but likely started somewhat earlier. Additionally, daily river flow data and bias-corrected air temperature data (from Berkeley Earth) are available starting in ~1880, but not before. Since the Historical Model is based on Astoria water temperature and river flow data, it is most appropriate for the pre-1880 period. To avoid small discontinuities between model predictions, we applied a weighted average to the 5 years before and after the transition years (1880 and 1970). The weights were chosen to linearly vary between zero and one over 10 years. We later assess the validity of our modeling through comparisons of different models and in situ data.

Estimates of water temperature based on available data were produced for each station. For the rest of the article, we focused on the model made using Vancouver, Washington air temperature data, based both on its good skill (Table 1) and its long data set (starting in September 1849). Vancouver measurements from 1850 to 1868 are available from the FORTS data set, and records from 1868 to 1879 were infilled using Fort Colville, Washington (after experimentation with other data sets). Data from Berkeley Earth were used from 1880 to 2018, to remove the known bias caused by a station move in 1966. An overview of the Vancouver composite model is provided in Table S2. The overall RMSE of the composite Vancouver water temperature record compared to daily measurements from 1938 to 2018 is 0.91°C. Other statistical models of river temperatures in different systems perform similarly, with an RMSE range of 0.6°C–1.9°C (e.g., Benyahya et al., 2007; Wagner et al., 2011).

A sensitivity study showed that statistical models based on individual stations provides nearly the same skill as using empirical orthogonal functions (EOFs; Scott, 2020; see Data S1). Approximately 87%–88% of the variance within the system was accounted for through the first mode, and only 6%–7% and 1%–2% by the second and third modes. Hence, meteorological stations relatively far apart—such as Vancouver and Spokane, Washington—are equally capable of assessing water temperature at Bonneville Dam. Because a model based on EOFs produced a small (negligible) improvement in predictability, we therefore retained and analyzed the simpler station-based approach, here.

2.4 | Attribution through scenario definition

We explored the reasons for water temperature changes via model experiments by changing just one input parameter (e.g., air temperature) or model at a time, with other factors held equal. The effect of a changing climate is approximated by applying the air temperature climatology from two periods, 1880–1910 and 1988–2018, as inputs to the Pre-Dam model. The effects of changing river flow are approximated by applying the differences in river flows from the same two periods to the "Pre-Dam" and "Modern" models. The current effects of reservoirs and reservoir management are explored using the "Pre-Dam" and "Modern" models, using inputs from the same time period (2000–2018). Other potential climate-induced changes, such as changed evaporation or altered snow pack, cannot be accounted for. To determine how much the reservoir system has increased water temperatures, we also tested a scenario in which both the model coefficients and river flows are altered. Our linear approach cannot assess coupled, interacting changes (e.g., the effect of a changing landscape on air temperatures) or completely de-convolve changes that have multiple factors (such as altered river flow, which depends primarily on reservoirs and their management but is influenced by climate change). Nonetheless, as shown below, our attribution approach provides first-order insights into the factors causing altered water temperatures.

3 | RESULTS

3.1 | Measured and modeled water temperature changes

Both observations and our modeling show that river water temperatures have significantly increased and seasonal patterns have shifted

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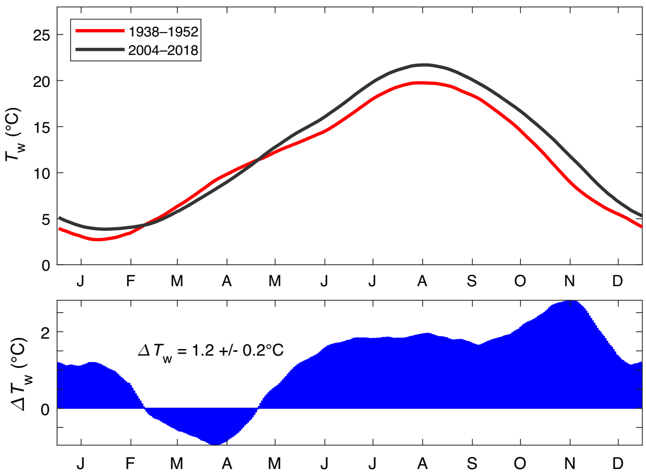

FIGURE 4 Measured change in T_W at Bonneville between 1938 and 2018. A river climatology was calculated based on 30-day average T_W for the periods 1938–1952 and 2004–2018. The uncertainty is based on the difference in standard deviations for each climatology period. [Color figure can be viewed at wileyonlinelibrary.com]

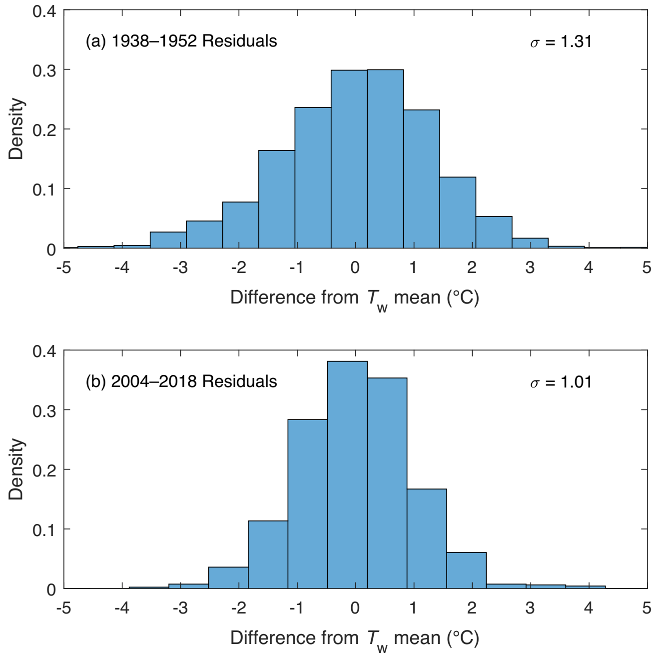

FIGURE 5 Comparison of histogram of water temperature residuals between the periods 1938–1952 and 2004–2018. The histograms have been normalized and the standard deviation is shown. [Color figure can be viewed at wileyonlinelibrary.com]

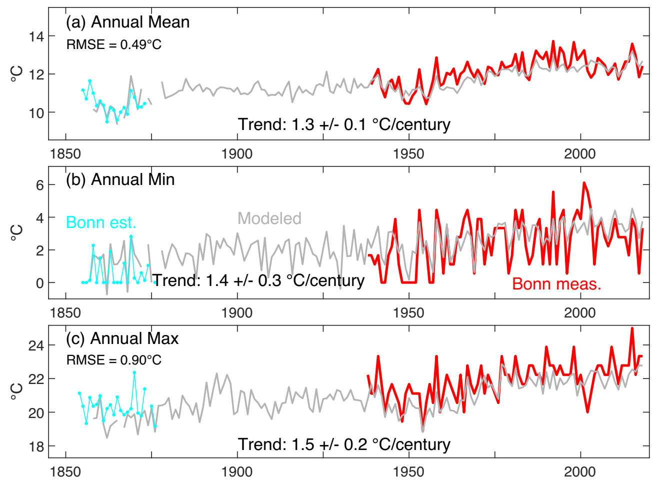

FIGURE 6 Annual mean, minimum, and maximum water temperature trends based on measurements (red: Bonneville; cyan: Bonneville estimated from Astoria) and the composite model (gray: Vancouver). A linear trend (based on model results) is included for each metric with the standard error of the slope of the regression. RMSE, root mean square error. [Color figure can be viewed at wileyonlinelibrary.com]

since the development of the Columbia River reservoir system in the 1930s. A river climatology calculated from measurements at Bonneville Dam for 1938–1952 and 2004–2018 shows an average annual water temperature increase of 1.2°C ± 0.2°C between these two periods (Figure 4). Seasonally, the largest measured increase occurs in the fall and early winter months (~2°C), while a statistically insignificant decrease in water temperature occurs during the early spring (Figure 4). A similar comparison between water temperatures of 1855–1875 and 1938–1952 suggests an increase of 1.0°C ± 0.3°C relative to the pre-dam period. Combined, the total measured increase over the past 160 years is ~2.2°C, with a larger rate of change observed since the mid-20th century. The statistical variance in water temperatures also decreased from 1938 to 1952 and 2004 to 2018, likely due to a more tightly regulated system (Figure 5).

Model estimates of the annual average, maximum, and minimum water annual water temperature agree well with measurements and depict a long-term upwards trend that is interspersed with significant interannual variability (Figure 6). The average rate of change in T_W at Vancouver is modeled to be 1.3°C ± 0.1°C/century, for a total simulated change of 2.2°C ± 0.2°C since the mid-19th century. These values agree well with existing literature and the empirical measurements discussed above. For example, Bottom et al. (2011) estimated a 2°C–3°C increase between May and December from 1890 to 2014, and Overman (2017) found a 1.5°C increase between 1938 and 2003. Additionally, an EPA report draft estimated a 1.5°C ± 0.5°C increase in the lower Columbia River since about the 1960s (U.S. EPA, 2018).

Annual minimum and maximum water temperatures are modeled to be increasing at 1.5°C ± 0.3°C/century and 1.4°C ± 0.2°C/century, respectively (Figure 6). Trends in the mean, maximum, and minimum are similar when composite models based on Portland and Spokane air temperature records are used (Table 2); because other records are generally shorter or incomplete, they are not included in our long-term trend estimate. Most modeled and measured trends agree, to within statistical confidence (Table 2). Overall, our confidence in the trends in extremes are less than the annual average. Thus, the RMSE for the annual mean Vancouver composite model was 0.49°C,

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TABLE 2 Estimated long-term trends for three statistical T_w models, each using a different air temperature input.

Trend (°C/century)	Vancouver	Portland	Spokane
Annual mean	1.3 ± 0.1	1.5 ± 0.2	1.2 ± 0.2
Annual min	1.4 ± 0.3	1.8 ± 0.4	1.6 ± 0.4
Annual max	1.5 ± 0.3	1.7 ± 0.3	1.5 ± 0.3

Note: These are linear trend estimates over the duration of the model and therefore may not fully capture the change in trends over time.

compared to values of 1.10°C and 0.90°C for the annual minimum and maximum, respectively (Figure 6 and Table 2).

Periods of particularly high water temperatures are correlated with climatic fluctuations (Figure 6). For example, the higher-than-usual maximum water temperatures observed in 1941, 1958, and 1998 (Figure 6) coincided with large El Niño events (Kaplan et al., 1998; Talke et al., 2020), though we note that other large El Niño events such as 1877 and 1983 were not particularly extreme for T_w. Similarly, cold periods such as the early 1950s show up in the minima of both measured and modeled records. These observations are broadly consistent with Petersen and Kitchell (2001), who noted correlations between Columbia River water temperatures and decadal climate variability such as the Pacific Decadal Oscillation. Nonetheless, several periods of bias appear within the measurement/model comparison. First, measured temperatures are biased high during the 1955–1970 period; it has previously been shown that during 1951–1953, water temperatures were likely higher in the Hanford Reach than downstream, while after the last production reactor closed in January 1971, 1986-1988 temperature upstream and downstream were similar (Becker & Gray, 1992). Similarly, model estimates of average water temperature are biased somewhat low during portions of the 1980s and 1990s. This bias may occur due either to the shift in the time of day measurements were made, or may reflect changes in reservoir management. For example, in the 1990s, in response to concerns about water temperature, a policy of selected releases of colder bottom water (rather than surface water) was begun (National Research Council, 2004).

Seasonally, the largest modeled increase in bimonthly averaged temperature occurs during the summer and fall months (July–December), with a long-term trend of 2.0°C ± 0.2°C/century on average (Figure 7). The smallest seasonal modeled T_W change occurs in the spring, with a statistically negligible trend of about −0.22°C ± 0.2°C per century estimated for the March and April time frame (Figure 7). As discussed below, these divergent seasonal trends are explainable by: a) engineered system alterations (e.g., reservoir management but also potentially land-use), b) climate change-induced trends in air temperature, and c) river flow decreases. Here, we note that modeled trends and interannual variability match measurements much better during the May–October period than the November–February period. The reasons are unclear, but might be related to the influence of coastal tributaries and/or the much larger divergence between inland and Coast Range alpine temperature patterns in winter because inland areas get much colder.

3.2 | Temperature exceedances

The overall increase in monthly temperatures, combined with the observed decrease in temperature variance, have combined to greatly alter the number of days per year that exceed the threshold of 20°C. Results suggest that the yearly maximum water temperature comes on average ∼1–2 weeks earlier in the year than it used to, compared to the mid-19th century (Figure 8). Furthermore, the time spent over the 20°C threshold has increased from as little as a few days a year in the 1800s (Figure 8) to as many at 100+ days (e.g., in 2015). Less obviously, the system before ∼1970 used to exceed, and then fall under, the 20°C threshold multiple times a year. The combination of increased average temperatures with reduced variance (see Figure 5) has combined to make the threshold exceedance essentially continuous in some years. Stated differently, the possibility of "temporal refugia"—temporary dips in system temperature below the 20°C threshold—has almost disappeared during mid-summer. Moderately to slightly different results are obtained using the statistical model vs data; for example, the average exceedances for the 1940–1950 decade was 27 days/year (measurements) and 13 days/year (model). For the 2000–2010 decade, the average threshold exceedance was 67 days/year (measurements) and 64 days/year (model; Figure 9).

On a decadally averaged basis, the number of days per year over 18°C and 20°C have each increased by about 40 days per year since the mid-1800s, to 100 and 60 days, respectively (Figure 9). Since the 1970s, the system has increasingly exceeded the 22°C threshold, yet this threshold was rarely if ever exceeded before 1940 (see also Figure 8). Although a tabulation of threshold exceedances is much more sensitive to measurement and model uncertainty than long-term trends, measurements and models agree well with each other on the decadal scale, for both 19th century and modern comparisons (Figure 9), and similar trends are observed for different thresholds. Due to climate change, the number of days per year over a threshold are projected to continue rising quickly (e.g., Mantua et al., 2010). Hence, we conclude that the increased number of warm-water days is a robust result and consistent with other studies.

The number of days below a threshold is a less studied water temperature change, but may also be relevant ecologically. The number of days per year that the system is lower than 2°C has decreased by 10–20 days since the mid-1800s, and was zero in the most recent decade (Figure 9). This modeled result is consistent with the observation that the Columbia River used to freeze over during some winters before 1940, but rarely does now (Spranger, 1996). Similarly, the number of days below 4°C has been cut by more than half, to about 30–35 per year today.

4 | DISCUSSION

Warming temperatures in the Columbia River carry both ecological and regulatory consequences. For example, frequent temperatures

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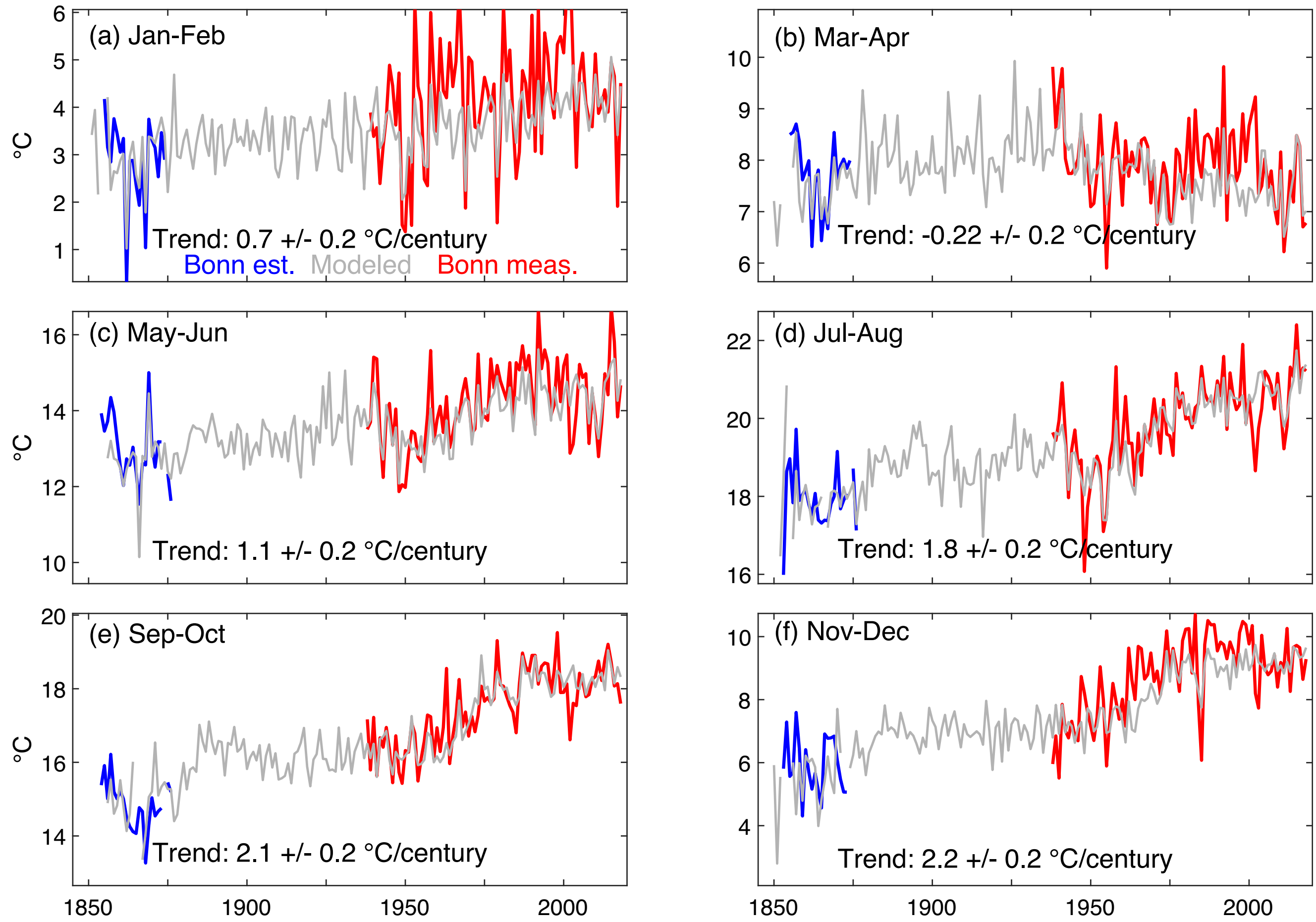

FIGURE 7 Seasonal trends in T_W are shown. The red line is the measured data from Bonneville and the gray line is the modeled result. The measured water temperature from the 1800s shown in blue is estimated Bonneville temperatures based on measurements from Astoria. [Color figure can be viewed at wileyonlinelibrary.com]

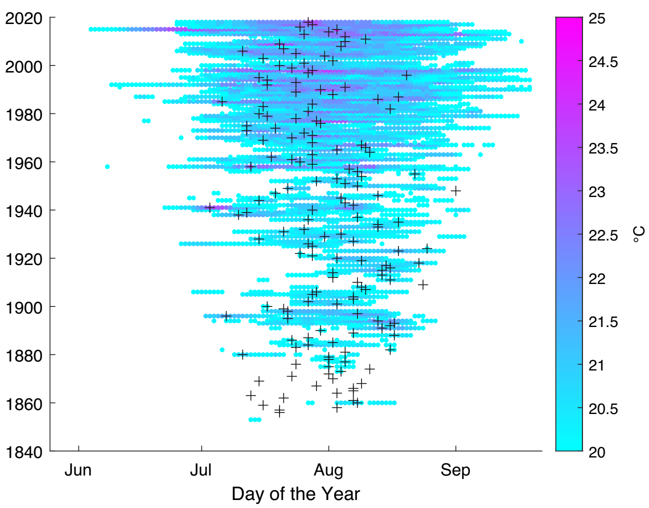

FIGURE 8 Number of days over 20°C for water temperature. The + sign indicates when the maximum water temperature for the year occurred. Measured data were used when available; when this was not possible for certain years, modeled results were used to fill gaps. [Color figure can be viewed at wileyonlinelibrary.com]

≥19°C produce a cellular stress response, thus risking Pacific salmon spawning migration failure (Jeffries et al., 2013). More days over the 20°C threshold put the Columbia River in regulatory non-compliance and impact Pacific lamprey (*Entosphenus tridentatus*; Clemens, 2022; Clemens et al., 2016; Clemens & Schreck, 2021). Generally, more days over the 20°C threshold indicate declines of summer fish occupancy, although ephemerally warm habitats may benefit cold-water fish growth in rivers where cooler habitat is also available (Armstrong et al., 2021). Increased winter temperatures also likely influence ecological processes and nutrient cycles associated with freezing or near-freezing air and water temperatures. Effects include the seasonality, health, and migration of native and invasive non-native flora and fauna (e.g., Richards et al., 2004; Saintilan et al., 2014; Whitfield et al., 2019). For these reasons, the increased November–February water temperature (Figure 7) likely carries important implications. Because anthropogenic influences on water temperature may in some cases be reversible (e.g., by river restoration or reforestation; see White et al., 2017), we next investigate causes of temperature change.

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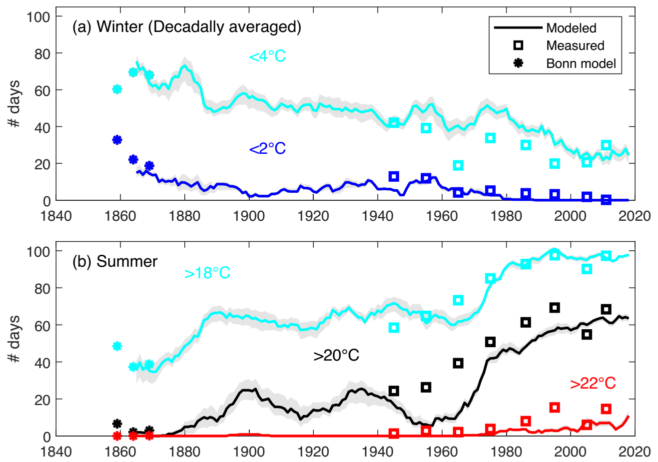

FIGURE 9 The decadally averaged number of days above and under various thresholds: (a) the number of cold days (below 2°C or 4°C thresholds) is decreasing, and (b) the number of warm days (above 18°C, 20°C, and 22°C) is increasing. The ridged circles represent modeled Bonneville temperatures, while the squares indicate true Bonneville measurements. The gray shaded area denotes model error of 2 standard deviations. [Color figure can be viewed at wileyonlinelibrary.com]

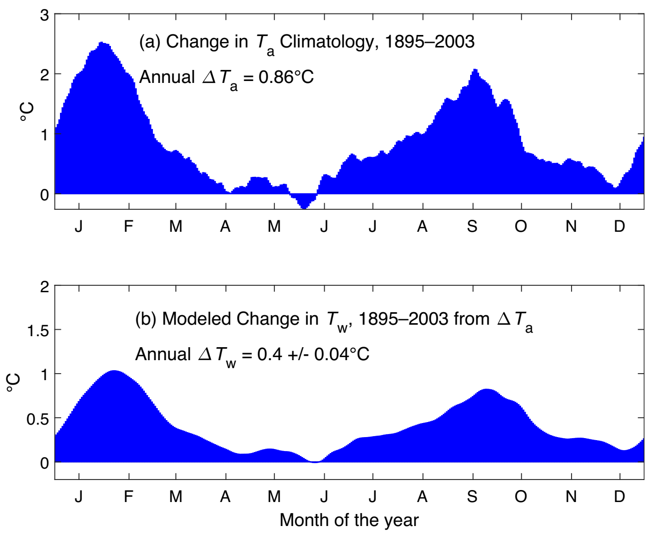

FIGURE 10 The modeled change in water temperature based solely on the changing climate (air temperature), using the Pre-Dam (1940s) Vancouver model. (a) The change in air temperature climatology from 1880 to 1910 and 1988 to 2018. (b) The modeled change in water temperature from 1880 to 2018. [Color figure can be viewed at wileyonlinelibrary.com]

4.1 | Causes of temperature change

Our statistical modeling approach enables the attribution of T_w changes to causes such as increasing air temperatures and altered river discharge. Between the 1880–1910 and 1988–2018 periods, annually averaged, daily maximum air temperatures in the Columbia basin in the bias-corrected Berkeley-Earth data (http://berkeleyearth.org/data/) increased by almost a degree Celsius: 0.86°C in Vancouver, Washington, 0.90°C in Portland Oregon, and 0.85°C in Spokane, WA. Based on our statistical model, the changes in water temperature based on these measurements are 0.4°C ± 0.04°C, 0.4°C ± 0.03°C, and 0.3°C ± 0.03°C (see e.g., Figure 10). Seasonally, air temperature drives the largest T_w increases during winter (January–February) and late summer/early autumn (August–October), with a maximum increase of about 1°C. Spring (April–June) and the November–December period show the least change, with increases in water temperature of <0.25°C on average (Figure 10). The late summer increase in air temperature, and smaller springtime increase, is consistent with other empirical observations and models of climate change in the temperate zone (Abatzoglou et al., 2014). The reason for the January–February increase in T_w may stem from a slowing of radiative heat loss due to increased average depth in the modern system with reservoirs; this result is consistent with measurements at other locations (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 2013). Projections of water temperature in Columbia River streams suggest that the greatest future changes will be distributed somewhat differently, with the largest shifts in spring and summer (3.5°C–5.2°C) and the smallest in winter and autumn (1.6°C–2.7°C; see Ficklin et al., 2014); a possible reason, at least for springtime, is the projected loss of snow pack.

Another effect of climate change on snow-fed rivers is changed annual river flow. As shown in Figure 2, flow in the Columbia River has decreased by 15%–17% on an annual basis, with a larger seasonal decrease of up to 40% between April and July. Both irrigation withdrawals and climate change have contributed approximately equally to the overall decrease in annual flow (Naik & Jay, 2011). The annual mean water temperature change due to decreased mean flows was estimated to be ~0.17°C ± 0.04°C using the "Modern" model for Vancouver (Figure 11). These results indicate what the water temperature change would have been, due to decreased river flows, if the reservoir system had been in place since the 1880s. Using the "Pre-dam" Vancouver model, the estimated annual mean water temperature change due to decreased flows was ~0.37°C ± 0.04°C (Figure 11). It is possible that the reduced sensitivity of T_w to altered river flow in the modern model may stem from the influence of water resources management, such as the release of cooler bottom water at some times of the year. Seasonally, the decrease in spring and summer river flows has caused a corresponding increase of 1°C–2°C in modeled water temperatures, depending on which model is used. Given the exceedances shown in Section 3.2, further increases in temperature at this time of year are likely to have greater consequences for aquatic species and ecosystems.

Another factor contributing to water temperature changes is the effect of the reservoir system. Changes in the thermal response of the system to forcing—that is, changes in the regression coefficients that represent the influence of input parameters on T_W (see Equation 2) are modeled to produce a greater effect than increased air temperature. When the "Modern" Vancouver model is run using river flow and air temperatures from the 2000–2018 period, the resulting water temperature is 0.8°C ± 0.15°C greater than the "Pre Dam"

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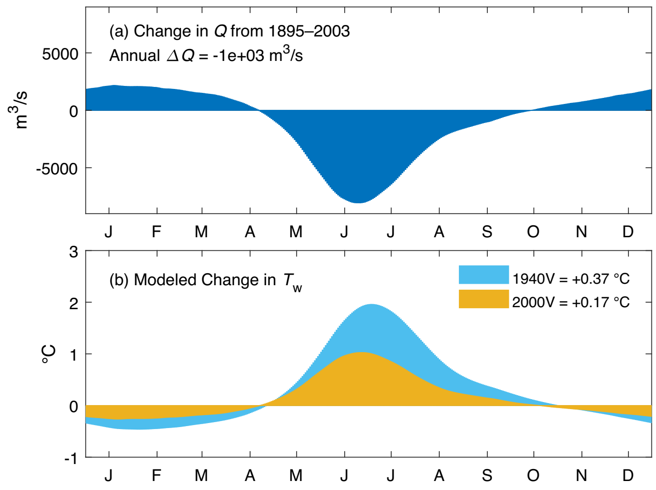

FIGURE 11 (a) The average change in river flow from 1880 to 1910 and 1988 to 2018 at the Dalles (USGS 14105700 Columbia River at the Dalles, OR). (b) The average modeled change in water temperature due to changes in river flow using the Pre-Dam (1940 V) and Modern (2000 V) Vancouver models. [Color figure can be viewed at wileyonlinelibrary.com]

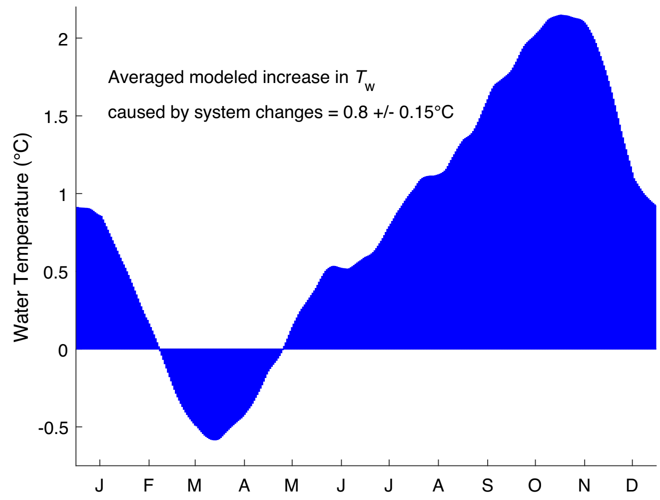

FIGURE 12 The estimated modeled change in water temperature based solely on changes to the system. This figure shows the difference in the Pre-Dam Vancouver model (1940 V) and Modern Vancouver model (2000 V) result when applied to the same set of air temperature and river flow data. [Color figure can be viewed at wileyonlinelibrary.com]

model run with identical forcing (Figure 12). Seasonally, the largest increase occurs in the fall, with a maximum change exceeding 2°C. The smallest increase and even a decrease occurs in the spring (Figure 12). These observations are consistent with the thermal effects that reservoirs have on rivers (Rounds, 2010). Nonetheless, other factors that influence water heating—such as width and depth of tributary creeks and rivers—may also influence water temperature (e.g., White et al., 2017) with possible system-scale effects. Similarly, the system-scale effects of riparian forest cover, upstream lakes, and soil type, could also contribute to this signal (Booth et al., 2014).

Applying the linear trend of 1.3°C ± 0.1°C per century (Figure 6), the total modeled water temperature change between 1880 and 2018 is ~1.8°C ± 0.1°C, where we have taken the mid-point of these periods for calculation. Our analysis suggests that about 22% of the total change (~0.4°C ± 0.04°C) is due to increased air temperatures (caused by climate change), about 45% of the total change is due to changes in the system response to forcing caused primarily by the reservoir system (~0.8°C ± 0.15°C), and about 11% (~0.2°C ± 0.2°C) is due to reduced river flow caused by factors such as irrigation withdrawals and climate-change induced alteration of the hydrological cycle. The sum of the various components (1.4°C) is less than the linear trend estimate, and leaves about 22% of the 1.8°C increase unattributed. It is possible that we are slightly underestimating the influence of air temperature, which was estimated to have changed 1.1°C in the Pacific Northwest since 1900 (Mote et al., 2019; Talke et al., 2023). We note that our attribution method is approximate and does not account for any non-linear effects within the river system. Stated differently, the impacts of the reservoirs, irrigation withdrawals, land use impacts (such as timber harvesting and reduced riparian shading), and climate change are likely interconnected, but to more accurately separate the individual effects may require process-based modeling.

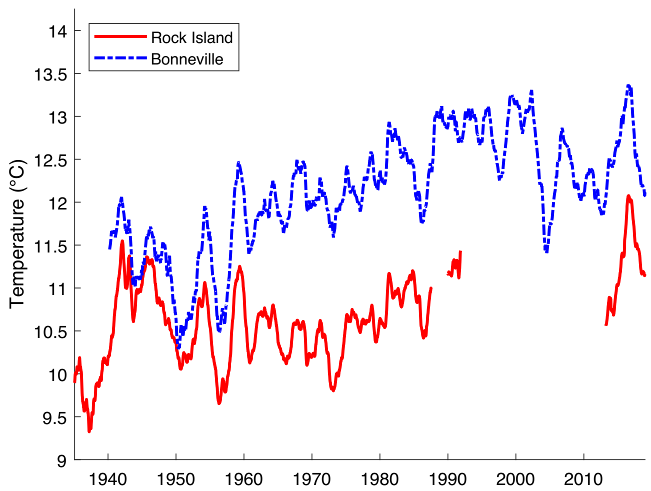

FIGURE 13 Measured water temperatures from Rock Island Dam (blue) and Bonneville Dam (orange) over time. The measurements are averaged over a 2-year period. [Color figure can be viewed at wileyonlinelibrary.com]

The increase in water temperatures within the Columbia River since the mid-20th century is also spatially variable, and this variability supports our interpretation that reservoirs are responsible for ~45% of heating effects. Specifically, the difference in water temperature between Bonneville Dam and Rock Island Dam has increased over time (Figure 13). From 1939 to 1952, Rock Island and Bonneville temperatures follow each other closely, with a small average increase of +0.5°C occurring over the nearly 500 km stretch of river and a decrease of 500 ft in vertical elevation from Rock Island to Bonneville. In the 1950s to 1960s, this temperature difference increases to +1.5°C at Bonneville, likely because of the heating caused at the

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Hanford nuclear site at approximately rkm 600 (Moore, 1968). However, the 1950s difference persists after Hanford operations stopped, and is found to be 1.6°C for the 2010–2018 period. Thus, more heating occurs between Rock Island and Bonneville today than historically, which may be due to the reservoir system. A contributing factor may be that tributaries between the two locations are also warmer than the historical system state. The increase in the along-river temperature gradient after 1952 validates the use of 1938–1952 as the Pre-Dam period.

4.2 | River system "memory"

Here, we examined how the lagged relationship between air and water temperatures has evolved with the construction of reservoirs. Air temperature regression coefficients show that the river system "memory" has changed over time (Figure 14). Specifically, the coefficients from the 1940s Vancouver model indicate that air and water temperature became decorrelated more quickly than did the coefficients from the 2000s Vancouver model. In the "Pre-Dam" 1940s model, it takes about 12 days for the air and water temperature correlation to decay to about 1/3 of its maximum. In the "Modern" 2000s model, a similar decorrelation takes about 22 days. This increased decorrelation time (increased thermal memory) is likely attributable to the increased storage and delayed releases that are characteristic of the modern reservoir system. The longer system memory helps explain the seasonal changes observed in water temperature (Figure 4)—in the modern system, the water temperature is influenced by heating (air temperatures) from earlier in the year, which tends to make spring-time water cooler and autumn water warmer. This greater thermal memory leads to smaller long-term changes in spring.

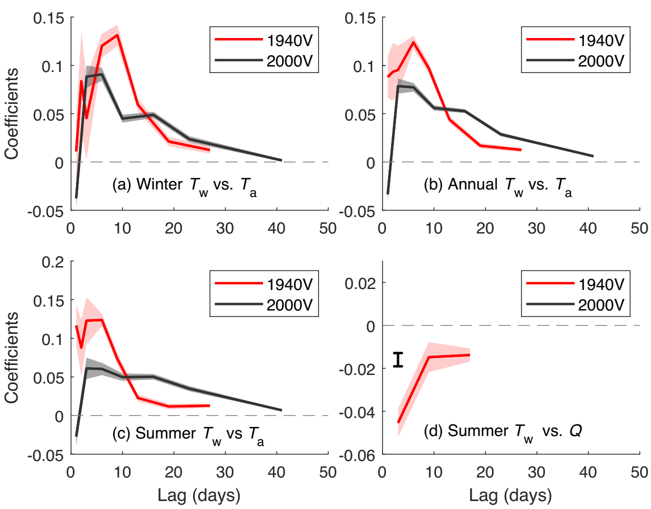

FIGURE 14 The air temperature coefficients plotted as a function of number of days lagged. The red line is the 1940s Vancouver (1940 V) decorrelation structure and the black line is the 2000s Vancouver (2000 V) correlation structure. [Color figure can be viewed at wileyonlinelibrary.com]

We note that the underlying air temperature measurements also show evidence of thermal memory, while spring-time changes in air temperature are smaller than autumnal changes (Figure 10). Thus, system changes (as represented by a changed correlation structure) are compounded by changes in the seasonal air temperature cycle (thermal forcing; see section 4.1).

Conversely, the maximum magnitude of the air-water correlation has decreased from the "Pre-Dam" model to the "Modern" model (Figure 14). A weaker T_a to T_w correlation implies that the modern river system is not as sensitive to short-term fluctuations and synoptic weather patterns, also consistent with a deeper system with larger capacitance. Mathematically, the depth term in the 1D heat balance equation (see Data S1) has increased, leading to smaller $\frac{\partial T}{\partial t}$. Consequently, it now takes longer for the river to heat in the spring and longer to cool in the fall. In the region upstream of Bonneville Dam, average depths historically varied from 3 to 15 m annually (U.S. Army, 1892, 1911), while today the depth is closer to 20–25 m (U.S. EPA, 2019). The observed changes in the river "memory" are directly related to time lags in the decorrelation structure (Figure 14; Stefan & Preud'homme, 1993). Using their approach, the time lags for the pre-dam system are estimated to be 5–25 days, depending on the time of year, compared to 32–40 days for the modern system (see Equation 1). This simple theoretical exercise explains why the modern system has a longer "memory," and supports the results from the statistical model (Figure 14).

Statistical results show that river flow was historically more correlated with water temperature than today. In the modern system, only average river flow within the past 10 days was statistically significant for T_w, compared to 17 days in the pre-Dam model (Figure 14d). The changes to the river-flow coefficients occur in large part because river depth is larger, but also because depth is much less variable now than historically, reflecting reduced flow variability (Figure 2). As a result of depth changes, the heating term is both of smaller magnitude and less variable, reducing the correlation with Q. Similarly, the along-channel temperature gradient in the Columbia River is larger today than the mid-20th century (Figure 13) in part due to increased residence time. Residence time is approximated *by* $L*A/Q$, where L is the length (unchanged), A is cross sectional area (increased due to depth changes), and Q is river discharge, the latter decreased by an annual average of ~15% on average since ca. 1900 and by 40%–45% during the spring freshet. The increased temperature gradient increases advective effects, though this is counteracted by increased cross-sectional area and reduced velocity (see eq. 1 in Data S1). Our statistical approach does not distinguish between advective and heating factors; moreover, the statistical approach only captures the average response, and may miss intermittent conditions in which discharge is important (e.g., when large temperature gradients could occur, as in a heat wave). Still, the river discharge has a smaller influence than air temperature on water temperatures, consistent with the scaling in eq. 3 that found that the advective term was a second order effect (see Data S1). Including river discharge only reduces RMSE by 0.01°C–0.03°C in the "Modern" model.

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The relatively small influence of river flow in the modern system suggests that modern management practice, in which preferential releases of cool bottom water are used to reduce temperatures for regulatory purposes (e.g., Rounds, 2010), has some, but limited, effectiveness. Our approach does not include the effects of stratification, however, and previous studies have found that releases of water from large storage reservoirs do have a cooling effect in mid-summer, but a heating effect in autumn (Rounds, 2010). Hence, some of the effects of cold water releases may be hidden in the water temperature climatology used in our modeling. Alternatively, our approach may not be sensitive enough to capture changing management practices. Focused hydrodynamic numerical modeling approaches that include a full heat budget are likely required to assess such questions. Nonetheless, previous research has shown that even relatively shallow, run-of-the-river reservoirs have contributed to warming trends, which agrees with the results shown here (Yearsley et al., 2001).

4.3 | Limitations of this analysis

An advantage of our statistical model is that we were able to capture the decorrelation time scales of the historical vs modern systems, through the use of daily records, and obtained change estimates over secular time scales. However, this data-driven approach is susceptible to biases and uncertainties in the underlying air and water temperature datasets, a problem that is not altogether eliminated even in numerical models. We have attempted to address this issue by using multiple air temperature data sets that have been bias-corrected, and by quantifying the variance between our primary Bonneville water temperature data set and other, shorter records (see section 2.2.1). Because all data sets show similar trends (see Table S4), our confidence in the general result—a ≥ 2° increase in water temperature since the mid-1800s—is high. Our attribution of causes is likely more uncertain, particularly for smaller effects, like that caused by flow. Future process-based studies may help to reduce this uncertainty.

The statistical model is able to quickly hindcast water temperature data during a period with no known measurements; however, at present, there are few ways to validate them beyond our comparison to the early Astoria record and other spot records. A 2-month record of daily measurements made in 1854 in Vancouver (U.S. War Department, 1855) suggests that our historical model may overestimate 19th century temperatures. The 1854 measurement showed that water temperature never exceeded 14°C between May and late July, a result that is 1°C–1.5°C colder than our model over a similar period. Unfortunately, there is little overlap between the extant Astoria record (continuous records start in July 1854; see Talke et al., 2020) and the Vancouver measurement, such that we cannot easily evaluate biases.

During the modern record, the method of data collection is an additional source of uncertainty. The specific location of temperature measurements at Bonneville Dam changed in 1997 from one of the dam's powerhouse turbine intakes to the dam forebay (Isaak et al., 2018). Also, the timing of daily measurements shifted from 8:00 AM to an unknown hour after 1992, introducing additional discontinuity in data collection methods. The personnel recording the measurements and the measurement details have also changed over the course of the 80-years data record. Such changes could create misleading trends or biases in water temperatures (U.S. EPA, 2003). To the extent possible, we have compared in situ measurements at other locations (e.g., 1941–1947 at Vancouver). Nonetheless, the congruence between water temperature trends at Bonneville with seasonal patterns of air temperature increases our confidence in the overall result. Results are also consistent with our understanding of the effects of reservoirs.

Additional limitations are inherent to our linear regression approach. For example, the modeling does not capture extreme temperatures as well as the average temperature. Because we used input water temperature data from primarily one measurement location (Bonneville Dam) situated near one elevation, we are unable to infer any spatial variability in water temperature. Thus, we do not directly simulate the actual water temperature that fish and other species may experience, for example, in cold-water refugia near the river bottom or in cold-water tributaries. Our modeling approach also does not discern between river flow effects caused by thermal advection (through the along-channel temperature gradient) and those caused by river-flow induced changes to depth. For evaluation of these higher order, nonlinear effects, a numerical modeling approach is needed. Nonetheless, our regression approach captures many of the important trends and variabilities in water temperature, and provides insights into the background temperatures present in the system and how/why they have changed.

Finally, we note that attribution of causes of change is inherently difficult. The various causes of system change build upon and interact with each other; hence, the sum of individual changes is not necessarily the same as the total change. Also, the lower Columbia River has changed in more ways than just the addition of dams and reservoirs. For example, the bathymetry, shading, and vegetation in and around the river has been altered significantly (Ke et al., 2013), along with significant irrigation diversion. There are also more indirect stressors such as urbanization of cities such as Spokane, WA and Portland, OR. Hence, the observed “climate change” and “reservoir” system effects may in part be driven by landscape factors and water-resource management practices. The combination of so many factors makes it difficult to differentiate and attribute the causes of change. Nonetheless, even approximately understanding the factors involved in changed water temperature is a critical step in prioritizing future conservation management strategies.

5 | CONCLUSIONS

In this study, we examined the evolution of water temperatures in the lower Columbia River between the 1850s and the present. We analyzed archival records and produced a suite of statistical models that characterize long-term trends. Using archival daily air temperature and daily river flow measurements as inputs, the modeling shows that

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there has been about a 2.2 ± 0.2°C increase in mean water temperature at Bonneville Dam (the upstream limit of tides) between 1850 and 2018. An approximately 1.2°C ± 0.2°C increase has occurred since ~1950. These results suggest that approximately half of the river's warming has occurred within the last 50 to 70 years. The rate of change has likely increased over time because the system has become more altered and because of the cumulative effects of climate change. A similar pattern of warming temperatures has been found in other studies and rivers around the world (Pohle et al., 2019; Webb & Nobilis, 1995). The increased mean water temperatures are attributed to increased air temperatures (22%), an altered system response to heating that is primarily caused by the reservoir system and its management (45%), and a decrease in river flow caused by irrigation withdrawals, evaporation, and climate change effects (11%). The remaining residual is unattributed, but likely reflects both limitations in the modeling approach and nonlinear interactions between different forcing factors.

Water temperature changes are not evenly distributed over the year. River temperatures increased around 2°C in the late summer and early fall from the mid-20th century to the present, consistent with other studies (U.S. EPA, 2018). Springtime temperatures, by contrast, are virtually unchanged since the 19th century. The altered river temperatures are correlated with similar patterns in air temperature, which are also observed to increase the most in fall, and the least in spring. The reservoir system has also increased the system memory and thermal inertia, such that the effect of winter and summer extend longer into the spring and fall, respectively. A related consequence of the reservoir system is that temperature variance has decreased. Hence, the system reacts less strongly to synoptic time-scale weather patterns, producing smaller excursions from the climatological mean. The combination of an increased mean, but decreased variance, has greatly increased the amount of time that water at Bonneville Dam exceeds a 20°C threshold, from ~0–10 days in the mid-19th century to 50–60 days in the early 21st century. Moreover, temperature exceedances are persistent over time, rather than intermittently distributed throughout the summer, leading to fewer "temporal refugia" for cold-water species in periods of extreme air temperatures.

Projections suggest that summer river temperatures will increase by up to 2°C by the end of the 21st century, due to a combination of drier summers, less snow pack, and increasing air temperatures (Isaak et al., 2018). Our results highlight that this amount of warming has already occurred. Thus, the total average difference between 1850s and 2100 conditions could approach 4°C, with larger differences during the fall. This increase likely has significant ecological implications for the viability of salmon and other endangered species (Jeffries et al., 2013). Importantly, warming water temperature predates the modern reservoir system, possibly due to landscape alterations in creek morphology and shading (White et al., 2017). The statistical model also reveals that building dams and reservoirs has fundamentally altered the response of water temperature to heating, with less variability and more thermal inertia as the result. Because the effects of landscape alteration, reservoir management, and climate change interact, a system-scale model is likely required to better predict and mitigate against future climate effects.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in PDXScholar at https://pdxscholar.library.pdx.edu/cengin_data/7/.

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