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A STATISTICAL INVESTIGATION OF LOWER COLUMBIA RIVER WATER
TEMPERATURE, 1915-2003

BY

CORINA CHRISTINA MAE OVERMAN

A thesis submitted in partial fulfillment
of the requirement for the degree of

BACHELOR OF SCIENCE
IN
CIVIL AND ENVIRONMENTAL ENGINEERING

Thesis Advisor:
Stefan Talke

Portland State University
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ABSTRACT

The Columbia River is home to anadromous salmon populations that migrate upriver every year to spawn. These fish require cool water temperatures (T_w) to survive. In recent years, high summer T_w in the Columbia River has caused increased mortality of salmon. Different possible explanations for increased T_w include climate change, deforestation, and decreased summertime streamflow (Q) due to dams. In this study, robust linear regression models of T_w based on air temperature (T_a) and Q were developed to examine the change in T_w over time. The data was separated into an historical period (1938-1956) and a modern period (1977-2003). Seasonal regression models were used for May through October (summer) and November through April (winter) for each period. Comparison of these models showed that T_w has become less sensitive to recent atmospheric heating and cooling. By contrast, analysis suggested that T_w has become more sensitive to variations in Q . Of the 1.5°C increase in maximum summertime T_w , approximately 1.3°C was due to dams and reservoir management based on changes in regression coefficients and average Q . A smaller, 0.2°C change was estimated to be caused by increasing T_a since the mid-20th century. While average maximum T_w has increased, both the statistical model and data suggest that the variability in T_w from its climatological average has decreased, probably due to reservoir management.

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1.0 INTRODUCTION

The Columbia River flows from British Columbia, Canada to the Pacific Ocean, and drains portions of British Columbia, Idaho, Oregon, Washington, and Montana (Figure 1). Major tributaries include the Snake and Willamette Rivers. Since 1933, fourteen hydroelectric dams have been built on the Columbia River. Additionally, there are nineteen dams on the Snake River (Yearsley, 2001) and over one hundred other dams on smaller tributaries in the Columbia River basin (NRC, 1996).

In addition to providing people with electricity and water, the river is home to several different species of salmon. These anadromous fish spend the first one to three years of their lives in the river before migrating to the ocean (Dittman and Quinn, 1996). As they near the ends of their lives, they return to the streams where they were born in order to spawn. Salmon are sensitive to water temperature (T_w), and require different temperature ranges at different life stages. T_w above a certain threshold can cause increased disease and mortality as well as decreased growth rates in juveniles. (Boyd and Sturdevant, 1997). The lethal maximum temperature threshold varies between species. Adult steelhead have the lowest, at 21°C (Carter, 2006).

Summer T_w in the Columbia River has increased during the twentieth century (Quinn and Adams, 1996; Quinn et al., 1997; Bottom et al., 2011; Crozier et al., 2011). In recent years, such as 2015, increased T_w has led to decreased salmon counts (NMFS, 2016). Possible explanations for higher T_w include climate change, change in streamflow (Q) due to dams (Bottom et al., 2011; Moore, 1967), and changes in riparian shading due to clear cutting and other land-use practices (Johnson, 2004).

Statistical models are often used to determine how changes to weather, climate, and hydrology may influence T_w (Moore, 1968; Bottom et al., 2011). Some statistical models of T_w use both air temperature (T_a) and Q as a basis function (e.g., Webb et al., 2003; Neumann et al., 2003), whereas other statistical models are regressed only against T_a (e.g., Stefan and Preud'homme, 1993; Erickson and Stefan, 1996; Pilgrim et al., 1998; Webb and Nobilis, 1997). The appeal of such models is that they are easy to develop and use, are based on readily available data, and can help explain seasonal, interannual, and long-term changes. In the Columbia River basin, Bottom et al.

(2011) developed a regression for T_w based on T_a and Q over the 1938-1956 period. Results suggested that dams and reservoir management caused an approximately 0.8°C increase in summertime T_w and a more than 2°C increase in the October and November time period. Similarly, Moore (1968) used regression models to show that the combined effects of dams and heating from the Hanford Nuclear Site accounted for a 1.8°C increase in July T_w in the Columbia River.

The purpose of this study is to develop a statistical model of T_w in the Columbia River that captures the effect of T_a and Q , both before and after most major main-stem dams were built. The general approach and the data used are similar to Bottom et al. (2011), and the results herein represent both an evolution of that effort and an independent check on those results. Compared to Bottom et al. (2011), this study uses biweekly rather than monthly averaged data, and defines summer/winter regressions as May through October and November through April, rather than January through June and July through December (see 2.0 Methods and 3.0 Results). Additional archival T_w data, including Astoria (monthly, 1925-1956) and Vancouver (1941-1947), have been recovered and digitized, and are used to check the representativeness of the T_w record at Bonneville Dam (1938-2003). Moreover, T_w data are subsampled to produce both a historical (1938-1956) and modern (1977-2003) statistical model, which enables analysis of possible changes to regression coefficients. Climatological means and anomalies in T_w are analyzed and interpreted.

The data analysis and statistical modeling attempt to address the fundamental question: *Why are water temperatures in the Columbia River increasing, and to what extent do reservoir management and climate change affect water temperature?* While a complex issue, the results presented here are an initial effort to quantify major factors that influence T_w over long time scales.

2.0 METHODS

2.1 Data

The primary water temperature (T_w) data used in this study came from scroll case measurements taken at Bonneville Dam on the Columbia River, located at the head of tides at river kilometer (rkm) 235, roughly 64 km upstream of Portland, Oregon (Figure 1). Measurements for the years 1938-1997 (<http://www.streamnet.org/files/407/StuTempData.html>) consist of one T_w value for each day. Additional data for the 1974-2003 period came from the United States Army Corps of Engineers (<http://www.nwdwc.usace.army.mil/cgi-bin/dataquery.pl?k=bon>). On days where these data sets overlapped, the arithmetic mean of the measurements from the two data sets was used to obtain a single daily T_w measurement. The latter data set primarily contains daily measurements, but for some days there are multiple measurements. In these instances, the arithmetic mean of all the measurements for the day was used as a daily average. For some days, there is no recorded T_w .

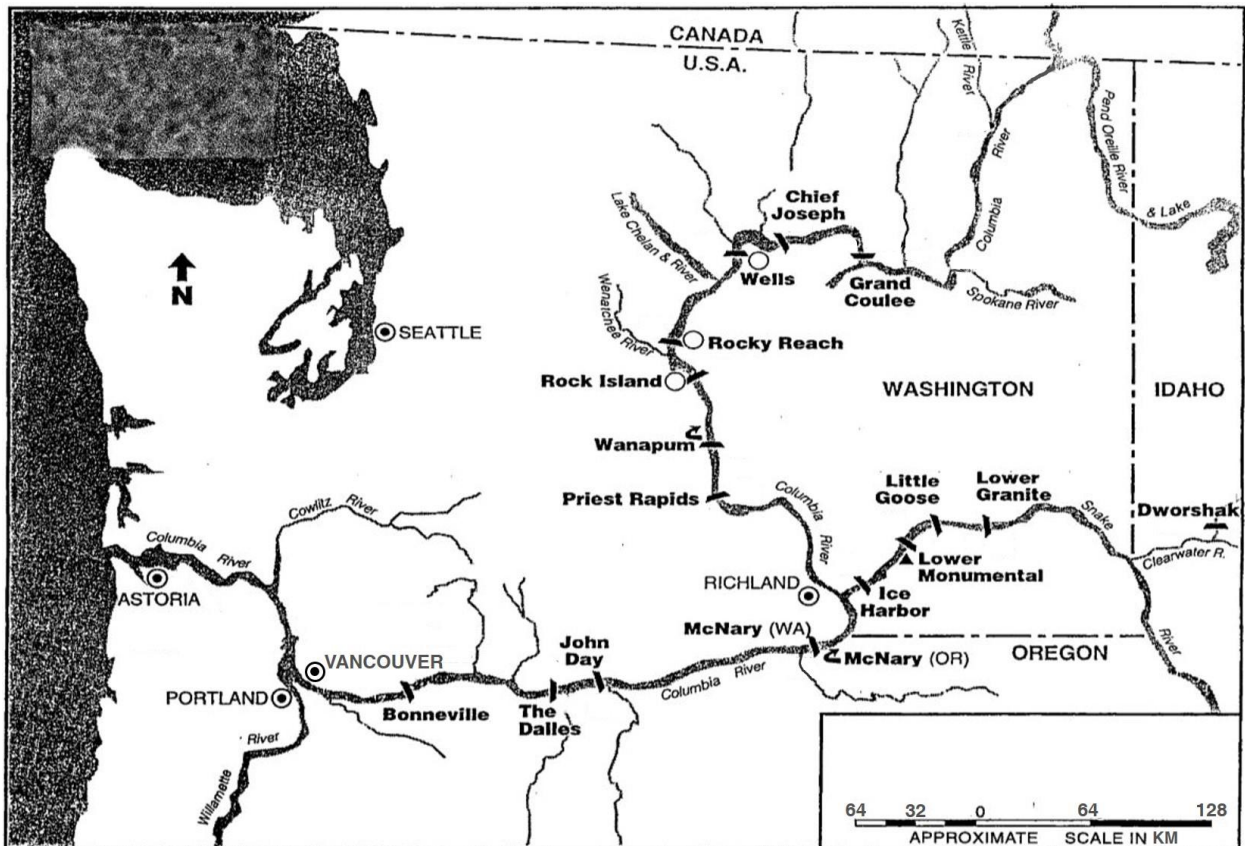


Figure 1. Map of the Columbia River in Oregon and Washington, adapted from Yearsley (2001).

In the entire sixty-five-year data set, there are 361 days with no T_w measurement. More recent data from Bonneville Dam will be analyzed in a follow-on study.

Daily mean discharge (Q) for the Columbia River was measured at The Dalles, approximately 70 km upriver from Bonneville Dam. The United States Geological Survey has continuous daily measurements dating back 1878 (<https://waterdata.usgs.gov/usa/nwis/uv?14105700> [May 2017]).

Following Bottom et al. (2011), biweekly average air temperature (T_a) data (1915-2003) for the Columbia River Basin was obtained for multiple sub-basins from the Surface Water Modeling group at the University of Washington (available from <http://www.hydro.washington.edu/Lettenmaier/Data/gridded/>) (Hamlet and Lettenmaier, 2005). To obtain an average T_a for the entire basin, measurements from each sub-basin were weighted by the relative area of the sub-basin to the entire basin.

Daily T_w and Q measurements were averaged over two-week periods to match the biweekly T_a data. The reference date for each two-week period is the average day of the period.

While the combination of the T_w , Q , and T_a data sets spans almost the entire period from 1938-2003, the years 1957-1976 were not considered in this analysis. This is because the river experienced excess heating from the Hanford Nuclear Site during those years (Bottom et al., 2011). Since part of this work aims to find trends in T_w , including these years would not accurately represent present conditions or historical conditions. The remaining years were separated into historical and modern periods. The historical period (1938-1956) represents the years when the river was less affected by dams and reservoir management. The modern period (1977-2003) represents the years when most of the existing dams had been constructed.

Monthly average T_w and density measurements from Astoria, Oregon (rkm 29) for 1925-1956 were obtained from United States Coast and Geodetic Survey records (USCGS, 1954; USCGS, 1954; USCGS, 1962). These were used to verify the results of estimated Bonneville T_w for 1925-1938, which were obtained using the statistical model described below.

Additional daily T_w measurements of the Columbia River from Vancouver, Washington (rkm 171), were available for 1941-1947 from the National Centers for Environmental Information (<https://>

www.ncdc.noaa.gov/EdadsV2/). These were digitized and compared with the other T_w measurements to assess accuracy and variance.

2.2 Theoretical Basis

The one-dimensional heat transfer in a river can be described by the following partial differential equation:

$$\frac{\partial T_w}{\partial t} = -\frac{1}{A} \frac{\partial Q T_w}{\partial x} + \frac{\partial}{\partial x} \left(K \frac{\partial T_w}{\partial x} \right) + \frac{\Sigma H}{\rho c_p d} \quad (1)$$

where T_w is a function of both along-channel distance (x) and time (t), A is the river cross-section, K is the dispersion coefficient, H is the net heat flux between the river and the atmosphere, ρ and c_p are the density and specific heat of water, and d is the river depth (Gu, 1998; Wagner et al., 2011). The first term on the right side of the equation, representing advection, as well as the second term, representing dispersion, are often small compared to the third term, representing atmospheric heat flux (Gu, 1998; Wagner et al., 2011). Neglecting these terms, Equation 1 can then be written

$$\frac{\partial T_w}{\partial t} = \frac{\Sigma H}{\rho c_p d} \quad (2)$$

Net heat flux comprises radiative flux, evaporative flux, and convective flux. The largest contributor to T_w change is radiative flux from incoming solar radiation (Wagner et al., 2011). T_a affects evaporative and convective fluxes in water, which are small, but T_a is also dependent on solar radiation (Moore, 1967). So, while T_a does not directly affect T_w , the two are positively correlated based on their mutual dependence on solar radiation (Johnson, 2004).

The rate at which a body of water heats and cools is inversely related to its volume. In a river, volume (and river depth) increases with Q , so increased Q will have a negative effect on T_w (Webb et al., 2003). Additionally, an increase in Q corresponds to an increase in stream velocity. This causes a parcel of water to have a shorter residence time and therefore less time to absorb heat (Mayer, 2012).

Based on these theoretical considerations, a statistical model can be developed to predict T_w based on T_a and Q . While the T_w/T_a correlation is not linear when T_a is below freezing or above 25°C

(Erickson and Stefan, 2000; Mohseni and Stefan, 1999; Morrill et al., 2005), linear regression models based on T_a do well at weekly or monthly time scales (Benyahya et al., 2007; Erickson and Stefan, 2000; Pilgrim et al., 1998; Webb et al., 2003). Such a model has the form

$$T_w(t) = \beta_0 + \beta_1 T_a(t) + \beta_2 Q(t) \quad (3)$$

where β_0 , β_1 , and β_2 are regression coefficients. Equation (3) can be modified by introducing a time lag to the T_a term, such that

$$T_w(t) = \beta_0 + \beta_1 T_a(t - 1) + \beta_2 Q(t) \quad (4)$$

where T_w at a given time is based on T_a from the previous time step. Stefan and Preud'homme (1993) showed that a time lag on T_a improves such models and that the ideal time lag increases with river size.

2.3 Statistical Model

Various linear regression models of T_w at Bonneville Dam based on Columbia Basin T_a and Q at The Dalles were tested for the historical and modern periods, separately. Variations included regressions based on January through December data, or regressions separated into two six-month subsets. Different time lag combinations of two or four weeks for T_a were tested for all models, as well as different sets of six-month periods. Model coefficients were calculated using robust regression with a weighting function given by Equation 5 (Ul-Saufie et al., 2012).

$$w = \frac{1}{(1 + r^2)} \quad (5)$$

Robust regression is less affected by outliers than ordinary least squares regression, so errors in the data do not influence the coefficient estimates as much. All coefficients considered for the final models were significant at a 95% confidence level.

Models were compared using their root mean squared errors (RMSE). This provides a measure of how well the model approximates measured data and is computed as

$$RMSE = \sqrt{\sum \frac{(\hat{y}_t - y_t)^2}{n}} \quad (6)$$

where \hat{y}_t is the predicted value, y_t is the measured value and n is the sample size. A lower RMSE represents a better model. RMSE's were calculated for the entire model as well as for annual maximum T_w . This tested how well a model approximated the measured annual maximum T_w .

Test statistics for checking whether two means or regression slopes were significantly different at a 95% confidence level were computed as

$$t = \frac{\bar{x} - \bar{y}}{\sqrt{\frac{s_x^2}{n} + \frac{s_y^2}{m}}} \quad (7)$$

where \bar{x} and \bar{y} are the means of each sample, s_x^2 and s_y^2 are the standard deviations of each sample, and n and m are the corresponding sample sizes. The degrees of freedom for the t-distribution were calculated using the Welch–Satterthwaite equation as follows:

$$df = \frac{\left(\frac{s_x^2}{n} + \frac{s_y^2}{m}\right)^2}{\frac{\left(\frac{s_x^2}{n}\right)^2}{n-1} + \frac{\left(\frac{s_y^2}{m}\right)^2}{m-1}} \quad (8)$$

3.0 RESULTS

3.1 Vancouver and Astoria

Water temperature (T_w) measurements taken at Bonneville Dam could be affected by natural spatial variability (e.g., top-to-bottom stratification), by daily heating and cooling cycles (if measurement times were inconsistent), or by measurement error. Before developing a regression model, the representativeness and accuracy of T_w measurements from Bonneville Dam were therefore checked against Astoria and Vancouver T_w records (Figures 2 and 3).

Results show that monthly-averaged T_w measurements at Bonneville Dam were sometimes slightly higher in the summer than Astoria, but much lower than Astoria in winter, with an overall RMSE of 1.26°C (Figure 2). Monthly average density measurements for Astoria for those years indicated that salinity was generally below 2 parts per thousand, indicating that the T_w measurements predominately represent river rather than ocean temperatures. For the months of May through October the RMSE was 1.02°C and for the months of November through April it was 1.46°C.

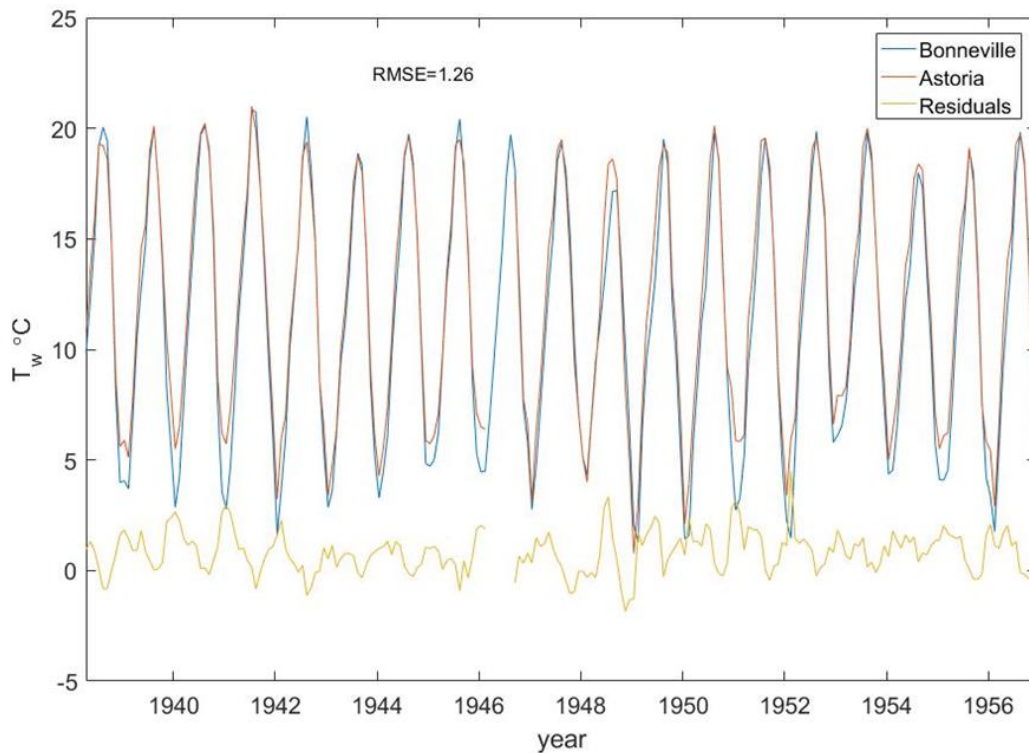


Figure 2. Monthly average water temperature (T_w) measured at Bonneville Dam and Astoria, 1925-1956. Residuals are Bonneville measurements subtracted from Astoria measurements.

The large differences in wintertime T_w may reflect the effect of warmer, wintertime river flow from coastal tributaries such as the Willamette River, which drain a more temperate region than the colder interior and may not be reflected in Bonneville (or Vancouver) measurements. Some heating of the lower Columbia River between Bonneville and Astoria may also occur in the winter. Though salinity intrusion during low flow conditions may also contribute to the warmer T_w at Astoria, the monthly averaged density measurements suggest this bias is small or negligible.

The representativeness and accuracy of T_w measurements from Bonneville Dam were also tested by comparing the daily measurements with Vancouver measurements for the years 1941-1947. This resulted in an RMSE of 0.67°C (Figure 3), indicating that the two data sets agree well.

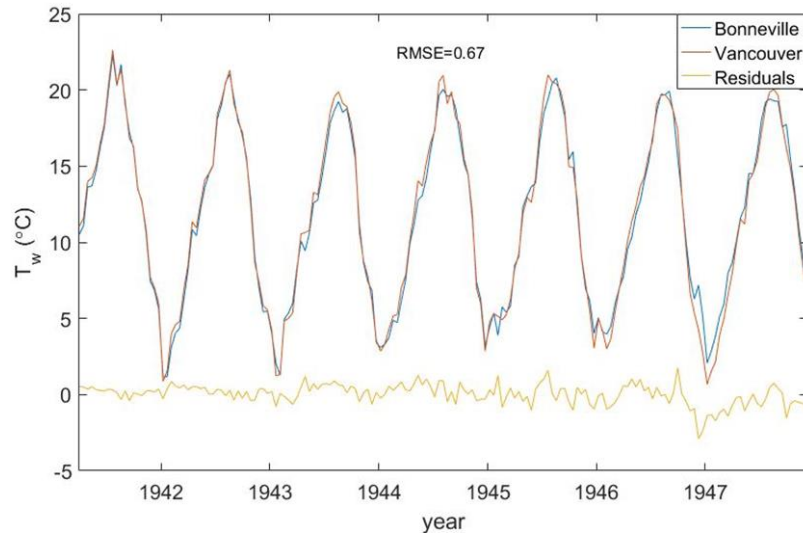


Figure 3. Biweekly average water temperature (T_w) measured at Bonneville Dam and Vancouver, 1941-1947. Residuals are Bonneville measurements subtracted from Vancouver measurements.

Monthly average T_w measurements for Bonneville Dam, Vancouver, and Astoria were compared for the years 1941-1947. Vancouver and Bonneville Dam T_w measurements generally matched well and were much closer to one another than to Astoria (Figure 4). The residuals and RMSE's between these three locations did not change much from 1941-1945, but in 1946 and 1947 there was a sharp increase in discrepancy between Astoria and Vancouver. Residuals and RMSE's between Bonneville Dam and Vancouver also increased in those years, but to a lesser extent (Figure 5). The increase in discrepancies between the three T_w data sets over time indicates that data quality likely decreased. The change in RMSE is more noticeable between Vancouver and

Bonneville and Vancouver and Astoria than between Bonneville and Astoria, suggesting that the problem lies with the Vancouver data.

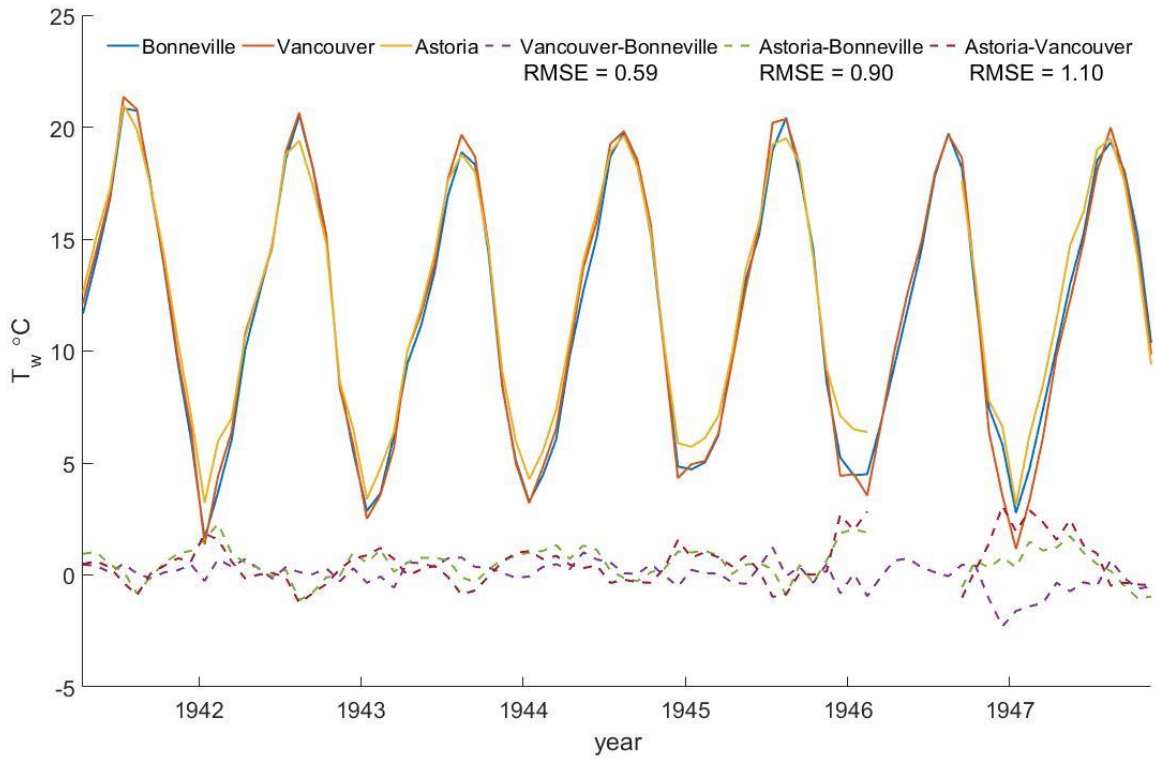


Figure 4. Monthly average water temperature (T_w) measured at Bonneville Dam, Vancouver, and Astoria with residuals shown by dotted lines, 1941-1947.

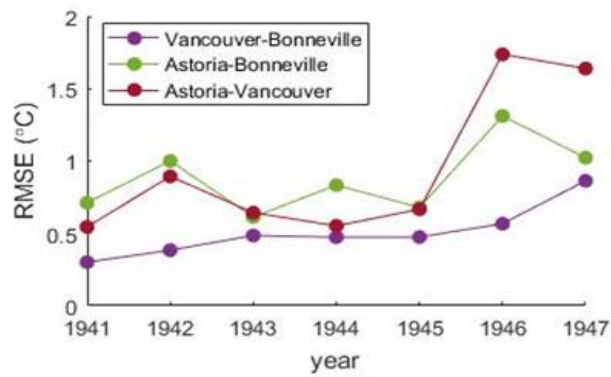


Figure 5. RMSE's between monthly average water temperature (T_w) measured at Bonneville Dam, Vancouver, and Astoria, 1941-1947.

3.2 *Climatology*

Climatological means of biweekly average T_w , air temperature (T_a), and flow (Q) were calculated for the modern and historical periods by taking the means of the biweekly averages for each two-week period across each record span. For example, all biweekly average T_w measurements with a reference date of January 7th for the years 1938-1956 were averaged to obtain the historical climatological mean T_w for that date. By comparing the climatological means for the historical and modern periods, long-term trends could be observed.

Climatology of biweekly average T_w shows that annual maximum T_w was 19.9°C on average during the historical period and 21.4°C during the modern period (Figure 6). During both periods, this maximum occurred in the middle of August. Springtime (March and April) T_w did not change much between the two periods, while modern T_w was at least 1.5°C higher on average in the summer and autumn months (between June and January). The greatest difference occurred during November, when T_w was 2.6°C higher on average during the modern period.

Biweekly average T_a did not change as much as T_w between the two periods. January through March T_a was 0.5°C to 1.8°C higher during the modern period, but during the rest of the year T_a fluctuated between 0.7°C lower to 1.3°C higher during the modern period (Figure 7). Annual maximum T_a occurred in late July during the historical period, but shifted to early August during the modern period. This may explain the apparent decrease in early July T_a , as the peak essentially shifted two weeks during the modern period.

Changes in Q were very dramatic between the two periods due to the increase in dams and reservoir management in the modern period. Average annual maximum Q decreased from close to 14,000 m³/s in the historical period to 8,000 m³/s in the modern period, while during November through March average Q was 1,000 to 2,000 m³/s higher in the modern period (Figure 8). This change in the annual hydrograph shows the effects of storage dams, where water is held during periods of naturally high Q and released later in order to optimize hydroelectric power generation and decrease risk of flooding. It is possible that long-term cycles such as the Pacific decadal oscillation also affected Q during these periods (e.g., Naik and Jay, 2005; 2011).

Figure 6. Climatological means of biweekly average water temperature (T_w) at Bonneville Dam for 1938-1956 and 1977-2003. Interquartile ranges (IQR's) show values between the first and third quartile in each data set. ΔT_w is the historical values subtracted from the modern values.

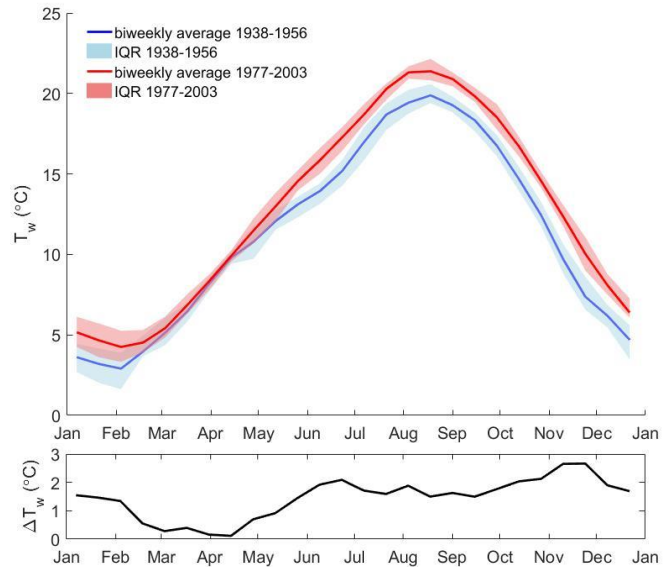


Figure 7. Climatological means of biweekly average air temperature (T_a) for 1938-1956 and 1977-2003. Interquartile ranges (IQR's) show values between the first and third quartile in each data set. ΔT_a is the historical values subtracted from the modern values.

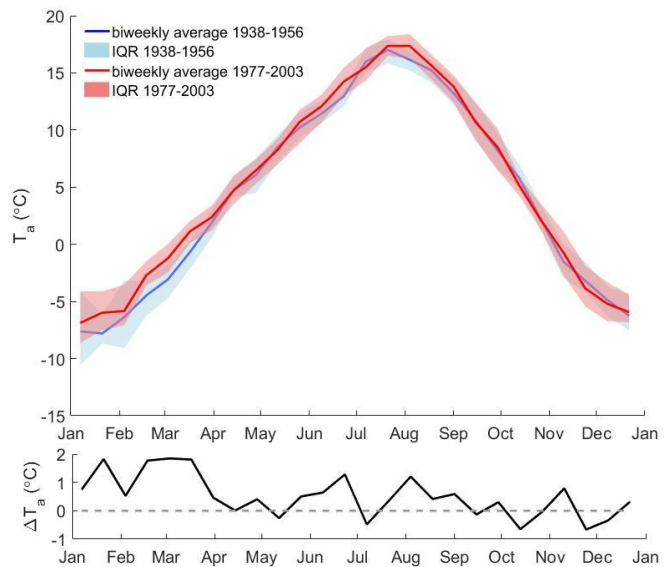
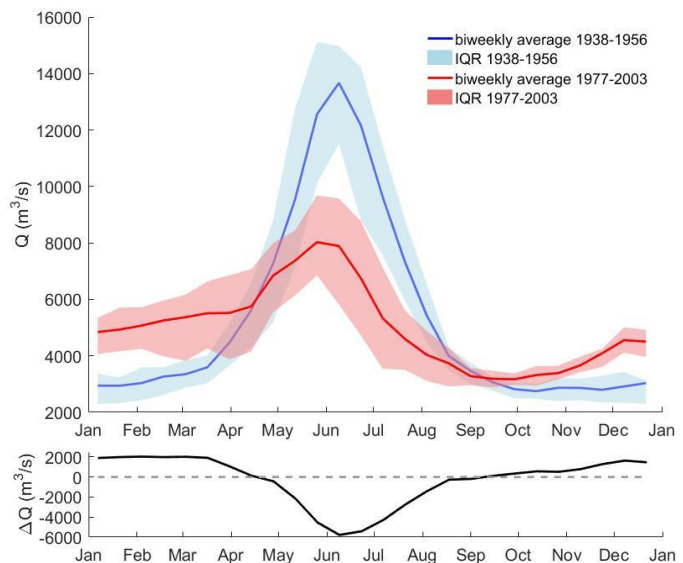


Figure 8. Climatological means of biweekly average discharge (Q) at The Dalles for 1938-1956 and 1977-2003. Interquartile ranges (IQR's) show values between the first and third quartile in each data set. ΔQ is the historical values subtracted from the modern values.



3.3 Historical Period

A simple way to test the efficacy of a statistical model (see results below) is to determine whether the model performs similarly to, or better than, climatology. Biweekly average T_w measurements at Bonneville Dam for 1938-1956 had an RMSE of 1.16°C when compared to the climatological average for that period (Figure 9).

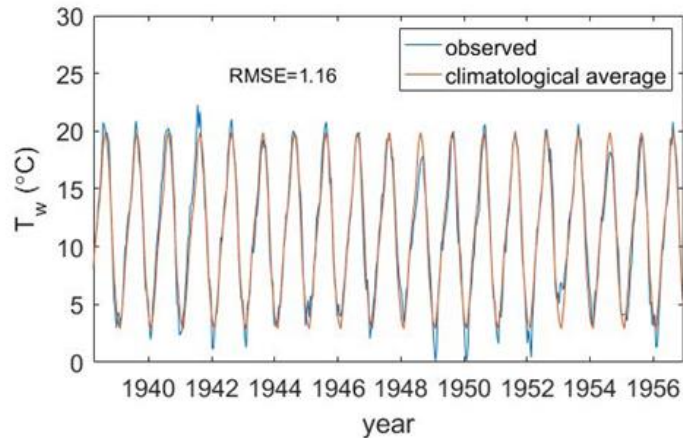


Figure 9. Comparison of biweekly average water temperature (T_w) at Bonneville Dam to climatological average, 1938-1956.

To develop a statistical model of T_w for the historical period, different time lags were tested for T_a . A two-week time lag on T_a was found to give the lowest RMSE. The lag probably occurs due to the travel time of water through the large Columbia River basin (Figure 1). Additionally, T_w responds more slowly to atmospheric heating than T_a due to its higher heat capacity.

Different combinations of six-month periods were also tested to develop seasonal regressions. Regressions using May through October (summer) and November through April (winter) produced the best results, as measured by the smallest RMSE. When Q was included in both the summer and winter regressions, the coefficient had a negative sign during summer and a positive sign during winter (Table 1). To visually assess how T_w was correlated with Q , T_a was binned into 1 degree subsets (e.g., $8.5\text{-}9.5^\circ\text{C}$), and scatter plots of Q and T_w were produced (Figures 10 and 11). Since a two-week time lag for T_a was used in the models, the T_w and Q measurements that occurred two weeks after each subset of T_a measurements were grouped together. Robust linear regression was used to determine the slope of the T_w/Q relationship for each T_a -binned subset. During summer months the relationship was typically negative (mean slope = $-0.235^\circ\text{C}/10^3\text{ m}^3/\text{s}$) as would be expected (Figure 10). During winter months the relationship was usually not significant (Figure 11), suggesting that a positive relationship between T_w and Q during winter was not statistically significant.

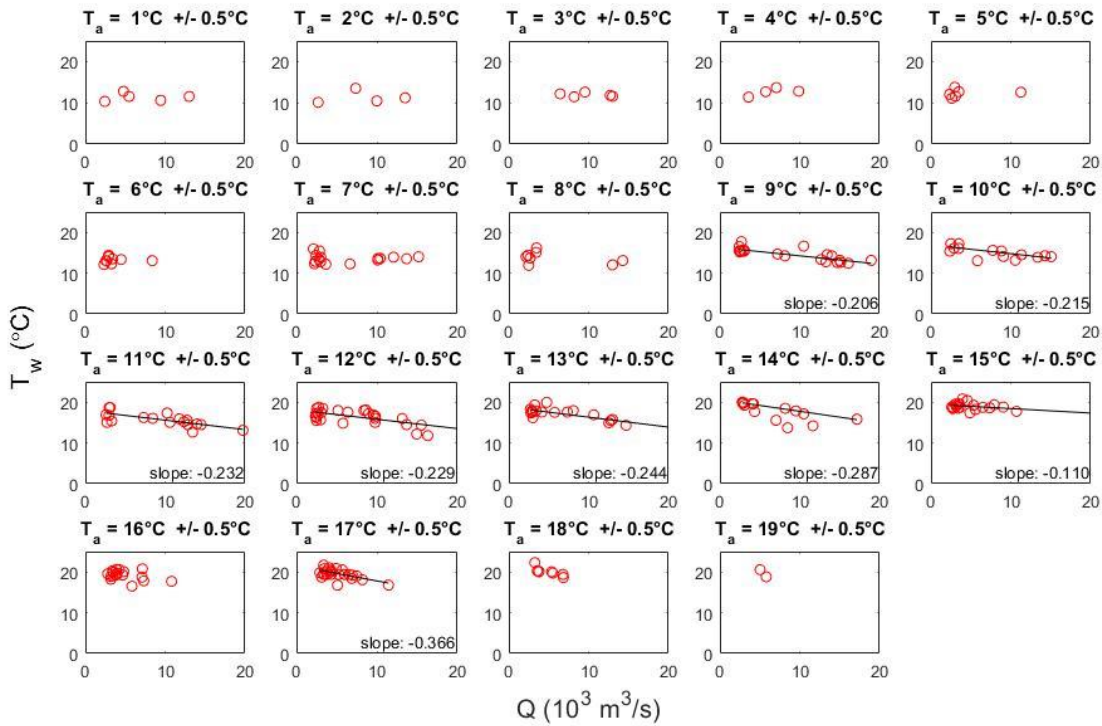


Figure 10. Comparison of relationships between biweekly average water temperature (T_w) at Bonneville Dam and flow (Q) at The Dalles at constant basin air temperature (T_a) during May through October, 1938-1956. Slopes are shown where a significant relationship was found.

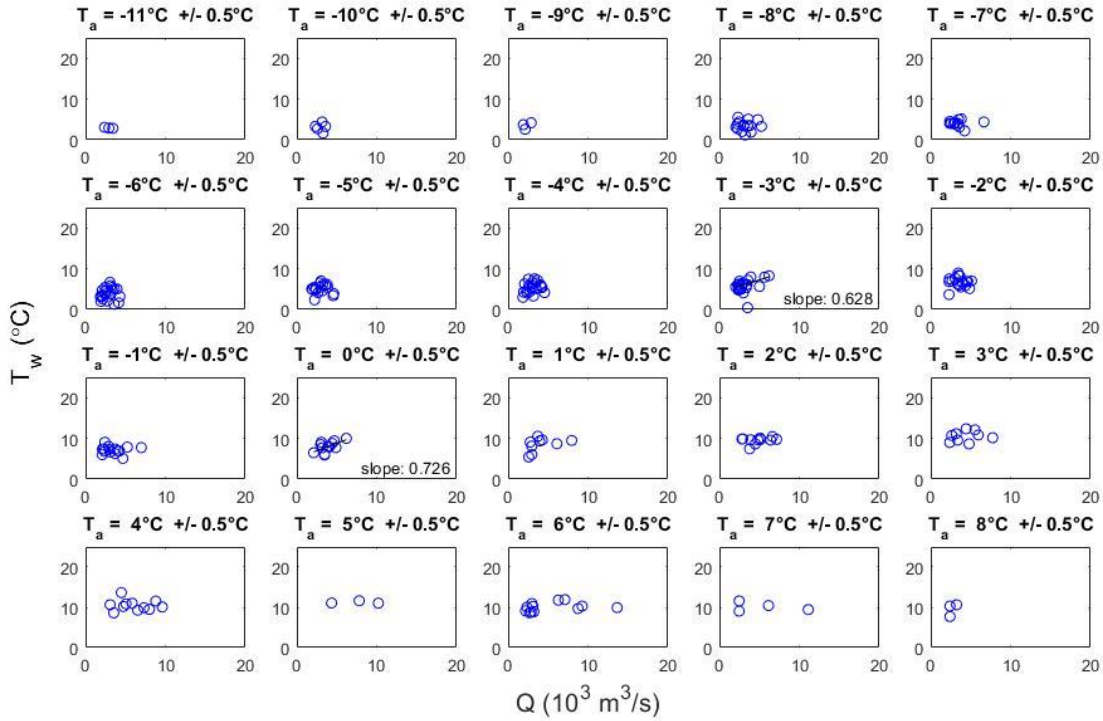


Figure 11. Comparison of relationships between biweekly average water temperature (T_w) at Bonneville Dam and flow (Q) at The Dalles at constant basin air temperature (T_a) during November through April, 1938-1956. Slopes are shown where a significant relationship was found.

Table 1. Regression coefficients for different water temperature models, 1938-1956.

	Entire Year	Seasonal		Seasonal without Q in Winter	
		May - Oct	Nov - Apr	May - Oct	Nov - Apr
Constant (β_0), °C	9.10 +/- 0.20	11.40 +/- 0.49	6.85 +/- 0.46	11.40 +/- 0.49	7.65 +/- 0.19
T_a coefficient (β_1), °C/°C	0.686 +/- 0.015	0.539 +/- 0.033	0.477 +/- 0.036	0.539 +/- 0.033	0.507 +/- 0.033
Q coefficient (β_2), °C/10 ³ m ³ /s	-0.155 +/- 0.032	-0.187 +/- 0.032	0.196 +/- 0.105	-0.187 +/- 0.032	-

Comparing the relationship between T_w and Q for the whole data set showed that during summer months T_w was high and Q varied from high to low (Figure 12). Although the winter T_w/Q relationship was generally not significant at constant T_a , there was a significant slope when all the points were considered together. During winter months T_w and Q were both generally below average. It is possible that the positive correlation between T_w and Q occurs because T_w increases during spring and early summer at the same time that Q is increasing. Figure 12 also shows that the T_w/Q relationship is more pronounced when Q is above 5,000 m³/s, which occurs mainly during May through August. For these reasons, Q was left out of the winter seasonal regression.

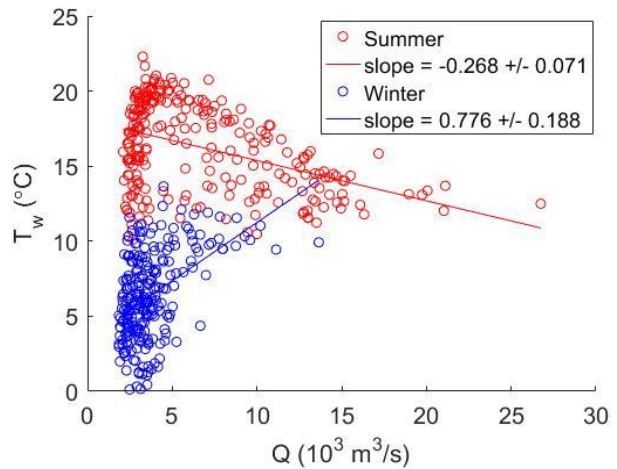


Figure 12. Comparison of relationship between biweekly average water temperature (T_w) at Bonneville Dam and flow (Q) at The Dalles for May through October (summer) and November through April (winter), 1938-1956.

The final model selected for 1938-1956 was based on a regression for May through October (summer) using T_a and Q and a regression for November through April (winter) using only T_a (Figure 13). For both regressions, T_a was lagged by two weeks. This model had an RMSE of 1.22°C, which is slightly lower than the RMSE of the model based on the entire year (Table 2). The model has a higher overall RMSE than the climatological average but a lower RMSE for maximum annual T_w (0.74°C versus 1.02°C). The RMSE for summer was 1.20°C, while for winter it was 1.33°C. This indicates that the summer regression is more reliable than the winter regression, possibly due to a nonlinear relationship between T_w and T_a at sub-zero T_a . The model did not

predict as well in years with unusual T_a and Q . For example, it under-predicted high summer T_w in 1941 when T_a was exceptionally high. Similarly, the model over-predicted summer T_w in 1948, coinciding with high Q that year.

Table 2. RMSE's for different water temperature models, 1938-1956.

	Entire Year	Seasonal	Seasonal without Q in Winter	Climatology
RMSE, °C	1.29	1.23	1.22	1.16
RMSE _{max} , °C	0.73	0.74	0.74	1.02

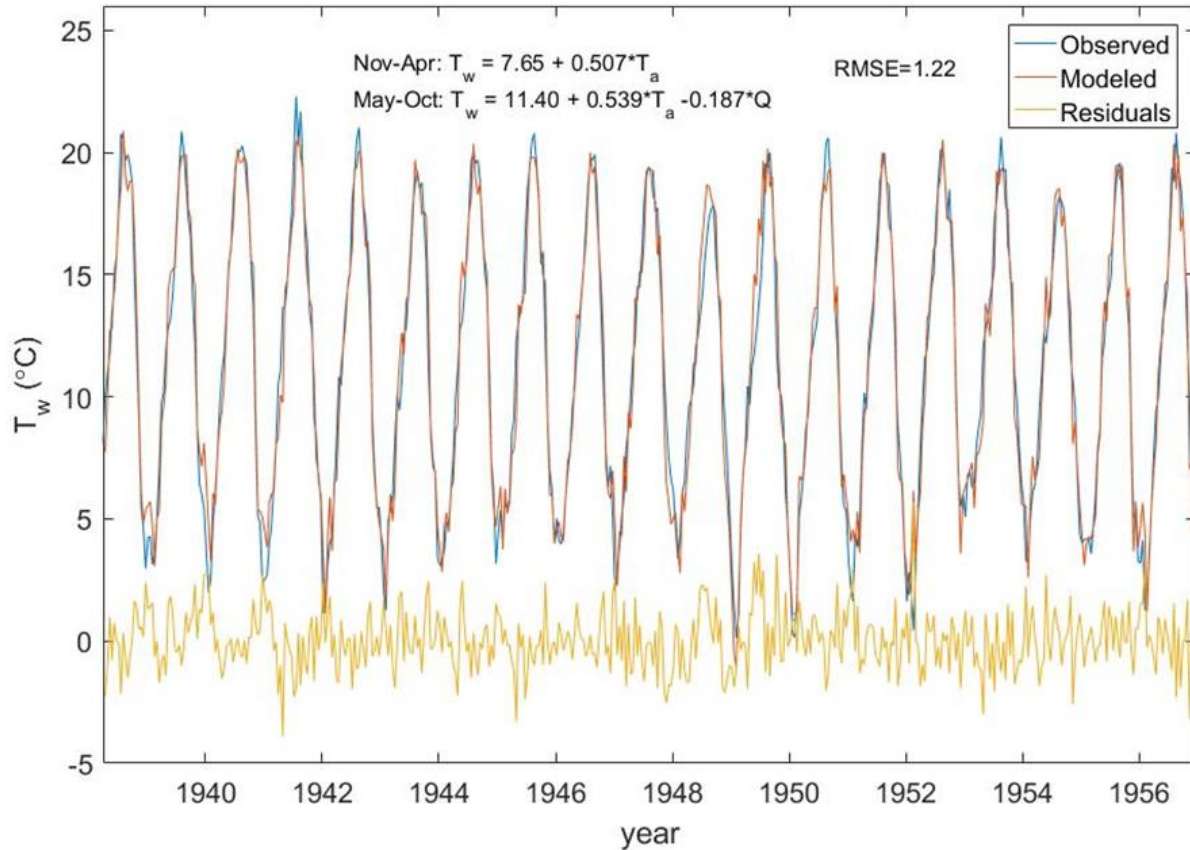


Figure 13. Modeled and observed biweekly average water temperature (T_w) at Bonneville Dam, 1938-1956. Residuals show observed measurements subtracted from model results.

3.4 Modern Period

Biweekly average T_w measurements from Bonneville Dam for 1977-2003 were compared to the climatological average for that period, resulting in an RMSE of 1.02°C (Figure 14). The methodology described in section 3.3 was followed to develop a statistical model for this period, including verifying the relationship between T_w and Q . Dividing the data seasonally gave a negative regression coefficient for Q for November through April (winter) as well as May through October (summer) (Table 3). Isolating T_w and Q relationships at constant T_a gave similar results as for the historical period. Slopes were negative (mean = -0.390 °C/10³ m³/s) during summer (Figure 15) and generally insignificant in winter (Figure 16) indicating that a negative Q coefficient in summer and no Q coefficient in winter was accurate. When all T_w and Q points were plotted together, there was a negative slope during summer and an insignificant slope during winter (Figure 17). Similar to the historical period, there was a more clear relationship between T_w and Q when Q was above 5,000 m³/s.

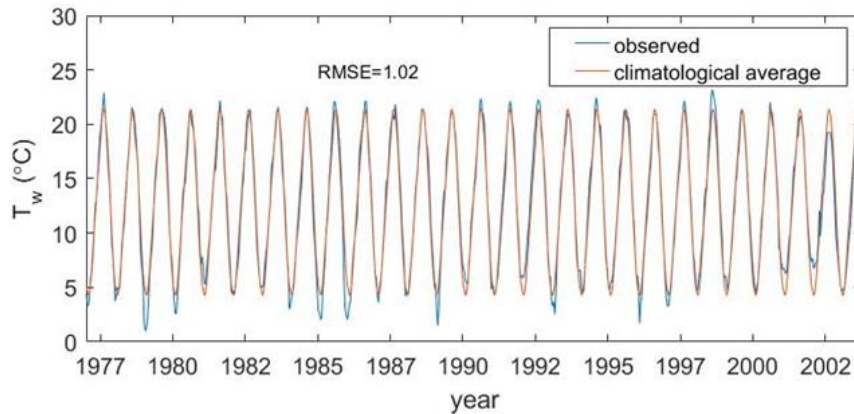


Figure 14. Comparison of biweekly average water temperature (T_w) at Bonneville Dam to climatological average, 1977-2003.

Table 3. Regression coefficients for different water temperature models, 1977-2003.

	Entire Year	Seasonal		Seasonal without Q in Winter	
		May - Oct	Nov - Apr	May - Oct	Nov - Apr
Constant (β_0), °C	10.95 +/- 0.33	13.89 +/- 0.47	9.44 +/- 0.57	13.89 +/- 0.47	8.40 +/- 0.18
T_a coefficient (β_1), °C/°C	0.686 +/- 0.015	0.483 +/- 0.026	0.519 +/- 0.035	0.483 +/- 0.026	0.516 +/- 0.035
Q coefficient (β_2), °C/10 ³ m ³ /s	-0.319 +/- 0.059	-0.318 +/- 0.052	-0.201 +/- 0.105	-0.318 +/- 0.052	-

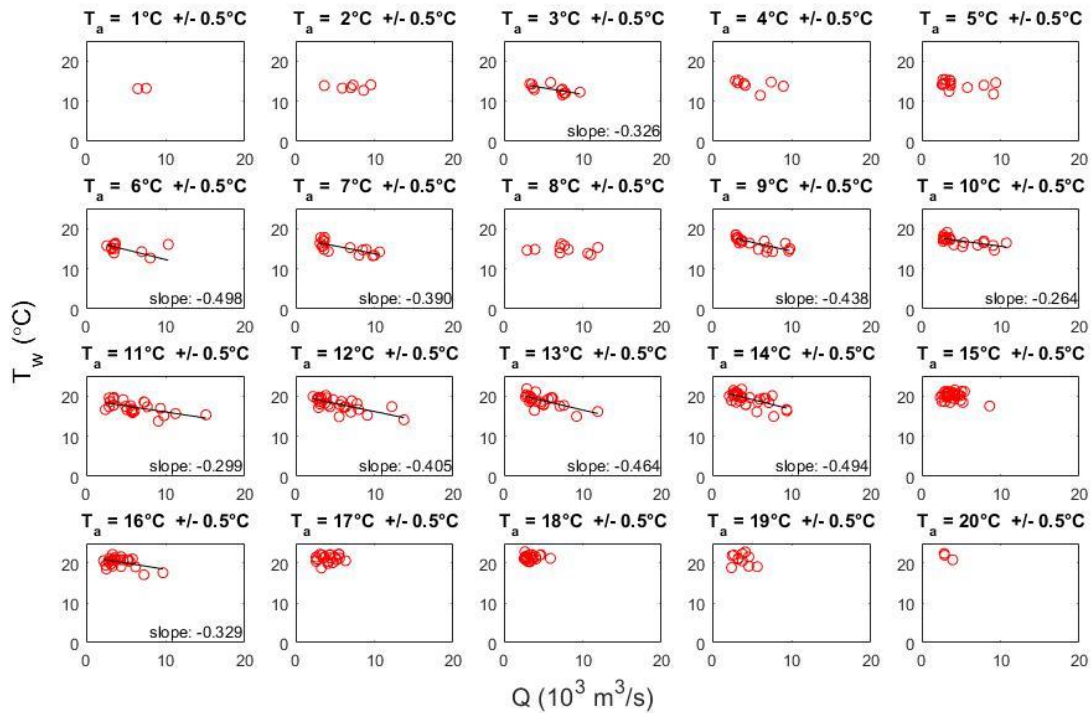


Figure 15. Comparison of relationships between biweekly average water temperature (T_w) at Bonneville Dam and flow (Q) at The Dalles at constant basin air temperature (T_a) during May through October, 1977-2003. Slopes are shown where a significant relationship was found.

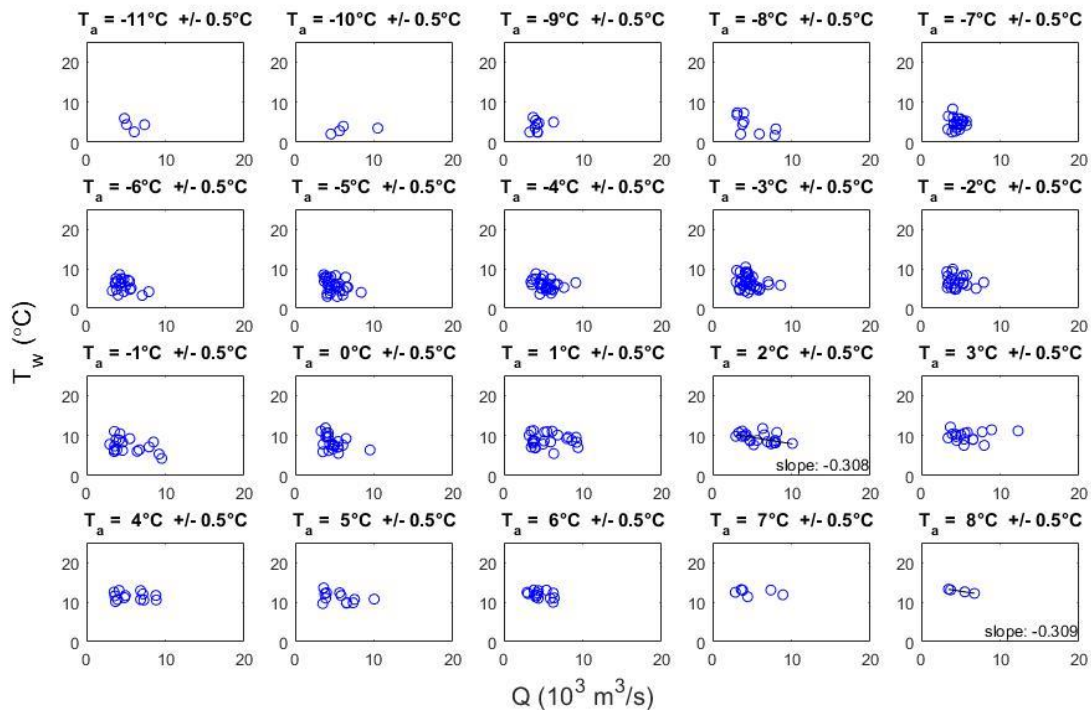
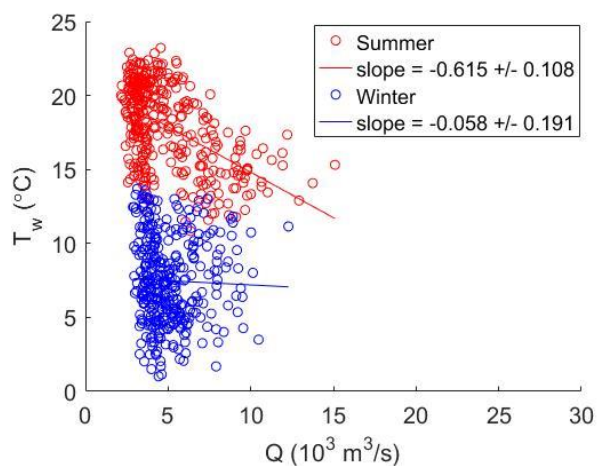


Figure 16. Comparison of relationships between biweekly average water temperature (T_w) at Bonneville Dam and flow (Q) at The Dalles at constant basin air temperature (T_a) during November through April, 1977-2003. Slopes are shown where a significant relationship was found.

Figure 17. Comparison of relationship between biweekly average water temperature (T_w) at Bonneville Dam and flow (Q) at The Dalles for May through October (summer) and November through April (winter), 1977-2003.



While it did not have the lowest RMSE, the final model chosen for the modern period had the same form and predictor variables as the one chosen for the historical period so that the two could be compared. T_a was lagged by two weeks and separate regressions were performed for May through October and November through April, with Q only included as a predictor variable in May through October (Figure 18). This model had an overall RMSE of 1.43°C, which was higher than the RMSE of 1.02°C obtained by using the climatological average (Table 4). The annual maximum T_w RMSE was also higher (0.94°C versus 0.81°C). While the statistical model is not as accurate overall as the climatological model, it better captures interannual variability. The summer regression had an RMSE of 1.11°C, while the winter regression had an RMSE of 1.48°C. This is similar to the historical model and may reflect the non-linear relationship between T_w and T_a at sub-zero T_a .

Table 4. Comparison of RMSE's for different water temperature models for 1977-2003.

	Entire Year	Seasonal	Seasonal without Q in Winter	Climatology
RMSE, °C	1.53	1.39	1.43	1.02
RMSE _{max} , °C	1.30	0.94	0.94	0.81

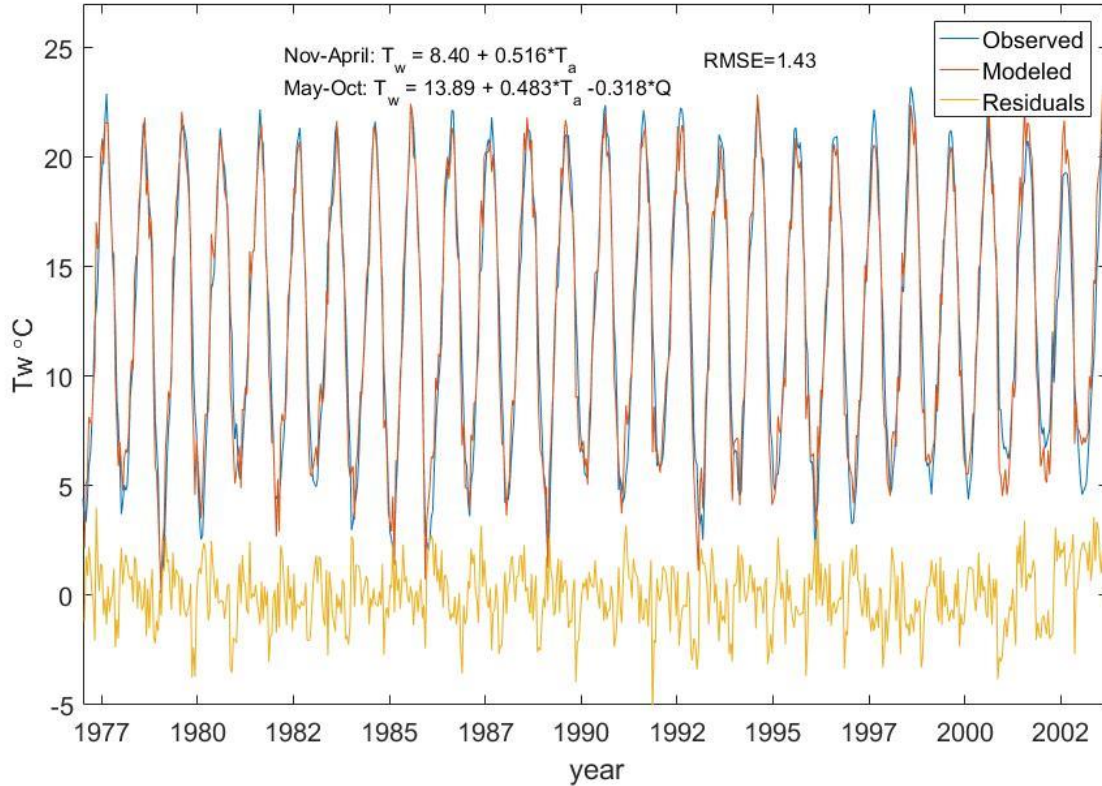


Figure 18. Modeled and observed biweekly average water temperature (T_w) at Bonneville Dam, 1977-2003. Residuals show observed measurements subtracted from model results.

3.5 Comparison

The historical and modern statistical models depend on three regression coefficients and two input variables, all of which can change over decadal and secular time scales as the heat balance and hydrology shift (Equations 3 and 4). Any long-term trends in T_a due to climate change produce altered T_w in the statistical model. By the same mechanism, changed summertime (May through October) Q will cause a shift in modeled T_w . The regression coefficients for T_a and Q denote the sensitivity of the river system to these parameters; any changes to these coefficients likely reflect changes to physical characteristics such as the mean residence time of a water parcel, the mean depth of the system, the amount of shading in riparian streams, or any other factors which affect the advection-diffusion equation (Equation 1).

A comparison of the T_a coefficients (β_1) for the historical and modern models (Equation 3) shows that the modeled T_w/T_a relationship in winter did not change significantly, whereas the modeled T_w/T_a relationship decreased significantly in summer from 0.539 °C/°C to 0.483 °C/°C (Table 5). A similar decrease in sensitivity over time is also observed in the response of T_w data to a T_a

perturbation from climatology (such as a heat wave). During the historical period, a 1°C anomaly in T_a from climatology corresponded to a $\sim 0.30^\circ\text{C}$ anomaly in T_w from climatology (Figure 19). During the modern period, the same T_a anomaly corresponded to a $\sim 0.23^\circ\text{C}$ anomaly in T_w (Figure 20). The differences in the T_w/T_a relationships between the historical and modern models and data indicate that the modern hydrological system has become less responsive to recent (two weeks prior) atmospheric heating and cooling in the basin, especially during summer months. It is possible that the system responsiveness to earlier atmospheric forcing has increased, but this has not yet been investigated.

The Q coefficient (β_2) increased dramatically in magnitude from $-0.187\text{ }^\circ\text{C}/10^3\text{ m}^3/\text{s}$ to $-0.318\text{ }^\circ\text{C}/10^3\text{ m}^3/\text{s}$ for the summertime model (Table 5). While this may indicate that Q produced a greater effect on T_w during the modern period, the change may also (in part) reflect an artifact of the regression. Because the dynamic range of Q was much lower during the modern period, any non-linearity in the T_w/Q relationship will be represented differently. In particular, as noted earlier, the sensitivity of T_w to Q appears to lessen (asymptote) during historical flood events such as 1948 (e.g., Figure 12). Therefore, the regression slope in Figure 12 would steepen if the analysis were confined to the same range of Q as Figure 17, i.e., if restricted to less than $15,000\text{ m}^3/\text{s}$.

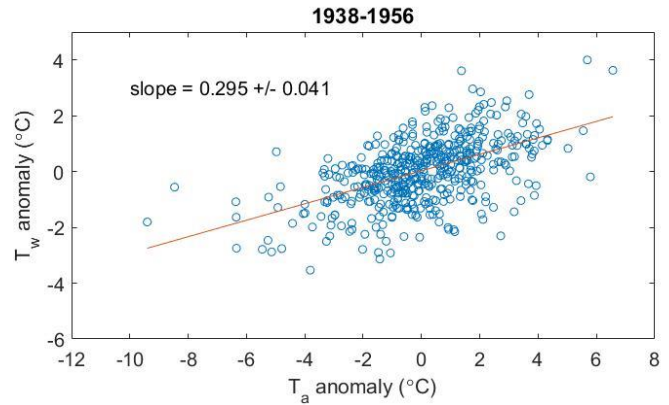


Figure 19. Measured water temperature (T_w) at Bonneville Dam deviation from climatological mean compared to measured basin air temperature (T_a) deviation from climatological mean, 1938-1956.

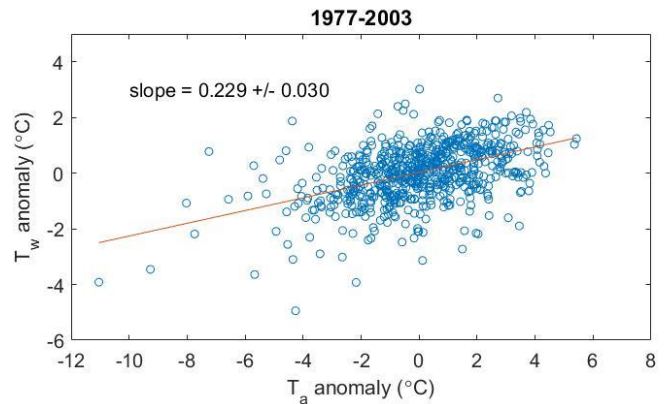


Figure 20. Measured water temperature (T_w) at Bonneville Dam deviation from climatological mean compared to measured basin air temperature (T_a) deviation from climatological mean, 1977-2003.

Table 5. Change in regression coefficients for 1938-1956 and 1977-2003.

	Historical Period	Modern Period	Difference	p-value
T_a Coefficient-Summer (β_1), °C/°C	0.539 +/- 0.033	0.483 +/- 0.026	- 0.056	0.01
T_a Coefficient-Winter (β_1), °C/°C	0.507 +/- 0.033	0.516 +/- 0.035	+ 0.009	1.29
Q coefficient-Summer (β_2), °C/10 ³ m ³ /s	-0.187 +/- 0.032	-0.318 +/- 0.052	- 0.135	0.00
T_w anomaly vs. T_a anomaly, °C/°C	0.295 +/- 0.041	0.229 +/- 0.030	- 0.067	0.01

The changes in biweekly average Q were much greater than the changes in T_a between the two periods (Figures 7 and 8), suggesting that changes in Q might better explain the changes in T_w . Decreases in summer Q are due in part to irrigation withdrawals and in part to storage reservoirs which hold water for later release (e.g., Naik and Jay, 2005; 2011). Storing water in these reservoirs allows it to heat more than under natural flow conditions due to an increased residence time. Moreover, an increased residence time implies that meteorological conditions can affect T_w over a longer time period. This observation can help explain the decrease in the regression coefficient β_1 for two-week-lagged T_a . (Table 5). Essentially, storage reservoirs act as heat capacitors that store heated T_w in the summer and slowly release it in autumn. This can be seen in the large increase in T_w during October and November in the modern period (Figure 6).

Another indicator of the effect of river management on T_w is the decrease in T_w deviation from climatology. During the historical period, the RMSE of observed T_w compared to climatology was 1.16°C (Figure 9), while during the modern period it was 1.02°C (Figure 14). The historical system was more natural and showed more variability, while the modern system is less variable, probably because dams and river management average out and dampen natural variability. Though it is possible that long-term improvements or changes in T_w measurement protocol reduce the measured variance, initial analysis suggests this is a relatively small factor. Indeed, as shown in Table 5, the confidence intervals in the regression coefficients are small, and the coefficients β_1 are significantly different in the historical and modern models.

Overall, an excellent agreement is found between modeled and measured changes in T_w . The modeled change is defined as

$$\Delta T_w = T_{w,M} - T_{w,H} \quad (9)$$

where $T_{w,M}$ is T_w predicted by the modern model with modern climatology as inputs, and $T_{w,H}$ is T_w predicted by the historical model with historical climatology as inputs. Based on Equation 9,

annual maximum T_w increased by 1.5°C. This matches the observed change of 1.5°C, indicating that the models accurately represent the change in annual maximum T_w over time.

The factors producing the modeled 1.5°C increase in annual maximum T_w are next investigated by considering the individual contributions of changed Q , T_a , and regression coefficients.

These terms in Equation 9 are first expanded by substituting Equation 4, such that

$$\Delta T_w = (\beta_{0,M} + \beta_{1,M}T_{a,M} + \beta_{2,M}Q_M) - (\beta_{0,H} + \beta_{1,H}T_{a,H} + \beta_{2,H}Q_H) \quad (10),$$

where the subscripts M and H denote the modern and historical model coefficients (β terms) or climatology (Q and T_a terms).

Rearranging Equation 10 gives

$$\Delta T_w = \beta_{0,M} - \beta_{0,H} + \beta_{1,M}T_{a,M} - \beta_{1,H}T_{a,H} + \beta_{2,M}Q_M - \beta_{2,H}Q_H \quad (11)$$

Based on the relationship between historical and modern coefficients and variables, Equation 11 can be written

$$\Delta T_w = \Delta\beta_0 + (\beta_{1,H} + \Delta\beta_1)(T_{a,H} + \Delta T_a) - \beta_{1,H}T_{a,H} + (\beta_{2,H} + \Delta\beta_2)(Q_H + \Delta Q) - \beta_{2,H}Q_H \quad (12),$$

where the Δ terms denote the change (difference) between modern and historical conditions. For example, $\Delta\beta_2 = \beta_{2,M} - \beta_{2,H}$.

After expanding Equation 12, the total change in modeled T_w becomes a function of 7 terms:

$$\Delta T_w = \underbrace{\Delta\beta_0}_1 + \underbrace{\Delta\beta_1 T_{a,H}}_2 + \underbrace{\Delta\beta_1 \Delta T_a}_3 + \underbrace{\beta_{1,H} \Delta T_a}_4 + \underbrace{\Delta\beta_2 Q_H}_5 + \underbrace{\Delta\beta_2 \Delta Q}_6 + \underbrace{\beta_{2,H} \Delta Q}_7 \quad (13).$$

In the equation above, terms 3 and 4 are influenced by changing T_a , terms 6 and 7 are influenced by changing Q , and terms 2, 3, 5, and 6 are influenced by altered system management and changing system characteristics. The β_o term is a fitting parameter in Equation 4 which represents (mathematically) the estimated T_w in the extreme case of no Q and zero T_a at a two-week time lag. Practically, the β_o term represents factors that are not being modeled (such as T_a or Q at a four-week lag). A change in summertime β_o (i.e., term 1) therefore reflects a change in the baseline

system properties and system response that are not modeled by the other terms. Estimated values for the 7 terms in Equation 13 are given in Table 6 for the August time frame, corresponding to the time of peak T_w .

Table 6. Calculated values of the individual variables in Equation 13, representing August conditions during the time period of annual maximum water temperature ($T_{w, max}$).

$\Delta\beta_0$	$\beta_{1,H}$	$\Delta\beta_1$	$\beta_{2,H}$	$\Delta\beta_2$	$T_{a,H}$	ΔT_a	Q_H	ΔQ
2.5°C	0.54 °C/°C	-0.06 °C/°C	-0.19 °C/10 ³ m ³ /s	-0.14 °C/10 ³ m ³ /s	17°C	0.4°C	5.4 10 ³ m ³ /s	-1.7 10 ³ m ³ /s

Table 7. Calculated values of terms in Equation 12 based on values in Table 6 showing contribution from each term to total modeled change in water temperature (T_w).

Term	1	2	3	4	5	6	7
	$\Delta\beta_0$	$\Delta\beta_1 T_{a,H}$	$\Delta\beta_1 \Delta T_a$	$\beta_{1,H} \Delta T_a$	$\Delta\beta_2 Q_H$	$\Delta\beta_2 \Delta Q$	$\beta_{2,H} \Delta Q$
Value, °C	2.5	-0.95	-0.02	0.19	-0.73	0.23	0.32

Overall, a relatively small portion of the 1.5°C increase in maximum T_w since the mid-20th century is directly attributable to T_a increases occurring at a two-week time lag (Table 7). Annual maximum T_a only increased by 0.4°C, which, by the statistical model, suggests a roughly 0.2°C increase in T_w (Table 7, term 4). The effect of the altered regression coefficient is even smaller—an insignificant difference of roughly 0.02°C is obtained when the T_a change of 0.4°C is scaled by the modern and historical β_1 coefficient (Table 7, term 3). These considerations suggest that slightly more than 10% (~12%) of the increase in summer T_w between the historical and modern periods was directly caused by climate change (Table 7, terms 3 and 4). Presumably, a comparison over a longer time scale might show a larger effect; this is left for a future study.

The direct effect of a changing hydrograph (at zero time lag) on peak T_w is also modeled to be a relatively modest 0.32°C (Table 7, term 7). When the effect of both ΔQ terms in Equation 13 are considered (terms 6 and 7), the direct contribution of an altered hydrograph to changing peak T_w is estimated to be ~0.55°C, or roughly 35% of total change (Table 7, terms 6 and 7). The relatively small, directly modeled influence occurs primarily because the measured difference in Q between the historical and modern periods (1,700 m³/s, Table 6) is relatively small during late summer. By contrast, the dramatically reduced hydrograph in May and June produces an increase of up to ~1.1°C on modeled T_w (Figure 7). Given the relatively long residence time of water in the system,

such changes may be influencing August T_w and may be folded into the change observed in the β_o coefficient (Table 7, term 1). More research is necessary on the influence of earlier time periods on measured data.

A comparison of the historical and modern models shows that the combined effects of changes in Q as well as regression coefficients accounts for nearly 90% (88%), or 1.3°C, of the change in annual maximum T_w (Table 7, terms 1, 2, 5, 6, and 7), although this is likely an overestimate because term 1 may reflect (in part) meteorological forcing at a larger time lag than two-weeks. Nonetheless, the overall small change in T_a climatology over the time periods considered here (Figure 7) and the discussion above suggests that climate change is likely a small influence. System changes, as well as alterations to Q , therefore likely drive change to T_w over the analyzed time period. However, while much of the long-term change in Q is likely due to dams and river management, some portion may be attributable to climate change and climate variability. The changes in Q between the two periods could be a result of changes in snowpack and precipitation in addition to reservoir management and irrigation withdrawals; therefore, a portion of the changed Q could also represent climate change (Naik and Jay, 2005; 2011). The changes in regression coefficients reflect the influence of reservoir management, since water responds differently to atmospheric heating and cooling in the modern, managed system. Changes in riparian shading and other factors are also likely important.

Overall, a modeled increase of 1.3°C in maximum summertime T_w due to altered Q and reservoir management is higher than the 0.8°C increase in summer T_w attributed to these factors by Bottom et al. (2011). Since some effect of climate change is included in the change in Q and β_o (Equation 4) the results are broadly consistent and support the conclusion that anthropogenic interventions into the system have dominated system changes since the mid-20th century. Nonetheless, as in Bottom et al. (2011), this result is approximate since some dams existed during the base period for the historical model.

3.6 Hindcasting

To estimate trends over climate-change relevant time scales and elucidate natural variability, it would be useful to extend the T_w record to pre-1938 conditions. Therefore, the historical model was used to hindcast T_w at Bonneville dam for 1915-1938, using the available Q and T_a data as inputs. Monthly average T_w measurements from Astoria from 1925-1938 were used to evaluate and ground-truth the statistical model results. Comparison of modeled T_w at Bonneville Dam to measured T_w at Astoria resulted in an RMSE of 1.69°C (Figure 21). This is 0.43°C higher than the RMSE of measured monthly average T_w at Bonneville Dam compared to Astoria for 1938-1956 (Figure 2).

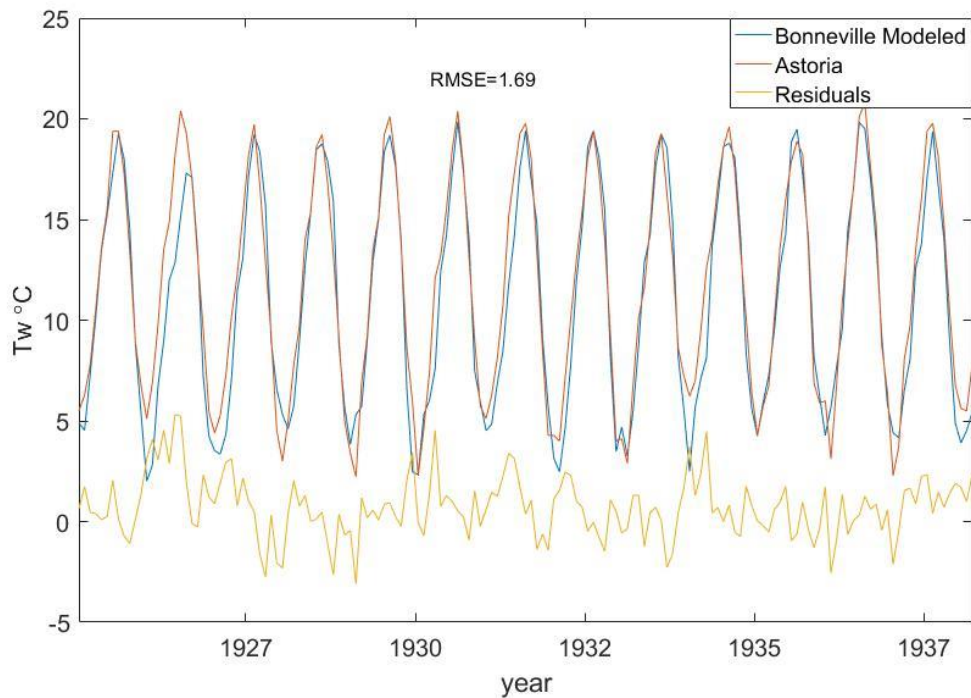


Figure 21. Measured monthly average water temperature (T_w) at Astoria compared to hindcast monthly average T_w at Bonneville Dam, 1925-1938. Residuals show modeled Bonneville Dam results subtracted from Astoria measurements.

A closer comparison suggests that much of the higher variance is driven by a few anomalous periods such as the winter and summer of 1926 or the winter of 1934. In several years, the model predicted higher winter and lower summer T_w at Bonneville Dam than at Astoria, exactly opposite of the general behavior noted for the 1938-1956 period (Figure 2). It is possible that the error in

T_a measurements is larger in the early 20th century, driving a larger variance. Moreover, the model may not represent identical conditions to the hindcasted period, since no dams existed prior to 1934. The modeled summer T_w was especially low in 1926, which could be explained by unusual conditions that year. During that year, peak Q was less than 7,000 m³/s, which was exceptionally low for the pre-management period. When 1926 was not included in the comparison of the modeled and observed T_w , the RMSE decreased to 1.48°C.

Hindcasted T_w for 1915-1938 did not show as much variability in summertime maximums as measured values did for 1938-1956 (Figure 22). The years with highest modeled T_w were 1926, 1930, 1931 and 1936. The highest T_w value for the 1915-1938 period occurred in 1936 and was 20.1°C, lower than the 1938-1956 period maximum of 22.3°C that occurred in 1941. There was much more variability in wintertime low T_w . The lowest modeled T_w occurred during the winters of 1919/20, 1928/29, 1929/30, 1935/36, and 1936/37. The accuracy of the model is likely not sufficient to determine whether T_w in the 1915-1938 period was statistically different than the 1938-1956 period.

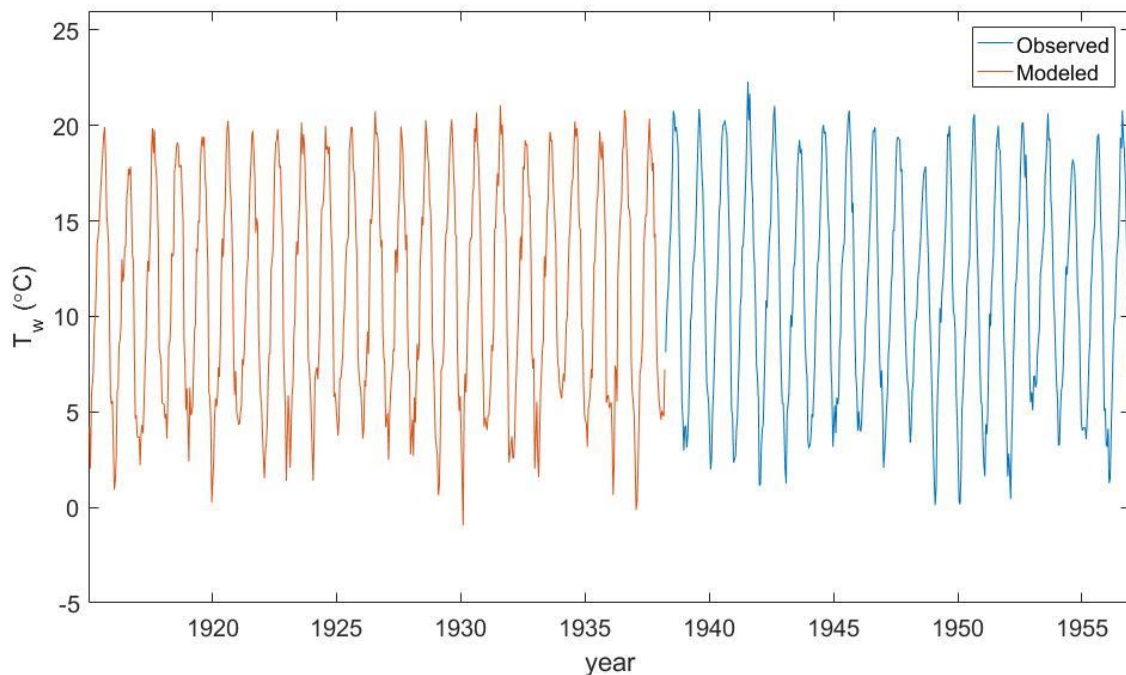


Figure 22. Hindcasted biweekly average water temperature (T_w) at Bonneville Dam, 1915-1938, shown in red and observed biweekly average T_w at Bonneville Dam, 1938-1956, shown in blue.

4.0 CONCLUSION

4.1 Summary

In order to study changes in water temperature (T_w) over time, linear regression models of T_w based on air temperature (T_a) and streamflow (Q) were developed for the Columbia River. Two periods were used for comparison: a historical period (1938-1956) when few main-stem dams existed on the river, and a modern period (1977-2003) when the river was more managed. The historical model performed better than the modern model, with an overall RMSE of 1.22°C, compared to 1.43°C. Neither model had a lower RMSE than the climatological average for the period, but both models better represented interannual variability.

Comparison of the models for the historical and modern periods showed that T_w was more sensitive to Q and less sensitive to T_a in summer during the modern period. The regression coefficient for Q was $-0.187\text{ }^\circ\text{C}/10^3\text{ m}^3/\text{s}$ for the historical period and $-0.318\text{ }^\circ\text{C}/10^3\text{ m}^3/\text{s}$ for the modern period. The regression coefficient for T_a was $0.539\text{ }^\circ\text{C}/^\circ\text{C}$ for the historical period and $0.483\text{ }^\circ\text{C}/^\circ\text{C}$ for the modern period. T_w anomalies from the climatological average were less sensitive to T_a anomalies during the modern period. These differences indicate that the T_w/T_a and T_w/Q relationships have changed over time, probably due to a combination of climate change and reservoir management. The increase in summer T_w due to system changes (e.g., reservoir management) and decreased Q was determined to be approximately 1.3°C.

The T_w model for the historical period was also used to hindcast T_w at Bonneville Dam for 1915-1938. These results were compared to monthly average T_w measurements from Astoria. The relationship between the model results and the measured data had a higher RMSE than the relationship between measured data at Bonneville Dam and Astoria for 1938-1956. This could be because the historical model is not suited for the pre-dam scenario, or because of errors in the Q or T_a data used for hindcasting or the T_w data from Astoria. Further investigation into these possibilities would be useful.

4.2 Next Steps

The models developed in this study could be improved by different methods of data processing. For example, the sub-basin T_a data could be weighted based on each sub-basin's flow contribution rather than area. Different time lags could be used for each sub-basin based on distance from

Bonneville Dam rather than one time lag for the entire basin average T_a . It is possible that these methods could better represent the physical nature of the system. More terms could also be added to the regression equation representing multiple time lags on T_a . This would give further insight into the delayed response of T_w to T_a in the modern, managed system.

Additional data could also be used to improve the models developed here. The PRISM Climate Group (<http://prism.oregonstate.edu/>), part of The Northwest Alliance for Computational Science and Engineering, maintains climate records dating back to 1895. This data would expand the T_a data sets used in the model development, which could lead to more accurate models. Similarly, T_w and T_a measurements through 2017 can be used to assess recent trends and variability, such as the hot summers of 2009 and 2015.

By improving the data used in these models, more accurate models could be developed that would better represent each time period. This would allow for more reliable comparisons between the models for different time periods, as well as better hindcasting capabilities. Additionally, Astoria T_w data from 1853-1876 compiled by Talke and Jay (2013) could be incorporated as a way to study T_w change over a longer period.

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