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Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State

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Abstract This study evaluates the sensitivity of Washington State's freshwater habitat of Pacific Salmon (*Oncorhynchus* spp.) to climate change. Our analysis focuses on summertime stream temperatures, seasonal low flows, and changes in peak and base flows because these physical factors are likely to be key pressure points for many of Washington's salmon populations. Weekly summertime water temperatures and extreme daily high and low streamflows are evaluated under multimodel composites for A1B and B1 greenhouse gas emissions scenarios. Simulations predict rising water temperatures will thermally stress salmon throughout Washington's watersheds, becoming increasingly severe later in the twenty-first century. Streamflow simulations predict that basins strongly influenced by transient runoff (a mix of direct runoff from cool-season rainfall and springtime snowmelt) are most sensitive to climate change. By the 2080s, hydrologic simulations predict a complete loss of Washington's snowmelt dominant basins, and only about ten transient basins remaining in the north Cascades. Historically transient runoff watersheds will shift towards rainfall dominant behavior, undergoing more severe summer low flow periods and more frequent days with intense winter flooding. While cool-season stream temperature changes and impacts on salmon are not assessed in this study, it is possible that climate-induced warming in winter and spring will benefit parts of the freshwater life-cycle of some salmon populations enough to increase their reproductive success

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(or overall fitness). However, the combined effects of warming summertime stream temperatures and altered streamflows will likely reduce the reproductive success for many Washington salmon populations, with impacts varying for different life history-types and watershed-types. Diminishing streamflows and higher stream temperatures in summer will be stressful for stream-type salmon populations that have freshwater rearing periods in summer. Increased winter flooding in transient runoff watersheds will likely reduce the egg-to-fry survival rates for ocean-type and stream-type salmon.

1 Introduction

Climate plays a crucial role in salmon ecology at every stage of their life cycle, but the relative importance of climatic factors is quite different for different salmon stocks. Key limiting factors for freshwater salmon productivity include thermal and hydrologic regimes; these depend on species, their life history, watershed characteristics, and to a great extent stock-specific adaptations to local environmental factors (e.g. Richter and Kolmes 2005; Beechie et al. 2008a; Crozier and Zabel 2006 and Farrell et al. 2008). Those stocks that typically spend extended rearing periods in freshwater (steelhead [*Oncorhynchus mykiss*], stream-type chinook salmon [*O. tshawytscha*], sockeye salmon [*O. nerka*] and coho salmon [*O. kisutch*]) are likely to have a greater sensitivity to freshwater habitat changes than those that migrate to sea at an earlier age (ocean-type chinook salmon, pink salmon [*O. gorbuscha*], and chum salmon [*O. keta*]). While it would be desirable to produce watershed-specific estimates of the aggregate effects of climate change on individual stocks of Pacific salmon in Washington State watersheds, scientific understanding of the interactions between climate and salmon productivity at each stage of each stock's life cycle is not yet adequate to do so. Even in cases where it is possible to carry out stock-specific assessments, such undertakings are beyond the scope of this statewide analysis. Instead we focus on a few direct, well-understood mechanisms whereby more easily predicted physical properties of the freshwater habitat for salmon directly influence salmon reproductive success (or overall fitness) at certain stages of their life cycle. Those physical properties are warm season stream temperature and the volume and time distribution of streamflow. We combine observations, statistical modeling, and hydrologic modeling to compare conditions of the past (1970–1999) with those under projected future climate scenarios for 30-year windows centered on the decades of the 2020s, 2040s, and 2080s. We do not, however, assess the impacts of climate change on cold season water temperatures and related impacts on salmon, and this choice directs our focus on negative, rather than postive, impacts of climate change on the freshwater habitat for Washington's salmon.

The overarching question to be addressed in this study is: How will climate change alter the potential reproductive success of Washington State's salmon, and where and under what conditions is freshwater habitat for salmon most vulnerable to direct hydroclimate (rising water temperatures and altered flow) effects of climate change? Guided by the Independent Scientific Advisory Board's (ISAB 2007) and Crozier et al.'s (2008a, b) reviews of climate change impacts on salmon productivity in the Columbia River Basin, we limit our study to focus on the following subsidiary questions:

What will be the role of climate change in coming decades on summertime water temperatures?

How will a changing climate affect summer low flows and flood peaks?

How, and in which watersheds, will these hydrologic changes likely affect the reproductive success for salmon?

We use three approaches to address these research questions. First, we employ the statistical modeling approach of Mohseni et al. (1998) to relate past surface air temperatures to stream temperatures, and apply these relationships trained on past climate in conjunction with projections of future air temperatures to predict corresponding future stream temperatures. Second, hydrologic models driven by future scenarios of surface air temperature and precipitation provide projections for changes in the statistics of summer low flows and flood peaks (Elsner et al. 2010). And third, the likely impacts of climate change on the reproductive success for salmon in Washington's watersheds are realized by combining salmon sensitivities described in the scientific literature with our scenarios for changes in the statistics of stream temperature and streamflows.

As previously noted, climate also influences estuarine and marine habitat for salmon. Interested readers can find informative reviews of climate impacts on marine habitat for PNW salmon by Pearcy (1992), Logerwell et al. (2003), and ISAB (2007).

2 Data and methods

2.1 Historical water temperature and air temperature data

Stream temperature has been monitored in both large rivers and smaller streams in Washington State by several different agencies. We used three different data sources covering a variety of time periods in this study (see Appendix A). Continuous summertime stream temperature data for 70 stations covering parts of the 2000 to 2007 period were obtained from Washington's DOE (http://www.ecy.wa.gov/programs/eap/fw_riv/rv_main.html#4). Hourly water temperature data from 32 stations in the Columbia River Basin covering parts of the 1995–2008 period were obtained from the US Army Corps of Engineers (USACE) Data Access in Real Time (http://www.cbr.washington.edu/dart/help/hgas_def.html). The U.S. Geological Survey (USGS) archives long-term daily water temperatures at various sites along the Columbia River Basin covering parts of the 1950–2000 period. Mean daily stream temperature data for 22 stations in the Columbia River Basin were obtained from the USGS archives (http://www.streamnet.org/online-data/temperature1.html). For the continuous and hourly data sets, daily average water temperatures were developed from the daily maximum and minimum temperatures. The daily averages were used to calculate mean weekly temperatures. The NOAA National Climate Data Center (NCDC) archives daily air temperature data for over 10,000 stations across the US Station data for daily air temperature were matched to eight of the water temperature sites based on location (within 10 km) and data were downloaded from NCDC (http://cdo.ncdc.noaa.gov/CDO/dataproduct). We also used gridded, historic surface air temperatures at 1/16° latitude by longitude spatial resolution for the 1915–2006 period (Elsner et al. 2010). Figure 1 shows August mean surface air temperatures averaged from 1970–1999 that were derived from station data and mapped to the 1/16° grid used in this study.

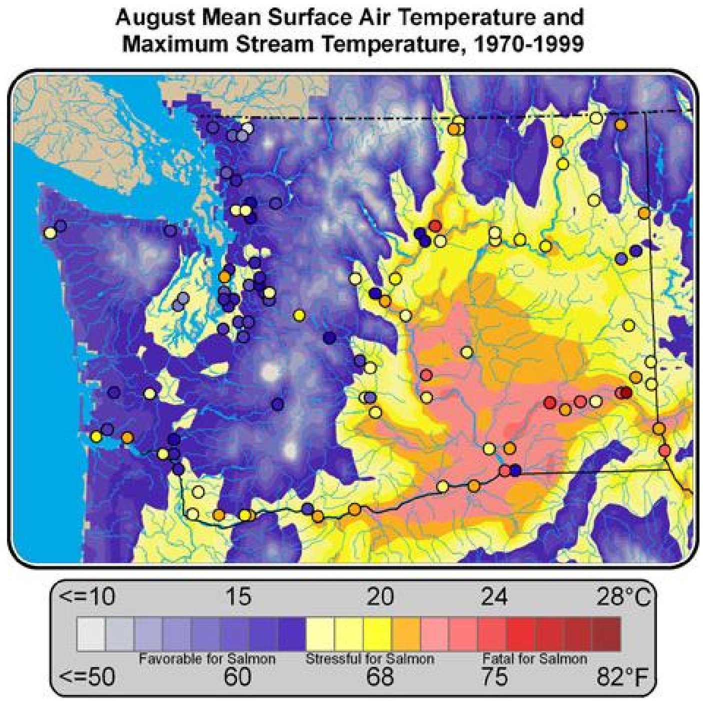

Fig. 1 *Color shading* shows the historic (1970–1999) mean surface air temperatures for August, and *shaded circles* show the simulated mean of the annual maximum for weekly water temperatures for select locations. Figure: Robert Norheim

2.2 Climate change scenarios

Our assessment of climate change impacts on stream temperature and streamflow in the twenty-first century originates from 19 of the 39 coarse-resolution (with typically 100–300 km grid-spacing) climate change scenarios for Washington State's surface air temperature and precipitation described by Mote and Salathé (2010). The 19 scenarios used in this report consist of output from 10 climate models run under A1B emissions, and nine models for B1 emissions. For our stream temperature modeling, we used air temperatures that were statistically downscaled from the global climate models to the 1/16° grid and from a monthly to daily timestep (Elsner et al. 2010). Our streamflow analysis is based on outputs from a hydrologic model that was forced by both air temperature and precipitation that were downscaled from the global climate models using the so-called "delta method" approach, wherein the coarse spatial resolution monthly average changes between future and historic averages are used to adjust the 1/16° gridded historic daily time series in order to represent future climate.

For both stream temperature and streamflow, we focus on the sensitivity of freshwater habitat for salmon to the A1B and B1 scenarios for future greenhouse gas emissions (SRES 2000). The A1B emissions scenario can be considered a "medium" warming scenario, (it is not the warmest of all the IPCC scenarios), and refers to a future where population peaks mid-century and there is very rapid economic growth and a balanced portfolio of energy technologies including both fossil fuels and high efficiency technology that is adopted rapidly. The B1 emissions scenario has lower emissions than A1B that result in less warming, and could be considered the "low" warming scenario. B1 refers to a future where population is the same as A1B, but there are rapid economic shifts toward a service/information economy, the introduction of clean and resource-efficient technologies and emphasis on global solutions to economic, social, and environmental sustainability (SRES 2000).

Based on the average of the 19 scenarios, these models project increases in annual temperature for the Pacific Northwest, compared with the 1980s, of 1.2°C by the 2020s, 1.9°C by the 2040s, and 3.2°C by the 2080s. Because the global climate models have just a few grid points that do a poor job resolving the topography in Washington State, the spatial gradients are very weak in the predicted changes for Washington's precipitation and surface air temperature. Changes in annual precipitation, averaged over all models, are small, but some models show large seasonal changes, especially toward wetter winters and drier summers. Most models predict summer warming exceeds the warming in other seasons, and the models with the most warming also produce the most summer drying (Mote and Salathé 2010).

Based on the 10-model average for A1B emissions, Pacific Northwest summertime temperatures are projected to increase 1.7°C by the 2020s, 2.7°C by the 2040s, and 4.7°C by the 2080s relative to the 1980s. The projections for summertime temperature increases from the 9-model average using B1 emissions are approximately 70% as large as those for the multi-model average using A1B emissions (Table 1). Also note that individual climate model projections for the same emissions scenario vary. For summertime temperature changes summarized in Table 1, the range of projected changes from individual models can be as extreme as 15% to 200% of the multimodel average.

As noted above, we use air temperatures derived from the statistically downscaled global climate model simulations to estimate summertime water temperatures for the twenty-first century, but in this study report only the multi-model averages for the A1B and B1 emissions scenarios, respectively.

Elsner et al. (2010) used another downscaling approach, known as the delta method, in the hydrologic model simulations that generated the daily streamflow data analyzed in this report. The delta method simply applies changes in monthly average temperature and precipitation from composite global climate model scenarios to the full daily time series of historic meteorological fields for 1915–2006. Composite forcing fields on a 1/16° grid for A1B and B1 emissions scenarios were developed from multi-model weighted averages of air temperature and precipitation, respectively. These forcing fields were then used to drive the variable infiltration capacity (VIC) hydrologic model simulations that produced daily time series of streamflow. The flood and low flow statistics from our analyses are calculated from simulated streamflow data derived from simulations forced by three separate 92-year driving data sets for each of the emissions scenarios (A1B and B1), one representing the climate for each of the future time horizons centered on the 2020s, 2040s, and 2080s, respectively.

Table 1 Multi-model average projected changes in June–July–August PNW air temperature for A1B (ten models) and B1 (nine models) emissions

Time interval	2020s			2040s			2080s		
Scenario	Low	Avg	High	Low	Avg	High	Low	Avg	High
A1B	0.43°C	1.7°C	3.4°C	1.3°C	2.7°C	5.1°C	2.7°C	4.7°C	8.1°C
B1	0.18°C	1.2°C	2.4°C	0.2°C	1.8°C	3.7°C	1.3°C	2.9°C	5.1°C

The statistically downscaled models represented here and used in our stream temperature modeling are: ccsm3, cgcm3.1 t47, cnrm cm3, echam5, echo g, hadcm, hadgem1 (A1B only), ipsl cm4, miroc 3.2, pcm1

Elsner et al. (2010) evaluated the VIC hydrologic model sensitivity to precipitation and temperature change (see their Tables 2 and 3). For example, they analyzed precipitation elasticity, or the fractional change in runoff compared to the fractional change in precipitation, and temperature sensitivities for six locations in the Yakima River basin. A 10% increase in precipitation caused an increase in runoff by a factor of 1.59 for the entire basin. An average daily temperature increase of 1°C, applied by increasing both minimum and maximum temperature, reduced basin runoff by approximately 2.45% to 5.77%, depending on location. Alternatively, the same average daily increase, by altering maximum temperature only, reduced runoff by 5.15% to 9.81%, depending on location.

2.3 Non-linear stream temperature regression models

Mohseni et al. (1998) used weekly average air temperature to predict weekly average water temperatures, and we use the same approach here using the data available for all of the sites (air and water temperatures). The regression models developed by Mohseni et al. (1998) show that the relationship between weekly air and water temperatures is best described by a nonlinear S-shaped function:

$$T_w = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_{a_i})}}$$

where T_w is the estimated weekly average stream temperature, μ is the estimated minimum stream temperature (set to ≥ 0 since the rivers in this study never freeze), α is the estimated maximum stream temperature, γ is a measure of the steepest slope of the function, β indicates the air temperature at the inflection point, and T_a is the average weekly air temperature. To estimate the parameters of the nonlinear function the least squares method was applied, minimizing λ, the sum of the squared errors (ε) between the observed and fitted values for water temperatures:

$$\lambda = \sum_{i=1}^{n} \varepsilon_i^2 = \sum_{i=1}^{n} \left(T_{\mathrm{obs}_i} - \mu - \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_{a_i})}} \right)^2$$

Many climate variables other than air temperature also influence water temperatures, and some of the sites in this study undergo seasonal hysteresis, which involves a lag in stream temperature response to air temperature. For example, this phenomenon occurs when streams receive an influx of cold snowmelt water in the spring and maintain a cooler thermal regime despite warming air temperatures. The effects of this process are apparent during the fall and spring seasons when the data scatter is greater around the fitted model. In these cases, two regressions were applied to the data based on the weekly values separately for the fall and spring seasons. Of the estimated parameters from the two fitted models, the higher α, the lower μ, and average of the two γ and β parameters were used to calculate T_w (Mohseni et al. 1998), so that ultimately only one fitted model was applied to each site.

The Nash-Sutcliffe coefficient (NSC) (Nash and Sutcliffe 1970) was used to determine the goodness of fit:

$$\mathrm{NSC} = 1 - \frac{\sum_{t=1}^{n} (T_w - T_{\mathrm{obs}})^2}{\sum_{i=1}^{n} \left(\overline{T}_{\mathrm{obs}} - T_{\mathrm{obs}_i} \right)^2}$$

In streams where seasonal hysteresis was suspected of playing a role in water temperatures, the average NSC from the two fitted regressions was calculated and if it exceeded the NSC calculated for a single fitted function, the stream was assumed to exhibit hysteresis. Of the 211 stations modeled, only the 124 streams with NSC values ≥0.7 were included in this study (Mohseni et al. 1998). Of these sites, 49 demonstrated hysteresis and had higher NSC values when fit to two functions. The range of water temperature observations extended from less than one year to more than 30 years for some sites depending on the data source. Since we focus on summertime weekly average temperatures, we included only those sites where summertime temperatures were available (weeks 25–40). Because we are modeling weekly average temperatures, we validate the development of regression models with just one to a few years of stream temperature observations if, according to the NSC criteria employed here, we are able to establish a robust relationship between a location's weekly average air and water temperature. We also assume that the statistical relationship between weekly average air and water temperature are stationary, both for past and future years.

2.3.1 Model validation and application

The eight sites with paired observed air and water temperature data were used to validate the models. Weekly averages of observed air (NCDC station data in Appendix B) and stream temperatures were calculated for each site. Using the statistical programs R 2.7 and SAS 9.1, we estimated the model parameters for each test site by fitting the observed weekly air temperatures to the observed weekly water temperatures with the regression model (Equation 1) using the least squares method (Equation 2). Each test site was matched to the nearest point in the 1/16° gridded dataset and the same method was applied using historic surface air temperature from this dataset (Elsner et al. 2010). The model parameters for each site generated by (a) the observed air temperatures (station data) and (b) the gridded historic air temperature data were nearly identical, as were the NSC values generated by using station data and gridded air temperatures for each of the eight sites, respectively. Given the strong correspondence between station data and gridded surface air temperature data series we felt justified in using the nearest grid-point time series in our temperature regression model for all sites.

All sites with observed water temperature data were matched to the nearest 1/16° point in the gridded dataset using ArcGIS 9.3. Model parameters were estimated using weekly surface air temperatures from the historic gridded dataset for each site. The regression parameter of interest in this study is the α-value, or maximum temperature. The models estimated an α-value within 2°C of the observed maximum temperature for 78% of the sites in this study. Similar to Mohseni et al. (1998), we found that the regression models more often underestimated the α-value in this study. For sites where seasonal hysteresis was detected and two regressions were applied, the model tended to underestimate fall temperatures and overestimate spring temperatures. We applied the regression model using the estimated parameters and the downscaled surface air temperatures for each climate change model (10 models for the A1B scenario and 9 models for the B1 scenario as made available by the IPCC) to estimate average weekly water temperatures for 19 future climate change scenarios at 124 sites. For each scenario, the projected weekly maximum water temperatures were identified for each model and averaged over the models into four 30-year intervals: 1970–1999, 2010–2039, 2030–2059, 2070–2099. Sites and time periods where weekly temperatures exceed 21°C were flagged as indicators for potential migration barriers and extreme thermal stress for salmon, although it is important to keep in mind that not all these sites are in stream reaches that typically host juvenile or adult salmon during the warmest summer months.

2.4 Stream temperature and streamflow criteria used for assessing impacts on salmon

Water temperature is a key aspect of water quality for salmonids, and excessively high water temperature can act as a limiting factor for the distribution, migration, health and performance of salmonids (e.g. McCullough 1999; Richter and Kolmes 2005; EPA 2007; Farrell et al. 2008). Excessively warm waters can inhibit salmon migration and breeding patterns, and reduce cold-water refugia and connectivity. When average water temperatures are greater than 15°C salmon can suffer increased predation and competitive disadvantages with native and non-native warm water fish (EPA 2007). Water temperatures exceeding 21–22°C can prevent migration. Furthermore, adult salmon become more susceptible to disease and the transmission of pathogens as temperatures rise, and prolonged exposure to stream temperatures across a threshold (typically near 21°C, but this varies by species) can be lethal for juveniles and adults (McCullough 1999; see Table 2).

Based on recent agency reviews, we chose a single critical threshold of a weekly average water temperature of 21°C as an indicator for thermal migration barriers and an elevated risk for fish kills. This choice greatly simplifies our analysis, but it does so at the expense of neglecting stock-specific, species-specific, and life-stage specific differences in thermal sensitivities of salmon. The Washington Department of Ecology (DOE) established water temperature standards for salmon habitat at various stages of their life history in Chapter 173–201A of the Washington Administrative Code (WAC), and these were subsequently reviewed by the Environmental Protection Agency (EPA 2007). The DOE and EPA express temperature thresholds for salmon as the 7-day average of the daily maximum temperature (7DADMax). Among adult salmon, the 7DADMax is lethal at ~23°C, migration is inhibited at ~24°C, and the risk of disease is elevated at ~14°C. The models we used in this study estimate weekly average temperatures (hereafter T_w) rather than 7DADMax, so we must use an appropriately adjusted criteria. The EPA (2007) determined

Table 2 Maximum weekly temperature upper thermal tolerances for salmonids

Species	Upper thermal tolerance
Cutthroat trout (*O. clarki*)	23.3°C
Rainbow trout (steelhead; *O. mykiss*)	24.0°C
Chum salmon (*O. keta*)	19.8°C
Pink salmon (*O. gorbuscha*)	21°C
Coho salmon (*O. kisutch*)	23.4°C
Chinook salmon (*O. tshawytscha*)	24°C

Based on the 95th percentile of maximum weekly mean temperatures where fish presence was observed (Eaton and Scheller 1996) that the 7DADMax is 3°C warmer than T_w. Therefore we identify sites where T_w exceeds 21°C (or 3°C less than the 7DADMax criteria) as the critical threshold for migration barriers and an elevated risk to fish kills for salmon (EPA 2007). Also note that Washington's DOE adopted a 17.5°C 7-DADMax (equivalent to a 14.5°C T_w) criterion to protect waters designated for 'Salmon Spawning, Rearing, and Migration use' where spawning occurs after mid-September and egg emergence occurs before mid-June (EPA 2007).

Characteristics of seasonal and daily streamflow variations can also serve as limiting factors for freshwater salmon habitat (Rand et al. 2006; Beechie et al. 2006). Seiler et al. (2003) found that the annual incubation flood magnitude was a significant predictor of freshwater survival rates for Skagit River chinook salmon, wherein larger floods resulted in smaller survival rates. Greene et al. (2005) found that the annual flood magnitude was a strong predictor of total lifecycle return rates for Skagit River chinook salmon. These findings could result from several different mechanisms linking peak incubation flows to early freshwater life-stage survival rates for salmon. Extreme flows during egg incubation periods can limit egg-to-fry survival rates by scouring redds, crushing eggs with mobilized gravels (Holtby and Healey 1986; Montgomery et al. 1996; DeVries 1997), or depositing fine sediments on redds that reduce available oxygen (Lotspeich and Everest 1981). Peak flows can also reduce the availability of slow-water habitats, which can flush rearing juveniles downstream from preferred habitats and subsequently reduce freshwater survival rates (Latterell et al. 1998).

It is also important to note that there are sometimes shared and sometimes different limiting environmental factors for different stocks and different species of Pacific salmon because of life history diversity and heterogenous habitat types. For example, studies by Beechie et al. (1994) and Reeves et al. (1989) indicate that the most important factors for juvenile coho freshwater survival are (1) the in-stream temperature during the first summer, combined with the availability of deep pools to mitigate high temperatures; and (2) temperature during the second winter, combined with the availability of beaver ponds and backwater pools to serve as refuges from cold temperatures and high streamflow events. Consequently, a particularly troublesome scenario for coho involves an increase in summer water temperature in combination with a decrease in summer streamflow and an increase in winter peak flows.

Battin et al. (2007) found that of the factors they evaluated for climate change impacts on ocean-type chinook in the Snohomish Basin, projected increases in extreme high flows by far had the greatest negative impact on the reproductive success of salmon.

2.5 Methods for extreme high and low flow analyses

The flood and low flow frequency statistics were calculated from Elsner et al's. (2010) projected and historic (1915–2006) daily flow simulations at 97 sites in Washington State (listed in Appendix C). Flood frequency was calculated by ranking the annual maximum flows and fitting the generalized extreme value distribution using the L-moments method (Wang 1997; Hosking and Wallis 1993; Hosking 1990). From the fitted probability distributions, the flood magnitudes with a 20-year return period were estimated for each time interval centered on the 1980s, 2020s, 2040s and 2080s.

Beamer and Pess (1999) found that stocks of chinook salmon in the Skagit and Stillaguamish rivers were unable to reproduce rapidly enough to "replace" themselves if peak flows during the intervals of egg incubation matched or exceeded the 20-year flooding event. The low flow statistic is the annual minimum 7-day consecutive lowest flow, to which the same probability distribution was fit as for flood flows. From the fitted distribution, we estimated 7Q2 and 7Q10, or the magnitude of the 2-year and 10-year return period 7-day low flow magnitudes, respectively, for each of the four 30-year time intervals. The results from these analyses were used to calculate the ratio of future to historic flooding and low flow magnitudes for each composite scenario/time interval (e.g. "A1B 2020s", or "B1 2040s"). From the downscaled, derived historic air temperature data set, the average December/January/February air temperatures (DJF) were calculated for each catchment for the 1970–1999 period to characterize wintertime temperature regimes. The projected return frequency of the historic 20-year flood was estimated and compared to each basin's DJF average temperature to typify each basin's sensitivity to warming temperatures.

3 Key findings/discussion

3.1 Summertime stream temperature projections

Maximum weekly water temperatures in Washington State are typically observed from late July through late August, similar to the period of climatologically warmest air temperatures. In Fig. 1 we show the downscaled historic averages for August surface air temperatures and simulated annual maximum weekly water temperatures for the 1970–1999 period. Many of the interior Columbia Basin's water temperature stations modeled in this study have maximum weekly water temperatures that exceed 21°C. In reaches that typically host salmon in the warmest summer months these locations already have periods with episodes of extreme thermal stress for salmon. For instance, summer water temperatures in the mainstem Columbia River sometimes reach lethal limits for sockeye salmon (Naughton et al. 2005), and frequently pose thermal migration barriers for fall chinook salmon (Goniea et al. 2006) and summer steelhead (High et al. 2006). Under historical conditions, all but one of the stations in our study with extreme high water temperature are located in eastern Washington. The western Washington exception in our data set is for the University Bridge station, located in a short channel between Portage Bay and Lake Union in Seattle. This site is located in a migration corridor for summer-running adult sockeye and chinook salmon.

Our stream temperature modeling predicts significant increases in water temperatures and thermal stress for salmon statewide for both A1B and B1 emissions scenarios. The projected annual maximum T_w patterns shown in Fig. 2 indicate there will be large increases in the number of stations that are especially unfavorable for salmon in summer (where $T_w > 21°C$). Figure 2 also shows the encroachment of summertime air temperatures with $T_a > 18°C$ becoming the norm for western Washington by the 2040s, and for this period only the higher elevations of the Cascades and Olympics have temperatures like those characteristic of the western Washington lowlands in the 1980s.

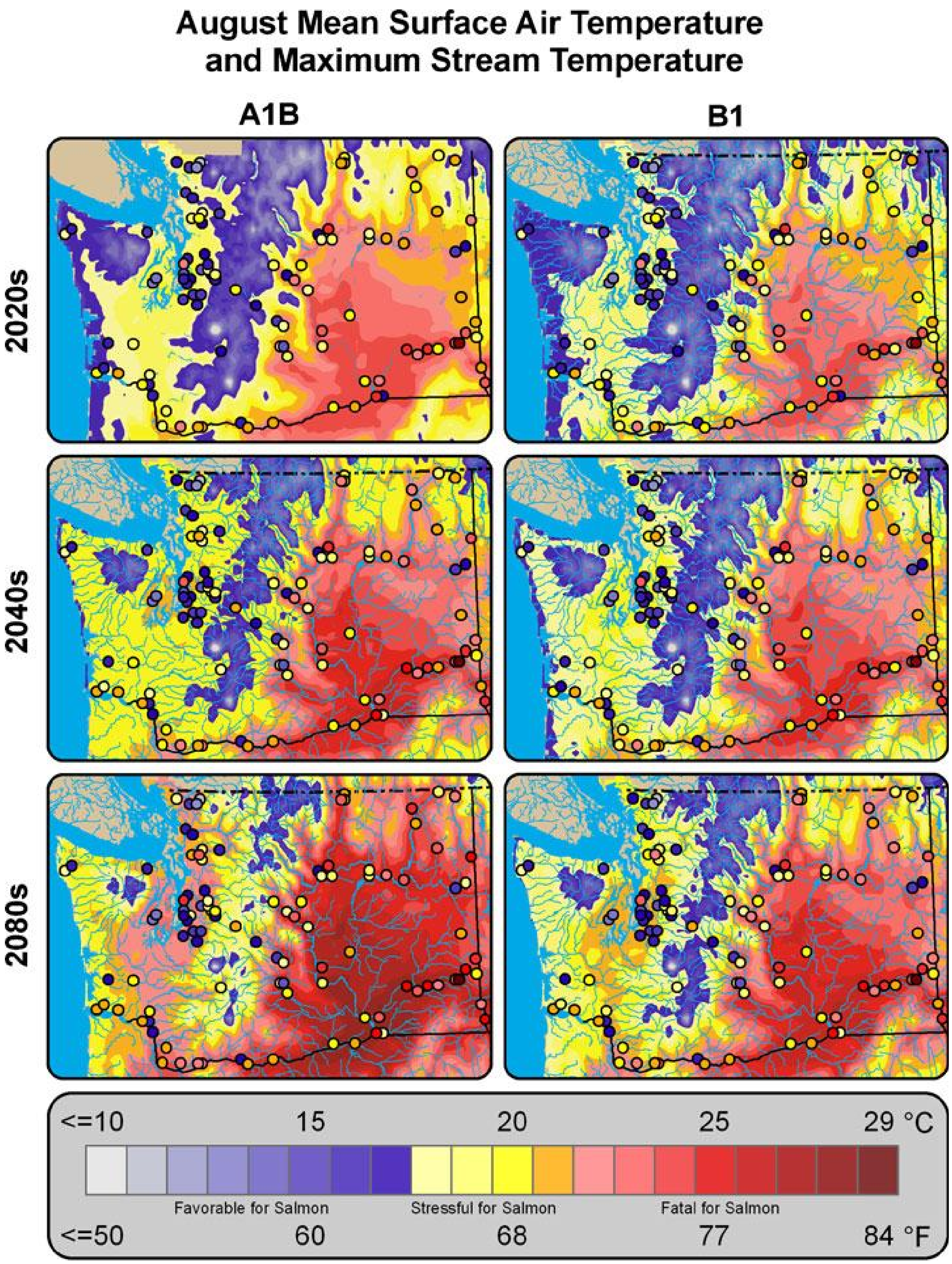

Fig. 2 As in Fig. 1, but here future climate scenarios for the 2020s, 2040s and 2080s are shown in the *top*, *middle* and *bottom panels*, respectively. Multi-model composite averages based on the A1B emissions are in the *left panels*, and those for B1 emissions are in the *right panels*. Figure: Robert Norheim

Future changes in the annual maximum T_w are shown in Fig. 3. For both A1B and B1 emissions scenarios in the 2020s, annual maximum T_w at most stations is projected to rise less than 1°C, but by the 2080s many stations on both the east and

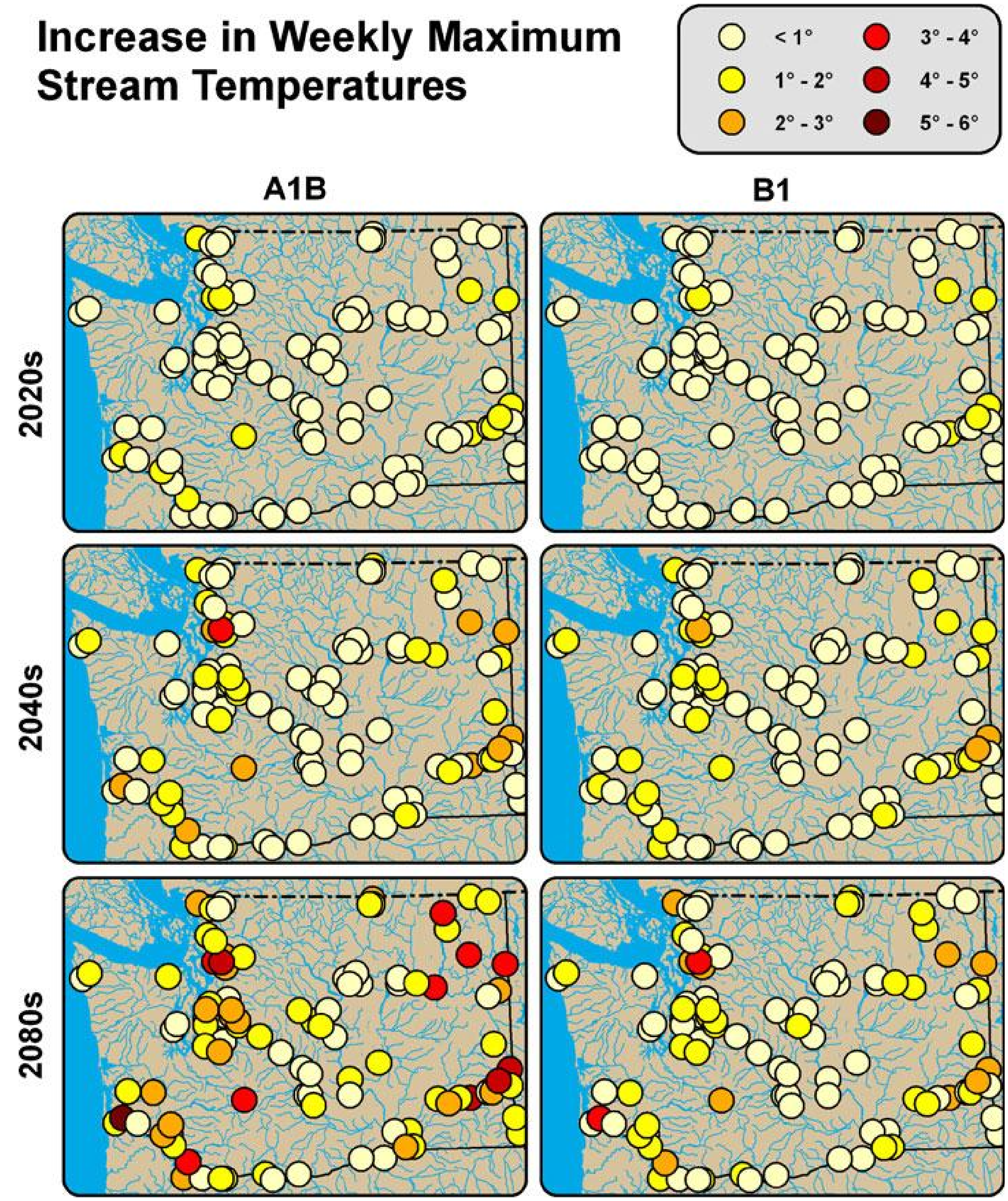

Fig. 3 Simulated increases in the annual maximum of weekly water temperatures (°C) relative to the 1980s for select locations in Washington State. *Top panels* show simulated changes for the 2020s, middle panels for the 2040s, and *bottom panels* for the 2080s. Composite A1B emissions scenarios are in the *left column*, composite B1 emissions scenarios are in the *right column*. Figure: Robert Norheim

west side of the Cascades warm by 2 to 5°C. Water temperatures projected under the A1B emissions scenarios become progressively warmer than those projected under the B1 emissions, and by the 2080s the differences are ∼1°C (recall that projected summertime air temperatures under A1B emissions are, on average, 1.8°C warmer than those under B1 emissions for the 2080s).

For either scenario, the projected increases in water temperatures proceed at about an equal pace on both sides of the Cascades, however shifts to increasingly stressful thermal regimes for salmon are predicted to be greatest for eastern Washington where the historic baseline for water temperatures are substantially warmer than those in western Washington. The histograms in Fig. 4 show that, in the 1980s, 41% of eastern Washington water temperature stations in our study had annual maximum T_w from 15.5–19.5°C, a category that indicates an elevated risk of disease for adult salmon (EPA 2007). The fraction of stations in this already compromised category declines to 22% in the 2080s, while the percentage of stations in higher stress categories increases by an equivalent amount. For the 55 western Washington stations we examine, 87% had $T_w < 19.5$°C in the 1980s, and this fraction declines to 71% of stations for the 2080s.

Climate change is also predicted to increase the frequency and persistence of thermal migration barriers and thermally stressed waters for salmon. The persistence of summertime water temperatures greater than 21°C is predicted to start earlier in the year, and last later in the year (Fig. 5). For most of the warmest stations we modeled $T_w > 21$°C persisted for 1-to-5 weeks (and up to 10 weeks at the University Bridge site) in the 1980s (from late-July to mid-August). By the end of the twenty-first century under A1B emissions, the period with $T_w > 21$°C is projected to persist for 10-to-12 weeks (from mid-June until early-September) at many stations in eastern Washington and along the lower Columbia River, including the Columbia River at Bonneville Dam, and the Lower Snake River at Tucannon. This prolonged duration of water temperatures unfavorable for salmon is also predicted for the Lake Washington/Lake Union ship canal (University Bridge). The expansion of the $T_w >$ 21°C season is predicted to increase considerably for the warmer streams in western

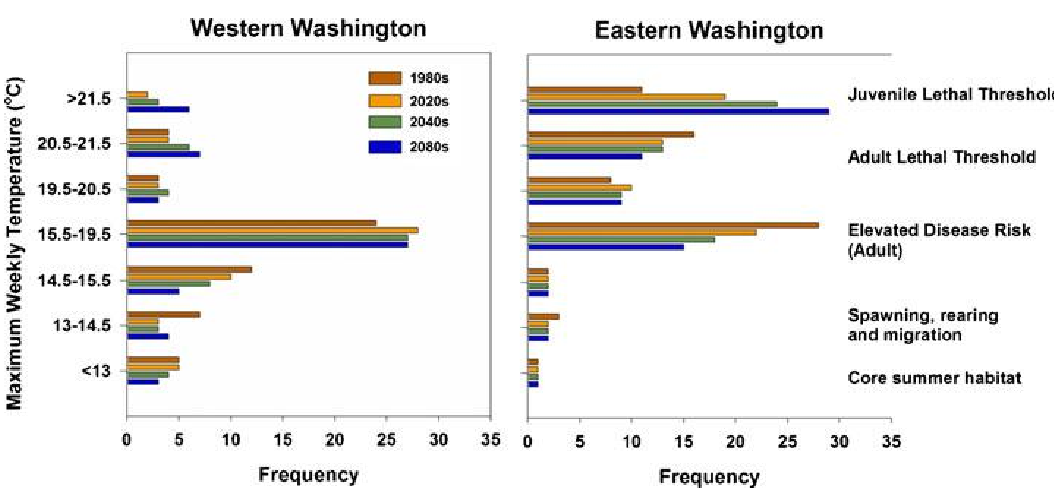

Fig. 4 Histograms of maximum weekly water temperature in western and eastern Washington State for the 1980s, 2020s, 2040s, and 2080s under A1B emissions scenarios (data produced from B1 emissions scenarios not shown). Water temperature stations east of the Cascade crest and upstream of the Dalles, OR, are considered to be in eastern Washington, and all others in western Washington. Habitat criteria listed at right for different temperature ranges are based on EPA (2007) guidance for all salmon species

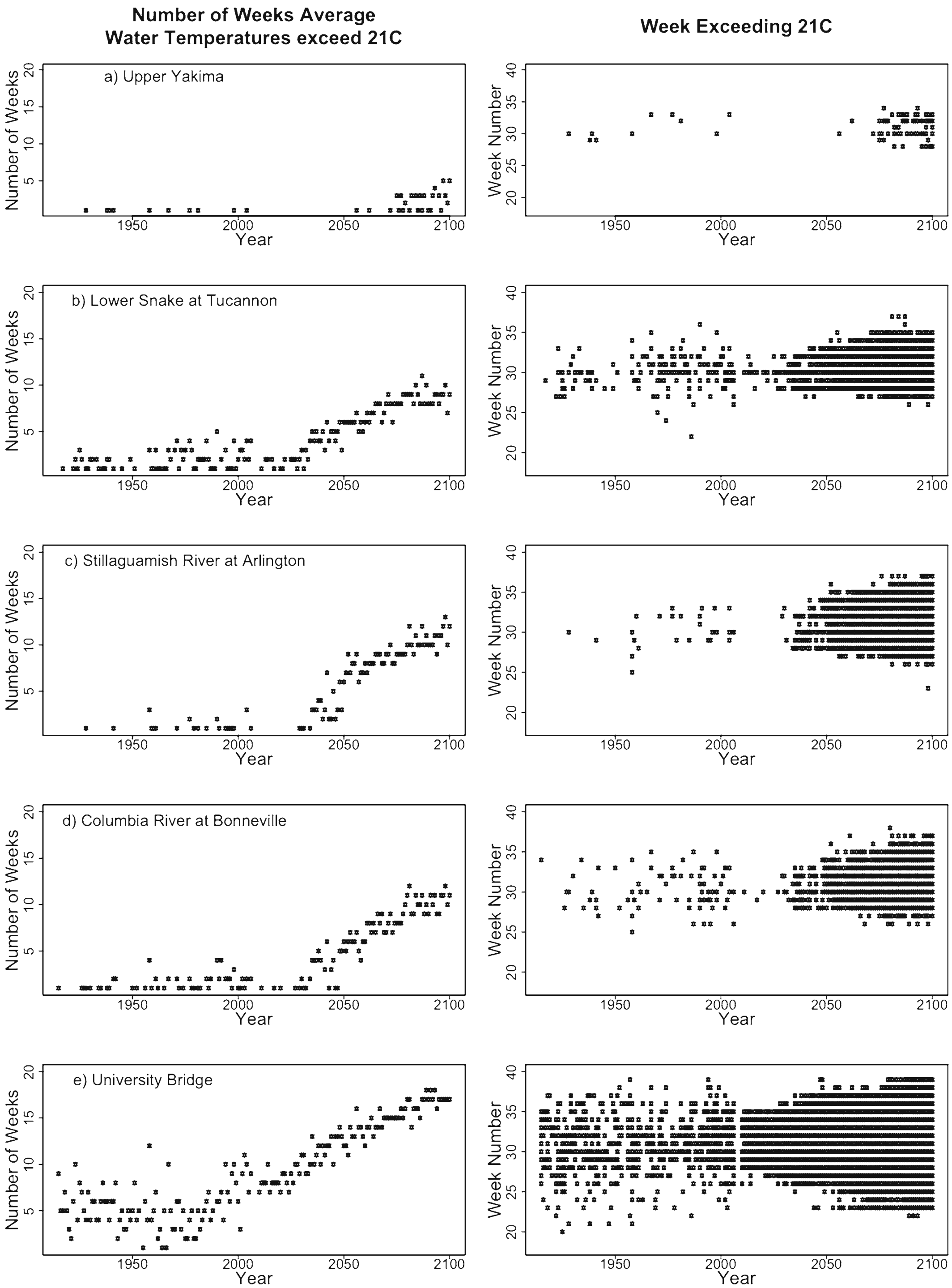

Fig. 5 Composite A1B emissions scenarios for simulated number of weeks that T_w exceeds 21°C (*left panels*) and the week number that weekly water temperature exceeds 21°C (*right panels*) for: **a** the Upper Yakima River, **b** Lower Snake River at Tucannon, **c** Stillaguamish River at Arlington, **d** Columbia River at Bonneville Dam, and **e** University Bridge, between Portage Bay and Lake Union, Seattle. Note that week 31 is approximately the first week of August

Washington like the Stillaguamish River at Arlington, where in recent years these conditions were observed zero to at most a few weeks each summer. For this station the period with $T_w > 21°C$ lasts up to 13 weeks by 2100 and is centered on the first week of August.

Each of the stations discussed in the previous paragraph is located in a key migration corridor for summer-running adult salmon on their spawning migration, indicating that at least some salmon populations in each watershed will likely experience substantial increases in thermal migration barriers and thermal stress.

Overall, extended thermal migration barriers are predicted to be much more common in eastern Washington compared with western Washington (Fig. 6). The rate of increase in the duration of the thermal migration barrier season is also sensitive to emissions scenarios—the A1B emissions pattern of change in the length of this season for the 2040s is quite similar to that for the B1emissions pattern in the 2080s. It also seems likely that climate warming will also reduce the availability of thermal refugia in many of Washington's watersheds, but this important issue is beyond the scope of this study.

3.2 Climate change impacts on streamflow

3.2.1 Shifts between snowmelt, transient, and rain-dominant watersheds

In Fig. 7 we classify runoff in Washington's watersheds (at the Hydrologic Unit Code 4 level) for historic and future periods as either snowmelt dominant, transient, or rainfall dominant based on their basin-averaged ratio of simulated April 1st snowpack to October–March total precipitation. For the 1980s snowmelt basins (where this ratio > 0.4) prevail in Washington's North Cascades and the eastside central Cascades. Transient basins (mixed rain and snow basins where the ratio lies between 0.1 and 0.4) are found on the north Olympic Peninsula and the middle elevations of the Cascades and interior Columbia Basin. Rainfall dominant basins (where the ratio < 0.1) are found in the low elevations of both eastern and western Washington. As projected climate warms for the 2020s, 2040s, and 2080s there is a clear transition for snowmelt basins to become transient basins, and transient basins to become rainfall dominant basins. By the 2080s, the hydrologic simulations predict a complete loss of snowmelt dominant basins in WA, and only about 10 basins remaining in the north Cascades classified as transient snow basins. Although the rate of transition is greater for the A1B emissions scenario, outcomes for the 2020s, 2040s and 2080s are very similar for the A1B and B1 scenarios, with differences in classification emerging for only a few specific basins in the 2040s and 2080s.

It is important to note that many large rivers which flow through WA, but whose basins are largely outside of the state (e.g. the Columbia, Snake, and Spokane Rivers), will show shifts towards transitional behavior, but will still be classified as snowmelt dominant for projected twenty-first century warming (Elsner et al. 2010).

3.2.2 The statistics of extreme high and low streamflow

The magnitude and frequency of flooding are predicted to increase most dramatically in the months of December and January for what are now Washington's transient runoff watersheds (Fig. 8), which we now see are characterized by mean winter temperatures within a few degrees of 0°C. Rain-dominant watersheds are predicted

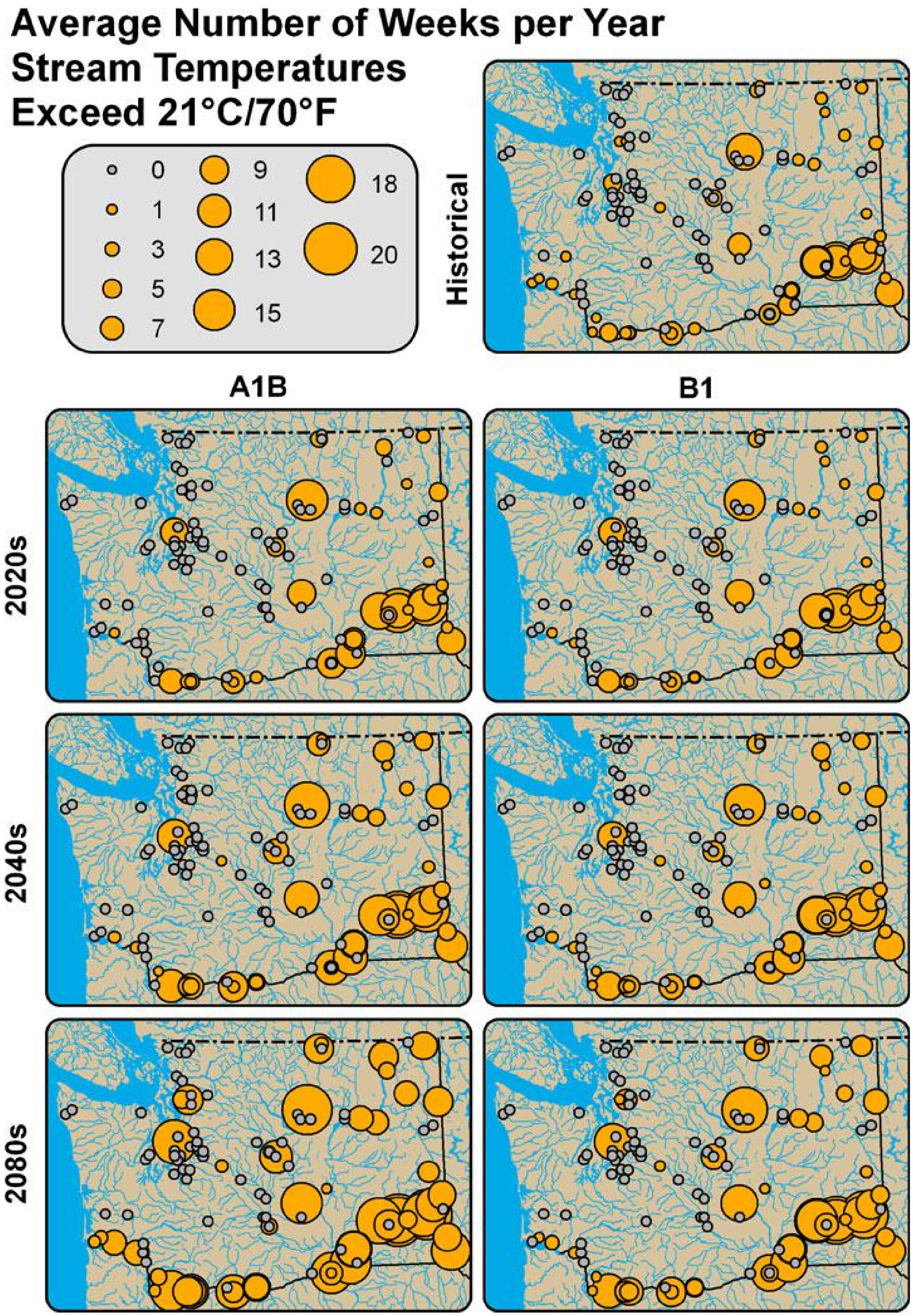

Fig. 6 Simulated changes relative to the 1980s in the average number of weeks per year when $T_w >$ 21°C for select locations in Washington State. *Top panels* show simulated changes for the 2020s, *middle panels* for the 2040s, and *bottom panels* for the 2080s. Composite A1B emissions scenarios are in the *left column*, composite B1 emissions scenarios are in the *right column*. Figure: Robert Norheim

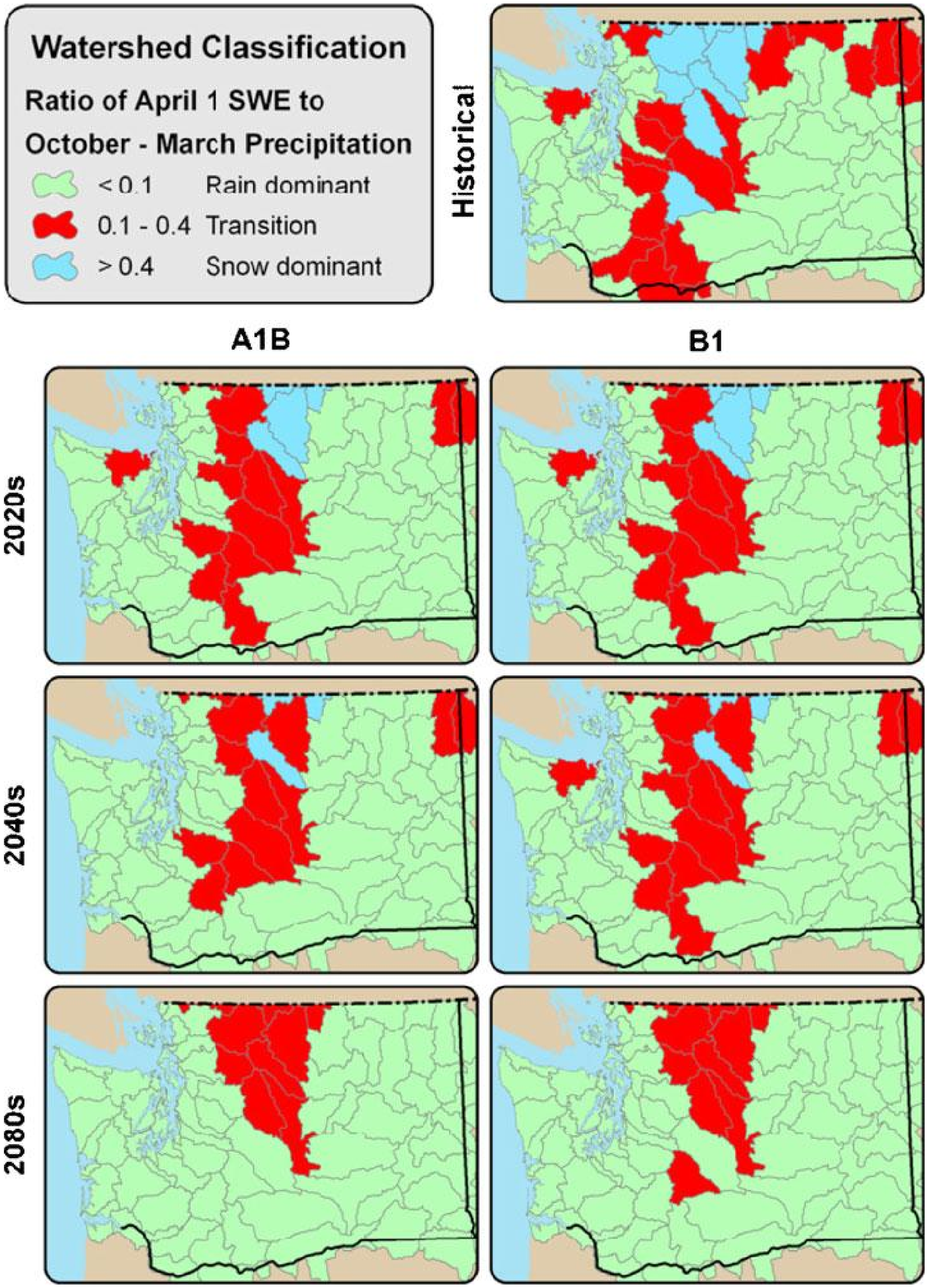

Fig. 7 Watershed classification maps for simulated runoff in the historic period (1970–99), 2020s, 2040s, and 2080s. Simulations using A1B emissions are in the *lower three rows of the left column*, while those using B1 emissions scenarios are in the *lower three rows of the right column*. Figure: Robert Norheim

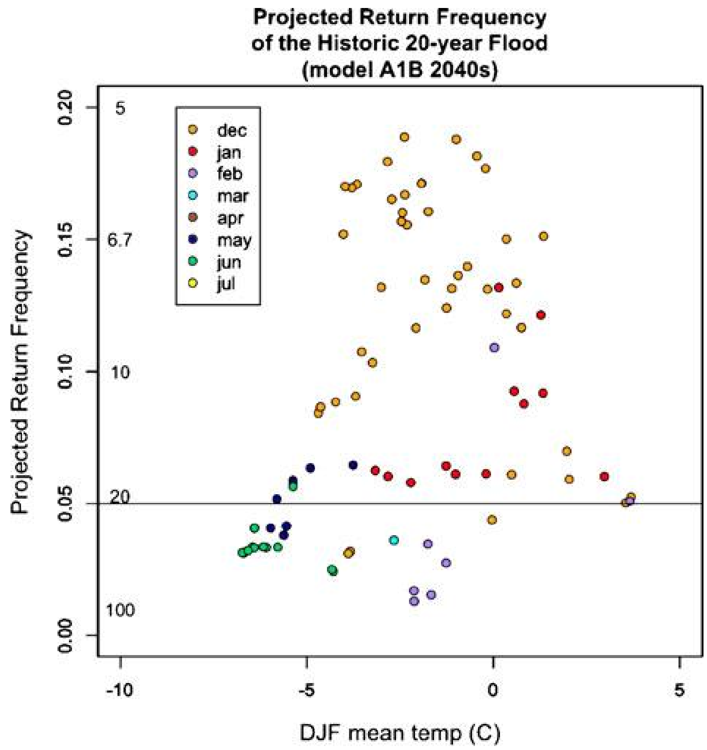

Fig. 8 Projected return frequency of the historic 20 year flood magnitudes as a function of the DJF average temperatures in each basin. Color coding in the scatter plots identifies the month when flooding is projected to peak in the A1B 2040s simulation: *orange* December, *red* January, *purple* February, *light blue* March, *brown* April, *dark blue* May, *green* June, and *yellow* July. Projected return frequencies are based on climate change simulations for composite A1B emissions scenarios for the 30 year averages centered on the 2040s relative to those for the historic simulation period 1915–2006

to experience small changes in flood frequency, and Washington's coldest snowmelt-dominated basins, where mean winter temperatures in the historic period were $< -5°C$, are predicted to experience a reduction in flooding that has historically been observed during exceptionally heavy snowmelt periods in late-spring and early-summer. Hydrological models indicate that warming trends will reduce snowpack (Elsner et al. 2010), thereby decreasing the risk of springtime snowmelt-driven floods.

Maps for projected changes in the return frequency of the historic 20-year flood are shown in Fig. 9. The largest increases in flood return frequency are predicted for transient runoff catchments located in Puget Sound, the west slopes of the Cascades in southwest Washington and in the lower elevations on the east side of the Cascades. Hydrologic modeling predicts a pattern of increased flooding magnitudes in western Washington and decreased or unchanged flooding magnitudes in eastern Washington that becomes more distinct for the later decades of the twenty-first century. The shifts in flood risk in each basin tend to monotonically increase or decrease through time (not shown). In other words, the increases or decreases in flooding magnitude of each basin generally become larger, with the same sign from the 2020s to the 2080s, with the greatest impacts (either positive or negative) occurring at the end of the twenty-first century. Emissions scenarios also play a strong role in the rate of change in flooding magnitudes, with the changes for A1B emissions in the 2040s being similar to those for the B1 emissions in the 2080s (not shown).

Reductions in the magnitude of summer low flows are predicted to be widespread for Washington State's rain dominant and transient runoff river basins in southwest Washington, the Olympic Peninsula, and Puget Sound (Fig. 10). For these locations, future estimates of the annual average low flow magnitude (7Q2, which is the 7 day

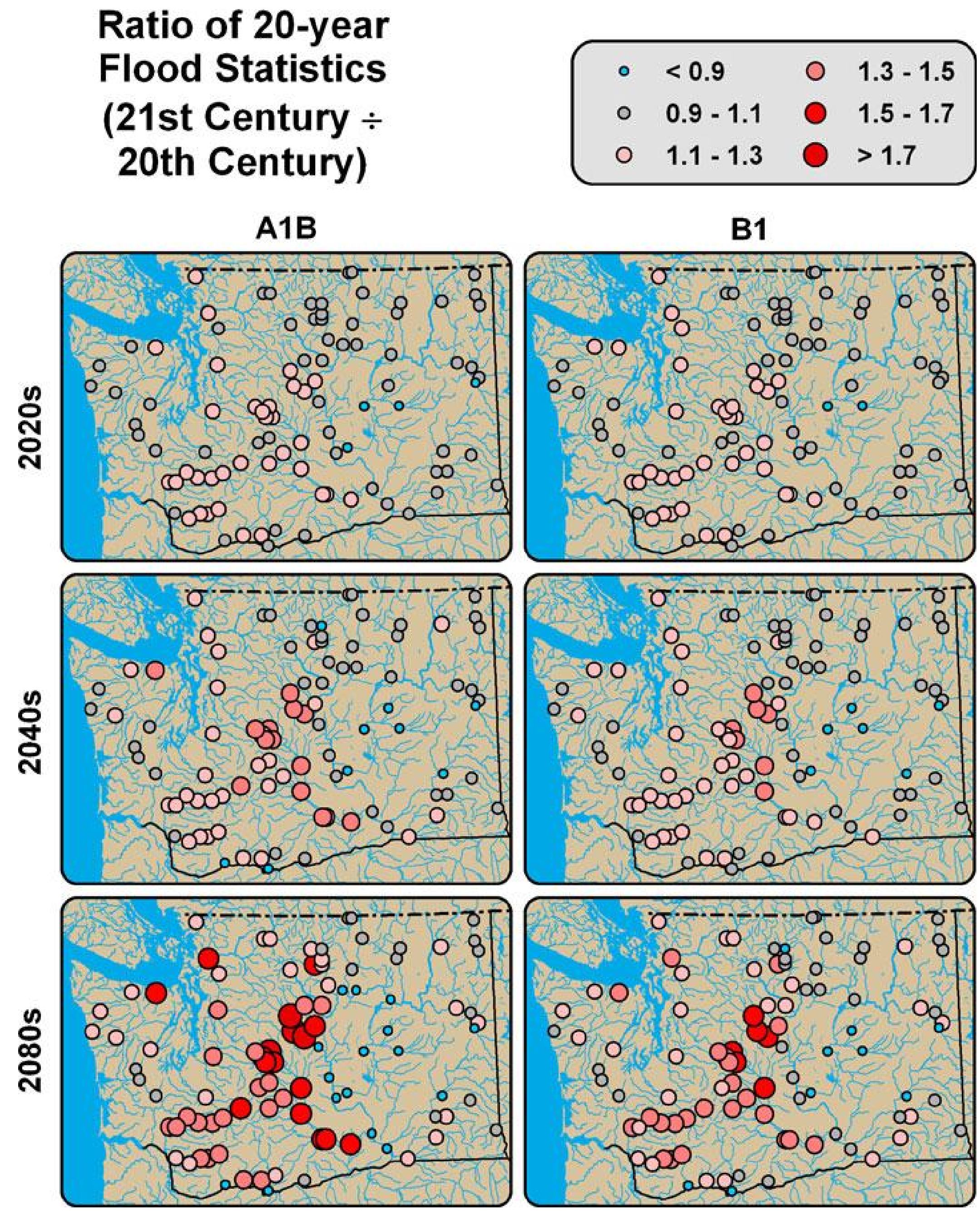

Fig. 9 Ratio of the 20 year flood magnitudes for simulated future and historic streamflows at select locations. *Top panels* show simulated changes for the 2020s, middle panels for the 2040s, and *bottom panels* for the 2080s. Composite A1B emissions scenarios are in the *left column*, composite B1 emissions scenarios are in the *right column*. Figure: Robert Norheim

average low flow magnitude with a 2 year return interval) are projected to decline by up to 50% by the 2080s under both the A1B and B1 emissions scenarios. The reduction in streamflow for more extreme (7Q10) low flow periods in rain dominant and transient runoff basins is also predicted to change by a similar amount, ranging from 5–40% (not shown). The magnitude of summer low flows are predicted to be

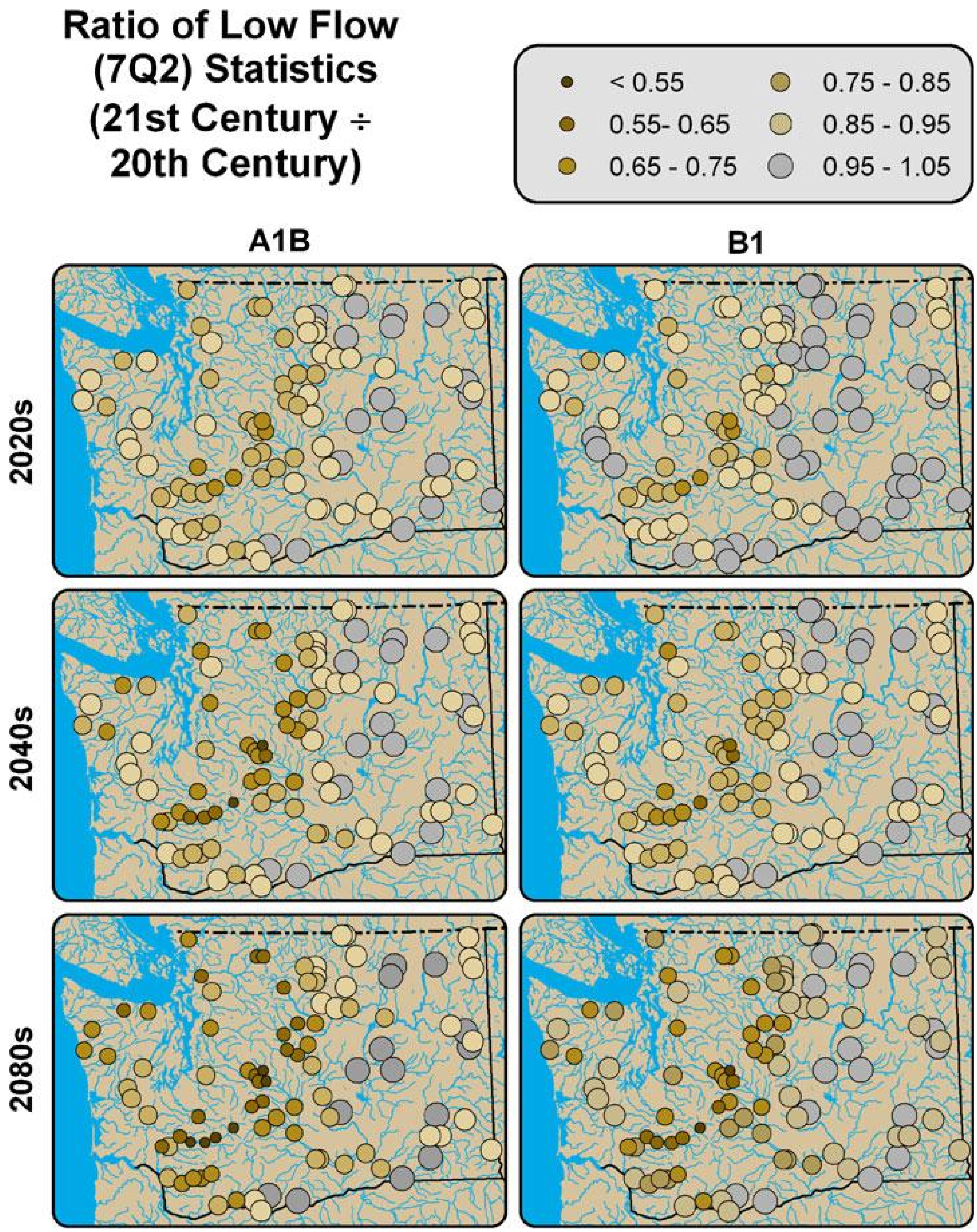

Fig. 10 Ratio of low flow (7Q2) statistics for simulated future and historic streamflows at select locations. *Top panels* show simulated changes for the 2020s, middle panels for the 2040s, and *bottom panels* for the 2080s. Composite A1B emissions scenarios are in the *left column*, composite B1 emissions scenarios are in the *right column*. Figure: Robert Norheim

relatively insensitive in most of the snowmelt dominated watersheds modeled in the interior Columbia Basin. However, the duration of the summer low flow period is projected to expand significantly in all watershed types (Elsner et al. 2010).

4 Assessment of impacts for Washington's salmon

Waples et al. (2008) note that, in general, existing salmon populations should have the capacity for responding to habitat changes that fall within the bounds of historical disturbance regimes—specifically, episodic disturbances that typically impact relatively small habitat patches relative to the spatial extent of evolutionarily significant population groups that are typically influenced by regional physiographic features. It remains an open question whether present day salmon populations in Washington State can adapt (either through phenological, phenotypic, or evolutionary responses) at rates required to deal with the combination of anthropogenic climate change and other habitat and ecosystem changes that will come in the next century (Crozier et al. 2008b).

In the absence of rapid adaptation to changing habitat conditions, our assessment or future stream temperature and stream flow changes and historical limiting factors points to widespread declines in the quality and quantity of freshwater habitat for Washington's salmon and steelhead populations. We summarize key climate change impacts on Washington's freshwater habitat for salmon in Fig. 11, and also show how those impacts are phased with key life stages for a generic ocean-type and stream-type salmon life history, along with generic summer-run and winter-run steelhead life histories.

Significant increases in stream temperature alone point to significant increases in thermal stress for Washington's salmon populations having a stream-type life history that puts them in freshwater during summer for either spawning migrations, spawning, rearing, or seaward smolt migrations. In the absence of thermal cues for initiating spawning migrations, temperature impacts on adult spawning migrations are projected to be most severe for stocks having summertime migrations. These include summer-run steelhead, sockeye, and summer chinook salmon populations in the Columbia Basin, and sockeye and chinook salmon in the Lake Washington system. Increased stream temperatures pose risks to the quality and quantity of favorable rearing habitat for stream-type chinook and coho salmon and steelhead (summer and winter run) throughout Washington because these stocks spend at least one summer (and for Washington's steelhead typically two summers) rearing in freshwater. Reductions in the volume of summer/fall low flows in transient and rainfall-dominated basins might also reduce the availability of spawning habitat for salmon populations that spawn early in the fall (e.g. Healey 1991). Predicted increases in the intensity and frequency of winter flooding in Washington's transient runoff basins will negatively impact the egg-to-fry survival rates for pink, chum, sockeye, chinook, and coho salmon due to an increased intensity and frequency of redd and egg scouring. However, the impact of increasing winter flooding will likely vary across species or populations because redd depth is a function of fish size (deeper redds will be less vulnerable to scouring and the deposition of fine sediments). Parr-to-smolt survival rates will likely be reduced for coho and stream-type chinook salmon and steelhead because increases in peak flows reduce the availability of slow-water habitats and causes increases in the displacement of rearing juveniles downstream of preferred habitats. Reductions in springtime snowmelt may negatively impact the success of smolt migrations from snowmelt dominant streams where seaward migration timing has evolved to match the timing of peak snowmelt flows.

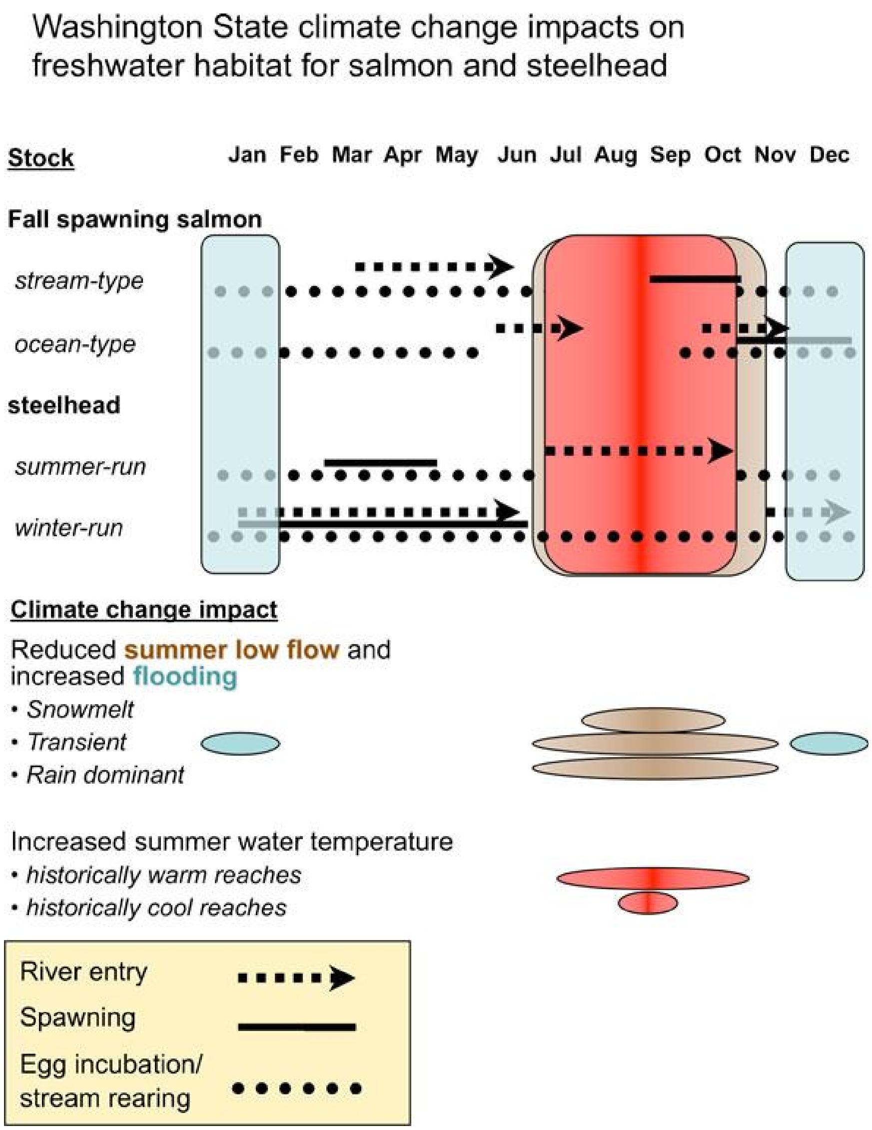

Fig. 11 Summary of key climate change impacts on Washington's freshwater habitat for salmon and steelhead, how those impacts differ for streams with different hydrologic characteristics, and how the timing for different impacts compare with the life history for generalized salmon and steelhead life history types. Example life history stages are shown for adult river entry (*broken arrows*), spawning (*solid lines*), and egg incubation and rearing periods (*dotted lines*) for generalized stocks. *Tan shading* highlights periods of increased flooding, *brown shading* indicates periods with reduced summer/fall low flows, and *red shading* indicates periods with increased thermal stress

Summer chum salmon stocks in Hood Canal are listed as threatened under the federal Endangered Species Act, and these populations have a unique life history that makes them especially vulnerable to the impacts of climate change. Adults return to spawn in small shallow streams in late summer, and eggs incubate in the fall and early winter before fry migrate to sea in late winter. The predicted climate change impacts for the low elevation Hood Canal and Puget Sound streams used by summer chum include multiple negative impacts stemming from warmer water temperatures and reduced streamflow in summer.

The Lake Washington ship canal is among the most thermally impaired water bodies for salmon in western Washington. Extreme summertime water temperatures frequently inhibit the upstream migration of adult chinook and sockeye salmon. Lake Washington sockeye salmon typically pass the Ballard Locks several months prior to spawning, apparently to avoid the Ship Canal's warm temperatures that occur in mid-to-late summer (Hodgson and Quinn 2002). Evidence for substantial pre-spawn mortality related to thermal stress has been obtained from tagging studies of returning adult Lake Washington sockeye in 2003 and 2004, where the proportion of tagged fish later recovered on spawning beds declined with later lake entry times that had water temperatures between 21 and 23°C (Newell et al. 2007). Additionally, elevated water temperatures in spring confer a competitive advantage to warm water predators, like smallmouth bass (*Micropterus dolomieui*), that can consume significant numbers of sockeye, coho, and chinook salmon and steelhead smolts on their seaward migrations through the ship canal (Tabor et al. 2004), but this impact may be limited by the relatively short length of the Lake Washington Ship Canal.

While cool-season stream temperature changes and impacts are not assessed in this study, it is possible that climate-induced warming in winter and spring will lead to earlier and perhaps longer growing seasons, increased aquatic food-web productivity, and more rapid juvenile salmon growth and development rates that benefit parts of the freshwater life-cycle of Washington's salmon (Schindler and Rogers 2009). This could potentially increase the full life-cycle productivity for Washington's salmon populations where the positive impacts outweigh the negative impacts identified in this analysis. Potential benefits of warmer stream temperatures for coho salmon were demonstrated in studies of clear-cut logging impacts in the Carnation Creek watershed of Vancouver Island, British Columbia (Holtby 1988). Logging in this watershed lead to substantial stream warming (0.7°C in December and over 3°C in August), which in turn contributed to postive growth responses in juvenile coho salmon, accelerations in the freshwater component of coho salmon life histories, and increases in overwinter survival rates for rearing juveniles. However, these changes in freshwater development appear to have been compensated by reduced marine survival rates associated with earlier smolt migrations to the ocean that may have been mis-matched to the optimal timing for ocean prey and/or predator fields. Holtby (1988) estimated that warmer stream temperatures increased the full life-cycle coho production in this system by ~9%. It seems likely that the potential for positive impacts of future stream warming are greatest in Washington's coldest streams, either in the maritime climatic zones of Western Washington or in high elevation stream reaches.

Because of the earlier timing of snowmelt and increased evaporation, most of Washington's river basins are projected to experience reduced streamflow in summer and early fall that results in an extended period of summer low flows, while rainfall-dominant and transient runoff basins are also projected to have substantially lower base flows. In combination with increased summertime stream temperatures, reduced summertime flow is likely to limit rearing habitat for salmon with stream-type life histories (wherein juveniles rear in freshwater for one or more years) and increase mortality rates during spawning migrations for summer-run adults.

5 Strategies for mitigating the impacts of climate change on Washington's salmon

A wide array of management options for mitigating the projected impacts of climate change on freshwater habitat for salmon exists, but many of those options will require trade-offs with other land and water uses in salmon watersheds. Options for mitigating future climate change impacts on salmon involve reducing the existing threats to their freshwater habitats caused by land and water use actions that impair natural hydrological processes (Beechie et al. 2008b). As shown in our analyses, the hydrologic processes that influence streamflow timing, volume, and stream temperature in Washington State streams are highly sensitive to projected changes in future climate. Many of the same hydrologic processes are also known to be highly sensitive to land and water use impacts.

Potential management options for mitigating stream temperature increases in response to climate change include reducing out-of-stream withdrawals during periods of high temperature and low streamflow, restoring floodplain functions that recharge aquifers, identifying and protecting thermal refugia provided by ground-water and tributary inflows, undercut banks and deep stratified pools, and restoring vegetation in riparian zones that provide shade and complexity for stream habitat. Restoring, protecting, and enhancing instream flows in summer are also key management options for mitigating the effects of projected trends toward warmer, lower streamflows as a consequence of climate change (IMST 2000; ISAB 2007).

Similarly, management strategies to reduce the risks posed to salmon habitat by extremely high flow events in fall and winter include the protection and restoration of off-channel habitat in floodplains where fish can find refuge from high energy flows. Additional options include limiting the expansion of effective impervious area (Booth and Jackson 1997), and retaining forest cover (reviewed by Moore and Wondzell 2005).

In watersheds with large storage reservoirs there may be opportunities to change reservoir operations in ways that mitigate the impacts of climate change on flooding. Where the infrastructure exists, strategic use of cold-water releases from reservoirs (e.g. Dworshak Dam on the Clearwater River in Idaho and Shasta Dam in the Sacramento River watershed in California) are now used to control downstream flow and temperature for salmon. Similar dam operations may be able to mitigate climate change impacts on summer water temperature and seasonally low streamflow at key times in other watersheds having similar infrastructure.

It is important to recognize that, in many basins, climate change will likely increase the demand for surface water and ground water in summer for such uses as irrigation for agriculture and municipal water supplies. This situation will require strategic policy thinking that recognizes trade-offs will have to be made between ecosystem protection and other water resource uses, and that clear decision guidance should be developed now in order to avoid protracted and potentially costly conflicts.

A particular challenge for watershed restoration efforts will be to match projects to both existing and future threats to salmon habitat. Battin et al's. (2007) study of climate change, restoration options, and their impacts on Snohomish ocean-type chinook salmon noted that most practical restoration actions are aimed at lower elevation floodplains, but that the most severe negative impacts for this stock were found in higher elevation spawning and rearing areas where the hydrologic sensitivity to climate change was greatest. Martin (2006) suggests that thermal refugia will increasingly be limited to the headwater reaches of Northwest streams, while future human population increases and the impacts on land and water use will be concentrated in low-elevation floodplains. He advocates renewed efforts to protect floodplains as migration corridors and to reconnect watersheds to largely protected headwater areas by removing dams and other barriers to upstream fish passage.

6 Research gaps and recommendations for future research

This analysis was based on a subset of single stations for streamflow and stream temperatures, yet these stations may not be representative of the complex and varied habitat features found within most salmon watersheds that provide critical refugia from stressful or even lethal water temperatures and streamflows. The widespread distribution and large magnitude of predicted negative impacts described in this study highlight an urgent need for mapping existing and potential thermal and hydrologic refugia in order to prioritize habitat protection and restoration efforts.

To date, there are few case studies aimed at understanding the impacts of climate change on restoration alternatives for specific watersheds and salmon stocks in Washington State. Yet, because salmon life histories are locally adapted and Washington's freshwater salmon habitat is diverse, such efforts should be given high priority where long-term investments in salmon habitat protection and restoration are considered. Battin et al.'s (2007) study of climate change and habitat restoration options for Snohomish chinook salmon provides an informative framework for carrying out such studies.

Because salmon life histories integrate across a complex network of freshwater, estuarine, and marine habitats, and because people compete directly and indirectly for resources that are important for salmon, an understanding of salmon ecology begs for integrated studies that cross multiple disciplines. For example, impacts of both climate change and ocean acidification on the ocean ecology of salmon are among the least understood, but possibly most important, aspects of salmon ecology in the coming decades (Fabry et al. 2008). Perhaps even more important for adaptation planning in Washington State are efforts to integrate so-called human dimensions of climate change into impacts studies for salmon. As noted by Miles et al. (1999), future climate change is likely to sharpen tradeoffs over water resources because it favors reductions in streamflows during summer when human demands and ecosystem needs for water are often greatest.

A better understanding for genetic and phenotypic adaptations in salmon is also needed to understand the capacity for adaptation, and whether adaptations might keep pace with future habitat changes (Crozier et al. 2008b). Most analyses of climate change impacts on salmon have assumed that the environmental sensitivities expressed by current populations will remain static in the future, yet this may not be the case. For example, summertime migrating stocks like sockeye salmon in already warm watersheds like Lake Washington will be faced with increasingly strong selection pressures that favor a shift in spawning migration timing away from what are projected to be increasingly warm and unfavorable water temperatures. But climate change might produce conflicting selection pressures at other life stages that, in combination, may not lead to a viable life history pattern (Crozier et al. 2008b).

An additional layer of uncertainty comes with the choice of downscaling methods used to create the surface air temperature and precipitation scenarios used in this work, and how well different downscaling approaches perform in estimating changes in the frequency and intensity of extreme events. For example, Salathé et al.'s (2010) regional climate modeling suggests that the statistically downscaled scenarios examined here likely underestimate the impacts of climate change on event-scale precipitation extremes and springtime surface warming in locations that lose their snowpack. These findings suggest that increased flooding frequency and magnitude in rainfall dominant and transient runoff watersheds may be more extreme than what we show in our analysis. Such changes in the frequency and intensity of extreme hydroclimate events will have important consequences for disturbance regimes that are important for in-stream habitat features and the reproductive success of salmon. Linking regional climate modeling to hydrologic modeling should be pursued to better evaluate the impacts of climate change on extreme events important for freshwater habitat for salmon.

7 Conclusions

Simulated stream temperatures under future climate scenarios highlight increased thermal stress on Washington's salmon populations in the warmest summer months. Our analysis predicts that a growing number of locations will experience increasingly longer periods with weekly average water temperatures that are high enough to cause thermal migration barriers and increase the risk of fish kills ($> 21^\circ$C). Generally speaking, the greatest thermal stresses on Washington's salmon are projected for watersheds in the interior Columbia Basin, while the least are projected for watersheds in western Washington. Among the sites modeled in this study, the Lake Washington ship canal stands out as the warmest water body in western Washington. Future climatic warming will exacerbate existing problems for both seaward migrating smolts and summer-run adult salmon (sockeye and chinook) that spawn in the Lake Washington basin. It is notable that Lake Washington sockeye salmon were introduced to the watershed from the Baker River population in north Puget Sound in the early 1900s, and that Lake Washington watershed itself was significantly modified with the construction of the Lake Washington ship canal and Ballard Locks from 1912–1917 (WWW: wdfw.wa.gov/fish/sockeye/background.htm).

Our analysis of hydrologic model output identifies a mix of streamflow impacts on Washington's salmon watersheds that depend largely on a basin's present-day hydroclimate characteristics. Flood magnitudes and frequencies are predicted to increase most dramatically in winter months for what have historically been Washington's transient runoff watersheds. Rain-dominant watersheds are predicted to experience small changes in flooding, while the coldest snowmelt-dominated basins (where winter temperatures were historically $< -5°C$) are predicted to experience a reduction in flooding that has historically been observed during exceptionally heavy snowmelt periods in late-spring and early-summer.

Our hydrologic simulations predict a complete loss of snowmelt dominant basins in WA by the 2080s along with a substantial reduction in the number and spatial distribution of transient snow basins. A reduction in the volume of summer low flows are predicted to be widespread for historically rain dominant and transient runoff river basins, which are mostly found in the Cascades, Olympics, and coastal and southwest Washington. The duration of the summer low flow period is projected to increase substantially for both transient and snowmelt dominant basins. For the interior Columbia River Basin, the combination of an extended period of summer and fall low flows and warmer water temperatures is very likely to be problematic for the many stream-type salmon and summer-run steelhead populations that migrate, spawn, and/or rear in freshwater during these periods.

In many cases, climate change promises to amplify many existing stresses on Washington's salmon in impaired watersheds, and at the same time will likely increase public and private demands for surface water and ground water in summer for such uses as irrigation for agriculture and municipal water supplies. In order to avoid protracted and potentially costly conflicts, this situation begs for strategic policy thinking that recognizes trade-offs between ecosystem protection and other water resource uses, and for clear decision guidance before such conflicts become too extreme.

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Appendix A

Table 3 Washington State stream temperature stations used in this study

Dataset[a]	Region[b]	Site	Latitude	Longitude	alpha	beta	gamma	mu	nsc
USACE	UC	Albeni Falls Forebay Pend Orielle River[c]	48.16	−117.09	24.81	11.62	0.19	0	0.92
USACE	UC	Albeni Falls Tailrace Pend Orielle	48.16	−117.09	31.05	15.09	0.14	0	0.94
USACE	UC	Anatone, WA. Snake River[c]	46.16	−116.97	28.28	12.18	0.13	0	0.66
DOE	PS	Bertrand Creek at Rathbone Road	48.91	−122.53	19.13	17.45	0.50	11.41	0.91
DOE	PS	Big Mission Creek at Highway 300	47.41	−122.91	16.52	9.84	0.18	0	0.81
DOE	PS	Big Soos Creek near Auburn	47.28	−122.16	15.44	15.30	0.73	10.55	0.94
USACE	LC	Bonneville Forebay, Columbia River[c]	45.66	−121.97	22.27	10.65	0.26	2.20	0.93
USACE	UC	Boundary (US/Canada) Columbia River[c]	48.97	−117.66	20.56	9.60	0.18	1.80	0.91
DOE	UC	Brender Creek near Cashmere	47.53	−120.47	18.87	17.23	0.24	8.75	0.86
DOE	LC	Burnt Bridge Creek at mouth	45.66	−122.66	24.31	20.24	0.24	12.00	0.80
USACE	LC	Camas/Washougal, WA. Columbia River[c]	45.66	−122.34	22.32	11.94	0.43	2.52	0.85
USACE	LC	Cascade Island (below Bonneville)	45.66	−121.97	23.18	12.53	0.28	3.15	0.90
DOE	PS	Cedar River at Logan Street, Renton	47.47	−122.22	18.88	18.49	0.40	11.84	0.84
DOE	OP	Chehalis River at Dryad	46.66	−123.22	21.21	17.28	0.58	12.21	0.70
DOE	PS	Cherry Creek at Highway 203	47.78	−121.97	16.88	17.68	4.41	13.41	0.93
USACE	UC	Chief Joseph Forebay Columbia River[c]	47.97	−119.66	18.71	9.63	0.31	3.54	0.79
DOE	UC	Chumstick Creek near Leavenworth	47.47	−120.34	13.38	19.37	0.64	9.69	0.96
USGS	UC	Colville River[c]	48.59	−118.09	22.85	12.05	0.18	0	0.89
DOE	UC	Colville River at Chewelah	48.28	−117.72	28.59	16.91	0.14	3.29	0.81
DOE	UC	Cowiche Creek at Powerhouse Road	46.66	−120.59	18.56	17.99	0.58	12.64	0.91
DOE	LC	Cowlitz River at Kelso	46.16	−122.91	16.71	16.54	0.60	11.91	0.76
DOE	UC	Crab Creek near Beverly	46.84	−119.84	25.05	14.28	0.23	0	0.93
DOE	UC	Deadman Creek at Holcomb Road	47.84	−117.22	21.37	12.86	0.13	0	0.93
DOE	UC	Deadman Creek near mouth	46.59	−117.78	27.15	26.11	0.22	11.70	0.91
DOE	PS	Des Moines Creek near mouth	47.41	−122.28	17.22	10.12	0.28	0	0.74
DOE	OP	Dickey River near La Push	47.97	−124.53	18.28	13.81	1.38	13.81	0.95
DOE	PS	Fauntleroy Creek near mouth	47.53	−122.34	14.49	17.74	0.72	12.33	0.84
USACE	UC	Grand Coulee Forebay Columbia River[c]	47.97	−118.97	19.33	9.47	0.30	3.85	0.84

USACE	UC	Grand Coulee Tailrace, Columbia River[c]	48.03	−118.97	18.79	9.82	0.26	3.77	0.74
DOE	PS	Griffen Creek at Highway 203	47.59	−121.91	17.43	18.80	0.54	11.77	0.82
USACE	UC	Ice Harbor Forebay Snake River[c]	46.22	−118.84	24.26	12.77	0.17	0.79	0.93
USACE	UC	Ice Harbor Tailrace Snake River[c]	46.22	−118.84	24.13	12.76	0.16	0.95	0.91
DOE	PS	Jim Creek at Whites Road	48.16	−122.03	20.94	17.84	0.38	11.45	0.79
DOE	PS	Jimmeycomelately Creek at Highway 101	48.03	−123.03	16.31	11.11	0.36	0	0.74
USACE	UC	John Day Forebay Columbia River	45.72	−120.72	22.17	14.01	0.26	5.34	0.85
USACE	UC	John Day Tailrace Columbia River[c]	45.72	−120.72	21.91	10.91	0.22	3.07	0.86
DOE	LC	Kalama River near Kalama	46.03	−122.84	17.33	17.60	0.85	12.18	0.71
DOE	UC	Kettle River near Barstow	48.78	−118.16	33.35	16.03	0.09	0	0.77
DOE	PS	Kimball Creek at Highway 202	47.53	−121.84	21.38	18.08	0.28	10.52	0.85
USGS	UC	Klickitat River at Klickitat[c]	45.72	−121.28	19.44	12.04	0.15	0.29	0.94
DOE	PS	Laughing Jacobs Creek near Mouth	47.59	−122.03	15.10	13.63	0.22	8.83	0.97
DOE	LC	Lewis River near Dollar Corner	45.84	−122.59	23.31	18.41	0.37	10.77	0.73
USACE	UC	Little Goose Forebay Snake River[c]	46.59	−117.97	31.26	15.20	0.21	1.81	0.87
USACE	UC	Little Goose Tailrace, Snake River[c]	46.59	−117.97	25.21	13.88	0.23	3.67	0.85
DOE	PS	Little_Mission_Cr._@_Hwy_300	47.41	−122.91	12.09	6.83	0.22	0	0.90
USGS	LC	Lower Columbia[c]	46.28	−123.84	21.43	10.39	0.40	3.31	0.87
USGS	LC	Lower Columbia at Clatskanie[c]	46.16	−123.03	22.97	11.54	0.24	2.60	0.84
USGS	LC	Lower Cowlitz[c]	46.28	−122.91	22.92	14.41	0.21	2.74	0.87
USGS	UC	Lower Crab[c]	47.03	−119.34	22.71	9.83	0.13	0	0.89
USACE	UC	Lower Granite Tailrace Snake River[c]	46.66	−117.47	23.89	11.82	0.24	0.46	0.91
USACE	UC	Lower Granite Tailrace Snake River[c]	46.66	−117.41	32.03	14.54	0.18	0.65	0.86
USACE	UC	Lower Monumental Forebay Snake River[c]	46.59	−118.34	27.00	13.54	0.19	0	0.85
USACE	UC	Lower Monumental Tailrace Snake River[c]	46.59	−118.34	26.74	13.86	0.18	2.09	0.84
USGS	UC	Lower Snake near Tucannon[c]	46.34	−117.03	22.83	12.95	0.19	0.98	0.91
USGS	UC	Lower Spokane[c]	46.53	−118.16	20.65	11.70	0.19	0	0.82
USGS	UC	Lower Yakima[c]	47.91	−118.34	30.17	18.54	0.11	3.14	0.91
DOE	UC	Manatash Creek at Manatash Road	46.97	−120.66	15.17	14.73	0.64	9.48	0.97
DOE	PS	Maple Creek at mouth	48.91	−122.09	10.77	16.54	0.90	9.48	0.79
USACE	UC	McNary Forebay OR. Columbia River[c]	45.91	−119.28	25.10	13.27	0.18	1.20	0.94
USACE	UC	McNary Forebay WA. Columbia River[c]	45.91	−119.28	22.15	12.54	0.20	2.04	0.94

Table 3 (continued)

Dataset[a]	Region[b]	Site	Latitude	Longitude	alpha	beta	gamma	mu	nsc
USACE	UC	McNary Tailrace Columbia River[c]	45.91	−119.28	21.44	12.33	0.21	2.08	0.94
USGS	UC	Methow River[c]	48.03	−119.91	17.75	9.01	0.19	0	0.90
USGS	UC	Mid-Columbia near Lake Wallula[c]	45.91	−119.66	21.32	12.71	0.18	2.61	0.87
DOE	PS	Miller Creek near mouth	47.47	−122.34	18.34	8.90	0.17	0	0.82
DOE	UC	Mission Creek near Cashmere	47.53	−120.47	36.91	23.54	0.08	0	0.92
DOE	UC	Moxee Drain at Birchfield Road	46.53	−120.47	22.62	10.59	0.16	0	0.84
USGS	UC	Naches River[c]	46.66	−120.53	14.90	10.56	0.21	0	0.81
DOE	LC	Naselle River near Naselle	46.34	−123.72	40.05	22.79	0.26	9.21	0.75
DOE	PS	Newaukum Creek near Enumclaw	47.28	−122.03	15.13	14.52	0.67	9.60	0.94
DOE	UC	Noname Creek near Cashmere	47.53	−120.47	19.35	17.20	0.21	8.44	0.85
DOE	PS	Nooksack River above Middle Fork	48.84	−122.16	12.41	16.21	4.24	10.63	0.90
DOE	PS	Nooksack River at North Cedarville	48.84	−122.28	15.66	16.83	0.61	11.15	0.76
USGS	UC	Okanogan River[c]	48.97	−119.41	24.17	13.45	0.15	0	0.92
DOE	UC	Okanogan River at Oroville	48.09	−119.72	25.05	10	0.20	0	0.85
USGS	UC	Palouse River[c]	46.91	−117.09	28.17	15.44	0.17	0	0.96
DOE	UC	Palouse River (South Fork) at Albion	46.78	−117.28	43.92	21.74	0.07	0	0.72
DOE	UC	Paradise Creek at the Border	46.72	−117.09	24.18	2.42	0.07	0	0.77
USACE	UC	Pasco, WA. Columbia River[c]	46.22	−119.09	20.26	13.85	0.27	3.41	0.92
DOE	PS	Patterson_Ck_near_Fall_City	47.59	−121.91	17.46	18.57	0.51	11.81	0.80
USGS	UC	Pend Orielle River[c]	48.91	−117.34	22.87	8.10	0.20	0.08	0.94
DOE	UC	Peone (Deadman) Creek	47.78	−117.41	14.78	16.22	0.48	10.46	0.86
DOE	PS	Pilchuck Creek at Bridge 626	48.22	−122.22	23.99	15.21	0.25	7.34	0.75
DOE	UC	Pine Creek at Rosalia	47.22	−117.34	22.40	14.18	0.24	7.04	0.94
USACE	UC	Priest Rapids Forebay Columbia River[c]	46.66	−119.84	19.71	12.60	0.26	4.34	0.88
DOE	PS	Puyallup River at Puyallup	47.22	−122.34	17.61	11.58	0.22	0	0.89
DOE	PS	Raging River at mouth	47.59	−121.91	19.75	18.00	0.68	11.99	0.86
USACE	UC	Rock Island Forebay, Columbia River[c]	47.34	−120.09	18.43	10.59	0.27	2.31	0.79
DOE	PS	Samish River near Burlington	48.53	−122.34	16.42	16.89	0.54	10.94	0.74
USGS	UC	Sanpoil River[c]	47.97	−118.66	24.48	13.38	0.17	0	0.97
USGS	UC	Similkameen River[c]	48.91	−119.41	21.51	11.02	0.19	0	0.90

DOE	UC	Similkameen River at Oroville	48.91	−119.47	24.50	11.67	0.18	0	0.86
DOE	PS	Skagit River above Sedro Woolley	48.47	−122.22	17.08	16.47	0.72	12.84	0.90
USACE	LC	Skamania, WA. Columbia River[c]	46.28	−123.47	21.05	11.07	0.79	0	0.82
DOE	PS	Snoqualmie at Valley Trail (RM 16)	47.53	−121.78	17.79	7.31	0.13	0	0.78
DOE	PS	Snoqualmie River above Carnation	47.53	−121.78	20.10	13.48	0.49	0	0.97
DOE	PS	Snoqualmie River at 468th Ave	47.47	−121.78	24.25	10.94	0.08	0	0.86
DOE	PS	Snoqualmie River at Bendigo	47.47	−121.78	17.31	5.90	0.13	0	0.71
DOE	OP	Soleduck River near Forks	48.03	−124.41	16.50	15.60	3.01	13.40	0.96
DOE	PS	Stillaguamish River at Arlington	48.22	−122.09	26.44	17.75	0.34	9.44	0.83
DOE	PS	Stillaguamish River at Cicero	48.28	−122.03	19.77	16.58	0.55	11.58	0.74
DOE	PS	Stillaguamish River near Darrington	48.28	−121.72	16.59	16.50	0.49	10.90	0.73
DOE	PS	Stimson Creek at Highway 300	47.41	−122.91	14.12	8.48	0.21	0	0.81
USACE	UC	The Dalles Forebay Columbia River[c]	45.66	−121.16	21.95	12.63	0.38	0	0.88
USACE	UC	The Dalles Tailrace Columbia River[c]	45.66	−121.16	22.35	11.38	0.21	0	0.89
DOE	PS	Thornton Creek (South Fork) 107th Ave	47.72	−122.28	18.24	8.38	0.18	0	0.80
DOE	PS	Tolt River near Carnation	47.66	−121.91	18.70	17.78	0.36	10.92	0.89
DOE	UC	Tucannon River at Powers	46.53	−118.16	27.96	17.11	0.12	2.59	0.71
DOE	PS	Union River near Belfair	47.47	−122.84	13.73	9.68	0.25	0	0.71
USACE	PS	University Bridge Lake Union, Seattle[c]	47.66	−122.34	24.46	13.25	0.30	6.36	0.94
USGS	UC	Upper Columbia River at Entiat[c]	47.66	−120.22	20.80	10.05	0.20	2.97	0.93
USGS	LC	Upper Cowlitz River[c]	46.59	−121.66	24.12	15.01	0.15	1.98	0.79
USGS	UC	Upper Yakima River[c]	47.34	−121.41	21.70	5.97	0.25	1.46	0.91
USGS	UC	Walla Walla River[c]	46.03	−118.78	20.12	14.52	0.16	1.06	0.70
DOE	UC	Walla Walla River near Touchet	46.03	−118.91	27.12	19.31	0.25	9.24	0.83
USACE	LC	Warrendale, OR. Columbia River[c]	45.66	−122.03	22.16	9.50	0.27	2.52	0.92
USACE	UC	Wells Tailrace Columbia River	47.97	−119.84	18.36	13.50	0.30	3.97	0.74

Table 3 (continued)

Dataset[a]	Region[b]	Site	Latitude	Longitude	alpha	beta	gamma	mu	nsc
USGS	UC	Wenatchee River[c]	47.47	−120.34	8.50	5.80	0.35	0	0.95
DOE	UC	Wenatchee River at Wenatchee	47.47	−120.34	24.16	14.08	0.21	0	0.93
DOE	UC	Wenatchee River near Leavenworth	47.66	−120.72	20.72	14.52	0.29	7.87	0.76
DOE	PS	White River at R Street	47.16	−122.09	17.63	17.74	0.52	11.00	0.80
DOE	UC	Wide Hollow Creek at Main Street	46.53	−120.47	21.84	8.19	0.12	0	0.85
DOE	OP	Willapa River near Willapa	46.66	−123.66	16.88	15.73	1.00	12.44	0.76
DOE	UC	Wilson Creek at Highway 871	46.91	−120.53	18.47	12.81	0.28	10.18	0.86
DOE	UC	Yakima River near Cle Elum	47.16	−121.03	17.69	8.97	0.34	0	0.81

[a]Dataset refers to origin of data: Washington Department of Ecology (DOE), US Army Corps of Engineers (USACE), US Geological Survey (USGS)
[b]Region refers to Upper Columbia River and tributaries upriver of the Dalles (UC), Lower Columbia and tributaries downriver of the Dalles, OR (LC), Puget Sound (PS), Olympic Peninsula (OP)
[c]Sites demonstrating hysteresis

Appendix B

Table 4 National climatic data center meteorological stations with air temperatures and matching water temperature study sites

Coop ID	NCDC station name	Matching study site
450844	Boundary Dam	Boundary (US/Canada) Columbia River
451630	Colville	Colville River at Chewelah
453883	Ice Harbor Dam	Ice Harbor Forebay Snake River
454841	Lower Monumental Dam	Lower Monumental Tailrace Snake River
455231	McNary Dam	McNary Forebay WA. Columbia River
457696	Skamania Fish Hatchery	Skamania, WA. Columbia River
457773	Snoqualmie Falls	Snoqualmie River at Carnation
459082	Wenatchee Pangborn AP	Wenatchee River at Wenatchee

National Climatic Data Center stations with air temperatures and matching study sites

Appendix C

Table 5 Locations with simulated streamflow used in this study

River Basin/site	Latitude	Longitude	Basin area (mi^2)
Pend Orielle River at Albeni Falls	48.63	−117.13	24,200
Nisqually River at Alder Dam	46.80	−122.31	286
Asotin Creek at Asotin	46.34	−117.06	323
Columbia River below Bonneville Dam	45.63	−121.96	240,000
Pend Orielle River at US/Canada Boundary	49.00	−117.35	25,200
Pend Orielle River near Ione	48.78	−117.42	24,900
Bumping River	46.87	−121.29	71
Chehalis River near Grand Mound	46.78	−123.03	895
Chelan River at Chelan	47.83	−120.01	924
Chehalis River at Porter	46.93	−123.31	1,294
Chewuch River at Winthrop	48.48	−120.19	525
Rufus Woods Lake at Bridgeport	47.99	−119.63	75,400
Cle Elum River near Rosyln	47.24	−121.07	203
Columbia River at Clover Island	46.22	−119.11	104,000
Colville River at Kettle Falls	48.59	−118.06	1,007
Cowlitz River at Castlerock	46.27	−122.90	2,238
Cowlitz River near Kosmos	46.47	−122.11	1,040
Cowlitz River at Randall	46.53	−121.96	541
Cowlitz River at Packwood	46.61	−121.68	287
Crab Creek near Beverly	46.83	−119.83	4,840
Crab Creek at Irby	47.36	−118.85	1,042
Crab Creek near Moses Lake	47.19	−119.26	2,228
Columbia River at Dalles	45.61	−121.17	237,000
Skagit River at Diablo Dam	48.72	−121.13	1,125
Dungeness River at Dungeness	48.14	−123.13	197
Elwha River near Port Angeles	48.06	−123.58	269
Entiat River near Ardenvoir	47.82	−120.42	203
Entiat River near Entiat	47.66	−120.25	419
Columbia River at Grand Coulee	47.97	−118.98	74,700
Gorge Reservoir near Newhalem	48.70	−121.21	1,159
Green River near Auburn	47.31	−122.20	399

Table 5 (continued)

River Basin/site	Latitude	Longitude	Basin area (mi^2)
Hangman Creek at Spokane	47.65	−117.45	689
Hoh River near Forks	47.81	−124.25	253
Snake River below Ice Harbor	46.25	−118.88	108,500
Yakima River at Kachess Reservior	47.26	−121.20	64
Kalama River near Kalama	46.05	−122.84	202
Yakima River at Martin	47.32	−121.34	55
Little Klickitat River near Wahkiacus	45.84	−121.06	280
Klickitat River near Pitt	45.76	−121.21	1,297
Lewis River at Ariel	45.95	−122.56	731
Lewis River near Cougar	46.06	−121.98	227
Snake River at Little Goose	46.50	−118.00	103,900
Snake River at Lower Granite	46.60	−117.40	103,500
Little Spokane River near Dartford	47.78	−117.50	698
Spokane River at Long Lake	47.84	−117.84	6,020
Cowlitz River below Mayfield Dam	46.50	−122.60	1,400
Methow River near Mazama	48.57	−120.38	373
Methow River near Pateros	48.08	−119.98	1,772
Methow River at Twisp	48.37	−120.12	1,301
Methow River at Winthrop	48.47	−120.18	1,007
Cowlitz River at Mossyrock	46.53	−122.42	1,170
Naches River near Cliffdell	46.90	−121.02	390
Naches River near Naches	46.75	−120.77	941
Stillaguamish River near Arlington	48.26	−122.05	262
Nooksack River at Ferndale	48.85	−122.59	786
Okanaogan River at Malott	48.28	−119.70	8,080
Okanogan River near Tonasket	48.63	−119.46	7,260
Palouse River at Hooper	46.76	−118.15	2,500
Columbia River below Priest Rapids Dam	46.63	−119.86	96,000
Queets River near Clearwater	47.54	−124.31	445
Quinault River at Quinault Lake	47.46	−123.89	264
Yakima River at Rimrock Reservoir	46.66	−121.12	187
Columbia River below Rock Island Dam	47.33	−120.08	89,400
Rock Creek at Old Highway 8 Bridge	45.75	−120.44	213
West Fork Sanpoil River near Republic	48.46	−118.75	308
Sanpoil River near Republic	48.48	−118.73	263
Satsop River at Satsop	47.00	−123.66	299
Similkameen River near Nighthawk	48.98	−119.62	3,550
Similkameen River at Oroville	48.93	−119.44	3,550
Skagit River near Mount Vernon	48.45	−122.33	3,093
Skokomish River near Potlatch	47.31	−123.17	227
Snohomish River near Monroe	47.83	−122.05	1,537
Spokane River at Spokane	47.66	−117.45	4,290
Stehekin River at Stehekin	48.33	−120.69	321
Lewis River	46.05	−122.20	480
Touchet River at Bolles	46.27	−118.22	361
Toutle River near Silver Lake	46.33	−122.83	496
Tucannon River near Starbuck	46.50	−118.07	431
Twisp River near Twisp	48.37	−120.15	245
Walla Walla River at State Line	46.03	−118.73	1,657
Columbia River at Wanapum Dam	46.90	−119.90	90,700

Table 5 (continued)

River Basin/site	Latitude	Longitude	Basin area (mi^2)
Columbia River below Wells Dam	47.95	−119.87	86,100
Wenatchee River at Monitor	47.50	−120.42	1,301
Wenatchee River at Peshastin	47.58	−120.62	1,000
Wenatchee River near Plain	47.76	−120.67	591
White River at Buckley	47.17	−122.02	427
White Salmon River near Underwood	45.75	−121.53	386
Wilson Creek near Almira	47.66	−118.93	327
Yakima River at Cle Elum	47.19	−120.95	495
Yakima River near Grandview	46.34	−120.20	5,400
Yakima River at Union Gap	46.53	−120.47	3,479
Yakima River at Easton	47.24	−121.18	~225
Yakima River at Kiona	46.25	−119.48	5,615
Yakima River at Mabtom	46.23	−120.00	5,359
Yakima River at Umtanum	46.86	−120.48	1,594
Lewis River at Yale	45.96	−122.33	596
Yakima River near Parker	46.51	−120.45	3,660

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