6: Salmon

Impacts of Climate Change on Key Aspects of 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 the frequency and magnitude of peak flow events because these physical factors are likely to be key pressure points for many salmon populations in Washington State. We evaluate the sensitivity of weekly summertime water temperatures and extreme daily high and low streamflows under multimodel composites for A1B and B1 greenhouse gas emissions scenarios. Simulations predict increasing water temperatures and increasing thermal stress for salmon in both western and eastern Washington state that are slight for the 2020s but increasingly large later in the 21st century. Streamflow simulations predict that the largest hydrologic sensitivities are for watersheds that currently have so-called *transient* runoff streamflows, those that are strongly influenced by a mix of direct runoff from autumn rainfall and springtime snowmelt. 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. Historically transient runoff watersheds will trend towards rainfall dominant basins and experience longer summer low flow periods, increased streamflow in winter and early spring, declines in the magnitude of summer low flows, and increases in winter flooding. The combined effects of warming stream temperatures and altered streamflows will very likely reduce the reproductive success for many salmon populations in Washington watersheds, but impacts will vary according to different life history-types and watershed-types. Salmon populations having a stream-type life history with extended freshwater rearing periods (*i.e.* steelhead, coho, sockeye and stream-type Chinook) are predicted to experience large increases in hydrologic and thermal stress in summer due to diminishing streamflows and increasingly unfavorable stream temperatures. Salmon with an ocean-type life history (with relatively brief freshwater rearing periods) are predicted to experience the greatest freshwater productivity declines in transient runoff watersheds where future warming is predicted to increase the magnitude and frequency of winter flooding that reduces egg-to-fry survival rates.

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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. 2008, Crozier and Zabel 2007, and Farrell et al. 2008). Those stocks that typically spend extended rearing periods in freshwater (steelhead, stream-type Chinook, sockeye and coho) are likely to have a greater sensitivity to freshwater habitat changes than those that migrate to sea at an earlier age (ocean-type Chinook, pinks, and chum). While it would be desirable to produce watershed-specific estimates of the aggregate effects of climate change on individual stocks of Pacific salmon (*Oncorhynchus spp*.) 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 at certain stages of their life cycle. Those physical properties are 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.

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 (2008) 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. 2009, this report). And third, the likely impacts of climate change on the reproductive

Table 1. Maximum weekly temperature* upper thermal tolerances for salmonids.

Species	Upper thermal tolerance
Cutthroat trout (O. clarki)	23.3 °C (73.9 °F)
Rainbow trout (steelhead) (O. mykiss)	24.0 °C (75.2 °F)
Chum salmon (O. keta)	19.8 °C (67.6 °F)
Pink salmon (O. gorbuscha)	21 °C (69.8 °F)
Coho salmon (O. kisutch)	23.4 °C (74.1 °F)
Chinook salmon (O. tshawytscha)	24 °C (75.2 °F)

*Based on the 95th percentile of maximum weekly mean temperatures where fish presence (juvenile or adult) was observed (Eaton and Scheller 1996).

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.

The sensitivity of stream temperature and streamflow to changes in climate vary within and between watersheds due to natural and anthropogenic factors that include watershed geomorphology, vegetative cover, groundwater inputs to the stream reach of interest, water resources infrastructure (dams and diversions), the amount and timing of streamflow diverted to out-of-stream uses, and the degree to which key hydrologic processes have been impaired by changes in watersheds.

Increasing summertime stream temperatures are likely to be a key pressure point for many salmon populations in Washington State. Following methods used in previous assessments of climate change impacts on stream habitat (Eaton and Scheller 1996, O'Neal 2002, Mohseni et al. 2003), here we evaluate the sensitivity of summertime weekly water temperature for reasons outlined below.

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). For salmon, excessively warm waters can inhibit migration and breeding patterns, and reduce cold-water refugia and connectivity. When average water temperatures are greater than 15 °C (59 °F) salmon can suffer increased predation and competitive disadvantages with native and non-native warm water fish (EPA 2007). Water temperatures exceeding 21-22 °C (70-72 °F) 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 1).

Previous studies have projected climate change impacts on weekly water temperatures in order to evaluate impacts on trout and salmon habitat in the U.S. O'Neal (2002) used 8 climate change scenarios with a 2090 summertime warming ranging from 2 to 5.5 °C to predict maximum weekly U.S. water temperatures. Locations that experienced a projected maximum weekly water temperature greater than the upper thermal tolerance limit for a species were considered lost habitat. The projected loss of salmon habitat in Washington ranged from 5 to 22% by 2090, depending on the climate change scenario used in the analysis.

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 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). 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. 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.

The WAC Chapter 173 provisions for in-stream resources protection program include several of Washington's river basins with regard to the changing summer low flows and how they impact salmon. Among the provisions stated in these programs is the maintenance of minimum flows for migrating fish.

In order to evaluate the impacts of climate change on summer low flows and flood peaks, we quantify projected changes in the statistics of extreme high and low flows through an analysis of daily streamflows simulated by a hydrologic model under past and future climate scenarios (Elsner et al. 2009, this report). The shifts in precipitation and temperature resulting from climate change will have a multifaceted effect on the streamflow variability since the sources feeding into the rivers in Washington State differ. Relatively warm river basins where surface air temperatures remain above freezing for most or all of the winter are rain-dominant and are found near the coast or at lower elevations in western Washington. Washington's coldest river basins are found in the higher elevation catchments of the Columbia Basin and North Cascades. In these basins winter surface temperatures remain well-below freezing for most or all of winter and have annual flows dominated by spring-summer snowmelt. Washington also has many salmon-bearing watersheds where streamflow is strongly influenced by both direct runoff from rainfall and springtime snowmelt because surface temperatures in winter typically fluctuate around the freezing point; these are referred to as *transient runoff* basins. Over the course of a given winter, precipitation in transient watersheds frequently fluctuates between snow and rain depending on relatively small changes in air temperature. Transient basins are found on the west slopes of the Cascades, the Olympics, and at lower elevation catchments draining the east slopes of the Cascades (Beechie et al. 2006, Hamlet and Lettenmaier 2007). Flooding intensity and timing in transient river basins is therefore dependent on temperature changes, amount of winter snow accumulation and subsequent spring snowmelt, and large-scale fall-winter storms. Low-flows in Washington's watersheds typically occur at the end of the summer and beginning of the fall. Extreme low-flow events can occur with rising summer temperatures, increasing evaporation, and in combination with reduced springtime snow pack and/or decreasing summer precipitation.

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), Loggerwell et al (2003), and ISAB (2007). However, an evaluation of the impacts of climate change on those habitats is beyond the scope of this study.

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 126 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 51 stations in the Columbia River Basin covering parts of the 1995-2008 period were obtained from the U.S. 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 34 stations in the Columbia River Basin were obtained from the USGS archives (http://www.streamnet.org/online-data/temperature1.html). For the continuous

August Mean Surface Air Temperature and Maximum Stream Temperature, 1970-1999

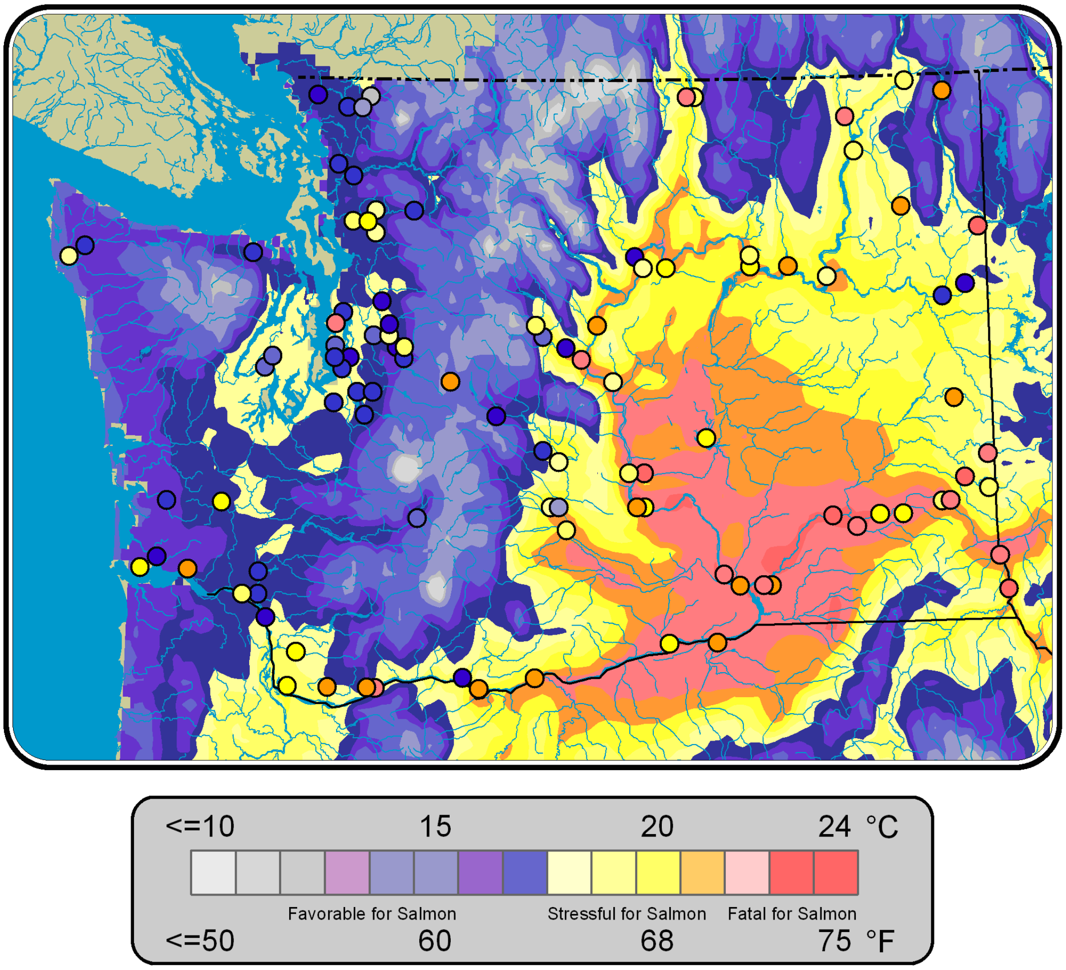

Figure 1. Color shading shows the historic (1970-1999) mean surface air temperatures for August, and shaded circles show the simulated mean of the annual maximum for weekly water temperatures for select locations.

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 U.S. 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 the downscaled, gridded, historic surface air temperatures at 1/16th degree latitude by longitude spatial resolution for the 1915-2006 period (Elsner et al. 2009, this report). Figure 1 shows August surface air temperatures averaged from 1970-99 that were derived from station data and mapped to the 1/16th degree grid used in this study.

2.2. Climate Change Scenarios

Our assessment of climate change impacts on stream temperature and streamflow in the 21st 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 (2009, this report). The 19 scenarios used in this report consist of output from 10 climate models run under A1B emissions, and 9 models for B1 emissions. For our stream temperature modeling, we used air temperatures that were statistically downscaled from the global climate models to the 1/16th degree grid and from a monthly to daily timestep (Elsner et al. 2009, this report). 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 1/16th degree 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 (2.2°F) by the 2020s, 1.9°C (3.4°F) by the 2040s, and 3.2°C (5.8°F) 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 2009, this report).

Based on the 10-model average for A1B emissions, Pacific Northwest summertime temperatures are projected to increase 1.7°C (3.0°F) by the 2020s, 2.7°C (4.9°F) by the 2040s, and 4.7°C (8.5°F) 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 2). Also note that individual climate model projections for the same emissions

Table 2. Multi-model average projected changes in June-July-August PNW air temperature for A1B (10 models) and B1 (9 models) emissions. 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.

Scenario	2020s			2040s			2080s		
	Low	Avg	High	Low	Avg	High	Low	Avg	High
A1B	0.43ºC (0.8ºF)	1.7ºC (3.0ºF)	3.4ºC (6.1ºF)	1.3ºC (2.3ºF)	2.7ºC (4.9ºF)	5.1ºC (9.1ºF)	2.7ºC (4.8ºF)	4.7ºC (8.5ºF)	8.1ºC (14.6ºF)
B1	0.18ºC (0.3ºF)	1.2ºC (2.2ºF)	2.4ºC (3.8ºF)	0.2ºC (0.4ºF)	1.8ºC (3.3ºF)	3.7ºC (6.6ºF)	1.3ºC (2.4ºF)	2.9ºC (5.2ºF)	5.1ºC (10.0ºF)

scenario vary. For summertime temperature changes summarized in Table 2, 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 21st century, but in this study report only the multi-model averages for the A1B and B1 emissions scenarios, respectively.

Elsner et al. (2009, this report) 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 global climate models to the full daily time series of historic meteorological fields for 1915-2006. Composite forcing fields on a 1/16th degree 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. Thus, the flood and low flow statistics from our analyses come from simulated streamflow data that came 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.

2.3. Non-linear Stream Temperature Regression Models

Mohseni (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:

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

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:

$$\lambda = \sum_{i=1}^{n} \varepsilon_i^2 = \sum_{i=1}^{n} (T_{obs_i} - \mu - \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_{a_i})}})^2 \qquad (2)$$

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:

$$NSC = 1 - \frac{\sum_{t=1}^{n} (T_w - T_{obs})^2}{\sum_{i=1}^{n} (\overline{T}_{obs} - T_{obs_i})^2} \qquad (3)$$

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 133 streams with NSC values ≥ 0.7 were included in this study (Mohseni et al. 1998). Of these sites, 12 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 feel justified in developing 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 develop 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 grid in the 1/16^{o} downscaled dataset and the same method was applied using historic surface air temperature from this dataset (Elsner et al. 2009, this report). The model parameters for each site generated by (a) the observed air temperatures (station data) and (b) the downscaled historic air temperature data were similar enough to support the use of the downscaled historic air temperature dataset in the development of stream temperature regression models for all of the stream temperature observation sites. We also compared the NSC values generated by station data and downscaled air temperatures for the eight sites. The range of these NSC values are nearly identical, 0.79 – 0.99 and 0.80 – 0.99 for station and downscaled data, respectively. The averages of NSC values for these test sites are also comparable, 0.90 for station data and 0.88 for downscaled data.

All sites with observed water temperature data were matched to the nearest 1/16^{o} grid point in the downscaled dataset using ArcGIS 9.3. Model parameters were estimated using weekly surface air temperatures from the historic downscaled 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 ^{o}C of the observed maximum temperature for 80% 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. 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 133 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 ^{o}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 reaches that typically host juvenile or adult salmon during the warmest summer months.

2.4. Methods for Extreme High and Low Flow Analyses

The flood and low flow frequency statistics were calculated from Elsner et al's. (2009, this report) 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, very much like the period of climatologically warmest air temperatures. In Figure 1 we show the downscaled historic averages for August surface air temperatures and simulated annual maximum weekly water temperatures for the 1970-99 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 (Goniea et al. 2006) and summer steelhead (High et al. 2006). All but one of the extreme water temperature stations in our study are located in eastern Washington. The western Washington exception in our data set is for water temperatures at University Bridge between Portage Bay and Lake Union in Seattle, a location in the middle of a migration corridor for summer-running adult sockeye and Chinook.

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 Figure 2 indicate there will be large increases in the number of stations that are especially unfavorable for salmon (T_w > 21 °C). Figure 2 also shows the encroachment of summertime air temperatures (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.

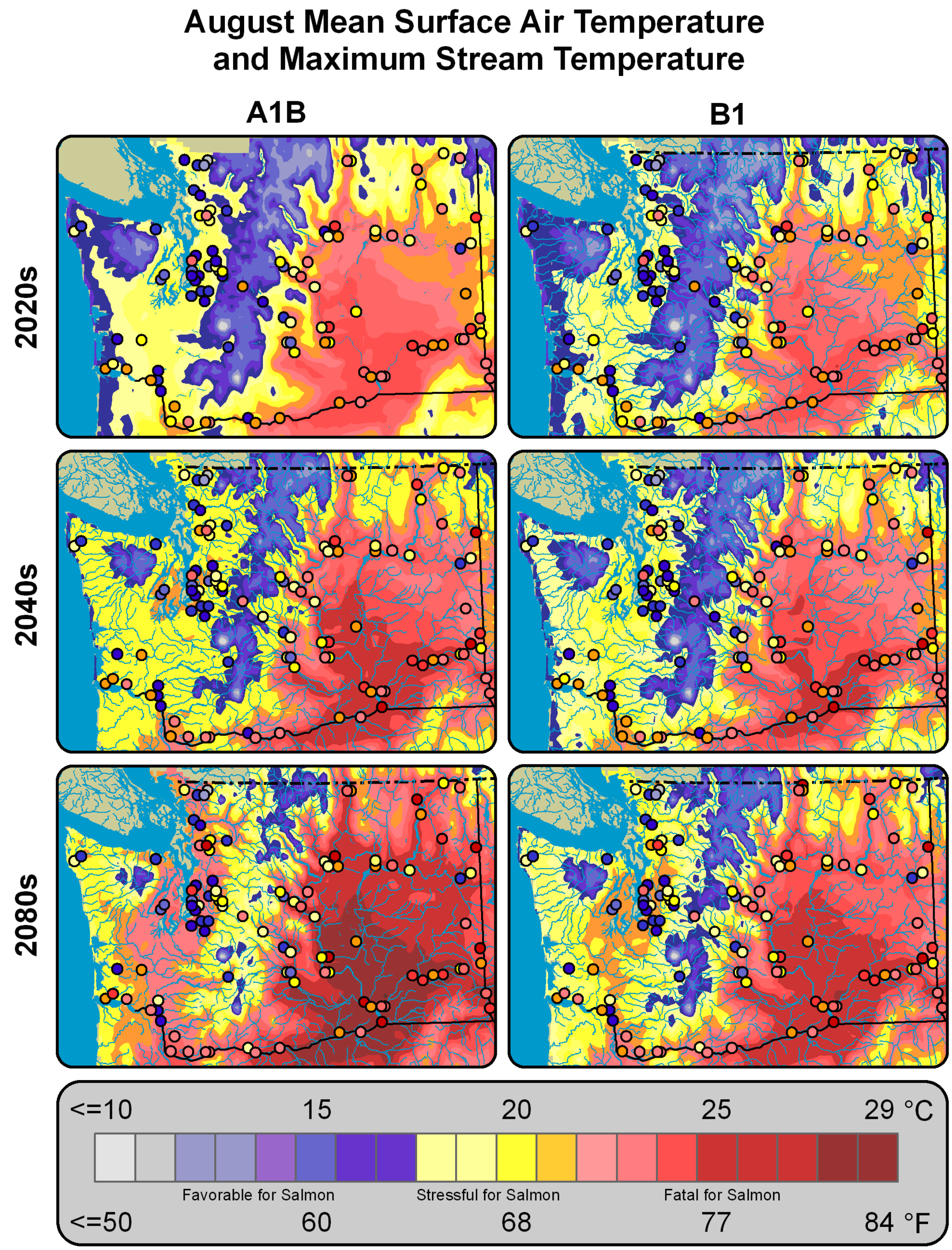

Figure 2. As in Figure 1, but here future climate scenarios for the 2020s, 2040s and 2080s are shown in the top, middle and bottom panels, respectively. Multi-model composite averages based on the A1B emissions are in the left panels, and those for B1 emissions are in the right panels.

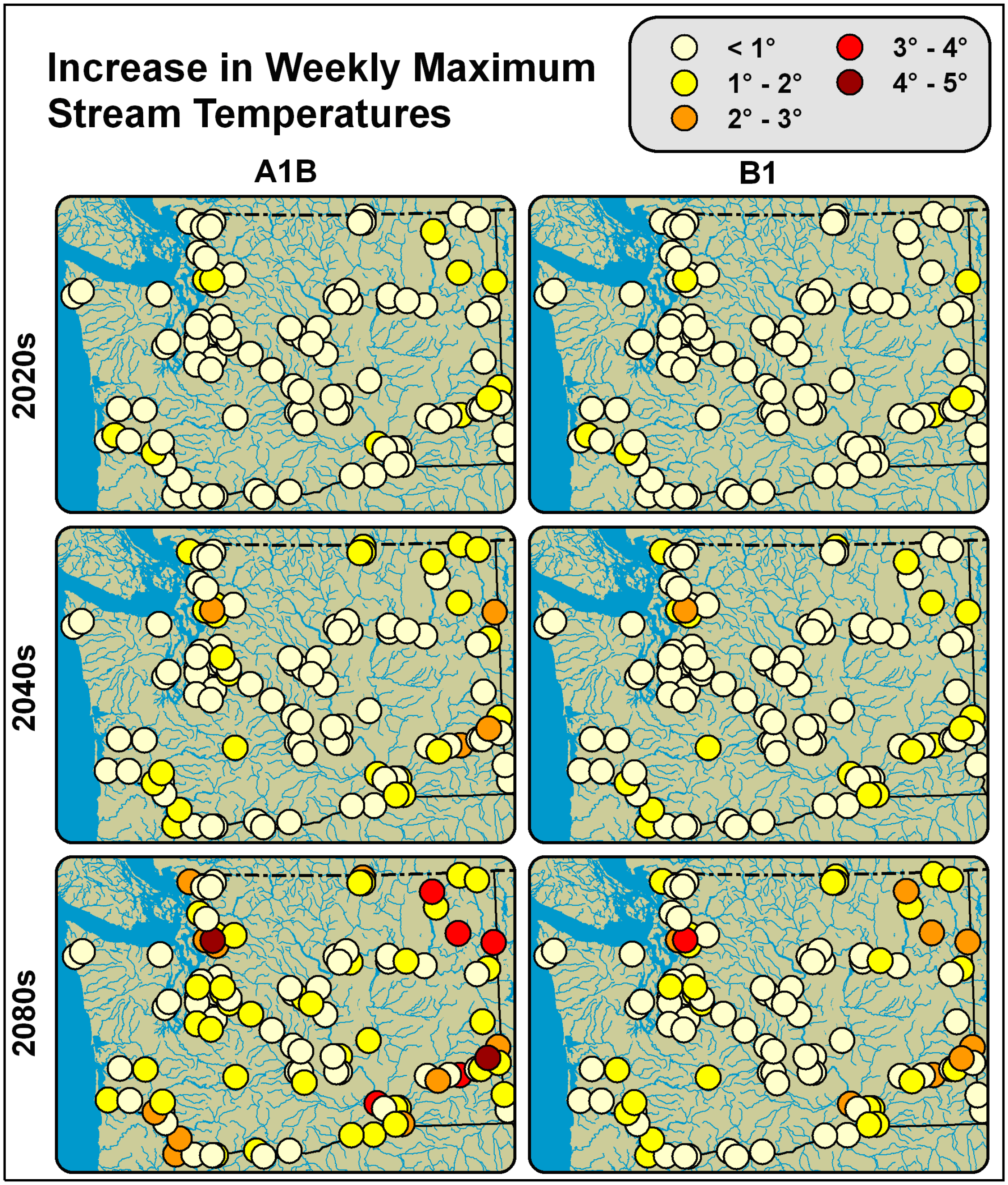

Figure 3. Simulated increases in the annual maximum of weekly water temperatures (°C) relative to the 1980s for select locations in Washington State. Top panels show simulated changes for the 2020s, middle panels for the 2040s, and bottom panels for the 2080s. Composite A1B emissions scenarios are in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

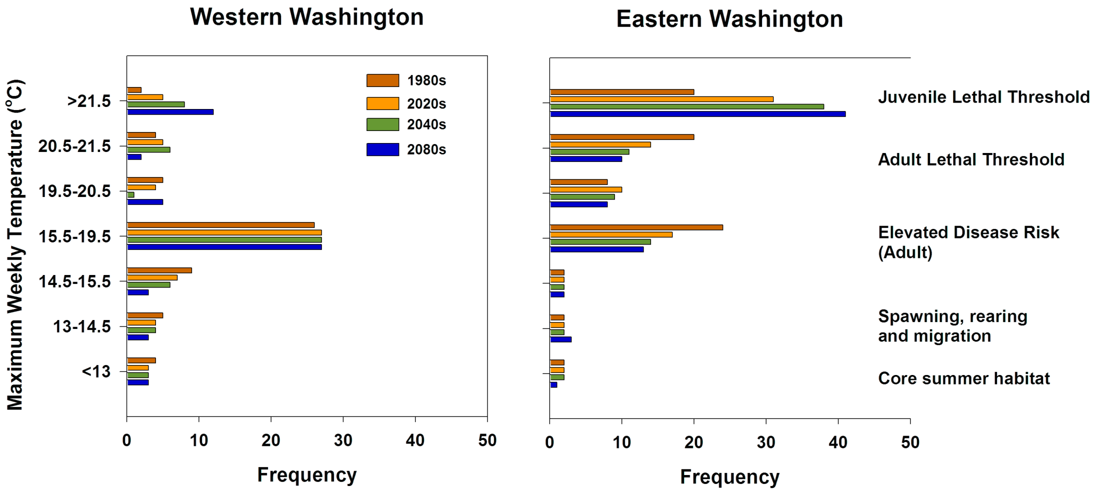

Figure 4. Histograms of maximum weekly water temperature in western and eastern Washington State for the 1980s, 2020s, 2040s, and 2080s under A1B emissions scenarios (data produced from B1 emissions scenarios not shown). Water temperature stations east of the Cascade crest and upstream of the Dalles, OR, are considered to be in eastern Washington, and all others in western Washington.

Future changes in the annual maximum T_w are shown in Figure 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 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 Figure 4 show that, in the 1980s, 31% 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. The fraction of stations in this already compromised category declines to 17% 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, 80% had T_w < 19.5 °C in the 1980s, and this fraction declines to 65% 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 (Figure 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). For the 2080s under A1B emissions, this period of extreme thermal stress and thermal migration barriers is projected to persist for 10-to-12 weeks (from mid-June until early-September) at

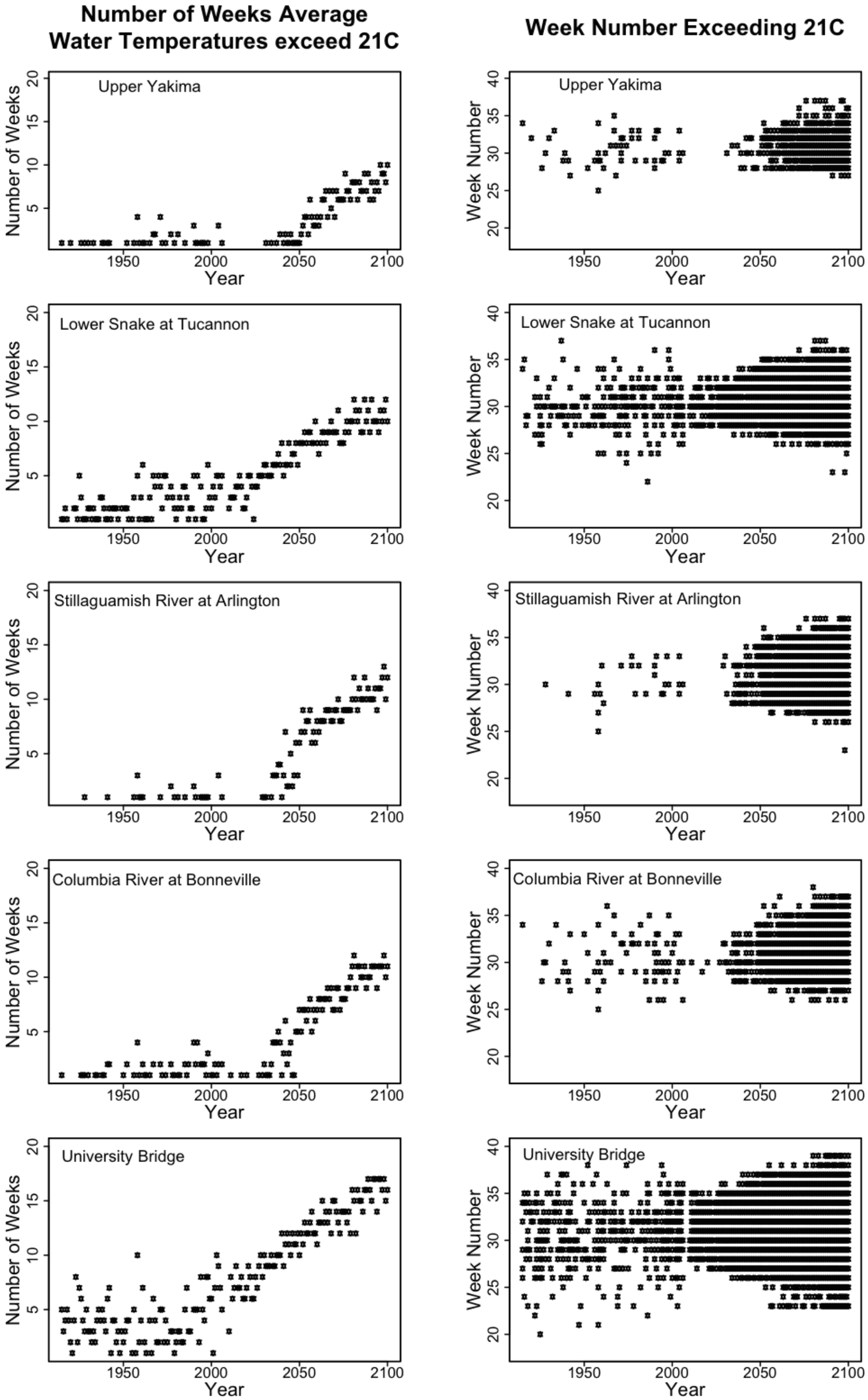

Figure 5. Composite A1B emissions scenarios for simulated number of weeks that T_w exceeds 21°C (left panels) and the week number that weekly water temperature exceeds 21°C (right panels) for: a) the Upper Yakima River, b) Lower Snake River at Tucannon, c) Stillaguamish River at Arlington, d) Columbia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

many stations in eastern Washington and along the lower Columbia River, including the Upper Yakima River, the Columbia River at Bonneville Dam, and the Lower Snake River at Tucannon. This prolonged duration of thermal stress 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 Washington like the Stillaguamish River at Arlington. For this station the period of extreme thermal stress and thermal migration barriers last 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 (Figure 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.

3.2. Climate Change Impacts on Streamflow

3.2.1. Shifts Between Snowmelt, Transient, and Rain-dominant Watersheds

In Figure 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 ration < 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 21st century warming (Elsner et al. 2009, this report).

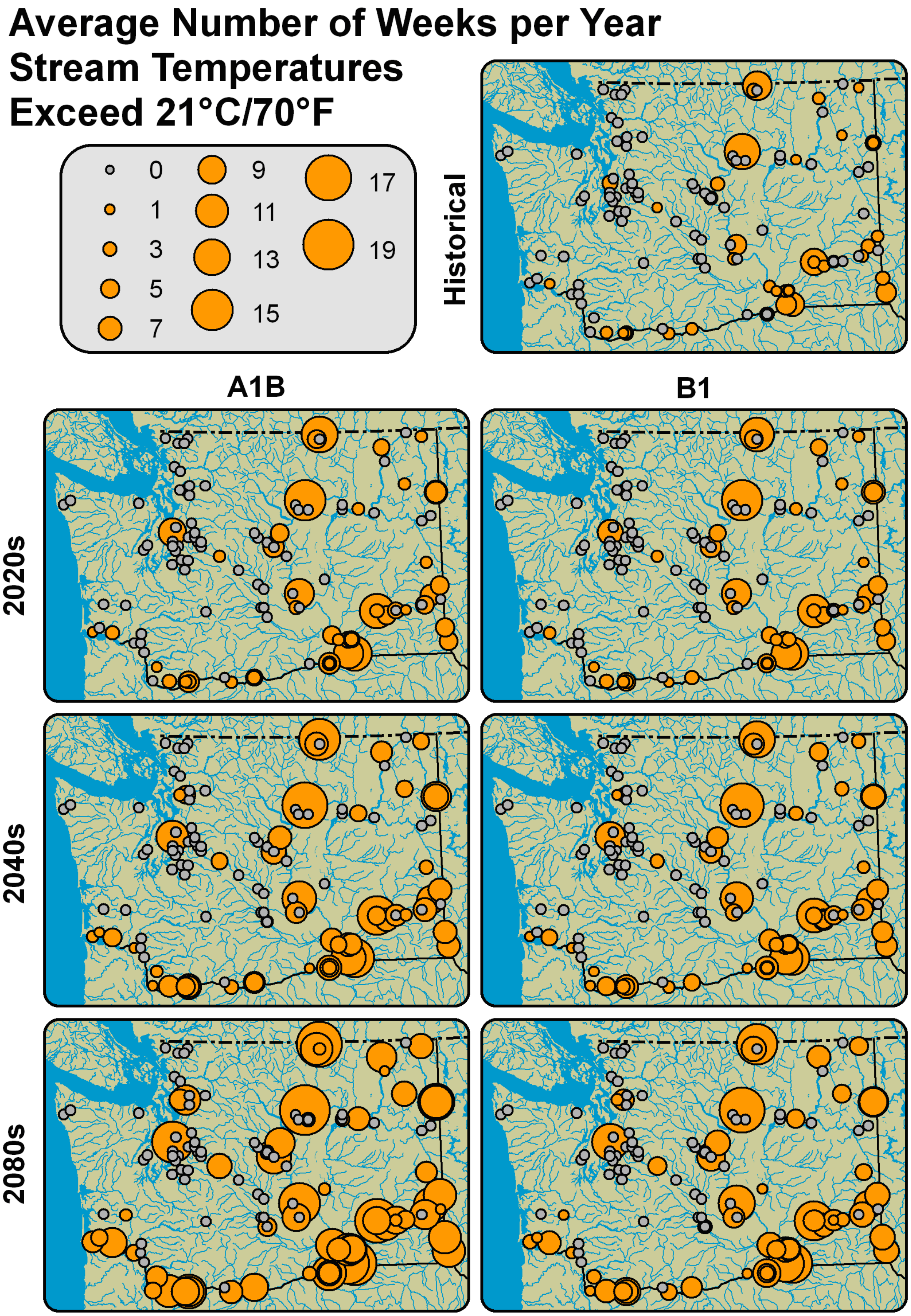

Figure 6. Simulated changes relative to the 1980s in the average number of weeks per year when T_w > 21°C for select locations in Washington State. Top panels show simulated changes for the 2020s, middle panels for the 2040s, and bottom panels for the 2080s. Composite A1B emissions scenarios are in the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

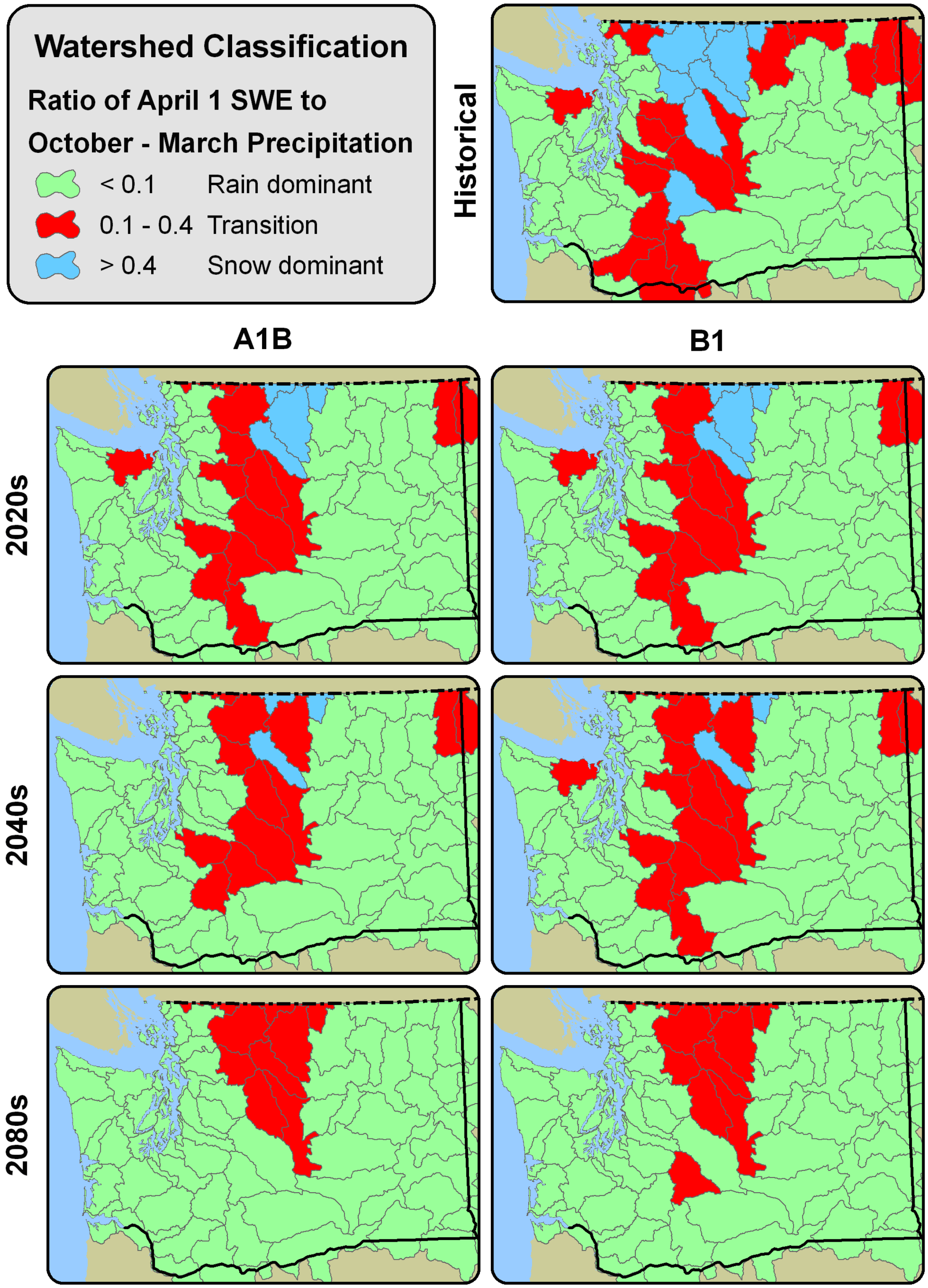

Figure 7. Watershed classification maps for simulated runoff in the historic period (1970-99), 2020s, 2040s, and 2080s. Simulations using A1B emissions are in the lower 3 rows of the left column, while those using B1 emissions scenarios are in the lower 3 rows of the right column.

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 (Figure 8), which we now see are characterized by mean winter temperatures within a few degrees of 0 °C. Rain-dominant watersheds are predicted 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. 2009, this report), thereby decreasing the risk of springtime snowmelt-driven floods.

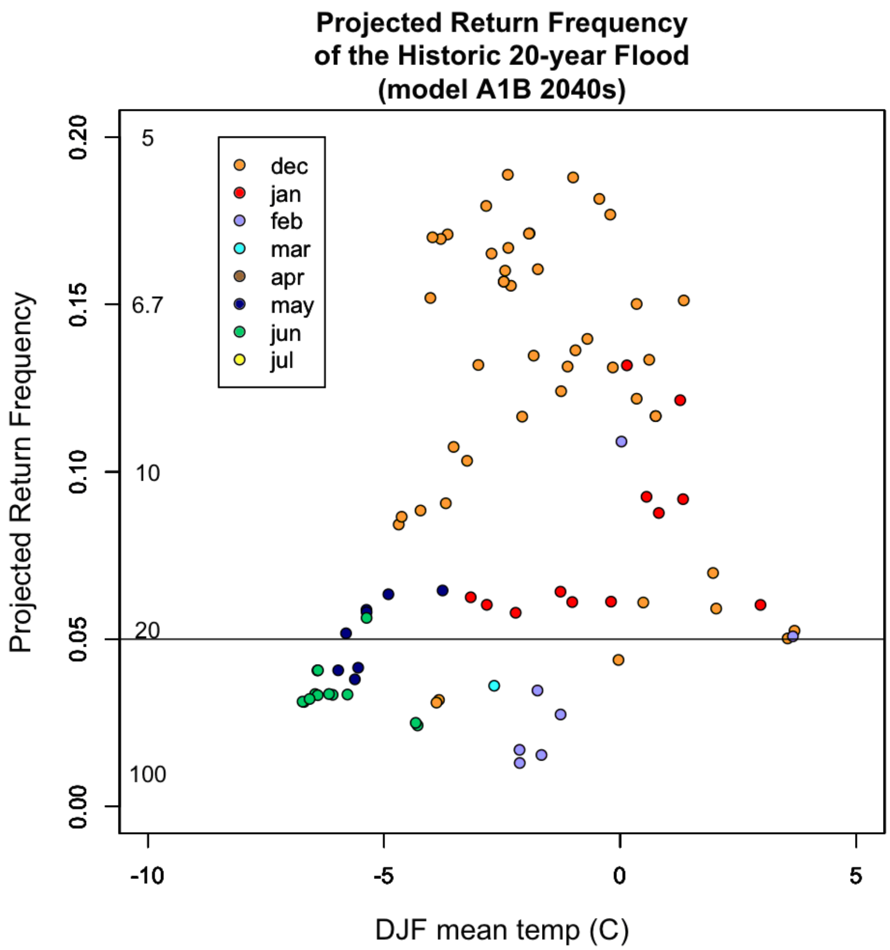

Figure 8. Projected return frequency of the historic 20 year flood magnitudes as a function of the DJF average temperatures in each basin. Color coding in the scatter plots identifies the month when flooding is projected to peak in the A1B 2040s simulation: orange = December, red = January, purple = 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.

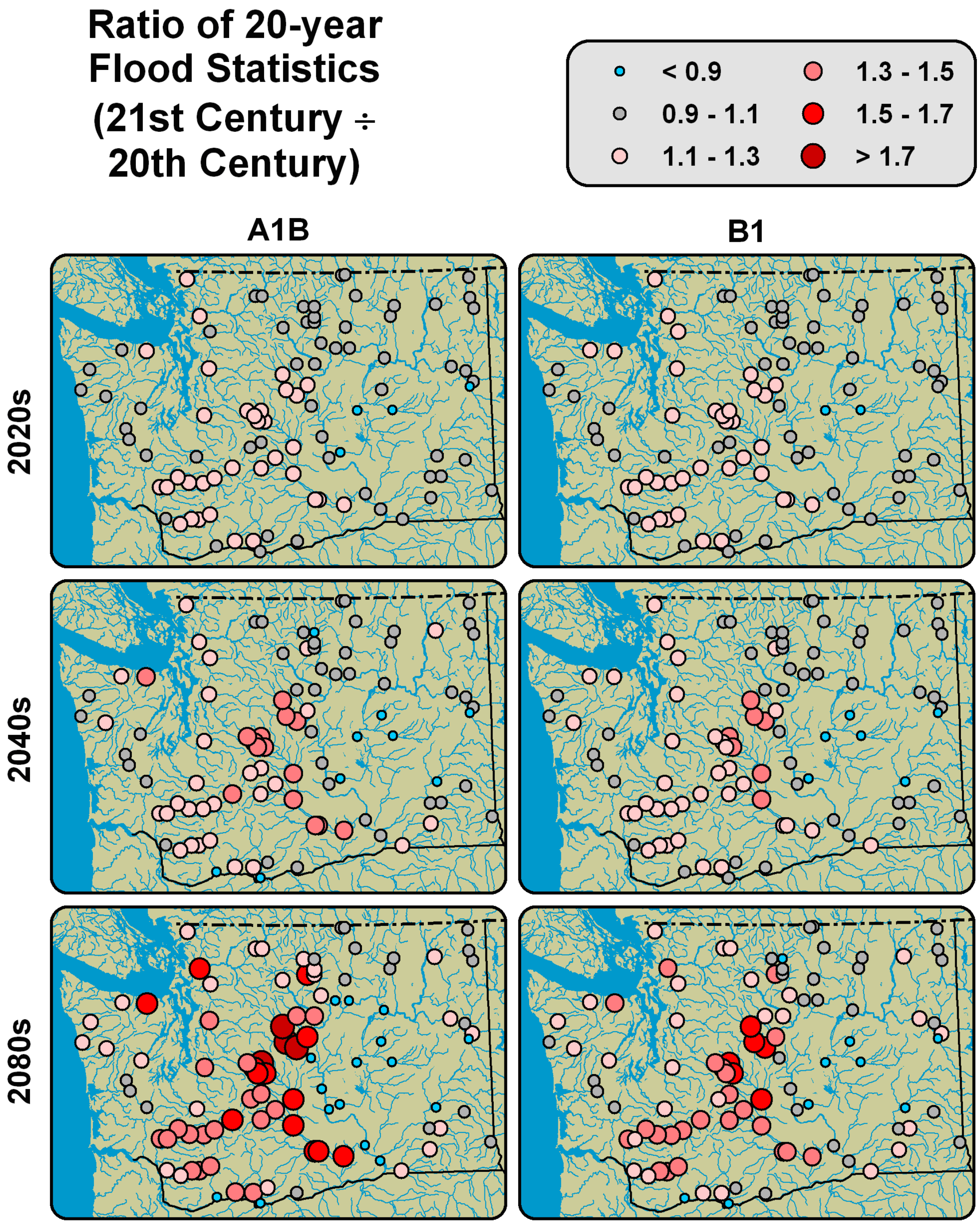

Figure 9. Ratio of the 20 year flood magnitudes for simulated future and historic streamflows at select locations. Top panels show simulated changes for the 2020s, middle panels for the 2040s, and bottom panels for the 2080s. Composite A1B emissions scenarios are in the left column, composite B1 emissions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

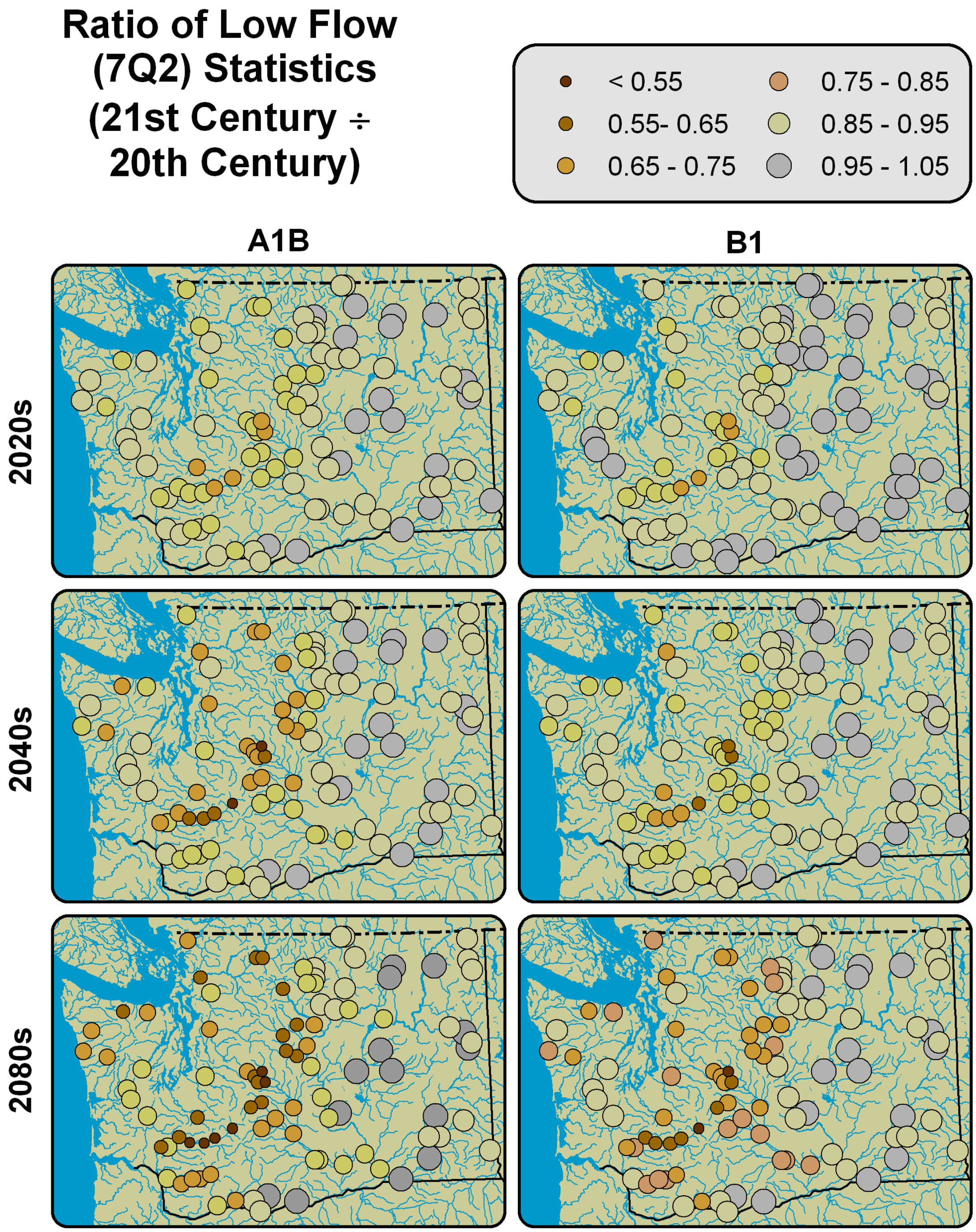

Figure 10. Ratio of low flow (7Q2) statistics for simulated future and historic streamflows at select locations. Top panels show simulated changes for the 2020s, middle panels for the 2040s, and bottom panels for the 2080s. Composite A1B emissions scenarios are in the left column, composite B1 emissions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

Maps for projected changes in the return frequency of the historic 20-year flood are shown in Figure 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 21st 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 21st century. Emissions scenarios also play a strong role in the rate of change in flooding magnitudes, with the pattern of changes for A1B emissions in the 2040s being similar to that 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 (Figure 10). Future estimates of the annual average low flow magnitude (7Q2, which is the 7 day average low flow magnitude with a 2 year return interval) are projected to decline by 0-50% 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 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 (not shown, but see Elsner et al. 2009).

4. Assessment of Changes in Critical Temperatures and Streamflow for Washington's Salmon

Assuming that the capacity for and the rate of adaptation (either through phenological, phenotypic, or evolutionary responses) in present day salmon populations are less than the intensity and rate of climate change in the 21st century, our assessment 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 Figure 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. 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

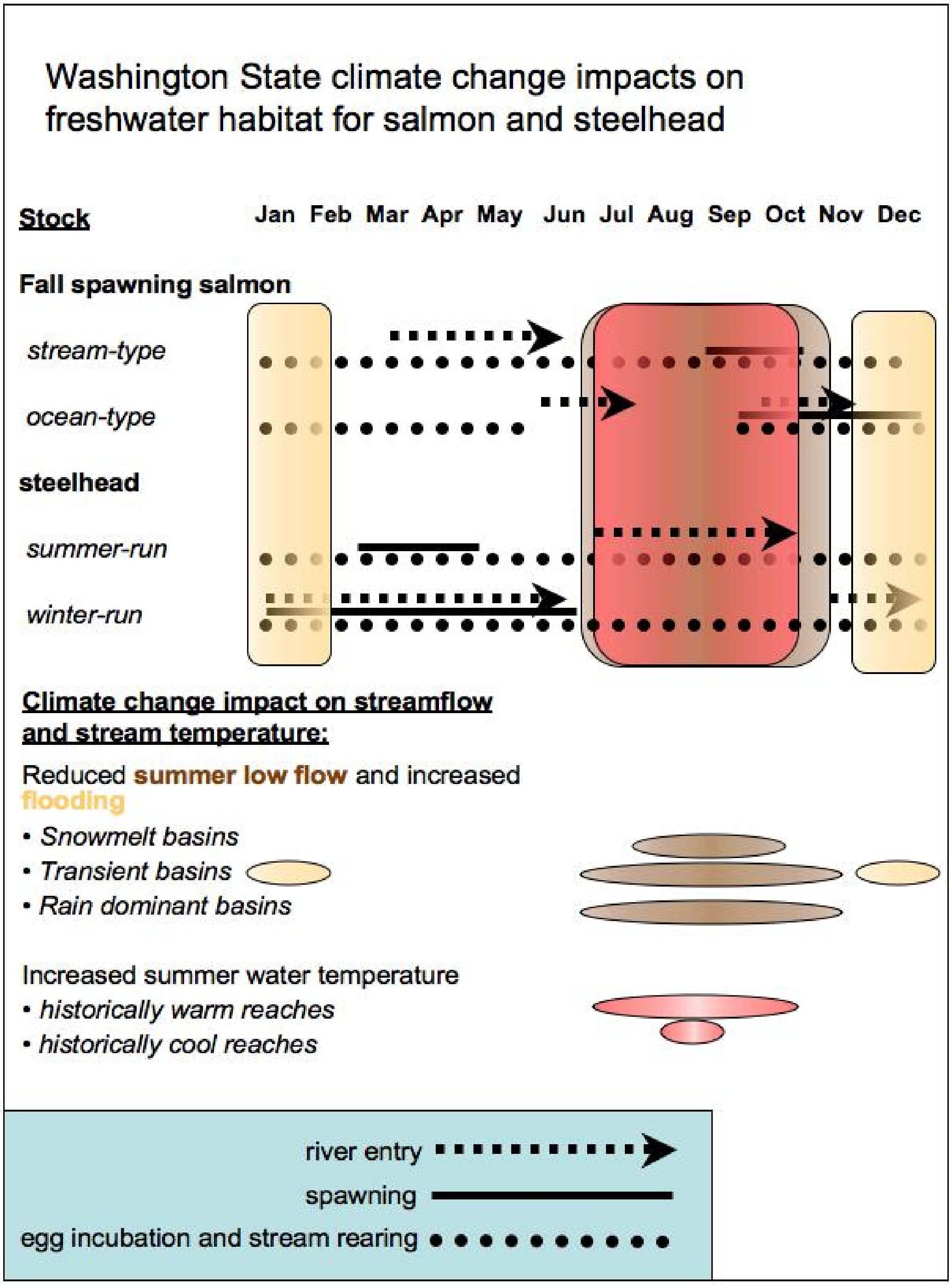

Figure 11. Summary of key climate change impacts on Washington's freshwater habitat for salmon and steelhead, how those impacts differ for streams with different hydrologic characteristics, and how the timing for different impacts compare with the life history for generalized salmon and steelhead life 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.

populations in the Columbia Basin, and sockeye and Chinook in the Lake Washington system. Increased stream temperatures pose risks to the quality and quantity of favorable rearing habitat for stream-type Chinook, coho and steelhead (summer and winter run) throughout Washington because these stocks spend at least one summer (and for Washington's steelhead typically 2 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, and the parr-to-smolt survival rates for coho, stream-type Chinook, and steelhead. And 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.

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, while 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, Chinook, and steelhead smolts on their seaward migrations through the ship canal (Tabor et al. 2004).

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

Generally speaking, 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. 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.

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. Likewise, strategic use of cold-water releases may be able to mitigate climate change impacts on summer water temperature and seasonally low streamflow at key times.

It is important to recognize that, in many basins, climate change will likely increase the demand for surface water in summer for such uses as irrigation for agriculture and municipal water supplies. This situation will require that 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. (2006) study of climate change, restoration options, and their impacts on Snohomish ocean-type Chinook 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. In contrast, Martin (2006) suggests that thermal refugia will increasingly be found at 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 (2006) study of climate change and habitat restoration options for Snohomish Chinook 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. 2008). Adaptive capacity may be among the most important issues facing Washington's salmonids yet this capacity is not well documented or understood. 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 in already warm watersheds like Lake Washington sockeye will be faced with increasingly strong selection pressures that favor a shift in spawning migration timing away from what are projected to be increasingly hostile 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. 2008).

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 (2009) 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 snow pack. 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. The distribution of stations, and the duration of time each year, where weekly water temperatures cause thermal migration barriers and increase the risk of fish kills (> 21 °C or 70 °F) are projected to expand with warmer summer temperatures. Generally speaking, the greatest thermal stresses 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 most thermally stressed 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.

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 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 in summer for such uses as irrigation for agriculture and municipal water supplies. In order to avoid protracted and potentially costly conflicts, this situation will require that 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 before such conflicts become too extreme.

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Appendix A: Washington State stream temperature stations used in this study.

Dataset[1]	Region[2]	Site/River Basin	Latitude	Longitude	alpha	beta	gamma	mu	nsc
USACE	UC	Albeni Falls Forebay Pend Orielle River	48.16	-117.09	23.1	12.18	0.27	5.63	0.82
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	46.16	-116.97	25.05	14.76	0.19	4.44	0.81
DOE	PS	Bertrand Creek at Rathbone Road	48.91	-122.53	19.11	17.44	0.5	11.41	0.91
DOE	PS	Big Mission Creek at Highway 300	47.41	-122.91	16.52	9.84	0.18	0	0.8
DOE	PS	Big Soos Creek near Auburn	47.28	-122.16	15.44	15.31	0.73	10.57	0.94
USACE	LC	Bonneville Forebay, Columbia River	45.66	-121.97	22.77	11.39	0.24	2.83	0.88
DOE	UC	Brender Creek near Cashmere	47.53	-120.47	18.87	17.21	0.24	8.73	0.86
DOE	LC	Burnt Bridge Creek at mouth	45.66	-122.66	24.42	20.26	0.24	11.93	0.8
USACE	LC	Cascade Island (below Bonneville)	45.66	-121.97	23.18	12.53	0.28	3.15	0.9
DOE	PS	Cedar River at Logan Street, Renton	47.47	-122.22	18.88	18.49	0.4	11.83	0.84
DOE	OP	Chehalis River at Dryad	46.66	-123.22	21.2	17.28	0.58	12.21	0.7
DOE	PS	Cherry Creek at Highway 203	47.78	-121.97	16.88	17.68	4.41	13.41	0.92
USGS	UC	Chief Joseph Dam Columbia River	47.97	-119.66	22.75	11.44	0.14	2.92	0.81
USACE	UC	Chief Joseph Forebay Columbia River*	47.97	-119.66	19.17	8.45	0.22	0	0.84
DOE	UC	Chumstick Creek near mouth	47.59	-120.66	13.38	19.37	0.64	9.69	0.96
DOE	UC	Chumstick Creek near Leavenworth	47.47	-120.34	13.15	16.83	27.3	10.88	0.91
USACE	UC	Boundary (US/Canada) Columbia River	48.97	-117.66	21.96	12.03	0.15	2.28	0.83
USGS	UC	Colville River	48.59	-118.09	21.98	12.58	0.17	0.67	0.88
DOE	UC	Colville River at Chewelah	48.28	-117.72	28.51	16.91	0.14	3.37	0.81
DOE	UC	Cowiche Creek at Powerhouse Road	46.66	-120.59	18.56	17.97	0.58	12.62	0.91
DOE	LC	Cowlitz River at Kelso	46.16	-122.91	16.71	16.54	0.6	11.92	0.76
DOE	UC	Crab Creek near Beverly	46.84	-119.84	25.05	14.28	0.23	0	0.93
USACE	LC	Camas/Washougal, WA. Columbia River	45.66	-122.34	22.43	12.74	0.32	5.13	0.87
DOE	UC	Deadman Creek near mouth	46.59	-117.78	27.08	26.07	0.22	11.71	0.91
DOE	UC	Deadman Creek at Holcomb Road	47.84	-117.22	21.36	12.85	0.13	0	0.93
DOE	PS	Des Moines Creek near mouth	47.41	-122.28	17.22	10.11	0.28	0	0.74
DOE	OP	Dickey River near La Push	47.97	-124.53	18.28	13.81	1.39	13.81	0.95
DOE	LC	Lewis River near Dollar Corner	45.84	-122.59	23.31	18.41	0.37	10.78	0.73
DOE	PS	Fauntleroy Creek near mouth	47.53	-122.34	14.49	17.73	0.72	12.32	0.85
USACE	UC	Grand Coulee Forebay Columbia River*	47.97	-118.97	19.64	9.85	0.26	2.39	0.86
USGS	UC	Franklin D. Roosevelt Lake	47.97	-118.97	22.31	11.49	0.15	2.99	0.81
USACE	UC	Grand Coulee Tailrace, Columbia River*	48.03	-118.97	19.18	10	0.23	2.86	0.79
DOE	PS	Griffen Creek at Highway 203	47.59	-121.91	17.44	18.8	0.54	11.77	0.82
USACE	UC	Ice Harbor Tailrace Snake River	46.22	-118.84	24.15	14.55	0.16	2.62	0.82
USACE	UC	Ice Harbor Forebay Snake River	46.22	-118.84	24.12	14.4	0.16	2.63	0.84
USACE	UC	John Day Forebay Columbia River	45.72	-120.72	22.17	14.01	0.26	5.34	0.85

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Appendix A: Continued.

Dataset[1]	Region[2]	Site/River Basin	Latitude	Longitude	alpha	beta	gamma	mu	nsc
USACE	UC	John Day Tailrace Columbia River	45.72	-120.72	22.03	13.99	0.26	5.72	0.83
DOE	PS	Jim Creek at Whites Road	48.16	-122.03	20.91	17.84	0.39	11.48	0.79
DOE	PS	Jimmeycomelately Creek at Highway 101	48.03	-123.03	16.32	11.1	0.36	0	0.74
DOE	LC	Kalama River near Kalama	46.03	-122.84	17.33	17.6	0.85	12.18	0.71
DOE	UC	Kettle River near Barstow	48.78	-118.16	33.34	16.02	0.09	0	0.77
DOE	PS	Kimball Creek at Highway 202	47.53	-121.84	21.38	18.08	0.28	10.51	0.85
USGS	UC	Klickitat River at Klickitat	45.72	-121.28	19.74	12.3	0.15	0.46	0.94
DOE	PS	Laughing Jacobs Creek near Mouth	47.59	-122.03	15.17	13.51	0.21	8.67	0.97
USACE	UC	Lower Granite Tailrace Snake River	46.66	-117.47	20.29	11.62	0.21	2.78	0.86
USACE	UC	Little Goose Forebay Snake River	46.59	-117.97	24.03	13.68	0.16	1.17	0.81
USACE	UC	Little Goose Tailrace, Snake River	46.59	-117.97	21.49	14.38	0.21	4.7	0.79
DOE	PS	Little_Mission_Cr._@_Hwy_300	47.41	-122.91	12.1	6.8	0.22	0	0.9
USACE	UC	Lower Monumental Forebay Snake River	46.59	-118.34	23.26	14.3	0.18	2.84	0.81
USACE	UC	Lower Monumental Tailrace Snake River*	46.59	-118.34	24.27	13.96	0.23	4.18	0.86
USGS	LC	Lower Columbia	46.28	-123.84	21.73	10.98	0.37	3.81	0.83
USGS	LC	Lower Columbia at Clatskanie	46.16	-123.03	22.81	12.51	0.23	3.01	0.81
USGS	LC	Lower Cowlitz	46.28	-122.91	19.36	13.94	0.22	3.36	0.85
USGS	UC	Lower Crab	47.03	-119.34	22.41	9.83	0.13	0.08	0.88
USGS	UC	Lower Snake	46.28	-119.22	31.25	19.94	0.11	3.38	0.91
USGS	UC	Lower Snake near Asotin	46.22	-118.91	24.06	14.3	0.17	2.05	0.84
USGS	UC	Lower Snake near Tucannon	46.34	-117.03	23.73	13.06	0.17	1.57	0.84
USGS	UC	Lower Spokane	46.53	-118.16	23.7	13.72	0.17	1.87	0.85
USGS	UC	Lower Yakima	47.91	-118.34	19.77	12.18	0.19	0.73	0.81
USACE	UC	Lower Granite Forebay Snake River	46.66	-117.41	24.48	13.59	0.16	2.57	0.81
DOE	UC	Manatash Creek at Manatash Road	46.97	-120.66	15.17	14.72	0.64	9.48	0.97
DOE	PS	Maple Creek at mouth	48.91	-122.09	10.77	16.55	0.9	9.48	0.79
USACE	UC	McNary Tailrace Columbia River	45.91	-119.28	22.67	13.62	0.17	2.93	0.82
USACE	UC	McNary Forebay OR. Columbia River*	45.91	-119.28	22.16	11.96	0.22	2.58	0.86
USACE	UC	McNary Forebay WA. Columbia River	45.91	-119.28	23.12	13.96	0.17	3.04	0.82
USGS	UC	Methow River	48.03	-119.91	18.15	9.32	0.18	0	0.88
USGS	UC	Mid-Columbia near Lake Wallula	45.91	-119.66	22.58	14.14	0.16	2.7	0.8
DOE	PS	Miller Creek near mouth	47.47	-122.34	18.33	8.91	0.18	0	0.82
DOE	UC	Mission Creek near Cashmere	47.53	-120.47	37.01	23.62	0.08	0	0.92
DOE	UC	Moxee Drain at Birchfield Road	46.53	-120.47	22.61	10.6	0.16	0	0.84
USGS	UC	Naches River	46.66	-120.53	14.19	12.92	0.16	0	0.74
DOE	LC	Naselle River near Naselle	46.34	-123.72	39.37	22.65	0.26	9.24	0.75
DOE	PS	Newaukum Creek near Enumclaw	47.28	-122.03	15.13	14.52	0.67	9.6	0.94

Appendix A: Continued.

Dataset[1]	Region[2]	Site/River Basin	Latitude	Longitude	alpha	beta	gamma	mu	nsc
DOE	PS	Stillaguamish River at Cicero	48.28	-122.03	19.77	16.57	0.55	11.57	0.74
DOE	PS	Stillaguamish River near Darrington	48.28	-121.72	16.59	16.5	0.49	10.9	0.73
DOE	UC	Noname Creek near Cashmere	47.53	-120.47	19.35	17.21	0.21	8.46	0.85
DOE	PS	Nooksack River at North Cedarville	48.84	-122.28	15.66	16.84	0.61	11.15	0.76
DOE	PS	Nooksack River above Middle Fork	48.84	-122.16	12.42	16.21	4.22	10.63	0.9
USGS	UC	Okanogan River	48.97	-119.41	31.08	11.98	0.11	0	0.95
DOE	UC	Okanogan River at Oroville	48.09	-119.72	25.05	10	0.2	0	0.85
USGS	UC	Palouse River	46.91	-117.09	27.71	13.33	0.16	0	0.83
USACE	UC	Pasco, WA. Columbia River*	46.22	-119.09	21.54	13.91	0.27	2.4	0.92
DOE	UC	Paradise Creek at the Border	46.72	-117.09	24.2	2.44	0.07	0	0.78
DOE	PS	Patterson_Ck_near_Fall_City	47.59	-121.91	17.46	18.57	0.51	11.81	0.8
USGS	UC	Pend Orielle River	48.91	-117.34	24.35	9.97	0.16	0	0.87
DOE	UC	Peone (Deadman) Creek	47.78	-117.41	14.77	16.23	0.48	10.47	0.86
DOE	PS	Pilchuck Creek at Bridge 626	48.22	-122.22	23.97	15.2	0.25	7.33	0.75
DOE	UC	Pine Creek at Rosalia	47.22	-117.34	22.41	14.16	0.24	6.99	0.94
USACE	UC	Priest Rapids Forebay Columbia River*	46.66	-119.84	20.62	13	0.23	3.21	0.9
DOE	PS	Puyallup River at Puyallup	47.22	-122.34	17.6	11.58	0.22	0	0.89
DOE	PS	Raging River at mouth	47.59	-121.91	19.74	18	0.68	11.99	0.86
USACE	UC	Rock Island Forebay, Columbia River	47.34	-120.09	18.61	13.72	0.25	3.93	0.7
DOE	PS	Samish River near Burlington	48.53	-122.34	16.42	16.89	0.54	10.95	0.74
USGS	UC	Sanpoil River	47.97	-118.66	24.01	13.24	0.17	0	0.97
DOE	UC	Palouse River (South Fork) at Albion	46.78	-117.28	43.86	21.69	0.07	0	0.72
DOE	PS	Snoqualmie River at Bendigo	47.47	-121.78	17.3	5.89	0.13	0	0.71
DOE	PS	Snoqualmie at Valley Trail (RM 19)	47.53	-121.78	17.79	7.3	0.13	0	0.78
DOE	PS	Snoqualmie River at 468th Ave	47.47	-121.78	24.1	10.79	0.08	0	0.86
DOE	PS	Stillaguamish River at Arlington	48.22	-122.09	26.42	17.75	0.34	9.44	0.83
DOE	PS	Thornton Creek (South Fork) 107th Ave	47.72	-122.28	18.23	8.38	0.18	0	0.8
USGS	UC	Similkameen River	48.91	-119.41	22.78	12.7	0.16	0	0.88
DOE	UC	Similkameen River at Oroville	48.91	-119.47	24.49	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	0.89
USACE	LC	Skamania, WA. Columbia River	46.28	-123.47	21.87	11.72	0.4	5.09	0.85
DOE	PS	Snoqualmie River above Carnation	47.53	-121.78	20.09	13.49	0.49	0	0.97
DOE	OP	Soleduck River near Forks	48.03	-124.41	16.5	15.6	3.02	13.4	0.96
DOE	PS	Stimson Creek at Highway 300	47.41	-122.91	14.09	8.48	0.21	0	0.8
USACE	UC	The Dalles Forebay Columbia River	45.66	-121.16	23.09	12.86	0.2	0	0.84
USACE	UC	The Dalles Tailrace Columbia River	45.66	-121.16	22.37	14.69	0.25	5.22	0.83
DOE	PS	Tolt River near Carnation	47.66	-121.91	18.69	17.77	0.36	10.92	0.89

Appendix A: Continued.

Dataset[1]	Region[2]	Site/River Basin	Latitude	Longitude	alpha	beta	gamma	mu	nsc
DOE	UC	Tucannon River at Powers	46.53	-118.16	27.97	17.09	0.12	2.56	0.71
USACE	PS	University Bridge Lake Union, Seattle	47.66	-122.34	24.1	13.37	0.3	6.8	0.92
DOE	PS	Union River near Belfair	47.47	-122.84	13.76	9.65	0.24	0	0.71
USGS	UC	Upper Columbia River at Entiat*	47.66	-120.22	22.69	10.4	0.18	1.62	0.93
USGS	UC	Upper Columbia River at Priest Rapids*	46.66	-119.91	22.31	11.63	0.19	1.41	0.92
USGS	LC	Upper Cowlitz River	46.59	-121.66	17.12	12.9	0.16	3.1	0.77
USGS	UC	Upper Yakima River	47.34	-121.41	22.54	6.42	0.23	1.38	0.92
USGS	UC	Walla Walla River	46.03	-118.78	30.41	17.43	0.16	3.63	0.93
DOE	UC	Walla Walla River near Touchet	46.03	-118.91	27.12	19.32	0.25	9.25	0.83
USACE	UC	Wanapum Forebay Columbia River*	46.84	-119.97	20.9	10.79	0.21	2.97	0.87
USACE	UC	Wanapum Downstream Columbia River*	46.84	-119.97	20.31	11.93	0.18	3.54	0.78
USACE	UC	Wells Forebay Columbia River*	47.97	-119.84	19.85	10.34	0.24	2.24	0.76
USACE	UC	Wells Tailrace Columbia River	47.97	-119.84	18.36	13.5	0.3	3.97	0.74
USGS	UC	Wenatchee River	47.47	-120.34	5.15	4.64	0.39	0	0.87
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	14.51	0.29	7.85	0.76
DOE	PS	White River at R Street	47.16	-122.09	17.64	17.74	0.52	10.99	0.8
DOE	UC	Wide Hollow Creek at Main Street	46.53	-120.47	21.8	8.19	0.12	0	0.85
DOE	OP	Willapa River near Willapa	46.66	-123.66	16.89	15.73	1	12.44	0.76
DOE	UC	Wilson Creek at Highway 871	46.91	-120.53	18.47	12.84	0.28	10.23	0.86
USACE	LC	Warrendale, OR. Columbia River	45.66	-122.03	22.24	10.2	0.26	3.09	0.88
DOE	UC	Yakima River near Cle Elum	47.16	-121.03	17.69	8.97	0.34	0	0.81

[1]Dataset refers to origin of data: Washington Department of Ecology (DOE), US Army Corps of Engineers (USACE), US Geological Survey (USGS).

[2]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).

*Sites demonstrating hysteresis.

Appendix B: 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: 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	24200
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	240000
Pend Orielle River at US/Canada Boundary	49.00	-117.35	25200
Pend Orielle River near Ione	48.78	-117.42	24900
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	1294
Chewuch River at Winthrop	48.48	-120.19	525
Rufus Woods Lake at Bridgeport	47.99	-119.63	75400
Cle Elum River near Rosyln	47.24	-121.07	203
Columbia River at Clover Island	46.22	-119.11	104000
Colville River at Kettle Falls	48.59	-118.06	1007
Cowlitz River at Castlerock	46.27	-122.90	2238
Cowlitz River near Kosmos	46.47	-122.11	1040
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	4840
Crab Creek at Irby	47.36	-118.85	1042
Crab Creek near Moses Lake	47.19	-119.26	2228
Columbia River at Dalles	45.61	-121.17	237000
Skagit River at Diablo Dam	48.72	-121.13	1125
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	74700
Gorge Reservoir near Newhalem	48.70	-121.21	1159
Green River near Auburn	47.31	-122.20	399
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	108500
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	1297
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	103900
Snake River at Lower Granite	46.60	-117.40	103500

Appendix C: Continued.

River Basin/Site	Latitude	Longitude	Basin Area (mi²)
Little Spokane River near Dartford	47.78	-117.50	698
Spokane River at Long Lake	47.84	-117.84	6020
Cowlitz River below Mayfield Dam	46.50	-122.60	1400
Methow River near Mazama	48.57	-120.38	373
Methow River near Pateros	48.08	-119.98	1772
Methow River at Twisp	48.37	-120.12	1301
Methow River at Winthrop	48.47	-120.18	1007
Cowlitz River at Mossyrock	46.53	-122.42	1170
Naches Rivernear 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	8080
Okanogan River near Tonasket	48.63	-119.46	7260
Palouse River at Hooper	46.76	-118.15	2500
Columbia River below Priest Rapids Dam	46.63	-119.86	96000
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	89400
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	3550
Similkameen River at Oroville	48.93	-119.44	3550
Skagit River near Mount Vernon	48.45	-122.33	3093
Skokomish River near Potlatch	47.31	-123.17	227
Snohomish River near Monroe	47.83	-122.05	1537
Spokane River at Spokane	47.66	-117.45	4290
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	1657
Columbia River at Wanapum Dam	46.90	-119.90	90700
Columbia River below Wells Dam	47.95	-119.87	86100
Wenatchee River at Monitor	47.50	-120.42	1301
Wenatchee River at Peshastin	47.58	-120.62	1000
Wenatchee River near Plain	47.76	-120.67	591
White River at Buckley	47.17	-122.02	427

Appendix C: Continued.

River Basin/Site	Latitude	Longitude	Basin Area (mi^2)
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	5400
Yakima River at Union Gap	46.53	-120.47	3479
Yakima River at Easton	47.24	-121.18	~225
Yakima River at Kiona	46.25	-119.48	5615
Yakima River at Mabtom	46.23	-120.00	5359
Yakima River at Umtanum	46.86	-120.48	1594
Lewis River at Yale	45.96	-122.33	596
Yakima River near Parker	46.51	-120.45	3660