

Summary of Climate Change Effects on Major Habitat Types in Washington State

Freshwater Aquatic and Riparian Habitats

Produced by the Washington Department of Fish and Wildlife,
and the National Wildlife Federation

July, 2011



Climate Change Effects on Freshwater Aquatic and Riparian Habitats in Washington State

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PREFACE

This paper is intended as a reference document—a “science summary”— for the Ecosystems, Species, and Habitats Topic Advisory Group (TAG), which is one of four topic groups working with state agencies to prepare a statewide *Integrated Climate Change Response Strategy*. The climate change response strategy was initiated by the state legislature (SB 5560) to help the state adapt to climate change.

The purpose of this paper is to provide TAG members with information on potential climate change effects on fish, wildlife, habitats, and ecosystems in freshwater environments so as to inform the assessment of priorities and the development of recommendations about adaptation responses. The paper is intended to summarize and organize relevant literature regarding observed changes, future projections and implications for biological communities.

This document draws from synthesis reports, government publications, non-profit publications, and peer-reviewed studies. These include the two primary reference documents for the Integrated Climate Change Response Strategy, which are:

- *The Washington Climate Change Impacts Assessment: Evaluating Washington’s Future in a Changing Climate* (WACCIA) (CIG, 2009); and
- *Leading the Way: Preparing for the Impacts of Climate Change in Washington. Recommendations of the Preparation and Adaptation Working Groups* (PAWG, 2008).

This document is for discussion purposes only and is not intended to be published or cited. In many cases, this document uses language taken directly from the cited sources. Readers should refer to and cite the primary sources of information.

Please note that we accepted information as it was presented in synthesis reports. Readers may wish to return to the primary sources utilized in those synthesis reports for more information. In cases where we accepted the interpretation of primary information as it was stated in a secondary source, we have provided the following note in the footnote: “Information as cited in [secondary source].”

As with most summary or synthesis efforts, this document reports the central findings from published literature and typically does not address the inherent complexity and uncertainty that may be present. This is especially true of future projections, which are often based on multi-model ensembles that do not perfectly capture the complexity of Washington’s unique climate systems and geographic variability. These projections are valuable primarily to identify a directional trend and a sense of magnitude. As an example of the inherent uncertainty of future projections, the WACCIA notes that multi-model ensembles of global climate projections may under-represent the local severity of climate change.¹

This paper is a joint production of National Wildlife Federation and Washington Department of Fish & Wildlife. Dan Siemann and Erin Morgan led the effort from NWF and Ken Warheit led

¹ Salathé, et al. (2009) Regional climate model projections for the State of Washington. In: WACCIA

the effort from WDFW. This draft benefitted from the review and input of Doug Inkley (NWF) and many WDFW scientists, including John Kerwin, Casey Baldwin, Dan Ayres, Mara Zimmerman, Marc Hayes, Tim Quinn, John Pierce, Hal Beecher and David Price.

We must emphasize that this discussion draft is neither comprehensive nor complete. In this complex and rapidly evolving field, we do not expect that we have identified all of the most up-to-date data or presented the complexity of climate projections. In addition, there are many gaps in knowledge, especially regarding climate change effects on specific habitats or locations. Still, we hope that this provides a starting point for discussion, and that readers will augment this with additional data to advance our understanding of climate impacts and responses.

GLOBAL AND REGIONAL CLIMATE TRENDS

CO₂ Concentrations – *global trends*

Today's atmospheric carbon dioxide (CO₂) concentrations are approximately 385 parts per million (ppm).² Over the past 800,000 years, atmospheric CO₂ concentrations have varied between about 170 and 300 ppm.³ Today's concentrations are approximately 30 percent higher than the earth's highest level of CO₂ over that time period.⁴

Temperature – *global and regional trends and projections*

Global average temperature has risen approximately 1.5°F since 1900, and is projected to rise another 2°F to 11.5°F by 2100.⁵ In the Climate Impact Group's *Washington Climate Change Impacts Assessment* (WACCIA) (CIG, 2009), Mote and Salathe project that annual temperatures in the Pacific Northwest will increase 2.2°F on average by the 2020s and 5.9°F by the 2080s; these projections are compared to 1970 to 1999 and averaged across all climate models.⁶ Rates of warming range from 0.2°F to 1.0°F per decade.⁷ Warming is projected to vary by season; increased temperatures are projected to be most pronounced in summer.⁸

Precipitation – *regional projections*

In WACCIA, Mote and Salathe (CIG, 2009) state that projected changes in annual precipitation for the Pacific Northwest (averaged across all climate models) are small: +1 to +2%.⁹ However, some of the models used projected an enhanced seasonal cycle in precipitation, with changes toward wetter autumns and drier summers.¹⁰ For summer months, a majority of models projected decreases in precipitation, with the weighted average declining 16% by the 2080s.¹¹ Some

² Information as cited in Karl et al. (eds) (2009). *Global Climate Change Impacts in the United States*. (U.S. government report)

³ Ibid.

⁴ Ibid.

⁵ Information as cited in Karl et al. (eds) (2009). *Global Climate Change Impacts in the United States*. (U.S. government report)

⁶ Mote and Salathe. (2009). Future Climate in the Pacific Northwest. In: WACCIA (CIG, 2009).

⁷ Ibid.

⁸ Mote and Salathe. (2009). Future Climate in the Pacific Northwest. In: WACCIA (CIG, 2009).

⁹ Ibid.

¹⁰ Mote and Salathe. (2009). Future Climate in the Pacific Northwest. In: WACCIA (CIG, 2009).

¹¹ Ibid.

models predicted reductions of up to 20-40% in summer precipitation; these percentages translate to 3- 6 cm over the season.¹²

In winter, a majority of models projected increases in precipitation, with a weighted average value reaching +9% (about 3 cm) by the 2080s under their higher-emissions modeling scenario (A1B); this value is small relative to interannual variability.¹³ Although some of the models predicted modest reductions in fall or winter precipitation, others showed very large increases (up to 42%).¹⁴

CLIMATE CHANGE EFFECTS ON WASHINGTON'S HYDROLOGY

Nationwide, the effects of climate change are projected to include increasingly severe storms and floods in some places and increasing droughts in other places.¹⁵ Some locations are expected to be subject to each of these conditions during different times of the year.¹⁶

In parts of the United States, observations show that over the past several decades, extended dry periods have become more frequent.¹⁷ Longer periods between rainfalls, combined with higher air temperatures, dry out soils and vegetation and cause drought.¹⁸ At the same time, flooding has become more severe as the most intense rainfall events have increased in their intensity. Climate change is projected to continue these trends.¹⁹

Water runoff, which accumulates in streams, lakes, wetlands, and other basins and reservoirs, is the amount of precipitation that is not evaporated or stored as snowpack, soil moisture or groundwater.²⁰ Runoff generally tracks precipitation, but other climate factors influence runoff as well.²¹ For example, droughts cause soil moisture reductions that can reduce expected runoff until soil moisture is replenished.²² Conversely, water-saturated soils can generate floods with only moderate additional precipitation and runoff.²³ Water saturated soils can also contribute to mass wasting events and landslides.²⁴

Based on information found in WACCIA (CIG 2009), PAWG (2008) and Karl (2009), the major climate driven effects on Washington's hydrology appear to be:

- Reduced snowpack and altered runoff regimes
- Reduced summer streamflows

¹² Ibid.

¹³ Ibid.

¹⁴ Ibid.

¹⁵ Information as cited in Karl, et al. (2009) *Global Climate Change Impacts in the United States*

¹⁶ Ibid.

¹⁷ Ibid.

¹⁸ Ibid.

¹⁹ Information as cited in Karl, et al. (2009) *Global Climate Change Impacts in the United States*.

²⁰ Information as cited in Karl, et al. (2009) *Global Climate Change Impacts in the United States*.

²¹ Ibid.

²² Ibid.

²³ Ibid.

²⁴ J. Kerwin, WDFW (pers. comm.)

- Increased flooding
- Increased water temperature
- Increased water pollution
- Altered soil moisture
- Altered groundwater
- Reduced glacial size and abundance

The remainder of this section describes these effects on hydrology. A subsequent section examines the effects of climate change on selected freshwater and aquatic habitats, including rivers and streams; lakes ponds and reservoirs; and wetland habitats. Finally, the paper examines climate change effects on salmon in freshwater habitats in Washington State.

Reduced Snowpack and Altered Runoff Regimes

According to CIG's *Washington Climate Change Impacts Assessment* (WACCIA) the Cascade Mountains partition Washington into two distinct climatic regimes.²⁵ The region west of the Cascades receives an average of approximately 1,250 mm of precipitation annually, while the region to the east of the Cascades receives slightly more than one-quarter of this amount [i.e., slightly more than 312 mm].²⁶ [Note that WDFW reviewer commented that the wettest places in Eastern Washington are wetter than the driest places in Western Washington, and thus reporting only the average precipitation can be misleading. Presenting ranges of precipitation for each region would be preferable, but we did not find this information prior to distributing this draft.]

Washington relies on cool season precipitation (October through March) and resulting snowpack to sustain warm season streamflows (April through September).²⁷ Approximately 75% of the annual precipitation in the Cascades falls during the cool season.²⁸

Small changes in air temperature can strongly affect the balance of precipitation falling as rain and snow, depending on a watershed's location, elevation, and aspect.²⁹ Washington is often characterized as having three runoff regimes:³⁰

- **Snow-melt dominant:** In snowmelt dominant watersheds, much of the winter precipitation is stored in the snowpack, which melts in the spring and early summer resulting in low streamflow in the cool season and peak streamflow in late spring or early summer (May-July).³¹ Snowmelt dominant watersheds have average winter temperatures of less than 21°F.³² The Columbia River basin, which drains from mountainous regions in

²⁵ Elsner, et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*.

²⁶ Ibid.

²⁷ Ibid.

²⁸ Snover and Miles (in review), in Elsner, et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*.

²⁹ Elsner, et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*.

³⁰ Hamlet and Lettenmaier (2007), in Elsner, et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*.

³¹ Elsner, et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*.

³² Ibid.

mainly Canada, Idaho, Oregon, Wyoming, and Washington, is a characteristic snowmelt dominant watershed.³³

- **Rain dominant:** Rain dominant watersheds are typically lower in elevation, and occur mostly on the west side of the Cascades.³⁴ They receive little snowfall.³⁵ Streamflow in these watersheds peaks in the cool season, roughly in phase with peak precipitation (usually November through January).³⁶ Completely rain dominant watersheds have average [winter] temperatures above 41°F.³⁷ The Chehalis River basin, which drains to the Washington coast, is a characteristic rain dominant watershed.³⁸
- **Transient:** Transient watersheds are characterized as mixed rain-snow due to their mid-range elevation.³⁹ These watersheds receive some snowfall, some of which melts in the cool season and some of which is stored over winter and melts as seasonal temperatures increase.⁴⁰ Rivers draining these watersheds typically experience two streamflow peaks: one in winter coinciding with seasonal maximum precipitation, and another in late spring or early summer when water stored in snowpack melts.⁴¹ Transient watersheds have average [winter] temperatures between 21°F and 41°F.⁴² The Yakima River basin, which drains to the Columbia River, is a characteristic transient watershed.⁴³

Washington's runoff regimes are largely affected by snowpack, which is typically measured by the April 1 Snow Water Equivalent (SWE). SWE is defined as the liquid water content of the snowpack.⁴⁴ In the Pacific Northwest, SWE on April 1 is an important metric for evaluating snowpack changes because the water stored in the snowpack on April 1 is strongly correlated with summer water supply.⁴⁵

Observed Changes

Snowpack in the Pacific Northwest is highly temperature sensitive and observations show that April 1 snowpack has already declined substantially throughout the region.⁴⁶ Snover et al. (2005) report that April 1 snowpack (measured as snow water equivalent, or SWE) has declined markedly almost everywhere in the Cascades since 1950.⁴⁷ These declines exceeded 25 percent at most study locations, and tended to be largest at lower elevations.⁴⁸ Stoelinga et al. (in press)

³³ Ibid.

³⁴ Ibid.

³⁵ Ibid.

³⁶ Ibid.

³⁷ Ibid.

³⁸ Ibid.

³⁹ Ibid.

⁴⁰ Ibid.

⁴¹ Ibid.

⁴² Ibid.

⁴³ Ibid.

⁴⁴ Elsner, et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*.

⁴⁵ Ibid.

⁴⁶ Information as cited in Karl, et al. (2009) *Global Climate Change Impacts in the United States*.

⁴⁷ Information as cited in Snover et al. 2005. *Uncertain Future: Climate change and its effects on Puget Sound*. (CIG report)

⁴⁸ Ibid.

examined snowpack data over a longer time period (1930-2007) and concluded that snowpack loss occurred at a rate of approximately 2.0% per decade, yielding a 16% loss.⁴⁹

Snover et al. (2005) report that freshwater inflow to Puget Sound has changed over the period 1948-2003 in the following ways:⁵⁰

- A 13% decline in total inflow due to changes in precipitation
- A 12 day shift toward earlier onset of snowmelt
- An 18% decline in the portion of annual river flow entering Puget Sound during the summer
- An increase in the likelihood of both low and unusually high daily flow events.

Stoelinga et al. (in press) found that the dates of maximum snowpack and 90% melt-out have shifted 5 days earlier since 1930. Karl et al. (2009) state that the peak of spring runoff shifted from a few days to as many as 30 days earlier in the second half of the 20th century.⁵¹ While factors such as land use practices and natural cycles of ocean-atmospheric change may drive recent observations, these changes are also generally consistent with expected consequences of global climate change.⁵²

Future Projections

Relative to late 20th century averages (1971-2000), WACCIA projects that April 1 SWE will decrease by 27-29% across the state by the 2020's, 37-44% by the 2040's, and 53-65% by the 2080's.⁵³ A study by Stoelinga et al. (in press) predicts that cumulative loss of Cascade spring snowpack from 1985-2025 will be only 9%.⁵⁴

According to WACCIA, climate change effects on SWE are projected to vary by elevation:

- **Below 1,000 meters (< 3,280ft):** the lowest elevations will experience the largest decreases in snowpack, with reductions of 36% to 37% by the 2020s to 62% to 71% by the 2080s (for B1 and A1B emissions scenarios, respectively – for a brief explanation of these scenarios, see “Emissions Scenarios” box p.8);⁵⁵
- **Between 1,000 and 2,000 meters (3,280 ft – 6,558 ft):** The mid level elevations will experience relatively intermediate decreases in snowpack of 25% to 27% by the 2020s and 51% to 63% by the 2080s;⁵⁶

⁴⁹ Stoelinga, M.T. et al. (in press), *A New Look at Snowpack Trends in the Cascade Mountains*. (primary literature)

⁵⁰ Information as cited in Snover et al. 2005. *Uncertain Future: Climate change and its effects on Puget Sound*. (CIG report).

⁵¹ Information as cited in Karl et al. (eds) (2009), *Global Climate Change Impacts in the United States* (See Regional Climate Impacts: Northwest). (U.S. government report)

⁵² Information as cited in Snover et al. (2005). *Uncertain Future: Climate change and its effects on Puget Sound*. (CIG report)

⁵³ Elsner, M.M. et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*. In: WACCIA (CIG, 2009).

⁵⁴ Stoelinga, M.T. et al. (in press), *A New Look at Snowpack Trends in the Cascade Mountains*. (primary literature)

⁵⁵ Elsner, et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*.

⁵⁶ Ibid.

- **Above 2,000 meters (≥ 6,558 ft):** The highest elevations will experience the least significant decreases in snowpack of 15% to 18% by the 2020s and 39% to 54% by the 2080s.⁵⁷

Reduced Summer Streamflows—Future Projections

A changing climate may affect the balance of precipitation falling as rain and snow and therefore the timing of streamflow over the course of a year.⁵⁸ Throughout Washington State, climate change is projected to result, on average, in earlier snowmelt and reduced summer flows, patterns that are not well represented in historical observations.⁵⁹

The already low flows of late summer are projected to decrease further due to both earlier snowmelt and increased evaporation and water loss from vegetation.⁶⁰ Projected decreases in summer precipitation would exacerbate these effects.⁶¹

Loss of spring snowpack will lead to widespread reductions in the magnitude of summer low flows for Washington State’s rain dominant and transient runoff river basins in southwest Washington, the Olympic Peninsula, and Puget Sound.⁶² Future estimates of the annual average low flow magnitude (the 7 day average low flow magnitude with a 2 year return interval, or 7Q2) are projected to decline by 0%-50% by the 2080s under the A1B and B1 emissions scenarios.⁶³ 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%.⁶⁴ In most of the snowmelt dominated watersheds in the interior Columbia Basin, the magnitude of summer low flows are predicted to

A1B AND B1 EMISSIONS SCENARIOS*

The A1B and B1 emissions scenarios are two of many emissions scenarios used by the International Panel on Climate Change (IPCC) to model climate change effects in futures with different levels of fossil fuel reliance. In the WACCIA, Climate Impacts Group chose A1B as the higher emissions scenario and B1 as the low emissions scenario to analyze 21st Century Pacific Northwest climate.

The A1B scenario represents a future of rapid economic growth in which energy sources are balanced between fossil and non-fossil fuels (with the assumption that energy use efficiency will improve with the introduction of new technologies).

The B1 scenario represents a future in which global economies are less material-intensive and based more on information and services. Clean and resource-efficient technologies are introduced and an emphasis is placed on economic, social, and environmental sustainability.

The WACCIA notes that recent CO₂ emissions have exceeded even the high end emission scenario used by the IPCC (A1F1).

* Sources: IPCC. 2007. *AR4, Working Group 1: The Scientific Basis. Section F.1 Box 5*; and Mote and Salathe (2009).

⁵⁷ Ibid.

⁵⁸ Elsner, et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*.

⁵⁹ Vano, et al. (2009), *Climate change impacts on water management and irrigated agriculture in the Yakima River Basin, Washington, USA*.

⁶⁰ Information as cited in Karl, et al. (2009) *Global Climate Change Impacts in the United States*.

⁶¹ Ibid.

⁶² Mantua, et al. (2009) *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*.

⁶³ Ibid.

⁶⁴ Ibid.

be relatively insensitive.⁶⁵ However, the duration of the summer low flow period is projected to expand significantly in all watershed types.⁶⁶

Reduced spring snowpack and summer streamflows will strain Washington's ability to meet growing, and often competing, water demands such as municipal and industrial uses, agricultural irrigation, hydropower production, navigation, recreation, and in-stream flows that protect aquatic ecosystems including threatened and endangered species.⁶⁷

Puget Sound Basin Projections

In the transient rain-snow watersheds of Puget Sound, snowpack is projected to decrease and seasonal streamflow is projected to shift from having two seasonal peaks to a single peak - a characteristic of rain-dominant watersheds.⁶⁸ By the 2080s, April 1 snowpack in the watersheds will be almost entirely absent.⁶⁹ [In other words, over the next 70 years, Puget Sound will transition from a transient rain-snow regime to an almost completely rain-dominated regime.]

The lower elevation watersheds in Puget Sound will experience the most significant snowpack decreases. For example, even in the 2020s, the valleys of the Upper Cedar and Green watersheds are projected to experience approximately 90% reductions in SWE, although the Sultan and Tolt River basins, which are located in higher elevations in Puget Sound, are projected to experience smaller reductions in the 2020s.⁷⁰ However, by the 2080s, SWE is projected to disappear in all four basins.⁷¹

Peak SWE is also projected to occur earlier in the season. In four Puget Sound watersheds [Cedar, Sultan, Tolt, and Green river basins], peak SWE is projected to shift 3 weeks earlier by the 2020s, from near week 26 (late March), which is the average historical peak (based on data from the 1980s) to near week 23 (early March).⁷² By the 2080s it is projected to shift 6 weeks earlier to near week 20 (mid-February).⁷³

Simulated streamflow at the reservoirs in the four Puget Sound basins [Cedar, Sultan, Tolt, and Green river] shows a consistent shift in the hydrograph (a graph of water discharge) toward higher runoff in cool season and lower runoff in warm season.⁷⁴ In the future, the double-peak hydrograph transforms into a single-peak hydrograph associated with increasingly rain-dominant behavior. The streamflow timing shift is mainly due to less frequent snow occurrence, and faster and earlier snow melt in these historically snow-rain mixed watersheds.⁷⁵

⁶⁵ Ibid.

⁶⁶ Ibid.

⁶⁷ Information as cited in Karl, et al. (2009) *Global Climate Change Impacts in the United States*.

⁶⁸ Elsner, et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*.

⁶⁹ Ibid.

⁷⁰ Elsner, et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*.

⁷¹ Ibid.

⁷² Ibid.

⁷³ Ibid.

⁷⁴ Ibid.

⁷⁵ Ibid.

Yakima River Basin Projections

In the Yakima River basin, April 1 SWE is projected to decrease by 31 to 34% by the 2020s, 43 to 53% by the 2040s and 65 to 80% by the 2080s, as compared to the 1980s.⁷⁶ Changes in snowpack projected for the Yakima basin are higher than projected average changes over the State as a whole.⁷⁷ Peak SWE is projected to shift earlier by one week by the 2020s, from the historical average near week 24 (mid-March) to near week 23 (early to mid- March).⁷⁸ By the 2080s, peak SWE is projected to shift four weeks earlier, to near week 20 (mid-February).⁷⁹

Peak streamflow in the Yakima River basin historically occurs near week 34 (mid-May) at the USGS gage at Parker.⁸⁰ Projections for the 2020s indicate that the peak streamflow will not shift significantly; however, increased streamflow in winter is expected.⁸¹ By the 2040s, the spring peak streamflow is projected to shift four weeks earlier to near week 30 (mid- to late April) and a significant second peak flow is projected in the winter, which is characteristic of lower elevation transient watersheds.⁸² By the 2080s, a significant shift in the hydrologic characteristics of the watershed are projected, as the spring peak is lost and peak streamflow is projected to occur in the winter near week 20 (mid-February) which is more characteristic of rain dominant watersheds.⁸³ Thus, over the course of the next 70 years warming will likely cause the Yakima River basin to shift from a transient basin to a rain-dominant basin.⁸⁴

In the Yakima Basin, climate change is expected to cause continued decline in snowpack and earlier snowmelt resulting in reduced water supplies.⁸⁵ Recent studies show that the Washington Cascade Mountains, from which the Yakima River drains, are likely to lose about 12% to 20% of their April 1st snowpack with 1°C (1.8°F) of warming, and experience a 27% reduction with a 2°C (3.6°F) temperature increase over a base period 1981-2005.⁸⁶ In general, the basin will transition to earlier and reduced spring snowmelt as the century progresses.⁸⁷

Snowpack declines are expected to exacerbate existing water shortages in the Yakima basin. Due to changes in seasonal patterns of runoff, the system is projected to become increasingly unable to meet deliveries to junior water right holders, and these increased occurrences of curtailments for junior water right holders may be substantial even in the 2020s.⁸⁸ Historically, the Yakima basin has experienced water shortages (years in which substantial prorating of deliveries to

⁷⁶ Elsner, et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*.

⁷⁷ Ibid.

⁷⁸ Ibid.

⁷⁹ Ibid.

⁸⁰ Ibid.

⁸¹ Ibid.

⁸² Ibid.

⁸³ Ibid.

⁸⁴ Ibid.

⁸⁵ Vano, et al. (2009), *Climate change impacts on water management and irrigated agriculture in the Yakima River Basin, Washington, USA*.

⁸⁶ Casola et al. (2008) and Elsner et al. (2009), as cited in Vano, et al. (2009), *Climate change impacts on water management and irrigated agriculture in the Yakima River Basin, Washington, USA*.

⁸⁷ Vano, et al. (2009), *Climate change impacts on water management and irrigated agriculture in the Yakima River Basin, Washington, USA*.

⁸⁸ Vano, et al. (2009), *Climate change impacts on water management and irrigated agriculture in the Yakima River Basin, Washington, USA*.

junior water users was required) in 14% of years.⁸⁹ Without adaptations, for the A1B emission scenarios, water shortages that occur in 14% of years historically increase to 32% (15% to 54% range) in the 2020s, to 36% in the 2040s, and to 77% of years in the 2080s.⁹⁰ For the B1 emissions scenario, water shortages occur in 27% of years (14% to 54% range), in the 2020s, 33% for the 2040s and 50% for the 2080s.⁹¹ Furthermore, the historically unprecedented condition in which the senior water rights holders suffer shortfalls occurs with increasing frequency in both the A1B and B1 climate change scenarios.⁹² Economic losses include lost value of expected annual production in the range of 5% to 16% percent, with significantly greater probabilities of annual net operating losses for junior water rights holders.⁹³ Without adaptations, projections of the A1B emission scenarios indicate that this value may increase to 32% (with a range of 15% to 54% over ensemble members) in the 2020s, and may increase further to 36% in the 2040s, and 77% in the 2080s.⁹⁴

- Note: Reviewers commented that this discussion of drought projections and impacts to agriculture does not mention reservoir operation and capacity. Under recent climatic conditions, some snowmelt is captured in reservoirs and released after the unconstrained snowmelt has already travelled downstream. If annual precipitation and runoff do not change drastically, then managing runoff storage and release will become increasingly important.

Increased Flooding—Future Projections

An increase in winter rainfall (as opposed to snowfall) as a result of climate change is expected to lead to more winter flooding in relatively warm watersheds on the west side of the Cascades.⁹⁵ Flood conditions in Washington are currently triggered most frequently in December-May.⁹⁶ As the climate warms, flood frequency is projected to increase in January-March and decrease in April-May.⁹⁷ This shift in timing is projected to occur progressively from the 2020s through the 2080s.⁹⁸ In addition, flood conditions are projected to occur more frequently, primarily due to surface processes transitioning toward more winter dominated flow.⁹⁹ Projected flood frequency also increases progressively from the 2020s through the 2080s.¹⁰⁰ By the 2080s, the frequency with which flood conditions are triggered becomes considerably higher than in the 2020s and 2040s.¹⁰¹

Changes in flood magnitude and frequency are projected to differ across watersheds:¹⁰²

⁸⁹ Ibid.

⁹⁰ Ibid.

⁹¹ Ibid.

⁹² Ibid.

⁹³ Ibid.

⁹⁴ Ibid.

⁹⁵ Information as cited in Karl, et al. (2009) *Global Climate Change Impacts in the United States*.

⁹⁶ Vano, et al. (2009), *Climate change impacts on water management in the Puget Sound region, Washington, USA*.

⁹⁷ Ibid.

⁹⁸ Ibid.

⁹⁹ Ibid.

¹⁰⁰ Ibid.

¹⁰¹ Ibid.

¹⁰² Mantua, et al. (2009) *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*.

- **Transient:** Historically transient watersheds (those whose mean winter temperatures are within a few degrees of 32°F) are predicted to experience the most dramatic increases in flood magnitude and frequency as warmer temperatures cause a transition to rain-dominant conditions.¹⁰³
- **Rain-dominant:** These watersheds are predicted to experience small changes in flood frequency due to minimal change in snowmelt.¹⁰⁴
- **Snowmelt-dominant:** Washington’s coldest snowmelt-dominated basins, where mean winter temperatures in the historic period were < 23°F, are predicted to experience a reduction in flooding that has historically been observed during exceptionally heavy snowmelt periods in late-spring and early-summer.¹⁰⁵ Hydrological models indicate that warming trends will reduce snowpack, thereby decreasing the risk of springtime snowmelt-driven floods.¹⁰⁶

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.¹⁰⁷ 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.¹⁰⁸ The increases or decreases in flooding magnitude of each basin generally become larger, with the same sign (either positive or negative) from the 2020s to the 2080s, with the greatest impacts (either positive or negative) occurring at the end of the 21st century.¹⁰⁹

Increased Water Temperature—Recent Observations and Future Projections

Increased air temperatures lead to higher water temperatures, which have already been detected in many streams, especially during low-flow periods.¹¹⁰ In WACCIA, Mantua et al. analyze stream temperature data from 211 monitoring stations in Washington state (71 in western Washington and 140 in eastern Washington)¹¹¹ and provide the following findings:

- **Statewide:** By the 2020s the annual maximum weekly average water temperature (T_w) at most monitoring stations studied is projected to rise nearly 1° C (1.8° F).¹¹² By the 2080s locations on both the east and west side of the Cascades are projected to warm by 2° to 5° C (3.6° to 9° F).¹¹³ Projected increases in water temperatures proceed at about an equal pace on both sides of the Cascades.¹¹⁴
- **Eastern Washington:** In the 1980s, 30% of eastern Washington water temperature stations in the study had annual maximum T_w from 59.9° - 67.1° F, a category that

¹⁰³ Ibid.

¹⁰⁴ Ibid.

¹⁰⁵ Ibid.

¹⁰⁶ Ibid.

¹⁰⁷ Mantua, et al. (2009) *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*.

¹⁰⁸ Ibid.

¹⁰⁹ Ibid.

¹¹⁰ Information as cited in Karl, et al. (2009) *Global Climate Change Impacts in the United States*.

¹¹¹ Mantua, et al. (2009) *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*.

¹¹² Mantua, et al. (2009) *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*.

¹¹³ Ibid.

¹¹⁴ Ibid.

indicates an elevated risk of disease for adult salmon.¹¹⁵ By the 2080s, the fraction of stations in this compromised category declines to 19%, while the percentage of stations in higher stress categories increases by an equivalent amount.¹¹⁶ Shifts to increasingly stressful thermal regimes for salmon are predicted to be greatest for eastern Washington where the historical baseline for water temperatures are substantially warmer than those in western Washington.¹¹⁷

- **Columbia Basin:** Many of the interior Columbia Basin's water temperature stations modeled in this study have maximum weekly water temperatures that exceed 21° C (69.8° F).¹¹⁸ In reaches that typically host salmon in the warmest summer months these locations already have periods with episodes of extreme thermal stress for salmon.¹¹⁹ For instance, summer water temperatures in the mainstem Columbia River sometimes reach lethal limits for sockeye salmon, and frequently pose thermal migration barriers for fall Chinook and summer steelhead.¹²⁰
- **Western Washington:** In the 1980s, 44% of western Washington water temperature stations in the study had $T_w > 67.1^\circ \text{F}$.¹²¹ By the 2080s, the number of stations reporting $T_w > 67.1^\circ \text{F}$ was predicted to rise to approximately 50%.¹²²

Ecological Responses to Increased Water Temperature

In lakes and reservoirs, higher water temperatures can lead to longer periods of summer stratification (when surface and bottom waters do not mix).¹²³ Dissolved oxygen is reduced in lakes, reservoirs, and rivers at higher temperatures.¹²⁴ Oxygen is an essential resource for many living things, and its availability is reduced at higher temperatures both because the amount that can be dissolved in water is lower and because respiration rates of living things are higher.¹²⁵ Low oxygen stresses aquatic animals such as coldwater fish and the insects and crustaceans on which they feed.¹²⁶ Lower oxygen levels also decrease the self-purification capabilities of rivers.¹²⁷

- Note: reviewer commented that in addition to effects of water temperature on oxygen, increased temperatures will also increase metabolic rates and demand for oxygen, food, and consequently, space for many cold-blooded organisms. Interactions will be made more intense as reduced space (water flow and water volume) combine with higher metabolic needs.

¹¹⁵ Ibid.

¹¹⁶ Ibid.

¹¹⁷ Ibid.

¹¹⁸ Ibid.

¹¹⁹ Ibid.

¹²⁰ Information as cited in Mantua, et al. (2009) *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*.

¹²¹ Ibid.

¹²² Ibid.

¹²³ Information as cited in Karl, et al. (2009) *Global Climate Change Impacts in the United States*.

¹²⁴ Ibid.

¹²⁵ Ibid.

¹²⁶ Ibid.

¹²⁷ Ibid.

Increased Water Pollution—Future Projections & Ecological Responses

Increased precipitation intensity and longer periods of low summer streamflows are expected to exacerbate the negative effects of water pollution, including sediments, nitrogen from agriculture, disease pathogens, pesticides, herbicides, salt, and thermal pollution.¹²⁸

Heavy downpours lead to increased sediment in runoff.¹²⁹ Increases in pollution carried to lakes, estuaries, and the coastal ocean, especially when coupled with increased temperature, can result in blooms of toxic algae and bacteria.¹³⁰ However, pollution has the potential of being diluted in regions that experience increased streamflow.¹³¹ Note that toxic algal blooms in coastal waters may also be the natural result of circulation patterns that elevate nutrient inputs.¹³²

Altered Soil Moisture—Future Projections

Vegetation relies heavily on soil moisture, particularly in the arid region of the state where summer precipitation is low.¹³³ In snow dominated watersheds such as the Columbia River basin, soil moisture tends to peak in spring or early summer in response to melting mountain snowpack.¹³⁴ In the summer, lower precipitation (along with clearer and longer days) and increased vegetative activity cause depletion of soil moisture, resulting in minimum soil moisture values in September.¹³⁵

- Note: A reviewer commented that increased carbon dioxide levels may increase vegetative growth and hence soil moisture depletion.

Projected soil moisture changes differ on either side of the Cascade Mountains:¹³⁶

- **West of the Cascades:** In the mountains and coastal drainages west of the Cascades, climate warming tends to enhance soil drying in the summer and, in combination with reduced winter snowpack and earlier snowmelt, causes decreases in summer soil moisture.¹³⁷
- **East of the Cascades:** In Eastside watersheds, summer soil moisture is primarily driven by recharge of snowmelt water into the deep soil layers. Increased snowpack at the highest elevations in some parts of the Cascades (tied to projected increases in winter precipitation) and subsequently increased snowmelt, are likely to cause greater overall infiltration [i.e., increased soil moisture].¹³⁸

¹²⁸ Information as cited in Karl, et al. (2009) *Global Climate Change Impacts in the United States*.

¹²⁹ Ibid.

¹³⁰ Ibid.

¹³¹ Ibid.

¹³² MacFadyen et al. (2008), *Influences of the Juan de Fuca Eddy on circulation, nutrients, and phytoplankton production in the northern California Current system*.

¹³³ Elsner, et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*.

¹³⁴ Ibid.

¹³⁵ Ibid.

¹³⁶ Ibid.

¹³⁷ Ibid.

¹³⁸ Ibid.

To quantify projected changes in soil moisture, WACCIA presents future projections as percentiles of simulated historic mean soil moisture (1916-2006).¹³⁹ Projected decreases in soil moisture are represented by percentiles less than 50 and projected increases are represented by percentiles greater than 50.¹⁴⁰ July 1 soil moisture is presented because this is the typical period of peak soil moisture which is critical for water supply in the State's arid regions.¹⁴¹

Projections of July 1 total soil moisture change generally show decreases across the State.¹⁴² By the 2020s soil moisture is projected to decrease to the 38th to 43rd percentile (A1B and B1, respectively).¹⁴³ By the 2040s, soil moisture is projected to decrease to the 35th to 40th percentile, and by the 2080s, it is projected to decrease to the 32nd to 35th percentile, with 50% being equal to mean historical values.¹⁴⁴

- Note: A WDFW reviewer commented that for the plateau between the Columbia and Snake rivers and for southeastern Kittitas County, Benton County, and eastern Yakima County, soil moisture is primarily a function of in-situ snowmelt or other precipitation (except for riparian areas). Therefore, in these areas soil moisture will depend on precipitation and temperature on site.
- Note: WDFW reviewers commented that this document does not address changes in soil temperature and its potential effects on aquatic and riparian habitats. For example, a number of invertebrates and amphibians are specialists in riparian habitats and are adapted to narrow temperature ranges. These organisms may be important prey species and could be negatively impacted by changes in soil temperatures. According to reviewers, soil temperature represents a large data gap and is not monitored as consistently as other physical climate change parameters.

Altered Groundwater

In many locations, groundwater is closely connected to surface water and thus trends in surface water supplies over time affect groundwater.¹⁴⁵ Changes in the water cycle that reduce precipitation or increase evaporation and runoff would reduce the amount of water available for recharge.¹⁴⁶ Changes in vegetation and soils that occur as temperature changes or due to fire or pest outbreaks are also likely to affect recharge by altering evaporation and infiltration rates.¹⁴⁷ More frequent and larger floods are likely to increase groundwater recharge in semi-arid and arid areas, where most recharge occurs through dry streambeds after heavy rainfalls and floods.¹⁴⁸

Shallow groundwater aquifers that exchange water with streams are likely to be the most sensitive part of the groundwater system to climate change.¹⁴⁹ Small reductions in groundwater

¹³⁹ Ibid.

¹⁴⁰ Ibid

¹⁴¹ Ibid.

¹⁴² Ibid.

¹⁴³ Ibid.

¹⁴⁴ Ibid.

¹⁴⁵ Information as cited in Karl, et al. (2009) *Global Climate Change Impacts in the United States*.

¹⁴⁶ Ibid.

¹⁴⁷ Ibid.

¹⁴⁸ Ibid.

¹⁴⁹ Ibid.

levels can lead to large reductions in streamflow and increases in groundwater levels can increase streamflow.¹⁵⁰ Further, the interface between streams and groundwater is an important site for pollution removal by microorganisms.¹⁵¹ Their activity will change in response to increased temperature and increased or decreased streamflow as climate changes, and this will affect water quality.¹⁵² Like water quality, research on the impacts of climate change on groundwater has been minimal.¹⁵³

Sea-level rise is expected to increase saltwater intrusion into coastal freshwater aquifers, making some unusable without desalination.¹⁵⁴ Increased evaporation or reduced recharge into coastal aquifers exacerbates saltwater intrusion.¹⁵⁵ In some areas of Washington State saltwater intrusion is already a concern due to excessive pumping of the aquifers.¹⁵⁶ In a survey of wells in Island County, 9% showed positive indications of intrusion and 27% showed inconclusive indications of intrusion (the remainder, 64%, showed no indications of intrusion).¹⁵⁷ In preventing saltwater intrusion, an important factor is the water level in the area between the well and the shoreline, because saltwater intrusion would first occur along the shoreline and then move inland as the situation worsened.¹⁵⁸ In addition, aquifers that are at critically low water elevation are at risk of saltwater intrusion if there is continued groundwater withdrawal.¹⁵⁹ However, saltwater intrusion due to sea level rise will be a serious concern only in a very narrow range along the coast, where the freshwater lens is already very shallow.¹⁶⁰ Saltwater intrusion is not a major risk for Washington State aquifers.¹⁶¹

Reduce Glacial Size and Abundance

Glaciers support a unique runoff regime and have been studied as sensitive indicators of climate for more than a century.¹⁶² Glaciers respond to climate by advancing with climate cooling and snowfall increase and retreating with climate warming.¹⁶³ The primary long-term climate trends that affect glaciers are changes in mean ablation-season temperature [i.e., the warm summer season, typically May-September] and winter-season snowfall.¹⁶⁴ *Ablation* refers to a reduction in the volume of glacial ice as a result of melting, evaporation, and calving.

Monitoring has occurred on several glaciers in Washington, including the South Cascade Glacier, Mount Rainier glaciers, and the Blue Glacier in the Olympic Mountains.¹⁶⁵ Some of the

¹⁵⁰ Ibid.

¹⁵¹ Ibid.

¹⁵² Ibid.

¹⁵³ Ibid.

¹⁵⁴ Ibid.

¹⁵⁵ Ibid.

¹⁵⁶ Huppert, et al. (2009), *Impacts of climate change on the coasts of Washington State*.

¹⁵⁷ Island County Environmental Health, (2005) as cited in Huppert, et al. (2009), *Impacts of climate change on the coasts of Washington State*.

¹⁵⁸ Huppert, et al. (2009), *Impacts of climate change on the coasts of Washington State*.

¹⁵⁹ Kelly, 2005, cited in Huppert, et al. (2009), *Impacts of climate change on the coasts of Washington State*.

¹⁶⁰ Huppert, et al. (2009), *Impacts of climate change on the coasts of Washington State*.

¹⁶¹ Ibid.

¹⁶² Pelto 2008

¹⁶³ Pelto 2006

¹⁶⁴ Ibid.

¹⁶⁵ Pelto 2006

longest Washington-based studies on changes in glacial thickness and extent have been conducted in the North Cascades. The North Cascades extend from Snoqualmie Pass north to the Canadian Border, and are host to 700 glaciers that cover 250 km² (~97 mi²) and yield 800 m³ (~28,252 ft³) of runoff each summer.¹⁶⁶

Glaciers in the North Cascades exhibit consistent responses to climate from year to year.¹⁶⁷ In most years, all glaciers respond in step with each other to variations in winter precipitation and summer temperature.¹⁶⁸ A decline in winter snowpack, due primarily to rising winter temperatures in the Pacific Northwest, has been observed in the North Cascades since 1976.¹⁶⁹ The following changes have also been observed in the past century in the North Cascades:

- A 0.6°C (1.08°F) increase in summer temperatures.¹⁷⁰
- 0.9°C (1.62°F) increase in winter temperatures.¹⁷¹
- A minor increase in precipitation.¹⁷²

The response time of North Cascade glaciers to climate change is comparatively short: 5-20 years for the initial response to a change in climate, and 30-100 years for a response that begins to approach equilibrium.¹⁷³ Because glaciers monitored in the North Cascades do not lose significant mass by calving or avalanching, the changes observed are primarily a function of winter accumulation and summer ablation on the glacier's surface.¹⁷⁴ Climate warming has reduced April 1 winter snowpack, decreased summer alpine streamflow, and placed some glaciers in jeopardy of completely melting away.¹⁷⁵ In fact, 53 glaciers in the North Cascades are reported to have disappeared since the 1950s.¹⁷⁶ These changes are discussed further in the sections below.

Changes in April 1 Snow Water Equivalent (SWE)

The mean April 1 SWE in the North Cascades in 2005 at USDA SNOTEL monitoring locations was the lowest since 1984.¹⁷⁷ The record indicated that April 1 SWE declined by 25% at five long-term monitoring stations in the North Cascades since 1946, whereas winter-season precipitation declined by only 3% at these stations.¹⁷⁸ Thus, most of the loss in winter SWE reflects increased melting of the snowpack or rain events during the winter season, leading to more winter melt and less snowpack accumulation.^{179,180} Although annual variability is high, the following trends were observed between 1946 and 2005:

¹⁶⁶ Information as cited in Pelto 2008

¹⁶⁷ Pelto 2008

¹⁶⁸ Pelto 2008

¹⁶⁹ Pelto 2008

¹⁷⁰ Information as cited in Pelto 2008

¹⁷¹ Information as cited in Pelto 2008

¹⁷² Information as cited in Pelto 2008

¹⁷³ Information as cited in Pelto 2006

¹⁷⁴ Pelto 2006

¹⁷⁵ Information as cited in Pelto 2008

¹⁷⁶ Ecology publication <http://www.ecy.wa.gov/pubs/0711016.pdf>

¹⁷⁷ Pelto 2006

¹⁷⁸ Pelto 2006

¹⁷⁹ Pelto 2006

- Summer temperatures exceeded 16°C (60.8°F) during four years from 1946 to 1983 (a span of 37 years), but exceeded the same mark nine years from 1984-2005 (a span of 21 years).¹⁸¹
- SWE reached the 1.5m water equivalent ten years from 1946-1983, but only two years from 1984-2005.¹⁸²

Changes in Glacial Extent

The current climate favors glacier retreat, as glaciers attempt to reach a new point of equilibrium.¹⁸³ However, the recent loss of several glaciers in the North Cascades raises the question as to whether glaciers can reach a new point of equilibrium with the current climate.¹⁸⁴ There are several ways to document changes in glacial extent, including calculations of mass balance, changes in a glacier's terminus, and characterization of a glacier's longitudinal profile.

Mass balance and longitudinal profiles: Measurements of surface mass balance (i.e., the difference between accumulation of water in winter and loss of water by ablation in summer) the most sensitive indicator of short-term glacier response to climate change.¹⁸⁵ Studies in the North Cascades for the period between 1984 and 2006 by Pelto (2006) and Pelto (2008) found that cumulative mass balance for the North Cascade glaciers is becoming increasingly negative, indicating that, instead of approaching equilibrium as the glaciers retreat, they are experiencing increasing disequilibrium with current climate.¹⁸⁶ Specifically:

- The mean cumulative mass balance loss was -12.4 m water equivalent, which is a minimum of 14.0 m (~46 feet) of glacier thickness lost.¹⁸⁷ This equates to 20-40% loss in glacier volume since 1984, given an average glacier thickness of 30-60 m (~98-197 feet).^{188,189}
- Longitudinal profiles completed in 2005 found that 10 of 12 glaciers examined were thinning dramatically along their entire length; this supports the conclusion that these North Cascade glaciers are in disequilibrium with current climate.¹⁹⁰

Glacial termini and thickness: Pelto (2008) found thinning occurring in the accumulation zone of some North Cascades glaciers, which indicates that a given glacier no longer has a substantial consistent accumulation zone (the accumulation zone is the region of the glacier that even at the end of summer melt season still retains snowpack from the winter season).¹⁹¹

¹⁸⁰ Pelto 2008

¹⁸¹ Pelto 2006

¹⁸² Pelto 2006

¹⁸³ Pelto 2006

¹⁸⁴ Information as cited in Pelto 2006

¹⁸⁵ Pelto 2006

¹⁸⁶ Pelto 2006

¹⁸⁷ Pelto 2008

¹⁸⁸ Pelto 2006

¹⁸⁹ Information as cited in Pelto 2006

¹⁹⁰ Pelto 2006

¹⁹¹ Pelto 2008

Pelto (2006) found that Easton Glacier was exhibiting the greatest thinning at its terminus; this suggests that it may be capable of retreating to a new stable position.¹⁹² However, Lower Curtis and Columbia Glaciers exhibited a more unstable form of retreat, where the accumulation zone itself was experiencing substantial thinning.¹⁹³ This observation, in conjunction with the observed terminus retreat, suggested that the entire glacier was out of equilibrium.¹⁹⁴ These two glaciers seem unlikely to be able to survive in anything like their present extent, given the current climate.¹⁹⁵

Additional findings by Pelto (2006) and Pelto (2008) include:

- Between 1979 and 1984, 35 of the 47 North Cascade glaciers observed annually had begun retreating.¹⁹⁶
- By 1992, all 47 glacier termini observed were retreating.¹⁹⁷
- By 2004, four glaciers had disappeared.¹⁹⁸
- Easton Glacier lost 46 m (~151 feet) of ice thickness since 1916, and 13 m (~43 feet) from 1984 to 2002.¹⁹⁹
- Lower Curtis Glacier lost 45 m (~148 feet) of ice thickness from 1908 to 1984, and an additional 6 m (~20 feet) from 1984 to 2002.²⁰⁰
- On Columbia Glacier, the ice thickness loss from 1911 to 1984 was 57 m (~187 feet), 11 m (~36 feet) from 1965 to 2002, and 8 m (~26 feet) from 1984 to 2002.²⁰¹ The glacier retreated 72 m (~236 feet) at its head and 119 m (~390 feet) at its terminus from 1984-2005.²⁰²
- From 1984-2005, Ice Worm Glacier retreated 165 m (~541 feet) at its head and 144 m (~472 feet) at its terminus.²⁰³
- 75% of the North Cascade glaciers observed (9/12) were thinning appreciably in the accumulation zone and were in disequilibrium with current climate.²⁰⁴

Overall, Pelto (2006) states that glacial retreat is ubiquitous, rapid and increasing.²⁰⁵ The study found no evidence that North Cascade glaciers are close to equilibrium.²⁰⁶ Their ongoing thinning indicates that all of the glaciers will continue to retreat in the foreseeable future.²⁰⁷ In

¹⁹² Pelto 2006

¹⁹³ Pelto 2006

¹⁹⁴ Pelto 2006

¹⁹⁵ Pelto 2006

¹⁹⁶ Pelto 2006

¹⁹⁷ Information as cited in Pelto 2006

¹⁹⁸ Pelto 2006

¹⁹⁹ Pelto 2006

²⁰⁰ Pelto 2006

²⁰¹ Information as cited in Pelto 2006

²⁰² Pelto 2008

²⁰³ Pelto 2008

²⁰⁴ Pelto 2008

²⁰⁵ Pelto 2006

²⁰⁶ Pelto 2006

²⁰⁷ Pelto 2006

cases where the thinning is substantial along the entire length of the glacier, no point of equilibrium can be achieved with present climate and the glacier is unlikely to survive.²⁰⁸

Changes in Alpine Streamflow

Glaciers are key sources of alpine summer streamflow and a critical water supply source in the North Cascades.²⁰⁹ The volume and timing of runoff in ice-covered areas of glacierized basins differs from ice-free areas.²¹⁰ The duration of snow cover is much longer and stable in ice-covered areas.²¹¹ In these locations, runoff correlates positively with temperature and negatively with precipitation.²¹² In years that are warm and dry, ice-free areas may experience a decrease in runoff due to the decrease in precipitation.²¹³ However, increased icemelt in ice-covered areas can augment runoff and compensate for this deficit.²¹⁴ In colder, wetter years, glacial melt decreases and runoff in ice-free areas increases due to an increase in precipitation and decrease in evaporation.²¹⁵ Glaciers can therefore function as “reservoirs” that dampen extreme runoff events.²¹⁶

In the North Cascades these natural reservoirs are shrinking rapidly, as is the summer runoff they provide.²¹⁷ The following changes have been observed in streamflow patterns as a result of changes in runoff:

- North Cascades alpine streamflow has increased 18% in the winter from 1963-2003 due to increased snow melt and the extent and frequency of rain events in the alpine zone.²¹⁸
- Mean spring streamflow has increased by only 1% in the alpine basins.²¹⁹
- Mean summer streamflow declined 20%.²²⁰

Stream hydrographs in glacial basins generally demonstrate less seasonal fluctuation than streams in non-glacial basins, because glaciers can contribute water during dry periods via melting, or store water during wet periods via snow accumulation.²²¹ However, as North Cascade glaciers continue to retreat and the area available for melting declines, overall glacier runoff will decline, providing less of a buffer during low summer streamflow.²²²

²⁰⁸ Pelto 2006

²⁰⁹ Information as cited in Pelto (2008), *Impact of climate change on North Cascade alpine glaciers, and alpine runoff*.

²¹⁰ Chen and Ohmura (1990), *On the influence of Alpine glaciers on runoff*.

²¹¹ Ibid.

²¹² Information as cited in Chen and Ohmura (1990), *On the influence of Alpine glaciers on runoff*.

²¹³ Chen and Ohmura (1990), *On the influence of Alpine glaciers on runoff*.

²¹⁴ Ibid.

²¹⁵ Ibid.

²¹⁶ Ibid.

²¹⁷ Pelto 2008

²¹⁸ Pelto 2008

²¹⁹ Pelto 2008

²²⁰ Pelto 2008

²²¹ Pelto 2008

²²² Pelto 2008

For example, warmer spring conditions have resulted in a 28% decrease in runoff in the non-glacier Newhalem Creek due to earlier melt and reduced winter snowpack.²²³ In contrast, in the glacierized Thunder Creek, runoff has only decreased by 3%.²²⁴ The difference is due in part to enhanced glacier melting.²²⁵ Glaciers contribute 35-45% of Thunder Creek's summer streamflow.²²⁶ The increased glacier melting resulting in reduced glacier volume from 1984-2004 has enhanced summer streamflow and offset a significant portion of the summer streamflow reduction observed in non-glacier basins.²²⁷ However, at some point the reduction in glacier area will exceed the increase in melting per unit area, meaning that glacier runoff will decline even with higher melt rates.²²⁸

In addition to changes in the volume of glacial runoff, a significant change in the timing of peak spring streamflow events from alpine streams has also been observed since 1950.²²⁹ For example, during a period of glacier equilibrium from 1950-1975, summer snowmelt events in glacier-dominated Thunder Creek accounted for 17 of the 26 highest peak flows.²³⁰ However, from 1984-2004, eight of the thirteen yearly peak flow events resulted from winter rain on snow melt.²³¹ The observed changes represent significant shifts in the annual hydrologic cycle in the alpine zone and alpine fed watersheds in the North Cascades.²³²

Discussion

Pelto (2008) states that continued glacier retreat is inevitable, and that the loss of glacier area will lead to further declines in summer runoff in glacier-fed rivers as the glacier area available for melting in the summer declines.²³³ Halofsky et al. (in press) affirm that the loss of glaciers, decreased snowpack, and earlier snowmelt with warming temperatures will reduce water availability in summer months in glacier- and snowmelt-fed streams, lakes, and wetlands.²³⁴ Although glaciers and snow fields currently provide habitat for only a few species, the loss of snowpack with warming may allow vegetation establishment in these areas, leading to improved habitat conditions for other high elevation wildlife species.²³⁵ In the short term, vegetation establishment will be limited to areas with substrate that is favorable to rapid soil development, such as shallow-gradient slopes with deep layers of fine-grained glacial till.²³⁶

- Note: Reviewers commented that Washington has no purely glacial streams; they are mixed with snowmelt-dominant and even some transient areas. Glacial streams have more extended summer flow and less drastic low flows. Typically they are turbid in

²²³ Pelto (2008), *Impact of climate change on North Cascade alpine glaciers, and alpine runoff*.

²²⁴ Ibid.

²²⁵ Ibid.

²²⁶ Information as cited in Pelto (2008), *Impact of climate change on North Cascade alpine glaciers, and alpine runoff*.

²²⁷ Pelto (2008), *Impact of climate change on North Cascade alpine glaciers, and alpine runoff*.

²²⁸ Pelto 2008

²²⁹ Pelto 2008

²³⁰ Pelto 2008

²³¹ Pelto 2008

²³² Pelto 2008

²³³ Pelto 2008

²³⁴ Information as cited in Halofsky et al. (in press)

²³⁵ Halofsky et al. (in press)

²³⁶ Halofsky et al (in press)

summer and clear in winter, unlike snowmelt-dominant streams. Glaciers are locally important in some basins, such as tributaries to the Skagit and Wenatchee. Glacial streams in western Washington have supported spring Chinook salmon and bull trout more than some other stream types have.

CLIMATE CHANGE EFFECTS ON FRESHWATER HABITATS

Every species has a temperature range in which it thrives and a range in which it can survive.²³⁷ Extreme temperature events, whether acute or chronic, can stress plants and animals.²³⁸ Such stressors can exacerbate pressures from competition, predation, invasive species, habitat change, diseases, contaminants, and habitat fragmentation.²³⁹ If average temperatures continue to rise as a result of climate change, plant and animal species may be confronted by thermal stress to which they cannot adapt.²⁴⁰ This will force plant and animal species to shift to new habitats to avoid high temperatures, or be extirpated.²⁴¹

Unfortunately, many aquatic species are limited in their ability to migrate.²⁴² For example, vernal pool and freshwater lake species are likely to be more susceptible to extirpation because their habitats could completely dry up.²⁴³ In addition, fish and amphibian species will experience increased stream and lake temperatures that will affect their food supply and fitness.²⁴⁴ Warmer air and water conditions could also influence the introduction and spread of undesirable species and/or pathogens and their associated diseases.²⁴⁵ These are only a few of the effects that could result from a changing climate.

This section describes natural disturbance regimes, existing anthropogenic effects and projected climate change effects on freshwater habitats in Washington State. Some sub-sections draw solely from a single source, and where this occurs, that source is referenced in the section header.

Climate Change Effects on Rivers and Streams

USGS has identified 24 major river basins within Washington State, including major rivers such as the Columbia, Snake, and Chehalis.²⁴⁶ The Washington Dept. of Ecology has identified 62 Water Resource Inventory Areas (WRIAs) that include both river basins and clusters of independent streams.

²³⁷ California Natural Resources Agency (2009), *California Climate Adaptation Strategy*.

²³⁸ Ibid.

²³⁹ Ibid.

²⁴⁰ Ibid.

²⁴¹ Ibid.

²⁴² California Natural Resources Agency (2009), *California Climate Adaptation Strategy*.

²⁴³ Ibid.

²⁴⁴ Ibid.

²⁴⁵ Ibid.

²⁴⁶ USGS (2008), *Washington State River Basins*. (website)

Increases in air temperature will result in increased water temperatures in many streams and rivers, thereby altering ecological processes and species distributions.²⁴⁷ For example, the lifecycles of many aquatic organisms depend on temperature, and warmer water could increase organism growth rates and ecosystem production.²⁴⁸ If food is not limiting, invertebrate populations in streams and rivers may increase and provide a larger food source for fish.²⁴⁹ However, warmer temperatures may also increase the rate of decomposition, which could affect the amount of food available for invertebrates and fish.²⁵⁰ Temperatures can also control the timing of biological events such as reproduction and development (i.e., phenology). Poff et al. (2002) cite an example of invertebrates in far northern rivers of the United States that require prolonged periods of near freezing temperatures in winter, followed by rapid increases in spring temperature, in order for eggs to hatch. River temperature is also a main determinant of community composition, and a general increase in temperature could cause communities to migrate upstream, or invasive species to spread.²⁵¹

Species that occupy habitats at the southern limit of their temperature range will likely need to move northward or to higher elevation to find thermally-suitable habitat and avoid extirpation.²⁵² Their ability to do so (and hence vulnerability to temperature change) will depend on their method of migration and the availability and connectivity of movement corridors.²⁵³ For example, some fish populations may be able to move upstream into headwater areas that are generally cooler.²⁵⁴ In Eastern Washington, steelhead currently barred from using the Chiwawa River due to cool temperatures may be able to expand their range into this relatively pristine habitat if temperatures warm.²⁵⁵ In contrast, fish populations already occupying headwater areas may decline as no further upstream habitat exists.²⁵⁶ These challenges, combined with other restrictions on movement (e.g., fragmented habitat, dams, etc.), could result in an overall reduction in abundance or biodiversity within a watershed.²⁵⁷

Poff et al. (2002) cite a U.S. study that examined the effect of a 7.2°F increase in air temperature on stream temperatures and fish habitat. The study estimated increases in maximum weekly water temperatures as a result of air temperature increases, and determined the effect on thermally-suitable habitat for fish species.²⁵⁸ The authors of that study found that thermally-suitable habitat for 57 fish species that require cold or cool water (including trout, salmon, and perch) would decline by about 50%.²⁵⁹ In particular, Poff et al. (2002) point out that trout and salmon will be vulnerable to climate warming; in contrast, habitat for species that flourished in extremely warm water was predicted to increase. Some fish populations may survive by moving

²⁴⁷ Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change*.

²⁴⁸ Ibid.

²⁴⁹ Ibid.

²⁵⁰ Ibid.

²⁵¹ Euro-Limpacs (N.D.), *Climate Change and Freshwater* (website).

²⁵² Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change*.

²⁵³ Ibid.

²⁵⁴ Ibid.

²⁵⁵ Casey Baldwin, WDFW (pers. comm.)

²⁵⁶ Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change*.

²⁵⁷ Ibid.

²⁵⁸ Information as cited in Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change*.

²⁵⁹ Information as cited in Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change*.

into cool-water refuges fed by groundwater, or by moving northward or into higher elevations in places where temperatures currently limit their range.²⁶⁰

- Reviewers noted that most studies on lethal temperatures for fish are done with constant temperature changes. This differs from real river temperatures, which fluctuate on a daily basis. Salmonids tend to react to changes in mean temperatures rather than extreme daily temperatures.
- Reviewers noted that climate change could also result in shifts in life history characteristics, e.g., in steelhead. Fitness advantages could shift from resident fish to anadromous or vice versa.
- Reviewers noted that there are cases where warming could expand a species' range. For example, the Chiwawa River in eastern Washington has about 25 miles of high quality habitat that currently is not used by steelhead for spawning. If April water temperatures warmed, this habitat might be available for spawning and become a productive fish habitat.

In addition to warming temperatures, species will respond to changes in magnitude and timing of events associated with changing precipitation patterns. Seasonal patterns of precipitation and runoff influence species composition and productivity in aquatic and wetland areas.²⁶¹ In snowmelt-dominated areas, the lifecycles of many species have evolved around predictable springtime peak flows whereas, in rain dominant areas, species life cycles have evolved around predictable wintertime peak flows.²⁶² Thus, geographically distinct populations of the same species may be differentially adapted to watershed-specific flow patterns.²⁶³

For example, the timing and spatial distribution of fish spawning activities may minimize the cost and maximize the benefits of high flow events.²⁶⁴ Negative impacts of high flow events include scouring of the streambed and increased siltation that destroys fish eggs or involuntarily displaces fry.²⁶⁵ In contrast, fish species that spawn during the winter months, such as Coho salmon and winter steelhead, depend on high flow events to reach the upper extents of their spawning habitat.²⁶⁶ If the timing of peak flow events in current snowmelt-dominated systems shifts to an earlier timing, the impacts may be negative for fall spawning species (with eggs in the gravel during winter months) but positive for winter spawning species that rely on flows to access spawning habitats.²⁶⁷ Reductions in spring flow events predicted for snowmelt-dominated systems will likely have negative impacts on other organisms that rely on high spring flows.²⁶⁸

If warmer temperatures produce a shift from snow to rain in higher or more northerly basins, this could reduce summer base flows in streams; in turn, habitat for invertebrates and fish would decrease and there would be less recharge into riparian groundwater tables that support tree

²⁶⁰ Information as cited in Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change*.

²⁶¹ Information as cited in Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change*.

²⁶² Mara Zimmerman, WDFW (pers. comm.)

²⁶³ Mara Zimmerman, WDFW (pers. comm.)

²⁶⁴ Information as cited in Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change*.

²⁶⁵ Mara Zimmerman, WDFW (pers. comm.)

²⁶⁶ Mara Zimmerman, WDFW (pers. comm.)

²⁶⁷ Mara Zimmerman, WDFW (pers. comm.)

²⁶⁸ Mara Zimmerman, WDFW (pers. comm.)

communities.²⁶⁹ Some areas may dry into small pools, crowding the remaining organisms or even killing organisms that cannot withstand longer dry periods.²⁷⁰ For example, summer low flows are an important limiting factor for Coho salmon production.²⁷¹ In addition, lower water levels could expose organisms to harmful U.V. radiation.²⁷² Finally, reduced flows could cut fish off from floodplain habitat, reduce nutrient inputs from floodplain wetlands, and reduce aquatic productivity and diversity.²⁷³

Water quality is also expected to decline as a result of climate change. Since less oxygen dissolves in warmer water, water quality will decline for aquatic organisms that have a high oxygen demand.²⁷⁴ In addition, alterations in the magnitude and timing of precipitation could result in shifts in flood magnitude and frequency.²⁷⁵ This could increase the input of nutrients and pollutants into water sources, degrading water quality and contributing to species decline.²⁷⁶

Climate Change Effects on Lakes, Ponds, and Reservoirs

Lakes and ponds are inland bodies of freshwater that are naturally formed by processes such as glacial retreat. Major lakes in Washington include Lake Washington, Lake Chelan, and Lake Ozette. Although there is no precise definition delineating lakes from ponds, lakes are generally larger and deeper, such that sunlight cannot penetrate to the bottom and waters stratify due to temperature differences in the summer.²⁷⁷ Reservoirs are similar to lakes but are constructed by humans, and levels are generally controlled by an outlet at a dam (e.g. Lake Roosevelt). Natural lakes that have been dammed may also function as partial reservoirs.

The consequences of climate change for a given lake, pond, or reservoir will depend on the physical and chemical features of the ecosystem, which are driven by qualities such as water depth, atmospheric heat absorption, nutrient supply from the watershed, and water residence time.²⁷⁸ Temperature increases could have a variety of effects on lakes. First, climate change expressed by increased water temperatures is expected to enhance the symptoms of eutrophication through increases in primary production and declines in oxygen storage capacity.²⁷⁹ For example, warming may increase the potential for the production of nuisance algae and eliminate deep, cool refuge areas for large fish.²⁸⁰ Lakes may experience a longer stratification period in summer and a single circulation period in winter.²⁸¹ This could enhance eutrophication and lead to oxygen depletion in deep zones during summer, eliminating refuges

²⁶⁹ Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change*.

²⁷⁰ Ibid.

²⁷¹ Mathews and Olson. 1980. *Factors affecting Puget Sound coho salmon (Oncorhynchus kisutch) runs*.

²⁷² Ibid.

²⁷³ Ibid.

²⁷⁴ Ibid.

²⁷⁵ Ibid.

²⁷⁶ Ibid.

²⁷⁷ New Hampshire Dept. of Environmental Services (2003), *Environmental Fact Sheet: Lake or Pond – What is the Difference?*

²⁷⁸ Ibid.

²⁷⁹ Ibid.

²⁸⁰ Ibid.

²⁸¹ Euro-Limpacs (N.D.), *Climate Change and Freshwater* (website).

for coldwater-adapted fish species.²⁸² Water quality may also decline if changes in the amount and timing of precipitation produce an increase in nutrients, sediments, and pollutants entering a lake.²⁸³

Poff et al. (2002) note that in some areas, small eutrophic lakes remain hypoxic in winter because ice cover prevents oxygenation from the atmosphere. In these locations, warming may actually enhance fish survival by reducing ice cover.²⁸⁴

Lake levels may change directly as a result of climate. In areas that become drier, lake levels would be expected to drop, while in wetter areas levels may actually rise.²⁸⁵ Declining lake levels could expose littoral habitats, reduce water to lake fringe wetlands, and reduce available habitat for fish and other organisms.²⁸⁶ In areas where summer inflows decline, dissolved nutrients may remain longer in lakes, increasing productivity and likely contributing to algal blooms.²⁸⁷

The ranges of fish and other aquatic species may shift as a result of warming; however, actual migrations will require dispersal corridors that are available and accessible to these populations.²⁸⁸ For example, warm-water fish may move into northern lakes via connecting streams and support a more diverse or productive fishery. However, this could also result in unexpected interactions among new species assemblages.²⁸⁹

Climate Change Effects on Wetland Habitats

Wetlands generally occur in areas where surface runoff is slow, water infiltration is restricted, or ground water is discharging. In other words, wetlands occur in places where water collects on or near the land surface long enough for aquatic communities to develop.²⁹⁰ The patterns of water depth and the duration, frequency, and seasonality of flooding characterize the hydrologic regime of a wetland.²⁹¹ In turn, patterns of “wetness” strongly influence vegetation and faunal community composition.²⁹² Regional wetland types range from wet meadows and forested wetlands to fens, bogs, slope wetlands, seeps, and riparian wetlands, among others.²⁹³

²⁸² Ibid.

²⁸³ Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change*.

²⁸⁴ Ibid.

²⁸⁵ Ibid.

²⁸⁶ Ibid.

²⁸⁷ Ibid.

²⁸⁸ Ibid.

²⁸⁹ Ibid.

²⁹⁰ Winter (2000), *The vulnerability of wetlands to climate change: a hydrologic landscape perspective*.

²⁹¹ Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change*.

²⁹² Ibid.

²⁹³ U.S. Army Corps of Engineers (2008) *Interim Regional Supplement to the Corps of Engineers Wetland Delineation Manual: Western Mountains, Valleys, and Coast Region*. US ACoE: Washington D.C. ERDC/EL TR-08-13. 154 pp. Available online at: <
http://www.usace.army.mil/CECW/Documents/cecwo/reg/west_mt_intersupp.pdf>

The U.S. Congress, Office of Technology Assessment (1993) identifies three main ways that climate change could affect wetlands: increases in temperature, changes in precipitation and soil moisture, and increases in carbon dioxide.

- First, increases in air temperature could result in faster rates of evaporation and transpiration. This would cause a decline in water inputs and water availability within a wetland unless rainfall also increased.²⁹⁴ Drying would likely occur first at the edges of wetlands, reducing their size or extent.²⁹⁵ Warmer temperatures could also increase decomposition rates, changing the amount of organic material stored in a wetland as well as nutrient availability.²⁹⁶ Warmer temperatures may increase the susceptibility of seasonal wetlands to drought and fire, which would decrease vegetation and habitat.²⁹⁷ Alternatively, warmer temperatures could boost productivity by lengthening the growing season;²⁹⁸ however, this could also alter species' growth and reproduction.²⁹⁹
- Second, changes in precipitation and soil moisture are also likely to affect wetlands. Areas that become drier could experience greater disturbance (i.e., reduction in area) than those that become wetter. Changes in hydrology could also influence wetland productivity and important processes such as decomposition and nutrient cycling.³⁰⁰
- Finally, although carbon dioxide could potentially enhance photosynthesis and productivity for some wetland plants, the effects of increased atmospheric CO₂ concentrations on wetland plant communities in general are difficult to predict.³⁰¹ Poff et al. (2002) point out that species have different levels of sensitivity to enhanced CO₂, and vegetation may shift as plants that are more sensitive outcompete less sensitive species. However, the effect of enhanced CO₂ may have less of an effect on wetland plants than differences in water use efficiency, exposure to damage from insects or pathogens, or changes in the activity of soil bacteria.³⁰² Human inputs of nitrogen and phosphorus into wetland systems may also mask vegetation responses to CO₂ enrichment.³⁰³ All of these factors can influence plant community structure, making it difficult to generalize about the effect of CO₂ enrichment on wetlands.³⁰⁴

Both Winter (2000) and Poff et al. (2002) state that the effects of climate change on a given wetland can likely be best evaluated by understanding the inputs, discharges, and patterns of water flow within the wetland and its landscape context. Wetland vulnerability to climate change is related to the flow characteristics of ground water and surface water, and interactions between

²⁹⁴ Information as cited in U.S. Congress, Office of Technology Assessment (1993), *Preparing for an Uncertain Climate – Vol. 2, Ch.4.*

²⁹⁵ Ibid.

²⁹⁶ Ibid.

²⁹⁷ Ibid.

²⁹⁸ Ibid.

²⁹⁹ Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change.*

³⁰⁰ Information as cited in U.S. Congress, Office of Technology Assessment (1993), *Preparing for an Uncertain Climate – Vol. 2, Ch.4.*

³⁰¹ Information as cited in U.S. Congress, Office of Technology Assessment (1993), *Preparing for an Uncertain Climate – Vol. 2, Ch.4.*

³⁰² Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change.*

³⁰³ Ibid.

³⁰⁴ Ibid.

those sources and the atmosphere.³⁰⁵ Winter (2000) notes that all wetlands fall somewhere in a continuum between receiving water entirely from precipitation or entirely from groundwater. Wetlands that only receive water from precipitation are highly vulnerable to changes in climate, whereas those that receive primarily groundwater from large, regional systems (and aquifers) may be buffered from climate change (unless the groundwater source is also substantially affected).³⁰⁶ In order to determine the vulnerability of an individual wetland, one could assess the contribution of different water sources to the wetland's overall hydrologic regime.³⁰⁷

For example, peat-based wetlands such as acidic peat bogs are dominated by precipitation inputs. If climate dries, these wetlands would be expected to contract, with their organic soils oxidizing, subsiding, and contributing CO₂ emissions to the atmosphere.³⁰⁸ As a result, locally unique species may be lost, and there may be changes in topography, water movement, and susceptibility to fire in the wetland.³⁰⁹ In contrast, a wetter climate might result in an expansion of these wetland types, if no barriers exist.³¹⁰ As in bogs, alpine tundra is also likely to shrink as temperatures warm³¹¹ and vegetation restricted to cold thermal regimes in alpine wetlands is expected to decline.³¹²

A second example includes wetlands that are generally fed by groundwater discharge and streams and are located in headwater regions.³¹³ For groundwater-dominated fens, warmer temperatures may eventually increase groundwater temperatures such that species will be lost at the current southern limit of their range.³¹⁴ The vulnerability of a wetland to climate change may depend on the volume of precipitation and groundwater discharge in its upstream watershed.³¹⁵ Headwater wetlands may already be located at geographically high elevations, and have only small, upstream watersheds feeding their hydrology.³¹⁶ The geographic position of these wetlands may also limit their ability to migrate. Therefore, these wetlands may also be moderately to highly vulnerable to climate change.³¹⁷

For wetlands associated with surface waters, climate change impacts on their adjacent rivers, streams, or lakes will affect the wetland. In riparian wetlands, stream dynamics and hydrology are important factors driving the location of these habitats, where specific flooding and substrate conditions are necessary for these systems to establish.³¹⁸ The vulnerability of wetlands dominated by surface-water inputs will depend on the effects of climate on their upstream

³⁰⁵ Winter (2000), *The vulnerability of wetlands to climate change: a hydrologic landscape perspective*.

³⁰⁶ Ibid.

³⁰⁷ Ibid.

³⁰⁸ Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change*.

³⁰⁹ Ibid.

³¹⁰ Ibid.

³¹¹ Information as cited in U.S. Congress, Office of Technology Assessment (1993), *Preparing for an Uncertain Climate – Vol. 2, Ch.4*.

³¹² Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change*.

³¹³ Winter (2000), *The vulnerability of wetlands to climate change: a hydrologic landscape perspective*.

³¹⁴ Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change*.

³¹⁵ Winter (2000), *The vulnerability of wetlands to climate change: a hydrologic landscape perspective*.

³¹⁶ Ibid.

³¹⁷ Ibid.

³¹⁸ Johnson and O'Neil (2001), *WHROW*.

watersheds.³¹⁹ Winter (2000) lists the following examples of adverse effects to the water supply of riparian wetlands: (1) reduction of precipitation in headwaters areas, (2) reduction of groundwater contribution to the stream, and (3) increase in transpiration from valley bottom vegetation.

Warmer temperatures are predicted to shift the timing of peak flows from seasonal snowmelt in some rivers. This would affect floodplain wetlands that rely on peak flows as a water source.³²⁰ A shift in the timing of peak flow events will impact which species and life stages can access and use flood plain habitat for rearing. Similarly, lake-fringe wetlands will respond to seasonal or interannual changes in lake levels.³²¹ For groundwater-fed wetlands, wetter climates could eventually translate into higher water tables and the expansion of wetland areas, while drier climates would result in wetland contraction.³²² In addition, wetlands fed by regional groundwater sources may have relatively sustained water inputs, and therefore be somewhat buffered from changes in climate.³²³ However, small systems fed by local groundwater discharge may be more vulnerable because of their small watersheds.³²⁴

Riparian wetlands in arid regions of the western United States are particularly vulnerable to degradation if hotter and drier conditions occur as a result of climate change.³²⁵ Reduced rainfall, combined with increased temperatures and evaporation, could cause some small, seasonal streams and their wetlands to dry up.³²⁶ Riparian wetlands may be able to adapt to climate change by migrating along river edges.³²⁷ Overall, in areas where conditions are wetter, wetlands may expand, while drier and hotter conditions may cause rivers to shrink and wetlands to retreat.³²⁸

Overall, the U.S. Congress Office of Technology Assessment (1993) identifies depressional wetlands in arid or semiarid areas, riparian wetlands in the arid West, and tundra wetlands (often peat-based), as being highly vulnerable to climate change and likely to face difficulties in adapting. As that report states, depressional wetlands may be subject to lower water tables as a result of higher temperatures, increased evaporation, and decreased precipitation. Riparian wetlands in arid regions would also be threatened by drier conditions and by competition for water.³²⁹ Any wetland that is already degraded as a result of human actions (e.g., pollution, water diversion, fragmentation), may also be particularly vulnerable to climate change impacts.³³⁰ As the report summarizes, wetland species may respond in three interrelated ways as

³¹⁹ Winter (2000), *The vulnerability of wetlands to climate change: a hydrologic landscape perspective*.

³²⁰ Ibid.

³²¹ Ibid.

³²² Ibid.

³²³ Winter (2000), *The vulnerability of wetlands to climate change: a hydrologic landscape perspective*.

³²⁴ Ibid.

³²⁵ Information as cited in U.S. Congress, Office of Technology Assessment (1993), *Preparing for an Uncertain Climate – Vol. 2, Ch.4*.

³²⁶ Ibid.

³²⁷ Ibid.

³²⁸ Ibid.

³²⁹ Information as cited in U.S. Congress, Office of Technology Assessment (1993), *Preparing for an Uncertain Climate – Vol. 2, Ch.4*.

³³⁰ Information as cited in U.S. Congress, Office of Technology Assessment (1993), *Preparing for an Uncertain Climate – Vol. 2, Ch.4*.

the environment changes around them: they may change, migrate, or decline. Which response prevails will depend on where a wetland lies in the landscape, its size, its hydrology, the health of its vegetation, and other physical, biological, and anthropogenic factors that have shaped it over time, combined with the rates at which regional patterns of temperature, precipitation, and evaporation change.³³¹

Wetlands provide important functions and services that could be jeopardized by climate change. Wetlands contribute to the biodiversity of the landscape by housing both unique species and wildlife searching for refuge from human activities in surrounding ecosystems.³³² Climate change could induce plants and animals living in wetlands to shift their location; however, organisms will face barriers to migration such as dikes, dams, altered fire regimes, invasive species, and degraded water quality.³³³

For example, riparian wetlands function as habitat for waterfowl and fish, and provide food for 75% of the wildlife species in arid western lands.³³⁴ However, these wetlands comprise only 1% of the west as a whole, and 80% of riparian habitat has already been lost due to grazing and water diversion for agriculture and municipalities.³³⁵ The impacts of climate change will overlay current disturbances, further reducing the ability of riparian wetlands to perform functions such as stream bank maintenance, erosion reduction, flood buffering, and filtration of sediments and nutrients.³³⁶ For all floodplain wetlands, climate change-induced alterations affect their ability to cycle nutrients and to provide food and habitat for wildlife.³³⁷ Ultimately, these areas may also change as a result of disturbance, development, and climate change impacts to their upstream watersheds, modifying or eliminating the hydrology that defines the wetlands themselves.³³⁸ Anthropogenic responses to climate change will also affect riparian wetlands; if conditions become drier, human demands for groundwater will increase, decreasing the amount of water available in aquifers to feed wetland systems.³³⁹

It is important to recognize that, although climate change poses potential threats to wetlands, current activities that degrade and destroy wetlands may threaten these habitats even more acutely.³⁴⁰ Even if it does not become the primary driver of wetland loss, climate change is likely to aggravate stresses such as agriculture, development, and pollution.³⁴¹ As the U.S. Congress, Office of Technology Assessment (1993) notes about the lower-48 states, because the United States has already lost more than half of the wetlands it contained 200 years ago (over 100

³³¹ U.S. Congress, Office of Technology Assessment (1993).

³³² Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change*.

³³³ Ibid.

³³⁴ Information as cited in U.S. Congress, Office of Technology Assessment (1993), *Preparing for an Uncertain Climate – Vol. 2, Ch.4*.

³³⁵ Ibid.

³³⁶ Ibid.

³³⁷ Euro-Limpacs (N.D.), *Climate Change and Freshwater* (website).

³³⁸ Information as cited in U.S. Congress, Office of Technology Assessment (1993), *Preparing for an Uncertain Climate – Vol. 2, Ch.4*.

³³⁹ Poff et al. (2002), *Aquatic Ecosystems & Global Climate Change*.

³⁴⁰ Information as cited in U.S. Congress, Office of Technology Assessment (1993), *Preparing for an Uncertain Climate – Vol. 2, Ch.4*.

³⁴¹ Ibid.

million acres), the potential for climate change to spur further losses and degradation could pose a significant threat to valued functions of wetlands.³⁴²

CLIMATE CHANGE EFFECTS ON SALMON

Washington Dept. of Fish and Wildlife (WDFW) lists seven species or subspecies of salmon that occur in Washington State that are divided into stocks with different genetic characteristics.³⁴³ The status of these stocks as of 1999 is presented in Figure 1. Although salmon (*Oncorhynchus spp.*) and other coldwater fish species are already at risk due to human development in watersheds, they will also be affected by climate change.³⁴⁴ Climate plays a crucial role in salmon ecology at every stage of their life cycle, but the relative importance of climatic factors differs between salmon species and stocks.³⁴⁵ For example, thermal and hydrologic regimes (i.e., patterns of temperature and water flow) limit the productivity of salmon in freshwater; these limitations differ according to species, life history stage, watershed characteristics, and stock-specific adaptations to local environmental factors.³⁴⁶ With climate change, factors such as flooding and thermal connectivity will change in space and time, influencing different aspects of salmon life history stages.³⁴⁷ This will be beneficial for some salmon stocks and detrimental for others.³⁴⁸ A depiction of the salmon lifecycle is presented in Figure 2.

³⁴² U.S. Congress, Office of Technology Assessment (1993)

³⁴³ WDFW (1999), *Salmon Facts: An information guide to our state's natural treasure*. (website)
<http://wdfw.wa.gov/outreach/fishing/salmon.htm>

³⁴⁴ Karl et al. (2009), *Global Climate Change Impacts in the United States*.

³⁴⁵ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁴⁶ Information as cited in Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁴⁷ Mara Zimmerman, WDFW (pers. comm.)

³⁴⁸ Mara Zimmerman, WDFW (pers. comm.)

Figure 1: Excerpt from Part II of “Extinction is Not an Option: Statewide Strategy to Recover Salmon” by the Washington State Joint Natural Resources Cabinet (1999), which shows the status of salmon, steelhead, Bull trout and Dolly Varden stocks in WA.

Table 2. Regional and statewide summary of salmon and steelhead² and Bull trout and Dolly Varden³ stock status

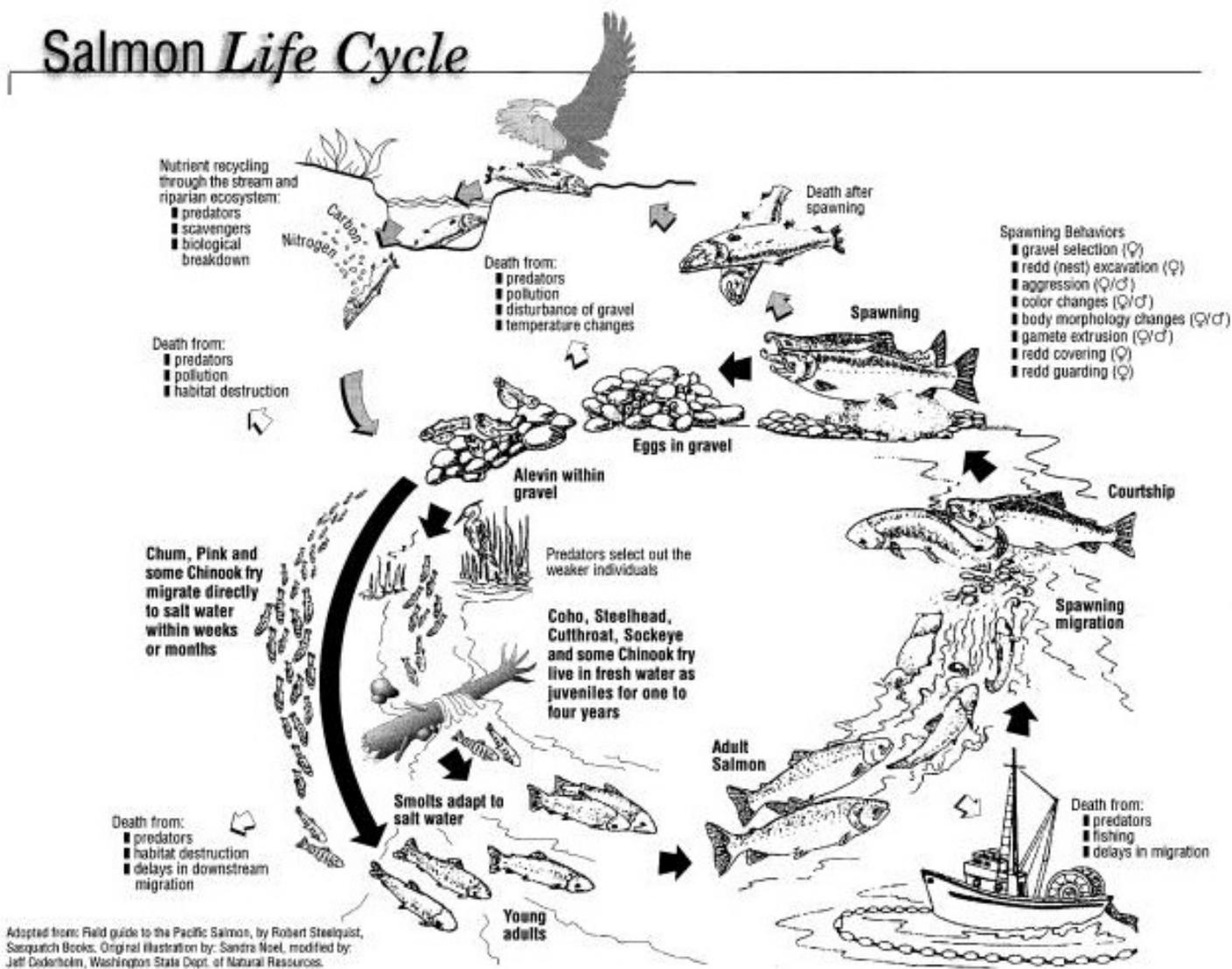
	<u>HEALTHY</u>		<u>DEPRESSED</u>		<u>CRITICAL</u>		<u>UNKNOWN</u>		<u>EXTINCT⁴</u>	
	Salmon/ Steelhead	Bull Trout Dolly Varden	Salmon/ Steelhead	Bull Trout Dolly Varden						
PUGET SOUND										
North Puget Sound	27	2	12	0	4	0	28	7	0	0
South Puget Sound	40	0	7	0	1	0	13	6	1	0
Hood Canal	17	1	11	0	1	0	7	2	0	0
Strait of Juan de Fuca	9	1	14	0	5	0	12	3	0	0
TOTALS	93	4	44	0	11	0	60	18	1	0
COASTAL										
North Coast	35	1	4	0	0	0	33	5	0	0
Grays Harbor	21	0	3	0	0	0	4	1	0	0
Willapa Bay	9		1		0		5		0	
TOTALS	65	1	8	0	0	0	42	6	0	0
COLUMBIA										
Lower Columbia	18	0	35	1	0	0	7	0	0	0
Upper Columbia	11	9	35	1	1	6	4	34	0	0
TOTALS	29	9	70	2	1	6	11	34	0	0
515 TOTAL STOCKS	187	14	122	2	12	6	113	58	1	0
% OF TOTALS FOR SALMON AND STEELHEAD	43%		28%		3%		26%		0%	
% OF TOTALS FOR BULL TROUT AND DOLLY VARDEN		18%		3%		8%		72%		0%

² Source from 1992 Washington State Salmon and Steelhead Stock Inventory (SASSI)

³ Source from 1998 Salmonid Stock Inventory (SaSI)-Bull Trout/Dolly Varden Appendix

⁴ The Extinct rating is included here to identify any current and future losses of stocks identified during the annual review and inventory of Washington’s wild salmonid stocks.

Figure 2: Excerpt from Part II of “Extinction is Not an Option: Statewide Strategy to Recover Salmon” by the Washington State



Joint Natural Resources Cabinet (1999), depicting a generic salmon lifecycle.

This section draws largely from Chapter 6 of WACCIA, *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*, by Mantua et al. (2009) to describe ways in which climate change affects key aspects of freshwater salmon habitat in Washington State.

Salmon life histories integrate across a complex network of freshwater, estuarine, and marine habitats, and that salmon will be affected by climate changes in both the freshwater and marine environments.³⁴⁹ For example, the impact of ocean acidification and other marine climate changes on the ocean ecology of salmon are among the least understood, but possibly most important, aspects of salmon ecology in the coming decades.³⁵⁰ Mantua et al. (2009) suggest the following resources as informative reviews of climate impacts on marine habitat for Pacific Northwest salmon:

- Pearcy, W.M. 1992. *Ocean ecology of North Pacific salmonids*. Washington Sea Grant, Seattle (USA): 179 pp.
- Logerwell, E.A., N.J. Mantua, P. Lawson, R.C. Francis, and V. Agostini. 2003. Tracking environmental processes in the coastal zone for understanding and predicting Oregon Coho (*Oncorhynchus kisutch*) marine survival. *Fisheries Oceanography* 12(6): 554-568.
- Independent Scientific Advisory Board (ISAB). 2007. Climate change impacts on Columbia River Basin fish and wildlife. ISAB Climate Change Report. Available online at <http://www.nwcouncil.org/library/isab/isab2007-2.htm>.

In their analysis, Mantua et al. (2009) focus on only a few, well-understood linkages between the physical properties of freshwater habitat and salmon reproductive success: namely, stream temperature and the volume and timing of streamflow.³⁵¹ This information is summarized below.

Changing Thermal Regimes

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.³⁵²

While salmon are under threat from a variety of human activities, warming temperatures are also a growing source of stress.³⁵³ Rising temperatures affect salmon in several important ways.³⁵⁴ As

³⁴⁹ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁵⁰ Information as cited in Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁵¹ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁵² Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁵³ Karl et al. (2009), *Global Climate Change Impacts in the United States*.

³⁵⁴ Karl et al. (2009), *Global Climate Change Impacts in the United States*.

precipitation increasingly falls as rain rather than snow, it feeds floods that can wash away salmon eggs incubating in the streambed.³⁵⁵ Warmer water leads eggs to hatch earlier in the year, so the young are smaller and more vulnerable to predators.³⁵⁶ Warmer conditions increase a fish's metabolism, taking energy away from growth and forcing the fish to find more food; unfortunately, earlier hatching of eggs could mean fish foraging patterns no longer sync with availability of insect prey.³⁵⁷ Earlier melting of snow leaves rivers and streams warmer and shallower in summer and fall, and diseases and parasites tend to flourish in warmer water.³⁵⁸

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.³⁵⁹ For salmon, excessively warm waters can inhibit migration and breeding patterns, and reduce cold-water refugia and connectivity.³⁶⁰ 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.³⁶¹ Water temperatures exceeding 21-22 °C (70-72 °F) can prevent migration.³⁶² 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 ~70° F, but this varies by species) can be lethal for juveniles and adults.³⁶³

Observations

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.³⁶⁴ In reaches that typically host salmon in the warmest summer months these locations already have periods with episodes of extreme thermal stress for salmon.³⁶⁵

Two examples illustrate negative effects that high summer temperatures can have on salmon. First, summer water temperatures in the mainstem Columbia River sometimes reach lethal limits for sockeye salmon, and frequently pose thermal migration barriers for fall Chinook and summer steelhead.³⁶⁶ Second, extreme summer water temperatures in the Lake Washington ship canal

³⁵⁵ Karl et al. (2009), *Global Climate Change Impacts in the United States*.

³⁵⁶ Karl et al. (2009), *Global Climate Change Impacts in the United States*.

³⁵⁷ Karl et al. (2009), *Global Climate Change Impacts in the United States*.

³⁵⁸ Karl et al. (2009), *Global Climate Change Impacts in the United States*.

³⁵⁹ Information as cited in Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁶⁰ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁶¹ Information as cited in Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁶² Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁶³ Information as cited in Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁶⁴ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁶⁵ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁶⁶ Information as cited in Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

frequently inhibit the upstream migration of adult Chinook (and in extreme years also sockeye), while elevated water temperatures in spring confer a competitive advantage to warm water predators, like smallmouth bass (*Micropterus dolomieu*), that can consume significant numbers of sockeye, Coho, Chinook, and steelhead smolts on their seaward migrations through the ship canal.³⁶⁷

Future Projections

Previous studies have projected climate change impacts on weekly water temperatures in order to evaluate impacts on trout and salmon habitat in the United States.³⁶⁸ O'Neal (2002) used 8 climate change scenarios with a 2090 summertime warming ranging from 35.6°F to 41.9 °F to predict maximum weekly U.S. water temperatures.³⁶⁹ Locations that experienced a projected maximum weekly water temperature greater than the upper thermal tolerance limit for a species were considered lost habitat.³⁷⁰ 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.³⁷¹

Mantua et al. (2009) found that annual maximum weekly average water temperatures (T_w) at most of the water temperature monitoring stations used in their analysis were projected to rise under future scenarios of climate change. In addition, the number of monitoring stations characterized by high-stress conditions for salmon was projected to increase. Specifically, they predicted that:

- T_w was projected to rise less than 1.8°F in stations across the state by the 2020s, but between 3.6°F to 9°F by the 2080s.
- 11% of temperature stations with a T_w from 59.9- 67.1°F (category indicating an elevated risk of disease for adult salmon) were projected to shift into an even higher stress category by the 2080s (as compared to the 1980s).³⁷²

In addition, the persistence of summer water temperatures particularly unfavorable for salmon (>69.8 °F) was predicted to start earlier in the year, and last later in the year.³⁷³ Mantua et al. (2009) compared future modeling scenarios to a baseline situation from the 1980s in which most of the water temperature monitoring stations located in the warmest areas had $T_w > 69.8^\circ\text{F}$ that generally persisted for 1-to-5 weeks (from late-July to mid-August).³⁷⁴ In contrast, model results indicated that:

³⁶⁷ Information as cited in Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁶⁸ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁶⁹ Information as cited in Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁷⁰ Information as cited in Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁷¹ Information as cited in Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁷² Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁷³ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁷⁴ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

- Under A1B emissions, the period of extreme thermal stress and thermal migration barriers was projected to persist for 10-to-20 weeks (from mid-June until early-September) by the 2080s at 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 Tucannon³⁷⁵ This prolonged duration of thermal stress is also predicted for the Lake Washington/Lake Union ship canal (University Bridge).³⁷⁶
- The $T_w > 69.8$ °F season was predicted to expand and increase considerably for the warmer streams in western Washington like the Stillaguamish River at Arlington, but less severely for the colder waters of the Upper Yakima.³⁷⁷ For these stations the period of extreme thermal stress and thermal migration barriers lasted up to 20 weeks by 2100 and were centered on the first week of August.³⁷⁸

Shifts to increasingly stressful thermal regimes are predicted to be greatest for eastern Washington where the historical baselines for water temperatures are substantially warmer than those in western Washington.³⁷⁹ Overall, extended thermal migration barriers are predicted to be much more common in eastern Washington compared with western Washington.³⁸⁰

Discussion

Salmon populations in Washington that have a stream-type life history that puts them in freshwater during summer for either spawning migrations, spawning, rearing, or seaward smolt migrations may experience significant increases in thermal stress.³⁸¹ 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).³⁸² Temperature impacts on adult spawning migrations are projected to be most severe for summer steelhead, sockeye, and summer Chinook populations in the Columbia Basin, sockeye and Chinook in the Lake Washington system, and in other streams that are already experiencing excessively warm stream

³⁷⁵ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁷⁶ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁷⁷ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁷⁸ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁷⁹ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁸⁰ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁸¹ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁸² Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

temperatures in mid-summer.³⁸³ 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 two summers) rearing in freshwater.³⁸⁴

Changing Hydrologic Regimes

Characteristics of seasonal and daily streamflow variations can also serve as limiting factors for freshwater salmon habitat.³⁸⁵ For example, a study of Chinook in the Snohomish Basin found that extreme high flows as a result of climate change had the greatest negative impact on projections of salmon reproductive success.³⁸⁶ 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.³⁸⁷

Projected Changes

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.³⁸⁸ 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.³⁸⁹

Discussion

Reductions in the volume of summer/fall low flows in transient and rainfall-dominated basins may reduce the availability of spawning habitat for salmon populations that spawn early in the fall.³⁹⁰ 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.³⁹¹ Reductions in springtime snowmelt may negatively impact the

³⁸³ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁸⁴ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁸⁵ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁸⁶ Information as cited in Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁸⁷ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁸⁸ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁸⁹ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁹⁰ Information as cited in Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁹¹ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

success of smolt migrations from snowmelt dominant streams where seaward migration timing has evolved to match the timing of peak snowmelt flows.³⁹²

Species-Specific Examples Of Loss

- In Washington, threatened summer chum salmon stocks in Hood Canal have a unique life history that makes them especially vulnerable to the impacts of climate change.³⁹³ 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.³⁹⁴ 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.³⁹⁵
- In the United States, losses of western trout populations may exceed 60 percent in certain regions.³⁹⁶ About 90 percent of bull trout, which live in western rivers in some of the country's most wild places, are projected to be lost due to warming.³⁹⁷
- Studies suggest that up to 40 percent of Northwest salmon populations may be lost by 2050.³⁹⁸

³⁹² Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁹³ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁹⁴ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁹⁵ Mantua et al. (2009), *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State*. WACCIA, Chapter 6.

³⁹⁶ Information as cited in Karl et al. (2009), *Global Climate Change Impacts in the United States*.

³⁹⁷ Information as cited in Karl et al. (2009), *Global Climate Change Impacts in the United States*.

³⁹⁸ Information as cited in Karl et al. (2009), *Global Climate Change Impacts in the United States*.

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