

## SECTION 6

# How Will Climate Change Affect Water in Washington?

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*Washington is projected to experience decreases in snowpack, increases in stream temperatures, and widespread changes in streamflow timing, flooding, and summer minimum flows. Annual streamflow volumes are not projected to change substantially. Climate change is projected to result in more frequent summer water shortages in some basins, while others remain unaffected – vulnerability is likely greatest in fully allocated watersheds with little management flexibility. Recent research has largely confirmed previous research, but has contributed increased understanding of the local- and water-use specific implications of climate change. New datasets provide a comprehensive set of projections that can support long-range planning.*

- 1. As is the case for much of the western U.S., Washington is projected to experience decreasing snowpack, a shifting balance between snow and rain, increasing stream temperatures, and changes in streamflow timing, flooding, and summer minimum flows.** The largest changes are projected for mid-elevation basins with significant snow accumulation (today’s so-called “mixed rain and snow” watersheds; Figures 6-1 and 6-2, Table 6-1).<sup>[A][1]</sup>

### **Drivers of change: Temperature and precipitation**

- *All scenarios project continued warming* during this century, and most scenarios project that this warming will be outside of the range of historical variations by mid-century (Section 3 of this report). As a consequence, there is high confidence in the warming-related changes in water resources.
- *Projected changes in precipitation are mixed.* Changes in precipitation are less clear, and are generally projected to be smaller than natural year-to-year variability. As a result, there is much lower confidence in the precipitation-dependent changes in water resources.

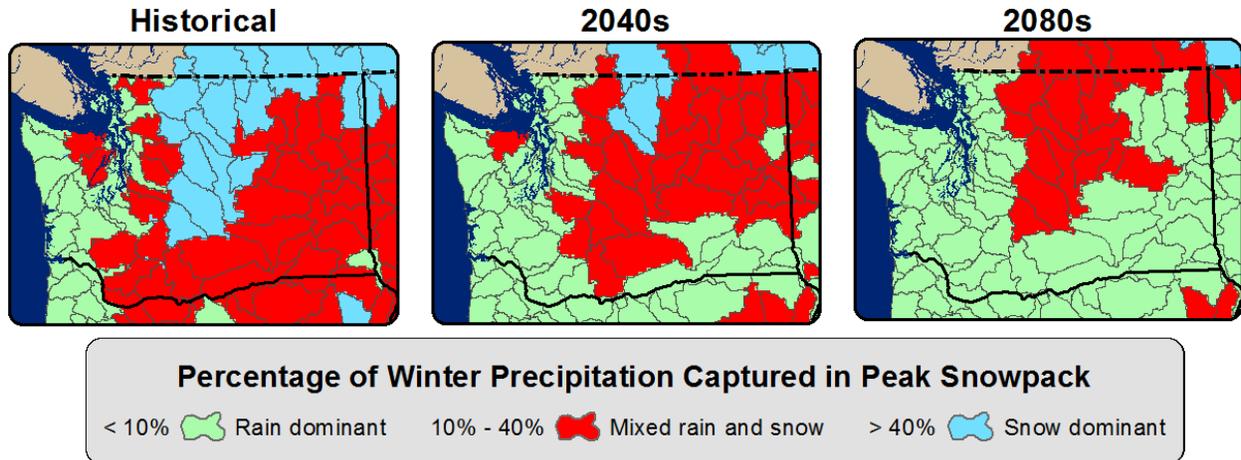
### **Natural water storage**

- *Declining snowpack.* Average spring snowpack in Washington is projected to decline by –56 to –70% by the 2080s (2070-2099, relative to 1916-2006).<sup>[B][C][D][2]</sup>

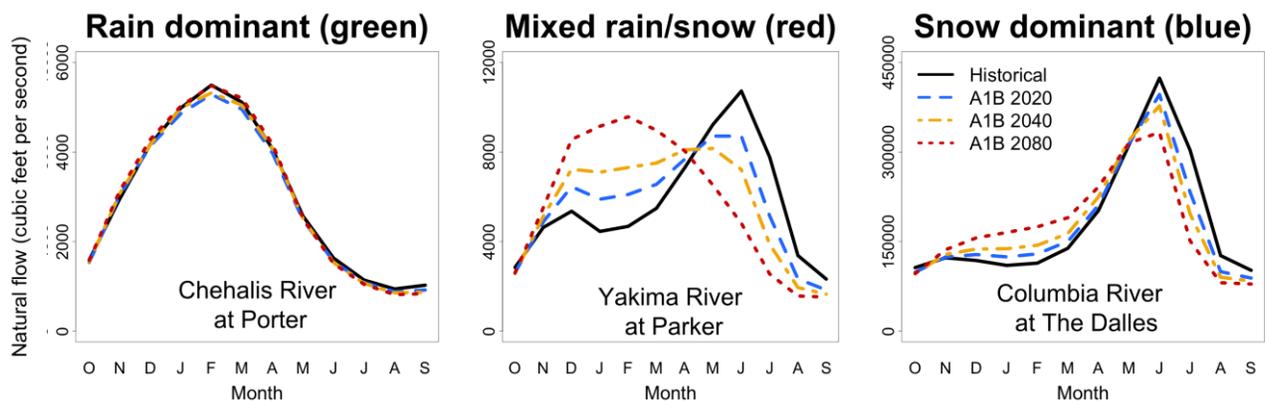
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<sup>A</sup> Watersheds are classified based on the proportion of precipitation that falls as snow versus rain during winter (October-March). “Rain dominant” basins (i.e., watersheds with warm winter temperatures), receive less than 10% of winter precipitation as snow. In contrast, colder watersheds are classified as “snow dominant” if they receive more than 40% of winter precipitation as snow. “Mixed rain and snow” basins are middle elevation basins, near the current snowline, that receive between 10 and 40% of winter precipitation as snow. These different basin types will experience different impacts of climate change. Washington watershed classifications are shown in Figure 6-1.

<sup>B</sup> These numbers indicate changes in April 1<sup>st</sup> Snow Water Equivalent (SWE). SWE is a measure of the total amount of water contained in the snowpack. April 1<sup>st</sup> is the approximate current timing of peak annual snowpack in the mountains of the Northwest.



**Figure 6-1.** Changing hydrology with warming. Maps above indicate current and future watershed classifications, based on the proportion of winter precipitation stored in peak annual snowpack. Graphs below indicate current and future average monthly streamflow for these watershed types. Both compare average historical conditions (1916-2006) and projected future conditions for two time periods, the 2040s (2030-2059) and the 2080s (2070-2099), under a medium greenhouse gas scenario (A1B). Green shading in the maps indicates *warm* (“rain-dominant”) watersheds, which receive little winter precipitation in the form of snow. In these basins, streamflow peaks during during winter months and warming is projected to have little effect (below, left). Blue indicates *cold* (“snow-dominant”) watersheds, that is, cold basins that receive more than 40% of their winter precipitation as snow. Depending on elevation, these basins are likely to experience increasing winter precipitation as rain and increased winter flows (below, right). The most sensitive basins to warming are the *watersheds that are near the current snowline* (“mixed rain and snow”), shown in red. These are middle elevation basins that receive a mixture of rain and snow in the winter, and are projected to experience significant increases in winter flows and decreases in spring flows as a result of warming (below, center). *Source: Hamlet et al., 2013.<sup>[3]</sup>*



**Figure 6-2.** Changes in the seasonality of streamflow for three example watersheds in the Pacific Northwest: The Chehalis River, a warm basin (left); the Columbia River, a cold basin with source waters at high elevations (right) and the Yakima River, a middle-elevation basin near the current snowline (middle). *Source: Elsner et al., 2010.<sup>[2]</sup>*

- *Shrinking glaciers.* There are no published projections of Northwest glacier response to climate change, although most Northwest glaciers are in decline (Section 2) and one study found that only 2 of the 12 North Cascades glaciers with annual measurements are expected to survive the current climate.<sup>[4]</sup> In the North Cascades, 10% to 44% of total summer streamflow is estimated to originate from glaciers, depending on the watershed.<sup>[5]</sup>

### Watershed type and streamflow conditions

- *Changing watershed type.* The dominant form of precipitation in most Washington watersheds will be rainfall by the end of the 21<sup>st</sup> century (Figure 6-1). In contrast, many have historically been strongly influenced by snowfall in winter. The one exception is the North Cascades, where snow accumulation is projected to remain important through 2100.
- *Earlier streamflow timing.* The spring peak in streamflow is projected to occur earlier in mixed-rain and snow and snow dominant basins (see red and blue shading in Figure 6-1). For instance, peak streamflow is projected to occur 4 to 9 weeks earlier by the 2080s (2070-2099, relative to 1917-2006) in four Puget Sound watersheds (Sultan, Cedar, Green, Tolt) and the Yakima basin (Figure 6-2).<sup>[D][2]</sup>
- *Small increase in annual streamflow.* Annual streamflow is projected to increase by +4.0 to +6.2% on average for Washington State by the 2080s (2070-2099, relative to 1970-1999). These changes are likely to be dwarfed by natural year-to-year variations in streamflow totals through the end of the century.<sup>[D][2]</sup>
- *Increasing winter streamflow.* Winter streamflow is projected to increase by +25 to +34% on average for Washington State by the 2080s (2070-2099, relative to 1970-1999).<sup>[D][2]</sup>
- *Declining summer streamflow.* Summer streamflow is projected to decrease by -34 to -44% on average for Washington State by the 2080s (2070-2099, relative to 1970-1999).<sup>[D][2]</sup>
- *Increasing stream temperatures.* Stream temperatures are projected to increase in response to warming and decreases in summer streamflow. Projections for 124 stream temperature locations across the state find that more sites will experience temperatures that elevate stress for adult salmon.<sup>[6]</sup> Many will exceed thermal tolerances for the entire summer season by 2080 (2070-2099), despite rarely being in excess of these temperatures in the recent past.<sup>[7]</sup>

<sup>C</sup> Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate impacts. These are described in the text as follows: "very low" refers to the RCP 2.6 scenario; "low" refers to RCP 4.5 or SRES B1; "medium" refers to RCP 6.0 or SRES A1B; and "high" refers to RCP 8.5, SRES A2, or SRES A1FI – descriptors are based on cumulative emissions by 2100 for each scenario. See Section 3 for more details.

<sup>D</sup> Average projected change for ten global climate models, averaged over Washington State. Range spans from a low (B1) to a medium (A1B) greenhouse gas scenario.

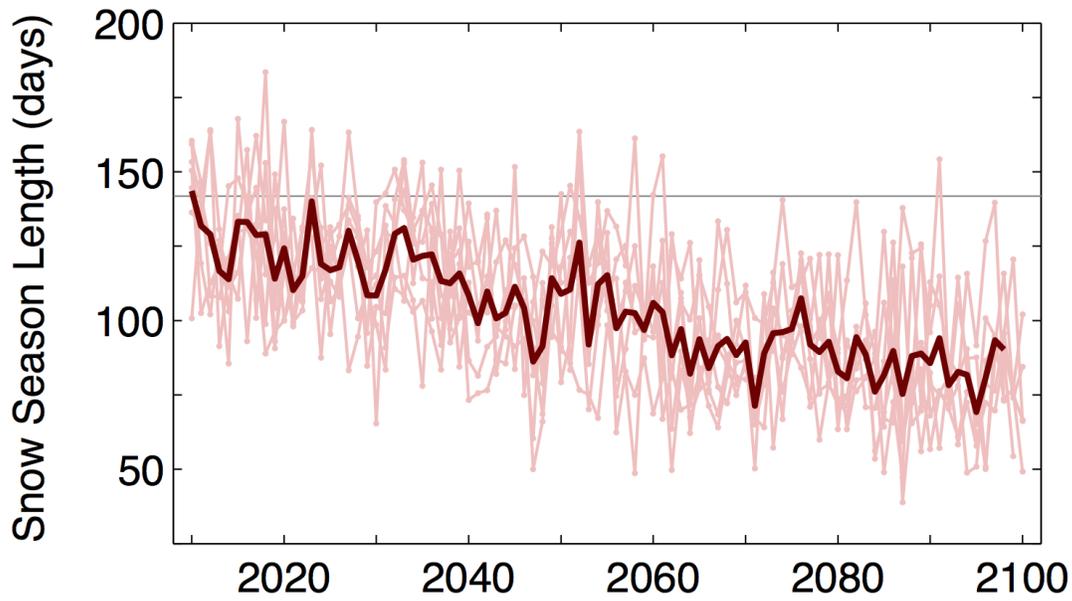
## Streamflow extremes

- *Flooding*
  - *Projected changes range from modest decreases to large increases in extreme river flows depending on location and watershed type.* The highest river flows are generally expected to increase in rain-dominant and in mixed rain and snow watersheds. Some snow dominant watersheds will see flood increases, while others experience decreases. Projections for specific Washington locations can be found here: <http://warm.atmos.washington.edu/2860/products/sites/>.
  - *Increases in heavy rainfall events could further increase flood risk.* Heavy rainfall events are projected to become more severe by mid-century (Section 3 of this report). On average in the Northwest, the number of days with more than 1 inch of rain is projected to increase by +13% ( $\pm 7\%$ ) for the 2050s relative to 1971-2000.<sup>[8]</sup> Preliminary results suggest an increase in the number of heavy rain events occurring in early fall.<sup>[9]</sup> These changes may result in more severe flooding in rain dominant and mixed rain and snow basins.
  - *Changes in flood management may not be sufficient to mitigate increases in flood risk.* In the upper Skagit basin, for instance, with current flood management practices, the 100-year flood is projected to increase by 24% by the 2080s (2070-2099, relative to 1916-2006)<sup>[E]</sup>; simulations indicate that changes in water management can only mitigate 7% of this projected increase.<sup>[10]</sup>
  - *Sea level rise will exacerbate coastal river flooding.* Higher sea level can increase the extent and depth of flooding by making it harder for flood waters in rivers and streams to drain to the ocean or Puget Sound. Initial research on this issue suggests that the amount of area flooded in the Skagit would increase by up to 74% by the 2080s when accounting for the combined effects of sea level rise and larger floods.<sup>[11]</sup>
- *Minimum flows.* Low summer streamflow conditions are projected to become more severe in about 80% of watersheds across Washington State. Rain dominant and mixed rain and snow basins show the greatest and most consistent decreases in minimum flows, while changes for snow dominant basins are smaller. Changes are more pronounced west of the Cascade mountains because there is “less water to lose” east of the Cascades – historical conditions are already very arid in interior Washington.<sup>[F][12]</sup>

- 2. Year-to-year variability will continue to cause some periods that are abnormally wet, and others that are abnormally dry.** For the foreseeable future, Washington will continue to experience years and decades with conditions that temporarily mask or amplify the projected changes in water resources (Figure 6-3), even as long-term trends continue.

<sup>E</sup> Projected change based on the ECHAM5 global climate model and the A1B greenhouse gas scenario.

<sup>F</sup> Results for a low (B1) and medium (A1B) greenhouse gas scenario for 112 medium-sized watersheds in Washington.



**Figure 6-3.** Shorter snow season with warming; large year-to-year variability. Projected length of the snow season, in days, for middle elevations (4,000 to 5,000 ft) for the Cascade mountains in Oregon and Washington. The plot shows projected snow season length from seven individual climate models (thin pink lines) and the average among all models (thick red line) for a medium greenhouse gas scenario (A1B). For comparison, the average snow season length for 1950-1999 was 142 days (shown as the gray horizontal line). Although the length of the snow season is clearly expected to decrease significantly over this century, individual years with substantially longer or shorter snow seasons than the general declining trend are also expected to occur. *Data source: Hamlet et al. 2013<sup>[B]</sup>*

**3. These changes will have far-reaching consequences for people, infrastructure and ecosystems across the state.** Climate change impacts on water resources will pose increasing challenges in the decades ahead. The examples below indicate the potential sector-specific consequences of climate change in the absence of management adjustments to reduce impacts. Although not included in these projections, changes in water management to alleviate impacts on one sector – i.e., hydropower production, irrigation or municipal supply, or instream flows for fish – could exacerbate impacts on other sectors.<sup>[13]</sup>

- *Irrigation water supply.* In the Yakima basin, warming is projected to increase the frequency of water shortage years – i.e., years in which water delivery is curtailed due to insufficient streamflow – from 14% of years historically (1940-2005) to 43-68% of years by the 2080s (2070-2099).<sup>[D][14]</sup>
- *Hydropower production.* In response to increases in winter and decreases in summer streamflow, hydropower production in the Columbia River basin is projected to increase by +7 to +10% in winter and decrease by –18 to –21% in summer by the 2080s (2070-2099, relative to 1917-2006).<sup>[D][15]</sup> Regional power planners have expressed concerns over the existing hydroelectric system’s potential inability to provide adequate summer electricity given the combination of climate change, demand growth, and operating constraints.<sup>[16][17]</sup>

- *Fish and aquatic ecosystems.* Warming streams, declining summer flows, and increasing flood risk are all expected to negatively affect coldwater fish populations such as salmon<sup>[18]</sup> and trout.<sup>[19]</sup> Trout populations in the western US are projected to experience a decline of –33 to –77% in suitable habitat area by the 2080s (2070-2099, relative to 1985-2004) under a high greenhouse gas scenario.<sup>[G][19]</sup> Warming streams are projected to negatively affect salmon health, migration, and survival (see above).
- *Flood protection and stormwater management.* Increases in flooding can increase the cost of protecting and maintaining infrastructure, affect water quality via increasing sediment and nutrient loads, and result in increased landslide risk (Section 10).<sup>[20]</sup>
- *Municipal water supply.* Assuming no change in demand, new sources of supply or significant changes in operating procedures, water supply for Everett is projected to remain near 100% reliability (no water shortages) through the 2080s (2070-2099, relative to 1917-2006) and decrease to 63-96% for Tacoma under low and medium greenhouse gas scenarios.<sup>[H][21]</sup> Climate change is also projected to increase demand.<sup>[22][23]</sup> For Seattle, supply is projected to exceed demand in nearly all years, and the City has identified no or low-cost system modifications to mitigate climate change-related supply reductions, keeping supply above demand under all climate change scenarios examined.<sup>[I][22]</sup>
- *Shortened ski season.* Historically (1971-2000), Washington ski areas have experienced warm winters (average December-February temperature above freezing) anywhere from 0 to 33% of the time, depending on location. In response to a warming of +3.6°F – the lower end of the range projected for mid-century (Section 3) – warm winters would occur 33 to 77% of the time.<sup>[J][26]</sup>
- *Small increase in irrigation demand projected for eastern Washington.* Forecasted eastern Washington water demand in the 2030s (2020-2049, relative to 1977-2006) indicates a small increase in demand for irrigation (+4% assuming historical cropping patterns, for a mid-range future climate scenario.<sup>[K][27]</sup>
- *Small increases in municipal demand projected for the greater Seattle area.* Municipal demand in Seattle is projected to increase by 1% in 2025, 2% in 2050, and 5% in 2075

<sup>G</sup> Change in the length of stream habitat that is suitable to one of the following four trout species: cutthroat (*Oncorhynchus clarkia*), brook (*Salvelinus fontinalis*), brown (*Salmo trutta*), and rainbow (*Oncorhynchus mykiss*).

<sup>H</sup> Average water supply reliability projected by ten global climate models. Range stems from a combination of variations among two different reservoirs supplying water to Tacoma, as well as a low (B1) and medium (A1B) greenhouse gas scenario.

<sup>I</sup> These results are based on a simplified analysis using projections from IPCC 2007.<sup>25</sup> Seattle Public Utilities is currently updating their assessment using 40 new projections from the 2013 IPCC report.<sup>24</sup>

<sup>J</sup> The ski areas evaluated for Washington State were: Bluewood, Mt. Spokane, Mt. Baker, Crystal Mountain, Mission Ridge, White Pass, the Summit at Snoqualmie, Stevens Pass, and Hurricane Ridge.

<sup>K</sup> Projected change is based on a low greenhouse gas scenario (B1) obtained using the HADCM global climate model, which was found to be near the middle of the range among projections for 2030. This projection does not include potential changes in the crop mix in response to climate change, which would likely reduce the impacts on water supply.

(relative to 2000), assuming current population forecasts and no new conservation measures, based on a high greenhouse gas scenario.<sup>[L][22]</sup>

- *Greatest vulnerability in highly allocated basins with little management flexibility.* Vulnerability to projected changes in snowmelt timing is probably highest in basins with the largest hydrologic response to warming and lowest management flexibility – that is, fully allocated mixed rain and snow watersheds with existing conflicts among users of summer water. In contrast, vulnerability is probably lowest where hydrologic change is likely to be smallest (in rain-dominant basins), where institutional arrangements are simple, and current natural and human demands rarely exceed current water availability.<sup>[H][28][29][30][31]</sup>

**4. Many Washington communities, government agencies, and organizations are preparing for the impacts of climate change on water resources.** Most are in the initial stages of assessing impacts and developing response plans; some are implementing adaptive responses. For example:

**River flooding**

- *Preparing King County infrastructure for projected flooding increases:*
  - *Levee improvements and relocation of at-risk structures.* King County formed a new Flood Control District in 2007 to increase capacity for addressing regional flood risks due to climate change and other factors, increasing local funding for flood risk reduction efforts ten-fold.<sup>[32]</sup>
  - *Widening bridge spans.* King County has replaced 15 short span bridges with wider span structures (including the Tolt Bridge over the Snoqualmie River) and 42 small culverts with large box culverts. These changes will increase resilience to major flooding.<sup>[M]</sup>
- *Addressing extreme flood risk to Interstate-5 in Skagit County.* A federally funded pilot project will support development of a series of site-specific adaptation options to improve the resilience of Interstate 5 and state routes in the Skagit basin. These will complement flood hazard reduction strategies proposed by the U.S. Army Corps and Skagit County.

**Drinking water supply**

- *Ensuring supply exceeds demand for Seattle.* Seattle has undertaken numerous evaluations of climate change impacts and potential response options, including identifying no or low-cost system modifications to mitigate climate change-related supply reductions and demand increases. The City’s analysis indicates that no new source of water supply is needed before 2060 and that, under the warmest scenario considered,

<sup>L</sup> Projection based on the IPSL global climate model coupled with a high greenhouse gas scenario (A2).

<sup>M</sup> Presentation by Matt Kuharic, Senior Climate Change Specialist, King County Department of Natural Resources and Parks to the Washington State Climate Change Impacts Steering Committee, April 27, 2010.

available supply would exceed forecasted demand if all modifications are implemented. Depending on the relative timing of system modifications and climate change impacts, climate change could increase the frequency of requests to customers to curtail water use.<sup>[22]</sup>

- *Redesigning the Anacortes Water Treatment Plant.* Climate change projections for increased flooding and sediment loading in the Skagit River led to design changes for the City of Anacortes' new \$65 million water treatment plant (under construction in 2013). The altered design includes elevated structures, water-tight construction with minimal structural penetrations and no electrical control equipment below the current 100-year flood elevation, and more effective sediment removal processes.<sup>[33][34]</sup>

### **Long-range water planning**

- *The Yakima basin long-term water management plan.* Development of the Yakima River Basin Integrated Water Resource Management Plan included an evaluation of the likely efficacy of a suite of water management strategies and storage options under various climate change scenarios. While the Integrated Plan improves basin water supply conditions for all scenarios considered, specific outcomes will be very different under different climate conditions. Under the “moderately adverse” climate change scenario<sup>[N]</sup> and demand growth, supplies for proratable irrigation districts would be 61% in a severe one-year drought with the Integrated Plan, as opposed to 27% without (compared to 37% during the one-year drought in 2005).<sup>[35]</sup>
- *Long-range water resources planning in the Columbia Basin.* The U.S. Army Corps of Engineers, the Bureau of Reclamation, and the Bonneville Power Administration collaborated on an assessment of climate change impacts on Columbia River Basin hydrology and water management to support decisions on the Columbia River Treaty and future biological opinions. The three federal agencies are integrating new climate change data derived from this work into their ongoing modeling and planning efforts.<sup>[36]</sup>

*For more details on projected impacts on Water Resources, see Table 6-1.*

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<sup>N</sup> Corresponds to the low end of the range projected for mid-century (Section 3).

***Additional Resources for Evaluating Hydrologic Impacts***

The following resources provide location-specific information about climate change impacts to support identification and reduction of risks associated with a changing climate.

- **Climate and hydrologic scenarios.** The Climate Impacts Group provides historical data and future projections of temperature, precipitation, snowpack, streamflow, flooding, minimum flows, and other important hydrologic variables for all watersheds and 112 specific streamflow locations in Washington State, as well as for locations throughout the Columbia River basin and the western US.  
<http://warm.atmos.washington.edu/2860>,<sup>[3]</sup> <http://cses.washington.edu/cig/>
- **Water supply and demand forecast.** The *Columbia River Basin long-term water supply and demand forecast*<sup>K</sup> provides historical data and projected changes in water supply and agricultural demand as a result of climate change. Other demand forecasts (municipal, hydropower, and instream flows) do not incorporate climate change. Results are available for each individual Water Resource Inventory Area (WRIA) in eastern Washington and the Columbia River basin as a whole.  
<http://www.ecy.wa.gov/programs/wr/cwp/forecast/forecast.html>

**Table 6-1.** Projected changes in water resources.

<i>Variable</i>		<i>Projected Long-term Change</i>
<i>Snow</i>	<i>Snowpack</i>	<p>Declines</p> <ul style="list-style-type: none"> <li>▪ Declines projected for <i>all</i> greenhouse gas scenarios; specific amount depends on the amount of greenhouse gases emitted.</li> <li>▪ Projected change in Washington-average April 1<sup>st</sup> snowpack<sup>[B]</sup>; range from a low to a medium greenhouse gas scenario): <ul style="list-style-type: none"> <li>2040s (2030-2059, relative to 1916-2006): -38 to -46%</li> <li>2080s (2070-2099, relative to 1916-2006): -56 to -70%<sup>[D][2]</sup></li> </ul> </li> </ul>
	<i>Glaciers</i>	<p>Declines expected, but there are no published projections for Northwest glacier response to climate change.</p> <ul style="list-style-type: none"> <li>▪ An evaluation of current glacier status found that only 2 of the 12 North Cascades glaciers with annual measurements are expected to survive the current climate.<sup>[4]</sup></li> <li>▪ In the North Cascades, 10% to 44% of total summer streamflow is estimated to originate from glaciers, depending on the watershed.<sup>[5]</sup></li> </ul>
<i>Streamflow</i>	<i>Annual</i>	<p>Mixed, but most models project a small increase in annual streamflow, on average for Washington State.</p> <ul style="list-style-type: none"> <li>▪ Total annual streamflow is projected to increase slightly. <ul style="list-style-type: none"> <li>2040s (2030-2059, relative to 1917-2006): +2.1 to +2.5%</li> <li>2080s (2070-2099, relative to 1917-2006): +4.0 to +6.2%<sup>[D][2]</sup></li> </ul> </li> <li>▪ Changes are small relative to year-to-year variability in streamflow, and models disagree on the direction of change.</li> </ul>
	<i>Winter</i>	<p>Mixed, but most models project an increase in winter streamflow, on average for Washington State.</p> <ul style="list-style-type: none"> <li>▪ Winter (Oct-Mar) streamflow change: <ul style="list-style-type: none"> <li>2040s (2030-2059, relative to 1917-2006): +20 to +16%</li> <li>2080s (2070-2099, relative to 1917-2006): +25 to +34%<sup>[D][2]</sup></li> </ul> </li> <li>▪ Changes are small relative to year-to-year variability in winter streamflow, and models disagree on the direction of change.</li> </ul>
	<i>Summer</i>	<p>Mixed, but most models project a decrease in summer streamflow, on average for Washington State.</p> <ul style="list-style-type: none"> <li>▪ Summer (Apr-Sep) streamflow change: <ul style="list-style-type: none"> <li>2040s (2030-2059, relative to 1917-2006): -30 to -23%</li> <li>2080s (2070-2099, relative to 1917-2006): -44 to -34%<sup>[D][2]</sup></li> </ul> </li> <li>▪ Changes are small relative to year-to-year variability in summer streamflow, and models disagree on the direction of change.</li> </ul>

Variable	Projected Long-term Change
<i>Streamflow timing</i>	<p>Peak streamflows are projected to occur earlier in many snowmelt-influenced rivers in the Northwest.</p> <ul style="list-style-type: none"> <li>Peak streamflow is projected to occur 4 to 9 weeks earlier by the 2080s (2070-2099, relative to 1917-2006) in four Puget Sound watersheds (Sultan, Cedar, Green, Tolt) and the Yakima basin.<sup>[D][2]</sup></li> </ul>
<i>Stream temperatures</i>	<p>Warming</p> <ul style="list-style-type: none"> <li>By the 2080s (2070-2099, relative to 1970-1999)<sup>[O]</sup>, more stream locations are projected to experience weekly summer stream temperatures stressful to adjust salmon (in excess of 67°F):<sup>[6]</sup> <ul style="list-style-type: none"> <li>Eastern Washington: 19% more sites</li> <li>Western Washington: 16% more sites</li> </ul> </li> <li>Many stream locations projected to exceed 70°F for the entire summer season by 2080 – resulting in waters that are warm enough to impede migration and increase the risk of fish kills.<sup>[7]</sup></li> </ul>
<i>Flooding</i>	<p>Increases in most watersheds</p> <ul style="list-style-type: none"> <li>Projected changes in streamflow volume associated with the 100 year (1% annual probability) flood event, by basin type, in Washington State for the 2080s (2070-2099, relative to 1916-2006): <ul style="list-style-type: none"> <li>Rain dominant watersheds: +18% (range: +11 to +26%)</li> <li>Mixed rain-snow watersheds: +32% (range: -33 to +132%)</li> <li>Snow dominant watersheds: -2% (range: -15 to +22%)<sup>[F][P][12]</sup></li> </ul> </li> <li>Projected changes in heavy rainfall (Section 3 of this report) are not included in the above projections. Preliminary research indicates an increase in the proportion of heavy rain events occurring in early fall. Both changes will likely increase flood risk in rain dominant and mixed rain and snow watersheds, especially west of the Cascade crest.<sup>[9]</sup></li> </ul>
<i>Minimum flows</i>	<p>Decreased flow in most watersheds</p> <ul style="list-style-type: none"> <li>Projected changes for changes in 7Q10 flows,<sup>[Q]</sup> by basin type, in Washington State for the 2080s (2070-2099, relative to 1916-2006): <ul style="list-style-type: none"> <li>Rain dominant watersheds: -14% (-44 to -3%)</li> <li>Mixed rain-snow watersheds: -15% (-60 to +14%)</li> <li>Snow dominant watersheds: -6% (-12 to +4%)<sup>[F][P][12]</sup></li> </ul> </li> </ul>

<sup>O</sup> Average projected change for 124 stream locations across Washington State. Projections are made using ten global climate models and a medium greenhouse gas scenario (A1B).

<sup>P</sup> Watersheds were defined as rain dominant if the average winter temperature (Dec-Feb) was greater than 35.6°F (+2°C), mixed rain and snow if the average winter temperature (Dec-Feb) was between 21.2 and 35.6°F (-6 to +2°C), and snow dominant if the average winter temperature (Dec-Feb) was below 21.2°F (-6°C).

<sup>Q</sup> The 7Q10 flow is the lowest 7-day average flow that occurs on average once every 10 years. 7Q10 flows are a common standard for defining low flow for the purpose of setting permit discharge limits.

<i>Variable</i>	<i>Projected Long-term Change</i>
<b>Water Resources</b>	
<i>Irrigation water supply</i>	<p>Increase in water short years in the Yakima River basin, in which water delivery is curtailed to junior water rights growers.</p> <ul style="list-style-type: none"> <li>▪ Likelihood of shortfalls: <ul style="list-style-type: none"> <li>Historical (1975-2004): 14%</li> <li>2020s (2010-2039): 24 to 27%</li> <li>2040s (2030-2059): 31 to 33%</li> <li>2080s (2070-2099): 43 to 68%<sup>[D][14]</sup></li> </ul> </li> </ul>
<i>Hydropower production</i>	<p>Increase in winter, decrease in summer</p> <ul style="list-style-type: none"> <li>▪ Average change for the Columbia River basin for the 2080s (2070-2099, relative to 1917-2006): <ul style="list-style-type: none"> <li>Winter increase: +8 to +11%</li> <li>Summer decrease: -17 to -21%<sup>[D][15]</sup></li> </ul> </li> <li>▪ Annual average cost of lost hydropower for 2030 (relative to 2010) is projected to be \$120 million<sup>[R]</sup>, although estimates range from a slight gain in revenue to much larger losses.<sup>[16]</sup></li> </ul>
<i>Fish and Aquatic Ecosystems</i>	<p>Decline in interior western U.S. trout populations for the 2080s (2070-2099, relative to 1985-2004) for a high greenhouse gas scenario:</p> <p>Suitable habitat extent: -47% (-35 to -77%)<sup>[G][19]</sup></p> <p>Warming stream temperatures are projected to negatively affect salmon health, migration, and survival (see above).</p>
<i>Municipal Water Supply</i>	<p>Changes in climate affect municipal water supply reliability differently for the three cities of Everett, Seattle, and Tacoma.</p> <ul style="list-style-type: none"> <li>▪ Historically, all three cities have had at least 99% reliability, meaning that at most 1% of years experience water delivery shortfalls.</li> <li>▪ Assuming no changes in demand, new sources of supply or significant changes in operating procedures, projected reliability for the 2080s (2070-2099, relative to 1917-2006): <ul style="list-style-type: none"> <li>Everett: 100%</li> <li>Tacoma: 63 to 96%<sup>[H][21]</sup></li> </ul> </li> <li>▪ For Seattle, supply is projected to exceed demand in nearly all years, and the City has identified no or low-cost system modifications to mitigate climate change-related supply reductions, keeping supply above demand under all climate change scenarios examined.<sup>[1][22]</sup></li> </ul>
<i>Ski Season</i>	<p>More warm winters</p> <ul style="list-style-type: none"> <li>▪ Probability of a warm winter (average Dec-Feb temperature above freezing) for Washington State ski resorts:</li> </ul>

<sup>R</sup> Estimated using an intermediate climate change scenario for the 2040s (2030-2059), and linearly interpolating the changes in temperature and precipitation to 2030.

<i>Changing Water Demand</i>	Historic (1971-2000): 0 to 33%, depending on location With +3.6°F <sup>[S]</sup> warming: 33 to 77% <sup>[26]</sup>
	Small increase projected for the near term for the Columbia River basin <ul style="list-style-type: none"> <li>▪ Irrigation demand projected to increase by +4% in eastern Washington by the 2030s (2020-2049; relative to 1977-2006), for a low greenhouse gas scenario.<sup>[K][27]</sup></li> </ul> Small increases in municipal demand projected for the greater Seattle area. <ul style="list-style-type: none"> <li>▪ Municipal demand is projected to increase by 1% in 2025, 2% in 2050, and 5% in 2075 (relative to 2000), assuming current population forecasts and no new conservation measures, based on a high greenhouse gas scenario.<sup>[L][22]</sup></li> </ul>

- [1] Raymondi, R. R. et al., 2013. Water Resources: Implications of changes in temperature and precipitation. Chapter 6 in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*, Washington D.C.: Island Press.
- [2] Elsner, M.M. et al., 2010. Implications of 21st century climate change for the hydrology of Washington State. *Climatic Change* 102(1-2): 225-260.
- [3] Hamlet, A.F. et al., 2013. An overview of the Columbia Basin Climate Change Scenarios Project: Approach, methods, and summary of key results. *Atmosphere-Ocean* 51(4): 392-415. doi: 10.1080/07055900.2013.819555
- [4] Pelto, M.S. 2010. Forecasting temperate alpine glacier survival from accumulation zone observations. *The Cryosphere* 4(1): 67-75.
- [5] Riedel, J. and M.A. Larrabee, 2011. *North Cascades National Park Complex Glacier Mass Balance Monitoring Annual Report, Water Year 2009: North Coast and Cascades Network*. Natural Resource Technical Report NPS/NCCN/NRTR—2011/483. National Park Service, Fort Collins, Colorado.
- [6] Environmental Protection Agency, 2007. Biological evaluation of the revised Washington water quality standards. US EPA, Seattle.
- [7] Mantua, N. et al., 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. *Climatic Change* 102(1-2): 187-223.
- [8] Mote, P.W., et al., 2013. Climate: Variability and Change in the Past and the Future. Chapter 2 in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*, Washington D.C.: Island Press.
- [9] Salathé, E.P. Jr et al., 2013. Estimates of 21st Century Flood Risk in the Pacific Northwest Based on Regional Climate Model Simulations. Submitted
- [10] Lee, S-Y. and A.F. Hamlet, 2011. *Skagit River Basin Climate Science Report*, a summary report prepared for Skagit County and the Envision Skagit Project by the Department of Civil and Environmental Engineering and The Climate Impacts Group at the University of Washington.
- [11] Hamman, J.J., 2012. *Effects of Projected Twenty-First Century Sea Level Rise, Storm Surge, and River Flooding on Water Levels in Puget Sound Floodplains and Estuaries*. Master's Thesis, University of Washington.
- [12] Tohver, I. et al., 2013. Impacts of 21st century climate change on hydrologic extremes in the Pacific Northwest region of North America. *Journal of the American Water Resources Association*, in press.
- [13] Payne, J. T. et al., 2004. Mitigating the effects of climate change on the water resources of the Columbia River basin. *Climatic Change*, 62(1-3), 233-256. doi: 10.1023/B:CLIM.0000013694.18154.d6

<sup>S</sup> +3.6°F relative to 1971-2000 is near the low end of warming projected for mid-century.

- [14] Vano, J.A. et al., 2010. Climate change impacts on water management and irrigated agriculture in the Yakima River Basin, Washington, USA. *Climatic Change* 102(1-2): 287-317.
- [15] Hamlet, A.F. et al., 2010. Effects of projected climate change on energy supply and demand in the Pacific Northwest and Washington State. *Climatic Change* 102(1-2): 103-128.
- [16] Northwest Power and Conservation Council, 2013. *The Sixth Northwest Electric Power and Conservation Plan*. <http://www.nwcouncil.org/energy/powerplan/>
- [17] Markoff, M. S. and A.C. Cullen. 2008. Impact of climate change on Pacific Northwest hydropower. *Climatic Change* 87(3-4): 451-469.
- [18] Battin, J. et al., 2007. Projected impacts of climate change on salmon habitat restoration. *Proceedings of the National Academy of Sciences* 104(16): 6720-6725.
- [19] Wenger, S.J. et al., 2011. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. *Proceedings of the National Academy of Sciences* 108(34): 14175-14180.
- [20] Oregon Department of Land Conservation and Development, 2010. *The Oregon Climate Change Adaptation Framework*. [http://oregon.gov/ENERGY/GBLWRM/docs/Framework\\_Final\\_DLCD.pdf](http://oregon.gov/ENERGY/GBLWRM/docs/Framework_Final_DLCD.pdf)
- [21] Vano, J.A. et al., 2010. Climate change impacts on water management in the Puget Sound region, Washington State, USA. *Climatic Change* 102(1-2): 261-286.
- [22] Seattle Public Utilities, 2013. *2013 Water System Plan: Our Water. Our Future*. Volume 1, July 2012. <http://www.seattle.gov/util/MyServices/Water/AbouttheWaterSystem/Plans/WaterSystemPlan/index.htm>
- [23] VanRheenen, N.T. et al., 2003. Evaluating potential climate change impacts on water resource system operations: Case studies of Portland, Oregon and Central Valley, California. *Water Resources Update* 124: 35-50.
- [24] (IPCC) Intergovernmental Panel on Climate Change. 2013. *Working Group I, Summary for Policymakers*. Available at: [http://www.climatechange2013.org/images/uploads/WGIAR5-SPM\\_Approved27Sep2013.pdf](http://www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf)
- [25] (IPCC) Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- [26] Nolin, A.W., and C. Daly. 2006. Mapping “at risk” snow in the Pacific Northwest. *Journal of Hydrometeorology* 7(5): 1164-1171.
- [27] Yorgey, G.G. et al., 2011. *Technical Report – 2011 Columbia River Basin Long-Term Water Supply and Demand Forecast*. WA Department of Ecology, Ecy. Pub. #11-12-011.
- [28] Palmer, R.N. and M.A. Hahn, 2002. The Impacts of Climate Change on Portland's Water Supply: An Investigation of Potential Hydrologic and Management Impacts on the Bull Run System. Report prepared for the Portland Water Bureau, University of Washington, Seattle. 139 pp.
- [29] Hamlet, A.F., 2011. Assessing water resources adaptive capacity to climate change impacts in the Pacific Northwest Region of North America. *Hydrology and Earth System Sciences* 15(5):1427-1443, doi:10.5194/hess-15-1427-2011.
- [30] EPA, 2010. *Climate Change Vulnerability Assessments: A Review of Water Utility Practices*. U.S. EPA Report 800-R-10-001 U.S. Environmental Protection Agency.
- [31] King County Department of Natural Resources and Parks, cited 2009: *Synthesis of the Regional Water Supply Planning Process*. <http://www.govlink.org/regional-water-planning/docs/process-synthesis.htm>
- [32] King County, Washington. 2012. *Strategic Climate Action Plan*. December 2012. [http://your.kingcounty.gov/dnrp/climate/documents/2012\\_King\\_County\\_Strategic\\_Climate\\_Action\\_Plan.pdf](http://your.kingcounty.gov/dnrp/climate/documents/2012_King_County_Strategic_Climate_Action_Plan.pdf)
- [33] City of Anacortes, 2012. “City of Anacortes, Water Treatment Plant, Climate Change Impact Mitigation.” Presentation to Washington State Senate Environment Committee by City of Anacortes Public Works, Committee Working Session, November 30.
- [34] Reeder, W.S. et al., 2013. Coasts: Complex changes affecting the Northwest's diverse shorelines. Chapter 4 in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*, Washington D.C.: Island Press.

- <sup>[35]</sup> U.S. Bureau of Reclamation, 2011. *Yakima River Basin Study, Volume 1: Proposed Integrated Water Resource Management Plan*. WA Dept of Ecology publication no. 11-12-004.
- <sup>[36]</sup> U.S. Bureau of Reclamation, 2011. *Climate and Hydrology datasets for use in the River Management Joint Operating Committee (RMJOC) Agencies' Longer-Term Planning Studies. Part IV – Summary*.