
SECTION 3

How will Climate Change Affect the Water Cycle?

The Puget Sound region is projected to experience an ongoing decrease in snowpack and glaciers, a continued shift from snow to rain, increasing stream temperatures, a continued shift to earlier peak streamflows, an increase in the frequency and extent of flooding, and declining summer flows. These changes, which have widespread implications for people, infrastructure, and ecosystems, will be most pronounced in mid-elevation basins that have historically received a mix of rain and snow during winter. Most Puget Sound watersheds will be rain-dominant by the end of the 21st century. Combined with sea level rise and an increase in the intensity of heavy rain events, the decrease in snow accumulation will contribute to a widespread increase in the frequency and size of winter flood events. Impacts on water users and ecosystems vary, but generally point to increased competition for water during the summer and increased flood risk in winter. Efforts to address hydrologic impacts are increasing, particularly in the areas of flood risk reduction, water supply planning, and hydropower.

Climate Drivers of Change

DRIVERS *Changes in snowpack, streamflow, and other aspects of the water cycle are driven by changes in temperature, heavy rainfall, and seasonal precipitation.* Non-climatic factors, including reservoir management and changes in land use and land cover can also have an important influence.

- *Observations show a clear warming trend, and all scenarios project continued warming during this century.* Most scenarios project that this warming will be outside of the range of historical variations by mid-century (see Section 2).^{1,2} As a consequence, there is high confidence in the warming-related changes in water resources.
- *Heavy rain events are projected to become more intense.* Current research is consistent in projecting an increase in the frequency and intensity of heavy rain events.³
- *Most models are consistent in projecting a substantial decline in summer precipitation.* Projected changes in other seasons and for annual precipitation are not consistent among models, and trends are generally much smaller than natural year-to-year variability. Overall, there is much lower confidence in the precipitation-dependent changes in water resources.²
- *Although climate is a major driver of changing hydrology, there are other factors that*

can have an important effect on streamflow and water availability. For instance, changes in land use and land cover – both due to development and forest management – can dramatically affect the hydrology of the region.⁴ Similarly, many watersheds contain reservoirs, which are often used to control the timing and amount of river flows. Changes in reservoir operations can have substantial effects on streamflow, and represent potential adaptation opportunities. Although some studies have recently begun assessing the combined effects of changes in climate, water management, and land use,^{4,5,6,7} previous studies have typically evaluated the effect of climate change in the absence of changes in other factors influencing the region’s hydrology. Unless otherwise noted, the hydrologic projections cited in this report consider only the effects of climate change, against which the effects of other changes can be compared.

Observed Changes in Snow, Ice, and Streamflow

OBSERVED Long-term changes in snow, ice, and streamflows reflect the influence of warming on the hydrology of the Puget Sound region.^A

- *Spring snowpack is declining.* Spring snowpack fluctuates substantially from year-to-year, but declined by about –25% (or about –4%/decade) in the Washington Cascades^B from the mid-20th century to 2006.^{8,9,10} This trend is due primarily to regional warming, but reflects the influence of both climate variability and change.^{11,12} Natural variability can dominate over shorter time scales. For example, there was an apparent (though not statistically-significant) increase in spring snow accumulation from 1976 to 2007.^{C,8}
- *Most Puget Sound glaciers are in decline.* Observed decreases range from a –56% ($\pm 3\%$) loss of glacier area in the North Cascades (1900-2009)¹³ to a –34% decline in area in the Olympic Mountains (1980-2009).¹⁴ In addition to the observed declines in glacier area, observations show consistent decreases in glacier volume and the total number of glaciers remaining.^{14,15} One recent study found that the number of glaciers in the Olympics had declined by –31% (from 266 glaciers in 1980 to 184 in 2009).¹⁴ Trends vary substantially from decade-to-decade. For example, total glacier area in the North Cascades declined rapidly for the first half of the 20th century, followed by a period of little change, then an additional decline since the 1990s.^{13,16} In the North Cascades, 10% to 44% of total summer streamflow is estimated to

^A Throughout this report, the term “Puget Sound” is used to describe the marine waters of Puget Sound and the Strait of Juan de Fuca, extending to its outlet near Neah Bay. The term “Puget Sound region” is used to describe the entire watershed, including all land areas that ultimately drain into the waters of Puget Sound (see “How to Read this Report”, page vi).

^B Many characteristics of Puget Sound’s climate and climate vulnerabilities are similar to those of the broader Pacific Northwest region. Results for Puget Sound are expected to generally align with those for western Oregon and Washington, and in some instances the greater Pacific Northwest, with potential for some variation at any specific location.

^C In this section, trends are reported if they are statistically significant at the 90% confidence level or more.

originate from glaciers, depending on the watershed.¹⁷

- *Trends in annual streamflow are weak, but dry years are becoming drier for some rivers.* There is no statistically significant trend in annual average streamflow.^{18,19} However, some Puget Sound rivers show a statistically significant trend towards lower streamflow in dry years (i.e.: “dry years get drier”).^{18,20,21}
- *The timing of streamflow is shifting earlier.* The spring peak in streamflow is occurring earlier in the year for many snowmelt-influenced rivers in the Puget Sound region (observed over the period 1948-2002) as a result of decreased snow accumulation and earlier spring melt.²²

Projected changes in Hydrology

PROJECTED *As is the case for much of the western U.S., the Puget Sound region is projected to experience decreasing snowpack, a continued shift from snow to rain, increasing stream temperatures, earlier streamflow timing, increased flooding, and declining 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 3-1 and 3-2, Table 3-2).^{D,E,23}

PROJECTED *Snowpack and glaciers in the Puget Sound region are projected to decline.* As air temperatures warm, snow is projected to accumulate less in winter and melt more rapidly in spring and summer.

- *Snowpack is projected to decline.* Average spring snowpack in the Puget Sound region is projected to decline by –42% to –55% by the 2080s (2070-2099, relative to 1970-1999), on average, for a low and a high greenhouse gas scenario.^{F,G,H,I,24}

^D 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 air 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 changes as a consequence of warming. Washington watershed classifications are shown in Figure 3-1.

^E In this section, projected changes are primarily reported for the 2080s. Longer planning horizons are often most applicable to infrastructure planning, water resource management, and forest management. Other management situations (e.g., agriculture, public health) are more suited to shorter planning horizons.

^F 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; “moderate” 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 1 for more details.

^G These numbers indicate changes in April 1st Snow Water Equivalent (SWE). SWE is a measure of the total amount of water contained in the snowpack. April 1st is the approximate current timing of peak annual snowpack in the mountains of the Northwest. Changes are only calculated for locations that regularly accumulate snow (historical April 1st SWE of at least 10 mm, or about 0.4 inch, on average).

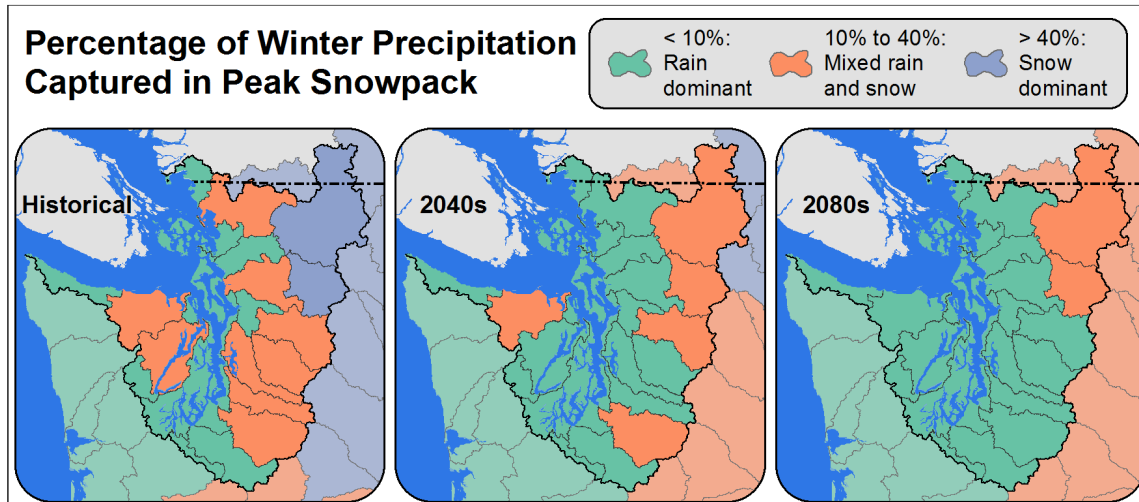
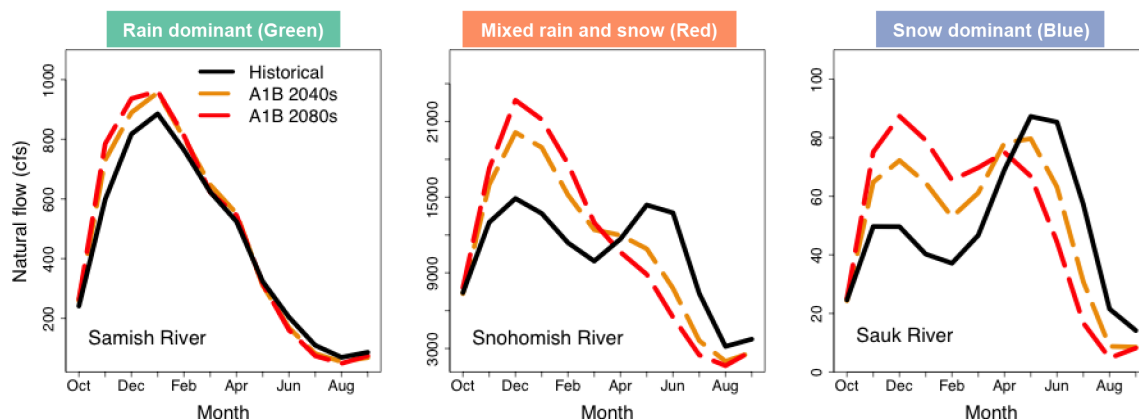


Figure 3-1. Models project a dramatic shift to more rain-dominant conditions in Puget Sound watersheds. Maps above indicate current and future watershed classifications, based on the proportion of winter precipitation stored in peak annual snowpack. Graphs below indicate current and future average monthly streamflow for these watershed types. Both compare average historical conditions (1970-1999) and average projected future conditions for ten global models, two time periods: the 2040s (2030-2059) and the 2080s (2070-2099), and a moderate 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 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 shading in the maps. 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 and summer flows as a result of warming (below, center). By the end of the 21st century, Puget Sound will no longer have any snow dominant watersheds, and only a few remaining that can be classified as mixed rain and snow. *Data source: Hamlet et al., 2013.*²⁴



- *Although only two studies have assessed the implications of 21st century climate change for Puget Sound glaciers, both indicate that continued recession is likely.* One study found that only two of the 12 North Cascades glaciers with annual measurements are expected to survive under current climate conditions, regardless of future warming.²⁷ Another study modeled glacier response in three Puget Sound tributaries (Thunder Creek and the Cascade and Nisqually Rivers). All scenarios showed that glaciers remained in 2100, but that glacier area declined substantially, particularly after mid-century.²⁸

PROJECTED As watersheds become increasingly rain dominant, streamflow is projected to increase in winter and decrease in spring and summer, and the timing of peak flows is projected to shift earlier. Although total annual streamflow is only projected to change slightly, the seasonal timing of streamflow is projected to shift earlier in snow-influenced watersheds, with warming bringing higher flows in winter and lower flows in summer. Changes in streamflow are smaller in lowland basins due to the lack of winter snow accumulation; in these basins, land use and development patterns may have a larger influence than climate change.

- *Watersheds will become increasingly rain-dominant.* By the end of the 21st century, the dominant form of precipitation in most Puget Sound watersheds will be rainfall (Figure 3-1). In contrast, many have historically been strongly influenced by snowfall in winter. The two exceptions are the Upper Skagit and Sauk watersheds in the North Cascades: due to their relatively higher elevation, snow accumulation is projected to remain important through 2100, in spite of substantial declines in winter snowpack.
- *Streamflow timing is projected to shift earlier.* 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 3-1). For the 12 major Puget Sound watersheds analyzed, peak streamflow is projected to occur about two to six weeks earlier, on average, by the 2080s (2070-2099, relative to 1970-1999) for a moderate greenhouse gas scenario (A1B).^{J,K,L,24}

^H Projected change for ten global climate models, averaged over Puget Sound. Range spans from a low (B1) to a moderate (A1B) greenhouse gas scenario.

^I There are two principal datasets that are often used to evaluate hydrologic projections for Puget Sound and the greater Pacific Northwest: (1) The latest set of projections, developed by Mote et al. in 2015,²⁵ which stem from the newer 2013 IPCC report,²⁶ and (2) the previous set of projections, developed by Hamlet et al. in 2010,²⁴ based on the climate projections used in the IPCC's 2007 report.³² Although newer, the more recent projections appear to have temperatures that are too cold in mountainous areas. For this reason, most of the results presented in this section stem from the 2010 dataset. For comparison, we have included a summary of the newer projections in Appendix A.

^J Projected changes in streamflow were calculated for 12 Puget Sound watersheds. Listed in clock-wise order, starting at the US-Canadian border, they are: the Nooksack R. at Ferndale (USGS #12213100), Samish R. Nr. Burlington (USGS #12201500), Skagit R. Nr. Mt Vernon (USGS #12200500), Stillaguamish R. (Flows were obtained for the NF Stillaguamish R. Nr. Arlington, USGS #12167000, then scaled to the river mouth based on the ratio of basin area and total precipitation), Snohomish R. at Snohomish (USGS #12155500), Cedar R. at Renton (USGS #12119000), Green R. at Tukwila (USGS #12113350), Nisqually R. at McKenna (USGS #12089500), Puyallup R. at Puyallup (USGS

- *Projected increase in annual streamflow is small.* Annual streamflow is projected to increase by +6 to +7% on average for the Puget Sound region by the 2080s (2070-2099, relative to 1970-1999).^{H,24} These changes are likely to be dwarfed by natural year-to-year variations through the end of the century.
- *Winter streamflow is projected to increase.* Total winter streamflow for the Puget Sound region is projected to increase by +28 to +34% on average by the 2080s (2070-2099, relative to 1970-1999).^{H,24}
- *Summer streamflow is projected to decrease.* Total summer streamflow for the Puget Sound region is projected to decrease by -24 to -31% on average by the 2080s (2070-2099, relative to 1970-1999).^{H,24}
- *There are no published projections of changing streamflow variability.* Although the shift to a more rain dominant regime could lead to more variability in winter streamflow, no study has quantified the effect.
- *Most streamflow projections do not consider the effects of reservoir operations.* Although there are exceptions (discussed below), few of the published studies account for the effects of reservoir management on changing streamflows. In basins with sufficient reservoir capacity, some of the previously cited changes (e.g., decreasing summer streamflow) could potentially be mitigated via changes in flow regulation.
- *Land-use change could have a greater effect than climate change on the magnitude and timing of streamflow in some lowland basins.* One study recently evaluated changes in streamflow due to land cover and climate change for the Puget Sound basin for 2050 (2035-2065, relative to 1970-1999), based on a moderate (A1B) greenhouse gas scenario.^M The simulations showed that changes in streamflow for snow-influenced watersheds are primarily driven by climate change, but that low-elevation (rain dominant) watersheds could be more strongly influenced by changes in development and land use.^{5,7} The climate change simulations did not include recent projections for an increase in the intensity of heavy rain events (see below),²⁹ which could alter the results for lowland basins.

PROJECTED Flood risk is projected to increase. Multiple factors combine to drive large increases in flood risk: declining snowpack, intensifying heavy rain events, and rising seas.

- *Peak river flows are projected to increase.* The highest river flows are expected to increase by +18% to +55%, on average, for 12 Puget Sound watersheds^L by the

#12101500), Skokomish R. Nr. Potlach (USGS #12061500), Dungeness R. at Dungeness (USGS #12049000), and Elwha R. at McDonald Bridge Nr. Port Angeles (USGS #12045500).

^K Calculations are based on the change in streamflow “Center Timing” (CT). CT is defined as the day of the water year (starting on October 1st) when cumulative streamflow reaches half of its total annual volume.

^L Projected change for ten global climate models for a moderate (A1B) greenhouse gas scenario.

^M Land use and land cover change scenarios, which were compared to climate change projections, were based on the years 2002, 2027, and 2050.

2080s (2070-2099, relative to 1970-1999), based on a moderate (A1B) greenhouse gas scenario.^{H,24} Although most scenarios project increases in flood flows, some project small decreases for rain dominant watersheds, where changes in winter snow accumulation are minor. These projections do not include projected increases in the intensity of heavy rain events.

- *Increases in heavy rainfall events could further increase flood risk.* Heavy rainfall events are projected to become more severe by mid-century (see Section 2). Global models project that the heaviest 24-hour rain events in the Pacific Northwest will intensify by +19%, on average, by the 2080s (2070-2099, relative to 1970-1999).^{N,3} These changes are not included in current hydrologic change modeling for the region, but would likely lead to a further increase in peak streamflows, adding to the projected increases cited above.^{24,25}
- *Changes in flood management may not always be sufficient to mitigate increases in flood risk.* In the Skagit River, for instance, with current flood management practices, the magnitude of the 100-year peak streamflow event is projected to increase by +49% on average by the 2080s (2070-2099, relative to 1970-1999).^O Simulations indicate that even with changes in water management designed to decrease peak flows, the 100-year flood flow will still increase by +42% (only 7% less than with current practices). The risk of flooding remains high because the dams on the Skagit only affect a portion of the watershed – other major uncontrolled tributaries contribute substantially to downstream flooding.^{P,5,6}
- *Sea level rise will exacerbate coastal river flooding.* Higher sea level can increase the extent, depth, and duration of flooding by making it harder for flood waters in rivers and streams to drain to Puget Sound. In the Skagit River floodplain, the area flooded during a 100-year event is projected to increase by +74% on average by the 2080s (2070-2099, relative to 1970-1999), when accounting for the combined effects of sea level rise and larger floods.^{Q,30,31,32} A similar study found that the 10-year event would flood +19% to +69% more area in the lower Snohomish River floodplain by the 2080s.^{R,33}

^N Projections are based on an analysis of the 99th percentile of daily water vapor transport, the principal driver of heavy rain events in the Pacific Northwest. Projections stem from 10 global climate model projections and a high greenhouse gas scenario (RCP 8.5). Projected changes in intensity were evaluated for latitudes ranging from 40 to 49N. Although global models are coarse in spatial scale, previous research has shown that they can adequately capture the dynamics that govern West coast storms and heavy precipitation events.

^O Projected change based on five global climate models and a moderate (A1B) greenhouse gas scenario.

^P Results are based on a reservoir operations model, five global climate model simulations, and the moderate A1B greenhouse gas scenario.

^Q Sea level rise projections were obtained from the 2007 IPCC report³²; streamflow projections were based on 10 global climate model projections and a moderate (A1B) greenhouse gas scenario. Flood simulations assume all levees would remain intact, although they could be overtopped. When levee failure scenarios are included, the increase in flooded area is much less pronounced. With levee failure, much of the floodplain would be inundated even in the absence of climate change – increased flows and higher sea levels do increase water depths, but do not significantly change the area flooded.

PROJECTED Low flow extremes are projected to become more severe.

- *Summer minimum flows are projected to lower.* Low summer streamflow conditions are projected to become more acute in all Puget Sound watersheds analyzed, decreasing by –16% to –51% on average for the 2080s (2070-2099, relative to 1970-1999).^{L,24} Rain dominant and mixed rain and snow basins show the greatest and most consistent decreases in minimum flows; changes in snow dominant basins are smaller.³⁴ These projections do not account for expected changes in the supply of meltwater from glaciers.
- *Summer meltwater from some glaciers may initially increase, but the supply of meltwater is projected to decline sharply by the end of the century.* Projections indicate that glaciers may augment minimum flows through mid-century due to the increased rate of melt, but nearly all scenarios show a sharp decline in glacial meltwater in the late 21st century as glaciers diminish further in size.²⁸

PROJECTED Water temperatures are projected to increase. Stream temperatures are doubly affected by climate change: both by warmer air temperatures and declining summer flows.

- *Stream temperatures are projected to increase.* River and stream temperatures generally track air temperatures, but do not change as rapidly. In Puget Sound, stream temperatures are projected to increase by +4.0°F to +4.5°F by the 2080s (2070-2099, relative to 1970-1999),^{S,35} in response to increasing air temperature and decreasing summer streamflow.
- *Puget Sound rivers are projected to more frequently exceed thermal tolerances for cold-water fish species.* By the 2080s, the number of river miles with August stream temperatures in excess of thermal tolerances for adult salmon (64°F) and charr (54°F)^{T,36} is projected to increase by 1,016 and 2,826 miles, respectively.^{S,35} Many are projected to exceed thermal tolerances for the entire summer season, despite rarely being in excess of these temperatures in the recent past.³⁷
- *The duration of time exceeding thermal tolerances is projected to increase.* One study examining 37 Puget Sound stream monitoring stations found that 12 of the 37 sites currently experience weekly average stream temperatures in excess of 64°F.^{T,36} By the 2080s (2070-2099, relative to 1970-1999), these 12 streams are projected to experience an increase in the duration of stream temperatures above the 64°F

^R 2070-2099, relative to 1970-1999. Projections are based on 10 global climate model simulations and the moderate (A1B) greenhouse gas scenario.

^S Based on a composite of ten global climate model projections for a moderate (A1B) greenhouse gas scenario.

^T In this report we use the regulatory thresholds listed in EPA (2007),³⁶ which defines 12°C (54°F) and 17.5°C (64°F) as the criteria for protecting adult charr and salmon, respectively. Note that some analyses consider the average monthly water temperature for August, which will likely result in an underestimate of the implications for maximum weekly August temperatures. Optimal water temperature ranges for Pacific salmon are species-, life-stage-, and size-dependent, so individual responses to warming streams will vary.

threshold, ranging from an average annual increase of +0 to +7.5 weeks.^{U,44}

PROJECTED *Year-to-year variability will continue to cause some periods that are abnormally wet, and others that are abnormally dry.* For the foreseeable future, the region will continue to experience years and decades with conditions that temporarily mask or amplify the projected changes in water resources, even as long-term trends continue. For example, even late in the 21st century individual years can have as much spring snowpack as the historical average, in spite of substantial declines overall.

PROJECTED *These changes will have far-reaching consequences for people, infrastructure and ecosystems across the Puget Sound region.* Climate change effects 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 the effects on one sector – i.e., hydropower production, irrigation or municipal supply, or instream flows for fish – could exacerbate the effects on other sectors.³⁸

- *Hydropower production is projected to decrease in summer, and increase in winter and spring.* Hydropower production is projected to reflect the seasonal changes in streamflow: increases in winter, and decreases in summer. Estimating the specific effects on hydropower systems is challenging, given the relatively rapid changes in demand, energy markets, and regulation. For the Skagit watershed, hydropower production is projected to increase in winter and spring and decrease in summer, though there is debate about the exact amount of change, given the large influence of reservoir management.^{P,39} In the Columbia River basin, an important source of power for much of Puget Sound, hydropower production is projected to increase by +5% in winter (January-March) and decrease by -12 to -15% in summer (July-September) by the 2040s (2070-2099, relative to 1970-1999).^{H,V,40} These declines could translate into an inability to meet summer power demands with hydropower alone – this would require energy suppliers to seek other energy sources, possibly at higher cost.^{41,42}
- *Many Pacific salmon populations could be harmed by warming stream temperatures, increasing winter peak flows, and decreasing summer low flows.* These changes may affect salmon growth and survival across many life stages and habitats,⁴³ particularly for salmon populations that have an in-stream rearing life stage (e.g., steelhead, stream-type Chinook salmon, sockeye salmon, and Coho).⁴⁴ Some species and sub-populations may remain relatively unharmed by climate change or may have access to cold water “refugia” within their normal range, affording them some

^U Based on an average of 10 global climate model projections and a moderate (A1B) greenhouse gas scenario.

^V The Columbia River Treaty, which governs flood control and power generation benefits provided by Columbia basin reservoirs in the U.S. and Canada, is due to be updated. Any revisions to the treaty may require changes in reservoir operations on both sides of the border, which would have consequences for hydropower.

protection from increased temperatures elsewhere. Population diversity may also provide a buffer for species decline, as populations that are more adapted to warm conditions survive and reproduce in greater numbers (see Section 10).

- *Flood protection and stormwater management could become more costly.* 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 (see Sections 5 and 12).⁴⁵
- *Existing studies find that the reliability of municipal water supply is largely unaffected.* 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 1970-1999) and decrease to 93-96% for Tacoma under low and moderate greenhouse gas scenarios.^{W,X,46} For Seattle, previous studies found that supply is projected to exceed demand in nearly all years through the end of the 21st century.^{46,47} Current work, based on the high end of the latest set of climate projections, suggests that Seattle's water supply could be more strongly affected by warming.^Y
- *Small increases in municipal demand are 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 (relative to 2000), assuming current population forecasts, no new conservation measures, and the warming projected based on a high greenhouse gas scenario.^{Z,46,47}
- *Consequences for management are likely to be greatest in snow-influenced basins where water conflicts already exist.* 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.^{W,48,49,50,51}
- *The ski season is projected to shorten.* Historically (1971-2000), Washington ski areas have experienced warm winters (average December-February air 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 (see Section 2) – warm winters would occur 33 to 77% of the

^W Reliability is defined as the probability of meeting municipal water supply demand in a given water year (Oct-Sep).

^X 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 moderate (A1B) greenhouse gas scenario.

^Y Based on preliminary results from research conducted by Seattle Public Utilities. At the time of this writing, the full set of model results have not yet been analyzed.

^Z Projection based on the IPSL global climate model coupled with a high greenhouse gas scenario (A2).

time.^{AA,52}

Climate Risk Reduction Efforts

CLIMATE RISK REDUCTION *Many Puget Sound communities, government agencies, and organizations are preparing for the effects 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:

- *King County has begun modifying its flood infrastructure in preparation for projected flooding increases.* New projects include:
 - *Levee improvements and flood-risk reduction activities.* King County formed a new Flood Control District in 2007 to increase county capacity for addressing regional flood risks due to a variety of factors, one of which was climate change. The creation of the new District resulted in a ten-fold increase in local funding^{BB} for flood risk reduction efforts. Accomplishments in 2014 include mapping of channel migration hazards along the Cedar River, completing a critical levee extension project, implementing five projects that raised structures in flood zones, and purchasing forty-two acres of floodplain on the Tolt, Snoqualmie, Cedar, and White rivers (including 20 acres in Pierce County). Public ownership of this land and removal of structures will reduce flood risks and preclude development in these flood prone areas.^{53,54}
 - *Widening bridge spans and increasing the resilience of roads.* As of 2012, King County had replaced 15 short span bridges with wider span structures and 42 small culverts with large box culverts. These changes will increase resilience of bridges and roads to major flooding. In many cases these wider structures also allow for the movement of a variety of wildlife along the river's edge during normal flows and elevated flood events thereby protecting wildlife connectivity between critical habitats.⁵³ King County's Road Services Division^{CC} will incorporate information about changes in future flooding, storm size and frequency, and landslide risk projections into roads maintenance and preservation programs and projects.⁵⁴
- *Preparing interstate and state routes in the Skagit River basin for climate change.* WSDOT recently completed a project which developed site-specific adaptation

^{AA} 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.

^{BB} Funding for the Flood Control District comes from a county-wide property levy of 10 cents per \$1,000 assessed value. This amounts to \$40 per year on a \$400,000 home. The levy raises roughly \$36 million a year.
<http://www.kingcountyfloodcontrol.org/>

^{CC} King County's Road Services Division maintains roads, bridges, culverts, and other related infrastructure in unincorporated King County.⁵⁴

options to improve the resilience of Interstate 5 and state routes in the Skagit basin (Figure 12-2). For example, in response to Skagit River flooding on North SR 9 WSDOT highlighted two options that will reduce flood concerns for this route and will improve transportation infrastructure resilience to future flood events: (1) develop a new road alignment out of the floodway, and (2) raise the road in existing alignment.⁵⁵ This work complements flood hazard reduction strategies proposed by the U.S. Army Corps and Skagit County.

- *Washington State is incorporating climate change in multi-benefit flood risk management.* Through the Floodplains by Design program, the Washington State Department of Ecology is beginning to incorporate climate risk into state funding programs by prioritizing floodplain infrastructure projects that provide holistic solutions that consider the effects on people, agriculture, and ecosystems. Many projects – such as the Calistoga levee setback project in Orting – result in additional storage for flood waters, thus reducing the downstream risk of flooding. Project proposals are evaluated, in part, on the extent to which they address the risks posed by climate change.

Drinking water supply:

- *Seattle is taking steps to ensure supply exceeds demand for Seattle.* Seattle Public Utilities 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 water supply reductions and demand increases. Previous analyses undertaken by the City indicate that no new source of water supply is needed before 2060 and that, under the warmest scenario considered, available supply would exceed forecasted demand if all modifications are implemented. Depending on the relative timing of system modifications and climate change effects, climate change could increase the frequency of requests to customers to curtail water use.⁴⁷
- *The new Anacortes Water Treatment Plant was designed to be robust to climate change.* 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 (completed 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.^{56,57}

Long-range planning:

- *The 2009 Regional Municipal Water Supply Outlook included an assessment of the effects of climate change on water supply.* The report was developed by the Central Puget Sound Water Supply Forum, a collaboration among cities and agencies within Snohomish, King, and Pierce Counties. The Outlook included an evaluation of the combined effects of changing municipal supply and demand in 2007, along with an evaluation of possible water supply and conservation projects. Under all climate

change and demand scenarios, the study found that existing water supplies are sufficient to meet demands through 2050. By 2060, the municipal water supply shortage could be as great as 100 million gallons per day,^{DD} though the study also identified about 400 million gallons per day in water supply and conservation projects.⁵⁸ Scenarios are currently being evaluated for an updated edition of the report.

For more details on projected effects on Rivers and Streams, see Tables 3-1, 3-2 and 3-3.

^{DD} Based on 3 statistically-downscaled global model projections and a low (B1) and high (A2) greenhouse gas scenario.

Additional Resources on Current and Future Water Resources

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

- **Western U.S. Streamflow Metrics.** Modeled flow metrics (e.g.: peak streamflow, flow timing) for streams in the Western U.S. for historical and future climate change scenarios. Data available for the Pacific Northwest, which includes the Puget Sound catchment.
http://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml
- **USGS Water Watch.** Map of current streamflow compared to historical flow for Washington. <http://waterwatch.usgs.gov/?m=real&r=wa>
- **Climate, hydrologic, and vegetation change scenarios.** The Pacific Northwest Climate Impacts Research Consortium recently completed a new set of projections, which include changes in climate, hydrology, and vegetation. The projections are produced at a daily time step and a spatial resolution of about four miles, and are based on the newest set of climate model projections (IPCC 2013,²⁶ see Section 1). <http://climate.nkn.uidaho.edu/IntegratedScenarios/index.php>
- **Climate and hydrologic scenarios.** The Climate Impacts Group provides downscaled daily historical data and projected future temperature, precipitation, snowpack, streamflow, flooding, minimum flows, and other important hydrologic variables for all watersheds and specific streamflow locations throughout the Columbia River basin and the western U.S. The projections are produced at a daily time step and a spatial resolution of about four miles, and are based on the previous set of climate model projections (IPCC 2007).³²
<http://warm.atmos.washington.edu/2860>,²⁴ <http://cig.uw.edu/datasets/wus/>⁵⁹
- **Coastal Resilience Floodplain Explorer.** The Nature Conservancy has created a web-based mapping tool that combines sea level projections with other information on land use, infrastructure, and ecosystems. Users can also upload their own data for viewing alongside existing layers.
<http://maps.coastalresilience.org/pugetsound/>⁶⁰

Table 3-1. Observed changes in water resources.

<i>Variable</i>	<i>Observed Change</i>								
Hydrology									
<i>Snowpack</i>	<p>Long-term trends in snowpack show a robust decline.</p> <ul style="list-style-type: none"> ▪ Washington Cascades snowpack decreased by about –25% (or about –4% per decade) between the mid-20th century and 2006, with a range of –15 to –35% depending on the starting date of the trend analysis (which ranged from about 1930 to 1970).^{8,9,10,11} ▪ The frequently-reported increase in snowpack in recent decades (1976–2007) is not statistically-significant and is most likely the result of natural variability.⁸ ▪ There are no published studies that have assessed observed changes in snowpack specific to the Puget Sound basin. Most have focused on the Washington Cascades or Pacific Northwest as a whole. 								
<i>Glaciers</i>	<p>Observations show declines in the number, area, and volume of Puget Sound glaciers.</p> <ul style="list-style-type: none"> ▪ Mt. Rainier: –14% decline in glacier volume (1970-2008)⁶² ▪ Olympic Mtns: –34% decline in glacier area (1980-2009)¹⁴ –31% decline in number of glaciers (1980-2009).¹⁴ ▪ North Cascades: –56±3% decline in glacier area (1900-2009)¹³ <p>Trends in glacial melt vary from decade to decade.</p> <ul style="list-style-type: none"> ▪ Example: North Cascades ¹³ <table style="margin-left: 40px;"> <tr> <td>1900-1958:</td> <td>–46±5% decline in glacier area</td> </tr> <tr> <td>1958-1990:</td> <td>–1±3%</td> </tr> <tr> <td>1990-2009:</td> <td>–9±3%</td> </tr> <tr> <td><i>Overall:</i></td> <td>–56±3% ¹³</td> </tr> </table> ▪ In the North Cascades, 10% to 44% of total summer streamflow is estimated to originate from glaciers, depending on the watershed.¹⁷ 	1900-1958:	–46±5% decline in glacier area	1958-1990:	–1±3%	1990-2009:	–9±3%	<i>Overall:</i>	–56±3% ¹³
1900-1958:	–46±5% decline in glacier area								
1958-1990:	–1±3%								
1990-2009:	–9±3%								
<i>Overall:</i>	–56±3% ¹³								
<i>Annual Streamflow</i>	<p>Dry years are becoming more dry.</p> <p>Trends in annual streamflow are relatively small in comparison to year-to-year variability, and almost none are statistically significant.^{18,19} However, a study examining 43 Pacific Northwest gauges (including 5 in Puget Sound) found declining trends in dry years (25th percentile in annual flow), ranging from –19% to –31% (1948-2006), with 3 of the 5 Puget Sound gauges</p>								

<i>Variable</i>	<i>Observed Change</i>
<i>Timing of Peak Streamflow</i>	<p>showing a statistically-significant trend.¹⁸</p> <p>The timing of streamflow is shifting earlier for most locations.</p> <ul style="list-style-type: none"> The spring peak in Puget Sound streamflow has shifted earlier in many snowmelt-influenced rivers. The shift ranges from no change to about 20 days earlier (1948-2002).²²

Table 3-2. Projected changes in water resources.

<i>Variable</i>	<i>Projected Long-term Change^H</i>
Snow	
<i>Snowpack</i>	<p>Snowpack is projected to decline substantially</p> <ul style="list-style-type: none"> Declines projected for <i>all</i> greenhouse gas scenarios; specific amount depends on the amount of greenhouse gases emitted.^F Projected change in April 1st snowpack^G, on average for Puget Sound:^{H,24} <p>2040s (2030-2059, relative to 1970-1999):</p> <p>low emissions (B1): -23% (range: -34 to -6%)</p> <p>moderate emissions (A1B): -29% (range: -47 to -4%)</p> <p>2080s (2070-2099, relative to 1970-1999):</p> <p>low emissions (B1): -42% (range: -59 to -12%)</p> <p>moderate emissions (A1B): -55% (range: -83 to -17%)</p>
<i>Glaciers</i>	<p>Although only two studies have assessed the implications of 21st century climate change for Puget Sound glaciers, both indicate that continued recession is likely.</p> <ul style="list-style-type: none"> 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.²⁷ Another study modeled glacier response in three Puget Sound tributaries (Thunder Creek and the Cascade and Nisqually Rivers). All scenarios showed that glaciers remained in 2100, but that glacier area declined substantially, particularly after mid-century.²⁸

Streamflow	
<i>Annual</i>	<p>Annual streamflow is not projected to change substantially, and some models project increases while other project decreases.</p> <ul style="list-style-type: none"> ▪ Change in annual streamflow, on average for Puget Sound:^{H,24} <p>2040s (2030-2059, relative to 1970-1999): low emissions (B1): +2% (range: -17 to +14%) moderate emissions (A1B): +5% (range: -9 to +18%)</p> <p>2080s (2070-2099, relative to 1970-1999): low emissions (B1): +6% (range: -5 to +18%) moderate emissions (A1B): +7% (range: -7 to +22%)</p>
<i>Winter</i>	<p>Most models project an increase in winter streamflow.</p> <ul style="list-style-type: none"> ▪ Change in Winter (Oct-Mar) streamflow, on average for Puget Sound:^{H,24} <p>2040s (2030-2059, relative to 1970-1999): low emissions (B1): +15% (range: -11 to +37%) moderate emissions (A1B): +22% (range: +8 to +48%)</p> <p>2080s (2070-2099, relative to 1970-1999): low emissions (B1): +28% (range: +13 to +58%) moderate emissions (A1B): +34% (range: +12 to +64%)</p> ▪ Changes are comparable to year-to-year variability: by the 2080s, the average projected change is near the high-end of the historical range (1950-1999).
<i>Summer</i>	<p>All scenarios project a decrease in summer streamflow.</p> <ul style="list-style-type: none"> ▪ Change in Summer (Apr-Sep) streamflow, on average for Puget Sound:^{H,24} <p>2040s (2030-2059, relative to 1970-1999): low emissions (B1): -16% (range: -24 to -8%) moderate emissions (A1B): -19% (range: -33 to -11%)</p> <p>2080s (2070-2099, relative to 1970-1999): low emissions (B1): -24% (range: -37 to -11%) moderate emissions (A1B): -31% (range: -46 to -13%)</p> ▪ Changes are comparable to year-to-year variability: by the 2080s, the average projected change is near the high-end of the historical range (1950-1999).
<i>Streamflow timing</i>	<p>Peak streamflows are projected to occur earlier in many snowmelt-influenced rivers.</p> <ul style="list-style-type: none"> ▪ Change in the timing of peak streamflow for 12 Puget Sound

watersheds for the 2080s (2070-2099, relative to 1970-1999).

Average and range for a moderate (A1B) greenhouse gas scenario:^{L,24}

Nooksack R.:	-27 days (-40 to -19 days)
Samish R.:	-40 days (-53 to -30 days)
Skagit R.:	-22 days (-36 to -13 days)
Stillaguamish R.:	-37 days (-48 to -29 days)
Snohomish R.:	-37 days (-49 to -29 days)
Cedar R.:	-37 days (-49 to -30 days)
Green R.:	-38 days (-50 to -31 days)
Nisqually R.:	-34 days (-45 to -25 days)
Puyallup R.:	-18 days (-30 to -9 days)
Skokomish R.:	-46 days (-56 to -38 days)
Dungeness R.:	-15 days (-35 to -6 days)
Elwha R.:	-28 days (-41 to -20 days)

Stream temperatures

Water temperatures are projected to increase.

- Puget Sound rivers are projected to increasingly experience average August stream temperatures stressful to salmon (in excess of 64°F) and char (in excess of 54°F).
- Increase in the number of river miles in excess of thermal tolerances, on average for the 2080s (2070-2099, relative to 1970-1999) and a moderate (A1B) greenhouse gas scenario, for 12 Puget Sound watersheds:^{S,35}

Nooksack R.:	+205 mi. (>54 °F),	+136 mi. (>64 °F)
Samish R.:	+14 mi. (>54 °F),	+27 mi. (>64 °F)
Skagit R.:	+566 mi. (>54 °F),	+121 mi. (>64 °F)
Stillaguamish R.:	+176 mi. (>54 °F),	+103 mi. (>64 °F)
Snohomish R.:	+517 mi. (>54 °F),	+262 mi. (>64 °F)
Cedar R.:	+70 mi. (>54 °F),	+5 mi. (>64 °F)
Green R.:	+173 mi. (>54 °F),	+73 mi. (>64 °F)
Nisqually R.:	+179 mi. (>54 °F),	+24 mi. (>64 °F)
Puyallup R.:	+311 mi. (>54 °F),	+9 mi. (>64 °F)
Skokomish R.:	+120 mi. (>54 °F),	+3 mi. (>64 °F)
Dungeness R.:	+32 mi. (>54 °F),	+0 mi. (>64 °F)
Elwha R.:	+64 mi. (>54 °F),	+0 mi. (>64 °F)

All Puget Sound Rivers:

	+2826 mi. (>54 °F),	+1016 mi. (>64 °F)
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- Many stream locations projected to exceed 70°F for the entire summer season by the 2080s – resulting in waters that are warm enough to impede migration and increase the risk of fish kills.³⁷

Flooding

Most scenarios project an increase in peak flows..

- Projected change in streamflow associated with the 100-year (1% annual probability) flood event for 12 Puget Sound watersheds, on average for the 2080s (2070-2099, relative to 1970-1999):^I

Average and range for a moderate (A1B) greenhouse gas scenario:^{L,24}

Nooksack R.:	+27% (+9 to +60%)
Samish R.:	+23% (-9 to +101%)
Skagit R.:	+42% (+4 to +86%)
Stillaguamish R.:	+29% (+2 to +76%)
Snohomish R.:	+23% (+1 to +58%)
Cedar R.:	+19% (+2 to +37%)
Green R.:	+32% (+15 to +73%)
Nisqually R.:	+18% (-7 to +58%)
Puyallup R.:	+37% (+10 to +88%)
Skokomish R.:	+23% (+4 to +59%)
Dungeness R.:	+55% (+20 to +116%)
Elwha R.:	+29% (+5 to +50%)

- Projected changes in heavy rainfall (Section 2 of this report) may be underestimated in the above projections. Recent research, using regional climate model simulations, indicates that heavy rain events will increase more than in the statistically-based projections cited above. This would lead to larger increases in flood risk.²⁹
- Changes in flood management may not be sufficient to mitigate increases in flood risk. In the Skagit River, for instance, simulations indicate that changes in water management are largely ineffective at mitigating increased flood risks.^{P,6}
- Increase in the area flooded due to the combined effects of high river flows and sea level rise, for the 2080s (2070-2099, relative to 1970-1999):

Skagit R. (100-yr event, average change): +74%^{Q,30,31}

Lower Snohomish R. (10-yr event, range): +19% to +69%^{R,33}

Minimum flows

Streamflow is projected to decline for summer minimum flows.

- Projected changes in summer minimum streamflow (7Q10)^{EE} for 12 Puget Sound watersheds,^J on average for the 2080s (2070-2099, relative to 1970-1999).

Average and range for a moderate (A1B) greenhouse gas scenario:^{L,24}

Nooksack R.:	-27% (-38 to -13%)
Samish R.:	-18% (-26 to -7%)

^{EE} 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.

	<p>Skagit R.: -51% (-65 to -38%)</p> <p>Stillaguamish R.: -22% (-32 to -7%)</p> <p>Snohomish R.: -26% (-33 to -17%)</p> <p>Cedar R.: -25% (-32 to -13%)</p> <p>Green R.: -16% (-21 to -7%)</p> <p>Nisqually R.: -27% (-35 to -17%)</p> <p>Puyallup R.: -27% (-39 to -16%)</p> <p>Skokomish R.: -18% (-22 to -8%)</p> <p>Dungeness R.: -35% (-45 to -27%)</p> <p>Elwha R.: -39% (-49 to -27%)</p> <ul style="list-style-type: none"> ▪ 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.³⁴ ▪ The above projections do not account for contributions from melting glaciers. Projections indicate that glaciers may augment minimum flows in the near term due to the increased rate of melt, but nearly all scenarios show a sharp decline in meltwater in the late 21st century as glaciers diminish in size.²⁸
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Table 3-3. Projected impacts on water uses.

<i>Variable</i>	<i>Projected Long-term Change</i>
Water Resources	
<i>Fish and Aquatic Ecosystems</i>	Increasing peak flows, decreasing summer low flows, and warming stream temperatures are all projected to negatively affect salmon across many life stages and habitats, ⁴³ particularly for salmon populations that have an in-stream rearing life stage (e.g., steelhead, stream-type Chinook salmon, sockeye salmon, and Coho). ⁴⁴ (Section 10 of this report).
<i>Hydropower production</i>	<p>Increasing winter and spring production, decreases in summer.</p> <ul style="list-style-type: none"> ▪ <i>Skagit River basin.</i> Hydropower production (for Ross, Diablo, Gorge, Upper Baker, and Lower Baker dams) is projected to increase in winter and spring and decrease in summer, though there is debate about the exact amount of change, given that changes in reservoir operations can have a large effect on production.^{P.39} ▪ <i>Columbia River basin.</i> Much of the power supplied to Puget Sound communities is generated by the Columbia River system. Projected changes in system-wide hydropower production, on average, by the 2080s (2070-2099, relative to 1970-1999)^{H,V}: <p style="padding-left: 40px;">January-March: +8% to +11%</p>

<i>Variable</i>	<i>Projected Long-term Change</i>
<i>Municipal Water Supply</i>	<p style="text-align: center;">July-September: -21% to -17%</p> <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"> ▪ Historically, all three cities have had at least 99% reliability, meaning that at most 1% of years experience water delivery shortfalls. ▪ Assuming no changes in demand, new sources of supply or significant changes in operating procedures, projected reliability for the 2080s (2070-2099, relative to 1970-1999): <ul style="list-style-type: none"> <li style="margin-left: 40px;">Everett: 100% <li style="margin-left: 40px;">Tacoma: 93 to 96%^{W,46} ▪ For Seattle, previous studies found that supply is projected to exceed demand in nearly all years through the end of the 21st century.^{46,47} Current work, based on the high end of the latest set of climate projections, suggests that Seattle’s water supply could be more strongly affected by warming.^Y
<i>Municipal Water Demand</i>	<p>Small increases in municipal demand projected for the greater Seattle area.</p> <p>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, and the warming projected based on a high greenhouse gas scenario.^{Z,47}</p>
<i>Ski Season</i>	<p>More warm winters</p> <ul style="list-style-type: none"> ▪ Probability of a warm winter (average Dec-Feb air temperature above freezing) for Washington State ski resorts: <ul style="list-style-type: none"> <li style="margin-left: 40px;">Historic (1971-2000): 0 to 33%, depending on location <li style="margin-left: 40px;">With +3.6°F^{FF} warming: 33 to 77%⁵²

^{FF} +3.6°F relative to 1971-2000 is near the low end of warming projected for mid-century.

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