Climate Change Impacts on Tacoma Power Watersheds

Cushman Dam #2, Mason County, Washington (Tacoma Power)

Prepared by

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Contents

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Executive Summary

In spring 2015, Tacoma Power contacted the Climate Impacts Group to update a 2010 analysis of climate change impacts on streamflows into reservoirs used by Tacoma Power to generate hydropower. This includes the Cowlitz River, the North Fork of the Skokomish River, and the Nisqually River. Climate and hydrologic projections were evaluated for the near-term future (2020-2049, or conditions representative of the 2030s)[1] for use in analyses being conducted by Tacoma Power for their Integrated Resource Plan, which has a planning horizon of 2035. Tacoma Power also requested temperature projections for the City of Tacoma, which can affect power demand, and information on how climate change may affect streamflows and hydropower production on the Columbia River, which supplies over 50% of Tacoma's power.

Two greenhouse gas scenarios were used in the analysis: one assuming low 21st century greenhouse gas emissions (RCP 4.5) and another assuming high greenhouse gas emissions (RCP 8.5) (Van Vuuren et al. 2011). While the two emissions scenarios present very different trajectories of change by 2100, differences between the scenarios prior to mid-century are fairly small and based largely on the warming that is already "in the pipeline" as a result of past emissions. All changes in temperature and streamflow are relative to simulated temperature and streamflow for the late 20th century (1970-1999) unless noted otherwise.

Projected Changes in Temperature

Annual average temperature at Joint Base Lewis-McChord in Tacoma is projected to rise by +2.8 to +3.3°F, on average, by the 2030s with individual model projections ranging from +1.8 to +5.6°F. The change projected for the hottest daily maximum temperatures of the year (TMAX_p90, _p95, and _p99; see Table 4) is similar to the warming projected for summer (Jun-Aug) temperatures: about +3.5 to +4°F, on average. Due to the mild summer climate of this location, only a modest increase in cooling degree days is projected. In contrast, annual heating degree days are projected to decline by −800 to −960 degree days, on average. Projected warming also increases the number of frost-free days (+13 to +15 days, on average).

[1] Natural fluctuations, such as El Niño and La Niña, can alter the climate of any single year even as the climate warms in the long term as a result of rising greenhouse gas emissions. Because of this, analysis of single years is not recommended. Using a 30-year window centered on the year 2035 (2020-2049) minimizes the influence of year-to-year variability. We recommend interpreting the years 2020-2049 as 30 different examples of conditions in 2035.

Projected Changes in Streamflow

Streamflow projections were evaluated for four sites of interest to Tacoma Power: Mossyrock and Mayfield Dams on the Cowlitz River, Alder Dam on the Nisqually River, and Cushman Dam on the Skokomish River. In all cases, annual streamflow is projected to change very little, with some models projecting decreases and others projecting increases. The lack of model agreement on the direction of change in annual streamflow is expected since annual precipitation – by far the most important factor governing near-term changes in annual streamflow – is not projected to change substantially and could decrease or increase depending on the model and greenhouse gas scenario selected.[2]

The seasonal distribution of runoff, however, is projected to change. Warmer conditions projected for the 2030s will result in more precipitation falling as rain during cool season, decreased snow accumulation, earlier snowmelt, and less snowmelt contribution to summer flows. Higher freezing elevations associated with warmer temperature also increase total runoff production during winter storms, thus increasing flood risk.

All four sites exhibit this shift to increased flows in winter and decreased flows in summer. On average, models project an increase of +13% to +24% in December through March streamflow ("cool season") and a −27% to −34% decrease for May through October ("warm season") streamflow. Across all sites, the maximum increase relative to the historical baseline occurs in January (+30% for the North Fork Skokomish River at Cushman Dam) and February (+31% for the Cowlitz River at Mossyrock Dam). The maximum decrease is in June (−56 % for the North Fork Skokomish River at Cushman Dam). For both warm and cool seasons, the range among model projections for any one site is much larger than the differences in the changes projected for each of the four sites.

Another way to view the seasonal changes in streamflow is as a shift in peak flow timing. For the relatively colder Cowlitz River, peak flow timing shifts from May historically to January by the 2030s. For the relatively warmer Nisqually and North Fork Skokomish Rivers, the seasonal timing of streamflows shifts from dual peaks in the historical period (the largest in December) to a single rain-dominant peak in January.

Consistent with projected changes in seasonal hydrology, flood magnitudes are projected to increase across the sites by the 2030s in comparison to historical flood flows, while low flows (7Q10) are likely to decrease by about 30% for all four dams. Generally, the variability in

[2] Precipitation in the Pacific Northwest has a large range of natural variability, which makes it more difficult to determine when rising greenhouse gas emissions cause precipitation to change in ways that would not be caused by variability. Additionally, GCMs have a more difficult time capturing the processes associated with precipitation, whereas models have greater skill in simulating temperature.

monthly streamflows is projected to remain unchanged, although there is some indication that the highest flows during cool season might increase.

Climate Change Impacts on Hydropower Production in the Columbia River System

The Columbia River plays a pivotal role in energy production in the Pacific Northwest, producing approximately 70 to 80% of the Pacific Northwest's electricity annually (USBR 2011a) and over 50% of Tacoma Power's annual supply. Relative to simulated historical (1916-2006) streamflow, mean annual runoff for the Columbia River at The Dalles is projected to increase +1.2 to +3.7% by mid-century (USBR 2011b). Seasonal streamflow changes include higher fall and early winter streamflows, earlier peak runoff, and lower spring and summer streamflows. These changes will increase hydropower generating capacity within the Columbia system in the winter months while decreasing generating capacity in the summer. Seasonal demand for power is also likely to be affected by climate change, although changes in demand related to climate change may be secondary to increases driven by population growth.

Secondary impacts on hydropower production in the Columbia system will also come as a result of climate change impacts on the western U.S. power grid and energy markets, energy transmission infrastructure, and potential renegotiation of the Columbia River Treaty in the coming decade. While only 15% of the Columbia basin is located in Canada, the Canadian portion provides 35% of total annual streamflow, 50% of peak flows, and an estimated 50% of late summer streamflow (Vaddey 2010; Hamlet 2013). These proportions are likely to change as a result of the differential impacts of climate change on snowpack on the U.S. portion versus the Canadian portion of the basin, and will affect the major issues around which the Treaty may be renegotiated (flood control, hydropower, and ecosystem-based function[3]).

[3] As of June 12, 2015 (Columbia Basin Bulletin 2015)

1 Introduction

Climate change is projected to transform the behavior of many rivers in the Pacific Northwest, affecting the timing and volume of streamflows used for hydropower generation, fish flows, water supply, and other uses (Dalton et al. 2014). In spring 2015, Tacoma Power contacted the Climate Impacts Group to update a 2010 analysis of climate change impacts on streamflows into reservoirs used by Tacoma Power to generate hydropower. This includes the Cowlitz River, the North Fork of the Skokomish River, and the Nisqually River. Climate and hydrologic projections were evaluated for the near-term future (conditions representative of the 2030s) in comparison to the recent past (1970-1999). In addition, Tacoma Power requested temperature projections for the City of Tacoma, which can affect power demand, and information on how climate change may affect streamflows and hydropower production on the Columbia River, which supplies over 50% of Tacoma's power. Findings from the analysis are presented in this report.

2 Approach

2.1 Climate Projections

Evaluating climate change impacts requires developing spatially relevant scenarios of projected changes in temperature, precipitation, and other variables influencing streamflows. For this study, we used climate and hydrologic projections stemming from the newly available Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012; Table 1). Projections were obtained for 10 global climate models (GCMs) and two greenhouse gas scenarios: a low greenhouse gas scenario (RCP4.5) and a high greenhouse gas scenario (RCP 8.5) (Van Vuuren et al. 2011; Table 2). The 10 GCMs were selected from a larger set of CMIP5 simulations based on their ability to accurately represent the climate of the Pacific Northwest (Rupp et al. 2011).

GCM projections are spatially very coarse due to the high computational cost of running a coupled set of complex climate models across the entire globe. As a consequence, GCM output must be "downscaled" to obtain projected changes in climate at local scales. We used statistically downscaled climate projections developed using the Multivariate Adaptive Constructed Analogues approach (MACA, Abatzoglou and Brown 2011). The MACA downscaling was applied to the historical (1950-2005) and two future projections (2006-2099, one for each RCP) for each of the ten GCMs described in Table 1, producing gridded climate projections at 0.0625-degree resolution (about 5 km x 7 km).

Table 1. Global Climate Models used in this study. The models were obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012) multi-model archive, in which international climate modeling centers coordinate to develop projections based on a common set of assumptions.

Model Name	Institution	Atmospheric Model Resolution (Lon. x Lat.)	Vertical Levels in Atmosphere
bcc-csm1-1-m	Beijing Climate Center, China Meteorological Administration	1.12 × 1.12	26
CanESM2	Canadian Centre for Climate Modeling and Analysis	2.8 × 2.8	35
CCSM4	National Center of Atmospheric Research, USA	1.25 × 0.94	26
CNRM-CM5	National Centre of Meteorological Research, France	1.4 × 1.4	31
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization/ Queensland Climate Change Centre of Excellence, Australia	1.8 × 1.8	18
HadGEM2-CC	Met Office Hadley Center, UK	1.88 × 1.25	60
HadGEM2-ES	Met Office Hadley Center, UK	1.88 × 1.25	38
IPSL-CM5A-MR	Institut Pierre Simon Laplace, France	2.5 × 1.25	39
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	1.4 × 1.4	40
NorESM1-M	Norwegian Climate Center, Norway	2.5 × 1.9	26

Climate change impacts on temperature and streamflow were evaluated for 2020-2049 (2030s), relative to 1970-1999 (1980s). This timeframe was requested by Tacoma Power to align with the planning horizon used in Tacoma Power's Integrated Resource Plan. A 30-year averaging window was used to account for the fact that shorter-term natural variations (e.g., due to El Niño) can temporarily mask or amplify the long-term trends driven by greenhouse gas emissions.

2.2 Temperature Projections

Temperature changes were evaluated for the site of current weather observations at National Weather Service station KTCM (Tacoma/McChord Air Force Base, WA, located at 47.1N, 122.5W). Temperature variations at this site are used by Tacoma Power as a benchmark for assessing changes in power demand. Using the statistically downscaled MACA projections described previously, results were obtained for the grid point closest to KTCM (located at 47.2N, 122.5W). Projections were evaluated for daily average, maximum, and minimum temperatures, in addition to the metrics described in Section 2.4.4.

Table 2. Greenhouse gas scenarios used in this study. The scenarios, known as Representative Concentration Pathways (or RCPs; Van Vuuren et al. 2011), represent projected changes in the concentration of greenhouse gases in the atmosphere as a result of changes in land use, population growth, and other factors that influence global greenhouse gas emissions.

IPCC Fifth Assessment Report (2013) scenario	Scenario characteristics	Projected atmospheric concentration, 2100 (in CO_2-eq)[4]	Related qualitative description
RCP 4.5	A low scenario in which greenhouse gas emissions stabilize by mid-century and fall sharply thereafter	602 ppm	"Low"
RCP 8.5	A high scenario that assumes continued increases in greenhouse gas emissions through the 21st century	1275 ppm	"High"

2.3 Hydrology Projections

Hydrologic projections were obtained from the newly-developed *"Integrated Scenarios for the Future Northwest Environment"* project (Mote et al. 2015). The dataset was developed by using statistically downscaled climate projections from MACA to drive the Variable Infiltration Capacity model (Liang et al. 1994, Gao et al. 2010). VIC is a physically based, macro-scale hydrologic model which simulates all aspects of the hydrology affecting surface and shallow groundwater (Figure 1). Downscaled daily meteorological data – precipitation, maximum and minimum air temperature, and wind speed – are used as inputs to run the VIC model. The VIC model has been widely used to assess the hydrologic impact of climate change on a number of watersheds over the Pacific Northwest and

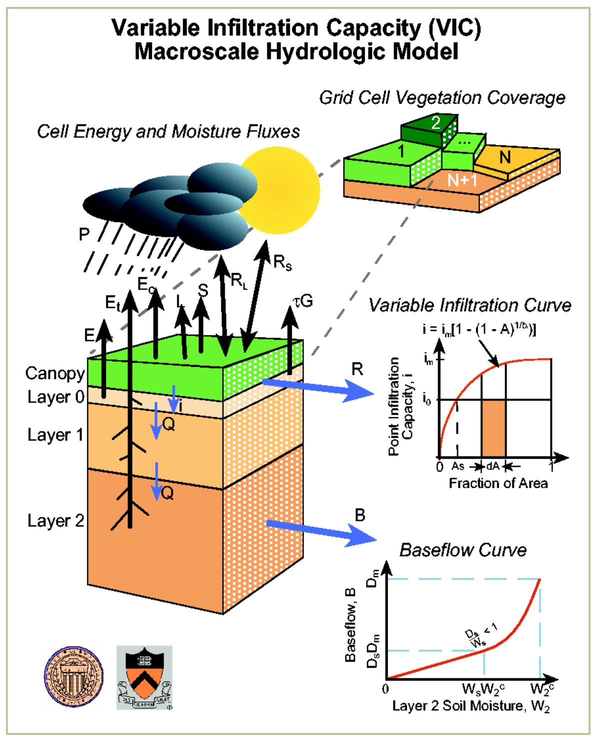

Figure 1. Schematic diagram of the land surface representation, and water and energy budgets in the VIC hydrologic model.

[4] CO_2-equivalent is a measure of the combined global warming potential of all greenhouse gases, but is referenced to the more commonly cited atmospheric CO2 concentration. The current CO_2-equivalent concentration is about 400 parts per million (ppm). In 2000, it was 380 ppm.

over the western U.S. (e.g., Hamlet et al. 2013). We used the most recent VIC model (version 4.1.2), implemented at the MACA resolution of 0.0625-degrees to simulate runoff and baseflow at each grid cell.

VIC simulations of runoff and baseflow from each grid cell were routed along stream channel network using the “RVIC” streamflow routing model (Hamman et al. 2015) to produce routed streamflow. Routed streamflows were produced for four gauge sites on the Cowlitz, Nisqually, and Skokomish Rivers (Table 3). The routed flows at each site were then bias-corrected to match naturalized streamflow observations using a quantile mapping approach (Snover et al. 2003, Vano et al. 2010) applied to monthly flows.

Table 3. Streamflow sites requested by Tacoma Power. Each is associated with a reservoir that provides power to the City of Tacoma.

Site	Lat	Lon	Basin Area (sq mile)
Cowlitz River at Mossyrock Dam	46.5344	-122.4261	1154
Cowlitz River at Mayfield Dam	46.5039	-122.5886	1400
North Fork Skokomish River at Cushman Dam	47.4231	-123.2225	97.9
Nisqually River at Alder Dam	46.8014	-122.3103	286

2.4 Statistical Methods

Temperature and streamflow changes were evaluated using three criteria: changes in the monthly mean, monthly variability, and changes in particular metrics of interest (e.g. for streamflows: extreme high and low flows).

2.4.1 Monthly Means

Monthly changes were evaluated for the years 2020-2049 relative to 1970-1999. Mean monthly values were determined for each time period (streamflow in cubic feet per second, or cfs, and temperature in degrees Fahrenheit, or °F). For streamflow, the percent change relative to the historical period (1970-1999) was also calculated, while a simple difference was used for temperature.

2.4.2 *Monthly Variability*

In addition to estimating the projected changes in the monthly means, we also examined whether the projected distribution (or year-to-year variability) of monthly values would be significantly different from the historical range. Changes in year-to-year variability were evaluated using 30 years of monthly data from each of the 10 GCMs (i.e. 30 × 10 = 300 values were evaluated for each month). Results are shown in terms of absolute values (cfs for streamflow; °F for temperature) and as a "normalized anomaly", defined as a means of differentiating between changes in the monthly mean and changes in the distribution. For the latter, we used modified Pardé-coefficients (Meile et al. 2011, Pardé 1933), defining the "normalized streamflow anomaly" as follows:

$$Normalized\ Streamflow\ Anomaly \ = \frac{(Q_{mon,i} - \overline{Q_{mon}}\ )}{\overline{Q_{year}}}$$

where $Q_{mon,i}$ is the monthly streamflow for the i^{th} year, $\overline{Q_{mon}}$ is the mean monthly streamflow, and $\overline{Q_{year}}$ is the mean annual streamflow (all in units of cfs). A positive value for the normalized anomaly means that the monthly streamflow for that particular year is above the average, and the magnitude of the anomaly shows the excursion relative to mean annual streamflow. The anomaly is normalized relative to mean annual (as opposed to monthly) streamflow in order to avoid over-emphasizing changes in the summer months when streamflows are particularly low relative to other parts of the year. For temperature, we simply evaluated the difference between each month's temperature and the average for that month (again drawing from all 30-years from each of the 10 GCM projections). In both cases, these "normalized anomalies" can be used to evaluate changes in monthly variability without conflating those changes with changes in the 30-year mean.

2.4.3 *Extreme Flows*

Extreme low and high flows were computed following the methodology described in Salathé et al. 2014 and Tohver et al. 2014. Flood flows were computed for return intervals of 10, 15, 20, 25 and 30 years. To estimate flood magnitude, the maximum daily flows were extracted for each water year (October to September) at each site. These were ranked for each 30-year period and fitted to a generalized Extreme Value (GEV) distribution with L-moments (Wang 1997, Hosking and Wallis 1993, Hosking 1990).

The lowest consecutive 7-day flows with a 10-year return interval (7Q10) were also estimated as a measure of extreme low flows. For the extreme low flow analysis, the same procedure used for estimating flood magnitude was followed, except the minimum 7-day consecutive running average streamflows were selected for each water year instead of maximum daily flows.

2.4.4 *Temperature Metrics*

Changes in daily temperature were used to calculate a suite of metrics of potential relevance to power demand (Table 4). Each metric was calculated separately for each year then averaged over the 30-year historical and future time periods.

Table 4. Temperature metrics used in this study. These were chosen to provide additional information relevant to assessing projected changes in power demand.

Metric ID	Definition
CDD_75F	Cooling degree days; based on daily average temperature and a base temperature of 75°F.
HDD_65F	Heating degree days; based on daily average temperature and a base temperature of 65°F.
FFdys	Number of days with daily minimum temperature >32F.
TMIN_p01	Daily minimum temperature: 1st percentile.
TMIN_p05	Daily minimum temperature: 5th percentile.
TMIN_p10	Daily minimum temperature: 10th percentile.
TMAX_p90	Daily maximum temperature: 90th percentile.
TMAX_p95	Daily maximum temperature: 95th percentile.
TMAX_p99	Daily maximum temperature: 99th percentile.
TAVG_p01	Daily average temperature: 1st percentile.
TAVG_p05	Daily average temperature: 5th percentile.
TAVG_p10	Daily average temperature: 10th percentile.
TAVG_p90	Daily average temperature: 90th percentile.
TAVG_p95	Daily average temperature: 95th percentile.
TAVG_p99	Daily average temperature: 99th percentile.

3 Results

3.1 Temperature

Temperature projections for Tacoma (Figure 2, Tables 5 and 6) show a consistent picture of warming across all seasons and metrics. There is a tendency towards greater warming in summer than in winter though the range among the 10 model projections overlaps substantially for the two seasons. In addition to the monthly and seasonal changes listed in Table 5, Table 6 lists the projections for the 15 daily temperature metrics in Table 4. The latter reveal interesting patterns of changes, ranging from the low values for cooling degree days to the relatively large changes projected for the highest extremes of daily maximum temperatures. The variability in monthly temperatures (Figure 3) is not projected to change substantially.

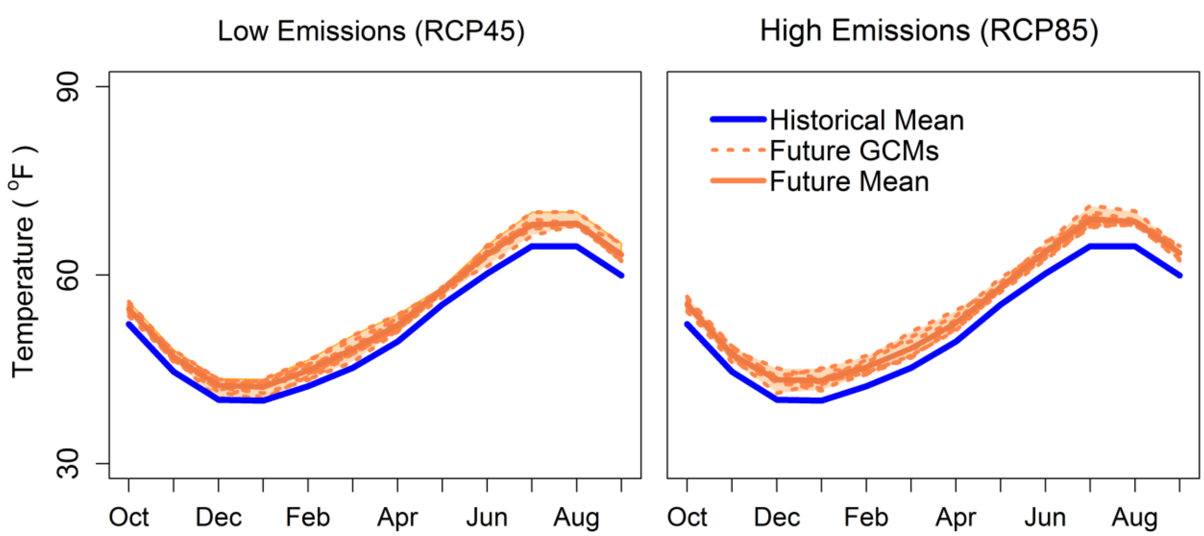

Figure 2. Thirty year monthly means of daily average temperature at Joint Base Lewis-McChord. Results are shown for the recent past (1970-1999, blue) and 2030s (2020-2049, orange), for a low (RCP 4.5, left) and a high (RCP 8.5, right) greenhouse gas scenario. Results for each of the 10 global models are shown for the future projections, with the average model projection shown with the thick orange line. An average of the 10 models is shown for the historical simulations.

Table 5. Historical and future projected temperature (°F) at Joint Base Lewis-McChord, for the average among all 10 GCMs. Results are shown for the historical period (1970-1999) and 2030s (2020-2049) for a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario. The table includes both absolute temperatures and changes relative to the historical baseline, the latter showing the range among all 10 GCMs.

				Change Relative to Historical Mean (Range)	
Month	***Historical***	***RCP 4.5***	***RCP 8.5***	***RCP 4.5***	***RCP 8.5***
Oct	52.2	54.6	55.3	+2.4 (+1.0 to +3.6)	+3.1 (+1.8 to +4.9)
Nov	44.6	47.0	47.4	+2.4 (+1.3 to +3.3)	+2.8 (+1.1 to +4.1)
Dec	40.2	42.4	43.3	+2.2 (+0.4 to +3.6)	+3.1 (+1.4 to +4.9)
Jan	40.0	42.2	43.2	+2.2 (+0.0 to +3.7)	+3.2 (+1.4 to +5.2)
Feb	42.3	44.9	45.3	+2.6 (+0.9 to +4.0)	+3.0 (+1.8 to +4.6)
Mar	45.2	48.2	48.3	+3.0 (+1.1 to +5.0)	+3.1 (+1.7 to +5.6)
Apr	49.4	52.1	52.4	+2.7 (+1.5 to +4.1)	+3.0 (+1.5 to +4.8)
May	55.3	57.6	58.1	+2.3 (+0.7 to +3.0)	+2.8 (+2.1 to +4.1)
Jun	60.3	63.3	63.7	+3.0 (+0.7 to +4.6)	+3.4 (+2.0 to +5.5)
Jul	64.6	68.0	68.9	+3.4 (+1.5 to +5.3)	+4.3 (+2.9 to +6.4)
Aug	64.6	68.3	68.5	+3.7 (+2.5 to +5.7)	+3.9 (+3.1 to +5.8)
Sep	60.0	63.2	63.5	+3.2 (+2.3 to +5.3)	+3.5 (+2.4 to +4.5)
Annual	51.6	54.3	54.8	+2.8 (+1.8 to +5.1)	+3.3 (+2.8 to +5.6)
Dec-Feb	40.8	43.2	43.9	+2.3 (+0.9 to +3.2)	+3.1 (+1.8 to +4.6)
Jun-Aug	63.2	66.5	67.0	+3.4 (+1.8 to +3.8)	+3.9 (+2.5 to +4.3)

Table 6. As in Table 5, but showing the results for the temperature metrics listed in Table 4.

					Change Relative to Historical – Mean (Range)	
Metric	***Units***	***Historical***	***RCP 4.5***	***RCP 8.5***	***RCP 4.5***	***RCP 8.5***
CDD_75F	deg-days	3	18	23	+15 (+7 to +26)	+20 (+8 to +38)
HDD_65F	deg-days	5010	4210	4060	−800 (−1040 to −490)	−960 (−1230 to −720)
FFdys	Days	309	322	324	+13 (+7 to +23)	+15 (+11 to +22)
TMIN_p01	°F	21.1	22.4	24.3	+1.3 (−3.6 to +3.7)	+3.2 (+0.5 to +7.8)
TMIN_p05	°F	28.2	30.7	31.8	+2.5 (+0.6 to +3.9)	+3.6 (+2.0 to +5.1)
TMIN_p10	°F	31.2	33.8	34.6	+2.6 (+1.4 to +3.7)	+3.4 (+2.3 to +4.8)
TMAX_p90	°F	77.7	81.4	82.0	+3.7 (+2.4 to +5.4)	+4.4 (+3.4 to +5.6)
TMAX_p95	°F	81.4	85.1	85.8	+3.7 (+2.8 to +5.3)	+4.4 (+3.4 to +5.5)
TMAX_p99	°F	87.4	91.3	92.1	+3.9 (+2.8 to +5.1)	+4.7 (+3.2 to +6.1)
TAVG_p01	°F	29.1	30.4	32.0	+1.4 (−2.3 to +3.4)	+3.0 (−0.3 to +6.7)
TAVG_p05	°F	35.7	38.0	39.0	+2.4 (+0.4 to +3.5)	+3.4 (+1.4 to +5.0)
TAVG_p10	°F	38.7	41.2	42.0	+2.5 (+0.7 to +3.6)	+3.2 (+2.1 to +4.2)
TAVG_p90	°F	65.1	68.6	69.1	+3.5 (+2.3 to +5.2)	+4.0 (+3.0 to +5.6)
TAVG_p95	°F	67.8	71.3	71.9	+3.5 (+2.6 to +5.2)	+4.1 (+2.9 to +5.5)
TAVG_p99	°F	72.4	76.1	76.8	+3.7 (+2.7 to +5.1)	+4.4 (+3.3 to +5.9)

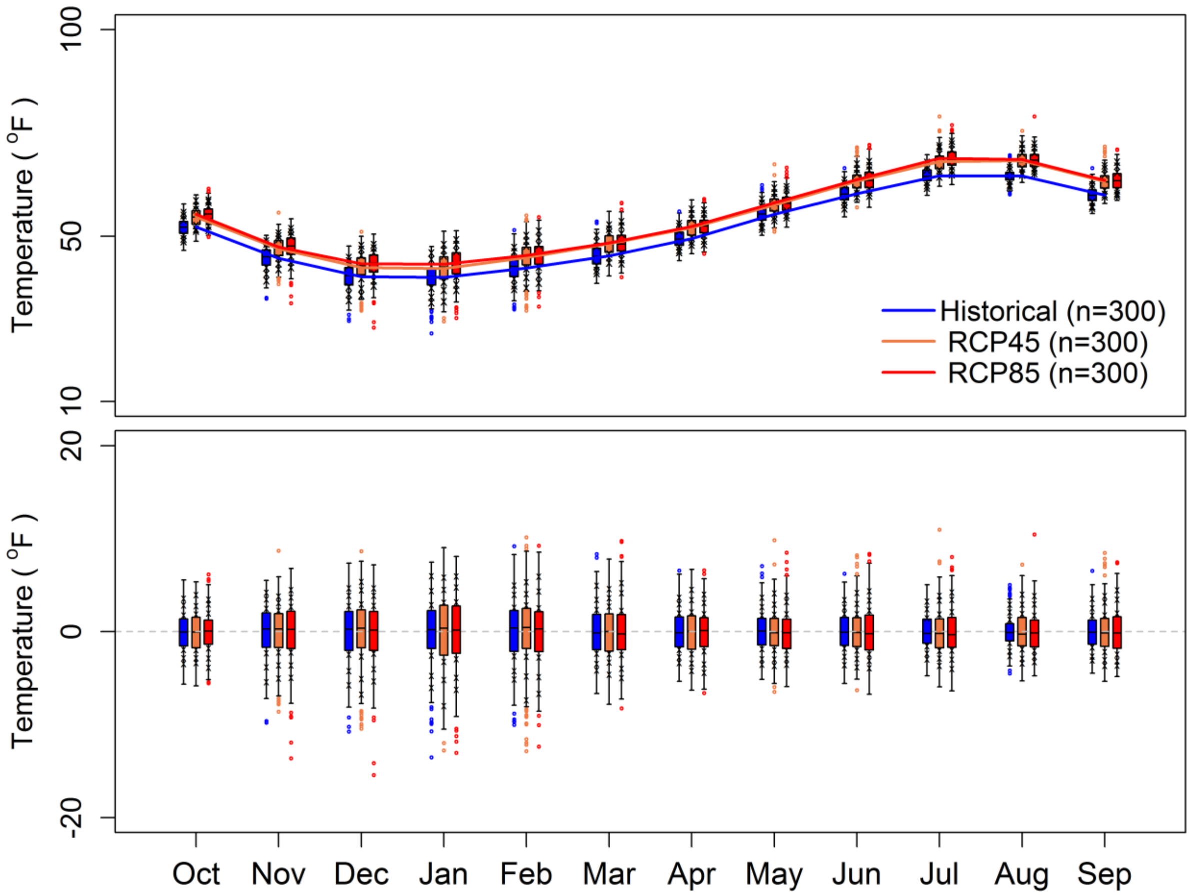

Figure 3. Variability in monthly Temperature for KTCM at Joint Base Lewis-McChord. Figures show the distribution of monthly average temperature for all 10 GCMs, with the top panel showing absolute temperature and the bottom showing the anomaly relative to the monthly average for each scenario, both in °F. Box and whisker plots are included for each month for historical (blue) as well as RCP 4.5 (orange) and RCP 8.5 (red). The boxes show the median (solid horizontal line within box), 25th and 75th percentiles (box limits), while the whiskers extend beyond the boxes out to a distance of 1.5 times the interquartile range. All points that extend beyond the whiskers are defined as outliers and plotted individually as open circles.

3.2 Monthly Streamflows

All four of the basins considered in this effort are mixed rain and snow watersheds under the current climate. Streamflow peaks in both December and May (see blue lines in subsequent figures) due to the onset of fall rains and spring snowmelt, respectively. The relative importance of snow versus rain is reflected in the relative magnitude of these two streamflow peaks: the North Fork Skokomish River and the Nisqually River are warmer basins, with the highest peak coinciding with winter storm season, while the Cowlitz River is a colder basin, resulting in a more important contribution from snowmelt in spring.

Continued warming will cause winter precipitation to fall increasingly as rain instead of snow, and also result in less snow accumulation and earlier snowmelt. Although there are some variations among model projections, all models are consistent in showing that warming will increase cool season streamflows (December to March) but decrease summer and fall streamflows (May to October) by the 2030s relative to the recent past.

Natural variability will continue to result in short-term (ranging from annual to several decades) fluctuations in streamflow from year-to-year. The projections indicate that the future range of variability will remain generally the same as the distribution observed historically. Although there is some indication that the highest flows during the cool season will increase in magnitude, this represents a small handful of points evaluated (generally less than 5 out of 300). Further work would be needed to determine if this is statistically significant.

3.2.1 Cowlitz River at Mossyrock Dam

Results for the Cowlitz River at Mossyrock (Figure 4, Table 7) show the anticipated shift to increased early winter flows and decreased flows in spring and summer, shifting peak flow timing from May, historically, to December by the 2030s. Annual flows are not projected to change substantially, with some models projecting decreases and others projecting increases.

Figure 5 shows the historical and projected variability in monthly flows. For cool season flows, future streamflow variability is generally within the range of historical variability. There do, however, appear to be a handful of the highest streamflow years that exceed the historical range – these are consistent with the projected increases in flood magnitude, shown below. For summer and fall seasons when streamflows are projected to decrease, projected flows are within the range of past variability.

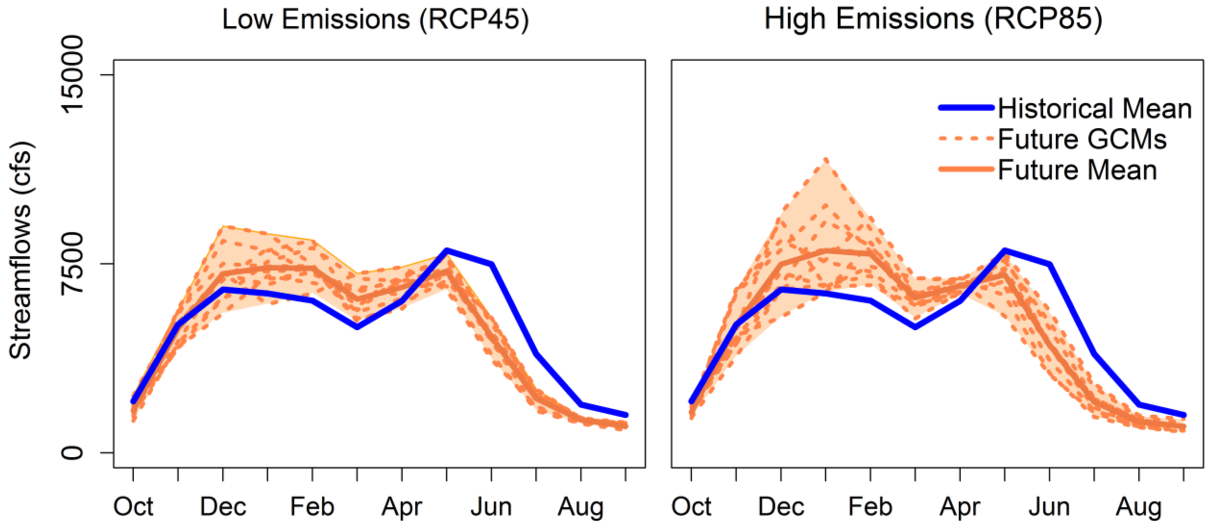

Figure 4. Average monthly streamflows for the Cowlitz River at Mossyrock Dam for the recent past (1970-1999, blue) and 2030s (2020-2049, orange), for a low (RCP 4.5, left) and a high (RCP 8.5, right) greenhouse gas scenario. Results for each of the 10 global models are shown for the future projections, with the average model projection shown with the thick orange line. An average of the 10 models is shown for the historical simulations.

Table 7. Simulated monthly flows for the Cowlitz River at Mossyrock Dam, for the average among all 10 GCMs. Results are shown for the historical period (1970-1999) and 2030s (2020-2049) for a low (RCP 4.5, left) and a high (RCP 8.5, right) greenhouse gas scenario. The table includes absolute flows (cfs) and percent change relative to the historical baseline (%), the latter showing the range among all 10 GCMs.

	Mean Flows (cfs)			***Change (%)***	
	Historical	**RCP 4.5**	**RCP 8.5**	**RCP4.5**	**RCP 8.5**
Oct	2,046	1,687	1,621	−18 (−41 to +4)	−21 (−35 to −4)
Nov	5,090	4,931	5,070	−3 (−22 to +8)	0 (−31 to +27)
Dec	6,488	7,110	7,491	+10 (−11 to +37)	+15 (−21 to +56)
Jan	6,329	7,352	8,030	+16 (−9 to +37)	+27 (+1 to +98)
Feb	6,041	7,334	7,896	+21 (+2 to +36)	+31 (+8 to +56)
Mar	4,987	6,105	6,156	+22 (+6 to +45)	+23 (+2 to +41)
Apr	6,031	6,576	6,624	+9 (−2 to +21)	+10 (+3 to +17)
May	8,034	7,218	7,065	−10 (−20 to −2)	−12 (−31 to −2)
Jun	7,483	4,609	4,279	−38 (−49 to −24)	−43 (−57 to −27)
Jul	3,924	2,158	2,018	−45 (−57 to −35)	−49 (−64 to −35)
Aug	1,915	1,300	1,230	−32 (−40 to −23)	−36 (−48 to −26)
Sep	1,505	1,060	1,053	−30 (−39 to −17)	−30 (−44 to −12)
Annual	59,870	57,442	58,533	−4 (−9 to +2)	−2 (−12 to +7)
Dec-Mar	28,935	32,834	34,643	+17 (+8 to +28)	+24 (+4 to +55)
May-Oct	24,905	18,032	17,266	−28 (−38 to −20)	−31 (−44 to −18)

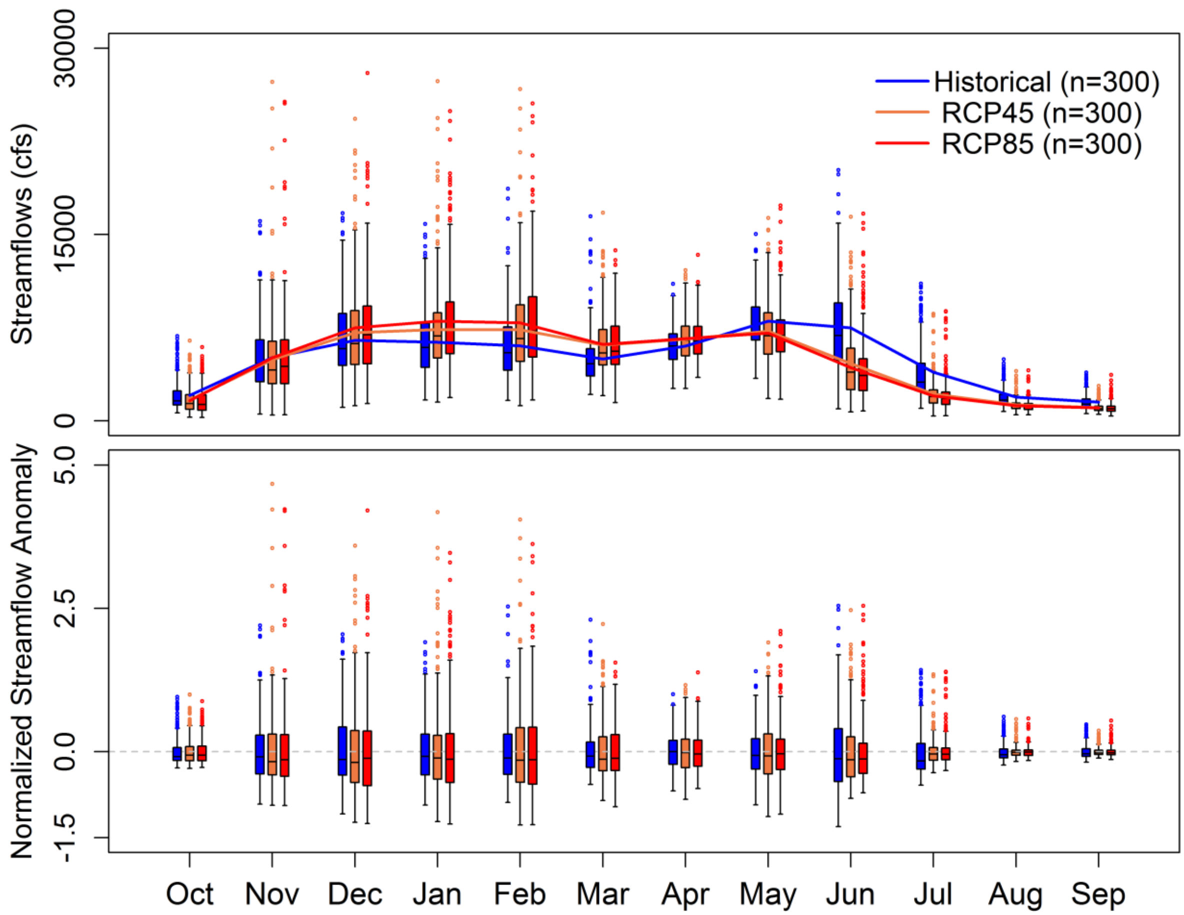

Figure 5. Variability in monthly flows for the Cowlitz River at Mossyrock Dam. Figures show the distribution of monthly streamflows for all 10 GCMs, with the top panel showing absolute flows in cfs and the bottom showing the normalized streamflow anomaly, described above. Box and whisker plots are included for each month for historical (blue) as well as RCP 4.5 (orange) and RCP 8.5 (red). The boxes show the median (solid horizontal line within box), 25th and 75th percentiles (box limits), while the whiskers extend beyond the boxes out to a distance of 1.5 times the interquartile range. All points that extend beyond the whiskers are defined as outliers and plotted individually as open circles.

3.2.2 Cowlitz River at Mayfield Dam

Results for the Cowlitz River at Mayfield Dam (Figure 6, Table 8) also show the shift to increased early winter flows and decreased flows in spring and summer, resulting in a shift of the peak flow timing from spring to early winter. Annual flows are not projected to change substantially, with some models projecting decreases and others projecting increases.

Figure 7 shows the historical and projected variability in monthly flows. For cool season flows, future streamflow variability is generally within the range of historical variability. As with Mossyrock Dam, a handful of the highest streamflow years do exceed the historical range – as above, these are consistent with the projected increases in flood magnitude. For summer and fall seasons when streamflows are projected to decrease, projected flows are within the range of past variability.

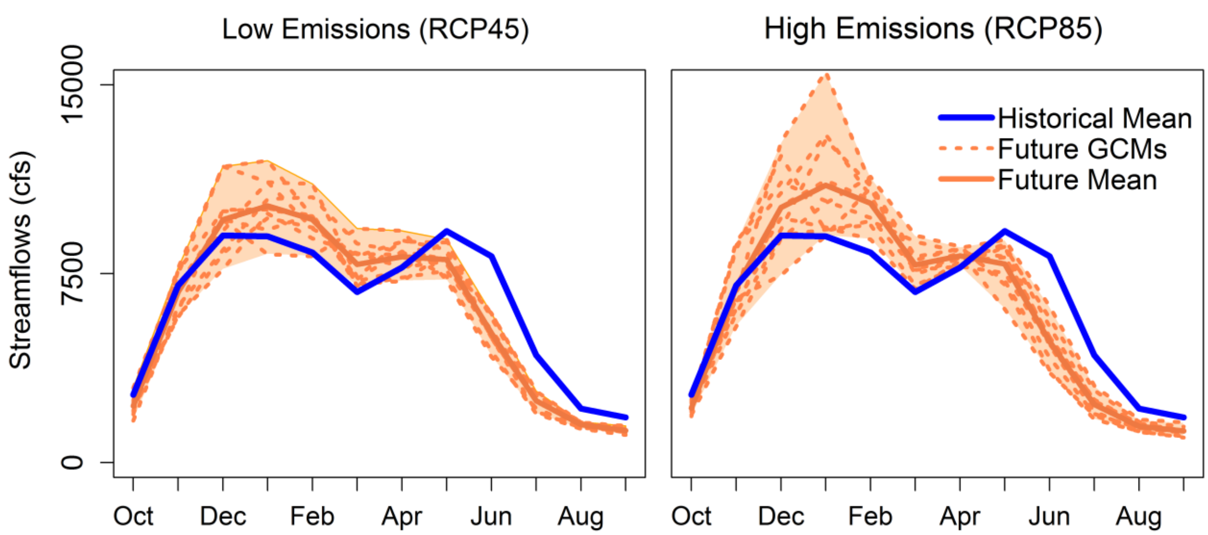

Figure 6. Average monthly streamflows for the Cowlitz River at Mayfield Dam for the recent past (1970-1999, blue) and 2030s (2020-2049, orange), for a low (RCP 4.5, left) and a high (RCP 8.5, right) greenhouse gas scenario. Results for each of the 10 global models are shown for the future projections, with the average model projection shown with the thick orange line. An average of the 10 models is shown for the historical simulations.

Table 8. Simulated monthly flows for the Cowlitz River at Mayfield Dam, for the average among all 10 GCMs. Results are shown for the historical period (1970-1999) and 2030s (2020-2049) for a low (RCP 4.5, left) and a high (RCP 8.5, right) greenhouse gas scenario. The table includes absolute flows (cfs) and percent change relative to the historical baseline (%), the latter showing the range among all 10 GCMs.

	Mean Flows (cfs)			***Change (%)***	
	Historical	**RCP 4.5**	**RCP 8.5**	**RCP4.5**	**RCP 8.5**
Oct	2,689	2,247	2,158	−16 (−41 to +4)	−20 (−33 to −5)
Nov	7,036	6,774	6,966	−4 (−18 to +6)	−1 (−29 to +23)
Dec	9,017	9,646	10,132	7 (−12 to +31)	12 (−21 to +48)
Jan	8,982	10,199	11,010	14 (−10 to +32)	23 (0 to +85)
Feb	8,339	9,654	10,296	16 (−3 to +26)	23 (+7 to +39)
Mar	6,776	7,874	7,855	16 (+3 to +39)	16 (−1 to +34)
Apr	7,749	8,176	8,209	6 (−6 to +19)	6 (−3 to +13)
May	9,194	8,058	7,890	−12 (−22 to −4)	−14 (−32 to −4)
Jun	8,194	5,135	4,805	−37 (−48 to −24)	−41 (−55 to −27)
Jul	4,263	2,456	2,305	−42 (−55 to −32)	−46 (−59 to −33)
Aug	2,141	1,501	1,434	−30 (−37 to −21)	−33 (−43 to −24)
Sep	1,787	1,267	1,254	−29 (−36 to −16)	−30 (−42 to −11)
Annual	76,163	72,989	74,315	−4 (−9 to +3)	−2 (−12 to +6)
Dec-Mar	40,150	44,149	46,261	+13 (+4 to +23)	+19 (+2 to +44)
May-Oct	28,265	20,664	19,845	−27 (−37 to −19)	−30 (−42 to −17)

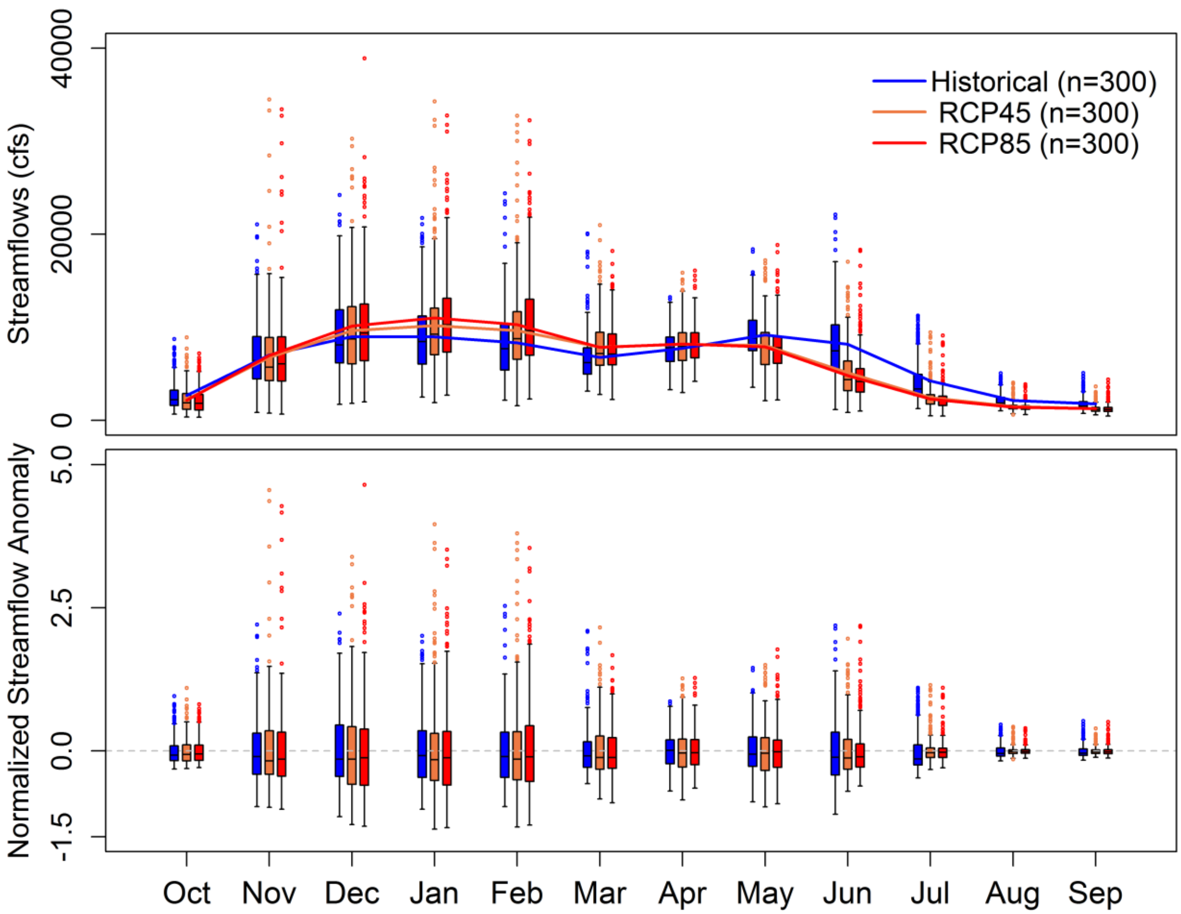

Figure 7. Variability in monthly flows for the Cowlitz River at Mayfield Dam. Figures show the distribution of monthly streamflows for all 10 GCMs, with the top panel showing absolute flows in cfs and the bottom showing the normalized streamflow anomaly, described above. Box and whisker plots are included for each month for historical (blue) as well as RCP 4.5 (orange) and RCP 8.5 (red). The boxes show the median (solid horizontal line within box), 25th and 75th percentiles (box limits), while the whiskers extend beyond the boxes out to a distance of 1.5 times the interquartile range. All points that extend beyond the whiskers are defined as outliers and plotted individually as open circles.

3.2.3 Nisqually River at Alder Dam/ Alder Lake (Alder)

The Nisqually River at Alder Dam is also a mixed rain and snow watershed that shows the dual rainfall / snowmelt peaks in monthly streamflow, although the proportion of runoff occurring during the peak rainy season is much larger than for the two reservoirs on the Cowlitz River.

Results (Figure 8, Table 9) show the expected shift to increased early winter flows and decreased flows in spring and summer. As a result, the seasonal timing of streamflows will be shifted from dual peaks in the historical period (the largest in December) to a single rain-dominant peak in January. As with the previous streamflow sites, annual flows are not projected to change substantially, with some models projecting decreases and others projecting increases.

Figure 9 shows the historical and projected variability in monthly flows. For cool season flows, future streamflow variability is generally within the range of historical variability. A handful of the highest streamflow years do exceed the historical range – as above, these are consistent with the projected increases in flood magnitude. For summer and fall seasons when streamflows are projected to decrease, projected flows are within the range of past variability.

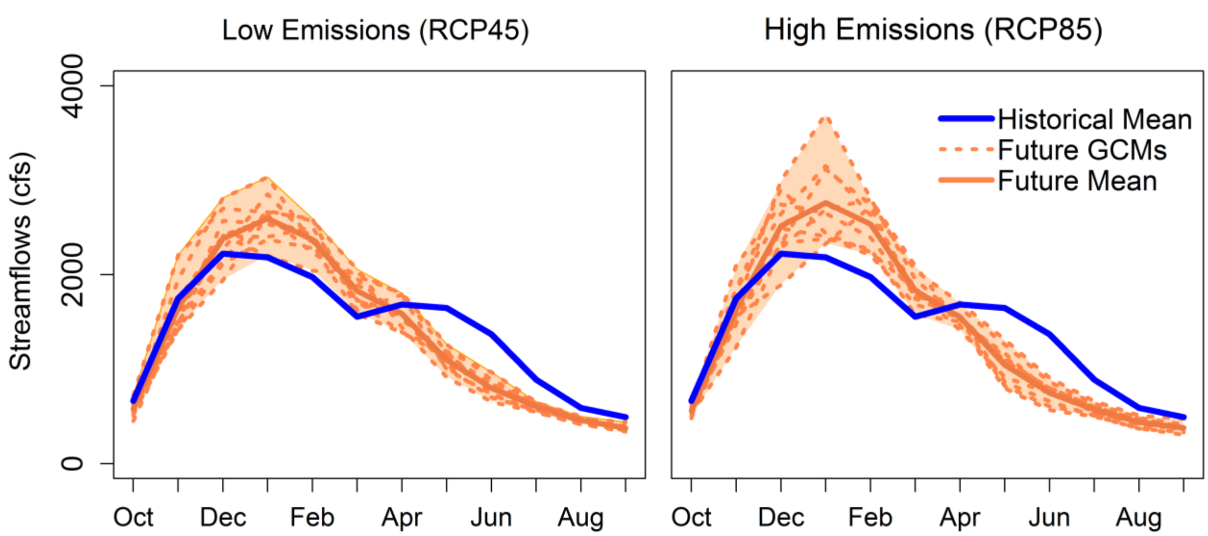

Figure 8. Average monthly streamflows for the Nisqually River at Alder Dam for the recent past (1970-1999, blue) and 2030s (2020-2049, orange), for a low (RCP 4.5, left) and a high (RCP 8.5, right) greenhouse gas scenario. Results for each of the 10 global models are shown for the future projections, with the average model projection shown with the thick orange line. An average of the 10 models is shown for the historical simulations.

Table 9. Simulated monthly flows for the Nisqually River at Alder Dam, for the average among all 10 GCMs. Results are shown for the historical period (1970-1999) and 2030s (2020-2049) for a low (RCP 4.5, left) and a high (RCP 8.5, right) greenhouse gas scenario. The table includes absolute flows (cfs) and percent change relative to the historical baseline (%), the latter showing the range among all 10 GCMs.

	Mean Flows (cfs)			***Change (%)***	
	Historical	**RCP 4.5**	**RCP 8.5**	**RCP 4.5**	**RCP 8.5**
Oct	663	576	558	−13 (−36 to +3)	−16 (−28 to −3)
Nov	1,749	1,648	1,635	−6 (−19 to +25)	−7 (−33 to +12)
Dec	2,224	2,381	2,517	+7 (−8 to +26)	+13 (−20 to +41)
Jan	2,184	2,597	2,762	+19 (−3 to +40)	+26 (+7 to +82)
Feb	1,977	2,372	2,536	+20 (+1 to +35)	+28 (+7 to +46)
Mar	1,555	1,829	1,835	+18 (−2 to +35)	+18 (−5 to +38)
Apr	1,686	1,586	1,548	−6 (−19 to +12)	−8 (−14 to −1)
May	1,649	1,097	1,045	−33 (−47 to −22)	−37 (−54 to −20)
Jun	1,369	799	746	−42 (−52 to −24)	−46 (−59 to −36)
Jul	888	605	574	−32 (−40 to −20)	−35 (−44 to −27)
Aug	590	458	437	−22 (−30 to −11)	−26 (−37 to −15)
Sep	490	376	379	−23 (−31to −14)	−23 (−38 to 0)
Annual	17,023	16,324	16,573	−4 (−9 to 2)	−3 (−11 to +5)
Dec−Mar	9,688	10,826	11,286	+16 (+8 to +26)	+22 (+6 to +44)
May−Oct	5,649	3,912	3,739	−31 (−42 to −22)	−34 (−47 to −22)

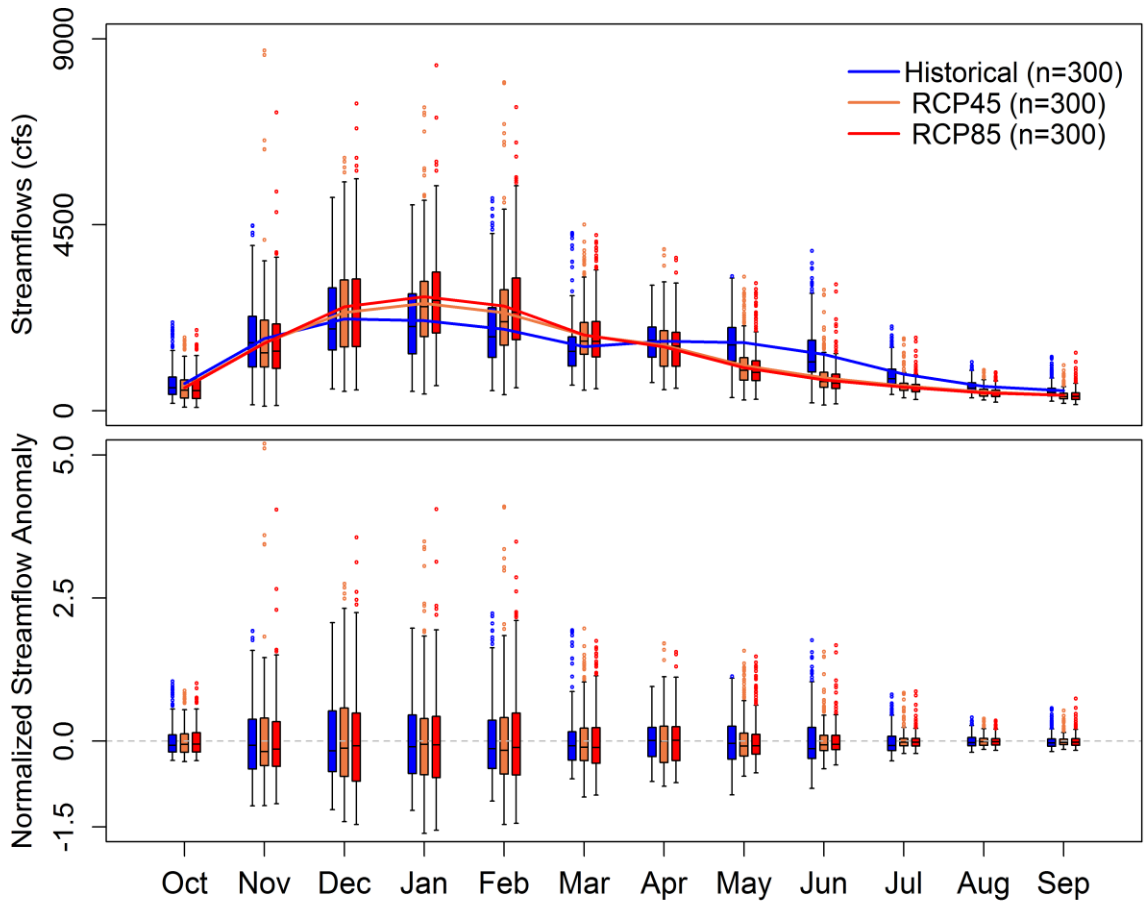

Figure 9. Variability in monthly flows for the Nisqually River at Alder Dam. Figures show the distribution of monthly streamflows for all 10 GCMs, with the top panel showing absolute flows in cfs and the bottom showing the normalized streamflow anomaly, described above. Box and whisker plots are included for each month for historical (blue) as well as RCP 4.5 (orange) and RCP 8.5 (red). The boxes show the median (solid horizontal line within box), 25th and 75th percentiles (box limits), while the whiskers extend beyond the boxes out to a distance of 1.5 times the interquartile range. All points that extend beyond the whiskers are defined as outliers and plotted individually as open circles.

3.2.4 North Fork Skokomish River at Cushman Dam

The annual hydrograph for the North Fork Skokomish River at Cushman Dam has a large streamflow peak in December that is driven by rainfall, and a smaller secondary peak in May due to snowmelt. Although snowmelt is still an important source of spring and summer streamflow, it is less dominant than in the other watersheds evaluated in this study.

Nonetheless, consistent with the other three basins, projections (Figure 10, Table 10) show increases in early winter flows and decreased flows in spring and summer, resulting in a shift of the seasonal timing of streamflows from dual peaks in the historical simulations to a single rain-dominant peak in January. As with the other sites, annual flows are not projected to change substantially, with some models projecting decreases and others projecting increases.

Figure 11 shows the historical and projected variability in monthly flows. For cool season flows, future streamflow variability is generally within the range of historical variability. A handful of the highest streamflow years do exceed the historical range – as above, these are consistent with the projected increases in flood magnitude. For summer and fall seasons when streamflows are projected to decrease, projected flows are within the range of past variability.

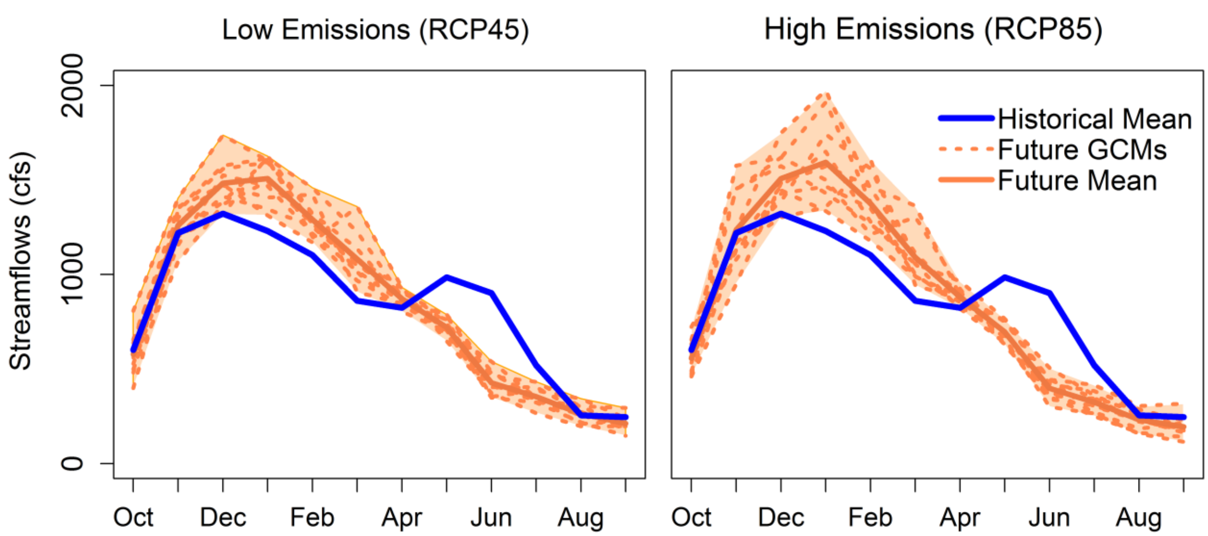

Figure 10. Average monthly streamflows for the North Fork Skokomish River at Cushman Dam for the recent past (1970-1999, blue) and 2030s (2020-2049, orange), for a low (RCP 4.5, left) and a high (RCP 8.5, right) greenhouse gas scenario. Results for each of the 10 global models are shown for the future projections, with the average model projection shown with the thick orange line. An average of the 10 models is shown for the historical simulations.

Table 10 Simulated monthly flows for the North Fork Skokomish River at Cushman Dam, for the average among all 10 GCMs. Results are shown for the historical period (1970-1999) and 2030s (2020-2049) for a low (RCP 4.5, left) and a high (RCP 8.5, right) greenhouse gas scenario. The table includes absolute flows (cfs) and percent change relative to the historical baseline (%), the latter showing the range among all 10 GCMs.

	Mean Flows (cfs)			***Change (%)***	
	Historical	**RCP 4.5**	**RCP 8.5**	**RCP4.5**	**RCP 8.5**
Oct	601	578	557	−4 (−39 to +31)	−7 (−30 to +35)
Nov	1,221	1,261	1,236	+3 (−9 to +14)	+1 (−24 to +25)
Dec	1,322	1,484	1,508	+12 (+1 to +31)	+14 (−4 to +35)
Jan	1,231	1,508	1,595	+23 (+6 to +33)	+30 (+10 to +75)
Feb	1,103	1,290	1,376	+17 (+9 to +33)	+25 (+7 to +50)
Mar	862	1,082	1,091	+26 (+8 to +56)	+27 (+12 to +64)
Apr	824	871	881	+6 (−1to +13)	+7 (−6 to +20)
May	986	721	697	−27 (−32 to −20)	−29 (−37 to −19)
Jun	902	427	398	−53 (−62 to −38)	−56 (−67 to −46)
Jul	520	353	325	−32 (−48 to −13)	−38 (−52 to −23)
Aug	255	263	232	+3 (−21 to +34)	−9 (−40 to 23)
Sep	246	212	195	−14 (−36 to +35)	−21 (−50 to 31)
Annual	10,073	10,049	10,091	0 (−5 to +7)	0 (−5 to +8)
Dec−Mar	5,739	6,625	6,806	+19 (+10 to +26)	+23 (+12 to +42)
May−Oct	3,510	2,553	2,403	−27 (−41 to −16)	−32 (−46 to −16)

Distributions of monthly historical and projected streamflows (Figure 11) show that future variability is similar in range to the observed historical variability. In winter months, the highest flow years in the projections do appear to show an increase relative to similar high-flow years in the historical simulations – this is generally consistent with the projected increases in flood magnitude, discussed in Section 3.3.

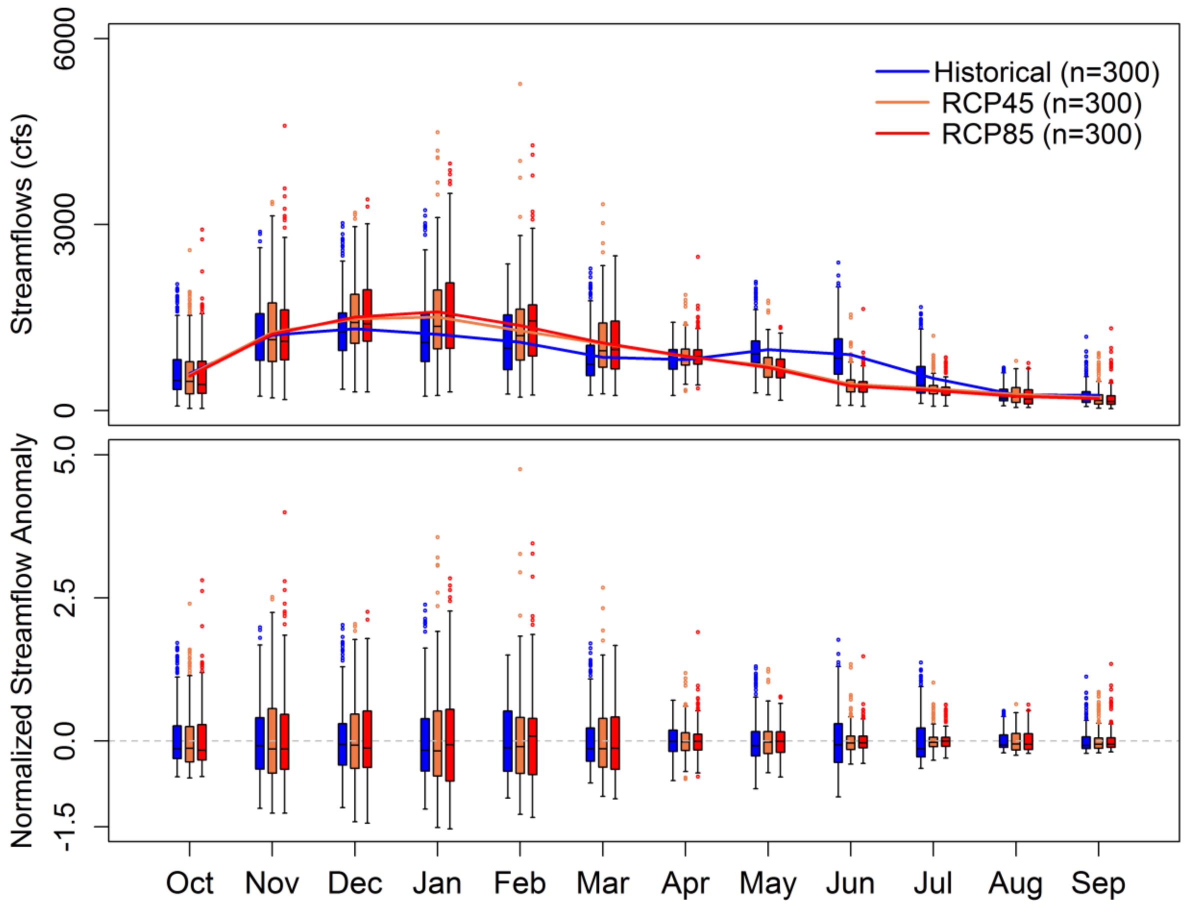

Figure 11. Variability in monthly flows for the North Fork Skokomish River at Cushman Dam. Figures show the distribution of monthly streamflows for all 10 GCMs, with the top panel showing absolute flows in cfs and the bottom showing the normalized streamflow anomaly, described above. Box and whisker plots are included for each month for historical (blue) as well as RCP 4.5 (orange) and RCP 8.5 (red). The boxes show the median (solid horizontal line within box), 25th and 75th percentiles (box limits), while the whiskers extend beyond the boxes out to a distance of 1.5 times the interquartile range. All points that extend beyond the whiskers are defined as outliers and plotted individually as open circles.

3.3 Extreme Flow Analysis

Historical and projected flood and low flow magnitudes for all four dams considered in this report are shown in Figures 12 and 13. Projected changes in flow extremes were evaluated for the 10-, 15-, 20-, 25-, and 30-year flood as well as the 10-year minimum in 7-day low flows (7Q10). Although there are some variations among GCMs and sites, flood risk is projected to increase, on average, at all locations by the 2030s under both emission scenarios, relative to 1970-1999 (Table 11). The projected increases in flood risk are a result of both higher freezing elevations (more precipitation falling as ran) and increasing in storm intensity associated with climate change. Decreases in 7Q10 flows are also consistent (about -30% on average) across all four sites.

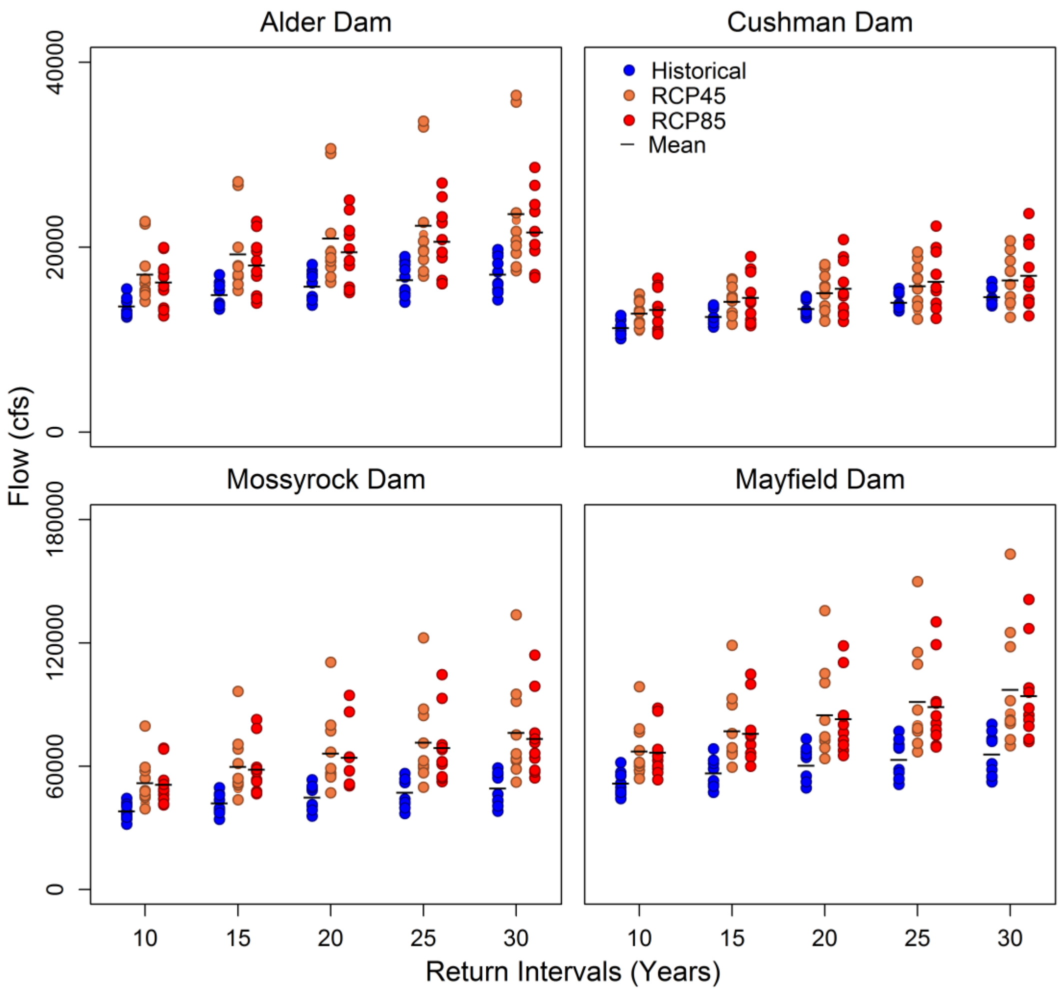

Figure 12. The 10-, 15-, 20-, 25- and 30- year flood statistics at Alder, Cushman, Mossyrock and Mayfield Dams for the historical (blue) and future time periods forced by the high (RCP 8.5, red) and low (RCP 4.5, orange) emission scenarios.

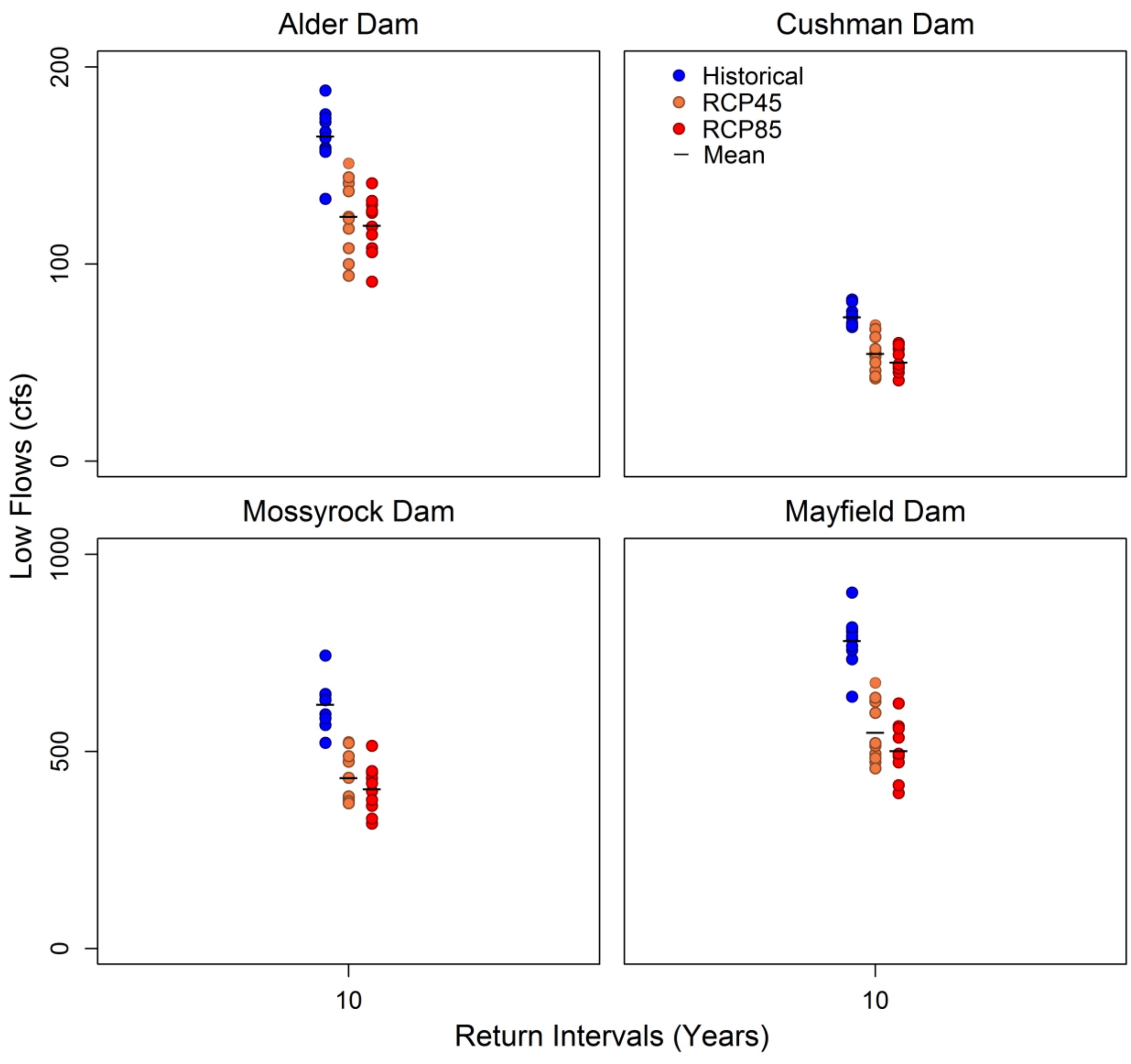

Figure 13. The 7-day minimum low flow statistics with a 10-year return period at Alder, Cushman, Mossyrock and Mayfield Dams for the historical (blue) and future time periods forced by the high (RCP 8.5, red) and low (RCP 4.5, orange) emission scenarios.

Table 11. Simulated flood and low flow statistics for all four streamflow sites. Results are shown for the historical period (1970-1999) and 2030s (2020-2049) for a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario. The table includes absolute flows (cfs) and percent change relative to the historical baseline, the latter showing the range among all 10 GCMs.

		Mean Flows (cfs)			*Change (%)*	
Site	**Statistic**	**Historical**	**RCP 4.5**	**RCP 8.5**	**RCP4.5**	**RCP 8.5**
Alder	10-yr flood	13,618	17,070	16,198	+25 (+3 to +62)	+19 (−13 to +41)
Cushman	10-yr flood	11,288	12,827	13,229	+14 (−4 to +36)	+18 (−8 to +52)
Mossyrock	10-yr flood	38,115	51,870	51,101	+35 (+16 to +91)	+34 (−2 to +64)
Mayfield	10-yr flood	51,674	67,312	66,740	+30 (+11 to +78)	+29 (+0 to +57)
Alder	15-yr flood	14,850	19,257	18,049	+29 (+1 to +71)	+22 (−13 to +49)
Cushman	15-yr flood	12,473	14,107	14,548	+13 (−4 to +39)	+17 (−5 to +57)
Mossyrock	15-yr flood	41,959	59,838	58,389	+42 (+18 to +109)	+39 (+0 to +70)
Mayfield	15-yr flood	56,637	77,098	75,828	+36 (+10 to +94)	+34 (+3 to +63)
Alder	20-yr flood	15,755	20,970	19,473	+33 (+0 to +79)	+24 (−13 to +55)
Cushman	20-yr flood	13,350	15,058	15,527	+13 (−4 to +42)	+16 (−4 to +60)
Mossyrock	20-yr flood	44,875	66,252	64,220	+47 (+17 to +123)	+44 (+2 to +80)
Mayfield	20-yr flood	60,345	84,930	83,041	+40 (+8 to +106)	+38 (+5 to +70)
Alder	25-yr flood	16,449	22,352	20,602	+35 (−1 to +86)	+26 (−14 to +61)
Cushman	25-yr flood	14,026	15,796	16,284	+13 (−7 to +43)	+16 (−6 to +63)
Mossyrock	25-yr flood	47,172	71,526	68,994	+51 (+16 to +135)	+47 (+1 to +90)
Mayfield	25-yr flood	63,231	91,343	88,909	+44 (+7 to +117)	+41 (+2 to +79)
Alder	30-yr flood	17,053	23,602	21,610	+38 (−2 to +91)	+28 (−14 to +67)
Cushman	30-yr flood	14,616	16,442	16,945	+12 (−9 to +45)	+16 (−8 to +66)
Mossyrock	30-yr flood	49,210	76,365	73,358	+55 (+14 to +146)	+50 (−3 to +100)
Mayfield	30-yr flood	65,766	97,209	94,248	+47 (+6 to +126)	+44 (−1 to +87)
Alder	7Q10	165	124	120	−25 (−39 to −5)	−27 (−39 to −11)
Cushman	7Q10	73	55	50	−25 (−49 to +0)	−31 (−50 to −12)
Mossyrock	7Q10	619	433	404	−30 (−43 to −16)	−34 (−50 to −19)
Mayfield	7Q10	780	548	501	−30 (−44 to −14)	−36 (−51 to −21)

4 Climate Change Impacts on Hydropower Production in the Columbia River System

The Columbia River plays a pivotal role in energy production in the Pacific Northwest, producing approximately 70 to 80% of the Pacific Northwest's electricity annually (USBR 2011a). Flows on the Columbia River are also managed for flood control, anadromous fish flows, irrigation, navigation, and recreation via more than 400 federally and locally operated dams in the U.S. and Canada (USBR 2011b).

Climate change is expected to have important impacts on seasonal and annual hydropower production in the Columbia system as a result of reductions in snowpack, shifts in the timing of peak streamflow, lower summer streamflows, and warmer summer stream temperatures. Demand for power is also likely to be affected by climate change, although changes in demand related to climate change may be secondary to increases driven by population growth. This section provides a summary of projected changes in Columbia River hydrology, hydropower generation, and demand. Broader impacts on hydropower production in the western U.S. and potential renegotiation of the Columbia River Treaty are also briefly discussed. Impacts on flood control, anadromous fish flows, and other water uses for the Columbia are outside the scope of this study and therefore not included here.

4.1 Projected Changes in Pacific Northwest Climate and Columbia River Hydrology

Changes in Columbia River hydrology as a result of climate change are principally driven by increasing temperatures and seasonal changes in precipitation. Climate change scenarios for the Pacific Northwest show increases in annual and seasonal temperature through the end of the 21st century, with the amount of warming varying based on future greenhouse gas emissions (e.g., low versus high) and time period of interest (e.g., 2040s versus 2080s) (Figure 14, Table 12) (Mote et al. 2010, Kunkel et al. 2013, Mote et al. 2013). Precipitation changes are less pronounced due primarily to the large range of natural variability in observed precipitation in the Pacific Northwest. Although models disagree on the direction of change, most scenarios project a small increase in average annual precipitation and an enhanced seasonal cycle, i.e., wetter winters and drier summers.

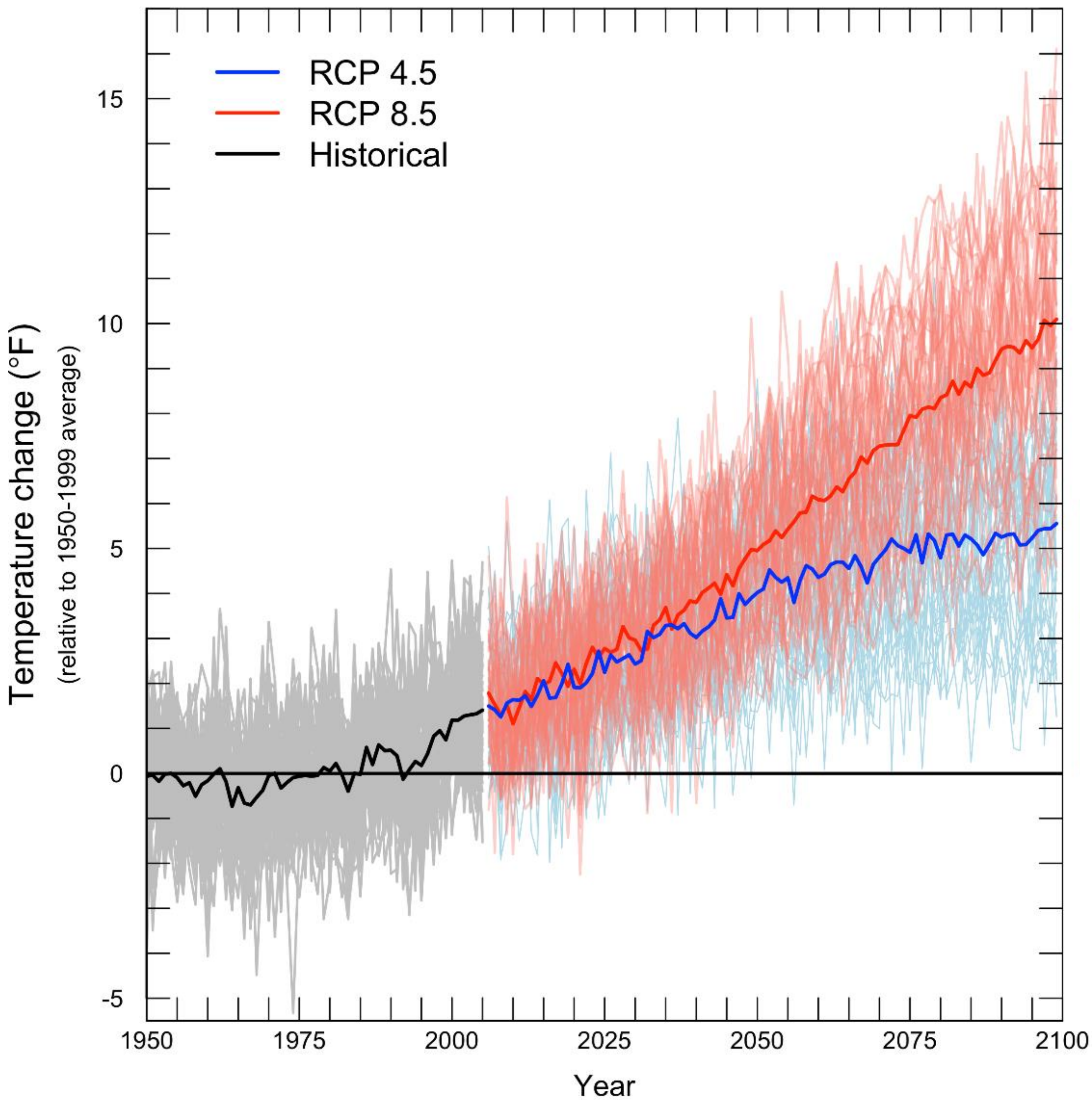

Figure 14. Projected increases in average annual temperatures for the Pacific Northwest relative to the average for 1950-1999 (gray horizontal line). The black line shows the average simulated temperature for 1950–2005, while the grey lines show individual model results for the same time period. Thin colored lines show individual model projections for two emissions scenarios (low: RCP 4.5, and high: RCP 8.5), and thick colored lines show the average among model projections for each scenario. Figure source: Climate Impacts Group, based on climate projections used in the IPCC 2013.

Table 12. Projected increases in average annual and seasonal temperature for the Pacific Northwest, relative to the average for 1950-1999, for two emissions scenarios (low: RCP 4.5, and high: RCP 8.5). (Mote et al. 2013, as summarized in Snover et al. 2013)

Temperature	**Projected Change** for the 2050s (2041-2070), relative to 1950-1999	
Average Annual		Low emissions (RCP 4.5): +4.3°F (range: +2.0 to +6.7°F) High emissions (RCP 8.5): +5.8°F (range: +3.1 to +8.5°F)
Seasonal	*Winter*	Low emissions (RCP 4.5): +4.5°F (range: +1.6 to +7.2°F) High emissions (RCP 8.5): +5.8°F (range: +2.3 to +9.2°F)
	Spring	Low emissions (RCP 4.5): +4.3°F (range: +0.9 to +7.4°F) High emissions (RCP 8.5): +5.4°F (range: +1.8 to +8.3°F)
	Summer	Low emissions (RCP 4.5): +4.7°F (range: +2.3 to +7.4°F) High emissions (RCP 8.5): +6.5°F (range: +3.4 to +9.4°F)
	Fall	Low emissions (RCP 4.5): +4.0°F (range: +1.4 to +5.8°F) High emissions (RCP 8.5): +5.6°F (range: +2.9 to +8.3°F)

A key impact associated with rising temperatures is loss of snowpack. The Pacific Northwest holds the highest fraction of “warm snow” (snow falling between 27°F and 32°F) in the continental U.S. (Mote et al. 2008). As a result, even moderate amounts of warming can have a large impact on snowpack as more winter precipitation falls as rain rather than snow.

April 1 snowpack in the Columbia River Basin is projected to decline by −19% for the 2020s (for both scenarios), −23% and −29% for the 2040s, and −38% and −52% for the 2080s for a low (B1) and moderate (A1B) greenhouse gas emissions scenario, respectively, relative to 1916-2006 (Hamlet et al. 2013). Losses are more acute at lower and middle elevations where average winter temperature is already close to the freezing threshold (Figure 15). Higher elevations, including portions of the upper Columbia basin in British Columbia, generally remain cold enough to continue accumulating snow through mid-century. As a result, model results show that some high elevation areas in British Columbia experience small *increases* in snowpack until the 2040s as a result of slight increases in winter precipitation (Hamlet et al. 2013, Murdock and Sobie 2013). Any potential buffer to changing hydrologic conditions south of the border diminishes after mid-century, however, as the amount of winter warming becomes more significant at higher elevations (Hamlet et al. 2013, Murdock and Sobie 2013).

The impact of increasing temperatures and reductions in snowpack on seasonal runoff volume is considered “the single characteristic of all the climate change scenarios that most impacts the projects on the Columbia River and its tributaries” (USBR et al. 2011b, p.44). How much

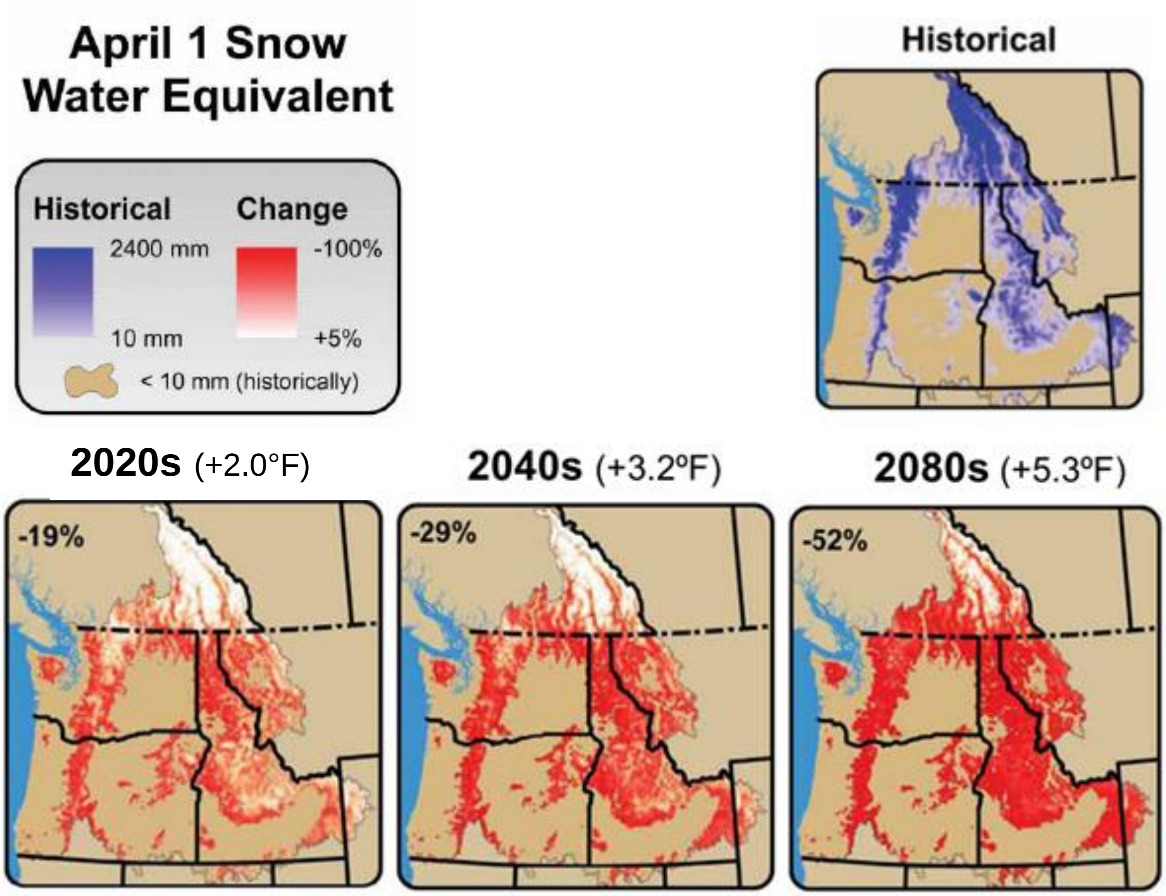

Figure 15. Simulated historical 1 April snow water equivalent (SWE) for the Columbia River Basin (upper right) and projected percentage change in 1 April SWE, relative to 1916-2006, for a moderate (A1B) greenhouse gas emissions scenarios. The associated change in mean annual temperature for the A1B scenario for each time period is also shown. Figure source: Hamlet et al. 2013.

streamflow volume and timing change will vary by location but a basin-wide aggregation of those change is seen in streamflow projections for the Columbia River at The Dalles (Figure 16). Relative to simulated historical (1916-2006) streamflow, mean annual runoff is projected to increase +1.2 to +3.7% by mid-century (USBR 2011b). Seasonal changes include higher fall and early winter streamflows (due to the shift in winter precipitation to more rain), earlier peak runoff (due to warmer temperatures), and lower spring and summer streamflows (due primarily to lower snowpack, earlier snowmelt, and increased evapotranspiration) (Table 13) (Elsner et al. 2010, USBR et al. 2011b, Hamlet et al. 2013, Raymondi et al. 2013).

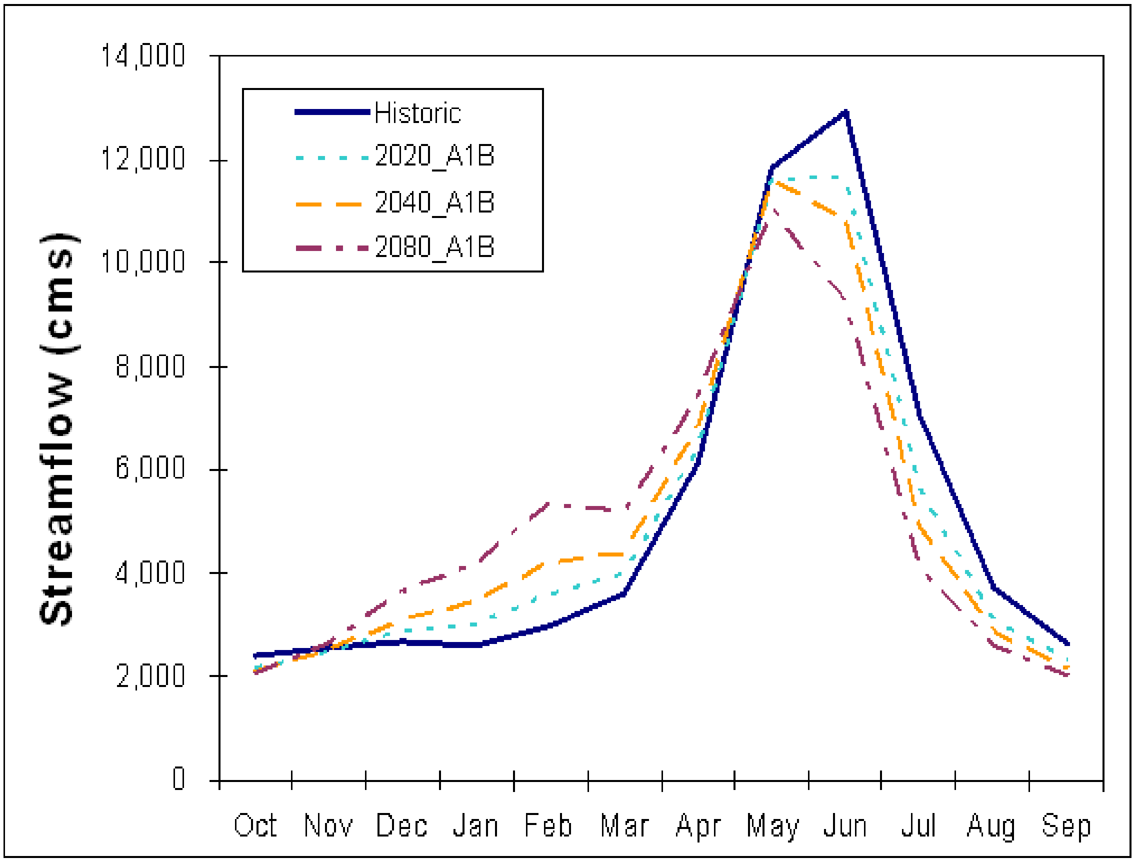

Figure 16. Simulated long-term mean modified streamflow for the Columbia River at The Dalles, OR for three climate change scenarios based on a moderate (A1B) emissions scenario. Figure source: Hamlet et al. 2010.

Table 13. Projected change in unregulated flows for the Columbia River at The Dalles for the 2020s and 2040s, as % of normal, relative to the simulated historical period (1929-1998). Projections for each time period are based a set of six GCMs run with a low (B1) and moderate (A1B) emissions scenario (BPA 2011, USBR et al. 2011a).

Seasonal Flows	**2020s (2010-2039)**	**2040s (2030-2059)**
January - April	+8% to +50%	−5% to +70%
June - August	−20% to −5%	−35% to −5%

4.2 Impacts on Hydropower Generation

Climate change impacts on hydropower generation vary seasonally and over time based primarily on seasonal changes in streamflow. Overall, annual hydropower generation in the Columbia system decreases slightly (e.g., −2.0% to −3.4% by the 2040s, see Table 14, Figure 17) (Hamlet et al. 2010, USBR 2011a). In the near to mid-term (through 2040), this decrease is considered within the range of variability in annual generation experienced by Bonneville Power in recent decades (1989–2008) (USBR 2011a).

The relatively small change in annual production masks larger seasonal changes that could be important to management of the system. Higher cool season streamflows increase winter (Jan-Mar) hydropower generation +4.7 to +5.0% by the 2040s and +7.7% to 10.9% by the 2080s, relative to 1970-1999 (Hamlet et al. 2010; Table 14).[5] Conversely, lower summer streamflows

Table 14. Summary of simulated annual and seasonal (e.g., OND = Oct, Nov, Dec) hydropower production in percent (top) and TeraWatt-hrs (bottom) for a low (B1) and moderate (A1B) greenhouse gas emissions scenario, relative to historic base case (1917-2006). From Hamlet et al. 2010.

%	Annual	OND	JFM	AMJ	JAS
Historic	100.00	100.00	100.00	100.00	100.00
2020-A1B	96.63	98.05	101.04	96.29	89.04
2020-B1	99.23	101.26	104.53	98.04	91.36
2040-A1B	96.62	99.41	104.96	94.78	84.65
2040-B1	98.02	100.91	104.66	96.51	87.86
2080-A1B	96.85	102.82	110.87	91.83	79.24
2080-B1	97.43	102.90	107.69	93.99	82.94

TeraWatt-hrs	Annual	OND	JFM	AMJ	JAS
Historic	120.98	22.30	33.38	43.62	21.68
2020-A1B	116.90	21.86	33.72	42.00	19.31
2020-B1	120.04	22.58	34.89	42.77	19.81
2040-A1B	116.89	22.16	35.03	41.34	18.35
2040-B1	118.58	22.50	34.93	42.10	19.05
2080-A1B	117.17	22.92	37.01	40.06	17.18
2080-B1	117.87	22.94	35.94	41.00	17.98

5 For a low (B1) and moderate (A1B) greenhouse gas scenario (Hamlet et al. 2010).

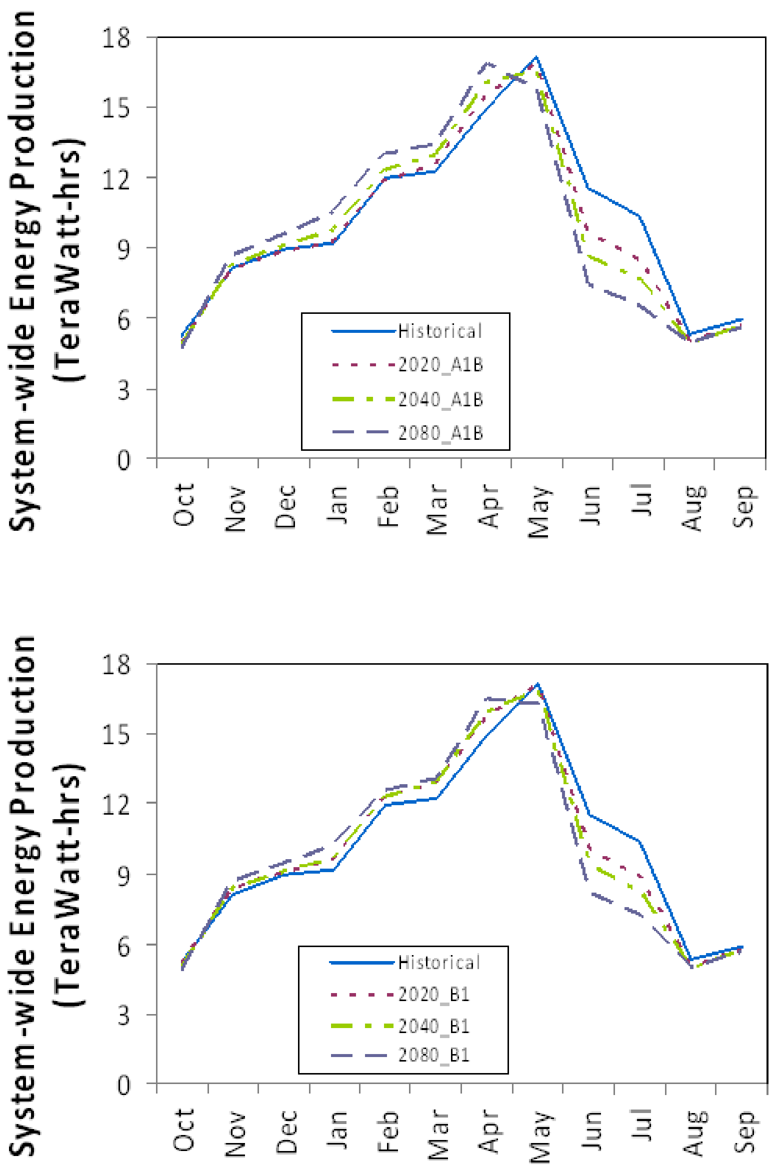

Figure 17. Simulated long-term mean, system-wide hydropower production from the Columbia River basin for six climate change scenarios. Top panel shows results for the A1B scenario. Bottom panel shows results for the B1 scenario. Figure source: Hamlet et al. 2010.

(July-Sept) decrease summer hydropower generation by −12.1 to −15.4% by the 2040s and −17.1% to −20.8% by the 2080s, relative to 1970-1999. These changes do not take into account the impact of changes that may be required to adapt competing water uses or to meet potential revisions to the Columbia River Treaty (see Section 4.4 for more on indirect effects related to climate change).

Although the projected changes in annual production through mid-century are generally within the range of recent variability, drought years could create significantly greater challenges depending on the timing of the drought (USBR et al. 2011b). Simulations of critical drought years from the 20th century (e.g. 1937, 1977, 2001) in a changing climate show lower winter hydropower production than average, however those impacts are on par with reductions found in the 20th century simulations (Hamlet et al. 2010). The impact of future winter droughts on winter power generation is somewhat mitigated by increased cool season precipitation and higher winter streamflows. In contrast, the impact of winter drought on projected spring and summer (April–September) power generation is larger than comparable scenarios in the 20th century due to declining snowpack and reductions in spring and summer streamflows, which could decrease by as much as −30% to −40% during periods of drought (Hamlet et al. 2010, USDOE 2013). However, in the near- to mid-term (through the 2040s), the variability in streamflows as it affects dam operations is expected to remain within the variability observed in the 20th century (USDOE 2013).

4.3 Impacts on Energy Demand

Changes in future energy demand reflect the combined effects of population growth and changing temperatures. Per capita residential heating energy demand is projected to decrease as winter temperatures warm, reducing overall demand in Washington State by −12% for the 2020s relative to 1970-1999 (Hamlet et al. 2010). Increased heating energy demand from population growth swamps this per capita decline, however, resulting in a net increase in overall winter energy demand in Washington State through the end of the century (+22 to +23% for the 2020s, +35 to +42% for the 2040s, and +56 to +74% for the 2080s, relative to 1970-1999) (Hamlet et al. 2010).

Changes in average cooling energy demand[6] are significant in terms of percent change (+170 to +206% for the 2020s, +370 to +564% for the 2040s, and +997 to +1873% for the 2080s, relative to 1970-1999) but still remain small overall relative to total heating energy demand (*ibid*, see Table 3). Residential cooling demand in Washington State is projected to increase to +1.7 to +2.0% (2020s), +2.6 to +3.8% (2040s), and +4.8 to +9.1% (2080s) of total energy demand, relative to 1970-1999, due to the combined effects of population growth, warmer summer air temperatures, and expanded use of air conditioning (Hamlet et al 2010). Decreasing summer streamflows will make it more difficult to meet growing summer demands.

4.4 Other Considerations

Climate change impacts on Columbia River hydropower production can also arise indirectly as a result of the need to adapt to impacts on other water uses in the system. This includes actions

[6] Projections for air conditioning penetration used in Hamlet et al. 2010 were based on residential air conditioning market penetration only.

taken to address lower summer water supply for irrigation and municipal and industrial uses and increasing stress for salmon due to warmer summer water temperatures and lower summer streamflows (Mote et al. 2003, ISAB 2007, Vano et al 2010, USBR et al. 2011a, Raymondi et al. 2013). Discussion of these impacts is outside the scope of this report and therefore not included here.

A 2012 study (Sale et al. 2012) conducted by Oak Ridge National Laboratory for the U.S. Dept. of Energy reflected the blending of these direct and indirect effects when identifying risks to Bonneville Power Administration operations and contract practices resulting from near term (2010–2024) and mid-term (2025–2039) hydrologic impacts. Stated risks were:

- "Slight decrease in annual generation in the near-term period (2010–2024) projection and in the summer period in particular
- Increased stress to salmon as a result of rising temperatures and changing streamflow
- Increased risk to Cascade Basin projects' ability to maintain summer water quality and minimum flow objectives
- Expectation that energy demand and use will increase as a result of higher air temperatures
- Long-term increase in streamflow volatility resulting in reduced surplus sales, changes in seasonal pricing and eventual increase in rates for customers."

(Sale et al. 2012, verbatim from p.41)

A key issue identified by Bonneville Administrators for rate payers is the question of whether the hydrologic impacts from climate change will affect electricity rates and take-or-pay contract rates for the Federal Columbia River Power System (USDOE 2013). While take-or-pay contracts are designed around expectations of variability in the timing and amount of power, it is unclear at this time if climate change will affect contract rates over time. It is also unclear at this time as to how and when bulk power contracting practices will need to change as a result of climate change impacts.

Secondary impacts on hydropower production in the Columbia system will also come as a result of climate change impacts on the western U.S. power grid and energy markets. Declining snowpack and lower spring and summer flows are projected throughout the western U.S. and will affect generation capacity in those systems to varying degrees (e.g., Christensen et al. 2004, VanRheenan et al. 2004, USBR 2011a, GAO 2014). Nationally, annual federal hydropower production could decrease 1 to 2 TWh (median value) through 2040, relative to 1989-2008 (Kao et al. 2014). However, the range of uncertainty in this estimate is large (± 9 TWh).

Non-hydro energy generation and processing may also be affected. For example, warmer summer temperatures and increasing water stress in the U.S. west and other regions of the country may result in:

- Reduced operations or temporary closures at generation facilities due to inadequate cooling water supply or water that is either too warm to use for cooling purposes or too warm to discharge;
- Reduced effectiveness of photovoltaic electricity generation;
- Reduced efficiency of geothermal facilities; and
- Reduced transmission efficiency and capacity. (GAO 2014, Dell et al. 2014)

Looking across a range of generation technologies, Bartos and Chester (2015) found that climate change could reduce average summer generating capacity within the service region of the Western Electricity Coordinating Council (WECC) by −1.1% to −3.3% by mid-century (2040-2060, relative to 1949-2010). The impacts of a 10-year drought would be more severe (reductions up to −7.2 to −8.8%). The capacity of conventional thermoelectric generation technologies were most affected, while hydropower capacity across the WECC region was found to be fairly resilient within this time frame due at least in part to limitations of the study approach.[7]

Transmission infrastructure in the U.S. west is also at higher risk of damage from forest fires, which are projected to increase in the coming decades due to the combined effects of warmer temperatures and increased stress from drought and insects (Littell et al. 2010, Joyce et al. 2013, Stavros et al. 2014). These additional pressures on U.S. energy infrastructure could affect availability and price of energy on wholesale energy markets, although little is known about how prices may change in response to climate change impacts (most work has been focused on assessing the impacts of greenhouse gas mitigation policies on energy prices) (CCSP 2007).

Another major consideration for future hydropower generation in the Columbia system is the potential renegotiation of the Columbia River Treaty. Implemented in 1964, this Treaty governs flood control management and hydropower generation between Canada and the U.S. The Treaty provided payment from the U.S. to Canada for construction and management of three dams in Canada for flood control (Duncan, Mica, and Keenleyside [also known as Arrow] Dams). A fourth dam, Libby Dam, was also constructed in Montana as part of the Treaty (Libby Dam's reservoir extends into Canada). Combined, the four reservoirs constructed for the Treaty provide 51% of the total storage in the Columbia system (BPA and ACOE 2013).

U.S. payment for flood control benefits from the Treaty dams covered benefits provided through September 2024 (BPA and ACOE 2014). Construction of the dams also allowed for increased power generation downstream in the U.S. The additional power generation benefit is shared

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7 According to the authors, hydropower capacity projections for the WECC region were limited to an annual timescale due to uncertainty about reservoir operations and projected water demands.

equally with Canada in what is known as the "Canadian Entitlement" and has been delivered daily to British Columbia since 2003.[8]

While the Treaty has no official expiration date, flood control provisions in the Treaty will be altered automatically in 2024. Additionally, either party can choose to terminate certain provisions any time after September 16, 2024 after providing the required 10 years' notice of intent to terminate. Some flood control would still be required regardless of whether the Treaty is terminated, however U.S. payment for those benefits would increase. Termination of the Treaty would also eliminate the Canadian Entitlement.

The original Treaty did not take into account other water uses in the Columbia system, including water needed for fish flows and ecosystem benefits, navigation, recreation, irrigation, and municipal and industrial water uses. Discussions regarding the future of the Treaty will likely be affected by the need to consider these additional water uses; the U.S. State Department announced on June 12, 2015 the intent to include "ecosystem-based function interests" in its draft negotiating position (in addition to flood control and hydropower) (Columbia Basin Bulletin, 2015).

The impacts of climate change on the Columbia are central to Federal discussions on the Treaty. While only 15% of the Columbia basin is located in Canada, the Canadian portion provides 35% of total annual streamflow, 50% of peak flows, and an estimated 50% of late summer streamflow (Vaddey 2010; Hamlet 2013). These proportions are likely to change as a result of the differential impacts of climate change on snowpack in the U.S. versus Canadian portion of the basin, as described previously, and will affect all three of the major issues around which the Treaty may be negotiated.

Studies on the impacts of climate change on Columbia River streamflows were undertaken by Bonneville Power Administration, the U.S. Army Corps of Engineers, and the Bureau of Reclamation in the late 2000s to inform initial recommendations to the U.S. State Department on renegotiation of the Treaty (e.g., USBR et al. 2011a,b). Additional studies based on the newest greenhouse gas emission scenarios will be completed in 2016 (Columbia Basin Bulletin, 2014).

[8] After construction of the four Treaty dams was completed in 1973, Canada sold its entitlement for a period of 30 years (ending in 2003) to a consortium U.S. utilities for a lump sum payment of $254 million (BPA and ACOE 2013).

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