Climate Change Impacts on Water Management in the Puget Sound Region, Washington, USA

Julie A. Vano[1], Nathalie Voisin[1], Lan Cuo[1,2], Alan F. Hamlet[1,2], Marketa McGuire Elsner[2], Richard N. Palmer[3], Austin Polebitski[1], and Dennis P. Lettenmaier[1,2]

Abstract

Climate change is projected to result, on average, in earlier snowmelt and reduced summer flows, patterns that are not well represented in the historical observations used for planning and reliability analyses by water utilities. We extend ongoing efforts in the Puget Sound basin cities of Everett, Seattle, and Tacoma to characterize differences between historic and future streamflow and the ability of the region's water supply systems to meet future demands. We use future streamflow simulations for the 2020s, 2040s, and 2080s from the Distributed Hydrology-Soil-Vegetation Model (DHSVM), driven by climate simulations archived by the 2007 Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). We use ensembles of streamflow predictions produced by DHSVM forced with multiple downscaled ensembles from the IPCC climate models as inputs to reservoir system models for the Everett, Seattle, and Tacoma water supply systems. Over the next century, under average conditions all three systems are projected to experience a decline and eventual disappearance of the springtime snowmelt peak in their inflows. How these shifts impact water management depends on the specifics of the reservoir system and their operating objectives, site-specific variations in the influence that reductions in snowmelt have on reservoir inflows, and the adaptive capacity of each system. Without adaptations, average seasonal drawdown of reservoir storage is projected to increase in all of the systems throughout the 21st century. The reliability of the three water supply systems in the absence of demand increases is, however, generally robust to climate changes through the 2020s, and in the 2040s and 2080s reliability remains above 98% for the Seattle and Everett systems. With demand increases, however, system reliability is progressively reduced by climate change impacts.

1. Introduction

The Puget Sound basin receives most of its precipitation in the winter, whereas municipal water use is greatest in the summer. Most of this incremental increase in demand is for residential and commercial landscape irrigation. In the Pacific Northwest, heavy winter precipitation poses challenges in managing floods while extended periods of low precipitation in summer and early fall pose challenges in meeting municipal water demands and in maintaining instream flows for environmental purposes. Water managers rely on reservoirs and storage of winter precipitation in mountain snowpack to provide inflows into reservoirs and to maintain instream flows in the summer and fall. Climate change is predicted to result in warmer temperatures that will reduce snowpack and cause earlier snowmelt runoff, reduced summer flows, higher winter flows (Mote et al. 2005, Milly et al. 2005, Knowles et al., 2006, IPCC, 2007, Cuo et al. 2008a) and a general loss of stationarity of the climate system (Milly et al., 2008). Therefore, managing water supply systems to provide sufficient water throughout the summer may become more challenging.

Municipal water suppliers in the Puget Sound basin have already taken steps to evaluate the implications of possible future climate conditions on the reliability of their systems (Palmer, 2007; SPU, 2007). Wiley and Palmer (2008) used downscaled output from four IPCC (2007) General Circulation Models (GCMs), specifically ECHAM4, HadCM3, GFDL_R30, and PCM models, to evaluate the potential impacts of climate change in the 2020s, and 2040s on the Seattle water supply system. Traynham (2007) used downscaled output from three different IPCC (2007) GCMs (GISS_B1, ECHAM5_A2, and IPSL_A2 models) to evaluate the potential impacts of climate change on the Seattle, Tacoma, and

[1]Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington
[2]Climate Impacts Group, University of Washington, Seattle, Washington
[3]Civil and Environmental Engineering, University of Massachusetts Amherst, Amherst, Massachusetts

Everett water supply systems (Figure 1). Polebitski et al. (2008) extended this work to include the proposed White River water source that would use Lake Tapps water to serve members of the Cascade Water Alliance, which includes municipalities in the rapidly growing areas east of Seattle, and would assume some of Seattle's future water demand. Taken together, the results of these three studies suggest that projected climate change may impact the yield of each system, that each system will respond differently, and that changes in system operating policies can help to mitigate impacts of climate change.

We build on these previous efforts to include more information about the range of potential effects of climate change on water supply systems in the Puget Sound basin and compare these potential hydrologic changes with changes in water demand. A major advance in this study as compared with previous efforts is the use of the full suite of GCM output that was archived by the IPCC (2007). Previous studies in general have not had access to such a large number of simulations of future climate, and therefore have not been able to incorporate the range of uncertainty represented by climate model simulations. For instance, Payne et al. (2004), Christensen et al. (2004), and Van Rheenen et al. (2004) all used downscaled output from a single GCM. More recent studies, prepared as the 2007 IPCC output began to be archived, have used what is sometimes termed a multi-model ensemble approach – that is, hydrologic, and water resources simulations, are performed using multiple climate model output sequences, or ensembles. Maurer (2007), in a study of hydrologic impacts of climate change in California, used 11 models and 2 global emissions scenarios. Christensen and Lettenmaier (2007) used essentially the same GCM ensembles and emissions scenarios in a study of the hydrologic and water resources sensitivity to climate change in the Colorado River basin. Hayhoe et al. (2007) used nine GCM ensembles and three emissions scenarios in a study of the hydrologic sensitivity to climate change in the northeastern U.S. In this analysis, we use A1B and B1 IPCC emissions scenarios with 20 and 19 GCM models for A1B and B1 respectively. Mote and Salathé (2009, this report) provide details of IPCC emissions scenarios and discuss why these emission scenarios were selected. The larger number of GCM ensembles that we were able to include here allows us to develop a better understanding of the variability and especially the range of uncertainties of simulations of hydrology that may accompany future climate emissions scenarios, and the resulting impacts on water management. The ensemble members are taken as equally likely representations of future climate. In that respect, they are our best current basis for characterizing the uncertainty in future climate simulations, although they do not necessarily cover the entire range of future possibilities. For a further discussion of this point, the reader is referred to Mote and Salathé (2009, this report).

Our study follows closely on the work of Traynham (2007). We use the same reservoir system models for the Everett, Seattle, and Tacoma water supply systems and the same hydrological model (Distributed Hydrology-Soil-Vegetation Model). However, we have enhanced the long-term data sets used to force the hydrologic models considerably. The distributed spatial resolution is higher (we use a 1/16th degree latitude-longitude daily historical data set), and the base period is much longer than was previously available (1917 to 2006). Furthermore, adjustments to the data have been

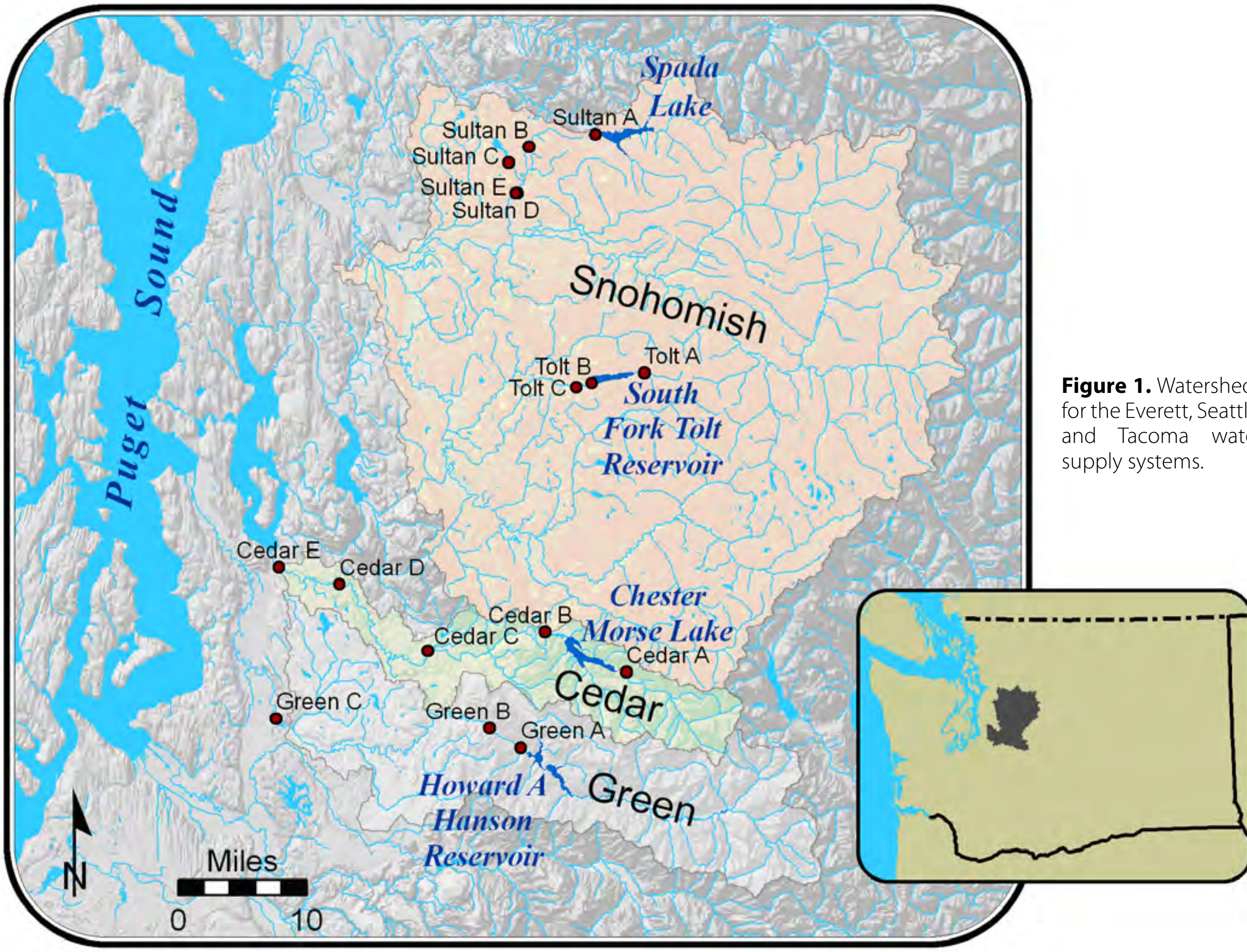

Figure 1. Watersheds for the Everett, Seattle, and Tacoma water supply systems.

incorporated to avoid spurious trends in the historic record. Elsner et al. (2009, this report) describe these improvements in an accompanying paper.

In this paper, we first describe briefly the three water supply systems that were analyzed, and water management models of each of the three systems. We then use the models to explore how without adaptations the performance of the three systems is expected to respond to changes in climate over the next century and to changes in water demand.

2. Site Descriptions

Cascade Mountain precipitation is the source of most of the water used by the major population centers of the Puget Sound, including King County (Seattle and Bellevue), Pierce County (Tacoma), and Snohomish County (Everett). In all three systems snowpack plays an important role in shaping the seasonal cycle of reservoir inflows. The Snohomish (including the Sultan and Tolt Rivers), Cedar, and Green River basins (Figure 1, Table 1), provide water to Everett (Sultan River), Seattle (South Fork Tolt and Cedar Rivers), and Tacoma (Green River). These three water supply systems each have unique physical characteristics, management histories, and operating objectives. These factors also determine how these basins are impacted by and may be able to adapt to climate change. One important indicator

Table 1. Reservoir system statistics.

Reservoir	total capacity ($1000m^3$)	total capacity (acre-ft)	active capacity (m3)	active capacity (acre-ft)	ratio of storage to demand	people served	firm yield in 2006[B] (cms)	firm yield in 2006[B] (mgd)
Everett								
Spada	188,700	153,000	169,500	137,400	1.56	550000 [C]	8.8	200
Seattle								
Chester Morse	104,400	84,600	59,800	48,500 [A]	0.42	1,350,000	7.5	171
South Fork Tolt	71,400	57,900	52,000	42,200 [A]	0.85			
Tacoma								
Howard Hanson	130,700	106,000	68,600	55,600[A]	1.46	302,000	4.6	105

[A] active capacity as parameterized in reservoir model without adaptations

[B] data from Miller (2008)

[C] personal communication with Jim Miller, January 2009.

of the susceptibility of these systems to climate change is how strongly the seasonal runoff cycle is affected by snow accumulation and melt. For strongly snow-affected basins, the extent to which the basin is likely to transition along the continuum from snow-dominated to mixed rain-snow to rain-dominated (see Elsner et al. 2009, this report) suggests how average seasonal hydrographs may shift. The size of the reservoir storage capacity relative to mean annual inflow, the relative amount of spring and summer inflow, the municipal and industrial (M&I) and instream flow demands, and the overall adaptive capacity of the water system, including the system's decision-makers, are also key determinants of how each of the systems might respond to climate change. Systems within the Puget Sound basin, compared to reservoirs elsewhere in the western U.S., have little carry-over storage from year-to-year. Characteristics for each of the systems are summarized below.

2.1. Everett Supply System

The Jackson Hydroelectric Project is the source of most of the city of Everett's water supply. The City of Everett and the Snohomish County Public Utility District #1 (SnoPUD) are co-managers of the system. SnoPUD operates the Jackson projects for a variety of purposes during different times of the year, including hydropower production, water supply, flood control, and maintenance of environmental flow targets. Water is diverted from Spada Lake through a 13 km tunnel system to the 112 MW capacity Jackson Powerhouse. A portion of this water is provided to Lake Chaplain for Everett's water demand. They are currently providing 3.9 cms (cubic meters per second) (88 million gallon days (mgd)) and are anticipated to increase in the future (Traynham, 2007; SnoPud, 2008)). Under the system's recent FERC relicensing (Snohomish Public Utility Dist 1 and City of Everett, 2006), the system must be operated to protect and enhance instream fish habitat, and to mitigate turbidity effects of the reservoir and hydropower systems. Recently, Jackson Hydropower Project operators partnered with the University of Washington to assess methods for optimizing hydroelectric generation with climate and energy forecasts in real time (Alemu, 2008).

2.2. Seattle Water Supply System

The Seattle water supply system consists of the Chester Morse reservoir on the Cedar River, and the South Fork Tolt reservoir, as well as several relatively small groundwater sources. The system is managed by Seattle Public Utilities (SPU) for various objectives, the most important of which are municipal and industrial water supply and environmental flows (SPU, 2007). About 70% of the system's demand is provided by Chester Morse Reservoir, and the balance by the South Fork Tolt and other sources. The system currently serves over 1.3 million people. Despite population growth, total water use has declined from 7.5 cms (171 mgd) in 1989 due to system savings, aggressive conservation programs and price increases for both water supply and wastewater treatment (wastewater treatment charges for residential customers are linked to water consumption, and typically are about double the cost of water). System-wide demand is projected to stay below 6.6 cms (150 mgd) through mid-century due to expected reduction in wholesale sales to a group of suburban water users known as the Cascade Water Alliance and a policy commitment to pursue additional conservation programs to be implemented through 2030 that are projected to save an additional 0.7 cms (15 mgd). The Cascade Water Alliance expects to develop its own supplies that will ultimately satisfy 1.1 cms (25 mgd) by 2049 (Traynham, 2007). In addition to water supply, the Cedar River and South Fork Tolt River reservoir systems are operated to meet minimum in-stream flows to support salmon spawning and rearing (SPU, 2007).

2.3. Tacoma Supply System

Tacoma receives its water supply primarily from the Green River, a portion of which can be stored in the Howard Hanson Reservoir, with groundwater providing about 10% of water deliveries on an annual average basis. The reservoir, built in 1962, is operated by the U.S. Army Corps of Engineers, primarily for flood control purposes. The Green River drainage to Howard Hanson is much larger than that of any of the other systems. The first water right for flows in the Green River is for municipal water supply so water is passed through the reservoir for that purpose. The First Diversion Water Right (FDWR) of 3.2 cms (113 cfs) was supplemented in 1995 with a Second Diversion Water Right (SDWR) for a maximum of 2.8 cms (100 cfs) also for consumptive use. The SDWR has instream flow limitations, although both diversion rights are constrained by the guarantee of minimum instream flows at Auburn (Green C in Figure 1). The capacity of Howard Hanson Reservoir is 131 million cubic meters (mcm), or 106 thousand acre-feet (taf), of which conservation is allocated 41 mcm (33.2 taf) for sustaining fish populations and the ecologic health of the river. Whereas, the city of Tacoma and its partners are allocated a total of 24.7 mcm (20 taf) for water supply. An ongoing project is intended to raise the pool 3.3 m (10 ft) to an elevation of 359 m (1,177 ft) to provide additional water storage for municipal water supply (USACE, 2008). Like the other systems, because of water conservation measures, Tacoma experienced its demand peak in 1989. In the future, Tacoma projects gradually increasing demands after the 2020s (Traynham, 2007). The project also includes increases in storage and fish enhancements to improve habitat and fish passage (USACE, 2008).

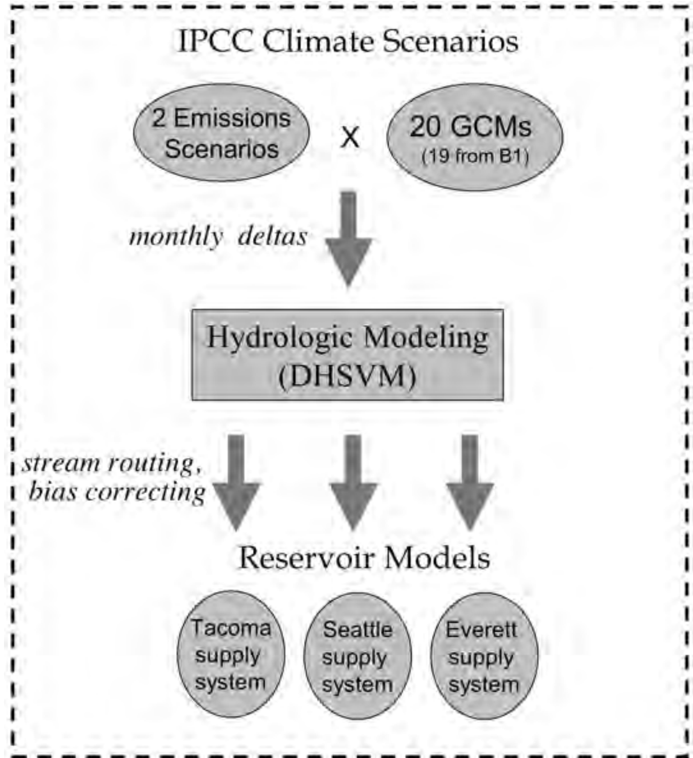

Figure 2. Multi-model process. Schematic of how climate model projections, hydrologc model, and water management models are connected.

3. Approach

We extended the multi-model ensemble approach as previously implemented by Christensen and Lettenmaier (2007), Hayhoe et al. (2007), and Maurer (2007) to explore climate impacts on the three reservoir systems (Figure 2). We used a physically-based hydrologic model driven by atmospheric forcings (precipitation, temperature) downscaled from GCM output as described in further detail in Elsner et al. (2009, this report). Our downscaling method consisted of the so-called delta method, in which the (daily) historic record of observations is perturbed by an additive (daily temperature maxima and minima) or multiplicative (daily precipitation) amount that is constant for each month in the 2020s (representing monthly averages from the transient GCM records from 2010-2039 for both A1B and B1 emission scenarios), 2040s (2030-2059) and 2080s (2070-2099) respectively. We removed bias attributable to uncertainties in the hydrological model, parameters and meteorological forcings (see Elsner et al., 2009, this report) using the quantile mapping method described in Snover et al. (2003) and Wood et al. (2002). Elsner et al. (2009, this report) describe the hydrologic simulations resulting from application of the delta method to develop inflow sequences for the Distributed Hydrology-Soil-Vegetation Model (DHSVM) for each of the three watersheds, all of which were based on the historical period from 1916 to 2006 (water years).

Simulations were performed for six composite delta scenarios (in which the delta values were averaged over all 20 (A1B) and 19 (B1) emissions scenarios for the 2020s, 2040s, and 2080s). Simulations were also performed for the 39 individual GCMs in the 2020s time period. The A1B emissions scenario is similar to what is sometimes termed a 'business as usual', whereas the B1 emissions scenarios represents the effects of more resource-efficient technologies intended eventually to stabilize greenhouse gas emissions at 550 ppm by 2100 (IPCC, 2007). However, for practical purposes, through about 2050, the two emissions scenarios are quite similar.

It is important to recognize that the delta method for downscaling results in hydrologic simulations that are quasi-stationary for the climate of the reference year – that is, a 2020s A1B simulation is effectively a 1916-2006 period with perpetual 2020s climate with A1B emissions. While this is artificial (and is to be contrasted with the transient approach used in other recent studies, such as Christensen and Lettenmaier (2007), Maurer (2007), and Hayhoe et al. (2007), it does have the advantage that transient changes in hydrology are not confounded with natural variability. For each water management model, simulations were evaluated by comparing historical flow (simulated flow using observed climate) with observed streamflow for the historical period, and then by comparing simulated reservoir storage generated using both historical and observed inflows as input to the water management (reservoir) model. Once we were satisfied that reservoir model performance for the historical period was comparable using simulated and observed flows (Section 4.1.1), we performed reservoir model simulations with the hydrology model output produced using the downscaled climate change forcings (Section 4.1.2).

3.1. Hydrologic Simulations

Historical and future streamflow simulations for the 2020s, 2040s, and 2080s were performed using the Distributed Hydrology-Soil-Vegetation Model (DHSVM) as described in Elsner et al. (2009, this report) and Mote and Salathé (2009, this report). Future climate is projected to have additive temperature and multiplicative precipitation changes as summarized in (Table 2) that result in hydrologic changes.

Water management models that require daily inflows are particularly sensitive to small biases that may be introduced by hydrologic simulations. For example, an unrealistic sequence of low flows may result in system shortfalls, whereas if actual flows have more variability the system can recover before shortfalls occur. For this reason, simulated inflows were bias corrected at locations used in the management models in such a way that the probability distributions of the historical simulated values matched those of the observations. This adjustment was performed for all reservoir inflow values, which included two inflows in the Green River basin, five in the Cedar, three in the Tolt, and five in the Sultan. Elsner et al. (2009, this report) provide more details on how well historical runs represent hydrology prior to bias correction. After bias correction, reservoir inflows closely match observations (Figure 3).

As described in Elsner et al. (2009, this report) DHSVM was calibrated for a 10-year period at upstream gages in the Cedar (USGS Gage 12115000, Cedar River near Cedar Falls), Green (USGS Gage 12104500, Green River near Lester), Snohomish (USGS Gage 12141300, Middle Fork Snoqualmie River near Tanner), and S.F. Tolt River (USGS Gage 12147600, South Fork Tolt River near Index). When observed values were not available, historic records were reconstructed. During the calibration period, the relative error in annual mean streamflow ranged from -10 to 2% (See Elsner et al. 2009, this report).

Table 2. Climatic changes in annual precipitation and temperature.

	2020s (2010-2039)		2040s (2030-2059)		2080s (2070-2099)	
	A1B	**B1**	**A1B**	**B1**	**A1B**	**B1**
% Change in Annual Precipitation	+0.2%	+1.9%	+2.1%	+2.2%	+4.9%	+3.4%
% Change in Cool Season Precipitation	+2.3%	+3.3%	+5.4%	+3.9%	+9.6%	+6.4%
% Change in Warm Season Precipitation	-4.2%	-0.9%	-5.0%	-1.3%	-4.7%	-2.2%

Notes: Cool season defined as October through March, while warm season is defined as April through September.

	2020s (2010-2039)		2040s (2030-2059)		2080s (2070-2099)	
	A1B	**B1**	**A1B**	**B1**	**A1B**	**B1**
Change in Annual Temperature (°C)	+1.18	+1.08	+2.05	+1.57	+3.52	+2.49
Change in Cool Season Temperature (°C)	+1.05	+1.01	+1.83	+1.42	+3.24	+2.33
Change in Warm Season Temperature (°C)	+1.31	+1.16	+2.26	+1.71	+3.79	+2.66

3.2. Water Management Modeling

Daily streamflow (1916-2006) from the DHSVM simulations was used as input to water resources models (WRMs) that simulate the operations of the three reservoir systems. Water year 1916 was used as spinup for the WRMs and 1917-2006 was used for the analysis. The models are essentially the same as in Palmer (2007), Traynham (2007), and Polebitski et al. (2007).

All WRMs run at a daily time step using GoldSim software. GoldSim is an object-orientated language tailored to represent reservoir systems that serve diverse needs such as municipal supply, flood control, environmental flows, and hydroelectric power. Inputs to the reservoir models include flows into the reservoirs as well as intervening flows to the system between the upstream inflow points and specified downstream control points (Figure 1). In the case of the Tacoma system, there are two inflows: flows into Howard Hanson Reservoir (Green A) and the difference between Green C and Green B. The Seattle model has two inflows above its two reservoirs (Tolt A and Cedar A) and four intervening flows on the Cedar and two on the Tolt. The Everett model has two reservoir inflows (Sultan A and Sultan C) and three intervening flows. A description of these inflow locations and information from the Water Supply Planning Process for the Puget Sound region is contained in O'Neill and Palmer (2007). More detailed descriptions of each model have been prepared by the Water Resources Management and Drought Planning Group for the Seattle system (Traynham and Palmer, 2006), for

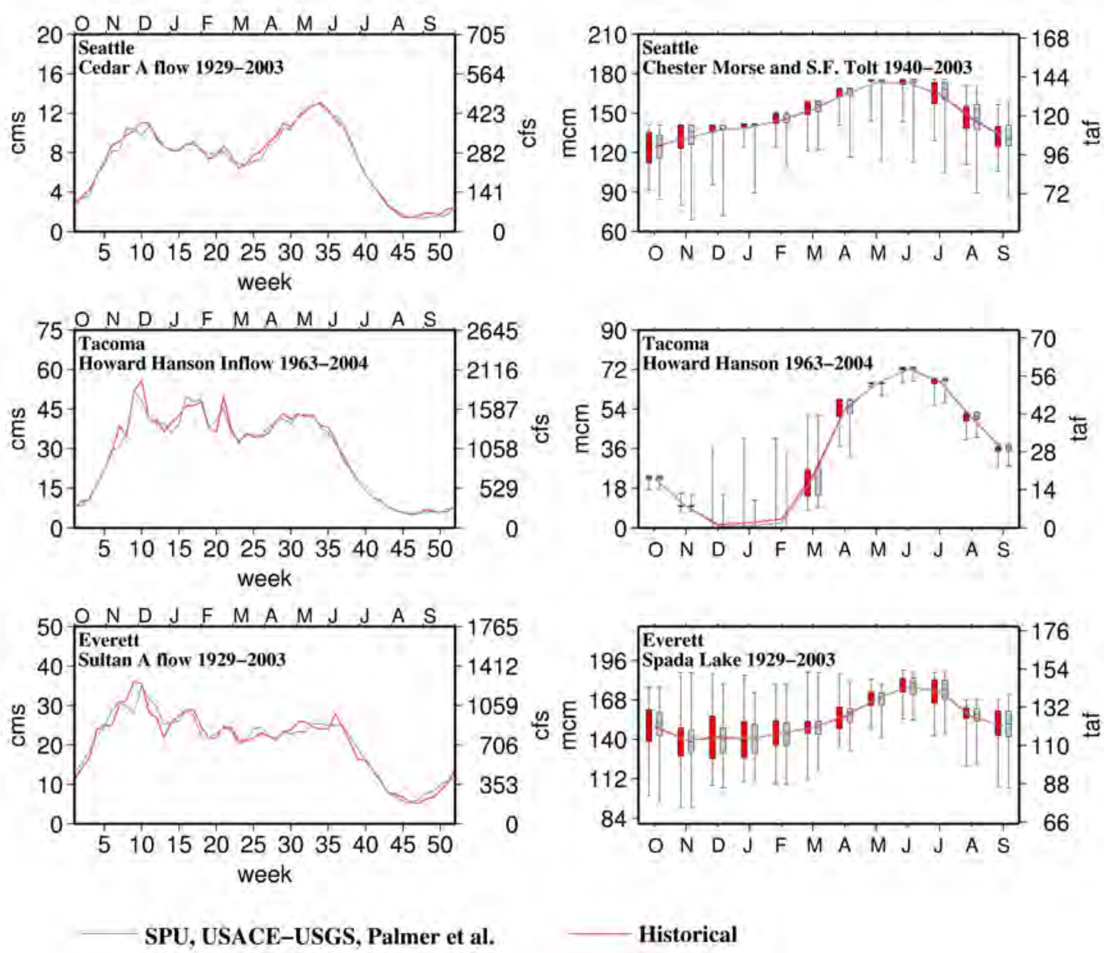

Figure 3. Historical reservoir inflows and storage. Reservoir inflows (left) and reservoir storage (right) for the three municipalities. In both graphs, the lines represent weekly averages. Bars on the right indicate box and whisker plots for individual months.

the Everett system (Enfield and Palmer, 2006), and for the Tacoma system (King, 2006).

Our focus in this study is on the effects of changes in supply and demand as related to a reference (current climate, defined as 1917-2006) simulation. For this reason, the existing reservoir models were used as described in the above references, aside from limited alterations to allow batch mode processing to automate the multiple runs for the three water management models. It is important to note that adaptations and alterations of reservoir operating policies is an ongoing process; the representations of the three systems, as detailed in Section 2, does not include various alternatives being considered by the water utilities (i.e. optimizing hydroelectric generation with climate and energy forecasts). In addition to investigation of changes in reservoir inflows, the impact of concurrent changes in customer-driven demands was also evaluated. Techniques used to forecast future water demands may be significantly impacted by water pricing policies, water conservation efforts, changing technologies, and water reuse. Therefore, to investigate demands, we did not explicitly represent these changes but rather looked at the sensitivity of each system by increasing and decreasing current demands by 10%, 25% and 50% (Table 3). These values can then be compared with ongoing efforts by Central Puget Sound Water Suppliers' Forum (2009) to assess future demands.

To assess the performance of DHSVM inflow locations for the water

Table 3. Current and future water demands in cms (and mgd), as simulated in reservoir models.

	50%	75%	90%	**2000s**	110%	125%	150%
Everett	1.9 (44)	2.9 (660	3.5 (79)	3.9 **(88)**	4.2 (96)	4.8 (110)	5.8 (132)
Seattle	3.2 (74)	4.8 (110)	5.8 (132)	6.4 **(147)**	7.1 (162)	8.1 (184)	9.7 (221)
Tacoma	1.4 (32)	2.1 (49	2.5 (58)	2.8 **(65)**	3.1 (71)	3.1 (81)	4.2 (97)

* Values for the 2000s provided by utilities as outlined in Traynham (2007).

management models, in the Green River basin we used flows provided by the U.S. Army Corps of Engineers and U.S. Geological Survey from 1962 through 2004. In the Cedar and Tolt River basins we used observed and intervening flows estimated by the U.S. Geological Survey and Seattle Public Utilities for October 1928 through September 2003. In the Sultan River basin we used flows that were simulated as part of the Water Supply Planning Process for the Puget Sound region for the Sultan River from October 1928 through September 2003 (Palmer, 2007). As shown in Figure 3, reservoir system performance, simulated using the two sets of reservoir inflows, is quite similar not only in terms of (weekly) average values but also as indicated by interannual monthly storage variability. Reliability measures, not shown, are also in close agreement.

Table 4. Week number designations.

week number	date
1	1-Oct
5	29-Oct
10	3-Dec
15	7-Jan
20	11-Feb
25	18-Mar
30	22-Apr
35	27-May
40	1-Jul
45	5-Aug
50	9-Sep

Following performance evaluation for the historical reference periods, the water management models were run with inflows that resulted from forcing DHSVM with downscaled output from the various climate change models (20 A1B and 19 B1 models for 2020s, and composite flows for both A1B and B1 for the 2020s, 2040s, and 2080s). Hereafter we refer to a simulation using a water resources model forced with simulated historical flows as the "historical" simulation. We refer to "observations" as the simulation model output when forced with observed flows, and "climate change" runs as simulations when forced by predicted flows for a given climate change scenario. Output metrics for each reservoir system are quite different. While comparisons of relative changes across water systems adds insights into their susceptibility to climate change, it is important not to compare absolute values between systems because they all differ significantly in their operations and management goals.

In our presentation of results, years indicate water years (October - September). Most analyses are on weekly time steps with seasonal values reported as weekly averages. When weeks are numbered, they start on October 1 (see also Table 4).

4. Results

4.1. Seasonal Timing

In reservoir systems that depend on snowpack to enhance reservoir storage, delayed snowmelt results in greater effective storage capacity. In a warming climate, seasonality of streamflow may shift substantially, with more flow occurring on average in the winter due to precipitation falling as rain rather than snow, and a decline and possible disappearance of the spring snowmelt peak. Elsner et al. (2009, this report, Figure 10) provide a more detailed description of how the rivers that provide water for the Seattle, Tacoma, and Everett water supply systems are likely to respond to changes in snowpack in a warming climate.

4.1.1. Historic Reservoir Inflows and Storage

Figure 3 compares historical flows and simulated reservoir storage using both historical observed streamflows and historical simulations from DHSVM. In the Seattle system, seasonal average flows from 1929 to 2003 into the Chester Morse Reservoir have a well-defined double peak or "mixed" hydrograph as defined by Elsner et al. (2009, this report) with the first peak occurring on average in early December and the second, larger peak in mid-May. The double peak is captured in both the observed and simulated historical flows. Simulated storage (total of Chester Morse and South Fork (S.F.) Tolt Reservoirs) tracks the rule curve closely in both cases, but has less interannual variability in July through November for simulated historic, as compared with observed historical flows. Simulated inflows have higher minimum values as compared with observations, although maximum, 75^{th} percentile, median, and 25^{th} percentile comparisons of interannual variability across these 75 years are quite similar. In simulations using DHSVM-generated inflows, minimum storages tend to be higher than storage levels simulated using the observed inflows. Therefore, DHSVM inflows generate storage levels that are somewhat more conservative in a relative (simulation comparison) sense. Total interseasonal storage variations in Chester Morse and S.F. Tolt Reservoirs combined, as simulated by the reservoir model, average approximately 9.3 mcm (40 taf). In the more rain-dominated Tacoma system, seasonal average inflows into the Howard Hanson Reservoir from 1964 to 2004 are more variable throughout the year than in the Cedar and S.F. Tolt. Because this system is primarily operated for flood control, the active storage simulated by the reservoir model represents only the amount in the system allocated to conservation and municipal uses. Not surprisingly given the relatively small storage relative to mean annual inflows, seasonal and interannual variability of simulated storage for these purposes is quite similar for reservoir simulations that use observed and DHSVM inflows. Most interannual variability occurs in February and March, with 14 mcm (60 taf) of storage drawn down for wintertime flood control.

Average inflows from1929 to 2003 into Spada Lake, the largest reservoir within the Everett system, have a double peak hydrograph with the largest peak occurring on average in early December, and the second, less well-defined, peak occurring in early June in both inflow datasets. The system has only been in operation since 1965, however, inflow values have been estimated from 1929; therefore, the system was simulated for the longer period. Simulated storage is more variable between years than for the Seattle and Tacoma management systems. These variations reflect operating procedures that are less constrained by limited supply and high demand, and are determined more by operating considerations for hydropower production.

4.1.2. Future Reservoir Inflows and Storage

Figure 4 summarizes simulated future climate reservoir inflows and reservoir storage. In the Seattle system, the ensemble of climate change projections indicates a transition from a double peak hydrograph to one that peaks primarily in December. A similar trend in the Cedar and S.F. Tolt River hydrographs was reported by Wiley and Palmer (2008). By the 2020s, composite inflows into Chester Morse Reservoir (black line) already have an average December peak that exceeds the spring peak, and the range between the minimum and maximum scenario (gray area) deviates most during the December peak (by roughly 8.5 cms (300 cfs) as compared with 4.2 cms (150 cfs) for the mid-May peak). Shifts in the hydrograph become more pronounced throughout the 21st century, and by the 2080s, the second, snowmelt peak has disappeared entirely. Hydrograph shifts are more pronounced in the A1B emission scenarios, however differences for A1B and B1 scenarios are generally similar. In the end of March, all future scenario flows transition from being greater than historical to less than historical, primarily because of earlier snowmelt. These changes translate into an overall decline in simulated storage, especially in June to December. On average, without operational adaptations, the summer-fall decline (June-October) in storage is 7.4 mcm (6 taf) (ranging from 1.2 to 17 mcm (1 to14 taf) for the various ensembles) for the 2020s, 9.9 mcm (8 taf) for the 2040s, and 18.5 mcm (15 taf) for the 2080s.

On average, the Tacoma system undergoes flow shifts similar to the Seattle system (Figure 4, Howard Hanson graphs). However, because snowpack in the Green River above the reservoir are smaller in the current climate, the hydrographs are altered less. As with the Seattle system, in the future climate simulations flows switch from being greater than historic to less at the end of March. The wintertime peak increases about 24 cms (850 cfs) in the 2080s, whereas summer flows decline by about 1 cms (35 cfs). These flows result in simulated storage decreases between June to October by 3.2 mcm (2.6 taf) for the 2020s composite with a range of 1.7 to 6.8 mcm (1.4 to 5.5 taf) over ensemble members, 5.6 mcm (4.5 taf) for the 2040s composite, and 9.5 mcm (7.7 taf) for the 2080s composite. In early spring when conservation and water supply pools are allowed to fill, however, future reservoir storage may increase. The largest projected increases in storage are in March with increases of 4 mcm (3.3 taf) for the 2020s composite with a range of 0.25 to 11.3 mcm (0.2 to 9.2 taf) range over all ensemble members), and increases of 6.3 mcm (5.1 taf) for the 2040s composite and 8.8 mcm (7.1 taf) for the 2080s composite. Because the Tacoma system is managed in the winter for flood control, storage is drawn down quickly until March. For this reason, storage differences between A1B and B1 scenarios are slight, although as expected B1 mean storage is slightly closer to historic than is A1B.

The Everett system has the same general hydrograph shifts in seasonal reservoir inflows as Seattle and Tacoma. The early December peak increases by as much as 17 cms (600 cfs) and the snowmelt peak declines by as much as 14 cms (500 cfs) by the 2080s resulting in a primarily winter-flow driven system. The shift from flows being greater than historic to less occurs in early April. As a result, simulated future storage values in the Spada Reservoir transition from being greater than historic to being

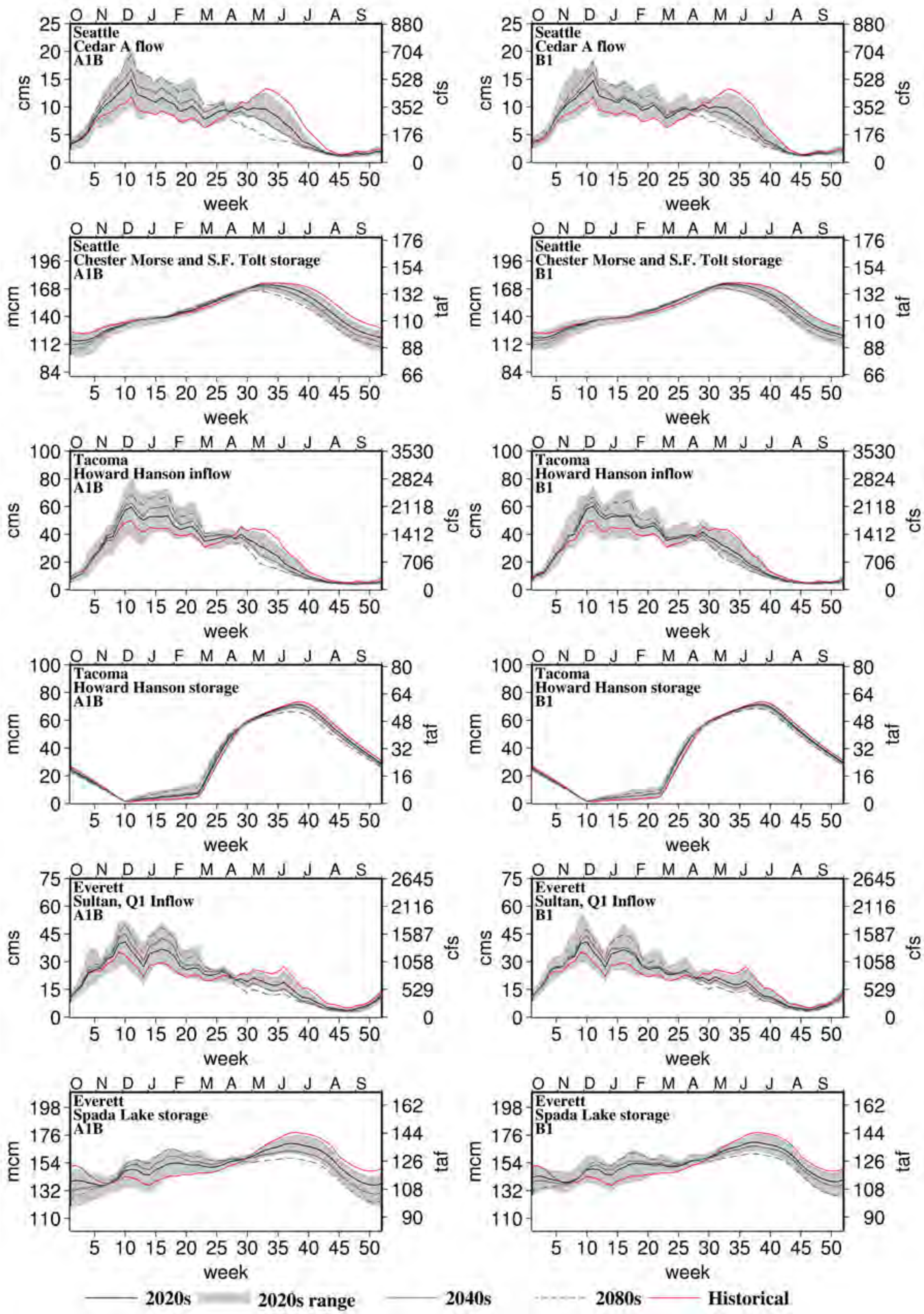

Figure 4. Future projections of reservoir inflows and storage. The red line indicates historical weekly averages from 1917-2006. Future projections are weekly averages across a similar time period that is representative of the 2020s (black line is the composite and the gray area represents the range of the in ensembles), the 2040s (gray line), and 2080s (dotted gray line). Week one begins on October 1.

less than historic at the end of April. Projected future reservoir inflows are greater than historic values by a maximum annual difference of 10.5 mcm (8.5 taf) in the 2020s A1B composite, 16.2 mcm (13.1 taf) in the 2040s, and 22.0 mcm (17.8 taf) in the 2080s. B1 scenarios have slightly smaller future changes, but again, the differences between A1B and B1 scenarios are slight. Winter storage in this system is more variable than for the Seattle or Tacoma systems as a result of the multiple reservoir operating purposes and generally large storage relative to water supply demand. For instance, as shown in Figure 3, Spada Reservoir storage in the month of January varies by as much as 76.4 mcm (61.9 taf) in the simulated 90-year period with typical year-to- year variations in the 125.8 to 150.5 mcm (102 to 122 taf) range (the 25th and 75th quantiles).

4.2. Municipal and Industrial Water Supply

Each of the three systems is impacted by shifts in its average seasonal inflow pattern, although the magnitude of the impact depends on numerous conditions including reservoir capacity, systems demands, the extent to which each system relies on a gradually melting snowpack to retain water from the winter to the summer, the adaptive capacity of each system, and specifics system operations (including objectives other than water supply). We explored the interaction of some of these factors as they are related to system reliability and reservoir storage change. We first analyze how the reliability of the systems change with water demand held constant at 2000s values (Section 4.2.1). We then compare these results with simulations when demands increase and decrease by 10%, 25%, and 50% for each climate change scenario (Section 4.2.2).

4.2.1. System Reliability

A system's ability to meet its demands, whether for instream flow requirements or consumptive use by water users, is necessary for long-term water planning. We calculate reliability on an annual basis to reflect the likelihood of meeting all demands during a water year (Tables 5a and 5b). In the Seattle system, we measure reliability as the percent of years within the model of which there were no municipal and industrial delivery shortfalls. The Tacoma system is operated with water allocated for multiple goals from multiple sources. The first diversion water right (FDWR) for municipal water supply and the minimum instream flow at Palmer (MIF), an existing requirement that the Corps of Engineers provides 3.1 cms (110 cfs) at the Palmer gage (Figure 1, Green B) with 98% reliability. When Tacoma's demands are not met by surface water, simulations allow for groundwater to be used as outlined by King (2006). In the Everett system, we investigate shortfalls for municipal water, which is allocated prior to hydropower.

Historical simulations show a reliability of 100% for Seattle's M&I, Everett's M&I, and Tacoma's FDWR and 99% reliability for Tacoma's MIF at Palmer. With 2000s water demands, we found that in all three systems, the only time reliability dropped below 98% (excluding Tacoma's MIF) in the 2020s B1 simulations was for the warmest and driest 2020s climate scenarios CCSM3 and ECHO_G. In the Seattle and Tacoma systems, 2 of 20 of the A1B ensembles and 2 of 19 for the B1 ensembles have reliability

Table 5a. Reliability and storage for A1B emissions scenarios.

AIB	Reliability			Seattle system: likelihood active capacity in October will drop below		
	Seattle	Tacoma FDWR	Tacoma MIF	**50% full** 55.9 mcm *(45328 af)*	**25% full** 28.0 mcm *(22664 af)*	**10% full** 11.2 mcm *(9067af)*
historical simulation	100%	100%	99%	34%	1%	0.0%
warmest and wetter:						
hadcm	99%	98%	92%	66%	11%	1.6%
miroc_3.2	100%	97%	82%	64%	11%	0.2%
miroc3_2_hi	100%	99%	89%	55%	5%	0.1%
ipsl_cm4	99%	99%	90%	61%	6%	0.3%
inmcm3_0	99%	99%	92%	72%	12%	0.3%
cgcm3.1_t47	100%	99%	92%	43%	3%	0.0%
warmest and drier:						
ccsm3	96%	95%	81%	80%	32%	7.8%
hadgem1	99%	96%	90%	58%	9%	0.0%
gfdl_cm2_1	99%	98%	96%	67%	12%	0.6%
warmer and drier:						
echo_g	96%	99%	93%	74%	19%	3.2%
fgoals1_0_g	99%	99%	90%	59%	11%	1.0%
pcm1	99%	99%	97%	58%	9%	0.0%
gfdl_cm2_0	100%	100%	96%	61%	6%	0.1%
giss_er	99%	98%	93%	52%	7%	0.7%
warmer and wetter:						
csiro_3_5	100%	100%	91%	51%	5%	0.1%
cgcm3.1_t63	100%	100%	92%	38%	2%	0.0%
giss_aom	100%	99%	95%	50%	5%	0.0%
cnrm_cm3	100%	99%	99%	58%	7%	0.0%
echam5	100%	99%	93%	43%	4%	0.1%
bccr	100%	99%	99%	43%	2%	0.0%
Composites						
2020	100%	99%	92%	58%	8%	0.2%
2040	99%	96%	79%	67%	11%	0.3%
2080	99%	93%	63%	71%	18%	1.6%

* Delta categories of warming and dry/wet are based on annual deltas.

**First Diversion Water Right=FDWR, Minimum Instream Flow=MIF

Table 5b. Reliability and storage for B1 emission scenarios.

B1 (wetter than A1B)	Reliability			Seattle system: likelihood active capacity in October will drop below		
	Seattle	Tacoma FDWR	Tacoma MIF	**50% full** 55.9 mcm *(45328 af)*	**25% full** 28.0 mcm *(22664 af)*	**10% full** 11.2 mcm *(9067af)*
historical simulation	100%	100%	99%	34%	1%	0.0%
warmest and wetter:						
miroc_3.2	100%	98%	90%	59%	7%	0.1%
miroc3_2_hi	100%	98%	82%	59%	7%	0.2%
ipsl_cm4	100%	99%	91%	42%	4%	0.1%
cgcm3.1_t47	100%	99%	90%	48%	3%	0.0%
cgcm3.1_t63	100%	100%	90%	52%	3%	0.0%
warmest and drier, or less wet:						
ccsm3	98%	95%	85%	71%	18%	3.0%
echo_g	97%	99%	88%	72%	19%	2.8%
hadcm	100%	98%	97%	45%	5%	0.0%
warmer and drier, or less wet:						
fgoals1_0_g	100%	99%	91%	44%	4%	0.1%
pcm1	100%	100%	97%	42%	1%	0.0%
echam5	100%	98%	96%	46%	5%	0.2%
gfdl_cm2_0	100%	100%	95%	55%	4%	0.1%
gfdl_cm2_1	100%	100%	97%	44%	3%	0.0%
warmer and wetter:						
csiro_3_5	100%	100%	96%	35%	1%	0.0%
giss_aom	100%	99%	95%	52%	5%	0.1%
giss_er	99%	99%	93%	53%	5%	0.2%
cnrm_cm3	100%	99%	98%	48%	2%	0.0%
bccr	100%	100%	98%	31%	1%	0.0%
inmcm3_0	100%	99%	93%	58%	8%	0.2%
Composites						
2020	100%	99%	92%	49%	4%	0.0%
2040	100%	99%	91%	57%	7%	0.2%
2080	99%	96%	75%	65%	12%	0.4%

* Delta categories of warming and dry/wet are based on annual deltas.

**First Diversion Water Right=FDWR, Minimum Instream Flow=MIF less than 98%). In the 2040s, the composite A1B scenario for the Tacoma system has a FDWR reliability of 96% and in the 2080s the reliability is 93% for A1B and 96% for B1, respectively. The MIF Palmer reliability for Tacoma is less; the 99% reliability in the historical simulation declines to 92% in the 2020s (81-99% range over ensemble members), 79% in the 2040s, and 63% in the 2080s for A1B emissions scenarios. Performance is slightly more robust in the B1 scenario, declining to 75% in the 2080s (see Table 5b). In the Everett system, because the system's water supply capacity is much greater than current demands, the reliability in all simulations is 100%.

Because changes in reliability are only sensitive to conditions when shortfalls occur, another measure of how likely the system is to fully meet delivery requirements is minimum reservoir storage, which provides a measure of system stress. For the Seattle system, we therefore used as a performance measure the fraction of years when there was any occurrence of current active capacity storage (Table 1) dropping below 50%, 25%, and 10% in the month of October, which is typically when reservoir storage in this system is lowest.

Assessed in this way, reservoir performance under the A1B emissions scenarios is always degraded relative to historic. In the B1 scenarios, this is also true except for the 2020 BCCR GCM climate scenario, which has a smaller likelihood of lower reservoir values in October than the historical simulation. For the composite scenarios, performance is progressively degraded through the century, i.e., 2040s performance is worse than 2020s, and 2080s is worse than 2040s. In the historical simulations, there is a 34% likelihood that reservoirs drop below 50% of active capacity in October. In the 2020s for A1B, this increases to 58% (38 to 80% range over ensemble members), which increases further to 67% in the 2040s and 71% in the 2080s for composite scenarios for the latter two periods. For B1 scenarios, these values are smaller, with a 49% (range over ensemble members of 31 to 72%) probability of October storage levels being less than 50% of capacity in the 2020s, and for the 2040s and 2080s composites, 57% in the 2040s, and 65% in the 2080s. The likelihood of reservoirs dropping below 25% and 10% active capacity reflects similar patterns. Performance for the dry and warm CCSM3 GCM simulation has the lowest 2020s performance with a 7.8% likelihood of storage less than 10% minimum for A1B emissions and 3% for B1 emissions. Again, all simulations reported in this section are for water demand at 2000s values.

4.2.2. Future Water Demands

Results thus far have focused on reservoir system performance associated with a changing future climate with water demand fixed at 2000s values, and with current reservoir operating practices. Water demands are, however, likely to change over the study period, so we investigated the effects of these changes as well. We run simulations of both increases and decreases in demand of 10%, 25%, and 50% (Table 3) of 2000s values for the historic and composite 2020s, 2040s, and 2080s climate projections. We compare reliability measures, as assessed in Section 4.2.1, in each reservoir system model for all the demand projections (Table 6). The reliability, as predicted by each reservoir model, reflects system-specific components that are not

Table 6. System reliability with variations in demand.

	Reliability (historic)				Reliability (2020s)				Reliability (2040s)				Reliability (2080s)			
	Seattle	Tacoma (FDWR)	Tacoma (Palmer MIF)	Everett	Seattle	Tacoma (FDWR)	Tacoma (Palmer MIF)	Everett	Seattle	Tacoma (FDWR)	Tacoma (Palmer MIF)	Everett	Seattle	Tacoma (FDWR)	Tacoma (Palmer MIF)	Everett
					AIB											
50%	100%	100%	99%	100%	100%	99%	97%	100%	100%	97%	90%	100%	100%	95%	68%	100%
75%	100%	100%	99%	100%	100%	99%	96%	100%	100%	97%	88%	100%	100%	93%	66%	100%
90%	100%	100%	99%	100%	100%	99%	96%	100%	100%	97%	84%	100%	100%	93%	64%	100%
100% (current demand)	**100%**	**100%**	**99%**	**100%**	**100%**	**99%**	**92%**	**100%**	**99%**	**96%**	**79%**	**100%**	**99%**	**93%**	**63%**	**100%**
110%	99%	100%	99%	100%	97%	99%	92%	100%	98%	96%	79%	100%	94%	91%	63%	100%
125%	96%	100%	99%	100%	88%	97%	92%	100%	81%	93%	78%	100%	73%	91%	62%	100%
150%	74%	100%	99%	100%	57%	97%	92%	100%	49%	92%	77%	100%	38%	90%	62%	100%
					B1											
50%					100%	99%	97%	100%	100%	99%	95%	100%	100%	97%	82%	100%
75%					100%	99%	97%	100%	100%	99%	93%	100%	100%	96%	82%	100%
90%					100%	99%	95%	100%	100%	99%	91%	100%	100%	96%	77%	100%
100% (current demand)					**100%**	**99%**	**92%**	**100%**	**100%**	**99%**	**91%**	**100%**	**99%**	**96%**	**75%**	**100%**
110%					98%	99%	92%	100%	98%	98%	91%	100%	98%	96%	75%	100%
125%					93%	99%	92%	100%	88%	98%	89%	100%	82%	95%	75%	100%
150%					68%	98%	91%	100%	59%	98%	89%	100%	46%	95%	73%	100%

First Diversion Water Right=FDWR, Minimum Instream Flow=MIF

comparable across systems.

The current firm yield of the Seattle system as calculated by Seattle Public Utilities (2007) is 7.5 cms (171 mgd), which is 1.1 cms (24 mgd) greater than current demands. As a result, reliability with current demands is greater than 98% in the 2020s, 2040s, and 2080s for both A1B and B1 scenarios (Table 6). When demand increases, differences in reliability between the 2020s, 2040s, and 2080s climate projections become more apparent. With a 10% demand increase, reliability in the 2080s drops by 5% in A1B and 1% in B1 emissions scenarios, whereas with a 50% demand increase 2080s reliability decreases by 36%. These values are relatively close to the reliability Traynham (2007) reported (98.7% for a 2050 climate as simulated by IPSL_A2 GCM with projected future demands of 6.4 cms (145 mgd). These changes compare with 2075 reliability for 3 GCMs reported by Traynham of 86.8%, 93.4%, and 77.6% with simulated demands of 8.2 cms (187 mgd). Our results indicate for a 125% increase in demand (8.1 cms or 184 mgd), reliability in the 2080s would be near 73% in A1B and 82% in B1 emission scenarios (Table 6). Because managers regularly assess future conditions and make adjustments accordingly, operating near capacity is rare. For example, SPU's 2007 Water System Plan (2007) notes that, given current firm yield estimates for existing supply resources and demand forecasts, a new source of supply will be needed sometime after 2060 and the plan provides more details on these new supply alternatives.

In Tacoma's system, water allocations differ considerably from Seattle's and projects for increasing capacity are underway (these projects are not reflected in our reservoir model). Therefore, simulated effects of climate change on the current reservoir system and with current operations are more likely to lead to shortfalls. Because the system, as simulated by the reservoir model, is less buffered by a large difference between supply and demand, changes from climate and population growth are both evident as early as the 2020s (Table 6). With increases in water demand of 50%, the first diversion water right (FDWR) reliability of the Tacoma system decreases the reliability in the 2020s by 2%, in the 2040s by 4%, and in the 2080s by 3% for the A1B emissions scenario and by only 1% in all composite runs in the B1 scenarios. Simulated minimum instream flow at Palmer (MIF) reliability changes less when demands are incorporated into the model, as a result of reservoir operations which is based on various allocation pools. The metrics we use in this respect are not the same used as those used by Traynham (2007) who instead used a measure of Tacoma M&I reliability. Our values however capture the same relative trend. In general, the effects of changing climate and hydrology are problematic in the fall because the reservoir rules draw down flows before there is enough water in the reservoir to insure that fish flow targets can be met.

Everett's system is less sensitive to shortfalls in municipal and industrial demand than the other two systems because reservoir capacity and inflows are larger relative to water demands. Current firm yield is 8.8 cms (200 mgd), more than twice 2000s demands. Changes in demand of 50% in a 2080s climate are still not enough to create a shortfall. When current demand is doubled to 7.7 cms (175 mgd), it is only in the 2080s with impacts from both climate change and water demands increases that shortfalls occur, resulting in decreased reliability to 99% with the A1B and 99% for the B1 emission scenarios. Traynham (2007) reported 65.8%, 93.4%, and 63.2% reliability with 3 GCMs in 2075, with demand values of 8.6 cms (195.5 mgd). A demand level that is greater than twice the current demand.

In our analysis, the impact of 50% increases in demand on the Seattle system are more substantial than the same percentage demand increase on the Tacoma and Everett systems (Table 3). It is important to note, however, that changing future demands will depend not only on population growth, but also on water pricing policies, water conservation efforts, changing technologies, and that these factors will inevitably vary across the three systems as well.

4.3. Flood Control

The Howard Hanson Reservoir is primarily operated for flood control, with events of most concern occurring between October and March. To investigate how climate change may impact Tacoma's flood control, and thus impact summertime storage potential, we evaluated the average number of days per year when the system is under flood control operations in the 2020s, 2040s, and 2080s (Figure 5) relative to historical simulations. It is important to note that as in all other simulations, we used the delta method of producing reservoir inflows, and therefore, while the future climate inflows reflect the effects of changes in temperature and precipitation, they do not reflect possible changes in precipitation patterns (e.g., changes in precipitation frequency, and/or duration of storms).

Flood conditions in the reservoir model occur on days when flows at the Auburn gage are predicted to reach 12,000 cfs, which is specified in the water management model as when the inflows upstream plus the difference between Palmer (Figure 1, Green B) and Auburn (Green C) gages total 12,000

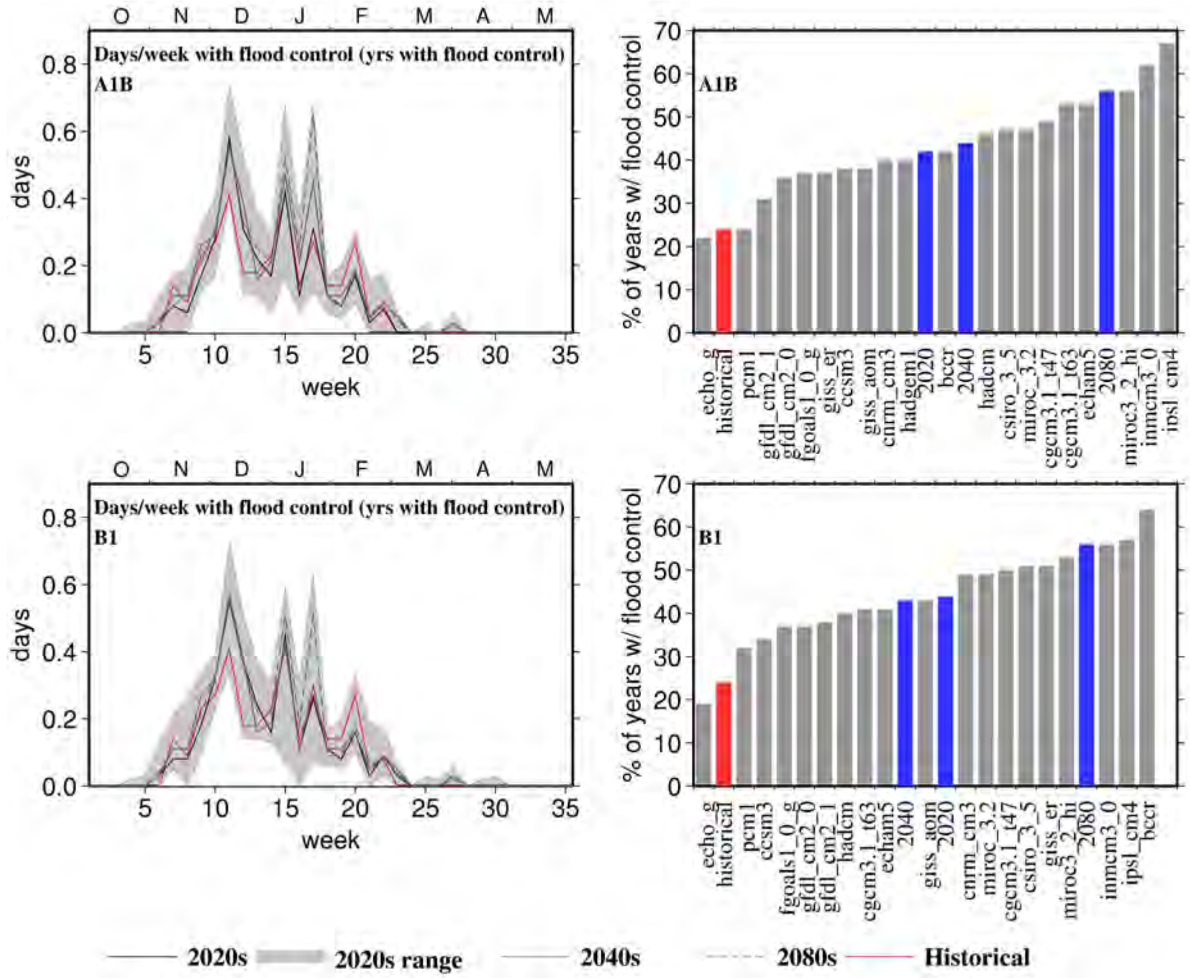

Figure 5. Flood control days (Tacoma).

cfs. Once this occurs, storage for flood control is allocated (King, 2006).

Figure 5, left panels show the change in seasonality of when flood conditions occur. The system is under flood control operations most frequently in December-May. As the climate warms, there is a shift in timing. This includes both a decrease in frequency of flood control in April-May and an increase in frequency in January-March, and these changes occur progressively from the 2020s through the 2080s.

The right panels of Figure 5 indicate the likelihood that flood conditions occur at least once in a year for all water management simulations (historic and all climate change projections). Simulations indicate that flood conditions may occur more frequently, with all but one 2020s scenario (ECHO_G) having a higher likelihood of flood conditions. The range between the models varies from less than 20% to more than 60% for the 2020s ensembles. The 2020s and 2040s composite runs have similar likelihoods of flood control conditions, related to the similarities in their peak flow. The 2040s B1 scenario is associated with less frequent flood conditions than the 2020s B1 scenario (by 1%). This is likely because of surface processes transitioning toward more winter-dominated flow. In the 2080s, however, the frequency with which flood operating conditions occur is considerably higher than in the 2020s and 2040s, with occurrence of more than one flood control day likely in more than 50% of years.

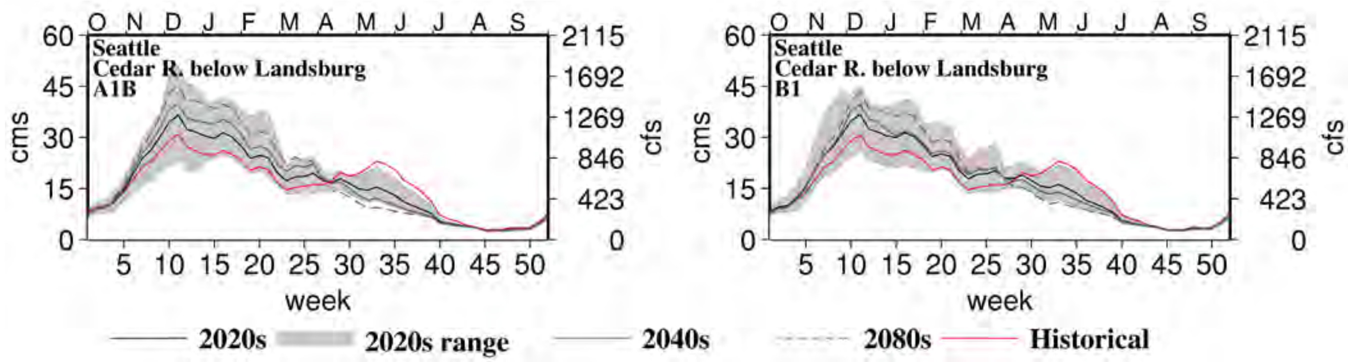

Figure 6. Environmental flows.

4.4. Environmental Flows

As an example of multiple-management objectives, in the Seattle system, priorities are given to instream flows over other water allocations. Within the Cedar, Landsburg (Figure 1, Cedar C) has been an important location in efforts to enhance fish habitat, especially for salmonids. To evaluate how the ability to meet environmental flow targets may change with climate, we compare changes in regulated flows at Landsburg as simulated by the Seattle system model using normal instream flow requirements (Traynham and Palmer, 2006) with current 2000s water demands (Figure 6). These flows do not account for potential adaptations such as accounting for flows for the supplemental block requirements curtailments and pumping dead storage. Normal and critical instream flow requirements, as instituted by the Habitat Conservation Plan (SPU, 2000), have been set according to studies on the needs salmonids present in the river system. These flows are lower than typical flows, never exceeding 8.2 cms (288 cfs) and declining in August and September to less than 3.0cms (108 cfs). Therefore shortfalls only occur in the most extreme climate change simulations in the 2020s and in the 2040s and 2080s for A1B. Shortfalls occur to a lesser extent in B1 emission scenarios, with shortfalls occurring only in the 2020s with the most extreme ensemble simulations and in the 2080s. These limited shortfalls occur in the late fall and early winter when instream flow requirements are greater than 6.1 cms (216 cfs) and shortfalls generally do not exceed 0.02 cms (0.9 cfs). These results are similar to those of Wiley and Palmer (2004, 2008) who showed that minimum instream flows at Landsburg were not dramatically impacted in near-term climate change simulations. There are, however, other effects such as increasing water temperature that warrant serious attention as discussed inBattin et al. (2007) and Mantua et al. (2009, this report).

4.5. Hydroelectric Power

Hydropower production, a key consideration in reservoir operations in the Everett system, generates flows through the Jackson power tunnel that are a function of the price of power, fish needs, and potential flooding. We simulated these future flows with yield constrained by the head, friction loss, and cavitation boundary of the Chaplain reservoir (Enfield and Palmer, 2006). Our simulations did not reflect the price of power or flood forecasts. Changes in inflow hydrographs are evident in the power tunnel

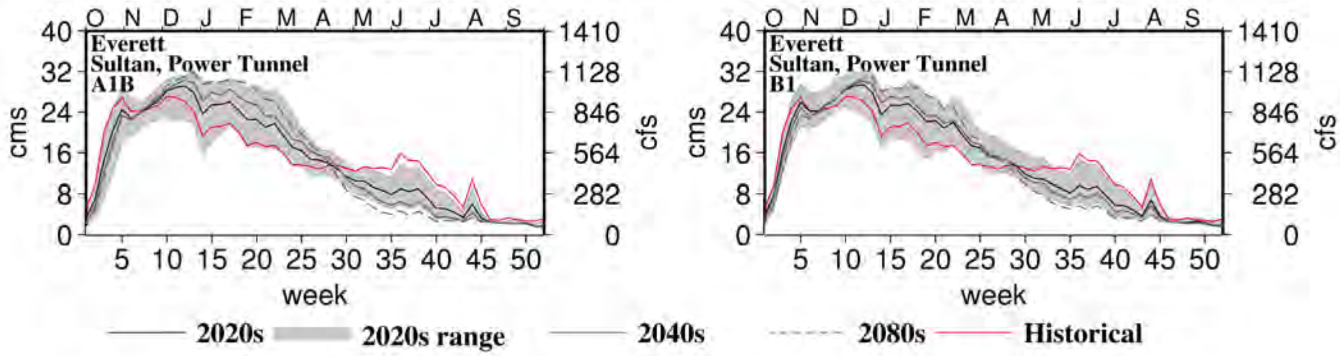

Figure 7. Hydroelectric power (Everett).

flow simulations (Figure 7). Generally, future climate change projections with current 2000s demands indicate there may be more power generation in the winter and less in the summer, which coincides with trends in energy production on the Columbia River basin (Hamlet et al., 2009, this report). Currently, the flows are highest in early December and peak slightly again in June. Peaks remain at approximately the same time of year, but the magnitude of the already large wintertime peak increases by 2 cms (70 cfs) with a range over ensemble members of 2.5 cms declines to 5 cms increases (-90 to 180 cfs) in the 2020s, 2 cms (110 cfs) in the 2040s, and 4.5 cms (160 cfs) in the 2080s (Figure 7). The peak in June, alternatively, declines by 6.8 cms (240 cfs) with a range over ensemble members of 2 to 10 cms (70 to 350 cfs) in the 2020s, 9.3 cms (330 cfs) in the 2040s, and 11.3 cms (400 cfs) in the 2080s for A1B emission scenarios. Changes relative to the historical simulation are slightly less in the B1 scenario.

5. Conclusions

The primary hydrological manifestation of climate change, which will affect each of the three major Puget Sound water supply systems to varying degrees, will be the decline and eventual disappearance on average of the springtime snowmelt hydrograph peak, and its replacement with an elevated winter runoff peak. These shifts are projected to become more pronounced throughout the century, although year-to-year variability in weather and inflows should still be expected. There will be years with snowmelt that is similar to current conditions, but years with high springtime snowmelt are projected to progressively become less frequent. The three water supply systems, with current operating policies and in the absence of demand increases, may be generally robust to changes through the 2020s, with reliabilities projected to remain above 98% in all cases. However, other aspects of system performance, such as reduced levels of summer and fall storage, may occur as early as the 2020s.

The primary reason for current robustness in the systems is that system demand has been reduced in recent years, particularly in the Seattle system. With increases in demands, the systems become less robust to impacts from climate change, notwithstanding that the changes in demand are modest aside from large demand increases late in the study period. For example, if Seattle's demand increases by 10%, reliability for the 2080s drops by 5% in A1B and 1% in B1 emissions scenarios relative to historic conditions, whereas with a 50% demand increase climate change impacts in the

2080s decreases reliability by 36%. Seasonal patterns of reservoir storage are affected to varying degrees in all three systems. Reservoir storage is generally projected to be lower from late spring through early fall, and ancillary operating objectives, such as hydropower production by the Everett system, flood control in Tacoma, and the ability of the systems to augment seasonal low flows, may be impacted. All of the analysis reported here, use current operating policies. Some mitigation of the effects we have identified can likely be achieved by changes in reservoir operating policies.

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