Impacts of Climate Change on Regulated Streamflow, Hydrologic Extremes, Hydropower Production, and Sediment Discharge in the Skagit River Basin

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Abstract

Previous studies have shown that the impacts of climate change on the hydrologic response of the Skagit River are likely to be substantial under natural (i.e. unregulated) conditions. To assess the combined effects of changing natural flow and dam operations that determine impacts to regulated flow, a new integrated daily-time-step reservoir operations model was constructed for the Skagit River Basin. The model was used to simulate current reservoir operating policies for historical flow conditions and for projected flows for the 2040s (2030–2059) and 2080s (2070–2099). The results show that climate change is likely to cause substantial seasonal changes in both natural and regulated flow, with more flow in the winter and spring, and less in summer. Hydropower generation in the basin follows these trends, increasing (+ 19%) in the winter/spring, and decreasing (- 29%) in the summer by the 2080s. The regulated 100-year flood is projected to increase by 23% by the 2040s and 49% by the 2080s. Peak winter sediment loading in December is projected to increase by 335% by the 2080s in response to increasing winter flows, and average annual sediment loading increases from 2.3 to 5.8 teragrams (+ 149%) per year by the 2080s. Regulated extreme low flows (7Q10) are projected to decrease by about 30% by the 2080s, but remain well above natural low flows. Both current and proposed alternative flood control operations are shown to be largely ineffective in mitigating increasing flood risks in the lower Skagit due to the distribution of flow in the basin during floods.

Keywords: Skagit River hydrology, reservoir operations, flooding, low flows, hydropower, sediment load

Introduction

The Skagit River Basin in the North Cascades extends from headwaters in southwestern British Columbia to the mouth of the river in the Puget Sound lowlands (Figure 1). Major tributaries to the Skagit River are the Upper Skagit River, the Baker River, the Cascade River, and the Sauk River. Since the beginning of European-American settlement in the mid-19th century, the Skagit River Basin has been extensively altered by human activities such as logging and conversion of floodplain areas for agricultural and urban development (Beechie et al. 2001, Cuo et al. 2009). These activities con-

tinued through the early 20th century, resulting in the development of some of the richest farmland in the world, as well as a number of small cities including Burlington, Sedro Woolley, and Mount Vernon (Kunzler 2005). In the second half of the 20th century, and particularly since the completion of Interstate-5 in the mid-1960s, urban/suburban development and population growth in the Skagit lowlands has intensified. The construction of dikes, levees, and tide gates have helped protect farmland and small cities from flooding, but dike and levee failures frequently occur during flooding at the 30-year return interval. Thus flooding and flood-plain management are major issues in the basin. Five major dams were constructed in the Upper Skagit River and the Baker River between 1924 and 1959. These projects generate hydropower and

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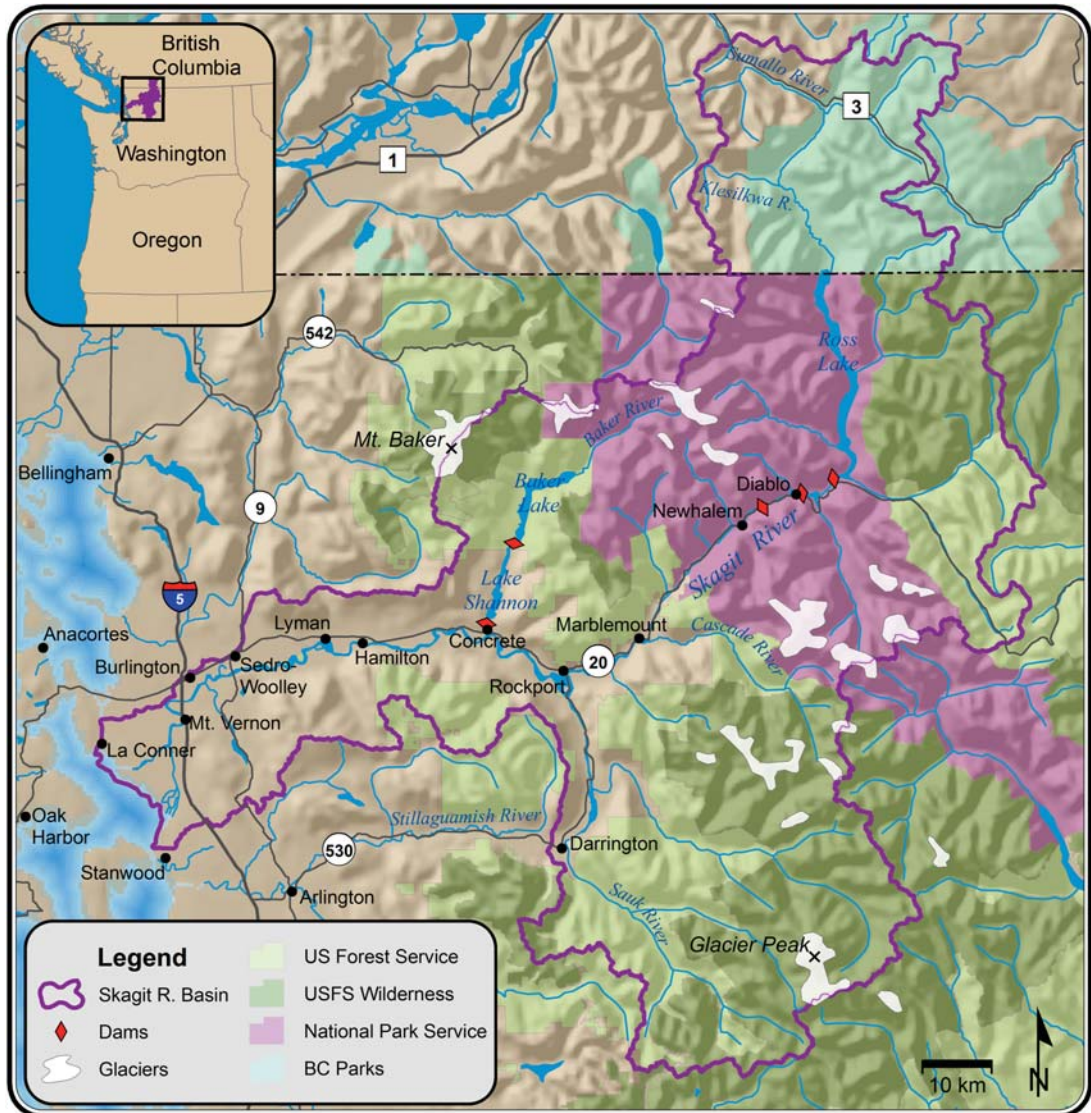Email: hamlet.1@nd.edu

Figure 1. Key geographic features of the Skagit River Basin. (Note that only the largest glaciers are shown on the figure) (Source: Lee and Hamlet 2011).

provide flood control, recreation opportunities, and diverse ecosystem services. The Sauk River, which is designated as a Wild and Scenic River, is essentially undeveloped and provides pristine fish habitat and many other ecosystem services in the basin, as well as economically important recreation opportunities such as fishing, boating, and rafting.

Impacts of Regional Climate Change on the Pacific Northwest and Skagit River Basin

Climate change is projected to bring substantial changes to the Pacific Northwest (PNW) climate (Mote and Salathé 2010). Projected changes in future temperature and precipitation are different for different global climate models (GCMs) (Mote and Salathé 2010), however, all the GCM

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simulations from the Coupled Model Intercomparion Project (Phase 3) (CMIP3) used in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) project increases in PNW temperature through the 21st century (Mote and Salathé 2010). For the Skagit River Basin, the projected ensemble-average temperature increase for the A1B emissions scenario is about 3.2 °C (5.8 °F) by the 2080s (2070–2099) compared to historical average temperature (Lee and Hamlet 2011). This is a somewhat smaller change compared to the PNW as a whole. Although no statistically significant changes in annual precipitation are projected for the PNW, substantial seasonal changes in precipitation are projected for both the PNW and the Skagit River Basin including wetter winters, springs and falls, and drier summers (Mote and Salathé 2010, Lee and Hamlet 2011).

Several previous hydrologic modeling studies have demonstrated that projected future changes in temperature and precipitation are likely to significantly alter the hydrologic response of PNW rivers (Mote et al. 2003, Elsner et al. 2010, Hamlet et al. 2013, Lee and Hamlet 2011). For the Skagit River Basin, dramatic shifts in the seasonal timing of flow from spring to winter, and more severe extreme events (floods and low flows) are projected (Hamlet et al. 2013, Lee and Hamlet 2011). More frequent and severe floods are projected due to the combination of increasing winter precipitation and higher freezing elevations during winter storms that increase runoff production in moderate elevation areas (Neiman et al. 2011, Lee and Hamlet 2011, Tohver et al. 2014, Salathé et al. 2014). Extreme low flows are also projected to become more intense throughout the Skagit River Basin due to drier summers, reduced snowpack, earlier snowmelt and increased evapotranspiration associated with warmer temperatures (Hamlet et al. 2013, Lee and Hamlet 2011). The projected changes in seasonal hydrologic response and extreme hydrologic events are expected to influence flood control, hydropower generation, sediment loading, and instream flow augmentation in late summer, creating impacts to ecosystems, regional and local energy supply, water quality, and the local economy. For example, more severe and prolonged summer low flows combined with increased water temperatures are likely to impact salmon and trout populations (Mantua et al. 2010, Hamlet et al. 2010a), resulting in negative impacts on the ecosystem and local fisheries (Garibaldi and Turner 2004, SITC 2009). Projected changes in flood timing and magnitude are also expected to alter sediment loads to the Skagit delta (Czuba et al. 2011), which provides important habitat for fish and other aquatic species.

Previous studies of changes in the basin's hydrologic response and its consequences (Hamlet et al. 2013, Hamlet et al. 2010a) did not consider the effects of reservoir operations on hydrologic impacts. Following an earlier pilot study by Lee and Hamlet (2011), we report here on simulations using a new integrated daily-time-step reservoir operations model for the Skagit River Basin used to assess the impacts of climate change on daily and monthly flows and extreme high and low flows under regulated conditions. Prospects for adaptation to changing flood risks are considered by simulating not only current reservoir operating policies but also alternatives proposed by the U.S. Army Corps of Engineers and Skagit County (discussed in more detail in the Methods section). We also investigate the impacts of climate change on hydropower generation, and sediment loading under current reservoir operating policies. The study addresses the following research questions:

1. How does climate change affect the magnitude and timing of monthly flow and hydrologic extremes (floods and low flows) under natural and regulated conditions?

2. How do the projected changes in the hydrologic response of the Skagit River influence monthly hydropower generation and suspended sediment loading?

3. Do alternative flood control operating policies have the potential to reduce flood risks in comparison with current flood control operations?

Methods

Synopsis

Observed temperature and precipitation data from water years (October–September) 1916–2006

were used to generate historical streamflow time series using a macro-scale hydrology model. Five different GCM s, forced by the A1B greenhouse gas emissions scenario (Nakićenović et al. 2000), were used to generate hydrologic model simulations of streamflow for future conditions. A new daily-time-step reservoir operations model was then used to evaluate the combined effects of dam operations and changes in natural streamflow on daily and monthly flow conditions, hydrologic extremes, hydropower production, and sediment load in the basin.

Variable Infiltration Capacity (VIC) Hydrologic Model

The Variable Infiltration Capacity (VIC) hydrologic model (Liang et al. 1994) implemented at 1/16 latitude/longitude resolution over the PNW (version 4.07) (Elsner et al. 2010, Hamlet et al. 2013) was used to generate streamflow time series for this study. The VIC model is a physically based, spatially distributed, macro-scale hydrologic model which solves the water and energy balance for each model grid cell. VIC requires daily inputs of precipitation, maximum and minimum air temperature, and wind speed, which were previously developed for the Columbia Basin Climate Change Scenarios Project (Hamlet et al. 2013). Additional driving variables such as short-wave (solar) and long-wave (thermal) radiation, relative humidity, vapor pressure and vapor pressure deficit were derived by the model from the primary meteorological inputs. In addition to these forcing variables, snow model parameters and parameter files for soil and vegetation were developed at 1/16th degree resolution over the PNW (Elsner et al. 2010). VIC simulations of runoff and baseflow from each grid cell were post-processed using a daily-time-step routing model (Lohmann et al. 1996) to produce the routed streamflow at each site needed to drive the reservoir simulation model discussed below. Streamflow simulations were then bias corrected to match naturalized streamflow observations using a quantile mapping approach outlined by Snover et al. (2003) and Hamlet et al. (2003). Historical baseline simulations were run from water years 1916–2006.

The VIC hydrologic model used in this study doesn't include glacier dynamics. Because glaciers in the Skagit River Basin currently contribute approximately 12–18% of summer (May–September) runoff (Jon Riedel, North Cascades National Park, personal communication; Lee and Hamlet 2010) and are expected to be significantly smaller or gone by the 2080s, our estimate of future reductions in summer hydropower production and summer low flows may be lower than actual.

Climate Change Scenarios

We used five different GCMs that were statistically downscaled using the Hybrid Delta approach (Tohver et al. 2014) for two 30-year future time periods: the 2040s (2030–2059) and 2080s (2070–2099). Based on a previous study by Hamlet et al. (2013) that assessed extreme flows under natural (i.e. unregulated) conditions, we selected five GCMs that represent the range of flood statistics at the Skagit River near Mount Vernon for the 2040s and 2080s. Statistically downscaled meteorological data for the 2040s and 2080s were used to force the VIC hydrologic model and streamflows from the VIC model were used as inputs to the SkagitSim reservoir operations model (discussed below).

The Hybrid Delta method (see Appendix A of Tohver et al. 2014 for more details) used quantile mapping techniques to produce transformed monthly and daily observed climate data (water years 1916–2006) for future conditions relative to the historical period (1970–1999). The future scenarios produced by the Hybrid Delta method have the same duration and basic time series behavior as the historical record, representing 91 years of observed variability (water years 1916–2006) combined with systematic shifts in climate simulated by the GCMs for the 2040s and 2080s. In the rest of the paper, we will refer to the corresponding historical dates in the future projections by giving the dates in single quotes (i.e. '1985–2006').

A single dynamically downscaled climate projection for the ECHAM5 global climate model with the A1B emissions scenario (Salathé et al. 2014) was used to produce VIC and SkagitSim

projections for a companion paper in this special issue (Hamman et al. 2016). For our study, however, the range of values provided by statistically downscaled results was important to the analysis, and motivated our choice to use the five-member ensemble of Hybrid Delta projections.

Skagit Simulation (SkagitSim) Reservoir Operations Model

A daily-time-step reservoir operations model called SkagitSim was developed specifically to support this study. SkagitSim represents the major physical characteristics of the Skagit River Basin and simulates dam operations at Ross, Diablo, and Gorge dams in the Upper Skagit River basin owned by Seattle City Light (SCL) and at Upper Baker and Lower Baker dams in the Baker River basin owned by Puget Sound Energy (PSE) (Figure 2). The flow in the unregulated Sauk River was combined with inflows from the Cascade River and other smaller tributaries to estimate incremental inflows from these uncontrolled portions of the system (Figure 2). The model was coded in STELLA (version 8.1) using reservoir simulation algorithms described by Hamlet (1996) and Hamlet and Lettenmaier (1999). The model was driven by bias-corrected daily natural (i.e. unregulated) streamflow data produced by the VIC hydrologic model (as described above).
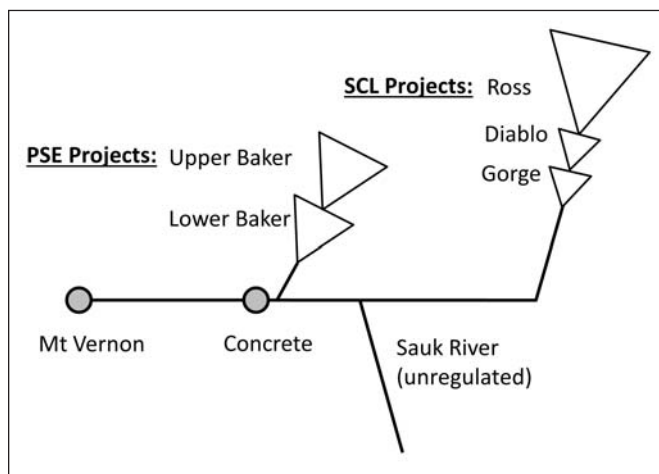

Figure 2. Schematic diagram for the SkagitSim reservoir operations model. Triangles represent dams and reservoirs, and filled circles represent river checkpoints for the Skagit River at Concrete and Mount Vernon.

SkagitSim was used to examine the impacts of climate change on several key water resources objectives in the basin, including flood control, hydropower production, extreme low flows, and suspended sediment load. Simplified versions of dynamic instream flow targets to protect salmon and steelhead redds during spawning periods were also included in SkagitSim, based on current SCL operating rules.

Hydropower Simulation in SkagitSim— SkagitSim simulates hydropower generation for SCL and PSE projects. Storage to elevation relationships at Ross and Upper Baker dams and typical tail-water elevations were used to estimate the net head at each dam as a function of reservoir storage. The quantity of hydropower generated was estimated as a function of the net head, flow through the penstocks to the hydropower turbines, and the combined efficiency of the turbines/generators. Monthly energy targets for both projects were estimated using historical monthly average energy production from observed data. In the model, these baseline values were then multiplied by a fixed fraction for each water year to calculate different monthly energy targets. Energy target fractions for each water year were then calibrated to closely reproduce reservoir drawdown at Ross Lake and Upper Baker Lake in each year. Finally, these calibrated energy target fractions were related to Ross April–September inflow volumes via least squares linear regression. This regression equation was then used to select energy targets for all historical years, and for all future years in the climate change scenarios. Thus the simulated energy targets for SCL and PSE projects respond dynamically both to observed climate variability and climate change in the simulations via simulated April–September inflow volumes at Ross. Daily energy targets were obtained by dividing the monthly total energy target by the number of days per month. Subject to available reservoir storage and the penstock capacity (flow capacity) at each hydroelectric plant, the model simulates the release of sufficient

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water from the two Ross and Upper Baker dam to meet the daily energy targets specified for each group of projects in each time step.

Flood Control Operations in SkagitSim—The currently authorized flood control storage in the Skagit River Basin is 239 M m^3 (194,000 acrefeet): 148 M m^3 (120,000 acre-feet) at Ross dam on the Upper Skagit River and 91 M m^3 (74,000 acre-feet) at Upper Baker dam on the Baker River (Table 1) (FEMA 2009). Storage space at Lower Baker dam is not formally allocated for flood control, but can nonetheless be used for additional flood protection on an on-call basis (Steward and Associates 2004).

Ross and Upper Baker dams are operated to provide full flood storage evacuation of 148 M m^3 by December 1 and 91 M m^3 by November 15, respectively. Ross dam is gradually drawn down from October 1 to produce at least 74 M m^3 (60,000 af) of flood storage by November 15 and to provide required full flood storage by December 1 (R. Tressler, Seattle City Light, personal communication). Similarly, Upper Baker dam is required to provide 20 M m^3 (16,000 af) of flood storage by November 1 and 91 M m^3 of full flood storage by November 15 (Steward and Associates 2004, Puget Sound Energy 2006). The model incorporates these operational requirements by linearly interpolating between the target elevations to provide a daily reservoir storage target (flood control rule curve).

When forecasted instantaneous peak runoff at Concrete is 2,550 cms (90,000 cfs) or higher, the U.S. Army Corps of Engineers operates Ross

TABLE 1. Storage characteristics of major reservoirs in the Skagit River Basin (Source: FEMA 2009). Units: million cubic meters (M m^3) and acre-feet (af).

Reservoir	Flood Control Storage (M m^3)	Maximum Usable Storage (M m^3)
Ross	148 (120,000 af)	1298 (1,052,300 af)
Diablo	0	94 (76,220 af)
Gorge	0	8 (6,770 af)
Upper Baker	91 (74,000 af)	222 (180,128 af)
Lower Baker	0	144 (116,700 af)

dam in coordination with Upper Baker dam to reduce peak flow in the lower Skagit River Basin by using the available reservoir storage (Puget Sound Energy 2006, FEMA 2009). The model incorporates these operations by reducing the outflow from each storage dam in the system in an attempt to bring the total daily average flow at Concrete below 1,770 cms (62,500 cfs) (~ 70% of the instantaneous peak value of 2550 cms based on the observed ratio of daily average to instantaneous peak flows). Note, however, that in large flooding events this is not possible even if all inflows above the dams are captured in storage. The amount of flow reduction at each storage dam is allocated in the model so that the proportion of the total flow reduction is the ratio of the inflow to each dam divided by the total inflow to both storage dams. That is:

$$RossFloodFrac = \frac{Inflow_{Ross}}{(Inflow_{Ross} + Inflow_{UBaker})}$$

$$UBakerFloodFrac = \frac{Inflow_{UBaker}}{(Inflow_{Ross} + Inflow_{UBaker})}$$

where RossFloodFrac is the fraction of the total flow reduction allocated to Ross, and UBakerFloodFrac is the fraction of the total flow reduction allocated to Upper Baker.

During flood events, simulated reservoir storage is allowed to rise above the normal full pool level (flood control curve), but is constrained to remain below the maximum flood capacity of the reservoir (which is above the normal flood control rule curves). After the flood event is over (i.e. when simulated flows at Concrete fall below 1,770 cms), the extra water stored during the flood event is released until the reservoir is again at or below the normal flood control curve. These releases from storage are made in such a way that they will not cause flows above 1,770 cms at Concrete to occur.

In an effort to provide better flood protection in the lower Skagit valley, Skagit County recently proposed increasing flood storage in Upper Baker dam to 185 M m^3 (150,000 af) and starting drawdown of the dam one month earlier than current operations (Steward and Associates 2004, Skagit

County 2008). Other alternatives being considered by Skagit County include increasing flood storage in Ross Reservoir from 148 to 222 M m^3 (180,000 af) (Skagit County Board of Commissioners, [D. Munks, K. A. Dahlstedt, and T. W. Anderson], personal communication). These alternatives provide increased flood storage and start flood evacuation on September 1 (one month earlier than current operations) both at Ross and Upper Baker dams. We simulated these alternative reservoir operations to explore their effectiveness in the context of climate change adaptation to increased flooding in the future projections.

Extreme Flow Analyses

We used the 100-year flood magnitude (Q_{100}) and the lowest consecutive 7-day flows with a 10-year return interval (7Q10) as measures of extreme high and low flows, respectively. To estimate Q_{100}, the maximum daily flows were extracted for each water year at each site to produce a time series of annual peak flows. Generalized Extreme Value (GEV) distributions were then fitted to these data using L-moments derived from probability weighted moments (Wang 1997, Hosking and Wallis 1993, Hosking 1990), from which the 99th percentile flow was calculated (i.e. Q_{100}). For the 7Q10 flow analyses, the same procedure used for estimating Q_{100} was followed, except the minimum 7-day running average streamflows were selected for each water year instead of maximum daily flows, and the 10th percentile of these annual extrema was calculated. The dates when the annual peak flows occur in the simulations were also used to examine potential timing shifts of extreme high flows in response to a changing climate.

Suspended Sediment Transport Calculations

Curran et al. (in review) used measurements of suspended sediment loading in the Skagit River near Mount Vernon from 1974–1993 and 2006–2009 to develop suspended sediment transport equations using a flow duration/transport curve approach (Julien 1998). Power law relationships for different flow ranges were derived as follows:

$$Q_s = 0.003Q_w^{2.27}, \quad Q_w < 849 \text{ m}^3/\text{s},$$

$$Q_s = 1.49 \times 10^{-7} Q_w^{3.74}, \quad 849 \text{ m}^3/\text{s} \leq Q_w \ 1,875 \text{ m}^3/\text{s}$$

$$Q_s = 6.3Q_w^{1.41}, \quad Q_w > 1,875 \text{ m}^3/\text{s}$$

where Q_s is the suspended sediment discharge in megagram per day and Q_w is the daily average water discharge in cubic meters per second at Mount Vernon. These equations were used to evaluate the impacts of climate change on sediment loading based on the assumption that this relationship between sediment loading and streamflow remains the same in the future. We argue that this approach is likely to produce a conservative estimate of future impacts, since loss of snowpack and increased winter soil moisture projected for climate change scenarios (Hamlet et al. 2013) will likely increase sediment transport from runoff and new sediment producing areas exposed in the basin in winter.

Evaluation of the SkagitSim Model

In this section, we evaluate the performance of the SkagitSim model. Observed USGS records such as reservoir elevations at headwater storage dams, daily flow and daily-average annual peak flows in the lower Skagit River Basin were used to validate the model (Figures 3–6). Figure 3 shows observed and simulated reservoir elevations at Ross and Upper Baker dams and a daily time series of observed and simulated flows at Mount Vernon. The simulations capture the observed seasonal and inter-annual variability in daily flows and reservoir elevations reasonably well ($R^2 \geq 0.6$), however, there are frequently substantial errors at daily time scales.

During a flood event, the storage that has been evacuated earlier is used to reduce the flow downstream of the dam (as discussed above). To evaluate the performance of the model during flood control operations, reservoir storages, flood control curves and daily flows are plotted for two flood events: November 1990 flood and November 1995 flood (Figure 4). Both storms produced two peak flow events. For the first peak in the 1990 event (~ 4000 cms), Upper Baker dam is filled above the flood control curve to reduce the peak while storage in Ross Lake increases to the normal flood control curve. For the second peak of the 1990 flood (about 5000 cms), both Upper Baker and Ross Lake are

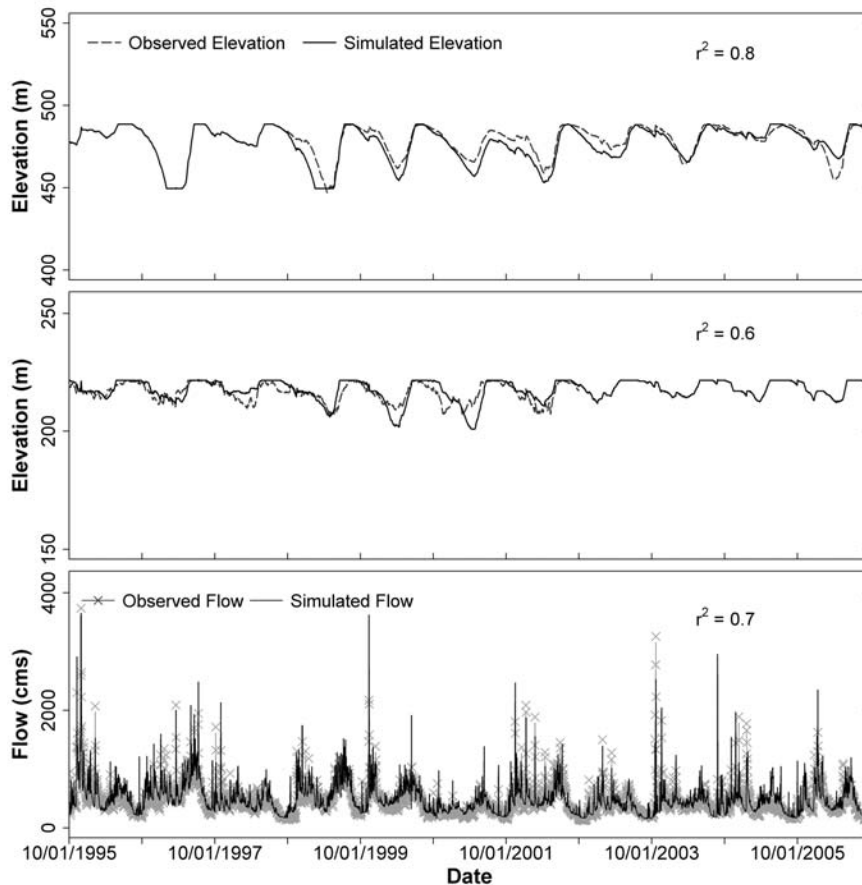Climate Change Impacts in the Skagit River Basin   29

Figure 3. Time series of simulated and observed elevations at Ross dam (top) and Upper Baker dam (middle) and simulated and observed regulated flows at the Skagit River near Mount Vernon (bottom) for water years 1996–2006.

filled above their respective flood control curves to reduce the peak flow at the lower Skagit River, and then return to their flood control curves. The response is similar in the 1995 flood. Regulated peak flows also closely match observations in these cases. This shows that storage is being used in a realistic way in the simulations to reduce the downstream flow during floods. Comparison of simulated reservoir elevations with observations during 1990 and 1995 floods (not shown) further confirms that increases in storage during flood events are realistically simulated by the model and that the proportional allocation of storage for flood control between Ross and Upper Baker projects in the model is consistent with actual operations. Despite good overall agreement, in

some cases (and especially pre-1985) there are substantial errors in the simulated peak and low flows (Figures 5–6). These are attributable to a) errors in the timing and magnitude of high and low flows produced by the hydrology model, b) changes in reservoir operating policies and energy demand through time (especially pre-1985), and/ or c) errors in storage that provide greater or lesser flood storage in the simulations in comparison with observations.

Figure 5 evaluates the performance of the model in reproducing the observed cumulative distribution function (CDF) and time series of daily peak flows for the Skagit River near Concrete and the Skagit River near Mount Vernon from water years
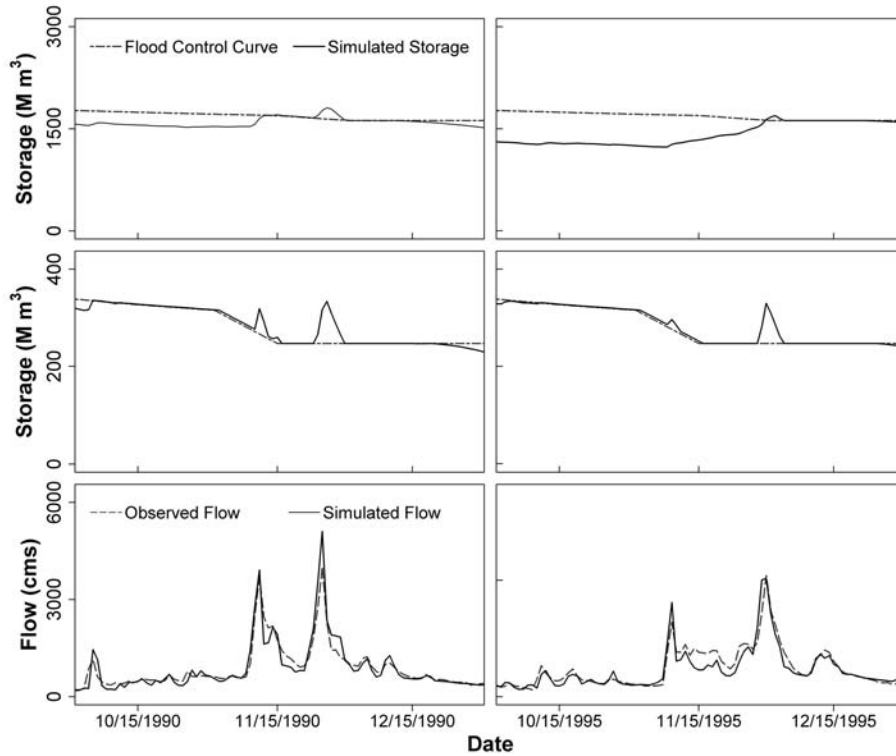
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Figure 4. Simulated reservoir storage and flood control curves for Ross dam (top) and Upper Baker dam (middle) and comparison of simulated daily flows with observed flows at the Skagit River near Mount Vernon (bottom) for November 1990 flood (left) and November 1995 flood (right).
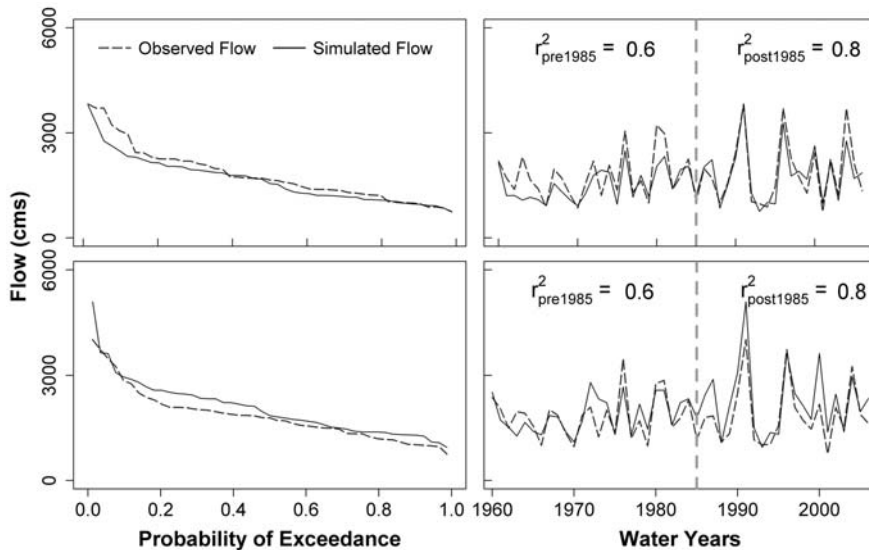

Figure 5. Cumulative distribution function (CDF) (left) and time series (right) of observed and simulated daily-time-step annual peak flows for water years 1960–2006 for the Skagit River near Concrete (top) and the Skagit River near Mount Vernon (bottom).

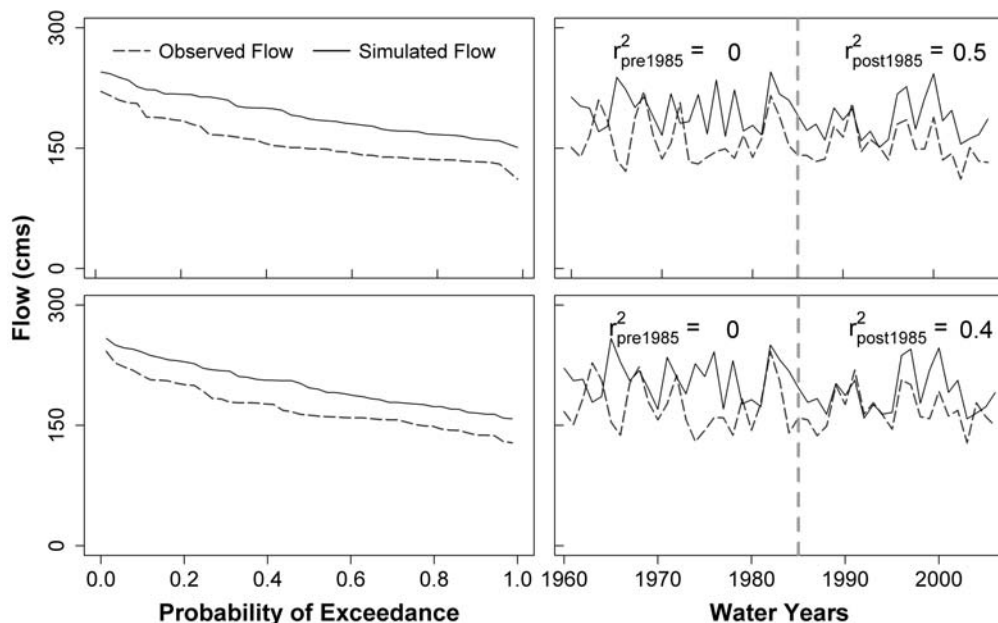Climate Change Impacts in the Skagit River Basin   31

Figure 6. Cumulative distribution function (CDF) (left) and time series (right) of observed and simulated 7-day low
flows for water years 1960–2006 for the Skagit River near Concrete (top) and the Skagit River near Mount
Vernon (bottom).

1960–2006 (when both Ross and Upper Baker dams are present in the system).

The model simulates the probability distribution and time series of observed daily peak flows reasonably well ($R^2 \geq 0.6$), but there is substantial disagreement in the time series at both sites before about 1985, due in part to changing in flood control and hydropower operations through time. Observed flows at Mount Vernon are also substantially influenced by inundation of side channels during high flows and dike and levee failures, which are not explicitly simulated by the model. For instance, dikes have failed more than 80 times since 1894 in the Skagit River basin, including five dike failures in 1990 (City of Anacortes 2004). Because the model best reproduces the CDFs of annual peak flows (Figure 5, left panels), we focus our attention primarily on these metrics (and GEV distributions fitted on the CDFs) in the future projections rather than on individual extreme events.

Simulations of annual minimum 7-day low flows show a high bias (22% for Concrete and 16% for Mount Vernon) in comparison with

observations, especially prior to 1985 (Figure 6). Regulated low flows are particularly sensitive to late summer energy targets and associated reservoir releases in the model simulations. Our hypothesis is that the bias in the 7-day low flows is related primarily to our use of scaled average energy targets, and also no simulation of energy forecasts or lower weekend energy production. Although some caution should be used in interpreting the low-flow results because of the model bias, percent changes in low flows are a meaningful measure of the sensitivity to climate change.

Results

In this section, we begin by evaluating changes in mean monthly streamflow at the Skagit River near Mount Vernon under natural and regulated conditions. Secondly, the impacts of climate change on hydropower generation and sediment loading are assessed for current reservoir operating policies. Finally we evaluate historical and future hydrologic extremes (floods and low flows) using both current and alternative flood control operations.
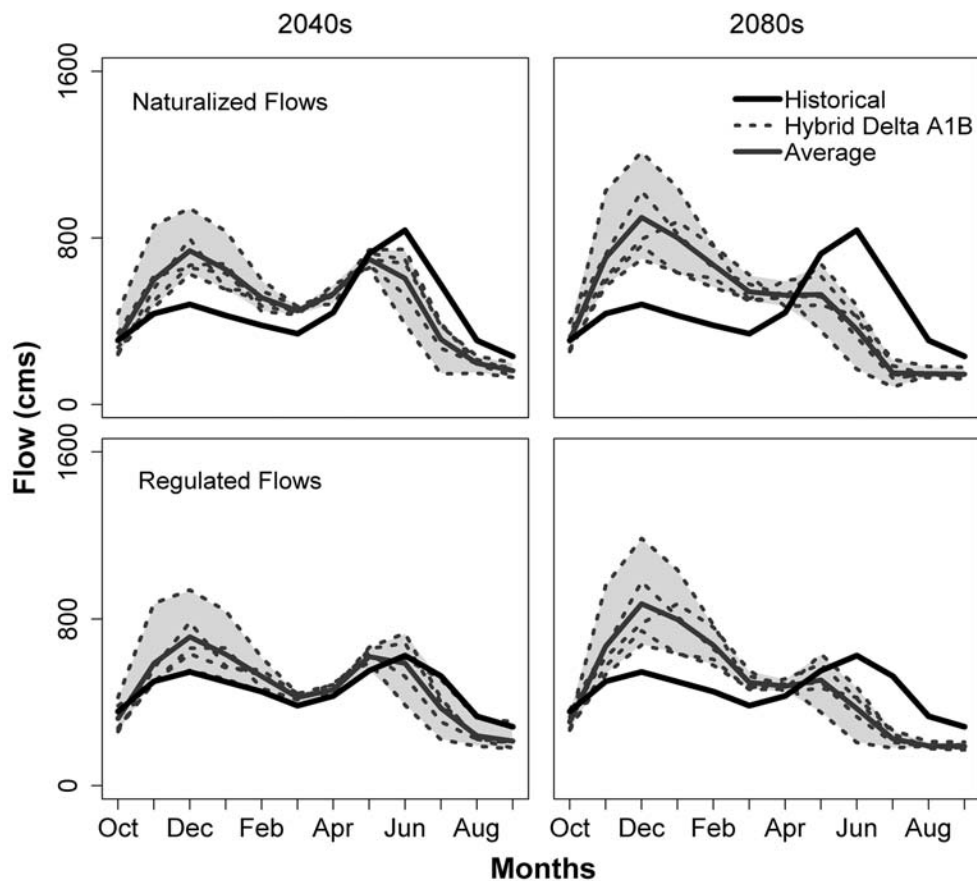
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Figure 7. (Top panels) Simulated monthly average streamflow at the Skagit River near Mount Vernon under natural conditions for the 2040s (left) and 2080s (right). (Bottom panels) Same as above except for regulated conditions.

Changes in Mean Monthly Streamflow under Natural and Regulated Conditions

Figure 7 (top panels) shows projected changes in mean monthly hydrographs for the Skagit River near Mount Vernon under natural conditions. For historical simulations, the Skagit River near Mount Vernon shows dual peaks in June and December, which are typical hydrographs for mixed rain and snow watersheds in the Cascades (Elsner et al. 2010, Hamlet et al. 2013). Streamflows for the Skagit near Mount Vernon are projected to increase in the cool season (October to March) and decrease in summer (June to September) in response to climate change. By the 2080s, the seasonal timing of streamflows is dramatically shifted from dual

peaks in the historical period (the largest in June) to a single rain-dominant peak in December.

Average December flow from the five hybrid delta simulations for the 2080s is slightly above historical peak flows in June. The ensemble-average December flow for the 2080s is projected to increase by 7% (- 17% to + 45%) relative to historical June flow under natural conditions (top right panel of Figure 7). Changes in flow under regulated conditions are similar in character to changes in natural flow (bottom panels of Figure 7), except the projected peak monthly flows in the future scenarios are both earlier (in December) and substantially larger than historical values in June. The ensemble-average December flow for the

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2080s is projected to increase by 40% (+ 8% to + 90%) relative to historical June flow under regulated conditions, which is a much larger percent increase in comparison with natural conditions.

Changes in Hydropower Generation

The potential effects of climate change on the hydropower generation under current operating policies are examined for the two energy companies in the Skagit River Basin: Seattle City Light (SCL) (top panels of Figure 8), Puget Sound Energy (PSE) (middle panels of Figure 8) and the combined energy production (SCL+ PSE) (bottom panels of Figure 8). Projections from the five GCM simulations show small changes in mean annual hydropower generation for both projects but substantial changes in seasonal hydropower generation. The mean annual hydropower generation is projected to decrease by 0.7% (- 9% to + 9%) by the 2040s and increase by 0.2% (- 5% to + 9%) by the 2080s for SCL projects and to increase by 0.9% (- 7% to 6%) by the 2040s and decrease by 1.9% (- 5% to + 3%) by the 2080s for PSE projects. Although projected changes in mean annual hydropower generation are small, hydropower production is projected to increase in winter and decrease in summer (Figure 8) in response to streamflow timing shifts (shown in bot-

tom panels of Figure 7). By the 2080s, hydropower generation for the whole Skagit River Basin (sum of all generation) is projected to increase by 19% (+ 12% to + 28%) in winter and spring, but decrease by 29% (+ 27% to + 31%) in summer (bottom right panel of Figure 8). These results are generally consistent with previous studies for the Columbia River Basin and Washington State (Hamlet et al. 2010b) and for the Skagit River Basin (Hamlet et al. 2010a, Seattle City Light 2010). Projected increases in winter hydropower generation are expected to be beneficial, since increased generation would likely help to meet projected increases in winter electricity demand due to population growth (Hamlet et al. 2010b) but the projected decrease in summer hydro-
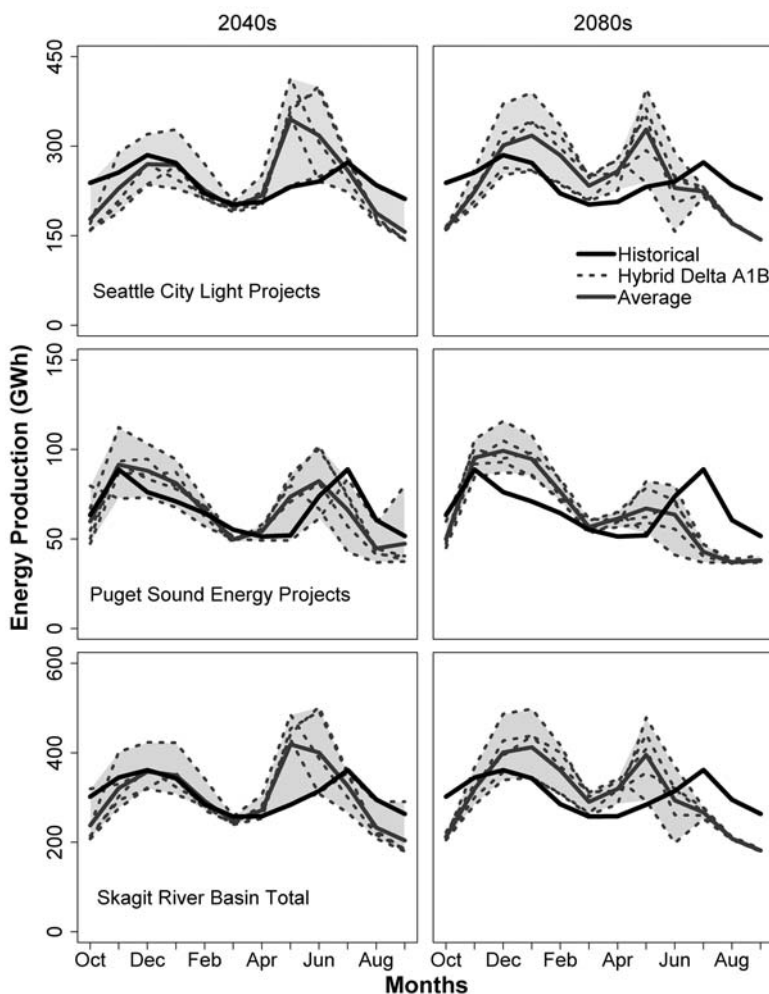

Figure 8. Simulated monthly average hydropower production from Seattle City Light Projects (top), Puget Sound Energy Projects (middle), and the Skagit River Basin total (bottom) for the 2040s (left) and 2080s (right) under current operating policies.
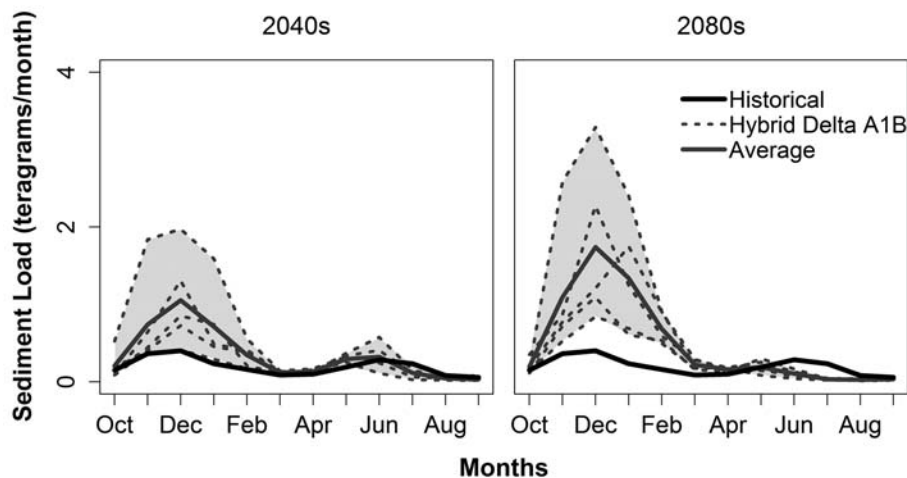
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Figure 9. Simulated monthly average sediment loading for the Skagit River near Mount Vernon for the 2040s (left) and 2080s (right).

power generation is likely to pose challenges to water system managers because rapid increases in cooling energy demand are projected in the same months due to both population growth and warming (Hamlet et al. 2010b).

In comparison with SCL projects, the seasonality of hydropower generation from PSE projects is much more sensitive to climate change. By the 2080s, peak hydropower generation for PSE projects shifts from July to December (middle right panel of Figure 8), while peak hydropower generation from SCL projects shifts from dual peaks in December and July to dual peaks in January and May (top right panel of Figure 8).

Impacts to Sediment Loading

Changes in suspended sediment loading under current reservoir operating policies are projected for the 2040s and 2080s (Figure 9). The results show that sediment load is likely to increase dramatically in the cool season but decrease in the summer in comparison with historical conditions. By the 2080s, for example, peak sediment delivery at the Skagit River near Mount Vernon is simulated to increase by 376% (+ 140% to + 730%) during December–February but decrease by 76% (- 60% to - 90%) during July to September in comparison with historical simulations. The timing of peak sediment loading is projected to change from dual peaks in June

and December for the historical simulations to a strongly winter-dominant peak in December for the 2040s and 2080s, which is consistent with the projected timing shift of streamflow from a mixed rain and snow watershed to a rain dominant watershed (bottom panels of Figure 7). The average annual sediment load from five GCMs shows a steady increase though time, reaching an ensemble-average of about 4.1 teragrams/year by the 2040s and 5.8 teragrams/year by the 2080s, in comparison with the historical baseline average of 2.3 teragrams/year. Increase in sediment loading in the lower basin could be both a benefit and a threat to ecosystems and society. For example, an increased sediment load may help to mitigate the projected loss of marsh and shallow water habitat in the Skagit delta as sea level rises if sediment is routed to areas of need (Czuba et al. 2011, Lu et al. 2010, PALS 2008). At the same time, increased suspended sediment load has been shown to cause negative effects on many aquatic species (Grossman et al. 2007, 2011; Lotspeich and Everest 1981). Increased suspended sediment loading may also reduce channel carrying capacity over time, resulting in reduced flood conveyance and increased water elevations during flooding, and/or the need for dredging, and may also interfere with the operation of tide gates. We hypothesize that increases in bed-load sediment transport may exacerbate these impacts.

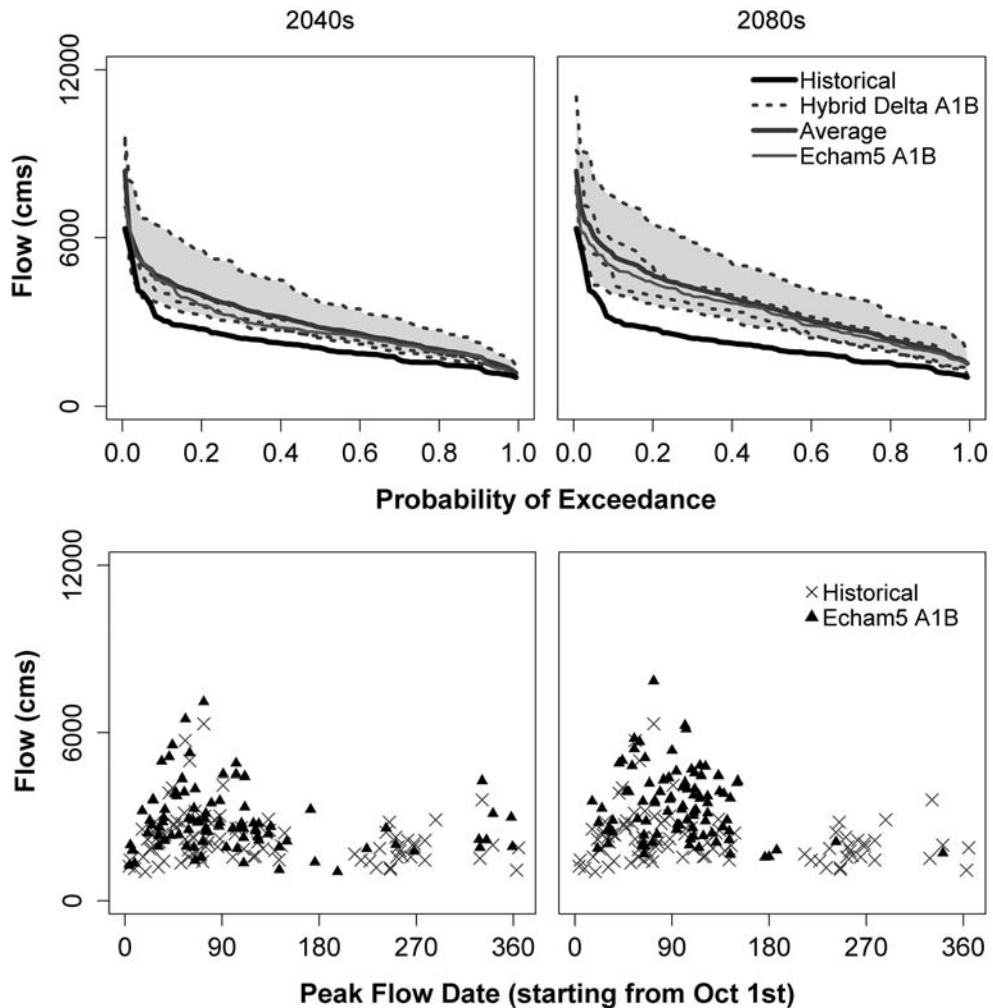Climate Change Impacts in the Skagit River Basin   35

Figure 10. (Top Panels) Cumulative distribution functions (CDFs) of annual peak flows for historical and future projections (based on 91 years of data in each case) under natural conditions for the 2040s (left) and 2080s (right). (Bottom Panels) Same as above except for projected changes in annual peak flow dates and magnitude using Echam5 A1B emissions.

Changes in Hydrologic Extremes

The impacts of climate change on hydrologic extremes such as changes in annual peak flows (Figure 10), changes in floods (Q_{100}) and low flows (7Q10) (Figures 11 and 13) are projected under natural and/or regulated conditions. The top panels of Figure 10 show the CDFs of annual peak flow for historical and future time periods under natural conditions. Increases in flood intensity are shown across all return intervals, however the largest percent changes are most apparent for the lower return intervals. This effect is discussed in

more detail by Tohver et al. (2014), but results from the effects of atmospheric rivers that produce the largest historical flood events (Salathé et al. 2014). These storms are warm enough that there is little increase in contributing basin area with additional climate change warming. For smaller, colder peak flow events in the historical record, the warming in the climate change scenarios strongly increases contributing basin area, resulting in larger increases in peak flows. Among five GCMs forced by the A1B emissions scenario, the CDF from the Echam5 is close to that from
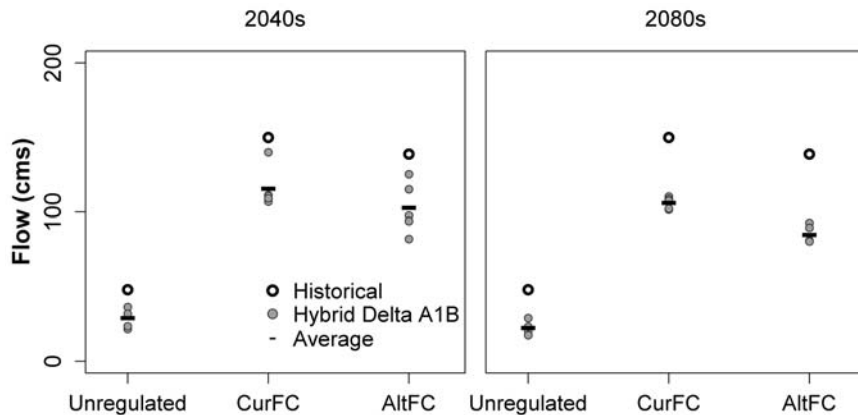
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Figure 11. The magnitude of 7Q10 at the Skagit River near Mount Vernon for unregulated flows and for regulated flows under current flood control operations (CurFC) and alternative operations (AltFC) for the 2040s (left) and 2080s (right).

ensemble-average for the 2040s and 2080s (see top panels of Figure 10). Thus we examine changes in timing and magnitude of annual peak flows using the Echam5 A1B scenario as a representative climate change scenario (bottom panels of Figure 10). The simulations show that climate change is likely to cause larger and earlier annual peak flows as warming intensifies through the 21st century. For historical simulations, annual peak flows occur in fall/winter 71% of the time (65 of 91 water years) and 29% in spring/summer. For the climate change scenario, the magnitude and frequency of fall/winter peak flows increases, and spring/summer peak flows become increasingly infrequent. For the 2080s scenarios, for example, all but five peak flow events (95%) occur in cool season as compared to 71% in the historical simulations.

SkagitSim simulates not only current flood control operating policies but also alternative flood control operating policies discussed above (earlier and deeper flood evacuation) (Figure 11). The magnitude of Q_{100} increases through the 21st century for both regulated and unregulated conditions. As expected, Q_{100} under natural conditions is greater than Q_{100} for regulated conditions in each time period. Under current flood control operations, the future Q_{100} increases by 23% (- 7% to + 87%) by the 2040s and 49% (+ 2% to + 119%) by the 2080s relative to the historical regulated Q_{100}. Although the alternative flood control operations reduce Q_{100} in comparison with current flood

control operations, projected Q_{100} under alternative flood operations increases by 21% (- 4% to + 65%) by the 2040s and 42% (+ 3% to + 100%) by the 2080s relative to historical baseline (i.e. the additional reduction in Q_{100} under alternative operations is only 2% for the 2040s and 7% for the 2080s relative to current operations). Thus the alternative flood control operations are shown to be largely ineffective in mitigating the increased flood risks in the lower basin at daily-time-step. This result is somewhat counter-intuitive. Peak flows are increasing in the scenarios, so why does increased flood storage not capture more of these increased flows and reduce the downstream peak?

To help understand these effects we choose the top five largest unregulated floods based on the projected flows for the 2080s at the Skagit River near Mount Vernon and examined the contribution of flows from different parts of the basin. The flows at Mount Vernon are spatially disaggregated into three portions: inflows entering the system above the two headwater storage dams (Ross and Upper Baker), and total inflows downstream of both dams (Other) (Figure 12). For the top five floods, daily inflows to Ross and Upper Baker dams are smaller than their current flood control storages of 148 M m^3 at Ross dam and of 91 M m^3 at Upper Baker dam except in two cases when daily inflows to Ross dam are 180 and 167 M m^3 for the 2080s. Thus the increased flood storages are, in general, not helpful in reducing the flood risks, and the

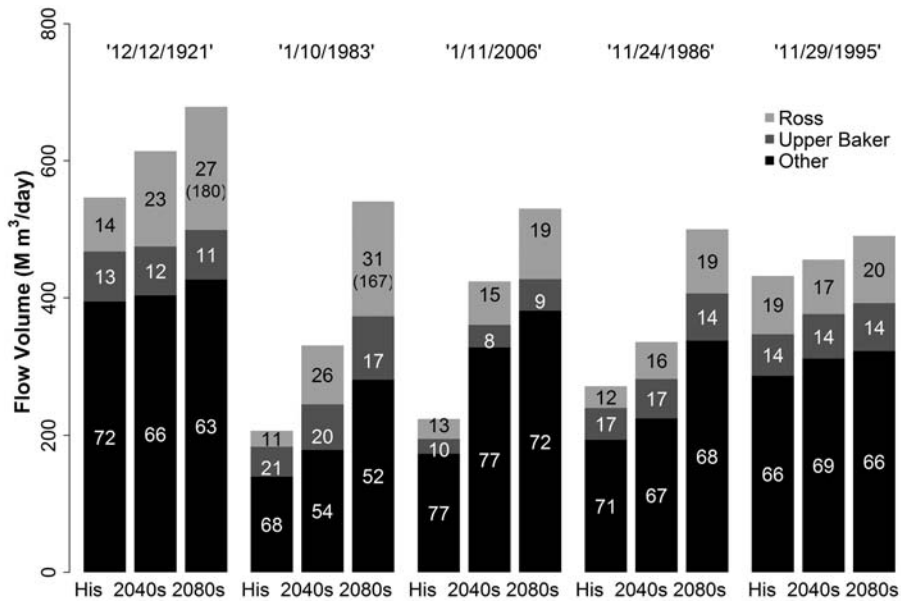Climate Change Impacts in the Skagit River Basin   37

Figure 12. Portions of total inflows above Ross dam, above Upper Baker dam and below dams (other) for the top five largest unregulated floods at the Skagit River near Mount Vernon for historical run and for the 2040s and 2080s associated with Echam5 A1B emissions scenario. Numbers in the bar plots show percentage of inflow to each part over the total flows at Mount Vernon. Two numbers in parenthesis show actual flow volumes in M m^3.

potential reductions in flows are relatively minor. In other words, the current levels of flood storage at the upstream projects are already large enough to capture all but the most extreme climate change floods, and proposed increases in headwater flood storage produce only a minor improvement in two events. Furthermore, inflows below the dams are a relatively large portion (+ 54% to + 77%) of the total flows at Mount Vernon (Figure 12), and these flows intensify through the 21st century. Therefore even fully capturing the inflows in the headwaters does not compensate for overall increases in flooding in the lower basin. Finally, although floods are projected to occur systematically earlier overall, earlier evacuation is also not effective in preventing the largest floods, because all of the five largest floods shown in Figure 12 occur after the middle of November when both headwater storage dams provide full flood storage in the simulations. Note also that the largest floods in the historical record show relatively modest increases in the future (i.e. '1921' and '1995' floods), whereas the more modest floods increase more substantially (i.e. '1983', '2006'

and '1986' floods). As discussed above, this is because increased contributing basin area due to warming is a larger factor in the modest historical events (Tohver et al. 2014).

The lowest consecutive 7-day average flows with a 10-year return interval (7Q10) are used as a metric to evaluate the impacts of climate change on extreme low flows at the Skagit River near Mount Vernon (Figure 13). The lowest consecutive 7-day flows occur during September and October for both historical and future conditions. The magnitude of extreme low flows increases dramatically when dam operations are simulated, because under the current operating policies, the dams release water to produce hydropower or to reach their flood control curves in the same months that low flows occur under natural conditions. As a result, 7Q10 values are substantially higher under regulated conditions in comparison with natural conditions.

More severe extreme low flows are projected as loss of snowpack, earlier snowmelt, decreased summer precipitation, and increased evaporation
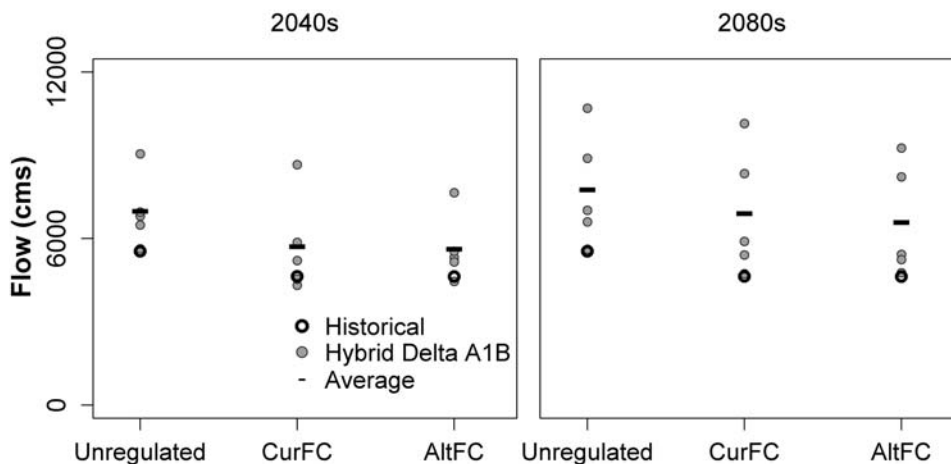
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Figure 13. The magnitude of Q_{100} at the Skagit River near Mount Vernon for unregulated flows and for regulated flows under current flood control operations (CurFC) and alternative operations (AltFC) for the 2040s (left) and 2080s (right).

intensify through the 21st century. For current operating conditions, for example, all simulated 7Q10 values for the climate change are lower than historical baseline and the central tendency of the projected 7Q10 values are 77% (71% to 93%) and 71% (68% to 74%) of the historical baseline values for the 2040 and 2080s, respectively. Alternative flood control operations which use more storage and earlier evacuation cause further reductions in extreme low flows, although all of the future projections under regulated conditions are well above historical 7Q10 levels for unregulated flows. Note that simulated extreme low flows shown in Figure 13 show a systematic high bias in comparison with observations (see Figure 6 and discussion above).

Discussion

This study provides model simulations of regulated daily and monthly streamflow, hydrologic extremes (floods and low flows), hydropower production, and sediment load for both historical conditions and a range of future climate change projections for an ecologically important and vulnerable Pacific Northwest watershed.

Under current climate, the Skagit River Basin is a mixed rain and snow watershed that shows dual peaks in winter and spring (the largest in June) (Table 2). Climate change is projected to increase

flow in winter and spring and decrease flow in summer, altering the seasonal timing of flow in the Skagit in the 2080s to a single rain-dominant peak in December under unregulated conditions. These results are consistent with previous studies (Elsner et al. 2010, Hamlet et al. 2013). When dam operations are considered, projected shift in the seasonal timing of flows is similar with unregulated conditions but projected percent changes in peak monthly flows relative to historical values are much larger than changes in unregulated conditions. i.e. changes in the ensemble-average December flow for the 2080s relative to historical June flow increase from 7% under natural conditions to 40% under regulated conditions.

The projected shift in the seasonal timing of flow affects the magnitude and timing of hydropower production and sediment loading as shown in Table 2. Seasonal changes in PSE energy production are more pronounced than changes in SCL energy production. Increasing hydropower production in winter will likely be a benefit to the region, but adapting to reductions in hydropower generation during summer will likely present increasing challenges to utilities (Hamlet et al. 2010b). Increasing pressure to use reservoir releases of cold water to sustain thermal refugia for temperature sensitive fish downstream may also present additional challenges.

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TABLE 2. Historical and ensemble-average future simulations of regulated monthly flow (cms) for the Skagit River near Mount Vernon, monthly energy production (GW-hr) for SCL and PSE projects and monthly suspended sediment load (gigagrams) for the Skagit River near Mount Vernon under current flood control operations.

| | Flow (cms) | | | Energy Production (GW-hr) | | | | | | Sediment Load (gigagrams) | | |
| | | | | SCL | | | PSE | | | | | |
Month	Historical Baseline	2040s	2080s	Historical Baseline	2040s	2080s	Historical Baseline	2040s	2080s	Historical Baseline	2040s	2080s
Oct	357	324	308	239	178	162	63	60	50	150	206	195
Nov	502	587	670	256	229	224	89	92	95	363	741	1093
Dec	547	715	874	285	270	302	76	88	99	401	1054	1741
Jan	499	631	798	272	269	318	71	81	95	235	713	1339
Feb	452	525	675	221	226	285	64	66	76	160	346	684
Mar	385	423	497	202	198	234	55	50	57	87	120	222
Apr	431	461	478	207	217	258	51	54	61	99	131	158
May	553	620	507	232	345	328	52	74	67	188	294	187
Jun	625	588	371	241	318	230	74	82	64	286	322	106
Jul	526	372	225	273	260	224	89	66	43	233	115	31
Aug	333	240	191	235	188	171	61	45	37	80	44	26
Sep	283	214	190	212	157	143	52	47	38	57	35	35

Dramatic changes in magnitude and timing of sediment load are projected at the Skagit River near Mount Vernon, with peak sediment load in December increasing from the historical baseline average of 0.40 teragrams/month to ensemble-average of 1.74 teragrams/month (+ 335%) by the 2080s (Table 2). Dec–Feb total sediment discharge is simulated to increase by 376% for the 2080s over baseline conditions (increasing by nearly a factor of five). It is uncertain whether the increased winter sediment load will be a net benefit or detriment to the Skagit delta. On the one hand, an increase in suspended sediment loading might result in negative effects on many aquatic species. On the other hand, increasing sediment loading may help mitigate the projected loss of marsh and shallow water habitat in the Skagit delta due to rising sea levels by effectively rebuilding the delta, especially if sediment is routed to areas of need and similar changes in bed-load processes follow the increasing winter flow regime.

The regulated 100-year flood under current operations is projected to increase relative to the historical baselines, though regulated Q_{100} is less than unregulated Q_{100} in each time period (that is, current flood control operations continue to reduce the overall flood risk in the future). Al-ternative flood control operations that increase flood control storage in headwater reservoirs and evacuate storage one month earlier than current operations are shown not to be effective in mitigating the projected higher flood risks in the climate change scenarios. Increased flood storage in headwater projects can only capture the flows above the projects, which are a relatively small portion of the total flow in the lower basin during floods, but can't capture flows from the larger unregulated tributaries (e.g. the Sauk River) that are projected to substantially increase. Barring the construction of new storage dams in the unregulated portions of the basin (which seems unlikely), these results support the argument that climate change adaptation efforts in the Skagit River basin to mitigate flooding will need to focus primarily on floodplain management strategies rather than alternative dam operations.

Regulated extreme low flows under current operations are projected to decline due to projected increase in evapotranspiration and reduction in summer precipitation. Alternative flood control operations produce a further reduction in 7Q10 values in comparison with current flood control operations (Table 3). 7Q10 values under regulated conditions, however, are substantially higher than

TABLE 3. Historical and ensemble-average future simulations of Q_{100} (cms) and 7Q10 (cms) for the Skagit River near Mount Vernon for unregulated flows and for regulated flows under current flood control operations (CurFC) and alternative operations (AltFC).

Month	Q_{100} (cms)			7Q10 (cms)		
	Historical Baseline	2040s	2080s	Historical Baseline	2040s	2080s
Unregulated	5545	6992	7768	48	29	22
CurFC	4637	5718	6909	150	116	106
AltFC	4632	5627	6586	139	103	85

historical 7Q10 values for natural conditions in all time periods, suggesting that ecosystem impacts resulting from the changing low-flow regime may be relatively modest in the Skagit main stem.

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