Effects of Climate Change on Extreme Low-Flows in Small Lowland Tributaries in the Skagit River Basin

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Source: Northwest Science, 90(1) : 44-56

Published By: Northwest Scientific Association

URL: https://doi.org/10.3955/046.090.0105

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Abstract

Management of extreme low-flows requires fundamental trade-offs between water extraction for human use (e.g. for irrigation and municipal water supply) and in-stream flows to protect aquatic ecosystems. In the context of protecting endangered salmon and other cold-water fish species in small streams, extreme low-flows are one of the most important aspects of the flow regime. We quantify projected changes in low-flow magnitude and timing for several lowland tributaries of the Skagit River basin in response to regional climate change. Ten hydrologic model simulations of mid-21st century (2030–2059) streamflows are compared against a historical period (1917–2006). Each of the hydrologic simulations are forced by atmospheric variables developed from respective CMIP3 global climate model (GCM) output downscaled to 1/16th degree resolution using the Hybrid-Delta downscaling method. Baseline historical simulations are forced by historical gridded meteorological data sets of temperature and precipitation, and additional meteorological variables reconstructed using the MTCLIM weather preprocessor. Hydrologic simulations were performed using the Distributed Hydrology Soil Vegetation Model (DHSVM) implemented at 30–m resolution. Analysis of the DHSVM streamflow simulations projects future low-flows in Skagit lowland tributaries will decrease by 5–20% and low-flow conditions will persist on the order of a week longer into early fall. For the Samish and Nookachamps basins, the projected changes in future low-flow regimes are larger than for the smaller basins included in the study. Projected changes in near-average low-flows are larger and more consistent between different climate change scenarios than are projected changes for the most extreme low-flow events.

Keywords: Skagit basin hydrology, lowland tributaries, climate change impacts, extreme low flows

Introduction

The effects of climate change on river flow in the Pacific Northwest (PNW) have been studied in a number of previous assessment efforts using the Coupled Model Intercomparison Project, Phase 3 (CMIP3) scenarios associated with the IPCC Fourth Assessment Report. Although results vary from site to site, in general, warming and loss of snowpack combined with increasing precipitation in fall, winter, spring and decreasing precipitation in summer cause increasing flow in cool season (Oct–March) and decreasing flow in warm season (April–Sept) (Elsner et al. 2010, Hamlet et al. 2013). On the west slopes of the Cascades, increasing extreme high-flows in early winter and decreases in extreme low-flows in late summer are the norm for many river basins in the Pacific Northwest, particularly in the mixed rain and snow zone (Lee et al. 2016, Tohver et al. 2014, Salathé et al. 2014).

Changes in flow in the Skagit main stem at Mt. Vernon (USGS 12200500) follow these general trends. Projected hydrographs for future conditions show dramatic increases in monthly flow in winter and decreasing flow in summer by the 2040s and 2080s (Lee et al. 2016, this issue). High- and low-flow extremes in the Skagit main stem increase in intensity (higher highs and lower lows). The projected 100-yr flood for the Skagit River at Mount Vernon increases in magnitude by 49% under present day regulated conditions for the 2080s scenarios (Lee et al. 2016), and extreme low flows (7Q10) (the 7-day average annual extreme low flow with a 10-year recurrence interval) are projected to decline by 29%. An important caveat for extreme low-flows in the main stem, however,

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is that under baseline conditions regulated 7Q10 values are nearly three times their natural counterpart. This is because typical demand for electrical power in late summer and early fall results in substantial releases from upstream hydropower dams (Lee et al. 2016). Thus even with a 30% reduction in extreme low-flows under regulated conditions, 7Q10 values remain well above natural low-flow values (Lee et al. 2016). These results support the hypothesis that even though there are substantial reductions in extreme low-flows on a percent basis in response to regional climate change scenarios, the impacts to ecosystems due to changing low-flow regimes may not be very great in the Skagit main stem.

The sensitivity to changing climate in the tributaries, however, is likely to be quite different from the main stem. These systems are not affected by releases from upstream storage reservoirs, and 7Q10 values are generally less than or equal to natural values due to extraction for water supply. Thus, if these systems experience a reduction in extreme low-flows, the impacts to ecosystems may be much larger than those experienced in the main stem Skagit, particularly for cold-water fish like salmon and steelhead (Mantua et al. 2010). In this study, using a physically based fine-scale hydrologic model, we simulated the impacts of changing climate on four relatively small tributary watersheds in the Skagit lowlands.

Methods

The fine-scale Distributed Hydrology Soil Vegetation Model (DHSVM) (Wigmosta et al. 1994, 2002) was used to simulate streamflow in four tributary watersheds in the Skagit Lowlands (Figure 1) for historical and future periods. The model was configured to run at 30 m resolution, and incorporates static geospatial information such as land surface elevation, vegetation coverage, soil type, and soil depth. Higher resolution elevation and vegetation data were aggregated to 30 m resolution. Soil depth is estimated from slope and upstream contributing

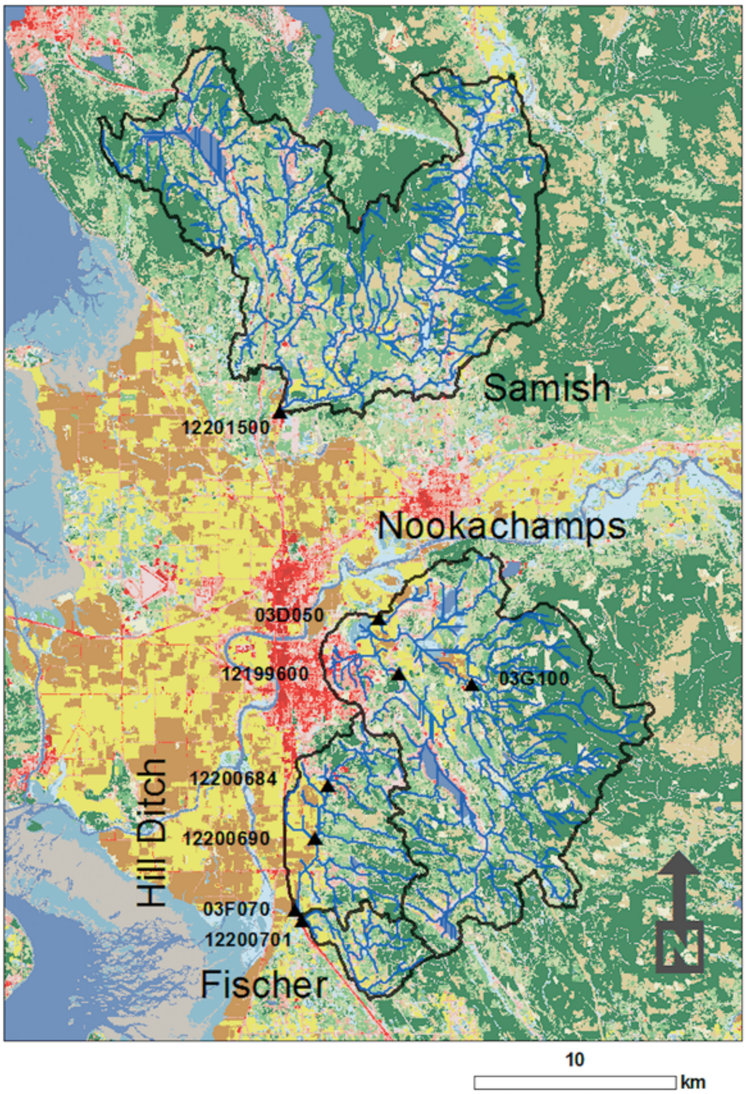

Figure 1. Map of the study domain, streamflow locations included in the study, and their respective contributing basin areas. Red and yellow areas on the map show heavily developed areas in the Skagit lowlands.

area, properties derived from the high-resolution digital elevation model. A lower resolution (150 m) soil type layer (Cuo, et. al. 2009) was resampled to produce data at 30 m resolution. Figure 1 shows a map of the hydrologic model domain, watersheds analyzed in the study, and streamflow gauging locations. Additional information on the streamflow gauging locations is shown in Table 1.

The hydrologic model was forced using 1/16th degree daily-time-step gridded meteorological data from 1916–2012 including precipitation, temperature, and wind variables. From these daily forcings, higher resolution 3-hourly forcing data were constructed using the Variable Infiltration Capacity (VIC) model weather preprocessor, which fits hourly splines through minimum and maximum daily temperature. Total daily precipitation was distributed equally through the eight 3-hour periods in the day. The derived 3-hourly data also includes relative humidity, incoming shortwave radiation, and outgoing long-wave radiation derived by the VIC weather preprocessor (based on MTCLIM–USDAFS, 1989) from precipitation and daily maximum and minimum temperature.

The historical forcing dataset used for the Hybrid Delta downscaling of GCM scenarios spans a shorter period from 1916–2006 (based on PRISM climatology version 1 and the Cooperative Observing Network (Co-op)) and is the baseline time series for our assessment of hydrologic change. To aid in the comparison of modeled historical streamflows to observations in the Nookachamps, Fischer, and Carpenter Creek (Hill Ditch) watersheds, where observations were largely made after year 2005, an updated forcing dataset spanning through year 2012 was used to drive the simulations so that concurrent streamflow records could be analyzed. The 1916–2012 dataset incorporated PRISM climatology version 3 and the NOAA Global Historical Climatology Network–Daily (GHCN–D) station data, updates which enable consistent extension from 2006 through 2012. The 2040s future period (2030–2059) forcing data was constructed using the Hybrid Delta downscaling and bias correction methodology (Tohver et al. 2014) for a set of ten Global Climate Models (GCMs) forced by the A1b emissions scenario (Mote and Salathé 2010, Hamlet et al. 2013). The Hybrid Delta method imparts the monthly statistical properties of the simulated future climate (derived from GCMs) onto the historic 1916–2006 dataset. That is, the future forcings share the daily time series of the historic 1916–2006 record but are adjusted to have the same monthly cumulative distribution function (CDF) of a given GCM scenario for the

TABLE 1. Additional information about streamflow gauging locations shown in Figure 1.

Station ID (Source)	Basin	Location	Position	Duration
03D050 (ECY)	Nookachamps Cr.	near mouth	mouth	WY 2000, n = 15
03D050* (Two outliers removed from the data set)	Nookachamps Cr.	near mouth	mouth	WY 2000, n = 13
12199600 (USGS)	Nookachamps Cr.	Baker Heights	1 (west)	200607–200809
03G100 (ECY)	Nookachamps Cr.	E. Fork (Beaver Lake Road)	1 (east)	WY 2001, 2006–2008
03F070 (ECY)	Carpenter Cr. (Hill Ditch)	Cedardale Road	mouth	WY 2000, n = 21
12200690 (USGS)	Carpenter Cr. (Hill Ditch)	Conway	1	200610–200703
12200684 (USGS)	Carpenter Cr. (Hill Ditch)	Bacon Road, Mt. Vernon	2	200704–200809
12200701 (USGS)	Fischer Cr.	(Conway)	mouth	WY 2006, 2007
12201500 (USGS)	Samish R.	N|A	mouth	WY 1941–1971, 1997–2012

future period (2030–2059 in our case) (See Tohver et al. 2014 for additional technical details on the Hybrid Delta downscaling technique). DHSVM simulations for the historical base case and 2040s future scenarios were 90 years long, based on the period from 1917–2006 (water year 1916 was used for hydrologic model spin-up).

Model Evaluation—As noted above, the fine-scale model parameters used in this study were derived from larger-scale modeling efforts carried out by Cuo, et al. (2009, 2011). For the calibration period used in the large-scale study, annual mean relative error, daily N-S model efficiency (Nash and Sutcliffe, 1970), and monthly N-S were reported at 9%, 0.75, and 0.83 (0.85 for monthly validation), respectively, at USGS gage 121740000 (Ruby Creek at Newhalem, WA). Constrained by short and non-continuous historical streamflow observations for the Nookachamps, Carpenter Creek (Hill Ditch), and Fischer Creek basins, and encouraged by generally good model performance for the longer and mostly continuous Samish River record (1941–1971, 1997–2012) (Table 2) additional model calibration was not undertaken here.

Figure 2 shows time series comparisons of daily simulated and observed streamflows for select basins and water years on linear and log scales. Figure 3 compares the observed and simulated cumulative distribution function (CDF) for the extreme 7-day low flow extracted from each water year for the Samish River. By removing the bias in the median of the CDF by shifting the curve upwards on the plot, the variability of the bias-corrected CDF is compared with the observed CDF.

The time series plots in Figure 2 show that the simulations for the Samish River capture the daily variability of streamflows and their seasonality reasonably well, but the simulated hydrograph recession is more intense than observed and extreme low flows have a substantial low bias. The timing of extreme low flows, however, closely matches the observations. The low bias in the simulated extreme low flows for Fischer Creek and the Samish River tributaries suggests that groundwater storage capacity may be too low in the model, which results in a more rapid rate of streamflow recession than actual and lower extreme low flows. Figure 3 shows the observed and simulated extreme 7-day low flow CDFs for the Samish River site. For uncorrected historical simulations, the CDF is biased low in comparison with the observations, and the simulated CDF with the bias in the median value removed shows less variability in the extreme 7-day low flows from the model simulations in comparison with observations. As we will show in subsequent sections, projected climate change results in a systematic shift to lower low flows in most sites. Based on Figure 3, the model likely underpredicts these

TABLE 2. Daily streamflow statistics for concurrent observed and simulated records for stations included in the study. N-S is Nash Sutcliff Efficiency score, *n* is the sample size of concurrent data sets, statistics for observed and simulated streamflow data sets are assembled from concurrent daily streamflow data sets (in units of cms).

Station	N-S	n	Obs. max	Obs. mean+std	Obs. min	Sim. max	Sim. mean+std	Sim. min
03D050	-0.52	15	11.1	4.78 + 3.59	0.1189	8.19	3.12 + 2.85	0.3675
03D050*	0.67	13	8.21	4.14 + 3.31	0.1189	8.19	3.48 + 2.89	0.4429
12199600	0.58	817	7.79	1.30 + 1.64	0.0017	11.32	0.98 + 1.50	0.0292
03G100	0.45	1462	21.37	1.63 + 1.83	0.0623	13.94	1.53 + 1.66	0.107
03F070	0.78	16	4.22	0.93 + 1.06	0.0368	6.36	0.78 + 1.53	0.0248
12200690	0.12	183	6.6	0.57 + 1.02	0	4.24	0.75 + 0.75	0.0115
12200684	-1.33	549	4.87	0.18 + 0.39	0.002	1.16	0.13 + 0.19	0.0055
12200701	0.56	731	1.13	0.20 + 0.22	0.0065	2.64	0.25 + 0.36	0.0046
12201500	0.82	14038	142.15	6.90 + 8.05	0.4248	88.11	6.80 + 8.72	0.2418

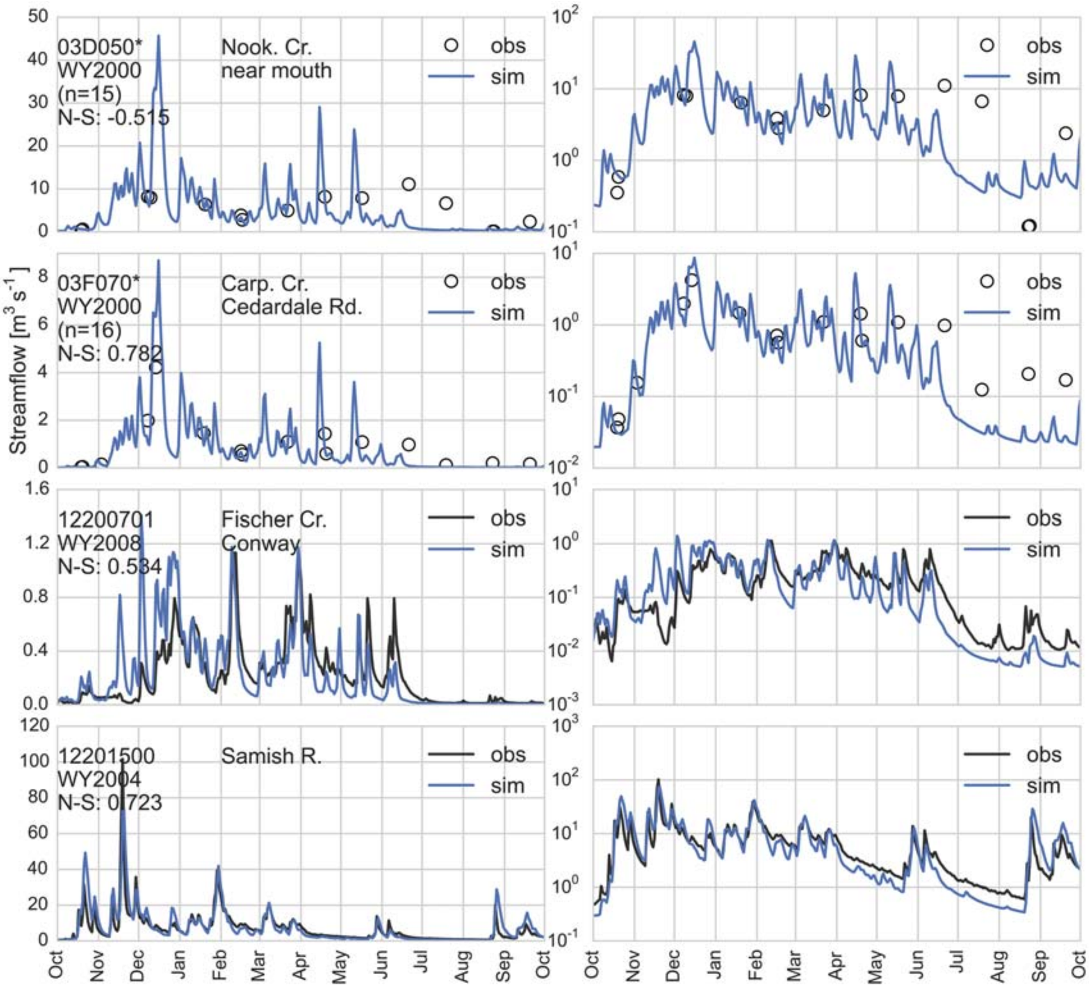

Figure 2. Simulated vs. observed streamflow for selected streamflow locations. Right panels show untransformed data, right panels show log-transformed data. Inset tables show the sample size (n) of the data set and the Nash Sutcliffe (NS) Efficiency scores.

relative changes in extreme low flows somewhat. That is, simulated percent changes in measures such as 7Q10 will likely be conservative (somewhat lower than actual).

Downstream (03F070) and upstream sites (12200684) in Carpenter Creek (Hill Ditch) respectively have relatively few observations and show inconsistent simulation error characteristics for low flows (Figure 2). More observed streamflow data is needed at these sites to better evaluate the model simulations. Fischer Creek (12200701) for WY 2006 and WY 2008 have consistently good NSE scores overall and well-timed but low-biased low flows. In 2008, Fischer Creek shows evidence of errors in driving data for individual storms. In particular, some of the high flow events are captured well, whereas others are markedly higher than observations. Attempts to calibrate the model would not be successful unless errors in driving data could be removed or avoided. For the Samish River site (12201500), which has the longest observed record by an order of magnitude, the simulation captures the site's daily variability and the timing and seasonality of high and low flows, but has recession and low-flow bias similar to Fischer Creek.

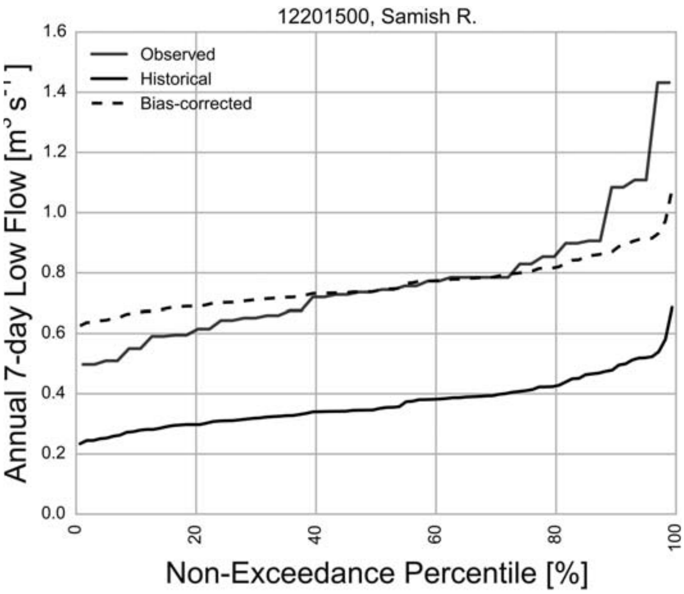

Figure 3. Simulated and observed CDFs of 7dELF for the Samish River. A bias corrected simulated CDF is shown as a dashed line.

Additional model calibration might improve the absolute value of the low-flow simulations for Nookachamps Creek and the Samish River; however, the other streamflow sites do not have sufficient data for calibration or evaluation of extreme low flows. Quantile-based bias correction schemes (Snover et al. 2003) could also be used to further address these deficiencies in the model simulations. To avoid potential confusion, however, we prefer to show unadjusted simulations and the simulated changes relative to these values in a consistent way for all sites. This choice reflects our overall objective to identify systematic changes in the low-flow CDFs and extreme values, rather than to simulate an accurate absolute value of the extreme low-flows for each site (which for many sites are not known).

Estimation of 7Q2 and 7Q10—Following model evaluation, long-term hydrologic simulations (1917–2006) for historical and Hybrid Delta downscaled future climate scenarios (2030–2059) were made. From these, the magnitude and date of the lowest 7-day average flow from each water year of the simulations was cataloged. In the rest of the paper we will refer to these values as 7-day extreme low-flows (7dELFs). Generalized Extreme Value (GEV) probability distributions were fit to the 7dELF time series using L moments to estimate the GEV parameters (Tohver et al. 2014). From the fitted distributions 7Q2, 7Q10 (the 7dELF for each water year with a recurrence interval of two and ten years respectively) were estimated for both the historical baseline simulations and future scenarios. Thus there is a 10% chance that the 7dELF would be below 7Q10 in any given year, and a 50% chance that the 7dELF would be below 7Q2.

Evaluating Changes in Seasonal Timing of Extreme Low Flows—To characterize the changes in the seasonal timing of 7dELF as a function of their magnitude (see Figure 8), we also ranked the individual 7dELF values for each water year (1917–2006) from lowest to highest (i.e. rank 1 to 90) and then examined average timing shifts for different groups: a) high values (rank 71–90), b) medium values (rank 36–55), and c) low values (rank 1–20). Note that the average of values of rank 44 and 45 is the median for this data set, which is also close to the mean of the 7dELFs.

Scatter Plots Showing Systematic Shifts in Extreme Low Flows—To make Figure 9, data from the simulated historical and 2040s 7dELF series for the Samish River were ranked and then grouped into x-y pairs for each rank position (1–90), where x was the historical value of the 7dELF for the specific rank position, and y was the future 7dELF for the same rank position. Thus for each rank position there are 10 x-y data points, one for each GCM scenario. These are then plotted all together as a scatter plot. Ensemble means for each rank position are also identified.

Results

Figure 4 shows the monthly mean hydrographs for all stations. For the largest basins, the lowest monthly flows generally occur in August/

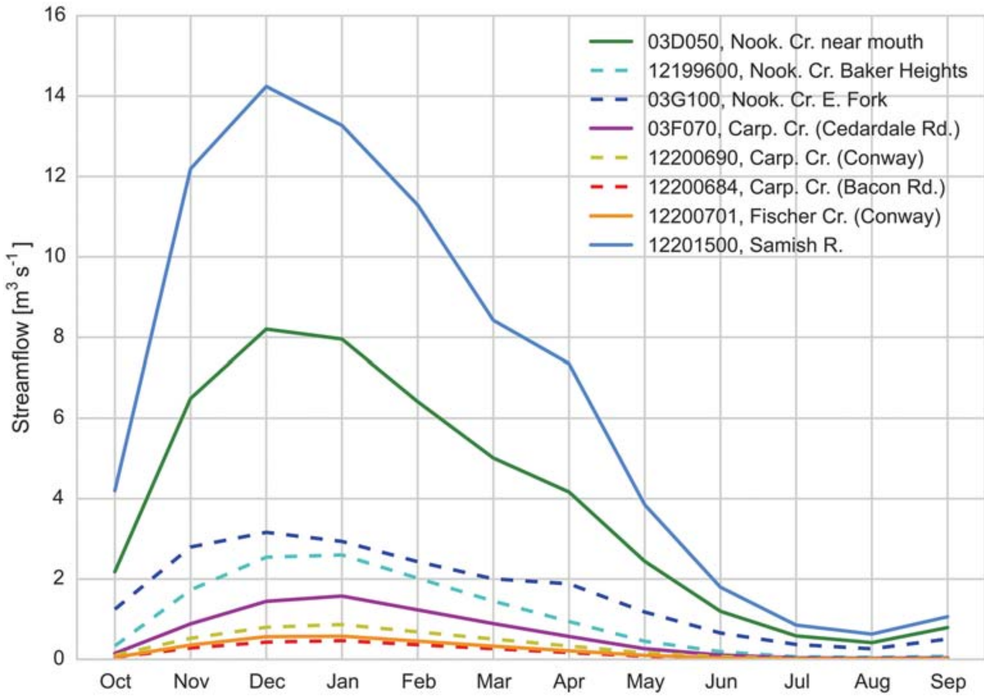

Figure 4. Composite monthly average hydrographs for each streamflow location.

September, before the end of the WY, whereas in the smaller basins, occurrences frequently span across into the new WY. Simulated historical and projected future monthly flows for the Samish River (Gage: 12201500) (Figure 5a) show the characteristic shift in streamflow timing that accompanies warmer air temperatures and shifts in the seasonality of precipitation in many other PNW hydrologic studies (Snover et al. 2003, Elsner et al. 2010, Hamlet et al. 2013, Vano et al. 2010). All but one of the 2040s ensemble members are above the historical baselines in cool season (Oct–March) and below historical baselines in warm season (May–Sept) (Figure 5b). Model projections for October months are split between equal numbers of scenarios that show increasing flow, and those that show reductions in flow (Figure 5b). Seasonal hydrographs in the other rain dominated basins are similar in character. The differences in streamflow response in October relate to unique changes in ET, late-summer soil moisture, and precipitation for each GCM scenario, which advance or delay streamflow response in the early fall.

Changes in 7dELFs, which typically occur in September in the historical baseline simulations, essentially follow the reductions in warm season flows. Figure 6 shows historical 7dELF CDFs plotted with the range and ensemble mean for the ten 2040s CDFs from the ten climate change scenarios. Figure 7 shows the resulting percent change in 7Q10 and 7Q2 for each GCM scenario and the ensemble mean. The Samish River and Nookachamps Creek show reductions in the ensemble mean of about 5–15% for 7Q10, and changes in 7Q2 are larger, with reductions ranging from 10–20%. Changes in 7Q2 and 7Q10 in Carpenter Creek (Hill Ditch) and Fischer Creek are smaller, about 5% for both (Figure 7). Samish River simulated 7dELFs show greater percent decreases as the 7dELF magnitude increases (Figure 6).

For the climate change scenarios, in addition to systematically lower 7dELFs, the 7dELF occurrence dates shift later in the year (Figure 8). These effects are caused by decreased summer/early fall precipitation, increased ET due to warming, and reduced soil moisture in late summer/early fall

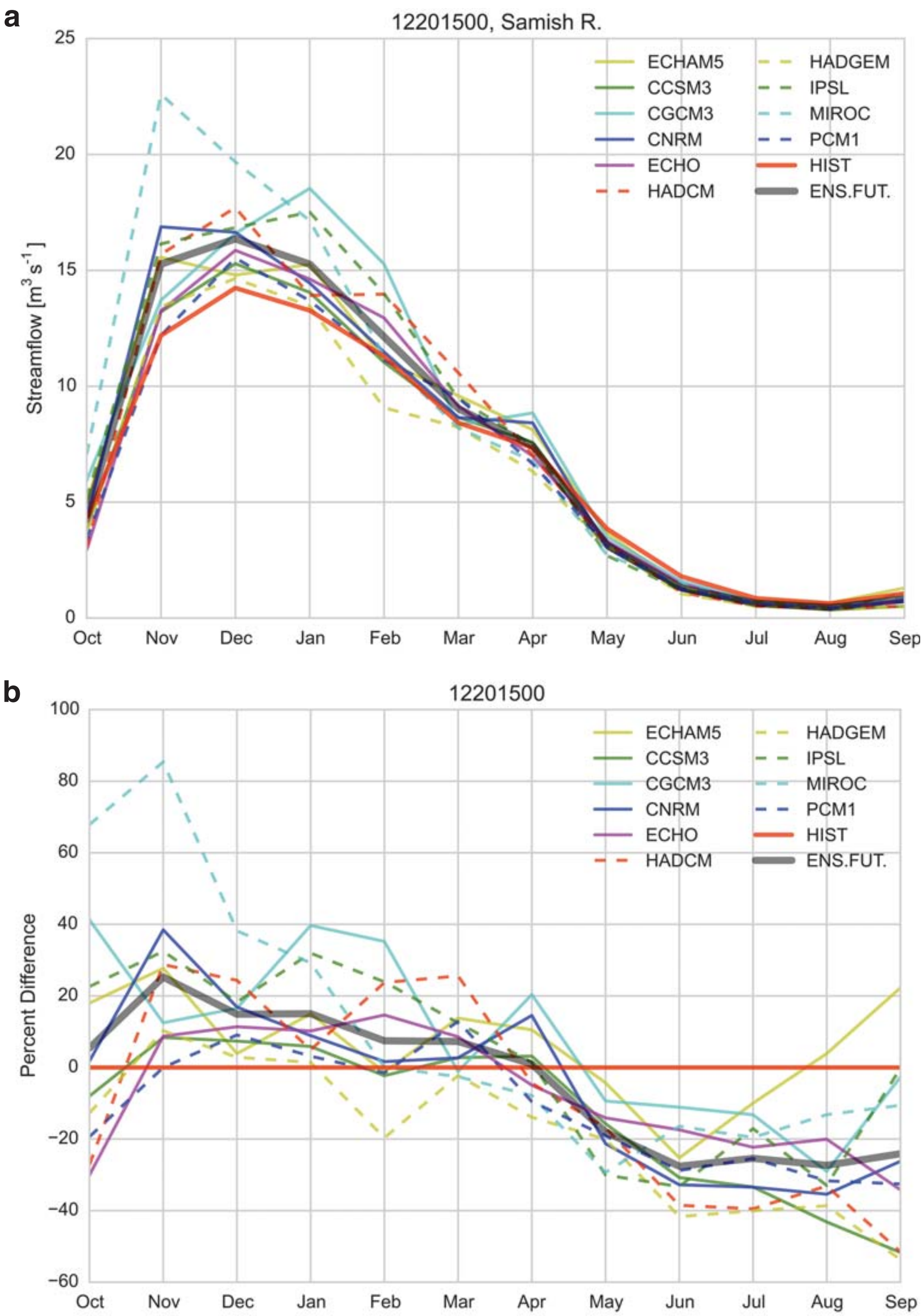

Figure 5. a) Historical vs. monthly hydrographs for the Samish River. Historical (red), 2040s future ensemble mean (gray). Color and line scheme for individual 2040s ensemble members are shown in the legend. b) Percent change in monthly hydrographs, future relative to the historical baseline in each month. Historical (red), future ensemble mean (gray).

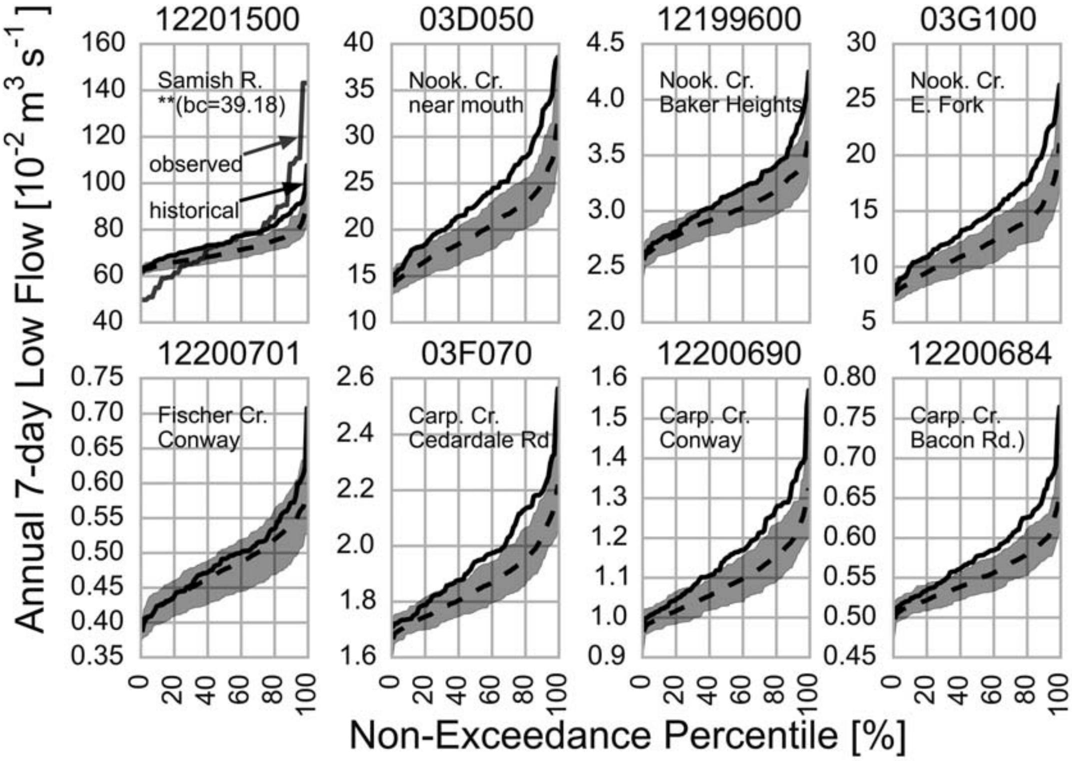

Figure 6. Historical vs. projected future CDFs of 7dELFs for selected streamflow locations. The simulated values for the Samish R. are shifted upwards by 39.18 x 10^{-2} m^3 s^{-1} to remove the bias in the mean in the historical simulations.

which effectively delay recharge to groundwater and the associated streamflow response in the early fall. For the lowest group of 7dELFs (rank 1–20 of 90 simulated years), the shift in the ensemble mean for the date of the 7dELFs is only a few days later, and Carpenter Creek (Hill Ditch) and Fischer Creek show essentially no change in timing for the ensemble mean. For medium 7dELFs (rank 36–55 of 90) the shift is on the order of a week later for all but Carpenter Creek, which shifts by only a few days (Figure 8). The highest 7dELFs (rank 71–90 of 90), show small shifts of a few days towards later dates (Figure 8). Changes for individual ensemble members, however, show that larger shifts are possible, particularly for Nookachamps Creek and the Samish River.

Although there is not a strong consensus in the individual scenarios regarding the direction of change, timing shifts toward later dates are typically larger than shifts toward earlier dates. Correspondingly, the ensemble mean low-flow timing shifts towards later dates in most cases. The results are similar in character for the other streamflow sites—uncertain direction of change when individual GCM projections are examined, but generally larger shifts towards later low-flow timing.

The changes in timing for the medium 7dELFs (Figure 8, rank 36–55 of 90) are clearer and more robust. For the Samish River, for example, all but two scenarios show later timing, six of ten scenarios show timing about two weeks later than their historical counterparts, and the two remaining scenarios show relatively small shifts on the order of 4–7 days earlier. The results are qualitatively similar for the other river sites.

The scatter plot by rank grouping (Figure 9) shows the relative change in the 7dELF as a function of the magnitude (rank) of the 7dELFs. For the Samish River, the percent decrease in 7dELFs increases in absolute value with the magnitude of 7dELFs (Figure 9). One hypothesis explaining this

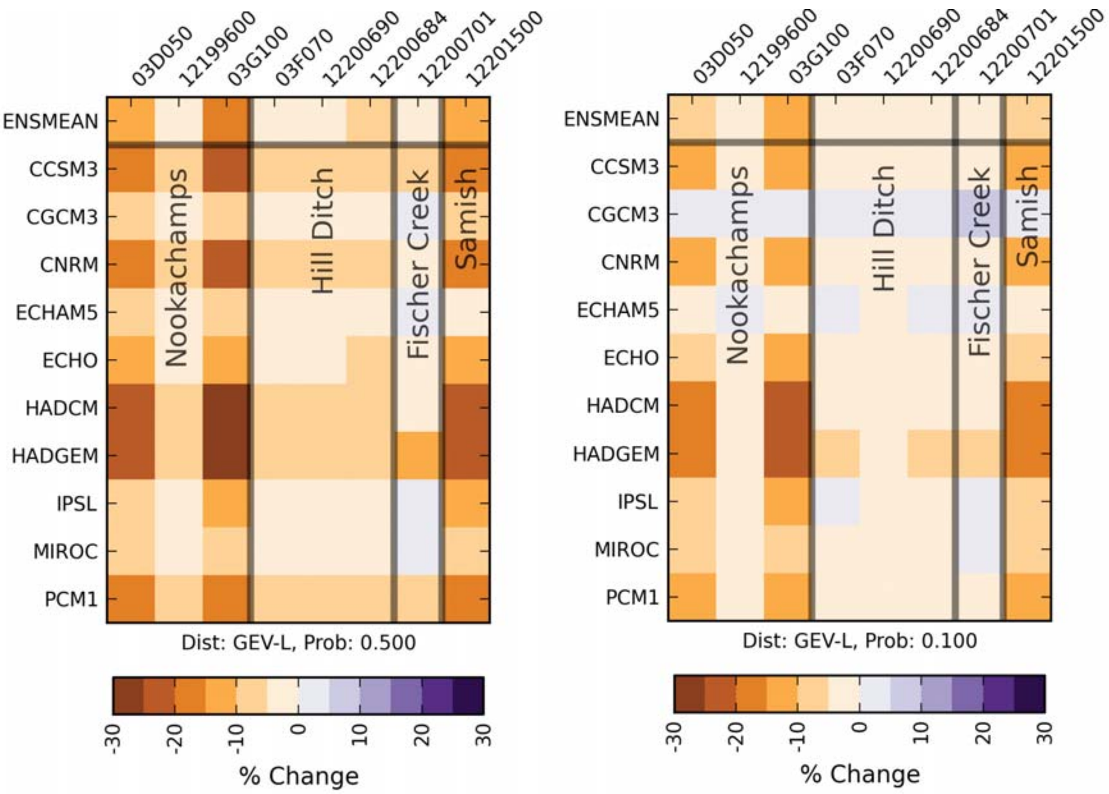

Figure 7. Percent changes in 7Q2 (left panel) and 7Q10 (right panel) for four tributaries. Negative quantities indicate a reduction in the magnitude of 7Q2 or 7Q10 in the 2040s simulations relative to historical baselines. Ensemble mean changes are shown in the first row, with results for individual ensemble members associated with each GCM scenario shown below.

relationship is that the most extreme low flows are associated with the driest summers, for which reductions in summer precipitation in the future scenarios have relatively little effect. For relatively large 7dELFs, caused by wetter conditions in late summer, projected reductions in summer precipitation have a more pronounced effect.

Discussion

Projected climate change for the 2040s will generally result in increased flow in cool season (Nov–Mar) and decreased flow in warm season (April–Oct) in the Skagit lowland tributaries included in this study. These effects are similar to those projected for many other rain-dominated and mixed rain and snow basins in the PNW in past hydrologic modeling studies.

Extreme low-flow regimes for tributaries in the Skagit lowlands are not projected to be radically different from historical baselines, but show systematically reduced 7dELFs and a tendency towards low flows occurring later in the year for the ensemble averages. Ensemble mean 7Q2 and 7Q10 values are projected to decrease by 5% to 20% for different streamflow locations. Changes in the Nookachamps Creek and the Samish River (-5 to -20%) are generally more pronounced than Carpenter Creek (Hill Ditch) and Fischer Creek watersheds (~ -5%), possibly because of more snow accumulation in Nookachamps Creek and the Samish River, and the systematic loss of this storage mechanism in the future scenarios. The relative decreases in 7Q2 (-10 to -20%) are also generally larger than the changes in 7Q10 (-5 to -15%) for the Samish and Nookachamps.

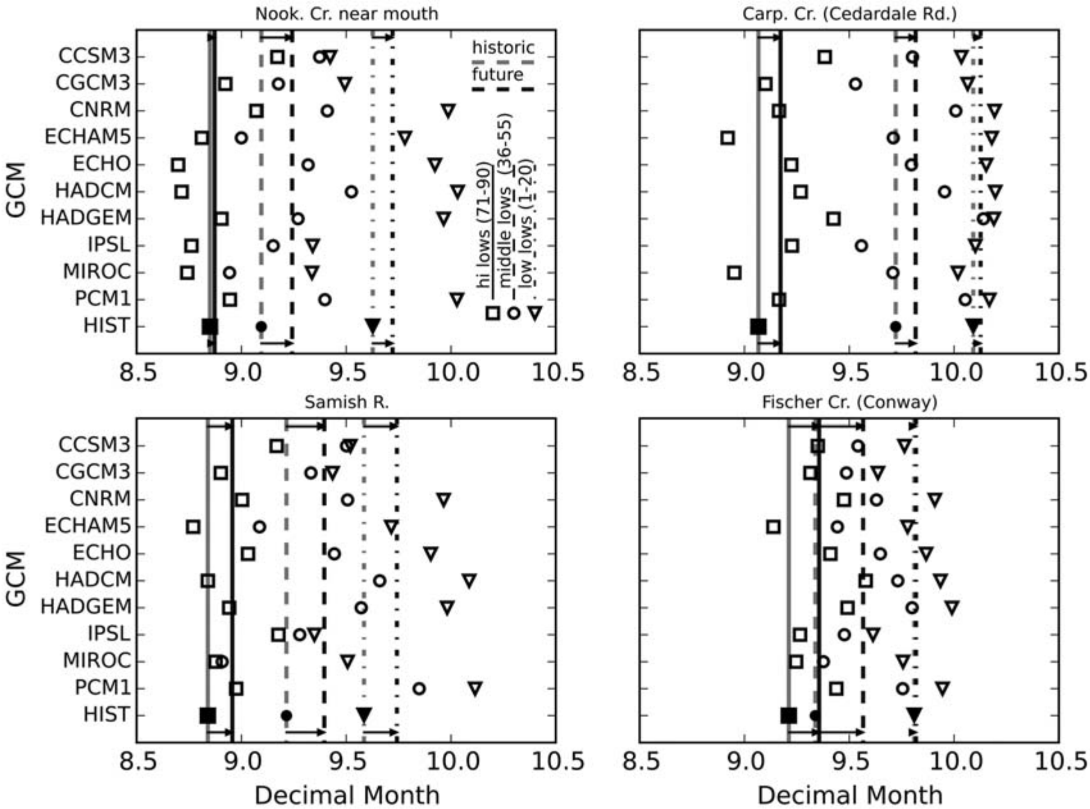

Figure 8. Changes in seasonal timing of 7dELFs for four selected streamflow locations. Open square symbols show the average timing of the lowest 7dELFs (rank 1-20), open circles show the medium 7dELFs (rank 36-55), and open triangles show the highest 7dELFs (rank 71-90). The arrows show the shift in the timing of 7dELFs between the simulated base case and ensemble mean for each of the three rank groupings.

As discussed above, the relative importance of reductions in summer precipitation on 7Q2 and 7Q10 likely explains this difference in response.

The average timing of extreme low-flows for historical baselines varies from early September to late September for different streamflow sites. In response to projected climate change for the 2040s, the average timing of extreme low-flows is projected to shift later in the calendar year by a few days to a week (varies with site and intensity of low-flows). For the most extreme 7dELF (rank 1–20 of 90), the direction of change is uncertain, with about equal numbers of scenarios showing earlier and later low-flow timing, although there is some tendency for larger shifts towards later dates. Changes in the timing of medium 7dELFs (rank 36–55 of 90) are projected to be larger (~ 1 week later) and the results are more robust, with the majority of ensemble members pointing to substantially later low-flow timing.

Even though the onset of fall rains is unaltered in the Hybrid Delta climate change scenarios (only the magnitude of the monthly precipitation means is altered), our results suggest that changes in the timing of the onset of fall rains (usually in early October in the historical baseline simulations) may also be an important determinant of the low-flow timing in the future. That is, if the fall rains come systematically earlier or later in the future, we would expect the low-flow timing to move earlier or later in fall, respectively. Dynamical downscaling approaches (e.g. Salathe et al. 2014) could be used to explore this issue in future work.

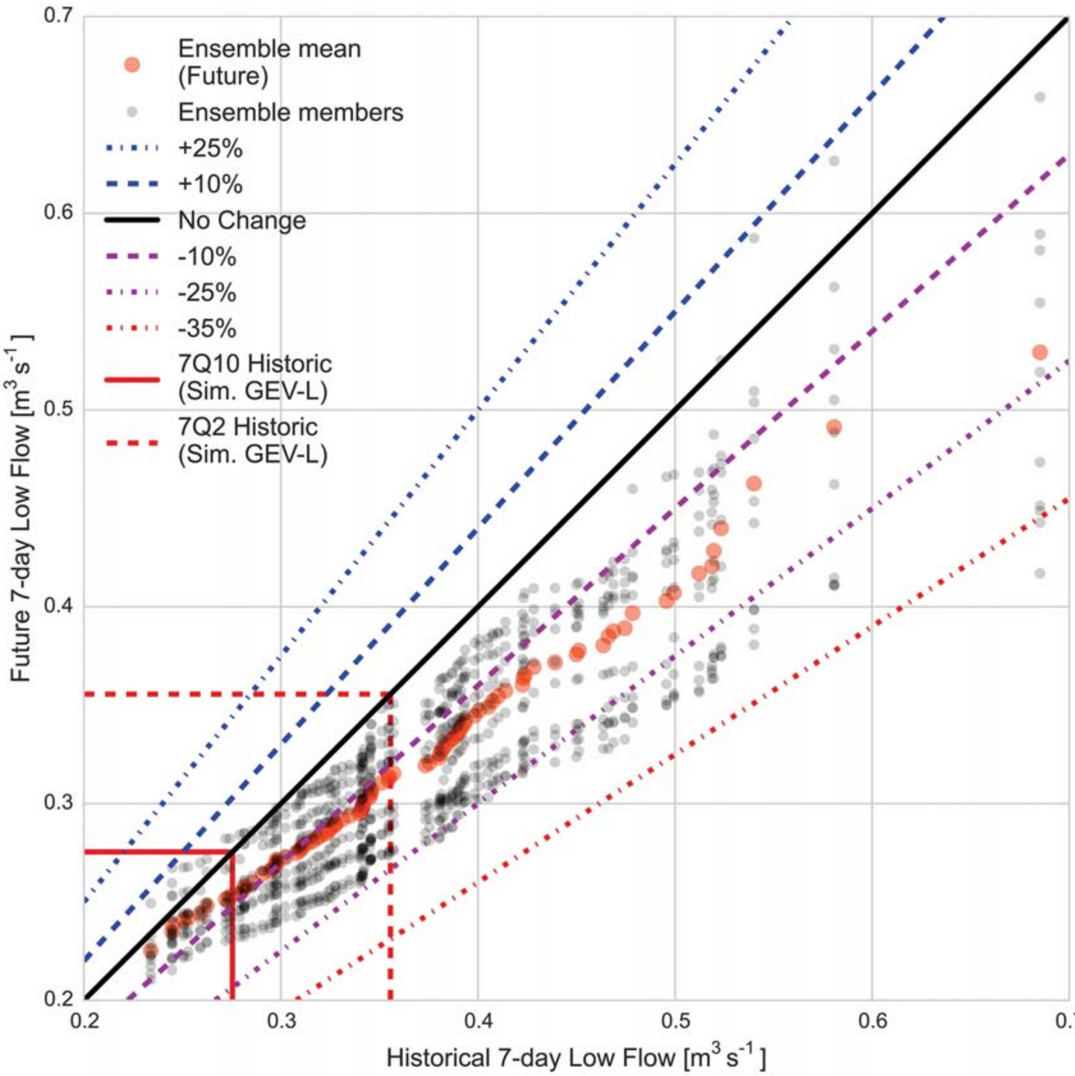

Figure 9. Scatter plot of historical and future 7dELF arranged as x-y pairs (x = base case 7dELF, y = projected future 7dELF) according to rank position in the data set. For each rank position there are 10 x-y pairs, each corresponding to one GCM scenario.

Acknowledgments

This project has been funded wholly or in part by the United States Environmental Protection Agency under an agreement with the Swinomish Indian Tribal Community. The contents of this document do not necessarily reflect the views and policies of the Environmental Protection Agency.

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Received 02 January 2015

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