Future Sea Level, Streamflow and Stream Temperature Projections for the Squaxin Island Tribe

CLIMATE IMPACTS GROUP

GUILLAUME MAUGER

JASON WON

MATT ROGERS

CANDACE PENN

ERICA MARBET

Dec 2023

EARTHLAB
UNIVERSITY of WASHINGTON

PHOTO CREDIT: Erica Marbet, Squaxin Island Tribe

ACKNOWLEDGEMENTS:

This study was funded by the Squaxin Island Tribe through grants from the Bureau of Indian Affairs (BIA) and the Northwest Climate Adaptation Science Center (CASC). Data collection by the Squaxin Island Tribe was the foundation for this work, including streamflow, stream temperature, and survey elevations. The authors would also like to thank Kevin Hanson at Kitsap County for his help identifying and obtaining streamflow and stream temperature observations, and the Mason Conservation District for their work to obtain the survey elevations used in the sea level rise analysis.

CITATION:

Mauger, G.S., J. S. Won, M. Rogers, C. Penn, E. Marbet (2023). Future Sea Level, Streamflow and Stream Temperature on Salmon-Bearing Streams of the Squaxin Island Tribe. Report prepared for the Squaxin Island Tribe. Climate Impacts Group, University of Washington. http://dx.doi.org/10.6069/camm-gk20

Table of Contents

Section 1: Administrative Information

Award Recipient: Guillaume Mauger, gmauger@uw.edu, (206) 685-0317

Agency/Institution: Climate Impacts Group, University of Washington

Project title: Future Sea Level, Streamflow and Stream Temperature on Salmon-Bearing Streams of the Squaxin Island Tribe

Agreement number: G21AC10711-00

Date of the report: January 13, 2024

Period of time covered by the report: 09/01/2021-08/31/2023

Actual total cost of the project: CASC funding: $79,934.48; BIA funding: $30,030.92

Section 2: Public Summary

The purpose of this study was to produce localized sea level rise, streamflow, and stream temperature projections for use by the Squaxin Island Tribe. The Tribe is concerned about climate change impacts on salmon resources in Totten and Little Skookum Inlets, home to numerous salmon bearing streams. In addition, the Tribe's headquarters, many residences, and other important infrastructure are located at relatively low elevations near Skookum Inlet, and could be at risk of flooding due to sea level rise. We quantified future extreme coastal water levels, accounting for both sea level rise and storm surge, to evaluate how often areas of interest to the tribe may be at risk of flooding in the future. To assess potential impacts on salmon, we modeled current and future streamflow for two key watersheds of interest to the Squaxin Island Tribe: Skookum and Kennedy Creeks. We also modeled current and future water temperature in Skookum Creek.

We find that sea level rise is projected to dramatically increase the frequency of inundation during storm surge events (Tables 10 and 11). For streamflow, we find modest increases in winter flows, but more substantial increases for peak flows and decreases for low flows, with implications for salmon (Tables 12-14). Water temperatures are projected to warm, with our model projecting increases of over 4ºC in summer, on average, by the 2080s. We recommend further analysis and/or refinement of the low flow and stream temperature results, since these can be quite sensitive to modeling uncertainties.

Section 3: Project Summary

The purpose of this project was to provide technical analyses in support of climate resilience planning by the Squaxin Island Tribe (SIT). Specifically, we assessed changes in sea level, streamflow, and stream temperature, which can affect salmon, infrastructure, and other key priorities of the Tribe. Prior to this study, no fine-scale hydrologic or stream temperature modeling had been conducted for any of the creeks of interest to the Squaxin Island Tribe.

The Tribe's headquarters, many residences, and other important infrastructure are located at relatively low elevations near Skookum Inlet, and could be at risk of flooding due to sea level rise. We quantified future extreme coastal water levels, accounting for both sea level rise and storm surge, to evaluate changes in the frequency at which coastal water levels exceed key elevations of interest to the Tribe. Specifically, we combined long-term tidal observations from Seattle with tidal predictions for the Arcadia, which is closer to Little Skookum Inlet, where most of the Tribe's interests are located. Using projected sea level rise from Miller et al. (2018), we assessed the current and future frequency of exceedances.

We find that sea level rise is projected to dramatically increase the frequency of inundation during storm surge events. Although many of the elevations surveyed by the Squaxin Island Tribe are beyond the reach of sea level extremes, now and in the future, many others are either currently at risk of flooding or will be at risk in the future due to sea level rise. Our analysis confirms that even small amounts of sea level rise can lead to large changes in the frequency of flooding. This is due to the relatively small differences between extreme event magnitudes in Puget Sound: for example, we estimate that the 100-year event at Arcadia is just over 14 inches higher than the 2-year event. This means that a sea level rise of just 14 inches, which all studies agree is highly likely over the coming decades, would result in a 50-fold increase in the frequency of today's 100-year flood event.

Prior to this study, no fine-scale hydrologic or stream temperature modeling had been conducted for any of these creeks. Most climate and hydrologic projections for the region (e.g. Hamlet et al. 2013, Chegwidden et al. 2019) have been done at a scale that is too coarse for small creeks, and none have included the dynamically-based approach to "downscaling" coarse-scale global model projections, which recent research shows is needed to properly capture changes in precipitation extremes (Salathé et al. 2014). We addressed each of these limitations in our modeling of streamflow changes for two key watersheds of interest to the Squaxin Island Tribe: Skookum and Kennedy Creeks. We also modeled current and future water temperature in Skookum Creek. This work builds off of a recent BIA grant to the Suquamish tribe, separate from the current project, in which a similar approach was applied to the Chico Creek watershed (Mauger et al. 2021a).

Our streamflow results project modest increases in winter flows (4 to 14%, on average, for the 2080s; Table 9), larger increases in peak flows (13 to 31%, on average, for the 2080s; Table 10), and notable decreases in low flows (-9 to -20%, on average, for the 2080s; Table 11). The water temperature projections reflect the combined effects of decreased streamflow and higher air temperatures, showing increases of over 4ºC in summer, on average, by the 2080s. As with the low flows, this translates to many more days above 16ºC, the Washington State water temperature standard for protecting salmonids, and an increasing prevalence of days above 22ºC. These new projections represent a significant improvement over the results that were previously available for Skookum and Kennedy Creeks. Prior work involved modeling that was much too coarse for small creeks, was based on statistical downscaling which does not adequately represent changes in precipitation extremes, was not calibrated for these locations, and only provided daily streamflow and monthly average water temperature projections. The current modeling addresses each of these limitations, and is calibrated specifically to the Skookum and Kennedy Creek watersheds. Nonetheless, model limitations are important to consider when evaluating these results. We recommend further analysis, and possibly refining the model calibrations, to further ensure the accuracy in these projections. In particular, we found that calibration of the stream temperature model was difficult, and should be revisited to ensure the projections are sufficiently accurate. Similarly, low flows are difficult to model and could be sensitive to small discrepancies between the observations and the model.

We recommend three general approaches for building on the technical findings of this work. First, as noted above, we recommend additional analyses to further validate and/or refine the low flow and stream temperature results. This could involve revisiting the model calibrations. In parallel with these efforts, it would be helpful to develop independent estimates of impacts, for example by using observations of notable past events as analogs for future conditions.

Second, we recommend building on the sea level rise and streamflow modeling to evaluate the future depth and extent of flooding in Skookum Creek. Our modeling provides the volume of streamflow during flood events, and the height of extreme water levels in Little Skookum Inlet, but does not model the depth and extent of flooding associated with these events. This could be important for identifying areas at risk of flooding due to peak flow events, or as a result of the combined effects of sea level rise and peak flows on Skookum Creek. In addition, such maps can be a helpful communications tool since the results are much easier to intuit than what we are able to provide here.

Finally, we recommend additional work to understand the Tribe's vulnerability to these impacts. Specifically: the current assessment has been primarily focused on the exposure to climate change – how sea level, streamflow, and water temperature are projected to change in the future. To assess climate vulnerability, two other pieces of information are needed: (1) the "sensitivity" to these changes – how impacts scale with future changes, and (2) the "adaptive capacity" – how can people and ecosystems respond to and recover from these impacts. Work to better understand these complementary aspects of vulnerability would help clarify if and when the current projections pose a problem, and also if additional refinement of the projections is necessary.

Section 4: Report Body

Purpose and Objectives

The Squaxin Island Tribe (SIT) is descended from maritime people who have lived and prospered along the shores of the southernmost inlets of the Salish Sea for millennia. Squaxin leaders signed the Medicine Creek Treaty with the U.S. Government in 1854, reserving the right to hunt, gather and fish at all usual and accustomed places. Tribal members continue to this day to exercise their Treaty rights for subsistence, ceremonial and commercial purposes. The federal government maintains a trust responsibility for Tribal interests.

The Tribe is concerned about climate change impacts on salmon resources in Totten and Little Skookum Inlets, home to numerous salmon bearing streams (Figure 1). Primary salmonid species in these watersheds are chum salmon, coho salmon, and cutthroat trout. Other species are detected on occasion. Coho are the most sensitive to elevated temperatures, and they are also in decline relative to chum and cutthroat. In Skookum Creek, for example, coho are not detected in the lower mainstem in summer. Though the peak of Coho and Chum and coho spawning occurs in October and November respectively, the first arrivals trickle in as early as late September (Kuntz 2021). Extensive habitat studies of cutthroat trout spawning habitat indicate optimal stream conditions for spawning, and those are dependent on a certain streamflow regime (Boessow et al. 2020). Hydrologic changes brought on by climate change could affect spawning conditions for cutthroat by changing the frequency of occurrence of optimum flows in February through June.

Salmon are a cultural and subsistence resource that is traditionally gathered by the Squaxin Island Tribe. Given the potential for climate change to exacerbate existing threats on salmon populations, there is a need to quantify climate change impacts in order to plan restoration and conservation efforts accordingly.

Puget Sound lowland streams are commonly fed by groundwater from extensive layers of glacial sediments. In both Kennedy and Skookum Creeks, the valley bottoms have thinner layers of more recent glacial and alluvial sediments. However, the two creeks differ in that their headwaters and tributaries come from basalt foothills. As a result, their hydrologic characteristics differ greatly: storm peak lag time, peak magnitude, runoff ratio, baseflow, and low flows all differ from watersheds with more groundwater. Of primary interest is the scant cold late-summer baseflow that would normally sustain juvenile coho in other creeks but is much less abundant in Skookum and Kennedy Creek, making them more vulnerable to climate change than other Puget lowland streams.

Prior to this study, no fine-scale hydrologic or stream temperature modeling had been conducted for any of these creeks. Most climate and hydrologic projections for the region (e.g. Hamlet et al. 2013, Chegwidden et al. 2019) have been done at a scale that is too coarse for small creeks, and none have included the dynamically-based approach to "downscaling" coarse-scale global model projections, which recent research shows is needed to properly capture changes in precipitation extremes (Salathé et al. 2014).

A primary focus of this work was to develop high resolution hydrologic model projections for two key watersheds of interest to the Squaxin Island Tribe: Skookum and Kennedy Creeks. We also modeled current and future water temperature in Skookum Creek. This work builds off of a recent BIA grant to the Suquamish Tribe, separate from the current

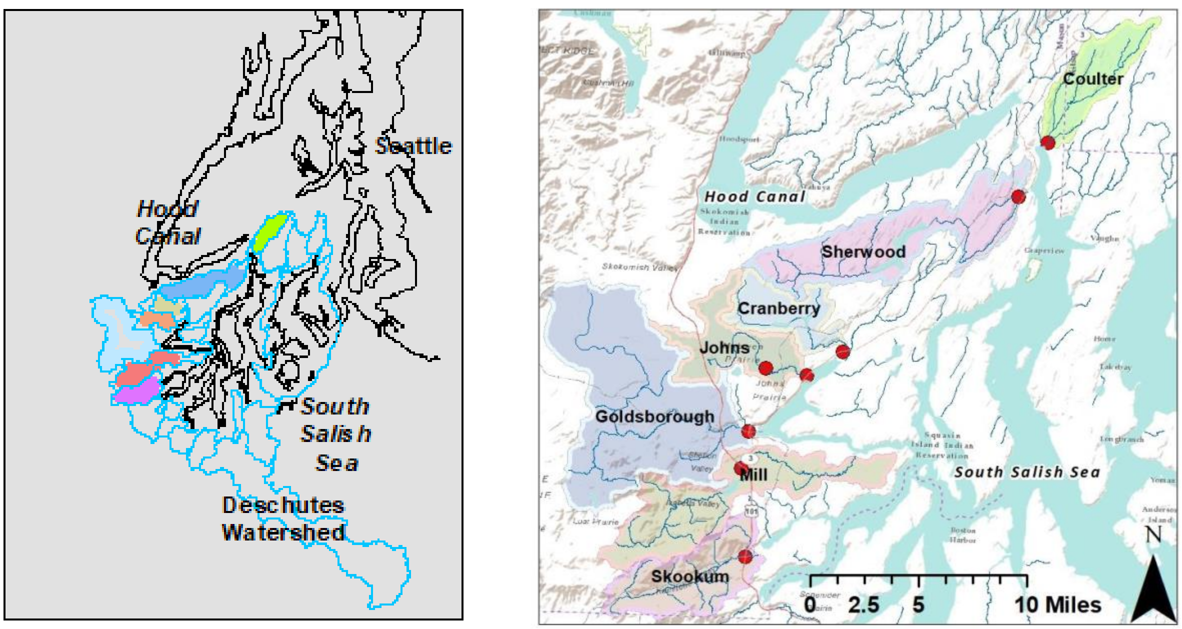

Figure 1. Regions of interest to the Squaxin Island Tribe. The left-hand map shows the Squaxin Fishing Usual and Accustomed Area outlined in blue; these watersheds drain to the seven southern inlets of the South Salish Sea. The highlighted watersheds are shown in more detail in the right-hand map. The Tribe maintains streamflow gauging stations in each of these watersheds and funds USGS to maintain the Goldsborough station, with annual 30% matching from USGS. Kennedy Creek is located just south of Skookum Creek.

project, in which a similar approach was applied to the Chico Creek watershed (Mauger et al. 2021a).

Another concern of the Tribe is sea level rise. The Tribe's headquarters, many residences, and other important infrastructure are located at relatively low elevations near Skookum Inlet, and could be at risk of flooding due to sea level rise. We quantified future extreme coastal water levels, accounting for both sea level rise and storm surge, to evaluate changes in the frequency of coastal floods.

Organization and Approach

Sea Level Rise

Observations

Table 1 lists the water level observations used for the sea level rise analysis. The predictions for Arcadia included only the timing and elevation of high and low tides. For Seattle, we obtained hourly water level observations for the full record of available data. All estimates were obtained relative to the average minimum daily tide (Mean Lower Low Water, or MLLW).

Table 1. Tide gauge data used in this study.

Station	ID	Source	Lat. / Lon.	Notes
Arcadia, Totten Inlet, WA	9446666	NOAA	47.1967N / 122.9383W	Predictions Only
Seattle, WA	9447130	NOAA	47.6033N / 123.3400W	Observations: 1899-Present

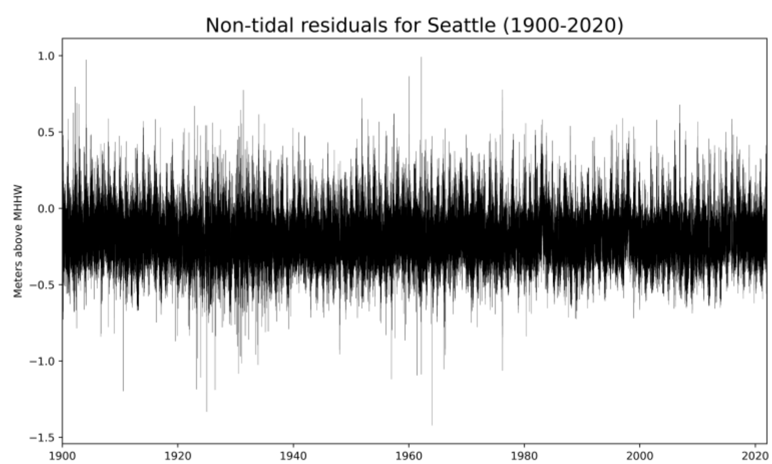

Figure 2. Non-tidal residuals, after detrending, for the Seattle tide gauge.

In order to estimate extreme water levels for Arcadia, we combined the observations from Seattle with the predictions at Arcadia. First, we created the non-tidal residual (NTR) time series for Seattle. To do this, we subtracted the Seattle tidal predictions from the water level observations to arrive at an hourly time series of anomalies relative to the tidal predictions. One outlier was found in the Seattle observations, on 09/02/1916 at 17:00 GMT; this data point was excluded from the analysis. Since past sea level rise trends may have been different for Seattle and Arcadia, we removed the linear trend (estimated at 2.08 mm/yr, on average). The detrended NTR time series for Seattle is shown in Figure 2.

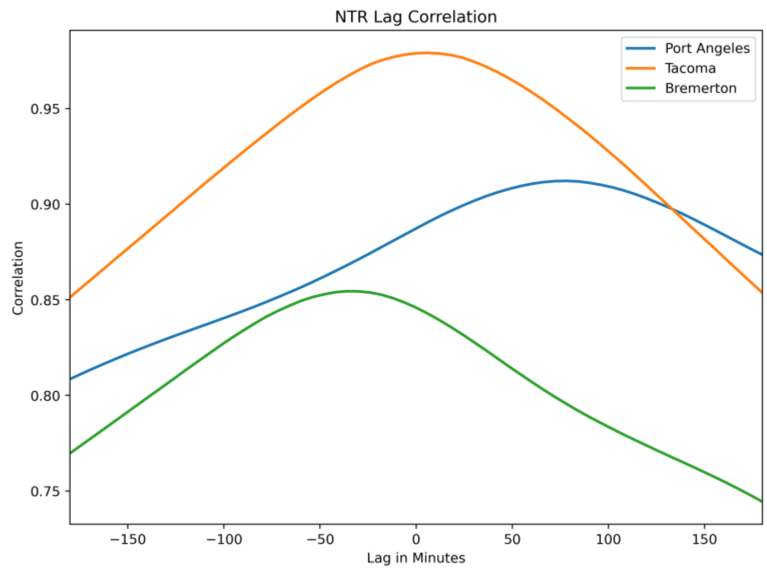

Figure 3. Lag correlations between non-tidal residuals at Seattle and the Port Angeles, Tacoma, and Bremerton tide gauges.

Next, we estimated the lag between tidal anomalies occurring in Seattle and at Arcadia. Since there are no tidal observations at Arcadia, we used other gauges at a range of distances west of the Seattle gauge. Specifically, we compared the NTR time series at Port Angeles, Tacoma, and Bremerton with the NTR time series at Seattle for the duration of the overlapping records to get a sense of how fast the anomalies travel through Puget Sound (Figure 3). The onset of the anomalies for these locations relative to Seattle suggests that the anomalies at Seattle lag the anomalies at Port Angeles by about 80 minutes, at Tacoma by about 6 minutes, and precede the anomalies at Bremerton by about 36 minutes.

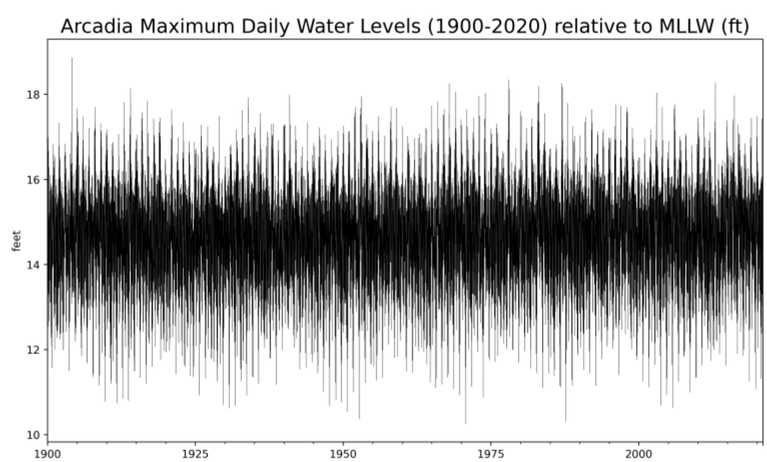

Figure 4. Reconstructed time series for maximum daily water levels (Mean Higher High Water, or MHHW) for Arcadia.

The results for Bremerton are likely the most relevant to Arcadia; since Arcadia is west of Bremerton, we assume a events at Arcadia precede those in Seattle by 30-60 minutes. Since our tidal data has a temporal resolution of one hour, we approximated this as a one hour lead on the Seattle NTR time series. We then added the lagged NTR values at Seattle to the maximum daily predicted tide (so-called "Mean Higher High Water", or MHHW) time series at Arcadia, according to the timing given for high tides in the predictions. The long-term trend in sea level was also removed from the tidal predictions, so that current and future extreme water level statistics could be evaluated as a snapshot in time. The result is a reconstructed time series in MHHW for the Arcadia tide gauge (Figure 4).

Finally, we note that this approach assumes that the highest daily water levels occur during high tide. It is conceivable, however, that large NTRs could result in a high water level at some other time than the peak in high tide. Although we do not anticipate this being a large source of error, future work could explore the implications of this assumption by developing hourly predictions for Arcadia.

Sea Level Rise Projections

We used the sea level rise projections from Miller et al. 2018 because they provide the most detailed estimates of sea level rise for Washington State. Separate projections are provided for each 10 km segment of Washington's coastline; we used the results for the segment encompassing the Arcadia tide gauge. The projections are probabilistic; we used the 99%, 50%, and 1% probabilities (low, median, high) in our analysis. Finally, based on consultation with our collaborators at the Squaxin Island Tribe (Erica Marbet and Candace Penn, personal communication), we used the results for the high-end (RCP 8.5) greenhouse gas scenario. This scenario is also consistent with the hydrologic projections described in the next section.

Analysis

Our collaborators at the Squaxin Island Tribe provided survey elevations, obtained in partnership with the Mason Conservation District, for 94 locations of interest to the Tribe (Erica Marbet and Candace Penn, personal communication). Using the reconstructed water level time series at Arcadia and the desired sea level rise scenarios, we assessed current and future risks in two ways:

1. Average number of days per year when MHHW at Arcadia exceeds prescribed elevations, and

2. Current and future return intervals at the same prescribed elevations.

For the first analysis, we added the relative amount of sea level rise for each scenario to the reconstructed water level time series at Arcadia. For each water level threshold supplied to us, we then determined the average number of days per year over that threshold in the record for each probability (99%, 50%, and 1%), scenario (RCP 8.5), and time period (2050 and 2100). The result is an estimate of future days per year in which the water level will exceed that threshold.

For the second analysis, we fit a generalized extreme value (GEV) distribution to the maximum yearly water levels obtained from the reconstructed water level time series at Arcadia. The GeV fit is performed using L-moments. Using the fit we can determine the return interval for any of the surveyed elevations obtained from the Squaxin Island Tribe. For each sea level rise projection, we then add the projected change to the CDF and determine the new return interval for each of the same elevations. Because of accuracy concerns, we do not report return intervals shorter than a 1.5-year event or larger than a 150-year event.

Streamflow and Stream Temperature

Observations

Table 2. Observations used in the streamflow and stream temperature modeling.

	Station	Source	Lat. / Lon.	Years
Precip.	Sanderson Field	Squaxin IT	47.2384N / 123.1415W	1932-2013
Streamflow	Skookum Creek	Squaxin IT	47.12596N / 123.10015W	2004-2020
	Mill Creek	Squaxin IT	47.19305N / 123.09886W	2004-2020
	Kennedy Creek (ID: 12078400)	USGS	47.07694N / 123.12583W	1960-1971
	Kennedy Creek	Thurston Co.	47.09507N / 123.09135W	1984-2017 (monthly)
Water Temp	Skookum Creek	Squaxin IT	47.12596N / 123.10015W	2003-2020
	Kennedy Creek at Old Olympic Hwy	Thurston Co.	47.09506N / 123.09135W	1984-2021

All relevant observations are listed in Table 2. Daily streamflow observations for Kennedy Creek are only available for 1960-1971, before the beginning of our historical dataset, and the other observations at Skookum Creek are made manually, on a monthly basis. As a result, neither of the direct observations for Kennedy Creek can be used for calibration. We explored several approaches to developing a proxy dataset for flows on Kennedy Creek. Specifically:

1. Using a multi-linear regression using precipitation from the Sanderson Field weather station, and
2. By scaling observed flows from adjacent creeks.

The multiple linear regressions used the previous day's precipitation, the total precipitation from the previous 2 weeks, the total precipitation from the previous 90 days, and a constant. We performed regressions using precipitation measurements directly as well as with log-transformed precipitation. Neither approach was able to adequately reproduce the time series of observed flows at Kennedy Creek.

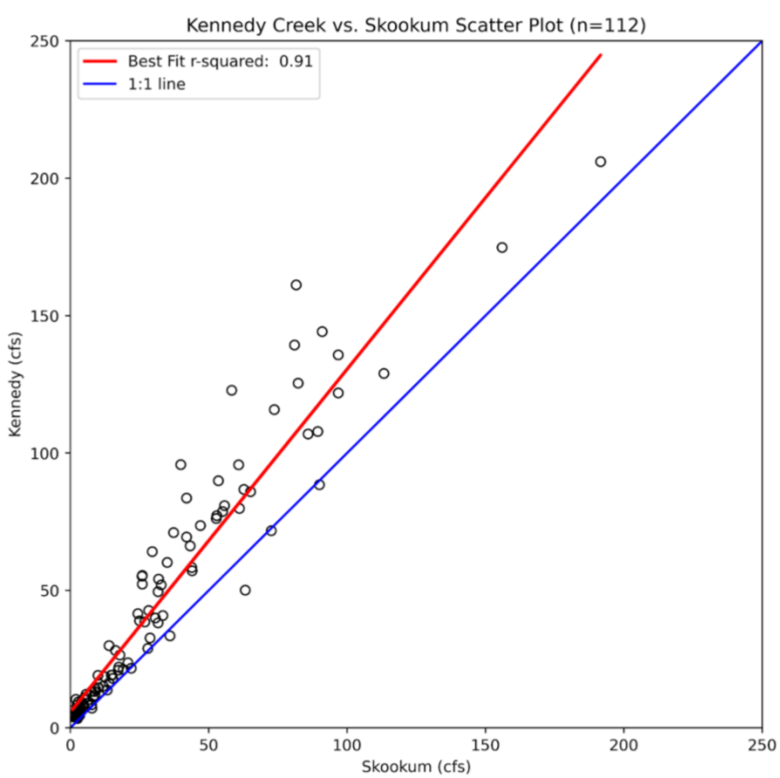

Figure 5. Comparison between observed flows on Skookum Creek (x-axis) and Kennedy Creek (circles). The red line shows the linear regression (slope=1.2477), the blue line is the 1:1 line.

In the second approach we used the flows obtained by Thurston County in their monthly site visits, associating those observations with Skookum Creek observations on the same days. Figure 5 shows the results from a linear regression using all available simultaneous daily data for Kennedy Creek and Skookum Creek. Flows on Skookum Creek and Kennedy Creek are highly correlated (r^2=0.91), suggesting that a linear regression could be used to estimate flows on Kennedy Creek based on observed flows in Skookum Creek. The ratio of the areas of the Kennedy Creek watershed to the Skookum Creek watershed is 0.994, whereas the linear fit shows that flows on Kennedy are larger (Figure 5). A result we used the slope of the linear regression to scale the Skookum Creek flows.

The results from the linear regression approach are shown in Figure 6. The figure compares scaled flows from Skookum, using the slope of the linear regression, with the observed Kennedy Creek flows from Thurston County. These show that the scaled Skookum flows tend to be biased high for low flows but otherwise show no systematic bias for higher flows.

Figure 7 shows a hydrograph comparison between observed flows at Kennedy Creek and two different scalings applied to flows at Skookum Creek – one using the slope of the linear

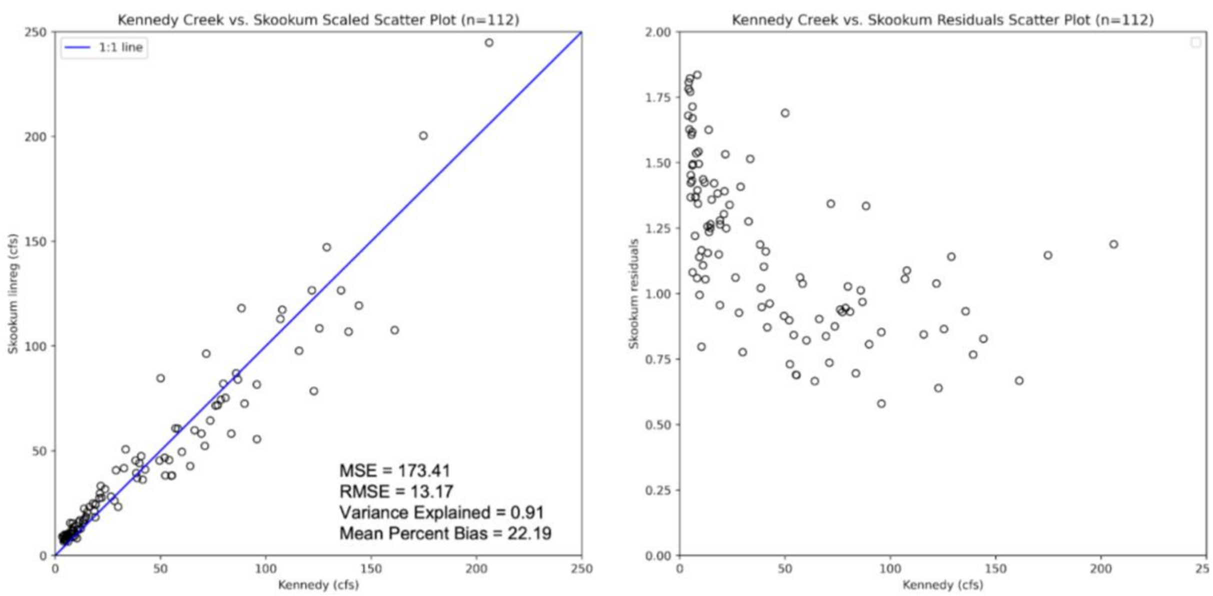

Figure 6. Left: Scatter plot comparing observed daily Kennedy creek flow (x-axis) with scaled flows from Skookum Creek based on the linear regression (slope=1.2477). Right: Scatter plot of the ratio of scaled Skookum flows to observed flows on Kennedy Creek.

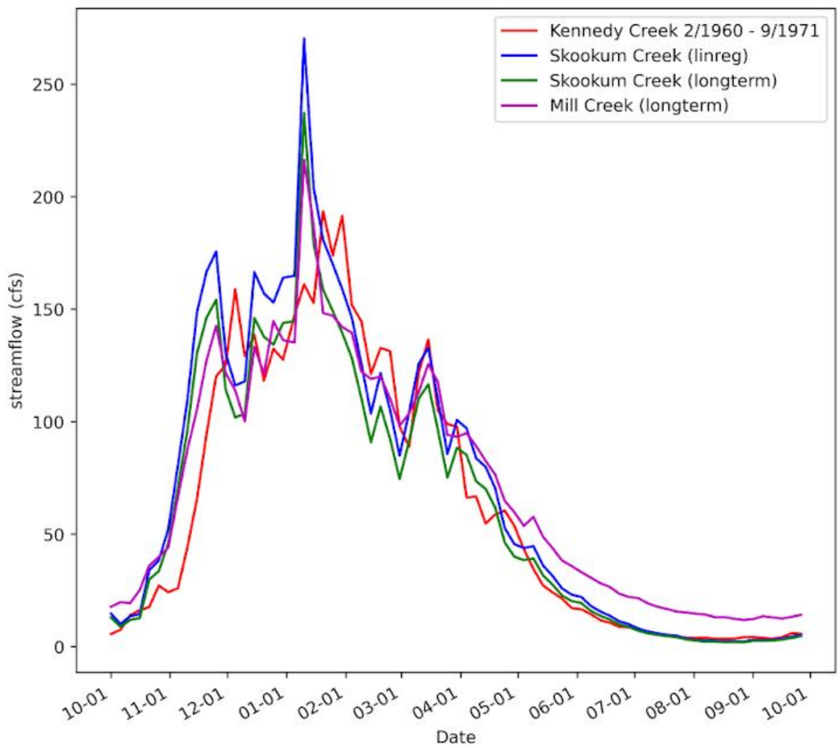

Figure 7. Comparing the annual hydrograph of streamflow for observed (red) and estimated flows on Kennedy Creek. Plot shows the average flows, by pentad (i.e., 5-day averages), for the water year (Oct 1 – Sep 30). Plot includes Skookum flows scaled by the linear regression (blue), by the ratio of annual flows (green), and the latter approach applied using observed flows in Mill Creek.

regression and another using the ratio of annual average flow between Kennedy and Skookum Creeks – and scaled flows at Mill Creek using the ratio of annual average flows between Kennedy and Mill Creeks. The scaled flows from Mill Creek do not track with Kennedy flows well, specifically showing larger magnitude flows in summer and fall. Both of the scalings compare well with the observations; we chose to use the linear regression approach for the current work.

We note that none of the comparisons in Figure 7 are perfect. Part of the disagreement between these estimates is likely a result of climate variability. To investigate this, we compared yearly total accumulated precipitation at Sanderson Field from October 1st to November 1st for 1960-1971 and 2004-2018. We chose these date ranges to overlap with the Kennedy and Skookum Creek flow observations, respectively. We found that the mean total accumulated precipitation at Sanderson field for the more recent time period (2004-2018) was about 31% larger than the historical mean (or about 1.75 inches more, on average). This suggests that the fall rainy season consistently began earlier and/or included more total precipitation in the more recent time period compared to the historical time period. This likely explains the difference in the onset of high fall streamflow between Kennedy Creek and Skookum Creek seen in Figure 7.

Climate Data

This section describes the “downscaled” global climate model (GCM) projections used in the current study, and how they were validated and bias-corrected for use in the hydrologic modeling. As noted above, recent research has emphasized the need to use regional climate model projections (or “dynamical downscaling”) in order to better quantify changes in extreme precipitation (e.g., Salathé et al. 2014). In this work we made use of existing regional climate model simulations, all performed using the Weather Research and Forecasting model (WRF; Skamarock et al. 2005). Key features of the WRF simulations used in this project are summarized in Table 3; these are described in greater depth in the sections that follow.

Observationally-Based Historical Climate Dataset

Past hydrologic studies have typically used interpolated estimates of daily weather on model grid cells (e.g., Hamlet et al. 2013, Chegwidden et al. 2019). A novel aspect of the current approach is that we use dynamically downscaled historical meteorology, as is done for the climate change simulations. This has a number of advantages. First, we are able to use hourly meteorology as opposed to daily; a significant improvement given that instantaneous flows – the basis for many regulations and design standards – are not well correlated with daily-average flows, whereas the correlation is high for hourly flows. Second, regional models have been shown to better represent spatial variations in weather variables, particularly in complex topography or where observations are sparse. Finally, by using the same regional climate model for both the historical and climate change simulations, we ensure that the hydrologic model is better adapted to our approach for assessing future changes in hydrology.

For this historical dataset we used an implementation of WRF developed by Ruby Leung and colleagues at the Pacific Northwest National Laboratory (PNNL; hereafter, we refer to the historical WRF simulation as “WRF-NARR”). The dataset is produced using WRF version 3.2, with a model domain covering all of the western U.S., at an hourly time step and a spatial resolution of 6 km (Chen et al. 2018). Boundary conditions are taken from the North American Regional Reanalysis (NARR; Mesinger et al. 2006), and the simulation spans the

Table 3. Dynamically-downscaled Weather Research and Forecasting (WRF) model simulations used in the current study.

Name	Type	Source	Bdry. Cond.	# of Sims	Time Step	Spatial Res.	Years
WRF-NARR	Historical	PNNL	NARR	1	1 hr	6 km	1981-2015
WRF-CMIP5	Climate Change	UW Atmos. Sci.	CMIP5 (Table 2)	12	1 hr	12 km	1970-2099

years 1981-2015. Reanalysis datasets are essentially internally-consistent collections of weather observations; they are created by combining massive amounts of environmental observations in a Bayesian model framework that synthesizes them into the best estimate of the atmospheric state for each time step. NARR is produced for North America at a spatial resolution of 32 km.

Future Climate Dataset

A new ensemble of regional climate model projections was recently produced in collaboration with Cliff Mass in UW's department of Atmospheric Sciences (hereafter referred to as "WRF-CMIP5"). GCM projections were obtained from the Climate Model Inter-comparison Project, phase 5 (CMIP5; Taylor et al. 2012). GCMs were primarily selected based on Brewer et al. (2016), who evaluated and ranked global climate models based on their ability to reproduce the climate of the Pacific Northwest. The new ensemble of WRF projections includes one simulation for each of the GCMs listed in Table 4. All of the new projections are based on the high-end Representative Concentration Pathway (RCP) 8.5 scenario (Van Vuuren et al. 2011). Simulations were performed using WRF version 3.2, implemented following Salathé et al. (2010, 2014). The innermost domain, at 12-km resolution, encompasses the U.S. Pacific Northwest. Simulations span the years 1970-2099 at an hourly time step. The model, and model configuration, are described in detail in Lorente-Plazas et al. (2018) and Mass et al. (2022). In addition, Mauger et al. (2019) discuss approaches for using RCP 8.5 projections as an analog for what might be projected for the RCP 4.5 scenario. For example, temperature changes for the 2080s in the RCP 4.5

Table 4. The twelve global climate models (GCMs) used as input to the regional model simulations. Horizontal resolution is given in degrees latitude × degrees longitude; "Vertical Levels" refers to the number of layers in the atmosphere model for each GCM. All simulations are based on the high-end RCP 8.5 greenhouse gas scenario (Van Vuuren et al. 2011).

Model	Center	Resolution	Vertical Levels
ACCESS1-0	Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia/ Bureau of Meteorology, Australia	1.25° × 1.88°	38
ACCESS1-3	Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia/ Bureau of Meteorology, Australia	1.25° × 1.88°	38
bcc-csm1-1	Beijing Climate Center (BCC), China Meteorological Administration	2.8° × 2.8°	26
CanESM2	Canadian Centre for Climate Modeling and Analysis	2.8° × 2.8°	35
CCSM4	National Center of Atmospheric Research (NCAR), USA	1.25° × 0.94°	26
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization (CSIRO) / Queensland Climate Change Centre of Excellence, Australia	1.8° × 1.8°	18
FGOALS-g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	2.8° × 2.8°	26
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory, USA	2.5° × 2.0°	48
GISS-E2-H	NASA Goddard Institute for Space Studies, USA	2.5° × 2.0°	40
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	1.4° × 1.4°	40
MRI-CGCM3	Meteorological Research Institute, Japan	1.1° × 1.1°	48
NorESM1-M	Norwegian Climate Center, Norway	2.5° × 1.9°	26

projections appear to correspond approximately to the projections for the 2040s or 2050s in the RCP 8.5 projections.

Climate Data Bias-Correction

Past experience has shown that the WRF results cannot be used directly in hydrologic modeling because of biases that lead to unrealistic hydrologic results (e.g. Mauger et al. 2021b). In this project we adapted an approach developed by Bandaragoda and Hamlet (personal communication), in which gridded averages of monthly temperature and precipitation from the PRISM dataset (Parameter Regression on Independent Slopes Model, 2022; Daly et al. 2008) are used to adjust the WRF-NARR simulation to develop a baseline correction for use in the hydrologic model. We chose to use PRISM as opposed to individual station comparisons (e.g. Sanderson Field, Kamilche) because it likely includes these data while also accounting for topographic and other effects on the distribution of temperature and precipitation variations.

We developed the monthly adjustments by comparing the area average PRISM and WRF-NARR temperature and precipitation for all grid cells within 15 km of the Skookum and Kennedy Creek watersheds. The result was a set of 12 scalings for each variable (additive for temperature, multiplicative for precipitation). These were applied to all time steps in the WRF-NARR simulations (e.g. all temperature estimates for any time step occurring in January were adjusted by the same amount).

As described below, we applied an additional correction to the precipitation estimates for Kennedy Creek based on comparisons between modeled and observed streamflow. Specifically, we increased the precipitation estimates by 10% for Kennedy Creek. This likely reflects a topographic enhancement of precipitation in Kennedy Creek that is not captured by the WRF model.

Six meteorological variables are required to force the hydrologic model simulations: temperature (°C), relative humidity (%), precipitation (m), wind speed (m/s), incoming shortwave radiation (W/m^2), and incoming longwave radiation (W/m^2). Wind estimates from the model were scaled down by 50%, based on previous comparisons with observations across Washington State (Mauger et al. 2021b). Humidity and shortwave radiation estimates were not bias-corrected. Longwave was estimated using an empirical formulation (Dilly and O'Brien, 1998; Unsworth and Monteith, 1975), which previous research suggests is superior to WRF longwave estimates (Currier et al. 2017).

The WRF-CMIP5 bias-correction involved first interpolating them from their native 12-km grid to the 6 km WRF-NARR grid, using a bi-linear interpolation. We then compared the historical average for each model simulation against the average for the same years (1981-

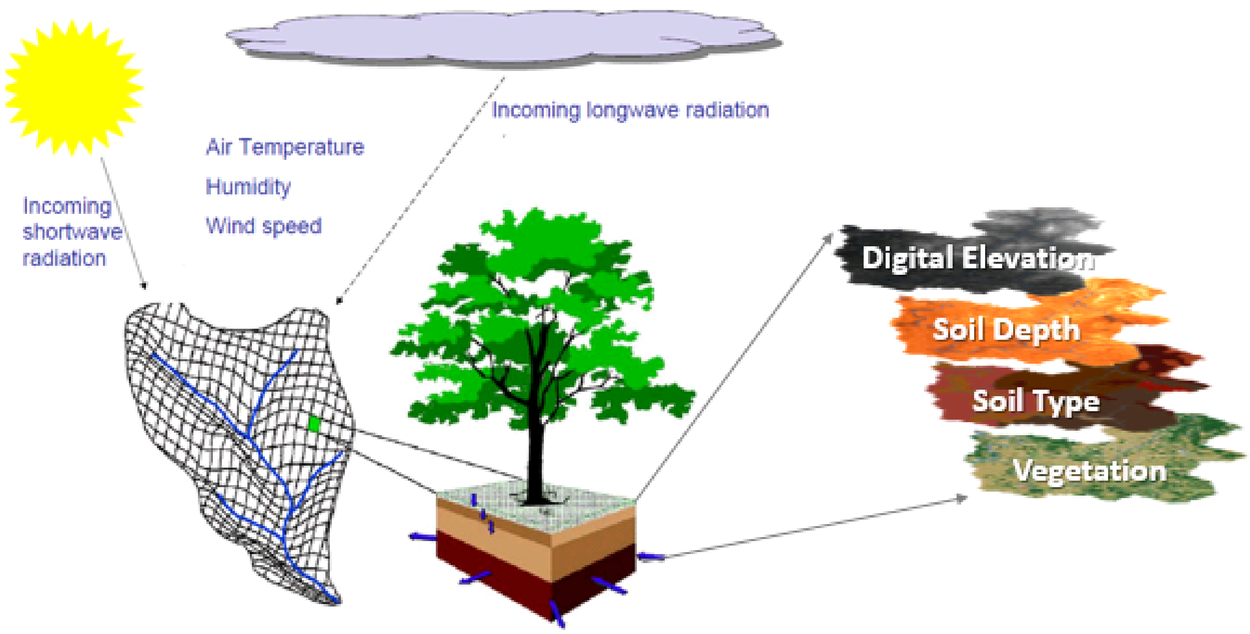

Figure 8. Diagram of DHSVM model and its inputs.

2020) in the bias-corrected WRF-NARR results. This comparison provided monthly bias-correction factors, or scalings, to be applied to each time step in the WRF-CMIP5 simulation, which were then used to create the DHSVM inputs. Different bias-corrections were applied to each climate model projection (Table 4). Longwave was then recomputed using the same empirical formulation described above.

Hydrologic Model

We modeled the hydrology of the two watersheds using the Distributed Hydrology Soil Vegetation Model (DHSVM; Wigmosta et al. 1994). DHSVM is an open-source model maintained by PNNL (http://dhsvm.pnnl.gov/). DHSVM has been widely applied in the mountainous western United States (e.g., Storck et al., 1998, Bowling and Lettenmaier, 2001; Whitaker et al., 2003) and for assessing the impacts of climate change (e.g., Elsner et al. 2010, Vano et al. 2010, Cuo et al. 2011, Cristea et al. 2014, Naz et al. 2014, Murphy and Rossi 2019, 2020, Mauger et al. 2016, Lee et al. 2018, Mauger et al. 2020) and land use (e.g., Sun et al. 2013, Cuo et al. 2009, 2011) on streamflow.

The DHSVM is a physically-based, spatially-distributed hydrological model that accounts for physical processes affecting the distribution of precipitation, partitioning of rain vs. snow, and tracking the movement of water on and through landscapes. As illustrated in Figure 8, the model represents the spatial distribution of evapotranspiration, snow cover, soil infiltration and moisture, and runoff across a watershed in a distributed fashion, requiring model inputs of geographic and climate information (Wigmosta et al. 2002). The model simulates one or more unsaturated soil layers and a saturated bottom layer. Subsurface flow in the saturated zone is based on a quasi-equilibrium approach described by Wigmosta and Lettenmaier (1999). The DHSVM represents snow accumulation and melt by calculating the full surface energy balance independently at each model grid cell, accounting for terrain shading effects, radiation attenuation, wind modification and snow-canopy processes (Wigmosta et al. 1994, Storck 2000, Storck et al. 2002, Andreadis et al. 2009, Sun et al. 2018, Sun et al. 2019). Prior research has shown that DHSVM snow simulations are sensitive to the choice of both incoming shortwave and longwave radiation, with melt initiation and rate more sensitive to longwave than shortwave radiation (Hinkelman et al. 2015). Stream channel routing is performed using a storage accounting scheme, which allows the user to produce hydrographs at any location along the channel network. Typical spatial resolution of DHSVM implementations range from about 10 m to 200 m.

Model Setup

For this study we used DHSVM version 3.2, which includes a number of updates, most notably a new canopy gap component with enhanced radiation transmittance schemes and physical processes controlling snowpack evolution in forest gaps (Sun et al. 2018, https://github.com/pnnl/DHSVM-PNNL). We implemented the model at a resolution of 90 m and used a 1-hour time step for improved resolution of peak flows.

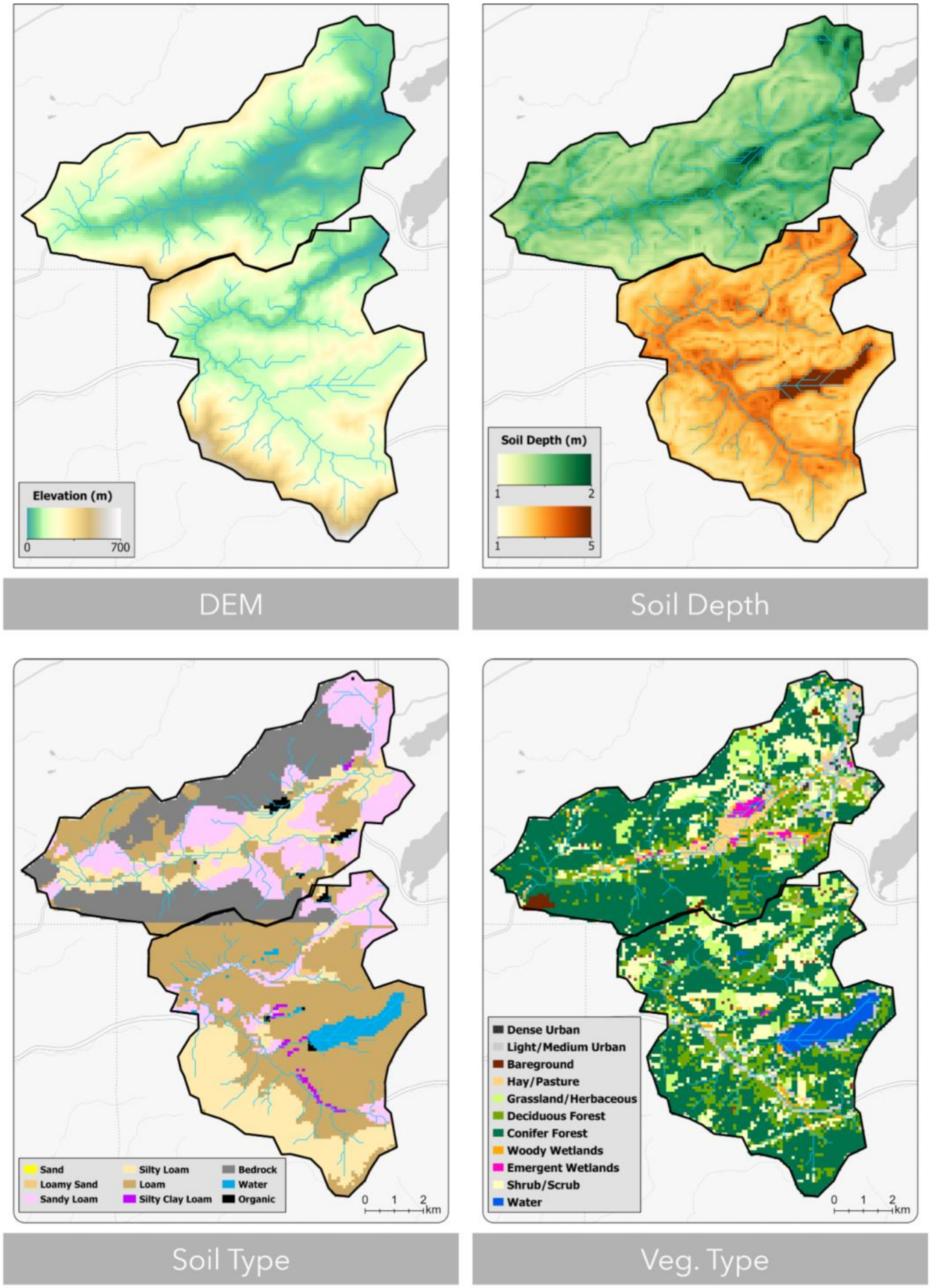

Figure 9. Maps showing the DHSVM DEM, soil depth, soil types, and vegetation distributions for the Skookum and Kennedy Creek models.

Topography and Stream Network

The digital elevation models (DEM) were downloaded from the National Elevation Dataset (http://viewer.nationalmap.gov/basic/) (Elevation products, 3DEP). The DEM (top left panel in Figure 9) provides a base layer of spatial information and is used to generate watershed boundaries using ArcGIS hydrology modeling tools. DHSVM-PNNL Python scripts that drive ArcGIS tools are used to develop a stream network based on a user-defined contributing area. Simulated streamflows are routed through the stream network based on flow direction relationships from upgradient (higher elevation) to downgradient (lower elevation) grid cells and stream channel segments.

Land Cover

We generated the land cover grids based on the National Land Cover Database 2016 update (NLCD; Homer et al. 2020, Jin et al. 2019, Yang et al. 2018). This is the most recent national land cover product, with a 16-class land cover classification scheme applied at a spatial resolution of 30 meters based on Landsat satellite data and created by the Multi-Resolution Land Characteristics Consortium (Homer et al. 2015). Land cover grids were resampled to 90 m resolution. Land cover is dominated by evergreen forest in the upper elevations while the lower elevations are more developed with urban and agricultural classifications (Table 5; bottom right panel in Figure 9).

Table 5. Land cover classifications used as input to the DHSVM model.

ID	NLCD IDs	Land Cover Type
1	23, 24	Dense Urban (>75%)
2	21, 22	Light / Medium Urban (<75%)
3	31	Bare Ground
4	12	Snow / Ice
5	81	Hay / Pasture
6	71	Grassland/Herbaceous
7	41, 43	Mixed / Deciduous Forest
8	42	Conifer Forest
9	90	Woody Wetlands
10	95	Emergent Herbaceous Wetl.
11	52	Shrub / Scrub
12	82	Orchard
13	11	Water

Soil Parameters

The Digital General Soil Map of the United States, or STATSGO dataset (NRCS 2017) was developed for regional and national studies designed for broad planning and management uses requiring estimates of soil characteristics. The soil units are distributed as spatial and tabular datasets with 1-kilometer resolution for the conterminous United States. In our study areas, the STATSGO database contained seven different soil map units in each watershed from which DHSVM soil parameters can be derived. Silt and loam units make up the majority of both basins (bottom left panel in Figure 9).

Soil Depth

Soil depths are defined empirically based on elevation and local slope using DHSVM-PNNL Python scripts (https://github.com/pnnl/DHSVM-PNNL). The algorithm generates thin soils on steep slopes and ridge tops and thick soils on gentle slopes and in depressions, within a user-defined defined range. We altered soil depths as a proxy for the geological and land cover differences altering the timing of flow through each watershed (1.0 – 2.0 m for the Skookum Creek model and 1.0 – 5.0 m for the Kennedy Creek model; top right panel in Figure 9).

DHSVM Calibration

As mentioned in previous sections, calibration involved first determining if additional bias-adjustments should be applied to the meteorological inputs, then adjusting the soil properties to improve simulations. This was done manually, via sensitivity tests, in which we evaluated alternatives based on their relative skill at reproducing the observations. Specifically, we compared the time series of average annual flow, average monthly flows, daily streamflow time series, and the cumulative distribution function (sometimes referred to as the “flow-duration curve”). Multiple criteria were used in order to ensure a holistic assessment of the strengths and weaknesses of each model configuration.

First, we made two additional adjustments to the meteorology as part of the interpolation from the 6 km meteorological data to the 90 m DHSVM grid. For temperature, we assumed monthly temperature lapse rates according to Minder et al. (2010). For precipitation, we used high-resolution (800 m) precipitation estimates from PRISM to distribute precipitation within each 6 km grid cell. Different adjustments were applied to each calendar month, based on a comparison between the long-term averages for PRISM and WRF-NARR.

Second, we performed model tests, to identify adjustments to the climate data, or to the model parameters, that could improve the calibration. In our testing for Skookum Creek, we found that adjustments to the soil depth range could improve the simulations. Specifically, we found that a narrower range in soil depth of 1-2m led to the best model

Table 6. Model evaluation scores for the Skookum and Kennedy Creek DHSVM simulations. Comparisons are based on daily average flows for the years 1981-2020. Metrics are the correlation (r), Nash-Sutcliffe Efficiency (NSE), NSE for log-transformed flows (NSELOG), Kling-Gupta Efficiency (KGE), root mean square error (RMSE, CFS), and average percent bias (PBIAS, %).

Site	r	NSE	NSELOG	KGE	RMSE	PBIAS
Skookum Creek	0.77	0.48	0.77	0.73	0.07	-9.21
Kennedy Creek	0.77	0.58	0.81	0.73	0.08	0.04

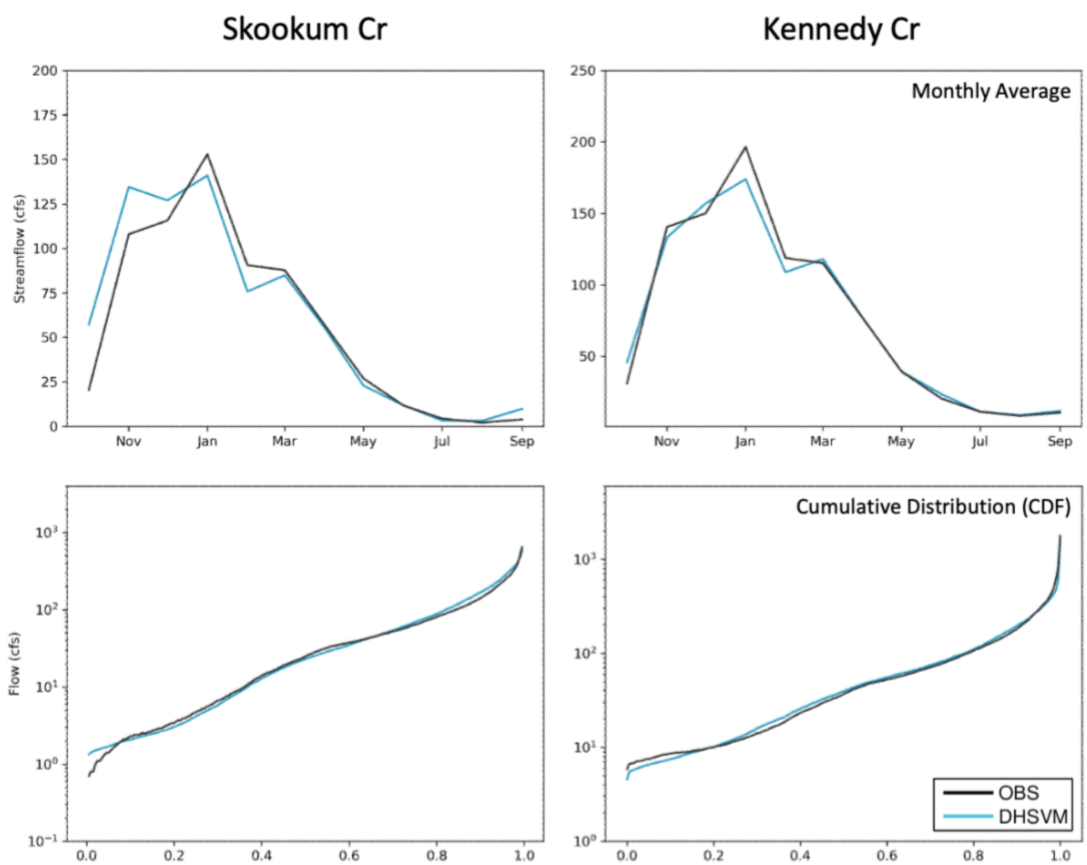

Figure 10. Observed and modeled monthly flows (top) and the cumulative distributions in daily flows (CDFs, bottom) for Skookum and Kennedy Creeks. Comparisons are based on the full observational record: 2005-2020.

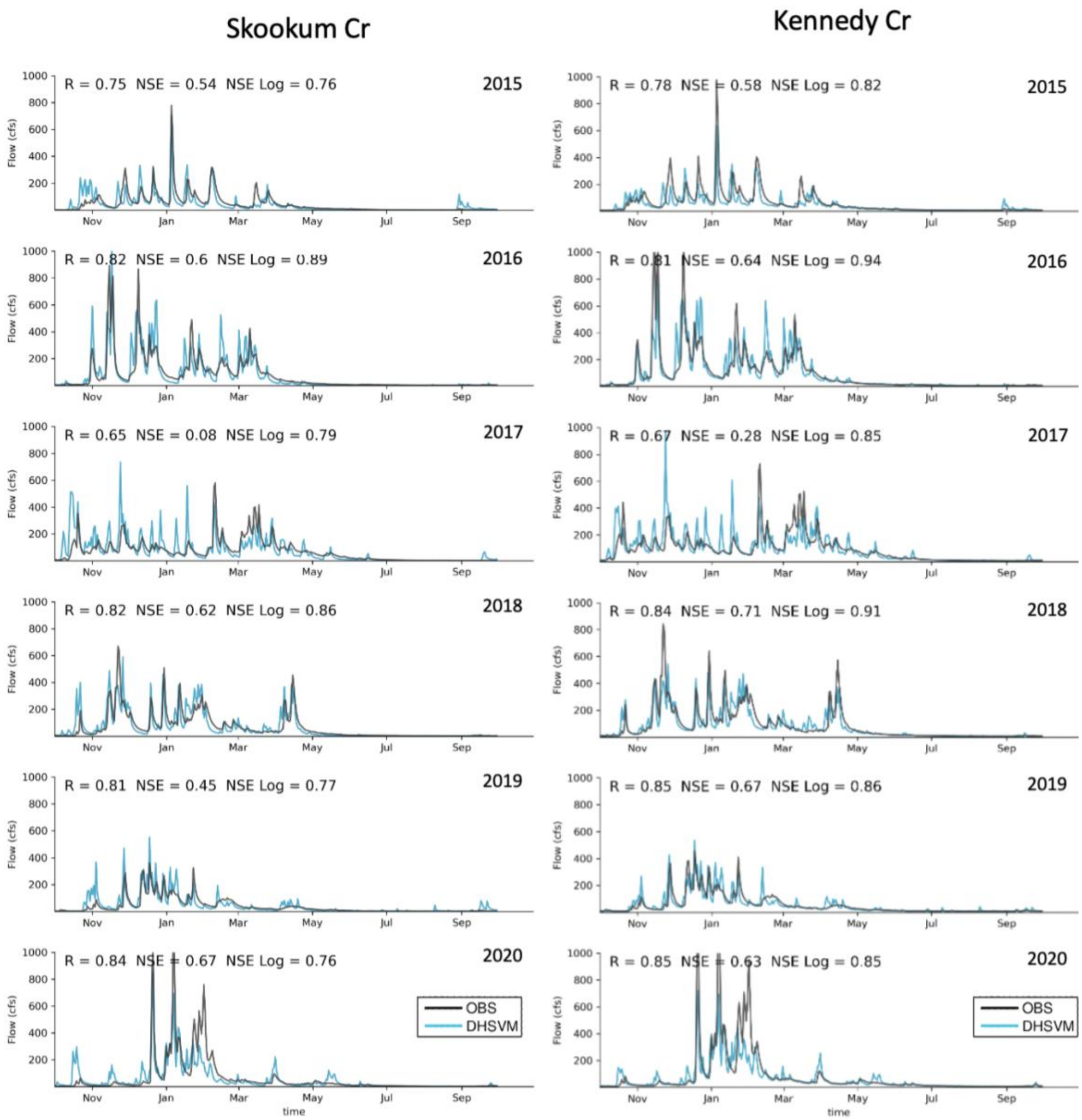

Figure 11. Observed and modeled daily flows for Skookum and Kennedy Creeks. Results are shown for water years 2015-2020; comparisons for other years are similar.

agreement with the observations. When we tested the Kennedy Creek model, we found that scaling precipitation up by 10% led to improved results, and that a soil depth range of 1-5m resulted in the best model performance. We believe the larger soil depth range for Kennedy Creek is likely more reflective of the hydraulic effects of Summit Lake than differences in the soil properties of the two watersheds. Since DHSVM does not simulate lakes, the deeper soils serve as a way to emulate the effect of the lake on flows.

Neither model proved sensitive to biases in temperature, which is not surprising since winter snow accumulation is not important in either watershed, and evaporation is more sensitive to relative humidity than temperature. We also tested soil properties such as saturated hydraulic conductivity and the exponential decrease parameter in the infiltration curve. Again, neither had a significant effect on the simulations.

Model skill scores are shown in Table 6, and comparison plots are shown in Figures 10 and 11. The model's Nash-Sutcliffe Efficiency (NSE) score is adequate, but lower than preferable for typical hydrologic modeling applications. It is worth noting that the NSE scores calculated based on the log of the flows ("NSELOG") are much higher, indicating stronger model performance at low flows. Similarly, the high KGE scores are also an indication of strong model performance. Our experience is that NSE scores are generally lower when using regional climate model simulations for the calibration simulation, as we have done here (i.e. by using WRF-NARR). This is likely because the simulation does not exactly reproduce the timing and intensity of precipitation events. For this reason we focus more on the comparisons between the long-term average and the cumulative distribution (CDF) in daily flows, as shown in Figure 10. We nonetheless include the daily flow comparisons for transparency; these show that some events appear to be missed by the WRF-NARR simulation, and when events are captured they can sometimes be lagged relative to the observations. This is likely the reason for the lower skill scores. As noted in the introduction, we have chosen to use the dynamically downscaled projections because research indicates they provide improved estimates of the change in precipitation, particularly extreme precipitation events.

Stream Temperature Model

Due to limited data availability in Kennedy Creek, we only modeled stream temperature for Skookum Creek (Table 2). We employed a process-based water temperature model that integrates DHSVM with a vector-based stream temperature model ("River Basin Mode", or RBM; Yearsley 2009) and a riparian shading model (Sun et al. 2015). DHSVM-RBM explicitly represents both overland surface and subsurface hydrology related to stream temperature dynamics, simulating streamflow and water temperature throughout the DHSVM stream network, at the same 1 hour time step. DHSVM-RBM has been used to project changes in water temperature in a small urban watershed (Mercer Creek, WA; Sun et al. 2015), in larger Puget Sound rivers (Cao et al. 2016), as well as in small semi-rural watersheds on the Kitsap and Olympic peninsulas (Murphy and Rossi 2019, 2020). Recently DHSVM-RBM was used to project changes in the temporal pattern of water temperature for the Sauk River, and changes in both spatial and temporal patterns of water temperature in the Snoqualmie River Watershed (Lee and Fullerton 2020).

RBM Calibration

The model parameters used to configure RBM fall into three categories. First, the Mohseni parameters, which relate air temperature to headwater stream temperature following Mohseni et al. (1998). Second, the Leopold parameters, which relate flow rate to channel geometry and stream velocity (Leopold and Maddock 1953). And finally, riparian shading: DHSVM-RBM includes riparian vegetation height, stream width, crown diameter, leaf area index (LAI), and canopy to bank distance (Sun et al. 2014).

We obtained estimated riparian conditions from our collaborators at the Squaxin Island Tribe (Erica Marbet, personal communication), who provided approximate estimates of tree height, buffer width, overhang, and canopy bank distance across the watershed.

Paired air and water temperature measurements, maintained by the Squaxin Island Tribe, allowed us to obtain initial estimates of the Mohseni parameters. We then adjusted these based on sensitivity tests to optimize the results at the Skookum Creek gauge. Model tuning was implemented by hand via trial and error, with an emphasis on the warmest water temperatures for June 1st through September 30th. Final calibrated values were as follows:

- Air temperature smoothing parameter: 0.1.
- Mohseni parameters: alpha=20, beta=14, mu=6, gamma=0.25.
- Leopold coefficients:
    - d_a=0.4, d_b=0.8, d_{min}=1.0 (depth);

- $u_a=0.9$, $u_b=0.21$, $u_{min}=0.5$ (velocity).

Our tests showed that the model would need substantial adjustments to provide accurate simulations of hourly and daily water temperature, and that doing so would be well beyond the scope of the current study. As a result, our results focus on 7DADMAX (the 7-day average in daily maximum water temperatures). Even with 7DADMAX, biases remained after calibration of the model. To correct for these, we performed a simple bais correction in which we removed the mean temperature bias for June-September from each time step (e.g. the WRF-NARR bias was +2.05°C). Model scores, based on these bias-corrected results, are shown in Table 7.

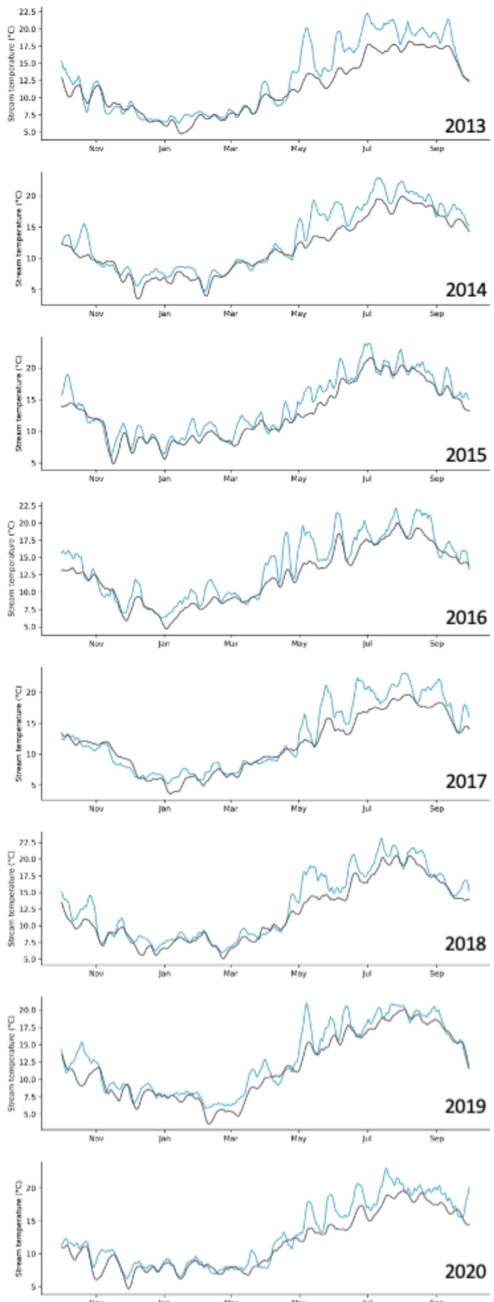

Figure 12. Observed (black) and model bias-corrected (blue) 7DADMAX for Skookum Creek. Results are shown for water years 2015-2020.

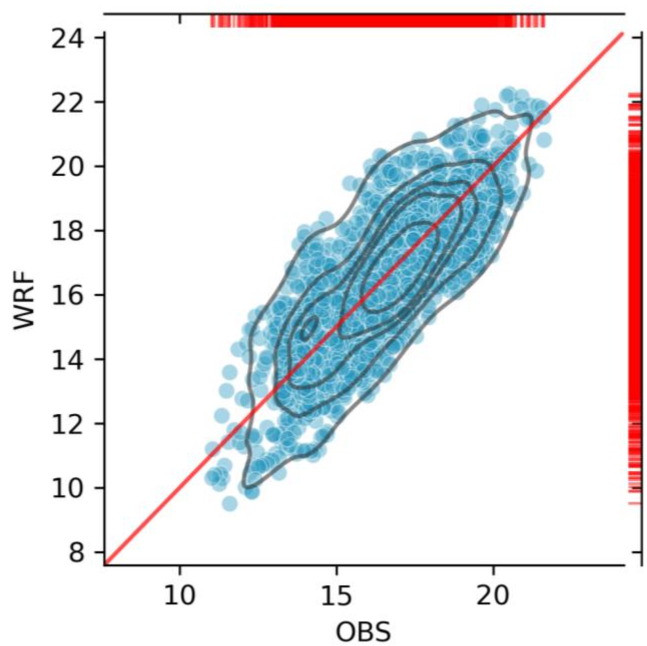

Figure 13. Scatter plot comparing observed and model bias-corrected Jun 1 – Sep 30 7DADMAX for Skookum Creek.

Figure 12 shows a time series comparison between observed and model bias-corrected temperature for Skookum Creek, and Figure 13 shows a scatter plot comparing observed and modeled 7DADMAX for June 1st - September 30th.

The results are much better for 7DADMAX than for hourly or daily water temperatures. As

Table 7. Model evaluation scores for the Skookum Creek RBM, for June 1st – September 30th. Metrics are the correlation (r), Nash-Sutcliffe Efficiency (NSE), Kling-Gupta Efficiency (KGE), root mean square error (RMSE, CFS), and average percent bias (PBIAS, %).

	Metric	r	NSE	KGE	RMSE	PBIAS
Jun 1 – Sep 30	Hourly	0.67	-0.95	0.44	2.83	11.40
	Daily	0.69	-0.66	0.60	2.48	11.14
	7DADMAX	0.81	0.61	0.81	1.29	-1.05
	7DADMIN	0.83	-2.09	0.74	3.14	19.70

above, the timing of events in the WRF-NARR meteorology does not exactly match the observations, leading to lower scores. Finally, the RBM model appears to be too responsive to changes in weather conditions, resulting in larger variations than the observstions – further calibration could likely improve on these results.

Post-Processing and Analysis

DHSVM Streamflow Projections

All streamflow results are provided at the model time step of 1 hour. In addition, we processed streamflow results by calculating the metrics listed in Table 8; these were specifically requested by our partners at the Squaxin Island Tribe. Results for each of the 12 WRF-CMIP5 simulations are provided in both time series format (1970-2100) and averaged over four 30-year time periods: “1980s” (1970-1999), “2020s” (2010-2039), “2050s” (2040-2069), “2080s” (2070-2099). We use 30 years because it is the convention in climate change studies – chosen as a compromise between the need to detect changes over time while minimizing sensitivity to random short-term variability. For reference, results are also provided for the WRF-NARR simulation and the observations (1981-2020).

For each of the above time periods, we computed extreme statistics by fitting a GEV distribution with L-moments to estimate extreme precipitation statistics – following the methodology described in Salathé et al. (2014) and Tohver et al. (2014) – based on findings that indicate it is superior to the Log-Pearson Type 3 distribution (Rahman et al. 1999 & 2015, Vogel et al. 1993, Nick et al. 2011).

One challenge with the extreme statistics is that 30-year periods require extrapolation to encompass the rarest events (e.g., 50-year, 100-year, 500-year). Although extrapolation leads to greater uncertainty in the flood frequency estimates, it is common practice in flood studies as we rarely have enough observed data to encompass these rare events.

Table 8. Streamflow metrics used to summarize the DHSVM results. Monthly averages, peak flow statistics, and low flow statistics are calculated for all sites. All other metrics are only calculated for one lower mainstem location on each creek: Skookum Cr at Hwy 101 and Kennedy Cr at Old Olympic Hwy.

	Name	***Definition***
Both Watersheds	Monthly Average Flow	Time series of average streamflow for each month
	Peak Flow Statistics	Magnitude of 1.1-, 2-, 10-, and 100-year events (or 90%, 50%, 10%, and 1% annual chance of exceedance). Based on maximum hourly flow for each water year.
	Low Flow Statistics	Magnitude of 2- and 10-year extreme (or 50% and 10% annual chance of non-exceedance). Based on minimum 7-day average flow for each water year.
	Start of Low Flow Season	Last day of calendar year, before Aug 15th, with flow > 20 CFS
	End of Low Flow Season	First day of calendar year, after Aug 15th, with flow > 20 CFS
Skookum Cr	Instream Flow Rule	Number of days during the period of July 15 to Sept. 30 with 7-day average flows below instream flow rule of 3 cubic feet per second (cfs).
	Spring Flows	Number of days during Feb. 1 through June 15 when 7-day average flow is within the range of 10-30 cfs at the Hwy. 101 gage
	Low Flow Events	Number of days in the June 1 through October 1 period when 7-day average flow in Skookum Creek goes below 2 cfs
Kennedy Cr	Instream Flow Rule	Number of days during the period of Aug. 1 to Sept. 30 when 7-day average flow in Kennedy Creek is below the instream flow rule of 7 cubic feet per

Table 9. Stream temperature metrics used to summarize the RBM results.

	Name	Definition
Skookum Cr	Max 7DADMAX	Maximum annual 7-day average of the daily maximum temperatures
	Max 7DADMIN	Maximum annual 7-day average of the daily minimum temperatures
	Num. days above 16°C	Number of days between June 1 and Sept. 30 when Skookum Creek 7DADMAX goes above 16°C
	Num. days above 22°C	Number of days between June 1 and Sept. 30 when Skookum Creek 7DADMAX goes above 22°C

Nevertheless, the effects of this greater uncertainty should be considered when using the extrapolated data.

RBM Stream Temperature Projections

The results for stream temperature are processed in much the same way as described above for streamflow. However, results are only provided based on 7-day averages, because our testing found that the model was not sufficiently accurate at shorter time steps (see calibration discussion, above). Two additional metrics are included, focused on the number of days with 7DADMAX above the Washington State water temperature standard of 16ºC and the potentially lethal threshold of 22ºC (Table 9).

A Focus on the Relative Changes

In order to minimize the effect of model biases on the projections, we recommend focusing on the change in flows and water temperature, relative to the historical baseline provided by each WRF-CMIP5 simulation. By considering only the relative change, you remove any absolute biases that may be present in the model estimates. If the long-term change is desired, relative to the climate of the past, we recommend using the "1980s" as the baseline. If changes relative to present-day conditions are desired, we recommend using the "2020s" as the baseline. Projected changes should be calculated separately for each GCM, relative to its own historical estimates.

Project Results, Analysis, and Findings

Sea Level Rise

Based on survey elevations obtained from our collaborators at the Squaxin Island Tribe, we assessed current and future sea level rise risks for specific locations of interest to the Tribe. Our analysis focused on two measures of risk: (1) the number of days per year, on average, with water levels above a particular elevation, and (2) the current and future return interval

Table 10. The number of days per year when the estimated maximum water level at Arcadia exceeds selected elevations of interest to the Squaxin Island Tribe. Projections are based on high greenhouse gas scenario (RCP 8.5) and the low-end (99%), median (50%), and high-end (1%) probabilities for future sea level rise.

	Old Olympic Highway Residences (218A)	IEI Foundation (216)	Firehall Sewer Vault (236)	Legal Services Sewer Main Vault (238)	Shoreline Residences - Whitener Road (243)	Daycare Footbridge Abutment (251)	Clam Fresh on Gosser Rd (999)
Elevation (MLLW)	26.78 ft	22.78 ft	23.51 ft	20.39 ft	30.32 ft	23.9 ft	18.3 ft
Current	0	0	0	0	0	0	0.07
2050 (99% probability, RCP 8.5) (0.3ft)	0	0	0	0	0	0	0.18
2050 (50% probability, RCP 8.5) (0.8ft)	0	0	0	0.01	0	0	1.0
2050 (1% probability, RCP 8.5) (1.4ft)	0	0	0	0.01	0	0	5.4
2100 (99% probability, RCP 8.5) (0.8ft)	0	0	0	0	0	0	1.0
2100 (50% probability, RCP 8.5) (2.3ft)	0	0	0	0.14	0	0	37.14
2100 (1% probability, RCP 8.5) (5.0ft)	0	0.36	0.02	99.5	0	0.01	342.84

for water levels exceeding that elevation. Results for all locations of interest are provided in a spreadsheet; this section provides results for a subset of the locations of interest.

Results from the first analysis are shown in Table 10. Some locations of interest are never at risk, even for the highest sea level rise projections in 2100 (e.g. Old Olympic Highway residences). Others are not at risk yet but will be by the end of the century (e.g. Legal Services Sewer Main Vault). Finally, some areas are already at risk, and sea level rise will lead to steady increases in the number of days with flood risk each year (e.g. Clam Fresh on Gosser). This first analysis is best suited for elevations that are exceeded relatively frequently, now or in the future.

Table 11. As in Table 10 except showing the current and future return intervals for each selected location.

	Old Olympic Highway Residences (218A)	IEI Foundation (216)	Firehall Sewer Vault (236)	Legal Services Sewer Main Vault (238)	Shoreline Residences - Whitener Road (243)	Daycare Footbridge Abutment (251)	Clam Fresh on Gosser Rd (999)
Elevation (MLLW)	26.78 ft	22.78 ft	23.51 ft	20.39 ft	30.32 ft	23.9 ft	18.3 ft
Current	>150-yr	>150-yr	>150-yr	>150-yr	>150-yr	>150-yr	16-yr
2050 (99% probability, RCP 8.5) (0.3ft)	>150-yr	>150-yr	>150-yr	>150-yr	>150-yr	>150-yr	7-yr
2050 (50% probability, RCP 8.5) (0.8ft)	>150-yr	>150-yr	>150-yr	>150-yr	>150-yr	>150-yr	2-yr
2050 (1% probability, RCP 8.5) (1.4ft)	>150-yr	>150-yr	>150-yr	137-yr	>150-yr	>150-yr	<1.5-yr
2100 (99% probability, RCP 8.5) (0.8ft)	>150-yr	>150-yr	>150-yr	>150-yr	>150-yr	>150-yr	2-yr
2100 (50% probability, RCP 8.5) (2.3ft)	>150-yr	>150-yr	>150-yr	9-yr	>150-yr	>150-yr	<1.5-yr
2100 (1% probability, RCP 8.5) (5.0ft)	>150-yr	4-yr	30-yr	<1.5-yr	>150-yr	102-yr	<1.5-yr

To understand changes in less frequent events, we used the second approach (Table 11), in which we calculated the return interval under current and future sea level. We did this by fitting a Generalized Extreme Value distribution, using L-moments, to the historical time series of maximum yearly water level values. The fitted GeV distribution can then be queried to obtain the return interval for any elevation within its range. We estimated future return intervals by simply shifting the GeV fit upwards by corresponding sea level rise projection. We do not provide estimates for elevations that are either below the 1.5-year or above the 150-year event elevations; our methods cannot reliably provide accurate estimates for either. The large changes in return frequency are in part a result of the shallow slope of the water level cumulative distribution function, the return intervals can change rapidly, in some cases going from a >100-yr event under current conditions to a <1.5-year event by the end of the century (e.g. Legal Services Sewer Main Vault).

Streamflow

This section summarizes the changes in streamflow for the Skookum and Kennedy Creek DHSVM simulations. These are naturalized flows, meaning that changes in water use or other management choices could alter flows in the future in ways that either exacerbate or mitigate the effects of climate change. Similarly, our results do not account for changes in land cover, either due to changes in management or wildfire.

As discussed in previous sections, all results are based on the bias-corrected hourly WRF-CMIP5 forcings (temperature, precipitation, humidity, wind, and shortwave radiation), and the empirical longwave estimates described above. Although the climate data are bias-corrected, no bias-correction is applied to the streamflow estimates. To control for biases in the projections, our results focus on percent changes in streamflow whenever possible (i.e., we calculate the percent change for a given GCM projection relative to the historical estimate from that same GCM). We nonetheless present many of our results using absolute flow estimates, because these are often more intuitive and often what is needed to delve into the impacts.

Monthly Flows

Consistent with the observed and naturalized flows, historical simulations show that Skookum and Kennedy Creeks are rain-dominant basins, where streamflow peaks in winter during the rainy season, then decreases through spring and summer until the rains pick

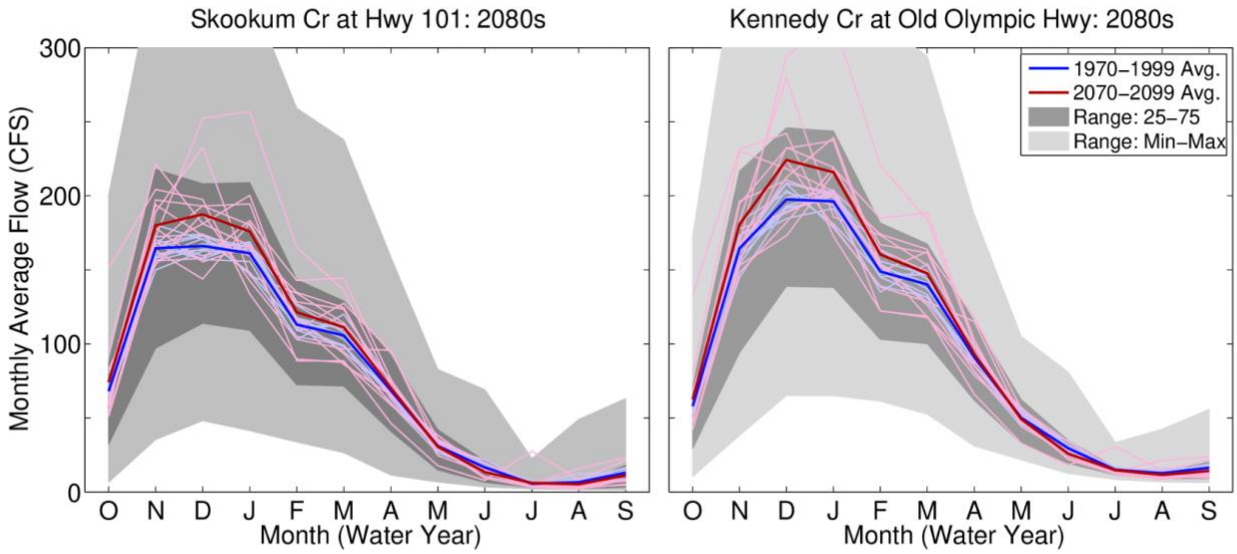

Figure 14. Historical and future monthly flows for Skookum and Kennedy Creeks. Each line shows the results for one WRF-CMIP5 projection: historical (1980s) in blue and 2080s in red. Thick lines show the model average, thin lines the individual model projections. For comparison with the lines, which show the 30-year averages, the grey shading shows the model-estimated historical range in monthly flows (25^{th}-75^{th} percentile: dark grey; min-max range: light grey).

back up again in fall (Figure 14, Table 12; additional figure in Appendix). Although warming could result in increased evaporation, the changes are not consistent among models, and the primary effect of climate change is in the intensification of heavy rains, resulting in a slight increase – on average – in winter flows.

Peak Flows

Peak flows in both basins are projected to increase for nearly all models, return intervals, and time periods that we considered (Table 13,

Table 12. Projected change in monthly average flows for lower river sites on each creek: Skookum Creek at Hwy 101 and Kennedy Creek at Old Olympic Hwy. Results show the percent change for the 2080s (2070-2099) relative to the 1980s (1970-1999).

	Skookum Cr	Kennedy Cr
OCT	-7% (-24%, +124%)	-10% (-26%, +124%)
NOV	+7% (-9%, +33%)	+8% (-11%, +46%)
DEC	+14% (-17%, +60%)	+14% (-17%, +56%)
JAN	+9% (-18%, +53%)	+8% (-13%, +56%)
FEB	+7% (-24%, +42%)	+8% (-22%, +45%)
MAR	+5% (-21%, +44%)	+6% (-20%, +43%)
APR	-4% (-35%, +61%)	-3% (-30%, +42%)
MAY	+0% (-49%, +35%)	-2% (-39%, +23%)
JUN	-16% (-57%, +19%)	-12% (-41%, +15%)
JUL	-21% (-39%, +370%)	-10% (-19%, +102%)
AUG	-33% (-69%, +164%)	-18% (-31%, +74%)
SEP	-27% (-62%, +86%)	-22% (-40%, +46%)

Figure 15). Assessing trends in extremes is difficult, since they are by definition rare events – this undoubtedly adds some noise to the projected changes, and this noise is likely greater for the largest events (e.g., 50-year, 100-year). One approach we recommend is to focus on the smaller and more frequent extreme events, since these are likely well-

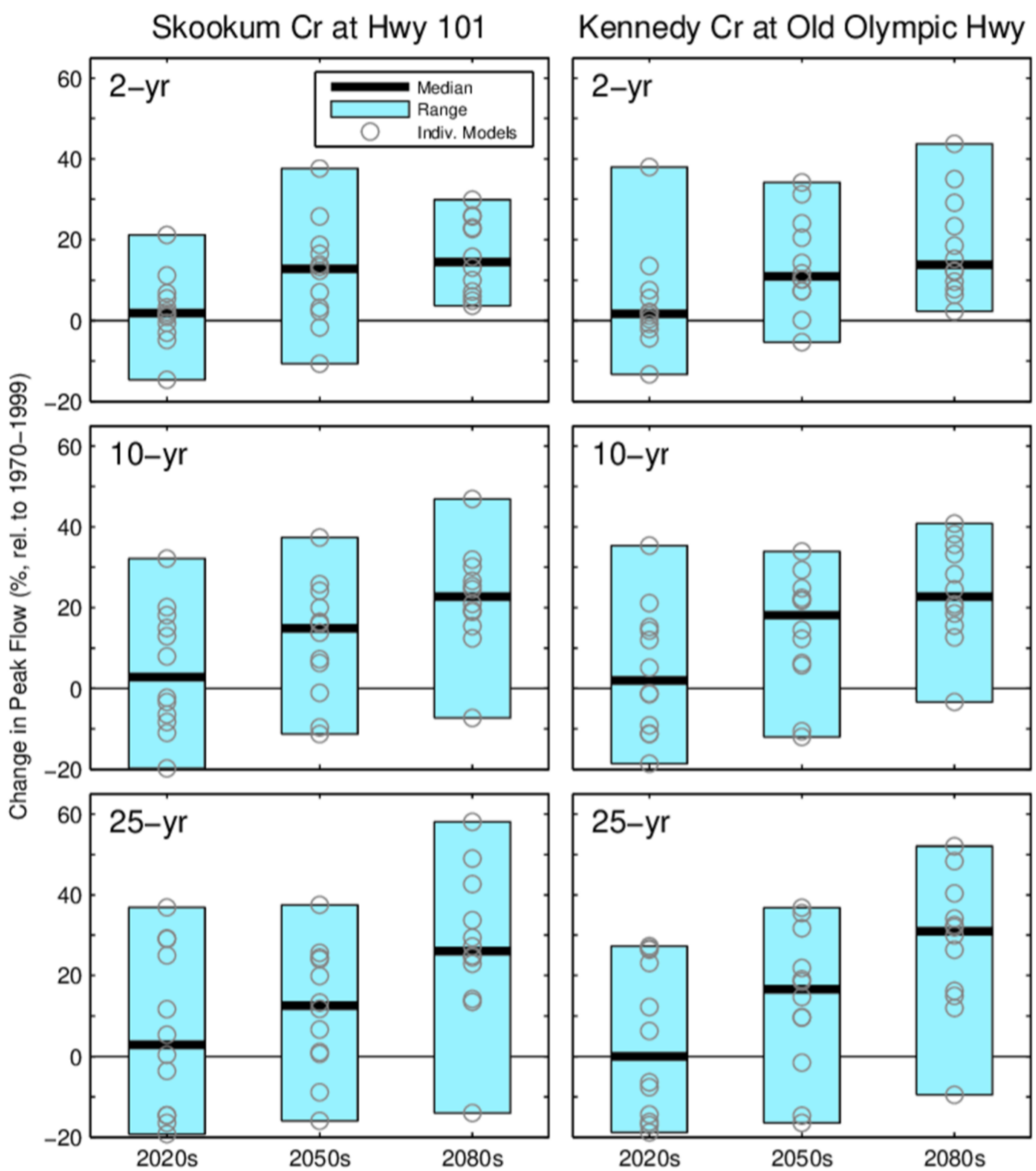

Figure 15. Projected change in peak daily flows for Skookum and Kennedy Creeks. Results are in percent, relative to 1970-1999, for the 2-, 10-, and 25-year events.

captured by our 30-year sampling periods and therefore less influenced by natural variability. Regardless, the projections clearly show an increase through the 21st century, with minor changes (on average) today (2020s), and progressively larger increases through

Table 13. Projected change in peak daily flow extremes for all streamflow sites. Results are provided for the 2080s (2070-2099) relative to 1970-1999.

	Site	Median	25th / 75th	min / max
2-yr	Skookum Cr at Hwy 101	+14%	+7% / +24%	+4% / +30%
	Skookum Creek at lower Hwy. 108 Bridge	+16%	+7% / +25%	+4% / +30%
	Little Creek at Skookum Creek	+15%	+7% / +24%	+4% / +30%
	Hurley Creek at Skookum Creek	+18%	+6% / +23%	+2% / +36%
	Skookum Creek at upper Hwy. 108 Bridge	+18%	+8% / +26%	+4% / +30%
	Kennedy Cr at Old Olympic Hwy	+14%	+9% / +26%	+2% / +44%
	Kennedy Creek at Falls	+13%	+9% / +26%	+3% / +43%
	Kennedy Creek Summit Lake Outlet	+17%	+8% / +25%	-2% / +40%
10-yr	Skookum Cr at Hwy 101	+23%	+17% / +28%	-7% / +47%
	Skookum Creek at lower Hwy. 108 Bridge	+23%	+17% / +28%	-7% / +47%
	Little Creek at Skookum Creek	+23%	+17% / +28%	-7% / +47%
	Hurley Creek at Skookum Creek	+23%	+19% / +28%	-6% / +45%
	Skookum Creek at upper Hwy. 108 Bridge	+25%	+16% / +28%	-6% / +48%
	Kennedy Cr at Old Olympic Hwy	+23%	+17% / +34%	-3% / +41%
	Kennedy Creek at Falls	+23%	+16% / +34%	-4% / +41%
	Kennedy Creek Summit Lake Outlet	+23%	+14% / +33%	-4% / +43%
25-yr	Skookum Cr at Hwy 101	+26%	+19% / +38%	-14% / +58%
	Skookum Creek at lower Hwy. 108 Bridge	+26%	+18% / +37%	-13% / +57%
	Little Creek at Skookum Creek	+26%	+19% / +38%	-14% / +58%
	Hurley Creek at Skookum Creek	+28%	+21% / +35%	-11% / +60%
	Skookum Creek at upper Hwy. 108 Bridge	+27%	+19% / +36%	-11% / +53%
	Kennedy Cr at Old Olympic Hwy	+31%	+16% / +37%	-9% / +52%
	Kennedy Creek at Falls	+31%	+15% / +36%	-10% / +52%
	Kennedy Creek Summit Lake Outlet	+33%	+10% / +46%	-12% / +52%

to the end of the century. Median projections for the end of the century range from +14% to +32%, depend on the location in question.

Low Flows

Low flows are also projected to decrease for nearly all models, durations, return intervals, and time periods that we considered (Table 14, Figure 16). However, for low flows there appears to be less model agreement than for the peak flow projections. Another difference with the peak flow projections is that changes appear to be occurring sooner for low flows. Results vary among models and metrics, but some show that the region has already

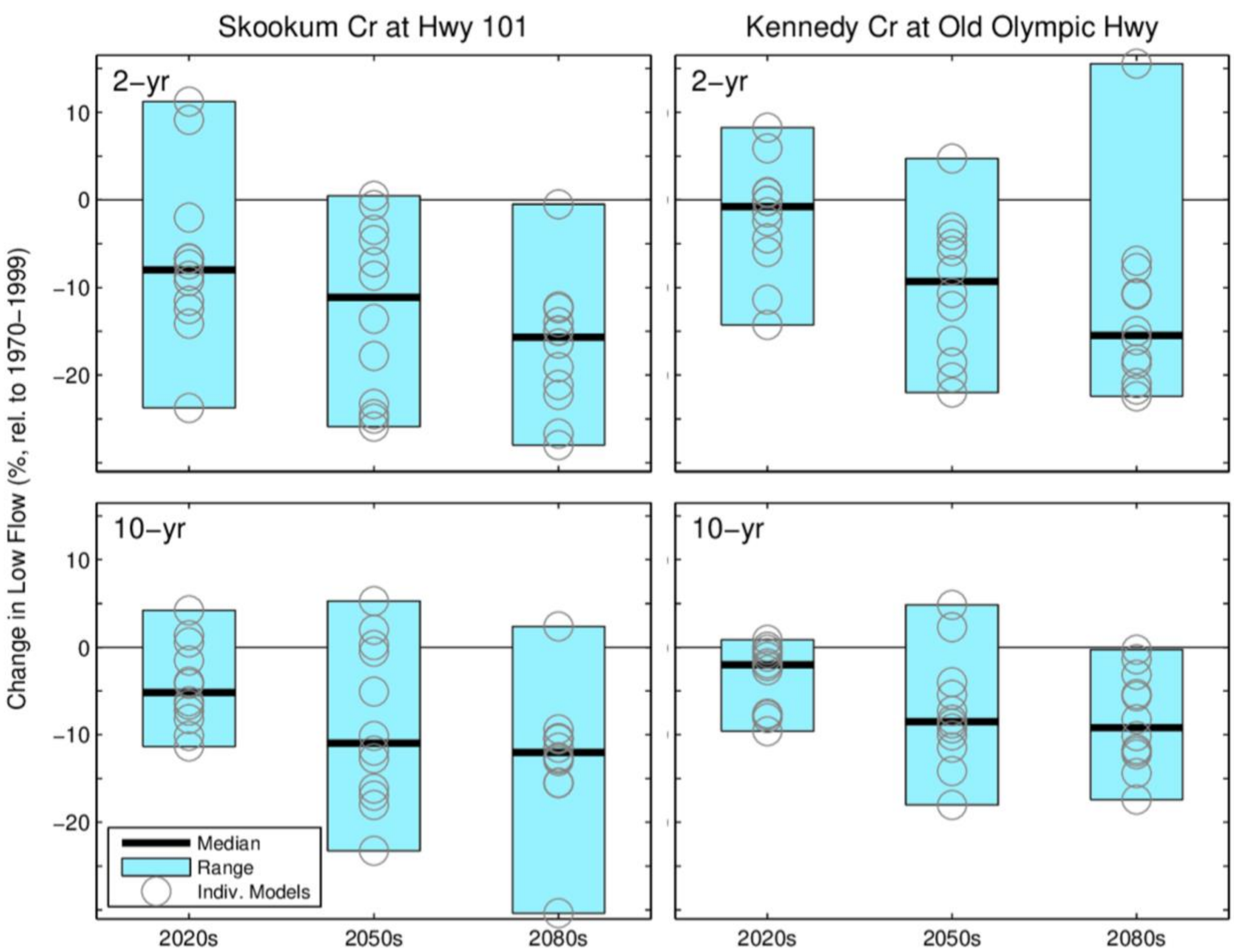

Figure 16. Projected change in low flows for Skookum and Kennedy Creeks. Results are shown in percent, relative to 1970-1999, for the 2-, and 10-year extremes in 7-day minimum flows.

Table 14. Projected change in low flow extremes for all streamflow sites. Results are provided for the 2080s (2070-2099) relative to 1970-1999.

	Site	Median	25th / 75th	min / max
2-yr	Skookum Cr at Hwy 101	-16%	-22% / -13%	-28% / -1%
	Little Creek at Skookum Creek	-16%	-22% / -13%	-28% / 0%
	Skookum Creek at lower Hwy. 108 Bridge	-16%	-23% / -13%	-28% / -1%
	Hurley Creek at Skookum Creek	-18%	-22% / -11%	-29% / +6%
	Skookum Creek at upper Hwy. 108 Bridge	-18%	-23% / -16%	-32% / -6%
	Kennedy Cr at Old Olympic Hwy	-15%	-20% / -9%	-22% / +16%
	Kennedy Creek at Falls	-14%	-19% / -9%	-23% / +13%
	Kennedy Creek Summit Lake Outlet	-20%	-25% / -15%	-33% / +7%
10-yr	Skookum Cr at Hwy 101	-12%	-14% / -10%	-30% / +2%
	Little Creek at Skookum Creek	-13%	-14% / -11%	-30% / +3%
	Skookum Creek at lower Hwy. 108 Bridge	-13%	-15% / -11%	-31% / +2%
	Hurley Creek at Skookum Creek	-10%	-13% / -3%	-25% / +1%
	Skookum Creek at upper Hwy. 108 Bridge	-12%	-16% / -11%	-33% / +1%
	Kennedy Cr at Old Olympic Hwy	-9%	-12% / -4%	-17% / 0%
	Kennedy Creek at Falls	-9%	-12% / -4%	-16% / 0%
	Kennedy Creek Summit Lake Outlet	-15%	-22% / -10%	-26% / -1%

experienced modest decreases in low flows, ranging from no change to a 10% decrease, on average, for the 2020s relative to the 1980s. Model projections become more consistent, and slightly larger, through the end of the century. Projected decreases for the 2080s range from -6% to -17%, on average.

An alternative way of considering low flows is to look at the duration of the low flow season. Figure 17 shows the change in the timing of the low flow season, defined as the first and last days with flows below 20 CFS. In addition to showing that the low flow season is much shorter for Kennedy Creek, these show a clear increase in the duration of low flows for both Creeks. Specifically, projections for both creeks suggest the low flow season will be 16-17 days longer, on average, by the 2080s. Results for similar metrics are shown in Figure

18, which lists the number of days that flows are below certain thresholds or within a particular range, as defined in Table 8. These show the largest increases in the number of days with extreme low flows on Skookum Creek, with smaller increases in extreme low flows for Kennedy Creek. Almost no change is projected for flows in springtime.

Low flows are more challenging to model accurately because they are more sensitive to assumptions about groundwater, soil properties, land cover, and how each of these affect the water balance. The calibration results indicate satisfactory performance for all flows, and the "NSELOG" scores – which are a better test of the model's low flow performance – are very good. Nonetheless, there are biases in the flow estimates relative to the observations, particularly for low flows. This is why we show the percent change in low

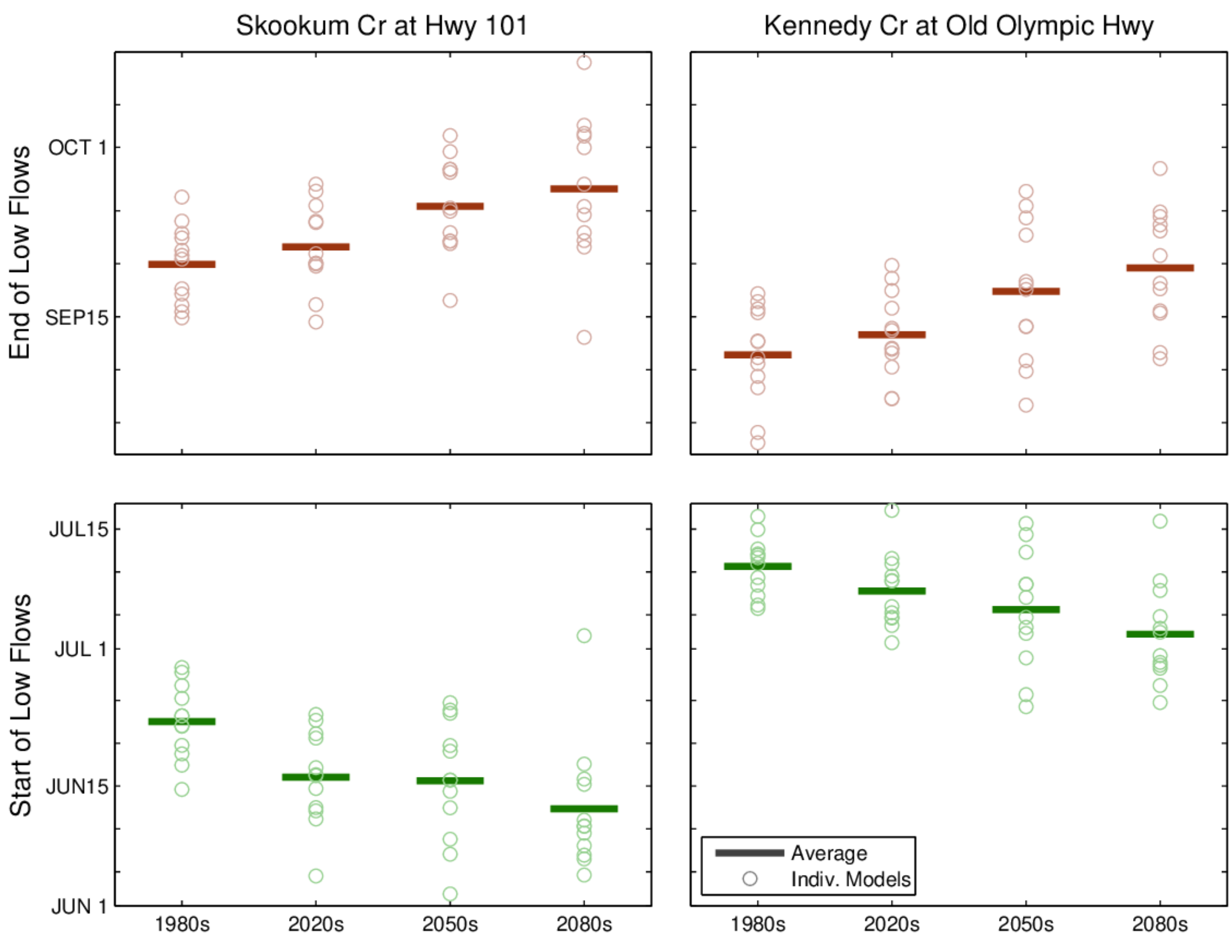

Figure 17. Historical and projected start and end of the low flow season for Skookum and Kennedy Creeks, defined as the first and last days with flows below 20 CFS.

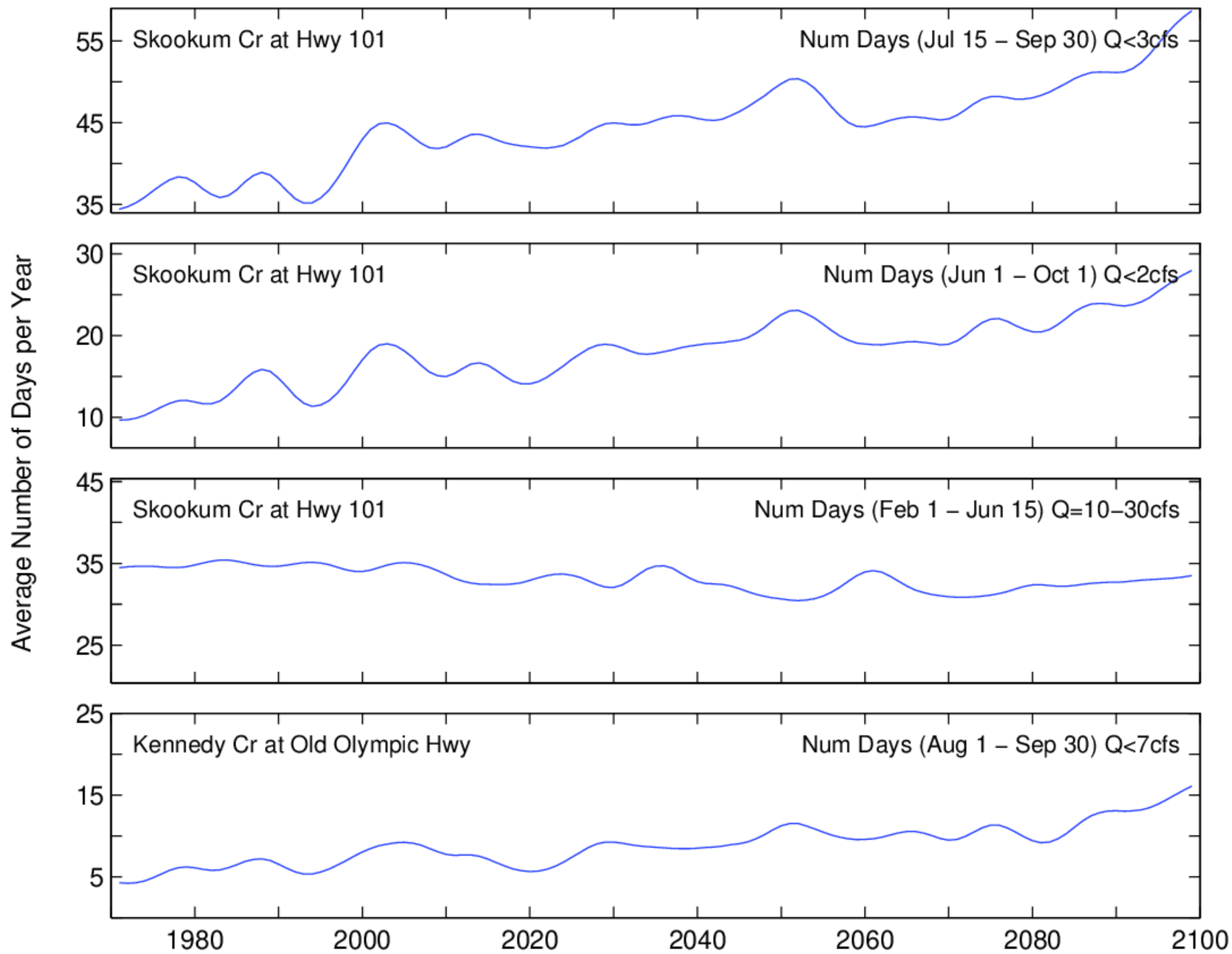

Figure 18. Time series of the "number of days" metrics listed in Table 7. Plots show the average among the 12 WRF-CMIP5 simulations, smoothed with a 15-year gaussian filter to facilitate interpretation.

flow extremes in Figure 16 and Table 14; by doing so we remove the absolute bias in the modeled estimates. Estimates of the duration in low flows (Figure 17), and the number of days metrics (Figure 18), are more sensitive to model biases because these absolute biases are harder to control for. For example, for Skookum Creek the observed duration of the low flow season is about 150 days per year, on average, whereas the model's historical average is about 90 days per year. For Kennedy Creek the observed duration is about 115 days per year, on average, whereas it is about 65 days in the model. Similar disagreements are present for the other "number of days" metrics in Table 8. While it is possible that the changes estimated in Figures 17 and 18 are nonetheless correct, further analysis would be needed to confirm these results. Future work could explore alternative ways of making these estimates, for example by bias-correcting the flows to match observations before assessing changes, and/or obtaining independent estimates of flow changes to see if they corroborate the current results.

Stream Temperature

This section summarizes the changes in stream temperature for the Skookum Creek RBM simulation. Results are provided for the location of the existing water temperature gauge (Table 2), which is co-located with the streamflow gauge at the Highway 101 crossing. As

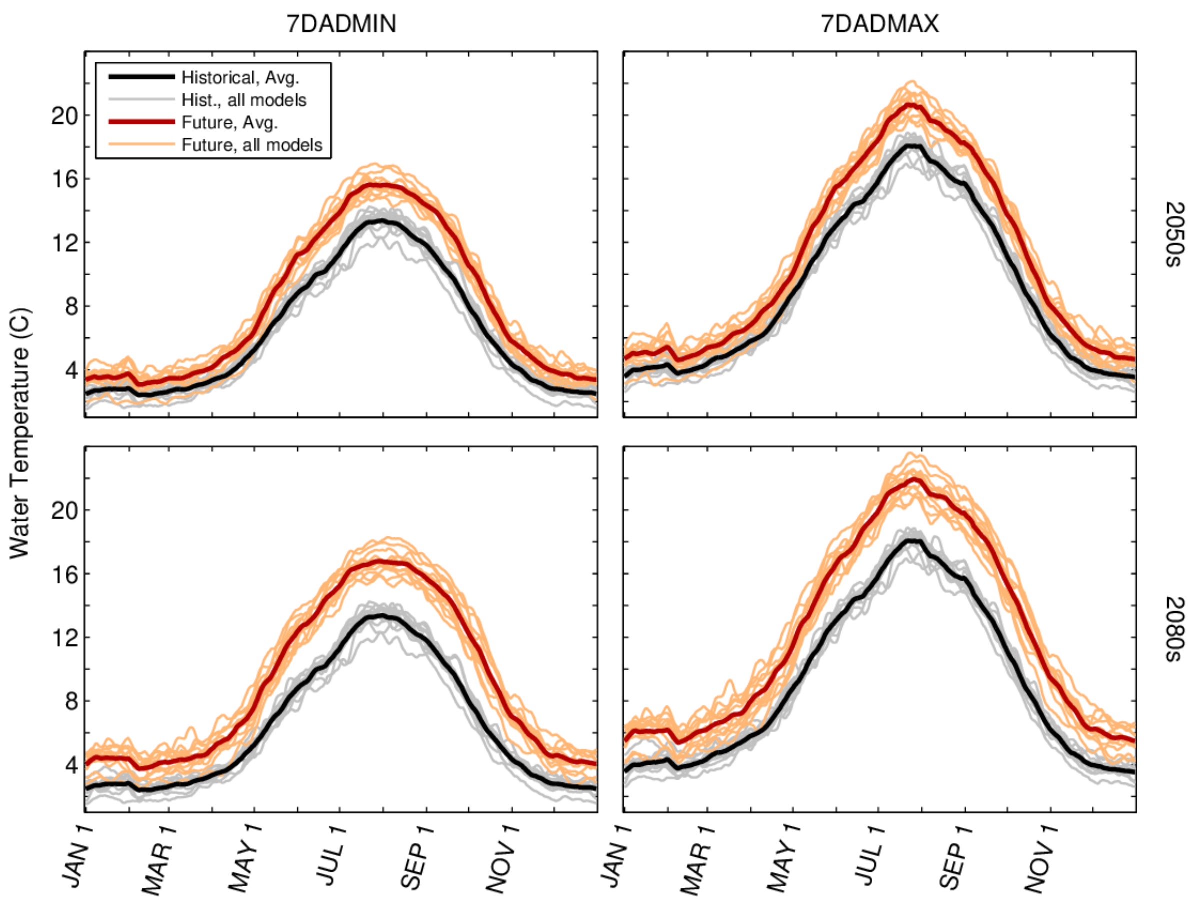

Figure 19. Historical and future 7DADMIN (left) and 7DADMAX (right) flows for Skookum Creek at Highway 101. As in Figure 12, each line shows the results for one WRF-CMIP5 projection. The grey lines show the historical average (1970-1999), while the yellow/red lines show the average for the 2050s and 2080s.

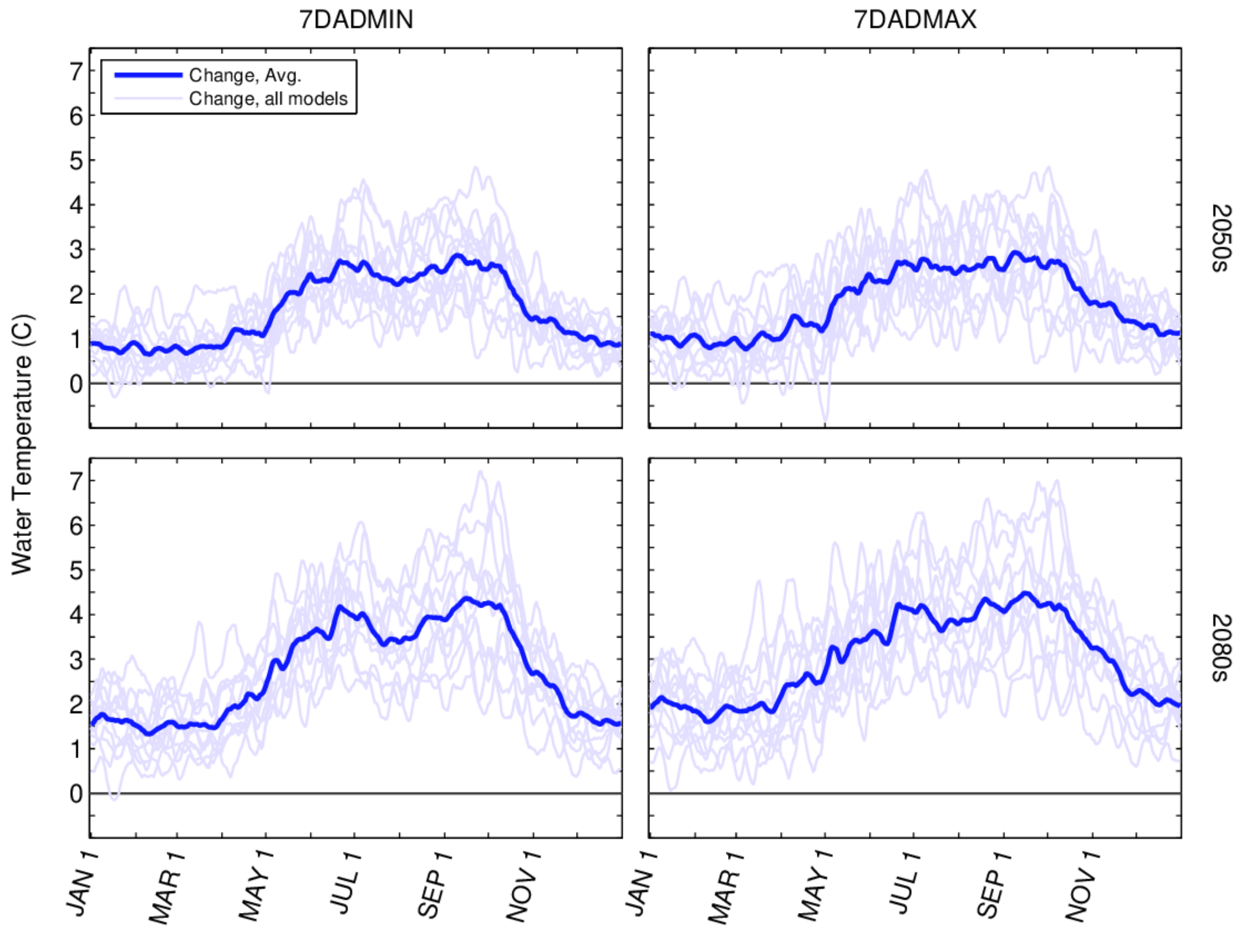

Figure 20. As in Figure 19 except showing the projected change in water temperature. The horizontal black line highlights the zero line, where anything above that line denotes warming.

noted above, we are focusing on 7-day average flows because in calibration we found that the model could not be adequately tuned to provide accurate hourly or daily water temperature estimates. In addition, we found it necessary to further bias correct the results of the RBM simulations: as noted above we removed the mean bias in June-September 7DADMAX (2.05°C) to obtain the results shown above (Table 7; Figures 12, 13). As indicated by the bias correction, calibration of the model proved challenging. In future work we recommend revisiting the calibration to improve the fit to the observations, and developing alternate estimates of future water temperature for comparison with the RBM results.

The annual cycle in 7DADMIN and 7DADMAX are shown in Figure 19, comparing historical simulations with the projections for the 2050s and 2080s. Figure 20 includes the same four plots, but showing projected change in water temperature. These show substantial warming throughout the year, with increases in summer about double those in winter. Warming for 7DADMIN and 7DADMAX are similar, though appear to be slightly larger for 7DADMIN.

Figure 21 shows the results for the number of days with 7DADMAX above 16°C and 22°C, following the metrics defined in Table 8. Both show clear increases in the number of days

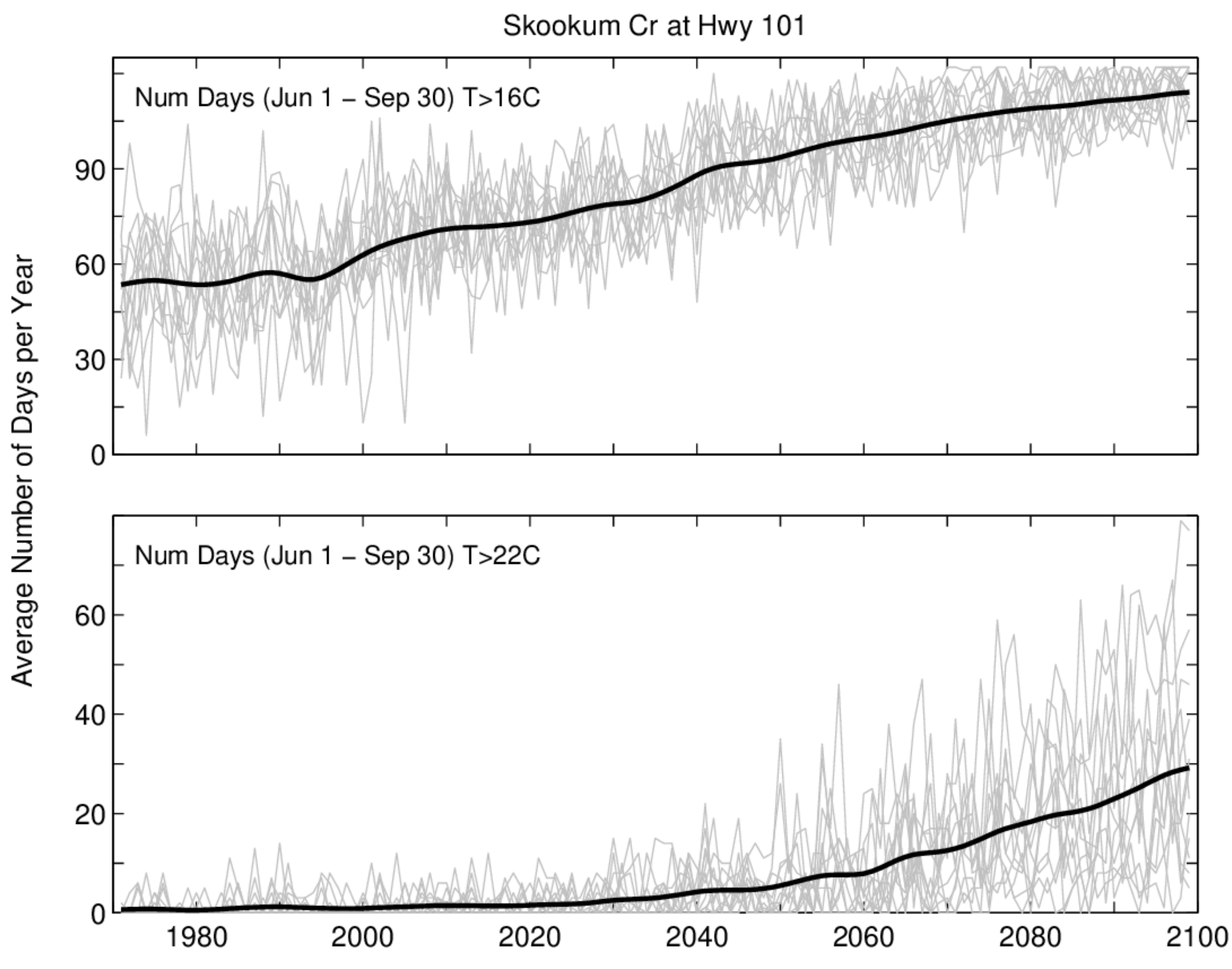

Figure 21. Time series of the number of days with 7DADMAX above 16°C (top) and 22°C (bottom; see metric definitions in Table 8). Plots show the average among the 12 WRF-CMIP5 simulations, smoothed with a 15-year gaussian filter to facilitate interpretation (thick black line), and the results for the individual models (without smoothing) in grey.

per year exceeding each threshold. Specifically, the number of days above 16°C are projected to double, on average, and the number of days above 22°C are projected to increase from nearly zero to almost 30 days per year, on average, by the end of the century. The number of days above 16°C are projected to increase fairly steadily throughout the century, whereas exceedances above 22°C are projected to acccelerate in the second half of the century.

Conclusions and Recommendations

Sea Level Rise

Sea level rise is projected to dramatically increase the frequency of inundation during storm surge events. Although many of the elevations surveyed by the Squaxin Island Tribe are beyond the reach of sea level extremes, now and in the future, many others are either currently at risk of flooding or will be at risk in the future due to sea level rise. Our analysis confirms that even small amounts of sea level rise can lead to large changes in the frequency of flooding. This is due to the relatively small differences between extreme event magnitudes in Puget Sound: for example, we estimate that the 100-year event at Arcadia is just over 14 inches higher than the 2-year event. This means that a sea level rise of just 14 inches, which all studies agree is highly likely over the coming decades, would result in a 50-fold increase in the frequency of today's 100-year coastal flood event.

Streamflow and Stream Temperature

The primary pathway for climate change to influence streamflow in Skookum and Kennedy Creeks is via changes in precipitation. The watershed is too warm to accumulate snowpack in winter, so there is no snowmelt effect on flows. Evapotranspiration (ET) could be another pathway for climate change impacts, particularly in summer when precipitation is relatively low. However, models project very little change, and possibly even slight increases, in humidity for the region. This suggests that the evaporative demand – as measured by potential evapotranspiration, for example – may not increase in the future in spite of substantial warming. Further research is needed on the topic of ET, which is generally not well understood, but based on our current understanding of climate change impacts we expect that precipitation will be the primary driver of changes in streamflow for Skookum and Kennedy Creeks.

Models project only small changes for seasonal and annual precipitation in the region (e.g. Mauger et al. 2015). Specifically: models project small increases in annual and winter precipitation and decreases in summer precipitation, though there is a wide range among model projections. In contrast, models more consistently project increases in extreme precipitation (e.g. Warner et al. 2015), projecting modest changes through mid-century, then accelerating thereafter. Given these projections, we expect modest increases in winter and modest decreases in summer streamflow as well as extreme low flows. Flood peaks, in contrast, are expected to increase in late century due to the higher intensity precipitation events.

Our streamflow results are generally consistent with these expectations. We find modest increases in winter flows (4 to 14%; Table 9), and larger increases in peak flows (13 to 31%; Table 10), on average, for the 2080s. However, the projections for low flows are larger, and there is more consistency among models than we expected (-9 to -20%; Table 11), on average, for the 2080s. There are two possible explanations for this: (1) projected changes in summer precipitation for this location are more pronounced than for the region as a whole, or (2) the models are projecting a larger change in ET than expected. Since low flows are projected to decrease, the models show marked increases in the number of days below specific low flow thresholds in each year, though these results are very sensitive to model biases and should be explored further to better assess their accuracy.

Water temperature is expected to warm due to climate change in response to decreases in summer streamflow and increases in air temperature. Climate change could also alter vegetation composition, but we did not consider land cover change in the current study. Warming is projected to be significant for the region; air temperature projections for Puget Sound show an average warming of 5.1ºC by the 2080s (relative to 1970-1999) and individual model projections range from 4.1ºC to 6.7ºC (Mauger et al. 2015).

The water temperature projections reflect the combined effects of decreased streamflow and higher air temperatures, showing increases of over 4ºC in summer, on average, by the 2080s. As with the low flow thresholds, this translates to many more days above the 16ºC, the Washington State water temperature standard for protecting salmonids, and an increasing prevalence of days above 22ºC. However, these results come with an important caveat, which is that we recommend further work to calibrate the stream temperature model. Calibration proved quite difficult for this model and there was not sufficient time to adequately refine the model. Since the results are likely quite sensitive to model calibration, we recommend further work to refine the calibration and produce independent estimates of water temperature change.

Prior work involved modeling that was much too coarse for small creeks, was based on statistical downscaling which does not adequately represent changes in precipitation extremes, was not calibrated for these locations, and only provided daily streamflow and monthly average water temperature projections. The current modeling addresses each of these limitations, and is calibrated specifically to the Skookum and Kennedy Creek watersheds. In addition, an important achievement in the current study was the incorporation of new dynamically downscaled projections in a hydrologic and stream temperature modeling study. This is particularly important in rain-dominant basins such as Skookum and Kennedy Creeks, where statistical downscaling is unlikely to accurately represent future changes in precipitation patterns.

Two key limitations of the current study are that we do not model deep or confined groundwater, and we do not consider possible changes in land cover and water management. Each of these could significantly alter the response of the watershed to climate change. In addition, our model does not account for the hydraulic and temperature implications of Summit Lake on Kennedy Creek. These and other issues are discussed in the section below.

Interpreting the results

Interpretation of these results, particularly given the focus on rare extreme events, can be challenging. Following are a few considerations to keep in mind when reviewing the results:

- Projected changes will always be governed by a combination of random variability and long-term trends due to climate change. This is particularly true for changes in extremes: Since by definition these events are rare, it is difficult to accurately assess how rapidly they will change. Although even the 2080s projections can be significantly influenced by natural variability, it can be helpful to focus on these late century projections since this is when the projected changes will be largest relative to natural variability.
- The WRF model used in this study has a spatial resolution of 12 km. This spatial resolution is not sufficient to estimate variations in weather conditions – current or future – across the watershed. Although the Skookum and Kennedy Creek watersheds are relatively small, it is possible that variations in weather conditions across each watershed could have an important influence on flows. Such variations would not be captured in the current modeling.
- A limitation of complex hydrologic models such as DHSVM is that there are more parameters to tune than there are observations with which to estimate them. This

means that it is possible for calibration to lead to "the right answer for the wrong reason". This is an especially challenging issue with climate change, since a model that performs well under current conditions may not be able to accurately capture changes in flow under future climate conditions. We have tested the model calibration in multiple ways in order to avoid this pitfall, but cannot be sure that the issue does not remain.

- DHSVM does not capture the effect of Summit Lake in Kennedy Creek. This means that the flow retention associated with the lake is not captured by our modeling. It may be worth considering if and how Summit Lake may alter the response to warming – either the projected changes in peak flows, low flows, or water temperature – and whether or not additional modeling is needed to quantify this effect.

- Shallow unconfined groundwater, as in any basin with permeable soils, will always play an important role by absorbing precipitation and releasing it to streams over the days and weeks following a rain event. The DHSVM model can approximate these shallow groundwater processes via its three soil layers. In contrast, DHSVM is not able to capture deep or confined groundwater. Although deep or confined aquifers are unlikely to play a major role in the hydrology of Skookum and Kennedy Creeks, we note that such processes would not be captured in DHSVM and, if important, a different model would be needed to capture such changes.

- In a recent study comparing evapotranspiration estimates, Milly and Dunne (2017) found that most hydrologic models dramatically overestimate future changes in evapotranspiration. This includes the Penman-Monteith method used in DHSVM. This could have important implications for summer flows, and would be important to estimate correctly in any future study evaluating the implications of possible changes in land cover. This is one reason we recommend exploring alternate ways of estimating potential changes in low flows.

- This project has focused on quantifying the changes in streamflow and water temperature due to climate change. To assess climate vulnerability, two other pieces of information are needed: (1) the "sensitivity" to these changes – how impacts scale with future changes, and (2) the "adaptive capacity" – how much these changes can be mitigated by changes in land use and water management or salmonid life history characteristics. Work to better understand these complementary aspects of vulnerability would help clarify if and when the current projections pose a problem for the Squaxin Island Tribe.

- The current work does not account for changes in land cover, whether due to natural or human causes. In reality, changes in land cover due to property ownership, population growth, wildfire, or a variety of other factors could all have consequences for both streamflow and water temperature. None of these are accounted for in the current study. Instead, these results are meant to quantify changes in streamflow and water temperature in the absence of other changes, providing a benchmark for comparison with other management or policy choices that may affect instream conditions.

The science of climate change will continue to evolve over time due to changes in greenhouse gas scenarios, global climate models, downscaling approaches, and the hydrologic and stream temperature modeling used to make localized streamflow and water temperature estimates. In addition, further refinements to the existing approach could result in improved model estimates of current and future conditions.

Future Work

The current analysis is not sufficient to model the area and depth of flooding due to sea level rise or changing streamflow, nor can it be used to assess their combined effects on flooding. Flood depths and extents can be modeled using a hydraulic model. Fortunately, an existing hydraulic model has already been developed for Skookum Creek. We recommend using this model to estimate current and future flood depths and extents.

The sea level rise approach used here is quite simple. Sea level variations at the Seattle gauge may not be representative of variations that are experienced at Arcadia, or the mouth of Skookum Creek. Future work could be updated with more localized estimates of sea level variations in Little Skookum Inlet, either through modeling or through new tidal observations. New modeling will soon be available from the USGS PS-CoSMoS program (Puget Sound Coastal Storm Monitoring System); these could be used to obtain independent estimates of extreme water levels. Similarly, new tidal observations, either at

Arcadia or within Skookum Inlet, would be particularly valuable for both real-time monitoring, and for evaluating the local characteristics of storm surge over time. Even if temporary, local tide gauge observations could be used to develop updated tidal predictions or further define the relationship with longer-term term observations such as those at Seattle.

As outlined in previous sections, there are limitations to the streamflow and stream temperature models used in this study. Addressing these limitations could lead to changes in the projections and provide greater confidence in the accuracy of the results. We recommend two general approaches to updating and refining these projections over time, with the goal of improving the information available for planning:

1. Update these models as methods and approaches improve over time, and
2. Develop independent estimates of likely changes in streamflow and stream temperature.

Now that the models have been developed, less work is needed to further refine them and thereby improve on the climate projections. Additional work could simply involve revisiting model calibration and further exploring the parameter space to ensure the models provide the best estimates possible. For example, DHSVM testing could determine if model performance could be improved with further adjustments to the climate inputs or changes to the soil parameters. Similarly, the RBM testing could evaluate the effects of further changes to the model parameters. Larger efforts at model improvement could involve gathering new data, testing new approaches to developing the meteorological inputs, or integrating the results obtained from groundwater and lake models. Streamflow and water temperature modeling could also be integrated with habitat or fish models to better capture potential impacts on salmonids. Finally, given the similarity in the modeling approaches, there may be opportunities to collaborate with the Point No Point Treaty Council as they continue to refine and update their modeling.

Independent estimates of climate change impacts would also bring greater confidence to the results. As above, these can be fairly simple to undertake or more complex. One possibility, in order to better understand baseline conditions, would simply be to evaluate existing observations (air temperature, precipitation, streamflow, water temperature, etc.), to determine if changes have already been observed. Another fairly simple option would be to consider notable past events as analogs for future conditions: for example, by looking at how low flows respond to conditions such as a summer heat wave or the time elapsed since the last rain event. Ideally such analyses would consider impacts on fish populations, relating these to particular climate conditions. Once sensitivities like these have been quantified, they can be compared to climate projections to see how often such conditions may occur in the future. A more involved way to obtain independent estimates of changes would be to use other models. Numerous other hydrologic models are available, each of which has advantages and disadvantages. Similar approaches could be taken for stream temperature. Regardless of the approach – whether refining existing models or developing new independent estimates of change – further examination of the results will lend greater confidence to the findings, thereby providing better support for climate-resilient planning.

Planning requires more than just understanding the implications of climate change. In addition, managers need to know which interventions are likely to be needed, which are most effective, and how the answers to these questions vary across the watershed. As above, some questions can be answered with relatively little effort. For example, the existing models presented in this study can be used to look at the implications of land cover change on streamflow and stream temperature. This can involve very detailed planning scenarios (e.g., targeted riparian buffers) or coarser testing meant for illustration purposes (e.g., estimating flows and water temperature under pre-settlement conditions). For example, the Tulalip Tribe is currently modeling the impacts of forest management on flow and stream temperature. Additional work could involve other models that capture forest dynamics (e.g., VELMA, Mckane 2014) or more complex ecosystem management decision support models (EMDS, Murphy et al. 2018).

Finally, we emphasize that these are questions that many communities and tribes around the region are asking. From a modeling point of view, the domain of the regional climate model used to develop these projections covers the entire Pacific Northwest, and the models used here can be applied elsewhere provided observations can be obtained or estimated for use in calibration. This means that the same approach used here could be applied to other watersheds and communities around the region, and that there may be opportunities collaborate with these communities as they work to interpret similar results and put them to use. As interest in this work grows, additional coordination may be warranted to capitalize on economies of scale.

Outreach and Products

All model results can be obtained from the project website:

https://cig.uw.edu/projects/future-sea-level-streamflow-and-stream-temperature-on-salmon-bearing-streams-of-the-squaxin-island-tribe/

The sea level rise results are compiled into a single spreadsheet that includes all sites surveyed by the Squaxin Island Tribe, along with the current and future projections for (a) average number of days per year exceeded, and (b) return interval for water levels reaching that elevation.

Figure 22 illustrates the file structure for the streamflow and stream temperature results. Time series files and 30-year averages are provided for the DHSVM and RBM results as described above and listed in Tables 7 and 8. These are included in separate files for each model: one for the WRF-NARR simulation and one for each of the WRF-CMIP5 simulations (labeled according to the names of the GCMs listed in Table 2). Files are labeled according to the model and metric evaluated. For example, the peak flow time series files include the suffix "_PeakFlows.csv", while the

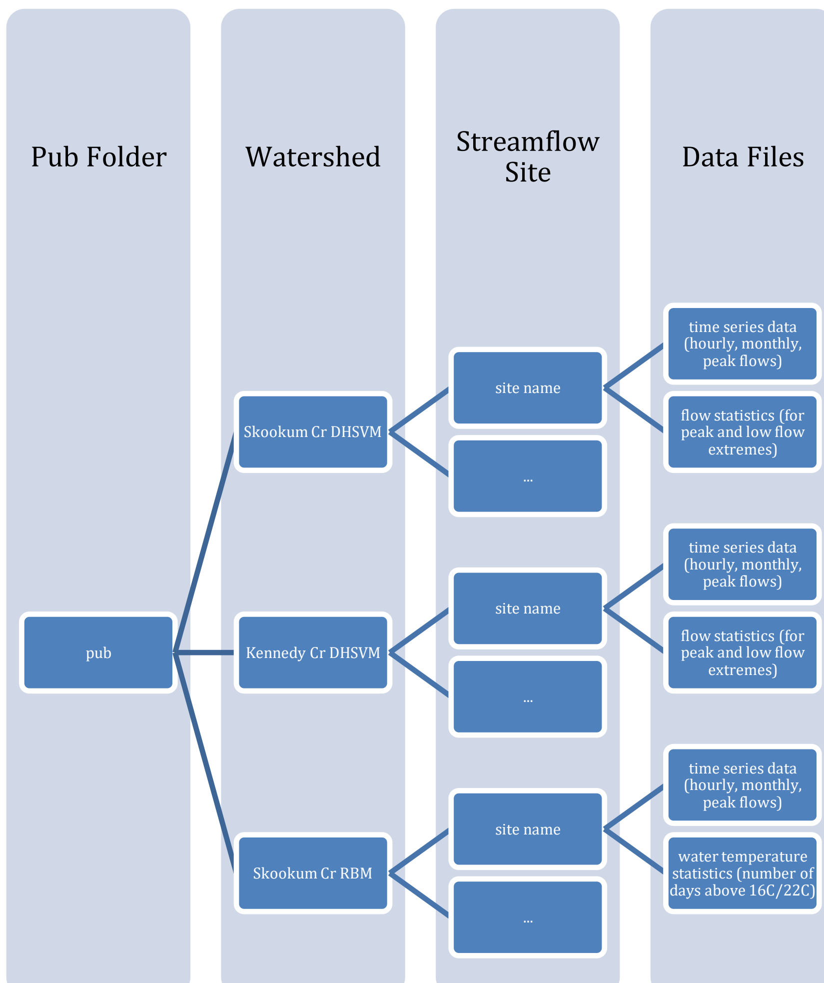

Figure 22. Data structure for the model results.

peak flow statistics have the suffix "_PeakStats.csv".

The authors will continue to support interpretation and outreach by the project collaborators at the Squaxin Island Tribe. Otherwise, no additional outreach is currently planned.

Section 5: References

Andreadis, K. M., Storck, P., & Lettenmaier, D. P. (2009). Modeling snow accumulation and ablation processes in forested environments. Water resources research, 45(5).

Boessow, S.N., H.A. Beecher, and K.K. Gates. 2020. Spawning habitat suitability for coastal cutthroat trout: Microhabitat and mesohabitat. Aquatic Conserv: Mar Freshw Ecosyst. 2020;1–14. https://doi.org/10.1002/aqc.3431

Bowling, L. C., & Lettenmaier, D. P. (2001). The effects of forest roads and harvest on catchment hydrology in a mountainous maritime environment. Water Science and Application, 2, 145-164.

Brewer, M. C., & Mass, C. F. (2016). Projected changes in western US large-scale summer synoptic circulations and variability in CMIP5 models. Journal of Climate, 29(16), 5965-5978. https://doi.org/10.1175/JCLI-D-15-0598.1

Chegwidden, O. S., Nijssen, B., Rupp, D. E., Arnold, J. R., Clark, M. P., Hamman, J. J., ... & Xiao, M. (2019). How do modeling decisions affect the spread among hydrologic climate change projections? Exploring a large ensemble of simulations across a diversity of hydroclimates. Earth's Future, 7(6), 623-637. https://doi.org/10.1029/2018EF001047

Chen, X., Leung, L. R., Gao, Y., Liu, Y., Wigmosta, M., & Richmond, M. (2018). Predictability of extreme precipitation in western US watersheds based on atmospheric river occurrence, intensity, and duration. Geophysical Research Letters, 45(21), 11-693. https://doi.org/10.1029/2018GL079831

Cristea, N. C., Lundquist, J. D., Loheide, S. P., Lowry, C. S., & Moore, C. E. (2014). Modelling how vegetation cover affects climate change impacts on streamflow timing and magnitude in the snowmelt-dominated upper Tuolumne Basin, Sierra Nevada. Hydrological processes, 28(12), 3896-3918.

Cuo, L., Lettenmaier, D. P., Alberti, M., & Richey, J. E. (2009). Effects of a century of land cover and climate change on the hydrology of the Puget Sound basin. Hydrological Processes: An International Journal, 23(6), 907-933.

Cuo, L., Beyene, T. K., Voisin, N., Su, F., Lettenmaier, D. P., Alberti, M., & Richey, J. E. (2011). Effects of mid-twenty-first century climate and land cover change on the hydrology of the Puget Sound basin, Washington. Hydrological Processes, 25(11), 1729-1753.

Currier, W. R., Thorson, T., & Lundquist, J. D. (2017). Independent evaluation of frozen precipitation from WRF and PRISM in the Olympic Mountains. Journal of Hydrometeorology, 18(10), 2681-2703. https://doi.org/10.1175/JHM-D-17-0026.1

Daly, C., Halbleib, M., Smith, J. I., Gibson, W. P., Doggett, M. K., Taylor, G. H., ... & Pasteris, P. P. (2008). Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. International Journal of Climatology: a Journal of the Royal Meteorological Society, 28(15), 2031-2064. https://doi.org/10.1002/joc.1688

Dilley, A. C., & O'brien, D. M. (1998). Estimating downward clear sky long-wave irradiance at the surface from screen temperature and precipitable water. Quarterly Journal of the Royal Meteorological Society, 124(549), 1391-1401. https://doi.org/10.1002/qj.49712454903

Hamlet, A. F., M. M. Elsner, G. S. Mauger, S. Y. Lee, I. Tohver, and R. A. Norheim. 2013. An Overview of the Columbia Basin Climate Change Scenarios Project: Approach, Methods, and Summary of Key Results. Atmosphere-Ocean 51:392-415. https://doi.org/10.1080/07055900.2013.819555

Hinkelman, L. M., Lapo, K. E., Cristea, N. C., & Lundquist, J. D. (2015). Using CERES SYN surface irradiance data as forcing for snowmelt simulation in complex terrain. Journal of Hydrometeorology, 16(5), 2133-2152.

Kuntz, D. 2021. Personal communication with Daniel Kuntz, biologist about annual spawner inventories by the Squaxin Island Tribe.

Lee, S.-Y., G.S. Mauger, and J.S. Won. 2018. Effect of Climate Change on Flooding in King County Rivers: Using New Regional Climate Model Simulations to Quantify Changes in Flood Risk. Report prepared for King County. Climate Impacts Group, University of Washington. https://cig.uw.edu/publications/effect-of-climate-change-on-flooding-in-king-county-rivers-using-new-regional-climate-model-simulations-to-quantify-changes-in-flood-risk/

Lorente-Plazas, R., Mitchell, T. P., Mauger, G., & Salathé, E. P. (2018). Local enhancement of extreme precipitation during atmospheric rivers as simulated in a regional climate model. Journal of Hydrometeorology, 19(9), 1429-1446. https://doi.org/10.1175/JHM-D-17-0246.1

Mass, C. F., Salathé Jr, E. P., Steed, R., & Baars, J. (2022). The mesoscale response to global warming over the Pacific Northwest evaluated using a regional climate model ensemble. Journal of Climate, 35(6), 2035-2053. https://doi.org/10.1175/JCLI-D-21-0061.1

Mauger, G.S., J.H. Casola, H.A. Morgan, R.L. Strauch, B. Jones, B. Curry, T.M. Busch Isaksen, L. Whitely Binder, M.B. Krosby, and A.K. Snover. 2015. State of Knowledge: Climate Change in Puget Sound. Report prepared for the Puget Sound Partnership and the National Oceanic and Atmospheric Administration. Climate Impacts Group, University of Washington, Seattle. doi:10.7915/CIG93777D. https://cig.uw.edu/resources/special-reports/ps-sok/

Mauger, G.S., S.-Y. Lee, C. Bandaragoda, Y. Serra, J.S. Won, 2016. Refined Estimates of Climate Change Affected Hydrology in the Chehalis basin. Report prepared for Anchor QEA, LLC. Climate Impacts Group, University of Washington, Seattle. https://doi.org/10.7915/CIG53F4MH

Mauger, G.S., J.S. Won (2019). Expanding the ensemble of precipitation projections for King County. Report prepared for the King County Department of Natural Resources. Climate Impacts Group, University of Washington, Seattle. https://cig.uw.edu/publications/expanding-the-ensemble-of-precipitation-projections-for-king-county/

Mauger, G.S., J.S. Won, N. Cristea (2021a). Projected Changes in Streamflow and Water Temperature in Chico Creek, Kitsap County. Report prepared for the Suquamish Tribe. Climate Impacts Group, University of Washington, Seattle. https://doi.org/10.6069/A5T2-TP41

Mauger, G.S., J. Robinson, R.J. Mitchell, J. Won, and N. Cristea (2021b). Climate Change & Flooding in Snohomish County: New Dynamically-Downscaled Hydrologic Model Projections. Report prepared for Snohomish County. Climate Impacts Group, University of Washington. https://doi.org/10.6069/SQJ2-DF62

Miller, I.M., Morgan, H., Mauger, G., Newton, T., Weldon, R., Schmidt, D., Welch, M., Grossman, E. 2018. Projected Sea Level Rise for Washington State – A 2018

Assess-ment. A collaboration of Washington Sea Grant, University of Washington Climate Impacts Group, Oregon State University, University of Washington, and US Geologi-cal Survey. Prepared for the Washington Coastal Resilience Project. https://cig.uw.edu/publications/projected-sea-level-rise-in-washington-state-a-2018-assessment/

Minder, J. R., Mote, P. W., & Lundquist, J. D. (2010). Surface temperature lapse rates over complex terrain: Lessons from the Cascade Mountains. Journal of Geophysical Research: Atmospheres, 115(D14). https://doi.org/10.1029/2009JD013493

Murphy, R. and Rossi, C. (2019). Modeling the Effects of Forecasted Climate Change on Fish-bearing Streams in Western Washington State. Report prepared by the Point No Point Treaty Council. http://climate.pnptc.org/wp-content/uploads/2019/09/PNPTC_StreamflowModeling-_Phase1_TechnicalSummary_FINAL.pdf

Murphy, R. and Rossi, C. (2020). Effects of Forecasted Climate Change on Stream Temperatures of Fish-bearing Streams in Western Washington State. Report prepared by the Point No Point Treaty Council. http://climate.pnptc.org/wp-content/uploads/2020/06/PNPTC_RBMstreamTempModeling_TechnicalSummary_FINAL.pdf

Naz, B. S., Frans, C. D., Clarke, G. K. C., Burns, P., & Lettenmaier, D. P. (2014). Modeling the effect of glacier recession on streamflow response using a coupled glacio-hydrological model. Hydrology and Earth System Sciences, 18(2), 787-802.

PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu, version M3. data created 2021-10-29, accessed Nov 2022.

Salathé, E. P., Leung, L. R., Qian, Y., & Zhang, Y. (2010). Regional climate model projections for the State of Washington. Climatic Change, 102, 51-75. https://doi.org/10.1007/s10584-010-9849-y

Salathé Jr, E. P., Hamlet, A. F., Mass, C. F., Lee, S. Y., Stumbaugh, M., & Steed, R. (2014). Estimates of twenty-first-century flood risk in the Pacific Northwest based on regional climate model simulations. Journal of Hydrometeorology, 15(5), 1881-1899. https://doi.org/10.1175/JHM-D-13-0137.1

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Duda, M. G., ... & Powers, J. G. (2008). A description of the advanced research WRF version 3, NCAR Technical Note. National Center for Atmospheric Research: Boulder, CO, USA. http://opensky.ucar.edu/islandora/object/technotes%3A500/datastream/PDF/download/citation.pdf

Storck, P., Bowling, L., Wetherbee, P., & Lettenmaier, D. (1998). Application of a GIS-based distributed hydrology model for prediction of forest harvest effects on peak stream flow in the Pacific Northwest. Hydrological Processes, 12(6), 889-904.

Storck, P. (2000). Trees, snow and flooding: An investigation of forest canopy effects on snow accumulation and melt at the plot and watershed scales in the Pacific Northwest.

Storck, P., Lettenmaier, D. P., & Bolton, S. M. (2002). Measurement of snow interception and canopy effects on snow accumulation and melt in a mountainous maritime climate, Oregon, United States. Water Resources Research, 38(11), 5-1.

Sun, N., J. Yearsley, N. Voisin, and D.P. Lettenmaier. 2015. A spatially distributed model for the assessment of land use impacts on stream temperature in small urban watersheds. Hydrological Processes 29: 2331-2345 https://doi.org/10.1002/hyp.10363

Sun, N., Wigmosta, M., Zhou, T., Lundquist, J., Dickerson-Lange, S., and Cristea, N. (2018). Evaluating the functionality and streamflow impacts of explicitly modelling forest–snow interactions and canopy gaps in a distributed hydrologic model: Hydrological Processes, v. 32, p. 2128–2140, https://doi.org/10.1002/hyp.13150

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society, 93(4), 485-498. https://doi.org/10.1175/BAMS-D-11-00094.1

Unsworth, M. H., & Monteith, J. L. (1975). Long‐wave radiation at the ground I. Angular distribution of incoming radiation. Quarterly Journal of the Royal Meteorological Society, 101(427), 13-24. https://doi.org/10.1002/qj.49710142703

Vano, J.A., Voisin, N., Cuo, L. et al. Climate change impacts on water management in the Puget Sound region, Washington State, USA. Climatic Change 102, 261–286 (2010). https://doi.org/10.1007/s10584-010-9846-1

Warner, M. D., Mass, C. F., & Salathé, E. P. (2015). Changes in winter atmospheric rivers along the North American west coast in CMIP5 climate models. Journal of Hydrometeorology, 16(1), 118-128. https://doi.org/10.1175/JHM-D-14-0080.1

Whitaker, A., Alila, Y., Beckers, J., & Toews, D. (2003). Application of the distributed hydrology soil vegetation model to Redfish Creek, British Columbia: model evaluation using internal catchment data. Hydrological processes, 17(2), 199-224.

Wigmosta, M. S., L.W. Vail, and D.P. Lettenmaier. 1994. A distributed hydrology-vegetation model for complex terrain, Water Resources Research 30:1665–1680. http://www.hydro.washington.edu/Lettenmaier/Models/DHSVM/

Wigmosta, M. S., & Lettenmaier, D. P. (1999). A comparison of simplified methods for routing topographically driven subsurface flow. Water Resources Research, 35(1), 255-264.

Wigmosta, M. S., Nijssen, B., Storck, P., & Lettenmaier, D. P. (2002). The distributed hydrology soil vegetation model. Mathematical models of small watershed hydrology and applications, 7-42.

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., ... & Rose, S. K. (2011). The representative concentration pathways: an overview. Climatic change, 109(1), 5-31. https://doi.org/10.1007/s10584-011-0148-z

Appendix: Additional Figures

This section includes additional figures requested by our collaborators at the Squaxin Island Tribe. They are included here for reference.

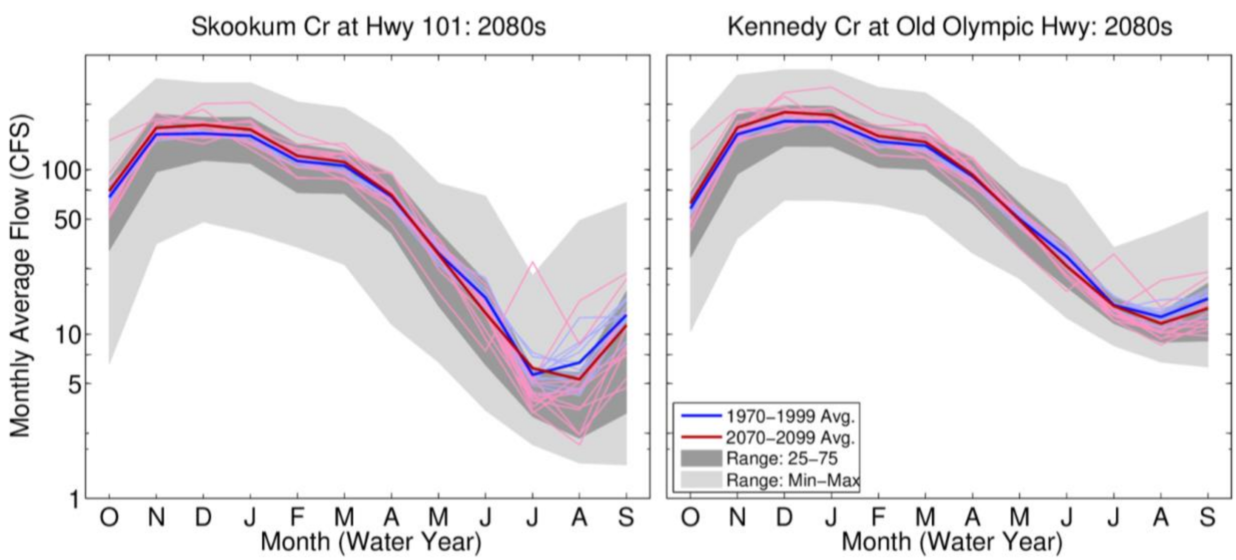

Figure A1. As in Figure 14, except showing the log of the flows on the y-axis. *Description:* Historical and future monthly flows for Skookum and Kennedy Creeks. Each line shows the results for one WRF-CMIP5 projection: historical (1980s) in blue and 2080s in red. Thick lines show the model average, thin lines the individual model projections. For comparison with the lines, which show the 30-year averages, the grey shading shows the model-estimated historical range in monthly flows (25^{th}-75^{th} percentile: dark grey; min-max range: light grey).