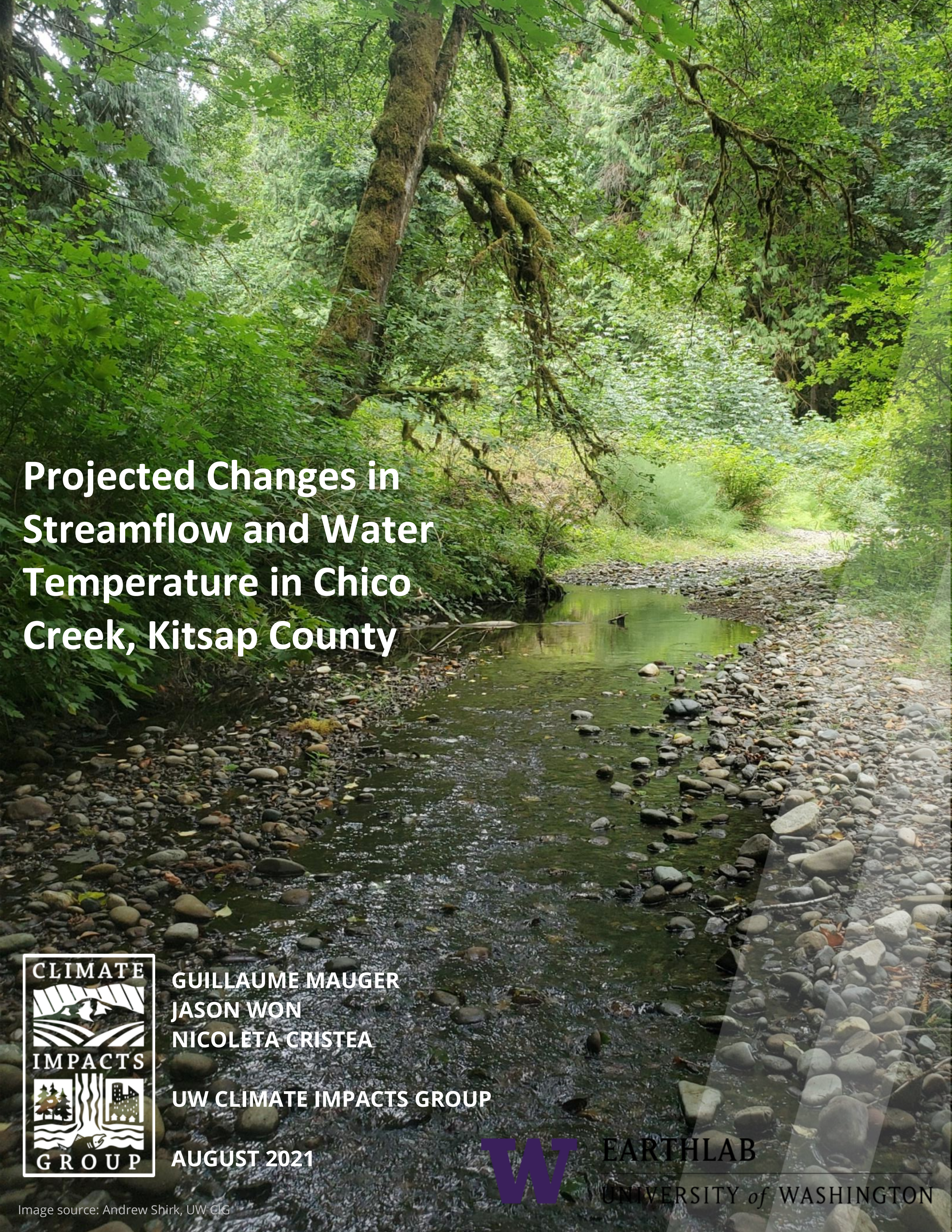

Projected Changes in Streamflow and Water Temperature in Chico Creek, Kitsap County

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UW CLIMATE IMPACTS GROUP

AUGUST 2021

Image source: Andrew Shirk, UW CIG

Juvenile coho salmon in lower reach of Wildcat Creek, tributary to Chico Creek, August 2021. Photo credit: Tiffany Royal, Northwest Indian Fisheries Commission.

COVER IMAGE: Lower reach of Lost Creek, tributary to Chico Creek, August 2021. *Photo credit:* Steve Todd, Suquamish Tribe

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ACKNOWLEDGEMENTS: This work was funded by the Bureau of Indian Affairs through an Adaptation Planning and Data Development Grant and Cooperative Agreement with the Suquamish Tribe. The authors thank Steve Todd for his help and input throughout the project, and Tom Ostrom and Paul Williams for their thoughtful comments on this report.

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Executive Summary

The purpose of this study is to understand future streamflows and water temperatures, for use in assessing the impacts of climate change on salmonids in the Chico Creek Watershed. This information is intended to help the Suquamish Tribe prioritize conservation and restoration actions. To do this, we developed a high-resolution, physically-based hydrological and water temperature model for the Chico Creek watershed, quantifying future changes in streamflow and summer water temperature.

Our findings show minimal changes in seasonal average and annual minimum flows. In contrast, models project larger changes in peak flows and substantial increases in water temperature. Specifically, nearly all models project increases in the 2-year peak flow event throughout the century, with a model-average increases of ~10-15% by the 2080s (relative to 1980-2009). Water temperature is projected to warm substantially, with annual maximum 7DADMAX (the 7-day average in daily maximum water temperatures, used in many water quality regulations) projected to increase from +2.1ºC to +2.9ºC, on average, by the 2080s (as above, relative to 1980-2009). Similarly, models project dramatic increases in the number of days exceeding temperature standards for salmon in summer.

Although the models are well calibrated and perform well in many of the tests that were applied, there are important limitations to consider. In particular, groundwater is not adequately represented in the model, nor is the effect of the lakes. Kitsap Lake in particular is known to substantially affect water temperatures downstream of the lake. In addition, this study does not consider the effects of land cover change, whether due to climate change or land use and restoration actions. Additional work would be needed to understand the implications of these limitations, either through additional model refinement or by developing independent estimates of future flows and water temperatures.

Background

Chico Creek (Figures 1 and 2) and other watersheds in Puget Sound support Suquamish Tribe fisheries by providing important salmonid refugia, including high quality spawning, rearing, and migration habitat for chum, coho, and chinook salmon and steelhead and cutthroat trout (May and Peterson, 2003). However, these watersheds have been impaired by human land use practices including timber harvest, the removal of beaver, agriculture, road construction, residential and commercial development, and increased competition for water resources. These human activities have altered the hydrologic regime (higher peaks and lower baseflows), decreasing ecological productivity, complexity, and biodiversity in riparian and aquatic systems, and posing a threat to the long term resilience of native

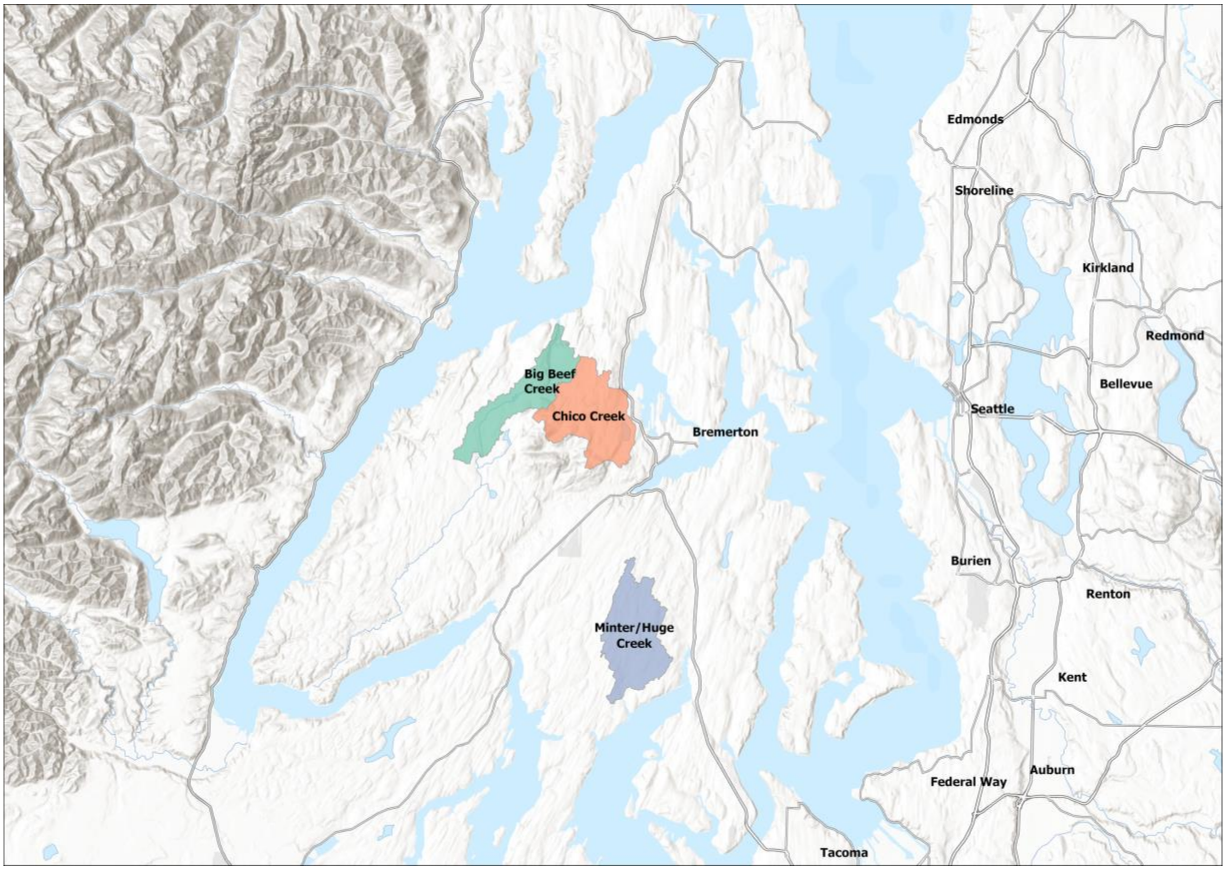

Figure 1. Area map showing Chico Creek as well as Big Beef and Minter (Huge) Creeks, for reference, all located on the Kitsap Peninsula in western Puget Sound.

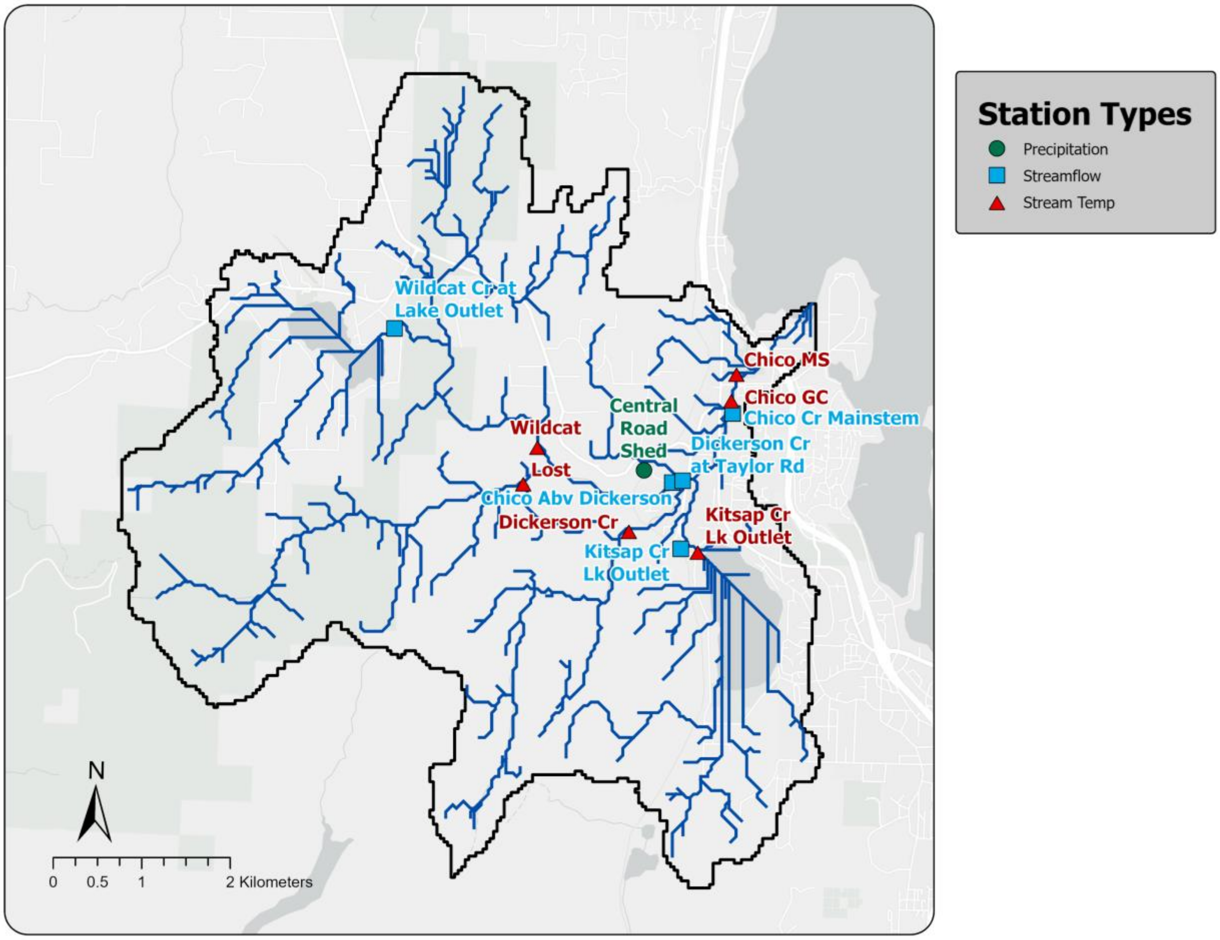

Figure 2. Map of Chico Creek, showing the observing locations highlighted in Table 1 and the model stream network.

salmonid populations in the Chico Creek watershed (Haring, 2000; Natural Systems Design, Inc., 2014).

During most of the summer, water temperature in lower Chico Creek exceeds the standard 7-day average daily maximum (7DADMAX) of 16°C for Core Summer Salmonid Habitat set by the Washington State Department of Ecology. Projected air temperature increases and precipitation changes are likely to exacerbate this trend in the future, threatening the persistence of salmon, primarily for species that reside in freshwater during summer months (i.e., coho, steelhead, cutthroat trout). A warmer climate is also likely to intensify heavy rain events known as atmospheric rivers (Warner et al. 2015; Espinoza et al. 2017), which will significantly influence the hydrology of rain-dominant watersheds such as Chico Creek and its tributaries. Floods can directly harm salmonids by washing eggs out of redds (egg nests), causing physical harm to some fish, and by prematurely flushing juvenile salmon and their invertebrate prey downstream. An assessment of the Chico Creek Watershed (Natural Systems Design, Inc. 2014) identified potential future impacts on hydrology and stream temperature in the watershed, based on findings from regional studies. Similarly, the Point No Point Treaty Council recently modeled future streamflow and water temperature on several Kitsap peninsula watersheds including Stavis, Seabeck, Big Beef and Little Anderson creeks (Murphy and Rossi 2019, 2020). However, no specific assessment of these projected changes has been conducted for the Chico Creek watershed, and few if any detailed studies have examined these effects on small rain-dominated watersheds. In addition, all previous studies in the region have used statistical downscaling, and recent research has shown that dynamical downscaling is needed to accurately capture changes in rain intensity (Salathé et al., 2014).

In recent years there have been significant efforts by the Suquamish Tribe, Kitsap County, and other partners to implement fish passage and other habitat restoration projects, and to secure conservation protections for riparian corridors to benefit salmon. The purpose of this study is to understand future stream flows and water temperatures, for use in assessing the impacts of climate change on salmonids in the Chico Creek Watershed. To do this, we developed a high-resolution, physically-based hydrological and water temperature model for the Chico Creek watershed, quantifying future changes in streamflow and summer water temperature. This information will help the Tribe prioritize conservation and restoration actions.

Data

Observations

Table 1 lists the weather and stream observations considered for the analysis. The weather stations were used for evaluating the gridded meteorological datasets described in the following section. Figures 3-8 show the time series, and relationships among, daily observations for each station. Although in some cases other observations were available, those highlighted (shading) in Table 1 were chosen for the analysis – primarily based on data quality, length of record, and overlap with the time period for the historical simulations (1981-2015).

Table 1. Monitoring locations for observations used in the analysis. AWN stands for AgWeatherNet, operated by WSU; and KPUD stands for Kitsap Public Utility District. The shading highlights stations that were used for model evaluation; other stations were not used in the remainder of this study.

Variable	Stream Name/Station	Source	Lat.	Long.	Period of Record
Air Temp.	Poulsbo.S	AWN	47.6564N	122.6479W	2013-2019
Precipitation	Central Road Shed	KPUD	47.5873N	122.7206W	2010-2019
Streamflow	Chico Creek #12072000	USGS	47.5903N	122.7083W	1948-1950, 1962-74
	Big Beef Cr #12069550	USGS	47. 6408N	122.7839W	1970-1981, 1996-2012
	Huge Cr # 12073500	USGS	47.3894N	122.6978W	1947-1969, 1978-2019
	Chico Cr Mainstem	KPUD	47.5933N	122.7075W	1991-1996, 2001-2009
	Chico Cr at Taylor Rd ("Chico Abv Dickerson")	KPUD	47.5861N	122.7163W	2001-2003, 2012-2019
	Kitsap Cr at Lake Outlet	KPUD	47.5794N	122.7121W	2001-2005, 2011-2019
	Dickerson Cr at Taylor Rd	KPUD	47.5863N	122.7148W	2001, 2003-2005
	Wildcat Cr at Lake Outlet	KPUD	47.6012N	122.7587W	2001-2019

Variable	Stream Name/Station	Source	Lat.	Long.	Period of Record
Water Temp.	Lost	Suquamish	47.5859N	122.7387W	2002-2019
	Lost Smolt	Suquamish	47.5874N	122.7350W	2017-2019
	Wildcat	Suquamish	47.5895N	122.7367W	2002-2019
	Wildcat Smolt	Suquamish	47.5877N	122.7345W	2017-2019
	Upper Dickerson	Suquamish	47.5690N	122.7280W	2018-2019
	Upper WF Dickerson	Suquamish	47.5708N	122.7384W	2018-2019
	Dickerson Cr	Suquamish	47.5814N	122.7226W	2002-2019
	Upper Kitsap	Suquamish	47.5525N	122.7131W	2018-2019
	Kitsap Cr at Lk outlet	Suquamish	47.5795N	122.7123W	2002-2003, 2019
	Chico Mainstem nr Golf Course ("Chico GC")	Suquamish	47.5948N	122.7078W	2002, 2004, 2006-2007
	Chico Mainstem ("Chico MS")	Suquamish	47.5974N	122.7070W	2002, 2005, 2009,2011-2012, 2014-2019

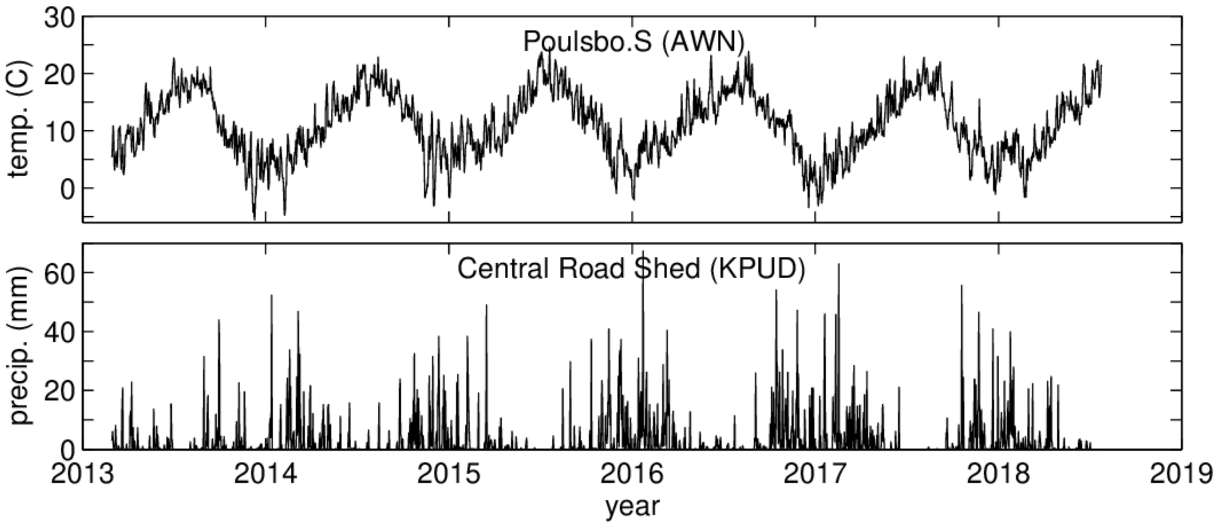

Figure 3. Daily air temperature observations from the AgWeatherNet Poulsbo.S station (top, °C), and daily precipitation observations from the KPUD Central Road Shed rain gauge (bottom, mm).

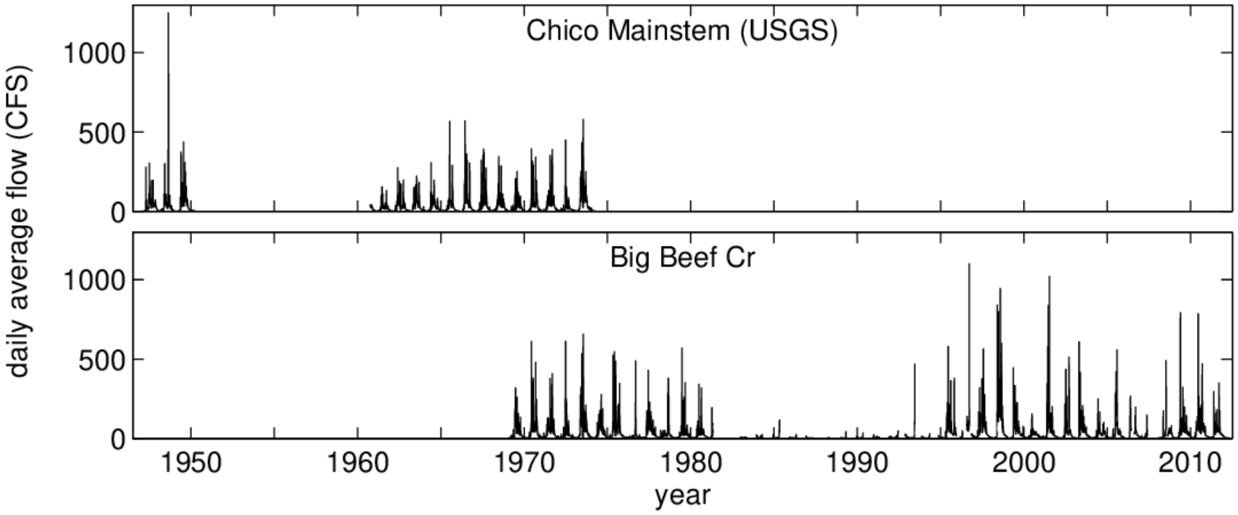

Figure 4. Daily streamflow time series, in CFS, from the USGS streamflow gauges at Chico Creek (top) and Big Beef Creek (bottom). Results from these gauges were not used in the analysis due to either a lack of recent observations (Chico Mainstem gauge; observations end in 1974) or because summer flows in adjacent watersheds were found to correlate poorly with those in Chico Creek (Big Beef Creek).

Streamflow Data Evaluation

Streamflow observations are fairly limited in Chico Creek. As a result, a first analysis looks at nearby gauges to see how observations at the USGS mainstem Chico Creek gauge correlate with observations at other nearby gauges with long-term streamflow observations (Figure 5). This analysis shows a close correlation with all three nearby gauges, but a particularly strong agreement with flows at Big Beef Creek, which includes observations spanning from 1969-2012

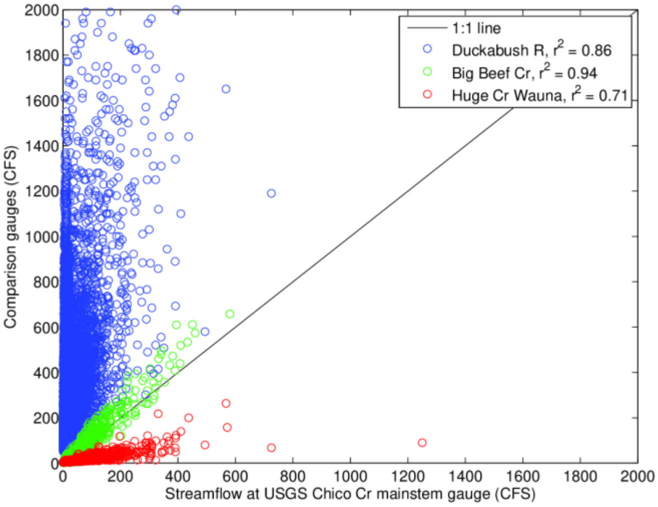

Figure 5. Comparing daily streamflow at the USGS mainstem Chico Creek gauge with observations from three other nearby USGS gauges with long-term records.

(Figure 4). This is in contrast with the USGS Chico Creek gauge, which does not have any observations after 1974 (Figure 4). A comparison of flows during just the month of August revealed much lower correlations. This is not surprising, given the much larger role played by land cover and geology, as well as surface and groundwater withdrawals, during low flow periods. In addition, gauges may not be able to accurately monitor flows when they are quite low (e.g.: less than 1 CFS).

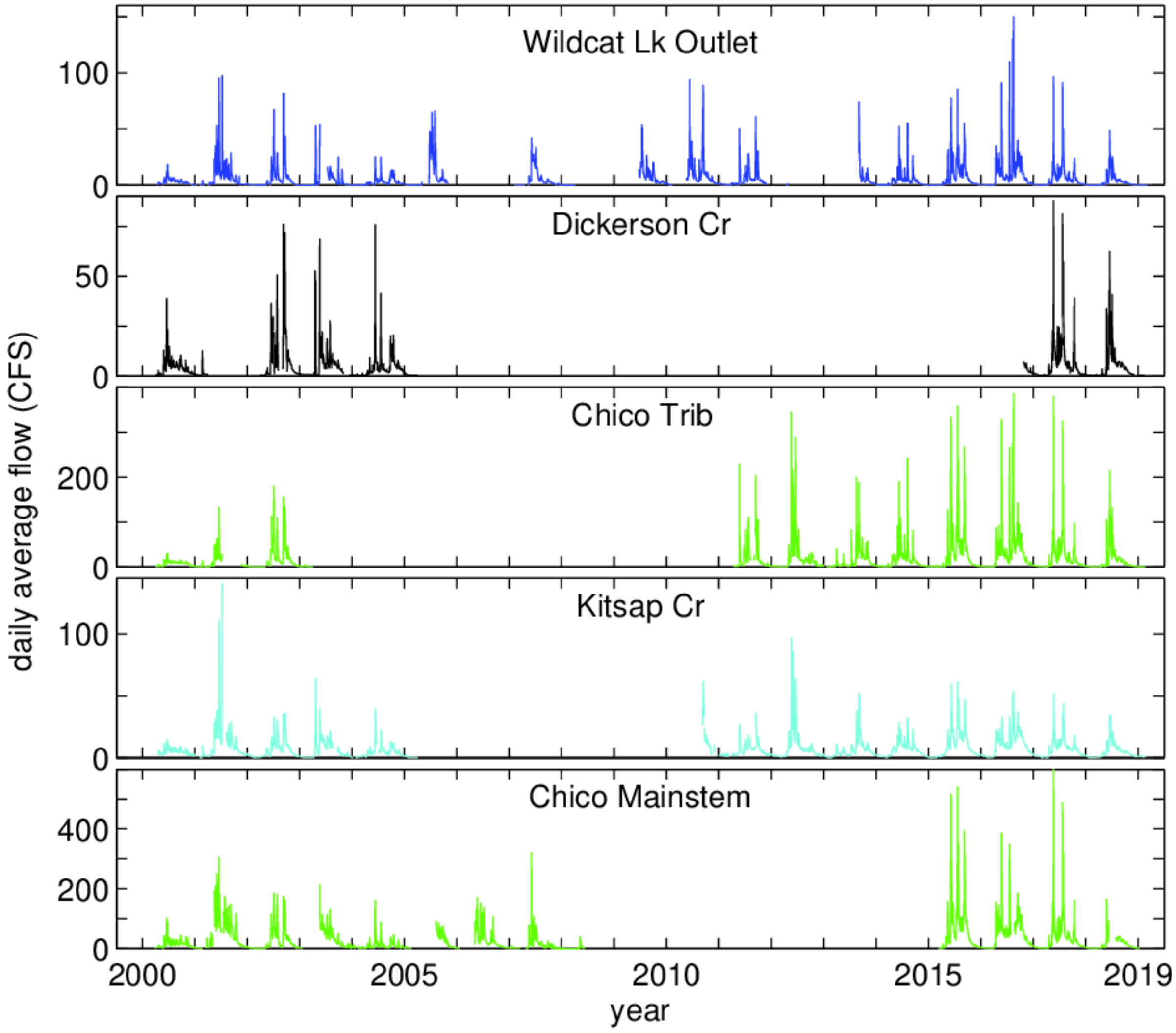

Figure 6. Daily streamflow time series, in CFS, from the KPUD streamflow gauges within the Chico Creek watershed.

Observations at the Kitsap Public Utilities District (KPUD) gauges are also sparse, but have better overlap with the period of record for the historical climate simulation (1980-2015, Figure 6). Correlations between the three KPUD gauges indicated a strong relationship between flow at each location, but again emphasized the differences in summer low flow patterns for each tributary. Although the lack of overlap with the PNNL-WRF simulation (1981-2015) is not ideal, the low correlation between low flows in Big Beef and Chico Creek suggests that KPUD gauges remain the best option for calibration.

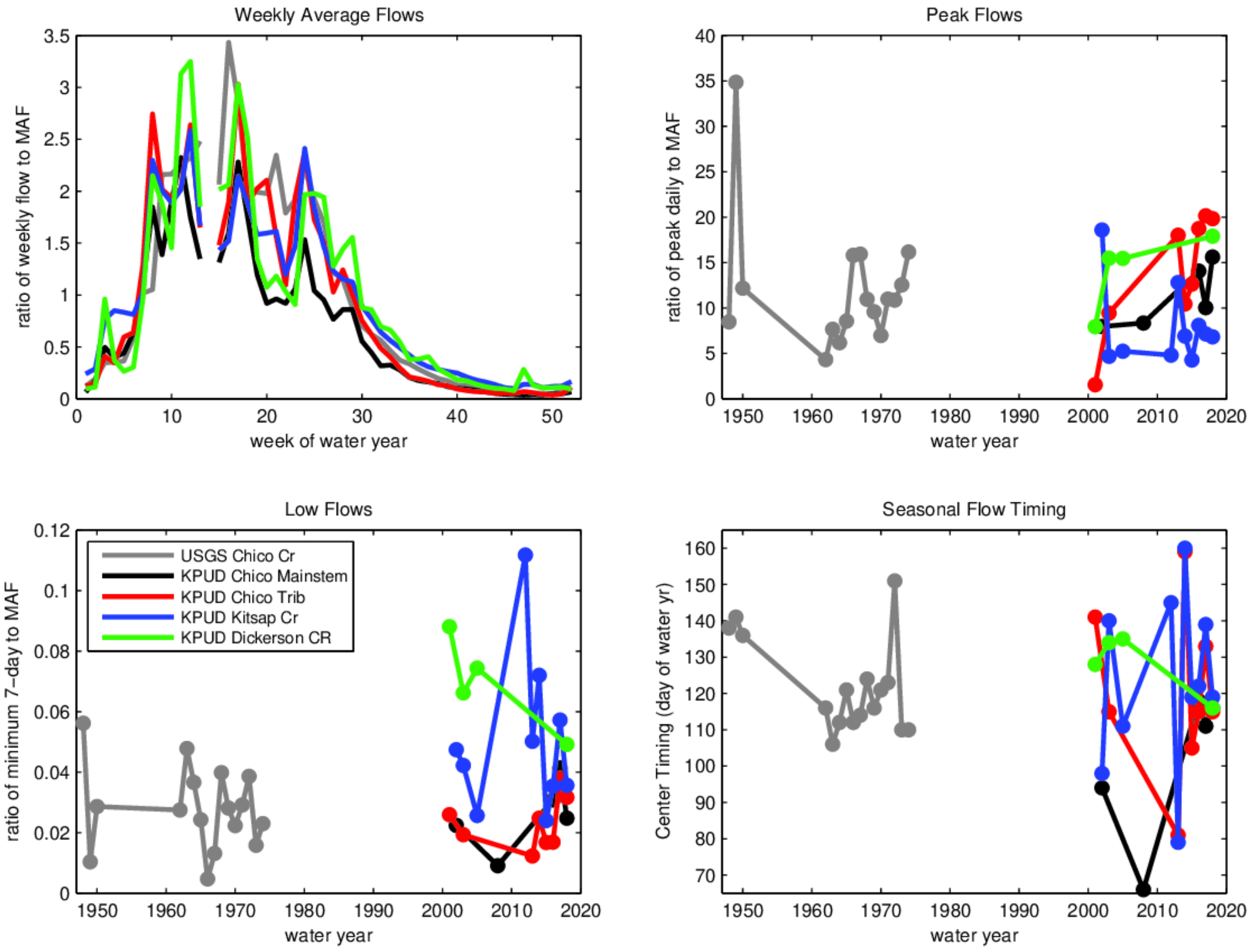

Figure 7. Streamflow comparisons across four Chico Creek gauges. All flow values are normalized by mean annual flow (MAF) in order to allow for apples-to-apples comparisons across gauges. "Center Timing" is the day when half of the water year's flow has passed.

In order to better understand both the climatology of streamflow and possible changes over time, Figure 7 shows a series of plots that summarize monthly flows, peak flows, low flows, and the timing of streamflow at four Chico Creek gauges. Since absolute flows are different at each location, the flow estimates are all normalized in order to be able to compare results across gauges. These show remarkably similar patterns in the annual cycle of streamflow. This suggests that calibration to one sub-basin (e.g, the Dickerson Creek gauge) should generally be adequate for calibrating the hydrologic model for the entire watershed.

Figure 8 shows the time series of water temperature from the 12 stream temperature gauges listed in Table 1. As noted in the table, some of these only include measurements taken after 2015. Since these do not overlap with the historical climate simulation, they were not included in the present analysis.

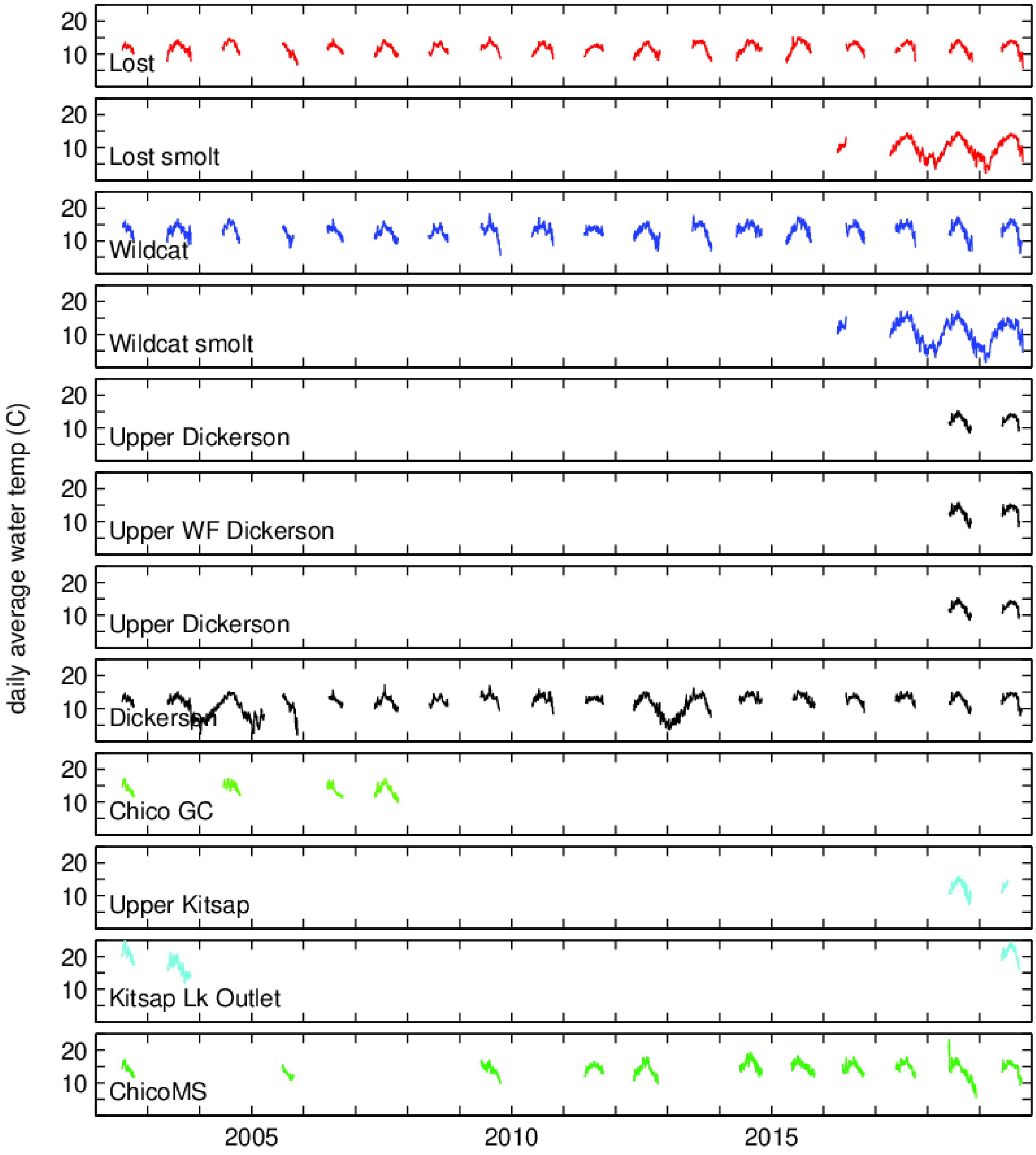

Figure 8. Daily water temperature time series (ºC) within the Chico Creek watershed (Data from Suquamish Tribe).

Gridded Climate Datasets

This section describes the downscaled climate 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 2; these are described in greater depth in the sections that follow.

Table 2. 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-OBS	Historical	PNNL	NARR	1	1 hr	6 km	1981-2015
WRF-GCM	Climate Change	UW Atmos. Sci.	CMIP5 (Table 2)	13	1 hr	12 km	1970-2099

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). 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 engineering design standards, and the empirical relationships to channel geometry, are typically based on instantaneous peak 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 hydrologic model and the climate change simulations, we ensure that the hydrologic model is better adapted to accurately reflect the implications of climate change for hydrology.

For the 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-OBS”). 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 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 the UW’s Department of Atmospheric Sciences (hereafter referred to as “WRF-GCM”). 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 3. All of the new projections are based on the high-end RCP 8.5 scenario (Van Vuuren et al., 2011), with the exception of the ACCESS 1.0 GCM, for which an additional simulation was also produced for the low-end RCP 4.5 scenario. 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 and a spatial resolution of 12 km. The model, and model configuration, are described in detail in Lorente-Plazas et al. (2018) and Mauger et al. (2018). Best practice in climate impacts assessment is to consider several greenhouse gas scenarios – for example, results for the low-end RCP 4.5 scenario for comparison with the high-end RCP 8.5 projections. In our case this is not an option – only RCP 8.5 projections have been dynamically downscaled for the region. 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 projections appear to correspond approximately to the projections for the 2040s or 2050s in the RCP 8.5 projections.

Table 3. The twelve global climate models (GCMs) used as input to the regional model simulations. All simulations are based on the high-end RCP 8.5 greenhouse gas scenario (Van Vuuren et al., 2011). A low-end scenario was also produced for the ACCESS 1.0 model, resulting in two separate projections for this GCM. Model resolution is given in degrees latitude x degrees longitude.

Model	Center	Resolution	Vertical Levels
ACCESS1-0	Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia/ Bureau of Meteorology, Australia	1.25 x 1.88	38
ACCESS1-3	Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia/ Bureau of Meteorology, Australia	1.25 x 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

Climate Data Evaluation

In order to evaluate the need for bias-correction of the meteorological inputs to the hydrologic simulation, we have compared the weather observations listed in Table 1 with modeled temperature and precipitation from the WRF-OBS simulation.

Figure 10 shows a summary of the temperature comparisons. In general, this shows good performance for temperature observations, with a slight cool bias of on average 0.7°C. As shown in Mauger et al. (2019), the WRF simulations generally do not correlate well with observations on an hourly time scale. This is reflected in the bottom plot, which shows a correlation of r^2=0.34 between the hourly observations and the model, even though on average the values are within the same range. This is not true for daily average temperature, which is highly correlated (r^2=0.92) with the observations.

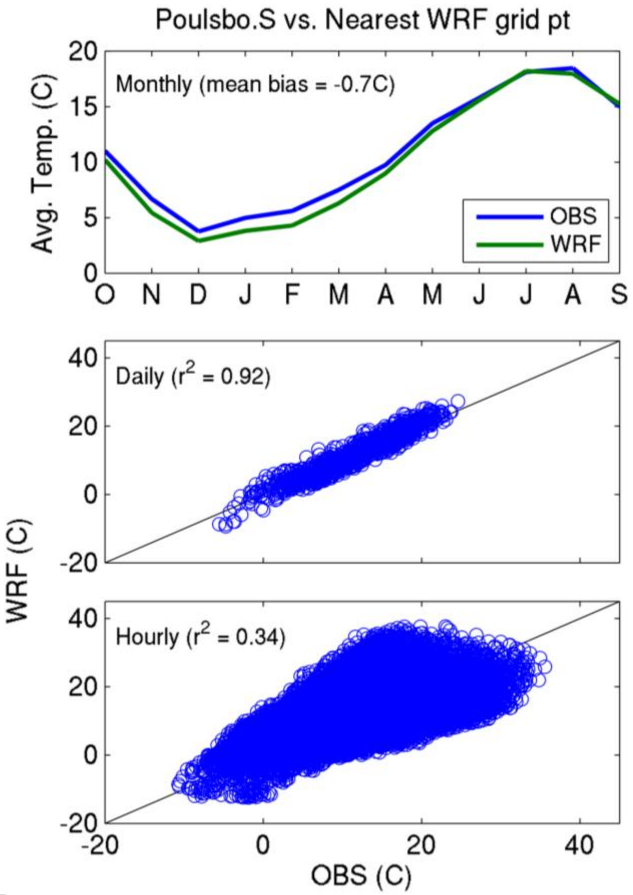

Figure 9. Comparing average monthly, daily, and hourly temperature for the AWN observations at Poulsbo with results from the nearest WRF-PNNL grid point.

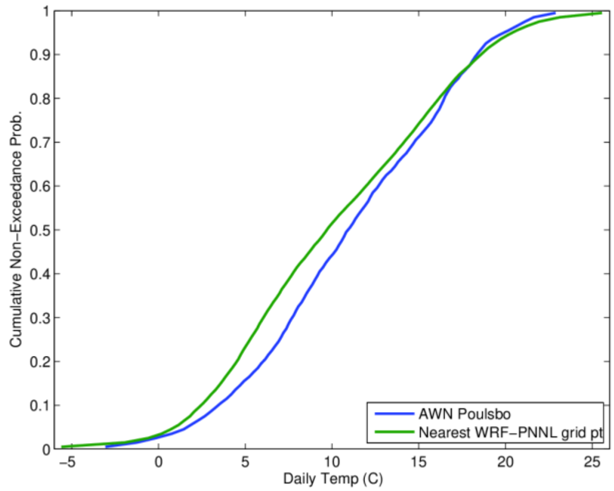

Figure 10. As in Figure 9 except comparing the cumulative distributions in modeled and observed hourly temperature.

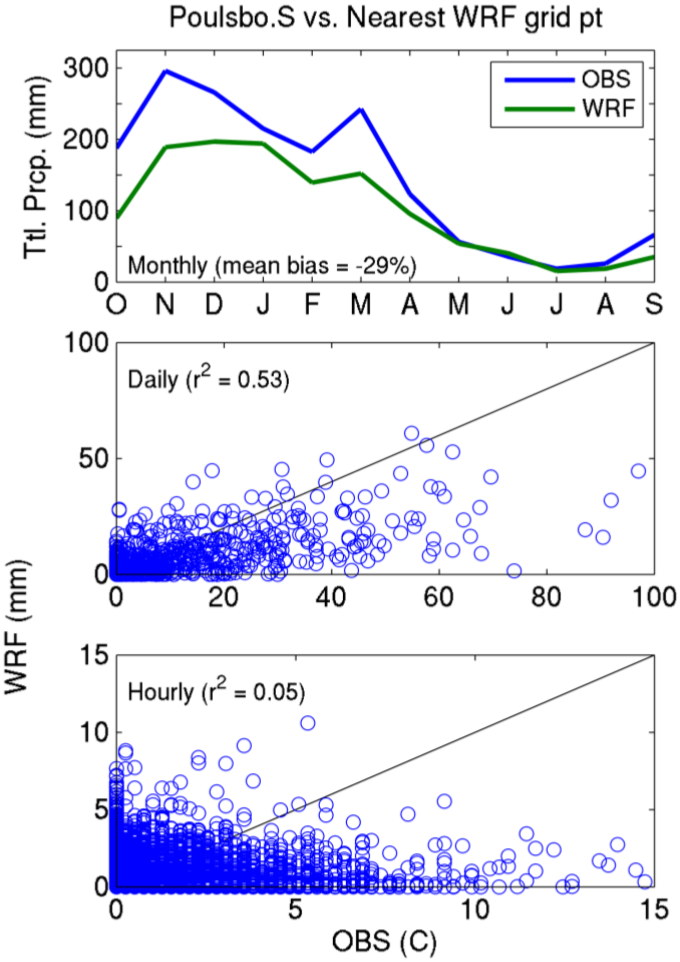

Figure 11. Comparing average monthly, daily, and hourly precipitation for the KPUD Central Road Shed gauge with results from the nearest WRF-PNNL grid point.

Based on Figure 9 it appears that a simple scaling of temperature should be sufficient to adjust WRF temperatures to align with observations. However, an inspection of the cumulative distribution of temperature suggests that the biases are not evenly distributed across the probability distribution. Figure 10 shows that WRF has a cool bias for most observations, as noted above, but that it is actually biased too warm for the upper end of the distribution. A final analysis considered the bias in temperature as a function of precipitation intensity (not shown). Though less relevant to Chico Creek, this can be important in places where the amount of snow accumulation during storms can significantly affect flood risk. This comparison indicated that temperature biases are not strongly related to precipitation intensity for Chico Creek. Although the monthly and quantile-based comparisons do indicate that the bias is variable, we chose to apply a constant bias-correction, based on the annual average bias of -0.7°C, applied to the historical temperature time series. The primary reason for this simple approach is to avoid altering the projections by using a bias correction that was too complex. Previous work has found that complex bias correction approaches can introduce biases in the climate projections (e.g., Mauger et al. 2016).

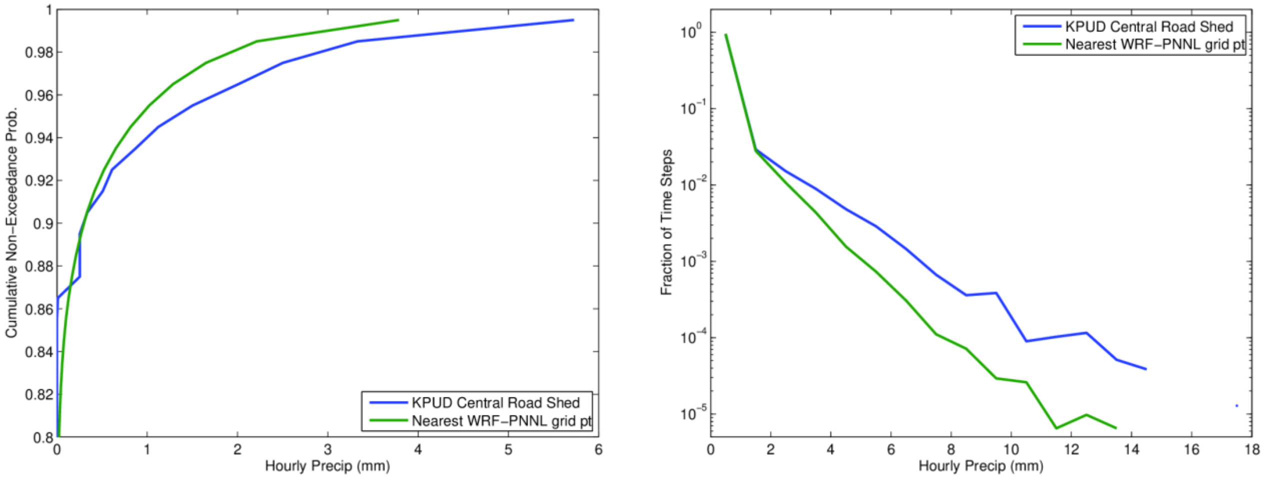

Figure 12. Precipitation extremes are biased low in the WRF-PNNL simulation. The left-hand plot compares the cumulative distribution functions for hourly precipitation, while the right-hand plot counts the proportion of time steps at a given precipitation intensity. Observations are obtained from the Kitsap PUD Central Road Shed gauge and simulated precipitation from the nearest WRF-PNNL grid point.

As with temperature, precipitation shows a relatively low correlation with the observations, as expected (Figure 11). Figure 12 shows that the intensity is too low across nearly all intensities, possibly because of a smaller number of events overall. Overall, precipitation intensity is biased dry, by about 35% on average. Given the magnitude of this bias, we compared WRF precipitation against other gauges in the area (Figure 13). These comparisons corroborated the dry bias seen in the Central Road Shed comparisons, but suggest that the bias is not as pronounced. As with temperature, we chose to apply a simple scaling of +20% to all precipitation time steps in the historical WRF simulation, corresponding to the average bias among nearby rain gauge stations.

Humidity, Winds, and Radiation

Six variables are required as input to 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). Humidity estimates from WRF were not bias-corrected. Although observations are available, tests indicated that adjustments to humidity could frequently lead to over-saturated air or other physically implausible

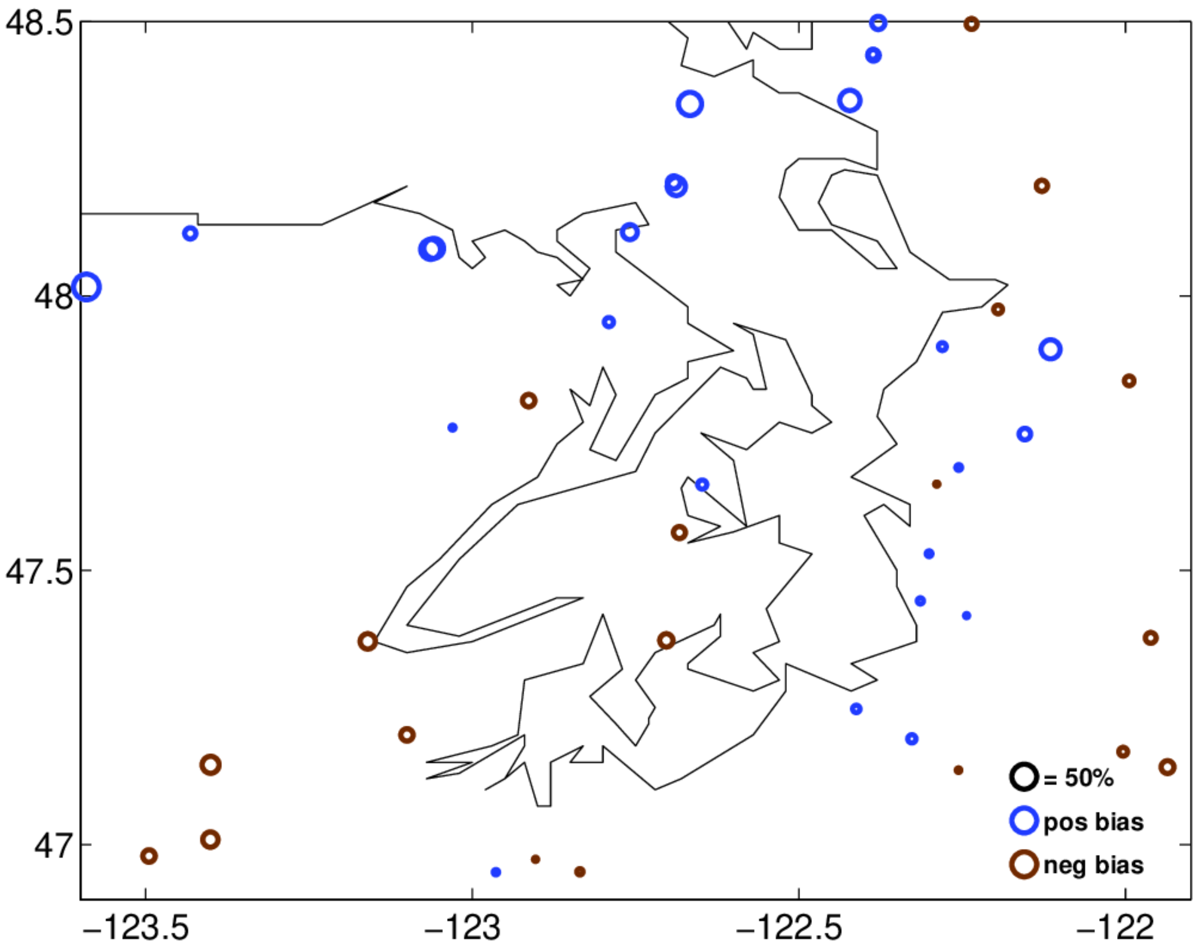

Figure 13. Precipitation biases in the WRF historical simulation are spatially variable but relatively consistent across the Kitsap peninsula. Each circle shows the average bias in annual precipitation when compared to nearby rain gauges. Larger circles correspond to a larger bias, and the color indicates the sign of the bias.

conditions. Future work could develop an improved approach, in which the relative humidity is corrected, then converted to vapor pressure deficit as used by the VIC model. Similarly, winds and shortwave radiation were taken directly from the WRF results without bias correction.

No observational comparisons were made for longwave radiation because very few observations exist. Instead, WRF longwave estimates were 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).

Meteorological Inputs

To develop model inputs, we averaged the results for the four WRF-OBS grid points closest to Chico Creek (47.56740N/122.76710W, 47.57360N/122.68740W, 47.62120N/122.77630W, and 47.62730N/122.69650W), using the average latitude and longitude as the input location: 47.59737N, 122.73183W. We then simply applied the corrections noted above – for temperature and precipitation – uniformly to each time step.

To develop inputs for the future simulations, we bi-linearly interpolated the WRF-GCM simulations to the input WRF grid location (47.59737N, 122.73183W). We then compared the historical average (1981-2015) for each model simulation against the average over the same time period in the bias-corrected WRF-OBS results. This comparison provided the bias-correction factors to be applied to each WRF-GCM simulation, which were then used to create the DHSVM inputs for that simulation.

Hydrologic Model

We modeled the hydrology of Chico Creek using the Distributed Hydrology Soil Vegetation Model (DHSVM; Wigmosta et al. 1994). DHSVM is an open-source model, and is 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 the physical processes affecting the distribution of precipitation, partitioning rain vs. snow, and tracks the movement of water on and through the landscape using a distributed, deterministic approach. The model represents the spatial distribution of evapotranspiration, snow cover, soil moisture, and runoff across a watershed in a distributed fashion, requiring distributed model inputs of geographic and climate information (Wigmosta et al. 2002; Figure 14). The model contains two unsaturated soil

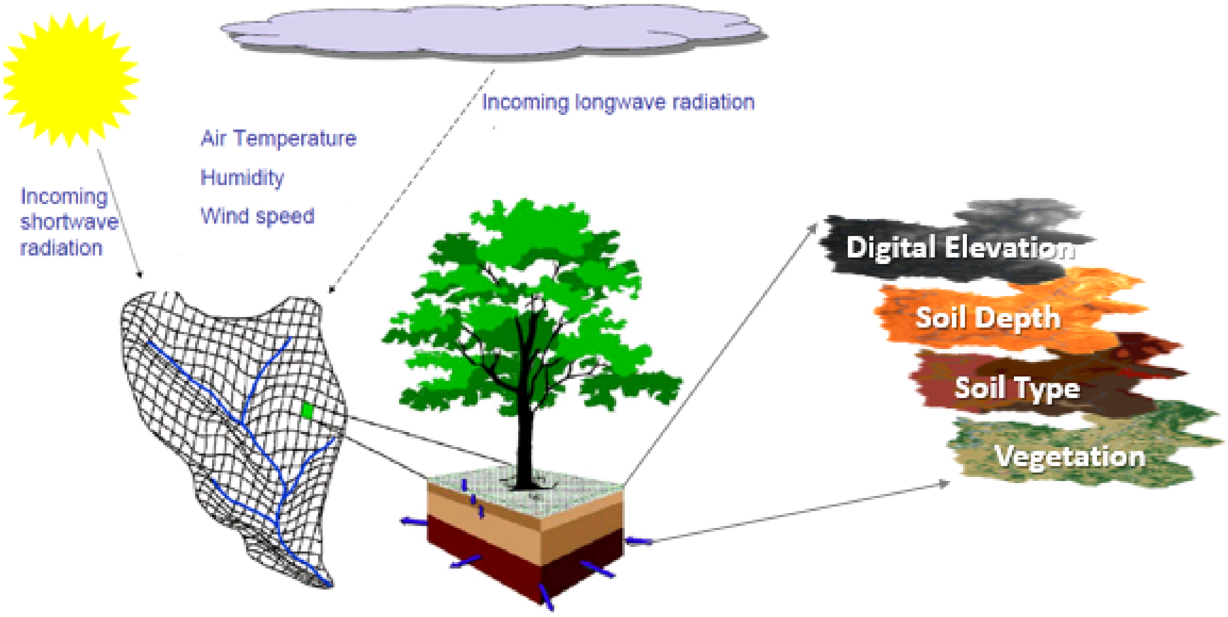

Figure 14. Diagram of DHSVM model and its inputs.

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, including 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). 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 is capable of producing hydrographs at any location along the channel network represented by the digital topography. 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 new python scripts that facilitate creation of the stream network and related inputs for the model (https://github.com/pnnl/DHSVM-PNNL). We implemented the model at a resolution of 40 m and used a 1-hour time step for improved resolution of peak flows.

Topography and Stream Network

The digital elevation models were downloaded from the National Elevation Dataset at http://viewer.nationalmap.gov/basic/ (Elevation products, 3DEP). The DEM (Figure 15) provides the base layer of spatial information and is used to generate soil depth, stream network and watershed boundaries using ArcGIS tools such as ArcGIS hydrology modeling tools and Arc Macro Language scripts (Wigmosta et al. 2002). The stream network is used to route streamflow using flow direction relationships between upstream (higher elevation) and downstream (lower elevation) grid cells.

Land Cover

We updated the land cover based on the National Land Cover Database 2016 update (NLCD; Homer et al., 2020; Jin et al., 2019; Yang et al., 2018; Table 4). This is the most recent national land cover product, with a 16-class land cover classification scheme applied at a

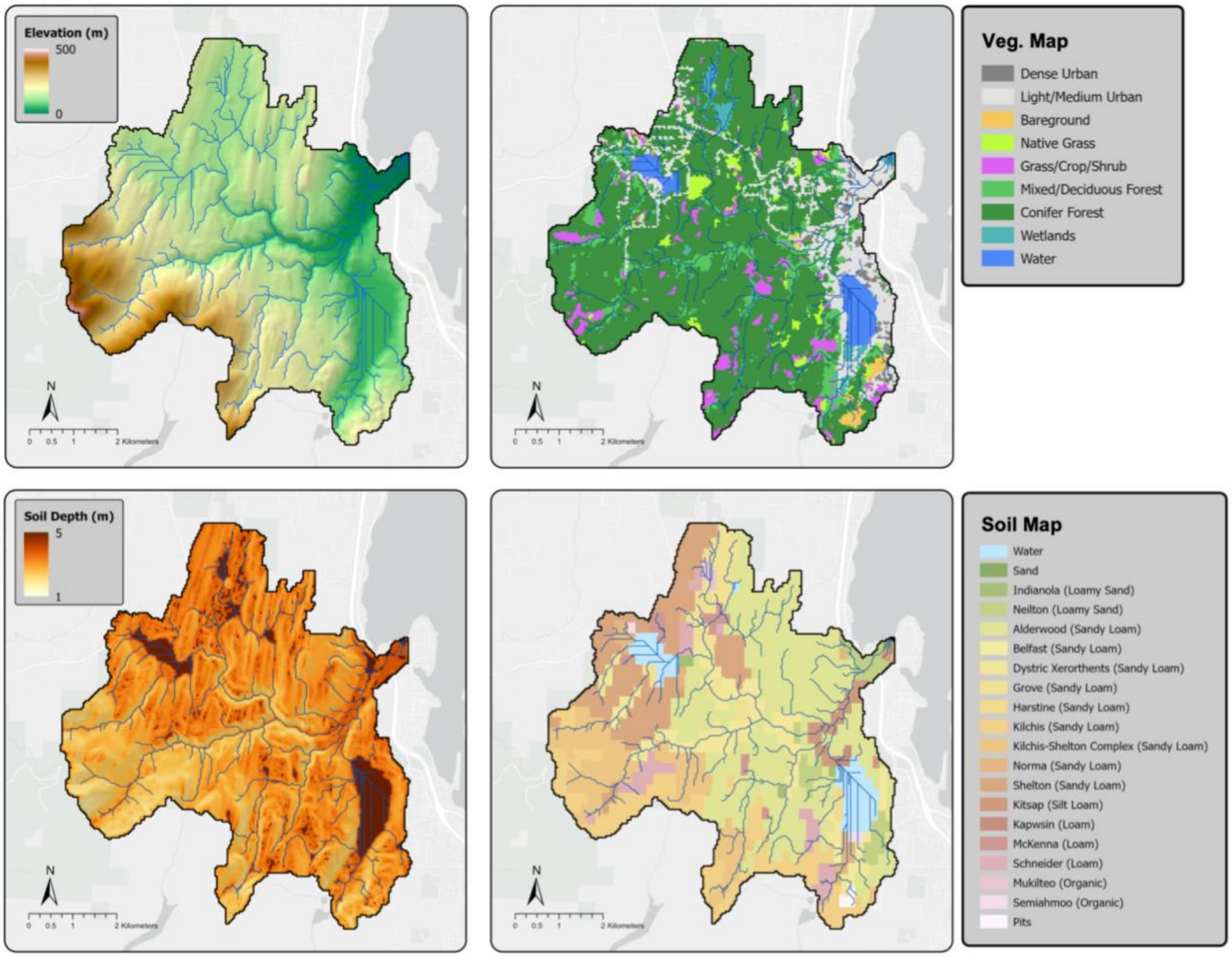

Figure 15. Maps showing the DHSVM DEM, vegetation, soil depth, and soil types for the Chico Creek DHSVM model.

spatial resolution of 30 meters based on Landsat satellite data and created by the Multi-Resolution Land Characteristics Consortium (Homer et al, 2015). Much of the basin is covered by evergreen forest, while the lower basin is highly developed (Figure 15).

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. The geospatial data maps soil units on a 1-kilometer resolution grid for the conterminous United States by weighting average soil values computed by aggregating soil layers. The STATSGO database resolves 16 different soil map units from which DHSVM soil parameters can be derived. Sandy loam is one of the major soil types in the basin (Figure 15).

The STATSGO soil descriptions are fairly coarse relative to the scale of the Chico Creek watershed. This can limit the model's ability to be tuned in calibration by lumping disparate parts of the watershed together, for example, by assigning the same soil properties to valley bottoms and their adjacent slopes, if both are characterized as sandy loam. In order to address this issue we divided the soil types based on the "soil series": Alderwood, Kilchis-Shelton Complex, and Shelton (Figure 15). This allowed us to calibrate parameters for each soil series separately in calibration.

Table 4. 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 Depth

Soil depths are defined empirically based on elevation, local slope, and contributing area. This algorithm gives thin soils on steep slopes and ridge tops and thick soils on gentle slopes and in depressions, within a defined range of 1.0 – 3.0 m (Figure 15).

Model Calibration

Prior to calibration we checked model parameters related to meteorological variations across the basin. The most important of these is the temperature lapse rate, used to adjust between the elevation at which the climate inputs are provided, and the elevation of each 40 m grid cell. We set the temperature lapse rate to the standard -6.5 °C/km, imposed a

Table 5. Parameters and soil types used in the calibration. The soil types are named according to their geologic classifications; all three are described as sandy loam. Lateral Conductivity is expressed in m/s; Rain LAI and Exponential Decrease are unitless.

Parameter	Range	Soil Type	Final
Rain LAI (interception)	0.0119 – 0.000099	N/A: Veg.	0.002249
Lateral Conductivity (m/s)	0.0000001 – 0.01	Alderwood	0.001419
		Kilchis-Shelton Complex	0.006646
		Shelton	0.004546
Exponential Decrease	0.1 – 2	Alderwood	1.424280
		Kilchis-Shelton Complex	0.584437
		Shelton	1.707751

precipitation lapse rate of +0.9 m/km. Finally, we assumed all precipitation falls as snow when temperatures are below -1.0 °C, as rain when temperatures are above +0.5 °C, and a mix of the two for temperatures in between.

Since DHSVM does not simulate lake hydraulics, we focused the calibration on Dickerson Creek (Table 1), comparing results against the other locations to understand how performance at Dickerson Creek relates to model performance elsewhere.

We performed sensitivity tests, identifying parameters that could be adjusted to improve the match between simulated and observed streamflow. These identified the following parameters: “RainLAI”, which governs rain interception from the vegetation canopy, and lateral saturated conductivity (m/s) and exponential decrease for three soil types. We used ranges for each parameter value based on the published literature (Table 5).

We calibrated the model, varying the above parameters, using a multi-objective complex evolution global optimization method (MOCOM-UA) which was developed by the Land Surface Hydrology group at the University of Washington, following the approach of Yapo et al. (1998). The objective of the model calibration was to maximize the “NSElog” (Nash-Sutcliffe Efficiency, or NSE, calculated based on the log of the observed and modeled flows), while also monitoring improvements to the correlation and traditional NSE. Whereas the correlation and NSE are most affected by improvements in the simulation of peak flows, the NSElog places greater emphasis on low flows relative to the other metrics.

Comparisons between observed and simulated daily flows are shown in Figure 16; comparisons for all years are available on the project website (see "Web Tool and Data Access", below). Model evaluation scores are shown in Table 6. Other sites that were not used to calibrate DHSVM are also included in the tables. These generally show good correlations (daily $r^2 >= 0.76$) but absolute biases that can be large for some locations.

In order to better illustrate the comparisons, Figure 17 shows scatterplots comparing observed and modeled flows – again for Dickerson Creek. Since low flows are a major concern for management, an additional scatter plot is shown for June 15th through September 15th only. Both show a strong correlation with observations, with some scatter but minimal systematic bias in one direction or the other.

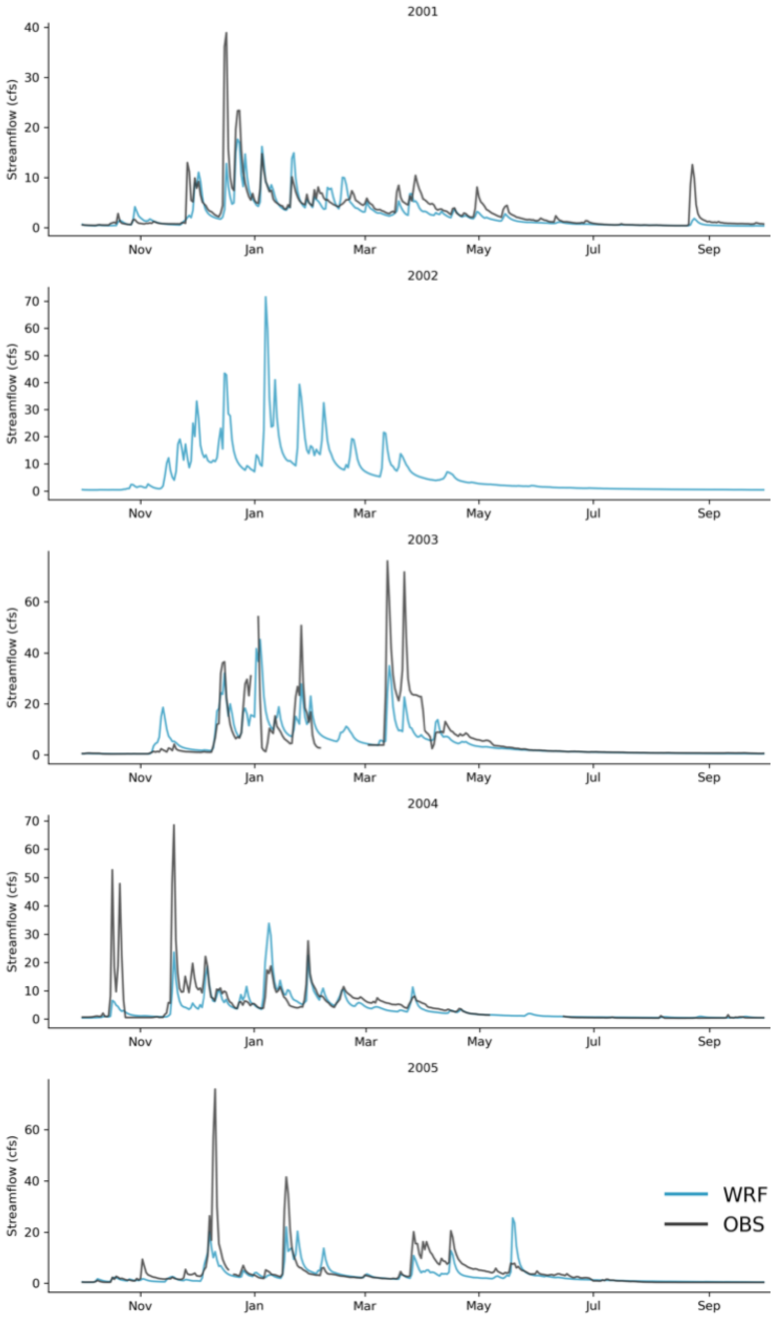

Figure 16. Observed and modeled daily flows for Dickerson Creek. Results are shown for water years 2001-2005. Results for other years are available on the project website.

Table 6. Model evaluation scores for daily flow estimates from the Chico Creek DHSVM. Model results were compared to observations using the squared correlation (r^2), Nash-Sutcliffe Efficiency (NSE), Kling-Gupta Efficiency (KGE), and the NSE and KGE calculated on the log of flows, to place greater emphasis on low flow performance.

Site Name	r^2	NSE	NSElog	KGE	KGElog
Wildcat Creek	0.80	-1.29	0.04	-0.74	-0.58
Dickerson Creek	0.71	0.48	0.80	0.48	0.79
Chico Creek Above Dickerson	0.83	0.65	0.74	0.68	0.63
Kitsap Creek	0.76	0.36	0.76	0.63	0.86
Chico Creek Mainstem	0.79	0.17	0.49	0.27	0.60

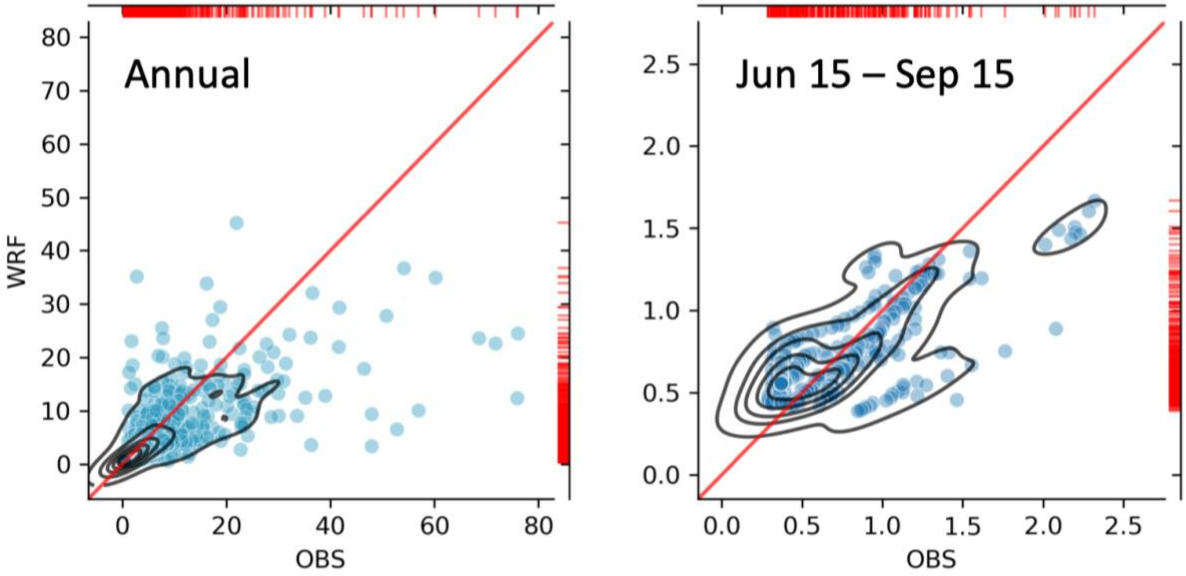

Figure 17. Scatter plots comparing observed and modeled flows, at Dickerson Creek, for the entire year (left) as well as just June 15th through September 15th (right). Contour lines show the joint distribution, and the rug plots on the top and right axes show the distribution for the observations and the model, respectively. All values are in CFS. Some Jun-Sep flows exceed 2.5 CFS; these are excluded in the associated plot in order to focus on low flows.

All of the results above are based on flows at the Dickerson Creek gauge. As noted above, this was the focus for model calibration since it is not affected by Wildcat or Kitsap Lakes. For reference, Figures 18 and 19 compare the model and observed time series for the Chico Creek above Dickerson and Chico Creek Mainstem gauges (the locations for these gauges are shown in Figure 2).

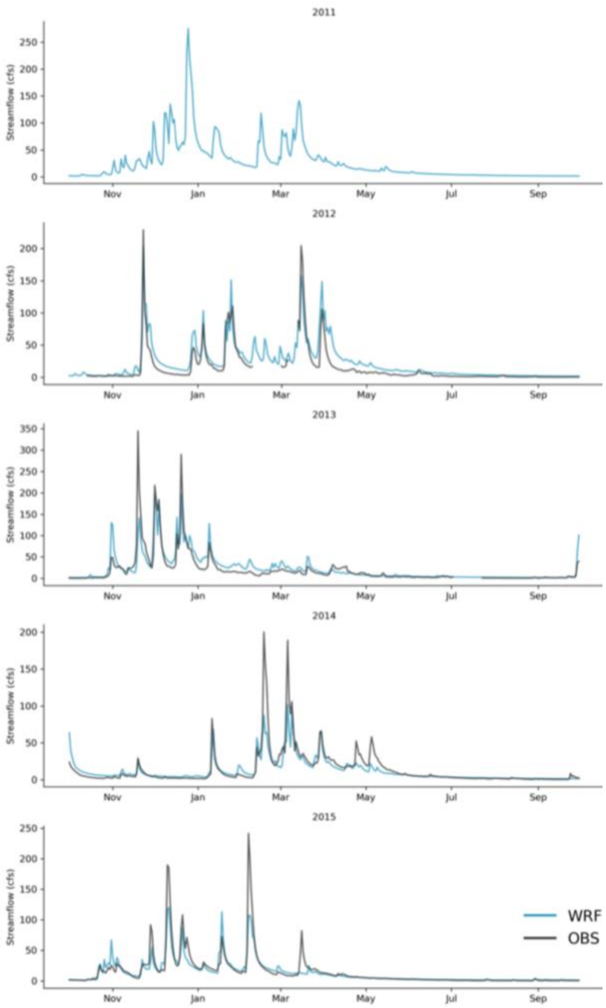

Figure 18. As in Figure 15 except showing results for Chico Creek above Dickerson for the years 2011-2015.

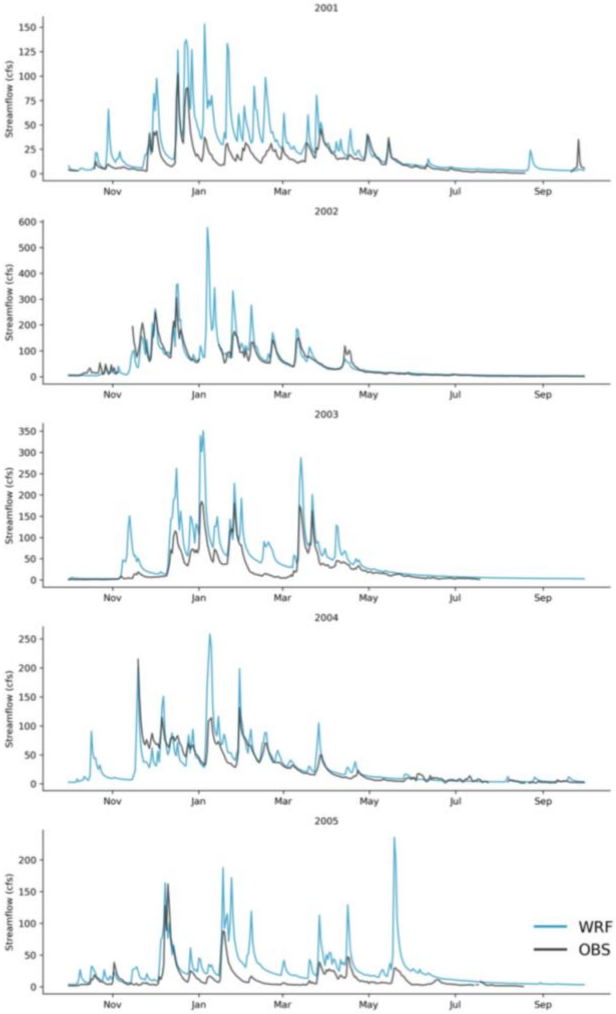

Figure 19. As in Figure 15 except showing results for Chico Creek Mainstem for the years 2001-2005.

Post-Processing

All streamflow results are provided at the model time step of 1 hour. In addition, we processed streamflow results by calculating monthly averages and extreme statistics.

A Focus on the Relative Change in Flow

In order to minimize the effect of model biases on the projections, we consider only the percent change in future flows relative to a historical baseline. By considering only the relative change we remove any absolute biases that may be present in the model streamflow estimates. For the historical period we use 1980-2009 while for each future period we follow the convention of using 30-year periods (2040-2069, 2070-2099). The 30-year future periods are a compromise between the need to detect changes over time and minimize the sensitivity to random short-term variability.

Extreme Flow Statistics

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).

Stream Temperature Model

We employed a process-based water temperature model that integrates DHSVM with a vector-based stream temperature model (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 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).

Model Configuration and Calibration

The model parameters used to configure RBM fall into three categories:

- Mohseni parameters, relating air temperature to headwater stream temperature following Mohseni et al. (1998),
- Leopold parameters, which relate flow rate to channel geometry and stream velocity (Leopold and Maddock 1953), and
- 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 collaborator at the Suquamish Tribe (Steve Todd, personal communication), who provided approximate estimates of tree height, buffer width, overhang, and canopy bank distance across the watershed.

Sensitivity tests indicated that the Leopold coefficients did not have a substantial effect on water temperature estimates. As a result, we used the default values for these parameters (depth: d_a=0.2, d_b=0.4, d_{min}=0.5; velocity: u_a=0.9, u_b=0.21, u_{min}=0.5).

Paired air and water temperature measurements, maintained by the Suquamish 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 Dickerson Creek gauge. Model tuning was implemented by hand via trial and error, with an emphasis on the warmest water temperatures for June 15th through September 15th. Final calibrated values were: alpha=6, beta=10, mu=2.4, gamma=0.5. We used the default air temperature smoothing parameter of 0.1.

Figure 20 shows a time series comparison between observed and modeled temperature for Dickerson Creek. For readability, the plot shows the time series in 7DADMAX (the 7-day average in daily maximum water temperatures). Focusing on June 15th-September 15th, Figure 21 shows a

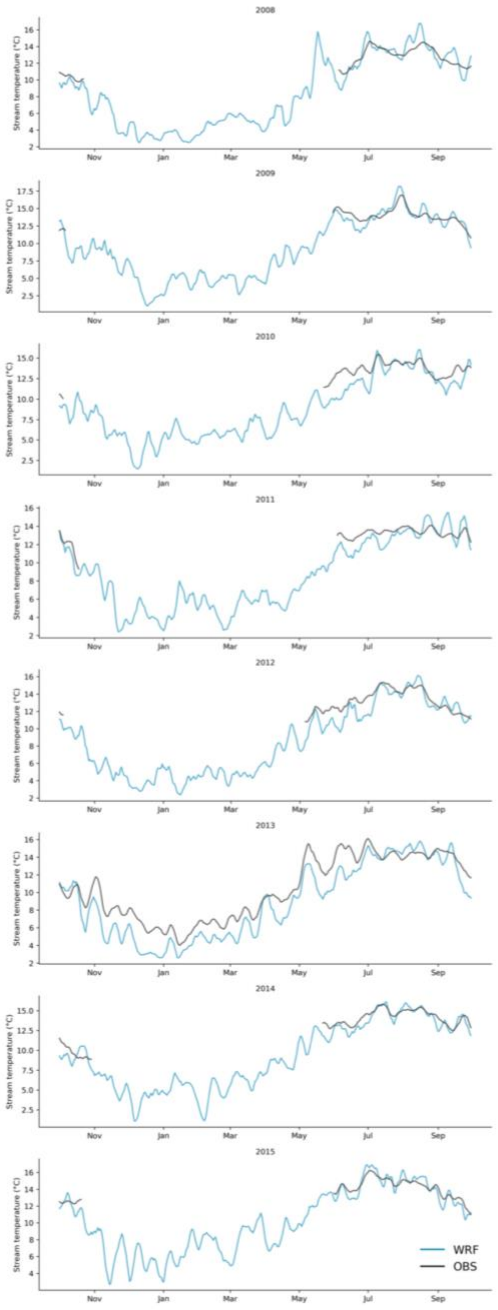

Figure 20. Observed (black) and modeled (blue) 7DADMAX for Dickerson Creek. Results are shown for water years 2008-2015.

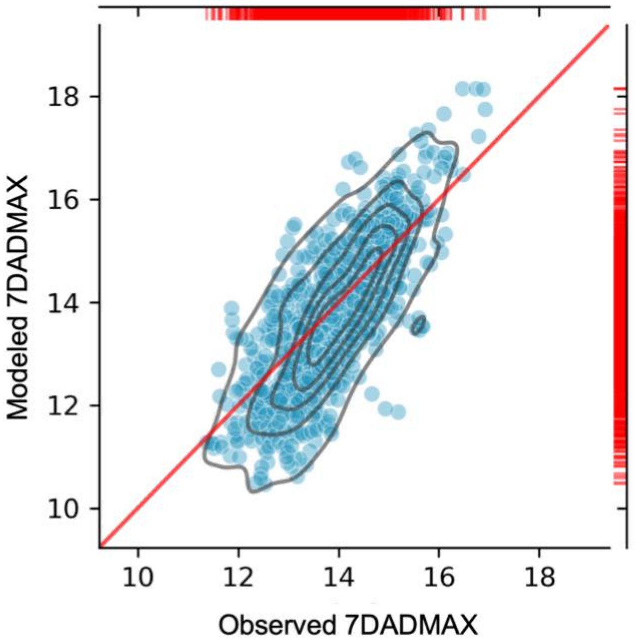

Figure 21. Scatter plot comparing observed and modeled Jun 15 – Sep 15 7DADMAX for Dickerson Creek.

scatter plot comparing observed and modeled 7DADMAX.

Model scores for all sites are shown in Table 6. A number of conclusions can be drawn from these results. First, the results are much better for 7DADMAX than for hourly water temperatures. This is expected given that the exact timing of events in the modeled historical meteorology do not exactly match the observations. Our stream temperature results suggest that averaging to daily improves the agreement substantially; by looking at 7-day periods – as in 7DADMAX – results are likely further improved. Second, the correlations are high for 7DADMAX, suggesting that the model response to weather variations is representative of conditions on the ground. Third, there remain significant absolute biases in temperatures that affect the scores for NSE, KGE, and RMSE. And finally, as with the streamflow results we see that there are particularly large biases in the model estimates downstream of Wildcat and Kitsap lakes. It is notable that even in these instances the correlations are strong, but results from these locations should nonetheless be treated with caution given that the lakes could significantly alter the sensitivity to warming in the future. For reference, Figure 22 shows the scatter plots for all other water temperature sites. Note that very little data is available at Kitsap Creek, which limits the comparison at that site.

Table 6. Model evaluation scores for Chico Creek RBM, for June 15th – September 15th. Model results were compared to observations using the squared correlation (r^2), NSE, KGE, RMSE (ºC), and MARE (ratio). Results are provided for both hourly water temperature and 7DADMAX.

	Station	r^2	NSE	KGE	RMSE	MARE
Hourly	Wildcat Creek	0.18	-5.1	0.17	3.61	0.22
	Lost Creek	0.11	-5.69	-0.09	2.85	0.19
	Dickerson Creek	0.17	-8.04	-0.25	3.13	0.2
	Kitsap Lake Outlet	0.04	-6.14	0.05	7.32	0.39
	Chico GC	0.02	-5.05	0.05	4.1	0.24
	Chico Creek Mainstem	0.0	-4.17	-0.08	5.1	0.27
7DADMAX	Wildcat Creek	0.67	0.01	0.79	1.26	0.07
	Lost Creek	0.68	0.38	0.72	0.81	0.05
	Dickerson Creek	0.61	0.14	0.5	0.86	0.05
	Kitsap Lake Outlet	0.31	-31.91	0.41	6.92	0.34
	Chico GC	0.49	-2.51	0.68	2.33	0.13
	Chico Creek Mainstem	0.41	-3.63	0.49	4.43	0.23

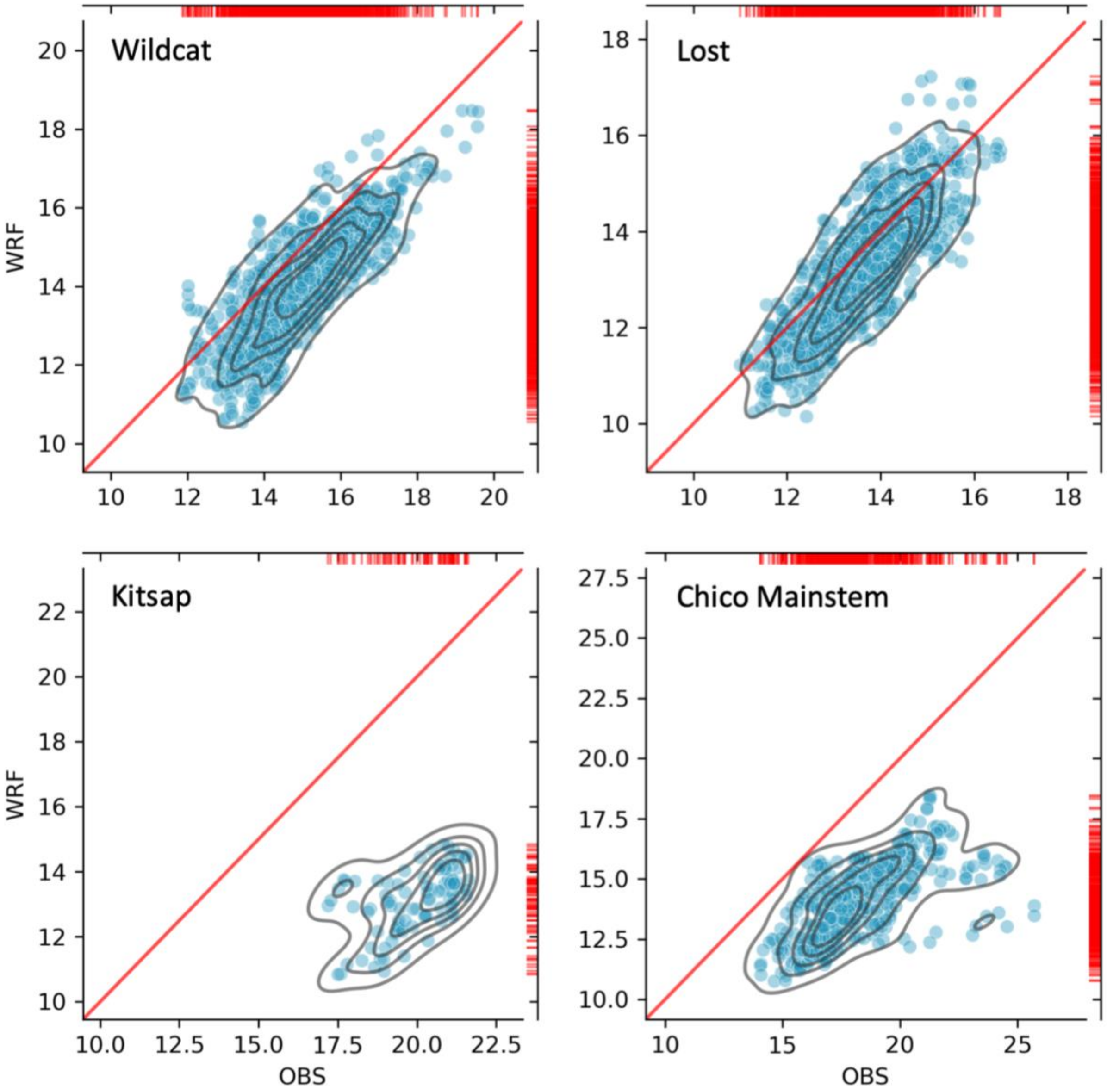

Figure 22. As in Figure 19 except showing results for the Wildcat Creek, Lost Creek, Kitsap Creek, and Chico Creek Mainstem sites. As noted in Table 1, the length and coverage of observations differs for each site.

Post-Processing

The results for stream temperature are processed in much the same way as described above for streamflow:

- All results are provided at the model time step of 1 hour; we also evaluate changes in monthly and extreme water temperatures,
- When possible, we focus on the relative change in temperature, in order to minimize the effect of model biases,
- We evaluate changes for 2040-2069 (“2050s”) and 2070-2099 (“2080s”) relative to 1980-2009,

In addition to monthly average changes, we assess the change in “7DADMAX”, defined as the 7-day average of daily maximum water temperatures. In our case, the daily maximum temperature is defined as the warmest hourly-average temperature in each day. Using 7DADMAX, we also calculate the number of days between June 15th and September 15th with a 7DADMAX greater than 16ºC.

RESULTS

This section summarizes the changes in streamflow and stream temperature in Chico Creek DHSVM and RBM simulations. We specify that these are naturalized flows because they do not include the effects of water withdrawals or lake hydraulics. Changes in water use, lake outflows, or a number of other land use management choices could alter flows in the future in ways that either exacerbate or mitigate the effects of climate change.

As discussed in previous sections, all results are based on the bias-corrected hourly WRF-GCM 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. This is because previous studies have shown that doing so can create artifacts that alter projected trends over time. In order to control for streamflow biases, our results are focused on the percent changes in

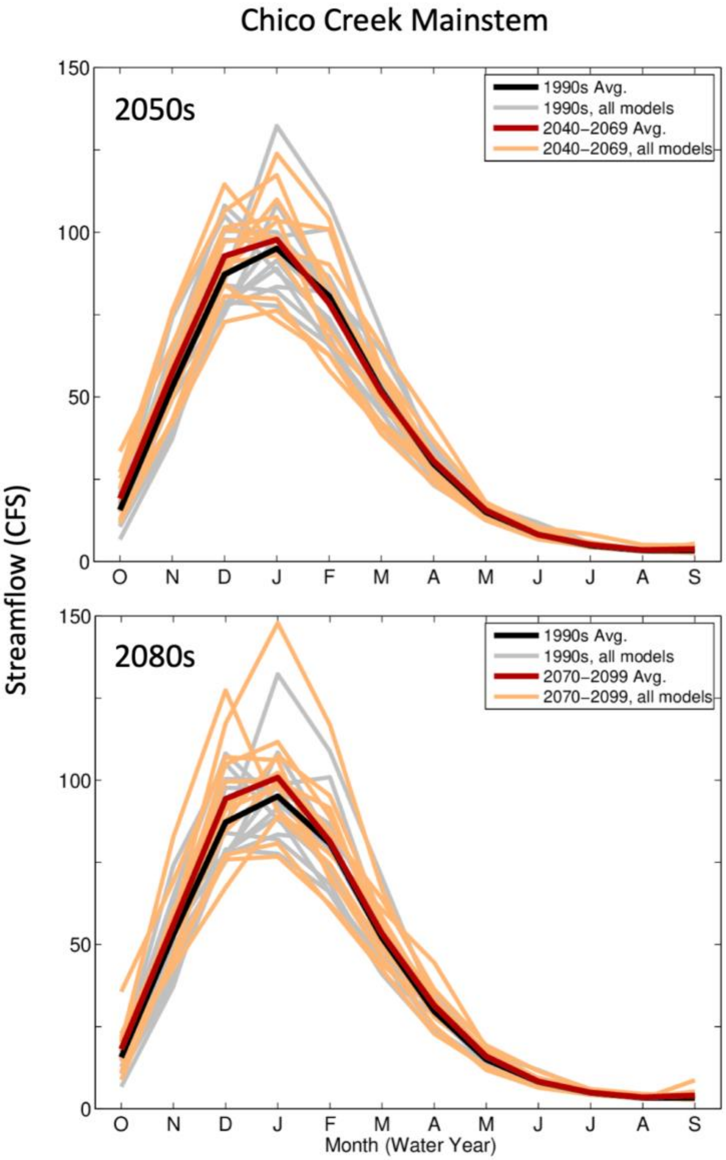

Figure 23. Historical and future monthly flows for the Chico Creek Mainstem site. Each line shows the results for one WRF-GCM projection. The grey lines show the historical average (1980-2009), while the yellow/red lines show the average for the 2050s (top) and the 2080s (bottom).

flows. We show absolute monthly flows because these are likely to be more reliable – based on the scores shown in Table 6 – and also because the seasonal changes in flow are easier to discern when considering absolute flows.

Streamflow Projections

Monthly Flows

Projected changes in streamflow in Chico Creek are likely to be primarily influenced by changes in the amount and seasonality of rainfall: Snowpack has historically had little effect on flows, and evaporation is unlikely to change significantly in the future. This is confirmed by the monthly average projections shown in Figure 23, with a general tendency towards slightly higher streamflow in winter, and very little change in flows in late summer. These results are consistent with previous studies (e.g., Hamlet et al. 2007), which showed that low elevation basins are primarily influenced by variations in precipitation.

Low Flows

On average, models project minimal changes in low flows. Individual models range from -10% to +10% and beyond, depending on the duration and return interval. 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 larger events (e.g., 10-year vs 2-year event).

Figure 24 shows the projected changes for the 2-year and 10-year events for both 1-day and

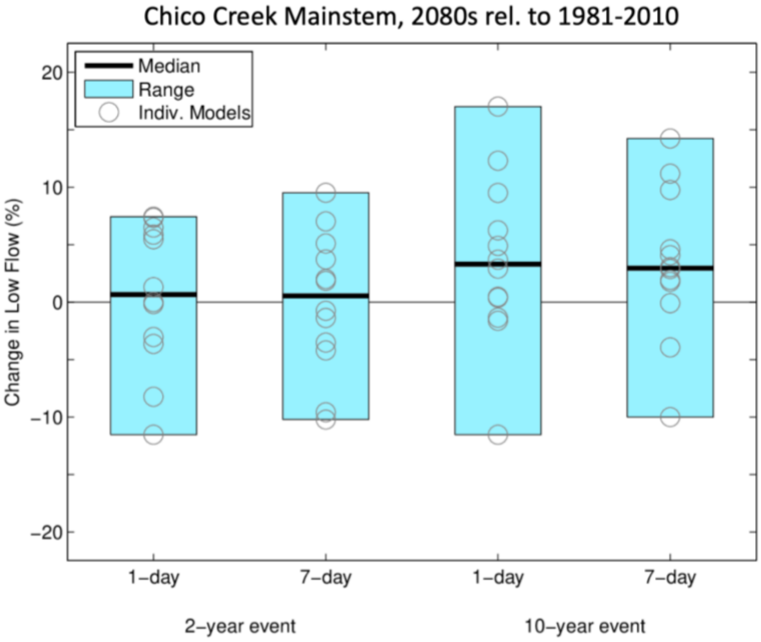

Figure 24. Projected change in low flows for the Chico Creek Mainstem site. Projected changes are shown for the 2080s (2070-2099) relative to 1980-2009.

Table 7. Projected change in the 10-year low flow event, for both 1-day and 7-day average flows, for all streamflow sites listed in Table 1. Results are provided for the 2080s (2070-2099) relative to 1980-2009.

Station	Durn.	Avg.	25th / 75th	min / max
Wildcat Creek	1-day	+3%	-2% / +9%	-13% / +18%
	7-day	+3%	-2% / +8%	-11% / +16%
Lost Creek	1-day	+3%	-2% / +11%	-18% / +22%
	7-day	+3%	-3% / +10%	-16% / +23%
Dickerson Creek	1-day	+4%	-2% / +11%	-14% / +21%
	7-day	+3%	-4% / +9%	-13% / +22%
Chico Cr Abv Dickerson	1-day	+3%	-2% / +9%	-14% / +19%
	7-day	+3%	-1% / +8%	-12% / +17%
Kitsap Creek	1-day	+4%	+2% / +7%	-7% / +12%
	7-day	+2%	-1% / +5%	-10% / +14%
Chico Creek Mainstem	1-day	+4%	0% / +8%	-12% / +17%
	7-day	+3%	+1% / +7%	-10% / +14%

7-day durations. Table 7 lists the projections for the 10-year event projections (for both 1-day and 7-day durations). These results suggest that climate change will have very little effect on low flows.

Peak Flows

On average, models project small increases in peak flows, with individual models ranging from small decreases to large increases. Increases are generally slightly larger for 1-hour than for 1-day peak flows. The projected changes appear

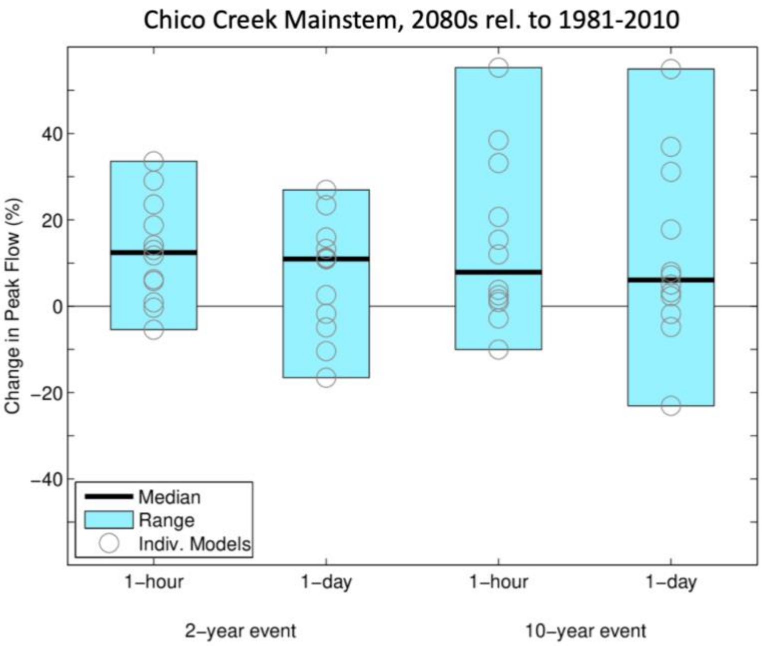

Figure 25. Projected change in peak flows for the Chico Creek Mainstem site. Projected changes are shown for the 2080s (2070-2099) relative to 1980-2009.

to also be larger for the more frequent 2-year event than for the 10-year event, though these differences may be a result of the fact that 10-year events are more rare, making it more difficult to accurately assess trends.

Figure 25 shows the projected changes for the 2-year and 10-year events for both 1-hour and 1-day durations. Table 8 lists the projections for the 10-year event projections (for both 1-day and 7-day durations). On average, models project increases ranging from +3% to +12% by the 2080s, relative to 1980-2009.

Table 8. Projected change in the 10-year peak flow event, for both 1-hour and 1-day average flows, for all streamflow sites listed in Table 1. Results are provided for the 2080s (2070-2099) relative to 1980-2009.

Station	Durn.	Avg.	25th / 75th	min / max
Wildcat Creek	1-hour	+9%	+1% / +29%	-9% / +60%
	1-day	+5%	+2% / +17%	-22% / +45%
Lost Creek	1-hour	+11%	+0% / +27%	-11% / +50%
	1-day	+5%	-1% / +30%	-25% / +68%
Dickerson Creek	1-hour	+12%	+0% / +28%	-13% / +54%
	1-day	+3%	-4% / +23%	-25% / +50%
Chico Cr Abv Dickerson	1-hour	+8%	+1% / +28%	-10% / +55%
	1-day	+6%	+0% / +27%	-24% / +56%
Kitsap Creek	1-hour	+9%	+1% / +24%	-10% / +54%
	1-day	+4%	-1% / +27%	-23% / +52%
Chico Creek Mainstem	1-hour	+8%	+1% / +27%	-10% / +55%
	1-day	+6%	+0% / +24%	-23% / +55%

Stream Temperature Projections

In contrast with the streamflow results, the water temperature projections show large changes in response to warming. This analysis focuses on 7DADMAX, the 7-day average of daily maximum water temperatures. All models project substantial stream warming. Given the relatively small changes in streamflow, this is likely primarily a response to warmer air temperatures. Projections show several degrees (°C) of warming and a large increase in the number of days above 16°C for all six temperature gauge sites evaluated for this study.

In this section we focus on the results for Dickerson Creek (Figure 26) because the lower mainstem sites are influenced by Kitsap Lake, which is not accounted for in the model. Results for Dickerson Creek show that by the end of the century, the high-end models indicate that 7DADMAX could remain above 16°C for nearly the entirety of June 15th – September 15th. The low-end models show much more modest increases, but nonetheless show substantial warming and much more frequent exceedances above 16°C.

Tables 9 and 10 summarize the results for all six stream temperature sites considered in this study. Projected warming for the annual maximum 7DADMAX ranges from 2-3°C, on average, depending on the site. All models and all sites show large increases in the number of days above 16°C. However, given the large cold bias for the sites that are downstream of Kitsap Lake, we recommend modeling the warming effect of Kitsap Lake before re-evaluating the projections in this way. Upstream of the Kitsap Creek confluence on Chico

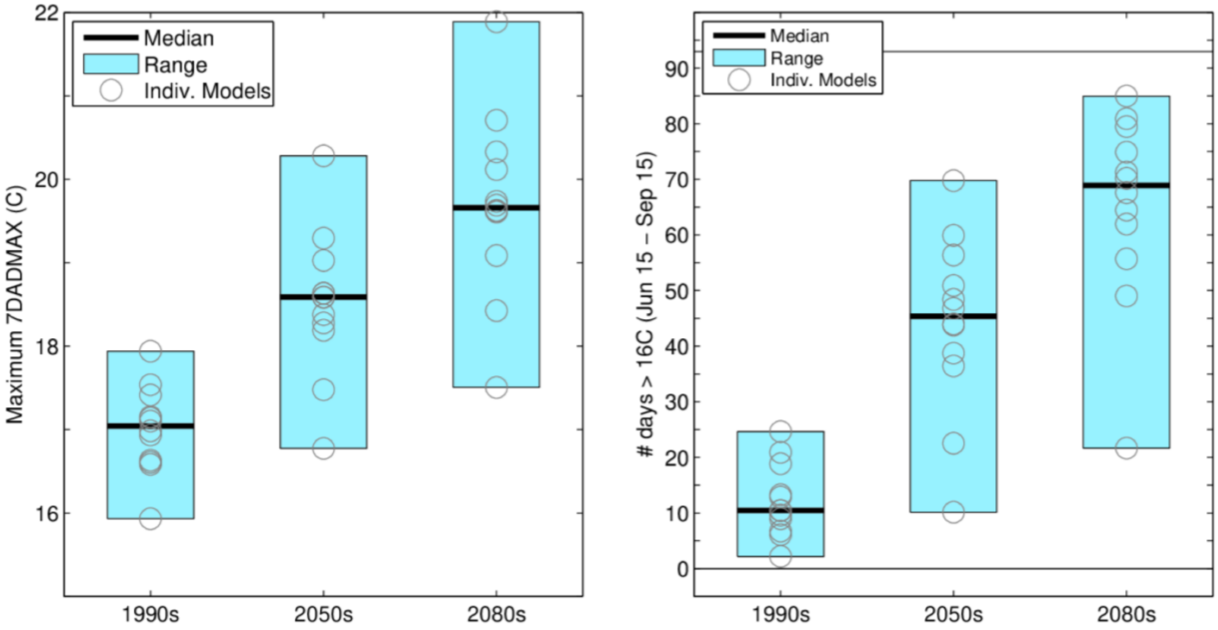

Figure 26. Historical and projected water temperatures for the Dickerson Creek site. The left-hand plot shows the maximum 7DADMAX for each time period, while the right-hand plot shows the number of days for June 15th through September 15th with water temperatures above 16°C. The horizontal black lines show the minimum (0) and maximum (93) number of days possible in any given year. Results are shown for Dickerson Creek because the model was found to have a strong cold bias for the sites that are downstream of Kitsap Lake.

Creek, Dickerson Creek goes from a historical average of 12 days with water temperatures above 16°C to an average projection of 65 days above 16°C by the end of the century. This amounts to more than two out of every three days in summer.

Table 9. Historical and projected annual maximum 7DADMAX (the 7-day average of daily maximum water temperatures, in °C) for the six stream temperature sites highlighted in Table 1. Results are provided for the historical time period (1980-2009) and the 2080s (2070-2099).

	Historical Avg.	2080s		
Station		**Avg.**	**25th - 75th**	**min - max**
Wildcat Creek	16.7	19.6	19.3 - 20.1	17.2 - 22.0
Lost Creek	15.4	18.1	17.9 - 18.5	15.9 - 20.3
Dickerson Creek	17.0	19.7	19.3 - 20.2	17.5 - 21.9
Kitsap Lake Outlet	16.5	18.6	18.5 - 19.0	16.7 - 20.5
Chico GC	19.6	22.1	21.7 - 22.7	19.9 - 24.4
Chico Creek Mainstem	17.3	20.1	20.0 - 20.6	17.6 - 22.4

Table 10. Historical and projected number of days between June 15 and Sept 15th with water temperatures above 16°C) for the six stream temperature sites highlighted in Table 1. Results are provided for the historical time period (1980-2009) and the 2080s (2070-2099).

	Historical Avg.	2080s		
Station		**Avg.**	**25th - 75th**	**min - max**
Wildcat Creek	9	62	54 - 76	16 - 84
Lost Creek	1	32	24 - 40	3 - 61
Dickerson Creek	12	65	59 - 77	22 - 85
Kitsap Lake Outlet	7	52	46 - 65	10 - 76
Chico GC	54	85	84 - 89	73 - 91
Chico Creek Mainstem	14	69	63 - 82	22 - 88

Web Tool and Data Access

All model results can be obtained from the project website:

https://cig.uw.edu/projects/projected-changes-in-streamflow-and-water-temperature-in-chico-creek-kitsap-county/

Figure 27 illustrates the file structure. The DHSVM model produces an hourly streamflow time series for each streamflow site. These are included in separate files for each model: one for the WRF-OBS simulation (named "pnnl") and one for each of the WRF-GCM simulations (labeled according to the names of the GCMs listed in Table 3). A monthly time series file is similarly provided in a separate file for each model. To facilitate analyses, a number summary files are included in the streamflow and stream temperature directories; these contain the historical and future averages for specific flow and temperature metrics of interest. For example, for low flows these include the 2-year and 10-year extremes in 7-day minimum flows, as well as the same extreme statistics for 1-day minimum flows.

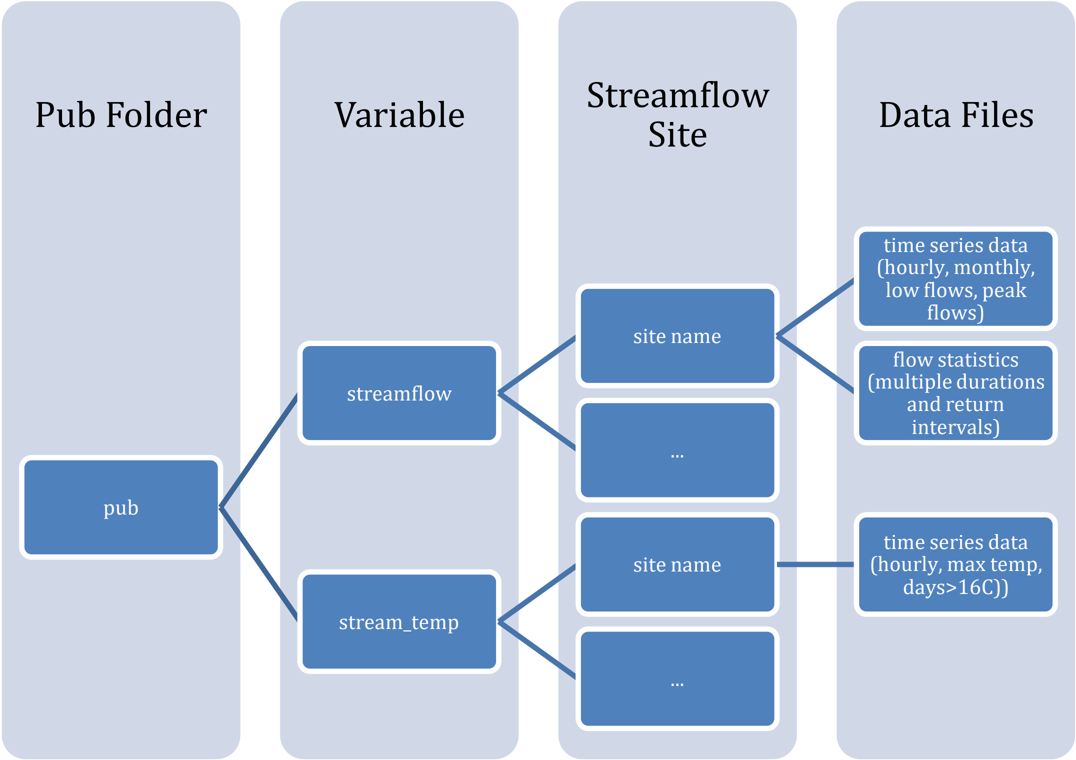

Figure 27. Data structure for the model results.

DISCUSSION

Findings

The primary pathway for climate change to influence streamflow in the Chico Creek watershed is 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 way that flows might be affected by climate change, particularly in summer when precipitation is relatively low. However, ET is typically around 10% of the annual water balance, with the remaining 90% ultimately exiting the basin as streamflow (although soil water storage can be important on a short-term basis, on an annual basis that water ultimately ends up in the stream). This means that ET would have to change substantially to make a big difference for flows. Although the balance is likely shifted in summer, when temperatures are warmer and precipitation is relatively low, an additional limitation on ET changes is that 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. For all of these reasons, we expect that precipitation will be the primary driver of changes in streamflow for Chico Creek.

Models project near-zero changes for winter and summer precipitation in Chico Creek, and more intense heavy precipitation for all seasons (Morgan et al. 2021). The seasonal projections indicate small increases in precipitation, ranging from roughly no change to +10%. These changes are small compared to year-to-year variability. Projected changes in extreme precipitation are generally larger than the seasonal changes. For example, nearly all models project increases in the 2-year event throughout the century, with a model-average increase of about +15% for the 24-hour duration and +35% for the 1-hour duration events by the 2080s (relative to 1980-2009).

Given the above changes in precipitation, we expect modest increases in winter and summer streamflow, as well as extreme low flows. Flood peaks, in contrast, are expected to increase due to the higher intensity precipitation events. Our streamflow results are consistent with these expectations. We find very small increases in winter and summer streamflow (~1-9%), and even smaller increases in extreme low flows (~3-4%). Peak flows are also consistent with the precipitation projections, showing average increases of ~10-

15% for the 2-year event. These results are very similar to the findings of Murphy and Rossi (2019) for similar watersheds in the Kitsap Peninsula region (Stavis, Seabeck, Big Beef, and Little Anderson). However, Murphy and Rossi (2019) did project larger increases in winter streamflow and larger decreases in summer streamflow, likely due to differences in the climate projections used in their study relative to the current analysis. Specifically, the new dynamically downscaled projections do not show a substantial decline in summer precipitation for Chico Creek, whereas the older statistically downscaled projections do. There are two reasons to call into question the older projections: (1) statistical downscaling simply reflects what the global climate models (GCMs) show for the region, which does not necessarily relate to potential changes in Chico Creek, and (2) GCMs are known to be limited in their representation of precipitation.

Water temperature is expected to warm due to climate change in response to changes in streamflow and air temperature. Climate change could also alter vegetation composition, though we did not consider land cover change in the current study. Given the small changes in streamflow outlined above, we expect that the primary climate driver of water temperature change will be warming air temperatures. Warming is projected to be significant for the region; 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 substantial warming trends for air temperature. The maximum 7DADMAX in each water year is projected to increase from +2.1ºC to +2.9ºC, on average, by the 2080s relative to 1980-2009. Individual model projections for the same quantity range from +0.2ºC to +5.1ºC, again for the end of the century. Another way of viewing these results is in terms of the number of days when 7DADMAX exceeds 16ºC, the Washington State water temperature standard for protecting salmonids. Focusing on the warm season (June 15th – September 15th), our simulations show that historically, Dickerson Creek had an average of 12 days each summer when 7DADMAX exceeded 16ºC. By the 2080s, this is projected to rise to 65 day per year, on average, with individual model projections ranging from 22 to 85 days. There are a total of 93 days from June 15th to September 15th. This means that some models suggest the 7DADMAX water temperatures will exceed 16ºC for nearly the entire summer season by the end of the century. Model results downstream of Kitsap Lake have a strong cold bias;

additional work would be needed to better account for the effect of Kitsap Lake before assessing projected changes at these locations. The same may be needed for Wildcat Creek downstream of Wildcat Lake. Nonetheless, our projections align closely with the results of Murphy and Rossi (2020) for Stavis, Seabeck, Big Beef, and Little Anderson Creeks.

An important achievement in the current study was the incorporation of new dynamically downscaled projections in a hydrologic modeling study. This is particularly important in rain-dominant basins such as Chico Creek, where statistical downscaling approaches could not capture future changes in precipitation patterns.

Consistent with the Murphy and Rossi (2019, 2020) studies, our results point to fairly minor changes in seasonal streamflow and low flows and relatively larger increases in peak flows. Water temperature changes are projected to be much more dramatic, especially when viewed through the lens of thermal tolerances for salmon. Both the current study and the Murphy and Rossi studies lack an adequate treatment of groundwater and ignore potential changes in land cover and water management scenarios; 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 both Kitsap and Wildcat lakes. These and other issues are discussed in the sections 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 Chico Creek is a small basin, it is possible

that variations in weather conditions across the 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 and RBM do not capture the effect of Kitsap and Wildcat lakes. This means that the flow retention and additional heating associated with these two lakes is not captured by our modeling. It may be worth considering if and how these two functions of the lakes may change in response to warming, 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 Chico Creek 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 Chico Creek, 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 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 salmonids in the watershed.

- 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

A primary objective of this study was to better understand the climate vulnerabilities of salmonid populations in Chico Creek, and by extension, other similar watersheds of interest to the Suquamish Tribe. As outlined above, there are limitations to the models and approaches used in this study. Addressing these limitations could lead to changes in the projections. 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 for Chico Creek, 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 higher-resolution soils data (e.g., SSURGO), more detailed vegetation cover, observationally-based soil depths, or using dynamically-downscaled estimates of evapotranspiration. Similarly, the RBM testing could evaluate the benefits of using lidar-based canopy heights, calibrating to metrics other than 7DADMAX, or calibrating to year-round water temperatures as opposed to summer only. Larger efforts at model improvement could involve gathering new data, testing new approaches to developing the meteorological inputs, or by 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 recent air temperatures or the time elapsed since the last rain event. Ideally such analyses would consider impacts for 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.

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. However, 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). Similarly, the Tulalip Tribe is currently completing a literature review of land management implications on flow and stream temperature, which could provide a basis for initial estimates of the potential benefits of changes in land management (NTA #2018-0970, *"Forest Management for Water and Climate Preparedness: assessing alternative forest actions individually and in aggregate for estimates of effectiveness in improving surface and groundwater management for salmon using future scenarios."*). 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 approach we used here could be evaluated for other watersheds and communities around the region. As interest in this work grows, additional coordination may be warranted to capitalize on economies of scale.

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