Modeling peak flow projections in the Nooksack River

Thesis Proposal for the Master of Science Degree,

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1. Problem Statement

The Nooksack River in northwest Washington State drains a 2,300 km^2 watershed and flows into Bellingham Bay. It provides freshwater for agriculture and industrial use and serves as a vital habitat for endangered salmon, a resource that is of cultural and economic importance to the Nooksack Indian Tribe. Previous hydrology modeling in the basin projects a reduction in snowpack and glacier extent as temperatures increase through the 21^{st} century (Dickerson-Lange and Mitchell, 2013; Murphy, 2016). As more landscape becomes exposed to rain rather than snow in the winter, peak flows and sediment delivery to streams will increase due to rapid runoff, resulting in salmon habitat degradation and increased flood risk (Knapp, 2018). Previous modeling was unable to depict accurate peak flows because daily meteorological forcings were disaggregated into 3-hour timesteps, thus not capturing high intensity, short duration rainfall events that are responsible for peak flows (Dickerson-Lange and Mitchell, 2013; Murphy, 2016). I will be using the Distributed Hydrology Soil Vegetation Model (DHSVM; Wigmosta et al., 2002) and newly projected 1-hour meteorological forcings (e.g., Mauger and Won, 2020) to predict the timing and magnitude of future peak flows in the Nooksack River. I hypothesize that peak flows will increase in both magnitude and frequency over the next century.

2. Introduction

The Nooksack River basin is a transient rain-snow basin in the North Cascades and drains into the Salish Sea (Figure 1), providing fresh water to regional municipalities and tribes, agriculture, and industry and serving as a habitat to endangered salmon. Historically, streamflow in the basin is supplied by precipitation and snowmelt in the fall and winter months and snow and glacier melt in the spring and summer months. There is growing concern regarding the impacts of climate change on streamflow and what the implications are for salmon habitat within the Nooksack River (Grah and Beaulieu, 2013). Transient rain-snow basins (e.g., the South Fork of the Nooksack) are particularly sensitive to changes in air temperature because slight shifts in temperature can determine whether precipitation falls as rain or snow (Hamlet et al., 2013; Mauger et al., 2015). Therefore, projected climate change will likely impact the timing, frequency, and magnitude of peak flows since streamflow is heavily influenced by changes in temperature and precipitation.

Global climate models (GCMs; also known as general circulation models) project that the average air temperature in the Puget Sound region will increase by 4.1°C to 6.7°C by the end of the 21st century (Mauger et al., 2015). As a result, more precipitation will fall as rain rather than snow, increasing the potential for more rapid runoff as more steep landscape becomes exposed due to a declining snowpack, and heavy rain events will become more frequent and intense (Mauger et al., 2015; Warner et al., 2015). Studies in other western Washington watersheds have shown that the magnitude and frequency of peak flows will increase through the 21st century as a result of the projected changes to precipitation patterns and snowpack extent (Lee et al., 2018). Previous hydrology modeling in the Nooksack River basin was unable to generate accurate future peak flows because the meteorological forcings used in the modeling were disaggregated from daily data, thus not accurately capturing high intensity, short duration precipitation events.

My objective is to predict how projected climate change will change peak flow magnitude and frequency in the upper Nooksack River basin. I will improve upon previous hydrology modeling within the upper Nooksack basin by incorporating historical and projected meteorological forcings with a 1-hour timestep that were dynamically downscaled from GCM data using a regional climate model (e.g., Mauger and Won, 2020). The modeling results will be used by Nooksack Tribe scientists and stormwater managers to inform decisions regarding salmon habitat restoration and preservation and flood risk mitigation.

3. Background

3.1 Physical Characteristics of the Nooksack River Basin

The Nooksack River basin is located primarily in Whatcom County in northwest Washington State and ranges in elevation from sea level to 3,286 meters at the peak of Mt. Baker (Figure 1). The upper Nooksack basin, and the focus of this study, encompasses an area of 1,550 km^2 and is comprised of three main subbasins: the North, Middle, and South Forks. The North and Middle Fork basins have high relief, ranging from approximately 40 meters near North Cedarville, WA to the peak of Mt. Baker. The South Fork basin has a lower relief, ranging from 67 to 2,135 meters on South Twin Sister mountain. The three subbasins each drain into their respective forks of the Nooksack River and converge into the main stem near Deming, WA (Figure 1).

The bedrock geology of the Nooksack River basin is characterized by Paleozoic and Mesozoic-aged metamorphic rocks of the Northwest Cascade System and Tertiary-aged sedimentary rocks of the Chuckanut Formation (Booth et al., 2003; Tabor et al., 2003). The bedrock units are exposed in the higher elevations of the basin and are overlain by unconsolidated glacial and alluvial deposits in the lowland valleys. The majority of unconsolidated deposits were deposited through large-scale Quaternary glaciation and post-glacial processes, such as mass-wasting events and alluvial processes. The last major glaciation of western Washington deposited a variety of glacial deposits through the advance and retreat of the Cordilleran ice sheet approximately 15,000 to 20,000 years ago (Booth et al., 2003). Most of the surficial glacial deposits, collectively named the Vashon Drift, are from the advance and retreat of the ice sheet during the Vashon Stade. These glacial deposits include advance lacustrine and outwash, till, ice-contact and marginal, recessional, and glaciomarine drift (Booth et al., 2003). The most abundant soil types that characterize the upper Nooksack basin are loam (38.7%), gravelly loam (24.5%), and silt loam (13.3%) according to the State Soil Geographic (STATSGO) database (USDA, 1998; Figure 2).

The National Oceanic and Atmospheric Administration's (NOAA) Coastal Change Analysis Program (C-CAP) characterizes landcover in the upper Nooksack basin as predominantly evergreen forest (65.3%) with less abundant deciduous forests, mixed forests, and shrubland (20.4%). In the lowlands of the basin, where agriculture exists, landcover is characterized by cultivated lands, pasture, and grasslands (4.2%), wetlands (1.8%), urban areas

(1.2%), and water (0.3%). In the higher reliefs, barren land (5.2%) and snow and ice (1.6%) are the dominant landcover classes (NOAA, 2016; Figure 3).

Mt. Baker contains 12 significant glaciers, making it the largest contiguous network of glaciers in the North Cascades (Pelto and Brown, 2012). Within the North and Middle Fork basins, glaciers on Mt. Baker and Mt. Shuksan comprise an area of approximately 33.1 km^2 as of 2009, with the majority of glaciers being located in the North Fork. The South Fork basin is much less glaciated due to its relatively low relief, with only a few small glaciers located on Twin Sisters mountain. Pelto and Brown (2012) have shown that glacial volume on Mt. Baker has decreased by approximately 11-20% since the year 1990. Previous glacier modeling in the upper Nooksack basin has projected that glacier extent will decrease by as much as 88% by the end of the 21st century under Representative Concentration Pathway (RCP) 8.5, which is the high greenhouse gas emission scenario quantified by the Intergovernmental Panel on Climate Change (IPCC; Murphy, 2016). The Nooksack River relies on glacial melt to support baseflow in the late summer season. Glacial recession poses a threat to fish habitats and surrounding communities that rely on the Nooksack River as a water resource (Grah and Beaulieu, 2013).

The Puget Sound region experiences a maritime climate. In the winter, a low-pressure system, named the Aleutian Low, brings cool, moist air to the region from the north, resulting in cool, wet winters (Moore et al., 2008). In the summer, the Aleutian Low retreats to the north towards the Aleutian Islands of Alaska, resulting in dry, warm summers in the Puget Sound region. Additionally, climate in the region is influenced by annual and decadal climatic events such as the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO). El Niño events typically bring warmer temperatures to the region due to warmer ocean temperatures in the Pacific, while La Niña events produce cooler temperatures. PDO events, which last on the order of decades, bring warmer temperatures to the region during positive oscillations and cooler temperatures during negative oscillations.

Due to the maritime climate and topographic relief of the North Cascades region, precipitation within the Nooksack basin is highly variable and sensitive to small changes in temperature. The North and Middle Forks are classified as snow-dominated basins because they receive more than 40% of their winter precipitation as snow, while the South Fork is classified as a transient rain-snow basin because approximately 10-40% of its winter precipitation falls as snow due to its relatively low relief compared to the North and Middle Forks (Dickerson-Lange and Mitchell, 2013; Hamlet et al., 2013). Most of the precipitation within the basin falls in the winter and spring months and ranges from less than 1 meter/year in the lowlands to more than 4 meters/year in the mountains based on a 30-year (1981-2010) average of annual precipitation (PRISM Climate Group, 2014). Historically, at elevations above 2000 meters, annual snow accumulation ranges from 8 to 10 meters (Bach, 2002).

3.2 Climate Change in the Puget Sound Region

Average annual air temperature in the Puget Sound region has increased by about 0.7°C over the last century (Mote and Salathé, 2010; Abatzoglou et al., 2014; Mauger et al., 2015). During that same time span, spring (March through May) precipitation has increased by 27%, while the other seasons showed no statistically significant evidence that precipitation trends have changed (Mauger et al., 2015). Additionally, the frequency and intensity of heavy precipitation has increased into the 21st century, though few studies show statistically significant results.

Future trends in temperature and precipitation in the region have been quantified by various studies through the use of global climate models (e.g., Mote and Salathé, 2010; Rupp et al., 2017). Relative to the 30-year average from the years 1970-1999, average annual air temperature is projected to increase by 2.4°C to 4°C by the 2050s (30-year average from 2040-2069) and 4.1°C to 6.7°C by the 2080s (30-year average from 2070-2099) based on the high emissions scenario RCP 8.5 (Mauger et al., 2015). Precipitation is more difficult to project due to the topography of western Washington. Projections indicate that precipitation will increase (11%) in the winter months and decrease (-27%) in the summer months by the 2080s based on emission scenario RCP 8.5 (Mauger et al., 2015). Additionally, the frequency and intensity of heavy precipitation events (e.g., atmospheric rivers) are projected to increase through the 21st century (Warner et al., 2015). Based on the RCP 8.5 scenario, the heaviest 24-hour precipitation events (i.e., the 99th percentile of annual 24-hour precipitation) will intensify by 22% and increase in frequency to 7 days per year by the 2080s compared to the historical 30-year average (1970-1999) occurrence of 2 days per year (Mauger et al., 2015).

Many studies have concluded that as temperatures increase through the 21st century, transient rain-snow basins, such as the South Fork of the Nooksack basin, will become rain-dominant basins due to more precipitation falling as rain rather than snow (Hamlet et al., 2013; Tohver et al., 2014; Mauger et al., 2015; Murphy, 2016). The hydrograph of a transient rain-snow basin will shift from a two-peak hydrograph to a single-peak hydrograph due to a decrease in snow-water equivalent (SWE) and earlier spring snowmelt, thus indicating that streamflow within the Nooksack basin will be affected by climate change (Dickerson-Lange and Mitchell, 2013; Mauger et al., 2015; Murphy, 2016).

3.3 Streamflow

The timing and magnitude of streamflow in the Nooksack River is heavily influenced by temperature and precipitation. These factors control the amount of precipitation that falls as rain or snow, the extent of the snowpack, and the timing and rate of snowmelt in the basin. Historically, rainfall and rain-on-snow events are the largest contributors to streamflow in the Nooksack River in the fall and winter, while snow and glacial melt are the largest contributors in the spring and summer (Dickerson-Lange and Mitchell, 2013; Grah and Beaulieu, 2013; Murphy, 2016). Between the 2005 and 2020 water years, average discharge of the Nooksack River recorded at the North Cedarville USGS stream gauge (downstream of Deming in Figure 1) was approximately 104 cubic meters per second (cms; USGS, 2021). Heavy rainfall events, such as atmospheric rivers, can increase discharge by an order of magnitude (e.g., 1,594 cms in November 2007; 1,436 cms in January 2009), resulting in substantial downstream flooding in the lowlands of the Nooksack basin.

Projected changes of temperature and precipitation in the Pacific Northwest over the next century will affect streamflow in Puget Sound watersheds (Elsner et al., 2010; Hamlet et al., 2013; Tohver et al., 2014; Mauger et al., 2015; Vano et al., 2015). Snowpack will decline and glaciers will recede due to increasing temperatures and more precipitation falling as rain rather than snow (Mauger et al., 2015). These changes will decrease the amount of snowmelt and glacier melt that is available to contribute to streamflow in the spring and summer, thus decreasing streamflow for those seasons. A reduced snowpack will expose a larger area available for rainfall runoff to streams, thus increasing winter streamflow due to more precipitation falling as rain. Previous hydrology modeling within the Nooksack basin has shown similar results in snowpack, glacier, and streamflow changes (Figure 5; Dickerson-Lange and Mitchell, 2013; Murphy, 2016).

As winter streamflow increases, the magnitude of peak flows will also increase. Peak flows are high magnitude streamflow events that occur after heavy rainfall and usually last for hours or days depending on the duration of rainfall, the size of the source area, and rain-on-snow timing (Ryberg et al., 2017). Projections within the Nooksack basin and other Puget Sound basins indicate that spring peak flows will shift to earlier in the year as temperatures increase and the timing of peak snowmelt occurs earlier (Dickerson-Lange and Mitchell, 2013; Mauger et al., 2015; Murphy, 2016; Lee et al., 2018). The magnitude of peak flows is projected to increase due to heavier and more intense rain events and more landscape becoming available for rapid runoff (Warner et al., 2015; Lee et al., 2018). In the higher elevations of a basin, where snowpack persists year round, rain-on-snow events will increase in frequency due to a shift from snow to rain (Musselman et al., 2018). Therefore, the amount of water available for runoff will increase, thus increasing the magnitude and frequency of peak flows.

3.4 Peak Flow Hazards

Projected changes of temperature and precipitation over the next century will affect peak flows in Puget Sound basins and have negative impacts on salmon habitat and flood severity. Salmon runs in the Nooksack basin have declined by 92-98% since the late 1800s, which is mainly due to habitat degradation (Grah and Beaulieu, 2013). Salmon habitat restoration and preservation in the Nooksack River is a major focus of the Nooksack Tribe because they depend on salmon for cultural and economic purposes. Peak flows can degrade salmon habitat through stream sedimentation, redd scour, and stream network alteration which can strand juveniles by disconnecting side channels (Goode et al., 2013; Grah and Beaulieu, 2013). Additionally, peak flows can increase the mortality of rearing juveniles due to a lack of flood refugia (e.g., natural log jams; Beechie et al., 2013). High magnitude peak flows can also increase flood severity and frequency, leading to the destruction of property and salmon habitat restoration efforts (e.g., engineered log jams; Mauger et al., 2015; Lee et al., 2018). Determining the frequency and magnitude of future peak flows will provide Nooksack Tribe officials and Whatcom County river and flood managers with the information necessary to improve salmon habitat restoration efforts and mitigate future flood risk by improving flood infrastructure and updating flood maps.

3.5 Hydrologic Modeling

Hydrologic numerical models provide a way to predict future hydrologic conditions for water resource and stormwater management purposes. The DHSVM was co-developed by researchers at the University of Washington and the Pacific Northwest National Laboratory (PNNL; Wigmosta et al., 1994, 2002). The DHSVM is a physically based, spatially distributed model that uses physical and empirical relationships to solve for energy and mass balance equations at each grid cell. The model requires gridded inputs of basin elevation, landcover, soil type and thickness, and a stream network. These grids are then forced with projected meteorological inputs (temperature, precipitation, wind speed, humidity, short- and longwave radiation) to simulate basin hydrological response variables such as snow accumulation and melt, evapotranspiration, soil storage, and streamflow.

The DHSVM has been used extensively throughout Washington State and within the Nooksack basin to quantify the effects of climate and landcover change on hydrology (e.g., Elsner et al., 2010; Dickerson-Lange and Mitchell, 2013; Du et al., 2014; Murphy, 2016; Frans et al., 2018; Lee et al., 2018; Sun et al., 2018; Freeman, 2019; Clarke, 2020). Previous modeling in the Nooksack basin was unable to capture the effect of high intensity rainfall events on peak flows because model forcings were statistically downscaled from daily meteorological data and disaggregated into 3-hour time steps (Dickerson-Lange and Mitchell, 2013; Murphy, 2016). To better capture rainfall intensity and more accurately assess peak flow timing and magnitude in the Nooksack River, I will use 1-hour historical and projected meteorological forcings that are dynamically downscaled using the Weather Research and Forecasting (WRF) model (Skamarock et al., 2005). In addition to producing meteorological forcings that will better resolve atmospheric processes at a finer temporal scale, dynamical downscaling uses physical principles (e.g., law of thermodynamics and fluid mechanics) that are expected to hold true under climate change; whereas statistical downscaling techniques assume that the statistical relationships used to transform GCMs will stay consistent with climate change, which may not be the case for extreme climate change (e.g., RCP 8.5; Fowler et al., 2007; Salathe et al., 2007).

4. Methods

4.1 DHSVM GIS Basin Setup

The DHSVM requires digital grids that represent the spatial variability of topography, landcover, and soil characteristics within the Nooksack basin. These spatial inputs include elevation, a watershed boundary, landcover, soil type and thickness, and a stream network. The grids were generated at a 150-meter resolution using publicly available data, tools within ArcGIS Pro, and Python scripts.

Digital elevation models (DEMs) for a large portion of Washington State were created from light detection and ranging (LiDAR) data, and were compiled and made accessible by the Washington Department of Natural Resources (WA DNR, 2017). The DEMs of the Nooksack basin have a 1-meter resolution that I mosaiced and resampled to a 150-meter resolution using tools within ArcGIS Pro. The watershed boundary of the upper Nooksack basin was defined using the mosaiced and resampled DEMs, ArcGIS Pro hydrology tools, and a pourpoint that depicts the grid cell to which the entire basin drains. Soil type data is derived from the State Soil Geographic (STATSGO) database, which was produced by a combination of agencies collectively known as the National Cooperative Soil Survey (USDA, 1998). I converted the data from vector to raster form at a 150-meter resolution and reclassified the data into seven DHSVM soil classes (Figure 2). Landcover data is from the 2016 NOAA C-CAP gridded dataset which uses spectral reflectance data from Landsat imagery to classify different landcover types (NOAA, 2016). The native 30-meter gridded data were resampled and reclassified into ten DHSVM landcover and vegetation classes (Figure 3). The soil thickness grid and stream network data files were generated by a Python script that was developed by researchers at the PNNL (Figure 6). The script requires a DEM and watershed boundary grid as inputs and uses ArcGIS hydrology tools to generate a stream network and a soil thickness grid as a function of slope, upstream drainage area, and elevation.

4.2 Historical Meteorological Forcings

The meteorologic inputs required by the DHSVM are temperature, relative humidity, precipitation, wind speed, and incoming solar and longwave radiation at a defined time step. Due to the lack of long-term historical meteorological data in the Nooksack basin, a gridded dataset of simulated historical meteorological forcings must be used. The simulated historical meteorological forcings that I will be using to calibrate the DHSVM were generated by researchers at PNNL using the WRF model (Chen et al., 2018). The WRF model uses physical and empirical relationships to simulate regional atmospheric processes at a user-defined time step (e.g., 1-hour) and a fine spatial resolution (e.g., 6 km) in order to capture the orographic effects, land-water contrasts, and mesoscale circulations that characterize the Puget Sound's climate and weather. Boundary and initial conditions for the WRF model are created from the North American Regional Reanalysis (NARR; Mesinger et al., 2006), which uses massive amounts of meteorological observations from various weather stations and remote sensing datasets to create a reanalysis dataset that provides the best estimate of atmospheric conditions for each timestep at a spatial resolution of 32 km.

The gridded WRF-generated historical forcings indicate an over-production (positive bias) of precipitation on the east side of the Cascades in WA and an under-production (negative bias) on the west side. Additionally, WRF-generated temperature forcings are too cold (negative bias) compared to historical observations. To better match the observed meteorological data recorded at weather stations and SNOTEL (SNOpack TELemetry) sites in the basin, the historical WRF-generated forcings will be bias-corrected. I am currently working with Guillaume Mauger of the Climate Impacts Group at the University of Washington to bias-correct the WRF forcings. The bias-correction method involves comparing the average value for a meteorological variable over the entire WRF simulation period (1981-2015) to valid observational data from that same time period for each weather station. An average bias is then determined from all the comparisons and a uniform scaling factor is applied to correct for the bias in each meteorological variable. Historical WRF-generated forcings implemented with the DHSVM have been used in other studies to successfully simulate historical peak flows (Lee et al., 2018; Mauger and Won, 2020).

4.3 DHSVM Calibration

Using the historical WRF-generated meteorological forcings as inputs, I will calibrate the DHSVM by comparing simulated streamflow and SWE outputs to observed streamflow and SWE measurements at various USGS stream gauges and SNOTEL sites throughout the basin (Figure 1). Historical streamflow data is available from the North Cedarville USGS stream gauge on the main stem of the Nooksack River, in addition to three other USGS stream gauges within each of the subbasins. Historical SWE and precipitation measurements are available from three Natural Resources Conservation Services (NCRS) SNOTEL sites, one located within each subbasin.

The calibration process involves systematically changing temperature, precipitation, and soil parameters until simulated streamflow and SWE are statistically similar to observed values.

The parameters that provide the most sensitivity to simulated streamflow and SWE response include precipitation and temperature lapse rates, snow parameters, saturated lateral hydraulic conductivity, porosity, and wilting points (Du et al., 2014; Sun et al., 2019). The predictive skill of the model and accuracy of the streamflow calibration will be assessed using the Nash-Sutcliffe efficiency (NSE) and Kling-Gupta efficiency (KGE) coefficient method (Nash and Sutcliffe, 1970; Gupta et al., 2009). Model performance is deemed satisfactory once daily and monthly flow simulations at the watershed scale achieve an NSE value of 0.5 or greater, a KGE value of 0.5 or greater, and a coefficient of determination (R^2) of 0.6 or greater (Moriasi et al., 2015). NSE and R^2 values will be computed for each model run, and simulated historical and observed streamflow and SWE will be visually compared using the statistical software package R.

4.4 DHSVM Simulation

I will use the calibrated DHSVM and dynamically downscaled projected meteorological forcings to predict future streamflow in the Nooksack River. Similar to the historical meteorological forcings, the projected meteorological forcings dynamically derive from the WRF model, which uses GCMs as boundary conditions to simulate future regional climate (Mauger et al., 2018). GCMs lack the resolution that is needed to capture the effect of mountainous topography on precipitation, and therefore regional climate models (i.e., the WRF model) are used. The projected forcings will span the time period 1970-2099 at a timestep of one hour and a spatial resolution of 12 km in order to capture the heavy precipitation events that are responsible for peak flows and will be generated by researchers at the University of Washington Climate Impacts Group (CIG). I will model 13 datasets of WRF-generated meteorological forcings that represent 12 different GCMs (Table 1). The GCMs were generated as part of the Climate Model Inter-comparison Project phase 5 (CMIP5) in which international modeling groups created a set of future climate simulations that were driven by various greenhouse gas scenarios (e.g., RCP 4.5 and 8.5) quantified by the IPCC's 5th assessment report (Pachauri et al., 2015). For 12 of my simulations, I will be modeling streamflows using meteorological forcings from GCMs that were created using the high greenhouse gas scenario (RCP 8.5), and the 13th simulation will use meteorological forcings based on the moderate greenhouse gas scenario (RCP 4.5). RCP 8.5 is the primary greenhouse gas emission scenario that will be used for projected simulation because it is the scenario that current greenhouse gas emissions are trending towards. Additionally, previous studies have shown that RCP 8.5 projections in the mid-century correspond reasonably well with RCP 4.5 projections in the late-century (Mauger and Won, 2020). Projected simulations will be performed on a 20-node server available in the Institute of Watershed Studies in Huxley College.

4.5 Data Analysis

DHSVM-simulated streamflows will be analyzed for each model run representing a different GCM using methods similar to Lee et al. (2018), Mauger and Won (2020), and Dickerson-Lange and Mitchell (2013). In order to account for annual and decadal climate variability, such as ENSO and PDO events, I will group the streamflows and SWE outputs over 30-year normals, centered on the years 1996 (hindcast), 2055, and 2085. I will compare simulated historical streamflows and SWE, referred to as hindcasts, to simulated future streamflows and SWE to assess how these parameters change over time (e.g., the timing of peak snowmelt and streamflow, changes to the shape of the hydrograph). I will visualize and compare historical and future daily peak flows for each 30-year normal by creating statistical figures using Python and R software. To assess the magnitude and frequency of future peak flows, I will generate frequency curves that represent 2, 10, 50, and 100-year streamflow magnitudes for both the 2055 and 2085 normals (e.g., Mauger and Won, 2020). To assess how the magnitude and frequency of future peak flows change compared to historic peak flows, frequency curves for simulated historic 2, 10, 50, and 100-year streamflow magnitudes will be generated for the GCM hindcast normal (e.g., Robinson et al., 2021).

5. Expected Results

Previous hydrology modeling within the Nooksack River basin has shown that as air temperatures increase, snowpack will decrease and more precipitation will fall as rain rather than snow, thus increasing winter streamflows (Dickerson-Lange and Mitchell, 2013; Murphy, 2016). Moreover, heavy rainfall events (e.g., atmospheric rivers) and rain-on-snow events are projected to increase in intensity and frequency (Mauger et al., 2015; Warner et al., 2015; Musselman et al., 2018). An increase in bare landscape, more intense and frequent rainfall events, and a greater amount of precipitation falling as rain will increase the amount of water that is available for runoff, therefore increasing the magnitude and frequency of peak flows within the upper

Nooksack River basin. Previous modeling was unable to successfully estimate the magnitude of future peak flows because daily precipitation forcings were disaggregated into 3-hour time steps, therefore not accurately capturing the effect of high intensity, short duration rainfall events on streamflow. By using new WRF-generated meteorological forcings with a 1-hour time step that will better depict heavy rainfall events, I hypothesize that my model will be able to successfully estimate future peak flow magnitudes.

I predict that the magnitude and frequency of extreme peak flows will increase in all three forks of the Nooksack River in the upper portion of the basin due to projected changes in temperature and precipitation. Due to the different physical characteristics within each subbasin, I suspect that future peak flows in the South Fork will respond differently to climate change compared to peak flows in the North and Middle Forks. As the South Fork changes from a transitional basin to a rain-dominated basin, peak flow magnitudes and hydrograph response will likely show similar changes compared to other rain-dominated basins, such as the Stillaguamish basin (Robinson et al., 2021). The snow-dominated North and Middle Forks will likely change to transitional basins, in which peak flow magnitudes will be driven by rain-on-snow events and less snowmelt will contribute to streamflow in the early spring, thus resulting in a smaller secondary peak on the hydrograph during that time. I predict that the North Fork will experience the greatest increase to peak flows because a large portion of its source area will change from snow-covered to bare landscape, resulting in the potential for more rapid runoff.

My main research outcomes will be to develop frequency curves, return intervals, and magnitude estimates of extreme peak flows within the upper portion of the Nooksack River basin. Future extreme peak flow magnitudes and recurrence interval estimates will be used by the Nooksack Tribe in their efforts to restore salmon habitat and prevent future habitat degradation through the installation of engineered log jams. Other uses for these results include the comparison of modeled projected snowpack and streamflow to previous studies in the upper Nooksack basin and to update flood maps and stormwater infrastructure (e.g., levees) along the Nooksack River. Additionally, the calibrated model can be used for future stream temperature modeling and mass wasting susceptibility mapping within the upper Nooksack basin.

6. Dissemination

I intend to present my research and results through either a poster or oral presentation at a conference that is concurrent with my research topic (e.g., NWCASC). Additionally, I will be updating scientists of the Nooksack Indian Tribe Department of Natural Resources with my modeling results and peak flow analysis via progress reports and oral presentations. I also intend to develop a manuscript of my thesis research for a peer-reviewed journal.

7. Timeline

Task	3/21	4/21	5/21	06/21	07/21	08/21	09/21	10/21	11/21	12/21	01/22	02/22	03/22	04/22	05/22	6/22
Literature review	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Basin setup	X	X														
WRF processing	X	X	X													
Model calibration		X	X	X	X	X	X									
Statistical analysis		X	X	X	X	X	X	X	X	X	X	X	X			
Writing, drafting, reporting	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Thesis tabling and defense															X	X

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9. Tables

Table 1: List of GCMs that will be dynamically downscaled using the WRF model to create 13 datasets of historical and projected meteorological forcings.

Global Climate Model	Research Center	Representative Concentration Pathway (RCP)
ACCESS1-0	Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia/ Bureau of Meteorology, Australia	4.5 and 8.5
ACCESS1-3	Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia/ Bureau of Meteorology, Australia	8.5
BCC-csm1-1	Beijing Climate Center (BCC), China Meteorological Administration	8.5
CanESM2	Canadian Centre for Climate Modeling and Analysis	8.5
CCSM4	National Center of Atmospheric Research (NCAR), USA	8.5
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization (CSIRO) / Queensland Climate Change Centre of Excellence, Australia	8.5
FGOALS-g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	8.5
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory, USA	8.5
GISS-E2-H	NASA Goddard Institute for Space Studies, USA	8.5
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	8.5
MRI-CGCM3	Meteorological Research Institute, Japan	8.5
NorESM1-M	Norwegian Climate Center, Norway	8.5

10. Figures

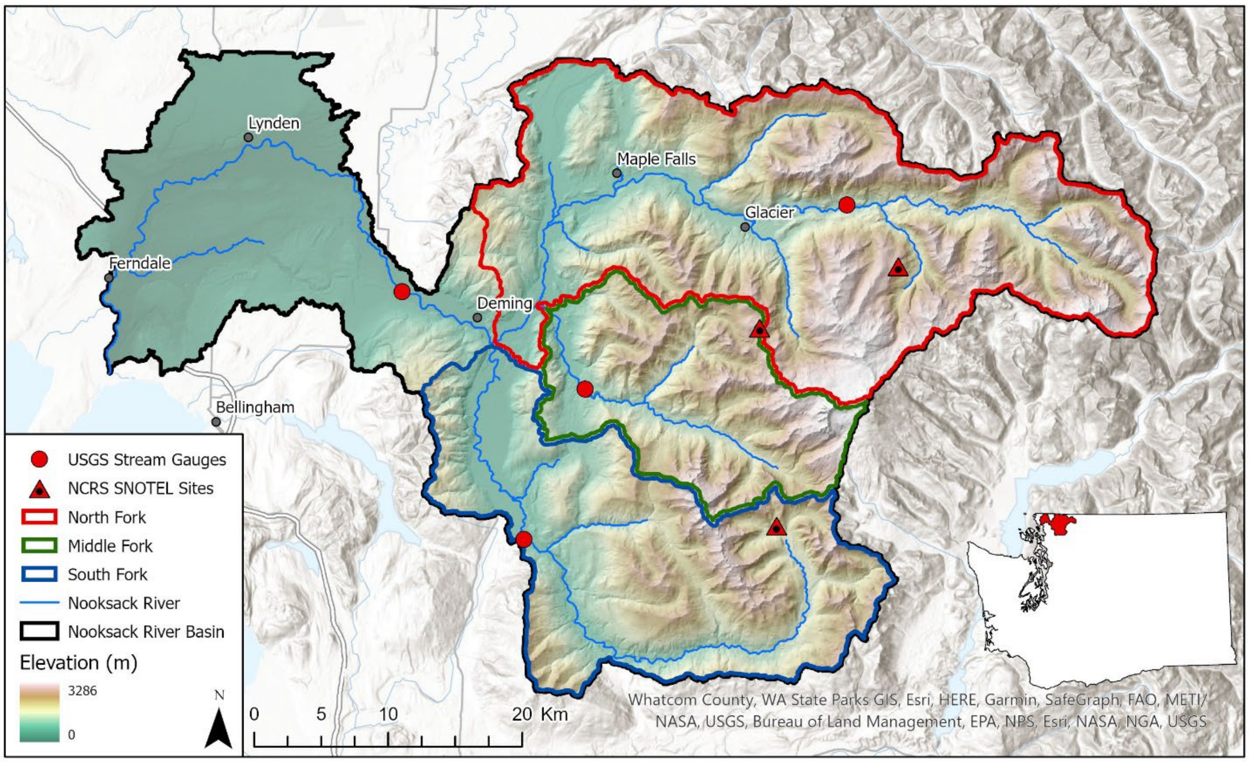

Figure 1: The Nooksack River basin is located in the North Cascades, Washington State. The upper Nooksack basin is the focus of this study and comprises of three main subbasins: North Fork, Middle Fork, and South Fork. The model will be calibrated using streamflow data at USGS stream gauges and SWE data at SNOTEL sites within each of the three subbasins.

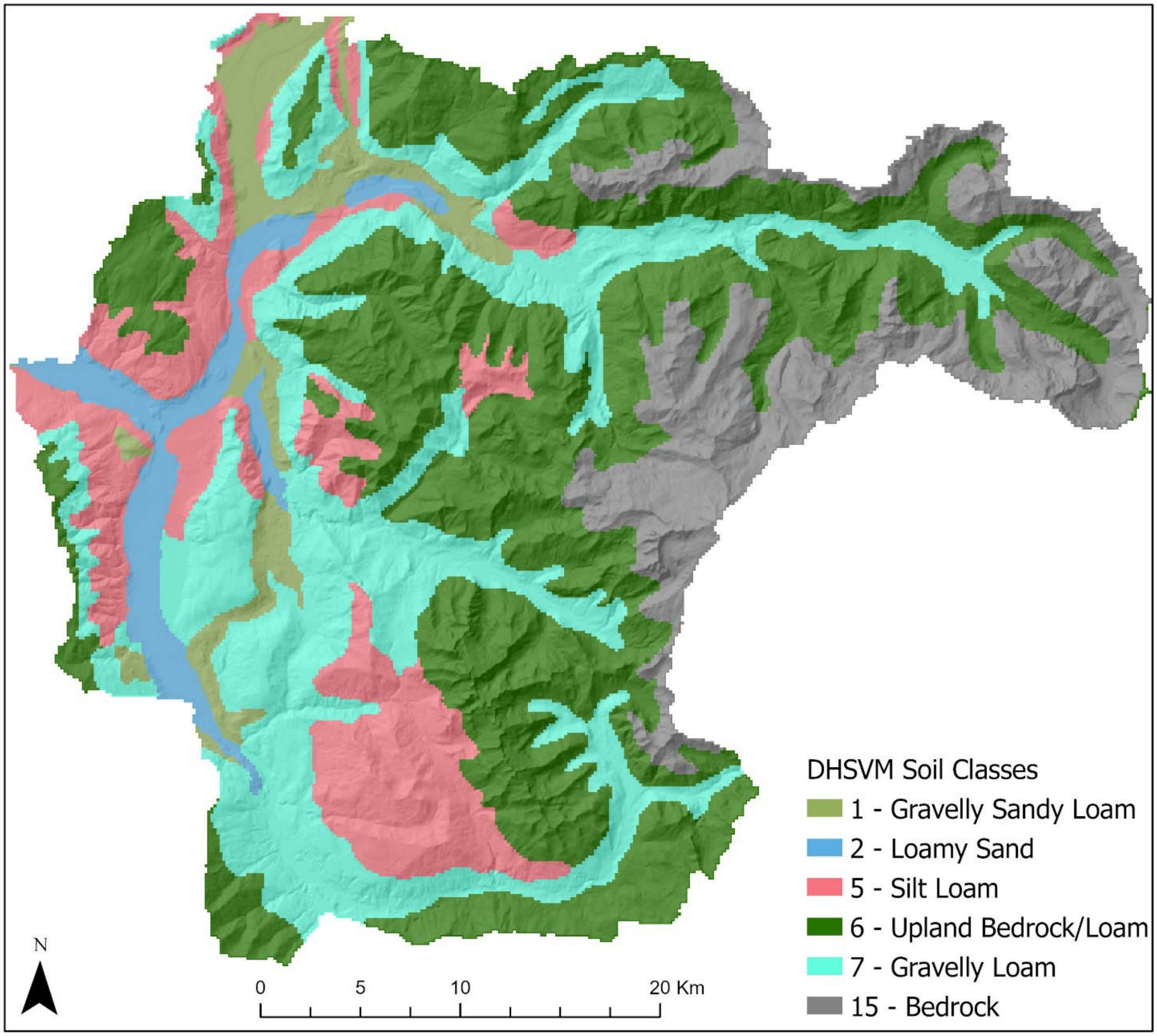

Figure 2: Soil classes within the upper Nooksack basin. The data derives from the STATSGO dataset and was converted from polygons to gridded data at a 150-meter resolution. The data was reclassified to correspond with soil classes within the DHSVM configuration file.

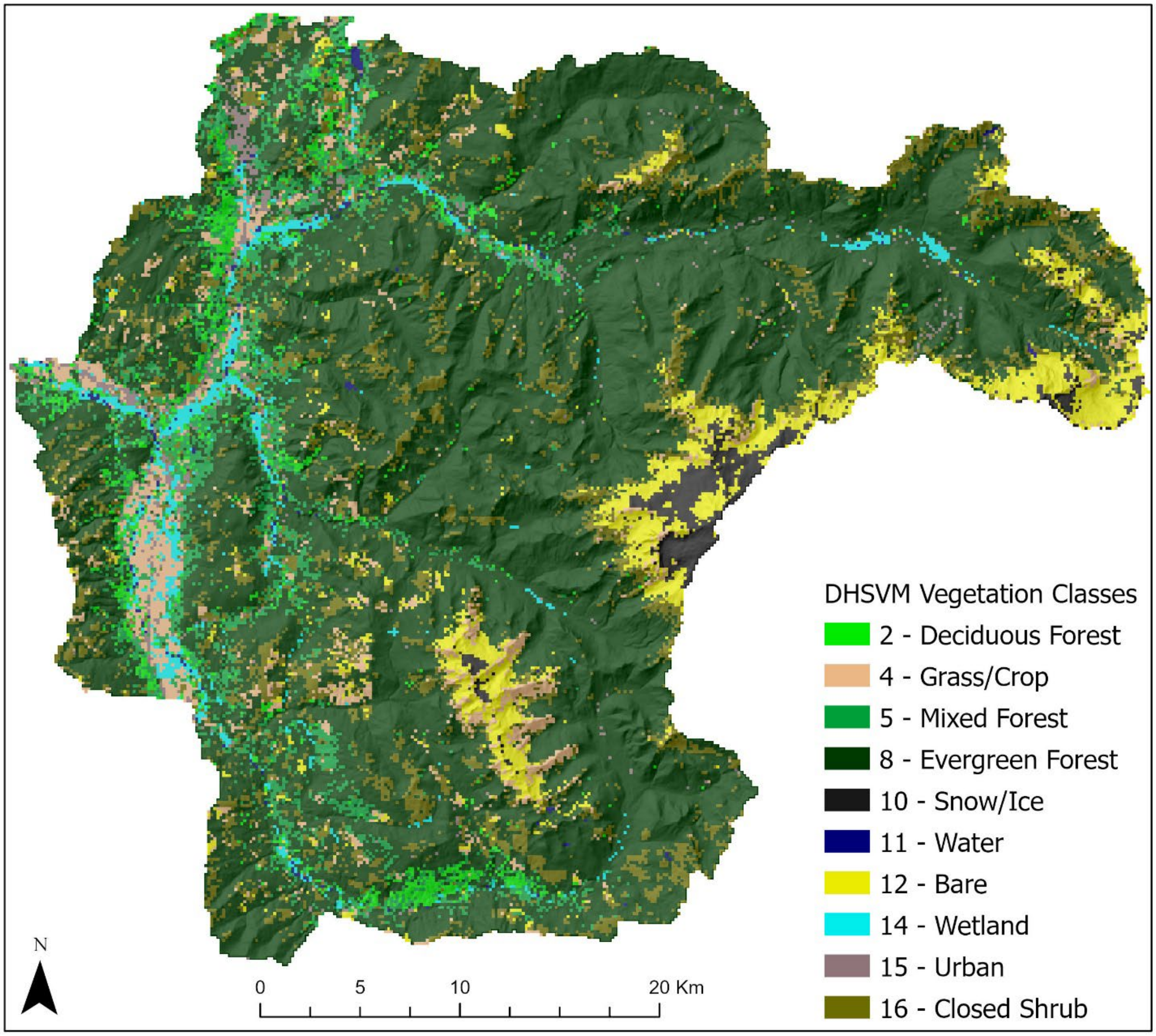

Figure 3: Landcover classes within the upper Nooksack basin. The data derives from the NOAA C-CAP 2016 gridded dataset and was resampled from a 30-meter resolution to a 150-meter resolution. The data was reclassified to correspond with landcover and vegetation classes within the DHSVM configuration file.

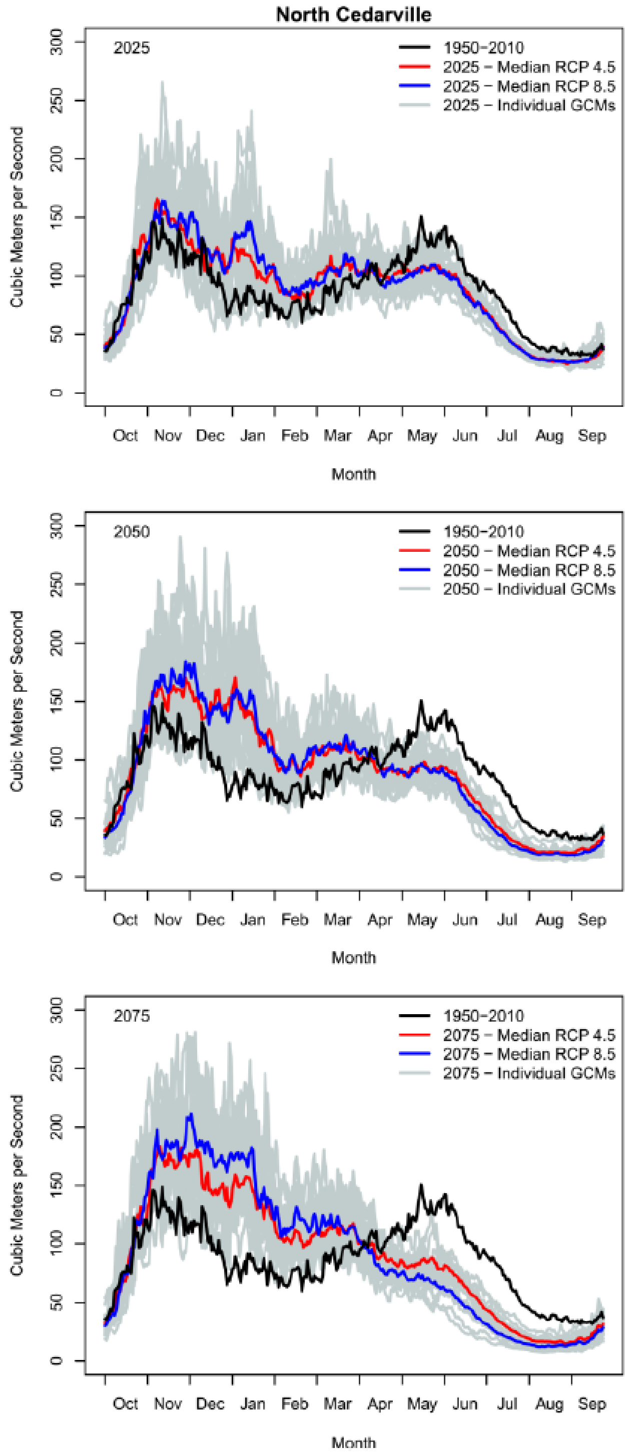

Figure 4: Simulated daily median streamflow discharge at the North Cedarville USGS stream gauge location for 10 GCMs under RCP 4.5 and 8.5 scenarios. The black line represents simulated historical daily median streamflow and shows a two-peak hydrograph representative of transient rain-snow basins. As more precipitation falls as rain rather than snow and snowmelt occurs earlier in the year, the hydrograph of a transient basin will transition into a single peak (Murphy, 2016).

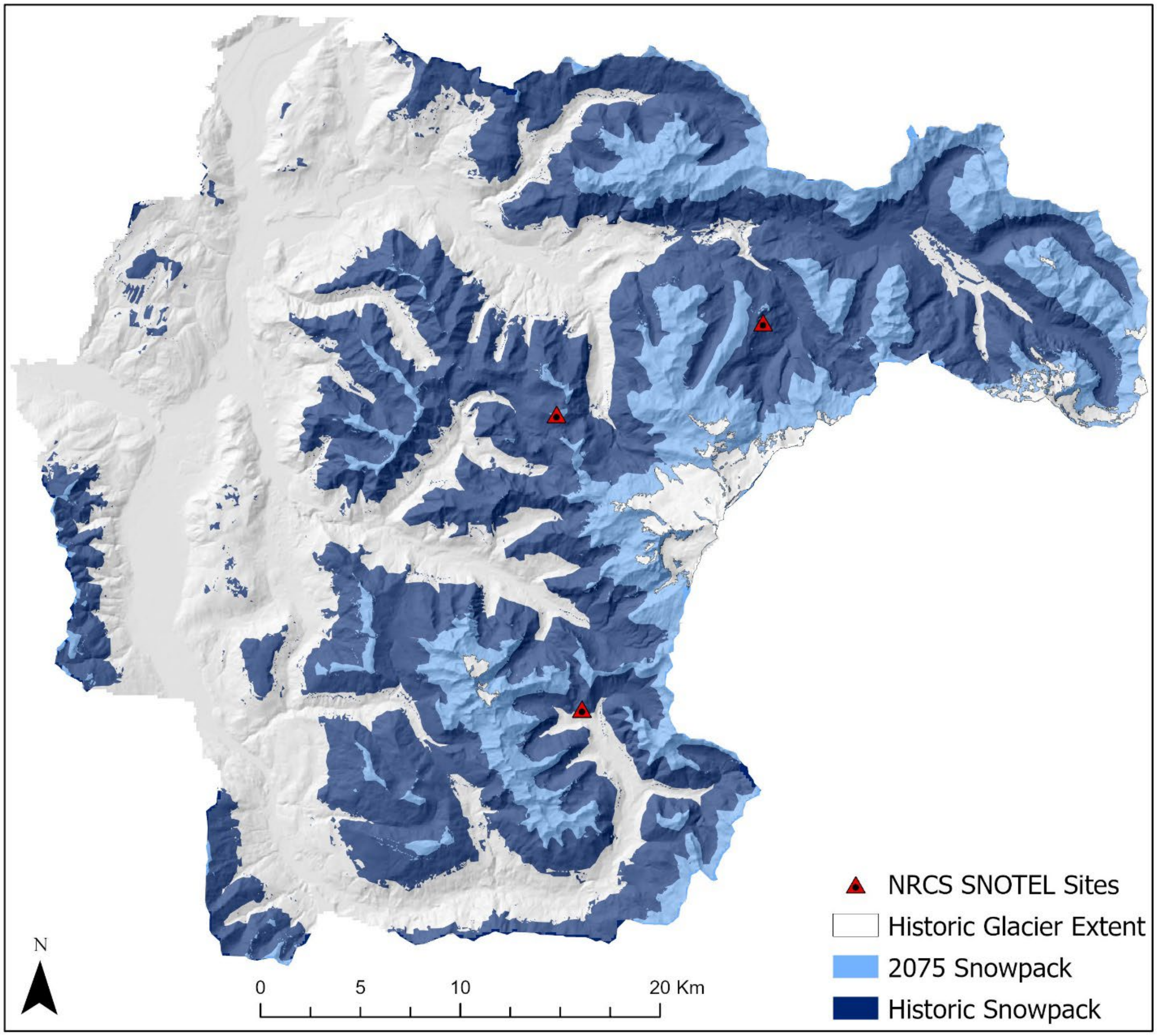

Figure 5: Snowpack and glacier extent within the upper Nooksack basin. Previous modeling indicates that snowpack and glacier extent will decrease through the 21st century as temperatures increase and more precipitation falls as rain rather than snow (Dickerson-Lange and Mitchell, 2013; Murphy, 2016). The snowpack coverages are modeled 30-year median snow coverages in January, centered on the years 1995 (historic snowpack) and 2075 (2075 snowpack) for a GCM with an RCP 8.5 scenario (Murphy, 2016).

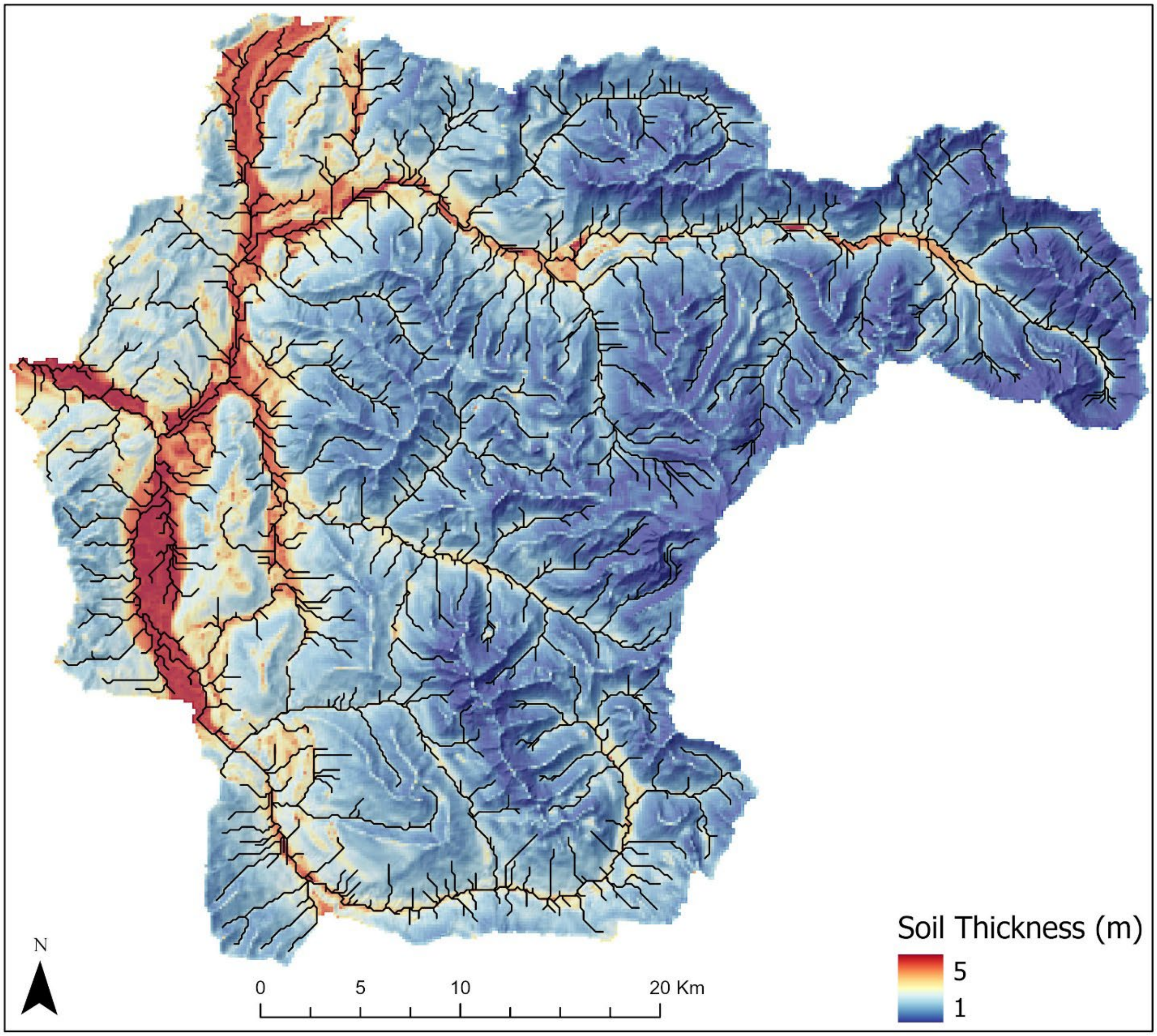

Figure 6: Soil thickness and stream network within the upper Nooksack basin. A python script, inputted with a basin DEM and watershed boundary, executes an ArcGIS workflow that generates a soil thickness grid map at a 150-meter resolution and a stream network consisting of line segments.