Assessing the Impact of Forest Harvest Scenarios on Streamflows in the Nooksack River Basin

Thesis Proposal for the Master of Science Degree,
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1.0 Problem Statement

Understanding how forest harvest scenarios can impact snowpack, runoff, and streamflows is crucial to protecting the welfare of salmon species and managing critical landscapes susceptible to flooding, such as the Nooksack River Basin of Northwest Washington (Figure 1). Previous hydrology modeling in the Nooksack Basin indicates that projected warming will push snowlines to higher elevations, reducing winter snowpack and resulting in less snowmelt runoff that will increase stream temperatures threatening critical salmon habitat (Dickerson-Lange and Mitchell, 2014; Murphy, 2016; Truitt, 2018; Paul, 2023). These modeling studies have yet to investigate forest harvest practices that can impact snow accumulation, soil-water storage, and streamflows. I will use the distributed-hydrology-soil-vegetation model (DHSVM; Wigmosta et al., 1994; Wigmosta et al., 2002) to test the hypothesis that select forest harvesting will increase low summer streamflows due to increased snow accumulation and melt and soil-water content; and peak streamflows due to more rapid runoff and rain-on-snow processes. Both historical and projected climate scenarios will be considered. The results of this study will assist in watershed management decisions and help protect the habitat of endangered salmon.

2.0 Introduction

The Nooksack River basin is located in northwest Washington State, drains into Bellingham Bay, and is a significant regional water source (Figure 1). The Nooksack River provides a habitat for fish populations and is widely used by regional tribes and the public for drinking water, agriculture, and industrial uses. Due to the region's maritime climate, the Nooksack basin is a transient rain-snow basin, making it more susceptible to temperature changes (Dickerson-Lange and Mitchell, 2014; Murphy, 2016). As the climate continues to warm, more winter precipitation is projected to fall as rain, pushing snowlines to higher elevations (Dickerson-Lange and Mitchell, 2014; Paul, 2023). The projected reduction in glacial area and snowpack results in lower spring and summer streamflows and higher stream temperatures, further threatening endangered salmon species (Truitt, 2019). In addition to more winter precipitation falling as rain rather than snow, models also project higher-intensity winter rainfall events (Warner et al., 2015). With steeper, snow-free landscapes receiving extreme rainfall events, peak flow magnitudes and frequencies are projected to increase, resulting in more flooding, slope mass wasting, and stream sediment delivery (Knapp, 2018; Paul, 2023).

In an ongoing effort to adapt to a changing climate, the Nooksack Indian Tribe is concerned with how forest harvest practices can help adapt to the effects felt by climate change (Morgan and Krosby, 2020). Since the late 1800s, western Washington has been the center of the timber harvesting industry because of the abundance of harvestable land. The upper Nooksack River basin covers about 1,500 square kilometers, about 40% of which retains an annual snowpack expected to decrease as climate change brings warmer winters. About 50% of the forested landscape in the upper Nooksack Basin is harvestable and harvesting and growth stages have been shown to influence snow accumulation, melt, and streamflow (e.g., Coble et al. 2020). Due to the high number of low-intensity rainfall events in the PNW, about 30% of the rainfall is intercepted (Stork et al., 2002; Fischer et al., 2023). Forest harvests (gaps) allow for less interception by evergreen trees and less longwave radiation from trees reaching the snowpack, resulting in more snow accumulation. More shading and sheltering of snow in the gaps from surrounding trees reduce wind and solar radiation, allowing for augmented snow retention and slower melt which increases soil water retention (Sun et al., 2018).

The objective of this study is to understand how forest harvest scenarios will impact snow accumulation, melt, soil-water content, and streamflows in the Nooksack River basin under historical and future conditions. I will modify a preceding DHSVM hydrology model (i.e., Paul, 2023) for the upper Nooksack basin to incorporate forest harvests using a dynamic grid process to model how streamflows will change with forest harvesting (Green and Alia, 2012; Schorbus and Alila, 2013; Sun et al., 2018; Figure 6). I will first focus on the Skookum Creek basin set up at a higher resolution to assess the sensitivity of the model to forest harvests. Skookum Creek is in a 59 km^2 basin and is a cold-water tributary to the South Fork of the Nooksack basin and is situated in mainly coniferous landcover that is harvestable and receives a seasonal snowpack.

The results of my modeling efforts will aid the Nooksack Tribe scientists and Whatcom County Flood Managers in deciding how to go forward with adaptation plans to protect salmon habitat and mitigate flood risks.

3.0 Background

3.1 *Basin Characteristics*

The upper Nooksack comprises (~1500 km^2) three subbasins: The North, Middle, and South Forks. The three basins join near Deming, WA (Figure 1). Annual average discharge into Bellingham Bay is about 3,000 - 4,000 cfs (Dickerson-Lange and Mitchell, 2014). Elevations in the basin range from the mouth of the river at sea level to 2,135 meters in the South Fork and to the peak of Mt. Baker at 3,286 meters in the North and Middle Forks. Precipitation in the winter and snowmelt in the spring and early summer support high streamflows. In addition to groundwater, low streamflows in late summer in the North and Middle Forks are sustained by high-elevation snow and glacier melt from about 31.6 km^2 of glaciers on Mt. Baker and Mt.

Shuksan (Fountain et al., 2007). However, periods of low streamflows in the South Fork are sustained by snowmelt and groundwater due to the lack of sizable glaciers. Skookum Creek is a subbasin of the South Fork with a drainage area of about 59 km^2 and ranges in elevations of approximately 150 meters near the stream monitoring gauge to 2,070 meters at the South Twin of the Twin Sister Mountains (Figure 5; USGS, 2023). The Skookum Creek basin will be used for model sensitivity analyses of the effect of harvesting on streamflows at a smaller scale and higher resolution. Skookum was chosen because of the convenient presence of a USGS stream gauge with historical data dating back to 1998 and the overall nature of the subbasin and harvestable landscapes. The Whatcom Land Trust stewards about 2400 acres in the Skookum Basin.

The Northwest Cascade Range is composed of Paleozoic to Mesozoic aged metamorphic rock, which contributes to the bedrock of the Nooksack basin and is accompanied by the Tertiary Chuckanut Sandstone Formation (Booth et al., 2003; Tabor et al., 2003). Multiple periods of glaciation and glacial retreat caused mass wasting events during the Quaternary period ending with the last significant glacier retreat of the Cordilleran ice sheet about 15,000 to 20,000 ya (Booth et al., 2003). They left behind what is known as the Vashon Drift, composed of worked-over bedrock and various glacial deposits. These deposits serve as parent material for the soils of the Nooksack Basin today, abundant in loam (38.7%), gravelly loam (24.5%), and silt loam (13.3%), according to the State Soil Geographic (STATSGO) database (USDA, 1998; Figure 4).

The Pacific Northwest region is influenced by cool and wet winters due to Aleutian low-pressure cells, and warm and dry summers are due to Subtropical high-pressure cells (McLachlan et al., 2007; Wang et al., 2016). This climate pattern varies temporally due to El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) events (Mantua et al., 1997; NOAA, 2014). ENSO events are typified by a warmer and drier climate (El Niño) or a cooler and wetter climate (La Nina) every two to seven years. Similarly, PDO events experience warmer, drier, and cooler, wetter climates but, instead, remain every 20 to 30 years. Combinations of ENSO and PDO events can cause extreme precipitation or extreme temperatures, contributing to major floods and droughts in the area. The orographic effect causes considerable precipitation that varies spatially and temporally within the Nooksack basin. Precipitation ranges from around one meter per year in the lowlands and greater than four meters per year in the mountains, and about 75% of the annual precipitation occurs between October and April (PRISM Climate Group, 2020). The lower relief of the South Fork causes precipitation to fall between 10-40% as snow, whereas the North and Middle Forks are snow-dominated, receiving over 40% of snow precipitation (Dickerson-Lange and Mitchell, 2013; Hamlet et al., 2013).

3.2 *Forest-Hydrology Interactions*

According to the current DHSVM digital setup (Paul, 2023), landcover (based on the 2016 National Land Cover Database) in the upper Nooksack basin (east of Nugent's Corner, WA) consists of barren land (5.2%) and snow and ice (1.6%), while lower elevations are comprised of pastures, crops, and grasslands (4.2%), wetlands (1.8%), urban areas (1.2%), and water (0.3%). Evergreen forests dominate land cover in the Nooksack Basin at around 65.3%, followed by deciduous forests, mixed forests, and shrublands at around 20.4% (NOAA, 2016; Figure 2). Vegetation cover affects soil-water storage, snow accumulation, and melt timing in rain-snow-dominated basins like the Nooksack watershed. Precipitation intercepted by vegetation and stored on the canopy returns to the atmosphere through evaporation and sublimation and will not contribute to soil infiltration and storage. Vegetation also transpires water from the soil, accounting for an evaporative canopy loss. Both interception and transpiration are vegetation dependent and vary with type, stage of growth, and season, and is in-part quantified by the leaf-area index (LAI). LAI is a dimensionless index defined by the ratio of the canopy leaf area exposed to the atmosphere to the canopy projection area on the ground surface. Total evapotranspiration (ET) is the sum of the evaporative loss from intercepted precipitation, transpiration, and soil surfaces. The DHSVM accounts for these processes.

The Puget Sound area experiences distinct and important forest-snow interactions throughout the seasons. In the spring, snowmelt provides crucial water supply for the forests, replenishing soil moisture and supporting tree growth and overall ecosystem health. The melting snow also benefits understory plants, initiating their growth, and replenishes streams and rivers, ensuring a steady water supply for aquatic organisms and downstream ecosystems. In contrast, during peak flows in the fall and winter, saturated soils and rain-on-snow processes can contribute to extreme flooding and mass wasting events which can increase sediment load, negatively affecting stream channels and riparian zones.

Timber harvesting and stage of growth have been shown to influence snow accumulation and melt and low flows in the summer (e.g., Storck et al., 2002; Moore et al., 2004; Lundquist et al., 2013; Cristea et al., 2014; Perry and Jones, 2016; Dickerson-Lange et al., 2017; Segura et al., 2020). For example, canopy openings in forests may retain snowpack longer, resulting in higher soil-water storage and summer streamflows (Dickerson-Lange et al., 2017; Harpold et al., 2015; Roth and Nolin, 2017). A recent study documented increases in August streamflows with 40 m forest harvest gaps (Gap 40) in the South Fork of the Nooksack basin using the DHSVM (Dickerson-Lange et al., 2022; Abdelnour et al., 2011). The Gap 40 scenario consisted of cylindrical 40 m diameter unforested gaps that were simulated within all coniferous pixels above

700 m of elevation. Cylindrical gaps are established by the DHSVM gap module (Sun et al. 2018).

Forest harvesting can increase peak flows in snow-dominated basins in western Washington and British Columbia due to greater snow accumulation and melt in clear-cut areas (e.g., Whitaker et al., 2002; Grant et al., 2008). Peak flows in the Nooksack basin are projected to increase by about 34-60% by the end of the century due to a decline in the snowpack and increased rain leading to a direct influx of rainwater into streams, augmented by intensified winter rains like atmospheric rivers (Paul, 2023). Higher peak flows increase the risk of flooding and mass wasting events, increasing sediment load in lowland streams. Increases in sediment load can alter stream channels and constrict water movement, decrease bank stability, and increase erosion, threaten existing restoration efforts, and damage river infrastructure. Declining salmon runs are anticipated due to increased winter floods, exacerbated by higher peak flows leading to intensified egg survival risks and habitat displacement of juveniles (Paul, 2023). A study by Jones and Perkins (2010) found that forest harvests in transient snow-rain basins, like the Nooksack basin, would increase snowpack areas and snowmelt, increasing peak flows in a large basin setting. In comparison, there were much smaller increases in small basin settings, such as Skookum Creek (Jones and Perkins, 2010). Another study conducted a meta-analysis of postharvest data in four catchments, demonstrating how forest harvesting substantially increases the magnitude and frequency of floods on record. The findings indicate that the increase in net radiation associated with the conversion from longwave-dominated snowmelt to shortwave-dominated snowmelt in harvested areas, along with other basin characteristics, plays a significant role in flood frequency and magnitude increases (Green and Alila, 2012).

3.3 *Climate Change*

Climate change has been shown to have significant impacts in the Pacific Northwest, including increased flooding, inundation, erosion, saltwater intrusion, marine heatwaves, and decreases in snowpack and glaciated areas (Roop H.A. et al., 2020). Previous hydrology modeling in the Nooksack basin using the DHSVM indicates that warmer winter temperatures will result in more precipitation falling as rain rather than snow, reducing the overall winter snowpack, and a smaller snowpack will produce less snowmelt runoff (freshet), lowering spring and summer streamflows (Dickerson-Lange and Mitchell, 2014; Murphy, 2016; Paul, 2023). Stream temperatures are expected to increase above critical salmon habitat thresholds for more extended periods due to a loss of cool water inputs from a smaller spring freshet and lower streamflows, which will especially decline with projected warmer, drier summers (Truitt, 2019).

As projected snowlines reach higher elevations, a greater percentage of the landscape will receive more rainfall in the winter months than snow, leading to more rapid runoff, higher peak flows, and mass wasting susceptibility due to higher winter streamflows (Knapp, 2018). Previous modeling of the effect of projected climate change on peak flows and flooding risk in the Nooksack basin showed that annual peak flow magnitudes are expected to increase on average by around 35% by the end of the 21st century on the mainstem of the Nooksack (Paul, 2023). This modeling was based on a similar study in the Stillaguamish River basin just south of the Nooksack (Mauger et al., 2021; Robinson, 2022). A research gap identified in the Nooksack's climate change adaptation plan is the impact of forest harvesting on streamflows (Morgan and Krosby, 2020). As such, a climate adaptation strategy that the Nooksack Tribe aims to explore is how selective forest harvesting could increase snow accumulation at higher elevations, thus increasing summer streamflows and mitigating warming stream temperatures. Another component to consider is the potential effect of stand age management, or forest management based on tree age, on soil water content and use.

3.4 *Cultural and Economic Importance*

A primary stakeholder in previous and current modeling projects has been the Nooksack Indian Tribe, which has implemented an adaptation plan for the onset of climate change that includes the Nooksack River basin and its tributaries (Morgan and Krosby, 2020). The tribe is concerned about how projected warming climates will impact salmon habitat and their restoration efforts. Salmon populations are at risk due to a degraded habitat by development, farming practices, and the effects of a warming climate. Salmon are essential to the survival and cultural livelihood of the Nooksack Indian Tribe and other Puget Sound indigenous tribes, which is why there is great interest in understanding the impact of climate change on stream health (NWIFC, 2020). Salmon spawn in the late summer to early fall when water levels and water recharge are low, sufficient cool instream flows are essential to healthy salmon populations. Peak flows in the winter increase risk of flooding and sediment load, negatively impacting salmon habitat and restoration efforts as well as lowland communities and river infrastructure (Schorbus and Alila, 2013). Various studies have been done assessing changes in flow in the Nooksack with the onset of climate change (e.g., Dickerson-Lange and Mitchell, 2014; Murphy, 2016; Truitt, 2018: Knapp, 2018; Paul, 2023), but there is still much work to be done in adapting to a warming climate.

In addition to salmon, there are other culturally important species within the watershed that may be affected by changes in streamflow and soil water content, such as native huckleberry plants. Huckleberries thrive in well drained soils, so increased soil water content may negatively impact huckleberry species (USDA NRCS). Various species rely on the huckleberry as a food source including black bears, elk, and the black-tailed deer (Morgan and Krosby, 2017). There are many other species to consider regarding the impacts of harvesting on streamflows in the Nooksack watershed, especially with the onset of climate change.

4.0 Methods

4.1 *Numerical Modeling with DHSVM*

The distributed-hydrology-soil-vegetation model (DHSVM; Wigmosta et al. 1994; Wigmosta et al. 2002) is a physically based hydrology model that is supported by the Pacific Northwest National Lab (PNNL). The model uses basin characteristics and meteorological forcings and energy and mass balance relations to simulate hydrologic processes such as evapotranspiration, soil infiltration and transport, and snow accumulation and melt, as well as state variables such as stream discharge, snow water equivalent (SWE), ground and surface water storage, and vegetation and soil water content. The DHSVM simulates a water and energy balance through hydrologic processes at a grid-cell level. These cells are interconnected through flow pathways, which allows the model to represent the spatial variability of hydrological processes across the entire watershed. Digital grids specify the spatial variation of elevation, land cover, soil type and thickness, and stream networks. Paul (2023) modified digital elevation models (DEMs) from the Washington Department of Natural Resources (WADNR, 2017) light detection and ranging (LiDAR) database in ArcGIS Pro to create a watershed boundary and a 150 m gridded DEM. Landcover is based on the 30 m 2016 National Land Cover Database (NOAA, 2016) that was resampled to 150 m (Figure 2). Digital soil type data (Figure 3) are from the State Soil Geographic (STATSGO) database (USDA, 1998). A soil thickness grid (Figure 4) and stream network (Figure 1) were generated using a Python script and ArcGIS tools considering slope, elevation, and drainage area. Please see Paul (2023) for details of the basin setup.

The DHSVM is forced with meteorological inputs, including temperature (ºC), precipitation (m), wind speed (m/s), relative humidity (%), and short- and long-wave radiation (W/m^2) at each time step which drive the energy and mass hydrologic processes. I will use the same dynamically downscaled forcing data developed and used by Paul (2023) in the Nooksack basin. The historical dataset (WRF-Obs) was created by researchers at the PNNL using the Weather Research and Forecasting model (WRF; Chen et al., 2018) and bias-corrected by Paul (2023). The WRF-Obs dataset has a 1-hour timestep at a spatial resolution of 6 km and a time series ranging from 1981 to 2015. I will use the WRF-Obs for the DHSVM model calibration and historical model simulations. Projected meteorology data (WRF-GCM) were generated using the WRF model and 12 global climate models (GCMs) under a representative concentration pathway (RCP) of 8.5, the worst-case emissions scenario by Mass et al. (2022) and bias-corrected by Paul, 2023). The 12 WRF-GCM datasets, representing the carefully chosen GCMs, contain 1-hour timesteps, spatial resolutions bi-linearly interpolated to 6-km, and span 1970 to 2099. The WRF-Obs and WRF-GCM data details are in Mauger et al. (2021) and Paul (2023).

Forests play a crucial role in modifying hydrological processes by influencing various components of the hydrological cycle, including evapotranspiration, snow accumulation and melt, infiltration, groundwater recharge, and surface runoff. The presence of vegetation, particularly forests, can significantly impact these processes due to their interception and transpiration capabilities, and subsequently their effect on soil properties and water storage.

The DHSVM explicitly represents the effects of forests on hydrological processes. Forest canopies intercept a portion of the incoming precipitation. This intercepted water can evaporate back to the atmosphere, reducing the amount of water that reaches the ground as throughfall or stemflow (water dripping off leaves and flowing down the stems of plants). DHSVM accounts for the interception process based on vegetation properties and meteorological conditions. Specifically, the DHSVM calculates the capacity of the canopy to store intercepted water based on vegetation characteristics, such as leaf area index (LAI), canopy height, and stem density. These parameters determine the canopy storage capacity, i.e., the maximum amount of water that the canopy can hold. The DHSVM uses rainfall data (e.g., from weather stations or gridded datasets) to distribute the precipitation across the watershed based on global precipitation and temperature lapse rates. The model then calculates the fraction of rainfall that is intercepted by the canopy for each grid cell based on the canopy storage capacity and the existing storage.

Evapotranspiration (ET) is the combined process of water loss through evaporation from stored water in the canopy and soil and water transpired by plants. Forests typically have higher evapotranspiration rates compared to other land cover types. The DHSVM simulates ET using a Penman-Monteith approach, including ET from the forest canopy and understory. It considers solar radiation, air temperature, humidity, and wind speed to estimate the rate of evaporation from the canopy surface. The DHSVM estimates canopy transpiration based on vegetation properties, such as LAI, stomatal conductance, and available soil moisture. It also considers environmental conditions like solar radiation, temperature, humidity, and atmospheric demand to determine the rate of transpiration. Key variables that quantify the interception and transpiration of rain or snow are the overstory and understory leaf area index (LAI), which can vary by type, month, stage of growth, and height (Height). A higher LAI leads to increased interception rates as a denser canopy captures more precipitation before it reaches the ground. Additionally, higher LAI values result in greater transpiration rates, as there is more leaf surface area available for water vapor exchange. The overstory vegetation type (Type) on a pixel has a fractional coverage (FC), whereas the understory covers the entire pixel. An example of the variables for Evergreen Forest used in the configuration file for the DHSVM is shown in Figure 7. The magnitude of ET is subject to independent energy and mass balance relations to determine losses to the atmosphere or throughfall to the soil or snowpack below. ET regulates the soil-water content, which influences infiltration and runoff. Higher soil-water contents result in more runoff and soil-water transmission to streams.

Forests can enhance soil infiltration rates by promoting the development of a well-structured soil with a higher organic content. This process is essential for replenishing groundwater resources. Soils in the DHSVM have four layers. The thickness of the first three layers are defined by the vegetation root zone depths (Figure 7). The fourth layer thickness is the pixel soil depth less the root depth thicknesses. The DHSVM takes into account soil properties, including hydraulic conductivity and soil texture, to simulate the infiltration process. The hydraulic properties can vary for the first three layers, whereas the fourth layer takes on the properties of the third layer. The model tracks soil moisture content over time and calculates the amount of water that infiltrates the soil based on the incoming precipitation, throughfall, and stemflow. It considers the existing soil moisture and infiltration capacity to estimate the partitioning of water between infiltration and surface runoff. Additionally, vegetation types vary in root depths which has several impacts on soil infiltration. For example, deeper roots draw water from deeper soil layers which can allow for more infiltration and better soil stability, thus reducing surface water runoff and erosion. The DHSVM uses a "root zone" approach, where different vegetation types are characterized by specific root depths and hydraulic properties. Rooting depths are used to define soil thicknesses and water uptake by plants and the subsequent redistribution of water within the soil layers. The model simulates how water moves through the root zone, how much water is absorbed by plants, and how much water is stored in the soil.

Forests can reduce surface runoff by capturing and storing precipitation through the canopy and understory. This effect may attenuate peak flows during short light rain events which frequent the Puget Sound area. During intense rainfall events, interception's impact is minimal, as less water is retained on the canopy and a greater amount of throughfall reaches the ground. The DHSVM calculates overland flow based on the excess rainfall or snowmelt that cannot infiltrate the soil. It considers slope, soil properties, and vegetation cover to determine the flow velocity and direction. The model routes the overland flow through the network of hillslope and channel cells, considering topography and channel properties. In the DHSVM, overland flow moves over the entire pixel length in one time step (Dubin and Lettenmaier, 1999).

The combined effects of interception, evapotranspiration, infiltration, and runoff eventually contribute to streamflow in a watershed. The DHSVM simulates water movement from hillslopes to channels within the watershed. The model accounts for overland flow, subsurface flow, and lateral flow contributions from different parts of the catchment. Overland flow occurs when the soil cannot absorb all the incoming water, leading to surface runoff. It calculates the flow accumulation for each grid cell to determine the direction of water movement and route it downstream. This process ensures that the model correctly accounts for the spatial flow pathways throughout the watershed. As water is routed downstream, DHSVM considers the channel properties, such as channel slope, width, and depth, to estimate the flow velocity and water depth in the channels. The model integrates contributions from various cells to obtain the total streamflow at each point in the river network.

The DHSVM has different modules and representations of forest-related processes, and the model's structure can be customized to suit the specific characteristics of the study area and the available data. Two modules I will be exploring are the Canopy Gap Module (DHSVM V-3.2; Sun et al., 2018), which was used in Dickerson-Lange et al. (2022), and the Dynamic Vegetation Module (DHSVM-DV). The DHSVM-DV is an unpublished version of the DHSVM created by Zhuoran Duan in collaboration with Mark Wigmosta at the PNNL.

The canopy gap module in the DHSVM represents the dynamics of forest canopy openings, which occur due to timber harvesting, disturbances (e.g., fire, wind), or natural canopy turnover. The module accounts for the spatial and temporal changes in canopy cover, allowing the model to simulate the effects of canopy gaps on various hydrological processes. When a gap forms, it alters the interception, evapotranspiration, and radiation balance within the affected area. The module calculates the gap fraction, representing the proportion of the canopy that is open, and adjusts the parameters related to canopy interception and evapotranspiration accordingly. By considering canopy gap dynamics, DHSVM can better capture the temporal variability of hydrological processes in forested areas, providing more accurate assessments of soil moisture and streamflow dynamics in ecosystems influenced by periodic canopy disturbances.

The dynamic vegetation module in the DHSVM-DV simulates the spatial distribution of harvests and growth over time. It allows the model to account for changes in vegetation characteristics, i.e., the Type, LAI, FC, and canopy Height, as they respond to changing environmental conditions and disturbances. Through this dynamic representation, the model can adaptively simulate shifts in vegetation, reflecting the ecological succession and responses to land use changes. By incorporating these vegetation dynamics, the DHSVM-DV can better capture the influence of changing vegetation on hydrological processes, such snow accumulation and melt, as transpiration, interception, and soil moisture, streamflow will evolve over time.

4.2 *Calibrating to Summer Flows*

Calibration involves adjusting model parameters to match observed hydrological data, which improves the accuracy and reliability of the model's predictions. Previous calibrations of the DHSVM (Paul 2023) focused on peak streamflows, and daily and monthly streamflows and SWE were calibrated to better than satisfactory levels and will need minimal adjustments. Since my part of the work will focus more on low streamflows and SWE, these calibrations will need to be improved for the whole basin.

Calibration requires a statistically reasonable match to observed historical United States Geological Survey (USGS) streamflow observations and Natural Resources Conservation Service Snow Telemetry (NRCS SNOTEL) data in the Nooksack River basin (Figure 1). Three SNOTEL sites record historical SWE, one in each subbasin that varies in elevation (927 m, 1228 m, and 1515 m). There is a USGS stream gauge in each of the three forks of the Nooksack basin and one below the confluence of the forks at Cedarville. To calibrate the DHSVM, snow physics, temperature, precipitation, and soil parameters must be methodically changed so that the simulated streamflow and SWE are statistically comparable to the observed USGS streamflow and NRCS SNOTEL data. I will calibrate for up to 10 years of data when possible. Using Paul's (2023) gridded WRF metrological inputs and R-scripts, I will refine the calibration and validation of the DHSVM to historic low-flow and high-flow conditions. I will need to improve the calibrations for low summer flows and SWE. Several parameters are crucial for accurately representing low summer streamflows; soil and snow physics parameters especially need adjustments. Parameters related to soil characteristics, such as porosity, field capacity, and wilting point, influence water retention and drainage. Adjusting these parameters can impact how much water is available for streamflow during dry periods. Snow-related parameters like snowmelt rate, snowpack density, and albedo can influence the timing and magnitude of streamflows.

Comparing simulated and observed data involves multiple statistical measures that are important in determining the model's efficacy, including the King-Gupta efficiency (KGE) and the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970; Gupta et al., 2009). KGE and NSE determine the model's efficacy and whether the calibration is considered satisfactory when they yield values greater than 0.5 in concert with a coefficient of determination (R^2) of 0.7 or greater (Moriasi et al., 2015). A low root squared mean error (RMSE) shows minimal model residuals. These coefficients will be calculated in an R script for each model run, accompanied by a hydrograph containing observed and simulated streamflows.

4.3 *Develop Forest Harvest Scenarios and Modify them as Dynamic Grid Inputs*

I will generate a series of land cover grids in collaboration with my stakeholders to run the DHSVM forest harvest modeling experiments, including various parcels representing potentially harvestable land. I am using the 2016 Coastal Change Analysis Program dataset, an inventory of standardized raster-based land cover imagery at 30 m resolution (2016 C- CAP: NOAA, 2022), which was resampled to 150 m resolution. I will modify these in ArcGIS Pro to establish a collective of forest harvest scenarios. My harvest scenarios will be focused on evergreen forests.

Using Whatcom and Skagit County, WA State DNR, and US Forest Service datasets, I will compile the various parcels into more specific ownership categories, including WDNR, USFS, Commercial Timber, and Private. There are different endangered and protected species within these forests, so I will determine any protected areas that cannot be harvested to be excluded from my harvest scenarios. Using the raster calculator tool in ArcGIS Pro, I will find all areas that are in coniferous forests and choose varying elevations for my analyses. Susan Dickerson-Lange and Julia Jay of Natural Systems Design have shared the shape and raster files used in the South Fork, which I will use to validate the processes of assigning ownership and habitat protection (Dickerson-Lange et al., 2023; Figure 6).

Both peak and low streamflow harvest scenarios will be designated in coniferous forest and will vary in elevation band. Since low summer flows and soil-water retention are highly affected by ET and snow depth and snowmelt, chosen parcels will be focused in areas where there is a reliable amount of snow contributing to the late spring and early summer freshet and soil-water retention. The saturation extent during peak streamflows is high, so lower elevation clearcuts will be important to assess peak flows.

After I have harvestable areas, I will develop a series of harvest scenarios varying with aspect, size, elevation band, and ownership. To begin, I will examine the upper and lower bounds of clearcuts in a historical setting. An upper-bound scenario would include a complete change in vegetation attributes (e.g., removal of fractional coverage of the coniferous overstory) of all available harvestable lands, and a lower-bound scenario might include minimal vegetation change in each fork fed into the DHSVM. Other scenarios will be carefully thought out based on the results of the extreme cases, potential harvest schedules of ownership, and feasibility of implementation. My historical harvest grids will evolve as I progress forward in my understanding of the different vegetation attributes (See 4.5 Modeling experiments) that affect streamflows and SWE. Understanding these effects will help me determine the best scenarios for my projected analyses. All the forest harvests will be converted from gridded formats to ASCII (binary) formats recognized by the DHSVM.

4.4. *Skookum Creek for Sensitivity Analyses*

I will use the Skookum Creek subbasin of the South Fork of the Nooksack to test the sensitivities of peak and low flows at a smaller scale and higher resolution (Figure 5). The location of Skookum Creek is ideal for assessing the impacts of forest harvesting on low summer streamflows at a smaller and finer scale because the area includes a range of elevations, is a more natural system compared to the entire basin, and has a historical USGS stream gauge near its mouth. The landcover grid basis for the Skookum Creek study will have a 30 m resolution, which is the resolution of landcover available from the 2019 National Landcover Database grid (NLCD, 2019).

Skookum Creek has a USGS stream gauge that contains historical data dating back to 1998 and will be used to run simulations and calibrate the Skookum Creek subbasin to low summer streamflows (USGS, 2023). Low flows in the summer months are particularly sensitive to various factors, including snowmelt inputs, soil and vegetation characteristics, and groundwater in lowland stream channels. Because of this, low flows will be the primary focus of the sensitivity analysis. Currently, Dr. Mitchell is working on developing the Skookum DHSVM modeling setup, and I will help calibrate the model. I will create forest harvest grids for the Skookum Creek subbasin, like those done for the entire Nooksack basin. Please refer to section 4.3 for more details. The Skookum Creek will be a large focus of my project and will assist me in determining local scale effects of harvesting on streamflows and whether these effects are significant enough to apply to the whole basin where there is much more variability to consider.

4.5 *Modeling Experiments*

Once I calibrate the DHSVM to low flows, high flows, and SWE in the Nooksack River basin, I will begin numerical simulation experiments with my modified forest cover harvest grids. A previous study applied the standard version of the DHSVM to examine projected peak flows in the Nooksack basin using a static land cover grid, meaning that the land cover attributes, and vegetation variables remained unchanged throughout the simulation (Paul, 2023). I will modify this model to incorporate dynamic forest coverage changes to model how forest harvests may impact streamflows (Figure 6).

I will use techniques like Dickerson-Lange et al. (2022) used in the South Fork of the Nooksack basin to expand the modeling to include the North and Middle Forks. Dr. Mark Wigmosta's research group (specially Zhuoran Duan) at PNNL has developed a technique to dynamically read in changing vegetation variables as grids on predetermined pixels (i.e., Type, FC, LAI, and Height) as the model is running (DHSVM-DV). Dr. Mitchell has been spending part of his sabbatical working with Zhuoran learning the technique. Dr. Mitchell will coach me on the process in the summer of 2023, and I apply it to simulate harvests in coniferous forests.

My fundamental effort will be developing the modified dynamic vegetation grids based on my forest harvest analysis (see section 4.3) in ArcGIS Pro. For example, as discussed above, I will experiment with different harvest scenarios in a historical setting to understand how FC, LAI, and Height changes affect peak flows, low flows, and SWE within the Nooksack basin and low flows in the Skookum Creek subbasin. Dynamic vegetation gridded maps of the overstory

FC and LAI and the overstory and understory Height can be separately read in at a specified timestep, at a frequency that is to be determined. To initiate a harvest, dynamic vegetation maps of overstory FC, LAI, and Height may be reduced or increased in the designated harvested pixels at a specific timestep. I will work with my DNR stakeholders to determine growth rates of evergreen trees specific to the Western Cascades to modify FC, LAI, and Heights accurately. I may also need to account for transpiration as trees age which is not a linear process. My historical modeling experiments will run and be averaged over 30-year intervals, mimicking the South Fork study (Dickerson-Lange et al., 2023).

My historical exploration will drive the decisions on harvest scenarios for my projected exploration. For my projected analysis, I may use 12 scenarios based on 12 different GCMs, or choose a medium scenario as done in the South Fork by Dickerson-Lange et al. (2023). These decisions for my projected simulations will be increasingly clarified as I understand how the different variables affect streamflows.

4.6 *Data Analysis*

I will run a DHSVM baseline simulation for historical and projected climate cases using the dynamically downscaled forcing data developed and used by Paul (2023). I will repeat my DHSVM modeling analysis with each harvest scenario I generate. Simulated streamflow, SWE, will be analyzed using R-scripts to quantify changes to assess harvest scenarios. I will also examine changes in ET and soil-water contents at isolated pixels in treated and untreated forest regions. The scripts will calculate various statistical measures and output hydrographs, allowing for visual and statistical analysis. Many of my analyses will be similar to Dickerson-Lange et al., (2022) and Paul (2023). If there are apparent changes, I will create box plots to quantify the magnitudes of mean streamflow discharge, soil-water content, and SWE changes related to forest coverage change. I will also run multiple regression analyses on the historical scenarios to determine how strong the relationship is between forest coverage changes, and streamflow and SWE. I may also explore the impacts of harvest scenarios on wet and dry years (1999 and 2003, respectively, were used in Dickerson-Lange et al., 2022).

Once I determine and quantify changes in a historical setting, I will compare projected streamflow and SWE simulations to the historical simulations for each harvest scenario. I will run the same statistical analyses as done for historical simulations and against historical simulations to quantify future changes in addition to the effects of climate change. I may also compare my DHSVM modeling results in the South Fork to those from Susan Dickerson-Lange (2022) to determine if the impacts are statistically similar and if my results are accurate.

5.0 Expected Results and Potential Problems

The impact of a forest harvest scenario on snow accumulation and streamflow can vary depending on the management approach. If the frequency of harvests is increased while maintaining the same extent of the forested area, it will likely lead to increased snow accumulation and accelerated snowmelt. As a result, there would be a rise in streamflow during the early part of the summer, similar to the results of Dickerson-Lange et al. (2023). On the other hand, if the frequency of harvests remains the same, but the extent of the forested area is reduced, the effect would be different. In this case, the reduction in forest cover might lead to altered snow accumulation patterns and a modified snowmelt rate. Consequently, the streamflow dynamics would likely be impacted, but the exact changes would be influenced by the extent of the remaining forested area.

Harvesting at different aspects and elevations may also affect streamflow and snow accumulation. North-facing slopes receive less direct sunlight throughout the day, leading to colder conditions and slower snowmelt rates. Harvesting on north-facing slopes may have a smaller impact on snow accumulation and melt than harvesting on south-facing slopes. South-facing slopes receive more direct sunlight and warmer temperatures, resulting in faster snowmelt rates, so harvesting here could exacerbate snowmelt and lead to earlier peak streamflows. Forest harvesting at high elevations could have a larger impact on snow accumulation and melt than at lower elevations since temperatures are generally colder, and snow accumulates and persists for longer periods. Harvesting at lower elevations could have a less significant effect on snow accumulation and melt due to the milder temperatures and increased susceptibility to rain-on-snow processes. The combination of aspect and elevation can further amplify or mitigate the effects of forest harvest scenarios on snow and streamflow dynamics.

If my harvest scenarios look similar to the various gaps in Dickerson-Lang et al. (2023), I predict that forest harvest scenarios will increase low summer streamflows due to increases in snow accumulation, and thus SWE, in the harvested areas. Due to the increased precipitation from climate change and rain-on-snow processes, I expect that peak flows will also increase, which would increase flooding and sediment load. However, forest harvests may have little impact on streamflow. My historical analyses are meant to understand the sensitivities of the effect of vegetation coverage changes on streamflows and SWE. Testing various scenarios will allow me to understand these impacts thoroughly and determine what scenarios will be of most interest to test in a projected setting. If the results of my historical analyses show minimal to no streamflow and SWE changes, my projected analyses will need to change accordingly. In either case, there might still be impacts in a projected setting with climate change influences, so it is important to test projected impacts.

Creating my forest harvest grids is an evolving process that allows for potential roadblocks to arise. One of the potential challenges lies in determining the appropriate parameter values to represent growth in terms of LAI, FC, and Height. Finding accurate and relevant parameter inputs is essential to effectively model the growth and dynamics of vegetation in the given scenario. Another challenge arises from the model's limitation in representing adjacent shading effects. As a result, small-scale thinning or gap-cutting practices may not be fully represented in the model. This could lead to incomplete representations of the actual forest dynamics, particularly when dealing with fine-scale forest management actions that involve localized thinning or gap creation. Another potential challenge is the difficulty of discerning minor variations in streamflow from other uncertainties in the modeling process, such as the absence of roads in the model. This ambiguity may make it challenging to isolate and attribute specific causes to slight changes in streamflow. Using Skookum Creek for the study offers several advantages. Being a more natural system and covering a smaller area allows for a more focused examination, facilitating the identification of precise effects and reducing the impact of confounding factors.

The results of my simulations are meant to be communicated to the Nooksack Tribe scientists and Whatcom Flood Managers, regardless of if there are significant impacts or not, to assist with management decisions in the future.

6.0 Dissemination Plan

I intend to present my research at professional conferences e.g., the Northwest Climate Adaptation Research Center Climate Conference. I will periodically update my stakeholders with oral presentations and written progress reports. I also intend to develop a manuscript of my research to be published in a peer-reviewed journal.

7.0 Timeline

Task	3/23	4/23	5/23	6/23	7/23	8/23	9/23	10/23	11/23	12/23	1/24	2/24	3/24	4/24	5/24	6/24
Literature Review	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Forest Grids	X	X	X	X	X	X	X									
Model Calibration			X	X	X	X	X	X								
Statistical Analyses			X	X	X	X	X	X	X	X	X	X	X	X	X	
Thesis Writing	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Thesis Defense															X	X

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9.0 Supporting Figures

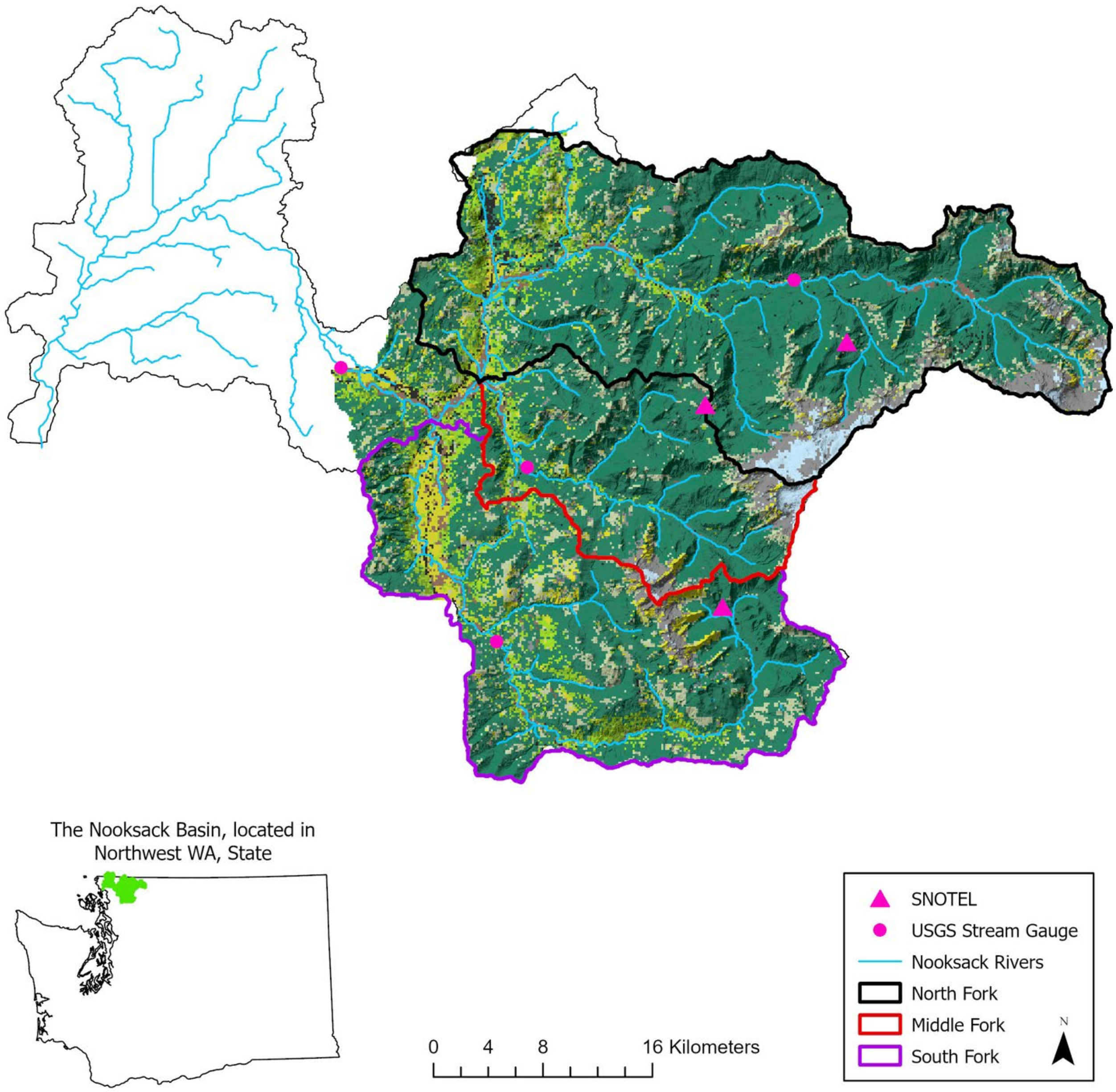

Figure 1. The Nooksack River basin in northwest Washington State and its major forks, North, Middle, and South outlined in black, red and purple, respectively. NRCS SNOTEL sites are represented as pink triangles, and USGS stream gauges are represented as pink circles. My research is focused on the Upper Nooksack River basin, which is represented by landcover, because there are less influences from human sources, such as, urbanization and agriculture. Details on landcover classes can be seen in Figure 2.

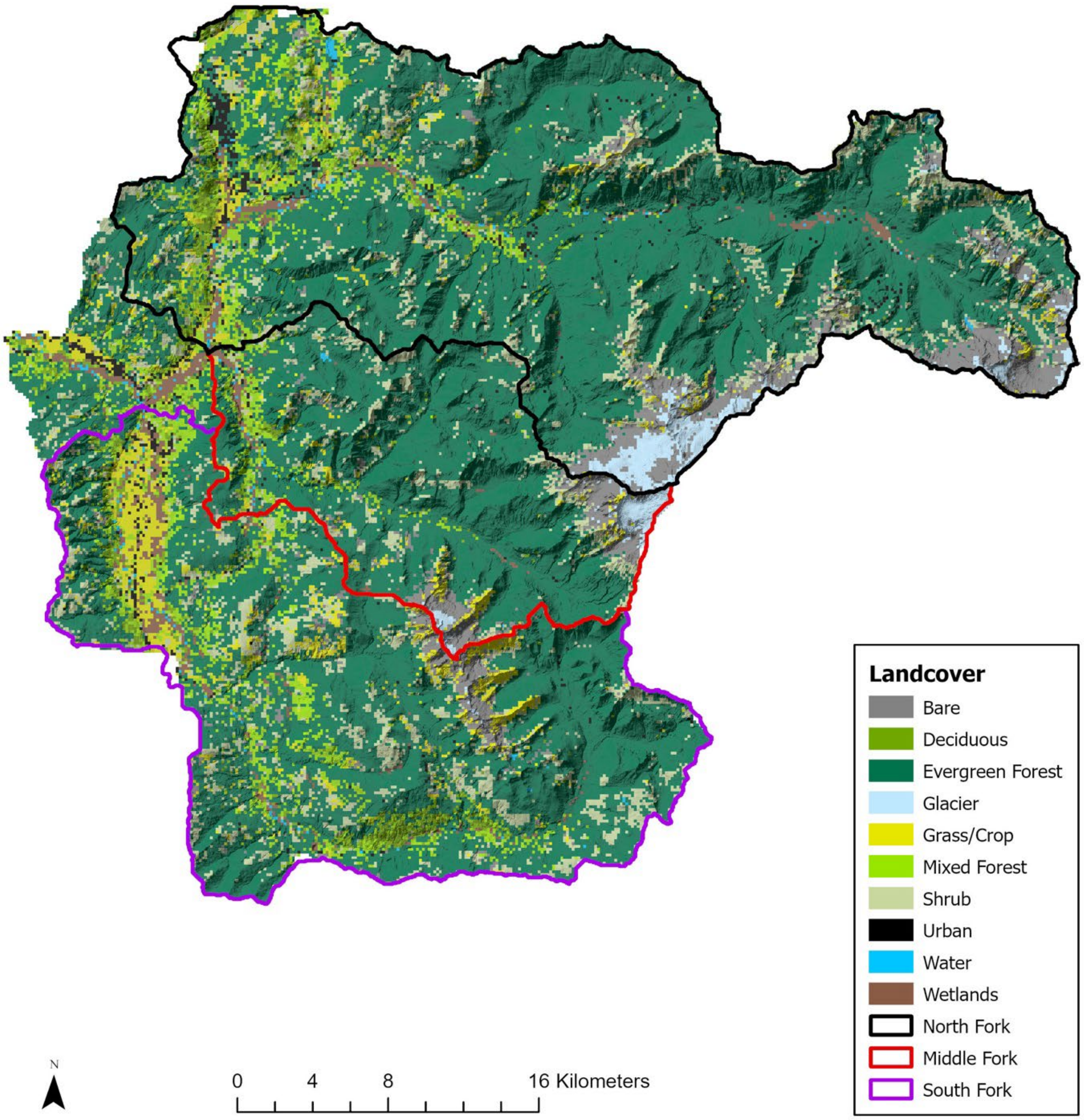

Figure 2. Landcover classes within the upper Nooksack basin obtained from the NOAA C-CAP 2016 gridded dataset. They were resampled from a 30-meter resolution to a 150-meter resolution and reclassified to correspond with land cover and vegetation classes within the DHSVM configuration file (Paul, 2023).

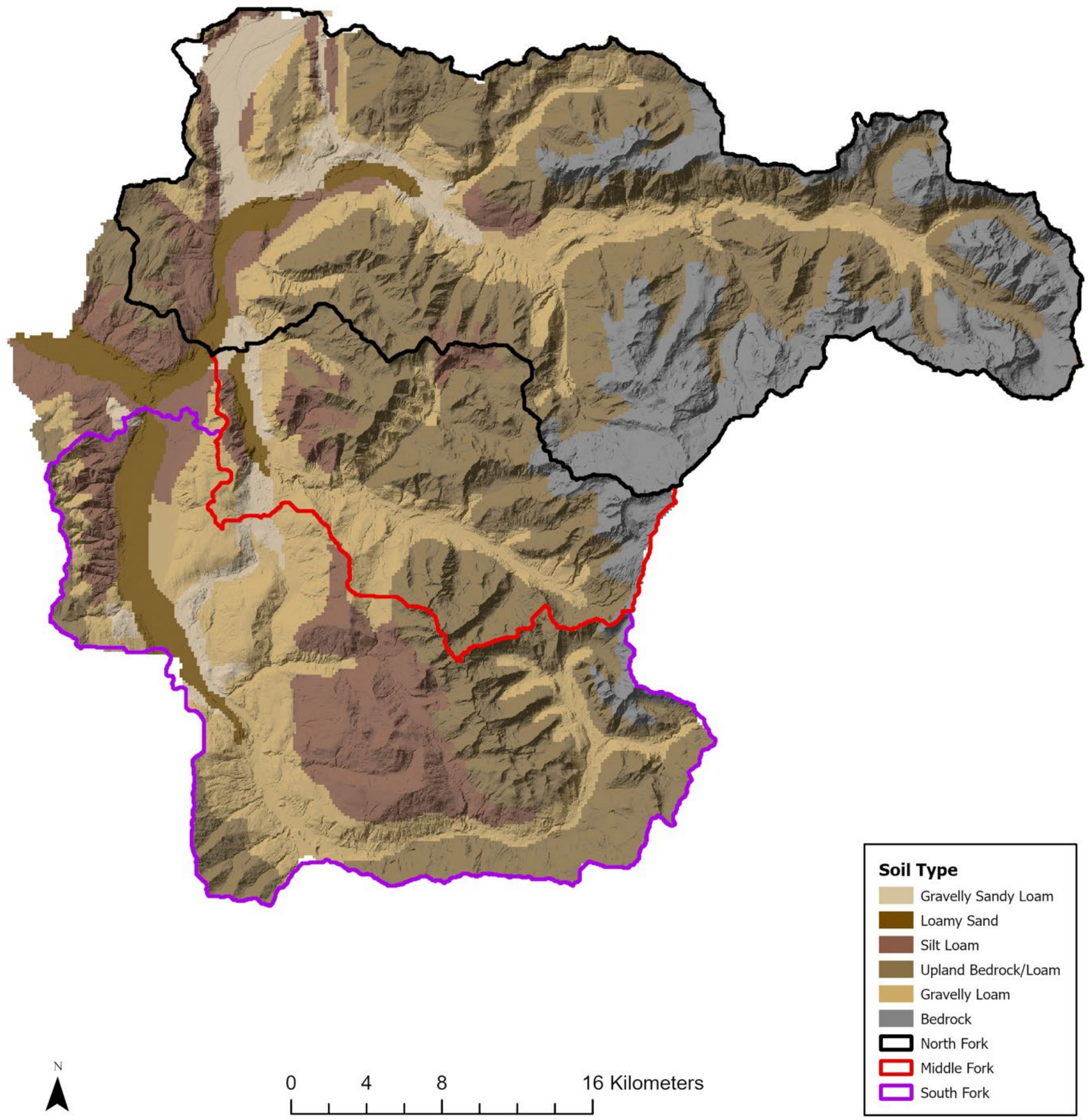

Figure 3. Soil types in the upper Nooksack basin, obtained from the STATSGO dataset, were converted to gridded data at 150-meter resolution and reclassified to correspond with soil classes within the DHSVM configuration file.

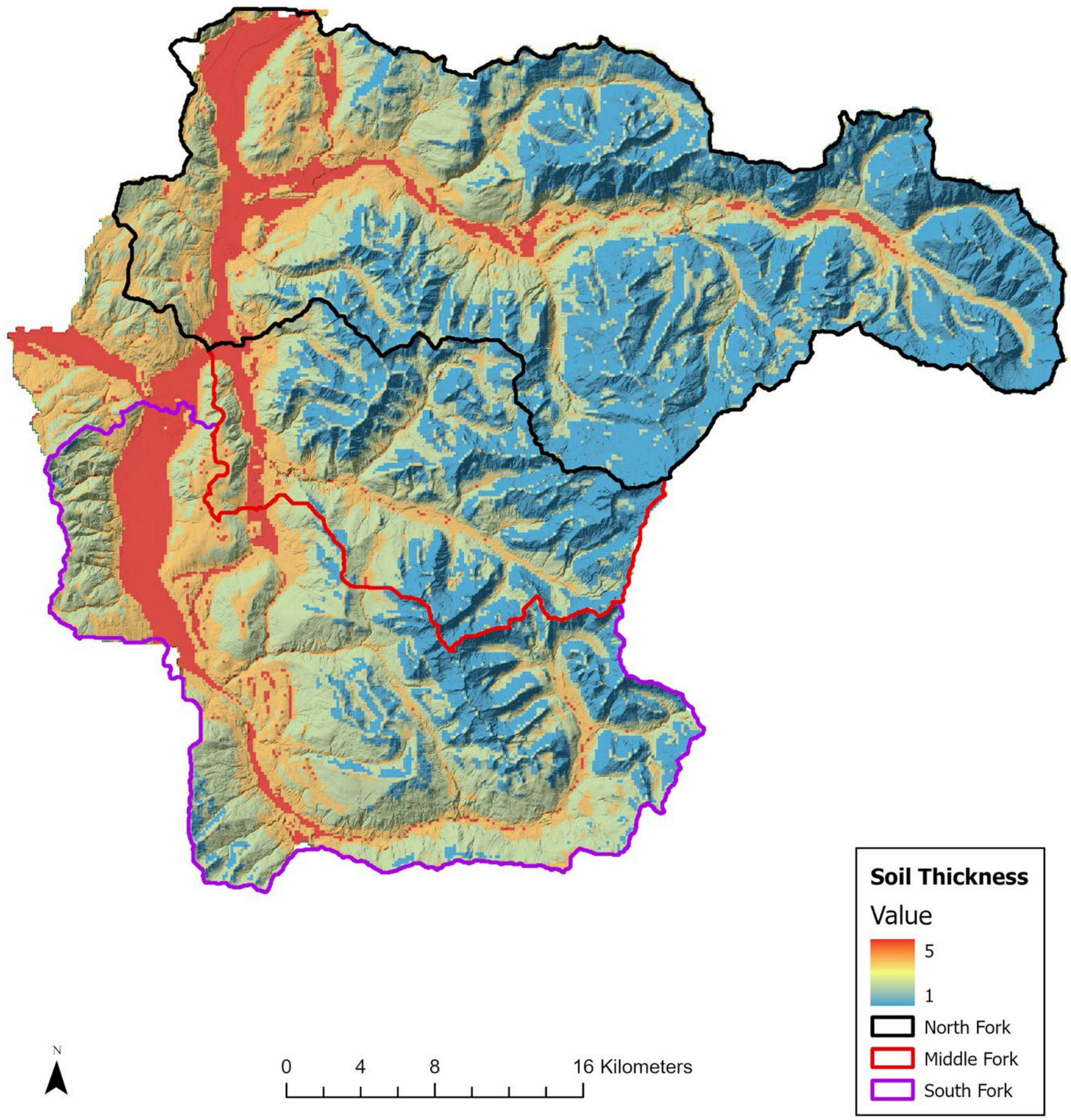

Figure 4. Soil thickness in the Nooksack basin, modeled by researchers at the Pacific Northwest National Laboratory. Thicknesses are modeled, ranging from 1 meter at higher and 5 meters at lower elevations.

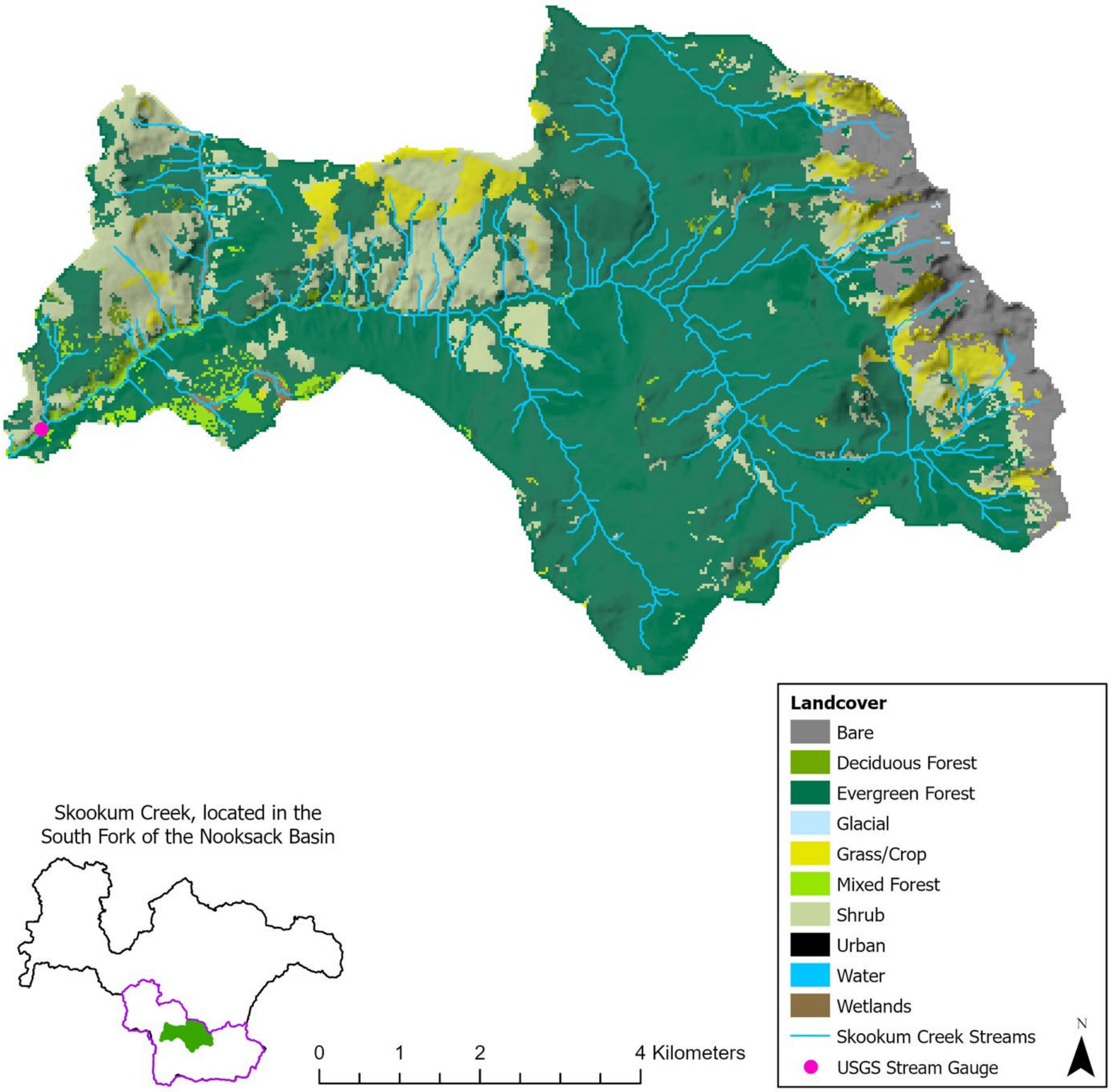

Figure 5. The Skookum Creek subbasin and 2019 landcover located in the South Fork of the Nooksack basin. Elevations range from approximately 150 to 2,070 meters, and the subbasin has a drainage area of about 56 square kilometers (USGS, 2023).

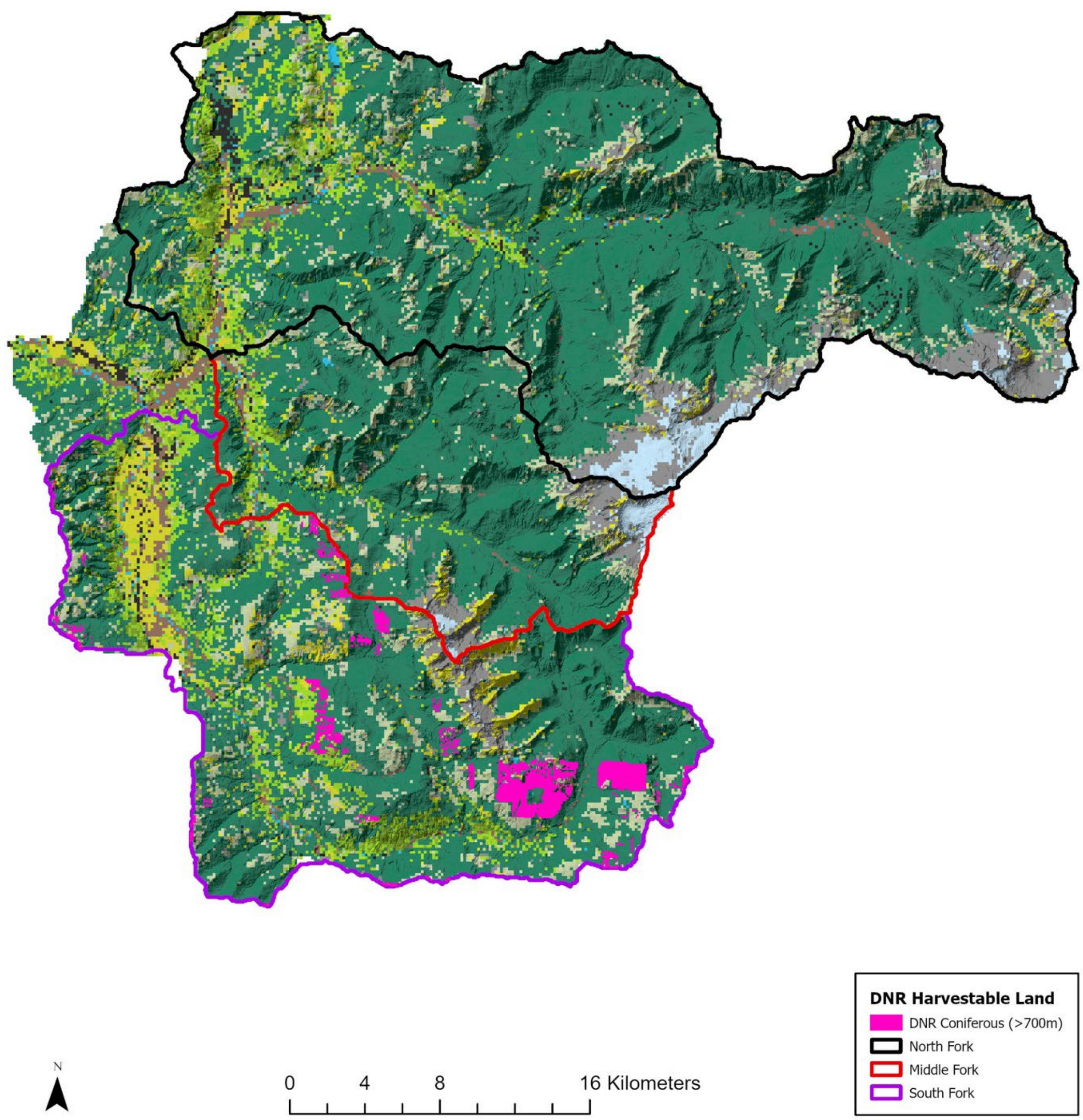

Figure 6. The pink region represents potentially harvestable land in coniferous forests above 700 meters, owned by the WA Department of Natural Resources. This coverage was created and used by Dickerson-Lange et al. (2023).

```
########################### Vegetation  8  #######################
Vegetation Description    8 = Evergreen Forest
Impervious Fraction       8 = 0.0
Detention Fraction        8 = 0
Detention Decay           8 = 0
Overstory Present         8 = TRUE
Understory Present        8 = TRUE
Fractional Coverage       8 = 0.9
Hemi Fract Coverage       8 = 0.9
Clumping Factor           8 =
Leaf Angle A              8 =
Leaf Angle B              8 =
Scattering Parameter      8 =
Trunk Space               8 = 0.5
Aerodynamic Attenuation   8 = 2.5
#Diffuse Radiation Attenuation    8 = 0.16
Diffuse Radiation Attenuation  8 = 0.215
Max Snow Int Capacity     8 = 0.03
Snow Interception Eff     8 = 0.6
Mass Release Drip Ratio   8 = 0.4
Height                    8 = 30 0.5
Overstory Monthly LAI     8 = 9.0 9.0 9.0 9.0 9.0 9.0 9.0 9.0 9.0 9.0 9.0 9.0
Understory Monthly LAI    8 = 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2
Maximum Resistance        8 = 2000 2000
Minimum Resistance        8 = 1333.2 855.54
Moisture Threshold        8 = 0.33 0.13
Vapor Pressure Deficit    8 = 4000 4000
Rpc                       8 = .108 .108
Overstory Monthly Alb     8 = 0.14 0.14 0.14 0.13 0.13 0.12 0.11 0.11 0.12 0.13 0.14 0.14
Understory Monthly Alb    8 = 0.19 0.19 0.19 0.19 0.19 0.19 0.19 0.19 0.19 0.19 0.19 0.19
Number of Root Zones      8 = 3
Root Zone Depths          8 = 0.10 0.25 0.40
Overstory Root Fraction   8 = 0.20 0.40 0.40
Understory Root Fraction  8 = 0.40 0.60 0.00
#Monthly Light Extinction 8 = 0.01 0.01 0.02 0.05 0.08 0.08 0.08 0.04 0.02 0.01 0.001 0.001
Monthly Light Extinction  8 = 0.065 0.065 0.065 0.065 0.065 0.065 0.065 0.065 0.065 0.065 0.065 0.065
```

Figure 7. Evapotranspiration variables for Evergreen Forest (Vegetation 8) that are used in the configuration file for the DHSVM. Fractional coverage represents the proportion of the ground surface covered by vegetation, while vegetation height defines the vertical dimension of the vegetation canopy. These parameters influence the interception of rainfall and the amount of evapotranspiration occurring within the vegetation canopy. Overstory LAI refers to the leaf area index of the overstory vegetation layer. LAI affects vegetation's interception of solar radiation, influencing the energy available for evapotranspiration.