Contributions of Glacial Meltwater to Streamflow at Thunder Creek, Using a Distributed Hydrology Model, North Cascades National Park, Washington

Thesis Proposal for the Master of Science Degree, Department of Geology, Western Washington University, Bellingham, Washington

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1.0 PROBLEM STATEMENT

I propose to examine the relationship between the streamflow and short-term climate changes observed in the glacial activity in the Thunder Creek watershed, using the newly developed Distributed Hydrology-Soil-Vegetation Model (DHSVM). The model will be calibrated to historical data and used to estimate glacial contributions to streamflow in the basin during the Little Ice Age maximum in the North Cascades. I will also apply the model to examine the impact of glacial retreat on streamflow.

2.0 INTRODUCTION

Glacial runoff studies are important because glaciers represent valuable resources that are vital components to hydrologic systems and aquatic ecosystems. Glaciers also influence soil development, the distribution of vegetation, and are indicators of climate change. Runoff from some glaciers in the North Cascades is currently being utilized for hydroelectric potential (e.g., Diablo, Ross, and Gorge Reservoirs by Seattle City Light; Baker Lake and Lake Shannon by Puget Power) and municipal capabilities (e.g., Nooksack River by the cities of Lynden, Ferndale, and Bellingham). Glaciers can be considered frozen reservoirs of water that have the ability to mediate yearly fluctuations in runoff by providing water in warm and dry years and storing water in cool and wet years. They also play an important role in seasonal drought buffering. Therefore, the study of glacier runoff is of both theoretical and practical importance (Fountain and Tangborn, 1985).

Thunder Creek is a glacially fed stream, near the mouth of which the U.S. Geological Survey (USGS) has operated a continuous gauging station since October of 1930 (Zembrzuski et al., 2001). It is located in North Cascades National Park (NOCA) and is a tributary to Diablo Reservoir on the Skagit River (Figure 1). The drainage area upstream from the gauge is 271.9 square kilometers and has a mean elevation of 1,768 meters (Fountain and Tangborn, 1985). A recent glacier inventory of NOCA (Granshaw, 2002) found that the watershed contained 51 glaciers that occupy an area of 36.8 square kilometers (approximately 13.4% of the basin). Thunder Creek’s glacial influence is primarily from North and South Klawatti, McAllister, Inspiration, Forbidden and Boston Glaciers, although contributions are made from smaller glaciers. NOCA has been
collecting detailed mass-balance data from North Klawatti glacier for the past eight years (Riedel et al., 1999). Estimates of the glacial contribution to summer runoff (May-September) in Thunder Creek based on this mass-balance data ranged from 23–45% of total summer runoff.

Hydrologic simulation (sometimes termed rainfall-runoff) modeling began in the 1950s and 1960s with the advent of the digital computer (Storck et al., 1998). The purpose was to predict streamflow based on observed meteorological variables (notably precipitation) at time scales short compared to catchment storm response times (usually sub-daily). Applications of hydrologic simulation models include design and planning (e.g., flood protection, hydroelectric power production), extension of streamflow records as well as streamflow forecasting. The first models were spatially lumped, meaning that they represented the effective response of an entire basin, without attempting to characterize the spatial variability of the response explicitly (Storck et al., 1998). In other words, lumped models average physical and vegetation characteristics over the entire basin or portions of the basin. HSPF (Hydrologic Simulation Program-Fortran) is an example of a lumped model and is widely used today by the USGS and other agencies. The expansion of desktop computing power and the introduction of the Geographic Information System (GIS) as a way to represent spatial data have paved the way for distributed hydrology models like DHSVM to capture the spatial variability of a watershed.

DHSVM is a physically based model that implements a digital elevation model (DEM), and soil type, soil thickness, and vegetation GIS databases as basin parameters (Figure 2). DHSVM models canopy interception, evaporation, transpiration, snow accumulation and melt, subsurface flow and runoff generation based on basic meteorological inputs of incoming solar radiation, air temperature, wind, humidity, and precipitation. The model uses established hydrological relationships to perform water mass balance simulations for each individual grid cell at a user defined time step. Digital elevation data are used to model topographic controls on incoming solar radiation, air temperature, precipitation and downslope water movement. Canopy evapotranspiration is represented via a two-layer Penman-Monteith formulation that incorporates solar radiation, and soil and vegetation characteristics (Wigmosta et al., 1994). Snow
accumulation and ablation are modeled using an energy balance approach that includes the effects of local topography and vegetation cover. Both saturated and unsaturated subsurface flow is also incorporated into the model using Darcy’s Law. Surface runoff is generated in a cell when the input of throughfall and snowmelt exceeds the infiltration capacity of the soil, or occurs on a saturated pixel, or when the water table rises above the ground surface (Wigmosta and Perkins, 2001).

A detailed hydrological evaluation of the Thunder Creek basin can be achieved using DHSVM, which could yield accurate assessments of the relationship between glaciers and their meltwater streams. Such models can help to predict and quantify future glacial contributions to streamflow if glaciers continue to retreat as they have during the last century. This, in turn, will improve our ability to assess the responses of alpine stream systems to changes in glacierization due to climate change.

3.0 BACKGROUND
3.1 Thunder Creek Watershed

To characterize stream discharge in Thunder Creek basin, it is important to consider the influence of topography, geology, glaciers, soils, vegetation and climate in the watershed. This is especially important when using DHSVM, since these are some of the main variables that the model uses.

3.1.1 Topography

The upstream boundaries of the watershed are defined by topographic highs (Eldorado, Forbidden and Boston Peaks, Mt. Logan, Mt. Arriva, and Buckner Mountain) and the downstream boundary was chosen to be just upstream of where Thunder Creek meets the high-water mark of Diablo Reservoir (Figure 3). Elevation ranges between 2770 meters (Mt. Logan) and 365 meters (Diablo Reservoir).

3.1.2 Geology

The bedrock in the Thunder Creek watershed is part of the crystalline core of the North Cascades. Rocks consist of Paleozoic and Mesozoic sedimentary and volcanic rocks which have been highly metamorphosed into schists and gneisses. These orogenic
rocks include mainly banded gneiss derived from the strata of the Chelan mountains terrane, orthogneiss, Eldorado orthogneiss, and minor pegmatite (Haugerud, 1989). The structure of the crystalline core is dominated by two north and northwest trending fault systems, the Strait Creek and Ross Lake fault systems. Bedrock composition and structure influence both soil development and topography of the watershed, two important factors in watershed modeling.

3.1.3 Glaciers

During the last 800,000 years there have been nine major glaciations in western North America (Imbrie et al, 1984). During the Pleistocene, alpine glaciers advanced and joined the Cordilleran Ice Sheet, forming deep, U-shaped valleys. At higher elevations, glacial activity eroded a complex system of arêtes, horns and cirques (Granshaw, 2002). During the last 10,000 years, glacier advances occurred at 4.7 ka, 2.8-2.6 ka, and during the last 700 years (Porter and Denton, 1967). The last period is known as the Little Ice Age (LIA) (Grove, 1988). Glaciers have been retreating throughout NOCA since the LIA ended in the late 19th century (Granshaw, 2002). Riedel (1987) identified eight major periods of glacial recession in the Cascade Range during the last 700 years, the two most recent of which occurred between 1820-1860 and 1880-1920.

3.1.4 Soils

There have not been any detailed soil surveys completed for the Thunder Creek basin to date. The only data available for the basin are from general map that divides the basin into three dominant soil texture classes, sandy-loam, loamy-sand and loam (Miller and White, 1998).

However, NOCA has recently completed surficial geology mapping and developed a hydrologic response model from that mapping for the Thunder Creek basin. The hydrologic response model predicts the ability of landtypes to absorb precipitation and snowpack melt.
3.1.5 Vegetation

Vegetation in the North Cascades is highly diverse, reflecting the spatial variability in climate and topography in the region. Three broad vegetation zones are represented in the Thunder Creek watershed including mixed conifer forest, subalpine forest, and alpine forest. The first zone consists mainly of western hemlock, western red cedar, Douglas fir and grand fir. The subalpine forest is dominated by mountain hemlock, subalpine fir and Engelmann spruce (Franklin and Dyrness, 1973). The alpine zone has been only been deglaciated since the LIA retreat and is being reoccupied by stunted trees and alpine meadow vegetation including subalpine fir and heather.

3.1.6 Climate

The climate in the Thunder Creek watershed is considered a maritime climate with mild winters of high precipitation and cool, dry summers. The location of the study area is within the belt of prevailing westerly winds, which bring moist air in from the Pacific Ocean. The Skagit River valley permits the moist maritime air to penetrate further east than at other places along the Cascade crest (Porter, 1977). Precipitation increases at high altitudes as the air cools and condenses as it rises over the North Cascades. The Thunder Creek watershed has a major hydrologic divide (between Thunder Creek and Fisher Creek) creating east-west variability in precipitation as well. Snow accumulation of 8-10 meters near an altitude of 2,000 meters is common (Fountain and Tangborn, 1985). Maximum precipitation occurs during the winter and the minimum occurs in midsummer. Since most of the winter precipitation occurs as snow, maximum runoff in the watershed is delayed until spring. The mean annual temperature at an elevation of 1844 meters (South Cascade Glacier) in the North Cascades is ~ 2˚ C and the mean July temperature is ~10˚ C (Porter, 1977).

3.2 Previous Work

3.2.1 Glacier Inventories and Mass Balance Estimates

The first comprehensive inventory of glaciers in the North Cascades was completed by Post et al. (1971) and was based on aerial photographs taken in the late 1950’s. According to the inventory, the Thunder Creek watershed contained 51 glaciers
with a total area of 39.3 square kilometers (approximately 14.2% of the basin) making it the most heavily glaciated basin in the North Cascades. Accumulation sources for the glaciers in the basin include direct snowfall and minor amounts of snowdrift. North Klawatti and McAllister glacier were classified as valley glaciers, and all others were classified as cirque, slope/irregular topography, or small ice/snow patch (Post, 1971). Post (1971) classified the termini of most glaciers to either be stationary or retreating slightly. Tangborn (1980) concludes that, for the period of 1884-1974, the Thunder Creek glaciers lost on average about 1.1 meters of water equivalent of ice per year. However, most of that loss occurred between 1900 and 1940 (Tangborn, 1980).

Granshaw (2002) has recently completed another glacier inventory of NOCA based on 1998 aerial photographs. According to this recent work, the watershed still had 51 glaciers that occupied an area of 36.8 square kilometers (approximately 13.4% of the basin). Granshaw (2002) also digitized his work, as well as Post’s (1971) inventory, into GIS datasets and digitized Post’s preliminary mapping of LIA glacier limits for a majority of NOCA. These LIA glacier limits correspond to recent LIA moraine mapping completed by NOCA. LIA extents for about 20% of the Thunder Creek basin are missing from this database. I filled in the missing data by examining aerial photographs to map LIA glacial features including moraines and trim lines.

The North Cascades National Park Service Glacier Monitoring Program began in the spring of 1993 to develop an understanding of regional mass balance of glaciers. Among the glaciers monitored are Noisy Creek, Silver, North Klawatti and Sandale because they represent a large elevation range and are located at the headwaters of watersheds with large hydroelectric operations. North Klawatti Glacier is in the Thunder Creek watershed. It is a valley glacier located south of Primus Peak, with an area of 1.46 square kilometers, or about 4% of the total glacier cover in the basin. The glacier feeds Klawatti Lake, which drains into Thunder Creek. Methods for the mass balance investigations include at least three visits to each glacier per year to measure winter accumulation and summer snowmelt. Measurements are taken at a series of points down the centerline of each glacier then integrated across the entire glacier surface to determine the annual mass balance for the glacier (Riedel, 1999). Results from the study of North Klawatti Glacier have compared well with mass balance records from South Cascade
Glacier (~15 km south of Thunder Creek), which the USGS has monitored since the mid 1950s.

3.2.2 Glacier-Runoff Studies

The importance of studying glacier runoff has been recognized for a number of decades. An enormous reserve of water is stored in the form of glacier ice: about three-fourths of all the fresh water in the world, or equivalent to precipitation over the entire globe for about 60 years (Meier, 1969). Glacial runoff studies in the North Cascades (Tangborn et al., 1975; Tangborn, 1980) have attempted to refine techniques to accurately predict glacial activity based on hydrological and meteorological records. Tangborn et al. (1975) compared glacial mass balance calculations for South Cascade Glacier by glaciological, mapping and hydrological methods. The hydrological method proved to be unreliable, predicting a 38% greater mass loss than the other methods. Tangborn (1980) developed a runoff-precipitation model to calculate glacier mass balances for glaciers in the Thunder Creek basin. The model compared runoff between Thunder Creek and South Fork Skykomish River (an unglacierized basin) and determined the difference in runoff between the two basins was due to storage (or release) of water in the glaciers of the Thunder Creek basin. This model shows general agreement with observed trends in the glaciers; however it is highly simplified and does not consider heterogeneities between the two basins (e.g., vegetation, topography and soils).

Meier (1969), Fountain and Tangborn (1985), Pelto (1991), and Krimmel (1992) have also examined the effect of glaciers on runoff variations in the North Cascades by comparing basins with and without glaciers. Their results indicated the presence of glaciers has a profound impact on the seasonal timing, volume and quality of runoff in a basin. Although these studies are important in showing the influence of glaciers on the hydrology of a basin, they do not attempt to quantitatively predict runoff.

As a part of their glacier-monitoring program, NOCA has been using mass balance measurements of North Klawatti glacier, glacier area and elevation to estimate the contribution of glacial runoff in the Thunder Creek basin from 1993 to the present (Riedel, 1999). NOCA’s estimates are based on assumptions that North Klawatti glacier mass balance measurements are representative of all the glaciers in the basin and a melt
season of May through September each year. One limitation with the melt season assumption is that glaciers actually begin to melt at different times from year to year and at different elevations within a year.

Scientists have also attempted to predict seasonal runoff in glacierized basins by specifically modeling snow and/or glacier melt (Rango et al., 1979; Martinec and Rango, 1986; Rango, 1991; Arnold, 1996). These models take advantage of daily cycles of temperature and solar radiation and generally yield acceptable results of glacier melt. However, they fall short of incorporating many important aspects of the hydrologic influences of a basin (e.g., vegetation, soils, precipitation, etc.).

3.2.3 DHSVM Studies

I plan to use DHSVM to simulate hydrologic responses in the Thunder Creek watershed because the model is one of the most advanced hydrologic models available and has been validated in other Cascade mountain basins. Wigmosta et al. (1994) originally developed DHSVM using the Middle Fork Flathead River in northwestern Montana. The model was run at a 3-hour time step over 180-meter grid spacing. Simulated results showed acceptable agreement (~2%) with recorded streamflow over a four-year calibration and verification period. DHSVM has since been successfully applied in some of the Pacific Northwest’s maritime and mountainous watersheds (e.g., Snoqualmie River, Little Naches River, Hard and Ware Creeks, Carnation Creek) (Storck et al., 1995; 1998; Wigmosta and Perkins, 2001). These basins ranged in size between 5.2 – 2900 km² and typically had high relief and were dominated by spring snowmelt and rain-on-snow events.

To successfully simulate runoff in the Thunder Creek watershed it is important to understand how DHSVM models snow/ice melt. DHSVM uses a two-layer energy and mass balance approach to simulate snow accumulation and melt (Storck et al., 1995). The energy balance components are used to model snowmelt, refreezing, and changes in the snowpack heat content. Energy exchange between the atmosphere, forest canopy and snowpack occurs to and from a surface layer. Energy exchange between the surface layer and the pack layer occurs via melt water, which percolates from the surface layer into the pack. The mass balance components represent snow accumulation/ablation, changes in
snow water equivalent (depth of water that would result from the complete melting of the snow in place (Dingman, 2002)), and water yield from the snowpack (Wigmiosta, et al., 1994). Precipitation occurring below a threshold temperature is assumed to be snow. During melting conditions the snow pack is assumed isothermal at 0° C (Storck et al., 1995). DHSVM accounts for energy advected to the snowpack by rain as well as net radiation, sensible heat, and latent heat. DHSVM is capable of simulating snow accumulation and melt over hourly, daily, and seasonal time scales. It can be applied where rain-on-snow is of concern and where spring snowmelt is dominant (Storck et al., 1995).

Glaciers in DHSVM can be treated in a number of ways. In short-term forecasting applications they are modeled as inexhaustible snowpacks (e.g., infinite supply of water) that are static in aerial extent. In this application, DHSVM maintains a snow-water equivalent of at least one meter in depth in all pixels that are specified as glaciers. The main limitation of the inexhaustible approach is that in long term modeling scenarios, glaciers will keep delivering water given the right melting conditions, but never decrease in size. Glaciers can also be modeled by specifying an initial amount of snow-water equivalent in each pixel of a glacier. The feature that maintains a snow-water equivalent for a glacier (inexhaustible model) can be turned off in the DHSVM source code, allowing the retreat or advance of glaciers to be simulated.

The major limitation of using DHSVM to model glaciers lies in the two-layer representation of a snowpack. To get snowmelt in DHSVM the entire snowpack must become isothermal and to get meltwater release, the liquid water content must increase above saturation (Storck, pers. comm.). Both of these assumptions begin to deteriorate when trying to model very deep snowpacks (e.g., glaciers). To address this limitation, I will examine strategies for incorporating a better representation of glaciers into DHSVM as modeling progresses.

4.0 PROPOSED RESEARCH

I propose to use DHSVM to examine the relationship between the streamflow and short-term climate changes observed in the glacial activity in the Thunder Creek watershed. Basin parameters will be represented in approximately 110,000 individual
50-meter grid cells for the watershed. I will calibrate the model to existing streamflow data collected by the USGS and meteorological (solar radiation, air temperature wind, humidity, and precipitation) data. I will use the model to estimate historical streamflow in the basin during the Little Ice Age maximum in the North Cascades. I will also apply the model to examine the impact of glacial retreat on streamflow. The main objectives of the research are to develop a working hydrology model of the Thunder Creek watershed that can be used for planning (hydroelectric power production), extending streamflow records back to the Little-Ice Age, and forecasting streamflow.

5.0 METHODS AND TIMELINE

The methods used to complete this study will be completed with technical assistance from the Puget Sound Regional Synthesis Model (PRISM) at the University of Washington (Storck, pers. comm.). Thus far, assistance has been in gathering and formatting the GIS data that DHSVM requires as described below. These steps were completed using the GIS software ARC/INFO.

5.1 DHSVM Input Requirements

DHSVM requires five GIS grids (DEM, watershed boundary, soil type, soil thickness and vegetation) a flow routing model and meteorological time-series data as inputs. A grid resolution of 50 by 50 meters was chosen to optimize processing speed of the model. DHSVM runs most efficiently when analyzing between 100,000 and 150,000 cells. A 50-meter grid resolution yields approximately 110,000 cells for the Thunder Creek watershed.

1. **DEM**: The DEM is the fundamental foundation on which DHSVM and all of its distributed parameters are based (Storck et al., 1995). The DEM for the study area was compiled using eight USGS 7.5-minute, 10-meter DEM files. I merged, filled, and converted them to 50 by 50 meter resolution using ARC/INFO software. The DEM was then clipped to the watershed boundary (Figure 4).

2. **Watershed Boundary**: The watershed boundary is used in as the analysis domain in DHSVM. It is also used as a mask to clip all other input grids to. This ensures that all input grids contain an identical number of pixels. I delineated the
watershed boundary grid from 50-meter DEM using the WATERSHED command in ARC/INFO (Figure 5).

3. **Soil Type:** I compiled the soil type grid from the Statsgo CONUS soils database representing dominant soil texture class (Miller and White, 1998). This is a countrywide soil grid with at 1000-meter resolution. I resampled the grid into 50-meter pixels and clipped it to the watershed boundary (Figure 6 A). Because of the coarse resolution of these data, I also used it in combination with a recent surficial geology map (from NOCA) of the Thunder Creek basin to create a more detailed soil type grid (Figure 6 B). DHSVM uses only the dominant soil type of each grid cell. All grid cells with identical soil classifications are then assigned one set of soil-dependant hydraulic parameters through a lookup table (Storck, et al., 1995).

4. **Soil Thickness:** Soil thickness data do not exist for the watershed, so I created this grid using an AML file (Arc-Macro-Language file that automates a number of ARC/INFO commands) provided by PRISM that was written for use in the Skagit River watershed. The AML uses a simple regression that made soil depths deeper on shallow slopes and areas of high flow accumulation (Figure 7). This method has provided acceptable results in basins similar to Thunder Creek. Minimum and maximum soil depths were set at 0 and 3 meters respectively.

5. **Vegetation:** Vegetation data were compiled from a landcover database for NOCA. The database is the result of a comprehensive inventory of the vegetation for the park using Landsat Thematic Mapper (TM) satellite imagery and field data collected in 1992. The data were in 25-meter resolution, so I resampled it into 50-meter pixels and clipped it to the watershed boundary. I also reclassified the vegetation classes in the dataset to the classification scheme used by DHSVM with the help of Dr. David Wallin (Huxley College, WWU). Lakes and glaciers are incorporated into the vegetation grid, so three vegetation grids were created representing LIA, 1950s (based on Post, 1971) and 1998 (based on Granshaw, 2002) glacial conditions (Figures 8 A-C). Although the Little Ice Age refers the time period (~1700-1850) where glaciers in the North Cascades were advancing, I am modeling LIA runoff as if all the glaciers in the Thunder Creek basin were at
their LIA maximum at one time step. Actual vegetation characteristics between each vegetation grid were assumed to be static and not changed. DHSVM uses only the dominant vegetation type of each grid cell. All grid cells with identical vegetation classifications are then assigned one set of vegetation-dependant hydraulic parameters through a lookup table (Storck, et al., 1995).

6. **Flow-routing Model:** Flow in stream channels will be routed using a flow routing model which represents a stream network by a series of cascading linear reservoirs. This linear storage algorithm has provided satisfactory results to a large range of basin sizes and topographic characteristics (Wigmosta and Perkins, 2001). I created the flow network by running an AML file provided by PRISM.

7. **Meteorological Data:** During the Summer of 2002, meteorological data will be compiled from the Diablo Dam weather station, Thunder Basin Snowtel snow survey site and Winter snow accumulation measurements made by NOCA on North Klawatti Glacier. Using all three data sources will allow me to estimate variations with topography due to the orographic effect in the basin. The west-east variability in precipitation will be evaluated by also analyzing data from the Ross Dam weather station, Swamp Creek and Rainy Pass Snowtel sites, and Sandalee Glacier, east of the Thunder Creek watershed. Neither the Diablo Dam weather station, nor the Thunder Basin Snowtel currently measures shortwave radiation. I will need to develop a strategy to estimate shortwave radiation over the basin based on radiation measurements from weather stations outside the basin (Harts Pass, Park Creek Ridge and Marblemount) and albedo measurements from South Cascade Glacier.

DHSVM can distribute point measurements of meteorological data over a basin in a number of ways. Interpolation methods such as nearest neighbor, inverse distance, and variable radius crestman are included as default choices in the DHSVM source code (Storck, pers. comm.). DHSVM also has the capability to use precipitation climatologies and temperature lapse rates to interpolate
precipitation and temperature vertically. Decisions on which methods to use will be made as modeling progresses.

5.2 Modeling

Modeling will take place starting in the Fall of 2002. DHSVM is written in ANSI-C and requires a Pentium 200 Mhz processor with 128 MB of RAM to run. I will be running DHSVM on a SUN E450 in the Computer Science department via a workstation in Dr. Robert Mitchell’s lab.

The model will be calibrated using historical streamflow and meteorological data from a two-three year period 1997-2000. The calibration period was chosen because it represents both negative and positive mass balance years for North Klawatti Glacier. I will use DHSVM to assess the glacial contribution to stream flow in Thunder Creek by comparing discharge from a glaciated and non glaciated representation of the basin. The model will also be used to evaluate the hydrologic characteristics of the basin during the Little Ice Age and to predict future runoff conditions based on potential glacier behavior (e.g., continued glacier retreat).

5.3 Expected Outcomes

Final products from this project will include:

1. A working distributed hydrology soils-vegetation model of the Thunder Creek watershed.
2. Comparison hydrographs for Thunder Creek with simulated and measured streamflow.
3. Comparison of simulated and NOCA estimated glacial runoff contributions.
4. Simulated hydrographs from the period of LIA glacial maximum.
5. Simulated hydrographs for future streamflow based on current climate trends and future climate predictions.
6. Analyses of the results and conclusions.
7. Assessment of a similar work on the Nooksack watersheds?
6.0 SIGNIFICANCE OF RESEARCH

As demand for water increases with increasing populations in the Northwest, sophisticated hydrology models are needed to accurately examine water recourses. The complexity of processes involved in the hydrologic cycle requires that hydrology models incorporate details about precipitation, evapotraspiration and runoff in order to make accurate predictions of future water resources needed for planning purposes. Humans in the northwest use water for residential, agricultural, industrial, hydroelectrical, and recreational purposes. Water is also needed to sustain delicate aquatic and terrestrial ecosystems.

The influence of glaciers on all of the above make hydrologic modeling in the North Cascades even more complex and important. A glacier is a frozen reservoir of water, were potential runoff resides from a few hours to thousands of years. Since glaciers can be indicators for climate change, they can be a link between climate change and hydrology. If a sophisticated hydrology model can accurately characterize a glaciers’ impact on the hydrologic cycle, it can be used to characterize the impact of climate change on they hydrology of a basin.
7.0 REFERENCES


Rango, A., 1988, Evaluating the effects of climate change on snowmelt hydrology of mountain basins, AGU 1988 fall meeting, EOS, Transactions, American Geophysical Union, v. 69, n. 44, p. 1203.


Sources to Find


Other Sources


* indicated sources that I have
Figure 1: Location map of the Thunder Creek Watershed located in North Cascades National Park (northern and southern sections, dark green), in northwest Washington State.
Figure 2: Conceptualized diagram of the DHSVM structure. Linked one-dimensional moisture and energy balance equations are solved independently for each model grid cell. Grid cells are allowed to exchange saturated subsurface flow with their eight adjacent neighbors. (Modified from Wigmosta et al., 1994; Nijssen et al., 1996).

Figure 3: Shaded relief map showing the characteristically steep terrain of the Thunder Creek watershed.
Figure 4: The digital elevation model is used as the fundamental input grid in DHSVM.

Figure 5: The watershed boundary is delimited from the digital elevation model (Figure 4). It represents 110,807 50-meter grid cells that will be analyzed by DHSVM.
Figure 6A: Soil type from Miller and White (1998) of the Thunder Creek watershed. The resolution of these data is considered very coarse (1000-meter) for modeling purposes of a basin this size.

Figure 6B: Soil type derived from NOCA surficial geology mapping of the Thunder Creek Watershed. The data are similar to Miller and White (1998), however the smaller resolution allows for the incorporation of bedrock and sand classifications.
Figure 7: Soil thickness grid generated from an AML file provided by PRISM. Soil thickness was set to vary from zero to three meters.

Figure 8A: Vegetation classifications of the Thunder Creek Watershed. LIA glacial extent of 22.5% glacier coverage.
Figure 8B: Vegetation classifications of the Thunder Creek Watershed. Mid 1950’s glacial extent of 13.3% glacier coverage.

Figure 8C: Vegetation classifications of the Thunder Creek Watershed. 1998 glacial extent of 12.8% glacier coverage.