Thesis Proposal

Modeling Sediment Yield in the Jones Creek Watershed using the Distributed Hydrology-Soil-Vegetation Model

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

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1.0 Problem Statement

The objective of my research is to evaluate the relationship between precipitation and streamflow and sediment yield in the Jones Creek watershed near Acme, WA. I will use the Distributed Hydrology-Soil-Vegetation Model (DHSVM) coupled with a sediment module to simulate hydrology and shallow mass wasting events and hill slope erosion. The model will be calibrated by comparing the simulations to field observations. After the DHSVM has been successfully calibrated to measured streamflow and sediment values in the Jones Creek watershed, I will perform numerical experiments to examine the effects of a variety of hypothetical precipitation scenarios on streamflow and sediment yield.

2.0 Introduction

The Jones Creek watershed is located in Whatcom County, WA, approximately 25 kilometers east of Bellingham (Figure 1). Jones Creek drains a portion of the east side of Stewart Mountain to the South Fork Nooksack River. The creek is part of the Acme Watershed Administrative Unit (AWAU), which encompasses the lower South Fork Nooksack River valley area. Due to high relief and rock conditions, there are a number of landslides hosted in the watershed. The largest of these is the deep-seated Darrington landslide.

The Darrington landslide lies on the north side of Jones Creek, directly adjacent to the creek channel (Figure 2). The 1600 m^2 unvegetated landslide toe serves as a significant source of sediment to the creek. Constant sediment delivery from the landslide to Jones Creek is most likely due to shallow mass wasting and hill slope erosion. Although fan stratigraphy suggests catastrophic deep-seated movement of the landslide has probably only occurred six times over the last 7,000 years, frequent debris flows sourced from the landslide are threatening the downstream community of Acme (KWL, 2004).

Acme is made up of approximately 100 buildings constructed on a 0.75 km^2 composite fan. The fan has developed from a number of Quaternary-aged deep-seated landslides and debris flows and debris torrents sourced in the Jones Creek watershed. Similar fans exist at the mouth of other steep drainages in the AWAU of the lower South Fork of the Nooksack River (Powell et al., 2010; Figure 3). Due to the hazard potential within the Jones Creek watershed, Whatcom County has commissioned multiple hazard assessment reports identifying debris flow hazard zones on the fan (e.g., Raines et al., 1996; KWL, 2004). One area that is at risk for debris flow damage is the Turkington Road bridge.

The Turkington Road bridge is located approximately 700 meters west of the confluence of Jones Creek with the South Fork Nooksack River (Figure 4). Multiple residences, as well as an elementary school, are located in the vicinity of the bridge. Debris flows and floods have resulted in considerable property damage in this area over the last thirty years. Whatcom County has significantly modified the channel near the bridge in an attempt to confine the stream during periods of high precipitation.

In 2009, the USGS installed a stream monitoring station at the Turkington Road bridge. The station records the stream stage every 15 minutes, from October through April of each year. An emergency alert system built in to the station is triggered by a sharp drop in stream stage. The emergency alert system is intended to warn area residents of an impending landslide dam outburst flood or debris flow. To most effectively predict the occurrence of debris flows, safeguards such as the emergency alert system must be paired with an understanding of the physical processes that cause debris flows.

The relationship between hydrology and watershed sediment yield depends on numerous factors, including vegetation cover, land use, rock and soil hydrologic and mechanical properties, and precipitation patterns. Numerical modeling is a useful tool for evaluating the relationship between these factors. The Distributed Hydrology-Soil-Vegetation Model, developed at the Pacific Northwest National Lab and the University of Washington, is a physically based, spatially distributed model that simulates a water and energy balance at the pixel scale of a digital elevation model (Wigmosta et al., 1994). The sediment module of the DHSVM incorporates the water balance simulations with slope stability and erosion calculations to predict a total watershed sediment yield (Doten and Lettenmaier, 2004; Doten et al., 2006). The DHSVM has been applied successfully at WWU to a number of previous research projects in similar settings (e.g. Chennault, 2004; Kelleher, 2006; Donnell, 2007; Matthews et al., 2007; Dickerson, 2010).

3.0 Background

3.1 Jones Creek Watershed

3.1.1 Geologic Setting

There are two bedrock units that underlie the Jones Creek watershed, separated by a northeast-trending fault (Figure 2). The upper two-thirds of the watershed are underlain by the Eocene-aged Chuckanut Formation sandstone. The lower third of the watershed is underlain by the Cretaceous-aged Darrington Phyllite. The Darrington Phyllite was likely derived from blueschist subduction-related metamorphism of marine sediments at 120-130 Ma (Brown, 1987). Extensive folding and faulting within the phyllite has created mechanically weak zones that can act as failure planes for translational and rotational bedrock slides. Soils derived from the Darrington Phyllite are rich in mica, graphite and various clay minerals. The mineral compositions of the soils make them prone to failure. Within the Jones Creek watershed, there are several areas of well-developed, phyllite-derived soils that appear to be failing by complex rotational and infinite slope-style mechanisms (KWL, 2004). Failure zones have also been identified in portions of the watershed underlain by the Chuckanut Formation. However, the majority of active landslides are hosted in the phyllite unit (KWL, 2004). Sediments derived from landslides in the watershed are transported by Jones Creek and are either deposited on the composite fan or delivered to the South Fork of the Nooksack River.

The composite fan covers an area of 185 acres between the base of Stewart Mountain and the South Fork Nooksack River flood plain. The fan apex is located approximately 1.2 kilometers upstream of the confluence of Jones Creek with the South Fork, and 500 meters upstream of the Turkington Road Bridge. The fan comprises poorly sorted sands and gravels and displays a general lack of bedding. The fan is constructed of both fluvial and debris flow deposits, but fan stratigraphy suggests that debris flow deposition dominates (KWL, 2004).

3.1.2 Basin Characteristics

The Jones Creek watershed is 6.7 km^2 in area, and ranges in elevation from approximately 85 meters to 940 meters. Three main reaches of Jones Creek can be defined based on channel gradient (KWL, 2004; Figure 4). Reach one has a mean channel gradient of 22 percent and includes the stream above the fan apex. Reach two has a mean channel gradient of six percent and includes the stream channel below the fan apex and above the Turkington Road bridge.

Reach three includes the stream channel below the Turkington Road bridge and above the confluence of Jones Creek with the South Fork Nooksack River. The channel in this reach has been significantly modified by Whatcom County and has a mean gradient of two percent.

The watershed was logged in the early to mid-1900s, and the majority of the current vegetation cover is second growth forest. Vegetation cover in the upper watershed is defined by mixed shrub, grassland, and coniferous forest. The lower watershed is primarily coniferous forest, with interspersed areas of mixed deciduous and coniferous forest. The lower portion of the fan has undergone significant urbanization and removal of tree cover, except for a 0.2 km^2 section of mixed forest that spans from the apex of the fan to the Turkington Road bridge (KWL, 2004).

3.2 Hydrologic Modeling

3.2.1 DHSVM Hydrology Model

DHSVM is a physically based, spatially distributed model. The foundation for DHSVM is a digital elevation model (DEM). Every grid cell in the DEM is assigned a characteristic vegetation class, soil class, and soil depth. Vegetation classes include parameters that define rooting depths, overstory and understory, and total evapotranspiration potential. Soil classes include parameters that characterize the hydraulic and mechanical properties of soils. Precipitation, air temperature, wind speed, relative humidity, short wave radiation and long wave radiation are applied as inputs to the model over a user defined time step (1 hour to 1 day).

DHSVM simultaneously simulates a water and energy balance for every grid cell at each time step (Wigmosta et al., 1994). Hydrologic processes considered in the model calculations include evapotranspiration, canopy interception, soil water infiltration, soil water storage, snow water equivalent, surface runoff and saturated subsurface flow. Water migrates between cells by saturated subsurface flow, or by overland flow. Overland flow occurs when precipitation intensity exceeds the infiltration capacity of the soil, or when the entire thickness of the soil column becomes saturated. Mobile water is eventually routed to the stream network and becomes part of the total stream discharge.

The DHSVM hydrology model was first validated for the 2900 km^2 Middle Fork Flathead River basin in northwestern Montana (Wigmosta et al., 1994). DHSVM has also been successfully used as a tool for investigation in to the effects of land use change on watershed hydrology. Various studies have examined the effects of logging roads, timber removal, watershed urbanization, and climate change on stream flow and the timing and magnitude of flood events (e.g., Bowling et al., 2000; Bowling and Lettenmaier, 2001; Cuo et al., 2008; Leung and Wigmosta, 1999; Storck et al., 1995; Storck et al., 1998; Wigmosta and Perkins, 2001).

3.2.2 DHSVM Sediment Module

The DHSVM sediment module was developed as secondary application of the DHSVM hydrology model (Doten et al., 2006). Depending on output from the hydrology model and the slope and mechanical properties of the soil, the sediment module simulates sediment flux to a stream by two processes: mass wasting and hill slope erosion (Figure 5).

The DHSVMS mass wasting algorithm is computationally intensive, and so only runs during the time step with the greatest basin saturation during a storm event. DHSVM uses a screening process for each grid cell prior to performing failure calculations, in order to maximize computational efficiency. First, each cell is checked for the presence of sediment. Cells without sediment are discarded from the screening process. Second, cells that do not meet a minimum user-defined surface slope are not considered likely candidates for slope failure and are discarded. Doten et al. (2006) noted that shallow failures rarely occur in soils with surface slopes below 10 percent, and used that as the minimum value for cells considered in the mass wasting algorithm.

All cells that are not discarded during the screening process are subject to a slope failure calculation based on an infinite slope model. The infinite slope model describes shallow translational failure in soils, either at an interface within a soil or at an interface between a soil layer and bedrock (Burton and Bathurst, 1998).   Failure occurs when the downslope component of the overlying soil weight overcomes the shear strength of the soil. Parameters that are considered in the failure calculation include pore water pressure, soil and root cohesion, the angle of internal friction of the sediment, and the soil and vegetation overburden weight. Material that fails is routed downslope by a rule-based scheme. Mass redistribution is controlled by the surface slope of downslope cells and the contribution of subsequent failures to the original volume of failed material. Material that reaches a stream channel is incorporated in to the stream and transported as part of the total stream sediment load. The sediment transport capacity of the stream is determined by an empirical relationship between stream power and sediment load (Doten et al., 2006).

Hill slope erosion is dependent on the sediment detachment potential of direct precipitation, leaf drip and surface runoff. Sediment detachment due to direct precipitation and leaf drip is calculated based on the vegetation canopy cover of each cell and a soil-erodibility coefficient. Sediment detachment due to overland flow is calculated based on flow depth and velocity. Detached sediment is routed downslope, dependent on the surface runoff transport capacity. As with the mass wasting algorithm, if sediment crosses a stream channel, it becomes entrained and continues as part of the total stream load.

The DHSVM sediment module was first validated for the 44 km^2 Rainy Creek basin in north central Washington State (Doten et al., 2006). Slope failures predicted by the model matched reasonably well with failures observed in a historical air photo survey. The total simulated sediment yield matched well with literature values based on basin size. Other successful applications of the sediment module include investigation in to the effects of forest fires, logging, and watershed urbanization on watershed sediment yield (e.g., Barik, 2010; Tangedahl, 2006).

3.3 Precipitation Threshold Estimations

A precipitation threshold curve establishes an approximate lower boundary for the magnitude and duration of precipitation required to initiate slope failure in a given locality. Threshold curves are created by plotting multiple slope failure events against antecedent precipitation conditions. For example, Chleborad (2004) determined a precipitation threshold for landslides in the Seattle, WA area by plotting 91 historical landslides according to 3-day and 15-day antecedent precipitation (Figure 6). Precipitation threshold curves are useful to gauge the accuracy of model predictions.

4.0 Proposed Research

I will use the DHSVM hydrology and sediment models to evaluate the relationship between precipitation and streamflow and sediment yield in the Jones Creek watershed. I will perform six main steps to accomplish this research goal: 1) develop the grid-based spatial inputs for the Jones Creek watershed; 2) collect meteorological data and format a time series for the model; 3) collect stream flow and sediment load data for Jones Creek; 4) calibrate the model to the measured stream flow and sediment load; 5) perform numerical experiments in order to evaluate the basin sedimentation response to a variety of antecedent precipitation scenarios and 6) compare the results of the numerical experiments to a precipitation threshold curve I will create for the Acme Watershed Administrative Unit.

5.0 Methods and Timeline

5.1 DHSVM Setup

I will follow the setup procedures for the DHSVM that are well-documented in the theses of former WWU graduate students (e.g., Dickerson, 2010 and Donnell, 2007). I used ArcGIS to create the grid-based DHSVM inputs (Figure 7). The grids merge spatial data with a DEM of the watershed. Digital elevation models, soil type and land cover data are available digitally from organizations such as the United States Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA), and the State Soil Geographic Database (STATSGO). I will use an Arc Macro Language script (AML) to estimate the soil thickness and a stream network for the watershed. The stream network is controlled by topography and defines the path and direction that the stream flow follows. Soil thickness in each grid cell is estimated based on slope and flow accumulation.

Depending on the size of the basin, DHSVM usually uses 10 to 150 meter grids for hydrology simulations. The sediment module requires higher-resolution grids to accurately depict small slope failures. Computation time can be prohibitively lengthy for simulations using the high-resolution grids. I will experiment with a variety of grid resolutions to optimize computation time.

There is not a DHSVM-recognized soil type that accurately characterizes the hydrologic and mechanical properties of the landslide, or the bank cuts directly upstream and downstream of the landslide. Therefore, I will have to define new DHSVM soil properties for these areas. This is an important part of the model setup, because the sediment yield simulations will not be accurate if the landslide is incorrectly characterized.

5.2 Data Collection

5.2.1 Stream Data

I will use a Marsh McBirney Flo-Mate and a wading to rod to take weekly stream flow measurements at Jones Creek from March, 2011 through March, 2012. It will be important to capture the full range of stream flow changes during winter storms. I will follow the USGS midpoint method for measuring stream discharge (Rantz, 1982). Every stream discharge measurement will be correlated with the corresponding stream stage to create a rating curve for Jones Creek. If I am successful in creating a rating curve, I will use it to correlate historical data from the USGS stage gauge to stream discharge.

The site I have chosen for taking stream discharge measurements is approximately 70 meters downstream of the Turkington Road Bridge. I chose this site based on three criteria that will result in the most dependable stream rating curve: 1) the site must to be located away from Turkington Road Bridge dredging area; 2) the site must have a single discrete channel that is not likely to undergo significant natural changes in channel geometry in the next year, and 3) the site must be located above the Jones Creek flood plain, where the creek frequently changes course.

5.2.2 Sediment Data

I will measure suspended sediment using a turbidity threshold sampling approach (Lewis and Eads, 2008). I will mount sampling instruments on the Turkington Road Bridge. The instrument setup includes an ISCO 3700 water sampling pump, a DTS-12 SDI turbidity sensor, and FTS HDL1 data logger. The turbidity sensor and a sampling hose will be suspended in the water column from the bridge. The data logger and water pump will be stored in a locked wooden box near the USGS stage station.

The data logger signals the water pump to take a sample when there is a sudden change in stream turbidity. The water pump stores the suspended sediment samples in 500 ml bottles. I will collect the bottles weekly, record the turbidity magnitude associated with each sample, and analyze each sample for total dissolved solids at the Institute of Watershed Studies at WWU. I will use these data to create a rating curve that relates suspended sediment concentration to turbidity. Continuous turbidity data can then be used as a proxy for suspended sediment concentration and be compared to DHSVM simulations (Lewis, 2002).

I will attempt to measure bed load sediment flux weekly, although significant bed load transport is most likely to occur only during high stream flow events. I will follow the USGS methodology for measuring bed load with Helley Smith-type samplers (Edwards and Glysson, 1988). A Helley Smith-type bed load sampler, which I will be able to construct, consists of a metal ring and porous sample bag attached to a handle. The sampler is placed sequentially on the bottom of the creek at 20 evenly spaced locations across the creek channel. Water and fine suspended sediment flowing through the metal ring passes through the porous sample bag, and coarse bed load sediment is trapped. The total amount of sediment trapped in a given amount of time can be correlated to the total bed load sediment flux for the creek.

5.2.3 Meteorological Data

I will use meteorological data from multiple weather stations as inputs to the DHSVM. The model requires temperature, wind speed, precipitation, humidity, shortwave radiation, and longwave radiation at intervals defined by the time step. The closest stations to the Jones Creek watershed are the Brannian Creek rain gauge, located eight km southwest of Acme, and North Shore meteorological station, located 15 km northwest of Acme (Figure 8). The City of Bellingham operates the stations. There are daily weather records from these stations that date to 1983, and hourly weather records that date to 2001. Because the DHSVM time step is on the order of hours, the Lake Whatcom station data will not be useful for simulating events prior to 2001. For simulations prior to 2001, I will use data from the Abbotsford and Clearbrook weather stations. The stations are located approximately 55 kilometers and north of the Jones Creek drainage, respectively (Figure 9). Hourly weather data is available from these stations dating to 1953.

5.3 Model Calibration

I will calibrate the DHSVM to the Jones Creek watershed by adjusting model parameters until the simulated values of stream flow and sediment discharge match the measured values. The parameters that have the greatest effect on simulated stream flow are soil hydraulic conductivity, and a precipitation-elevation lapse rate. Wigmosta et al. (1994), published model simulations that had correlation coefficients of at least 0.91 with observed values. I will use the Nash and Sutcliffe (1970) efficiency (E) and the coefficient of determination (r^2; Krause et al., 2005) to establish the goodness of fit between the modeled output and the measured observations.

5.4 Numerical Experiments

I will use the calibrated DHSVM to perform numerical experiments evaluating the watershed sedimentation response to various hypothetical precipitation scenarios, including rain on snow events, 100-year recurrence interval storms, etc. One goal of these experiments will be to determine the antecedent precipitation necessary to initiate debris flows. The experimental results could serve as a basis for land use management in the Acme area.

5.5 Precipitation Threshold

The Acme Watershed Administrative Unit encompasses a large portion of the South Fork Nooksack River valley and includes the Jones Creek watershed (Powell et al., 2010). I will estimate a precipitation threshold for the initiation of debris flows in the Acme Watershed AWAU by correlating historical debris flows to their respective antecedent precipitation conditions. I have chosen to examine the entire AWAU in order to estimate a precipitation threshold that is based on a robust data set.

The precipitation threshold will be compared to the DHSVM numerical experiments. It is unlikely that I will be able to observe an actual debris flow at Jones Creek during the course of this project. The precipitation threshold will provide an evaluation of the models ability to predict debris flows that I will not be able to achieve during the calibration process.

5.6 Timeline

Step	Planned Completion
• Develop grid-based inputs	Summer 2011
• Collect and format meteorological data	Summer 2011
• Evaluate the precipitation threshold curve	Fall 2011
• Collect stream flow and sediment data	Spring 2011-Spring 2012
• Calibrate the model	Winter 2012
• Numerical experiments	Winter 2012-Spring 2012

5.7 Expected Outcomes and Deliverables

The deliverables of this project include the following:

1. Measured stream discharge and sediment concentrations in Jones Creek for one year.

2. Simulations of stream discharge and sediment concentration in Jones Creek for one year.

3. A calibrated DHSVM for stream and sediment discharge in the Jones Creek watershed.

4. A numerical assessment of the relationship between precipitation, streamflow, and sediment yield in the Jones Creek watershed.
5. A precipitation threshold for the initiation of debris flow in the AWAU.

5.8 Potential Problems

5.8.1 Landslides

The Darrington Landslide is not the only landslide in the Jones Creek watershed. Other, smaller landslides are likely to be contributing sediment to the creek. Some of these landslides are at least partially vegetated and may not be easy to identify. Accurately characterizing the many major sediment sources in the watershed will be crucial for successful implementation of the model. I will examine air photos, LIDAR maps, and review the work of previous researchers to identify major sediment sources.

5.8.2 Channel Modification

Streamflow-rating curves require constant channel geometry over time. The Jones Creek channel geometry may not remain constant near the Turkington Road Bridge, due to the county dredging program and natural channel aggradation. If the channel changes significantly during the sampling period, I will not be able to develop a rating curve to use with the USGS historical stage data. In the event of significant channel modification, I will use my discrete stream discharge measurements to calibrate the model.

5.8.3 Bed Load Measurements

Accurately measuring bed load sediment flux is a challenging process that is often unsuccessful (e.g. Holmes, 2010). The USGS method I will use has been employed with some success, but it is possible or even likely that I will not be able to obtain accurate measurements of bed load sediment discharge. During most of the year, bed load sediment will probably be negligible and suspended load will serve as a sufficient approximation of the total sediment concentration in the creek. However, during high flow events, bed load sediment migration may be significant and difficult to measure.

5.8.4 Meteorological Data

Stewart Mountain has enough relief to influence local weather patterns. The Lake Whatcom weather station data may not be representative of the precipitation conditions in the South Fork Nooksack River valley. An Acme resident has been using a personal rain gauge to collect daily precipitation data since 1980. Because this project requires precipitation data on the hourly scale, I will not be able to directly use these data as model inputs. However, it will be useful to compare these data to the Lake Whatcom precipitation data to see if they are similar.

6.0 Significance of Research

There are hundreds of small mountain watersheds in the Pacific Northwest that are similar to the Jones Creek watershed. Understanding the relationship between precipitation and sediment yield is critical for land use planning and ecological health management in Whatcom County and throughout Washington State. Numerical modeling is an important tool for developing this understanding. This project will provide an increased understanding of the hydrologic and sediment transport processes specific to the Jones Creek watershed, and a continuing evaluation of the application of distributed hydrology models to small mountain watersheds throughout the Pacific Northwest.

7.0 References

Barik, M.G. 2010. Landslide Susceptibility Mapping to Inform Land Use Management Decisions in an Altered Climate: MS Thesis, Washington State University.

Bowling, L.C., P. Storck and D.P. Lettenmaier. 2000. Hydrologic effects of logging in western Washington, United States: Water Resources Research, v. 36 no. 11, p. 3223-3240.

Bowling, L.C. and D.P. Lettenmaier. 2001. The effect of forest roads and harvest on catchment hydrology in a mountainous maritime environment, in Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas, Water Science and Application, The American Geophysical Union, 2, p. 145-164.

Brown, E. H. 1987. Structural and accretionary history of the Northwest Cascades system Washington and British Columbia: Geological Society of America Bulletin, vol. 99, p. 201-214.

Burton, A. and J. C. Bathurst. 1998. Physically based modeling of shallow landslide sediment yield at a catchment scale: Environmental Geology, 35, p. 89–99.

Chleborad, A.F. 2004. Preliminary Evaluation of a Precipitation Threshold for Anticipating the Occurrence of Landslides in the Seattle, Washington Area: Open file report 03-463, U.S. Geological Survey.

Chennault, J. 2004. Modeling the contribution of glacial meltwater to stream flow in Thunder Creek, North Cascades National Park, Washington: MS Thesis, Western Washington University.

Cuo, L., D.P. Lettenmaier, B.V. Mattheussen, P. Storck, and M. Wiley. 2008. Hydrologic prediction for urban watersheds with the Distributed Hydrology-Soil-Vegetation Model:Hydrological Processes 22: p. 4205-4213.

Dickerson, S. 2010. Modeling the effects of climate change forecasts on streamflow in the Nooksack River basin: MS Thesis, Western Washington University.

Donnell, C. 2007. Quantifying the glacial meltwater component of streamflow in the Middle Fork Nooksack River, Whatcom WA using a distributed hydrology model: MS Thesis, Western Washington University.

Doten, C.O. and D.P. Lettenmaier. 2004. Prediction of Sediment Erosion and Transport with the Distributed Hydrology-Soil-Vegetation Model: Water Resources Series Technical Report No. 178.

Doten, C.O., L.C. Bowling, L.S. Lanini, E.P. Maurer and D.P. Lettenmaier. 2006. A Spatially Distributed Model for the Dynamic Prediction of Sediment Erosion and Transport in Mountainous Forested Watersheds: Water Resources Series Technical Report No. 178.

Edwards, T.K. and G.D. Glysson. 1988. Field methods for measurement of fluvial sediment: U.S. Geological Survey Open-File Rept. 86-531.

Holmes, R.R. 2010. Measurement of Bedload Transport in Sand-Bed Rivers: A Look at Two Indirect Sampling Methods: U.S. Geological Survey Scientific Investigations Report 2010-5091.

Kelleher, K. 2006. Streamflow calibration of two sub-basins in the Lake Whatcom Watershed, Washington using a distributed hydrology model: MS Thesis, Western Washington University.

Kerr Wood Leidal Associates. 2004. Jones Creek debris flow study: A report prepared for the Whatcom County Flood Control Zone District, Vancouver, British Columbia; 128 pp.

Krause, P., D.P. Boyle and F. Bäse. 2005. Comparison of different efficiency criteria for hydrological model assessment: Advances in Geosciences 5: p. 89-97.

Lapen, T.J. 2000. Geologic Map of the Bellingham 1:100,000 Quadrangle, Washington: WADNR Open File Report 2000-5.

Leung L.R. and M.S. Wigmosta. 1999. Potential climate change impacts on mountain watersheds in the Pacific Northwest: Journal of the American Water Resources Association 35(6): 1463-1471.

Lewis, J. 2002. Estimation of Suspended Sediment Flux in Streams Using Continuous Turbidity and Flow Data Coupled with Laboratory Concentrations: Turbidity and other sediment surrogates workshop.

Lewis, J. and R. Eads. 2008. Implementation Guide for Turbidity Threshold Sampling: Principles, Procedures, and Analysis: General Technical Report PSW-GTR-212. Arcata, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station.

Matthews, R., M. Hilles, J. Vandersypen, R. Mitchell and G. Matthews. 2007. Lake Whatcom Monitoring Report 2005-2006.

Nash, J.E. and J.V. Sutcliffe. 1970. River flow forecasting through conceptual models; Part I, A discussion of principles: Journal of Hydrology 10(3): p. 282-290.

Powell, J., L. Lingley and G Anderson. 2010. Reconnaissance study of landslides related to the January 2009 storm in the Acme watershed: Report for Washington State Department of Natural Resources Forest Practices Division.

Puget Sound LIDAR Consortium. 2006. Airborne LIDAR data set, Puget Sound Region.

Rantz, S. E. 1982. Measurement and Computation of Streamflow: Volume 1. Measurement of Stage and Discharge: U.S. Geological Survey Water-Supply Paper 2175.

Raines, M., O. Hungr, K.F. Welch, and P. Willing. 1996. Whatcom County Lower Nooksack River Comprehensive Flood Hazard Management Plan, Alluvial Hazards: Recommended Assessment Methodology and Regulatory Approach: Report prepared for KCM Inc., Seattle, WA; 27 pp.

Storck, P., D.P Lettenmaier, B.A. Connelly, and T.W. Cundy. 1995. Implications of Forest Practices on Downstream Flooding: Phase II Final Report, Washington Forest Protection Association, TFW-SH20-96-001; 100 pp.

Storck, P., L.C. Bowling, P. Wetherbee, and D.P. Lettenmaier. 1998. Application of a GIS-based hydrology model for prediction of forest harvest effects on peak streamflow in the Pacific Northwest: Hydrologic Processes, v. 12, no. 6, p. 653-65

Tangedahl, E.L. 2006. Utilization of the Distributed-Hydrology-Soil-Vegetation-Model(DHSVM) To Quantify Streamflow Changes and Slope Failure Probability Following the Snow-Talon Fire Near Lincoln Montana, USA.(DHSVM) To Quantify Streamflow Changes and Slope Failure Probability Following the Snowtalon Fire Near Lincoln Montana, USA: MS Thesis, University of Montana-Missoula.

Wigmosta, M.S., L.W. Vail, and D.P. Lettenmaier. 1994. A distributed hydrology-vegetation model for complex terrain: Water Resources Research, v. 30, no. 6, p. 1665-1679.

Wigmosta, M.S., and W.A. Perkins. 2001. Simulating the effects of forest roads on watershed hydrology: AGU, Water Science and Application, v. 2, p. 127-143.

8.0 Figures

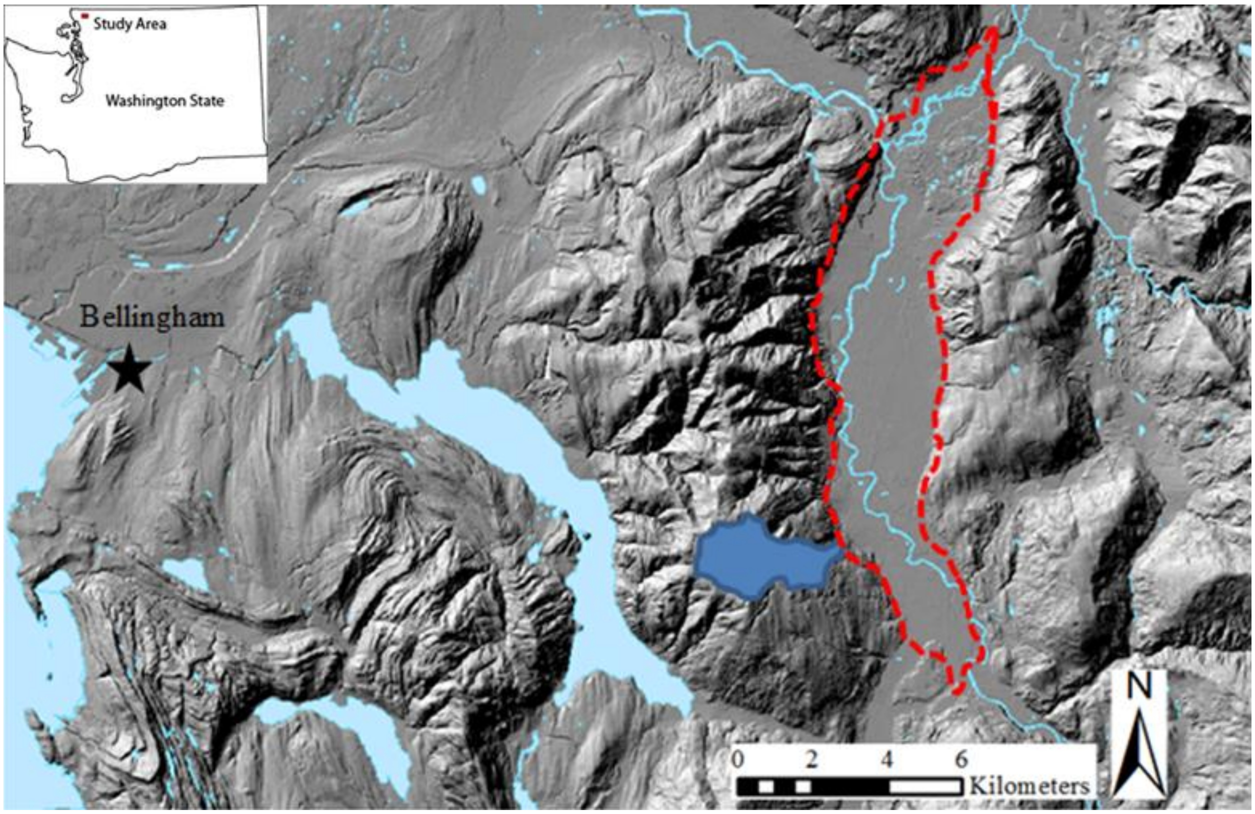

Figure 1: Location map of the Jones Creek watershed in relation to Bellingham, WA. The Jones Creek watershed is shaded in blue. The lower reach of the South Fork Nooksack River valley is outlined in red.

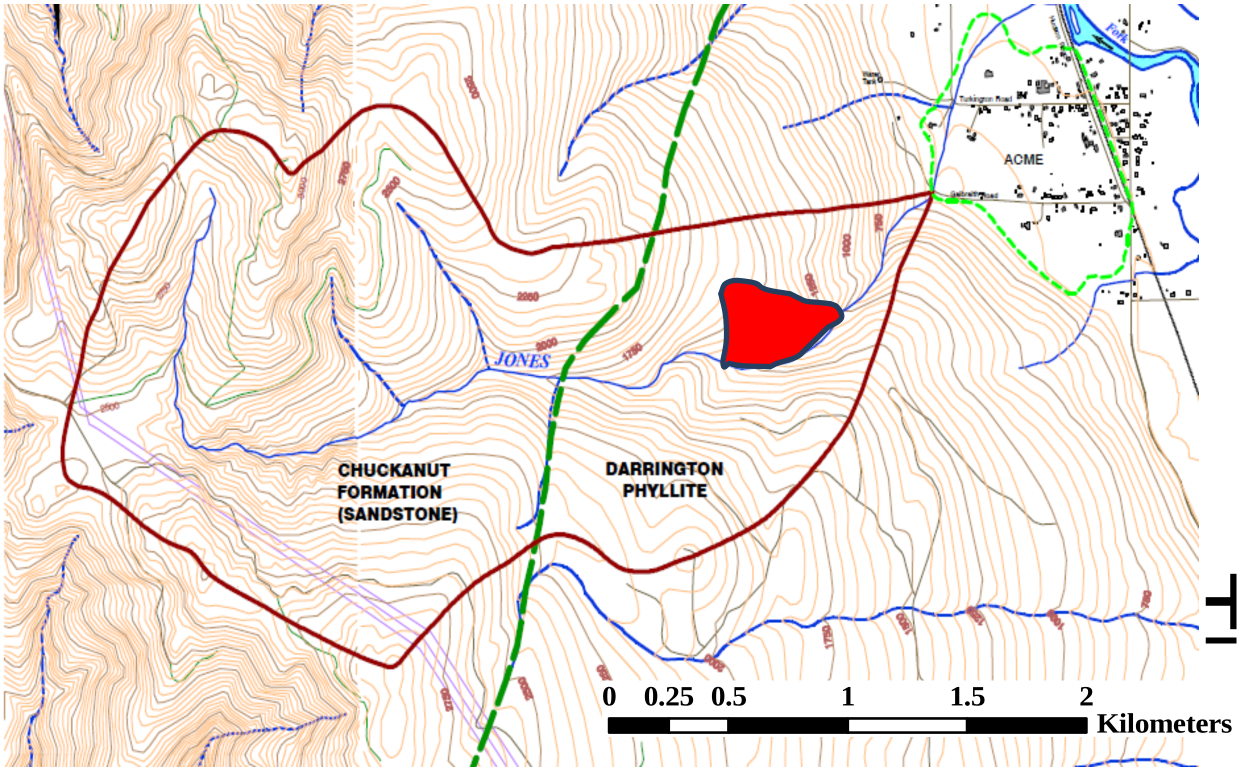

Figure 2: Geologic map of the Jones Creek watershed. The contact between the Chuckanut Formation and the Darrington Phyllite is shown as a green dashed line. The Darrington Landslide is shaded in red. The composite fan is outlined in light green. Modified from KWL (2004).

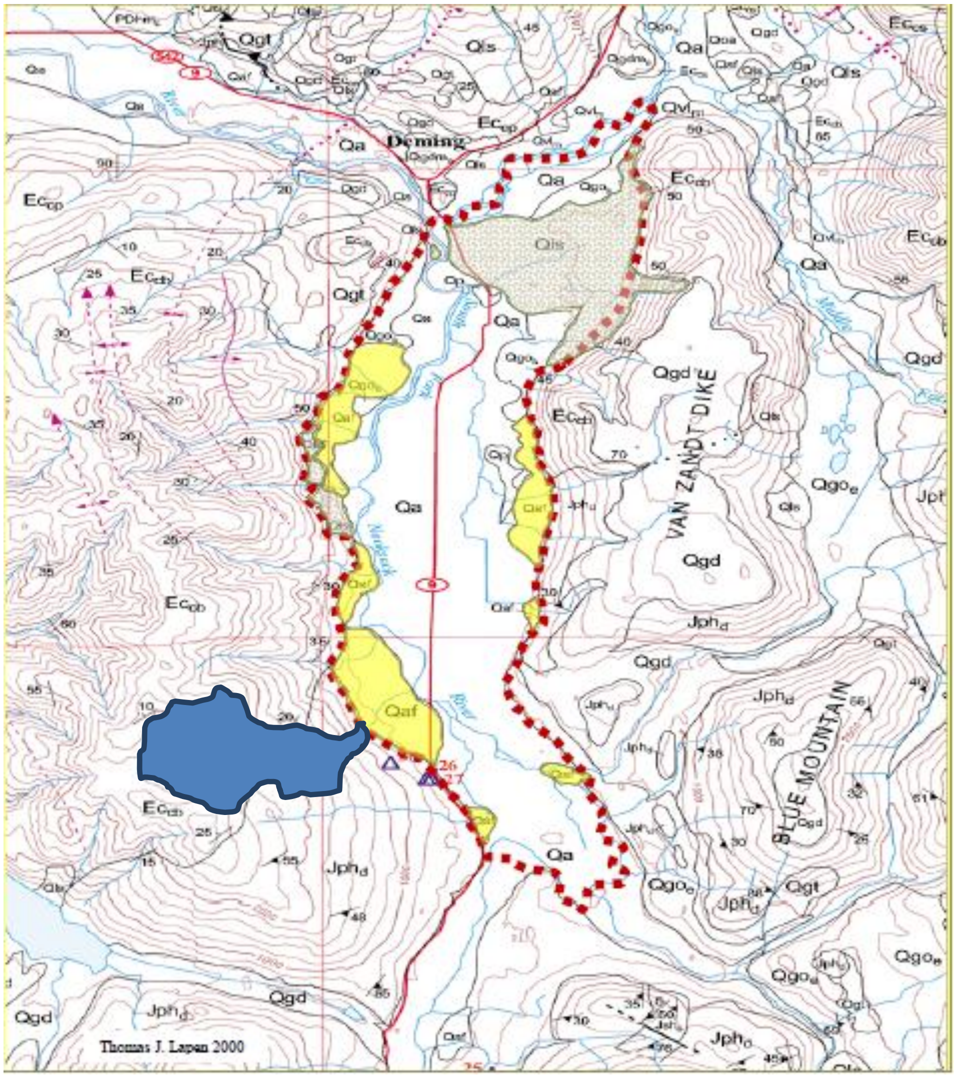

Figure 3: A portion of the Geologic map of the Bellingham 1:100,000 Quadrangle by Lapen (2000). The South Fork Nooksack River valley is outlined in red. The shaded yellow map units labeled 'Qaf' are Quaternary-aged alluvial fans. The fans are deposited at the mouths of numerous steep drainages in the South Fork Nooksack valley, including the Jones Creek watershed (shaded in blue). Modified from Powell et al. (2010).

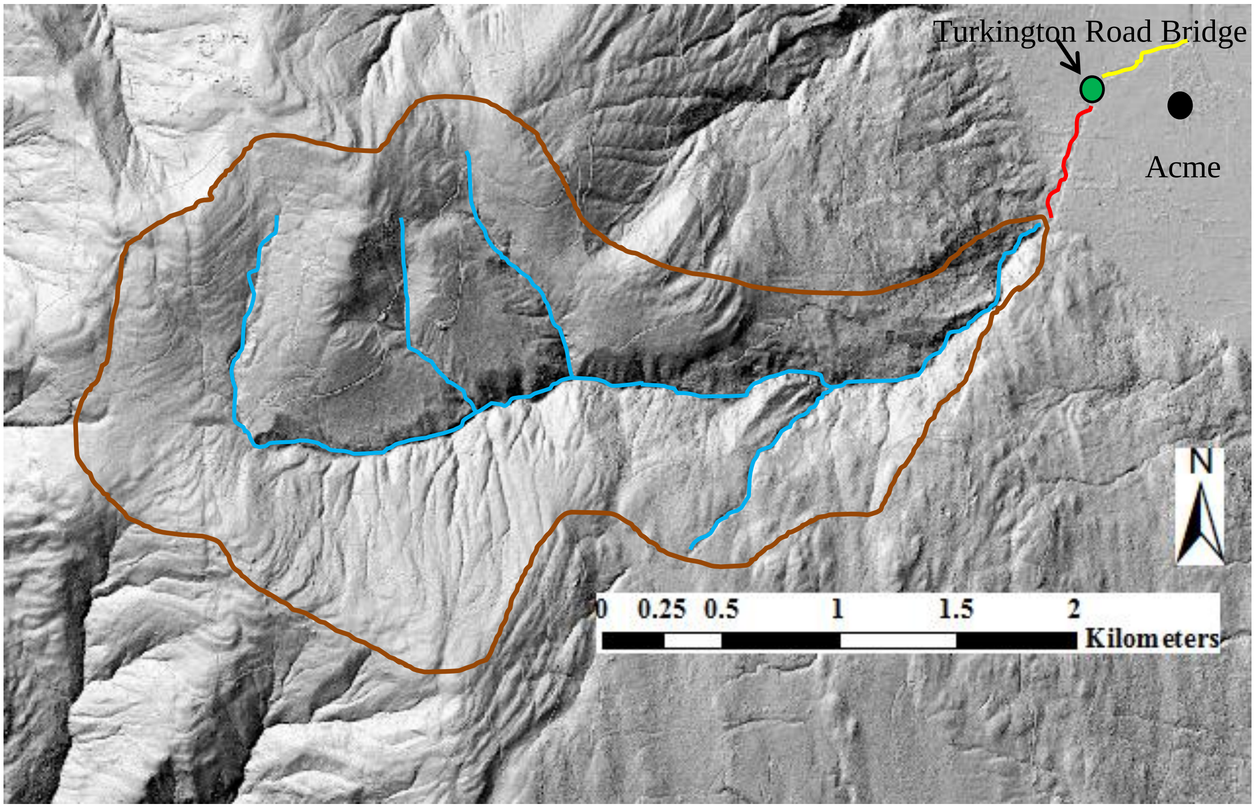

Figure 4: Bare-earth LIDAR hill shade map of the Jones Creek watershed west of Acme, WA. The watershed is outlined in brown. The location of the Turkington Road Bridge is shown as a green dot. Reach one of Jones Creek is shown in blue. Reach two is shown in red. Reach three is shown in yellow. LIDAR data from the Puget Sound LIDAR Consortium (2006).

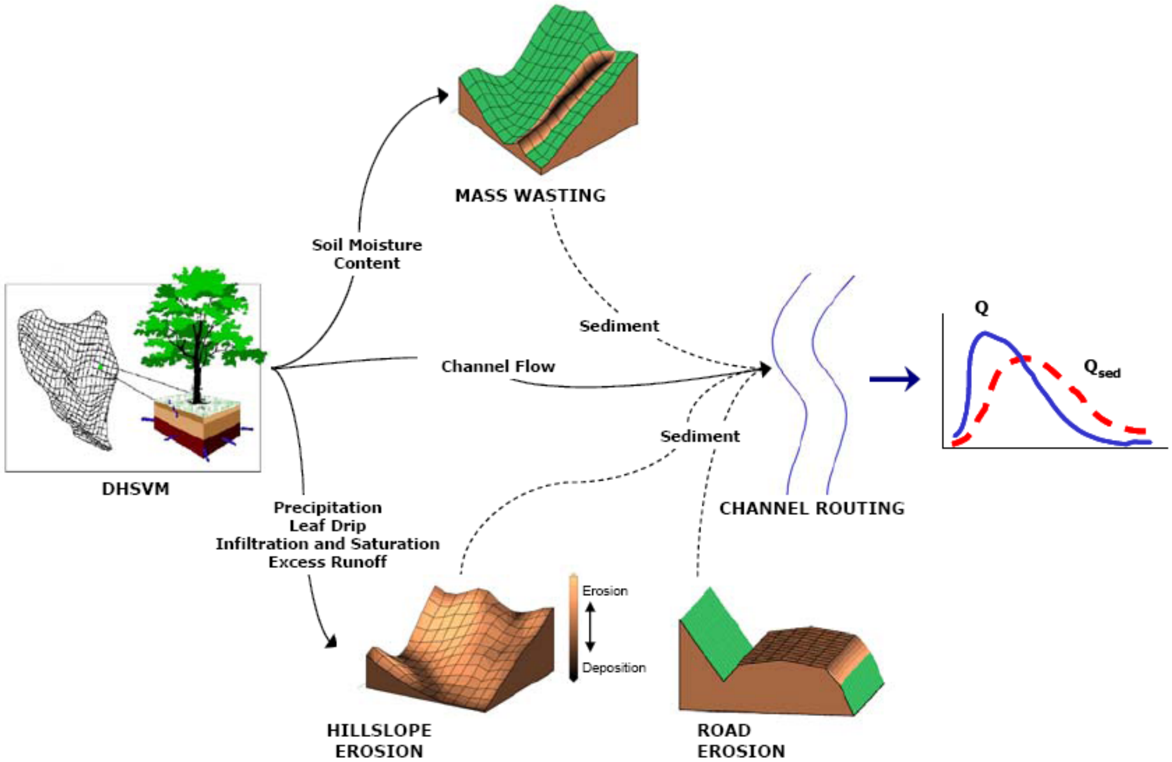

Figure 5: An overview of the three sediment transport processes considered in the DHSVM sediment module. This study will not consider road erosion. The graph in the figure represents the DHSVM simulated stream flow (blue line) and sediment discharge (dashed red line). From Doten and Lettenmaier (2004).

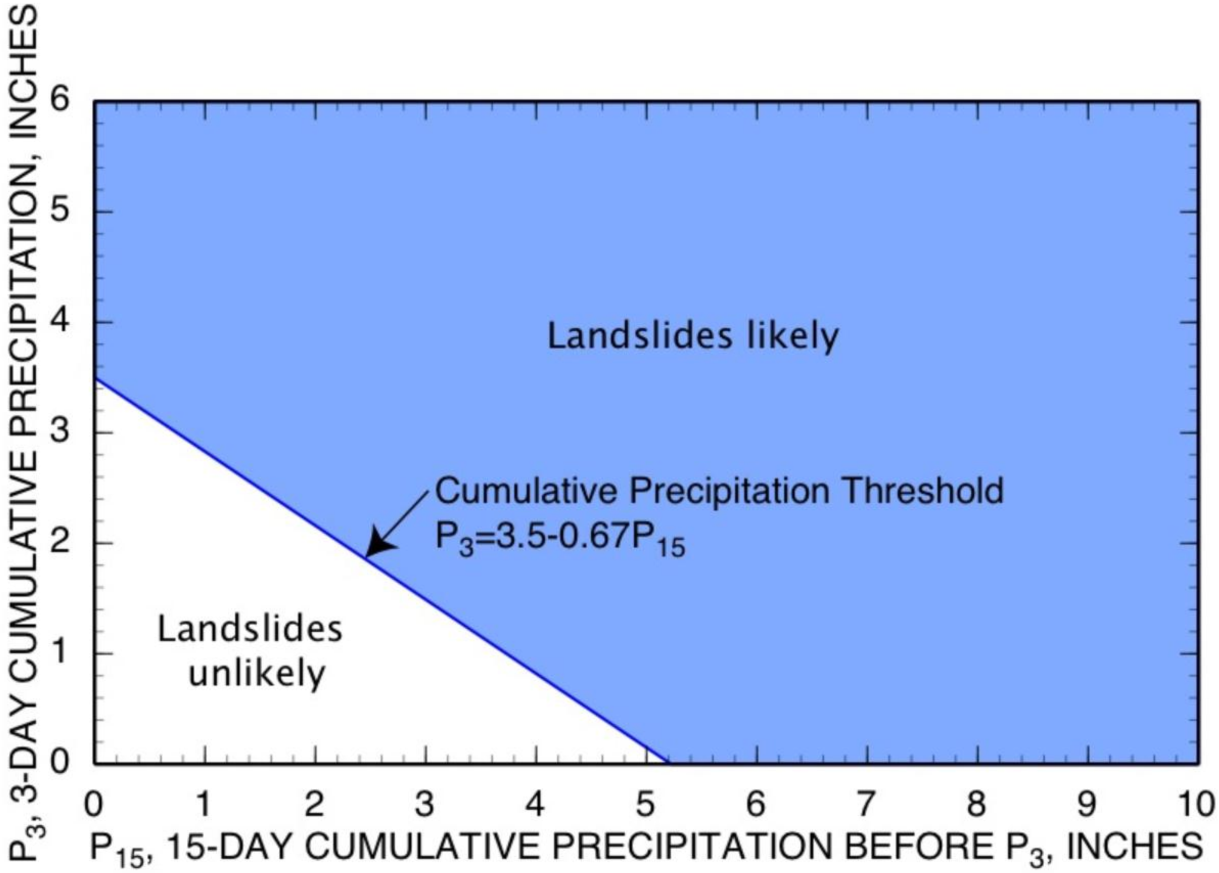

Figure 6: A precipitation threshold for landslides in the Seattle area. Chleborad (2004) created this threshold by plotting 91 historical landslides according to their respective 3-day and 15-day antecedent precipitation magnitudes. The cumulative precipitation threshold equation represents the lower boundary precipitation conditions likely to initiate landslides.

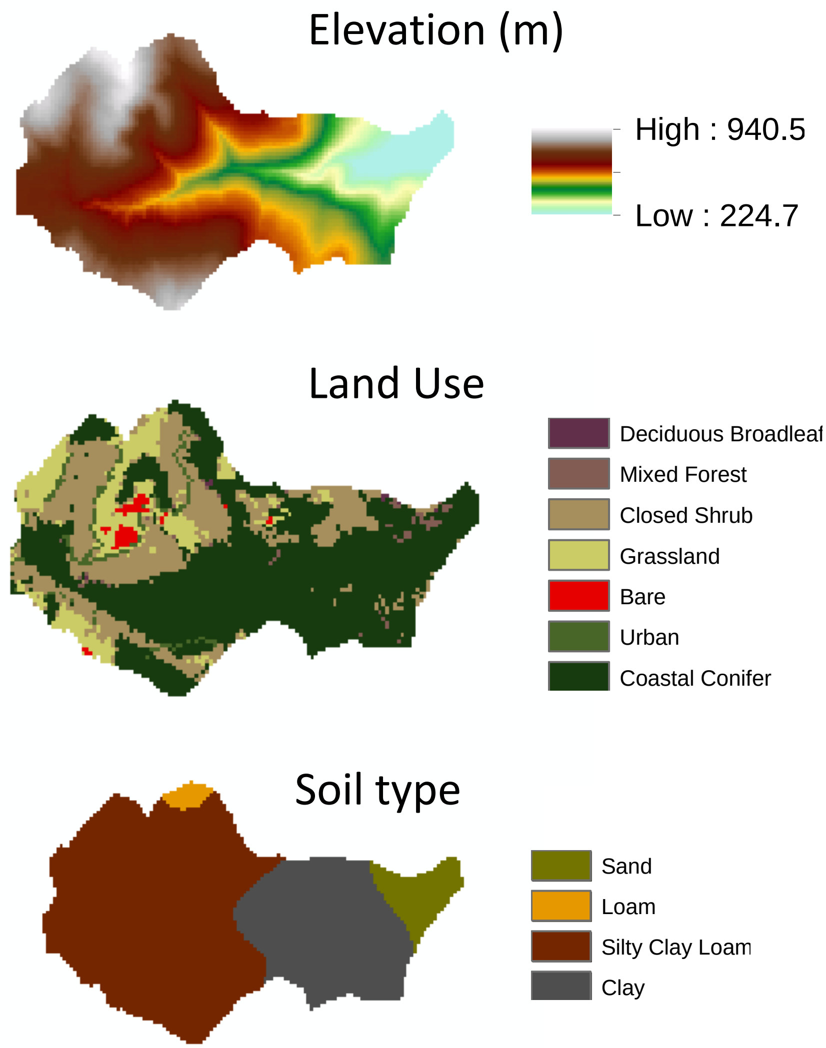

Figure 7: Grid-based DHSVM spatial inputs for the Jones Creek watershed, including elevation, land use, and soil type. The DHSVM spatial inputs are created by merging land use and soil type data with a DEM.

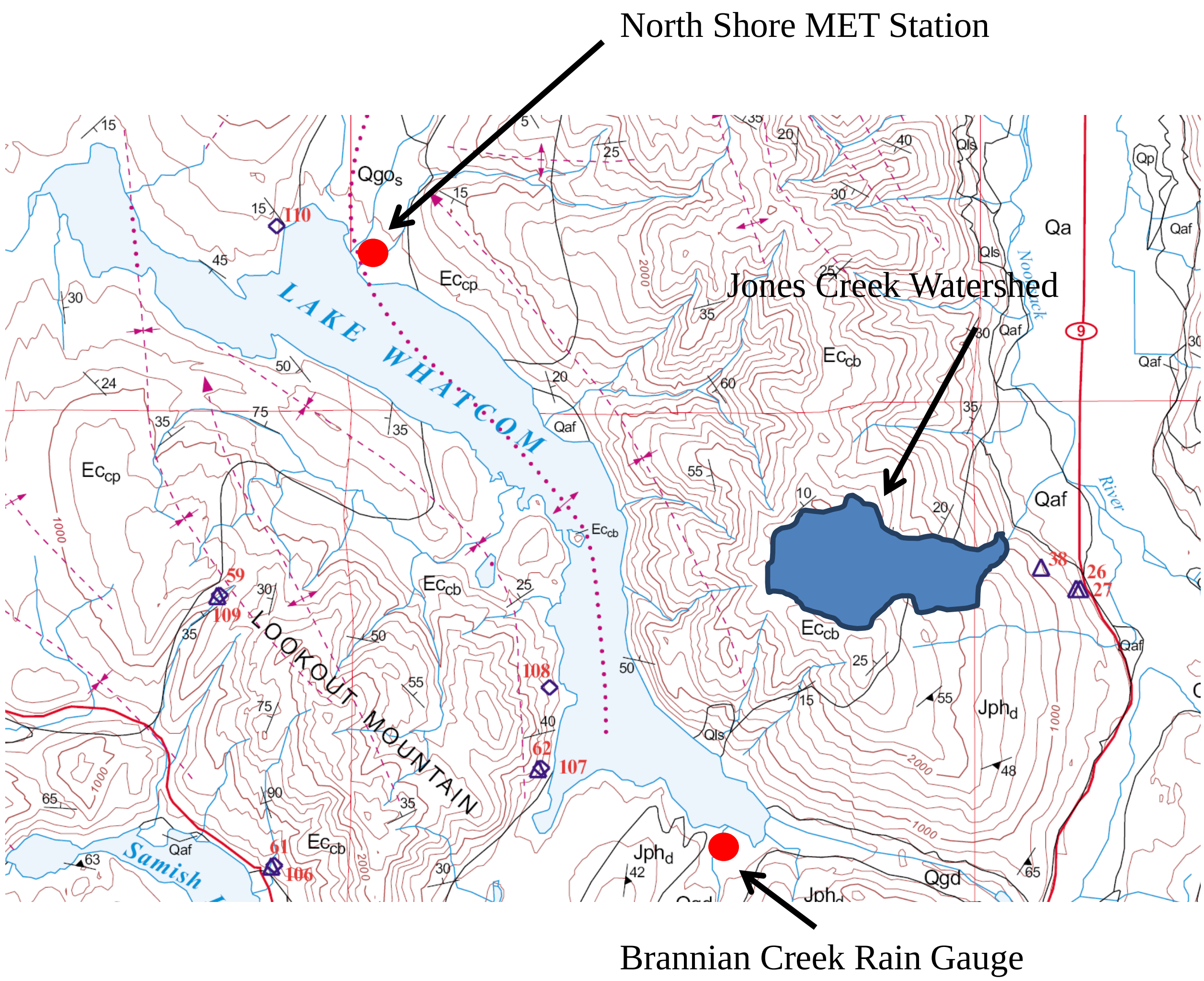

Figure 8: Location map of the Brannian Creek rain gauge and the North Shore MET station. The stations are located in the Lake Whatcom Watershed, west of the study location (shaded in blue). Modified from Lapen (2000).

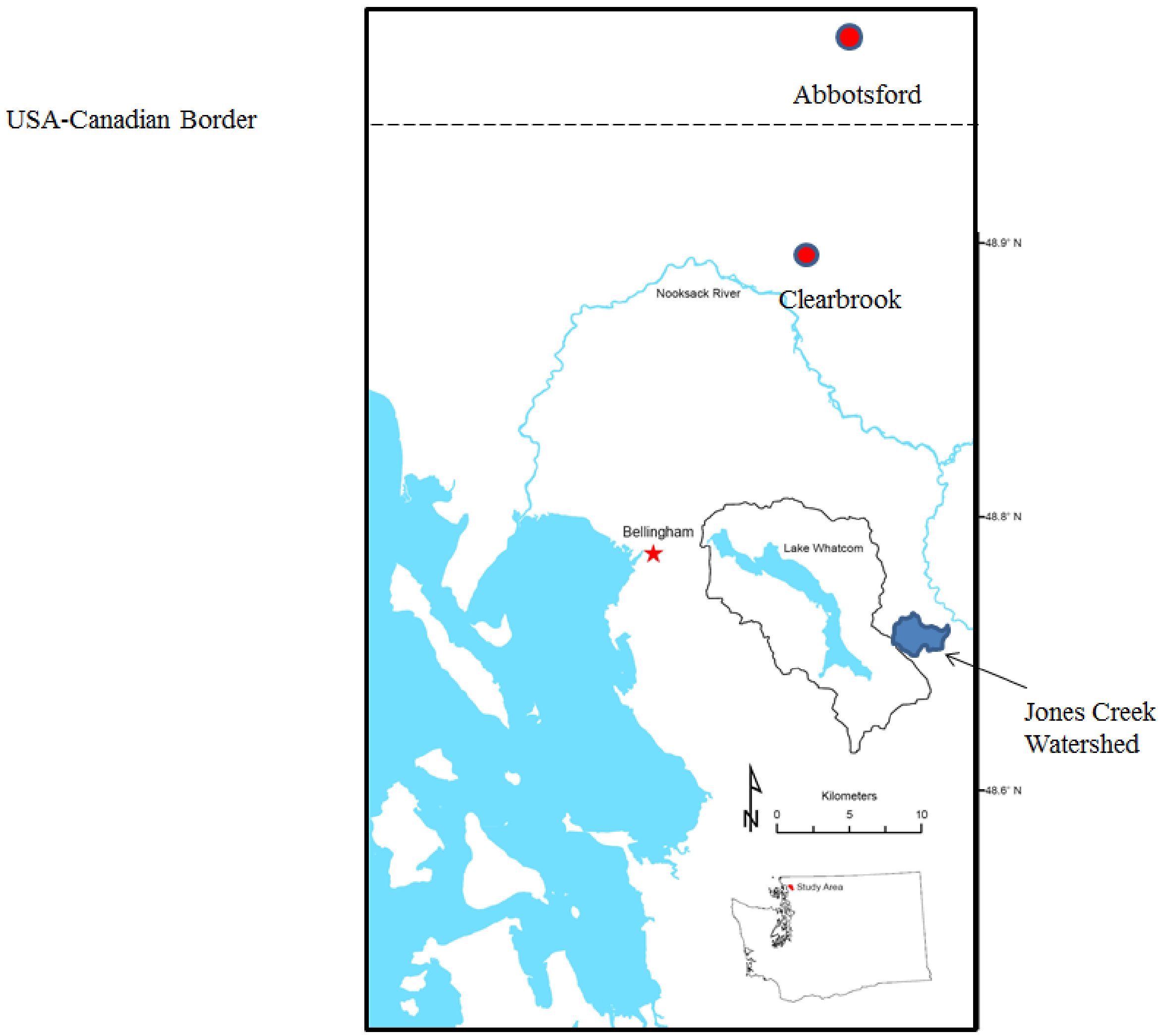

Figure 9: Location map of the Abbotsford and Clearbrook weather stations. The stations are located approximately 50 km and 30 km north of the study area, respectively. The study area is shaded in blue.