Modeling the Sediment Yield from Swift Creek Landslide 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

My objective is to estimate suspended sediment yield from the Swift Creek landslide feeding into the south fork of Swift Creek near Everson, WA, using a hydrologic model called the Distributed Hydrology-Soil-Vegetation Model (DHSVM). I will use DHSVM to determine the energy and mass budget for the watershed and quantify river discharge, and then apply a sediment module written for DHSVM to model suspended sediment concentration (SSC) in the river discharge. This approach will be useful for correlating the SSC to erosion from the toe of the landslide and for examining hydrologic processes controlling erosion and stream discharge.

2.0 INTRODUCTION

Swift Creek is a large active landslide in northwest Washington, east of the cities of Everson and Nooksack (Figure 1). Although the slide has not exhibited catastrophic movement historically, it does release large quantities of sediment to agricultural land and residential areas that poses a risk to human health because the slide material contains naturally occurring asbestos fibers (Bayer, 2006; EPA 2006). Previous research has estimated the total sediment discharge to be between 90,000 – 120,000 yds³/yr (McKenzie-Johnson, 2006) with an annual suspended sediment yield of 910 tons/km²/yr (Bayer, 2006).

This sediment is transported down Swift Creek and into the Sumas River often filling channels that have to be dredged to prevent flooding and road damage. In previous years the dredged material was piled next to the creek and used in a variety of ways, such as fill dirt in newly constructed residential areas.

Recent studies show that the asbestos fibers in the dredged landslide deposits could pose health risks to those who live, work, and play on or near the material (EPA, 2006). Because of the potential health risks, Whatcom County must determine how to dispose of the material now classified as hazardous waste (EPA, 2006). Knowledge of what factors affect the amount of sediment being eroded from the slide and an accurate quantification of the sediment discharge is crucial to develop remediation plans.

Numerical models have become useful tools for examining hydrologic and mass wasting problems such as those in the Swift Creek basin. At Western Washington University, DHSVM has been used to model river discharge for water budgets, forest cover effects on surface water and ground water, as well as glacial recession (e.g., Chennault, 2004; Kelleher, 2006; Donnell,
2007; Matthews et al. 2007). For this study I will employ DHSVM, a spatially distributed, physically based hydrologic modeling tool, along with additional modules to quantify sediment transport and predict slope stability. The DHSVM was developed by the University of Washington (UW) and the Pacific Northwest National Lab (e.g., Wigmosta et al., 1994; Doten and Lettenmaier, 2004; Doten et al., 2006).

3.0 BACKGROUND

3.1 Swift Creek Watershed

3.1.1 Geology

The Swift Creek landslide lies on the steep western slope of Sumas Mountain (Figure 1). Dragovich et al. (1997) identified two major bedrock units have been identified near the slide, the Huntingdon conglomerate and an ultramafic body primarily composed of serpentinite. A small deposit of glacial till is mapped on the south side of the slide (Figure 2).

The serpentinite body appears to form the basal slide plane of the landslide and is considered to be the source of the asbestiform material that results from rapid weathering and disaggregation of chrysotile fibers (Bayer, 2006). At toe of the slide, large blocks of Huntingdon conglomerate overlie the serpentinite from alluvial fan deposition (Dragovich et al., 1997). The conglomerate blocks at times become undercut and topple leaving massive boulders on top of the landslide toe. The conglomerate blocks also form local restrictions along Swift Creek downstream from the toe of the landslide.

3.1.2 Basin Characteristics

The basin containing the landslide is ~ 6.5 sq. km and has nearly 1000 m of relief ranging from ~35 m to ~1040 m altitude. The forest cover on Sumas Mountain is primarily coniferous with some deciduous growing in lower elevations, in pockets along stream gullies, and on the margins of the landslide. Much of the coniferous forest near the landslide has been logged. Several areas adjacent to the slide, both to the north and south, are presently clear cut. Swift Creek has two forks (Figure 3). The north fork has flows through forest until it converges with the south fork below the landslide. The south fork discharges the flanks and the toe of the landslide. From the toe, the stream flows down a narrow alluvial and bedrock channel with steep sides that are constricted with vegetation. Both forks flow year round, but the south fork is the
primary source of sediment downstream. At low flows in the summer, the stream becomes clear with little landslide-derived sediments; the stream bed generally scours slightly during these times. Flow during winter is moderate to torrential with high concentrations of suspended sediment during storm events; during this season there can be rapid channel infilling from high turbidity flows interspersed with intermittent scouring between storms. The sediment volumes deposited during infilling events greatly exceeds scouring, resulting in an overall annual aggradation of the stream bed. This dynamic setting makes it difficult to accurately measure stream discharge. Establishing an accurate rating curve to relate stage to discharge is not possible where the stream bed aggrades or erodes so dramatically.

3.1.3 Kinematics and Mineralogy

The slide is classified as slow moving and deep seated (McKenzie-Johnson 2004). There are three basic zones defined by their characteristic morphology and motion: the zone of depletion, the neutral zone, and the zone of accumulation (Figure 4). The zone of depletion comprises the upper third of the slide where thinning is occurring and is manifested by a series of extensional head scarps. The neutral zone comprises the central third where the slide is moving mainly as a coherent block with little internal deformation; consequently, this zone is covered with a dense stand of large evergreen trees. The zone of accumulation includes the de-vegetated toe. Here the slide is thickening and steepening. Small slides frequently initiate on the toe and release turbidity flows into the stream. These small surficial failures have been recorded by time lapse photography as part of the Western Washington Landscape Observatory (Linneman and Clark, 2006). In addition to small failures on the toe, abundant surface erosion results from rainfall on the unvegetated surface.

Slide velocity varies spatially. Maximum velocities occur at the toe and are as rapid as 30 m/yr (McKenzie-Johnson, 2004). Higher parts of the slide move ~4 m/yr. The greater velocities at the toe cause discontinuous expansion fractures to form at the top of the toe where the velocity gradient is greatest. The fractures are roughly parallel to surface contours indicating that surface flow is perpendicular to the slope. The fractures are typically centimeters in width and several meters in length and often form the head scarps to the small surface failures on the toe.
A common term for prolonged motion of this magnitude is creep (Radbruch-Hall, 1978). The velocities noted above are annual averages and vary seasonally, probably due to changes in the water table and its affect on the effective normal stress between particles (McKenzie-Johnson, 2004). Another possible cause for changes in rates of landslide creep includes earthquakes, as observed at the Point Firmin landslide in California (Miller, 1931). Although seismic induced changes have not been documented Swift Creek landslide, it is a viable mechanism for future changes in this seismically active area.

The best estimate for the depth of the shear plane is between 90 – 125 m (McKenzie-Johnson, 2004). This estimate was determined by projecting the head scarp trajectory to the toe high resolution topographic profile. At these depths, the stress-strain relationship and the mechanics of motion are not as well understood in comparison to shallow slides (Petley and Allison, 1997). McKenzie-Johnson (2004) made several alternative predictions of the depth and trajectory of the shear boundary based on different factor of safety values. The projected detachment trajectory combined with the slide area of ~550,000 m², indicates the landslide volume is between 3.5 x 10⁷ m³ to 5.1 x 10⁷ m³ (McKenzie-Johnson, 2004).

The composition of the landslide material has been determined by X-ray diffraction (XRD) and Scanning Electron Microscope (SEM) analyses (Bayer, 2006). Chrysotile asbestos fibers, derived from the serpentinite bedrock, comprise approximately 50% of the fine sediments being mobilized in the stream. Other minor constituents from the serpentinite are chlorite, illite, and hydrotalcite. The matrix of fine sediments contains abundant gravel, cobble, and boulder sized serpentinite, conglomerate, and a variety of other rocks eroding out of the glacial till on the southern head scarp of the slide (Figure 2).

4.0 PROPOSED RESEARCH

I plan to estimate an annual sediment yield from the landslide by modeling the sediment flux of Swift Creek resulting from surface erosion and mass wasting from the landslide using DHSVM and a new sediment module for DHSVM developed by researchers at the UW (Doten and Lettenmaier, 2004). To accomplish this research objective I will perform five tasks: 1) develop the grid-based input for the Swift Creek watershed; 2) collect and format the meteorological time series for the model; 3) collect stream discharge data for Swift Creek and calibrate the DHSVM stream-flow output to the measured data; 4) measure sediment
concentrations in the creek at various flow rates and calibrate the DHSVM to the measured sediment load; and 5) perform numerical experiments on the model outputs and analyze the results.

5.0 METHODS AND TIMELINE

5.1 Modeling Background

5.1.1 DHSVM Background

The DHSVM is a complex hydrologic numerical model designed to investigate hydrology, soil, and vegetation dynamics. It was originally developed by researchers at the UW and the Pacific Northwest National Lab for hydrologic studies of forested mountainous watersheds (Wigmosta et al., 1994; Wigmosta et al., 2002). The model calculates an energy and mass balance for each grid cell based on the physical relationships between the water and the soil, vegetation, and atmosphere (Figure 5). Gridded GIS data allow the model to accurately represent the inherent spatial heterogeneities that define the natural characteristics of a mountainous watershed. Meteorological inputs are distributed spatially at the DEM resolution and physical relationships are used to simulate evapotranspiration, snow accumulation and melt, infiltration, subsurface flow, runoff, and stream-flow processes.

Land-cover is divided into a two story canopy, the overstory and understory, and the soil. Correspondingly, there is a two layer rooting zone reflecting rooting depths of the overstory and understory. Movement of all precipitation through fall, snow melt, and stem flow that infiltrates into the soil is based on Darcy’s law. The dominant vegetation type is used to estimate leaf area index which directly affects evapotranspiration (ET). ET is estimated using the Penman-Montieth method. If infiltration exceeds ET and subsurface flow, the model predicts saturated overland flow directly feeding the stream channel. Essentially, water can leave a grid cell via direct evaporation, transpiration from vegetation, saturated subsurface flow, and saturated overland flow. The amount of mass exchanged between cells is calculated simultaneously for each cell. The effects of landcover changes can be explored by comparing changes in ET compared to changes in discharge (Vanshaar and Lettenmaier, 2001).
5.1.2 Turbidity Module Background

My research involves using the recently developed turbidity module designed for DHSVM. In two previous studies the turbidity module was used to estimate the amount of sediment entering streams by means of mass wasting due to logging road failures and deforestation within the Rainy Creek catchment, a tributary of the Wenatchee River, Washington state (Doten and Lettenmaier, 2004; Doten et al., 2006). The model produces plausible sediment yields compared with literature values for similar catchments and that ratios of landsliding and surface erosion rates are plausible compared to published rates for various watersheds in the Pacific Northwest.

The turbidity module predicts mass wasting and hill slope erosion. The module is grid-based and performs several calculations for each cell, which in turn influences the adjacent cells. The sediment module is coupled to DHSVM and relies on the stream flow output as an input for predicting mass wasting and erosion (Table 1).

To predict mass wasting, the module begins at the highest point in the watershed, and checks each cell for the presence of sediment and a slope greater than a user defined value. Doten and Lettenmaier (2004) used 10°. If both of these criteria are met, a factor of safety calculation is perform to determine if a failure occurred in that cell; if so, the sediment is moved to the cell immediately down slope of its present location where a new calculation will be performed. This process is carried out for each cell, and failure is allowed to continue and the mass is redistributed as long as the criteria for slope failure are met. If the mass happens to cross a stream path, the sediment is then removed from the factor of safety calculations and considered sediment entrained within the stream flow discharge.

Sediment flux derived from hill-slope erosion is based on the detachment energy of raindrops, leaf drip, and overland flow. Sediment can be moved by overland flow and relocated down slope and eventually into a stream. The algorithms are carried out on a cell by cell basis; each detachment mode is responsible for a certain amount of erosion based on the rainfall frequency, intensity, as well as the land-cover and soil type. The predicted sediment flux related to mass wasting and surface erosion are incorporated within the flow output of DHSVM to produce a sediment concentration in the stream.
5.2 Model Set Up and Data

I will use ArcGIS to develop the spatial data required to model the watershed and predict stream flow with DHSVM; these include digital elevation, soil type, soil thickness, landcover, and a stream network. The spatial data are accessed online from government agencies such as the USGS, USDA, and NOAA. Data from these sources will be used to define the watershed boundary and to define the physical characteristics of the watershed.

5.2.1 DHSVM stream flow set up

Digital Elevation Model (DEM)

The DEM is the foundation for the model. Aspect and slope grids will be created from the DEM in order to create the stream flow paths and to define the watershed boundaries (Figure 3). Topography is also an important variable in receiving solar radiation and precipitation. Air temperature and precipitation change with elevation, therefore lapse rates are applied to the physical hydrologic equations used in DHSVM.

The DHSVM is commonly run with 30 m or larger pixel resolution. I intend to run the model using a 10 m DEM derived from a down-sampled 2 m lidar DEM (USGS, 2006). I have chosen 10 m resolution so to increase computing time and such high resolution may or may not provide more accurate hydrologic results. Kenward and Lettenmaier (1997) compared several DEM’s that were produced using different methods for the Mahantango basin in Australia, a 7.2 km² basin. They concluded that the USGS and SIR-C methods for creating DEM’s were inappropriate for small basins due to the presence of significant elevation errors compared to a 5 m reference DEM created from low altitude aerial photography. Varying the horizontal resolution was a problem when considering flat areas; resolving flow paths was more difficult with lower resolution DEM’s and discharge was underestimated (Dubin and Lettenmaier, 1999). For this study, the down-sampled10 m DEM is more detailed than a typical USGS 10 m DEM but is not as memory intensive.

Stream Flow

A model of the stream flow within the basin is created from the DEM using an Arc-Macro-language (AML) script. Stream channels are established by determining the direction of flow of surface water that would be collected and transported through a stream.
Soil Thickness

Soil data will be created using the same AML that creates the stream flow model. This script uses a regression technique to estimate minimum and maximum soil depths based on slope and flow accumulation (Chennault, 2004).

Soil Type

Soil type data were collected from the STATSGO database compiled by the U.S. Department of Agriculture. The soils in the Swift Creek basin are primarily a silt loam with varying concentrations of gravel, from very gravelly to no gravel. The landslide material is unique and is not included in the STATSGO data so a new soil type with hydrologic properties will need to be created for this model. Creating a new soil type that realistically represents the landslide material will be a major problem because the mechanical and hydraulic properties will have to be assigned. This will require several iterations until the appropriate combination of properties is achieved and the model output matches the collected data.

Vegetation

I will use spatial vegetation data from the NOAA 2001 land-cover database. Today, there is extensive logging in the area with clear-cutting directly adjacent to the landslide on both the northern and southern sides. These land-cover changes will be accounted for in the GIS vegetation grid. The landslide area was once dense old growth coniferous forest mostly of Douglas fir. Remnants of this forest still exist in pockets in the center of the landslide where the it is moving coherently as a plug. Changes in landcover can significantly affect the hydrologic cycle of a watershed. A decrease in evapotranspiration can cause an increase in soil saturation which can lead to slope instability and increased erosion from overland flow.

Meteorology

The meteorological (MET) data required as input include precipitation, temperature, wind speed, humidity, solar radiation and long wave radiation. Most of these data will be from a weather station located at the top of the landslide’s toe. Temporal gaps in the MET data will be filled with data from two regional weather stations in Whatcom County, Clear Brook and North Shore. Both of these stations are nearby and in the same environmental setting (Figure 1).
5.2.2 DHSVM turbidity set up

Set up for the turbidity module will require determining module parameters for slope failure criteria such as minimum slope angle and sediment thickness. The module uses a tighter grid spacing than the stream flow model and will resample the 10 DEM I intend to use in order to be able to have failures that are a realistic size. On the Swift Creek landslide, scarp from small slope failures are roughly 2 m wide and several centimeters deep have occurred, so 2 m grid spacing seems optimum (Doten and Lettenmaier, 2004).

5.3 Stream Monitoring / Data Collection

To calibrate the model, actual stream discharge and sediment concentration data will have to be measured. I set up a stream gauging station at the bridge where Goodwin Road crosses Swift Creek. This station is capable of recording river stage and turbidity continuously using a methodology known as Turbidity Threshold Sampling (TTS). The TTS methods are commonly employed by the Pacific Southwest Research Station of the United States Forest Service (Lewis and Eads, 2008). This method allows researchers to examine how turbidity reacts to changes in discharge and to predict sediment flux. A sediment rating curve must be established by calibrating the turbidity sensor to actual sediment load by analyzing water samples for sediment concentration. A discharge rating curve must also be established in order to use stage as a proxy for discharge. This method allows the quantification of the full range of changes in sediment flux and discharge that occur in a fluvial system that cannot be determined with discrete intermittent sampling.

The gauging station is downstream of the confluence between the north and south fork of the creek (Figure 3). The flow is less turbulent here than it is upstream. The bed is also flatter and smoother and contains finer sediments, mainly sand and gravel, so there is less bed-roughness and therefore less turbulence.

I am primarily interested in the south fork of Swift Creek because it flows directly off the landslide, the primary source of the suspended sediment. However, I intend to supplement the stream gauging station data with periodic measurements above the confluence in both forks in order to determine a gradient of suspended sediment concentration with respect to distance from the landslide. In this way, a basic understanding of the north fork can be attained and estimates of water and sediment additions from the north fork can be factored out.
I mounted the stream gauging station following methods laid out by Lewis and Eads (2008). Instruments at the station include an ISCO 3700 water sampling pump to collect 24, 500 ml raw water samples. Turbidity is recorded by a DTS-12 SDI Turbidity sensor and logged with an FTS HDL1 data logger. The ISCO 3700 is triggered by the FTS HDL1 when the sensor detects rapid and sustained changes in turbidity. The ISCO 3700 and FTS data logger are contained in a weather proof housing attached to the side of the bridge along with a 12 volt battery for power. The turbidity sensor and water pump tubing are suspended into the water by a pole hanging vertically from a boom that extends out ~2 m from the bridge. This assembly is designed to allow the sensor to hinge in the direction of water flow; this will alleviate pressure from changing water velocities and allow objects to safely pass underneath. A stilling well is also constructed on the side of the river channel at the bridge in order to monitor creek stage. A Stevens Water shaft encoder and data logger measure stage by means of a float and counter weight looped around the shaft encoder pulley. Rising and falling stage cause the pulley to rotate, when calibrated correctly this rotation equates to a vertical distance.

The physical samples collected will be analyzed at the Institute for Watershed Studies for total suspended solids (TSS). The TSS method draws an aliquot of known volume from the sample after adequate mixing of the sample (ASTM, 2000). The aliquot is filtered, dried, and weighed. The dry weight of the clean filter is subtracted from the dry weight after filtration; the difference is divided by the volume of the aliquot to determine suspended sediment concentration (SSC). The SSC will be used to create a rating curve from the turbidity data to form a continuous model of sediment concentration (Lewis, 2002).

5.4 Model Calibration

Stream-flow calibration will require the modification of model relations such as precipitation lapse rate, soil thickness, soil type, and lateral hydraulic conductivity until the simulated discharge closely approximates the measured discharge (less than 5% difference). There will be a significant amount of gaps in the measured discharge due to the recurring changes in streambed morphology. Several times during the winter recording season, the stilling well was left dry when the stream altered course or dropped below newly deposited beds from recent high waters. This problem required persistent maintenance to keep water around the well. Even when the stilling well remained in the water, the change in stage often simply reflected a
change in the bed, not changes in discharge. To account for this problem, near weekly velocity profile measurements were recorded using a wading rod and a Marsh McBirney Flo-Mate velocity probe.

After completing stream-flow calibration, the sediment module will be applied to calibrate sediment concentration in the stream. In the turbidity module, slope failure criteria and mechanical properties of the landslide material will have to be adjusted until simulated sediment flux matches recorded sediment flux. The calibration process will involve re-running the model after each adjustment in order to determine the affect the change had on the output. For this reason, calibration will be time intensive.

5.5 Numerical Analysis

As a final step, I will conduct numerical experiments of data output from the fully calibrated model. I will experiment with different meteorological forcings to examine the response of the landslide wasting to the stream. The results will produce maximum, minimum, and average estimates for annual sediment fluxes to the floodplain, thereby providing Whatcom County managers a basis for making mitigation decisions. Because precipitation data inputs to the model can be varied, anyone using the model for predictive purposes can explore the response of the landslide to large storm events and other environmental changes (e.g., 100 year to 500 year rainfalls, deforestation, and climate change).

5.6 Expected Outcomes and Deliverables

The deliverables of this project are as outlined below:

1. A working stream gauging station capable of recording stage and suspended sediment concentration in a flashy stream.
2. A model of the Swift Creek watershed in DHSVM calibrated for river discharge.
3. A calibrated model of suspended sediment concentration (SSC).
4. Simulated hydrographs and SSC plots based on a one season period.
5.7 Potential Problems

The lack of any historical stream flow data for Swift Creek and the short duration of data collection involved in this study will make it difficult to calibrate the model and validate it based on previous years. Instead, this research project provides a base line study that will be important in gaining insight to the landslide and the Swift Creek watershed. This work will also lay a foundation for future work if the TTS methodology and stream gauge construction prove to be reliable in this situation. The flashy nature of Swift Creek has made it difficult to set up a stream monitoring system and instruments have repeatedly been lost in the attempt (Bayer, 2006). Having a bridge-mounted system capable of hinging over debris should increase the chances of instrument survival. If these methods are successful, as they have been for Lewis and Eads (2008), then the data collection can continue for future studies.

Another difficulty is determining the hydraulic and mechanical properties of the landslide material. This will be done in DHSVM by adjusting parameters for the pixels of the landslide until the simulated stream flow matches to the recorded stream flow to within 5%. In this way a new soil designation will be created.

6.0 SIGNIFICANCE OF RESEARCH

This research will supply researchers and county planners with baseline stream-flow and sediment flux information as well as a working model of the Swift Creek watershed and the amount of asbestos containing suspended sediments being discharged from the landslide. The model will link sediment discharge with water discharge, give an understanding of what types (duration and intensity) of rain events contribute the most, and the time of year when sediment discharge is the highest. This information will be essential to the future development of remediation programs dealing with the landslide material. The model will allow for the assessment of external affects on the landslide such as climatic changes in temperature, precipitation, solar radiation, or physical changes such as deforestation due to logging or forest fires.
7.0 REFERENCES


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


Figure 1: Bare-earth LIDAR hillshade map showing the location of Swift Creek landslide east of Everson, Washington state. The Swift Creek watershed is shown in red just east of Everson on Sumas Mountain. Several weather stations are in close proximity to Swift Creek shown by the green triangles.
Figure 2: Geologic map of Swift Creek Landslide and adjoining areas. From Dragovich et al, 1997.
Figure 3: Hillshade of the Swift Creek watershed based on data from the 2006 USGS North Puget Sound LIDAR survey. The proposed monitoring station at Goodwin road marks the pour point of the basin. The landslide area is outlined.

Figure 4: Schematic longitudinal cross section of the landslide depicting the primary morphological zones: accumulation at the toe, plug flow in the neutral zone, and depletion due to extension and thinning near the head wall. From Mckenzie-Johnson, 2004.
Figure 5: Simplified diagram depicting the physical characteristics and interaction between grid cells in DHSVM. Each cell has its own aspect and slope and contains 3 substrate layers, and a vegetation canopy. The blue arrows indicate infiltration and lateral subsurface flow into and out of each cell.

Table 1: Table of inputs and outputs of the turbidity module.

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<tr>
<th>DHSVM Inputs</th>
<th>Sediment Module</th>
<th>Output</th>
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<tbody>
<tr>
<td>Soil Moisture</td>
<td>Mass Wasting</td>
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<td>Surface Water</td>
<td>Hillslope Erosion</td>
<td>Water discharge vs.</td>
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<td></td>
<td>Road Erosion</td>
<td>Sediment discharge</td>
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<td>Channel Flow</td>
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