Predicting Slope Failure in the Jones Creek Watershed, Acme, WA, using the Distributed-Hydrology-Soil-Vegetation Model

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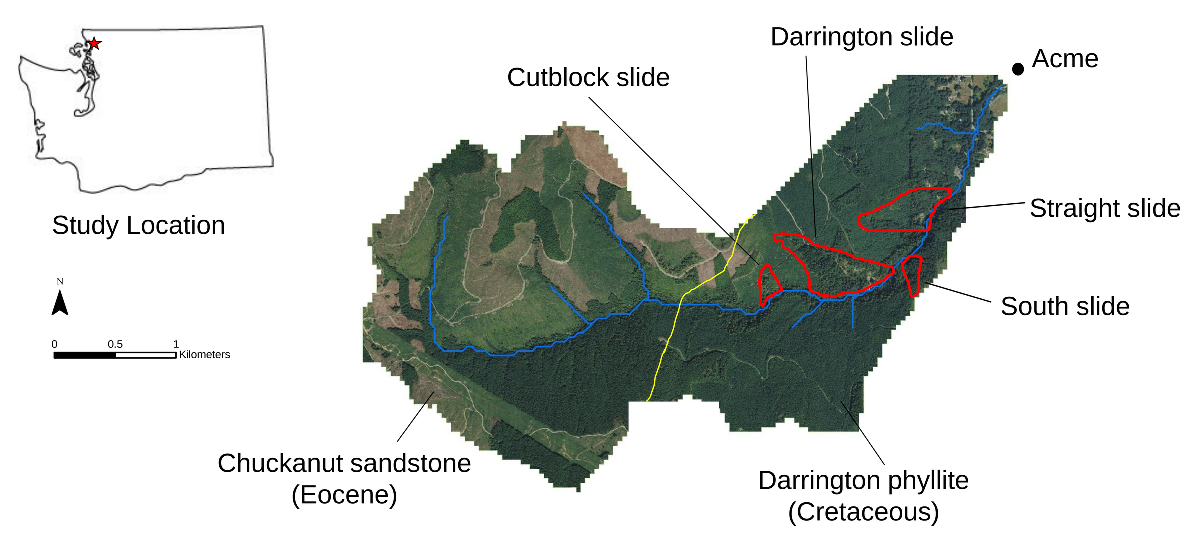
INTRODUCTION

Jones Creek Watershed

The Jones Creek watershed is a small mountain basin located west of Acme in Whatcom County, WA (Figure 1). The lower portion of the watershed is underlain by the Cretaceous–aged Darrington phyllite, a mechanically weak rock that is prone to developing unstable soils (Jakob et al., 2004). There are four major active landslides hosted in the phyllite, including the Cutblock, Darrington, Straight, and South slides (Figure 1). All of the landslides except the Cutblock have unvegetated toes situated directly adjacent to the creek channel. Shallow mass wasting events on the landslides during periods of intense precipitation can lead to debris flows that threaten Acme residents. Here we discuss the application of the DHSVM as a useful tool for identifying specific areas in the Jones Creek watershed that are susceptible to mass wasting during extreme precipitation events.



Basin Characteristics:

Watershed area: 6.7 km^2
Relief: 90m – 940m
Community: ~250 residents
~100 buildings

Figure 1: Air photo of the Jones Creek watershed. Landslides are outlined in red. The creek channel is shown in blue. The contact between the Darrington phyllite and Chuckanut sandstone is shown in yellow.

DHSVM

The Distributed Hydrology-Soil-Vegetation Model (DHSVM), developed at the University of Washington and Pacific Northwest National Laboratory, uses meteorological and spatially distributed physical data to simulate a water and energy balance at the pixel scale of a digital elevation model (Figure 2; Wigmosta et al., 1994). The model predicts soil infiltration, storage, surface runoff, and saturated subsurface flow for each pixel over a user-defined time step. Total stream flow is also predicted at the basin outlet. The more recently-developed DHSVM sediment module is dependent the simulated basin hydrology and uses a stochastic approach to predict surface erosion and infinite slope mass wasting (Doten and Lettenmaier, 2004). Surface erosion is not considered in this study.

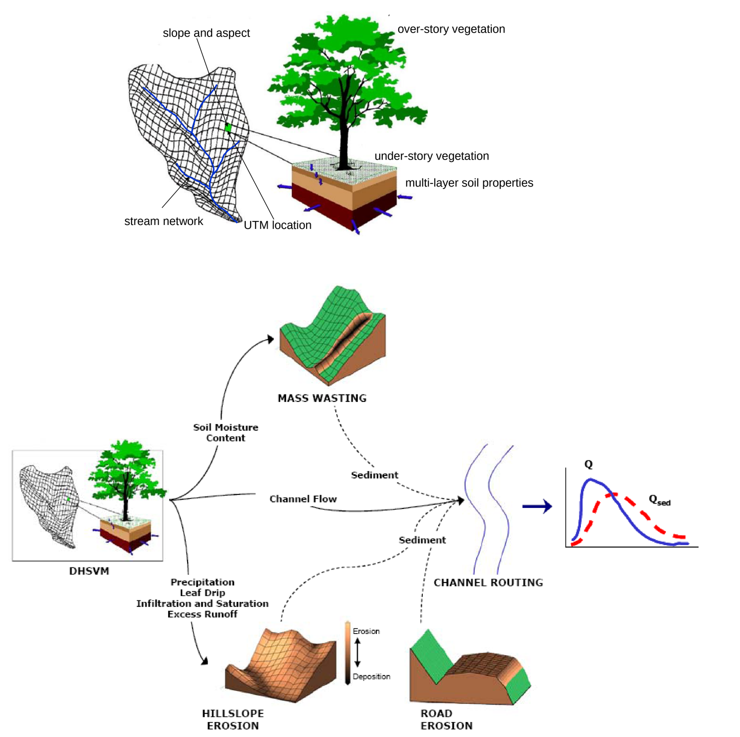


Figure 2: Conceptual setup for the DHSVM hydrology and sediment models (From Doten and Lettenmaier, 2004).

RESEARCH OBJECTIVES

We use the DHSVM to model stream flow and the infinite mass wasting component of the sediment module to simulate failure probability. Our intention is to use the model to quantify the relationship between historical precipitation and mass wasting in the watershed. To accomplish our research objectives we employ the following tasks:

- Develop the grid-based DHSVM inputs for the Jones Creek watershed.
- Collect and format a regional meteorological time series for the model (approximately 35 years).
- Collect stream discharge data at the basin outlet and calibrate the model to the measurements.
- Run the mass wasting component of DHSVM for a range of historical storm events and create precipitation threshold curves that relate antecedent precipitation to failure probability, following the methods of Godt (2004).
- Simulate the effects of reduced root cohesion and evapotranspiration due to timber harvest by pairing the January, 2009 storm event, which triggered slope failures throughout western Washington, with a shrub vegetation replacement class (Powell et al., 2010).

METHODS

Model Setup

Physical model inputs include a stream network and the following 30-meter resolution GIS data sets (Figure 3):

- Digital Elevation Model (Puget Sound LiDar Consortium)
- Soil Thickness (generated in ArcInfo AML)
- Soil Type (STATSGO database)
- Landcover (NOAA; Figure 3)

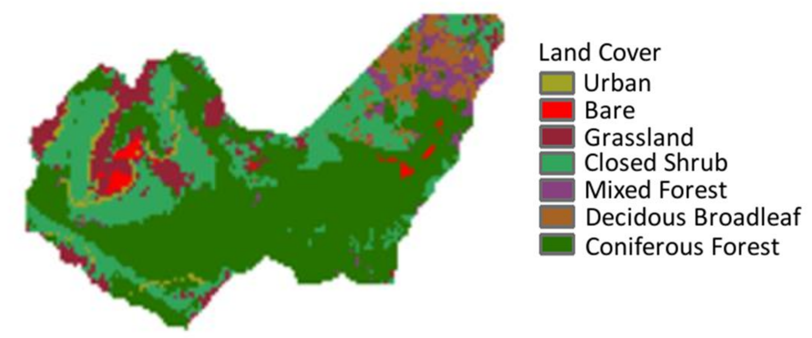


Figure 3: Land cover for the Jones Creek watershed.

We obtained hourly meteorological data from the nearby Abbotsford A station, British Columbia, Canada, which is located approximately 30 miles north of the study area. The station was selected for its long historical record of data. Meteorological model inputs include the following parameters:

- Temperature (C)
- Wind Speed (m/s)
- Relative Humidity (%)
- Longwave Radiation (W/m^2)
- Shortwave Radiation (W/m^2)
- Precipitation (m)

Stochastic Modeling with the Infinite Slope Equation

The infinite slope factor of safety (FS) equation describes planar failures in shallow soils (Figure 4). The equation is commonly used in modeling applications because it is computationally efficient and the variables are readily available from literature or field measurements. The equation is based on the concept that failures are hydrologically triggered when water table fluctuations cause local pore pressures to reduce soil shear strength below the imposed stresses (Doten and Lettenmaier, 2004; Hammond et al., 1992). The equation is solved cell by cell over a ten-meter DEM:

$$FS = \frac{C_r + Cs + cos^2\alpha[q_0 + \gamma(D - Dw) + (\gamma_{sat} - \gamma_w)D_w]tan\phi}{\sin(\alpha)\cos(\alpha)[qo + \gamma(D - Dw) + \gamma_{sat}D_w]}$$

FS = factor of safety
α = slope of ground surface (º)
D = total soil thickness (m)
D_w = saturated soil thickness (m)
C_r = root cohesion (kPa)
q_0 = vegetation surcharge (kPa)
C_s = soil cohesion (kPa)
ϕ = angle of internal friction (º)
γ_d = dry soil unit weight (kg/m^3)
γ = moist soil unit weight (kg/m^3)
γ_{sat} = saturated unit weight (kg/m^3)
γ_w = water unit weight (kg/m^3)

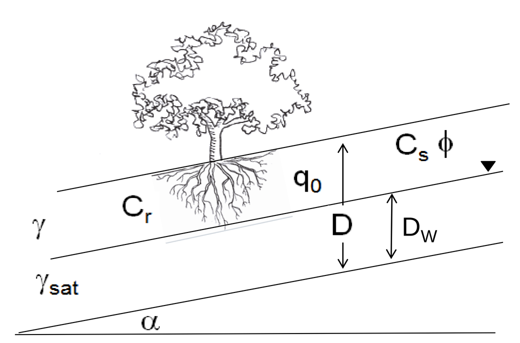


Figure 4: Conceptual setup of infinite slope failure. Modified from Hammond et al. (1992).

DHSVM uses a stochastic probabilistic approach to model slope instability. The advantage of this approach is that it is possible to quantify some of the uncertainty and variability associated with the parameters that govern slope instability (Hammond et al., 1992). Values for soil cohesion, root cohesion, angle of internal friction, and vegetation surcharge are chosen at random from probability distributions defined by the specific soil and vegetation type at each cell (Figure 5). We use literature values and distributions. Although values for soil cohesion and angle of internal friction are usually chosen from normal distributions, we use uniform distributions for these parameters to reflect the notoriously high degree of mechanical variability in active landslides.

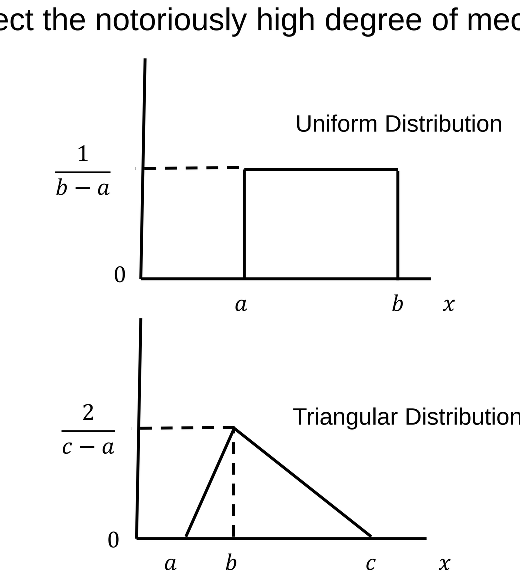


Figure 5: Probability distributions used in this study.

Mechanical Parameters

- **Landslide Soil Cohesion**:
  Uniform distribution, 7.5-13 kPa
- **Coniferous Forest Root Cohesion**
  Triangular distribution, 2-17 kPa, mode 9.5 kPa
  (no root cohesion on unvegetated portions)
- **Angle of internal Friction**:
  Uniform distribution, 25-32º
- **Vegetation Surcharge**
  Uniform distribution, 0.5-1.92 kPa
  (no surcharge on unvegetated portions)
- **Shrub Root Cohesion (harvest scenario)**
  Triangular distribution, 2-6 kPa, mode 4 kPa

The model solves the infinite slope equation for each cell *n* times (we chose 1000), selecting new values for the above variables for each iteration. The final model output is a cell-by-cell probability of failure (P):

$$P = \frac{x}{n}$$

where

P = model probability of failure
x = number of iterations where FS < 1
n = total number of iterations

RESULTS

Probability Thresholds

Mass wasting is simulated for 87 historical storms of a variety of magnitudes and durations. Each storm is plotted according to precipitation duration (hours) and intensity (centimeters per hour) and coded according to the failure probability at the toe of each deep seated landslide. Probability thresholds are then interpreted at 10 percent intervals (Figure 6). Storms with failure probability between 40 and 70 percent plot erratically and can not be subdivided in to more precise classes. Estimated thresholds for shorter storms compare favorably with the Godt (2004) intensity-duration threshold for the Seattle area, which has an exceedance probability of 42 percent (Figure 6). For longer storms, the Godt (2004) threshold predicts greater failure probability.

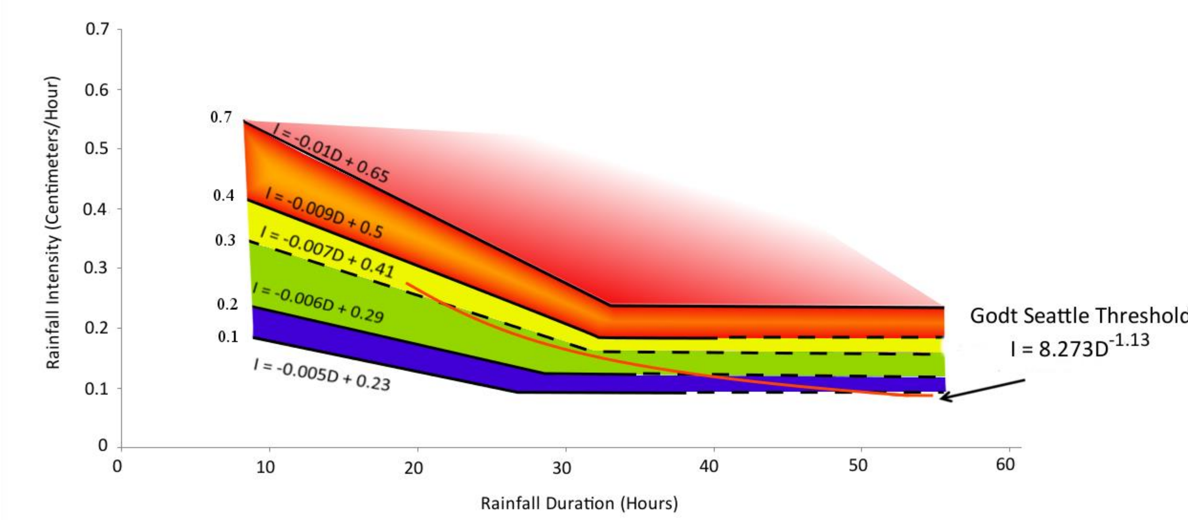


Figure 6: Interpreted rainfall intensity (I) and duration (D) failure probability thresholds for the Straight landslide. The Godt (2004) intensity-duration threshold, which has an exceedance probability of 0.42, is shown for comparison.

Timber harvest

In order to examine the potential effects of timber harvest on slope stability in the Jones Creek basin, two susceptibility maps are interpreted. The January, 2009 storm, which triggered numerous landslides and debris flows in the Acme valley, is used as a design event (Powell et al., 2010). The first map is based on current land cover conditions. The second map is based on total replacement of trees with shrubs, resulting in reduced root cohesion. A slope angle-failure probability relationship is established for each scenario and applied to a high-resolution (two meter) slope map of the watershed (Figure 7). The post-harvest reduction in root cohesion results in a widespread increase in failure susceptibility, including a 42 percent increase in the number of cells with a failure probability greater than 40 percent.

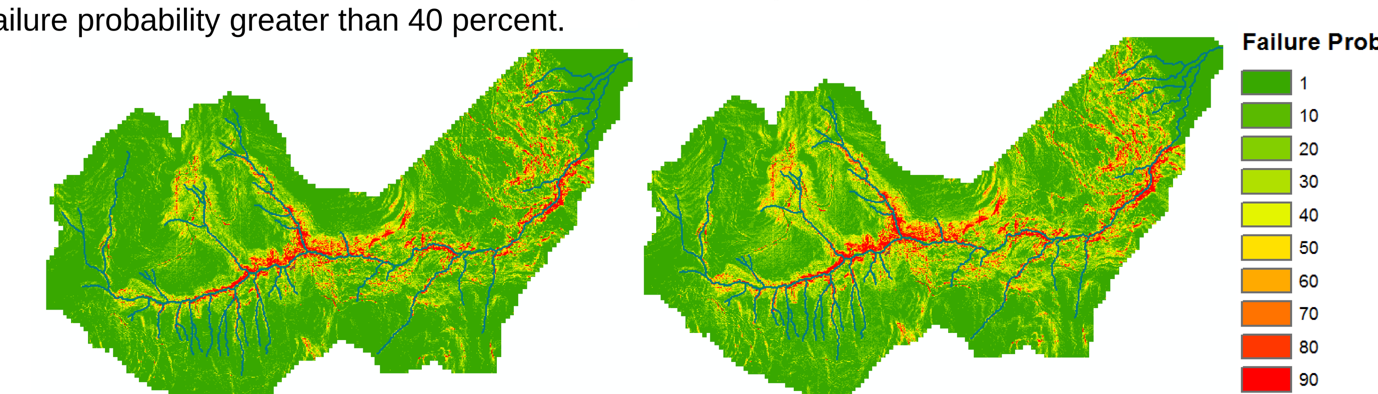


Figure 7: Failure susceptibility maps based on current land cover conditions (left; Figure 3) and a hypothetical harvest scenario in which all mature stand timber is replaced by shrubs (right).

DISCUSSION

The relationship between failure probability, basin saturation, and antecedent precipitation is erratic between 40 and 70 percent probability for both the South and Straight landslides. This could represent a transitional zone where small changes in soil saturation cause minor fluctuations around a factor of safety of one, and therefore significant variability in failure probability. Assuming the parameters that control failure have been adequately characterized, the forty percent failure probability thresholds can be thought of as a major break point above which failures are quite likely. An abrupt change in stochastic failure probability beyond a certain soil saturation level can be indicative of a real failure probability threshold, even if the actual exceedance probability differs from the modeled probability (Berti et al., 2012).

Modeled failure probability increases considerably under harvest conditions. Current logging prescriptions are defined for areas of mapped instability known as mass wasting units (MWUs) and are heavily dependent on slope, but were instituted before high resolution LiDar data became widely available (Crown Pacific, 1999). The results of this study suggest that the areas currently restricted to logging are probably not conservative enough, particularly along steep inner gorges in the middle reaches of the basin. Assuming that the 40 percent failure probability threshold represents a 'tipping point', logging buffers along the channel should be significantly widened.

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