Recent Advances in the Spatial and Temporal Modeling of Shallow Landslides

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Abstract: Factors that control the stability of mountain slopes may be in a tenuous state of equilibrium that can easily be upset by timber harvesting, vegetation conversion, and road construction. Shallow, rapid landslides are the dominant erosion and sediment delivery mechanisms in much of the steep terrain worldwide, especially where rainfall is high. Deep and dense tree root systems often contribute the additional component of soil shear strength necessary to insure long term stability of steep slopes. Road and foot paths may redistribute water onto marginally stable hillsides or hollows, promoting slope failure. Here we present a distributed shallow landslide model that captures the temporal dynamics of imposed management scenarios at the catchment scale. This physically-based model incorporates a planar infinite slope analysis module (based on factor of safety analysis), a kinematic wave groundwater module, and a module for continuous temporal changes in root cohesion and vegetation surcharge. The distributed landslide model is integrated with GIS and a topographic analysis, which partitions the basin into vector-based stream tube elements. Recent developments include evaluations of complex timber harvesting scenarios and assessing the effects of rainfall characteristics on landslide potential. Examples are presented showing the application of this landslide model to temporal scenarios of vegetation management in steep catchments. Benefits of using longer forest harvesting rotations are shown in a steep catchment on Vancouver Island, British Columbia. Potential applications of the model are discussed in managed tropical catchments where forest conversion may increase landslide potential. A major drawback of such distributed models is that they require rather intensive data inputs and are thus difficult to apply in remote areas.

Keywords: *Slope stability; Shallow groundwater modeling; Rooting strength; Forest management; Debris flow; Distributed modeling; Tropical forests*

1. INTRODUCTION

Shallow landslides triggered by rainfall constitute one of the major sources of sediment to stream channels in mountainous terrain. Additionally, such slope failures and debris flows resulting from these failures pose hazards for humans and investments, as well as cause extensive environmental damage. In forested or heavily vegetated areas, stormflow is typically routed through vegetated hillslopes as shallow subsurface flow (Weyman, 1973; Tsukamoto and Ohta, 1988). This subsurface water accumulates in various areas due to surface and subsurface topography and continuity of soil hydrologic pathways (Anderson and Kneale, 1982; Sidle et al., 2000). If combined with steep slopes and soils that overlie relatively impermeable substrate, pore water pressure develops and may trigger landslides. Such shallow, rapid landslides naturally occur in mountainous forest terrain, particularly in geomorphic hollows (also called zero-order basins) (Tsukamoto and Ohta, 1988; Sidle and Wu, 1999). Little can be done to prevent such slope failures and they are major contributors of natural sediment inputs to streams, albeit episodic. A common hydrologic sequence for shallow landslide initiation involves wet antecedent conditions followed by a prolonged period of rainfall with a burst of high intensity (e.g., Sidle and Swanston, 1982).

Forest management activities, particularly timber harvesting and roads, are known to exacerbate landslide potential. Numerous studies have noted a 2 to 10-fold increase in shallow landslide erosion about 3 to 15 years after timber harvesting (e.g., Endo and Tsuruta, 1969; O'Loughlin and Pearce, 1976; Megahan et. al., 1978; Wu and Sidle, 1995; Jakob, 2000). This increase is attributed to the deterioration of tree rooting strength following harvesting prior to the substantial regeneration of a vigorous forest stand (Sidle, 1991; Watson et al., 1999). Independent tests of the effects of timber removal on rooting strength based on mechanical straining of roots (Abe and Ziemer, 1991; Watson et al., 1997) have verified these observations. In warm climates, removal of vegetation may alter the water budget of the site and promote unstable conditions via reduced evapotranspiration. Forest roads also increase landslide potential by concentrating road drainage onto unstable hillslopes, removing support at the cutslope, overloading the fillslope, and oversteepening the cut- and fillslopes (Sidle et al., 1985). Studies have shown that landslide erosion from road right-of-ways is 25 to 350 times higher than in undisturbed forest (e.g., O'Loughlin and Pearce, 1976; Gray and Megahan, 1981). Landslide erosion rates from forest roads in steep terrain range typically range from 20 to 45 t $ha^{-1}yr^{-1}$.

Several approaches have been used to assess the effects of timber harvesting on shallow landslide potential. At the most general and qualitative levels are terrain evaluation procedures that utilize topographic, geomorphic, and geologic information to generate broad categories of landslide hazard related to potential harvesting activities (e.g., Howes and Kenk, 1988). In regions where good site data (including remotely sensed data) and landslide records are available, the effect of land use can be evaluated by weighted multi-factor overlays in GIS (e.g., Carrara et al., 1991). Both of these methods are only semi-objective either in the development or application phases and much emphasis is placed on the characteristics of existing landslides or expert knowledge. Recently, distributed, physically-based modeling has been applied to mountainous terrain to analyze the potential for shallow rapid landslides in time and space (Montgomery and Dietrich, 1994; Wu and Sidle, 1995; van Westen and Terlien, 1996). Of these distributed landslide models, only dSLAM (Wu and Sidle, 1995) and later modifications (Integrated Dynamic Slope Stability Model, IDSSM; Dhakal and Sidle, 2003a,b) are capable of incorporating temporal and spatial changes in rooting strength related to timber harvesting into simulations of landslides. This paper presents an overview of some of these recent developments and applications of this physically based landslide model, including problems in applying such a model in managed tropical catchments.

2. BACKGROUND AND DESCRIPTION OF THE LANDSLIDE MODEL

Wu and Sidle (1995) originally developed the distributed shallow landslide model (dSLAM) and applied it to various short-term timber harvesting scenarios. The basis for dSLAM is a conceptual, non-distributed shallow landslide model (Sidle, 1992) that incorporates: (1) infinite slope stability analysis; (2) continuous temporal changes in root cohesion and tree surcharge; and (3) stochastic influence of rainfall on pore water pressure. This earlier model quantified the effects of various timber harvesting strategies on temporal failure probability of a particular site. While applications of dSLAM in coastal Oregon accurately estimated landslide erosion during a major storm event (Wu and Sidle, 1995), the model could not effectively address complex or evolving scenarios of long-term forest management practices. Debris flows were routed using a simple algorithm of tributary junction angle and channel gradient.

The newly developed IDSSM combines GIS with topographic, distributed subsurface hydrologic, and vegetation models and operates on a PC-based system (Dhakal and Sidle, 2003a,b). IDSSM allows for sophisticated simulations of the long-term effects of forest management practices on landslide initiation at the catchment scale. Detailed rainfall data can be integrated into the model from long-term records to simulate dynamic and distributed groundwater response. We apply the model to forests with relatively deep organic horizons and permeable soils; thus, infiltration capacity is assumed to exceed rainfall intensity (i.e., Hortonian overland flow does not occur). In cases where the forest floor has been extensively disturbed or where little protective litter exists, modifications to the model would be needed to account for Hortonian overland flow. The latest version of the distributed landslide model includes three basic sub-models: (1) TopoTube; (2) distributed slope analysis sub-model II (dSLAMII); and (3) RoadNet. Also, several debris flow routing schemes are available. These models interface with ARCINFO or ArcGIS for data input and display.

3. QUANTIFYING DYNAMIC FACTORS IN THE LANDSLIDE MODEL

Dynamic parameters in the distributed landslide model include: (1) vegetation rooting strength; (2) tree surcharge; (3) soil infilling (following landsliding); (4) rainfall; and (5) pore water pressure. Other soil physical and geotechnical parameters, as well as site characteristics are assumed to be static (and user specified) for the period of simulation. The infinite slope model that assesses the factor of safety (FS) for landslide susceptibility at any given time during the simulation was modified as follows to include the effects of root strength, differences in unit weights of soil above and below a water table, and tree surcharge

$$FS = \frac{C + \Delta C + [((Z-h)\gamma_m + h\gamma_{sat} - h\gamma_w)\cos^2\beta + W\cos\beta]\tan\phi}{[(Z-h)\gamma_m + h\gamma_{sat}]\sin\beta\cos\beta + W\sin\beta} \quad (1)$$

where, C is the effective soil cohesion (kPa), ΔC is the cohesion attributed to root strength (kPa), Z is the vertical soil depth (m), β is the slope gradient (degrees), ϕ is the angle of internal friction (degrees), W is tree surcharge (kPa), h is the vertical height of the water table, γ_{sat} is the unit weight of saturated soil (kN m^{-3}), γ_m is the unit weight of unsaturated soil (above the water table) (kN m^{-3}), and γ_w is the unit weight of water (kN m^{-3}). For FS ≤ 1, a landslide should occur.

3.1. Vegetation Rooting Strength

Using root cohesion data based on mechanical straining and uprooting tests, and back-calculations after slope failure for a number of forest types, Sidle (1991) developed a negative exponential relationship of root strength change following timber harvesting

$$D = e^{-kt^n} \tag{2}$$

where, D is the dimensionless root cohesion parameter for decay (actual root cohesion divided by maximum possible root cohesion), t is the time since harvesting in years, and k and n are empirical constants. Root strength decay was related to species dependent and likely depends on soil temperature. Root strength regrowth after harvesting has been quantified by Sidle (1991) as

$$R = (a + be^{-kt})^{-1} + c \tag{3}$$

where, R is the dimensionless root cohesion parameter for regrowth, and a, b, c, and k are empirical constants which define the sigmoid regrowth curve. The sum of the root regrowth and decay curves represents the relative net root cohesion for the site. This relative net root cohesion (also dimensionless) multiplied by the maximum or "equilibrium" root cohesion for the specified vegetation type (ΔC_{max}), yields the actual root cohesion at any given time after timber harvest [$\Delta C(t)$]. Hypothetical examples of changes in net root cohesion are given for several vegetation management scenarios in Figure 1.

3.2. Vegetation Surcharge

At the time of timber harvesting, the tree surcharge (W) is reduced: to 0 for clearcutting; proportional reductions for partial cuts. Increases in vegetation surcharge after timber harvesting reflect rates tree regeneration, and can be described by the same general sigmoid function as root strength regrowth (Equation 3). However, Sidle (1992) showed that tree surcharge has only a minimal influence on FS.

Surcharge and rooting strength for many management cycles is simulated by overlaying effects of prior vegetation removal on a more recent removal. Such long-term simulations can identify potential cumulative effects of timber harvesting (Sidle, 1991; 1992).

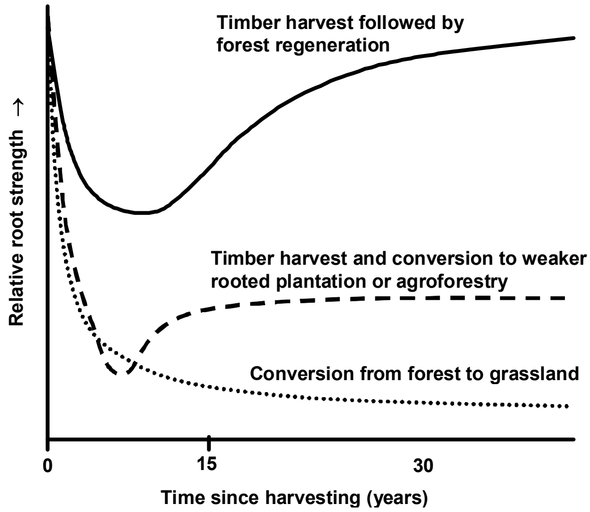

Figure 1. Changes in root strength for: (1) timber harvesting and subsequent forest regeneration; (2) forest removal and conversion to agronomic species, and (3) forest conversion to grassland.

3.3. Soil Infilling Following Landsliding

For long-term slope stability simulations, it is necessary to estimate the rate of infilling of previous landslide scars. Once a landslide occurs in a geomorphic hollow, a recovery process is set into motion (Shimokawa, 1984; Reneau et al., 1986). Infilling of hollows may span a period of several decades to several tens of millennia (Shimokawa, 1984; Reneau et al., 1986; DeRose, 1996). The infilling process is a complex set of hydrologic, geomorphic, and biological feedbacks that consist of surface wash, frost heave, dry ravel, slumping around the headwall, small landslides, inputs of woody debris, bioturbations (from animals), and soil creep. Infilling is generally rapid at first, dominated by inputs of sediment and wood, and progressively slower as sloughing and erosion give way to chronic processes such as soil creep. Infilling is described by a sigmoid function for modeling infilling of landslide scars (Sidle, 1987)

$$Z(t) = Z_0 + a_1 e^{(b_1/t)} \tag{4}$$

where, Z(t) is the vertical soil depth at time t after failure (m), Z_0 is the soil depth remaining after failure (m), $a_1 = Z_\infty - Z_0$, Z_∞ is the upper limit of soil accretion (m), t is the time since failure (yr), and $b_1 = -2t_i$, where (t_i, Z_i) is the inflection point of the soil recovery curve.

3.4. Rainfall

Rainfall inputs to the landslide model can either be actual rainstorm records or rainfall events generated from historical data or from theoretical distributions using Monte Carlo techniques. Such flexibility facilitates long-term simulations of landsliding, as well as allows for the analysis of specific hyetograph characteristics that trigger landslides. The temporal distribution of rainfall intensity can be used to select the time step in the model; in most cases, a 1-h time step was used. The timing and numbers of landslides simulated for two different storms in Carnation Creek, Vancouver Island, British Columbia, are shown in Figure 2.

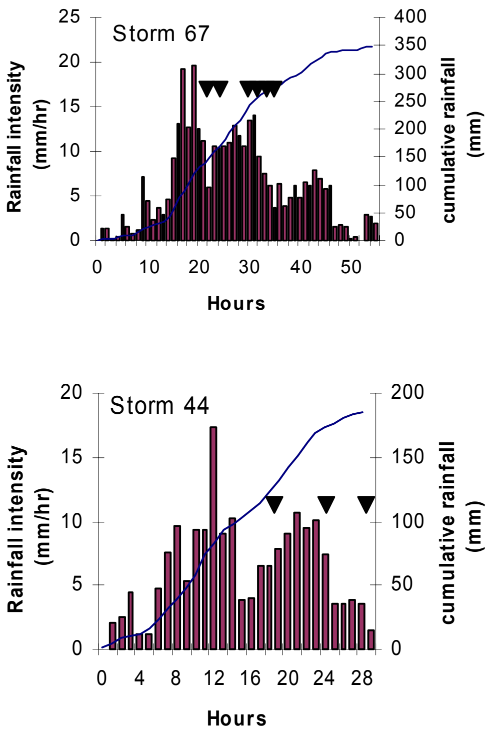

Figure 2. Two simulated storms in Carnation Creek catchment, British Columbia; solid line shows cumulative rainfall; triangles are landslide occurrences (after Dhakal and Sidle, 2003b).

3.5. Pore Water Pressure

Real-time or synthetic rainfall inputs drive the spatially distributed pore water pressure response. Pore pressures are assessed using a combined subsurface-surface kinematic wave modeling approach (Takasao and Shiba, 1988). Infiltrated water is routed downslope in saturated soils overlying a relatively impermeable substrate using the TopoTube model, based on Moore et al's. (1988) TAPES-C model. This model uses a stream tube method that subdivides the catchment into irregular polygons via adjacent contour lines and adjacent streamlines. The approach provides a more realistic depiction of the underlying hydrogeomorphic processes compared to regular grid systems. Infiltration capacity of the soil is always assumed to exceed the rainfall intensity, thus, only saturated overland flow is considered. The one-dimensional form of the continuity equation applied to each element is

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = \frac{iA_e}{\Delta x_e} \qquad (5)$$

where, A (m^2) is apparent cross-sectional flow area, i is rain intensity (ms^{-1}), Q is discharge per unit width (m^3 s^{-1} m^{-1}), A_e is plan area of the element (m^2), and ΔX_e is flow distance along a stream line through the element (m).

4. FOREST MANAGEMENT EFFECTS ON SLOPE STABILITY – EXAMPLES

The current version of the distributed landslide model permits simulation of various scenarios of clearcutting and partial cutting, including variable rotation lengths, different levels of partial cutting, variable root regrowth and decay characteristics, and cumulative effects of multiple timber harvests. Earlier applications of the model assessed spatially distributed landslide erosion during a major rainstorm (178 mm) in November 1975 in a 1.18 km^2 forested catchment in the Oregon Coast Ranges. Simulated volume (733 m^3) and numbers (4) of landslides in the basin agreed closely with values measured in the field (734 m^3 and 3, respectively) after the storm (Wu and Sidle, 1995). Although the exact locations of the actual landslides are not available, simulated landslides occurred in the general locations of these disturbances. All simulated and actual landslides occurred in sites that were clearcut in 1968; most failures occurred in hollows (Sidle and Wu, 1999). The timing coincides with the period of minimum rooting strength after logging at the site. Additionally, all elements in the basin with FS values less than 2.0 at the end of the simulated storm were also clearcut in 1968.

Recent investigations of the effects of changing rotation length on temporal landslide occurrence in Carnation Creek, British Columbia, showed that by successively increasing rotation length over four harvesting cycles the total volume of landslides and long-term effects were reduced compared to simulations with four rotations of successively decreasing rotation length (Figure 3).

5. POTENTIAL MODEL APPLICATION IN TROPICAL FORESTS

Distributed, physically based landslide modeling has not been applied in tropical catchments. Given our findings related to rotation length (Figure 3) and likely changes in rooting strength

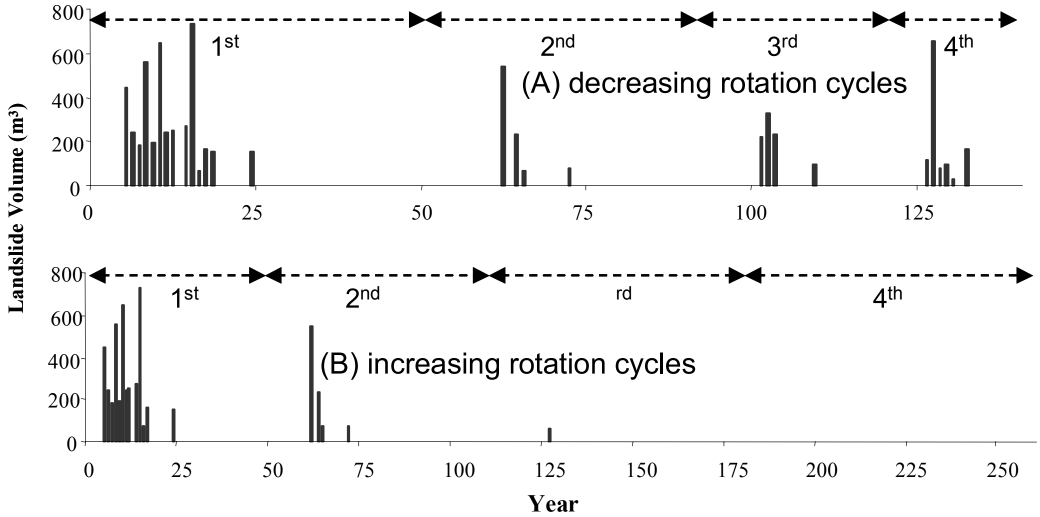

Figure 3. Simulated temporal distribution of landslide erosion in a 0.57 km^2 sub-catchment of Carnation Creek, Canada: (A) four clearcut cycles of decreasing rotation length, 50, 40, 30, and 20-yr; (B) four clearcut cycles of increasing rotation length, 50, 60, 70, and 80-yr (modified from Dhakal and Sidle, 2003a). Time zero represents the initial clearcut harvest for both scenarios.

that will occur as the result of extensive land cover change in the tropics (Figure 1), such applications are sorely needed. Tropical forests are usually managed with shorter rotations than temperate forests. Spatial mosaics related to small scale agroforestry operations present further challenges. Because of the higher year-round evapotranspiration in the tropics, this may need to be included in the landslide model. Such effects may exacerbate the impacts of timber harvesting on landslides as the result of higher antecedent soil water.

A major constraint in applying the landslide model in the tropics is the lack spatially distributed soils data in steep unstable sites. While earlier applications of the model using average soil parameters accurately simulated landslide locations (Wu and Sidle, 1995), such distributed parameters are desirable, especially where soil depths and properties vary greatly. Estimates of certain parameters can be made based on remote sensing and as these techniques improve they will be more useful for such applications; however, there are no substitutes for spatially distributed field data. The lack of adequate rain gauging networks in the tropics is also a major concern. While recent developments in real-time rainfall forecasting may benefit from the use of Doppler radar systems, coverage in the tropics remains very limited. Also, there remain many obstacles related to use of remotely sensed information under forested conditions (including Doppler radar). Other limitations include a general lack of knowledge of root strength characteristics of tropical trees, spatial variability in rooting strength, and soil infilling rates of failure sites. The use of detailed digital elevation models in the tropics areas will greatly facilitate landslide modeling efforts. Fortunately, these are becoming more accessible and offer promise for wider application of such distributed models.

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