Accounting for the stochastic occurrence of landslides when predicting sediment yields

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ABSTRACT Landslides may lead to sedimentation of streams and rivers in tropical environments over time periods of decades. Hence, it is important to account for the stochastic occurrence of landslides when predicting sediment yields, particularly in areas undergoing deforestation. A hillslope-stability simulation model is developed based on applying an infinite slope stability analysis and the groundwater model of Iida (1984) to a population of synthetic landslide sites. The decline of apparent root cohesion over time due to vegetation removal is included, and the random occurrence of landslides is generated by a rainfall model. The model is used to predict landslides and sediment yields in mature and second-growth forests, and in clearcuts in a basin in Washington State, U.S.A. The model is best suited for large basins with hundreds to thousands of well-defined landslide sites.

INTRODUCTION

A sediment budget quantitatively defines the processes and rates of sediment production and transport in a drainage basin. One purpose of a sediment budget is to predict sediment yields. Sediment budgets in tropical environments are useful for predicting the loss of reservoir capacity over time due to sedimentation, estimating the effects of forest clearing on sedimentation of streams and rivers, and evaluating the significance of a particular erosion process compared to others.

The accuracy, and therefore the usefulness of sediment budgets, depends on the ability to quantify the various processes and rates of sediment production and transport within drainage basins. Identification and measurement of relatively continuous processes, such as soil creep and fluvial sediment transport, may be accomplished by standard field techniques over several years. Though there is no substitute for field measurements of erosion and transport processes, it might be feasible to estimate rates of erosion and sediment transport based on studies in similar physiographic areas.

In some mountainous tropical environments, landslides may be an important source of erosion (Temple & Rapp, 1972; So, 1967). In addition, the increased rate of landslides often associated with resource extraction, such as deforestation, indicates that the landslide component must be accurately accounted for when predicting sediment yields.
In this paper we present a hillslope-stability simulation model which predicts the stochastic occurrence of landslides over time. The procedure employs deterministic components including a physically based groundwater model and generates the random occurrence of landslides by a rainfall model. The simulation model is applied to Smith Creek, a 1400 hectare basin in Washington State, U.S.A. to predict landslides and sediment yields during two - 37 year periods.

METHODS: MODEL DEVELOPMENT

The hillslope-stability simulation model determines the slope stability for a synthetic population of landslide sites over a specified time period. The model is composed of an infinite slope stability analysis that includes variation of root cohesion over time, the groundwater model of Iida (1984), and a rainfall model. The model is computer based and written in Fortran 77 programming language. The model contains several components which are outlined in the flowchart in Figure 1. Each of the components is discussed below.

The Infinite Slope Stability Analysis

The stability of landslide sites is calculated based on an infinite slope stability analysis. This analysis is applicable on slopes where the soil thickness is small compared to the slope length and where the failure plane is parallel to the slope surface, both of these are characteristics of the study area. According to Ward et al. (1979, 1981), the factor of safety (FS) can be written as:

\[
\frac{[2(C+\Delta C)/\delta wZ\sin2\theta] + [(L-M)(\tan\phi)/\tan\theta)]}{L} = FS
\]

where \( L \) is the term characterizing the weights of vegetation and sediment,

\[
L = q_o/\delta wZ + \delta s/\delta w(M) + \delta m/\delta w(1-M)
\]

C is the effective soil cohesion, \( \phi \) is the effective angle of internal friction, \( \Delta C \) is the apparent cohesion due to roots, \( \delta m \) is the unit soil weight at field capacity, \( \delta sat \) is the unit weight of saturated soil, \( \delta w \) is unit weight of water, \( \theta \) is the slope angle, \( Q \) is the surcharge stress caused by vegetation cover, \( M \) is the ratio of the saturated soil thickness to the total soil thickness above the failure plane, and \( Z \) is the vertical soil thickness.
Creating Synthetic Landslide Sites

Shallow-rapid landslides are often localized in specific areas on hillslopes. These areas are typically characterized by converging bedrock topography which results in deeper soils and thicker saturation layers during storms (Hack & Goodlett, 1960; Dietrich et al., 1987). Hence, hollows (Hack & Goodlett, 1960; Dietrich & Dunne, 1978), or zero-order basins (Tsukamoto et al., 1978) are preferential sites for landslides. In these terrains it is feasible to estimate the total number of landslide sites in a drainage basin by field measurements, and analysis of aerial photos and topographic maps.

It is generally not feasible to measure all the important variables (Equations 1 and 2) for more than a few landslide sites. Therefore, to account for variability within a large number of known sites a synthetic population of landslide sites can be created. The use of synthetic landslide sites would be helpful in the development of detailed sediment budgets. For example, the rate of infilling of landslide scars is site specific and will influence the probability of failure over time at that site. In addition, accurate accounting of the routing of sediment from landslides may require knowledge of the location of the site within the basin. In this context, the development of synthetic landslide sites has an advantage over other monte carlo simulation techniques which predicts landslides based solely on non-site specific probabilities.

If the sample mean ($\bar{x}$), sample standard deviation ($s$), and the form of the probability density function for each physical
characteristic of landslide sites can be estimated, then random sampling of a single value from each parameter distribution is combined to create a synthetic site. This is done until the required number of sites are created. This method is most appropriate for large basins having several hundreds to thousands of landslide sites because it is necessary that the characteristics of the synthetic population are similar to those of the real population. For a large number of sites (> 1000) this procedure is similar to that of monte-carlo simulation, where the accuracy of the simulation is dependent on numerous repetitive sampling from the parameter distributions. Only those sites which are stable in a non-saturated condition (FS > 1) comprise the synthetic population.

Variations of Root Cohesion over time

The cohesion provided by roots in soil has been well documented (Swanston, 1970; Burroughs & Thomas, 1977; O'Loughlin et al., 1982). The loss of apparent soil cohesion due to root deterioration following forest cutting has been evaluated by Ziemer & Swanston (1977) and Burroughs & Thomas (1977) among others. Ziemer (1981) has determined in Northern California that root strength declines rapidly following the first 8 to 10 years following timber harvest and then slowly increases as new understory and trees become established. During the first 8 years following timber harvest root strength declined to approximately 0.38 of pre-harvest levels and then began to increase slowly with full root strength realized in approximately 50 years (Ziemer, 1981). A temporary increase in root strength provided by understory vegetation occurred between 10 and 20 years.

To account for change in root strength over time after timber harvest we fit a mathematical function to Ziemer's data (1981).

Groundwater Model

The groundwater model of Iida (1984) is used to determine the saturation thickness in response to a particular rainfall intensity and duration. The model does not account for antecedent precipitation which has been shown to be important in initiation of landslides (Sidle et al., 1985). According to Iida (1984), water flowing parallel to bedrock has a horizontal component of interstitial velocity (Vs) equal to:

$$V_s = q/\zeta \cos \theta = k/\zeta \sin \theta \cos \theta$$

where q is the specific flux, $\zeta$ is the effective porosity and k is the saturated hydraulic conductivity. To estimate depth of flow, Iida derived the following:

$$H(t) = R_0/\zeta (t + \epsilon/2 \ V_s t^2)$$

where H is the depth of the saturated throughflow, Ro is the rainfall intensity, $\epsilon$ is the angle which defines the curvature of the hollow and which is positive for hollow-type slopes and negative for ridge-type slopes, and t is the time since beginning of rainfall.
\[ M = H/Z \] is calculated for use in equation 1 with \( t \) equal to the full duration of the storm.

An effective porosity \( (\zeta) \) for soils in Smith Creek basin of 0.41 has been estimated by Buchanan (1988). We estimated \( (\zeta) \) to be approximately 20 degrees on the average for Smith Creek basin. A saturated hydraulic conductivity of \( 5 \times 10^{-5} \) m/s for silty-sandy soils was used.

**Rainfall Model**

Time series of storms may be modelled as a stationary stochastic generating process in which both the duration and intensity of individual storms is considered to be distributed according to an exponential density function (Eagleson, 1972). The exponential distributions for rainstorm intensity \( (i) \) and duration \( (T) \) can be described by:

\[
f(i) = \frac{\exp(-i/m_i)}{m_i} \quad (5)
\]

and

\[
f(T) = \frac{\exp(-T/m_T)}{m_T} \quad (6)
\]

where \( f(\cdot) \) denotes the density function, and \( m_i \) is the mean storm intensity and \( m_T \) is the mean storm duration. This model has been tested by Eagleson (1972) and Beven (1987) and was found to adequately describe both intensities and durations of measured storms.

With a given \( m_i \) and \( m_T \), values of intensity and duration are randomly selected from the distributions (equations 5 and 6) for input into equation 4 \((Ro, t)\) to calculate the depth of saturated through-flow \( H(t) \).

The rainfall model requires accurate estimates for mean intensity and duration of rainstorms for a particular area. These data are often difficult to obtain unless hourly rainfall data are available. In addition, the duration and intensity which define a rainstorm must be selected. Though it is optimum to independently determine mean intensities and durations, it is possible to estimate the values by calibrating the model (see results).

Based on rainstorm mean intensity and duration the total number of storms per year is determined by:

\[
\text{# of storms} = \frac{P}{i^\Delta T} \quad (7)
\]

where \( P \) is the average total annual precipitation.

The total number of storms per year is estimated using equation 7, and this value multiplied by the specified number of years provides the length of a storm sequence. Each storm sequence is applied to all synthetic landslide sites, assuming that the spatial distribution of storms are the same over time. During the model simulation, a number of sequences of storms is generated. The larger number of storm sequences used the closer the average value of the predicted landslides come to the true probabilistic average value.
RESULTS: APPLICATION OF MODEL TO SMITH CREEK BASIN

Smith Creek is a fourth-order, 1400 hectare basin located in the foothills of the Cascade Mountains in Northwest Washington State, U.S.A. The basin is contained within the Chuckanut Formation, a unit which includes sandstone, conglomerate, and mudstone. Slopes range from 25 degrees to 40 degrees and are sculpted into numerous bedrock hollows. Soils are dominantly fine textured with large amounts of sands. Precipitation of approximately 150 cm per year supports stands of *Pseudotsuga menziesii*, *Tsuga heterophylla* and *Thuja plicata*.

Large landslides have been concentrated in bedrock hollows in Smith Creek basin (Syverson, 1984) though smaller landslides have been observed to occur outside of hollows. During the period 1947 to 1983 twelve landslides from hollows in 874 hectares of mature forests, 7 landslides in 103 hectares of clearcuts less than 20 years old, and 5 landslides in 194 hectares of second-growth forest less than 36 years old were inventoried by Syverson (1984) and Benda (in press). After approximately 15 to 20 years regenerating forests are referred to as second growth forests.

To determine amounts of available landslide sites in Smith Creek basin, the density of bedrock hollows was measured using 1:12000 aerial photos and topographic maps. Only areas in the basin with slope gradients greater than 30° were measured because landslides were not observed on slopes less than that. The distance between hollows measured on the contour averaged 110 m and ranged between 20 m to 210 m. Accounting for slope length which averaged approximately 610 m yielded an average density of one landslide site per 6.5 hectares. Accordingly there are 181 landslide sites in an area of 1171 hectares. Though this is a relatively small number of sites to be created by this technique, the availability of data on Smith Creek basin allowed us to run a model simulation for illustration purposes.

Buchanan (1988) analyzed the slope stability conditions for nine landslides which occurred in and adjacent to Smith Creek basin. Using this sample size, Buchanan (1988) estimated sample means and sample standard deviations for several site characteristics including unit weight of soil (\( \rho_m \))

\[
\bar{X} = 1330 \text{ kg/m}^3, \ S_X = 153 \text{ kg/m}^3
\]

friction angle (\( \phi \))

\[
\bar{X} = 33^\circ, \ S_X = 3.46^\circ
\]

and slope gradient (\( \theta \))

\[
\bar{X} = 34^\circ, \ S_X = 4.8^\circ
\]

the populations were assumed to be normally distributed. A uniform distribution of soil depths ranging from 0.5 m to 5 m which represented the minimum and maximum soil depths observed in the field was used in the development of the synthetic landslide sites because the mean, standard deviation and the form of the distribution of soil depths was not known. The vegetation surcharge determined by Buchanan (1988) was .23 Kpa. In addition, for the purposes of the following model application we have applied the simplifying assumption that the site characteristics are independent of one another.
Though the soils in Smith Creek basin are effectively non cohesive (Buchanan, 1988), our in-situ measurements using a Shear Graph indicated a nominal cohesion of approximately 1 kPa which we used in the analysis. A non-varying root cohesion of 8 kPa associated with old-growth forests in the study area (Buchanan, 1988) was employed in the development of the synthetic population.

One hundred and eighty-one synthetic landslide sites were created; a frequency distribution of the factor of safety for the sites is shown in Figure 2. Note that approximately 50% of the sites have a factor of safety less than or equal to 2 which is similar to the relatively low values associated with steep, forested slopes (Sidle et al., 1985). The frequency distribution of soil depths (above bedrock) for the 181 synthetic sites are shown in Figure 3. Though there is significant variation, soil depths were approximately evenly distributed over the range of 0.5 m to 5 m.

Data on mean storm intensity and duration for Smith Creek basin was not available. We selected an initial value based on our judgement. The hillslope-simulation model was used to predict the 12 landslides in mature forests in Smith Creek basin during 37 years for the purpose of calibrating the model. A mean storm intensity of 0.3 cm/hr and a mean duration of 7 hours predicted 11.3 of the 12 landslides. These mean rainstorm values were then used to predict landslides from clearcuts and second-growth forests.

There is on average 70 storms per year in Smith Creek basin according to equation 7 using an average annual precipitation of 146 cm per year, and an average storm intensity of 0.3 cm/hr and a mean duration of 7 hours. The time period of the simulation in Smith Creek basin was 37 years. This yielded a sequence with a length of 2,600 storms. The model was run for 10 sequences totalling 26,000 storms. Each year every individual landslide site was exposed to the same storm sequence.
The hillslope stability simulation model was used to predict landslides from 297 hectares of clearcuts and second-growth forests over a period of 37 years in Smith Creek basin. Forty-six landslide sites are contained in the 297 hectares of clearcuts (25% of the basin area). Though the 297 hectares of clearcut were created throughout the 37 year period from 1946 to 1983 in Smith Creek basin, for the purposes of the simulation model the entire 297 hectares of clearcuts were assumed to have occurred in 1946, and over time they evolved to second-growth forests. The same storm sequences were used as in the calibration of the model. This allowed for the matching up of landslides over time from mature forests, and clearcuts and second-growth forests in response to major storms.

The simulation model predicted an average of 15 landslides in 297 hectares of clearcut and second-growth forest (46 total landslide sites); the range was from 10 to 30. This compares to 12 landslides inventoried in Smith Creek basin during the period from 1947 to 1983 (37 years) (Benda, in press). Therefore, the simulation model overpredicted the number of landslides in harvested areas by 25%. The annual rate of landslides (\( \text{# landslides/total landslide sites/time} \)) predicted by the model of 0.0088/yr is similar to the rate of 0.0071/yr which was determined from field data in Smith Creek basin.

The minimum storm intensities and durations which were necessary to trigger failures in the model among the synthetic landslide sites in Smith Creek basin was 1.3 cm/hr and 20 hours. The minimum storm durations and intensities measured near Smith Creek basin which resulted in landslides during two different years ranged between 18 hours and 0.5 - 1 cm/hr to 14 hours and 1 cm/hr.

![Figure 3. Frequency distribution of the soil thicknesses of the synthetic landslide sites.](image-url)
The hillslope-stability simulation model generates the random occurrence of landslides over time based on a time series of storms. The occurrence and number of landslides which were predicted by the model in clearcuts, second-growth, and mature forests during the period 1947 to 1983 in Smith Creek basin are shown in Figure 4. For comparison, the simulation model was also applied to the entire basin using a non-varying root cohesion of mature or old-growth forests of 8 kPa; years 1893 to 1900 (37 years) in Figure 4. Though the model predicts landslides in old-growth forests note the increase in landslide activity approximately 8 years following timber harvest of 25% of the basin when root cohesion in the model is at its lowest (Figure 4). The higher rate of landslides from clearcuts in Smith Creek basin during 1947 – 1983 was confirmed by analysis of aerial photos and field surveys (Syverson, 1984). The model predicts a 3-fold increase in the number of landslides in clearcuts. This is similar to 7 field studies in the Pacific Northwest which reported increases of landslides in clearcuts relative to forests of between 1 and 8 times and an average of 3 (Sidle, et al., 1985).

The relative proportion and the timing of sediment yields attributed to landslides in Smith Creek basin was simulated by the model. The sediment volumes associated with landslides were estimated in the simulation model using nine field-measured values obtained in and near Smith Creek basin by Buchanan (1988). The landslide volumes were assumed to be uniformly distributed with a sample mean of 3160 m$^3$ and a sample standard deviation of 2215 m$^3$ (Buchanan, 1988). Sediment volumes were randomly selected from the uniform distribution and assigned to landslides as they occurred over time.

Figure 4. The number of landslides predicted over time by the model in Smith Creek basin.
The sediment yield to Smith Creek attributed to landslides in tons/year for two time periods (1863 - 1900, and 1947 - 1983) is compared to the other sediment producing processes in Figure 5. The other processes can be collectively accounted for by soil creep, which over long time periods, can encompass small stream-side landslides, treethrow, animal burrowing and streambank erosion (Dietrich & Dunne, 1978). This soil creep component accounted for approximately 210 tons/year (Benda, in press) compared to the sediment yield of landslides which ranged between zero and 68,000 tons/year (Figure 5). Therefore, the simulation model suggests that sediment yield to Smith Creek can vary annually by as much as a factor of 100 in undisturbed old-growth forests and by a factor of 250 when 25% of the basin has been harvested. This is due to the occurrence of simultaneous landslides during a given storm and the absence of landslides during many of the years (Figure 5).

DISCUSSION

The hillslope-stability simulation model applied to a population of synthetic landslide sites has an advantage over other monte carlo simulation techniques when it is necessary to account for specific site characteristics over time and space. One example may be a sediment budget where the rate of infilling of landslide scars following failure is site dependent and which influences the probability of failure through time.
The accuracy of this method is strongly dependent on the number of landslide sites which are created and the number of storm simulation sequences which are applied to the sites. Larger numbers assures that the predicted average number of landslides will approach the true probabilistic mean value. The number of landslides measured in the field may not represent the mean value, and therefore the predicted value may not compare to that obtained in the field.

Even though 181 sites is a relatively small sample, the model predicted the number of landslides in clearcuts and in second-growth forests with a fair degree of accuracy. The model produces a simulation of the occurrence of landslides over time (Figure 4) which may have little similarity to the real temporal sequence of landslides. For example, the simulation model predicts the occurrence of the 12 landslides in mature forests throughout the period 1947 - 1983 (Figure 4), yet 11 of 12 landslides actually occurred in 1983 during the most intense rainfall on record, when there was also snow on the ground. The temporal sequence of landslides in clearcuts and second-growth forests predicted by the model was similar to the actual occurrence of landslides which were more spread out over the 37 years. The occurrence of landslides over time in the model presented in Figure 4 is only one simulation of an infinite number of possible simulations. Yet, perhaps more importantly, the simulation indicates the stochastic nature of sediment supply which should be accounted for when constructing sediment budgets in mountainous tropical or temperate terrains.

It would be optimum to independently measure or estimate the mean intensity and duration of storms for use in the rainfall model. The calibration procedure, however, indicates the potential utility and flexibility of the model in the absence of such data.

The model could be improved in several areas. First, the groundwater and rainfall components could account for antecedent soil moisture conditions. Therefore, interstorm periods would be important in the determination of depth of the saturation layer and thereby the probability of failure. Second, hillslope and soil properties may be dependent upon one another, as pointed out by Hammond, et al., (1988). Determining the degree of covariance between parameters should improve the performance of the model.

The hillslope-stability simulation model could be used in the development of sediment budgets in tropical environments where landslides contribute significantly to sediment yields. The model may be particularly useful for predicting river and reservoir sedimentation over time scales of decades to centuries.

ACKNOWLEDGEMENTS

This study was supported by the U.S. Forest Service, Pacific Northwest Research Station, the Watershed Research Work Unit, Seattle, Washington. The paper was improved by reviews from Terrance Cundy and Barry Gall of the University of Washington.
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