Modelling Shallow Landslides Triggered by Rainfall in Tropical and Mountainous Basins

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Modelling Shallow Landslides Triggered by Rainfall in Tropical and Mountainous Basins

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Abstract

Shallow landslides triggered by rainfall in tropical environments are controlled by the weathering tropical profile and its water storage capacity. Although landslides triggered by rainfall are common in tropical and mountainous basins, few studies have been applied to the case of tropical regions, which are characterized by intense rainfall and deep weathering profiles. Thus, it is necessary to implement over these areas physical models and methodologies to determine the spatial location of landslides and their susceptibility level. In this work, a conceptual and physically based model called SHIA_Landslide (Simulación HIdrológica Abierta, or SHIA, in Spanish) that is supported by geotechnical and hydrological features occurring on a basin-wide scale in tropical and mountainous terrains is described. This model incorporates a comprehensive distributed hydrological tank model that includes water storage in the soil coupled with a classical infinite-slope stability analysis under saturated conditions. Additionally, this work presents the analyses and results of the implementation of the SHIA_Landslide model to estimate the landslides caused by a rainfall occurred on September 21st, 1990, in a basin of tropical and mountainous terrains of Colombian Andes. In less than 3 h, a precipitation of 208 mm fell within the study area, triggering more than 800 landslides. The results obtained by the model are compared with a landslide inventory presented during the event. Finally, the efficiency of SHIA_Landslide is evaluated in terms of landslide density and susceptibility classes (degree of fit and success-rate curve), and the prediction capacity by ROC (Receiver Operating Characteristics) analysis. It is possible to show a good performance of the model suggesting that SHIA_Landslide is able to simulate the physics involved on landslides triggered by rainfall in tropical and mountainous terrains.

Keywords

Physical model • Shallow landslides • Mountainous basin • Tropical basin • Large rainfall intensity

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Introduction

In tropical and complex terrains, landslides are one of the main causes of human and economic losses worldwide (Schuster 1996; Sidle and Ochiai 2006). Rainfall induced shallow landslides are a common problem in many tropical areas covered by thick residual soils and subjected to tropical rainfall regimes. In tropical environments and complex terrains like the Colombian Andes, a high percentage of these landslides are triggered by heavy or prolonged rainfall (Aristizábal and Gómez 2007).

Expanded land urbanization is increasing the vulnerability to landslides due to high concentration of population and lifelines along areas of higher landslide susceptibility. Therefore, landslide hazard assessment and early warning systems are becoming increasingly important (Caine 1980; Montgomery and Dietrich 1994; Finlay et al. 1997; Crosta 1998; Terlien 1998; Crozier 1999; Polemio and Petrucci 2000; Iverson 2000; NOAA-USGS 2005; Restrepo et al. 2008; Larsen 2008). A comparative analysis of the frequencies and impacts of various natural disasters has shown that overall damages arising from natural disasters occur more often than the capacity for society to prevail via their economic resilience (Guzzetti et al. 2005).

Although EWS (Early Warning Systems) are currently considered one of the most practical and effective measures for disaster prevention, just few EWS for shallow landslides have been implemented around the world based on empirical thresholds, and there is not any EWS supported by physical models. Much more work need to be carried out on this subject to reduce human and economic losses.

Most of the models proposed for shallow landslide prediction show very complex relationship with a great number of input parameters, or very simple functions letting out fundamental variables which play an important role on this subject. Furthermore, all these models available are applied just for very special environmental conditions that do not allow adjusting them to particular rainfall and terrain complexities such as the Colombian tropical Andes.

A conceptual and physically based model for shallow landslides triggered by rainfall in tropical environments and complex terrains than can be used as a basis for landslide early warning system was established in this study. It is named SHIA_Landslide (Aristizabal et al. 2015). This model was tested using a real case in the Colombian Andes validating the high capacity of prediction. The obtained results contribute to improve the understanding of the mechanism associated with slope instability and rainfall infiltration in mountainous areas located in rainy environments, where population pressure is leading to the expansion of development into landslide-prone areas.

Finally, the efficiency of SHIA_Landslide is evaluated in terms of landslide density and susceptibility classes (degree of fit and success-rate curve), and the prediction capacity by ROC analysis. The results show a good performance of the model when used to assess the susceptibility to shallow landslides triggered by large rainfall intensities on tropical mountainous basins.

SHIA_Landslide

SHIA_Landslide is a FORTRAN program for computing positive pore pressure changes as well as resulting changes in the safety factor due to rainfall infiltration, using a physical and conceptual based, distributed hydrological and geotechnical coupled model to provide an assessment of slope-failure condition.

Hydrological Component

The hydrological module to be implemented for the development of the model is based on the Open and Distributed Hydrological Simulation (in Spanish Simulación HIdrológica Abierta–SHIA) developed by Vélez (2001). It is formed by two fundamental components: a water balance that simulates the dominant hydrological processes in the catchment, and a routing component that simulates the flow of water through the river network.

Each grid cell corresponds to a system of five interconnected tanks that communicates with the respective tanks in the downstream cell, which represents water flow and storage as a hydrological response unit, including the following hydrological processes: interception, detention, infiltration, evapotranspiration, overland runoff, percolation, subsurface flow, and return base flow in the channels of the drainage system.

The first four tanks represent the runoff production processes of the basin, while the last tank represents the transfer process runoff thereof.

The first tank (T_1) is called static storage and represents interception and water detention in puddles and the capillary water storage in the soil-rooting zone, which is a function of field capacity and effective root depth. The only outflow from this storage is real evapotranspiration (E_1). The second tank (T_2) is called surface storage and represents water on the hill's sloped surface that is flowing over the slope and has not infiltrated. The third tank (T_3) represents the gravitational water storage in the residual soil between field capacity and saturation. This tank models the water column due to subsurface flow parallel to the slope surface through the soil layer and into the drainage system. The fourth tank (T_4) corresponds to the aquifer, where vertical flow represents the system's groundwater outflow and horizontal flow represents the base flow. The final tank (T_5) represents the stream flow channel at the cell level, where each cell is connected to the downstream cell according to the drainage network. A more detailed description of the Shia_Landslide model can be found in Aristizabal et al. (2015).

Geotechnical Component

The geotechnical module proposed here is based on the idea that the weathering soil profile increases soil density with depth with a corresponding decrease in hydraulic conductivity and, when the rainfall rate exceeds the percolation rate between the residual soil and saprolite, a perched water table, which correspond to the subsurface flow, starts to be formed.

The implicit assumption is that soil is in saturated conditions and that the subsurface flow in this saturated zone is roughly parallel to the slope; according to this fact, the stability conditions associated to the positive pore water pressure is constrained by the height of the perched water table.

To evaluate the factor of safety (FoS), the infinite-slope analysis is used. It is based on a simplified landslide geometry that assumes a planar slip surface on an infinitely extended planar slope, both laterally and distally. The factor of safety in the slope can be defined in terms of effective stresses, that is:

$$FoS = \frac{c' + (\gamma z \cos^2 \beta - u) \tan \phi}{\gamma z \sin \beta \cos \beta} \tag{1}$$

In which c' is the cohesion, γ is the unit weight of the soil, β is the slope angle, u is the pore water pressure, and ϕ is the friction angle.

Study Area

La Arenosa catchment was selected for the implementation and evaluation of the performance of the model. La Arenosa is located 160 km to the east of the Aburrá Valley, on the southeaster side of the Central Cordillera in the Antioquia region, Colombia. The catchment is formed by the confluence of the La Arenosa and Betulia streams, with an extension of 9.91 km^2.

Elevation ranges between 1000 m and 1900 m.a.s.l. The basin is highly dissected with hillslope lengths at the order of 40–60 m. Figure 1 shows the general topography and the distribution of slope gradients in the Territory. Most of the land area has slope angles ranging from 20 to 40°.

Granitic sandy residual soil covers the hillslopes, except for narrow ridges or steep slip scars with bedrock exposures. The majority of the study area is covered with crops and pasture. The geology of the study area consists of residual soils from granodiorite rocks covered in the gently sloping areas with slopes and fluviotorrential deposits, with a depth ranging from 3 to 20 m. Its dominant, granitic component is grey and medium to coarse-grained, and consists of cream or pale yellow feldspar, smoky quartz and smaller proportions of reddish-brown biotite and dark hornblend.

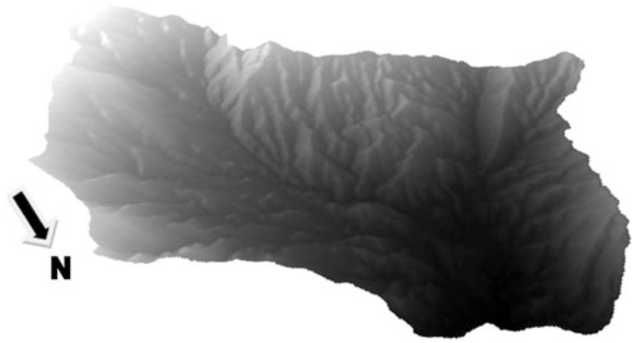

Fig. 1 General topography of the La Arenosa catchment. The basin is highly dissected with steep hillslopes

The saprolite is fairly well graded, being sandy silt to silty sand in texture with some gravel and small amount of clay. Relict joints of the parent rock are preserved in the saprolite zone, and can significantly alter the observed hydraulic conductivities of the surrounding soil matrix (INTEGRAL 1990).

The deposits are matrix supported and formed by granitic boulders and residual soils and vegetation debris. About 15% of the land area of the territory is covered with colluvium. Colluvium generally accumulates at footslopes or in gullies at upper levels. These deposits have resulted from landslide which took place in the geological past and are usually poorly consolidated with high cobble-boulder content, and abundant natural soil pipes (Mejía and Velásquez 1991).

A short duration, high intensity rainfall event impacted the basin of La Arenosa on 21 September 1990. In less than 3 h a precipitation of 208 mm with a maximum hourly intensity of 90 mm fell within the study area, triggering approximately 800 landslides. During this event, the population was strongly affected, 20 people were killed and 260 had to be evacuated, 27 houses were destroyed and 30 others were damaged, several bridges and more than 100 m of highway were ruined.

Evaluation of Model Prediction and Performance

The evaluation of the accuracy, robustness and reliability of a landslide susceptibility model is a difficult task, but an important issue. In this study the efficiency of

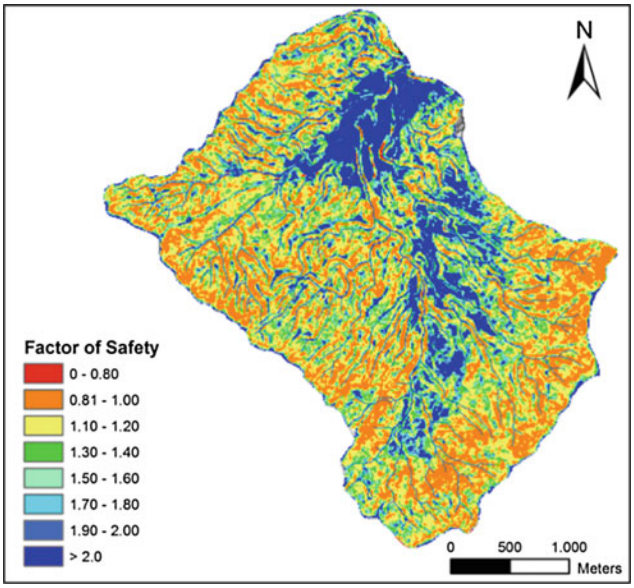

Fig. 2 Landslide susceptibility map of the La Arenosa catchment, classified according to factor of safety. Grill cells with FoS <1 are considered as failure cells

SHIA_Landslide is evaluated in terms of landslide density and susceptibility classes (degree of fit and success-rate curve), and the prediction capacity by ROC analysis. The landslide susceptibility map based on SHIA_Landslide model using September 21 rainstorm event as triggering factor is presented in Fig. 2.

ROC Analysis

A quantitative performance evaluation of SHIA_Landslide was accomplished through GIS-based, map overlay operations, and by calculating Receiver Operating Characteristic (ROC) values.

ROC analysis for assessment of performance of landslide models is based on the fact that each grid cell could be mapped using actual classes, called positive and negative class labels, according to landslide inventory databases, and predicted classes, called true and false class labels, produce by a model. There are four possible outcomes. If the grid cell is positive and it is classified as positive, it is counted as a true positive(the unstable area correctly classified as unstable); if it is classified as negative, it is counted as a false negative (the unstable area erroneously classified as stable). If the grid cell is negative and it is classified as negative, it is counted as a true negative (the stable area correctly classified as stable); and if it is classified as positive, it is counted as a false positive (the stable area erroneously classified as unstable).

Table 1 Confusion matrix from the ROC analysis for La Arenosa rainstorm event shown in Fig. 3

Classifier	Area (m^2)	Catchment area percentage (%)
Unstable areas		
TP	168.900	1.71
FN	50.500	0.51
Stable areas		
TN	7.306.700	74.06
FP	2.338.500	23.70

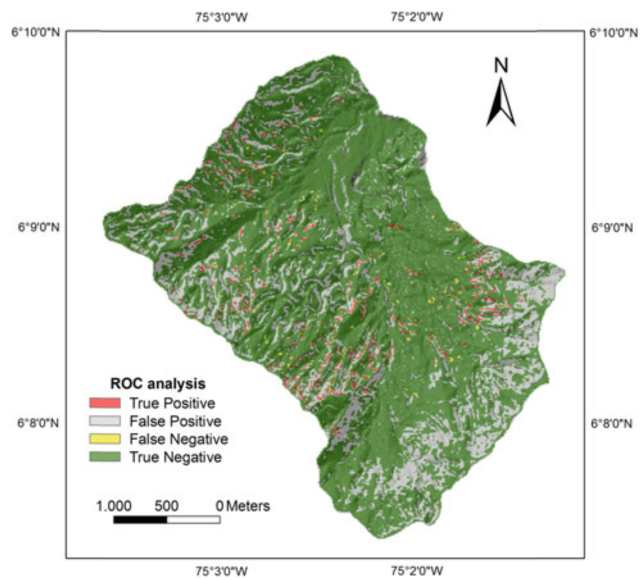

Fig. 3 ROC analysis map for La Arenosa rainstorm event

The model correctly predicted 77% of observed unstable areas and 76% of observed stables areas (Table 1). In contrast, the model erroneously predicted 93% of unstable grid cells provided for the model when actually landslide did not occur over them, and 0.52% of stable grid cells provided for the model where landslide indeed occurred (Table 1 and Fig. 3).

A great advantage of ROC analysis is that several metrics have been defined for evaluating models performance. During the performance evaluation sensitivity, specificity, false alarm, and precision of the simulations were calculated and used for a quantitative comparison (Table 2).

The true positive rate (TPR), also called hit rate, sensitivity, or positive accuracy, is defined as the ratio between true positives and the total actual positives; the true negative rate (TNR), also called specificity or negative accuracy, is the ratio between true negatives and the total actual negatives; the false positive rate (FPR), also called false alarm rate or negative error, is defined as the ratio between false positive and the total actual negatives; finally the positive

Table 2 Statistical indexes measuring the performance of SHIA_Landslide

Index	Value	Range
Hit rate	76.98	[0, 100]
False alarm rate	24.24	[0, 100]
Specificity	75.75	[0, 100]
Precision	0.067	–

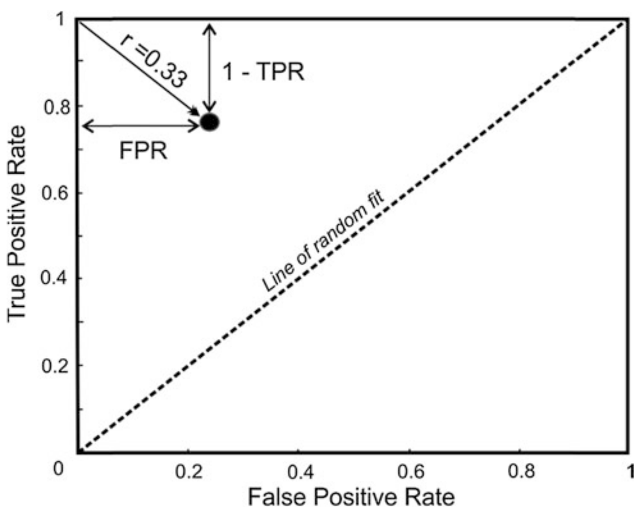

Fig. 4 ROC graph showing the results of SHIA_Landslide for La Arenosa 1990 event

predictive value (PPV), also called precision, is the ratio between true positives and the total predicted positives.

The TPR and FPR are used to plot the ROC graph in which the TPR is plotted on the y-axis and the FPR on the x-axis. A perfect prediction would be located at the upper left corner (0,1). The distance to perfect classification, proposed by Cepeda et al. (2010), is a measure of model performance. The smaller the r value, the better the model´s performance (Fig. 4)

$$r = \sqrt{FPR^2 + (1 - TPR)^2} \tag{2}$$

The r for SHIA_Landslide in The La Arenosa, 1990 event was 0.33 (Fig. 4).

Degree of Fit

The degree of fit evaluates the model in terms of landslide density within different susceptibility classes. It was calculated according to the following expression:

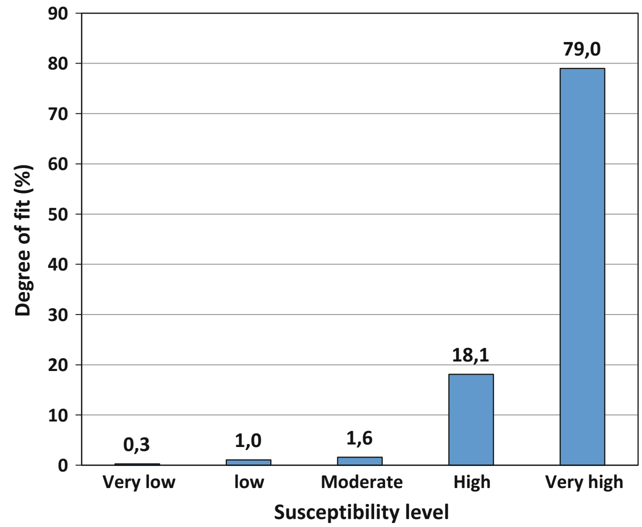

Fig. 5 Area analysis of the landslide susceptibility map. Degree of fit of susceptibility classes

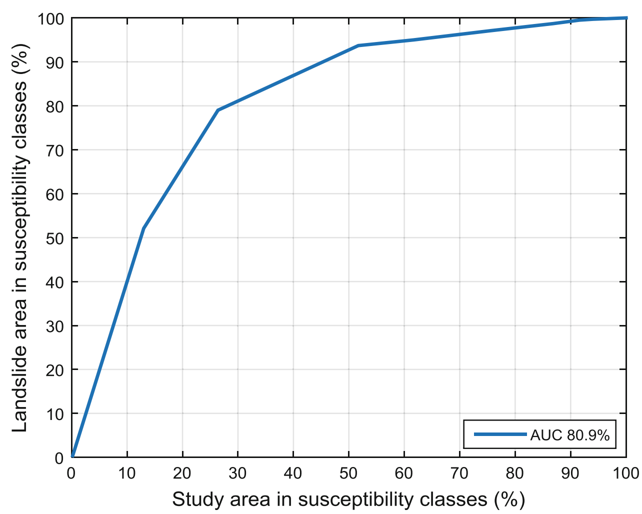

Fig. 6 Success rate curve for the La Arenosa catchment September 1990 rainstorm event using SHIA_landslide

$$D.F. = \frac{Z_i/S_i}{\sum Z_i/S_i} \tag{3}$$

where Zi is the area occupied by the rupture zones in the class of susceptibility and S_i is the area of the i class of susceptibility (Fernandez et al. 2003).

The smaller the degree of fit in the low susceptibility classes, and the higher it is in the high to very high susceptibility classes, the higher the quality of the susceptibility map.

The degree of adjustment required for the high and very high susceptibility classes reached 97.1% whilst for the low and very low classes it was only 1.3% (Fig. 5).

Success Rate Curve

The success of the model is represented by comparing the landslide density with the area of susceptible zone for different susceptibility levels. The success rate curve was obtained by comparing the landslide inventory map with the susceptibility map (Fig. 6). The area under the success rate curve (AUC) characterizes the quality and performance of the model. If the AUC is close to 1, then the result of the text is excellent. Conversely, an AUC result closer to 0.5 indicates a fairer test results. The AUC plot assessment results showed that the AUC value was 80.9.

Conclusions

In this paper, the SHIA_Landslide was used to estimate the landslides caused by a heavy rainfall occurred in a basin of tropical and mountainous terrains of Colombian Andes. The results obtained by the model showed a good agreement when compared with the landslide inventory presented during the event.

Performance of the model was evaluated in terms of landslide density and susceptibility classes (degree of fit and success-rate curve), and the prediction capacity by ROC analysis; a good performance of the model was shown, suggesting that the model can be used successfully in tropical mountainous watersheds, which are typically subjected to high rainfall intensities.

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