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ORIGINAL PAPER

Susceptibility assessment of shallow landslides triggered by rainfall in tropical basins and mountainous terrains

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Abstract This study presents the analyses and results of the implementation of the SHALSTAB model to study landslides caused by rainfall that occurred on September 21, 1990, in a basin of tropical and mountainous terrain in the Colombian Andes. In <3 h, 208 mm of precipitation fell within the study area, triggering more than 800 landslides. This event is unusual because of the huge number of landslides that took place. The results obtained by the model are compared to an inventory of landslides that occurred during the event, which shows a high overlap in spatial locations. Additionally, a receiver operating characteristics analysis shows that SHALSTAB is able to capture the physics involved in landslides triggered by rainfall in tropical and mountainous terrains; this suggests that the proposed model could be implemented successfully in a variety of similar tropical regions to identify slopes prone to failure due to rainfall with only a high-resolution digital elevation model and a few soil parameters.

Keywords La Arenosa catchment · SHALSTAB · Susceptibility assessment · Shallow landslide · Tropical basin

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1 Introduction

Landslides triggered by rainfall are common in tropical and mountainous terrains. Slope failures represent one of the most common causes of human and economic losses worldwide (Schuster 1996; Sidle and Ochiai 2006). For this reason, landslide susceptibility assessment has been a topic of great interest within the scientific community (Aleotti and Chowdhry 1999; Chacon et al. 2006). Although landslides can be attributed to many factors, including geology, geomorphology, hydrological conditions, soil characteristics, and human action, it is widely recognized that the most common triggering factor in tropical and complex terrains is rainfall infiltration.

Many researchers have studied the occurrence of landslides triggered by rainfall (e.g., Montgomery and Dietrich 1994; Iverson 2000; Crosta and Frattini 2003; Borga et al. 1998; Claessens et al. 2007). However, few studies have been performed in tropical regions, which are characterized by intense rainfall and deep weathering profiles. Thus, it is necessary to examine physical models of these areas and the methodologies used to determine the spatial locations of landslides and each slope's susceptibility level.

For landslide studies, physical models that include geotechnical and hydrological aspects have been proposed. These models are based on soil properties used to calculate the safety factor of an infinite slope that is subjected to an infiltration process, such models include LISA (Hammond et al. 1992), SINMAP (Pack et al. 1999) and for transient flow, CHASM (Anderson and Lloyd 1991) and TRIGS (Iverson 2000; Baum et al. 2002). One of the most recognized models, called SHALSTAB, was proposed by Montgomery and Dietrich (1994) and further tested by Montgomery et al. (1998, 2000). This model characterizes the topographic control on the distribution of shallow landslides. For a landslide susceptibility analysis, SHALSTAB applies a topographic index to evaluate soil saturation as a function of rainfall infiltration, suggesting that surface topography is a primary indicator of where shallow landslides are most likely to occur. SHALSTAB is a valuable model that can be applied without costly attempts at parameterization and needs little user training; additionally, the model can effectively identify areas with high landslide susceptibility under rainfall.

In the current study, the SHALSTAB model was implemented to estimate the spatial location of landslides triggered by a rainstorm in a basin of tropical and mountainous terrain. The model was evaluated using a real case that occurred in La Arenosa catchment on September 21, 1990, located at the Central Cordillera of Colombian Andes. During this rainstorm, more than 838 shallow landslides were triggered, moving approximately 1,5 million cubic meters of soil down steep slopes (Hermelin et al. 1992). The results obtained by the model and a comparison with an inventory of landslides that occurred during the event show a high coincidence in spatial locations. In addition, using a receiver operating characteristics (ROC) analysis, validation was completed using the unstable areas identified by the model and the existing landslide inventory. The model used was shown to be effective when applied to tropical mountainous watersheds, which are subjected to high rainfall intensities. This makes the model as a useful tool for application in other basins in the area and to perform sliding susceptibility studies.

2 Study area

La Arenosa catchment is located on the southeastern side of the Central Cordillera of the Colombian Andes. The catchment is part of the upper San Carlos River basin and is formed by the confluence of La Arenosa and Betulia streams with an extension of 9.91 km^2.

Elevation in the area ranges between 1.000 and 1.900 m.a.s.l. The basin is highly dissected with hill slopes with lengths of 40–60 m. The majority of the study area is covered with crops and pasture. Figure 1 shows the geographic localization of the La Arenosa catchment.

The area has a tropical humid climate with a mean annual precipitation of 4.300 mm and a mean annual temperature of 23 °C. The precipitation regime is dominated by high variability at both inter-annual and inter-seasonal scales. The monthly rainfall distributions show evident seasonal patterns with a significant difference between the rainy seasons, which extend from March to May and from September to November, and the dry seasons, which have a minimum rainfall in July.

The geology of the study area consists of residual soils from granodiorite rocks covered in gently sloping areas with fluviotorrential deposits to a depth ranging from 3 to 20 m. Its dominant, granitic component is gray, medium-to-coarse grained and consists of cream or pale yellow feldspar, smoky quartz and smaller proportions of reddish-brown biotite and dark hornblende.

These rocks have been severely weathered in situ. The progressive spheroidal decomposition of the granite has been rapid and extensive with an average weathering depth of 30 m; this is primarily due to chemical decomposition due to the humid tropical climate (Mejia and Velazquez 1991).

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

The deposits are matrix supported and formed by granitic boulders, residual soils and vegetation debris. Approximately 15 % of the land area of the territory is covered with colluvium. Colluvium generally accumulates at footslopes or in gullies at higher

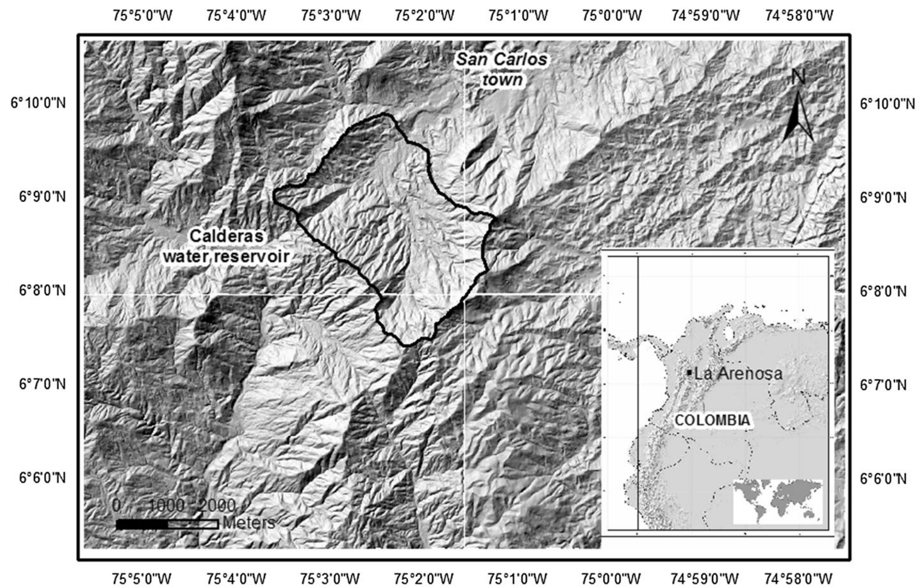

Fig. 1 Location of the La Arenosa catchment in the southeastern side of the humid tropical and complex terrains of Central Andean Cordillera in Colombia

elevations. These deposits have resulted from landslides in the geologic past and are usually poorly consolidated with high cobble-boulder content and an increased occurrence of natural soil pipes (Mejia and Velazquez 1991).

2.1 The September 21, 1990, rainstorm in La Arenosa catchment

A short duration, high intensity rainfall event impacted the basin of La Arenosa on the 21 of September in 1990. In <3 h, 208 mm of precipitation fell within the study area, triggering many landslides. This event is unusual due to the large number of landslides that occurred.

During this event, the population was strongly affected: 20 people were killed; 260 were evacuated; 27 houses were destroyed and 30 more were damaged; and several bridges and more than 100 m of highway were ruined. The Calderas Hydropower Energy Plant was

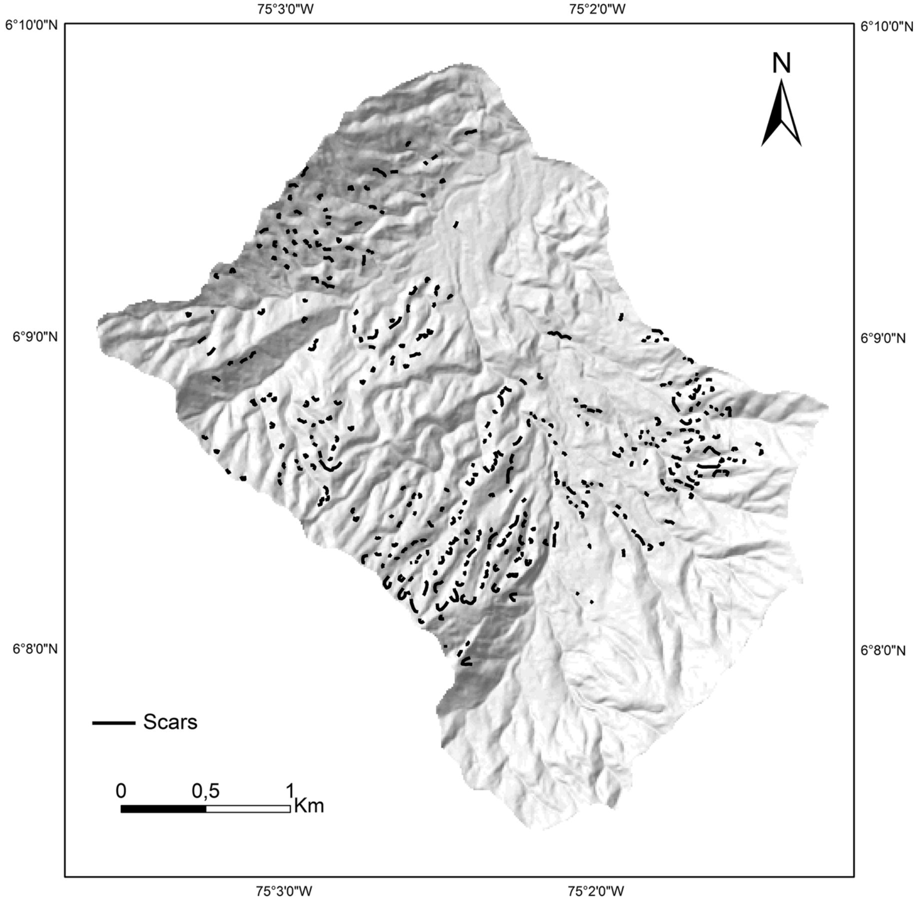

Fig. 2 Landslide scars produced by the September 21, 1990, rainstorm. *Black lines* show the inventoried landslide scars according to the landslide database created by Mejía and Velasquez (1991) and INTEGRAL (1990). DTM was built by the Instituto Geográfico Agustin Codazzi (IGAC) from aerial photographs and 10-m grid resolution. Aerial photographs and topographic maps of the southeastern area of the catchment were not available, making it impossible to document all La Arenosa landslides

flooded and severely damaged by large debris carried by La Arenosa Stream. Total losses were estimated at more than US $ 6 million (Hermelin et al. 1992).

Analysis of aerial photos and field investigations after the event allowed a partial reconstruction of the pattern and characteristics of the landslides in La Arenosa catchment. INTEGRAL (1990) and Mejía and Velasquez (1991) offered a partial landslide inventory and a comprehensive description of the landslides triggered during the event, obtained through the analysis of post-event aerial photos, field investigations and a detailed survey. It was reported that 838 soil slips were triggered in the entire upper basin for the San Carlos River; most of them transformed into debris flows. For La Arenosa catchment, 699 landslides were reported and all were classified as soil slips or mud/debris flows that moved either "very" to or "extremely" rapidly with high water content. Aerial photographs and topographic maps of the entire catchment were not available, making it impossible to document approximately 30 % of the total number of La Arenosa landslides. Figure 2 shows the locations of the inventoried landslides triggered by the rainstorm. Figure 3 shows the hourly rainfall histogram of this storm.

Landslides were initiated as shallow translational landslides. After the initial mobilization, rapid displacement occurred in a chaotic mixture containing a variable amount of water; the landslides scoured residual soil and vegetation downslope, incorporating soil and bedrock fragments. The movement evolved along the slopes under a quasi-viscous flow with a high velocity, increasing the sediment transport for superficial erosion along the channels.

The landslide bodies were small with respect to the flow length and slip surface, which was parallel to the slope surface. Field studies suggested that the depth of a failure surface was between 0.6 and 1.5 m. In all the examined cases, the failure surface is located at the contact of the residual soil with underlying saprolite. The majority of landslides were initiated within residual soils in hollows and open slopes with a slope steepness ranging from 35° to 42° (Mejía and Velazquez 1991).

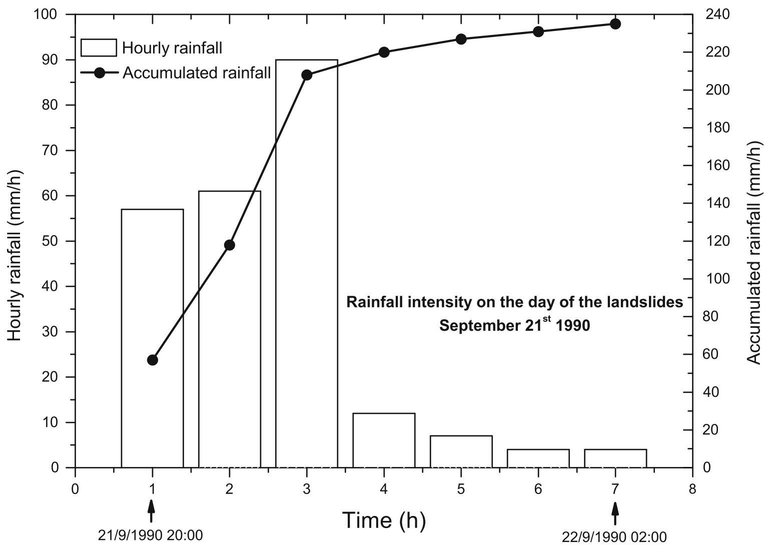

Fig. 3 Hourly rainfall histogram of the September 21, 1990, rainstorm. In <3 h, 208 mm of precipitation fell within the study area, triggering 838 landslides in La Arenosa catchment

3 SHALSTAB model

The SHALSTAB model (Montgomery and Dietrich 1994) employs the hydrological model TOPOG (O'Loughlin 1986), which uses steady-state rainfall to build the maps for the spatial pattern of wetness based on analysis of the upslope contributing area, soil transmissivity, and local slope. In the model, local wetness (*W*) is calculated as:

$$W = \frac{Qa}{bT \sin \theta} \quad (1)$$

where Q is the given steady-state rainfall (mm/d), a is the upslope contributing drainage area (m^2), b is the length across which flow is accounted for (m), T is the soil transmissivity when saturated (m^2/d), and θ is the slope angle. Assuming that the transmissivity does not vary with depth, it is possible to simplify Eq. (1) for the case $W \leq 1.0$ to:

$$W = \frac{h}{z} \quad (2)$$

where h is the saturated soil thickness and z is the total soil thickness. Combining Eqs. (1) and (2) yields the relative saturation of the soil profile:

$$\frac{h}{z} = \frac{Qa}{bT \sin \theta} \quad (3)$$

This equation shows that the relative saturation of the soil profile for a given rainstorm is controlled by the hydrologic ratio (Q/T), which is the magnitude of the precipitation event, and the topographic ratio ($a/b\sin\theta$), which captures the effects of the topographic convergence that concentrates the subsurface flow and consequently elevates the pore pressure (Dietrich et al. 1998).

The geotechnical component of SHALSTAB is based on an infinite slope form of the Mohr–Coulomb failure law:

$$\rho_s gz \sin \theta \cos \theta = C' + \left[\rho_s - \rho_w \frac{h}{z} \right] gz \cos^2 \theta \tan \emptyset \quad (4)$$

where ρ_s is the bulk density of the soil, ρ_w is the bulk density of water, g is gravitational acceleration, C' is the effective cohesion of the soil including the effect of the reinforcement by roots, and ϕ is the friction angle of the soil. This equation can be written in terms of h/z as:

$$\frac{h}{z} = \frac{\rho_s}{\rho_w} \left(1 - \frac{\tan \theta}{\tan \emptyset} \right) + \frac{C'}{\rho_w gz \cos^2 \theta \tan \emptyset} \quad (5)$$

Finally, coupling the hydrologic model (Eq. 3) and the slope stability model (Eq. 5) and rearranging in terms of the upslope contributing area and the length, the authors obtain:

$$\frac{a}{b} = \frac{T}{Q} \sin \theta \left[\frac{\rho_s}{\rho_w} \left(1 - \frac{\tan \theta}{\tan \emptyset} \right) + \frac{C'}{\rho_w gz \cos^2 \theta \tan \emptyset} \right] \quad (6)$$

From Eq. 6, it is possible to determine four conditions for the analyzed topographic elements. Topographic elements where *a/b* is greater than the right side of the equation are predicted to be unstable. In contrast, stable topographic elements have insufficient catchment area and wetness to fail, which indicates that *a/b* is smaller than the right side of the equation. Slopes that are stable even in saturated soil conditions (*h/z* = *1*) are called unconditionally stable and are governed by the following expression:

$$\tan\theta < \left(1 - \frac{\rho_w}{\rho_s}\right)\tan\emptyset + \frac{C'}{\rho_s g z \cos^2\theta} \tag{7}$$

Finally, slopes predicted to be unstable even when dry (*h/z* = *0*) are considered unconditionally unstable and are governed by the following expression:

$$\tan\theta \geq \tan\emptyset + \frac{C'}{\rho_s g z \cos^2\theta} \tag{8}$$

4 Model parameterization

A digital elevation dataset with submeter resolution was obtained from aerial photographs provided by the Instituto Geográfico Agustin Codazzi (IGAC). Spatial discretization of the model was obtained, splitting the study area into 99.060 of square grid elements with a raster size of 10 m according to the DTM. Morphometric parameters such as slope angle, flow direction and flow accumulation are calculated using the DEM and ArcGis 10.1 hydrologic tools. Figure 4 shows the watershed boundaries and the stream network extracted dataset using a Digital Elevation Model (DEM).

Soil descriptions, field tests and laboratory analyses of soil samples of La Arenosa catchment have been performed by Mejia and Velasquez (1991) and INTEGRAL (1990) after the landslide event. Using this information with soil typology correlation and field work corroboration based on the soils and land cover maps, those soil parameters were extended to the entire catchment. Finally, the parameter set was compared with the literature data to estimate a range of values to calibrate the model.

4.1 Soil strength and hydraulic parameters

According to previous studies, cohesion in the soils of La Arenosa ranges from 5 to 12.5 kPa, and the soil friction angle ranges from 16° to 24° in accordance with values reported in the literature for silty sands originating from weathering profiles of granitic rocks. The unit weight of saturated soil ranges from 18 to 18.8 kN/m^3, and the dry unit weight ranges from 14.3 to 14.9 kN/m^3.

One of the greatest uncertainties related to the study of the effect of water infiltration is related to the values of field permeability. For the soil profile of the study area, which corresponds to a sandy-loam texture, it is assumed that the values of permeability range from moderate to high. According to Lu and Likos (2004), sandy-loam soils have permeabilities between 10^{-7} and 10^{-3} m/s. Because of the large range of permeabilities for the soil, it was necessary to do a sensitivity analysis considering the range of permeability that, with different strength parameters and hydrological conditions, can more accurately represent the landslide scarp patterns produced by the September 21, 1990, rainstorm.

Additionally, a distributed soil thickness map of slope gradient was used. There is an assumed link between the thickness of the soil and the slope angle. For the site evaluated in the field, the soil depths were compared with slope inclinations, and all data were plotted and interpolated. Soil thicknesses ranged from 1 to 2.7 m, in which thin soil was found on

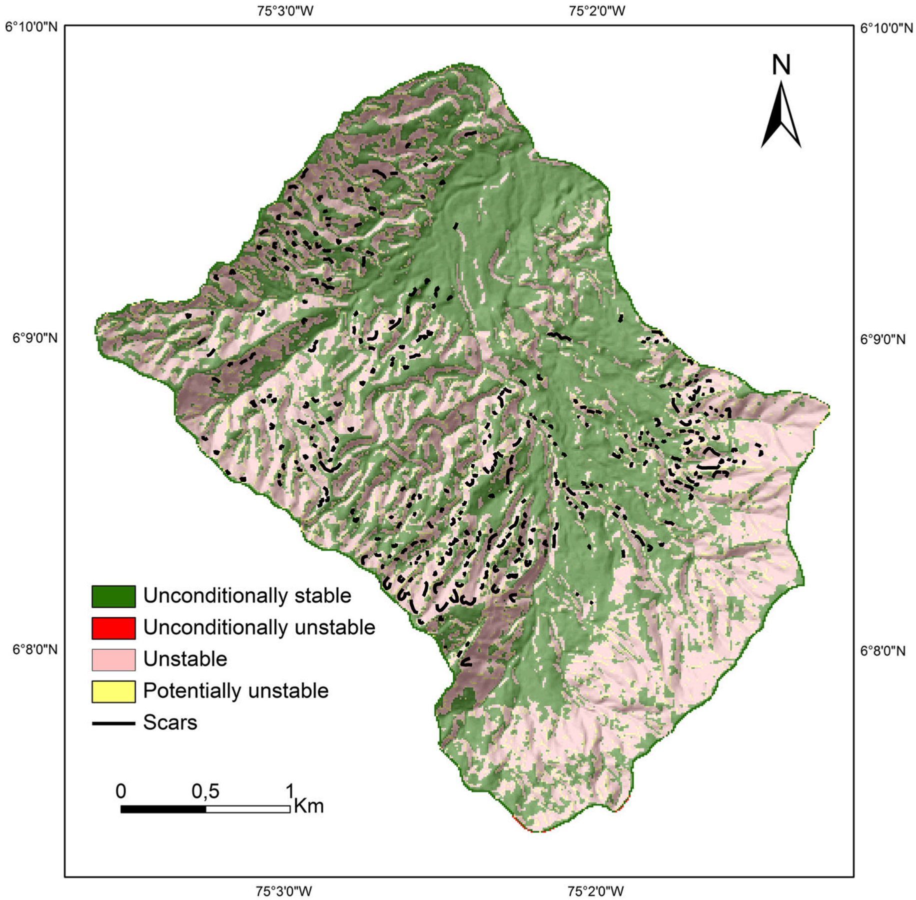

Fig. 4 Areas with landslide occurrence triggered by the September 21, 1990, rainstorm, as simulated by SHALSTAB using $q = 90$ mm/h

narrow ridges, and thick soils and colluviums accumulated at the bottom of the valleys (Aristizábal 2013).

Finally, it was assumed that the saturated permeability does not vary with the depth of the soil; it is also estimated that the transmissivity of the ground would be equal to:

$$T = kz \tag{9}$$

where k is the hydraulic conductivity of the soil.

5 Results and model validation

For the sensitivity analysis performed, it was found for the residual soil that a permeability of 5.44×10^{-6} m/s, a cohesion of 7.25 kPa, a friction angle of 27.6° and a saturated unit weight of 18 kN/m^3 matched the failures mapped in the event. These values are reasonable within the ranges shown. Similarly, for alluvial soil, the following parameters were used: a permeability of 1.33×10^{-6} m/s, a cohesion of 1 kPa, a friction angle of 34° and a saturated unit weight of 20 kN/m^3; however, these parameters do not influence the unstable areas because they are located at the bottom of the basin where the slopes are gentle.

With the parameters obtained in the sensitivity analysis, the map of susceptibility to landslides of La Arenosa catchment was compiled. Comparison of the observed landslide locations with the model predictions provided an assessment of model reliability (Fig. 2). Aerial photographs and topographic maps of the entire catchment were not available, making it impossible to document the landslide inventory of nearly 30 % of the total area, particularly along the southeastern of La Arenosa catchment.

The model performance is also related to the capacity of predicting a relatively small number of unstable pixels. The 350 landslide scars correspond to 2.194 pixels, which comprised only 2.2 % of the study area. Although INTEGRAL (1990) estimated that 16 % of the entire catchment was impacted by landslides during the September 21, 1990, rainstorm, there is only spatial certainty for this 2.2 %.

Considering these limitations, the analysis was based on three critical rainfall intensities (q) of 30, 60 and 90 mm/h. The results obtained by the rainfall intensity of 90 mm/h are the ones that best matched the failures recorded during the event, as shown in Fig. 4. This condition represents the largest hourly rainfall intensity registered during the September 21, 1990, event. A high coincidence of the potentially unstable areas identified by the model and the scars located by the landslide inventory is attained, suggesting that the model can successfully describe potentially unstable areas in the area and conditionally unstable areas triggered by the rainfall event.

Figure 4 shows the landslide susceptibility assessment map for La Arenosa catchment for the September 21, 1990, rainstorm. Unconditionally unstable and unconditionally stable areas are independent of the rainfall event. The stability condition of these areas is a function of cohesion, friction angle, unit weight of the soil and failure surface depth. Unconditionally stable areas for landslides triggered by rainfall correspond to 50 % of the total catchment area. These areas are stable under rainfall events due to very low slope angles, where the shear stress does not exceed the shear strength of the soil material. Unconditionally unstable areas are not significant (<0.03 %). All of these areas are located in the lower part of the catchment on the channel bank formed by alluvial sediments and are originated by fluvial erosion of streams rising over their banks; these areas are not direct consequences of rainfall. Comparing the susceptibility map with the landslide scars inventory, only 0.1 % of the observed scar cells are identified by the model as unconditionally stable.

50 % of the total watershed of the La Arenosa catchment is potentially unstable under rainfall conditions; these areas' stabilities are functions of the rainfall infiltration rate. According to the model in this area, 43 % of the pixels failed under a rainfall rate of 90 mm/h. This value of pixels decreased to 40 % for a $q = 60$ mm/h and 39 % for $q = 30$ mm/h.

5.1 ROC analysis

ROC analyses have been extensively used in recent years for comparative evaluation of landslide models. A ROC analysis is a technique for visualizing, organizing and selecting classifiers based on their performance and has been used extensively in signal detection theory to depict the trade-off between hit rate and false alarm rate classifiers, and many other fields, such as medical diagnostic testing, data mining, and evaluating and comparing algorithms (Fawcett 2006).

ROC analysis for landslide models performance is based on considering 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, as produced by a model. There are four possible outcomes (Fig. 5): if the grid cell is positive and it is classified as positive, it is counted as a true positive (i.e., the unstable area is classified as unstable); if it is classified as negative, it is counted as a false negative (i.e., the unstable area is classified as stable); if the grid cell is negative and it is classified as negative, it is counted as a true negative (i.e., the stable area is classified as stable); and if it is classified as positive, it is counted as a false positive (i.e., the stable area is classified as unstable).

The model predicted 90.6 % of the observed unstable areas; the other 9.4 % were predicted as stable but did experience landslides. Related to the observed stables areas, the 57.8 % were predicted as stable by the model, and the other 42.2 %, which were predicted as unstable, correspond to potentially unstable grid cells that did not fail during the simulated storm (Table 1).

A great advantage of ROC analysis is that several metrics have been defined for evaluating model performance. During the performance evaluation, sensitivity, specificity, false alarm and precision of the simulations were calculated and used for a quantitative comparison as follows:

Hit rate (%):

$$\text{True positive rate}(tp) = \frac{TP}{TP + FN} = \frac{\text{unstable grid cells classified as unstable}}{\text{unstable grid cells}} \tag{10}$$

Specificity (%):

$$\text{True negative rate}(tn) = \frac{TN}{TN + FP} = \frac{\text{stable grid cells classified as stable}}{\text{stable grid cells}} \tag{11}$$

False alarm rate (%):

$$\text{False positive rate}(fp) = \frac{FP}{TN + FP} = \frac{\text{stable grid cells classified as unstable}}{\text{stable grid cells}} \tag{12}$$

Precision (%):

Fig. 5 ROC analysis matrix

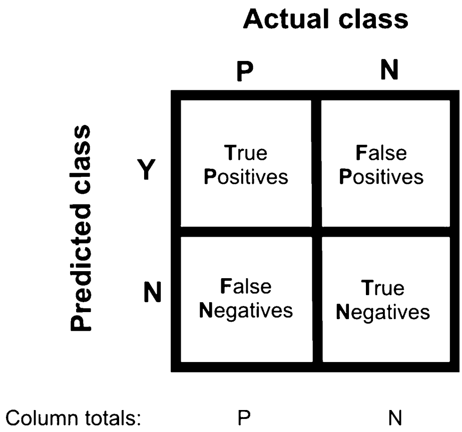

Table 1 Classification of stable and unstable zones

Classifier	SHALSTAB			
	Pixel	Area (m^2)	Total percentage (%)	Partial percentage (%)
Unstable areas				
TP	1.987	198.700	2.01	90.6
FN	207	20.700	0.21	9.4
Stable areas				
TN	55.957	5,595.700	56.49	57.8
FP	40.909	4,090.900	41.30	42.2

$$\text{Positive predictive value}(pp) = \frac{TP}{TP + FP} = \frac{\text{unstable grid cells classified as unstable}}{\text{unstable grid cells of the model}} \tag{13}$$

The true positive rate, also called hit rate, sensitivity or positive accuracy is defined as the ratio of the number of true positives to the number of total positives; the true negative rate, also called specificity or negative accuracy, is defined as the ratio of true negatives to total negatives; the false positive rate, also called false alarm rate or negative error, is defined as the ratio of false positives to total negatives; and the positive predictive value, also called precision, is defined as the ratio of true positives to total positives. Table 2 shows the statistical indices that measure the performance of SHALSTAB in La Arenosa catchment.

According to the analysis, SHALSTAB shows a high hit radio, suggesting an accurate prediction of failure areas (i.e., 91 %) and a large false alarm rate, indicating a large number of potentially unstable areas that did not fail during the simulated rainstorm (i.e., 42 %). SHALSTAB shows a considerable high hit ratio but at the same time an important false alarm rate. However, because of the incomplete landslide inventory, some of the potentially unstable areas obtained in the analysis cannot be confirmed with failure zones in the field, which finally results in an overestimation of the false alarm rate.

There are two types of discrepancies between the model outputs and the observed data: areas modeled as stable with actual landslides, and areas modeled as unstable without actual landslides. The first type of discrepancy indicates that SHALSTAB does not describe the landslide processes involved in that specific slope area or site-specific spatial variations in soil properties properly. Conversely, the second type of discrepancy corresponds to potentially unstable areas that did not fail in the given rainfall. From a practical point of view, the first type of discrepancy is the most critical because it does not permit preventative measures to be taken in those areas, while the second actually encourages conservative measures to manage landslide occurrences. Additionally, this second type of

Table 2 Statistical indexes measuring the performance of SHALSTAB

Index	SHALSTAB	Range
Hit rate	90.6	(0–100)
False alarm rate	42.2	(0–100)
Specificity	57.8	(0–100)
Precision	0.05	–

discrepancy may also mean that the slope could experience landslides under slightly different conditions and that prevention measures should be taken.

6 Discussion and conclusions

Susceptibility assessment of shallow landslides triggered by rainfall represents an important aspect of land management in mountainous regions. Although physical methods include rainfall as a triggering factor, most of the methods proposed in the literature are very complex and require a large number of parameters. The SHALSTAB model is based on coupling the infinite slope stability analysis with a very simple and intuitive hydrological model. SHALSTAB assumes that topography and contributing area are the primary controlling factors for shallow landslides triggered by rainfall, allowing the forecast of both the temporal and spatial distributions of shallow landslides triggered by rainfall.

SHALSTAB considers a steady flow condition, which is only valid for low intensity prolonged rainfall. This assumption allows the model to assess the susceptibility of a slope to instability in a specific region. In the case that pore water pressure responds very rapidly to rainfall, transient infiltration models show better performance but usually do not consider subsurface flow (Crosta and Frattini 2003).

The tendency of SHASLTAB to predict more unstable areas in a given rainstorm is because the model predicts the relative probability of failures. Areas with the same critical rainfall threshold will not all be predicted to fail in the same storm. For that reason, areas modeled as unstable without actual landslides are not necessarily stable and they correspond to potentially unstable areas that simply did not fail during the given rainstorm.

Furthermore, the hydrologic structure of SHALSTAB assumes that the hydraulic conductivity is uniform with depth and neglects the presence of natural pipes. Although the model has some limitations imposed by such assumptions, the results have proven reasonably successful. SHALSTAB shows a high hit ratio, suggesting an accurate prediction of failure areas.

There are still major uncertainties that should be considered for a complete modeling of shallow landsliding, such as lateral and vertical variability of hydrological and geotechnical parameters of the soil, unsaturated conditions, secondary permeability and subsurface flow complexity, and soil thickness. In the SHALSLTAB model, all important aspects are simplified; however, the obtained results show that the most significant parameters in a tropical environment and complex terrains have been accounted for in the analysis: topography and contributing area.

Another important point is that SHALSTAB only considers the initial failure of the soil. Further research should address the interactions between the initial failure and the resulting debris flow and fluvial sediment transport; this will provide coupled models for automated mapping of spatial patterns of failure potential and downstream hazards.

For the case study in the La Arenosa catchment, SHALSTAB was implemented using spatial variability of soil properties including the depth of the failure surface, allowing the analysis to be more consistent with actual conditions in the basin. The results obtained by the model and compared with the landslide inventory during the event show a high overlap in spatial location. With ROC analysis, 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. This makes this type of model as a useful tool for applications in other basins in the area that require landslide susceptibility analysis.

The proposed model can certainly make significant contributions in the development of land use plans, in which steps to prevent further occupation or intervention in these susceptible areas could be implemented. The model may also be used as a tool for prediction and be part of an early warning system.

The results obtained indicate that SHALSTAB is able to simulate the physics involved in landslides triggered by rainfall in tropical and mountainous terrain. Under these circumstances, SHALSTAB is a suitable model that identifies slopes prone to failure due to rainfall utilizing a high-resolution digital elevation model and few soil parameters, which are available in many locations.

There is great potential for new research to develop and implement physical and statistical models for early warning systems for landslides in tropical and mountainous terrains. These systems would reduce annual losses associated with such phenomena. The current practice of using statistical thresholds to identify landslide-producing storms can be made more useful if they are coupled with mechanistic models, such as that proposed, that are spatially explicit in identifying high-hazard areas (Casadei et al. 2003).

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Conflict of interest The authors declare that they have no conflict of interest.

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