REVISTA DE LA
ASOCIACIÓN GEOLÓGICA
ARGENTINA
www.geologica.org.ar

Volumen 80 (2)
MOVIMIENTOS EN MASA EN
LA REGIÓN ANDINA

Junio 2023

Physically-based models applied to rainfall thresholds for shallow landslides: literature review

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Editor: Sergio Sepulveda

Recibido: 17 de agosto de 2022

Aceptado: 15 de marzo de 2023

ABSTRACT

Landslides generate economic losses and human fatalities worldwide, especially in mountainous and tropical countries like Colombia. According to the Geohazards database, 10.438 landslides were registered in the Colombian Andes between 1921-2020, with almost 7.313 fatalities. The Colombian Andean region exhibits complex tropical hydrometeorological dynamics affected by different temporal and spatial scale climate processes. It comprises a diverse geological and geomorphological setting characterized by steep slopes and morphogenic conditions. It is represented by an active tectonic framework and high and deep tropical weathered soils from different parental materials predisposed to gravitational hillslope processes such as shallow landslides. Moreover, most of the Colombian population is established in the Andean region, occupying large hilly areas that need more planning control. This risk condition has encouraged the development of forecast models like rainfall thresholds and more complex and complementary tools like Early Warning Systems (EWS). This review is focused on the physically-based models used to define rainfall thresholds for shallow landslides or forecasting models in different regions of the world, considering different perspectives used to model the phenomenon: slope stability models, hydrological models, and coupled models (slope stability-hydrological). This paper opens the paradigm of the need that complex systems such as mountainous tropical catchments require to face the occurrence of shallow landslides under heavy storms associated with climate change and how physically-based models could be used to understand the distributed instability inside the catchments.

Keywords: rainfall threshold, shallow-landslides, catchments, morphometric parameters

RESUMEN

Definición de umbrales de lluvia para movimientos en masa superficiales a partir de modelos de base física: Revisión de la literatura. Los movimientos en masa generan pérdidas humanas y económicas alrededor del mundo, especialmente en países montañosos y tropicales como Colombia. De acuerdo con la base de datos Geohazards, entre 1921-2020 se registraron 10.438 en la región Andina colombiana causando al menos 7.313 muertes. La región Andina Colombiana exhibe una compleja dinámica hidrometereológica siendo afectada por procesos climáticos de diferente escala espacial y temporal. La región Andina está compuesta por un sistema geológico y geomorfológico caracterizado por altas pendientes y condiciones morfogenéticas representadas por un marco tectónico activo y suelos profundos altamente meteorizados a partir de diferentes materiales parentales que predisponen la ocurrencia de fenómenos gravitacionales tales como movimientos en masa superficiales. Por otro lado, la mayor parte de la población colombiana se encuentra establecida en la región Andina ocupando amplias zonas de alta pendiente sin medidas de planeación adecuadas lo que ha presentado una condición de riesgo en los últimos años, llevando al desarrollo de modelos de pronóstico tales como, umbrales de lluvia y modelos más completos y complejos como los Sistemas de Alerta Temprana (SAT). Esta revisión está enfocada en los modelos de base física usados para definir umbrales de lluvia o modelos predictivos en diferentes regiones del mundo, teniendo en cuenta diferentes perspectivas usadas para modelar el fenómeno: análisis de estabilidad, modelos hidrológicos y modelos acoplados (análisis de estabilidad-modelos hidrológicos). Este artículo abre el paradigma de la necesidad de entender los sistemas naturales complejos, como las cuencas tropicales montañosas que requieren enfrentar la ocurrencia de movimientos en masa superficiales bajo tormentas intensas asociadas al cambio climático y el rol de los modelos de base física para entender la distribución de la inestabilidad dentro de las cuencas.

Palabras clave: Debris Flow, slope stability, floodings, physically-based models, hazard.

INTRODUCTION

Landslides have taken thousands of lives worldwide in the last decades (Froude and Petley 2018). The UN Office for Disaster Risk Reduction (UNISDR) estimated that between 1998-2017 landslides affected 4.8 million people worldwide and caused more than 18000 fatalities. According to the Geohazards database (2020), between 1921-2020, 10438 landslides were recorded and caused almost 7313 deaths in Colombia. Some representative landslide disasters are Villatina in 1987, with 500 casualties (Flórez 2016), Paez in 1994, with 1110 fatalities (Martinez et al. 1995, Schuster et al. 1994), Gramalote event in 2010, which implied the evacuation of the entire town with 3000 people (SEG 2017) and Mocoa event in 2017 with almost 500 fatalities (Moreno-Murillo et al. 2019). Landslides are defined as physical phenomena that occur through a hillslope by the action of gravity (Pradhan et al. 2019). Hungr et al. (2013) describe a landslide as a rapid mass process that causes downslope movement of the mass of rock, debris, or soil induced by various external stimuli (Cruden 1989, Cruden and Varnes 1996).

Rainfall is the most common landslide-triggering factor (Sidle et al. 2019), with rainfall thresholds being the most used tool to forecast the possible occurrence of a landslide (Segoni et al. 2018). Endo (1969), Reichenbach et al. (1998), Godt (2004, 2006), and Guzzetti et al. (2007, 2008) defined rainfall thresholds as the rainfall conditions that, when reached or exceeded, increase the likelihood of triggering landslides. Those weather-induced landslides most often are shallow with typically translational slope failures a few meters thick of unlithified soil mantle or regolith that may occur wholly or partly in the unsaturated zone of hillslope environment (Caine1980, Cruden and Varnes 1996, Sidle and Ochiai 2006, and Maquaire and Malet 2006).

Physically-based or empirical methods can define rainfall thresholds. Empirical thresholds can use rainfall gauge-based data and landslide historical inventories (Floris et al. 2012, Chen and Wang 2014, Segoni et al. 2014, Galanti et al. 2018, Harilal et al. 2019, Soto et al. 2019, Marra et al. 2019). Additionally, empirical thresholds apply heuristic or statistical techniques such as frequency analysis (Brunetti et al. 2010, Peruccacci et al. 2017), Bayesian statistics (Berti et al. 2012), or conditional probability (Guzetti et al. 2007). In most of them, the rainfall measurements are obtained for specific rainfall events and antecedent rainfall conditions (Segoni et al. 2018) in which rain gauge networks measure rainfall (Jaiswal and van Westen 2009, Floris et al. 2012, Huang et al. 2015). As a restriction, empirical rainfall thresholds provide the landslide occurrence timing but not a spatial distribution or location.

Conversely, physically-based rainfall thresholds consider the spatial distribution or location of the landslides (Peres and Cancelliere 2014, Salciarini et al. 2019) by approaches grounded on physical laws that consider the occurrence of landslides by calculating the static (Montrasio et al. 2018, Zieher et al. 2017) or distributed safety factor (Simoni et al. 2008, Aristizábal et al. 2016, Lizárraga and Buscamera 2018, Rossi et al. 2019). The safety factor is based on the dynamic relationship between the resistance forces of the soil and the driving associated with rain instability effects, considering the impact of rainfall coupling hydrological and geotechnical models (Boogard and Greco 2018). This dynamic nature of subsurface hydrology depends on the complex interactions among precipitation parameters, physical properties, and heterogeneity of soils, bedrock, local geomorphology, vegetation, and associated biomass (Sidle et al. 2019). These factors influence the timing of landslides precipitation influence and antecedent soil moisture (Slide and Boogaard 2016, Mirus et al. 2018, Bezak et al. 2021), the mass type and failure mode (Weng et al. 2018), providing a broad understanding of the physical behavior of the rainfall along the hillslope and associated infiltration processes leading to have a spatial and temporal distribution of the phenomenon (Baum et al. 2010, Montrasio and Valentino 2012, Salciarini et al. 2012, Alvioli et al. 2014, Raia et al. 2014, Alvioli et al. 2015, Wu et al. 2015, Hsu et al. 2018, Fusco et al. 2019, Marin et al. 2019, Park et al. 2019, Marin 2020). On the other side, by defining physically-based thresholds may be incorporated, rainfall information with high-coarse spatial-temporal resolution data as ground-based radar rainfall (SIATA 2018, Mirus et al. 2018, Postance et al. 2017) and satellite precipitation estimates such as Tropical Rainfall Measuring Mission (TRMM) and the consolidate database from the satellite constellation GPM-IMERG (Robbins 2016, Leonarduzzi et al. 2017, Matthew et al. 2019). Additionally, gauge-based rainfall measurements such as IDF curves define the empirical relationship between rainfall intensity, duration, and frequency data (Eagleson 1970, Veneziano et al. 2007, Emmanouil et al. 2020) provides data that allows setting up different return periods (e.g., IDEAM, NOAA).

Different reviews have been developed about rainfall thresholds for landslides around the world (Wieczorek and Guzzetti 1999, Zêzere et al. 2016, Ramos-Cañón et al. 2015, Segoni et al. 2018, Gariano et al. 2020, Singh et al. 2021, Maturidi et al. 2022). This review explores the different grounded physically-based methodologies used for defining rainfall thresholds for shallow landslides in other regions and their application in the Colombian Andean tropical hillslopes and catchments.

CONSOLIDATED INFORMATION

This review will explore the different slope stability, hydrological, infiltration, and coupled (slope stability-hydrological) models and their components and parameters. To compile the main works where physically-based models are used to define rainfall thresholds or to assess rainfall-initiated shallow landslides, we consulted several databases such as Scopus (Science Direct), ASCE Library, and Springer Nature. The selected criteria are based on the year of publication (2005-2021) and their use, focusing on their mathematical structure and how they are applied to define rainfall thresholds or forecast shallow landslides along different hillslopes, catchments, or regional scales.

SLOPE STABILITY MODELS

Physically-based models are widely used to accurately represent geotechnical and hydrological processes involving a landslide occurrence. For example, geotechnical modeling considers the dynamic approach of limit equilibrium based on rigid block equilibrium analysis (Montgomery and Dietrich 1994), representing the effectiveness stresses through the hillslope, which results in the safety factor: a quantitative representation of the physical relationship between shear strength of the soil and shear stress required for equilibrium (Duncan et al. 2014). On the other hand, the hydrological processes involving the flow of water during storms through the hillslope are responsible for the decreasing safety factor because of the increasing soil pore water pressure and the loss of matric suction such as infiltration, vegetation impacts, and evapotranspiration consider as the principal shallow landslide triggers (Mirus et al. 2018).

Slope stability models allow the calculation of the safety factor. This physical-mathematical relationship involves understanding the pore-pressure limit-equilibrium behavior through a hillslope´s soil affected by external dynamic or hydraulic stimulus until reaching the instability or critical point of failure (Mohr-Coulomb). Slope stability models have different and several dynamic considerations. Also, their parametric inputs vary from the quality of the model to the case of study in which the model is applied and the spatial distribution and geometry of the slopes that will be assumed to analyze. This review will explore slope stability models for landslide occurrence, including their saturated and unsaturated infiltration considerations. (Table 1)

Statical equilibrium and distributed slope stability models have been developed from the slides method that Fellenius (1936) applied. Those models extend Mohr's circle concept of limit-equilibrium to calculate the safety factor (Janbu 1954, Terzaghi and Peck 1967, Hovland 1977, Michalowski 2002) from a 1D (Taylor 1948), 2D (Bishop 1955), and 3D (Hungr 1987, Hungr et al. 1989) geometric perspective, considering as input the hydro-geotechnical parameters of the soil, and the effects of rainfall by a rise or fall of the water table that increases the pore pressure in the soil in saturated conditions as a trigger factor.

Models for shallow-landslides (Table 1, Eq. 1,2) consider an infinite slope with unlimited extent which has constant conditions and constant soil properties at any given distance below the surface of the slope and assumes all forces are normal or parallel to the slope (Taylor 1948, Graham 1984), while water infiltration and groundwater flow patterns are modeled based on one-dimensional infiltration by the transient rainfall influence represented by pressure head distribution (Iverson 2000) and the product between the soil thickness and water density respectively, representing the increasing pressure heads or a rising groundwater table (Zhang et al. 2016). Those models have been applied in statical software such as Infinite Slope 3.0 (Infinite Slopes Project 2020), PISA-m (Haneberg 2007) and extended to GIS application in the work of Escobar-Wolf et al. (2021); the infinite model is also developed to spatially distributed modeling in large areas (Zhang et al. 2016) by the Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability (TRIGRS) software (Baum et al. 2002, Weidner 2018), SINMAP (Pack et al. 1998) applied in the novel work of Lin et al. (2021) and Shallow Slope Stability Model (SHALSTAB) (Dietrich et al. 1993) used in mountainous Colombian Andes by Aristizabal et al. (2015), and Shallow Landslides Instability Prediction (SLIP) (Montrasio and Valentino 2008) used by Marin et al. (2021) in a Colombian Andean catchment. Another improvement of the models mentioned is their capability to consider the capillarity pressure effects under unsaturated conditions over the water table (Casadei et al. 2003, Lee and Ho 2009) regarding the contribution of decreasing matric suction due to rainfall infiltration to the shear strength (Fredlund and Rahardjo 1993, Vanapalli and Fredlund 2000) (Table Eq. 4).

Circular two-dimensional slip surface stability models calculate the safety factor based on the circular arc method (Bishop 1960) and consider water pore-pressure distribution constant throughout the slope as the ratio between the pore-pressure at any point. The water bulk density times soil depth for a steady flow (Table 1 Eq. 3); the Bishop's physical concept is applied in commercial software such as SLIDE (Rocscience Inc.), SLOPE (GeoStru); GEO5 (Fine Spol S.R.O.); SLOPE/W (Seequent Limited Inc.), and others. The circular slope method proposed by Bishop is geometry extended in the work of Hungr (1987) from simple sidles to three-dimension columns assumptions (Table 1 Eq. 5), having implications in the dynamic assumption of forces between the columns and performing the results of the safety factor (Hutchinson and Sarma 1985). The 3D capability of this model was implemented initially in the microcomputer program CLARA-3 (Hungr et al. 1989) and later by the free software Scoops3D (Reid et al. 2015) applied in the works of (Weidner et al. 2019, Sabrina et al. 2020 and Van den Bout et al. 2021).

Other slope stability models consider biological effects such as the root cohesion effect in the soil-root system along the slip surface (Table 1, Eq. 6). Morgan and Rickson (1995) stated positive and negative effects associated with vegetation on slope stability, the positive effects from a hydrological point of view are conceived from the increasing of interception and evapotranspiration reducing pore pressure and from a mechanical point of view state that roots reinforce soil and thereby increase strength. The negative effects are considered from a hydrological point of view as the increasing permeability, increased infiltration, and thereby increased pore pressure, and mechanical point of view as the increasing weight or surcharge and thereby increased load on the slope. The application of (Table 1, Eq. 6), where is considering the root reinforcement variability (Masi et al. 2021), is used in the probabilistic stability 3D model- Probabilistic Multidimensional shallow Landslide Analysis PRIMULA developed by Cislaghi et al. (2017), another physically based model that considers the root reinforcement provided to the soil by vegetation is the HIgh REsolution Slope Stability Simulator HIRESSS developed by Rossi et al. (2013) used in the work of Cuomo et al. (2020). However, these models are still in development and are summited for further discussion. For better-detailed information, we recommended the review by Masi et al. (2021).

HYDROLOGICAL AND INFILTRATION MODELS

Hydrological modeling allows representation of the temporal and spatial distribution of water controlled by meteorological and topographic conditions: Rainfall and posterior infiltration and vertical flow through the hillslope and runoff processes. Infiltration is one of the essential landslide-triggering mechanisms, and it is controlled by the hydraulic conductivity characteristics of the soil (Cristiano et al. 2016). Under unsaturated soil conditions, the relationship between the matric suction and the volumetric water content (gravimetric water content or degree of saturation) is expressed by the soil water characteristic curve and permeability [SWCC] (van Genuchten 1980, Fredlung and Rahardjo 1993). This relationship predicts the volume change, shear strength, permeability, and heat conduction, allowing an understanding of the mechanical properties of unsaturated soils.

Several works have been developed modeling the water conductivity through soil considering saturated steady conditions based on Darcy´s laws: Degree of saturation, preferential flow, and Anisotropy where the flux is considered constant to time (Gardner 1958, Hodnett and Tomasella 2002, Napolitano et al. 2016, Mirus et al. 2017, Thomas et al. 2018, Sousa et al. 2021, Wang and Cheng 2021). For transient conditions of infiltration, the flow is considered to change through time spatially and temporally due to changes in the hillslope (Lu and Godt 2013), providing a broad understanding of the infiltration in the hillslope related to transient rainfalls assuming saturated (Freeze and Cherry 1979) (Table 2, Eq. 4) or unsaturated flow (Richards 1931, Iverson 2000) (Table 2, Eq. 2) in isotropic and homogeneous media.

Modeling the flow of water implies understanding the antecedent soil moisture conditions and its changes related to the infiltration of water, which is why the importance of soil moisture conditions in initiating landslides. In the work of Zhao et al. (2019), a distributed hydrological model SHETRAN is applied, which determined a soil wetness threshold by the soil wetness index (SWI) (Chen et al., 2016) simulating soil moisture evolution in response to rainfall conditions at a grid scale. The work of Emadi-Tafti and Ataie-Ashtiani (2019) shows that while soil moisture is essential, vegetation impact also has a vital role in triggering shallow landslides. They use the hydrological model SSHV-2D, which considers the roots of the trees having, as a result in their simulations, an increase of the safety factor of a slope and the effect of stabilizing surface layers of the soil from the effects of the root. Those results could help to assess the impacts of human activities, such

Table 1. Slope stability models and parameters

Model	Equation	Saturated	Unsaturated
(1)	$FS = \frac{\tan\phi}{\tan\alpha} + \frac{c - \varphi(Z,t)\gamma_w \tan\phi}{\gamma_s Z \sin\alpha \cos\alpha}$		✓
(2)	$FS = \frac{c' + (\gamma - Z - \gamma_w Z_w)cos^2\beta \tan\phi}{\gamma Z \sin\beta \cos\beta}$		✓
(3)	$FS = [\cot\beta - r_u(\cot\beta + \tan\beta)] \tan\phi' + (\cot\beta + \tan\beta) \frac{c'}{\gamma Z}$ $r_u = \frac{u}{\gamma Z} *$	✓	
(4)	$FS = \frac{c'}{\gamma_t D \sin\alpha_s \cos\alpha_s} + \frac{\tan\phi'}{\tan\alpha_s} + \frac{(u_a - u_w)\tan\phi^b}{\gamma_t D \sin\alpha_s \cos\alpha_s}$		✓
(5)	$FS = \frac{\sum R_{i,j}(c_{i,j}A_{i,j} + (N_{i,j} - u_{i,j}A_{i,j}) \tan\phi_{i,j}}{\sum W_{i,j}[R_{i,j} \sin\alpha_{i,j} + k_{eq} e_{i,j}]} \frac{1}{m_{\alpha_{i,j}}}$	✓	
(6)	$FS = \frac{C_c + [m_{\gamma_s} + (1-m)\gamma_m - m\gamma_w]D\, cos^2\beta \tan\varphi}{[m\gamma_s + (1-m)\gamma_m]D \cos\beta \sin\beta}$	✓	

(1) Taylor, (1948) Where ϕ is the soil friction angle, c is the soil cohesion, γ_s is the soil unit weight, γ_w is the groundwater unit weight, φ (Z,t) is the ground water pressure head, α the slope gradient, Z the vertical coordinate direction and t time. (2) Graham, (1984) where c^' is the effective cohesion, Z is the water table, Z_w is water level at distance Z, γ is the soil unit weight, γ_w is the groundwater unit weight and β is the slope angle (3) Bishop and Morgenstern (1960): where r_u is the ratio between the pore pressure and the total vertical stress at the same depth, u pore pressure and γZ total vertical subsurface soil stress at depth Z. (4) Adapted from Zhang et al., (2016) Where c' is the effective cohesion of a saturated soil, ϕ' is the effective angle of internal friction, ϕ^b is the angle indicating the rate of increase in shear strength related to matric suction, (u_a- u_w) is matric suction with u_a the pore air pressure and u_w pore-water pressure, γ_t total unit weight of the soil, α_s slope angles and *D* the depth of slip surface. (5) Adapted from Hungr et al., (1987) Where $R_{i,j}$ is the distance from the rotation axis to the geometric center of the potential sliding face of column, $c_{i,j}$ is the effective cohesion in column i,j, $A_{i,j}$ is the area of the trial surface, $W_{i,j}$ is the weight, $N_{i,j}$ is the normal force of column i,j , $e_{i,j}$ is the horizontal driving force moment arm, $\alpha_{i,j}$ is the apparent dip angle, k_{eq} is the horizontal pseudo-acceleration coefficient and $\phi_{i,j}$ is the effective internal friction angle and $m_{\alpha i,j}$= $cos_{\epsilon i,j}$+(sin$\alpha_{i,j}$ tan$\phi_{i,j}$)/ F_s, more details of the model can be accessible in (Reid et al., 2015) (6) From Selby (1993) where C_c is total cohesion from both soil and roots, γ_s is the saturated unit weight of soil, γ_w is the unit weight of water, φ is internal angle of soil friction, β is the hillsple angle and m is the ratio of water depth to soil depth calculated as m= h/Dcosβ , h is the subsurface flow height measured from orthogonal to the impermeable layer and D the soil thickness.

as intense erosion produced by deforestation and climate change effects associated with rainfalls with less frequency but higher intensity (Strauch et al. 2015). Other models that consider hydrological vegetation effects on slope stability are SHIA Landslide (Aristizábal et al. 2015); CHASM developed by Anderson and Lloyd (1991) and performed in the work of Wilkinson et al. (2002); SLIP4EX developed by (Greenwood 2006) and applied in work of (Danjon et al. 2008) and HYDROlisthisis (Anagnostopoulos et al. 2015).

Steady unsaturated conditions are used in the work of Yang et al. (2019), where the response of an expansive soil slope to an artificial rainfall infiltration in the in situ is numerically simulated by using the SEEP/W (Geo-Slope International Ltd. 2007) and the SWCC to reproduce the hydraulic behavior and the water content variation respectively.

COUPLED MODELS: SLOPE STABILITY-HYDROLOGICAL

Combined hillslope hydrology and slope stability analysis provides integrated modeling of the influence of preferential

Table 2. Hydrological and Infiltration models

Model	Equation	Steady	Transient
(1)	$i = k_s \frac{z_f + s_f + H}{k_s} = \theta_S - \theta_i \frac{dz_f}{dt}$	✓	
(2)	$\frac{\partial \theta}{\partial t} = \nabla \cdot (D \nabla \theta) - \frac{dK}{d\theta} \frac{\partial \theta}{\partial z}$		✓
(3)	$f_i = \frac{1}{2} S_e t^{\frac{-1}{2}} + \frac{1}{2}(K_1 + K_0)$	✓	
(4)	$\frac{\partial h}{\partial t} = D\left(\frac{\partial^2 h}{\partial^2 x} + \frac{\partial^2 h}{\partial^2 y} + \frac{\partial^2 h}{\partial^2 z}\right)$		✓
(5)	$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(D_x(\theta)\frac{\partial \theta}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y(\theta)\frac{\partial \theta}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z(\theta)\frac{\partial \theta}{\partial z}\right) + \frac{\partial K_z(\theta)}{\partial z}$		✓

(1) Green and Ampt (1912) where i is the infiltration rate (m/s), k_s is the saturated permeability coefficiente (m/s), z_f is the wet front depth (m), s_f is the wet front matric suction (m), H is the accumulated water depth (m), θ_S is the saturated volumetric moisture content, θ_i is the initial volumetric moisture content. (2) Philip (1957,1969) where, t is time, θ the volumetric water content, D the soil diffusivity, and Kthe hydraulic conductivity. (3) Eagleson (1978) where f_i is the infiltration rate, S_e is the infiltration, t time, K_1 is the hydraulic conductivity of soil at soil surface with water content θ and K_0 is the initial hydraulic conductivity. (4) Freeze and Cherry (1979) where D is the hydraulic diffusivity and ∂h/∂t is the variation of the pore-water pressure head in time t. (5) Richards (1931) where D is the water diffusivity for unsaturated soil, θ is the volumetric water content, K_z the hydraulic conductivity and t time.

flow in soil and the slope failure initiation associated with heavy rainfall, considered the main shallow landslides trigger in this work. Shao et al. (2016) applied a 1D Hydro-mechanical software HYDRUS-1D which integrated a dual-permeability model with an infinite slope stability approach (Table 1, Eq. 1,2) simulating the combined matrix flow and preferential flow as well as the complex subsurface flow processes. He et al. (2016) proposed the integrated model CRESLIDE applied in the work of Wang et al. (2020), predicting storm-triggered cascading flood and shallow landslides by coupling the distributed hydrological model CREST and the slope stability model SLIDE. The hydrological model CREST considers the antecedent soil moisture conditions and infiltration processes under various rainfall intensity and duration levels. In contrast, SLIDE considers the soil's spatially land cover data and mechanical parameters. Lu and Godt (2008) developed a closed-form equation to extend the infinite slope model for the evaluation of the safety factor under partially saturated conditions and to evaluate the trend of the safety factor to the changes in the soil hydrological parameters linked with rainfall infiltration (Bordoni et al. 2015). The SLIP model set up by Montrasio and Valentino (2008) considers some simplified hypotheses on the water down-flow and defines a direct correlation between the safety factor of the slope and the rainfall depth. This model has been implemented in the works of (Montrasio et al. 2011, 2012, Marin et al. 2020a).

The TRIGRS software developed to model the time and distribution of rainfall-induced shallow landslides by Baum et al. (2002) coupled a Darcian infiltration model associated with analytic solutions of Richards Equations (Iverson 2000) with a 1D infinite slope stability analysis assuming failure planes parallel to the ground surface (Taylor 1948), representing the rainfall infiltration resulting from storms that can have a duration ranging from hours to days (Alvioli and Baum 2016). Unlike the previously mentioned models, the TRIGRS model couples the hydrologic model with the stability analysis to calculate the safety factor (Godt et al. 2012; Lu et al. 2012). In the works of Tran et al. and He et al. (2017, 2021), the capability of TRIGRS was extended by applying it in combination with the distributed and 3D slope stability software Scoops3D developed by Reid et al. (2015) and used in the works of Zhang and Wang, (2019), and Marin and Jaramillo-Gonzalez, (2021), which modeled rotational landslides. The combination of TRIGRS and Scoops3D resulted in a better assessment of the physical phenomena by complementing the limitations of each one and forecasting different kinds of landslides, such as shallow landslides by TRIGRS and deep rotational landslides by Scoops3D. TRIGRS can be applied in large study areas, where a need for more information providing susceptibility maps allowing the knowledge of areas where detailed studies must carry on (Weidner et al. 2018, Ciurleo et al. 2018). TRIGRS has been applied in small tropical basins by Marin et al. (2020) and was used to determine rainfall intensity and duration (I-D) thresholds for shallow landslides; it also was used in tropical urban areas in the works of García-Aristizábal et al. (2018) and Marin et al. (2019). The information mentioned before showed the versatility that TRIGRS has to be applied in different physical conditions and targets and its capability to be applied on large scales.

COLOMBIAN CONTEXT AND DISTRIBUTED PHYSICALLY-BASED MODELS APPLICATION

The Colombian Andean region in Northwestern South America exhibits complex and variable hydro-meteorological dynamics with different temporal and spatial scales (Poveda 2004, Espinoza et al. 2020) and a diverse geological and geomorphological setting (Cediel and Shaw 2019). The Colombian Andean region is characterized by highlands with steep slopes associated with an active tectonic framework involving the interaction of different tectonic plates and the build-up of the orogenic systems (Ramos 2009), which have different structural behavior and differentiated geologic composition (Bayona et al. 2012, van de Lelij et al. 2016, Bustamante et al. 2017, León et al. 2018, van der Lelij et al. 2019). In addition, the tropical climate regime in Colombia (Stephens et al. 2018, Styamurty and Rosa 2019, Yepes et al. 2019) contribute to the development of deeply weathered soils. Consequently, the parental complex geologic and climate contexts are considered morphogenic conditions, which allow the predisposition to hillslope processes for landslides.

Besides, most of the Colombian population is established in the Andean region, where the principal cities are located, such as the capital district Bogotá with a population of 7674366 habitats, and Medellín city with an estimated 1999979 habitants (World Population Review 2023). In addition, the cities have a problem with land management due to the illegal occupation of steep zones at high risk for landslides, associated with internal and external migratory issues to the internal conflict in Colombia (UNHCR 2023).

This is why in recent years, the catastrophic events associated with landslides in Colombia (Garcia-Delgado et al. 2022) have encouraged the development of early warning systems and forecast models that accurately represent natural hazards that affect all kinds of civil infrastructure (Cepeda and Murcia 1988, Godoy et al. 1997, Echeverry and Valencia 2004, SIATA 2007, Huggel et al. 2007, IDEAM 2008, Aristizabal et al. 2010, Dominguez et al. 2010, Corpoguajira 2011, Acosta 2013, Vejarano 2013, Calle and Lozano 2014, SIRE 2014, Jerez 2014, DAGRAN 2021).

In Colombia, several methodologies have been applied to face the abovementioned problems of social, climate, and natural geological hazards. For example, in recent years, the works of Aristizábal et al. (2015, 2016) used the distributed hydrological SHIA Landslide model applied on a catchment-wide scale in tropical and mountainous terrains at “La Arenosa” catchment located on the south-eastern side of the Central Andean in the municipality of San Carlos in the Antioquia, Colombia region. The importance of applying the model in this catchment is to simulate the rainstorm on 21 September 1990, associated with a high-intensity rainfall of 208 mm precipitation in 3h and triggered many landslides that affected the population and several infrastructures (Aristizábal et al. 2015). The results of the simulations were hazard maps of landslides giving a spatial distribution of the landslides that were compared with the occurred landslides (inventory) during the rainstorm event showing good accuracy with 55.3% of the total catchment area of the “La Arenosa” being potentially unstable under rainfall conditions, in this way 77% of the pixel were correctly predicted. However, the model erroneously classified 22% of pixels as stable (Aristizábal et al. 2016).

In García-Aristizábal et al. (2019), the model TRIGRS coupled with the FOSM probabilistic method (First Order Second Moment) is applied on a catchment-wide scale in an urban zone of the municipality of Envigado in Antioquia region, Colombia at the Central Andes. The geotechnical data were obtained from the territorial planning studies and the historical rainfall data from rain gauges in the municipality. The deterministic simulations in TRIGRS considered the return of periods of 10 and 100 years for the most critical event. The FOSM probabilistic method evaluated them by showing hazard maps results where the most critical zones are associated with the high slopes and Quaternary unconsolidated soil units, meaning a good response of TRIGRS to represent soil infiltration rates under steady and transient regimes associated with different intensity-duration storm events. In the same catchment, Marin and Velásquez (2020) developed a parametric analysis by assessing the influence of the hydraulic soil properties during different rainfall events simulations using TRIGRS to define rainfall thresholds. The results showed that the increased saturated hydraulic conductivity did not produce a noticeable variation in the rainfall thresholds. Still, its range of applicability increases, and the starting point decreases (from larger to shorter durations). However, the rainfall threshold position had a more significant variation to the parameters of the soil water retention curve (Marin and Velásquez 2020), stating the model dependence on the soil hydraulic properties.

Marin et al. (2019, 2020a) implemented the TRIGRS in 93 distributed small-catchment scales in the Colombian Andes to show relationships between the morphometric parameters of the catchments with the rainfall threshold positions. The geotechnical data and morphometrics were obtained from planning management studies, and the rainfall data from rain gauges supported information to simulations under different intensities and durations. The results of this work show a unique response of each catchment to the same simulations even if they are closer, resulting in thresholds defined for specific catchments that cannot be extended to a different area. The catchment parameter most strongly affects the rainfall threshold position is the extent of terrain with slopes over 30° (Marin et al. 2020a).

In another work, Marin et al. (2021a, 2021b) developed a sensitivity analysis using the physically-based models TRIGRS, SLIP, and by Iverson (2000) in a scarce data catchment to wide-scale at “La Liboriana” catchment located in the Central Colombian Andes in the municipality of Salgar, Antioquia region, Colombia where on May 17, 2015, a channelized debris flow flooded the town. The spatial data for this work were obtained from ALOSPALSAR to get a digital elevation model of 12.5 m x 12.5 m; the geotechnical and hydraulic data were parameterized from the principal geologic units using literature methods (Hodnett and Tomasella 2002, Chowdury 2010) and the rainfall data from a rain gauge of IDEAM (Colombian National Weather Service) and a radar SIATA (https://siata.gov.co). The results of the simulations of each model were compared with the landslide inventory of May 18, 2015, using a ROC analysis. Thus, Marin et al. (2021a) stated that the SLIP model produces less critical results and is considerably less sensitive to low-intensity rainfalls in simulated conditions. Meanwhile, the Iverson and TRIGRS models decreased FS in the lower part of the catchment (low-intensity event) even though failures were not predicted (FS ≥ 1.0), concluding that the models demonstrated a moderately good performance considering the uncertainties of the input data. On the other hand, other models have been applied considering the effects of vegetation and eco-hydrological models, such as in the works of Muñoz (2018), where a slope stability model is developed relating the safety factor to soil moisture and Muñoz et al. (2018) where the influence of hydraulic parameters to the safety factor is assessed and validated by probabilistic approaches.

The application of the above-mentioned models and choosing them to assess the occurrence of shallow landslides in Colombia lies, from a hydrological point of view, in the capacity they have to model the steady and transient water infiltration patterns associated with the complex Andean climatic dynamics and from a geotechnical point of view in the broad parameters they can adopt to simulate the soil conditions in a diverse parental geological setting.

DISCUSSION AND CONCLUDING REMARKS

Colombia’s location in northwestern south America and the confluence between the Pacific and Atlantic oceans allow the occurrence of different climate processes, such as the influence of the Inter-Tropical Convergence Zone (ITCZ), the three low-level jets, the low-pressure Amazon climate system, the convectional topography processes, and various processes in both the Pacific and Atlantic oceans (Cerón et al. 2022) and the ENSO in both phases, warm (El Niño) and cold (La Niña) (Poveda et al. 2012, Carmona and Poveda 2014, Arias et al. 2015, Serna et al. 2018, Mesa et al. 2021). Furthermore, globally has been estimated that climate change has increased the intensity and frequency of heavy precipitation by about 7% per 1°C temperature increase (Seneviratne et al. 2021). Considering the complexity of Colombian precipitation patterns, the variation in space and time of rainfalls in Colombia due to climate change has been reflected in the occurrence of catastrophic events such as floodings (Sedano et al. 2013) and landslides (Sanchez and Aristizábal 2018, Aristizábal et al. 2022). This socio-environmental problem raises a challenge of understanding how the instability is distributed during heavy rainfall events within mountainous tropical catchments and how they respond to these effects.

Jaramillo-Gonzalez et al. (2021) propose an unpublished methodology that defines physically-based rainfall thresholds for shallow landslides simulating rainfall events with variable intensities and durations, using the coupled-distributed physically-based model TRIGRS in several catchments in the Colombian Andean region with diverse morphometric parameters and morphogenetic conditions. TRIGRS is selected to carry on the simulation for its capacity to model steady and transient water infiltration flows associated with heavy rainfall events with variable intensities and durations and its mathematical basis that allows the geotechnical parametrization of shallow-landslides (Table 1. Eq. 1; Table 2. Eq. 5). The goal of this methodology is performing a statistical analysis by calculating the area under the probability density function (PDF) (Evans et al. 2000, Weisstein 2023) from the resulted histogram of the calculated distributed safety factor by TRIGRS in the catchments, allowing to pursue a unique/natural threshold or limit condition for shallow-landslides in each catchment according to the correlation between the morphometric parameters of the assessed catchments and the resulted area under the probability density function.

Finally, physically based models provide the timing and location of shallow landslides by using geotechnical, hydrological, and topographical information, accurately forecasting natural phenomena, and aiding the development of early warning systems. However, it is required detailed information and parameters that sometimes are not available for a specific site; this is why it is necessary to keep looking for methodologies that allow the understanding of how the safety factor varies in catchments with different morphometric parameters that would enable having different hydrological responses and to various rainfall events due to variable climate and geological conditions in Colombia.

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