Effect of the Rainfall Infiltration Processes on the Landslide Hazard Assessment of Unsaturated Soils in Tropical Mountainous Regions

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Abstract

Natural disasters caused by meteorological phenomena are affecting countries of the world with increasing frequency, and they are producing severe damage to population and its infrastructure, hampering the economic development of the countries. The rainfall-induced landslides occur almost every year in all mountainous regions, and globally, 14% of economic losses and 0.53% of deaths from disasters caused by natural phenomena are attributed to landslides. For this reason, landslide risk assessment has become more applied in recent years. We present an assessment of the effect of rainfall infiltration on unsaturated soils on slope stability. Initially, a theoretical approach of the problem is presented, and a model of probabilistic analysis is described. Subsequently, an application of the model is carried out in an eastern zone of Medellin, Colombia. The probability of saturation and the landslide hazard are determined and validated considering the effect of a rainfall event registered in November 2010 that caused severe damages in the studied zone. The influence of infiltration under static scenario is evaluated using two different approaches, and the soil parameters for these evaluations are determined by field and laboratory tests. Finally, the effect of the rainfall infiltration processes on the landslide hazard assessment of evaluated unsaturated soils is determined.

Keywords: rainfall infiltration, slope stability, unsaturated soils, landslide hazard, wetting front progress, rainfall threshold

1. Introduction

Natural disasters caused by meteorological phenomena are affecting countries of the world with increasing frequency, and they are producing severe damage to population and its infrastructure, hampering the economic development of the countries. For this reason, landslide risk assessment has become more applied in recent years. The rainfall-induced landslides occur almost every year in all mountainous regions, and globally, 14% of economic losses and 0.53% of deaths from disasters caused by natural phenomena are attributed to landslides [1].

Landslide hazard assessment and the capacity to predict these phenomena has been a topic of great interest within scientific community to try to prevent human and economic losses aforementioned, by implementation of early warning systems (EWSs), and they have been applied to reduce the risk from natural hazards through monitoring devices designed to minimize the impact imposed by a threat [2]. In regard to the magnitude of the landslide issue, numerous studies have been developed in recent years, and they have increased the understanding of the causes involved in these morphodynamic processes. However, because of the complexity related to landslide occurrence, there is still great uncertainty in predicting their occurrence, considering three relevant aspects: magnitude, place, and periodicity.

The landslides often occur in environmental settings that are harsh for the conventional methods of landslide monitoring. For this reason, it considers pertinent and usefully combines physical models with ground-based monitoring technique on a GIS environment, since the aim is to minimize human losses and damage to infrastructure by a natural phenomenon such as landslides, preferably in urban zones, since the degree of urbanization is very important in relation to the potential damage.

This chapter presents an assessment of the effect of rainfall infiltration on unsaturated soils on slope stability. Initially, a theoretical approach of the problem is presented, and a model of probabilistic analysis is described. Subsequently, an application of the model is carried out in an eastern area of Medellin, Colombia. The probability of saturation and the landslide hazard are determined by simulating the effect of a rainfall event registered in November 2010 that caused severe damages in the city. Finally, the effect of infiltration under a static scenario is evaluated. Soil parameters for these evaluations are determined by field and laboratory tests.

2. Problem background

In highly populated and mountainous countries, quantifying landslide hazard and other risks associated with heavy rainfall is important, because landslides cause damage to property and loss of human lives. Due to high levels of impact on mass movements, this has generated a great interest in the study of related phenomena in an attempt to understand physical aspects [1, 3–6] and economy-related issues [7–10].

The behavior of natural slopes can be associated in a broad sense as a combination of often different and complex hydro-mechanical processes. These kinds of physical processes depend on the slope geometry, the nature, and the structure and hydro-mechanical properties of the soils. Also, the boundary conditions and the initial state of the slope must be considered. It is important to take into account that any action causing a change in the boundary conditions or even in the loading conditions is prone to trigger both strains and displacement; climatic factors can be considered among the main triggering causes of such displacements that may generate mass movement. Any modification of these factors influences the water content and the pore water pressure regime in the slope, hence the stress state, and the available strengths, possibly generating slope failure [11].

The hydro-mechanical and hydraulic conditions of the terrain and the state of saturation of the soil are determinant on the conditions of stability of slopes. The rainfalls have a double effect: reduce the soil cohesion and increase the pore pressure. This influence of the rainfall on slope stability depends of the duration and intensity of the rainfall. Usually, just a single factor becomes the triggering element, generating an almost immediate response, which is to mobilize slope materials. This triggering factor is generally rainfall or earthquakes. In tropical regions covered by residual soils and subjected to tropical rainfall regimes, a high percentage of these landslides are triggered by heavy, frequent, or prolonged rainfall [6, 12–15]. The role of rainfall infiltration on triggering landslides in tropical regions is being a challenge for geotechnical and geologists engineering [16].

Due to geological, geotechnical, and geomorphological uncertainties, it is usually difficult to predict where and when a landslide may occur. Nevertheless, it is generally recognized that changes in the water content of the soil imply changes like increase in pore pressure, decrease the effective stress of the soils, and, thus, reduce the shear strength [16]. Thus, understanding the physical conditions (i.e., if they are saturated or not) within variably saturated slopes when failures occur is needed for accurate assessment and prediction [17]. Many authors have been working worldwide on the subject of the rainfall-induced landslides, especially in countries like Italy, Switzerland, Spain, Taiwan, Singapore, and China. To do this, they have been proposed in the literature, empirical rainfall thresholds, and physically based models. Even in countries affected by the effects of intertropical convergence zone, area with high rainfall periods, such as Colombia and Brazil, have been joining forces for the generation of computer applications that allow the evaluation of slope stability based on empirical and physically based methods.

Understanding the processes that trigger a landslide is crucial to any successful landslide assessment and zonation. This topic is an active field of research worldwide, and it is required to find out the critical factors that trigger landslides. Research is required to establish the spatial and temporal prediction of hazardous zones and estimation on the probability and magnitude of future landslide. According to this, it considers the following research questions: Are the engineers relating the effect of infiltration on the instability of slope processes correctly? Can physically based models be used as a significant tool to evaluate the effect of infiltration process in slope stability? Proposed models reproduce the real phenomenon in an adequate form? The limitations of some techniques of evaluation and monitoring of landslides triggered by rainfall can be compensated or minimized with the advantages of other techniques used for the same purpose, so to be articulated to establish an integral proposal on this subject?

Some of the answers to the questions aforementioned are well known, also processes involved. However, some mismatches between theory and experiment exist yet. Hence, further investigations are required to understand better, if these gaps correspond to lacks in the theoretical background of the phenomena involved or to the experimental errors in field measurements.

Hence, the current approach involves several fronts to solve the complexity and uncertainty of the addressed problem:

- A numerical modeling to solve the system of equations describing the failure mechanism due to rainfall. In this part, it is included numerical modeling of slope stability, considering the effects of infiltration process and spatial variability of geotechnical and hydraulic parameter of soil.
- An experimental work in a laboratory with controlled conditions to evaluate how the propagation of water flows inside an unsaturated soil.
- An instrumentation of tests field for coupling of proposed theoretical and experimental models. This part will permit the validation of models under realistic conditions of geotechnical, geomorphologic and hydraulic parameters, and rainfall patterns.

These approaches clarify the effects of rainfall and its consequent infiltration in slope stability of unsaturated deposits of tropical mountainous regions.

3. Methodology

Quantitatively, the risk (R) can be defined in terms of the hazard $P[T]$, understood as the total probability of a threatening event that happens, and the vulnerability $P[C|T]$, understood as the conditional probability of damage considering that a failure has already occurred and the cost of the consequences C, by the equation:

$$R = P[T] \times P[C/T] \times C \tag{1}$$

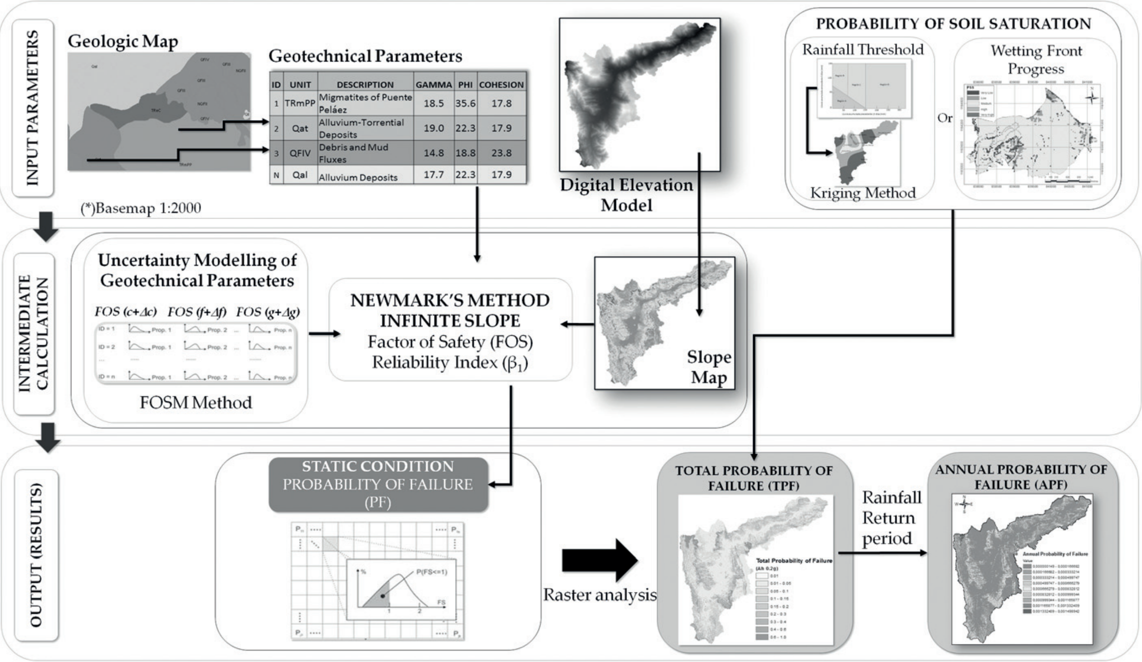
This paper emphasizes landslide hazard through a probabilistic methodology for hazard assessment, which uses methods as first order second method (FOSM) and failure thresholds.

3.1. Landslide hazard assessment

The methodology for the landslide hazard assessment was developed by [10, 18] through a calculation model based on FOSM. The methodology shown graphically in **Figure 1** allows calculating the total probability of failure (TPF) according to the theorem of total probability of failure of a slope by the equation:

$$TPF = P[T] = P_{fs} \times P_s + P_{fns} \times (1 - P_s) \tag{2}$$

where P_{fs} is the probability of slope failure due to the action of the rainfall in saturated condition, P_{fns} is the probability of failure where condition is not saturated, P_s is the marginal probability which the soil is in a saturation condition, and $(1 - P_s)$ is the marginal probability which the soil is not in this condition. The slope probability of failure in both saturated and unsaturated condition usually can be calculated in an independent way. However, determining the probability that the soil is in a saturated condition is complicated, especially due to the complexity of the phenomenon that considers variation of the conditions of soil water content. The effect of accumulated rainfall and that the occurrence of landslides is possible to be related



ID	UNIT	DESCRIPTION	GAMMA	PHI	COHESION
1	TRmPP	Migmatites of Puente Peláez	18.5	35.6	17.8
2	Qat	Alluvium-Torrential Deposits	19.0	22.3	17.9
3	QFIV	Debris and Mud Fluxes	14.8	18.8	23.8
N	Qal	Alluvium Deposits	17.7	22.3	17.9

Figure 1. Schematic methodology adopted for hazard assessment.

to the amount of rainfall through so-called failure thresholds or numerical models with physical base to estimate the probability of saturation [19].

The probabilities of failure P_{fs} and P_{fns} are calculated by reliability index (β_1), as the probability that the factor of safety (FOS) is less than unity:

$$\beta_1 = \frac{E[FOS] - 1}{\sigma[FOS]} \tag{3}$$

$$P_f = \Phi(-\beta_1) \tag{4}$$

where $E[FOS]$ is the deterministic value of FOS calculated with the mean values of the independent associate variables, and $\sigma[FOS]$ is the standard deviation of FOS, considering that the critical value of FOS is 1.0. Φ is the standardized normal probability distribution. The β_1 index is related to the probability of failure, allowing a more consistent stability assessment. The most common way to assess the slope stability is using limit equilibrium methods with planar or circular surfaces. Particularly, for regional analysis, the concept of infinite slope is often used [7]. The resulting expression for infinite slope model in this work is presented as below:

$$FOS = \frac{c + \left(\gamma H - \gamma_w \gamma H_w\right) \cos\beta^2 \tan\phi}{\gamma H \sin\beta \cos\beta}. \tag{5}$$

where H is the thickness of the failure zone [m], H_w is the water height measured from the failure surface [m], c is the soil cohesion [kPa], φ is the angle of internal friction of the soil [°], γ is the unit weight of soil [kN/m^3], γ_w is the unit weight of water [kN/m^3].

In mountainous tropical regions, landslides occur most often in rainy seasons in which increased soil saturation with consequent decrease in their cohesion and increased pore pressure are presented. The process of decrease in the shear strength due to changes in water content is a highly complex process, which is not considered in the development of this study. Therefore, the effect of saturation is taken into consideration only in the increase of the water pressure, and for purposes of analysis in this study, two situations were considered for the water height measured from the failure surface (H_w), one where the water level presented in the most critical condition was considered, i.e., $H_w = H$ to obtain P_{fs} and another favorable in which $H_w = 0$ to obtain P_{fns}. The eventual saturation condition of the soil is a random phenomenon that must be taken into consideration in the evaluation of the probability of landslides. In this case, it was considering the probability that the soil is saturated or not.

3.2. Probability of soil saturation (PSS) by rainfall thresholds

Slope stability in tropical areas is highly affected by rainfall but also depends on soil properties such as shear strength and hydromechanical properties. It has been identified that high-intensity rainfall affect slopes in well-drained residual soils (permeability coefficient of saturated soil $k_s \geq 10^{-4}$ m/s), while low intensity and long duration rains mainly affect poorly drained slopes ($k_s \leq 10^{-6}$ m/s), rainfall in which the intensity match k_s [20, 21].

In the other hand, it has been identified that the relationship between rainfall and landslides is influenced by conditions of preceding rainfall or accumulated rain on the ground before the triggering event [22–32], named thresholds of failure. There are proposed thresholds of failure in terms of the intensity of rainfall and the accumulated rainfall of several days [25], but in areas where insufficient rainfall information is available, thresholds have been set in terms of accumulated rainfall with precedent rainfall of 15, 30, 60, and 90 days and different durations of triggering events as 1, 3, or 5 days [22, 23]. Jaiswal and Van Westen [3, 27] conducted research in which empirical thresholds were used to estimate the probability of failure in slopes of roadways of southern India using the Poisson distribution.

The thresholds of failure can be used to assess the triggering effect of rainfall on landslides and the landslide hazard. Eq. (6) shows the relationship between rainfall and landslides in natural slopes of “La Iguana” river basin in the city of Medellin, Colombia, for assessing the landslide hazard [29]:

$$A = R_3 - 60 + 0.55R_{15} \tag{6}$$

where A is the hazard of landslide triggered by rainfall, R_3 is the 3-days antecedent rainfall, and R_{15} is the accumulated rainfall of 15 days preceding the R_3.

Eq. (6) was determined with 40 records of landslides and rainfall data of the meteorological station “San Cristobal” of the de Medellin public services company in the period 1980–2001. This threshold was exceeded by 95% of data processed. Later, [30] studied the relationship between rainfall and landslides in the department of Antioquia, Colombia, for the time period 1974–1998. With a total of 283 landslides, a threshold has been determined according to the equation:

$$R_3 = 75 - 0.5R_{15} \tag{7}$$

The similarity between Eqs. (6) and (7) results logical because "La Iguaná" river basin is located in the department of Antioquia, but the differences are associated with the use of different periods of time and geological considerations in the analysis. "La Iguaná" basin has high human intervention due to its proximity to hard urbanized areas of the city of Medellin. The threshold proposed by [30], which is presented in Eq. (7), is used by the early warning system of the Aburra Valley, Colombia-SIATA, to define the level of hazard [31]. In other works, has been identified as the most important constraint for the occurrence of landslides in the Aburra Valley are the long-term accumulative rainfall of around 60 mm in 30 days, 160 mm in 60 days, and 200 mm for 90 days by the seasonal rainfall.

For landslide hazard on roadways, Hidalgo and Assis [32, 33] presented a threshold as a relationship between precedent rainfall of 15 days and antecedent rainfall of 5 days. For precedent rainfall of 30 days, they reported exceedance rates greater than in the cases of 15 and 60 days. Considering that accumulated rainfall for 15 and 30 days are easier to obtain, thresholds based on rainstorms of 5-days duration and previous rainfall of 30 and 15 days are proposed, as shown in **Figure 2**. It is important to highlight that this relationship was determined with rainfall data of days when there were landslides of the manmade slopes of the roadway. Due to this, this threshold is lower than those defined by Eqs. (6) and (7) despite being located in the same river basin "La Iguana" [34].

In a methodology presented by [1], the thresholds are used to asses P_s. It is accepted that the condition given by the failure threshold represents a saturation condition conducive to landslides, with the already mentioned reduction of shear strength of the material due to the decrease in suction and pressure generation of pores [1, 20, 32]. The probability of saturation is calculated as the probability that the ordered pair accumulated rainfall preceding of 15 days

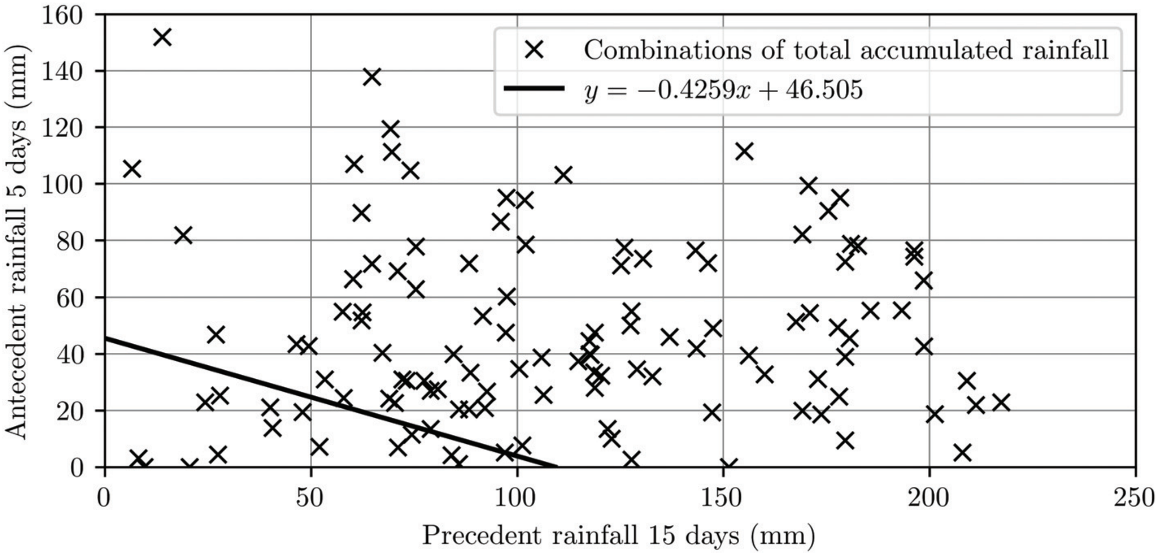


Figure 2. Combinations of total accumulated rainfall of 5 and 15 days, for days with landslide events [35].

(R_{15}) and, accumulated rainfall antecedent of 3 days (R_3), is above the failure threshold line for study area, i.e., soil is considered to be saturated if the relationship of the equation is true:

$$R_{3m} \geq R_3 \tag{8}$$

where R_{3m} is the accumulated rainfall from 3 days calculated from records of rainfall gauges, and R_3 is the accumulated rainfall from 3 days calculated using the equation for threshold calculation.

Based on the concepts presented above, records for each rainfall station were organized, and mobile windows from accumulated rainfall of 15 and 3 days were calculated for each date. Likewise, for each date, 3-days rainfall value was calculated using a threshold value defined by the threshold equation. The comparison between 3-days rainfall values was established as shown in Eq. (8). In order to establish the likelihood that the threshold was exceeded, the number of times which the threshold was exceeded along the records was determined, and then, this value of occurrences was divided by the total number of rainfall records, which for the methodology used in this work represents that soil reached the condition of critical saturation (**Figure 3**). The return period for these events is determined using a Gumbel distribution for the accumulated rainfall. After determining the probability that the soil is saturated according to data from meteorological stations, a geostatistical interpolation process to estimate the probability of saturation in each of the cells, its mean P_s is estimated spatially.

3.3. Probability of soil saturation (PSS) by physically based methods

The effect of rainfall on slope stability is due to a complex physical process involving the advance of the wet front and the consequent increase in pore pressure and reduction of soil cohesion. Coupled models that consider the gradual advance of the wet front have been developed [24, 33, 35–42]; however, obtaining the input parameters is difficult and expensive, so these are not yet in common use. Consequently, the most rigorous methods are still

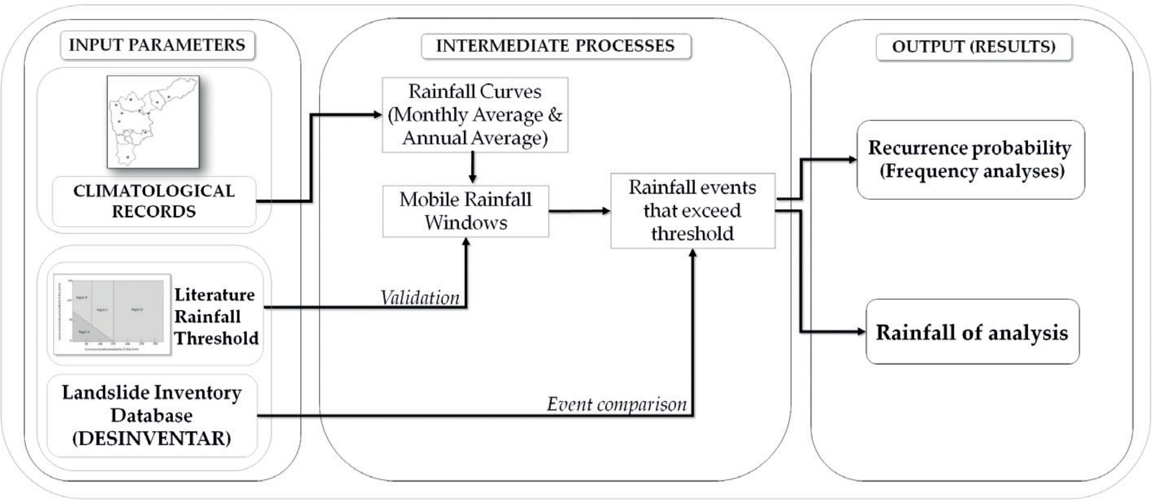


Figure 3. Schematic methodology adopted for exceedance probability and rainfall of analysis.

recommended only for preliminary assessments, and for special cases, when a good amount of measurements of the involved parameters is possible [40].

In recent years, slope stability analyses have been expanded to include coupled hydromechanical processes under variably saturated conditions. These analyses incorporate the variation of saturation, leading to more accurate assessments of slopes stability (under infiltration conditions), and demonstrate that a better physical representation of water flow and stress can be attained in unsaturated soils [17]. Hence, the analysis of seepage and coupled stress-deformation should be linked simultaneously [13]. Some recent studies are specifically focused on infiltration-induced landslides. However, most of these studies only consider slope failure below the groundwater table, overlooking the contribution of effective stress (suction stress) to the strength of the soil under transient unsaturated flow conditions [17]. Generally, these works use the Richards equation for water flux:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} - sen\alpha\right)\right] \tag{9}$$

where α is the angle between flux direction and horizontal plane, h is the pressure head, z is the coordinate of the parallel position to the flow direction, $K(h)$ is the hydraulic conductivity for a given pressure head, which in turn is a function of soil volumetric moisture content Θ, and t is the time. The relationship between the suction and the degree of saturation, or moisture content, is established by means of the soil water characteristic curve (SWCC), as shown in **Figure 4**.

There are several empirical models to describe the characteristic curves [43]. However, in this work, it is proposed to use the equation of Fredlund and Xing [44]. This is a model of three

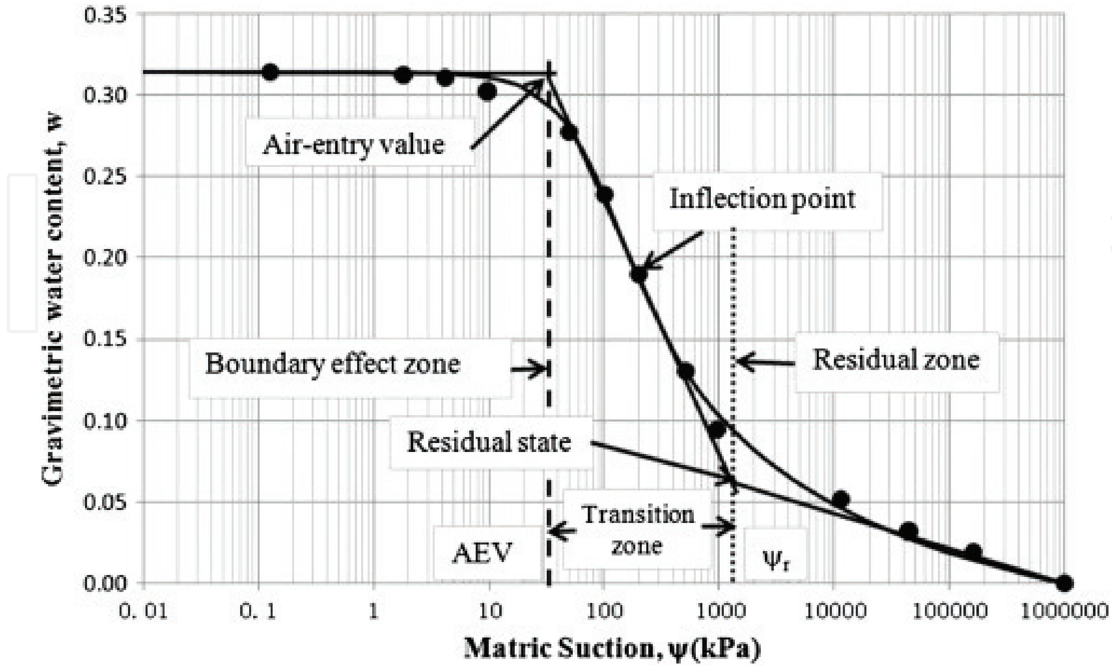


Figure 4. Zones of the soil water characteristic curve [46].

continuous parameters for the entire suction domain. The parameters of the model are related to the air inlet pressure (*a*), the distribution of pore sizes (*n*), and the symmetry of the curve (*m*). The model is based on the possibility of describing the distribution of soil pore sizes from statistical functions [45]. The proposed equation, obtained from integrating a law of frequency distribution in the suction domain, corresponds to:

$$\theta = \frac{1}{\left[\ln\left(e + \left(\frac{\psi}{a}\right)^{n}\right)\right]^{m}} \tag{10}$$

$$a = \psi_I \tag{11}$$

$$m = 3.67 \ln\left(\frac{\theta_s}{\theta_i}\right) \tag{12}$$

$$n = \frac{1.31^{m+1}}{m * \theta_s} * 3.72 * s * \psi_I \tag{13}$$

where Ψ is the matric suction, Ψ_I and θ_I are the coordinates of the inflection point, and θ_s is the saturated water content.

Most of the time, the infiltration evaluations are done in a deterministic way, which ignores the uncertainty that is present in this flow process. As it was presented above, it is necessary to estimate the probability of saturation in order to calculate the total probability of failure. There is a probabilistic analysis which ignores the spatial variability of the unsaturated deposits of soil and underestimates the probability of slope failure. Due to this, the effects of soil spatial variability on unsaturated slope have been scarcely studied. In this work, a probabilistic methodology that uses the FOSM method and the Richards' equation to obtain the probability of saturation is proposed. Similarly, in the β_1 index for *FOS*, for the saturation probability in terms of *Z*, a reliability index β_2 as a function of the hydraulic properties of the soil in addition to the wetting front progress modeled is defined as:

$$\beta_2 = \frac{E(Z_c) - Z_c}{\sigma_Z} \tag{14}$$

where Z_c is the deep (m) of the wet front, $E(Z_c)$ is the Z_c mean, and σ_Z is the standard deviation of Z_c obtained using the FOSM method described in Eqs. (3) and (4) taking as a function the Richards' equation.

To solve the Richards' equation, this methodology uses the CHEMFLO-2000 software [47], which is based on the finite difference method. Soil parameters (characteristic curve and saturated permeability) are required as input data. In this case, the Fredlund and Xing model is used and some borders conditions are defined as a flow rate, infiltration rate, or hydraulic load. Any of these boundary conditions requires that the rainfall characteristics of the zone be determined. To do this, it can use the following procedure (**Figure 5**).

- Getting rainfall information from meteorological stations near the study area. These rainfalls can be accumulated daily or with a higher resolution and must have records for at least 20 years.

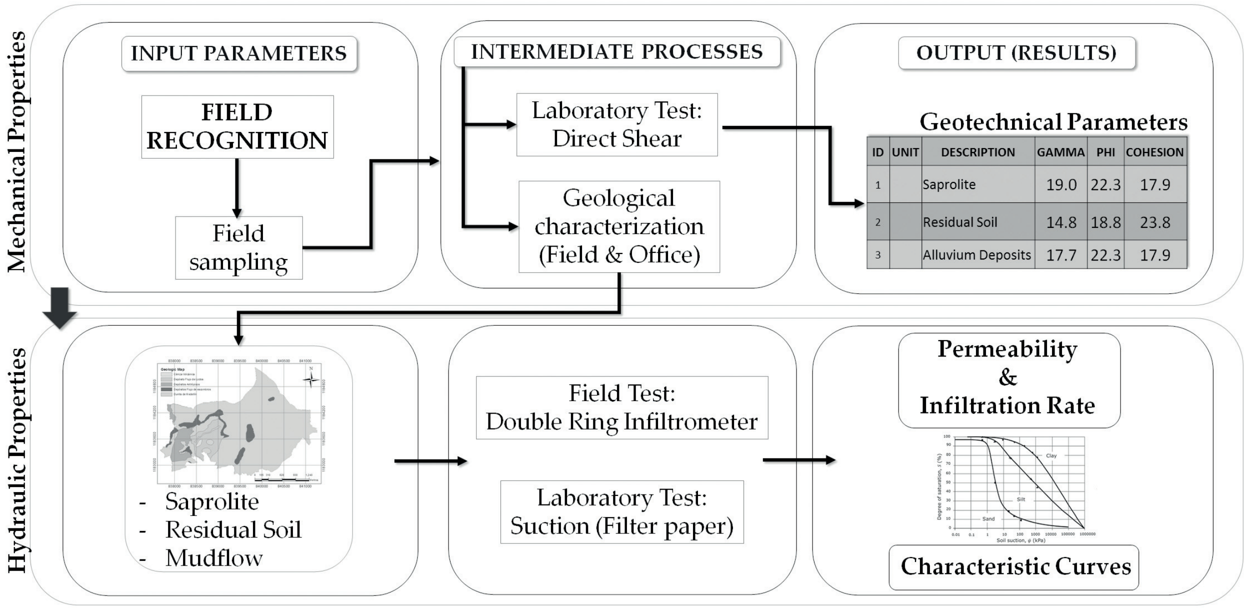


Figure 5. Schematic methodology adopted for infiltration assessment.

- To calculate the infiltration, process by which water penetrates from the surface into the soil, using the Horton, Green-Ampt, and the curve number (CN) models [49]. In the study of infiltration processes, a particular problem is to determine the variation of the soil infiltration capacity, the variation of the wetting front, and the suction of the soil that occurred during a rainfall event, since they influence the magnitude of the torrential avenues associated with this event.

4. Application case

The study area is located in the northwest of Colombia, on the eastern central slope of the Aburra Valley, in the city of Medellin. Specifically, the area is located in the “Llanaditas” neighborhood on the northwestern flank of the Aburra Valley (**Figure 6**).

4.1. Soil and rainfall characterization

The geology of the study area is predominantly characterized by the presence of dunites, slope deposits, and anthropic deposits. On the other hand, the statistical analyzes were carried out on soils of the predominant geological formations in the central area of the municipality of Medellin, the basement rocky is composed mainly of rocks corresponding to dunite from Medellin, which may be covered by slope deposits. Soil resistance parameters were obtained from the analysis of a database of 193 direct shear tests performed on unaltered samples located in the study area, of which 78 tests were performed on slope deposits, 56 on dunite residual soil, and the remaining 59 on saprolite of dunite from Medellin [49]. The results of the mechanical characterization of the materials and their variability are reported in **Table 1**.

Hydrological information was obtained from the “Villa Hermosa” meteorological station, which has 67 years of records that begin in July 1948 and end in July 2015. Different procedures

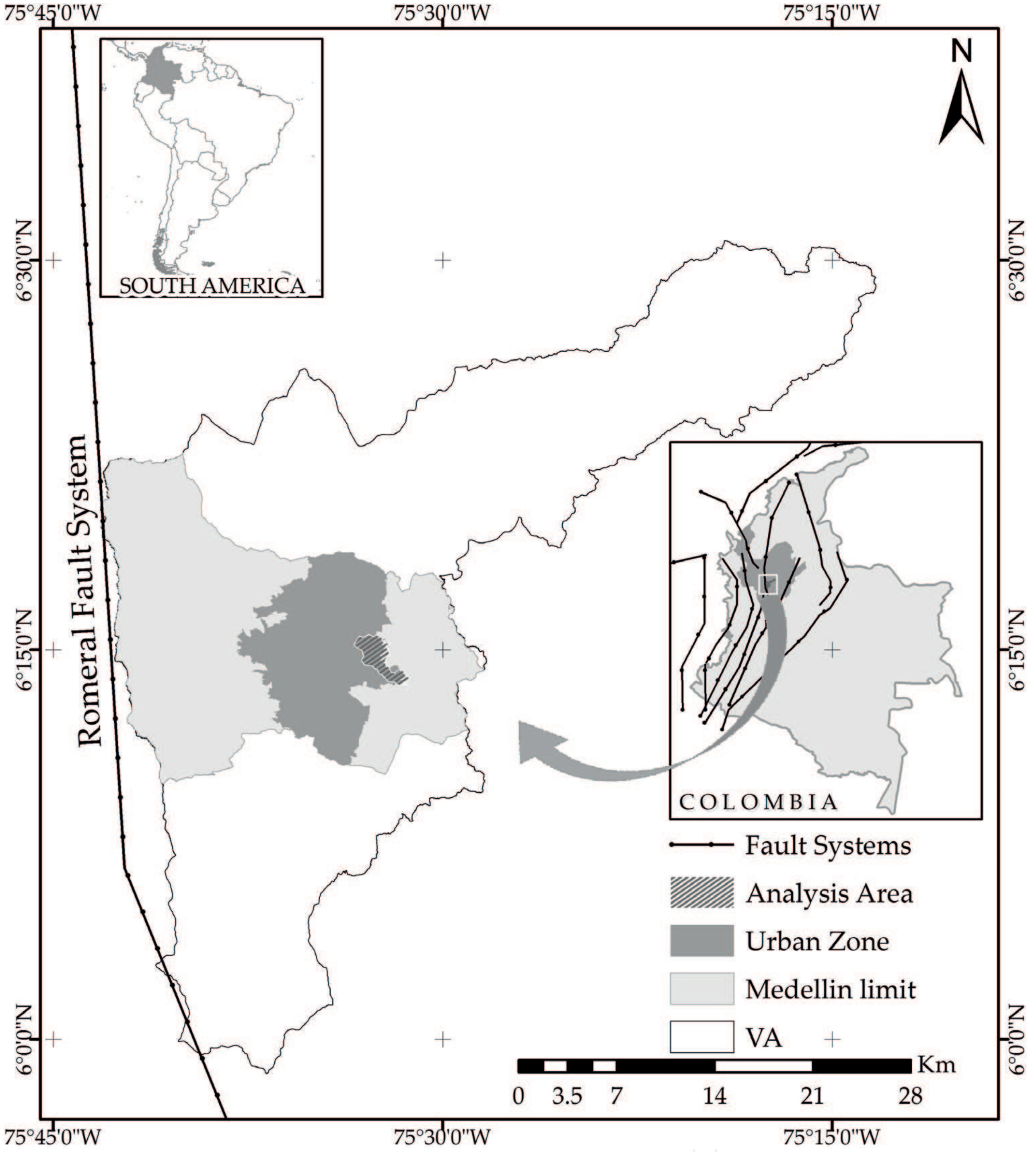


Figure 6. Study zone location [48].

were performed, which have as a fundamental principle, the processing of the rainfall data of the station. The average daily rainfall values are presented in **Figure 7**. Through the average annual cycle of monthly rainfall, two annual peaks were identified in the analysis period, corresponding to the months of May and October, months with average rainfall greater than 180 mm [19]. The daily rainfall was determined for the analysis period, and the calculation of the rainfall of the previous 3 and 15 days was carried out for the subsequent classification of the events, according to the thresholds defined by [31].

Geologic unit	Parameter	n	$\bar{x}$	σ	CV (%)
Mudflow	γ_h (kN/m^3)	78	14.42	1.47	8.45
	γ_d (kN/m^3)	78	11.72	2.11	18.03
	c (kPa)	78	19.91	10.42	52.34
	ϕ (°)	78	24.11	5.52	22.89
Residual soil	γ_h (kN/m^3)	56	17.75	1.21	6.84
	γ_d (kN/m^3)	56	12.04	1.59	13.19
	c (kPa)	56	20.76	14.66	70.62
	ϕ (°)	56	23.87	7.31	30.88
Saprolite	γ_h (kN/m^3)	59	17.29	1.41	8.16
	γ_d (kN/m^3)	59	10.96	1.95	17.79
	c (kPa)	59	15.56	12.11	77.8
	ϕ (°)	59	24.04	7.07	29.39

Table 1. Mechanical characterization of the materials [49].

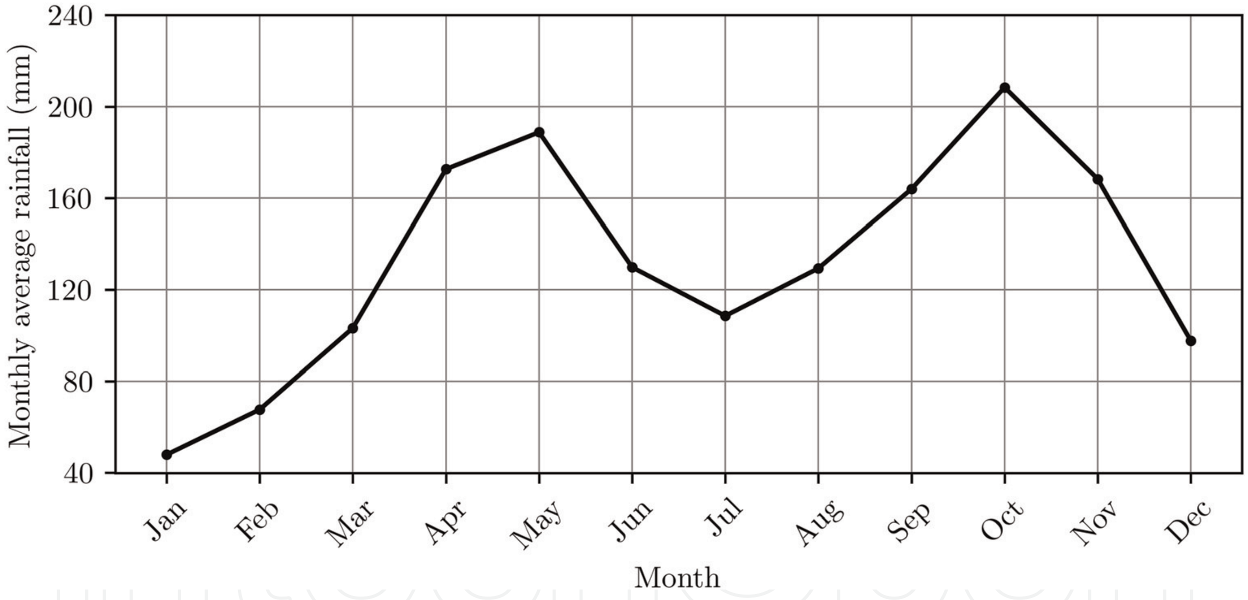


Figure 7. Average annual cycle of monthly rainfall for the period 1948–2015.

Subsequently, a day of analysis was selected that coincided with some database record within the historical records of landslides in the Aburra Valley [19]. The disaster that occurred on November 13, 2010, in "Villa Tina" neighborhood, urban area of the city of Medellin, was selected for the analysis, because it is located in the same area where "Villa Hermosa" station is located. In the area, there was a mass movement which was detonated by high-accumulated rainfall in the previous days [50] and that resulted in the death of one person, one person injured, one house destroyed, and two more houses were affected. **Figure 8** shows daily rainfall data for 18 days preceding the event, which according to the documented information

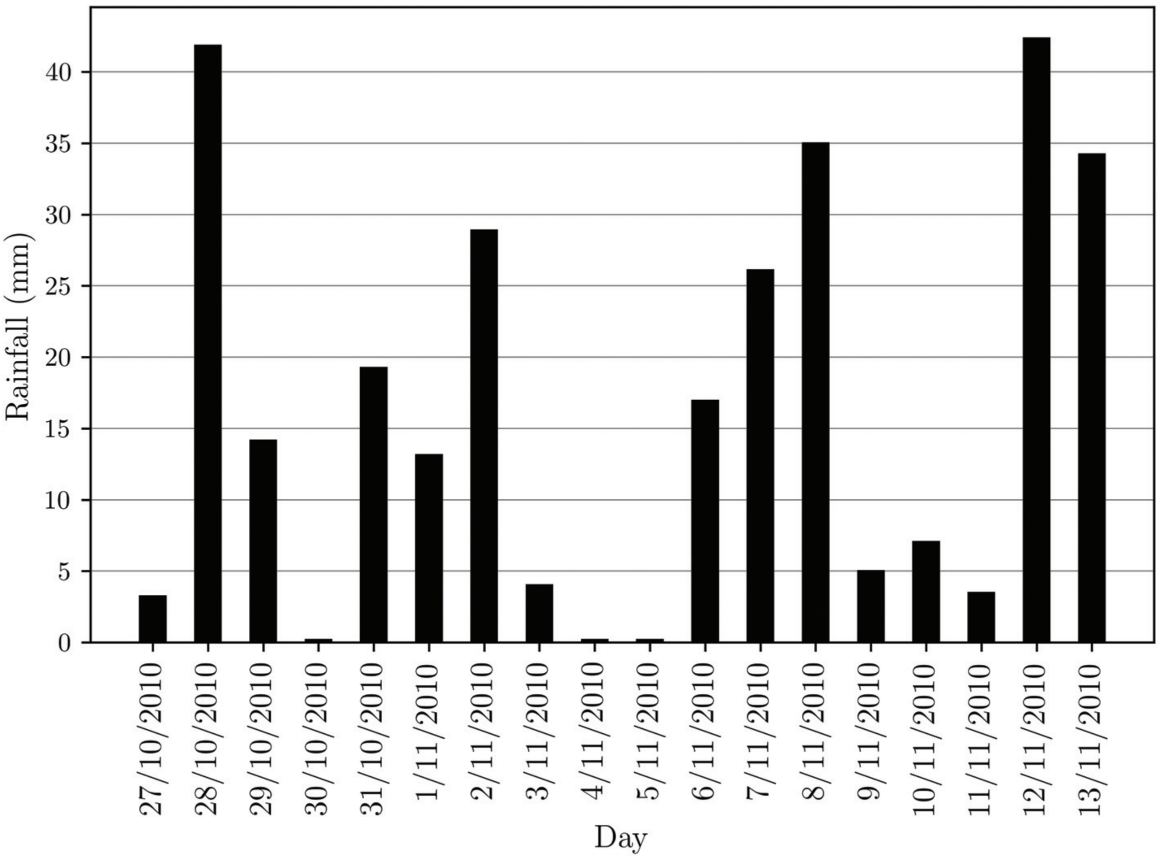


Figure 8. Daily rainfall of 18 days antecedent to the mass movement of day 13 of November 2010.

is the cause of the mass movement, also this accumulative rainfall is 296.4 mm, it has a return period of approximately 20 years; therefore, the probability of the event being exceeded is 5%.

In order to evaluate the probability of exceedance of the rainfall threshold, a frequency analysis of the data was performed, where the rainfall series of 18 days that exceed the threshold were selected, the annual maximum records were selected, and with these results, the probability of recurrence was determined for different return periods and confidence intervals according to the distribution functions proposed by Gumbel, Log-Normal, and Frechet (**Figure 9**). Alternately, field and laboratory tests were performed to measure soil hydraulic capacity. A double ring infiltration tests and suction tests with filter paper (in the laboratory) were performed for each geological formation of interest, with the aim to calculate the characteristic curve of these soils. The infiltration rate, which is the rate at which the water penetrates the soil through its surface, is expressed in mm/min, and its maximum value coincides with the hydraulic conductivity of the saturated soil.

Once defining the mechanical and hydraulic properties of the soil, the boundary conditions and hydrogeological properties of the soil were determined. Rainfall data were collected, allowing to validate the failure thresholds and the amount of water infiltrated in this punctual zone. For this purpose, rainfall data were collected with daily resolution in the analysis period. This information was processed in order to characterize the rainfall regimes of the area.

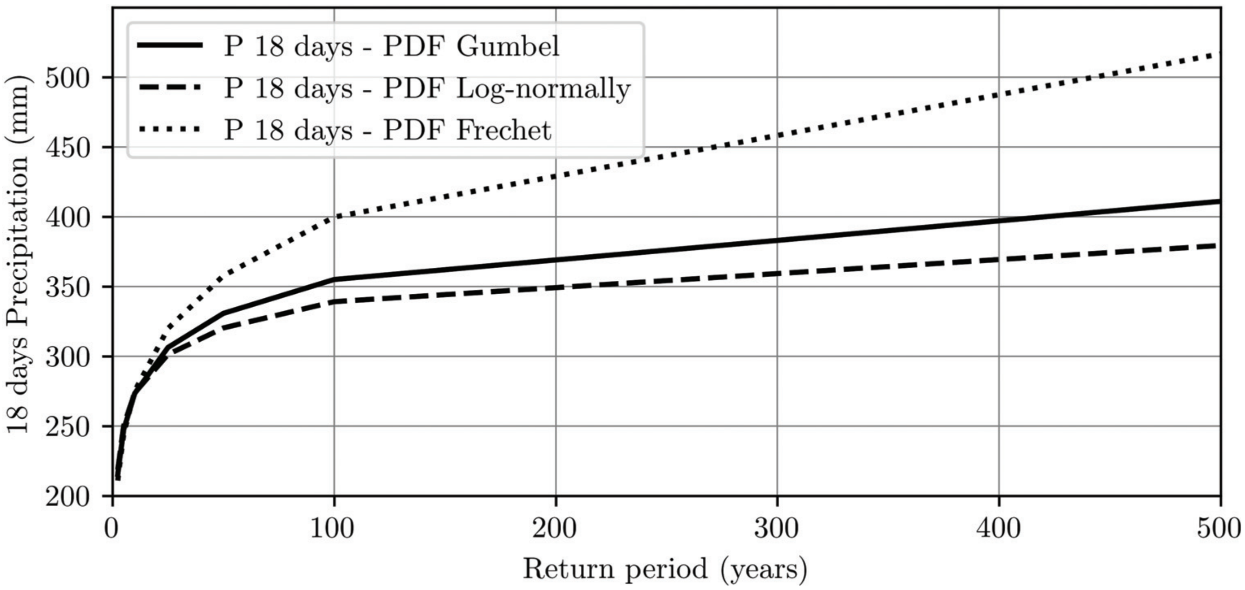


Figure 9. Probability of event exceedance for different return periods and different PDFs.

Subsequently, a rainfall event was established which exceeded the failure thresholds and that had been documented. For this event, the intensity of the rainfall was determined.

To validate the water flow through the soil by infiltration processes on the formations of the study area, it was necessary to quantify this phenomenon. For this reason, the Horton, Curve Number, and Green & Ampt models were used, which allow to calculate the amount of infiltrated water for an event of 18-days duration. **Table 2** presents the uniform infiltration rate for the analysis time (cm/h). The results obtained from the infiltration tests allowed to determine the permeability of soils. In the case of soils derived from the dunite from Medellin, at the level of residual soil and saprolite, the infiltration rate was 0.8 mm/min, and for the mudflow, it was 0.2 mm/min [19].

Suction tests with filter paper were also carried out in order to obtain the characteristic curves of the soil (**Figure 10**) and to determine the adjustment parameters for each of the models considering the theoretical characteristics curves presented in the literature by [51, 52].

Infiltration method	**Infiltration rate (cm/h)**	
	Residual soil	**Mudflow**
Curve Number CN (zone 1)	0.041	0.029
Curve Number CN (zone 2)	0.019	0.013
Horton	0.068	0.049
Green & Ampt	0.058	0.035

Table 2. Uniform infiltration rate [19].

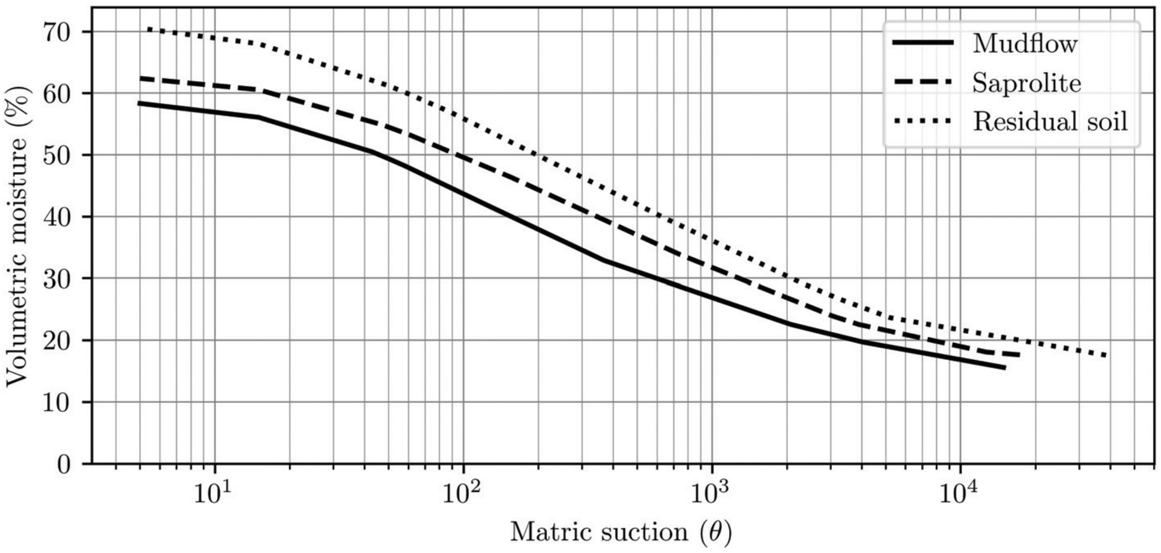


Figure 10. Soil water characteristic curve for tested soils.

4.2. Results obtained from probability of saturation using rainfall thresholds

Using the failure threshold defined in Eq. (8) and "Villa Hermosa" meteorological station data, a threshold exceedance probability of 17.81% was determined for the 67-year analysis; however, for a particularly rainy year such as 2010, the threshold exceedance was 39.72% (**Figure 11**).

4.3. Results obtained from probability of saturation using the physically based model

In order to evaluate the infiltration using the Richards' equation, the parameters corresponding to the characteristic curve, as well as the initial conditions and boundary

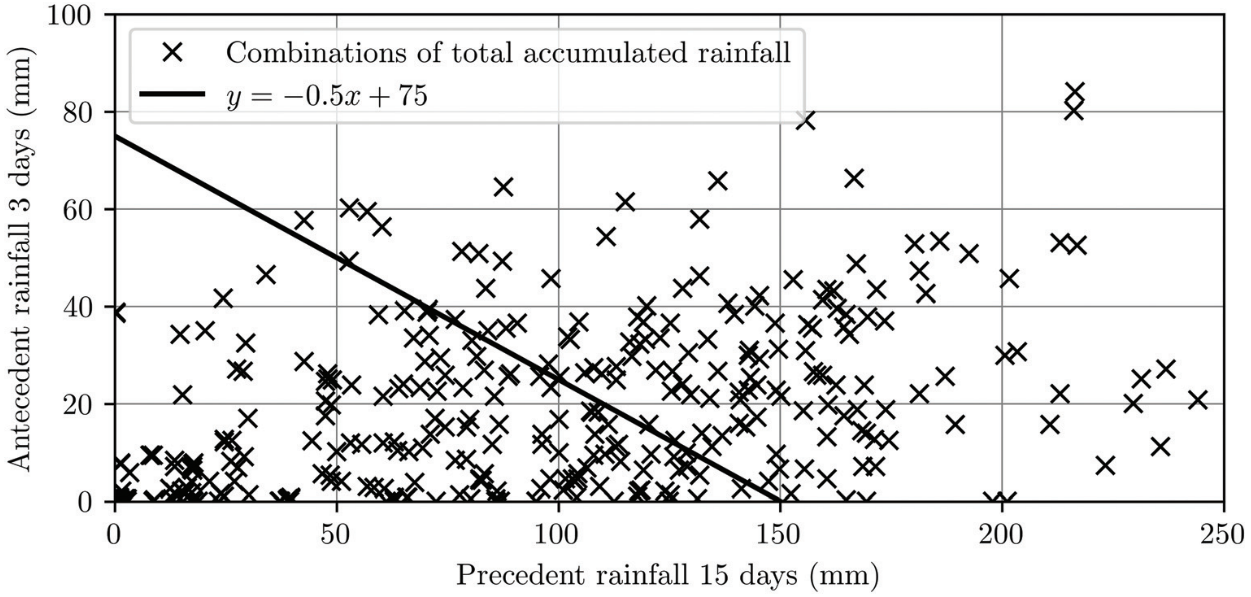


Figure 11. Probability of saturation through threshold exceedance (year 2010).

conditions described in [19], were entered into the numerical model (CHEMFLO-2000). Modeling the wetting front progress was identified considering the relationship between the moisture content and the soil suction, for a previously characterized rainfall event. To determine the probability of saturation, the first order second order method (FOSM) was used.

For this, the probability distribution of the wetting front progress was determined, in function of the random variables that condition this function (α, n, θ_s, θ_r). A modeling was done in the software, using the infiltration model of the curve method as the most conservative, the random variables were slightly modified by a parameter of variation α, which according to the literature can be assumed 10 (ten).

In order to determine the standard deviation of the selected parameters, a statistical base of 44 data was collected, which were collected from the literature and laboratory tests executed in the development of this work [19]. It reports the expected value and the reliability index for each formation of the hydraulic properties that allow to finally determine the probability of saturation (**Figure 12**).

4.4. Results obtained from landslide hazard assessment

The landslide hazard assessment was calculated as the probability of landslides occurring in the area using the ArcGIS software. The area was divided into a grid of 25 m, generating 7766 calculation elements. Each cell was assigned the shear strength parameters shown in **Table 1**. Likewise, each cell was assigned a saturation probability according to those determined in the previous sections for different depths of the wetting front progress and rainfall threshold. **Figure 13** presents the results of the hazard assessment in “Llanaditas” neighborhood, taking into account the failure threshold and the wetting front progress, respectively, considering different depths 0.2, 0.5, and 1 m.

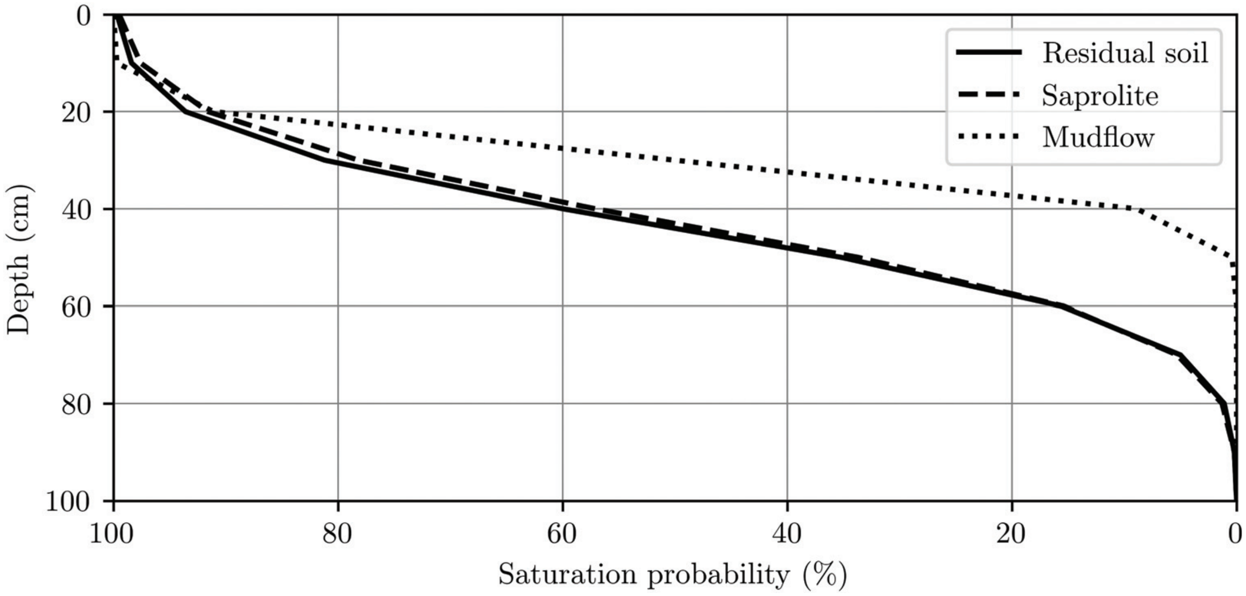


Figure 12. Probability of saturation according to depth, for each surface formation.

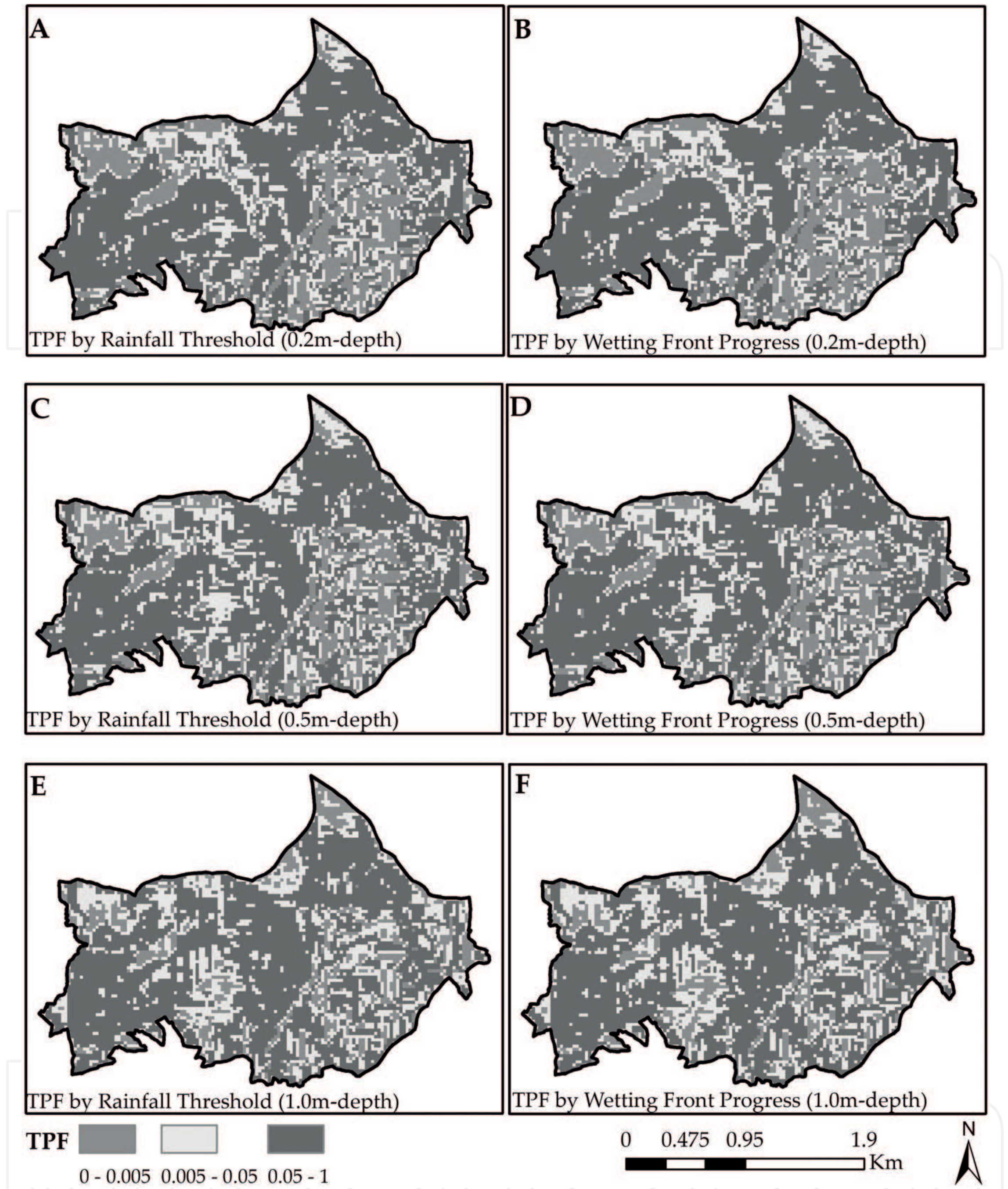


Figure 13. Total probability of failure (static condition) at different depths considering wetting front progress and rainfall. (A) TPF by rainfall threshold (0.2 m-depth), (B) TPF by wetting front progress (0.2 m-depth), (C) TPF by rainfall threshold (0.5 m-depth), (D) TPF by wetting front progress (0.5 m-depth), (E) TPF by rainfall threshold (1.0 m-depth), (F) TPF by wetting front progress (1.0 m-depth).

According to the stability analysis, it can be concluded that the stability condition of the slopes (in static condition) decreases with the increase of the probability of saturation, which occurs in the superficial strata (from 0.2 m), encouraging the configuration and/or evolution of instability phenomena of varying magnitude due to loss of shear strength. As shown in the **Figure 13**, between both empirical and physically based approaches, three evaluated scenarios present a difference approximately of 1% for the *TPF* intervals considered.

5. Conclusions

Rainfall is the main trigger of mass movements in tropical regions, so the evaluation of its effect on stability becomes increasingly important, leading to the generation of increasingly complex models.

There are several proposals to consider the effect of rainfall on slope stability, empirical models such as failure thresholds, and physically based analytical models. The approximate solution of these analytical models is more used today. A probabilistic approach such as the one presented in this work allows to incorporate in the analysis the different sources of uncertainty that affect the behavior of the infiltration in soils and permit evaluating the effect of the rainfall infiltration processes on the landslide hazard assessment of unsaturated soils in tropical mountainous regions.

It was observed that in the soils considered, the variation of the wetting front, in rain conditions such as those shown, only affects the most superficial layer of the soil, reason why the effect of the rains mainly generates faults of the shallow type.

The rainfall threshold approach is an efficient methodology to evaluate shallow landslide with respect to physically based approach (wetting front progress), because it requires less processing time, characterization soils, laboratory tests, and elaborated methodological approaches.

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