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HAZARD ESTIMATION FOR LANDSLIDES TRIGGERED BY EARTHQUAKES AND RAINFALL (ABURRÁ VALLEY-COLOMBIA)

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ABSTRACT

This article presents a hazard estimation for landslides triggered by earthquakes and rainfall in the Aburrá Valley in Colombia using a geographic information systems (GIS) platform. To carry out the estimation, a model that considers the topographical, geological, geotechnical, and hydrological characteristics of the studied area was developed. The model used is based on the Newmark's pseudostatic model and uses a probabilistic approach based on the technique of first order and second moment -FOSM-. The process calculates the probability of occurrence of a landslide triggered by an earthquake that produces an acceleration (Ah), considering the uncertainty of the geotechnical parameters and conditions of soil saturation.

KEYWORDS: earthquakes, GIS, hazard, landslides, Newmark.

ESTIMACIÓN DE LA AMENAZA POR DESLIZAMIENTOS DETONADOS POR SISMOS Y LLUVIA (VALLE DE ABURRÁ-COLOMBIA)

RESUMEN

En este artículo se presenta una estimación de la amenaza por deslizamientos detonados por sismos y lluvia en el Valle de Aburrá-Colombia, utilizando una plataforma de sistemas de información geográfica (SIG). Para esto se desarrolló un modelo que considera las características topográficas, geológicas, geotécnicas e hidrológicas de la zona en estudio. El modelo utilizado se basa en el modelo seudoestático de Newmark y utiliza un enfoque probabilista basado en la técnica del primer orden y segundo momento -FOSM-. El proceso calcula la probabilidad de que ocurra un deslizamiento dado que se presente un sismo que produzca una aceleración (A_h), considerando la incertidumbre de los parámetros geotécnicos y las condiciones de saturación del suelo.

PALABRAS CLAVE: amenaza; deslizamientos; Newmark; SIG; terremotos.

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ESTIMAÇÃO DA AMEAÇA DE DESLIZAMENTOS CAUSADOS POR TERREMOTOS E PELA CHUVA (VALLE DE ABURRÁ COLÔMBIA)

RESUMO

Em este artigo, é apresentada uma estimativa da ameaça de deslizamentos de terra causados por terremotos e chuva no Vale do Aburrá, Colômbia, através de uma plataforma de sistemas de informação geográfica (SIG). Para isso foi desenvolvido um modelo que considera as características topográficas, geológicas, geotécnicas e hidrológicas da área de estudo. O modelo utilizado é baseado no modelo seudoestático de Newmark e usa uma técnica probabilística com base na técnica da primeira ordem e segundo momento-FOSM-. O processo calcula a probabilidade de que ocorra um deslizamento dado que se apresente um tremor de terra, que produz uma aceleração (Ah) considerando a incerteza dos parâmetros geotécnicos e as condições de saturação do solo.

PALAVRAS-CHAVE: ameaça; deslizamentos de terra; Newmark; SIG; terremotos.

1. INTRODUCTION

In Colombia, mass movements and floods are the two natural phenomena that create the greatest hazards. This is due mainly to their various and different geological and physiographical characteristics, as they can be caused by natural or anthropic factors. As a particular case of this situation, the conditions in the mountainous zone of the city of Medellín and neighboring municipalities, in terms of terrain, climate, topography, geology, and other factors, make the region susceptible to geomorphodynamic processes that can affect both the population and the infrastructure (Vega, 2013).

In general, mass movements are caused by a combination of different triggering factors, such as earthquakes or rainfall, and they are a frequent cause of disasters around the world (Hidalgo 2013). Specifically in the Aburrá Valley (AV), mass movements have caused considerable economic and human losses. Due to human settlements and infrastructure projects on the valley's slopes, the risks associated with mass movements have increased in recent years. It is estimated that in the AV, 35% of damages to buildings and 74% of deaths due to natural phenomena are associated with mass movements (Aristizábal and Gómez, 2007), while at the global level, 14% of economic losses (Bonachea, 2006) and 0.53% of deaths due to disasters caused by natural phenomena are attributed to mass movements (Chowdhury et al., 2010).

Due to the high level of impact of mass movements, many studies of associated phenomena have been undertaken to understand the physical aspects (Jibson et al., 1998; Coronado, 2006; Jaiswal and Van Westen, 2009a and 2009b; Jaiswal et al., 2010; Delgado et al., 2006; AMVA, 2009) and economic aspects (Zêzere et al., 2005; Zêzere et al., 2008; Remondo et al., 2008; Godt et al., 2008; Salciarini et al., 2008; Vega, 2013) of mass movements.

Of special significance among these studies are those that focus on risk analysis and require hazard to be estimated before the studies' completion. However, the majority of these are based on susceptibility mapping. In the cases in which concepts of hazard are used, hazard is generally estimated with algebra using maps and historical information that do not consider the behavior of materials and potential failure mechanisms. Physical and probability-based models are alternatives for including failure mechanisms and the variability of parameters in hazard calculation.

This study presents an approach that considers physical and probability-based models to estimate the hazard of mass movements in the AV. A hazard evaluation for landslides caused by earthquakes and rainfall was carried out in a regional scale using a GIS application for the AV. This article presents the methodology, materials used, and results obtained in the hazard evaluation.

2. MATERIALS AND METHODOLOGY

A model for calculating slope stability was created considering the infinite slope model in order to estimate the hazard of landslides as the probability that a slope failure will occur, incorporating the concepts of critical acceleration and factor of safety.

For the case of landslides, the probability of failure P[T] will be understood as the probability that the slope will fail given that a disastrous event occurs. Although the failure could take place due only to gravity, it is more commonly caused by a triggering agent such as earthquakes or rainfall. **Figure 1** shows the methodology used, and the steps are described below.

Determining entry data

The information required by the model must be entered into the application in Raster format, corresponding to a regular grid of cells. In this case, square cells of 100m per side were used. Each type of material defined in the geology map was given parameters for resistance and unit weight. The model assigns these parameters to each cell and calculates the factor of safety and critical acceleration in the cell. To do so, it takes the angle of the predominant gradient based on the digital elevations model (DEM). The information used in the model corresponds to that used by Vega (2013):

- DEM:

We obtained the model representing the spatial distribution of elevations and topography in the area of study, which originally has a cell size of 10m (AMVA, 2007), which is adequate for this study given that larger cell sizes were used for the analyses, as is shown in **Figure 2b**.

Figure 1. Schematic representation of methodology used

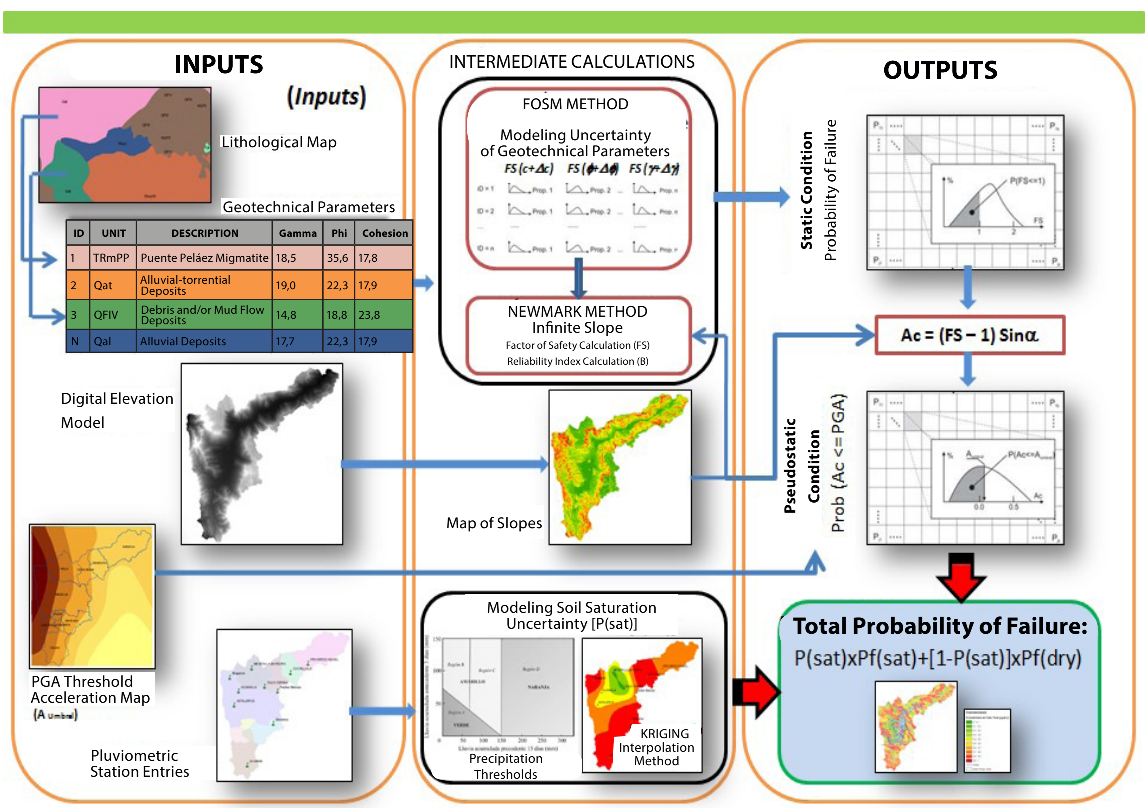
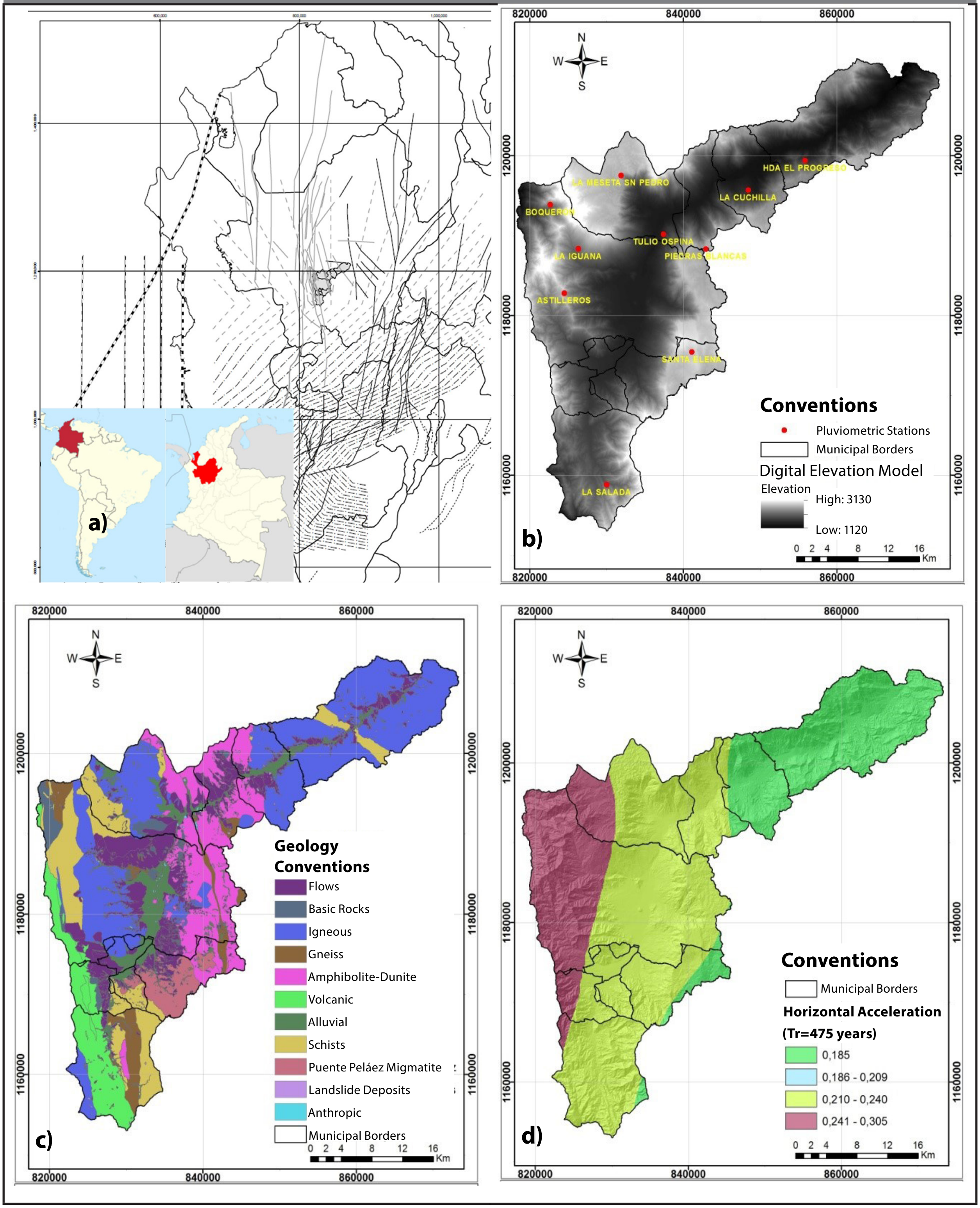


Figure 2. (a) AV's location and fault systems that affect it, **(b)** Digital terrain model, **(c)** Geological map, **(d)** Map of seismic accelerations (Modified from AMVA, 2007)



• Geological units:

The AV is located in the northern part of the Central Colombian mountain chain and is an elongated topographical depression, as is shown in **Figure 2a**. Due to its location, the AV is in an area of medium to high seismic hazard (AIS, 2010), and the main sources of hazard are earthquakes originating in the subduction zone in the Cauca-Romeral fault system and other smaller systems (AMVA, 2007). **Figure 2a** shows the main fault systems described in the AV's seismic microzonation.

According to AMVA (2007), the landscape conditions in the AV are framed by a narrow valley to the south which widens in the Medellín municipality, reaching about seven kilometers in width, then narrows again in the Copacabana municipality. In terms of elevation, there are variations in the mountains that surround the valley, which can reach up to 3000 meters in the San Miguel, Padre Amaya, and Boquerón peaks. The region also includes the high plateau zones of San Vicente, Rionegro, and Santa Elena in the east and Llano de Ovejas in the west.

The AV and the high plateaus that surround it show a varied geology with outcrops of lithological units that include rocks of different age, origin, and composition. In regards to age, there is a range from Paleozoic rocks to Quartinary deposits, and in terms of origin and composition, there are metamorphic rocks such as schists, amphibolites, migmatites, and gneiss; igneous rocks such as granodiorites, dunites, gabbros, and basalts; volcanic-sedimentary rocks and alluvial and slope deposits, as well as anthropic rocks (AMVA, 2007).

Based on the geological map shown in **Figure 2c**, the predominant soils in each sector of the AV were determined. According to the information presented in Vega (2013), Hidalgo (2013), and Hidalgo et al. (2012), each of these soils has been assigned the resistance and unit weight parameters shown in **Table 1**. For each soil, the table also shows the denomination used in the geological map and the values of the median (μ) and standard deviation (σ) attributed to each parameter complied by Vega (2013).

Table 1. Soil properties (Vega, 2013)

Geological unit	Descripción	Init weight (kN/m^3)		Friction angle (°)		Cohesion (kPa)	
		μ	σ	μ	σ	μ	σ
PZagC	Caldas granatiferous amphibolite	18,90	0,94	29,90	2,99	34,30	17,15
TRaM	Medellín ambhibolites	18,90	0,94	29,90	2,99	34,30	17,15
PZaAM	Minas Peak amphibolites	18,90	0,94	29,90	2,99	34,30	17,15
KcdA	Antioquia batholith	18,00	0,90	26,20	2,62	35,50	17,15
Qal	Alluvial deposits	17,70	0,88	29,00	2,90	35,00	17,50
Qat	Alluvial-torrential deposits	19,00	0,95	35,00	3,50	12,00	6,00
NFI	Debris and/or mud flow deposits	14,80	0,74	32,00	3,20	28,40	14,20
JKuM	Medellín dunites	16,00	0,80	24,00	2,40	30,00	15,00
TReaB	Baldias amphibolic schists	17,60	0,88	27,00	2,70	55,00	27,50
TReC	Cajamarca schists	17,60	0,88	27,00	2,70	55,00	27,50
PZeC	Caldas schists	17,60	0,88	27,00	2,70	55,00	27,50
KgSD	San Diego gabbro	18,10	0,90	33,20	3,32	31,70	15,85
KgC	Copacabana gabbros	18,10	0,90	33,20	3,32	31,70	15,85
JgR	Romeral gabbros	18,10	0,90	33,20	3,32	31,70	15,85
TRgLC	La Ceja gneiss	17,90	0,89	19,00	1,90	16,00	8,00
TRgP	Palmitas gneiss	17,90	0,89	19,00	1,90	16,00	8,00

Table 1. Soil properties (Vega, 2013)

Geological unit	Descripción	Init weight (kN/m³)		Friction angle (º)		Cohesion (kPa)	
		μ	σ	μ	σ	μ	σ
JKgmS	Sajonia mylonitic gneiss	17,90	0,89	19,00	1,90	16,00	8,00
Qll	Anthropic rocks	19,00	0,95	17,00	1,70	10,00	5,00
JKmbP	Picacho metabasites	19,00	0,95	25,00	2,50	22,00	11,00
KvQG	Volcanic member	19,00	0,95	27,00	2,70	30,00	15,00
KvsQG	Volcanic sedimentary member	19,00	0,95	24,00	2,40	25,00	12,50
TRmPP	Puente Peláez migmatites	18,50	0,92	27,50	2,75	17,00	8,50
JmI	La Iguaná mylonite	19,00	0,95	32,00	3,20	16,00	8,00
JuR	Romeral peridotite	19,00	0,95	24,00	2,40	30,00	15,00
KdA	Altavista stock	18,00	0,90	29,00	2,90	19,00	9,50
TRgA	Amagá stock	18,60	0,93	31,00	3,10	16,00	8,00
KcdE	Las Estancias stock	18,60	0,93	31,00	3,10	16,00	8,00
KcdML	Media Luna stock	18,60	0,93	31,00	3,10	16,00	8,00
KtO	Ovejas tonalite	18,60	0,93	32,00	3,20	16,00	8,00

- Rainfall data:

Hydrologically, the AV is characterized by a rainfall regimen that has traditionally been bimodal with two rainy periods approximately in the months of March-April-May and September-October-November. The highest precipitation values are between 2800 and 3200 mm/year, and they occur in the northern and southern parts of the basin. The lowest precipitation levels, between 1400 mm/year and 1800 mm/year, occur in the central zone of the basin and extend toward the western zone (AMVA, 2007).

This study made use of precipitation data accumulated on a daily basis from 10 pluviometric stations located in the AV with registry series between 20 and 50 years. **Table 2** shows the stations used with their respective location in geographical coordinates.

Table 2. Pluviometric stations used for consideration of variable rainfall

Name	Latitude (N)	Longitude (O)	Data Period	Missing Data (%)
La Iguana	6° 18'	75° 39'	1990-2003	11.5
La Cuchilla	6° 22'	75° 27'	1970-1990	10.8
Astilleros	6° 15'	75° 40'	1991-2003	7.3
Tulio Ospina	6° 19'	75° 33'	1969-2003	7.1
Piedras Blancas	6° 18'	75° 30'	1970-1981	30.1
Hacienda El Progreso	6° 24'	75° 23'	1973-2003	8.9
La Salada	6° 2'	75° 37'	1984-2004	10.9
Boquerón	6° 21'	75° 41'	1970-1990	11.2
La Meseta San Pedro	6° 23'	75° 36'	1970-2004	12.1
Santa Elena	6° 11'	75° 31'	1970-2002	10.7

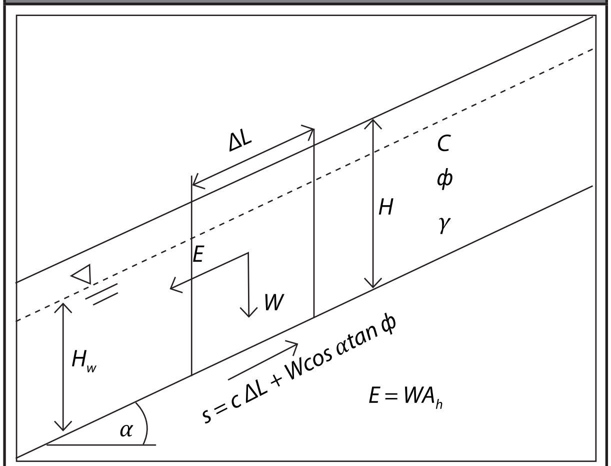
• Seismicity data:

For this case, we took one scenario given by the distribution of accelerations determined by the AV's seismic microzonation (AMVA, 2007) shown in **Figure 2d** and another with a uniform acceleration of 0.2g. For the evaluation presented in this article, we took the acceleration in the soil as the product of acceleration in the rock multiplied by the coefficient of importance, and the factors of vertical acceleration (*Fv*) assigned to each pixel according to the values determined in the *Normas Colombianas de Diseño y Construcción Sismo Resistente-NSR10* (Colombian Regulations for Earthquake-resistant Design and Construction-NSR10) (AIS, 2010).

Deterministic stability calculation

In order to consider the effect of earthquakes, we used the Newmark (1965) method, which is based on an infinite slope stability model. In accordance with the Newmark method for the evaluation of stability for landslides caused by earthquakes, the acceleration needed to cause a landslide, called critical acceleration (Ac), is calculated. To do so, pseudostatic methods are used in which the force due to the earthquake is added to the model as a fraction of the weight of the mass in movement. **Figure 3** below shows the expressions resulting from the infinite slope model that will be used in this study.

Figure 3. Diagram of model used for infinite slope



Both the static factor of safety calculated by the infinite slope method (*SFS*) and the critical acceleration (A_c) defined by Newmark (1965) are given by the following equations

$$A_c = (FSE - 1)\, sen\alpha \quad (1)$$

$$FSE = \frac{c}{\gamma H \cos\alpha \sin\alpha} + \frac{(\gamma H - \gamma_w H_w)\cos^2\alpha \tan\varphi}{\gamma H \cos\alpha \sin\alpha} \quad (2)$$

in which H is the thickness of the zone that fails [m], H_w is the elevation of water measured from the failure surface [m], c is the soil cohesion [kPa], φ the soil's internal friction angle [°], γ is the soil's unit weight [kN/m^3], γ_w is the water's unit weight [kN/m^3] and α is the terrain's average angle of inclination [°].

The resulting expression for critical acceleration for the infinite slope model is as follows:

$$Ac = \left(\frac{c}{\gamma H \cos\alpha \sin\alpha} + \frac{(\gamma H - \gamma_w H_w)\cos\alpha \tan\varphi}{\gamma H \sin\alpha} - 1\right) sen\alpha \quad (3)$$

In general, the critical acceleration results are indicators of the terrain's susceptibility, but they are not very indicative of the real hazard that exists. Therefore, the probability of failure (PF) must be calculated. To do so, the factor of safety is first determined for a defined value of acceleration (FSD), and based on this, the PF is calculated. In this case, FSD is determined with the expression:

$$FSE = \frac{c}{\gamma H(\sin\alpha + A_h \cos\alpha)} + \frac{(\gamma H - \gamma_w H_w)\cos\alpha \tan\varphi}{\gamma H(\sin\alpha + A_h \cos\alpha)} \quad (4)$$

in which A_h is the acceleration produced by the earthquake given as a fraction of the acceleration of gravity g.

Probability of failure

The probability of failure is determined as the probability that the values considered to be limit values will be exceeded. In the case of FSD, the probability of failure is determined as the probability that FSD will be less than the unit. In terms of critical acceleration, the probability of failure is determined as the probability that A_c will be greater than A_h.

One way of evaluating the probability of failure and at the same time quantifying the effect of uncertainty on the landslide hazard evaluation is the use of reliability techniques. Reliability is understood as the possibility a system has to complete the functions for which it was conceived. Reliability is determined using the reliability index which is related to a probability of failure. If we consider that the critical value of FSD is 1.0, the reliability index (β) of FSD is defined by the following expression: (Christian et al., 1994; Baecher and Christian, 2003):

$$\beta = \frac{(E[FSD]-1)}{\sigma\,[FSD]} \tag{5}$$

in which *E[FSD]* is the deterministic value of FSD calculated with the median values of the independent variables and σ*[FSD]* is the standard deviation of FSD.

The index β is related to the probability of failure, which allows for a more consistent evaluation of stability. It is worth noting that **Equation 5** is only valid if the Probability Distribution Function (PDF) of FSD is normal. When the probability distribution is different from normal, for example log normal, other formulations must be used (Christian et al., 1994; Baecher and Christian, 2003; and Rosenblueth, 1975).

The probability of failure is given by the portion of the area under the PDF curve of the *FSD* corresponding to *FSD* values of less than one (1). This can be determined based on any table of normal PDF with median zero (0) and standard deviation one (1). We must note that the normal distribution always gives greater probability values than the other distributions. Therefore, its use in stability evaluations gives a conservative approach (Baecher and Christian, 2003).

In this type of evaluation, one difficulty lies in being able to determine the PDF of the function being evaluated. In this case for FSD, probabilistic methods prove useful since they allow for determining the PDF of a dependent variable based on knowledge of the PDFs of the independent variables that generate it. According to Baecher and Christian (2003), among the methods most often used in statistics applied to geotechnics are the Monte Carlo method, the first order second moment (FOSM) method, and the point estimation method, among others. This study uses the FOSM method which, according to Baecher and Christian (2003), provides sufficient precision for engineering purposes, despite its simplifications.

The FOSM method uses the Taylor series to determine the probability distribution of a function with a number of random variables (Baecher and Christian, 2003). The advantages of this type of solution are due to the fact that the mathematical calculations are simplified and it is only necessary to know the moment values of the statistical distributions of the variables that make up the function. For N uncorrelated random variables, G(x_1, x_2,....., x_N), we have:

$$E[G] = G\left(\bar{x}_1\,\bar{x}_2\,,......,\,\bar{x}_N\right) \tag{6}$$

$$V[G] = \sum_{i=1}^{N}\left(\frac{\partial G}{\partial x_i}\right)^2 v\,(x_i) \tag{7}$$

in which $\bar{x}_i = E[x_i]$ corresponds to the median value of the variable x_i, $V(x_i)$ is the variance of variable x_i, $E[G]$ is the median or expected value of G, and $V[G]$ is the variance of G.

In the expressions above, the Taylor series was truncated at its second-order terms, meaning that the effects of the third and fourth probabilistic moments were disregarded. However, this approximation is considered completely acceptable for practical purposes (Baecher and Christian, 2003). The values of the derivatives can be obtained through analytical calculation, but it is more common and recommended to use the numerical approach suggested by Christian et al. (1994), according to which the derivative is estimated with the equation:

$$\frac{\partial G}{\partial x_i} = \frac{G\,(x_i + \Delta x_i) - G\,(x_i)}{\Delta x_i} \tag{9}$$

Similar to the way in which the index β is determined for FSD, for the probability of failure in terms of *Ac,* we can determine the occurrence of a reliability index b_1 defined as:

$$\beta_1 = \frac{(A_C - A_h)}{\sigma A_C} \tag{9}$$

in which A_c is the critical acceleration, A_h is the acceleration of the designed earthquake or the most likely earthquake in the area being studied, and σA_c is the standard deviation of the critical acceleration. In this case, the Ah values presented for the microzonation of the AV (AMVA, 2007) were used.

The probability of failure for the slopes was also calculated in terms of the action of an earthquake of probable magnitude. To do so, the accelerations given on the map shown in **Figure 2d** were used for a return period of 475 years.

General probability of failure

In the AV region, landslides occur most frequently in rainy periods in which there is an increase in soil saturation with a resultant decrease in soil cohesion and an increase in pore pressure. The process of reduction in shear resistance due to changes in water content is a highly complex process which was not considered in the development of this study. Therefore, in terms of the effect of saturation, only the increase on water pressure was taken into account, and for the purposes of analysis, this study considered two situations: one in which the water level is at the most critical condition, that is, H_w= H, and another favorable situation in which H_w=0.

For simplicity's sake, up until this stage the acceleration produced by the earthquake and the presence of water were considered to be deterministic variables, and therefore the probability of failure for the slope or hillside depended only on the variability of geotechnical parameters and pore pressure. The possible condition of soil saturation is a random phenomenon that must be taken into consideration in the evaluation of the probability of landslides. In this case, this was done by considering the probability that the soil is saturated or not. According to the total probability theorem, the total probability of failure for a slope is given by the equation:

$$P_{ft} = P_{fs} * P_s + P_{fns} * (1 - P_s) \quad (10)$$

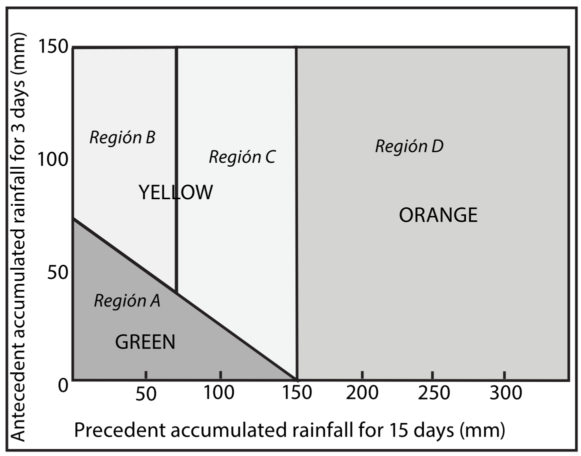
in which P_{ft} is the total probability of failure, P_{fs} is the probability of failure for the slope due to the action of the earthquake in saturated conditions, P_{fns} is the probability of failure in unsaturated conditions, P_s is the marginal probability that the soil is saturated, and (1-P_s) is the marginal probability that the soil is not saturated.

The probability of failure for the slopes in saturated and unsaturated conditions can be calculated independently, but determining the probability that the soil will be saturated is difficult due to the complexity of the phenomenon of variations in the soil's water content conditions. For the case of AV soils, there is little information that allows us to determine the probability that the soils will be saturated. However, in studies done by various authors (Echeverri and Valencia, 2004, Moreno et al. 2006, and Hidalgo et al., 2012), it has been established that the majority of landslides are caused by soil saturation due to the effects of accumulated rainfall and that the occurrence of mass movements may be related to the quantity of rainfall through what are referred to as failure thresholds. The *Sistema de Alerta Temprana del Área Metropolitana* (Metropolitan Area Early Alert System) (SIATA) has proposed that a failure threshold that relates rainfall accumulated for 3 days and rainfall accumulated for 15 days can be used for the AV (**Figure 4**). As **Figure 4** shows, this threshold had been proposed by Moreno et al. (2006) for the Department of Antioquia, in which the AV is located. The failure threshold is given by the equation:

$$R_3 = 70 - 0{,}47R_{15} \quad (11)$$

in which R_3 corresponds to the accumulated antecedent rainfall for 3 days and R_{15} corresponds to the accumulated precedent rainfall for 15 days.

Figure 4. Failure threshold proposed for Antioquia and the AV (Aristizábal et al., 2010)



This study supposes that the probability of soil saturation is related to the probability that the failure threshold will be exceeded. This consideration is a result of accepting that the condition given by the failure threshold represents a saturation situation favoring landslides with the aforementioned reduction in the materials' shear resistance due to the decrease of suction and the creation of pore pressure.

In the case studied by Hidalgo et al. (2012), the researchers calculated the probability that the threshold given by the accumulated rainfalls for 5 and 15 days would be exceeded, but in this study's case, we have calculated the probability of saturation as the probability that the ordered pair (R_{15}, R_3) are above the failure threshold line; that is, we consider that the soil will be saturated if the relationship of the following equation is fulfilled:

$$R_{3m} \geq R_3 \qquad (12)$$

in which R_{3m} is the accumulated rainfall for 3 days calculated from the pluviometric registries and R_3 is the accumulated rainfall for 3 days calculated with **Equation 12**.

Following the concepts presented above, for each of the pluviometric stations, we organized the registries and calculated the mobile windows of accumulated rainfall for 15 days and 3 days were calculated for each date. We also calculated the value of rainfall for 3 days for each date using the threshold defined in **Equation 11** and established a comparison between the values of rainfall for 3 days as is indicated in **Equation 12**. The number of times the threshold was exceeded during the registry period was determined, and this number of occurrences was divided by the total number of rainfall registries in order to establish the probability that the threshold was exceeded. For the methodology used in this study, this means that the soil reached a condition of critical saturation.

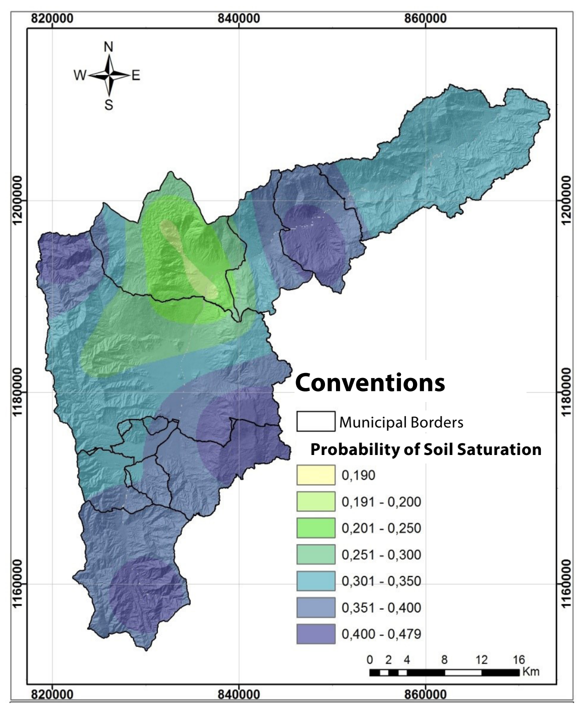
After determining the probability that the soil was saturated according to the data from each station, a geostatistical process was developed in order to estimate by interpolation the probability of saturation in each of the cells. The interpolation method used in this study corresponds to the Kriging Method, which is a non-biased linear estimator that allows researchers to generate continuous surfaces based on specific data and eliminate spatial variation tendencies given that the method assumes this variation is present in the data and causes measurement errors. **Figure 5** shows the distribution of the probability of saturation determined for the AV.

Programming the model

Based on this definition, we elaborated a model for determining hazard in terms of probability using programming and modeling techniques in the ArcGIS™ software's "ModelBuilder" Module.

The reliability index results obtained with **Equations 5** and **9** are exported to Microsoft Excel in order to calculate the PF, that is, the probability the FSD will be lower than the unit.

Figure 5. Distribution of the probability of soil saturation in the AV



3. ANALYSIS OF RESULTS

The model was initially run a series of times to calculate some analysis variables. Probabilities of failure were then calculated. Different depths from the failure surface of 2, 5, 10, and 20 meters were considered. Using the case of the failure surface at 5m deep as a point of reference, we observed an average decrease in FSD of 20% when the depth of the failure surface was 10m and of 30% when the depth was 20m.

The model was also run taking into account different phreatic levels (H_w) with the failure surface at 5m. Water levels of 0.3 and 5m were considered.

Using the results obtained with the failure surface at 5m and the water level coinciding with the failure surface (H_w=0) as a reference, we observed an average decrease of FSD of 20% when the water level was 3m and of 33% when H_w=5m. Although the mass movements registered in the AV are generally on the surface, that is, at depths around 2m, this study adopted a failure surface located at 5m of depth for the rest of the evaluations, considering that the effect evaluated is not only due to the presence of water but also due to seismic action. Considering that the most critical situation for the slope occurs when the water level coincides with the terrain's surface, H_w=5m was adopted as a pattern for evaluating instability due to the effects of water.

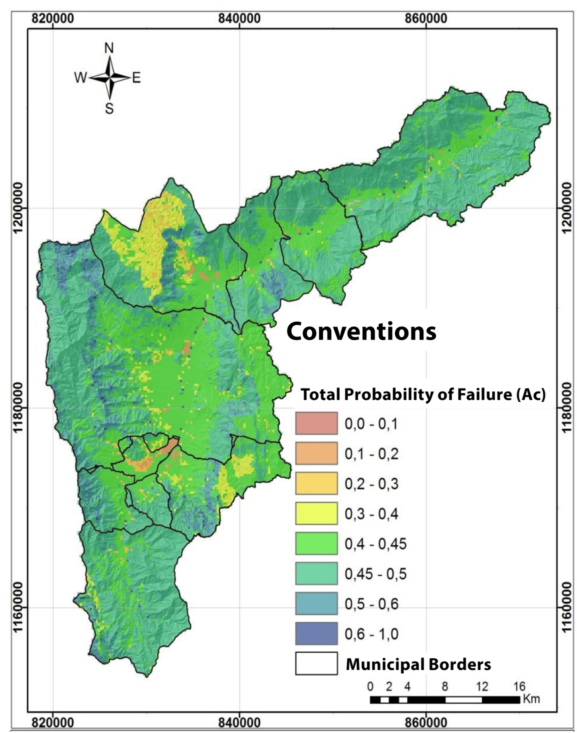
The critical acceleration in each cell was determined considering a failure surface at a depth of 5m and water conditions coinciding with the failure surface (H_w=0) and the terrain's surface (H_w=5m) respectively. Critical acceleration varies in wet conditions between 0 and 1.13g and in saturated conditions between 0 and 0.84g. However, until this stage the uncertainty of the soil parameters has not been considered in the determination of these values. Considering uncertainty and using **Equations 3** and **9**, the coefficient β_1 was calculated for the values of A_h shown in **Figure 2d** with a scenario of wet conditions (H_w=0) and saturated conditions (H_w=5m).

Supposing normal distribution, the total PF was calculated for each cell (**Figure 6**), finding a variation between 0.15 and 1.0, with the probabilities of failure in areas with gradients of more than 40% (22°) and unfavorable hydrological conditions such as those present in the northwest in the town of Palmitas and in the southeastern zone. The areas located in the central zone of the AV have softer gradients below 40%, which show probabilities of failure between 0.4 and 0.5 and make up approximately 86% of the area studied.

These probabilities of failure are given for an earthquake with a probability of exceedance of 10% in 50 years, which means that the annual probabilities of a landslide occurring due to an earthquake vary between $3x10^{-4}$ and $2x10^{-3}$. According to the distribution of the probabilities of failure and considering that the landslide hazard can be classified as very high (annual PF >0.2), high (0.02-0.2), medium (0.002-0.02), low (0.002-0.0002), very low (<0.0002) (Chowdhury et al. 2010), 99% of the AV's territory is in low to very low conditions of hazard of landslides caused by earthquakes, and 1% is in medium conditions of hazard.

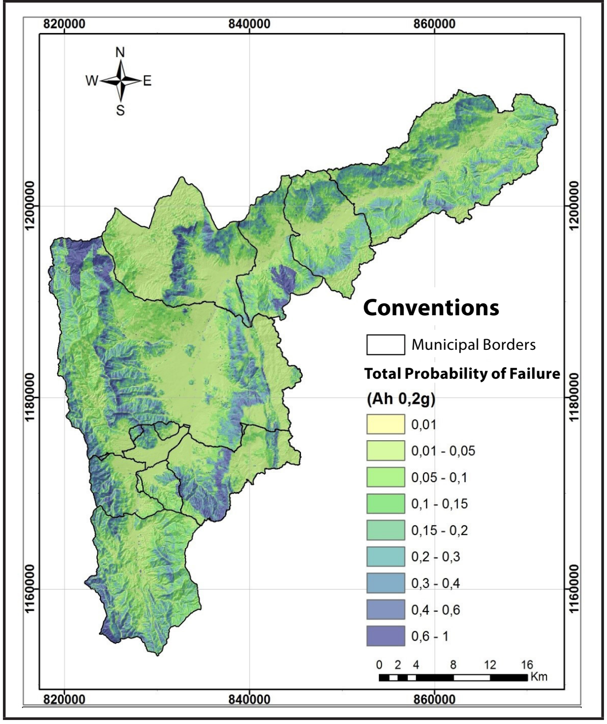
Likewise, **Equations 4** and **5** were used to calculated the FSD and the coefficient β for A_h values of 0.2g in a scenario with wet conditions (H_w=0) and saturated conditions (H_w=5m). Taking a normal distribution, the total PF of each cell was calculated (**Figure 7**), showing a variation between 0.1 and 1.0 with a similar distribution to that observed for A_c with the least favorable conditions in the northwest in the town of Palmitas and in the southeastern zone of the AV, and with the most stable conditions in the areas located in the central zone. The range of values for the probabilities of failure and their distribution are comparable, showing hazard zones similar to those established before, mainly including the zones with low and very low hazards.

Figure 6. Distribution of the total probability of failure P(A_h >A_c)



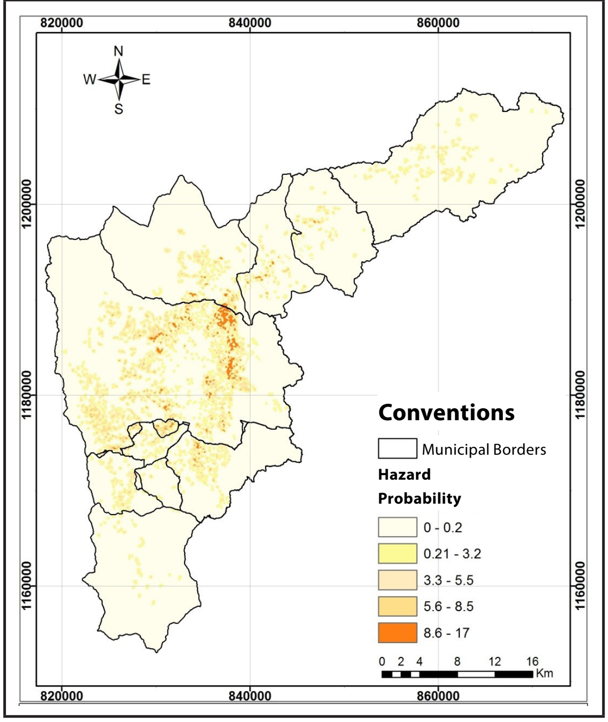
Comparing the results of this study with the results of the hazard evaluation for mass movements in the study "Amenaza, vulnerabilidad y riesgo por movimientos en masa, avenidas torrenciales e inundaciones en el Valle de Aburrá" (AMVA, 2009) shown in **Figure 8**, we see a certain coincidence between the zones located in the interior of the AV, especially in the municipality of Medellín, but not in the external zones, which can be explained by the fact that the AMVA (2009) analysis is based on the use of neural networks to determine the hazard. These require information regarding historical events, and this information is more abundant in the populated areas of the AV and scarce in the other zones, meaning that events cannot be predicted in these zones. Although the probabilities are generally moderate, we occasionally observe small areas with very high probabilities of failure that are shown as critical points in **Figure 9**.

Figure 7. Distribution of the total probability of failure for P(FSD<1.0) con A_h = 0.2g



In addition, in order to check the model's capacity for determining critical zones, we identified the sites with the worst stability conditions, determined as those cells that show an FSD of less than 1.2 in saturated conditions and with an acceleration of 0.2g (**Figure 9a**) or with the greatest total probabilities of failure. We have observed that the critical points identified are located in zones that are frequently affected by problems like those described in studies such as the project "Amenaza, vulnerabilidad y riesgo por movimientos en masa, avenidas torrenciales e inundaciones en el Valle de Aburrá." These are shown in **Figure 9b**.

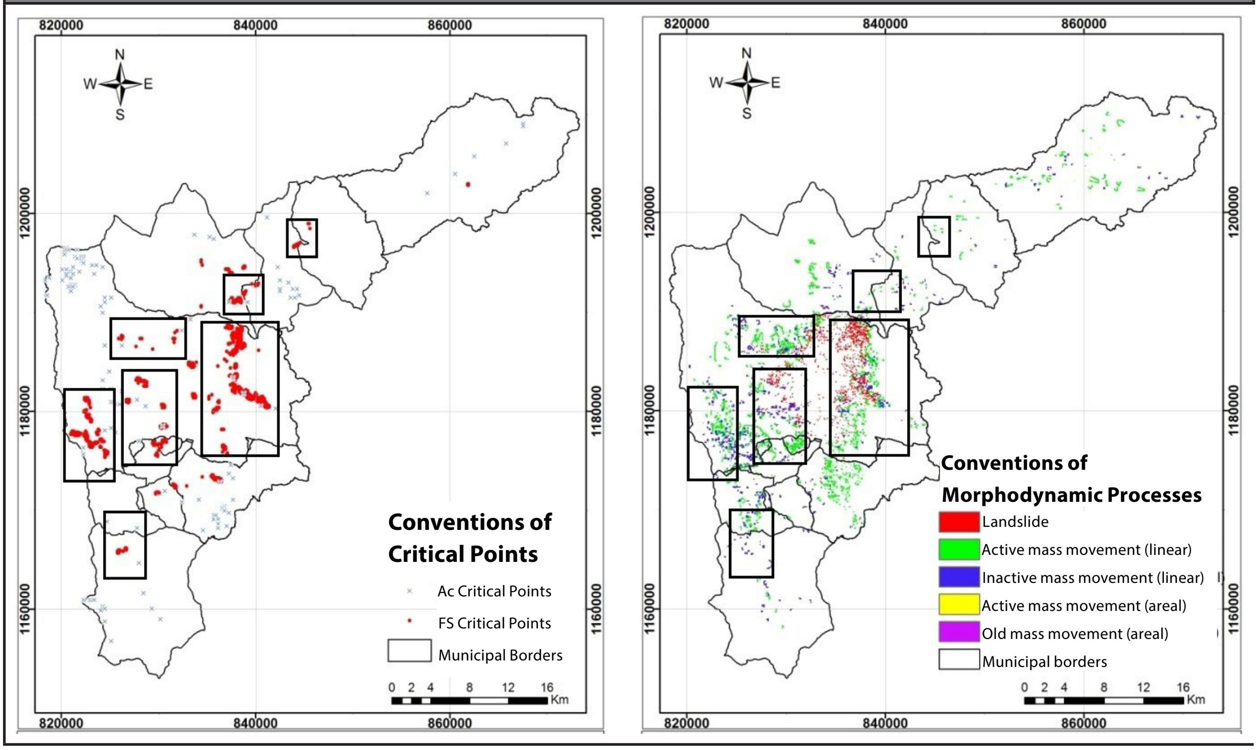
Figure 8. Hazard determined based on statistical data (AMVA, 2009)



In addition, in order to check the implemented model's ability to determine critical zones, we identified the sites with the worst stability conditions, determined as those cells that present SFS values less than 1.2 in conditions of natural water content and those cells in which Ac exceeds the horizontal acceleration of 0.2g stipulated for the city of Medellín in accordance with the *Norma Colombiana de Diseño Sismo Resistente* (Colombian Regulation for Earthquake-resistant Design) (AIS 2010) (**Figure 9a**).

We observed that the critical points identified are located in zones that have been affected by problems like the ones described by AMVA (2009) and that are inventoried in the *Departamento Administrativo de Gestión del Riesgo de Desastres* (Administrative Department of Disaster Risk Management) (formerly SIMPAD) registries and in the database of the DESINVENTAR project of the Metropolitan Area of the Aburrá Valley, which registers reports of morphodynamic processes that were the product of mass movements and occurred in a time interval of approximately 20 years between 1985-2006, which are shown in **Figure 9b**.

Figure 9. (a) Location of critical points. **(b)** Map of morphodynamic processes in the municipality of Medellin (1985-2006).



The highlighting rectangles in **Figure 9** show the zones obtained through a spatial analysis in which the critical points calculated show a percentage of coincidence with the inventory mentioned above of 61% for the case of critical points by SFS, which represent normal conditions on the hillsides. For the case of critical points by *Ac*, there was a 13% coincidence, which represents a scenario of an earthquake with an acceleration of 0.2g. These would be points where the factor of safety is lower than the unit.

4. CONCLUSIONS

The model elaborated allows us to estimate the hazard and the zone of influence due to mass movements caused by earthquakes considering the influence of saturation conditions due to rainfall.

The results found show that the model is robust in its identification of critical zones for stability. This information can be used to prioritize zones that must be studied in detail to guarantee the safety of the people and infrastructures located near the site.

It is probable that mass movements will occur if there is a seismic movement with the characteristics anticipated for the AV, and this probability increases if the soils are saturated.

In the scenario considered, with a seismic acceleration of 0.2g, the maximum probabilities of a landslide occurring are 99.96% under normal conditions of soil wetness and 100% under conditions of total soil saturation. The areas that show these values for probability of failure are the zones in which the towns of Palmitas, San Cristóbal, Altavista, and Santa Elena are located.

This study can serve as the basis for implementing an alert system for mass movements founded on physically-based models, as well as for the evaluation of hazards in order to establish a zonation in terms of annual probability of landslides occurring.

Future studies will complement this study with new analyses that allow for the evaluation of landslide risks and the inclusion of a greater quantity of data on rainfall. These future studies will also consider earthquakes with different recurrence periods, since this study was limited to earthquakes with return periods of 475 years.

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