Application of a Bivariate Statistical Method to the Study of Hazard Zoning by Mass Movements at a Scale of 1:25,000 in the Municipality of Villavicencio, Department of Meta

Sofía Navarro[1], Diego Medina[1*]

([1] *Servicio Geológico Colombiano, Colombia)*

email: snavarro@sgc.gov.co, *dmedina@sgc.gov.co, (571)2200200

Abstract

One of the objectives of the Servicio Geológico Colombiano (SGC in Spanish), whose parent agency is the Ministry of Mines and Energy as well as part of the National System of Science, Technology, and Innovation (SNCTI), following the provisions of Article 3 of Decree 4131 of 2011, is to advance surveillance and monitor threats of geological origin (earthquakes, volcanoes and mass movements). In line with this objective, products are generated that contribute to the planning of the country's development, providing basic information to guide the risk reduction measures of communities exposed to natural hazards and supporting the incorporation of risk management in territorial land-use plans of municipalities and watersheds (POT, PBOT, EOT, POMCAS in Spanish). In 2017, the SGC published the Methodological Guide for the Zoning of Hazards by Mass Movement at a Scale 1:25,000, meeting the requirements of the current regulations, such as Law 388 of 1997 and Decrees 879 of 1998, 3600 of 2007, 1807 of 2014, 1077 of 2015 and disaster risk management such as Law 1523 of 2012.

For the hazard analysis, the guide proposes three methodological stages. The first stage corresponds to a geoenvironmental characterization that includes an inventory of morphodynamic processes, determining factors (geology, geomorphology, land cover and soil use) and triggering factors (rain and earthquakes). The second stage comprises a susceptibility analysis performed by applying a bivariate statistical method combined with geomorphological criteria and field evidence for the different types of mass movements. The third stage is a characterization of the hazard (spatial and temporal probabilities and magnitude analysis).

In 2018, the SGC, in agreement with the Agustín Codazzi Geographic Institute (IGAC in Spanish), updated the zoning of hazards caused by mass movements at a 1:25,000 scale in the Villavicencio municipality, department of Meta, applying the bivariate statistical method proposed in The SGC Methodological Guide (2017).

1 INTRODUCTION

The zoning of hazards by mass movements at a scale of 1:25,000 (SGC, 2017) consists of three fundamental stages. The first stage is a geoenvironmental characterization that enables the formulation and verification of a hypothesis to establish a relation between different geoenvironmental or determining factors and the occurrence of mass movements. The second stage is the process of susceptibility zoning, applying a bivariate statistical method combined with geomorphological criteria and field evidence for the different types of mass movements. The third stage involves the characterization of the hazard, which is based on data analysis to determine the mass movements' occurrence frequency in terms of spatial and temporal probabilities and magnitude. Geoenvironmental characterization, susceptibility analysis and the effects of rain and earthquake triggers are fundamental inputs.

Because hazard zoning by mass movement does not represent a static condition over time (i.e. changes in land use, territorial environmental recovery and climate change can generate new hazard conditions from mass movements), the municipality of Villavicencio decided to update the studies conducted by INGEOMINAS in 2003. This also provided an opportunity to apply the methodological guide developed by SGC (2017).

2 LOCATION OF THE STUDY AREA

The study area belongs to Villavicencio municipality's countryside in the department of Meta. It has an area of 29,000 ha, bounded by the municipalities of El Calvario to the north, Restrepo to the east, Acacías to the south, and the department of Cundinamarca to the west. Hydrographically, it is located in the watersheds of the Guayuriba and Guatiquía Rivers (Figure 1).

3 GEOENVIRONMENTAL CHARACTERIZATION

The geoenvironmental characterization (GC)is used to establish the intrinsic characteristics of the territory, taking into account the information collected in the field, such as the morphodynamic processes inventory (MPI, including mass movements and erosion processes), surface geologic units (SGU), geomorphological subunits (GMSUs) and land cover and land use units. The GC is then used to formulate a hypothesis of the causes and mechanisms of mass movements that have been generated in the territory. Verification is performed through susceptibility modeling, explaining both the existing processes and those that may occur in the future.

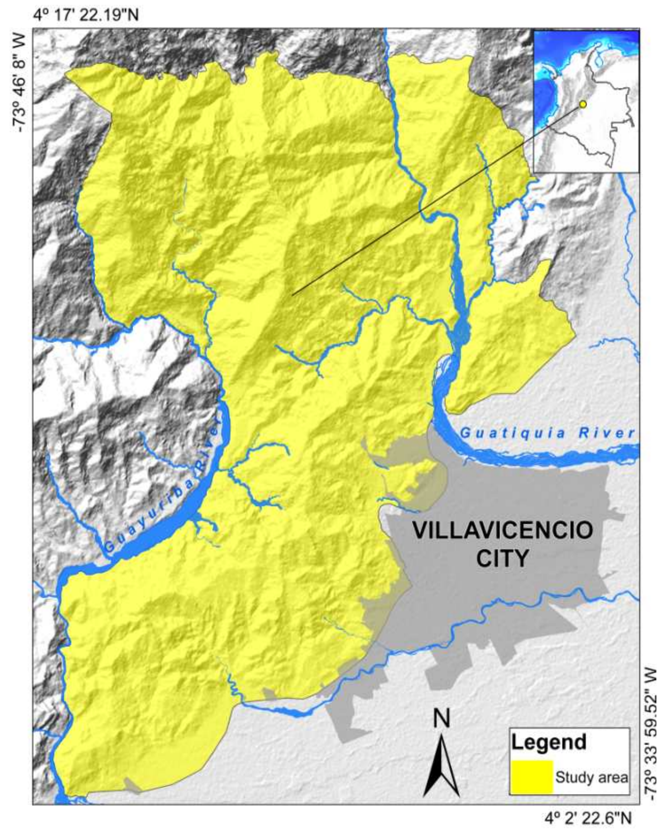

Figure 1. Location of the study area (Source: Authors' collection).

3.1 Morphodynamic process inventory (MPI)

It relates to the exogenous dynamic associated with the activity of some agents like wind, water, ice, and the earth's gravity that change the preexisting landscape. Mapping of the morphodynamic processes is performed with secondary information and interpretation of remote sensing images for subsequent field verification. The development of an inventory of morphodynamic processes aids in the understanding of the occurrence of mass movements and their most important characteristics, such as the date of occurrence, the location, the form, the dimensions, the factors that intervened, still do and will intervene in their occurrence or potential for occurrence, the mechanism that led to land failure, triggering factors, movement dynamics, and the magnitude and the intensity, among others.

A relevant aspect of the inventory is the possibility of performing a multi-temporal analysis that includes both mass movements and geomorphological features indicative of instability, including erosion (gullies, grooves, terraces, crowns, scars, etc.).

The MPI of the area of analysis yielded, at the time of the study, a total of 646 mass movements (628 processes among landslides, debris flow, rockfalls, and 18 creeps) and 160 gully erosion processes for a total of 801 morphodynamic processes (Figure 2).

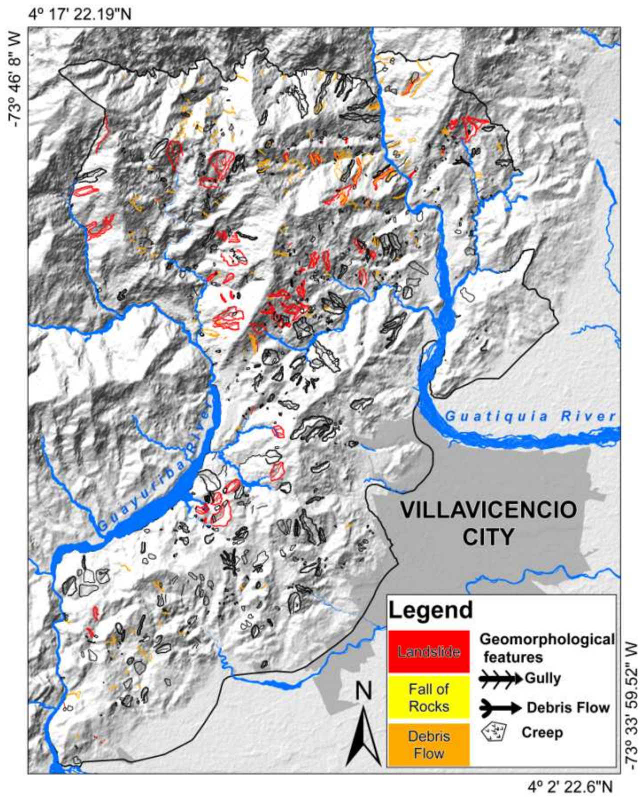

Figure 2. MPI Map for the Study Area (Amended from SGC and IGAC (2018).

3.2 Geology

The terrain geological conformation as a conditional factor into the occurrence of land movements is due to the presence of weak plastic, sensitive, collapsible or weathering materials, as well as the existence of structural discontinuities into rocky massifs or soils, often showing the same slope directions, among others.

The Andes Mountain Range in Colombia moves like a small tectonic plate, or microplate, along a system of faults that limits the eastern flank of the Eastern Cordillera, known as the Borde Llanero Fault System: Altamira-Suaza Fault to the south, Piedemonte Llanero Thrust Fault to the north-central region, and the fold belts (Ingeominas, 2001 and 2008).

The study area is located in the central-eastern part of Colombia on the foothills (Piedemonte Llanero) of the eastern flank in the Eastern Cordillera (Cordillera Oriental) and the Eastern Plains (Llanos Orientales).

In the area, different lithological units appear, such as metamorphic rocks of the Quetame Group, a product of low-grade contact metamorphism of the Pre-Devonian period, represented by the Susumuco and Guayabetal Formations, which appear at the NW end of the area. The rest of the area comprises sedimentary rocks of different periods, including the Gutiérrez sandstone, Pipiral shales and Capas Rojas del Guatiquía Formation of the Devonian–Pennsylvanian period; Las Brechas de Buenavista of the Jurassic; and the Caqueza Group, the Fómeque, Une, Chipaque and Palmichal Formations of the Cretaceous. The Palmichal Group that includes the Limbo and Corneta Formations represents the Paleogene-Neogene transition. Quaternary deposits are composed mostly of alluvial and hillside deposits. All these materials have been subjected to intense tectonic activity, thus becoming deformed, fractured and modified (INGEOMINAS, 2001 and 2008).

3.2.1 Surface Geologic Units (SGU)

The SGU refers to the material exposed on the surface of the terrain. From an engineering point of view, this material can correspond to soils or rocks. The SGU indicates the different types of rocks classified according to their origin and mineralogical composition, degree of weathering or alteration, hardness or strength and geological strength index (GSI). Soils are also differentiated according to their origin, mineralogical composition, classification genetics, characteristics and physical properties of the soil, composition of the particles, weathering, relict structures or discontinuities and some engineering properties.

The lithological units and outcropping deposits in the area mentioned above were classified in SGU according to their engineering properties. Within the study area, 30 SGU were categorized into bad, very bad and regular quality. Soils were classified according to their origin as transported soils or residual soils. Figure 3 shows the grouping of the SGU according to their classification.

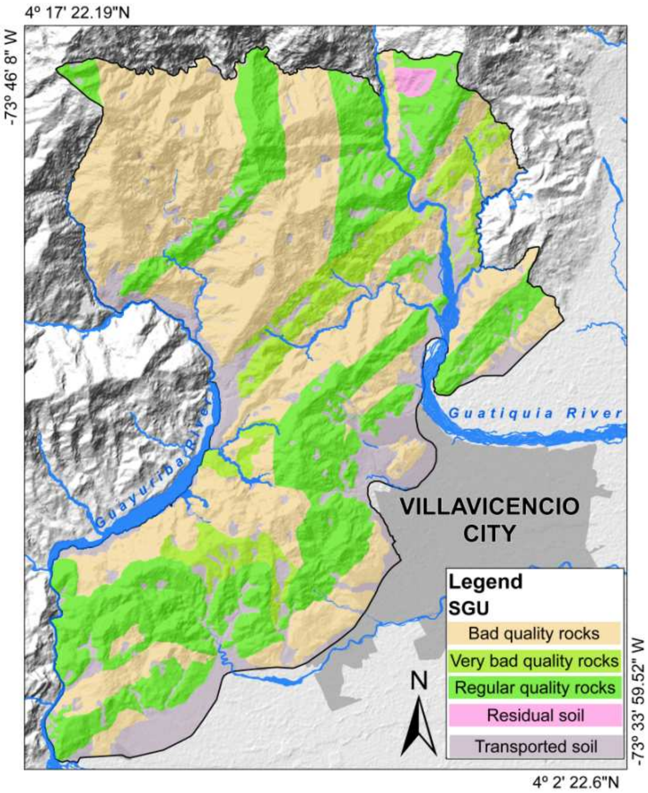

Figure 3. Map of Surface Geologic Units (Amended from SGC and IGAC (2018).

3.3 Geomorphology

Into the evaluation of landscape evolution and its relationship with the occurrence of morphodynamic processes, geomorphology is the most important factor to take into account. Therefore, in the geomorphological subunits mapping, it must identify both the subunits and some terrain characteristics than indicate the current and future dynamic of the zone.

The study area is located in the geomorphic structure corresponding to the northernmost part of the Andes orogenic belt, in the geomorphological province of the Eastern Cordillera. The zone is characterized by gorged valleys, with strong denudation processes, as a result of regional tectonics that imprints a high fracture density in the region, an attribute associated with the presence of geological fault corridors. The morphotectonic expression of this active faults system (Eastern plains foothill) includes fault escarpments, hanging and tilted terraces, and drainage control. According to the above, the morphogenetic environments that prevail in the area are structural, denudational and fluvial.

Geomorphological mapping of the zone was performed at the level of subunits associated with each of the morphogenetic environments mentioned as follows: 17 structural subunits, 11 denudational subunits and 14 units of fluvial origin. In Figure 4, the units are grouped by the morphogenetic environment.

Other geomorphological elements used in the method are the terrain slope and curvature. The slope is directly related to normal and tangential shear stresses in surface materials, as well as its influence on the amount of water on the slope. The curvature allows determining the degree of Concavity/Convexity through the radius of a cell curvature according to a vertical plane. The variable is related to mass movements to the extent that it indicates the degree of concentration or dispersion of surface drainage.

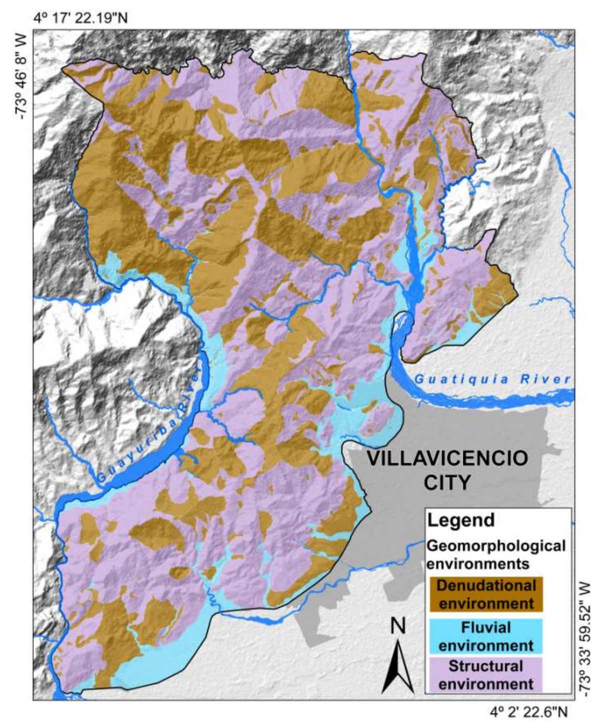

Figure 4. Map of Geomorphological Subunits (Amended from SGC and IGAC (2018).

3.4 Land Cover and Land Use Units

Land cover, its respective uses, and identification of changes are part of the determining factors in the occurrence of mass movements, mentioned and described in the methodological document for the zoning hazards of mass movements at a scale of 1:25,000 (SGC, 2017).

Landslides can be triggered by natural and man-made changes in the environment. Human-induced landslides can be the result of slope changes caused by terracing for agriculture, cut-and-fill processes for road construction, construction activity, mining operations, rapid releases from dams, changes in land cover such as deforestation and changes in irrigation or surface runoff.

The above elements are effects of the dynamics of change in the territory, which are identified through multi-temporal studies of land cover and/or land use. Therefore, when identifying the zones with land cover/land-use changes or greater dynamics and relating them to the different landslides, human-induced landslides can be identified (which are more preventable), based on activities practiced according to territorial use.

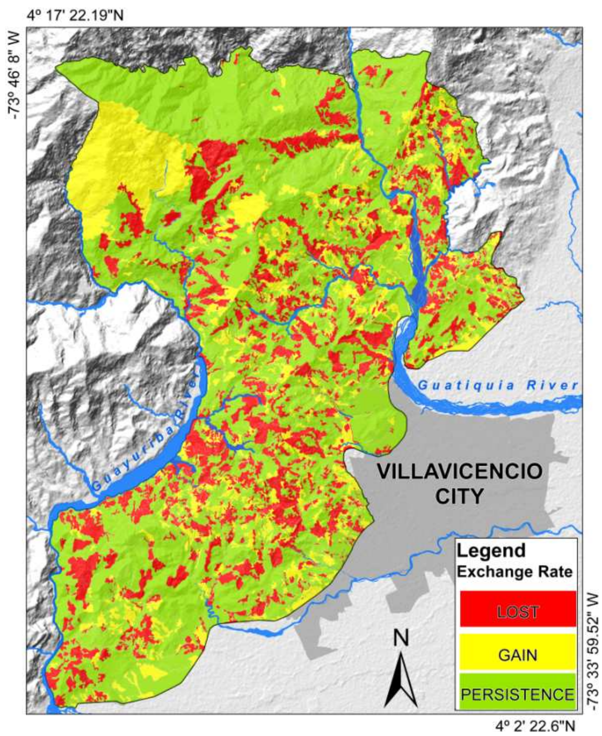

Figure 5. Type of cover change from 2005-2018, adapted from SGC and IGAC (2018).

The multi-temporal coverage analysis of Villavicencio municipality was based on two dates (2005-2007 for the previous time and 2017-2018 for the current time). This analysis determined changes in cover in terms of persistence, loss, and gain (Figure 5).

4 SUSCEPTIBILITY ANALYSIS

To analyze the susceptibility of the terrain to the occurrence of the slide and flow mass movements, a bivariate statistical method called Weights of Evidence (WofE) was applied. In this method, the association patterns between the determining factors were evaluated (slope, curvature, SGU, geomorphological subunits, and land cover units) concerning the unstable areas (inventory of slide and flow mass movements) using weighted values. For falls and torrential floods, the analysis was performed based on an empirical method involving geomorphic subunits indicative and defined from direct geomorphological mapping, slopes greater than 40° and surface geologic units of very poor, poor and fair quality. The unit of analysis was the pixel size of the digital elevation model, which was 12.5 m.

Modeling is based on the assumption that future movements will occur in conditions similar to those that have contributed in the past to the occurrence of mass movements: i.e. it is assumed that these factors remain constant over time.

4.1 Grouping Variable - Mass Movement Inventory

The grouping variable is the slide area, which corresponds to the zones identified as translational slides and flows. This area was rasterized and 70% was randomly chosen as the sample used for calculating the susceptibility function (19,707 pixels), and the remaining 30% (8,446 pixels) comprised the sample used for validating the function.

4.2 Failure Hypotheses

Once the secondary information analysis studies (geology, geomorphology, morphodynamic processes, etc.) and the multi-temporal photointerpretation of the study area, were complete, emphasizing the mapping of mass movements and erosion processes; the failure hypotheses were defined and evaluated or reframed in the field, to obtain the contributions of the determining factors (SGU, geomorphological subunits, land cover, and land use units) to the generation of mass movements. According to the above, the following premises were established for defining a failure hypothesis:

- Rock massifs are highly fractured from the influence of the fault systems, which at a general level, present two tendencies: the N-S tendency, the most important being the Susumuco, San Juanito, Guatiquía faults, and the NE-E tendency, such as the Quebrada Honda, Sapa, Servitá, and Cole Pato faults. The fracturing has promoted the processes of chemical weathering (oxidation and argillic alteration) and physical weathering.

- The structural arrangement of the discontinuities (stratification and diaclases) with dips greater than 30° along the natural slope of the terrain, promotes the development of mass movements, such as translational landslides and wedge-planar slides.
- The study area presents a high anthropogenic dynamic, which is related to production uses, a lack of protection from the selective logging of forests and the expansion of pastures, converted to silvopastoral uses. It includes many sites that are restricted to fallow lands or unused land, facilitating land instability and favoring gully type erosion processes.

4.3 Determining Factors and Weights of Evidence (WofE)

Applying the WofE method, several susceptibility models were performed using different combinations of determining factors. These analyses were based on knowledge of the study area and expert judgment. They were continued until finding the combination of factors that, in the final susceptibility function, produced the most significant weights to best explain the actual terrain conditions and to determine what are or will be the causes of slide-type mass movements in the study area (failure hypothesis).

Accordingly, the following determining factors used in the application of the WofE were defined for calculating slide-type mass movements: the slope of the terrain (Slo), curvature (Curv), SGU and land use (Cov).

The application of the bivariate statistical WofE method was performed by calculating the weights of each variable or factor conditioning the slide-type mass movements, based on the presence or absence of this type of movement in the different classes existing in each conditioning factor (the different types of rock quality, the different land cover and land use units, and the different ranges of curvature and terrain slope) obtaining positive Wi+ or negative Wi– weights.

Subsequently, the calculation of the final weight was performed, yielding a measure of the existing correlation between the analyzed conditioning factor and the mass movements. According to SGC (2017), the final weight is as follows:

$$Wf = Wi^{+} - Wi^{-} \qquad (1)$$

4.4 Calculation of the Susceptibility Function

After obtaining the final weights for each class of each conditioning factor, an algebraic sum was calculated for the final susceptibility by slide-type movements, which represents the final function of the landslide susceptibility index (LSI) according to SGC (2017), namely:

$$LSI = Wf\ (UGS) + Wf(Cov) + Wf\ (Slo) + Wf\ (Curv) \qquad (2)$$

4.5 Susceptibility Categories by Mass Movement

The following categorization is proposed for the susceptibility map of slide-type mass movements (SGC, 2017):

High susceptibility: contains more than 75% of all landslides

Medium susceptibility: contains a maximum of 25% of all landslides

Low susceptibility: contains less than 2% of all landslides

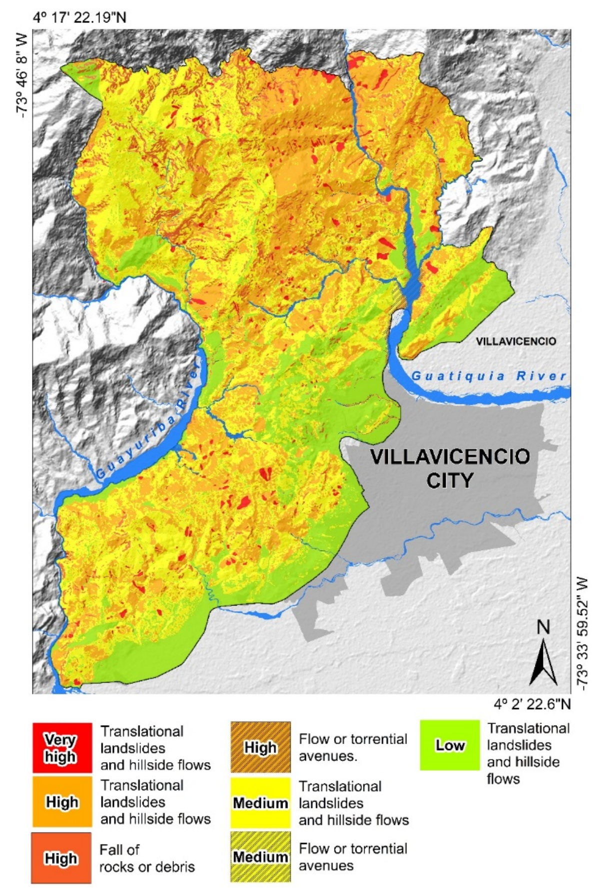

Figure 6. Susceptibility Map by Mass Movements (SGC and IGAC (2018).

The susceptibility map (Figure 6) contains the following susceptibility categories: susceptibility to landslides and hillside flows, very high with

2.22%, high with 32.43% of the total area, medium with 37.6% and low with 57%; susceptibility to falling rock, debris or soil, very high with 5.1%; and flow or torrential runoff mass movements, high with 1.9% and medium with 0.2%. Geomorphological features include gullies (active and inactive), areas affected by creep, and torrential drainages.

4.6 Analysis of the Threat by Mass Movements on a Scale of 1: 25,000

The characterization of hazards by the mass movement was constructed based on the susceptibility analysis, which in turn considers the relations between the morphodynamic processes, the geology, land use, land cover and the spatial possibility of the occurrence of landslides within the study area. Additionally, information was collected on rain and earthquakes that have affected the territory to establish their character as triggers and their relation with the occurrence of mass movements. The map product of this analysis is shown in Figure 7.

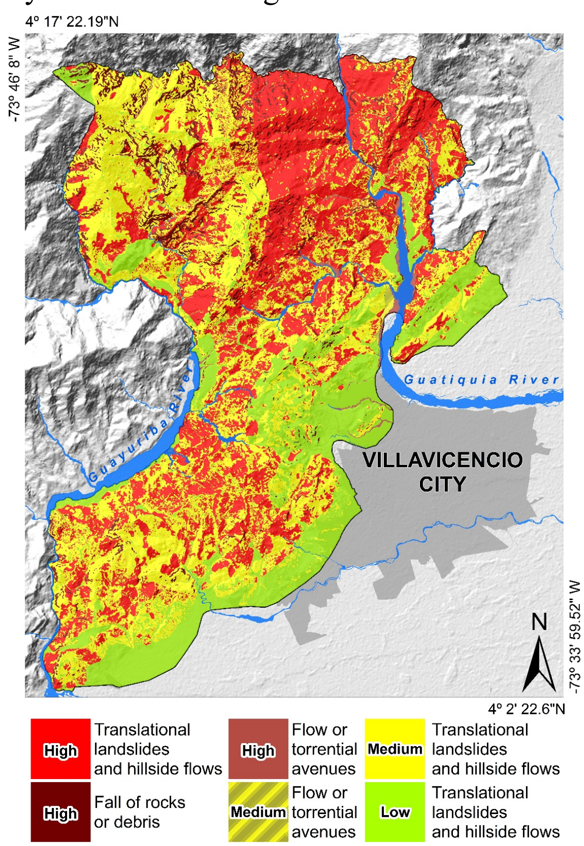

Figure 7. Hazard Map by Mass Movements (SGC and IGAC (2018).

The zoning comprised translational slides and hillside flows, namely: a high category of 34.6% of the total study area, a medium category of 37.6% and a low category of 20.6%. For the fall of rocks, debris or earth, the zoning was a high category of 5.1%, and for flow or torrential runoff types of a mass movement, the zoning showed a high category of 1.9% and a medium category of 0.2%.

5 CONCLUSIONS

The evaluation of susceptibility showed that the areas most likely to present mass movements are determined by moderate to steep slopes (16° - < 45°), in which structural and denudational environment geo forms predominate on sedimentary rocks classified as very poor, poor and fair, and in transported soils of colluvial origin.

These analyses corroborate the failure hypotheses proposed for the geoenvironmental characterization of the area, validating the successful application of the bivariate statistical method for the rural area of Villavicencio municipality.

The high hazard category by Landslides and hillside flows corresponds to hillside zones with predominant slopes ranging from 16-35°and from 35-55°, in which translational landslides and surface soil or debris flows (thickness < 3 m) are triggered in areas ranging from 130 m2 to more than 100,000 m2. To a lesser extent, creep processes are present, and in this area, mass movements related to extensive and deep gullying are commonly found. This hazard category is preferably associated with rocks classified as very bad, bad and regular, and with residual soils,

The medium hazard category by Landslides and hillside flows corresponds to hillside zones with predominant slopes ranging from 8-16° and from 16-35°, in which translational landslides and surface soil or debris flows (thickness < 3 m) are triggered in areas ranging from 370 m2 to more than 108,000 m2. To a lesser extent, creep processes are present, and in this area. This hazard category is preferably associated with rocks classified as very bad, bad and regular.

The high hazard category by Falling rock, debris or soil corresponds to hillside zones with predominant slopes > 40°, in areas ranging from 640 m² to more than 23,700 m². This hazard category is preferably associated with rocks classified as bad and regular.

In all hazard category, mass movements can be triggered by rains of more than 15 days or 600 mm and with a single daily rainfall greater than or equal to 60 mm, with return periods ranging from 1 to 15 years. Earthquakes can also trigger this type of process, preferably in areas influenced by events with a magnitude greater than 5 and of surface depths associated with return periods greater than 975 years.

The high hazard category by Flow or torrential runoff, occupies 560.8 ha (5.60 km2), with 1.9% of the study area, specifically in the Guatiquía river basin from sectors of the municipality of Calvario to the urban perimeter of Villavicencio, associated with the geomorphological subunits as areas of wandering of the active channel or alluvial channel, flood plains or plains, dejection cone, current fluvio-torrential fan and debris flow lobe, with thicknesses not greater than 3 meters with respect to the water surface and with smaller slopes at 10 °. In the Guatiquía river, the high susceptibility zones, which indicate a chaotic or even torrential regime, are associated with the tributary drainages: Q. la Sapa, Q. San Pablo, Q. Blanca (San Cristóbal), Q. la Guadua, Q. the Mendoza, Caño Leche and Q. blanca (Santa María Baja) to the mouths of the Argentina and La Negra streams.

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