Zoning of mass movement hazards in Colombia.

Gloria Ruiz[1] & Sofia Navarro[1*]

([1]Colombian Geological Survey, Colombia)

Email: gruiz@sgc.gov.co, *snavarro@sgc.gov.co

Abstract

Colombia is geographically diverse, as shown by its classification into five natural regions: the Andean, Caribbean, Pacific, Orinoquian and Amazonian regions. In addition, due to its geographic location, Colombia experiences particular geological, geomorphological, climatic, and seismic conditions, which, together with land use, causes changes to the land cover and the special characteristics of the regions. These changes can sometimes generate different types of mass movements, which have historically resulted in the loss of human life and economic livelihood due to the damage or destruction of property and infrastructure. Hazard zoning according to mass movements has therefore become a useful tool for land planning, risk management and, thus, development planning. This article presents the methodology used for hazard zoning due to mass movement at a scale of 1:100,000, which was applied systematically to 283 sheets at a scale of 1:100,000 and covered the Andean, Pacific and Caribbean regions to account for a total area of 550,411 km^2.

1 INTRODUCTION

Colombia is located geographically in the north-western corner of South America and occupies the intertropical confluence zone, which is a geologically complex region due to the influence of the South American, Nazca and Caribbean tectonic plates. Young mountain ranges exist in this region, and thus, earthquakes, volcanic eruptions and mass movements occur (DeMets, C., Gordon, R.G., Argus, D.F. and Stein, S., 1990; Freymueller, J.T. Kellogg, J.N. and Vega, V., 1993). Geographically, the continental territory of Colombia is divided into five natural regions according to their terrain, climate and soils, and these regions are called the Andean, Caribbean, Pacific, Orinoquía and Amazonian regions.

The Andean region is located in the centre of the country and is formed by three mountain ranges and the intramontane basin of the Cauca and Magdalena rivers, which cross the country from south to north. Large cities inhabiting approximately 70% of the country˘s population have developed in the Andean region, in which continuous mass movements occur, which generate the loss of human lives and economic livelihood due to damaged or destroyed property and infrastructure.

On the other hand, the Colombian Geological Survey (CGS, *Servicio Geológico Colombiano*), the entity responsible for assessing geologic hazards at the regional and national level, has generated national maps since 2001, which shows the distribution of the different levels of hazards caused by mass movements. The CGS generated the first version with a scale of 1:1,500,000 (Ingeominas, 2001a), which was later updated together with the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) in 2010 to achieve a scale of 1:500,000 (26 plates). The updated maps identified that this mass movement hazard is present in the Andean, Pacific and Caribbean regions (Ingeominas & IDEAM, 2010). Between 2012 and 2017, the CGS, along with the IDEAM and the departments of geology or geological engineering at seven universities, generated the National Map of Relative Hazards due to Mass Movements, which comprises 283 plates with a scale of 1:100,000 (MN100K). This article presents the methodology applied systematically in each of the plates to construct the said map and finally shows the statistical results of the different hazard levels in the country.

2 ZONING METHODOLOGY

Considering the purpose of the project, the zoning level and the scale, to make hazard and susceptibility analysis were applied the heuristic and direct analysis methods, which are appropriate for semi-regional scales. The heuristic method is based on categorizing and weighing the instability conditioning and triggering factors according to their expected influence on generating mass movements (Brabb, E.E., Pampeyan, E.H. and Bonilla, M.G., 1972; Nilsen & Wright, 1979; Anbalagan, R., 1992). To determine the categories of the susceptibility to mass movements, an analytic hierarchical process (AHP) was used, which consists of dividing a complex situation into its parts, arranging these parts or variables into a hierarchical order, assigning numerical values to subjective judgements about the relative importance of each variable and summarizing the judgements to determine which variable has the highest priority and will act under the influence of the situation outcome.

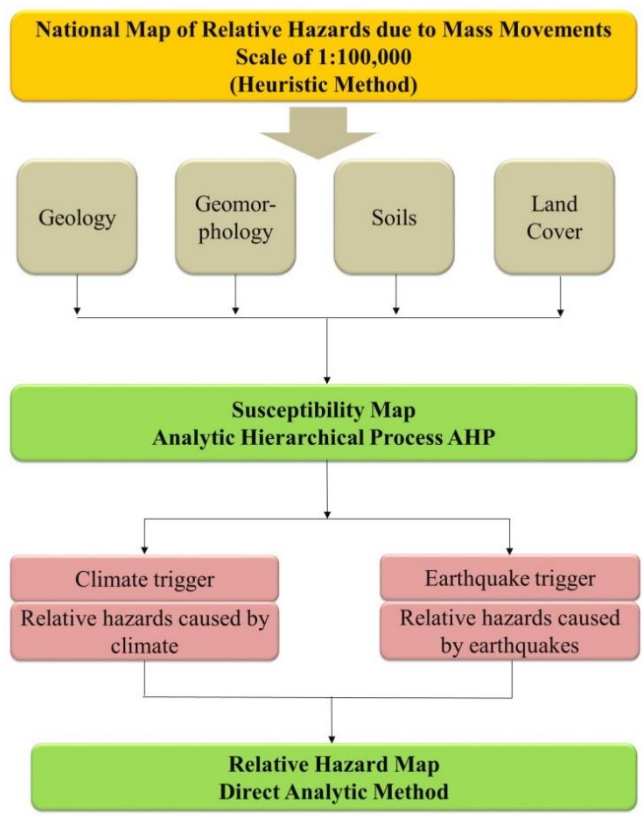

Figure 1. Diagram of the methodology used to construct the susceptibility and relative hazard due to mass movements zoning map, scale of 1:100,000 (CGS, 2013)

The heuristic method is classified as an indirect method because the results can be extrapolated to areas without mass movements, but where there is a similar combination of conditioning factors

(CGS, 2013). The conditioning factors or variables considered in the susceptibility model were: geology, geomorphology, edaphic soils and land cover. The triggering factors considered in hazard zoning were climate and earthquakes. Figure 1 shows the proposed model for the susceptibility and hazard zoning, including the methods used to obtain the final maps.

2.1 Geology

The geological characterization to construct the zoning of the susceptibility to mass movements includes the basic elements of properties and characteristics of the lithological units and the fracture density (Figure 2). Due to the scale, the mapping unit used was the Engineering Group, which was proposed by the Commission on Engineering Geological Mapping (1976). This unit is defined as the set of formations with similar paleogeographic and tectonic characteristics and with common lithological characteristics. Likewise, the structural discontinuities are considered, that is, the faults, folds or lineaments with geological origin that structurally control the behaviour of lithological units at the regional level.

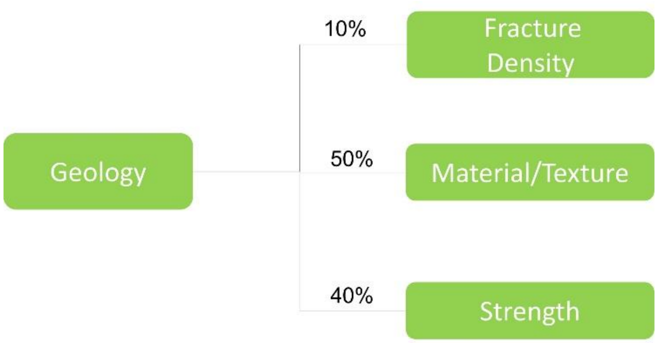

Figure 2 Geologic variables and variable respective percentages used to construct the susceptibility due to mass movements zoning map (SGC, 2013).

To analyse the lithological unit properties, the attributes of the material/texture, strength and fracture density were evaluated. For the unconsolidated deposits, the formation environment, type of material, topographic position, dynamics and stability conditions were evaluated. To derive the lithological units it was used the geological maps generated by the CGS at 1:100,000 scale, with their corresponding technical memories.

The fracture density was generated using the Colombian Geological Atlas 1:500,000 scale (Ingeominas, 2007), as well as the Database of active Colombian faults (Ingeominas, 2001b). The susceptibility rating was generated from the failures used in the Hazard Zoning by Mass Movements project with a scale of 1:500,000 (Ingeominas & IDEAM, 2010), including the displacement rates of structures with Quaternary deformations determined by Paris, G., Machette, M., Dart, R. and Haller, K. (2000) and the Seismic Hazard group of the CGS. It is assumed that at higher displacement, there is a greater degree of fracturing.

2.2 Geomorphology

Geomorphology studies the genesis, classification, processes and evolution of ancient and current landforms and their relationship with underlying structures (Carvajal, 2012). The geomorphological variables that were quantitatively and qualitatively assessed to construct the susceptibility due to mass movements zoning map included the geometric relationships of the terrain surface (morphometry), the mass movements present in the area, as well as the deposits or units of transported soils (morphodynamics) and the causes and processes that generated the landforms (morphogenesis) (Figure 3).

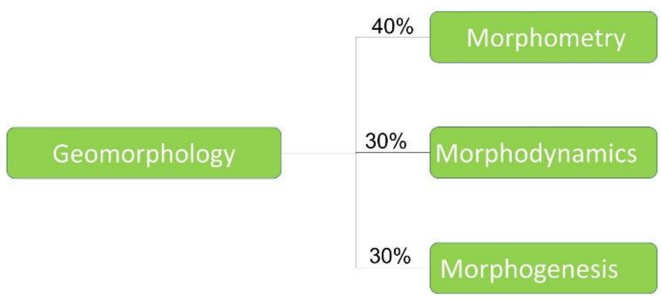

Figure 3. Diagram of the geomorphological variables and the respective variable percentages used to construct the susceptibility by mass movements zoning map (SGC, 2013).

To evaluate the morphogenesis variable, a mapping methodology was developed, which, from a morphogenetic analysis, defines the territory in a geomorphological evolutionary context; the morphogenesis variable was derived by applying this method to each sheet (SGC, 2012). The morphometry variable, as well as certain morphodynamic elements, were obtained from a terrain digital elevation model, which, in turn, was complemented by a detailed inventory of mass movements.

2.3 Soils

Soil, together with land cover, is the entry point and initial regulator of rain in an ecosystem. Water movement and its characteristics (runoff or surface flow, infiltration, capillarity, percolation, among others) tend to modify the state of matter and energy of the soil, affecting the soil properties and stresses without altering its nature (IDEAM, 2009, in SGC, 2013).

The genesis of soils starts from a lithological state, and their evolution takes them to a moment in time where they will have a capacity for and respond to the dynamics of vegetative cover, the climate incidence and the human intervention. To infer this capacity and response, this time focused on weathering and movement and to estimate how susceptible the soil is to mass movements, it is necessary to evaluate some characteristics, such as the texture, taxonomy, natural drainage, depth and type of clay or mineral. (Figure 4).

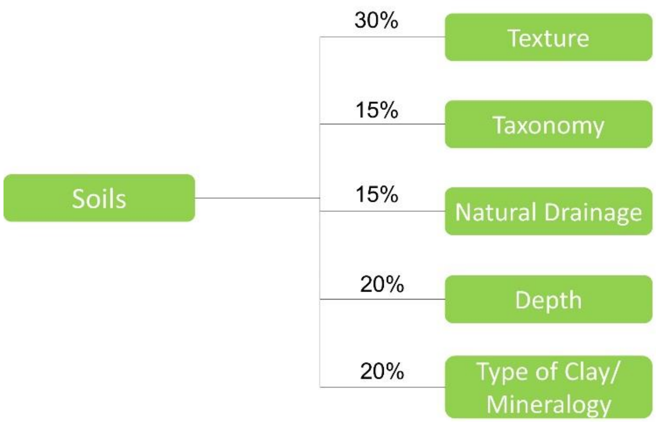

Figure 5. Diagram of the soil variables and respective variable percentages used to construct the susceptibility due to mass movements zoning map (SGC, 2013)

The information used to evaluate the susceptibility of the soil variable was taken from general soil studies at 1:100,000 scale, which were developed by the Agricultural Subunit of the Agustín Codazzi Geographical Institute (IGAC) for different years.

2.4 Land Cover

The land cover analysis and its relationship with mass movements are based on the role played by them on the natural dynamics of the earth surface, as much in the erosion processes regulation since the land cover root systems shape a sort of fabric that ties the shallow soil horizons- as in maintaining moisture balance of the soil surface and the environment, and in regulating the hydric balance by decreasing the water movement caused by surface runoff processes, making easier underground drainage.

Land cover changes contribute to the emergence of different processes, such as effects on the evolution of species, changes on the ecosystem deterioration, on the pattern of hydrological cycles, on the shapes of the terrain, producing landslides, flows, creep and erosion, among other effects. Taking into account the previous considerations, , for the land-cover variable susceptibility model the attributes considered were the root depth, the deep drainage, the evapotranspiration and the number of strata (Figure 5).

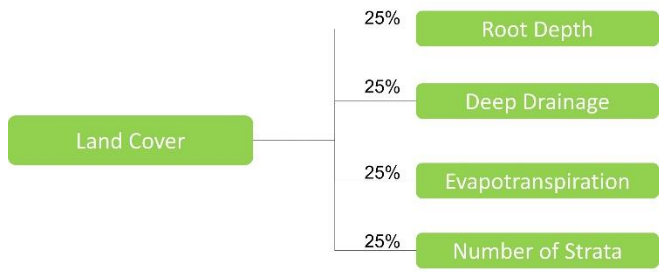

Figure 4. Diagram of the land cover variables and respective variable percentages used to construct the susceptibility due to mass movements zoning map (SGC, 2013).

The criteria, definitions and classification of the units used to survey land cover with a 1:100,000 scale were taken from the document National Land Cover Legend of the Earth Methodology, *CORINE Land Cover*, which was adapted for Colombia using a scale of 1:100,000 (IDEAM, 2010).

3 SUCEPTIBILITY ZONING

By applying the heuristic methodology using working tables obtained from experts, the susceptibility zoning model shown in Figure 6 was generated and applied systematically to the 283 sheets after the different variables joint were secured. Once the susceptibility was calculated, its cartographic representation was generated according to the following five categories: very high, high, medium, low and very low. Figure 7 shows the susceptibility map of mass movements in Colombia at 1:100,000 scale.

Figure 6. Susceptibility model (SGC, 2013).

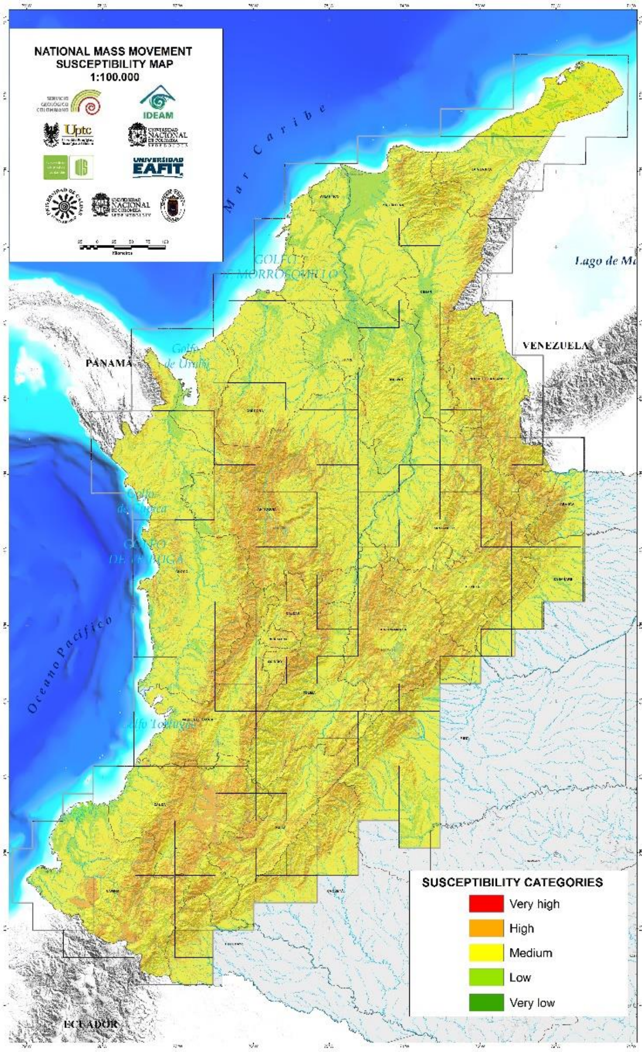

Figure 7. Susceptibility due to mass movements in Colombia map prepared with a 1:100,000 scale.

4 TRIGGERS

According to the methodology defined, the climatic and seismic triggers were evaluated and were calculated for the whole country.

4.1 Climate triggers

Colombia is located in the intertropical convergence zone and has a bimodal rainfall distribution in the Andean region and part of the Caribbean region and a unimodal distribution in the other regions; Colombia experiences frequent and intense rainfall, a condition that is strongly disturbed by the El Niño Southern Oscillation (ENSO) phenomenon, which causes hydrometeorological events, such as droughts, floods, torrential floods., and that triggers mass movement, among others (Guzmán D., Ruíz, J. F. and Cadena M., 2014). Based on the analyses of rain and climate and their relationship to mass movements, the climate trigger was constructed by considering the following hypotheses.

The annual mean precipitation and temperature affects the moisture content of the soil; i.e., in areas where the mean annual precipitation is high and the mean annual temperature is low, the soil moisture will be higher, which would contribute to the generation of more mass movements.

The more daily rainfall there is, the greater the saturation, increasing the probability of mass movements.

Therefore, the higher the background moisture content in the soil and the higher the daily maximum rainfall, the greater the probability of generating mass movements.

By considering the above mentioned facts, the data considered to construct the climate trigger variable were the mean annual precipitation and temperature and the spatial distribution of the maximum daily rainfall between 1987 and 2011, a return period of 25 years. By analysing these climatic factors, we determined their contribution to generating mass movements and thus establishing their categorization.

4.2 Earthquake triggers

Colombia is located in the so-called Pacific Ring of Fire and comprises a deformed domain, which is the result of a long geological evolution through which three major tectonic plates (the South America, Nazca and Caribbean plates) collided with each other. At present, the three plates approach each other (DeMets *et al.,* 1990; Freymueller *et al.,* 1993), causing deformations in the continental crust, volcanic activity, and intense seismic activity, which are processes that, in turn, trigger mass movements.

The seismic trigger used to construct the relative hazard due to mass movements zoning map was calculated by considering the maximum peak ground acceleration (PGA) of rock over a return period of 475 years, which was obtained from the Colombia earthquake hazard Evaluation (Ingeominas & National University of Colombia, 2010), calculated for a grid spaced every 0.1°, categorized and rated according to the contribution mass movements generation.

5 HAZARD ZONING

From the methodology just defined, each trigger was initially applied to the susceptibility map separately, generating hazard scenarios caused by climate and earthquake. Finally, the two triggers were applied simultaneously, each one with a different probability, generating the hazard map due to mass movements in Colombia at 1:100,000 scale. Four cartographic categories were used: very high, high, medium and low (Figure 8).

The predominant hazard level is medium, which covers 47.6% of the studied area, followed by the high hazard level, with a very similar percentage of 42.13%. Next is the very high hazard level (7.3%), which corresponds to unstable areas inventoried during fieldwork and is followed by the low hazard level that covers 2.9% of the studied area.

The high hazard level is mainly associated with soil deposits where rotational landslides and flows predominates; to highly fractured rocks with low strengths such as black shales and mudstones, where translational slides predominate, as well as in rock with different strengths where the rock falls predominates. The high hazard level is also associated with areas where land cover has been modified, from forests to pasture or from forests to cleared crops and pastures or to bare soils. The high hazard level occur mainly for maximum daily rainfall values of 150 to 220 mm and for PGA values between 200 and 300 cm/sec ^{2}.

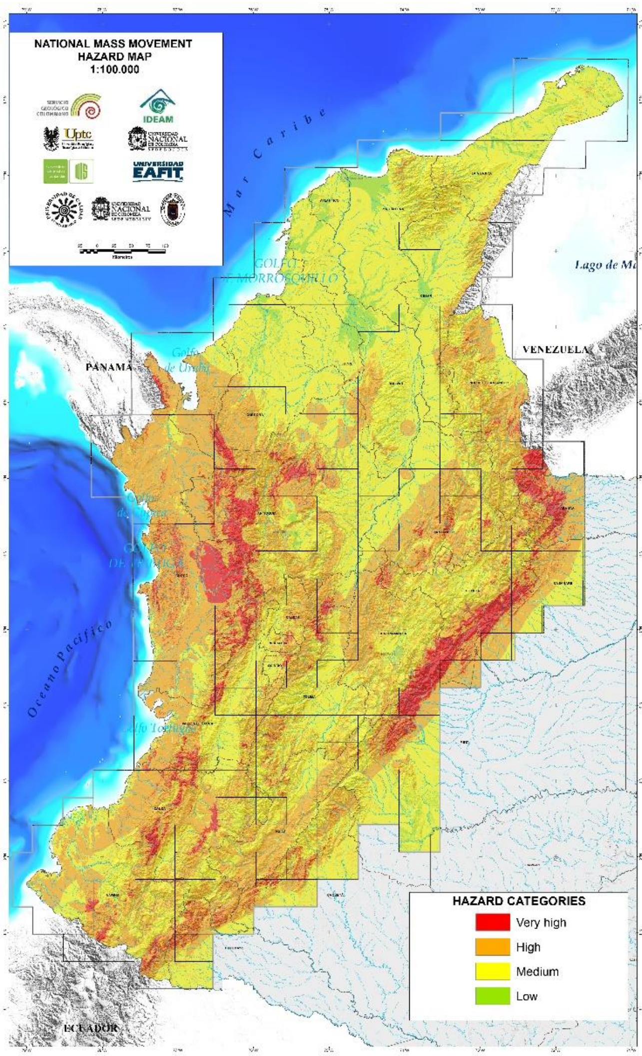

Figure 8. National map of the relative hazards due to mass movements prepared with a scale of 1:100,000.

6 UTILITY OF HAZARD ZONING AT A SCALE OF 1:100,000

The hazards due to mass movements map at a scale of 1:100,000 is a tool that can be used to successfully plan developments and is currently in the first stage of pre-feasibility and feasibility studies since, at the regional level, the map indicates areas that present different hazard levels. Therefore, this hazard map could aid studies conducted at finer scales in quantifying the mitigation work necessary to include in the projects and, in this way, to define the economic feasibility of the different layout alternatives. In Colombia, this information is mandatory for defining projects, as they are included in the reference terms of the different projects.

On the other hand, this map was honoured by the Colombian Society of Engineers with the 2017 Lorenzo Codazzi Award, owing to its `contribution to addressing the issue of hazard assessment due to mass movements, focused on territorial environmental management and disasters risk management_. The products generated in the MN100K project have been the subject of multiple consultations by organizations and the general public, such as National Planning Department, a government entity that used the national map of susceptibility due to mass movements with a scale of 1:100,000, for the development of the MUNICIPAL RISK INDEX FOR CAPACITY-ADJUSTED DISASTER RISK (2017). This hazard map has also been used by the Ministry of Agriculture to define the agricultural frontier such that high-hazard areas caused by changes in land use do not increase.

This information is the basis for Territorial Planning and Risk Management Plans of the departments and allows the Regional Autonomous Corporations to prioritize areas for further studies in their areas of competence.

The limits of the zoning map, both the susceptibility and hazard, are relative and should not be considered absolute. In addition, the conditions causing instability in the hazard zones or ranges are not homogeneous because they are defined by the different trigger scenarios, and one sector may be more affected by one of the variables than the others. Therefore, hazard maps should not be used to make decisions at local scales, because additional information is required for these scales, such as the characteristics and geomechanical parameters of the materials that comprise the terrain. In addition, it must be understood that the hazard zoning map does not predict the occurrence of mass movements.

All of the products can be consulted in digital format from the website of the SGC by using the SIMMA (Mass Movements Information System) link: http://simma.sgc.gov.co./#/. This information can also be downloaded in both pdf format and native format and can thus be incorporated into a Geographic Information System.

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