Modeling mass wasting susceptibility maps using heuristic methods in the Dosquebradas municipality, Colombia.

Alejandro Alzate Buitrago

Universidad Libre sectional Pereira. Civil Engineering Program

alejandro.alzateb@unilibre.edu.co

Abstract

In Colombia, especially in regions located in the Andes mountain range, the threat of mass wasting phenomena is one of the major concerns for authorities responsible for disaster prevention and response and territorial development. The municipality of Dosquebradas is located on the western flank of the central mountain range of the Andean region of Colombia. Heuristic methods were used to model susceptibility to mass wasting in the Dosquebradas municipality. The application of the hierarchical analysis (AHP) of variables and the arrangement of spatial information through geographic information systems (GIS) articulated this study with municipal requirements for the diagnosis of risk factors so that the results could be integrated with local planning. The mapped parameters chosen for the calculation of susceptibility to mass wasting processes in the municipality of Dosquebradas were the following: use and coverage of land (land uses); geology; slopes; surface formations; geomorphological units and ground elevation. These parameters were selected by taking into account specific knowledge of the municipal territory and the characteristics of the Dosquebradas river basin. The multicriteria evaluation method of analytical hierarchies (AHP) is applied in order to adjust the weight of the parameters as well as considering the subjectivity of the researchers. This method is classified in the Discrete Multicriteria Analysis group and uses both qualitative and quantitative variables in the pursuit of multiple targets. First, this method classifies the priorities of elements or variables (parameter maps in this case) by comparing elements in pairs according to certain criteria (their influence on the instability of the slopes) to establish their respective weights. The most relevant results of the investigation showed that for the municipality of Dosquebradas, the determining factors that held a greater weight for the potential activation of mass wasting processes were the slope and surface geological materials, followed by soil use and coverage. It is important to note that this last factor is the most dynamic and warrants special monitoring since the pressure of urban, agricultural and livestock activities is generating significant losses of forest cover and therefore increasing the susceptibility of the area to the occurrence of mass wasting processes. Finally, all the 96 landslides were mapped and compared to construct the final model and to create a landslide susceptibility index (ISD) for the municipality which divided risk into three categories: high, moderate and low susceptibility. The results presented here assign almost 92% of the mapped landslides into the high and moderate susceptibility categories. This method can be replicated in other territories where the lack of data hampers analysis.

1. INTRODUCTION

The term landslide is "attributed to those breakages of the slopes that take place along one or more discrete and continuous surfaces by means of shear mechanisms" (Santacana, 2001, p. 61). The susceptibility of mass wasting processes occurring is defined as "the propensity of the land to produce faults in the slopes" (Yalcin 2008, cited in Nguyen 2008, p. 70). In Colombia, especially in regions located in the Andes mountain range, the threat of mass wasting phenomena is one of the major concerns for authorities responsible for disaster prevention and response and territorial development. Vargas (2002) suggests that the accumulation of risk is associated with the increase in population and current styles of economic development. The risk is exacerbated when this growth is exclusive and marginal. It is well known that on hillside areas, urban expansion, agriculture and livestock farming and the loss of forest cover and ecosystem protection areas have led to an adverse cumulative effect on these territories, materialized in the occurrence of mass wasting processes of great magnitude and impact.

There are several methods for the identification of a territory's susceptibility to the occurrence of mass wasting processes; Corominas (1987) categorizes these in terms of instrumentation, recognition techniques and instability indexes. All methods imply a degree of recognition and diagnosis. In most cases, these methods tend to be expensive and complex. Similarly, Barredo *et al.* (2000) refer to three approaches used in the classification of landslide risk. They emphasize the detail and geotechnical rigor required for deterministic methods while highlighting the benefits of the heuristic method, where the proficiency and knowledge of the experts involved becomes a decisive factor for the validity and reliability of the method. In any case, it is necessary to specify that the evaluation of susceptibility and threat by mass wasting, is a "predictive technique" as suggested by Ogura and Macedo (2005) and that the product generated is the identification of the spatial conditions and temporality of threatening events.

Heuristic methods offer a good alternative for territories with significant deficiencies in the gathering of field information, and more generally, for data that supports the potential occurrence of mass wasting processes. These methods are based on categorizing and weighing variables that, in the opinion of a group of experts and the consideration of the territorial reality, are the cause of instability processes on slopes (Nilsen *et al.* 1979). Despite being considered indirect methods; their results can be extrapolated to a relative degree of certainty to predict threats for territories with similar conditions. Heuristic methods have been widely used by different authors (Nielsen *et al.* 1979; Brabb 1984; Varnes 1984; Wagner *et al.* 1988; Soeters and van Westen 1996), integrating and validating the results obtained using the spatial distribution of mapped landslides, through the use of geographic information systems (GIS).

One of the main limitations of the method is the degree of subjectivity attributed to the participating experts and the impossibility of comparing documents generated by different authors (Carrara *et al.* 1995). However, the accompanying use of GIS facilitates the collection and subsequent evaluation, analysis and processing of data, as cited by Barrantes C, et al. (2011), when they confirm that the (Mora-Vahrson methodology "allows an a priori analysis of large areas under threat of landslides" when making use of GIS.

For Mora and Vahrson (1994) the expert method is a quick way to classify the threat of landslides in tropical zones. They state that slopes, wet soil and geological materials are linked to the intrinsic properties inherent to the occurrence of landslides, while external factors such as rainfall and the vibratory effects associated with earthquakes should be considered detonating agents. Indeed, rainfall and seismic activity affect the threat of landslides in any territory. These statements acquire meaning and validity in two dimensions: firstly, when the intrinsic features inherent to the occurrence of landslides are defined and evaluated, reference is made to a territory's susceptibility to the occurrence of mass wasting, and this condition is compounded by the properties of detonating agents such as rain and earthquakes (Mora and Vahrson 1994). Secondly, this phenomenon is transcended to the threat by mass wasting processes, because of geo-mechanical disturbances that these agents have on geological materials.

In this study, a heuristic method for the mapping of susceptible zones for mass wasting was applied to the particular case study of the municipality of Dosquebradas, located in Colombia's Andean region. This case study is of interest due to its topographic and geomorphological conditions, rainfall regime, proximity to active seismogenic sources and the variety of geological materials (residual soils and rocks) that make up a highly complex territorial scenario from the perspective of disaster risk management. In fact, historically, the municipality of Dosquebradas has periodically been exposed to large landslides and floods. Such events are associated with increased rainfall during the wet periods of the region's bimodal climatic regime. It should be noted that, according to DesInventar (2017), among other threats, the socio-economic impacts associated with the occurrence of landslides and floods have been highly significant throughout the recorded history of the municipality of Dosquebradas, with 132 deaths, 16 disappearances and 94 homes destroyed by mass wasting processes.

2. DESCRIPTION OF STUDY SITE

The municipality of Dosquebradas is located in the south east of the Risaralda department, on the western flank of the central mountain range of the Andean region of Colombia. It has a surface area of 70.81 km², 13 km² correspond to the urban perimeter. It was created in 1972 as the 14th municipality of the department of Risaralda, standing out for its industrial potential and becoming the city with the greatest urban, physical and demographic growth. It is now the second most important municipality of the department of Risaralda after Pereira, its capital. The rainfall regime varies between 2600 and 3200mm per year, divided into two dry periods and two wet periods. The average temperature is uniform, and ranges between 21 and 22 degrees celsius (Corporación Autónoma Regional de Risaralda, 2009). Using the classification system created by Holdridge (1967), the basin of the Dosquebradas creek and the municipality as a whole is classified as very wet Premontane forest (bmh-PM).

Geologically, the municipality is made up of igneous rock from the Gabro-dioritic Stock of Pereira-Santa Rosa (Caballero and Zapata, 1984), as well as basalt and diabase from the Barroso Formation and fall deposit (volcanic ash). Metamorphic rock of the Arquía Group is also present: mainly chloritic, amphibolitic, sericitic and actinolytic schists and locally granatiferous amphibolites (Gonzáles, 1989). The local geology is also made up of sedimentary rocks, corresponding to recent alluvial and colluvial deposits and the Quindío Glacis (Pereira Formation) which is a set of volcanic, volcanodetritic and sedimentary rocks transported and deposited by fluvial means (Caballero and Zapata, 1983).

Tectonically the department of Risaralda is located on the western flank of the Central Mountain Range and the eastern flank of the Western Mountain range within the Cauca depression, dividing the region into two distinct regions. The western region encompasses inverse-type structures and low dip angle with predominant SSE-NNW courses, whereas the eastern region comprises high-angle reverse faults with a bearing component predominate both regions being limited by the Cauca-Almaguer fault. The Otun fault controls the structure of the Otun River as it passes through the municipality of Dosquebradas (CARDER, 2009). Additionally, the San Rosa (N70E / 75SE), Rodeo (N50E / 80-90W), Boquerón (N65E / 75SE) and Agua Azul faults (N20W / vertical) are considered to be satellite faults of the Cauca-Romeral faults megasystem, which structurally controls some contact between lithological units and affects their geomechanical features.

Geomorphologically the municipality is characterized by depositional geoforms: alluvial deposits, hydraulic fill deposits, fan deposits and deposits originated from flows and denudation which have resulted in subrounded to rounded hills, river escarpments from vertical to vertical, hills with sharp peaks and moderate slopes, hills with rounded tops and gentle slopes and hills with steep slopes. The predominant surface formations in the municipality's territory are associated with heterogeneous free-flowing anthropic fillers, alluvial deposits, colluvial deposits, mud-flow deposits, fall deposits, fluvio-volcanic deposits, saprolite from volcanic rocks and saprolite metamorphic rocks (Duque and Pareja, 1991).

Coffee and coffee with different consociations represent the highest land use (cover) with 35.66%, followed by forests (22.38%), managed pastures (21.88%), urban use (14.4%), clean crops (1.95%) and other uses (3.73%). It should be noted that coverage of the soil factor shows the greatest changes and dynamism in the municipal territory (CARDER, 2009).

3. METHODOLOGY

The heuristic method chosen to establish the susceptibility to mass wasting was Nguyen's (2008) mapping of mass wasting susceptibility based on indexes. Similar to Jian and Xiang-guo (2009), in this methodological proposal the author treats all factors as causative, and each is assigned a parameter map. The relative significance of each parameter map is evaluated according to the knowledge and expertise of the group of professionals (geologists, geotechnicians, engineers), who carry out a field inspection of mass removal processes in the study area. This feature is the main reason that the results from one study cannot be extrapolated in other areas (Hervás *et al.*, 2002).

The mapped parameters chosen for the calculation of susceptibility to mass wasting processes in the municipality of Dosquebradas were the following: use and coverage of land (land uses); geology; slopes; surface formations; geomorphological units and ground elevation.

These parameters were selected by taking into account specific knowledge of the municipal territory and the characteristics of the Dosquebradas river basin, where its morphometric, climatological, geological and territorial use and exploitation features and geomorphological evolution allow for the adequate inference of susceptibility and exposure to processes of mass wasting and flooding, as verified by historical disaster records (CARDER, 2009).

3.1. APPLICATION OF THE AHP MATRIXES (ANALYTIC HIERARCHY PROCESS)

According to Saaty (1980) and Hervás *et al.* (2002), the multicriteria evaluation method of analytical hierarchies (AHP) is applied in order to adjust the weight of the parameters as well as considering the subjectivity of the researchers. This method is classified in the Discrete Multicriteria Analysis group and uses both qualitative and quantitative variables in the pursuit of multiple targets. First, the method classifies the priorities of elements or variables (parameter maps in this case) by comparing elements in pairs according to certain criteria (their influence on the instability of the slopes) to establish their respective weights. Thus, a weight value is obtained for each class within the parameters evaluated.

A square matrix is used to establish parameter weights according to the AHP, with the number of rows and columns equal to the number of parameters used in the evaluation of susceptibility. Each element of the matrix is assigned a value that represents the relative significance of the factor of its row with respect to that of its column, according to the criteria defined in Table 1, from which preference grades are assigned from 9 to 1.

Tabla 1. Scale of preference between two parameters in AHP (Saaty 2000)

Scales	Degree of preference	Explanation
1	Equal	Two activities contribute equally to the objective
3	Moderate	Experience and judgment slightly to moderately favor one activity over another
5	Strong	Experience and judgment strongly or substantially favor one activity over another
7	Very strong	An activity is strongly favored over another and its dominance is shown in practice
9	Extreme	The evidence that favors one activity over another is of the highest degree possible of an affirmation

The AHP also allows for the evaluation of the inconsistency of the values used in the matrix. Saaty (2000) states that for a consistent reciprocal matrix, the largest value of the auto vector λ_{Max} should be equal to the number of comparisons n and proposes a measure of consistency called the Consistency Ratio, defined as follows:

$$IC = (\lambda_{Max} - n)/(n - 1) \quad (1)$$

It is necessary to check the coherence index (CI), the random index (RI) and the coherence ratio (CR), according to equations 1,2 and 3

$$CR = IC/RI \quad (2)$$

If the CR value is less than or equal to 10% the inconsistency is acceptable, but if the consistency ratio is greater than 10% the subjective judgment of the values assigned to the matrix elements needs to be reviewed. In this study, this procedure was implemented by the group of experts who qualified the factor matrix and the matrices of classes associated with each factor. Tables 2 and 3 show the qualified factors and classes, the values obtained in the classification of matrices concerning factors and classes and their ranking in ascending order of importance, which corresponds to their incidence on the occurrence of landslides.

Tabla 2. Parameter maps (factors) and definition of values /weights of importance in the occurrence of mass wasting processes

Factors	**No. classes**	**Importance**	**Ranking**
Slope	5	0,314	1
Use and Coverage	9	0,181	3
Geology (Lithology)	9	0,122	4
Surface formations	9	0,239	2
Elevation	4	0,055	6
Geomorphological units	6	0,088	5

Tabla 3. Classes associated with each parameter and definition of values/weights of importance in the occurrence of mass wasting processes

Factors	Classes	Weight	Ranking
Slope (degree)	0 - 12.5	0,057	5
	12.6 - 25.1	0,083	4
	25.2 - 37.3	0,144	3
	37.4 - 52.6	0,247	2
	52.7 - 86.5	0,468	1
Use and Coverage	Clean crops	0,238	1
	Natural forests	0,041	8
	Planted forests	0,063	6
	Mosaic	0,138	4
	Coffee	0,125	5
	Guadua Forests	0,055	7
	Pastures with stubble	0,142	3
	Managed pastures	0,161	2
	Urban zone	0,037	9
Geology (lithology)	Mafic rocks of Pereira	0,052	7
	Metamorphic rocks Arquia Group	0,087	5
	Sedimentary unit	0,117	4
	Barroso Formation	0,037	9
	Tectonic gap	0,259	1
	Recent alluvial deposits	0,192	2
	Volcanic mud flows	0,141	3
	Porphyry hypoabisal rocks	0,042	8
	Glacis of Quindio	0,073	6
Surface formations	Saprolite of quartz-sericitic schists	0,155	3
	Saprolite of diabasas	0,042	8
	Saprolite of hornblendic gabbro hornbléndico	0,063	7
	Saprolite of porphyry dacitic unit	0,083	5
	Fluvial volcano unit	0,070	6
	Alluvial valley fill	0,222	1
	Volcanic ash	0,033	9
	Saprolite of sedimentary unit	0,112	4
	Saprolite of graphite schists unit	0,220	2
Elevation (m.s.n.m.)	Altitude 1: 1285 - 1410	0,450	1
	Altitude 2: 1411 - 1500	0,081	4
	Altitude 3: 1501 - 1780	0,135	3
	Altitude 4: > 1781	0,334	2
Geomorphological units	Alluvial fan	0,052	6
	Alluvial valley	0,054	5
	Mountainous denudative	0,109	4
	Otun river slope fault escarpment	0,392	1
	Valley in "v"	0,240	2
	Hilly relief (piedmont area)	0,152	3

3.2. CALCULATION OF FINAL SUSCEPTIBILITY

The final integration of the factors (parameter maps: figure 7) and their respective classes define the Slip Susceptibility Index (ISD), which is the weighted sum of the weights of all the factors and classes defined (Nguyen 2008).

$$ISD = \sum_{j}^{n} Wjwij \quad (3)$$

ISD: Index of Susceptibility due to Landslides

Wj: Weight value for parameter j.

wij: Weight value of class i in parameter j.

n: number of parameters

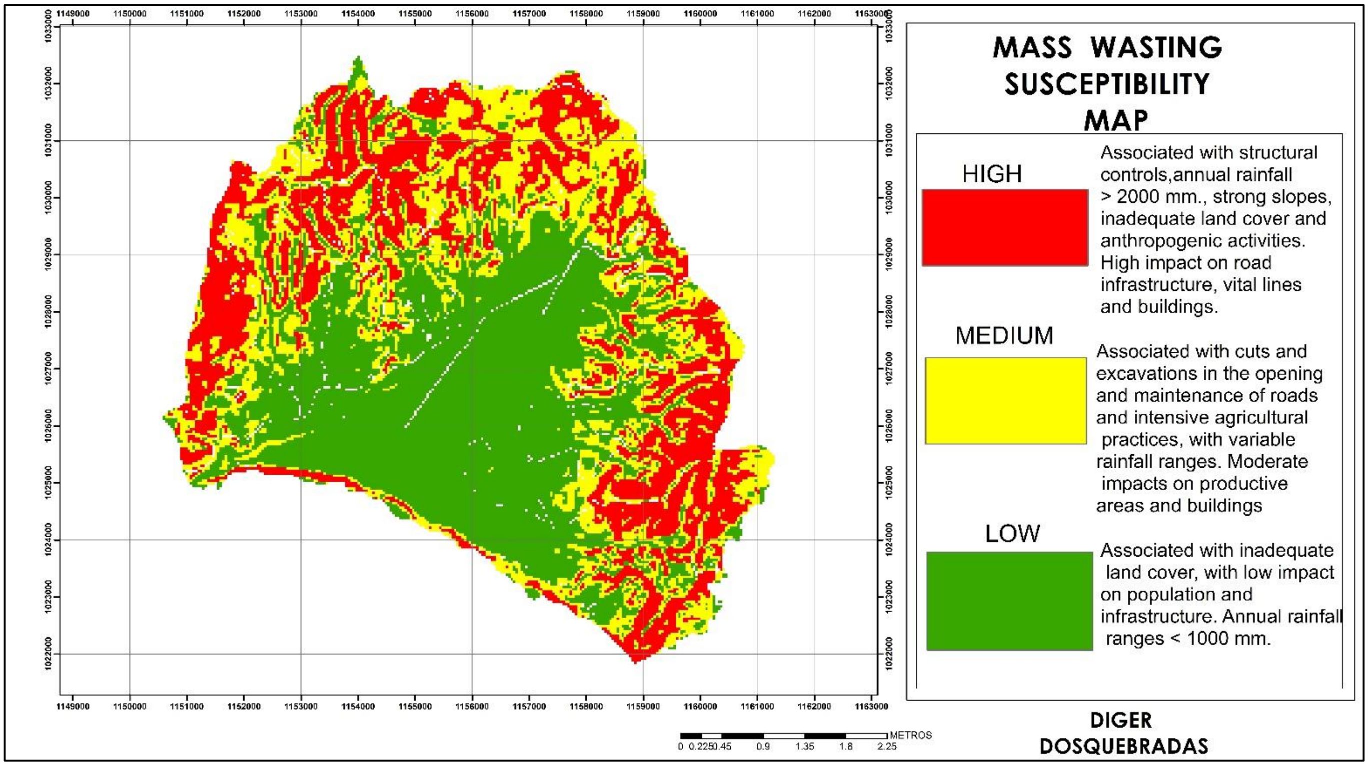

Figure 7. Map showing the susceptibility to mass wasting processes for the municipality of Dosquebradas, integrating the parameters slope, use and coverage, geology, surface formations; elevation and geomorphological units.

4. CONCLUSIONS

The susceptibility map of the Dosquebradas municipality was obtained, identifying the high, medium and low categories of risk for mass wasting processes. The parameters used were geology, surface formations, land use and cover, geomorphological units and elevation, along with their corresponding classes.

For the municipality of Dosquebradas, the determining factors that held a greater weight for the potential activation of mass wasting processes were the parameters slopes and surface geological materials, followed by soil use and coverage. It is important to note that this last factor is the most dynamic and warrants special monitoring since the pressure of urban, agricultural and livestock activities is generating significant losses of forest cover and therefore increasing the susceptibility of the area to the occurrence of mass wasting processes.

The validity and reliability of the method applied in this study for the modeling of mass wasting susceptibility is confirmed by the fact that the results obtained were accepted and validated by the Risk Management Department (DIGER) and the Secretariat of Municipal Planning and incorporated as an input into their Land Management Plan in the component Risk Management.

REFERENCES

Barredo, J., Benavides, A., Hervás, J., & van Westen, C. J. (2000). Comparing heuristic landslide hazard assessment techniques using GIS in the Tirajana basin, Gran Canaria Island, Spain. International journal of applied earth observation and geoinformation, 2(1), 9-23.

Caballero, H., & Zapata, G. (1983). Plancha Pereira No. 224, Escala 1: 100.000. Ingeominas, Bogotá.

Carrara, A., Cardinali, M., Guzzetti, F., & Reichenbach, P. (1995). GIS technology in mapping landslide hazard. In Geographical information systems in assessing natural hazards (pp. 135-175). Springer, Dordrecht.

Corominas, J. (1987). Criterios para la confección de mapas de peligrosidad de movimientos de ladera. Riesgos Geológicos. Serie Geología Ambiental. IGME, Madrid, 193-201.

Coporación Autónoma Regional de Risaralda CARDER (2009). Recuperado el 15 de noviembre de 2019 en https://www.carder.gov.co/index.php/intradocuments/webExplorer/diagn-sticos-riesgos-ambientales

González, H., 1989. Análisis de la nomenclatura estratigráfica de las rocas metamórficas (Litodema A) al este del límite oriental de la zona de la Falla de Romeral, Cordillera Central, Colombia. Ingeominas, Informe interno, 21 p. Medellín.

Hervás, J., Barredo, J.I. y Lomoschitz, A., 2002. Elaboración de mapas de susceptibilidad de deslizamientos mediante SIG. Teledetección y Métodos de evaluación multicriterio. Aplicación a la depresión de Tirajana (Gran Canaria). En: F.J. Ayala-Carcedo y J. Corominas (eds.). Mapas de susceptibilidad a los movimientos de ladera con técnicas SIG. Fundamentos y aplicaciones en España Instituto Geológico y Minero de España, 168-180.

Jian, W. & Xiang-guo, P., 2009. GIS-based landslide hazard zonation model and its application. Procedia Earth and Planetary Science 1:1198–1204.

Mora C, S. & Vahrson, W. G. (1994). Macrozonation methodology for landslide hazard determination. Bulletin of the Association of Engineering Geologists, 31(1), 49-58.

Nguyen, T.L., 2008. Landslide susceptibility mapping of the mountainous area in a Luoi district, Thua thien Hue province, Vietnam. PhD Thesis Vrije Universiteit Brussel. 255 p.

Nielsen TH, Wrigth RH, Vlasic TC, Spangle WE (1979) Relative slope stability and land-use planning in the San Francisco Bay region. California, US Geological Survey Professional.

Ogura, A., & Macedo, E. S. (2005). Procesos y riesgos geológicos. Division of Geology Institute for Technological Research of São Paulo-IPT. tic.uis.edu.co/aula2, 1.

Saaty, T. L. (1980). Analytic Heirarchy Process. Wiley StatsRef: Statistics Reference Online.

Santacana Quintas, N. (2001). Análisis de la susceptibilidad del terreno a la formación de deslizamientos superficiales y grandes deslizamientos mediante el uso de sistemas de información geográfica. Aplicación a la cuenca alta del río Llobregat. Universitat Politécnica de Catalunya.

Soeters, R., & van Westen, C. J. (1996). Landslides: Investigation and mitigation. Chapter 8-Slope instability recognition, analysis, and zonation. Transportation research board special report, (247).

Vargas, C. G. (1994). Metodología para la cartografía de zonas de susceptibilidad a los deslizamientos a partir de sensores remotos y SIG. Boletín Geológico INGEOMINAS, 34(1), 59-116.

Varnes DJ (1984) Landslide hazard zonation: a review of principles and practice. Natural Hazards, 3. Unesco, Paris

Yalcin, A. (2008). GIS-based landslide susceptibility mapping using analytical hierarchy process and bivariate statistics in Ardesen (Turkey): comparisons of results and confirmations. Catena, 72(1), 1-12.