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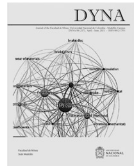

UNIVERSIDAD NACIONAL DE COLOMBIA

A data mining approach to the relationships between landslides and open-pit mining activity: a case study in Soacha (Cundinamarca)

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Abstract

Landslides caused by changes in land use, or by anthropic activities such as open-pit mining, constitute one of the most important socio-economic risk factors in countries with developing economies. This article presents an approach to the relationships between mining activity and the development of landslides in a pilot area located in Soacha, Cundinamarca. Through data mining analysis and the use of Geographic Information Systems (GIS), an evaluation of the possible relationships of these factors was carried out, including socioeconomic aspects. From an inventory of open-pit mining sites, the geomechanical characterization of soil and rock units, and the characterization of environmental and social variables, data were obtained to define variables whose relationships were determined by algorithms programmed in the GIS. The results show that there is an indirect relationship between open-pit mining activity and landslides development over the last four decades in the studied zone.

Keywords: urban development; landslides; land use; mining.

Una aproximación desde la minería de datos para la identificación de las relaciones entre deslizamientos y la actividad minera a cielo abierto: caso de estudio en Soacha (Cundinamarca)

Resumen

Los fenómenos de remoción en masa causados por cambios en el uso del suelo, o por actividades antrópicas como la minería, constituyen uno de los factores de riesgo socioeconómico más importantes en países con economías en desarrollo. Este artículo presenta un enfoque para la evaluación de las relaciones entre la actividad minera y el desarrollo de deslizamientos en un área piloto ubicada en Soacha, Cundinamarca. Mediante análisis de minería de datos y el uso de Sistemas de Información Geográfica (SIG), se llevó a cabo la evaluación de las posibles relaciones de estos factores, incluyendo aspectos socioeconómicos. A partir de un inventario de canteras, la caracterización geomecánica de unidades aflorantes, y la caracterización de variables ambientales y sociales, se obtuvieron datos que definieron variables cuyas relaciones se determinaron mediante algoritmos en el SIG. Los resultados muestran que existe una relación indirecta entre la actividad minera y el desarrollo de deslizamientos en las últimas cuatro décadas en el área estudiada.

Palabras clave: planificación urbana; deslizamiento de tierra; uso de la tierra; minería.

1. Introduction

The municipality of Soacha, Cundinamarca, including rural and urban areas, is the pilot area for this study. Its aim is to evaluate environmental conflicts associated with mining activity to establish the existence of a causal relationship between mining activity, urbanization processes and mass movements [1]. Currently, Soacha is the municipality with the highest population in Cundinamarca and the first industrial center of the department. In addition, it has the highest

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population growth rate in the country, at 22.3%, a figure that exceeds any growth rate in the world [2].

Mining is one of the main economic activities in the municipality. It consists of the open-pit extraction of construction materials such as gravel, sand, clay, and stones. Approximately 18% of stone materials used in the "Sabana de Bogotá" are produced in this area [3].

According to [4], Soacha is the most deprived municipality in Colombia. One of the problems is the settlement of substandard neighborhoods in high-risk social areas, due to the lack of clear boundaries between industrial and residential areas. There is mixed-use urban territory, where industry, commerce, education, and housing converge.

Mining is an activity as old as human civilization, but its arrival in regions with productive activities that are not based on mineral extraction modifies circumstances, changes daily life and forces communities to face the challenge of coexisting with the changes and new actors that this activity attracts, leading these communities to reformulate and rebuild a new vision of their future [5]. Mining activity generates issues related not only to economic decisions, but also to social decisions, creating conflicts between competing and related values and interests [6]. To obtain satisfactory answers about those complex relationships, we need parameters that allow us to compare the value of variables that have a weak explicit comparability [7]. Therefore, it is essential to reach an explicit and determining delimitation of the activity's own effects and of those that are its indirect product, i.e., it is necessary to define conflict sources and the conflicts themselves.

This situation converges in a distributive and economic conflict, as described by [7], that goes from local to global, an intimately related conflict that shows a clear environmental inequity that directly affects communities. There are several cases reported in the literature in which landslides induced by mining activity in the vicinity of populated centers cause an increase in the physical, social, and economic risks in the influence area and generate long-term impact on urban development [3,8].

One of the greatest difficulties is the large number of actors involved and the social values that are put at stake, which to a large extent forces the society involved as participant to take responsibility. There are political, cultural, and economic factors whose evaluation may vary according to the geographical region where the effects occur. That is why it is essential to establish measurable relationships between mining and the effects on the physical environment which produce various sorts of conflicts that impact the actors [7,9]. A clearer identification of causes and effects allows the actors involved to arrive at converging solutions that they can adopt in a more rational and objective way [10].

Environmental problems arise due to the ways in which each society develops its technological, organizational, economic and political processes and the manner these processes manifest in the planet's biophysical systems. Environmental problems are only solved to the extent that structural changes occur in the processes that generate culture [9,10], which can only be achieved through an objective determination of causes and effects.

Research about environmental issues and conflicts linked to mining activity has been tackled from alternative approaches rooted in human geography and economic geography. From these perspectives, territorial configurations and the social production of space and are riddled with conflicts [1,9,10].

Environmental conflicts arise when a social group perceives that the use, appropriation or meaning it gives to the territory is under threat due to the impacts that derive from the practices of other groups. The presence of an environmental problem does not imply per se the occurrence of a conflict; to have one, it is necessary that the groups involved have a dynamic of opposition [10-11]. Environmental conflicts around mining activity occur as a product of the physical-social relationship, in a defined time and space and under the influence of the ideas and visions of the social groups involved as active and passive actors [8,12].

This study uses data mining as a tool to connect the different variables considered in this study. Through data mining, it is possible to discover information in the form of patterns, changes, links, and significant structures of large amounts of stored data [9]. Data mining consists of obtaining: 1) dependency analysis 2) identification of classes, 3) description of concepts, and 4) detection of deviations, extreme cases, or anomalies [13]. Supervised and unsupervised techniques are used to perform data mining [10,13-16]. Among the supervised techniques are decision trees, neural induction, regression, and time series; and among the unsupervised techniques are deviation detection, segmentation, clustering, association techniques, and sequential patterns.

The question that motivated this research is: what kind of relationships are there between territory development, open-pit mining activity and mass movements within the framework of urban growth? This question arises in a context of sustainability for territories such as Soacha in the "Sabana de Bogotá" region. Additionally, given these results, how can one establish a relationship between the environmental conflicts that exists in the study area and mining activity?

This work aims to evaluate, using data mining, the possible causal relationship between open-pit mining activity and the generation of mass movement and landslide hazards, or its relationship to other causes such as urbanization processes and population growth, in the municipality of Soacha in the department of Cundinamarca [1]. Table 1 shows the main characteristics of the geological formations present in the municipality of Soacha and the approximate exploitation volumes.

Table 1.
Main characteristics of the geological formations present in the municipality of Soacha.

Formation	Type of rock	Exploitation volume (m^3/year)	Uses
Guadalupe-Plaeners	Sandstone/ Siltstone	~5500	Granular material for structural fillings
Guadalupe – Sandstone Labor	Sandstones	~6700	Granular materials for roads and fillings
Bogotá	Arcillolites	~550	Masonry

Source: Authors.

2. Methodology

The methodology implemented to analyze and identify existing relationships between mining activity and the generation of landslides included a multivariate analysis of qualitative, semiquantitative and quantitative variables of the different factors that define the relationships that this study addresses. Variables linked to the physical environment were identified and evaluated, variables such as ground cover and soil use in the different zones where open-pit mining occurred, geomechanic properties of the materials involved in mass movement processes, population density, average annual rainfall, and the geomorphology of slopes in the places affected by mining activity. On the other hand, institutional and socio-economic aspects linked to conflicts between mining and mass movement phenomena were evaluated in a qualitative manner through the aspects recorded in the official documents of the land-use plan of the municipality and the management information from the Office of the Mayor of the Municipality of Soacha. A multivariate statistical model was used, allowing us to establish relations between spatial variables using ARGIS as a spatial tool and SPSS for the statistical analysis.

The research included the following stages: 1) Field work in the inventory of quarries, mass movements and the description of the physical environment. 2) Information collection and analysis regarding the factors of the biophysical and socio-economic environment, and the factors to evaluate the conflicts between mining and mass movement. 3) Application of the spatial model of correlations in the GIS tool, applying discretization techniques, numbering and data mining between variables. 4) Results analysis and determination of relationships between open-pit mining/environmental conflicts and landslides. Fig. 1 shows the concept map of the stages implemented in the development of the project.

The variables in the generation of the relationships model used for stages 1 to 4 of the analysis are presented in (Table 2), which shows the denomination of the GIS analysis group in the "group" column, the name of the operator employed in the tool under "name", and the definition of the variables in the "definition" column; the last column refers to the topology of the object in the GIS tool.

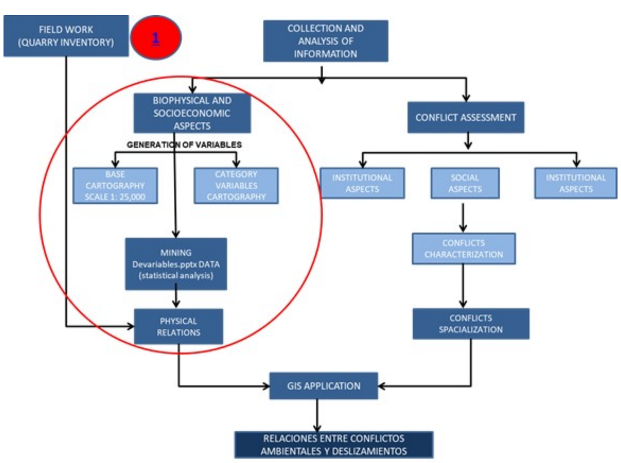

Figure 1. Methodology
Source: Authors

Table 2.
Variables for generating relationship model.

1. Primary variables			
Group	**Name**	**Definition**	**Topology**
Unstable zone or very high threat zone location	1. MOV	1. Fault zone centroid	Raster
Ground cover	2. VEG 3. CANT 4. ZONUR	2. Types of ground vegetation cover 3. Quarry classification: old / active 4. Urban or bare areas	Polygon
Geomechanics	FMS CALID	5. Presence of soil or rock 6. Classification of materials by origin	Polygon Raster
Average annual rainfall	7. NIV – FREATICO	7. Saturated and partially saturated areas	Polygon
Population density	8. DENS	8. Population occupation classification by density	Polygon
2. Digital elevation model (DEM)			
Elevation	**MDE**	**Height above sea level**	**Raster**
3. Secondary variables resulting from the DEM			
Hillside geometry	1. PEND	1. Slope	Raster
	2. ORIENT	2. Hillside Exposure Direction	Raster
	4. CURVAR	4. Terrain concavity / convexity degree	Raster
	5. ACUENCA	5. Cumulative basin area	Raster
Basin watershed	6. LONG	6. Cumulative maximum basin length weighted with the slope	Raster

Source: Authors.

The procedure used for the analysis between variables in stage 4 included the following steps [9]: a) Obtaining the sample, b) Cleaning the sample (analysis of errors introduced in the sample), c) Selection of the independent variables with the highest statistical significance to construct the discriminant function, and d) definition of the explanatory discriminant function of the relationships between the variables.

Documentary information was collected from national, departmental, and local institutions that have carried out work in the municipality of Soacha. This information collected corresponds to physical and environmental data linked to stability evaluation, mining activity and urbanization processes in the municipality [2-3,10-11].

The documentary information and digital bases of the physical environment included in stage 4 of the project can be summarized as follows: a) Base cartography at 1:25,000 scale in shp format (MOV), b) Geomechanically zoning map at 1:25,000 scale, in shp format (MOV), c) Ancient and active quarries location map in shp format, d) Inventory map of points with mass movements (MM), in shp format, e) Map of MM threats without earthquake and with earthquake at 1:25,000 in shp format, f) Map of current soil coverage and use at 1:25,000 in shp format, g) Water table map at 1:25,000 scale in shp format and, h) Population density map at 1: 25,000 scale [17].

In Fig. 2, we present the location of the study area.

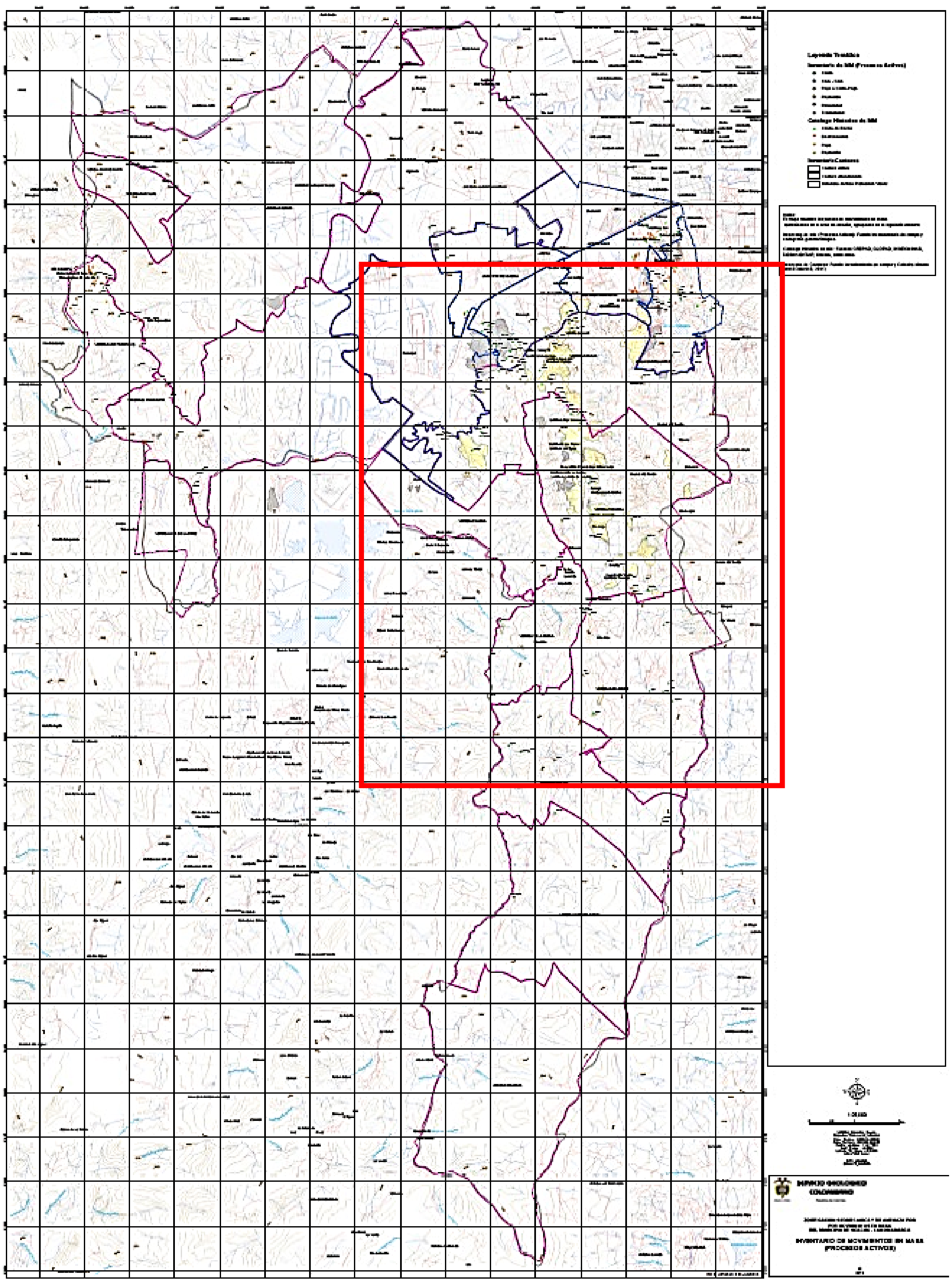

Figure 2. Study location area in Soacha municipality.
Source: [17]

Using the map of mass movement hazard (MOV), cells were selected on the digital base, locating the sites of conflict between mining activity and social conflict. The digital elevation model (DEM) for the application of the GIS was created using 281,736 points according to vectorization of 15*15 m cells. In each cell, the information was processed in the GIS application using a set of variables, whose combination allows establishing the possible relationships between these variables and the previously identified unstable zones.

3. Results

The results obtained from the GIS analysis and the variables derived from the DEM were grouped in the following output group descriptors: ACUENCA (characteristics of the morphology of the basin that contributes to the surface runoff correlated to mining), LONG (characteristics of the length of sliding mass correlated to mining), CURVAR (characteristics of the morphology in level curves correlated to mining), PEND (characteristics of the morphology of the terrains slopes correlated to mining activity), ORIENT (characteristics of the orientation of joints in rock mass outcrops with mass movements caused by mining), FMS (characteristics of mass movements correlated to mining activity), VEG (characteristics of the vegetation cover correlated to mining), ZONTUR (characteristics urban zoning correlated to open-pit mining processes), CALID (characteristics of the quality of institutional support correlated to mining activities), and CANT & DENS (characteristics of population density correlated to mining). These descriptors are presented in Table 1, which presents the values that characterize the logical correlation tests KOLMOGOROV-SMIRNOV.

ACUENCA and LONG show positive bias. The bias is more pronounced in ACUENCA because it represents flow accumulation controlled by the area's topography. Many cells show little flow accumulation, both in area and in length, because many of them are in streams, rivers, and cliff headwaters. Some cells show large flow accumulation from other cells which belong to main valleys, confluences with rivers or the lowest area of the main river. Therefore, even if a large area with a large basin or several different-sized basins are studied, as in our case, these variables will always present positive bias in its distribution, regardless of whether we treat the entire study area or take a sample from a specific area or a random sample.

The second group corresponds to the CURVAR variable, which represents the terrain curvature in terms of convexity, concavity, and flat areas. This variable presents a distribution that is very close to normal, and it is closed to the central values. This is because the value range oscillates from negative for concave cells to positive for convex cells, going through 0 in flat areas.

In the distribution of the PEND variable, low values predominate because the hillside areas are very localized, and their percentage compared to flat areas is lower. However, there are mountainous areas where medium and high values dominate. The slope's predominant values are between 10 and 20 degrees with an average of 15 degrees.

The range of the ORIENT variable depends, in the case of mountain areas, on the orientation of the main valleys.

The MDE variable presents a slight positive bias with different peaks for different heights.

The categorical variables FMS, VEG, CANT, ZONUR, CALID and DENS present a distribution that is far from normal, due to the nature of the variables and the small number of categories that they comprise. Histograms show a predominance of rocky materials on the ground, a predominance of areas occupied by vegetation, areas without quarries and low population density in most of the study area.

Table 3 shows the normality test (K-S Z) results of untransformed variables and their significance.

Variables weights in the discriminant function signify their influence and relative contribution in the generation of mass movements and therefore the relationship between them. Negative coefficients indicate a high influence towards stability. Positive coefficient values show a high influence towards instability (Tables 5-6).

Discriminant function obtained from the analyses is as follows:

MOV=0.365 VEG+0.101PEND+0.057FMS+0.138ZONUR+0.001MDE+0.05ACUENCATRANS-1.417CALID-0.026CURVAR-0.708 NIVFREA-0.01 ORIENT-2.513

Table 3.
Kolmogorov-Smirnov test

		DENS TRANSF	ACUENCA TRANSF	CALID TRANSF	FMS TRANSF	NIV FREA TRANSF	LONG TRANSF	VEG TRANSF
N		65567	49549	65561	65567	65567	65355	65567
Normal parameters [a] [b]	Average	2.0932	3.8438	0.6470	0.0631	0.2809	4.9245	0.7576
	Typical deviation	1.2467	0.6960	0.3741	0.1225	0.0752	0.4220	0.4285
Extreme differences	Absolute	0.4710	0.1470	0.2350	0.4870	0.5390	0.1050	0.4720
	Positive	0.4710	0.1210	0.2350	0.4870	0.3940	0.0820	0.2860
	Negative	-0.2860	-0.1470	-0.1470	-0.3030	-0.5390	-0.1050	-0.4720
Kolmogorov-Smirnov Z		120.6680	32.6620	60.2620	124.7470	137.9320	26.8060	120.8060
Asymptotic (bilateral) sig.		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

[a] Contrast distribution is Normal.
[b] Parameters calculated from these data.
Source: Authors

Table 4.
Total Variance explained

Comp.	Initial eigenvalues Total	Initial eigenvalues Var. %	Initial eigenvalues Accum. %	Extraction Sums of Squared Loadings Total	Extraction Var. %	Extraction Accum. %	Rotation Sums of Squared Loadings Total	Rotation Var. %	Rotation Accum %
1	4.744	36.940	36.490	4.744	36.490	36.490	4.539	34.919	34.919
2	1.642	12.632	49.122	1.642	12.632	49.122	13.827	13.827	48.746
3	1.284	9.878	59.000	1.284	9.878	59.000	1.257	9.668	58.414
4	1.095	8.424	67.424	1.095	8.424	67.424	1.171	9.010	67.424
5	0.987	7.593	75.016						
6	0.910	6.997	82.014						
7	0.716	5.506	87.520						
8	0.613	4.716	92.236						
9	0.467	3.595	95.831						
10	0.317	2.441	98.272						
11	0.183	1.404	99.676						
12	0.041	0.319	99.995						
13	0.001	0.005	100.000						

Source: Authors

Table 4 reports the Normality Test (K-S Z) results of transformed variables and their significance:

The data obtained show that there is no direct physical relationship between the conflicts perceived by communities versus instability areas due to mass movements in Soacha. Nor is there a direct relationship between mining activity and territory instability.

The sectors that appear to have greater conflict associated with mining activity are in rural areas, due to the change in the landscape and uses of the territory, aspects that affect and modify the environment and therefore the economic activities of the former occupants of that territory. The most negative perception is exhibited by the region's oldest inhabitants, who associate territory deterioration with mining activity, without considering other human factors such as urban growth in nearby municipality areas (Figs. 3-6).

Table 5.
Canonical discriminant functions coefficients

	Function 1
Vegetation	0.365
Slope (%)	0.101
Soil and rock types	0.570
Population density	0.000
Terrain orientation	-0.001
Concavity / convexity	-0.026
Urban areas	0.138
Type of material	-1.417
Elevation model	0.001
Water table	0.708
ACUENCA TRANSF	0.050
(Constant)	-2.513

Non-standardized coefficients
Source: Authors

Table 6.
Sorting results

Unstable areas			Predicted Stable areas	Predicted Unstable areas	Total
Original	Count	Stable areas	19769	5490	25259
		Unstable areas	3373	20917	24290
	%	Stable areas	78.3	21.7	100.0
		Unstable areas	13.9	86.1	100.0

Source: Authors

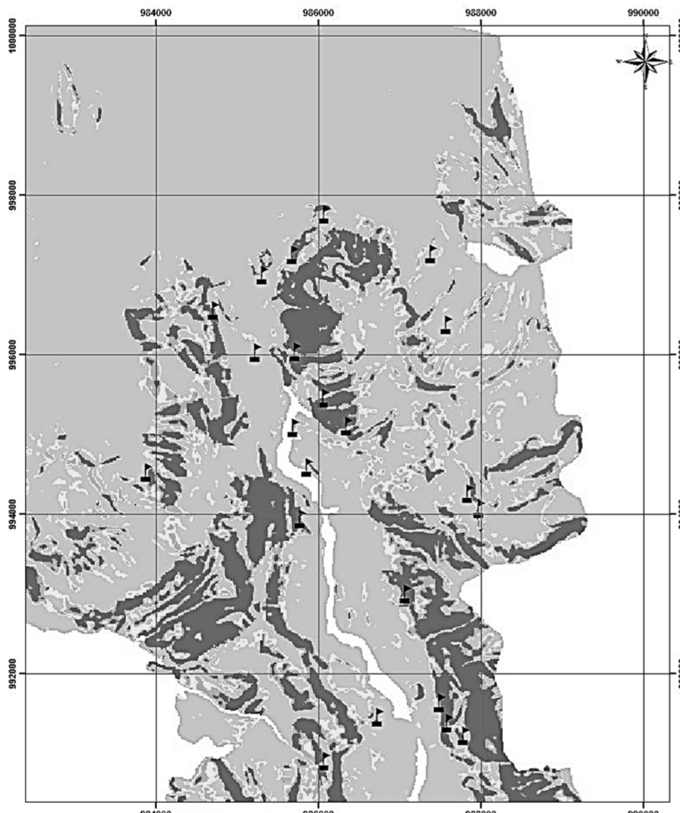

Figure 3. Mass movements areas location with environmental conflicts.
Source: Authors

Data analysis shows that there is no direct physical relationship between conflicts perceived by communities versus instability areas due to mass movements in the study area. The analysis also does not report a direct relationship between mining activity and territory instability.

It is important to note that sectors where there is a greater conflict associated with mining activity occur in rural areas, mainly due to landscape changes and land uses, which significantly affects and modifies the environment, affecting the economic activities of the oldest inhabitants of the territory.

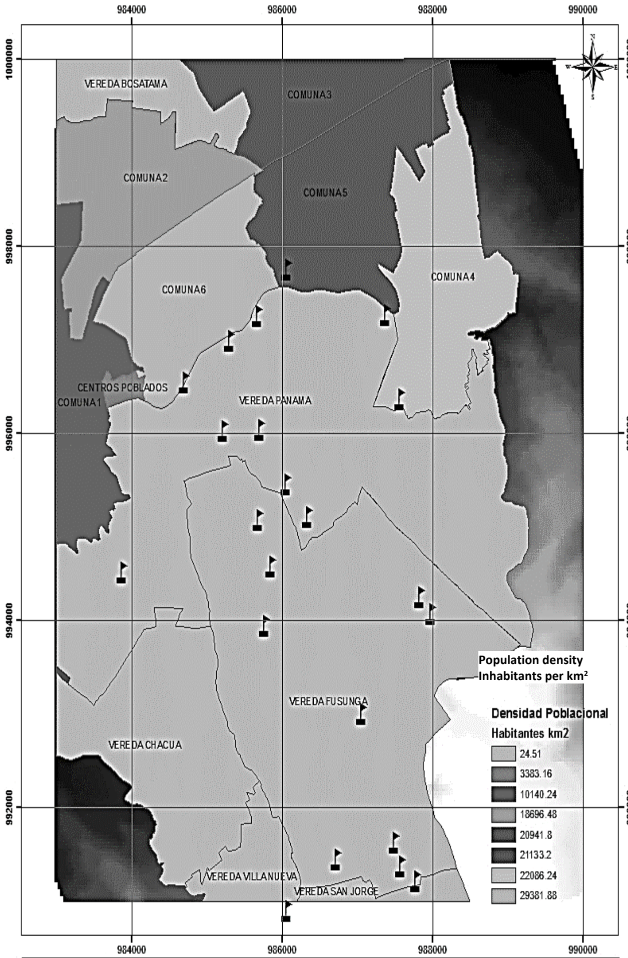

Figure 4. Population density - Quarries location
Source: Authors

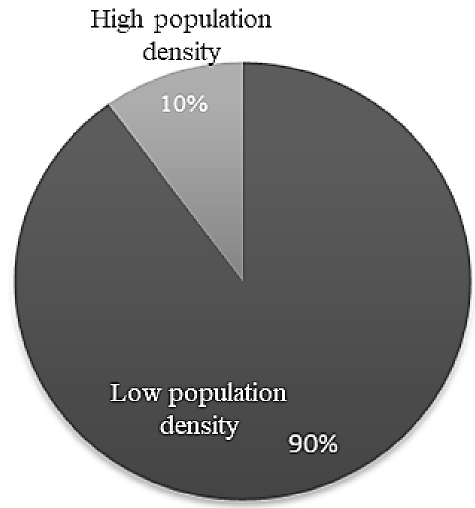

Figure 6. Percentage of population density distribution vs environmental conflicts due to mining.
Source: Authors

Figure 5. Environmental conflicts due to mining vs mass movements.
Source: Authors

4. Conclusions

This project developed a model which used different mathematical and computational tools for information integration (ARGIS) and analysis (SPSS) to evaluate relationships between variables.

The discriminant multivariate analysis method was used for the process of obtaining relationships between landslide-related factors and physical variables in the study area.

This method allows the use of categorical variables with input in the model in ordinal form and/or as binary variables, which protects the results from subjectivity by the group of experts and generates results only linked to evaluation data.

The generation of errors during prediction was possible due to the size of the cells and to obtaining a random sample from the evaluation sector.

The results of the statistical analysis of variables distribution and factor analysis are independent of the study area.

Results obtained by statistical analysis are dependent on the quality of the data collected in the field and geographically located.

The method allows the inclusion of variables required by the group of experts, in order to establish relationships between them and the physical effect evaluated, which in this case is landslides (mass movements).

Categorical variables do not show normal behavior; however, the normalization process does not significantly improve the results obtained.

The model included only physical variables obtained from field data, which were not weighted, which reduces the possibility that the results of the relationships evaluated are the product of subjective evaluations.

Use of computational tools such as ARGIS facilitated integration of purely spatial information with semi-quantitative data such as the identified environmental conflicts.

The results obtained by the process suggest some patterns of possible relationships between landslides and their causes, both natural and anthropogenic. However, they give rise to serious questions that should be addressed in future research.

The correlation coefficients obtained for the discriminant function in the study area allow establishing some relationship patterns. For instance, variables related to morphology (slope, curvature and terrain orientation) are not associated with instability areas; on the contrary, some of them (curvature and undulation) can favor the terrain stability.

Variables related to the type of materials present (soil or rocks) directly influence the appearance of instability areas. In this case, findings show that in most of the area, the surface materials are rocky, which positively favors soil stability. This is shown by the CALID factor, which represents the materials types and presents a negative value (favorable to stability) of -1.417.

Finally, the results of the evaluation of relationships between mining activity and landslides in the Soacha municipality, showed that mining activity (CANT variable) does not have a direct relationship with mass movements since their correlation coefficient is very close to zero. Therefore, it does not appear in discriminant function. On the other hand, urban areas (ZONUR) and modifications in land use (VEG) linked to anthropogenic activities in the area do show relationship. They present correlation coefficients of +0.138 and + 0.365 respectively, positive values that favor instability.

The ZONUR variable involves some areas that are currently for urban use but are former mining areas abandoned without an adequate closure. These areas have had strong urban growth, which modified soils use and management and generated areas of material exposure.

The presence of rocky materials in most of the study area surface is associated with stability zones. The FMS variable (soil or rock) shows a very high negative correlation coefficient (-1.417) that indicates its influence on the stability of the area.

The DENS variable, associated with population density, yielded very low coefficient results (close to zero) in all the analyses carried out. This allows us to establish that the number of inhabitants by itself is not the generator of instability processes, but rather the change in land use that occurs in the area where they settle.

Results from discriminant evaluation and superimposing environmental conflicts cases linked to mining activity in the study area allow us to conclude that these conflicts have a structural origin and are more related to conflicts of values and the social structure of the study area.

More than 90% of the conflicts that can be linked to mining activity are in rural areas and rural communities, who have seen their environment change as a result of mining. The conflict assessment does not show the same vision in urban areas. This may be because most of the inhabitants of urban areas are not originally from the region and have arrived there as a result of displacement or other immigration processes.

Most of the analyses regarding environmental conflicts in the municipality of Soacha have focused on extractive activity. However, efforts must focus on solving structural conflicts that have a social base, and on proposing a land-use plan that reduces the growth of urban areas in sectors of high physical sensitivity, such as the hillside areas.

According to the results obtained, mining activity in the municipality of Soacha must be analyzed from an institutional perspective. The goal is to allow mining to operate as a sustainable growth factor instead of a reason for conflict, which is what it has been so far. Communities must be involved, to promote a greater understanding of the reality of their territory and of appropriation mechanisms.

Based on the results obtained, it is possible to state that the environmental problems in Soacha have been reduced to their symptoms only (biogeophysical effects and impacts, and pollution), without conducting a serious analysis of the structural causes of conflict, which are more closely related to socio-cultural aspects.

The use of new variables such as population density, urban areas and quarries, allows us to conclude that this type of mathematical modeling is effective for generating results with high reliability (82% of the cases correctly classified).

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