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Landslide susceptibility mapping using fuzzy logic and multi-criteria evaluation techniques in the city of Quito, Ecuador

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ABSTRACT

Landslides are the most recurrent natural hazards in the Metropolitan District of Quito (DMQ), affecting sometimes lives but extremely frequently and severely the traffic and associated infrastructure. The present research proposes the calculation of the landslide susceptibility cartographic model in the city of Quito and its main highway, the Simón Bolívar avenue, using the Fuzzy logic and multicriteria evaluation techniques in geographic information systems (GIS). Based on the "Today and the past son key to the future" principle, landslides have been located using aerial photographs and field work. Based on the characteristics of historical landslides, photointerpreted and previous studies, the causal factors have been variable such as topography, structural geology, lithology, precipitation, water network, vegetation cover, among others. Each factor has been processed, analyzed and standardized according to its relationship to the occurrence of landslides, by means of a sinusoidal linked function that assigns to each element a degree of correlation [0,1] to the diffuse set. The landslide vulnerability map has been obtained from the combination of causal factors by map algebra, such as weighting techniques that include the hierarchical analysis process (HAP) and the weighted linear line (WLL), whose validation considered the locations of inventoried landslides. According to the susceptibility map, 5% of the direct study area has critical, 19% high, 58% average and18% low sensitivity. The quality of the results has been validated according to their standard error and adjustment value, being 0.216 and 78.4%, respectively.

Key words: Landslide susceptibility map, Fuzzy Logic, GIS, Simón Bolívar Highway.

INTRODUCCIÓN

Landslides constitute one of the most damaging natural hazards in mountainous areas generating human, material and economic losses (Álcantara–Ayala et al, 2006). According to statistics from the Center for Research on the Epidemiology of Disasters (CRED), landslides and other types of mass movement are responsible for 17% of all natural hazard fatalities worldwide (Lacasse et al., 2010), while economic and social losses due to such types of catastrophic events are able to be reduced by a more efficient land use and projection (Rajakumar, et al., 2007). Landslide risk (R) has been usually described as a function of the probability and consequence of landslides (Andersson-Skold et al., 2014)

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$$R = \int (P, C_i) \tag{1}$$

Where P is the probability of risk, and C is a vector C_i for all potential consequences. Quantifying potential consequences C_i such as loss of life or damage is difficult because of incomplete or limited historical records that affect population and infrastructure estimates at risk (Grahn and Jaldell, 2017). However, the probability of risk *(P)* has been analyzed from different evaluation approaches such as qualitative, through geological and geomorphological analysis (Park et al, 2013) and such as quantitative, considering causal factors and probabilistic methods, the same ones that have taken force due to computational and geospatial technological improvements (Bai, et al., 2010). However, the semi-quantitative have been through cause, effect and consequence where instability factors have been selected and weighted according to their relationship with the presence of the event and the occurrence of losses or damages. This has been previously applied within the risk classification system for cut and refill of slopes as well as for natural slopes in future development zones (Koirala and Watkins, 1988; Castellanos Abella and Van Westen, 2007).

The susceptibility maps of landslides have been developed through several methods, of which the most used are the inventory of landslides based on probabilistic techniques, the deterministic as well as the heuristic and statistical techniques (Guzzetti et al., 1999; Chiessi et al., 2016). The first three methods assign weights to a series of causal factors used according to the researcher's experience (Isik, 2009), while statistical analysis considers causal factors in areas with similar environmental conditions to those of past landslides (Park et al., 2013). Nowadays, non-parametric techniques such as cellular

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automata, Fuzzy logic and artificial neural networks are applied (Falaschi et al., 2009; Pradhan and Lee, 2010; Pradhan, 2013; Saro, et al., 2016).

Geographic Information Technology such as Remote Sensors (RS), Geographic Information Systems (GIS) and Global Positioning Systems (GPS) allow the management, assessment and identification of landslide risk. The use of GIS has been positioned because of its ease of collection and analysis of spatial data (Bayes, 2015; Pradhan, 2013). GIS supported by multicriteria decision analysis, such as: weighted average, analytical hierarchy process, weighted linear combination, order among others, are useful procedures for the recognition, evaluation and prognostication of risk by landslides (Feizizadeh & Blaschke, 2013). The most appropriate approach and methods for the evaluation of susceptibility and hazards to landslides have not been defined (Brabb, 1984), their selection depend on the characteristics of the study area both their baseline, historical, developed research and work scale (Hervás et al., 2012)

The risk assessment for landslides by means of cartography allows communication with direct involved persons for future impacts and public authorities responsible for risk management and prevention (Andersson-Sköld et al., 2013 Kjellgren, 2013; Andersson-Skold et al., 2014), allowing the development of effective strategies for stabilization of vulnerable areas, urban planning and implementation of infrastructure (Dahal & Dahal, 2017). According to Brabb, (Brabb, 1993), 90% of landslide losses could be avoided if the problem would have been previously recognized prior the catastrophic event (Pardeshi et al., 2013).

Therefore, the main aim of this study has been to generate a cartographic model of susceptibility to landslides of the city of Quito in general and its main highway named Simón Bolívar Avenue, using Fuzzy Logic methodology and multicriteria evaluation in GIS adjusted to historical records that allows the preventive evaluation of susceptible zones in order to avoid human and financial losses, as well as of infrastructure.

STUDY AREA

The study area evaluates the susceptibility of the main axis of the Simón Bolívar Avenue, Quito´s main highway from its southern end (Turubamba) along with its connection with the Bicentennial Avenue towards its northern end at the Pan-American Highway. In order to validate the results with historical information, we considered an area of indirect influence (AII) with an extension of approximate 393.3 Km^2, which included the zonal administrations of Los Chillos, Quitumbe, Eloy Alfaro, Manuela Sáenz, Tumbaco, Eugenio Espejo, Calderón and La Delicia, while the area of direct influence (ADI) comprised of some 22.53 Km^2 covering a radius of 275 m on each side of the main road axis (Fig. 1). The Simón Bolívar Avenue is the main highway of the city of Quito and forms part of its eastern peripheral ring. This highway has been conceived within the mobility plan as a traffic solution when connecting with the northern and southern sectors as well as the valleys bordering the Metropolitan District of Quito (MDQ; 2009; Google Earth Pro, 2017).

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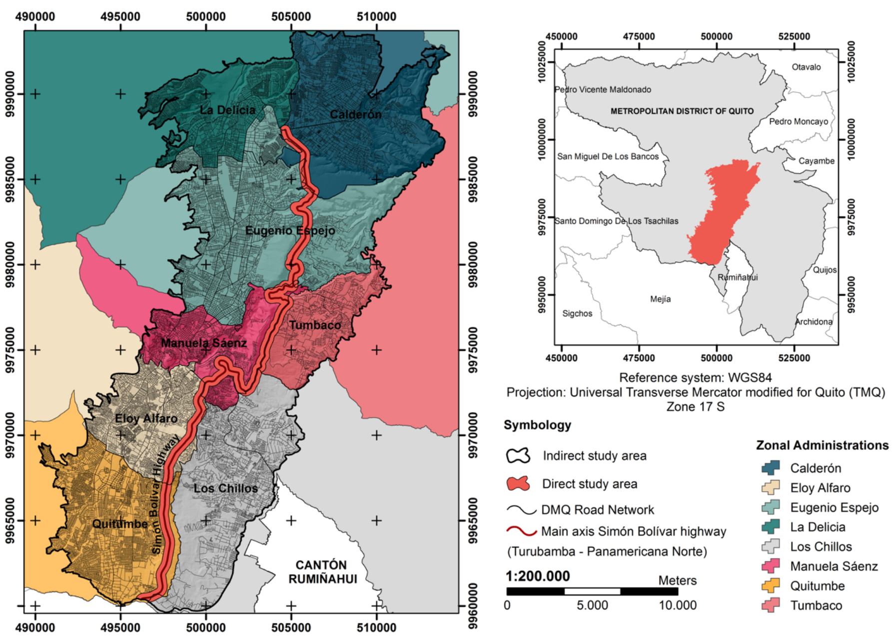

Figure 1. Location map of the study area

Within the ADI, the volcano - sedimentary fill comprises deposits of lava, agglomerates, tuffs, volcanic ash, layers of pumice and undifferentiated sediments being part of the geological formations such Machángara (Pleistocene) and Chiche as well as primary and colluvial volcanic deposits that have been generated during the Holocene (INIGEMM, 1978-1980). The topography varies between 1915 and 3380 meters above sea level (m.a.s.l.). The Machángara river crosses the road artery in the sector of Guápulo, which raised from the tributaries: Ortega, Shanshayacu, Rio Grande and Capulí or Machángara, conformed by 22.5 km and bordered by very steep slopes, is the main stream and more (EPMAPS), along with the Monjas River of the DMQ (El Comercio, 2015a), where 76.3% of urban wastewater flows from the south, center and north of the city to the level of the Guayasamín tunnel without any type of previous treatment (Moreano, 2010), having an organic load with 80% of domestic and 20% industrial origin, respectively (Reinoso Chisaguano, 2015). Soil is commonly used in infrastructure and the vegetation cover is made up of both wet and dry shrubs and broadleaf cultivated vegetation (Secretaría de Seguridad y Gobernabilidad del DMQ, 2015). The maximum precipitation is given to the southern sector of the city and decreasing towards the north (Secretaría de Seguridad y Gobernabilidad del DMQ, 2015).

Simón Bolívar Avenue is the first roadway with the highest vehicular traffic of the DMQ. Through there, 74,469 vehicles pass through (EPMMOP) (El Comercio, 2015b). However, there are six areas prone to landslides in the winter season (El Comercio, 2012). Its implementation in mountainous area, proximity to natural channels, deficient or absent channeling of rainwater, human settlements, anti-technical discharges of sewage and deforestation have influenced the frequency of landslides especially in the rainy winter season where their constant work of soil removal and maintenance represent a high public investment in rehabilitation and reconstruction, incurring high levels of congestion, human losses, and material, affecting infrastructure and commercial sectors (Toulkeridis et al., 2016).

In 2011, the road has been completely disabled for two weeks due to the landslide of 49,700 m^3 of land that registered 5 fatalities and 120 evacuated in the sector of Forest IV, (El Comercio, 2011), while the Municipality invested 636,478 dollars in stabilization works (Prensa Alcaldía de Quito, 2011). Considering the vulnerability of the road, the Metropolitan Public Company for Mobility and Public Works (EPMMOP) has taken precautionary measures through works of cleaning both the vegetation layer and ditches of coronation and tracks, slope profiling and implementation of complementary works for water eviction, in sectors such as El Madrigal, San Isidro de Puengasí, Chaquishahuaycu ravine, among others, where a variety of slope stabilization works have been performed (El Telégrafo, 2013).

In 2016, EPMMOP handled 28 landslides along Avenida Simón Bolívar, of which 11 have been in Guápulo and the remaining in the sectors Alma Lojana, Santa Rosa, Monteolivo, Las Bromelias, Miravalle 4, Oswaldo Guayasamín, Chaquishahuaycu Creek, Zámbiza, Algeria Alta, El Troje, Llano Chico, Granados, Guajaló, San Francisco, La Forestal and Nuns (EPMMOP).

In 2017, the DMQ recorded the highest precipitation levels of the last 30 years (Prensa Alcaldía de Quito, 2017), where main roads such as Av. Velasco Ibarra and Av. Simón Bolívar were heavily affected. Between October 2016 and May of 2017, Quito attended 965 emergencies, of which 443 have been landslides (El Universo, 2017). 14.7 million dollars have been allocated to the prevention and response plan for rainy season, plus further two million US Dollars from the emergency fund, where 1,870 officials have been mobilized for disaster prevention and care (Alcaldía de Quito, 2017, La Hora, 2017), a management that has been recurrent in previous years.

MATERIALS AND METHODS

The areas prone to landslides have been determined using a heuristic method, a qualitative analysis where a series of factors related to the occurrence of landslides is

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selected, hierarchized and weighed. The susceptibility of these landslides has been solved through decision tools applied in GIS (Andocilla et al, 2012; Ciampalini et al., 2016; Jaramillo et al., 2018: Zafrir et al., 2018) due to the ease of handling spatial information, versatility of representation and quality of results.

The applied methodology has been based on the principle "Today and the past are keys to the future" (REF), considering that: (1) Future landslides will have the same geological, geomorphological and water factors as those already in the past or in nearby previously studied areas; and (2) Causal factors will be represented by spatial data contained in a GIS database that will allow diffuse overlap (Maryam, 2011). The causal factors have been standardized using a membership function according to the relationship between the dependent variable (presence or absence of landslides) and independent variables (landslides / causal factors). The obtained results from each map factor have been weighted by hierarchical analysis (AHP) according to their relevancy with the occurrence of landslides.

DETERMINATION OF CAUSAL FACTORS

The causal or instability factors have been divided into conditioning factors and triggers, the former depending on the characteristics of the area such as topography, geology, lithology, soil type, drainage and vegetation cover (Dahal & Dahal, 2017). The second increase the probability of occurrence, being of natural origin such as earthquakes, precipitation intensity and natural or anthropic erosion due to land use and construction operations (Singh, 2010). Both of them vary significantly from one region to another

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(Pardeshi, Autade, & Pardeshi, 2013), so it has been fundamantal to determine them by means of a retrospective analysis. According to geomorphological factors, slope, climate and human intervention play an important role (Biju Abraham & Shaji, 2013).

According to the National Institute of Statistics and Censuses (INEC), rapid urbanization within the DMQ has increased settlements in inadequate areas such as slopes or edges of rivers and streams that produce vulnerable sectors especially in winter (Sepúlveda & Petley, 2015; Secretaría de Seguridad y Gobernabilidad, 2015). At the same time the implementation of roads in mountainous regions has generated problems of instability that geologists and civil engineers have been aware of (Silvers and Griffiths, 2006; Fookes et al., 1985; Transport Research Laboratory, 1997)

The scarce vegetation cover of steep slopes has been affected by forest fires, being one of the most frequent phenomena of the DMQ, where approximately nine events on the Simón Bolívar Avenue and surrounding areas have been registered in 2016 (Secretaria de Gestión de Riesgos, 2016; Cantuña et al., 2017).

Considering the historical record of landslides on Avenida Simón Bolívar in sectors such as Forestal IV (2011), Buenos Aires (2015), detour of Granados (2016 and 2017), El Troje (2017), Monteolivo (2017), Puengasí 2017), La Forestal (2017), as well as causal factors exposed in studies developed by the Municipality, projects in the Monjas - Ferroviaria - La Magdalena - Itchimbia area and the zonal administration Eugenio Espejo (Andocilla et al, 2012; Jaramillo et al., 2018; Zafrir et al., 2018). Generating or causal factors have been considered to be the topography, geology, lithology, vegetation cover, precipitation, water network and the main accessibility.

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Standardization, weighting and evaluation

As each factor has a different scale of measurement and cartographic representation (vector or raster) to perform a multicriteria analysis, therefore the input layers need to be standardized from their original values to values in a range of 0 to 1 according to the normalization formula (Equation (2)). The standardization has been performed by Fuzzy logic in order to assign to each element a membership value according to the degree of membership in the set. The membership function is of sinusoidal type whose value oscillates between 0 and 1 by the use of sine curves (Fig. 2) and cosine (Fig. 3) in a range of 0 to 90 º (π / 2 radians), its occupation will depend on the relationship between the analyzed variable and the probability of landslides (Zafrir et al., 2015). The limits of the function correspond to the maximum and minimum values of each factor taking into account that all values represent a level of risk.

Normalization:

$$N = \frac{V_o - V_{min}}{V_{max} - V_{min}} \tag{1}$$

Where: V_o: Original value; V_{min}: Minimum value and, V_{max}: Maximum Value.

Directly proportional (2nd Case):

$$\mu_A(V_o) = \sin\left(\frac{\pi}{2} \times \frac{V_o - V_{mín}}{V_{máx} - V_{mín}}\right) \qquad 0 \le \mu_A(V_o) \le 1 \tag{2}$$

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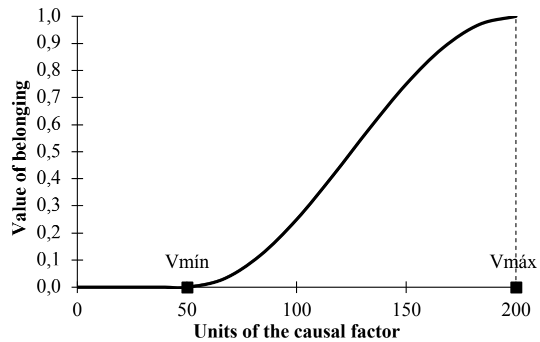

Figure 2. Sine curve belonging function from 0 to π/2 radians (Zafrir et al., 2015

Inverse proportional (3rd Case):

$$\mu_A(V_o) = \cos\left(\frac{\pi}{2} \times \frac{V_o - V_{mín}}{V_{máx} - V_{mín}} \right) 0 \leq \mu_A(V_o) \leq 1 \quad (3)$$

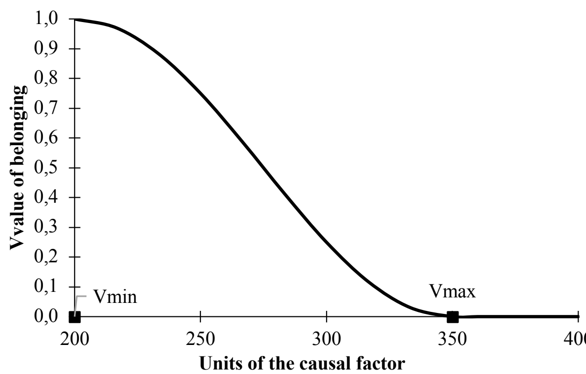

Figure 3. Curve belonging property Cosine range from 0 to π/2 radians (Zafrir et al., 2015)

Where $\mu_A(V_o) = 1$, si V_o belongs entirely to the set, $\mu_A(V_o) = 0$ si V_o does not belong to the set and $0 < \mu_A(V_o) < 1$ if V_o is partially in the set.

Table 1. Functions of belonging to each factor. The Sine and Cosine belonging functions have been evaluated from 0º to 90º

Factor	Relation parameter between:	Standardization Method: Fuzzy Logic

	Factor / Landslide	Sinusoidal belonging function
Slope	**Directly proportional:** The greater the value of the factor, the greater susceptibility to landslides	Sinus
Precipitation		Sinus
Plant cover		Sinus
Distance to communication routes	**Inversely proportional:** The lower the value of the factor, the greater susceptibility to landslides	Cosine
Distance to water resources		Cosine
Distance to geological faults		Cosine
Rock hardness		Cosine

RESULTS AND DISCUSSION

The landslides have been located and inventoried through aerial photographs taken in 2011 by the IGM, Digital Terrain Model and Ortho-mosaic scale 1: 1000 DMQ, provided by the Ministry of agriculture, livestock, aquaculture and fisheries based on the Project National System of Information and Management of Rural Lands and Technological Infrastructure (SIGTIERRAS), considering areas of rupture, bare soil and other typical geomorphological characteristics. The map of the sliding inventory has been used to evaluate the spatial distribution of landslides and to determine their triggering factors in the study area (Pradhan, 2013). A total of 45 landslides have been identified at Avenida Simón Bolívar, through photointerpretation and field tests with the use of a Global Positioning System (GPS) with a precision of 4 m.

Slope Map

The slope map has been generated from the scale curves 1: 5000 and MDT. Altitudes vary from 1915 m to 3380 m, where the maximum slope has been of 88.68°, and the minimum corresponds to flat areas with 0°.

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b) Vegetation cover map

The vegetation cover map has been weighted considering similar studies within DMQ (Loarte Merino, 2013; Zafrir et al., 2015), considering a susceptibility range from 1 (Low) to 5 (Very High).

Table 2. Weighting of plant cover based on Loarte Merino (2013)

Level I	Level II	Level III	Weighting
Forests and semi-natural areas	Planted vegetation of conifers	Pines and Cypress	1
	Planted vegetation of broadleafs	Grown Eucalyptus Young and regeneration Eucalyptus	1
	Vegetation in natural regeneration	Secondary forest Brush in regeneration Cork with trees Cork with bushes	1
Natural vegetation	Wet grasslands	Upper montane and montane paramo grassland Upper montane subhumid paramo grassland	2
	Dry grasslands	Interandean montane saxicolous vegetation	2
	Rainforests	Evergreen northern Andean forests High Andean paramo dwarf shrubland North Andean montane pluvial forest North Andean foothill pluvial forest Low montane seasonal evergreen forests	1
	Dry forests	Interandean dry forest Xeric riparian montane vegetation	1
	Humid bushes	High-andean shrubby paramo Northern Andes montane shrubland	2
	Dry bushes	Interandean dry bushes	2
Agricultural areas	Crops	Short cycle crops Semi-permanent and permanent crops Soils in preparation.	4
	Pastures	Cultivated pasture	5
		Natural pasture	3
Storage Areas	Infrastructure	Airports Buildings Greenhouses	2
Open spa	Bare soils of natural origin	Beaches	5
		Glaciers	4
		Rock	4

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	Bare soils of anthropogenic origin	Eroded soils Quarries	5
Waters capes	Water in natural channels	Rivers	3
	Water in artificial channels	Reservoirs	1

c) Precipitation map

The annual precipitation records for 25 years (1991-2015) have been provided by the National Institute of Meteorology and Hydrology (INAMHI), whose nearby stations have been listed in Table 3. The estimation of precipitation in stations with incomplete statistics have been performed using the average ratio completion method or the normal ratio (Equation (5)), recommended for mountain areas where the precipitation of nearby stations generally differ by more than 10%, by which the relationship between the station "x" and its nearby stations in a period has been considered (UNESCO - ROSTALC, 1982).

$$P_x = \frac{1}{n}\left[\left(\frac{N_x}{N_1}\right)P_1 + \left(\frac{N_x}{N_2}\right)P_2 + \ldots + \left(\frac{N_x}{N_n}\right)P_n\right] \qquad (4)$$

Where n represents number of rainfall stations with continuous recorded data close to the station "x", which will be completed in its registry; P_x represents precipitation of the station "x" during the time period to be completed; P_1 to P_n shall be the precipitation of nearby stations during the time period to be completed; N_x represents the annual average season precipitation of station "x"; N_1 to N_n represents the annual average precipitation of the stations nearby (Monsalve, 2009).

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The homogeneity of the data has been estimated by the average ratio completion method or the normal ratio being verified by double mass analysis, which consisted of constructing a cumulative double curve that relates the cumulative annual precipitation totals of the station *"x"* and its near station (Monsalve, 2009). The obtained correlation coefficients from the double mass curve for all the stations have been close to one, which evidenced the homogeneity of the data. The results have been verified by means of test of streaks, where their homogeneity has been confirmed. Table 3 illustrates the results of annual average precipitation of each station used for the mapping of Isoyetas.

Table 3. Results of the annual average precipitation

Code	Station	Coordinates		Altitude	Annual average precipitation
		Latitude	Longitude	z (m)	(mm)
M0002	LA TOLA	0º 13' 54.0" S	78º 22' 13" W	2480	844.02
M0003	IZOBAMBA	0º 21' 57.0" S	78º 33' 18" W	3058	1467.21
M0335	LA CHORRERA	0º 12' 06.0 " S	78º 32' 06" W	3165	1481.33
M0343	EL QUINCHE-PICHINCHA	0º 06' 31.2" S	78º 17' 53" W	2605	336.86
M0345	CALDERON	0º 05' 54.0" S	78º 25' 15" W	2645	546.00
M0353	RUMIPAMBA-PICHINCHA	0º 25' 51.8" S	78º 25' 6.8" W	2940	1853.86
M0354	SAN JUAN-PICHINCHA (CHILLOG.)	0º 17' 30.3" S	78º 37' 27.6" W	3440	1917.63
M0358	CALACALÍ INAMHI	0º 00' 05.9" N	78º 30' 46.3" W	2810	779.16
M0361	NONO	0º 02' 19.2" S	78º 33' 50.8" W	2710	946.81

d) Lithology Map

The lithology map has been weighted by a numerical scale where 1 represents the highest vulnerability and 6 the lowest, according to field experience. In flat areas, the effect of lithology has been reduced due to the absence of landslide vulnerability.

285 **Table 4.** Weighting of the Lithology

Lithology	Weighting
Agglomerate, undifferentiated lava	4
Andesites	5
Cangahua on colluvial deposits	3
Cangahua on sedimentary deposits Chichi Formation	3
Cangahua on sedimentary deposits of Atacazo volcano	3
Cangahua on volcanic deposits of Pichincha volcano	3
Cangahua on volcanic deposits of Ilaló volcano	3
Cangahua on undifferentiated volcanic deposits	3
Cangahua on volcanic – sedimentary deposits of Machángara	3
Ashes	3
Ashes with lapilli pumices	3
Natural or artificial water channel	6
Alluvial Reservoir	6
Colluvial Deposit	1,50
Lake deposits of ash	6
Lahar deposits	4
Landslide or collapse material	1
Natural or artificial water channel	6
Fillings	1,75
Artifitial fillings	1,75
Sediments of Chichi Formation	1
Undifferentiated Terrace	6
Terrace, Gravel	1,50
Terrace, Cangahua type	2
Undifferenciated volcanic deposits	1,50
Undifferenciated volcanic – sedimentary deposits	1
Volcanic deposits of Guayllabamba	1
Volcanic – sedimentary deposits of Machángara	2
Volcanic – sedimentary deposits of San Miguel	1

e) Other maps

The geological, hydric and road parameters have been analyzed by proximity using the "Euclidean Distance" tool (ArcGIS), distance from each cell in the raster to the nearest source (geological fault, river and road).

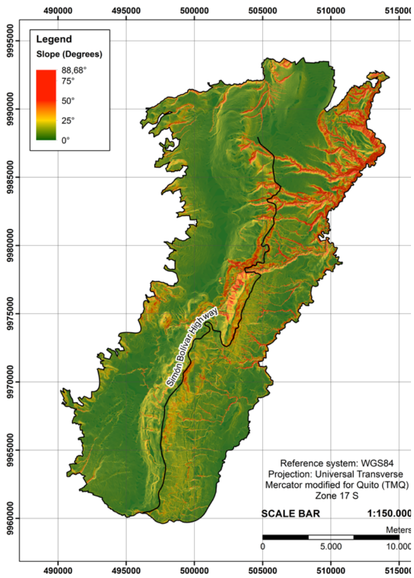

Figure 4. Slope map

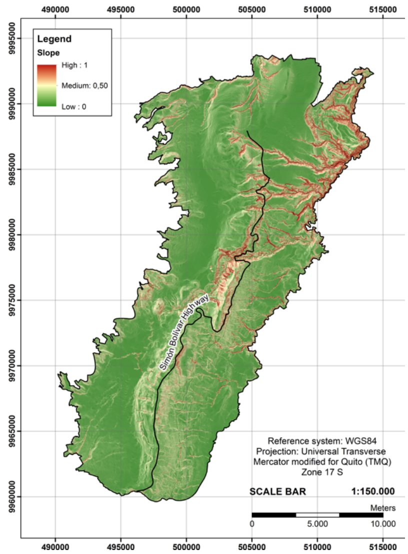

Figure 5. Normalized slope map

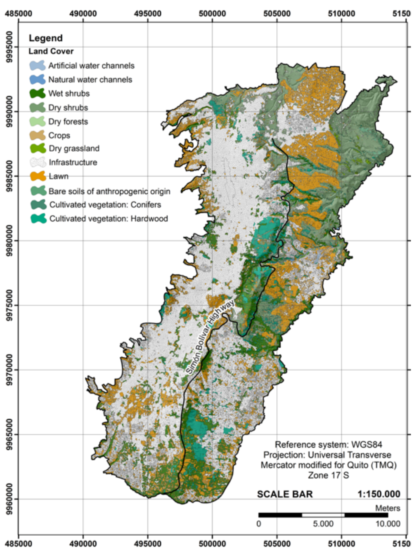

Figure 6. Map of land cover

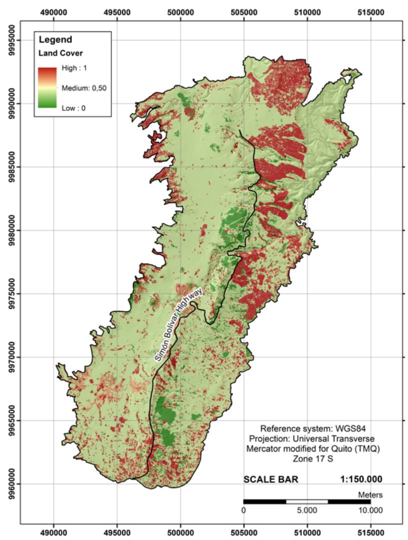

Figure 7. Normalized land cover

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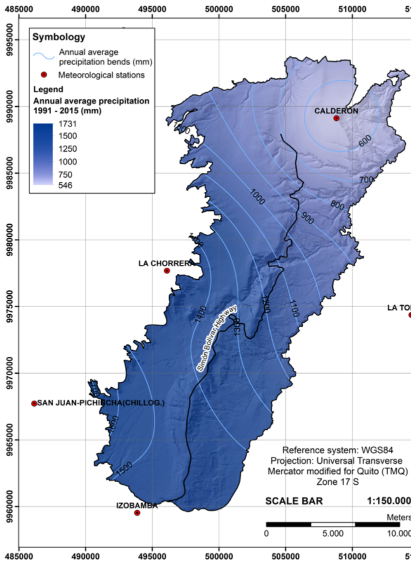

Figure 8. Annual average precipitation bends

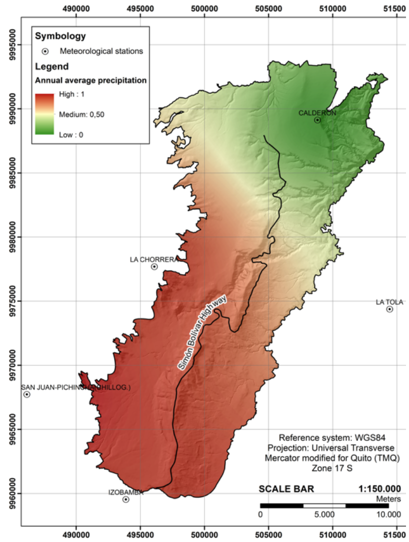

Figure 9. Normalized precipitation bends

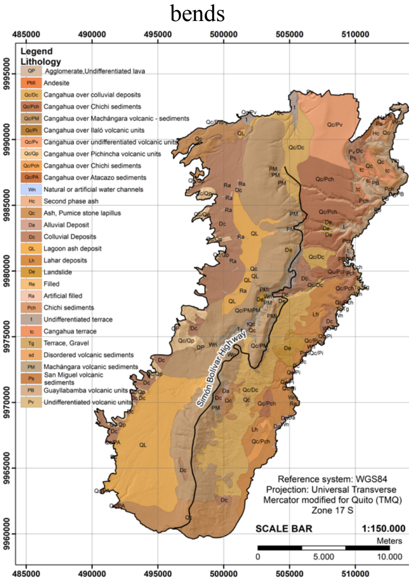

Figure 10. Lithology map

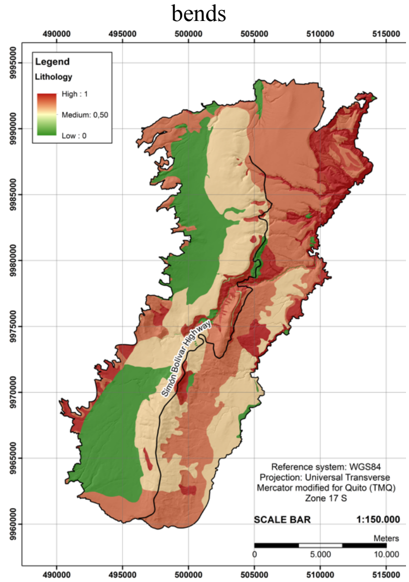

Figure 11. Normalized lithology map

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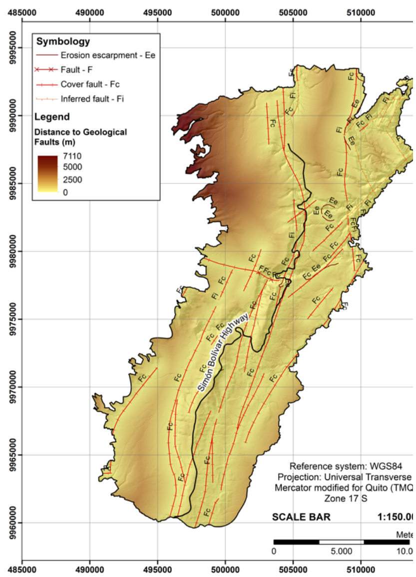

Figure 12. Map with distance of geological faults

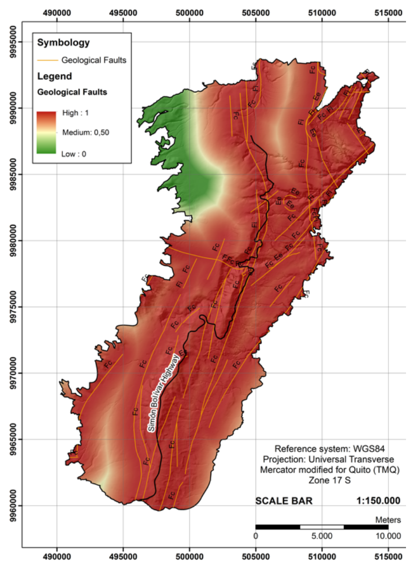

Figure 13. Map with normalized distance of geological faults

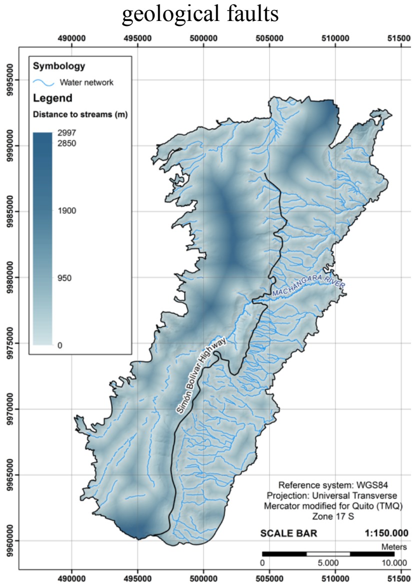

Figure 14. Map with distance to streams

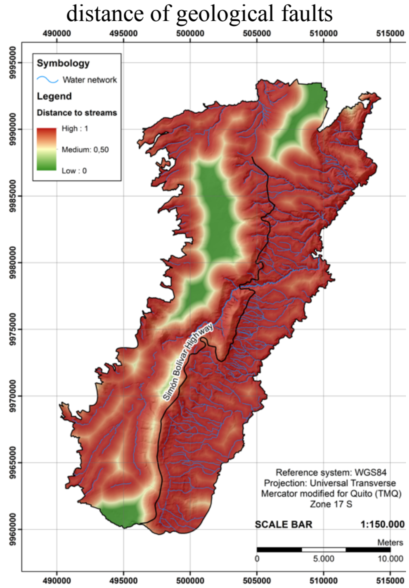

Figure 15. Normalized distance to streams

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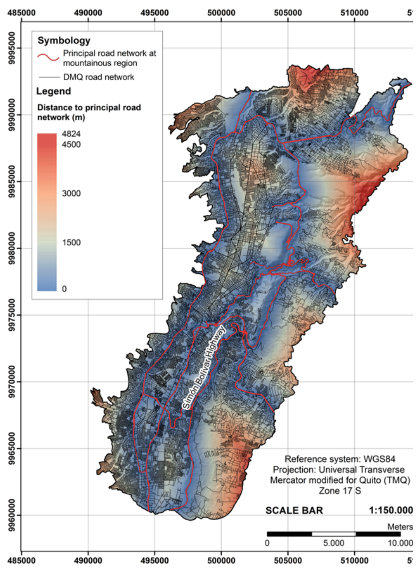

Figure 16. Map with distance to road network

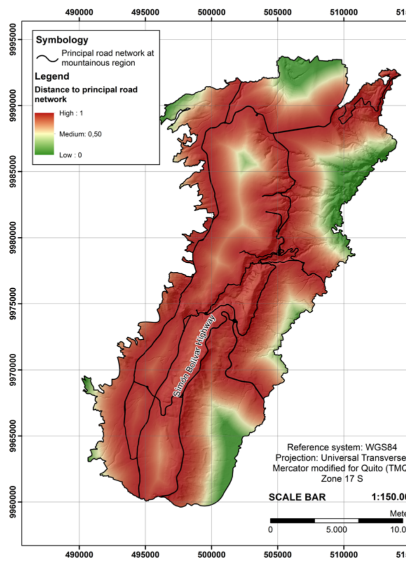

Figure 17. Map with normalized distance to road network

f) Map of susceptibility to landslides through the Hierarchical Analysis Method (AHP)

The matrix of AHP considers three principles: decomposition, comparative judgment and synthesis of priorities (Malczewski, 1996), through which the problem (and its weights) is decomposed in a hierarchical structure, whose weighting depends on the comparison of criteria by pairs and the multiplication between the respective hierarchical levels (Castellanos Abella & Van Westen, 2007). Assigned values range from ("much less important than"); 1 ("equally important than") and, 9 ("much more important than") (Saaty, 1980, Eastman, 2012).

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Table 5. Hierarchical analysis of causal factors

	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**Weighting**
(1) Slope	1	3	9	2	8	7	6	0,379
(2) Precipitation	1/3	1	7	1/2	6	3	2	0,159
(3) Plant cover	1/9	1/7	1	1/8	1/2	1/3	1/6	0,024
(4) Lithology	1/2	2	8	1	7	6	3	0,246
(5) Road distance	1/8	1/6	2	1/7	1	1/2	1/3	0,036
(6) River distance	1/7	1/3	3	1/6	2	1	1/3	0,054
(7) Geol. fault distance	1/6	1/2	6	1/3	3	3	1	0,102

*CR: 0,030

Weighted linear sum

The susceptibility map has been the result of the combination of causal factors with their respective weights obtained by AHP as shown in Equation (6)

$$I = \sum_{j=1}^{n} W_j \times x_{ij} \tag{5}$$

Where: I: Susceptibility index, W_j: factor weight j, x_{ij}: normalized value of each map and n: number of factors. Resulting in:

$$f_{(x)} = 0{,}379\, x_1 + 0{,}246 x_2 + 0{,}159\, x_3 + 0{,}102\, x_4 + 0{,}054\, x_5 + 0{,}036\, x_6 + 0{,}024\, x_7 \tag{6}$$

Where: x_1 : Pending; x_2: Lithology; x_3 : Precipitation; x_4: Distance to geological faults; x_5 : Distance to rivers; x_6 : Distance to roads y, x_7 : Vegetation cover.

Model Adjustment

$$N = Value_{Measured} - Value_{Calculated} \tag{7}$$

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$$N = 1 - Y$$
$$N = 1 - 0{,}1620 \qquad (8)$$
$$N = 0{,}838$$

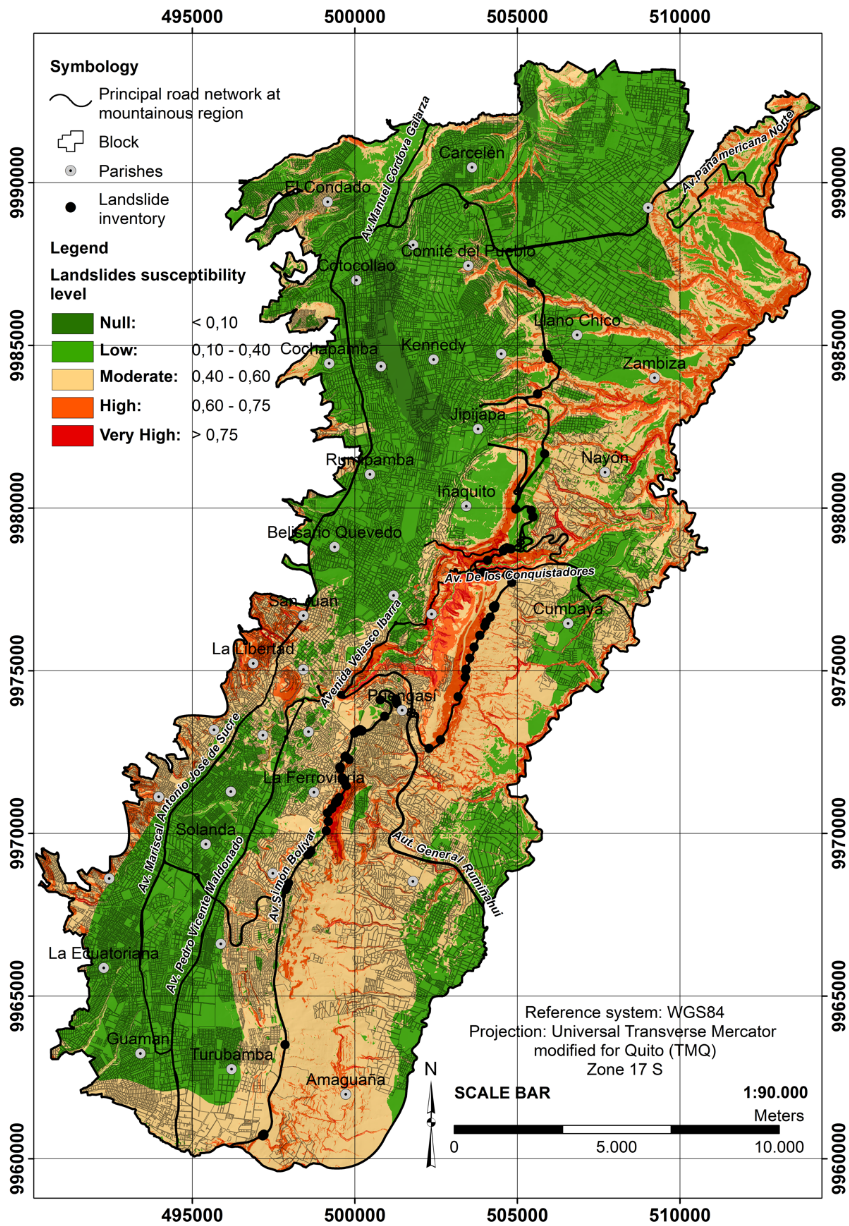
Where: $N{:}\,Adjustment$; $Value_{Measured}$: 1 or value of the sample points and, $Value_{Calculated}$: standard deviation of the resulting model.

Thus, the level of slip irrigation has been classified according to Anbalagan (1992), based on the model of Fuzzy logic obtained in a range of 0 to 1 (Maryam, 2011) and represented in color scales (Table 6).

Table 6. Slip susceptibility zonation according to the diffuse output membership functions.

Zone	**Fuzzy belonging function**	**Description level of susceptibility**	**Color of scales**
I	< 0.1	None	Dark green
II	- 0.40	Low	Light green
III	0.40 – 0.60	Medium	Yellow
IV	0.60 – 0.75	High	Orange
V	> 0.75	Critical	Red

The obtained susceptibility map from the combination of Fuzzy methodology and multicriteria evaluation yielded a standard error of 0.1620 with an adjustment value of 83.8%. Where 2% of AEI has critical susceptibility, 10% high, 37% average, 49% low and 2% nil. Within the AED, 5% have critical susceptibility, 19% high, 58% average and 18% low. The obtained results have been in accordance with the spatial distribution of landslides, together with historical records in areas such as La Ferroviaria, Guápulo, Oswaldo Guayasamín, Granados Connection, among others (Fig. 18). The new vulnerability map has a more detailed aspect of all used parameters when compared with the existing map of the municipality of Quito (Fig. 19).



330 **Figure 18.** Map of susceptibility to landslides derived from the AHP method.

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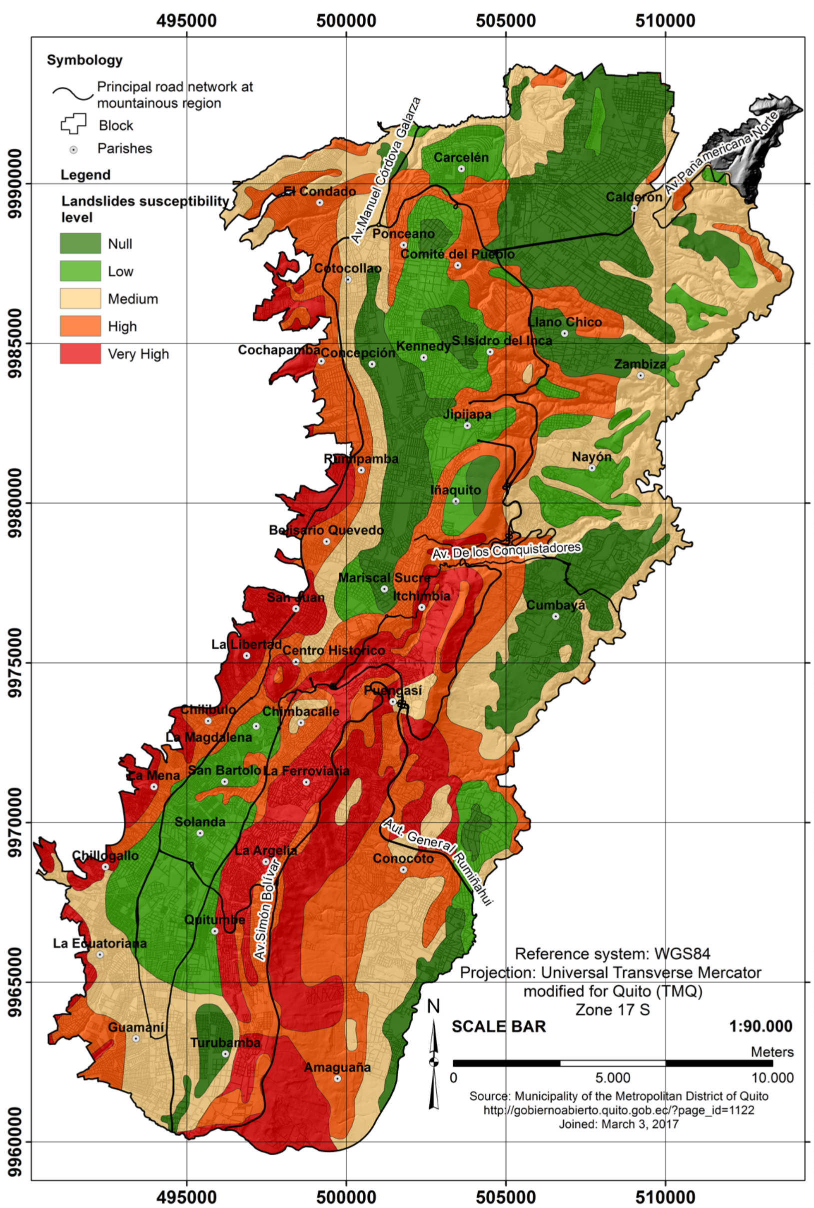

Figure 19. Previously existing map of the susceptibility to landslides from the municipality of Quito.

CONCLUSIONS AND RECOMMENDATIONS

The Simón Bolívar Avenue has a medium to high level of susceptibility to landslides, where the most critical sectors are located in the parishes such as La Ferroviaria, Puengasí and Itchimbía. A preventive analysis of the area certainly will be more economical than the implementation of corrective measures once the event has been triggered.

Topography and geology have been the factors that mainly defined the level of susceptibility as they condition the effect of detonators such as precipitation and anthropic intervention.

The parameters and methodology selected for the study area have been considered adequate and coincide with the factors established in the field.

The cartographic models of susceptibility to landslides have been useful tools for urban planning and implementation of strategic infrastructure such as road corridors and allow to locate new vulnerable areas beyond the historically recognized. Simuyltaneously they constitute the baseline for developing models for geotechnical and seismic zoning within the DMQ.

The fuzzy methodology combined with multicriteria analysis would have a better correlation with historical data and the spatial distribution of inventoried slides, if the information base of each factor provided by the competent entities would have been updated, validated and at scales of greater precision.

Social parameters such as land use, evolution of the urban spot in illegally constituted areas and implementation of strategic infrastructure at the edge of slopes should be included within the causal factors. The inventory of resources affected and at potential risk through multitemporal analysis would make it easier to estimate the human and economic losses that the landslides have generated and could affect the public and private sector.

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