Landslide susceptibility mapping through spatial modeling. Case of Antananarivo Renivohitra district, Madagascar

Hobiniaina Anthonio Rakotoarison, Raymond Rakotondrazafy

Abstract— **Landslides cause a large amount of casualties and economics costs. Heavy rainfalls are one of their main causes, especially in the tropical areas where cyclones strike every year. In Madagascar, the passage of the cyclone Chedza in 2015 caused significant damages, both human and material. Determining the likely areas of occurrence for natural disasters becomes a major issue in disaster management, particulary in countries with limited resources like Madagascar. The main goal of this study is to produce a map of landslide susceptibility of landslide-prone areas. It concerns a spatial modeling of Antananarivo's susceptibility to landslides by exploiting geo-environmental and climatic data. The Multicriteria Evaluation (MCE) model was used considering the predisposing and triggering factors of landslide. Data processing takes into account geology, environment, climate and topography. Model was validated through Receiver Operating Characteristic curve (ROC) using landslide inventory data and showed a satisfactory prediction with an Area Under Curve (AUC) of 80.9%.**

Index Terms— **Antananarivo Renivohitra, Landslide susceptibility, Madagascar, Multicriteria Evaluation model.**

I. Introduction

Highlight Landslides are geological disaster causing considerable material damage, consequential economic loss, but mostly significant human casualties. Worldwide, Petley (2012) referred more than 30,000 deaths in 7 years, from 2004 to 2010, caused by landslides [1]. By its geographical location, Madagascar is subject to a wide range of natural disasters. Its position in the tropical zone exposes it to the passage of cyclones and storms, which are the main causes of damages related to the wind but especially to the water such as landslides and floods. Heavy rainfall generates and triggers, for the most part, landslides. In 2015, Madagascar was hit hardly by the powerful tropical cyclone "Chedza" leaving over 170,000 victims and more than 80 deaths, in which 35% of the mortality are due to the landslide phenomena [2].

This paper focuses on the mapping of landslide susceptibility using spatial modeling. The availability of susceptibility, vulnerability and risk map is essential for a country where a community is frequently threatened by a natural hazard, especially the landslide. Therefore, anticipating the study of landslide hazard becomes an issue requiring a tool be able to provide to decision-makers accessible information, reliable and dynamic for predictive decision support (prevention), operational (action) and strategic (political). Currently, lots of researches rely on remote sensing and modeling the implementation of models which can reinforce or supplement field data [3].

For all these reasons, it is useful to have rapid and reliable means to determine the most exposed zones to landslide. From spatialized data, we will develop a multicriteria analysis by crossing data. The resulting model, of this study, has the advantage of relying on remote sensing (rainfall, elevation, etc.) which is free and can be updated regularly. In Madagascar, the lack of data concerning landslide is a big problem, thus the use of substitution data becomes necessary. The Multicriteria Evaluation (MCE) is a spatial modeling method adapted on lack of data and decision support [4]. The combination of its method and Geographical Information System (GIS) date back to the 90's with full integration by [5]. Generally, MCE is used in agriculture, logistic and one health domain [4], [6], [7]. In Burkina Faso, for example, it was used to identify the suitable areas for urban agriculture through mapping [8]. Currently, georisk domain exploits this method in the landslide study [9] - [11].

In this study, the term "landslide" encompasses all types of displacement without distinction (rock fall, mudslide, lavaka, erosion, etc.).

II. Materials and Methods

A. Study area

The study area corresponds to the district of Antananarivo Renivohitra, the capital city of Madagascar. The district is composed by six arrondissements (Fig. 1). It is crossed by two main rivers: Ikopa and Mamba. Ikopa appears at the southern boundary of the 4th arrondissement while Mamba lies in the northern limit of the study area. Mamba river is bordered by the 5th and 6th arrondissements. These rivers are characterized by rainfall regime depending, mainly, on average annual precipitation. In Antananarivo, the average annual precipitation is about 1,317 mm/year [12].

With respect to the hydrogeology, bedrocks are generally covered by a thick layer of altered lateritic. It has a relatively high capacity of water retention.

From a morphological point of view, the study area can be divided into three distinct zones:

- Overall, the center and the North represent an area of flood plain filled with recent sediment. These area are gently to no sloping (<5°) and constitute 50% of the study area.
- Hillside areas are found on the western part, of the study area, with an elevation ranging from 1,244 m to 1,437 m.

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The average slopes are between 5° and 15°. Occasionally, there are some slopes of 20°.

- The Southeast has different shapes and higher altitude. This area consists of chines interspersed with valleys. The average slopes are low at the bottom of valleys (<10°) and ranged between 10° and 20° on the sides. Areas with steeped slopes are found in higher altitude (>40°).

Geologically, the study focuses on a zone belonging to the Antananarivo domain which is dominated by meta-granitoids [13]. The study area can be divided as follow:

- Recent geological formation: the vast majority of zone is composed of quaternary alluvium. This formation is found on all low areas which constitute the alluvial plain of Antananarivo.
- Crystalline substratum: the hills and the upper zones of the study area are mostly composed of unaltered magmatic and metamorphic rocks (migmatitic granits and granitoïd migmatites, migmatites, chanockites). There is, also, presence of formations which are more or less altered. The presence of gneiss is also to be noted, especially, on the eastern part of the study area.
- Special facies: several special facies appear punctually on the study area. The southern part presents intrusions of granites named “granites of Ambatomainty”. Quartzite intrusions are also found within the granite domain at several locations in the study area. Other rarer facies (graphite, garnet, etc.) can appear punctually.

As regard to the geomorphology, field missions revealed two main soil typed: alluvial and ferralitic. Alluvial soils are found in the alluvial plain of Antananarivo and low areas. The ferralitic soils, resulting from the alteration of primary rocks, are found in the medium and high slopes. The type of soil varies according to the geological formation (gneiss, granite, etc.). However, the local sandy horizon (granite sand) may appear on upper zones. This horizon is the result of bedrocks alteration, including granites.

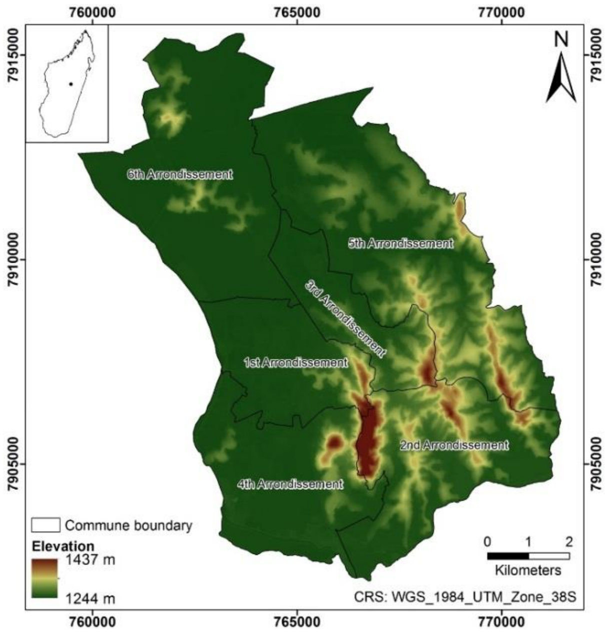

Fig. 1. Study area

B. Data sources

- The lithological data, covering the study area, were extracted from the geological map of Antananarivo and Manjakandriana (sheet n° P-Q 47) with a scale of 1/100,000. This map was provided by the geological survey service of Madagascar.
- Topographical data, such as elevation, slope gradient, curvature and aspect, were obtained from the processing of Shuttle Radar Topography Mission (SRTM) data. These data have a spatial resolution of 30m.
- The OpenStreetMap (OSM) international project provided data on road and hydrographical networks. The platform consists of the contribution of each user to update the different geographical information of a zone (road, building, etc.). The updated information is validated before being published. Data obtained from OSM are more accurate than those provided the national map service.
- The vegetation index was obtained by calculating the Normalized Difference Vegetation Index (NDVI) in the study area. SPOT 5 satellite images were used to create the NDVI.
- Due to the lack of national reliable climate data, rainfall data were extracted from the International Research Institute (IRI) library. These are daily data from remote sensing and provided by the US National Oceanic and Atmospheric Administration agency (NOAA).

With the exception of the geological map, all used data are free of charge and freely accessible or free through a partnership with suppliers. In this study, QGIS which is a free and open source software, was used.

C. Model construction

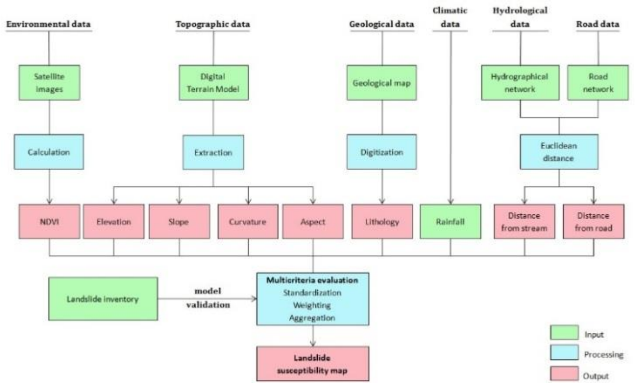

Fig. 2. Flowchart of model construction

Landslide susceptibility model was established following a well-defined flowchart (Fig. 2). Multicriteria evaluation approach was used. It is a common method for assessing and aggregating many criteria [4]. MCE spatial model allows assessing landslide susceptibility through risk gradients which provide necessary information for the concerned stakeholders on landslide risk management. It is considered as semi-quantitative method with participative approach and where stakeholders and experts bring their knowledge and expertise concerning landslide [14]. MCE mainly takes care of the mean to combine the information from several criteria to form a single index of evaluation. Criteria concern all involved variables in landslide susceptibility. Both Analytical Hierarchy Process (AHP) and Weighted Linear Combination (WLC) constitute the MCE method used in this study.

Criteria selection

Landslide is controlled by several criteria. The choice of the criteria was based on literature review and experts' experiences. Criteria were identified and categorized. These criteria were divided into constraints and factors [4]. Constraints are defined as masks that consider whether a zone will be part of the calculation or not. It uses a Boolean function by classifying the criteria in suitable area or not. In 1999, Eastman identified factors as criteria that define a certain degree of suitability for all regions [15]. They set aptitude areas which are expressed by continuous value. They act in a progressive way on the suitability following fuzzy logic function whereas the constraint is a limit factor. In this study, nine criteria were used (Fig. 3.).

Geological context, especially the **lithology**, is essential in the study of the landslides [16], [17]. Indeed, it conditions directly the strength and permeability of rocks and soils [18], but also lithology controls landslide such as lavaka [19]. Indirectly, geological context influences the type and the level of hazard concerned on the study area. After digitization of geological map and field data, the different lithological units were grouped into five classes (Fig. 3): (A) recent formations mainly composed of alluvium; (B) gneiss; (C) pyroxene gneiss; (D) migmatitic granites and granitoïd migmatites; (E) migmatites. Lithologic classes composed by unconsolidated formations are more susceptible to landslide phenomenon than zones whose rocks are "harder".

Elevation is a very important factor in the occurrence of landslide due to the fact that it affects the spatial variation of the hydrological conditions and slope stability [20]. Elevation in the Antananarivo Renivohitra district was categorized into five classes: 1,244m – 1,250m; 1,250m – 1,300m; 1,300 – 1,350m; 1,350m – 1,400m; 1,400m – 1,450m.

According to [11], "**slope gradient** is an important parameter as it controls the subsurface flow velocity after rainfall, the runoff rate and the soil water content". Several researches show the importance of slope in the susceptibility to landslide [16], [21] - [23]. Generally, the steeper the area, the more susceptible it is to landslide. The degree of susceptibility increases therefore proportionately with the importance of slope. In this study, slope gradient was divided into seven classes: 0° – 10°; 10° - 20°; 10° – 30°; 30° – 40°; 40° – 50°; 50° – 60° and > 60°.

Being a predisposing factor, **curvature** is also an important variable to landslide. It contributes, particularly, to water retention during rainy periods. Concave zones, i.e. area with negative curvature are more susceptible to landslide due to their higher water retention capacity. With a positive curvature, convex surfaces are less susceptible. Curvature data were classified in three: concave surface (<0), flat surface (= 0), convex surface (>0).

Slope aspect represents the orientation of the slopes in a given area. According to wind rose and clockwise, it varies from 0° to 360°. This variable is important in this study as it provides information on sun exposure and drying winds. Unlike the northern hemisphere zones, maximum sun exposure in Madagascar is South and Southeast facing. This exposure plays a major role in the conditioning of soil evapotranspiration and flora distribution [24]. The less the area is exposed to the sun, the more susceptible it is to landslide as this area is proving more favorable soil moisture. In this study, slope aspect was classified into nine classes respectively representing the following expositions: N, NE, E, SE, S, SW, W, NW and flat exposition [11].

NDVI plays significant role in the predisposition of landslide. A NDVI classification was performed using SPOT 5 satellite images. Each class was chosen according to their suitability for landslide. The study area was classified into five: -1 – -0.2; -0.2 – 0; 0 – 0.2; 0.2 – 0.4 and 0.4 - 1.

Distance from stream is important in this study because it has an influence in the stability of terrain. Indeed, the water saturation of the soil is inversely related to the distance from stream. A too close to a stream area is more susceptible to landslide than a remote area. By taking into account an equidistance of 50 m, around the stream, a calculation of Euclidean distance of the hydrographic network was carried out.

Several studies show the high frequency of landslide near roads [11], [25], [26]. This is because the majority of roads are bordered by road embankment and ravines, but also there is a poor drainage. The more the **distance from road** increases, the less the terrain is susceptible to slide. A buffer zone of 50 m has, also, been established based on the assumption that beyond this distance, the susceptibility is low.

Rainfall is a triggering factor in landslide phenomenon. In Madagascar, the number of weather station is very low. This number is limited to about 25 stations to cover the entire island which is 587,000 km². This gap significantly impacts the accuracy of climatic data. Substitution data, from remote sensing, were used to deal with this problem. According to its statistical distribution, average annual precipitation variable was used and was divided into two classes: < 1,460 mm; ≥ 1,460 mm.

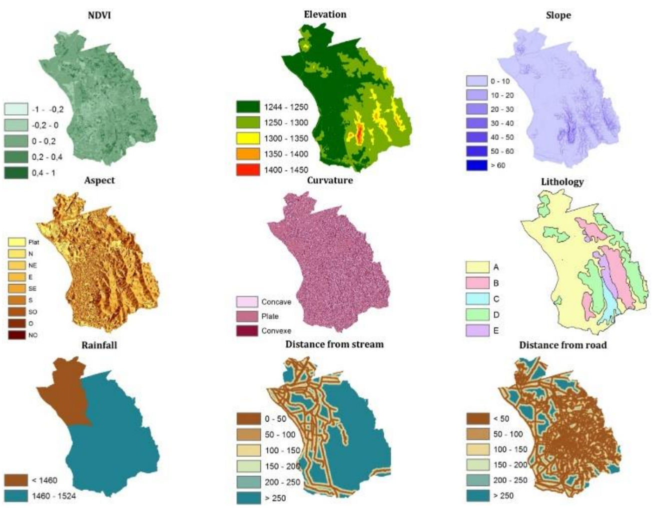

Fig. 3. Maps representing all variables used in the modeling and model validation. A, B, C, D, E: please refer to paragraph on lithology in "Criteria selection" section.

Factors standardization

In this study, no variable was considered as a Boolean constraint. Each criterion is integrated in a Geographic Information System to extract criteria maps. The latter are in different types (quantitative and qualitative) and units (for example: degree for slope and millimeter for rainfall). According to fuzzy logic, these criteria were standardized on a continuous scale of suitability ranging from least apt (0) to most apt (255). Unlike Boolean logic which is binary, values between 0 and 255 of fuzzy logic represent the transition between the totally unsuitable and the fully suitable. Fuzzy logic makes it possible to apprehend the real world [27]. This logic was used to standardize all model factors.

Factors were defined according to sigmoid membership functions (increasing, decreasing or symmetrical) and parameters attributed after consultation with the various actors and experts in the landslide domain. Once standardized, it will be possible to compare and combine the factors for each pixel in the study area.

Factors weighting

Factor weighting is the second stage of the MCE used in this work. It consists on assigning weights to each standardized factor according to their degree of relevance. It allows controlling the influence of the factors on the objective of the decision. The importance of the factors will depend on the weight assigned to each factor. In 1977, Saaty has established a weight scale, which ranges from 1/9 to 9, based on the pair-wise comparison of factors [28]. The intervention of the actors, as well as specialists in landslide hazard, is necessary to define the weights to be attributed to the factors. A consistency ratio (CR) is calculated to verify the consistency of the comparisons matrix by using Equation 1. To be acceptable, this ratio should be less than 0.1 [29].

$$CR = CI/RI \qquad (1)$$

were RI is a Random index and CI the Consistency Index which can be expressed as follow:

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad (2)$$

were λ_{max} the maximum eigenvalue of each factor and n the matrix size.

Criteria aggregation

WLC aggregation of criteria is the last stage in Multi-Criteria Evaluation. It consists on combining all factors by multiplying the weights from the weighting with each standardized factor and then adding them together. To exclude unsuitable areas, i.e. areas where there is no risk of landslide, this sum is multiplied with Boolean constraints. Aggregation is calculated using the following Equation:

$$S = \sum_{i=1}^{n} w_i X_i \prod_{j=1}^{m} C_j \qquad (3)$$

where S is the aptitude for an event, w_i is the weight of factor i, X_i is the factor i, C_j it the constraint j, n is the number of factors, and m is the number of constraints.

A gradient risk map of landslide will come out of this aggregation of criteria. The susceptibility was expressed on a continuous scale ranging from 0 (lowest susceptibility) to 255 (highest susceptibility) [30], [31].

D. Model validation

Landslide inventory data were used to validate the landslide susceptibility model. Area Under Curve (AUC) of Receiver Operating Characteristic curve (ROC) was the method adopted to validate the model performance [4], [32]. According to [32], AUC ranges from 0.5 to 1. AUC within a value of 0.5 is known as baseline of prediction and the value of 1 represents a perfect performance. From 0.7, the accuracy of a model is satisfactory [33].

III. Results and Discussion

According to their respective experiences, each stakeholder and expert, such a geomorphologist, was defined thresholds in relation to landslide susceptibility. Table 1 shows that slope and distance to rivers have the most and least influence on the occurrence of land movement with weights of 0.314 and 0.02 respectively. In decreasing order, other factors such as elevation, lithology, precipitation, NDVI, curvature, aspect, and distance to roads have weight values of 0.236; 0.110; 0.104; 0.082; 0.057; 0.052; and 0.025 respectively. In this study, the CR is 0.067 indicating a reasonable level of consistency in the pairwise comparisons.

Table 1. Pair-wise comparison matrix and weight of factors

	a	b	c	d	e	f	g	h	i	W
a	1	0.2	0.2	3	3	0.7	0.7	3	3	**0.082**
b		1	3	7	7	3	3	7	7	**0.314**
c			1	5	5	3	3	9	9	**0.236**
d				1	1	0.5	0.7	5	3	**0.057**
e					1	0.5	0.7	3	3	**0.052**
f						1	1	7	7	**0.110**
g							1	7	7	**0.104**
h								1	0.5	**0.020**
i									1	**0.025**
										CR = 0.067

Note: (a) NDVI, (b) Slope gradient, (c) Elevation, (d) Curvature, (e) Aspect, (f) Lithology, (g) Rainfall, (h) Distance from stream, (i) Distance from road and W: weight

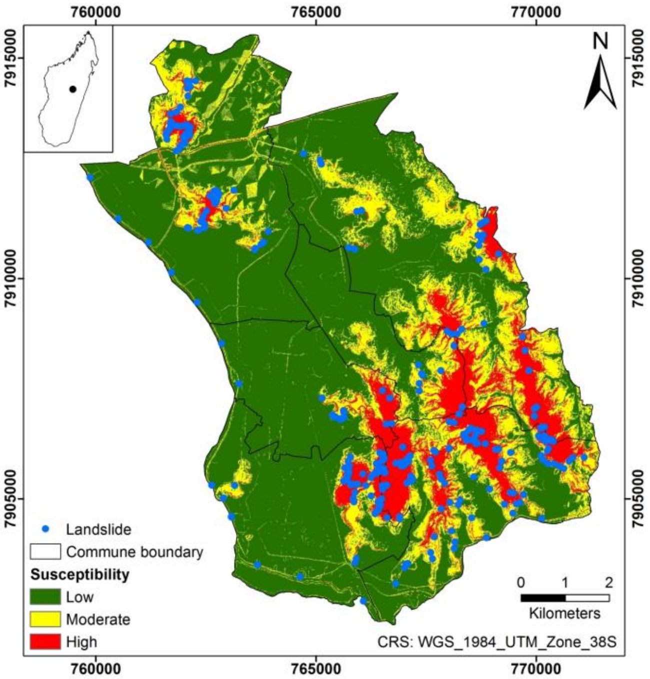

Fig. 4. Landslide susceptibility of Antananarivo Renivohitra district

The MCE, through the application of the WLC, made it possible to identify a landslide susceptibility map with a gradient ranging from 0 to 255 in the district of Antananarivo Renivohitra. Areas with gradient of 0 are considered to be lower susceptible areas, while areas with a suitability of 255 are areas of very high landslide susceptibility. According to the result of MCE, Fig. 4 presents the landslide susceptibility gradient of Antananarivo Renivohitra district. Three classes were chosen to classify it using Natural Jenks Break classification algorithm: low, moderate and high susceptibility. Areas with Moderate and High are mainly located in the southern and southeastern part of the district and correspond to the upper town areas, while the low susceptibility areas are located in the lower part of the district.

Table 2 shows the results of the ROC analysis. Using the "moderate" susceptibility class as a threshold, a sensitivity of 89.8% and a specificity of 62.5% were obtained for the Antananarivo Renivohitra district (Table 2).

Table 2. Result of ROC analysis

	Observations	
	Landslide	**No landslide**
High	TP : 272	FP : 106
Low	FN : 31	TN : 177

Accuracy: 76.621%
Sensibility: 0.,898
Specificity: 0.625

Note: TP (True Positive), TN (True Negative), FP (False Positive), FN (False Negative)

Associated with the landslide susceptibility model, the ROC showed an acceptable performance with an AUC of 0.809 (Fig. 5).

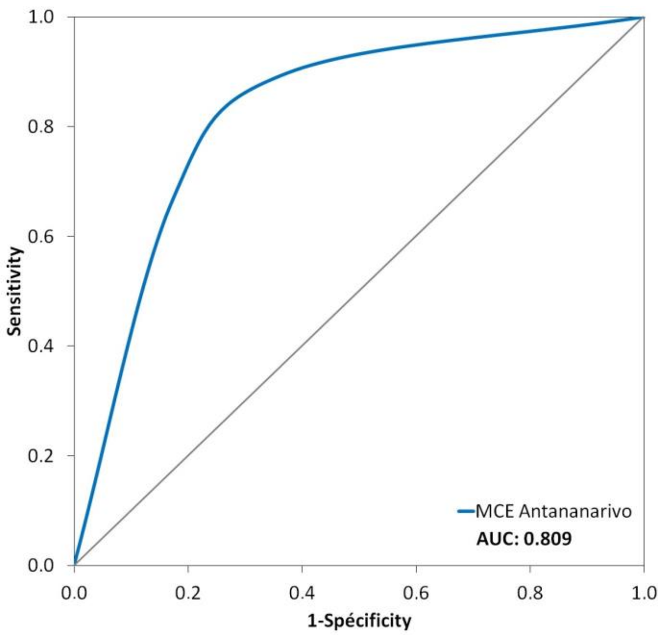

Fig. 5. ROC curve of the model for Antananarivo Renivohitra district

The WLC offers a reasonable result regarding the risks of misinterpretation. The use of Boolean logic, in the construction of the model, is a too strict solution. The most cautious of methods that we have adopted has shown an acceptable pace by offering a result on the right balance, so more secure. It also allows the total compensation of all factors [34]. Several studies on landslide spatial modeling, such as [35] - [37], consider the importance of structural faults variable but, unfortunately, due to the unavailable of data, it wasn't considered in this study. As pointed out by [38], the use of remote sensing analysis is more adapted to the tectonic pattern characterization in area with lack of relief, finite strain intensity and related tectonic transposition. The geological structure variable is important in landslide study as a predisposing factor. Despite the importance of lithology in the landslide study, it isn't always the main cause of their formation. Indeed, in a study of lavakas in Madagascar carried out by [39], authors concluded that « bedrock geology does not appear to be the primary driver for lavakas formation ».

IV. Conclusion

Landslide is limited by geological, topographical, environmental and climatic factors since they directly affect the stability of terrain that causes infrastructure damages and casualties. GIS combined with MCE, by their capacity for storage, management, analysis, modeling and display of spatially referenced data, appears as the most appropriate tool to apprehend spatial decision problems. This combination has improved the apprehension of susceptible of landslide areas. The resulting susceptibility map may be used as decision-support to target the potential zone at risk of landslide and then adapt management strategy.

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