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Landslides predisposing factors analysis in an urban expansion area in the municipality of Ipojuca-BR

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Abstract

In recent decades, the intense urbanization process in Brazil has led to the disorderly growth of cities in areas unsuitable for occupation regarding both the unfavorable geological and geomorphological characteristics; consequently, the number of people impacted by landslides has increased. In the coastal cities of Northeastern Brazil, such as those of the State of Pernambuco, there is a historical predominance of economic activities characterized by sugarcane monoculture, which has favored an increase in the income concentration; it was fundamental for a large part of population to occupy the region's slopes informally and without infrastructure developments. The municipality of Ipojuca, located on the coast of Pernambuco, is a sure example of this contextualization. Hence, this paper aims to identify and characterize the predisposing factors to translational landslides in the urban expansion area in Ipojuca; moreover, it intends to determine the relative contributions of each factor in the landslides' occurrence. The analysis was based on the translational landslides inventory and the application of bivariate analysis. Frequency rate (FR) was used to estimate the influence degree of the predisposing factors classes, and accountability (Acc) and reliability (Ri) were used to analyze the contribution of each factor in the landslides' development process. To accomplish this purpose, the landslide inventory map was cross-checked with the predisposing factor maps (geologic units, soil mapping units, land use, slope, drainage distance, plan curvature, profile curvature, curvature, and aspect) using Geographic Information Systems (GIS). The results of the FR application demonstrated that the areas with the highest probability of landslides are represented by the migmatitic gneiss complex (Px) and biotite granite (Ny3), which originate thick soils highly weathered, very clayey, and slopes over 27° on concave/ convergent hillsides, with significant concentration of surface and subsurface flow, directed to southeast and east. Acc and Ri indexes presented exceedingly different results; for the first one, the five most important factors were: geologic units, slope, soil mapping units, curvature, and drainage distance. For the second one, the main factors were: profile curvature, plan curvature, slope, land use, and geologic units. Ri index better represented the municipality reality. Ri considers the landslide density of the most relevant classes; therefore, it is credited by literature as the most important index to identify the foremost conditioning factors combination to improve landslide susceptibility predictive models, which make them more reliable.

1 INTRODUCTION

The increase in the number of people impacted by landslides in Brazil is connected to the intense urbanization process seen in the country over the past two decades. This process has led to cities disorderly growth in areas unsuitable for occupation due to their unfavorable geological and geomorphological characteristics. Moreover, few financial resources are allocated to preventive actions, such as mapping areas that may be affected by landslides (Fell et al., 2008); these actions aim to provide to authorities, decision-makers, civil defense, and civil society subsidies for the development of public policies, master plans, and other appropriate measures for correct land use and risk reduction.

Landslides are those movements in which there is a distinct zone of weakness that separates the sliding material from the more stable underlying material; they may be classified into two main types: rotational and translational (Varnes, 1984; Cruden and Varnes, 1996). Landslides are controlled by both predisposing environmental and triggering factors. The first ones are related to the terrain intrinsic characteristics and include some parameters, such as: topographic and morphometric (slope, aspect, curvature, relief amplitude, and drainage density), geological (rock types, presence of faults, fractures, and lineaments), soils (soil types, depth, and geotechnical properties), hydrological (drainage distance and soil moisture), geomorphological (physiographic units, terrain units, and geomorphological units), and land use and land cover. The triggering factors are related to precipitation, earthquake, volcanism, and anthropic actions (Van Westen et al., 2003; Zhu et al., 2014; Zhang et al., 2016; Reichenbach et al., 2018). Different landslides types present different predisposing factors associated, as well as the techniques to mitigate the damage caused by them depend on their typology (Zêzere et al., 2002; Zêzere et al., 2017).

Indeed, through landslides mapping and determining their conditioning factors in the past, it is possible to predict where and when other events may occur (Van Westen et al., 2006). This is the premise that underlies the statistical methods for evaluating the susceptibility to these processes since it compares landslides spatial distribution with parameters that are considered process' conditioning factors. Therefore, statistical methods are based on data and require the elaboration of inventory with high temporal and spatial qualities (Reichenbach et al., 2018). One of the main advantages of this approach is that the researcher may validate the importance of each factor and decide the input data, weight assignments, and data management (Aleotti and Chowdhury, 1999; Pardeshi et al., 2013).

In this sense, this paper aims to identify and characterize the predisposing factors, also known as conditioning factors, to translational landslides in the urban expansion area in the municipality of Ipojuca, located in the State of Pernambuco, Brazil; moreover, it intends to determine the relative contributions of each factor in the landslides' occurrence. The analysis was based on the translational landslides inventory and the application of bivariate analysis.

For this purpose, it was defined the frequency rate (FR) to estimate the influence degree of the conditioning factors classes (Lee, 2004; Lee et al., 2007); furthermore, two basic weights estimation methods, which are accountability (Acc) and reliability (Ri), were used to analyze the contribution of each conditioning factor in the landslide's development process (Greenbaum et al., 1995a,b).

Since the studied municipality was historically occupied by sugarcane cultivation, the population was concentrated in small urban centers in the three main districts: Ipojuca's center, Nossa Senhora do Ó, and Camela and their outskirts. The communities of Rurópolis and Bela Vista, which are areas considered informal settlements, emerged along the main highway. Notwithstanding, the expansion of the Industrial Port and District of Suape has been changing this scenario, and massive modifications are already being verified in the industrial production's connectivity axis. Thus, there is an urgent demand for spatial planning instruments that consider the municipality's physical characteristics to reduce disaster risks. These factors justified the delimitation of the study area since this was the region destined for urban expansion by municipal management.

This study is part of the project "Elaboration of the Geotechnical Map for urbanizing the municipality of Ipojuca, Pernambuco, in concern of the natural disasters", which is a partnership between the Brazilian Federal Government through the Ministry of the Cities and the Geotechnical Engineering Group of Slopes, Plains, and Disasters for the Federal University of Pernambuco (Gegep/ UFPE).

2 METODOLOGY

The methodology was based on this sequence of activities: first, definition of the study area; second, elaboration of thematic maps related to the inventory of landslide scars and their conditioning factors; and third, analysis of the relation between the conditioning factors and the landslide inventory.

2.1 Definition of the study area

The municipality of Ipojuca is located in the Metropolitan Region of Recife (RMR), in the Brazilian state of Pernambuco, and covers an area of 532.25 km². It is formed by three districts: Ipojuca's Center, Nossa Senhora do Ó, and Camela; besides, there are the tourist beaches villages of Porto de Galinhas, Muro Alto, Cupe, Maracaípe, Serrambi, and Toquinho. It also presents in its territory part of the Suape Industrial and Port Complex (Figure 1).

Hence, the economic dynamics related to the industrial and tourist complex undergo the municipality through a period of massive changes in the natural landscape. Nevertheless, as its territory is predominantly occupied by sugarcane cultivation, the districts and regions set for urban expansion are concentrated in small areas. Furthermore, there is a significant income concentration; consequently, the peripheral population from these districts and localities of Rurópolis and Bela Vista, with low purchasing power, has built its houses in hillside areas without adequate urban planning and infrastructure works. Thus, the risk of landslides and erosion processes has been raised in these areas.

In this context, in this paper, a section was taken to cover the set area for urban expansion by the municipal master plan. That area, which measures about 70 km², is located between Ipojucas' headquarters and Nossa Senhora do Ó, as shown in the location map in Figure 1.

2.2 Elaboration of the thematic maps

First, it was conducted a survey of the existing thematic bases, satellite images, and digital terrain models (DTM). All the thematic bases had to be elaborated or adapted to scale of 1:10,000; thus, their respective methodologies, as well as the obtained data's sources, are described as following:

Landslide scars inventory: in the office, the scars were mapped based on Quickbird Multispectral (2005/2006) and Panchromatic (2010) satellite images on the scale of 1:10,000 provided by Condepe/Fidem, and Google Earth Pro image (2013, 2014 and 2015) with orthophotos on the scale of 1:1,000, from 2013. The last one as the main reference. These orthophotos were provided by the Three-dimensional Pernambuco Project (Pernambuco State Government/ Secretariat of Economic Development), which consists of the aerophotogrammetric covering of the State.

Based on these multitemporal images, 41 translational landslides scars were mapped. Since the mapping unit selected was the grid cell with a spatial resolution of 2.5 meters, it was chosen the point representation located on the centroid, in the upper portion of the processes.

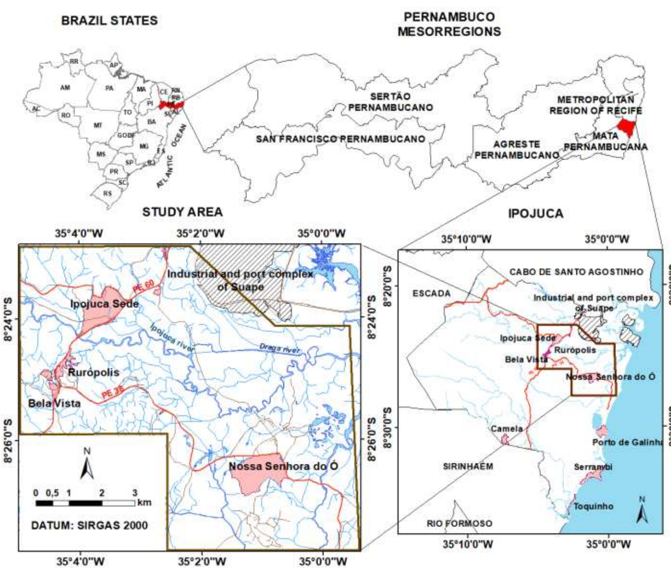

Figure 1. Location of the study area, Ipojuca municipality, State of Pernambuco, Brazil. Fonte: The authors

Geological Map: it was generated and supplied by the Gegep/ UFPE on a scale of 1:10,000. Then, 14 classes were defined: Algodoais Formation (Ka), Cabo Formation (Kc), Ipojuca Magmatic Suite - Ignimbrites (Kiig), Ipojuca Magmatic Suite - Rhyolite (Kirl), Ipojuca Magmatic Suite - Trachyte (Kitq), Biotite-granite (Ny3), Quartz-Sienyte (Ny5), Migmatitic gneiss complex (Px), Alluvial sands (Qal), Fluvial-lacustrine sediments (Qdfl), Mangrove clayey silica sediments (Qm), Beach sediment (Qp), Holocene sea terraces (Qth), Pleistocene sea terraces (Qtp).

Soil Map: soil mapping units were used. These units consist of soil associations elaborated by the Brazilian Agricultural Research Corporation (Embrapa) in 1:100,000 scale. However, to achieve a representation compatible with the 1:10,000 scale, fieldwork was done to perform the soils morphological recognition following the parameters recommended in the Manual of Soil Description and Collection in the Field stated by Santos et al., (2013). Once it was done, the information collected in the fieldwork was completed with data from existing surveys; subsequently, the needed map on a suitable scale was obtained. The associations applied were: AM (Marine quartz sands and Spodosol), AQ1 (Quartz sands), G1 (Gleysol, Cambisol, Alluvial Soils and Yellow and Grey Argisols) G2 (Gleysol, Cambisol and Alluvial Soils) G5 (Gleisol and Spodosol) HP1 (Spodosol), LA9 (Yellow Latosol, Yellow and Red-Yellow Argisol, Gleisol and Cambisol) PA_4 (Yellow and Red-Yellow Argisol) PV2 (Red-Yellow Argisol and Cambisol), PV3 (Red-Yellow Argisol, Cambisol and Litolic Soil) and SM (Mangrove Soil).

Land cover and land use: it was elaborated from photointerpretation and orthophotomaps vectorization techniques on the scale of 1:1000 (2013) in addition to obtaining control points in the field. The mapping units were defined based on Technical Manual of Land Use by IBGE (2013), meeting the fourth class of use, with detail compatible to the study's scale adapted to the municipality reality. Thus, 21 classes were defined: Informal settlements, Sugar cane, Urbanized areas, Industrial complex, Coconut grove, Water bodies, Horticulture, Diversified crops, Research and education establishment, Roads, Clay extraction, Single homes, Mangrove, Forest, Riparian forest, Exposed soil, Sugar cane plant, Shrub vegetation, Herbaceous vegetation, Commercial area, and Wetlands.

Topographic parameters: all the topographic parameters were generated by applying ArcGIS 10.1 tools and based on DTM. That model was obtained by LIDAR (Light Detection and Ranging) of the Pernambuco State with 50 cm spatial and 32 bits radiometric resolutions, which was provided by the Three-dimensional Pernambuco Project.

For the elaboration of both slope maps and horizontal and vertical curvature maps, the DTM was modified for 5 m spatial resolution and then to 2.5 m resolution. To prepare the slope maps, the Slope tool on ArcGIS 10.1 was used with intervals related to the hillside's inclination in degrees (°). Applying the natural breaks method, which better represented the existing slopes in the study area, seven slope classes were generated: 0° to 3°, 3° to 7°, 7° to 11°, 11° to 17°, 17° to 27°, 27° to 45°, and >45°.

The **horizontal and vertical curvature maps** were generated by the Curvature tool of Spatial Analyst, which is based on the methodologies proposed by Moore and Grayson (1991) and Zevenbergen and Thorne (1987). This tool provides three output raster options: profile curvature, plan curvature, and curvature.

Profile curvature expresses the hillside shape in the direction of its steepest inclination. Hence, it indicates how the slope behaves from its upstream to downstream, i.e., how it affects the flow acceleration and deceleration over the surface. On the one hand, negative values indicate a convex upwards surface; on the other hand, positive values indicate a concave. Values between -0.5 and 0.5 indicate that the surface is linear.

Plan curvature indicates the hillside shape in lateral terms, i.e., the hillside shape in a perpendicular orientation to that of the longitudinal profile expressing the changes in slope exposure. Positive values indicate that the surface is laterally convex; it means that there is a flow dispersion. Negative values indicate that the surface is parallel concave occurring flow concentration; values between -0.5 and 0.5 denote a linear surface.

Curvature is the result of the other two output rasters combination. Considering the extremes of maximum concentration and maximum dispersion, curvature is divided into three classes, too: concave/ concave (negative values), convex/ convex (positive values), and linear/ linear (range between -0.5 and 0.5).

The aspect map was generated by the Aspect tool of Spatial Analyst; nine classes, which represent the slope's direction, were created: flat, north, northeast, east, southeast, south, southwest, west, and northwest.

The drainage distance map was generated from the information extracted from DTM. Five classes with distances of 50 m were defined: 50, 100, 150, 200, and >200.

2.3 Definition of weights and predisposing factors analysis

The relation between the landslides distribution in the study area and their conditioning factors was analyzed as following: first, crossing of the inventory and the conditioning factors classes; second, definition of the prior probability; third, density calculation of cells occupied by landslides for each conditioning factor classes; fourth, frequency rate calculation and relative weight estimation for conditioning factors classes; and finally, importance quantification of the landslide conditioning factors.

First, the nine maps of predisposing factors and the inventory map were transformed into matrix data with 2.5 m spatial resolution, since the mapping unit chosen was the grid cell. Thus, the conditioning factors were cross-checked with the inventory by cross-tabulation; then, the number of slides' pixels for each conditioning factor class was obtained.

The prior probability related to landslide density for the entire study area was estimated. Next, the frequency rate for each conditioning factors class was calculated; the frequency ratio consists of the ratio between the landslide density in the class and the density of the entire area, as shown in the Equation 1:

$$FR_i = \left(\frac{Densclass}{Densmap}\right) = \left[\left(\frac{N(P_i)}{A_i}\right) / \left(\frac{\sum N(P_i)}{\sum A_i}\right)\right] \quad (1)$$

Where FRi is the frequency ratio of a conditioning factor class. *Denclass* is the landslide density existing in this class; *Densmap* is the landslide density for the entire area. Since the chosen mapping unit is the grid cell, $N(P_i)$ refers to the pixels' number occupied by landslides or erosion in that specific class, A_i is the pixels' number in this class, $\sum N(P_i)$ is the total pixels' number with landslides in the entire area, and $\sum A_i$ is the pixels' number in the entire area.

This methodology is normally applied in landslide susceptibility zoning (Lee, 2004; Lee et al., 2007; Yalcin et al., 2011; Sujatha et al., 2013; Pourghasemi et al., 2014; Das and Lepcha, 2019). Nonetheless, this paper sought to only determine the relative contribution of each class in the landslides' occurrence.

All classes that presented a frequency ratio higher than 1 were considered in the analysis since they have a high frequency concerning the average density of the study area. It is worth highlighting that the higher the proportion, the greater the relative weight of a given class (Castellanos, 2008).

Accountability (Acc) and reliability (Ri), which are two basic weights estimation methods, were used to analyze the contribution of each landslide conditioning factor. These methods were introduced by Greenbaum et al. (1995a,b); they are applied in several landslide susceptibility assessments works to identify the best conditioning factors combination to improve the predictive models' outcome (Catellanos, 2008, Blahut et al., 2010)

The accountability index refers to the sum of landslide cells with frequency ratio classes greater than 1; the result is divided by the number of landslide cells in the entire study area and multiplied by 100.

The reliability index is given by the sum of landslide cells with frequency ratio classes greater than 1; also, the result is divided by the sum of the areas from this specific class and multiplied by 100.

The two methods promote different results, but relevant ones for predicting susceptibility. Nevertheless, reliability is more important (Blahut et al., 2010).

3 RESULTS AND DISCUSSION

After crossing the inventory with the predisposing factors (geologic units, soil mapping units, land use, drainage distance, slope, plan curvature, profile curvature, and curvature and aspect) using GIS, the prior probability could be estimated. This probability was very low due to the extent of the study area and the low landslides' spatial distribution. In this case, the identified density for the whole area was $3{,}9\text{x}10^{-6}$. Subsequently, the normalization with the frequency ratio application made it easier to understand how much each class with a rate higher than 1 contributed to the processes' occurrence.

Hence, based on the results of the mentioned applications the main characteristics of the landslides' predisposing factors in the urban expansion area of Ipojuca will be described. That area is composed of the Ipojuca's center and the Nossa Senhora do Ó district, and the informal settlements of Rurópolis and Bela Vista, which are characterized by recent and precarious occupations.

The areas that are favorable for landslide development process are related to the geological units that make up the crystalline base, in the western portion area, represented by the migmatitic gneiss complex (FR = 6.64), which covers a large part of the Rurópolis' community and only 4% of the total area. This unit originates soils with a thickness higher than 15 m, quite weathered, represented by the unit LA9 (FR = 6.34), which is formed by an association of yellow Latosol in the hillside planed tops, and laterite and non-laterite red-yellow Argisol of medium clayey and very clayey texture in the slopes.

Latosols are normally stable and uniform in their set of characteristics; also, they present a good permeability. However, when Latosols have the vegetation removed for sugarcane cultivation or housing construction, and they are associated with the Argisols at the slopes, which are characterized by their textural gradient, it makes the environment more susceptible to landslides (Figure 2).

Figure 2. Disordered occupations on the slopes of the community of Rurópolis. Fonte: The authors.

Another important factor is related to the topography since the declivities found in the unit Px and the Ipojuca's Center, which is on the Biotite-granit - Ny3 (FR = 3.62), are quite steep between 27° and 45° (FR = 10.1) and above 45° (FR = 18.9). The landslides identified in this last slope class are mostly related to the vegetation removal and slopes' cutting for houses' construction in the areas of informal settlements (FR = 26.6) without the engineering knowledge and adequate infrastructure works, as well as cutting for roads' construction (Figure 2 and 3).

Figure 3. Slope cuts for road' construction. Fonte: The authors.

An aggravating factor is the occupation of hillsides with concave profile (FR = 5.8), which naturally provide a convergence of superficial and subsurface flows (FR = 9.75) (Figure 5), directed to the southeast (FR = 2.21), northeast (FR = 1.63), and east (FR = 1.58). The location of the landslides, predominantly on the slopes, in these directions, is harnessed to the municipality located on the Eastern portion of Brazil. This portion is massively influenced by the humidity that comes from the Atlantic Ocean, displaced by the southeast and northeast trade winds, mainly by the east and southeast winds. These winds are responsible for 30% to 40% of the rains from May to July, regarding the municipality rainy period (Kayano and Andreoli, 2009).

The vegetation removal with soil exposure (Soil Exposed, FR = 19.6) intensifies the occurrence of landslides, too. Besides, urban expansion without proper planning and infrastructure implementation in the urban centers' peripheries, as in the Ipojuca's center, was responsible for intensifying the landslides' occurrence in these areas (FR = 3.59).

The figure 4 represents the spatial distribution of the Frequency Ratios of main landslide's conditioning factors: curvature, slope, soil, geology, and land use / cover of the urban expansion area between the districts of Ipojuca and Nossa Senhora do Ó, municipality of Ipojuca.

The accountability and reliability indexes presented different results (Table 1); it was expected given their objectives.

Table 1. Results for accountability and reliability indexes

Factor	Acc	Ri	Order (Acc)	Order (Ri)
Geology	**95,35**	**0,00166**	1	5
Soil	**90,70**	0,00146	3	6
Land Cover/Use	53,49	**0,00194**	9	4
Drainage Distance	**67,44**	0,00011	5	8
Slope	**93,02**	**0,00216**	2	3
Curvature	**79,07**	0,00129	4	7
Plan curvature	67,44	**0,00746**	7	2
Profile curvature	65,12	**0,00848**	8	1
Aspect	67,44	0,00011	6	9

Fonte: The authors.

The accountability index highlighted the following order of factors' importance: geologic units, slope, soil, curvature, drainage distance, aspect, plan curvature, profile curvature, and use. It means that for the geology factor, the most relevant classes comprise 95% of the landslides, while the use factor comprises only 53% of the landslides. Nevertheless, the reliability index identified the following order of factors' importance: vertical curvature, horizontal curvature, slope, use, lithology, soils, curvature, drainage distance, and aspect.

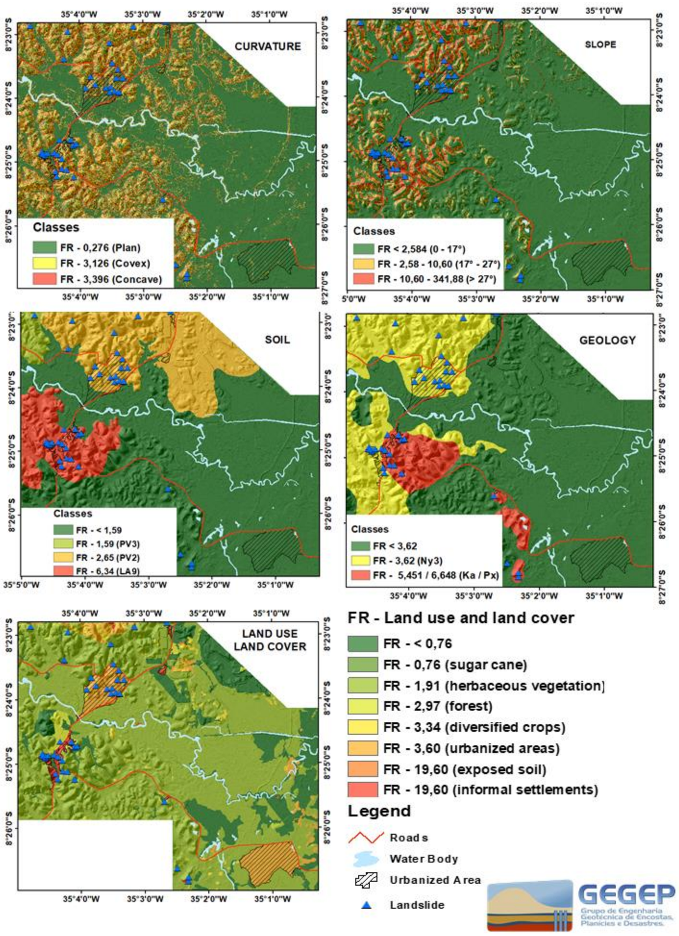

Figure 4. Spatial distribution of the conditioning factors´ Frequency Ratios: curvature, slope, soil, geology, and land use / cover, and inventory of the urban expansion area between the districts of Ipojuca and Nossa Senhora do Ó, municipality of Ipojuca.

Therefore, this index is considered more relevant for evaluating the proportion in the occupied area per landslides. Thus, use, profile curvature, and plan curvature, which appeared as slight determinants in the accountability index, contribute significantly to the landslide occurrence in the reliability index. It is noticed once the classes of the most determining factors present a significant landslides' amount in small extent classes when compared with the total study area. It may be exemplified by the slope factor, which indicated that 93% of the landslides were distributed in 17% of the total area, while the use factor presented 53% of the landslides distributed in 10% of the study area.

These results were compatible with the classes that presented the highest frequency rate, such as the slopes above 45° (FR=341), informal settlements (FR=29), exposed soil (FR=19), slope range between 27° and 45° (FR=10), and the hillsides with a concave profile (FR=7.5).

The results in this paper are following the geological and geomorphological reality of the municipality, since the slopes' shapes, especially the concave/convergents, are characteristic of the hillsides in the Pernambuco's Zona da Mata area, which quite dissected leading to the appearance of drainage headwaters.

4 CONCLUSION

In this paper, the inventory map was cross-checked with the predisposing factor maps, using GIS, for the urban expansion area of the municipality of Ipojuca, Pernambuco, Brazil. For this purpose, all maps were transformed into a raster with 2.5 m spatial resolution, and the pixels' numbers existing in each predisposing factor class were defined. Hence, it was possible to determine the prior probability and the landslide densities per class to calculate the frequency ratio, to determine the class weights, the accountability and reliability indexes, and the importance of each factor in the landslide development process.

The application of a high-resolution DTM was fundamental to identify the slopes, mainly those above 45° originated by the pattern of land use in the study area, such as ground cuttings for construction of houses and roads, which intensifies landslide occurrence. It led to a high probability of the slope factor. Besides, the land use was determinant to increase the contribution of the profile curvature and plan curvature factors. It was due to the significant occupation of the concave/ convergent areas, mainly in the informal settlements, increasing the contribution of these classes to the occurrence of landslides in the study area.

For the reliability index, the most important factors were vertical curvature, horizontal curvature, slope, use, and lithology; that index better represented the municipality reality. Therefore, the results demonstrated that the methodology applied to analyze the relation of the predisposing factors and the landslides distribution, by obtaining a high-quality inventory, was efficient.

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