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SCENARIOS OF SUSCEPTIBILITY TO SHALLOW LANDSLIDES USING THE SHALSTAB MODEL AND VALIDATION BY ROC CURVE, METROPOLITAN REGION OF RECIFE, NORTHEASTERN BRAZIL

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ABSTRACT
The Metropolitan Region of Recife (RMR), Northeastern Brazil, is home to a population of 630 thousand people who live in risk areas, with the town of Camaragibe standing out, where records of landslides are recurrent, especially in the rainy periods. Thus, in a susceptibility evaluation, the predictive mathematical models are relevant tools, the SHALSTAB (Shallow Slope Stability Model) especially. Therefore, this research was intended to define the best scenario that represents susceptibility to shallow translational landslides in the town of Camaragibe, based on a SHALSTAB prediction, and based thereon to analyze the relationship between natural and anthropic factors in the triggering of the processes. Six scenarios were created, based on physical values of the soil collected in the study area itself and on a high-resolution Digital Terrain Model. The choice of the best scenario was based on the construction of the ROC (Receiver Operating Characteristic) curve, which is an important validation test. The areas predicted to be the most susceptible are located on slopes with a declivity greater than 15º, with alternation of materials and porosity, and a depth of 5m. Anthropic alterations to the topography, and often the nonexistence of infrastructure, were substantial for the triggering of landslides.

Keywords: mass movements, inventories, mathematical models, shalstab, northeastern Brazil.

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CENÁRIOS DE SUSCETIBILIDADE A ESCORREGAMENTOS TRANSLACIONAIS RASOS USANDO O MODELO SHALSTAB E VALIDAÇÃO POR CURVA ROC, REGIÃO METROPOLITANA DO RECIFE, NORDESTE DO BRASIL

RESUMO
A Região Metropolitana do Recife (RMR) abriga uma população de 630 mil pessoas residindo em áreas de risco, se destacando o município de Camaragibe, onde são recorrentes os registros de escorregamentos, principalmente, nos períodos chuvosos. Modelos matemáticos preditivos são ferramentas relevantes na avaliação da suscetibilidade, ressaltando-se o SHALSTAB *(Shallow Slope Stability Model)*. O objetivo dessa pesquisa foi buscar o melhor cenário para representar a suscetibilidade a escorregamentos translacionais rasos no município de Camaragibe, baseado na previsão do modelo SHALSTAB, e a partir disso, analisar a relação entre fatores naturais e antrópicos na deflagração desses escorregamentos. Foram elaborados seis cenários baseados em valores de parâmetros físicos do solo e de um modelo digital do terreno de alta resolução. A seleção do melhor cenário foi baseada na construção da curva ROC *(Receiver Operating Characteristic)*, como importante teste de validação. As áreas previstas como as mais suscetíveis aos escorregamentos estavam localizadas sobre encostas com declividade superior a 15º, com alternância de materiais e porosidade, e profundidade de 5 m. Alterações antrópicas na topografia e, muitas vezes, a inexistência de infraestrutura foram cruciais para a deflagração dos escorregamentos.

Palavras-chave: movimentos de massa, inventários, modelos matemáticos, shalstab, nordeste do Brasil.

ESCENARIOS DE SUSCEPTIBILIDAD DE DESLIZAMIENTO TRASLACIONAL UTILIZANDO EL MODELO SHALSTAB Y VALIDACIÓN DE LA CURVA ROC, REGIÓN METROPOLITANA DE RECIFE, NORDESTE DE BRASIL

RESUMEN
La Región Metropolitana de Recife (RMR) alberga una población de 630 mil personas que residen en áreas de riesgo, con destaque para el municipio de Camaragibe, donde los deslizamientos son recurrentes, especialmente durante la época de lluvias. Los modelos matemáticos predictivos son herramientas relevantes en la evaluación de la susceptibilidad, destacando el SHALSTAB (Shallow Slope Stability Model). El objetivo de esta investigación fue encontrar el mejor escenario para representar la susceptibilidad a deslizamientos traslacionales someros en el municipio de Camaragibe, con base en la predicción del modelo SHALSTAB, y a partir de ahí, analizar la relación entre factores naturales y antrópicos en el desencadenamiento. de estos derrumbes. Se desarrollaron seis escenarios basados en valores de parámetros físicos del suelo y un modelo digital de terreno de alta resolución. La selección del mejor escenario se basó en la construcción de la curva ROC (Receiver Operating Characteristic), como importante prueba de validación. Las áreas pronosticadas como más susceptibles a deslizamientos se ubicaron en taludes con pendiente mayor a 15º, con alternancia de materiales y porosidad, y una profundidad de 5 m. Los cambios antropogénicos en la topografía y, muchas veces, la falta de infraestructura fueron cruciales para el desencadenamiento de deslizamientos.

Palabras clave: movimientos de masas, inventarios, modelos matemáticos, shalstab, nordeste de Brasil.

INTRODUCTION

Developing countries usually present, as noteworthy characteristics of their urbanization process, the occupation of areas that are unsuitable and risky for habitation, such as steep slopes, floodplains and valley bottoms, especially by disadvantaged populations. In Brazil, the occupation of areas at risk of landslides and flooding has been a recurring characteristic in many of its cities, wherein over eight million people reside in said areas, distributed among 825 towns (IBGE, 2018a; ALVALÁ *et al.,* 2019).

The Metropolitan Region of Recife (RMR), in the State of Pernambuco, Northeastern Brazil, is formed by 14 towns, predominantly in the coastal area. This region concentrates a radius of influence of 300km around the Pernambuco state capital (Recife), articulating a potential consumer market, representing 35% of the Gross Domestic Product of the Northeast (IPEA, 2015). On the other hand, it concentrates the highest number of recorded landslides in the state, especially in the rainy period, between the months of April and June, causing a series of economic, social and human losses (ALHEIROS and AUGUSTO FILHO, 1997; XAVIER; LISTO; NERY, 2022).

According to the Brazilian Institute of Geography and Statistics - IBGE (2018a), in the RMR 630,000 people inhabit areas susceptible to landslides, with the town of Camaragibe, located east thereof, standing out. The occurrences of such processes are recurrent, with records of casualties, such as in the event recorded in June 2019, triggered during a period of intense rainfall (172 mm in 24h), which caused nine casualties (APAC, 2019), as well as more recently in May-June 2022, with six casualties. Episodes such as these reinforce the importance of actions intended for the urban planning of said areas. Among them, the use of predictive tools to identify areas susceptible to landslides stands out, especially the use of the Geographic Information System (GIS). This tool has become fundamental for the better planning, especially of metropolitan regions, mostly due to its ability to swiftly and accurately generate the location of susceptible areas, often difficult to access for field surveys. Among said tools, those that stand out are the process inventory mapping, the Digital Terrain Models (DTM), the high-resolution satellite images, and the mathematical models on physical bases, such as the SHALSTAB (Shallow Landslide Stability) model (GUZZETTI *et al.,* 2012; SONG *et al*., 2021).

The mathematical models on physical bases, in their majority, evaluate susceptibility by combining stability models based on the theory of infinite slope and hydrological models, regardless of the prior occurrence of processes. They have been widely disseminated in international literature, especially after the 1990s, with the development and improvement of the GIS, responsible for the modifications and creation of new approaches of identification and evaluation of areas susceptible to said processes (MONTGOMERY and DIETRICH, 1994; CARRARA *et al*., 1995; WU and SIDLE, 1995; GUZZETTI *et al*., 1999; IVERSON, 2000; MORRISEY *et al*., 2001; PACK *et al*., 2001; DHAKAL and SIDLE, 2003; CALCATERRA *et al*., 2004; VAN WESTEN, 2004).

The experiences with the SHALSTAB model (MONTGOMERY and DIETRICH, 1994) have been resulting in susceptibility maps deemed satisfactory for several areas, with the classic works by Dietrich and Montgomery (1998) in Northern California (USA) standing out, in addition to more recent studies (e.g. MARTINS *et al*., 2016; KÖNIG *et al.,* 2019; JANG *et al.,* 2021; SHOU and CHEN, 2021).

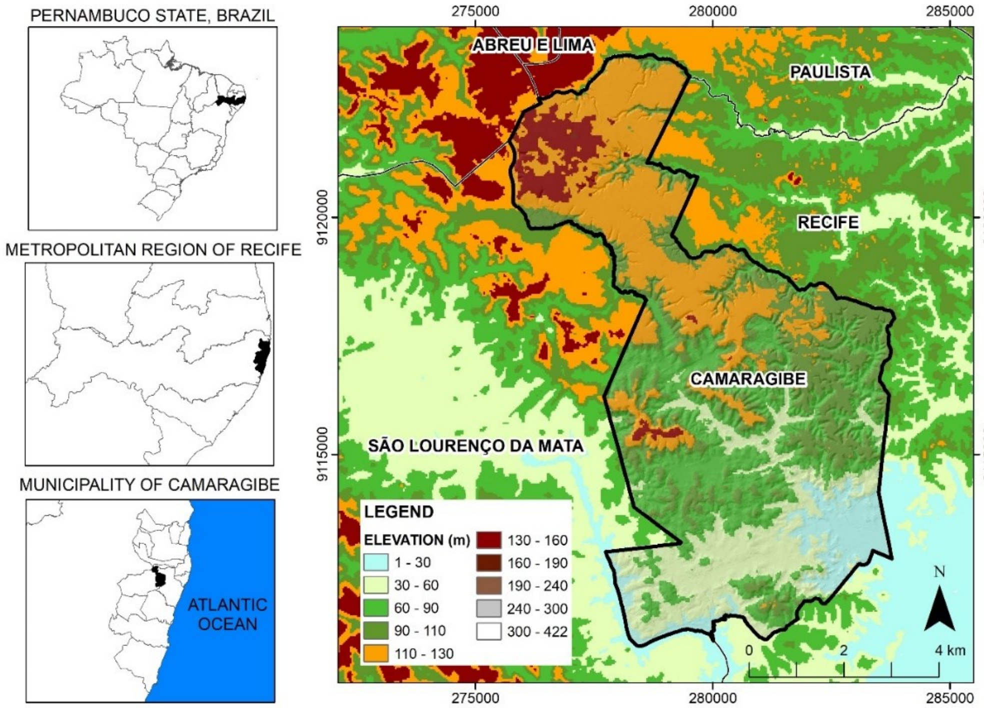
Under these conditions, considering the constant occurrence of landslides in the RMR, the purpose of this work was to define the best scenario that represents susceptibility to shallow translational landslides in the town of Camaragibe, based on the SHALSTAB model prediction and, based thereon, to analyze the relationship between natural and anthropic factors in the triggering of the landslides.

STUDY AREA: THE TOWN OF CAMARAGIBE WITHIN THE CONTEXT OF THE METROPOLITAN REGION OF RECIFE

The town of Camaragibe totals an area of 51.3 km^2, with altitudes that exceed 130m (Figure 1), and contains a population of 156,736 inhabitants, of which approximately 30 thousand inhabit areas considered to be at risk (IBGE, 2018a; IBGE, 2018b). Since the 16th century, a series of anthropogenic pressures characterizes the town landscape, by means of a great deforestation of the Atlantic Forest to implement sugarcane mills, throughout the growth of the textile industry in the 19th century and arriving at the current scenario of accelerated expansion caused by the urban macrocephaly of the neighboring towns (OLIVEIRA *et al*., 2006).

With regard to geology, the town has three great groups: (i) crystalline basement rocks in the central area of Camaragibe, (ii) sandy-clay sediments belonging to the Barreiras Formation, which are more expressive in the town and located in the entirety of its Center-North area, and (iii) alluvial deposits in the planer areas in the South of the town (BANDEIRA, 2003; FONSÊCA *et al*., 2016). The crystalline basement is formed by granite, migmatite, gneiss and mica schist. Some of the characteristics of the clay minerals produced by the granite, such as plasticity, play an important role in triggering the landslides (ALHEIROS and AUGUSTO FILHO, 1997). The Barreiras Formation is characterized as an extensive sedimentary cover over approximately 20 km of the surface of the RMR (ALHEIROS and AUGUSTO FILHO, 1997). On this surface there are sand and clay layers interspersed towards the top, producing different infiltration rates towards the base, which may favor landslides (ALHEIROS and AUGUSTO FILHO, 1997; BANDEIRA, 2003). Lastly, the alluvial deposit areas are formed by sand, grit and clay, of a continental origin, transported by the rivers and deposited along the fluvial channel. Due to their plane and low relief, the alluvial deposit areas do not interfere with the landslide processes.

Figure 1 - **Location and hypsometric map of the Municipality of Camaragibe**



Database: Three-Dimensional PERNAMBUCO Project (Projeto PERNAMBUCO Tridimensional, 2018).

The climate is classified as hot and humid tropical with average annual temperatures of 27ºC and average annual rainfall rate of 1,970 mm (APAC, 2021). The period between April and July concentrates 67% of the average annual rainfall, being characterized especially by the occurrence of convectional rainfall. Torrential rainfall in the town is generally caused by the Easterly Wave Disturbance (EWD) synoptic system.

Regarding the forms of relief, the town is within three morphostructural domains: (i) plains, (ii) coastal sedimentary plateau, and (iii) Borborema plateau (FONSÊCA *et al*., 2016). The plains, resulting from quaternary settlement, are characterized by plane accumulation models. They occur in a longitudinal and discontinuous manner along the fluvial channels of Camaragibe (FONSÊCA *et al*., 2016). The coastal sedimentary plateau (coastal tablelands) was developed from the regressive erosion of the heads that actively carve the loose sediments of the Barreiras Formation, which make up its substrate (ALHEIROS and AUGUSTO FILHO, 1997; FONSÊCA *et al.,* 2016). It has concave-convex slopes with steep declivities, of the hollow and nose types, and edges intersected by narrow and deep valleys (ALHEIROS and AUGUSTO FILHO, 1997; BANDEIRA, 2010). The landslides are constant in this domain, often influenced by the form of anthropic occupation of the area. The Borborema plateau domain is morphologically formed by convex slopes, with altitudes usually below 200m, with emphasis on the occurrence of erosive processes (FONSÊCA *et al.,* 2016).

As to the pedology, there is a predominance of the following types of soils: (i) latosols, associated with the crystalline basement, (ii) acrisols, formed by sedimentary clay or sandy-clay materials of the Barreiras Formation, and (iii) fluvial neosols, found in the planer areas (EMBRAPA, 2000).

Regarding the anthropic aspects, Camaragibe is characterized by the settlement of the disadvantaged population in very steep areas (the morphodynamic of the relief being quite constant), precariously established (slums) and subject to the risk of landslides, most of the time settled very close to the top and foot of the hillsides. The occupation process was marked by the exclusionary planning and dearth of infrastructure, with cuts and landfills being carried out; obstruction of the drainage networks with trash, saturation of the soil with wastewater, among other unsuitable practices.

MATERIALS AND METHODS

SHALSTAB MODEL

SHALSTAB is a deterministic steady-state mathematical model developed by Montgomery and Dietrich (1994), which calculates the susceptibility to shallow translational landslides in soil/rock contact, based on the compilation of a stability model based on the Infinite Slope Equation and a hydrological model, considering constant subsurface flows, based on the work carried out by Beven and Kirkby (1979) and O'Loughlin (1986) (Equation 1).

$$\frac{q}{T} = \frac{sen\theta}{a.b}\left(\left(\frac{C'}{\rho w.g.z.cos^2\theta.tan\phi}\right) + \left(\frac{\rho s}{\rho w}\right)\left(1 - \frac{tan\theta}{tan\phi}\right)\right)$$ **Equation 1**

***Where**: "a" is the contribution area or upstream drained area (m²); "b" is the unit contour length (m); "C'" is the soil cohesion (kPa); "g" is the gravity acceleration (m/s²); "θ" is the slope angle (degrees); "ρs" is the density (specific mass) of the saturated soil (Kg/m³); "ρw" is the water density (kg/m³); "q" is the rainfall in critical state necessary for the rupture (m/dia^{-1}); "T" is the saturated soil transmissibility (m²/dia^{-1}); "z" is the soil thickness (m) and "Φ" is the soil internal friction angle (degrees).*

In a GIS environment, the combination of such models is incorporated into the topographic parameters (slope angle and contribution area), derived from a Digital Terrain Model, and the mechanical properties of the soil: cohesion (*c'*), internal friction angle (*Φ*), soil thickness (*z*) and specific weight (*ρs*) (MONTGOMERY and DIETRICH, 1994). The model is based on the premise that the soils, in the presence of water, have low cohesion and friction angle and, associated with the topographic characteristics of the study area, calculates the balance of forces of the system.

The result of the general equation of the model generates, for each pixel, a value of susceptibility to landslides for the studied area, which susceptibility is made up of seven classes (from unconditionally stable and saturated to unconditionally stable and saturated). Such classes follow the condition presented by the equality between the drained area and contour unit ratio (a/b) and the hydrological ratio (q/T), wherein "q" is equivalent to rainfall in critical state (m day^1) and "T" to the saturated soil transmissibility (m^2 day^1) (MONTGOMERY and DIETRICH, 1994).

For purposes of presentation and analysis of the susceptibility scenarios herein, the original classes of the "log q/T > -2.2" model and "unconditionally stable and saturated" were grouped and considered to be of "low susceptibility"; classes "-3.1 < log q/T < -2.8", "-2.8 < log q/T < -2.5" and "-2.5 < log q/T < -2.2" were considered to be of "average susceptibility"; and lastly, classes "log q/T < -3,1" and "unconditionally unstable and saturated" were classified as "high susceptibility".

INPUT SHALSTAB PARAMETERS AND SUSCEPTIBILITY SCENARIOS

The parameters used to construct the susceptibility scenarios were divided into topographic (slope angle and contribution areas), common to all scenarios, and physical parameters of the soil (cohesion "***c'***", internal friction angle "***Φ***", specific weight "***ρs***" and depth "***z***"), with a variation among the scenarios. The topographic parameters were obtained from a high-resolution MDT (2 m), through the *PERNAMBUCO Tridimensional* project (PERNAMBUCO, 2016). The values of the physical properties of the soils (***c'***, ***Φ***, ***ρs*** and ***z***) were taken from the works by Bandeira (2003; 2010) and Silva (2007), based on soil samples collected at four points distributed throughout the area under study by this work (Figure 3).

The authors conducted direct shearing tests in laboratory, using samples collected in sites with sediments from the Barreiras Formation and the Crystalline Basement (Figure 3), at depths that ranged from 0.5m and 1.8m, as per the protocols of ASTM D3080-04. The test specimens were molded in the field, and later tested under saturated condition, as this condition is considered to be the most critical to trigger landslides during rainy periods (BANDEIRA, 2003; SILVA, 2007; BANDEIRA, 2010).

The values obtained by the abovementioned authors enabled a variety of data pertaining to the physical parameters of the soil and, due to that, a choice was made to distribute them in six scenarios referred to as *A1*, *B1*, *C1*, *A2*, *B2* and *C2*, as per the lithology of the study area (Table 1). Therefore, the values of parameters ***c'***, ***Φ*** and ***ρs***, pertaining to each sample collected on-site, were assigned to the areas with sediments from the Barreiras Formation and the Crystalline Basement (Table 1). Regarding parameter ***z***, a depth of 2m was considered for scenarios *A1*, *B1* and *C1*. From scenario *A2* onwards, parameter ***z*** was increased to 5m, keeping the values of the other parameters (***c'***, ***ρs*** and ***Φ***) used in the previous scenarios. The choice of these values for parameter ***z*** was based on the empirical observations of the scars of landslides that occurred in the study area during the fieldwork.

Table 1 - **Susceptibility scenarios (SHALSTAB) and physical parameters of the soil**

Scenario	Sediment lithology	*c'* (N/m^2)	*ρs* (kg/m^3)	*Φ* (°)	*z* (m)
A1	Barreiras Formation	3,700	1,898	31.2	2
	Crystalline Basement	3,800	1,994	29.4	
B1	Barreiras Formation	12,500	1,780	29.8	2
	Crystalline Basement	9,400	2,005	36.8	
C1	Barreiras Formation	0	2,017	34.6	2
	Crystalline Basement	3,800	1,994	29.4	
A2	Barreiras Formation	3,700	1,898	31.2	5
	Crystalline Basement	3,800	1,994	29.4	
B2	Barreiras Formation	12,500	1,780	29.8	5
	Crystalline Basement	9,400	2,005	36.8	
C2	Barreiras Formation	0	2,017	34.6	5
	Crystalline Basement	3,800	1,994	29.4	

Source: Bandeira (2003; 2010); Silva (2007)

INVENTORY OF LANDSLIDES AND SCENARIOS VALIDATION

The scenarios were validated based on an analysis of juxtaposition with an inventory of scars of landslides that occurred in Camaragibe between 2013 and 2017. The scar inventory was based on the historic records of landslides, provided free of charge by the Local Civil Defense. The records were geospaced in a GIS environment, and later vectorized in the form of polygons, representing the landslide scars. For such, we made a photointerpretation of historical images from software Google Earth Pro*,* from criteria based on Guzzetti *et al.* (2012): geometry (elongated aspect); absence of vegetation; position on the slope; color and texture differences and level curves. The vectorized scars were validated in fieldwork done in April, June and July 2018.

Based on the DTM, themed maps were generated, based on topography (declivity, aspect, curvature and contribution area). These maps were created to check the relationship between these parameters and the landslide inventory. For the validation, we initially used two indexes proposed by Gao (1993): (i) Distribution Frequency (DF), pertaining to the quantitative distribution of the susceptibility classes (ratio between the total of each class and the total number of pixels in the town of Camaragibe)

(Equation 2) and Scar Concentration (SC): ratio between the number of pixels of each class affected by the scars and the total of pixels affected in the town of Camaragibe (Equation 3).

$DF = \frac{N}{T} \times 100$ **Equation 2**

Where: DF (Distribution Frequency), N (number of cells in each class) and T (total basin cells).

$SC = \frac{NC}{Tc} \times 100$ **Equation 3**

Where: SC (Scar Concentration), NC (number of cells of each class affected by scars) and Tc (total affected cells in the basin).

In order to define the best susceptibility scenario, a second validation was made based on the construction of the ROC (Receiver Operating Characteristic) curve (FAWCETT, 2006), but only in the scenarios whose SC index exceeded 50% in the sum of the medium- and high-susceptibility classes (that is, in the scenarios of greater accuracy according to the first validation).

It was thus possible to verify the consistency between the areas considered most susceptible to landslides, according to the model, and the sites were landslides actually occurred, based on the scar inventory. Therefore, we were able to analyze the following agreements/disagreements: (i) cells classified as unstable, which coincided with scars (True Positive - TP), (ii) cells classified as unstable, which did not coincide with scars (False Positive - FP), (iii) cells classified as stable, which coincided with scars (False Negative - FN), and (iv) cells classified as stable, which did not coincide with scars (True Negative - TN).

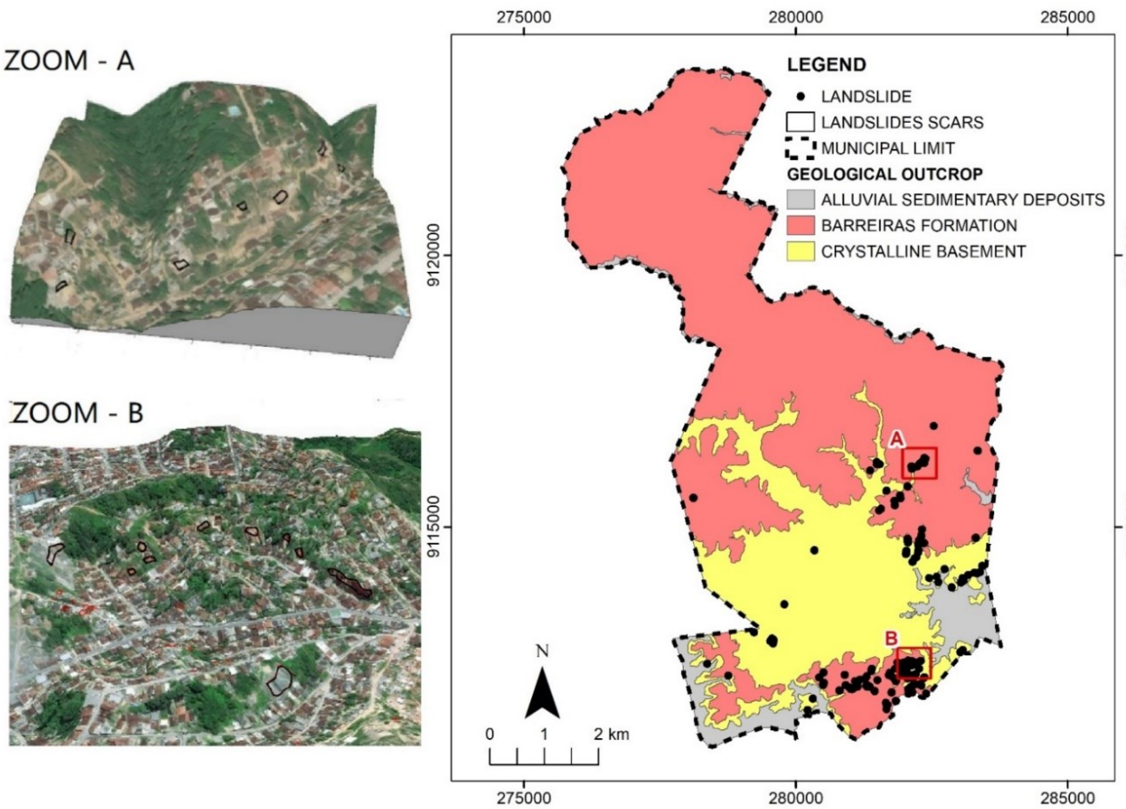
The ROC curve is based on two concepts: (i) sensitivity (model's ability to correctly predict the landslides), and (ii) specificity (mistaken predictions by the model, in which the occurrence of the event is detected at a site where no such event occurred). Through this operation, the Area Under the Curve (AUC) is verified, as a parameter to quantify the overall performance of the scenario. The AUC takes into account all sensitivity and specificity values. The greater the AUC, the better the performance of the scenario. According to the method, the AUC that yields values below 0.7 is deemed ineffective, while values between 0.7 and 1 are deemed effective (PRADHAM and KIM, 2016).

RESULTS

LANDSLIDE INVENTORY AND CONDITIONING FACTORS

We mapped out 151 landslide scars (Figure 2), predominantly located to the South and East of the town. These regions are characterized by slopes whose urbanization process occurred in an inadequate manner, on the sediments of the Barreiras Formation in contact with the Crystalline Basement. Many landslides are related, therefore, to the process of dissection of the coastal tablelands that bring up the Crystalline Basement. As a result of such process, morphodynamic zones of restoration of the relief are observed, the geotechnical properties of which, added to the occupation process, potentialize the occurrence of the gravitational processes.

Figure 2 **- Map of landslide scar inventory on the lithological base of Camaragibe. On the left, detailing of some of the scars mapped out in scale of detail (A and B)**



Source: Torres, Pfaltzgraff (2014)

The total area of the scars was equivalent to 12,781 m^2, corresponding to a total sediment volume of 25,563 m^3 (considering a rupture depth of 2m) and 63,907 m^3 (considering a rupture depth of 5m). A large part of such volume ends up being carried by water flows down to rivers, canals and rainwater collection systems, causing the silting thereof, favoring the occurrence of flooding or inundations.

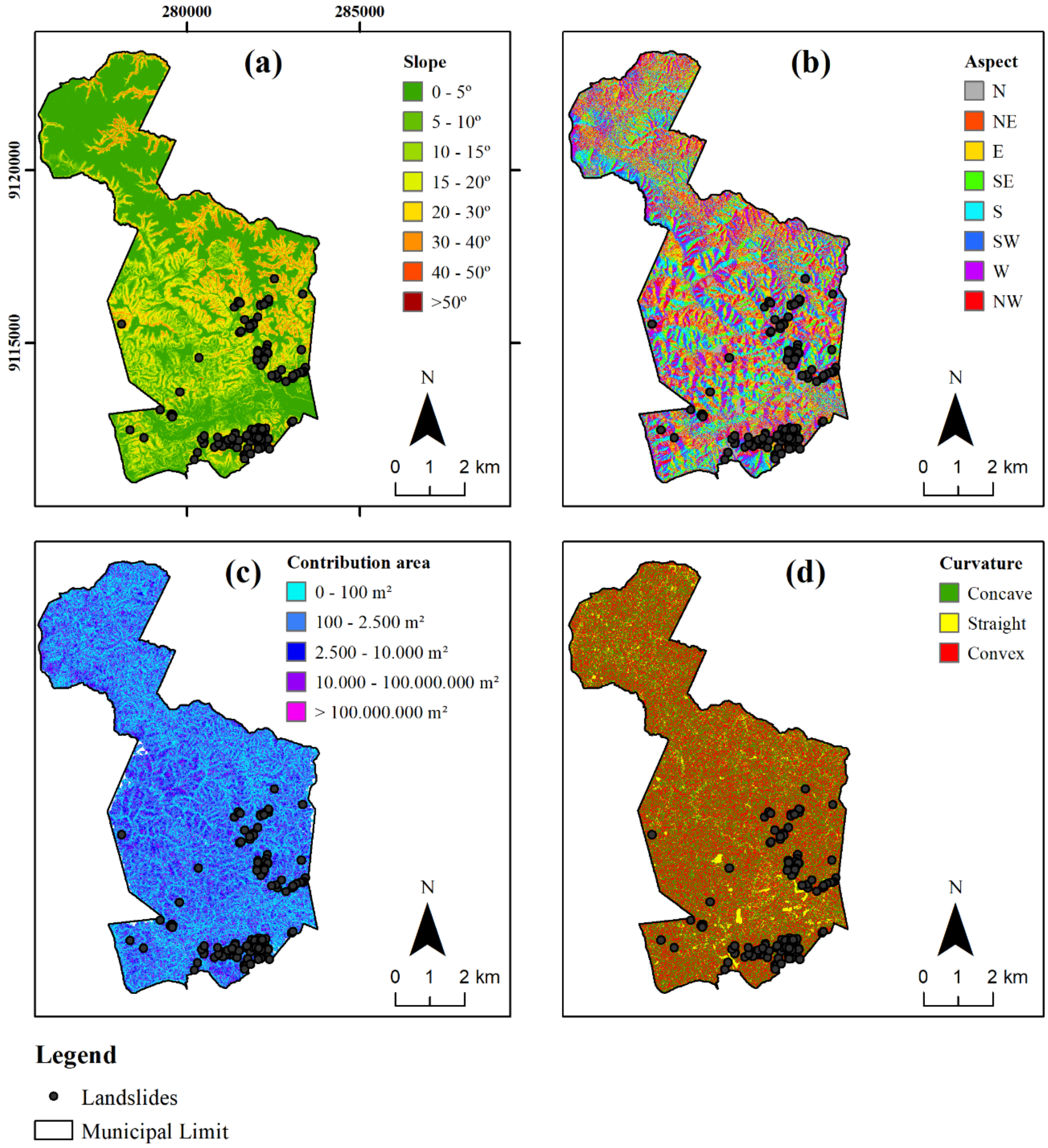
With regard to the topographic parameters (Figure 3 and 4), nearly two-thirds of the territory of the study area (DF = 60.37%) are formed by plane areas of low declivity (0º and 10º), followed by a DF = 11.64% of medium declivity and DF = 28% of terrains with high declivity (>15º) (Figure 5a and Figure 6a). We have found that the percentages of the SC index follow a trend of elevation to the 30º-40º class, declining from then onwards. This behavior was similar to the one found by Fernandes *et al.* (2004) in the basin of the Papagaio and Quitite rivers, and Bonini *et al.* (2020) in the basin of the Gurutuba river. The reduction of the SC in the greater declivities (from 40º onwards), like in the case of Camaragibe, is likely related to the variation caused by the inclination of such terrains on the rate of percolation of the surface outflow (GAO, 1993). Another explanation is based on the vegetation cover of such terrains, which reinforces the soil cohesion.

We found a balance in the DF of all classes of Aspect (Figure 4b), with slopes turned towards the North quadrant (14.03%) being subtly more prominent (Figure 5b). Regarding SC, we ascertained a predominance of slopes turned towards the Southeast (30.21%), followed by those turned towards the South (15.70%). Listo and Vieira (2011) and Bonini *et al*. (2020) also observed a predominance of scars in the classes turned South-Southeast. Such pattern is related to the location of these areas in the southern hemisphere, since the incidence of solar radiation is greater to the North, which factor contributes to the decrease of humidity in said soils.

In relation to the contribution area (Figure 4c), we found a predominance of areas with up to 10,000 m² (DF = 88.25%) (Figure 6c). These areas generally form the valley heads and yielded SC = 92.77%. In Camaragibe, the classes with the highest values of contribution area (10^8 m² and >10^8 m²) represent the valley bottoms and terrains with a reduced inclination, which are thus more susceptible to occurrences of flooding and inundations.

As to the curvatures of the slopes (Figure 4d), there was a balance in the DF of the concave and convex classes (46.74% and 46.67%, respectively) (Figure 4d). This result may be related to the quality of the resolution of the DTM used in this research, since the other works in the literature, which also used a high-resolution DTM (e.g. TEIXEIRA *et al*., 2015; BONINI *et al*., 2020), yielded little difference in the frequency values between these two classes. This same pattern of balance was observed in the SC index, with 49.31% in the convex class and 49.14% in the concave (Figure 5d).

Figure 3 - **Maps of Slope (a), Aspect (b), Contribution Area (c) and Curvature (d) of Camaragibe**

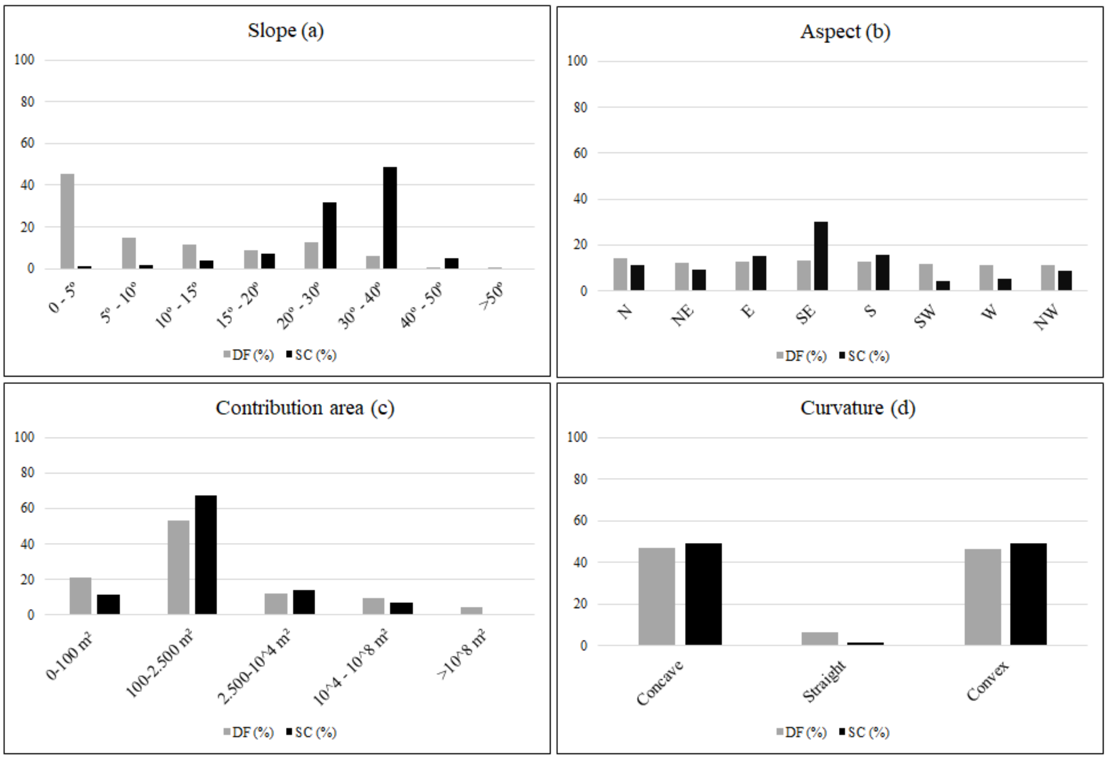


Source: Authors. Database: *PERNAMBUCO Tridimensional* Project (2018).

Even though the literature allows the concave slopes to present a greater susceptibility due to the concentration of surface and subsurface water flows (GAO, 1993; MONTGOMERY and DRIETRICH, 1994), the high concentration of scars in concave and convex cells may be related to further factors, from among which the intensity of rainfall, the declivity of the terrain and the mode of use and occupation stand out.

Fernandes *et al.* (2004) highlight that the landslides in tropical environments are driven by topographic variables, but factors linked to the land use and occupation are important variables to reduce or elevate the susceptibility in a given area. In general lines, despite the accelerated urbanization process, Camaragibe still has a considerable area of its territory formed by remnants of Atlantic Forest, especially in the central and northern regions. In these areas, uses intended for leisure activities predominate, with residential use coming in second.

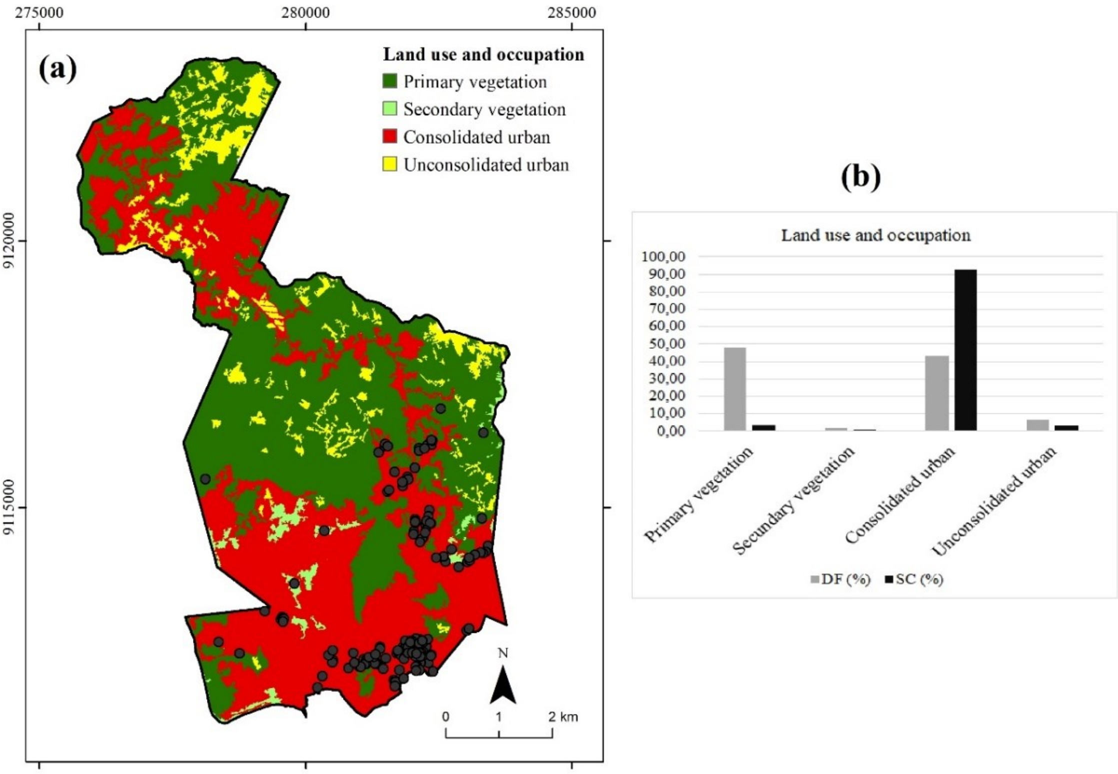
Figure 4 - **Percentages of the DF and SC indexes of the topographic parameters Slope (a), Aspect (b), Contribution Area (c) and Curvature (d).**



Source: Authors.

The use of land in Camaragibe is predominantly characterized by urban areas (either consolidated or undergoing consolidation process), and areas occupied by vegetation (either primary or secondary) (Figure 5a). The DF of the land use and occupation classes (Figure 5b) presented the primary vegetation class as predominant, with DF = 47.97%. This class pertains to natural vegetation, where trees prevail. The consolidated urban area class recorded DF = 43.12%, formed both by areas favorable to occupation and risk areas. The unconsolidated urban area class yielded DF = 6.71% and represents vacant plots and parcels. Lastly, the secondary vegetation class is characterized by areas that undergo a natural process of vegetation regeneration, with predominance of herbaceous and bush species. The DF of such class was 2.20%, being concentrated in the cells classified as low declivity (0º to 10º) (Figure 5b).

Figure 5 **- (a) Map of land use and occupation and landslide inventory; (b) Percentages of the DF and SC indexes of the usage classes**



Database: Google Earth Pro.

In relation to the SC index, the consolidated urban area class concentrated 92.57% of the scars, while the primary vegetation class only 3.72%. This low concentration of scars in sites with vegetation cover corroborates other researches that noted the stabilizing role played by vegetation on the soil (e.g. LEE *et al*., 2018; MACHADO *et al*., 2019). Thus, the landslides that occurred in the study area were significantly influenced by anthropogenic pressures, represented by the occupation of risk areas, lacking in infrastructure.

SUSCEPTIBILITY SCENARIOS AND VALIDATIONS

We generated six susceptibility scenarios (Figure 6) using SHALSTAB, and in all of them the low susceptibility class was predominant, with a minimum DF index of 87.1% and maximum of 100% (Figure 7a). However, the SC in the medium and high susceptibility classes was predominant in four of the six scenarios, with scenario IV standing out, having yielded the highest percentage of Scar Concentration (49.7%) in the high susceptibility class (Figure 7b).

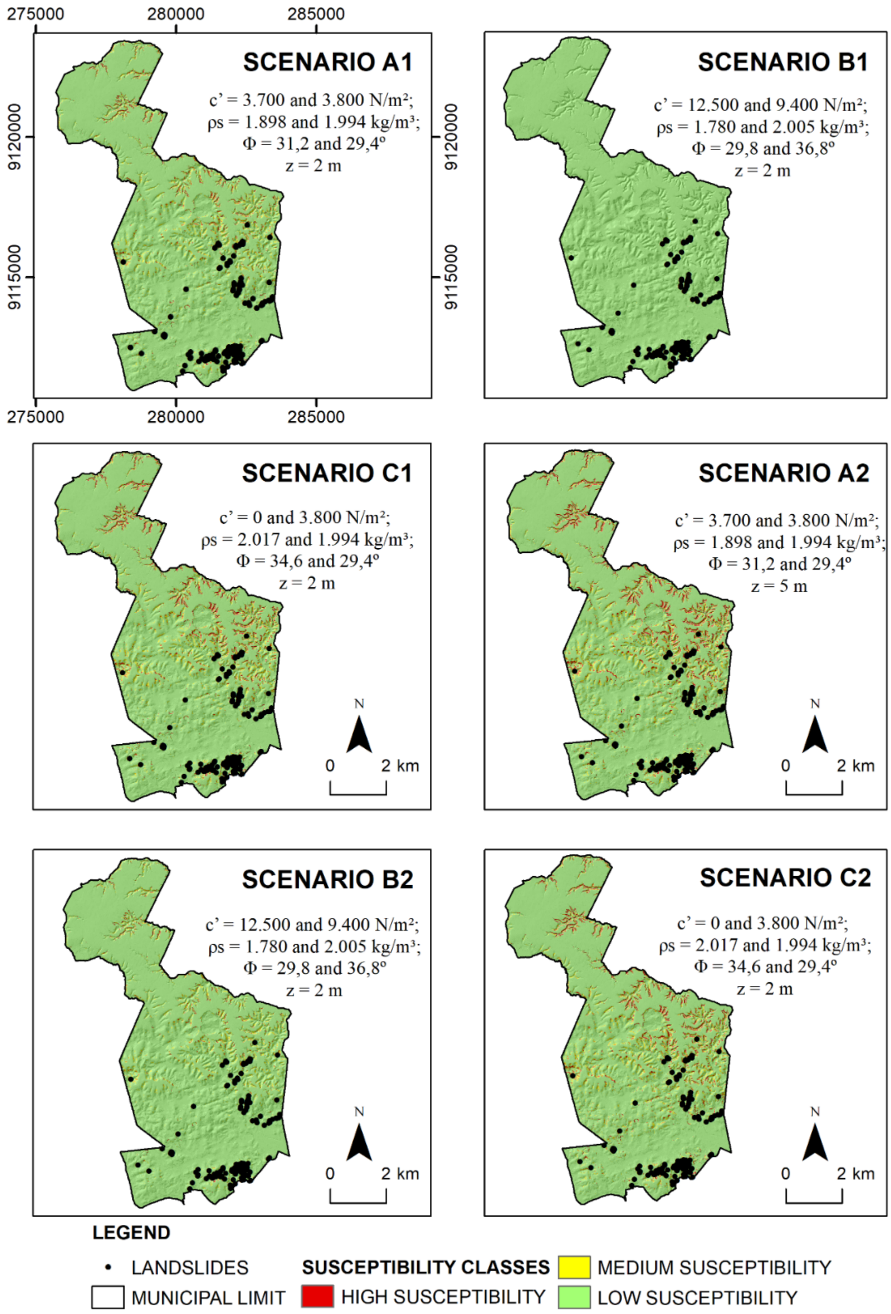
Scenario *A1* is made up, almost in its entirety, by the low susceptibility class (DF = 92.7%), followed by the medium susceptibility class (DF = 5.9%) and high susceptibility class (DF = 1.4%). The predominance of the low susceptibility class may be related to the values taken into account for parameters *z* (2 m), *c*' and *Φ*. According to Michel *et al.* (2021), the cohesive forces (*c*' and *Φ*) stand out under low normal tension conditions (shallow soils and not so steep declivity). The SC in such scenario showed a considerable number of scars in the low susceptibility class (46%). This percentage is credited to the high value of the DF index of said class, which situation culminated in the prediction of stable areas, even in steep terrains. The medium and high susceptibility classes recorded SC equal to 29.8% and 24.2%, respectively.

In scenario *B1,* the DF of the low susceptibility class was 100%, and thus deemed inconsistent. The complete situation of stability in such scenario may have been caused by the use of higher values of the physical parameters in the simulation (*c*' = 12,500 N/m^2 and 9,400 N/m^2; *Φ* = 29.8º and 36.8º), predicting a situation of elevated stability of the land, even in the steeper areas.

Scenario *C1* recorded DF = 89.8% for the low susceptibility class, while the medium and high susceptibility classes recorded DF equal to 7.3% and 2.9%, respectively. In comparison with scenario *A1*, there was a significant increase of the high susceptibility class by virtue of the null *c'* for the sediments of the Barreiras Formation. The low soil cohesion, combined with the elevation of parameter *ρs* and the declivity provided the ideal condition for the increase of the DF index of the medium and high susceptibility classes, and consequently the SC of said classes. Scenario *C1* presented balance in the SC index among all susceptibility classes, with 39.2% for low susceptibility, 32.3% for high susceptibility and 28.5% for medium susceptibility.

Scenarios *A2*, *B2* and *C2* yielded a pattern similar to the DF index, where there was a decrease of the percentage of the low susceptibility class and an increase of the medium and high susceptibility classes. This pattern is due to the increase of parameter *z*, since the greater depth taken into account for the prediction, jointly with the land declivity and parameter *ρs*, propitiate a condition wherein the cohesive forces gain a more reduced role in maintaining the soil stability.

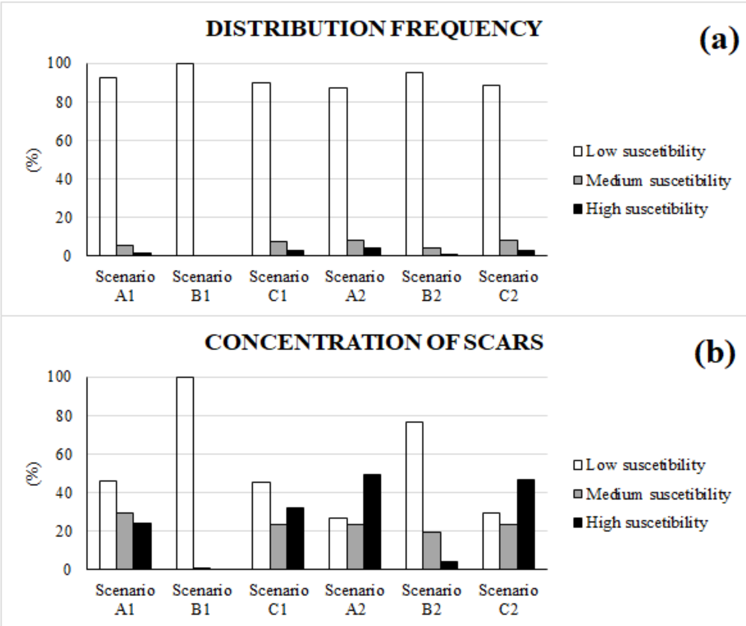
Figure 6 - **Scenarios of susceptibility to landslides created through the SHALSTAB model**



Source: Authors

Scenario *A2* recorded a decrease of 5.6% of the DF index in the low susceptibility class (87.1%). Such decrease was the greatest among the three scenarios. Scenario *B2* yielded a low susceptibility class with 94.9% (decrease of the DF by 5.1%), DF = 4.6% for the medium susceptibility class and DF = 0.6% for high susceptibility. Scenario *C2* varied little in comparison with *C1*: the low susceptibility class decreased by 1.2% (DF = 88.6%) and the medium and high susceptibility classes increased by 0.9% (DF = 8.2%) and 0.3% (DF = 3.2%), respectively. As to the SC index, scenario *A2* showed a decrease of scars in the low and medium susceptibility classes and a considerable increase in the high susceptibility class. The low susceptibility class decreased by 18.9% (SC = 27.1%), the medium susceptibility class decreased by 6.6% (SC = 23.2%), while the high susceptibility class increased by 25.5% (49.7%). Scenario *B2* recorded percentage values for the medium and high susceptibility classes equal to SC = 19.5% and SC = 4.1%, respectively. In spite of that, said values were insufficient to show a minimum of coherence with the landslide scar inventory. Lastly, scenario *C2* had a relevant increase in the high susceptibility class (14.6%) in comparison with the same class in scenario *C1*, totaling SC = 46.9%. The low and medium susceptibility classes yielded a SC index equal to 29.7% and 23.4%, respectively.

Figure 7 - **(a) Distribution Frequency of the susceptibility classes, and (b) Concentration of Scars**



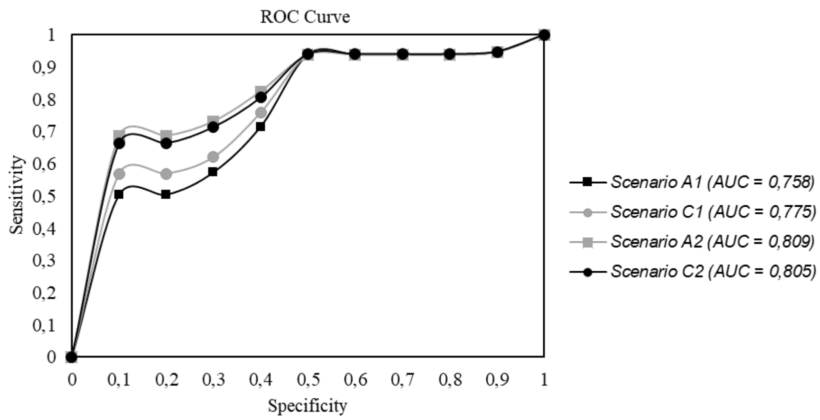
Source: Authors

The results of scenarios *A2*, *B2* and *C2* reinforce the high influence of declivity in SHALSTAB and how sensitive the model is to this parameter. Since Camaragibe has approximately 28% of its territory formed by areas with declivities greater than 15º, where 92.86% of the inventoried scars are located, it is admitted that such characteristic of the local topography overlaps with the other soil stabilizing forces and contributes to the increase of susceptibility in certain localities of the town.

The susceptibility scenario validation process was intended to measure the accuracy of the SHALSTAB model based on the scar inventory. Therefore, in relation to the ROC curve this stage considered only the scenarios that recorded an SC index lower than 50% in the low susceptibility class (more consistent ones) and thus scenarios *B1* and *B2* (low accuracy) were ignored.

In turn, scenarios *A1*, *C1*, *A2* and *C2* yielded satisfactory accuracy scenarios (Figure 8), of which lower values were used for the parameters *c'* and *Φ*. Thus, the SHALSTAB prediction for scenarios *A2* and *C2* may be considered satisfactory, with the former presenting a discreet superiority in relation to the latter. Therefore, scenario *A2* was considered to have the best performance to represent the susceptibility to landslides in Camaragibe (AUC=0.809).

Figure 8 - Validation of the accuracy of susceptibility scenarios by means of the ROC curve, out of which scenario A2 presented the best performance (AUC=0.809).

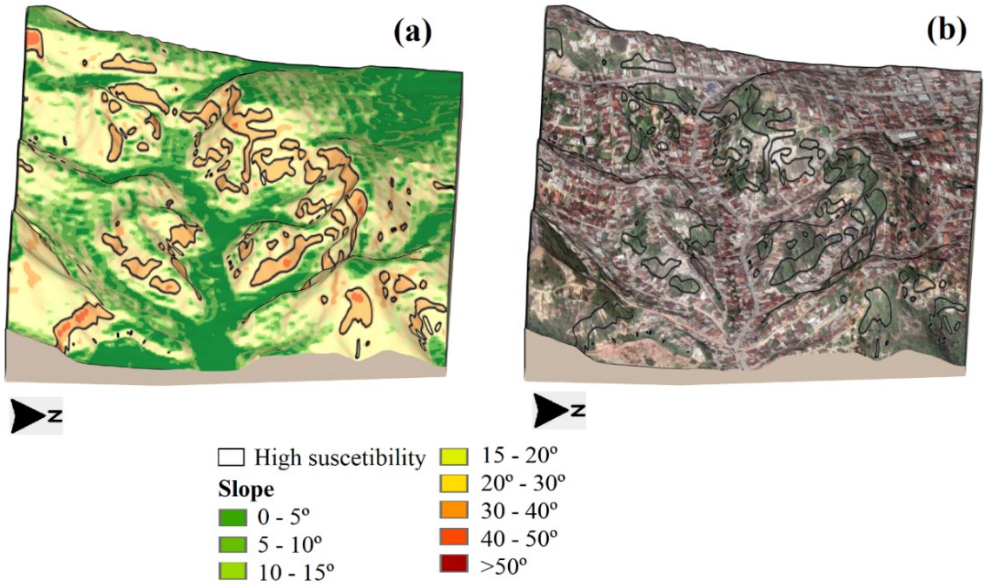


DISCUSSIONS

SHALSTAB is one of the most internationally widespread tools to predict areas susceptibility to landslides, but a great part of the works published until now applied the model to unpopulated areas or where there is low urban density (e.g. TEIXEIRA *et al.*, 2015; PRADHAM and KIM, 2016; MARTINS *et al.*, 2016; GUIMARÃES *et al.*, 2017; BONINI *et al.*, 2020; MICHEL *et al.*, 2021). Therefore, the researches that used the model in urbanized areas (e.g. LISTO and VIEIRA, 2012; KONIG *et al.*, 2019), such as in the case of Camaragibe, are more scarce.

The model prediction indicates that the areas with high susceptibility occur predominantly on hillsides with declivity >15º (Figure 9a). In general, these areas are preeminently formed by yellow acrisols, characterized by the presence of textural horizon B of low-activity clay or with high-activity clay, provided that it is conjugated with low saturation by bases (EMBRAPA, 2009). The risk in these areas is potentialized by anthropic occupation (Figure 9b).

Figure 9 - **(a) Three-dimensional cut of the DTM, where the high susceptibility areas can be seen on the steeper declivities, and (b) anthropic occupation of the high susceptibility areas**



Source: Created by the authors. Database: *PERNAMBUCO Tridimensional* Project (2018) and Google Earth Pro.

Going against results presented in other works, which indicated a concentration of areas of greater susceptibility in concave or rectilinear slopes (e.g. DIETRICH and MONTGOMERY, 1998; LISTO and VIEIRA, 2012; TEIXEIRA *et al*., 2015), in this research we found that the high susceptibility class is distributed in a balanced way over the concave and convex slopes. According to Gao (1993) and Dietrich e Montgomery (1998), the concave and rectilinear forms are more susceptible, as they concentrate water flows and present a faster elevation of the pressure loads during a rainfall event, resulting in a lower volume of rain necessary for the rupture.

In the case of Camaragibe, it is necessary to consider the alternation of materials found in the convex slopes and their respective porosities. Depending on the porosity of such material, the subsurface flow is directed upwards, entailing the rupture of that hillside.

The relationship between susceptibility and the contribution area demonstrates that the high susceptibility class is concentrated on the areas of up to 10,000 m², that is, sites representing drainage heads. It is notorious that in these areas there is a greater infiltration of water in the soil, potentialized by the presence of sandy-clay soils, which naturally have good infiltration and permeability rates. On the other hand, said areas still keep a good part of the primary vegetation and, among other contributions, help absorb surface water by the trees. The contribution from the vegetation to the land stability is evident when we observe, from the scar inventory, that drainage head areas considered to be of high susceptibility (and which maintain a better environmental conservation) do not record landslides.

According to Lee *et al.,* (2018) and Michel *et al.* (2021), the vegetation plays an important role in increasing cohesion. In shallower soils, the landslides are usually formed on the layers subsequent to the root zones (MICHEL *et al.,* 2021). Also according to these authors, the root cohesion exercises a certain influence on the Factor of Safety down to a depth of approximately 3m. In any case, the analysis made by these authors and what was observed in Camaragibe reinforce the importance of keeping the vegetation as a measure to reduce susceptibility to landslides.

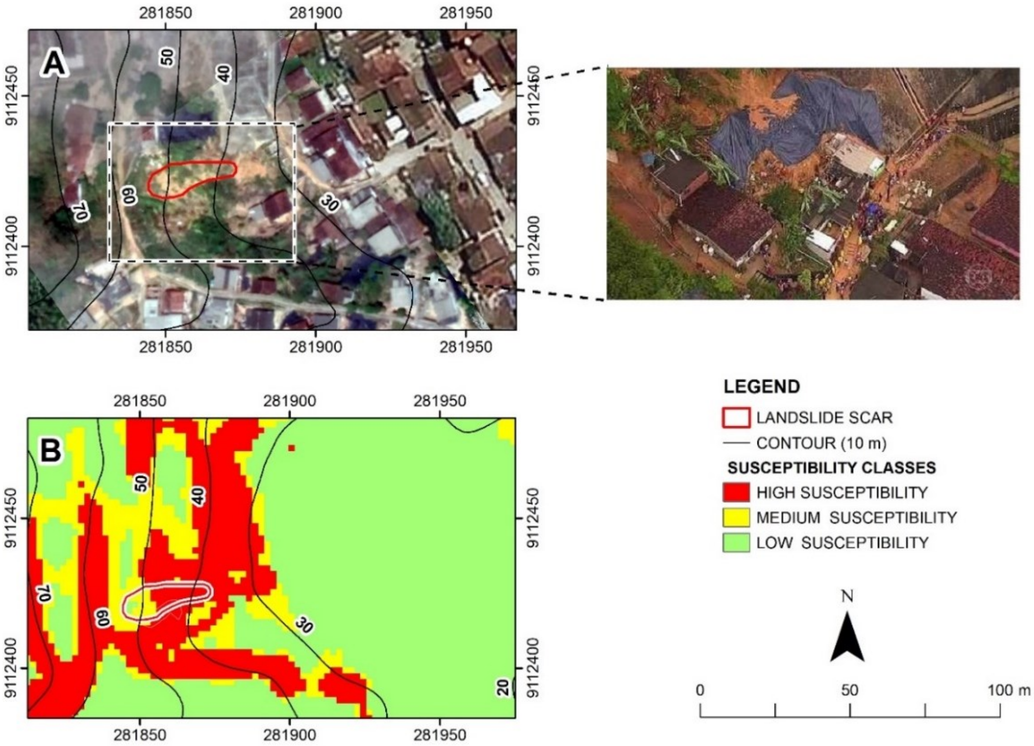
The model classified as low susceptibility certain areas where landslides were recorded, and an explanation for such is the influence of the anthropic factor in the triggering of the processes, which parameters are not taken into account by SHALSTAB. Anthropic interference produces sufficient effects to alter the properties that involve the parameters used in the model, which fact may have contributed to disturbing the susceptibility of such sites.

Within this context, Listo and Vieira (2012) observed that the building of properties in areas deemed to be at risk generally alters the original geometry of the slopes, producing a series of cuts and landfills with no technical control and topography stability analyses. This is what Machado et al., (2019) referred to as self-builds. This type of practice, associated with the influence of rainfall, results in a decrease of the safety factor, but said decrease may vary according to the geological, geomorphological, hydrological and climate characteristics (MENDES *et al*., 2018).

Empirical analyses in the sites predicted to have low susceptibility, where landslides were recorded, demonstrated that land use and occupation forms, characterized by the dearth or nonexistence of infrastructure, especially with regard to drainage, trigger the landslides. Mendes *et al.* (2018), upon studying the anthropic influence in the town of Campos do Jordão (state of São Paulo, Brazil), concluded that the leaks and launching of wastewater contribute to a faster saturation of the soil, even with the occurrence of low-intensity rainfall. In Camaragibe, actually substantial preventive actions, and not just emergency action such as tarpaulins, must be implemented.

Despite the alterations to the relief caused by the process of occupation of the slopes in Camaragibe, the susceptibility prediction by SHALSTAB is efficient. It classified as high susceptibility the region of the occurrence of landslides resulting in nine casualties, in July 2019 (Figure 10). The accuracy observed in the prediction by the model reinforces the contribution that may be made by the use of predictive models with physical bases for the environmental planning of towns where the presence of risk areas is intense, especially those where processes occur which are related to inadequate urbanization, such as in the metropolitan regions of Brazil and other developing countries.

Figure 10 **- Distribution of the susceptibility classes on the site of the landslide occurred in July 2019. (A) Aerial view of the scar, and (B) overlapping of the scar on the susceptibility classes**



Sources: Google Earth Pro; G1 PE (2019); PERNAMBUCO (2016).

CONCLUSIONS

The main contribution by this article is presenting landslide susceptibility scenarios with accuracy, swiftness and precision, including in precariously occupied areas, aiming at a better decision-making process and mitigation of disasters. Geotechnology tools, the deterministic mathematical modeling on physical bases among them, are excellent data generators to assist with the environmental planning at the most varied scales proposed. The SHALSTAB model is, therefore, efficient in predicting areas susceptible to shallow landslides, presenting low subjectivity, regardless of the prior occurrence of processes.

The process of precarious occupation of areas subject to gravitational movements is one of the main triggers of landslides, especially in cities and towns that form the Brazilian metropolitan regions. In the Metropolitan Region of Recife, the occupation of risk areas is the result of inefficiency of inspection and implementation of structural and non-structural actions.

The landslides that occurred in Camaragibe are triggered by anthropic interference destabilizing the relief and causing the rupture of the hillsides. Human action is able to alter a series of intrinsic characteristics related to the topography and mechanics of the soils, fostering hazardous situations especially during the periods of more intense rainfall. On the other hand, the maintenance of vegetation by the roots works as an element that adds cohesion to the soil.

The areas more susceptible to landslides in the town are located on the slopes with a declivity greater than 15º, formed by less cohesive soils, with alternation of materials and porosity. The situation is worsened by the form of use and occupation of the land, which removes the vegetation to build properties and paths without proper technical oversight.

Even in the intensely occupied areas, SHALSTAB can be used, obtaining considerable rates of accuracy in predicting susceptibility, assisting with the better control of more dangerous areas and pointing out which sites require greater technical apparatus for occupation.

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