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Papers

Mapping of Risk Areas Associated with Karst in Urban Area of the Municipality of João Pessoa-PB

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Abstract
The city of João Pessoa has relief features formed by karstic processes, called closed depressions. The natural dynamics of the karst relief is dominated by the process of dissolution of rocks, especially carbonates. The geological characteristics identified, and the conditions related to the evolution of the relief in the city place it in an area susceptible to the occurrence of karst processes, which adds to the strong urbanization process observed in the area. Thus, this article aimed to identify and characterize landforms developed by karstification processes to enable the analysis of risks in these environments, considering, in addition to natural susceptibility, aspects related to forms of urban uses and occupation. For this purpose, we mapped features of karst relief, called closed depressions. A map of susceptibility to karstification processes was created by using the map algebra technique, considering the factors of structural conditions, lithology, and geomorphology, as well as the conditions of urban occupation. Finally, the generated data were superimposed producing the classification of risk areas associated with karstic processes. The structural condition has been found to represent the preponderant factor for the risk conditions in the city of João Pessoa, Paraíba state, in addition to the impacts introduced in the karst system due to human activities, which sometimes represent the trigger for the occurrence of phenomena such as the opening of craters in urban areas.

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INTRODUCTION

In karst geomorphology, the dissolution process represents the trigger for typical forms of karst relief to develop, such as closed depressions and dolines. These environments present irregular soil surfaces and dissolution zones that may form subsidence zones (GUTIÉRREZ *et al.*, 2014).

Karst risks often derive directly or indirectly from human actions that may trigger impacts of unforeseeable consequences due to the peculiar features of karst environments, which present subsurface specific hydrodynamics, thus demanding to adopt specific methods considering the conditioning factors of karst environment and human dynamics (DE WAELE *et al.,* 2011; GUTIÉRREZ *et al.,* 2011, TRAVASSOS, 2011; LOBO, 2013; GUTIÉRREZ, 2016; NAWAZ *et al.*, 2020; GOMES *et al.,* 2021).

In urban areas, surface alterations resulting from human activities are more highlighted and appear almost always from the occurrence of risk situations, which, in turn, cause material and human damages to the inhabitants. In karst environments, urban alterations are even more highlighted in terms of great sensitivity of the system to changes in hydrological dynamics (DE WAELE *et al.*, 2011; HUANG et al., 2020), almost always represented by the disconnection of surface drainage from the subsurface due to burial of karst depressions where ponds occur, or by the introduction of turbulent flow into the system due to water supply line rupture or disruption of rainwater galleries. Added to these factors, the acidity of flows in motion in the water karst system in urban areas increases due to the disposition of domestic and/or industrial effluents into the soil (VESTENA *et al.*, 2002).

Planned actions to be implemented on the surface must consider subsurface features aiming to soften impacts (GUTIÉRREZ *et al.*, 2014). The authors also state that the construction of buildings over such altered features may generate damages to society since the changes in preexisting features may cause these areas to be regarded as stable in terms of risks, as in the case of buried depressions in the urbanization process.

The decrease in water level due to the impermeabilization process of closed depressions may cause loss of hydrostatic support, which, such as the overweight of buildings on the roof of karst cavities, may lead to land subsidence, thus representing a risk factor for resident populations (PEREIRA, 1998). Other phenomena, such as collapses, land subsidence, and flooding, are related to the evolution of a karst and may represent risks to the resident population, since they may compromise the structure of different types of buildings (LOLCAMA, 2002; MARÉCHAL *et al.*, 2008; ZENG and HUANG, 2018).

Such an issue is found in the city of João Pessoa, Paraíba state, and represents a relevant factor of their geo-environmental features. The geomorphological dynamics characterizing the area of the city is under the direct influence of subsurface processes resulting from geological/geomorphological features (FURRIER *et al.*, 2006; VITAL, 2015; VITAL *et al.*, 2020). Its land area is settled on the Paraíba Sedimentary Basin, whose limits presents a stratigraphy arranged in layers of rocks of marine (Limestone of Gramame Formation) and terrestrial origins (sandstones of the Beberibe/Itamaracá Formations). The sediments of the Barreiras Formation recover these layers and area constituted predominantly of clayey sediments (BARBOSA, 2007).

The Paraíba Sedimentary Basin ranges the occurrence of karst depressions associated with surface and subsurface manifestations of carbonates, whose origin is related to the dissolution process acting on limestones of Gramame formation (VITAL, 2015; VITAL *et al.*, 2020).

Risk situations in João Pessoa derive from favorable natural conditions provided by the karst relief, associated with the strong urbanization process observed in the city since the second half of the 20th century, characterized by fast, inadequate horizontal urban growth (RODRIGUEZ, 1980).

Therefore, the goal of this research was to identify risk areas associated with dynamic features of karst environments in the city of João Pessoa. For this purpose, we considered factors related to the physical-natural conditions that characterize the karst relief in the city area, as well as those derived from urbanization and risk-generating factors.

METHODOLOGICAL PROCEDURES

Initially, we delimited and mapped the closed depressions on the Global Mapper software based on the Digital Elevation Model (DEM) generated from images of the laser break sensor LiDAR (Light Detection and Ranging) captured in 2012, with two-meter spatial resolution, granted by Secretaria de Planejamento da Prefeitura Municipal de João Pessoa - SEPLAN/PMJP (2020), public agency responsible for territorial planning in the municipality of João Pessoa. The following work routine was applied: automatic extraction of drainages, automatic generation of level curves at a two-meter equidistance, manual delimitation of closed basins based on the drainages and level curves.

The elaboration of the susceptibility map to karst processes considered three factors: structural conditions, thickness of capstone layer in relation to the rock carbonatic layer, and geomorphology.

The map of lineaments and alignment of the closed depressions was elaborated based on the DEM and spatial alignment of the mapped features, respectively. This procedure consists of the manual vectorization of linear structures (drainages) identified in the elevation model and the vectorization of straight lines interconnecting the depressions on the QGIS 3.14 software (2021). Subsequently, the vectorial data were exported to the Spring 5.5.6 software (1996), which generated the rosettes of preferential directions for the lineaments identified and the alignment of depressions.

The geological map of the city of João Pessoa was adapted from a work scale used in this research – equivalent to 1:100,000 – from the map elaborated by the CPRM (2002) at the scale of 1:500,000 developed specifically for the Paraíba state. This procedure considered the partitioning of the relief from the DEM used in the research.

The thickness of rock formations was verified from the interpolation process of data referring to the altimetry of the layers in the Paraíba Sedimentary Basin. These data were extracted from documents containing information on the topography of the lithological layers described in data of tube wells collected on the platform of the Sistema de Águas Subterrâneas - SIAGAS (sd), of the Serviço Geológico do Brasil - CPRM (2019), which is a groundwater information system managed by the Brazilian Geological Service; Companhia de Águas e Esgotos da Paraíba – CAGEPA (2015), Agency of Waters and Sewages of Paraíba; and Agência Executiva de Águas - AESA (2015), which is public agency responsible for the management of underground and surface water resources in the State of Paraíba.

This procedure consists of creating a table containing the data described on the Microsoft Excel software (2016). Subsequently, the same table was imported to the Surfer 12 software (2014), on which the interpolation and generation processes of a surface model for each lithological layer were performed. Subsequently, we verified the topographic values of this model, reclassified the values, and assigned the weights for each group reclassified on the ArcMap 10,4 software (ESRI, 2016). The referred elevation models overlaid the mapping of the studied features to verify whether the occurrence of surface depressions was associated with subsurface depressions.

Geomorphology was analyzed based on the geomorphological mapping of the city of João Pessoa proposed by Barbosa (2015). The map overlaid the map of features selected for this study. Thus, the reclassification and assignment processes of weights for each geomorphological class considered the highest weight for the classes with the closed depressions selected for this study.

Finally, the reclassified values of each variable considered in the susceptibility analysis were subjected to the process of "map algebra" using the "raster calculator" tool on the ArcMap 10,4 software (ESRI, 2016). This process consists of weighting the values assigned to each variable, resulting on the susceptibility map to karst processes, which, in turn, based on information considered and respective assigned values, indicates the places that are more susceptible to manifest karst processes. Subsequently, this information was transformed from matrix format to vectorial format to allow to calculate the area of each susceptibility class and overlay of the urban registry of the city of João Pessoa.

The analysis of risks was performed based on the following procedures: overlay of the natural susceptibility map on the urban registry for the city of João Pessoa, definition of geomorphological risk classes, verification, field reports, and field sheet application.

The natural susceptibility map overlaid the urban registry on the ArcMap 10,4 software (ESRI, 2016) preceded by adjusting the data to a single reference system. Subsequently, we cut the shape referring to the urban registry data based on the susceptibility classes and accountability of the number of residences in the areas from the table of attributes of the information analyzed by means of a cartographic superposition technique.

RESULTS AND DISCUSSION

Mapping of closed depressions

We identified and mapped a total of 13 (thirteen) closed depressions (Chart 01). In general, all depressions occur over the sediments of the Barreiras Formation, which, in turn, represent the predominant geological surface manifestation in the city, with some points with the occurrence of the surface of Gramame and Beberibe Formations (Figure 01).

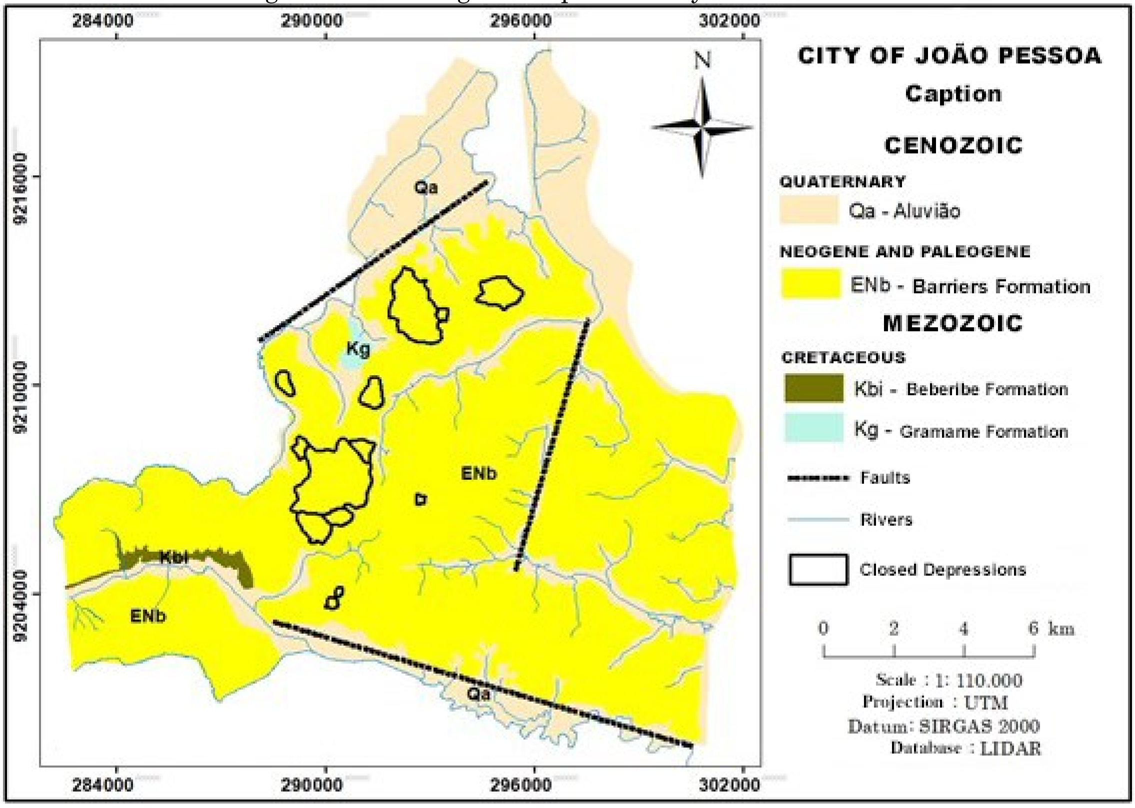
Chart 01 - Location of mapped depressions.

Depression	*UTM Coordinates*	*Address*
01	290,611.849 / 9,207,492.087	Três Lagoas, Bairro Oitizeiro.
02	293,157.140 / 9,211,753.969	Lagoa do Parque Sólon de Lucena, Bairro Centro
03	294,725.749 / 9,212,553.072	Av. Epitácio Pessoa, Bairro dos Estados / Expedicionários
04	289,812.746 / 9,205,893.881	Avenida das Indústrias, Distrito Industrial
05	291,203.777 / 9,209,741.413	Lagoa Antônio Lins, Av. Doutor Antônio Lins, Bairro Cruz das Armas
06	290,641.446 / 9,206,189.845	Rua Henrique Nascimento, Bairro Costa e Silva
07	291,174.181 / 9,208,143.208	Lagoa do Buracão, Av. Ana Nery, Oitizeiro
08	288,658.486 / 9,210,185.360	Rua Francisco José das Neves, Bairro Alto do Matheus
09	289,220.818 / 9,208,172.804	Rua Luiz Barbalho, Bairro Jardim Veneza
10	293,334.718 / 9,212,049.933	Av. Camilo de Holanda, Bairro Centro.
11	290,108.710 / 9,203,822.132	Via Perimetral Sul, Bairro Gramame.
12	292,742.790 / 9,206,663.387	Rua José Lins Sobrinho, Bairro João Paulo II
13	290,345.481 / 9,204,177.289	Via Perimetral Sul, Bairro Gramame.

Source: The authors (2021).

According to (Figure 04), the occurrence of closed depressions in the study area is conditioned to the lower thickness of the Barreiras Formation in relation to the Gramame Formation, coinciding with the denudation surfaces, regarding their geomorphology (Figure 05), in addition to the occurrence of linear structures and failures (Figure 03), represented by the structural alignment of the features. The overlay of this information on the map of closed depressions suggests that the surface manifestation of these relief features is associated with the conjugation of such factors.

Figure 01 – Geological map of the city of João Pessoa.

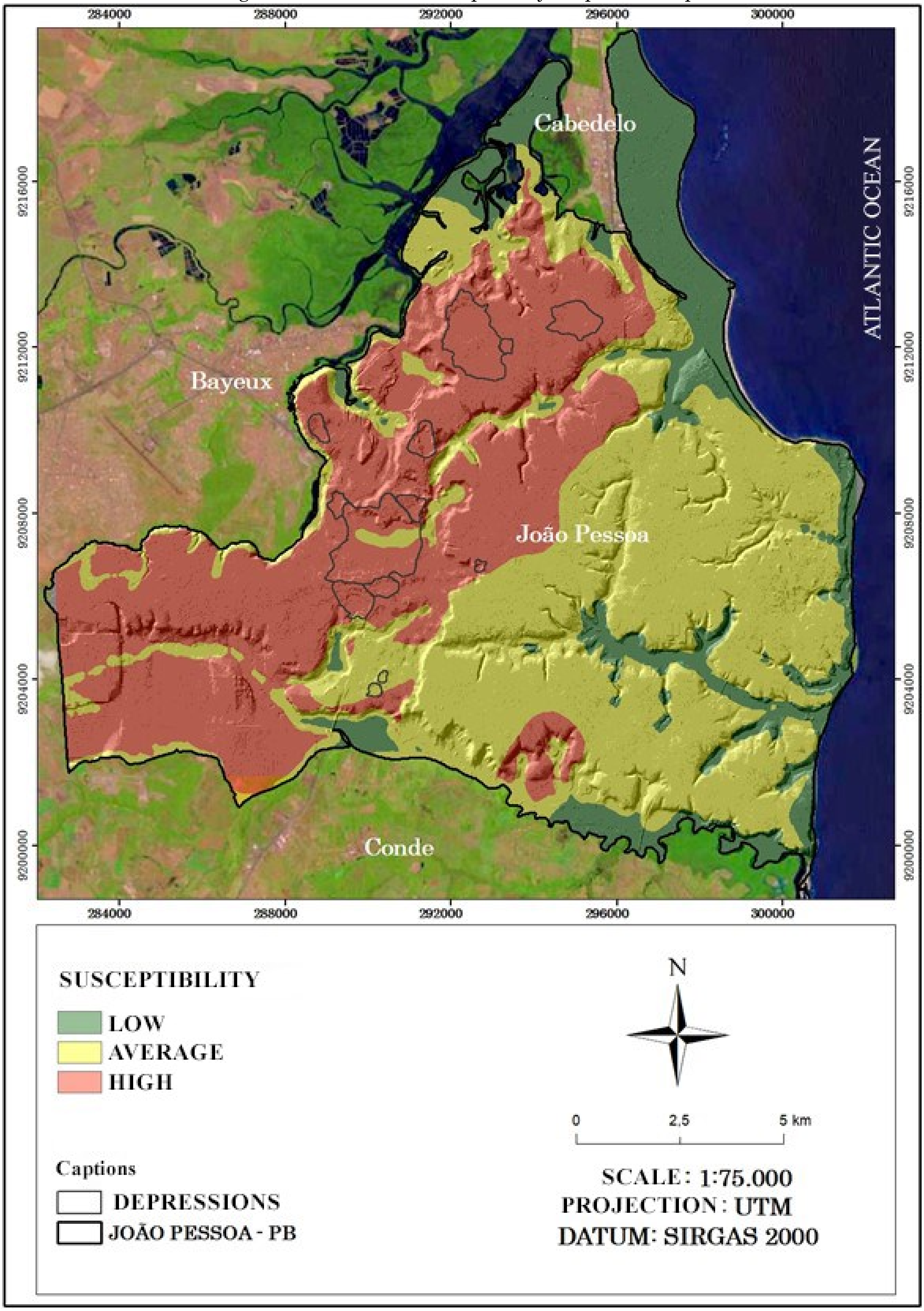


Source: Adapted from Brasil (2002).

Natural Dynamics Analysis

We classified the geomorphological risk areas associated with karst processes in the city of João Pessoa based on the analysis of natural-processes related factors responsible for the origin and evolution of features of this type of relief. Thereby, the following natural factors were considered: geology, regarding the thickness of the sedimentary capping layer (Barreiras Formation) over the carbonatic rock layer (Gramame Formation), structural factors, and geomorphology. Based on these factors, we built the natural susceptibility map to karst processes (Figure 02) aiming to indicate the areas where genetic and evolutionary phenomena of karst relief may be more active.

Figure 02 – Natural susceptibility map to karst processes.



Source: The authors (2021).

For this purpose, we assigned weights to the analyzed factors, according to Table 01, based on map algebra.

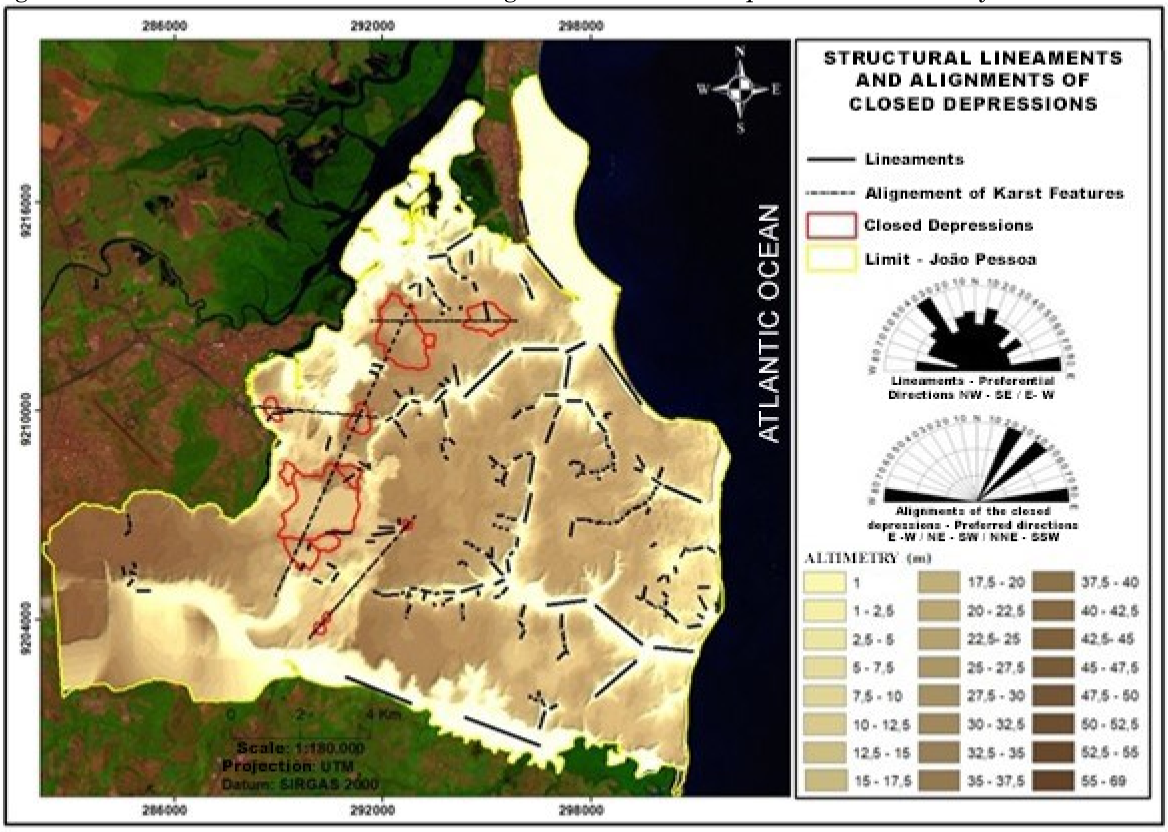
Table 01 - Weights assigned to the susceptibility factors analyzed.

Analyzed Factor	Weight
Geomorphology	0.50
Altimetry of Gramame F.	0.25
Thickness of Barreiras F.	0.25
Total	1.0

Source: The authors (2021).

Considering the alignment of the mapped closed depressions and structural conditions found in the study area, such structural conditions (Figure 03) are regarded as a "trigger" to the karstification process. The areas located between the depressions are under direct influence of structural conditions since it is in the weakness lines of the rocks that the surface fluids can percolate more easily, thus promoting the respective dissolution process.

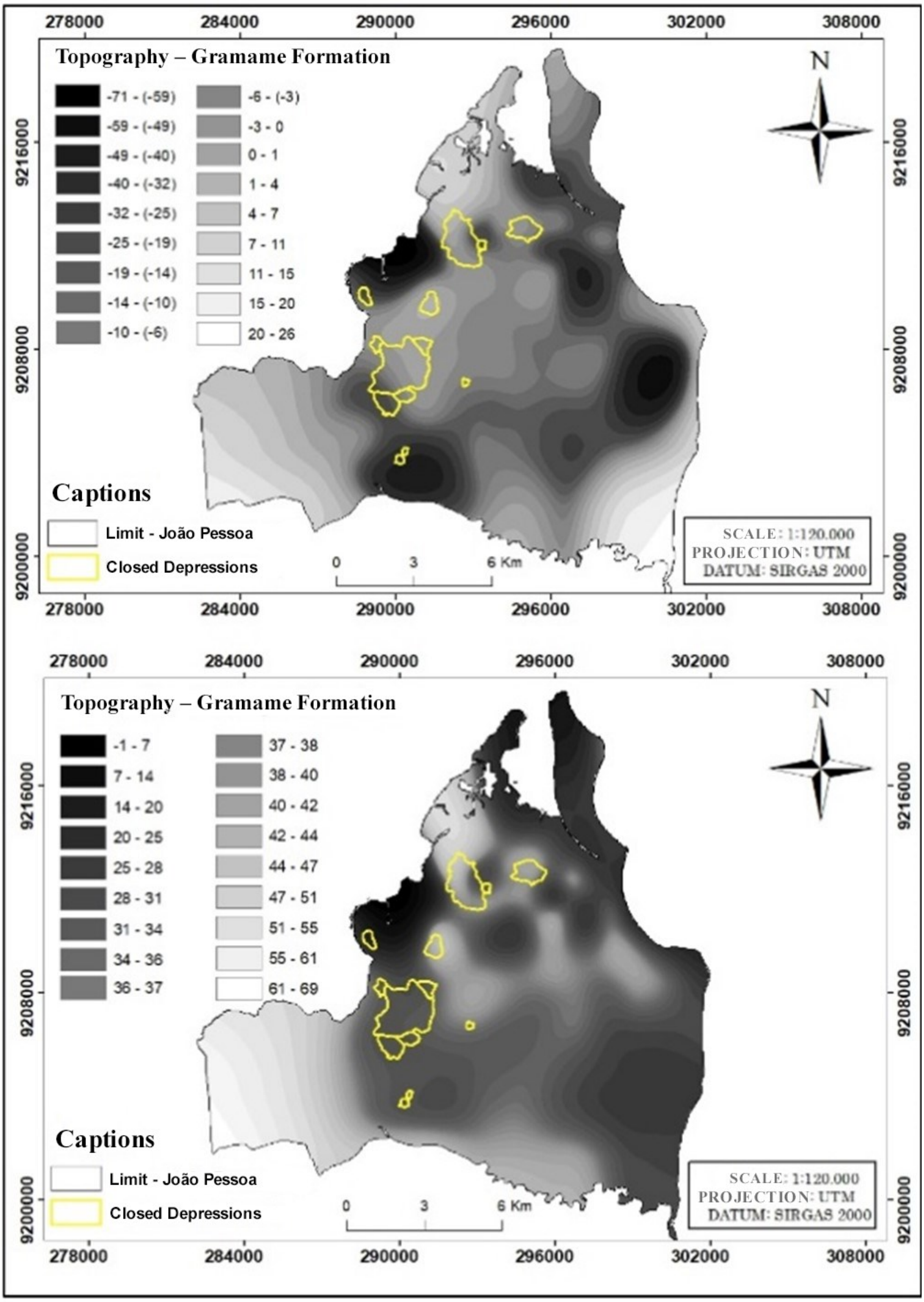
Figure 03 – Structural lineaments and alignment of closed depressions in the city of João Pessoa.



Source: The authors (2021).

Regarding the lithological layer thickness capping the carbonatic rocks (Figure 04), we considered that the lower thickness of the Barreiras Formation allows greater contact of surface flows with rocks of Gramame Formation. These areas show a greater proximity of carbonatic rocks to the baseline and even the occurrence of upwelling in some places. Thereby, the weight (0.25) was assigned to these two factors considering the coincidence between the lower thickness of the Barreiras Formation and lower depth of the Gramame Formation.

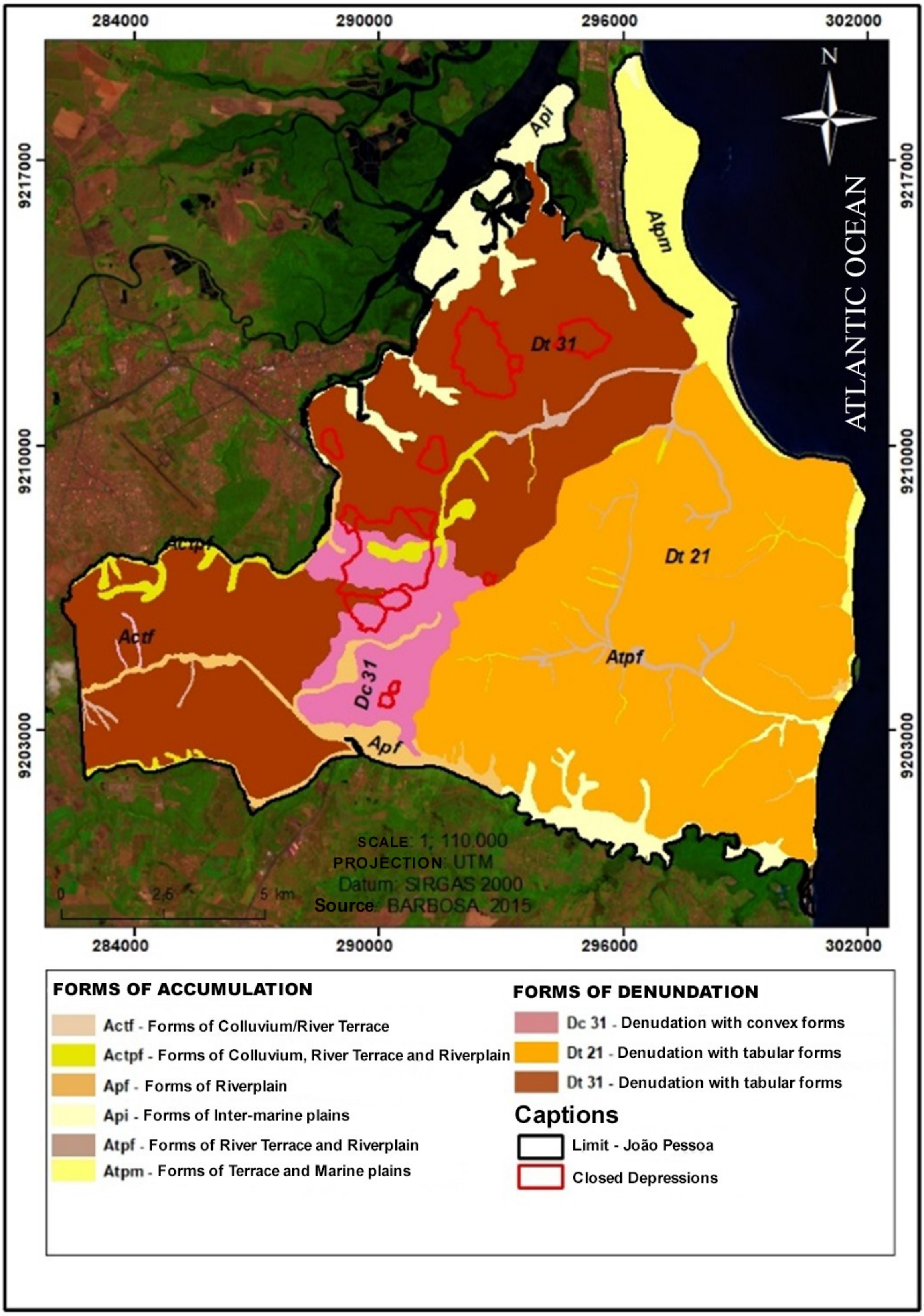
Figure 04 – Thickness of Barreiras and Gramame Formations in meters (m).



Source: The authors (2021).

Geomorphology (Figure 05) was assigned with weight (0.50), thus considered the most relevant factor in the analysis since all depressions occur on denudation surface with convex forms and denudation surface with tabular forms.

Figure 05 – Geomorphology of the city of João Pessoa/PB



Source: Adapted from Barbosa (2015).

Each factor was reclassified by assigning them weights with a variation from 1 to 3 according to their relevance in the susceptibility analysis (Figure 02), as in Table 02.

The thickness of the Barreiras Formation was divided in three classes by assigning weight 1 for a variation between 50 and 116 meters, weight 2 for variation between 25 and 50 meters, and weight 3 when the layer thickness did not exceed 25 meters (Table 02).

As for the altimetry of the Gramame Formation, we assigned a higher weight (3) to the altimetric variation established between 0 and 25 meters, considering that the closer the carbonatic rock is to the surface the greater its contact with surface flows. Based on such an assumption, weight 2 was assigned to the altimetric variation between -40 and 0 meters and weight 1 to the altimetric variation between -70 and -40 meters (Table 02).

Table 02 - Weights assigned to the thematic classes of each factor analyzed.

Weight	***Barreiras F. Thickness***	***Gramame F. Thickness***	***Geomorphology***
1	50 – 116 m	(-70) – (-40) m	Atpm / Api / Apf / Actpf
2	25 – 50 m	(-40) – 0 m	Dt 21
3	0 – 25 m	0 – 25 m	Dt 31 / Dc 31

Actf – Colluvium Forms / River Terrace; **Actpf** – Colluvium, River Terrace and Riverplains; **Apf** – Riverplain Forms; **Api** – Inter-marine Plains; **Atpf** – River Terrace and Riverplains; **Atpm** – River Terrace and Riverplains; **Dc 31** – Denudation with convex forms; **Dt 21** – Denudation with tabular forms; **Dt 31** - Denudation with tabular forms. Source: Barbosa (2015).

As the occurrence area of the mapped features coincide with denudation surfaces (Dt 31 and Dc 21), these geomorphological compartments were assigned with the maximum value of 3. The class defined as (Dt 21) constitutes a geomorphological denudation compartment with tabular forms, where the drainage network is denser than the compartment (Dt 31). The occurrence area of this compartment also coincides with the area of greater thickness of the Barreiras Formation – a criterion used to assign such factor with weight 2.

We assigned weight 1 to the remaining forms identified in the geomorphological mapping adopted in this research (Atpm / Api / Apf / Actpf), considering the absence of karst features in these compartments.

Analysis of human-occupation related factors

We found human-occupation related factors and imposed surface alterations caused by the urbanization process, as well as physical issues in building structures inside the areas where karst processes are more active.

Chart 02 describes the effects on the karst system derived from alterations introduced by natural dynamics and human actions in the city of João Pessoa (PB). These factors allow us to infer about situations that maximize the occurrence of phenomena in these environments, which can affect social routine, thus representing risk situations.

Chart 02 – Conditioning factors for developing risk situations in karst environment found in the city of João Pessoa/PB.

Factor	***Effect***	***(1)** Natural process* **(2)** *Human activities*	**Area of activity**
Natural susceptibility.	Natural formation of closed depressions.	(1) Structural climate; Carbonatic conditions; Lithology, Geomorphology	City of João Pessoa/PB
Soil impermeabilization.	- Reduced water infiltration into the soil; - Relegation of water table; - Lower hydrostatic pressure.	(2) Urbanization	Apparent in all features studied
Excavations	- Internal erosion cause favored by holes, vibrations, fluids of perfuration, and pumping. - It may induce flows of localized and turbulent underground waters	(2) Introduction of rainwater galleries.	Depression 03
Burial of depressions	- Disconnection of drainage surface with subsurface drainage; - Decrease of water table; - Lower hydrostatic pressure.	(2) Urbanization	Depressions 05, 07, and 09
Partial surface impermeabilization	- Higher potential of subsurface runoff; - Greater flow inside the depression; - Linear erosion.	(2) Urbanization	Depression 07

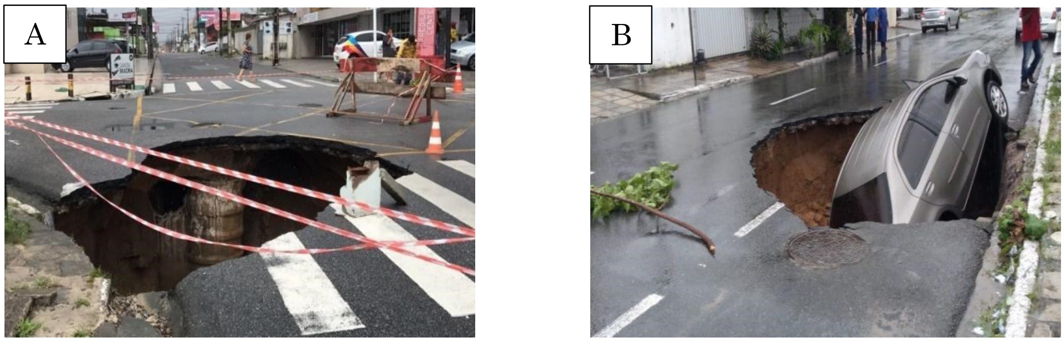
Source: The authors (2021).

Risk situations in karst environments are associated with the occurrence of geomorphological phenomena peculiar to these environments, such as land subsidence and collapse, affecting the social routine. Such phenomena represent a stage of natural evolution process of the karst relief; however, human actions may modify and/or maximize these processes from interventions related to activities like the exploration of underground water, irrigation, disposition of effluents in karst depressions, mining, in addition to the urbanization process itself upon the necessary surface alterations for occupation.

The main alteration produced by human intervention found in the study area occurs in the connection between the surface drainage and the karst system by altering the natural dynamics of flows. Such a scenario occurs in two moments: turbulent entry of flow derived from the system of rainwater galleries due to piping rupture from the fast increase of flow in the system in high-magnitude rainy events or through the burial of ponds.

In the first case, the turbulent entry of flow promotes the mechanical fast removal of disaggregated material, enlarging the vertical conducts that connect the karst system to the surface, which generates instability in the soil and consequently roof reduction in underground cavities (Figure 06). Such a scenario is more evident in the context of depression 03 (Figure 01).

Figure 06 – (A) Open crater at the intersection of *Expedicionário* and *Júlia Freire* avenues. (B) Open crater at *Rio Grande do Sul* Avenue, *Estados* district.



Source: Portal G1 Paraíba (2017). Source: Lira (2019).

In the second case, the burial of depressions with the occurrence of ponds represents a disconnection of the surface drainage from the underlying karst. The surface flow is represented by the direction of fluid of rainwater origin to the lowest point of the closed depressions, which associates with points of water table upwelling. The disconnection of surface and subsurface flows, which, in this case, occurs due to the burial de ponds, causes the water table to decrease and the hydrostatic pressure to reduce, resulting in a slow land subsidence process

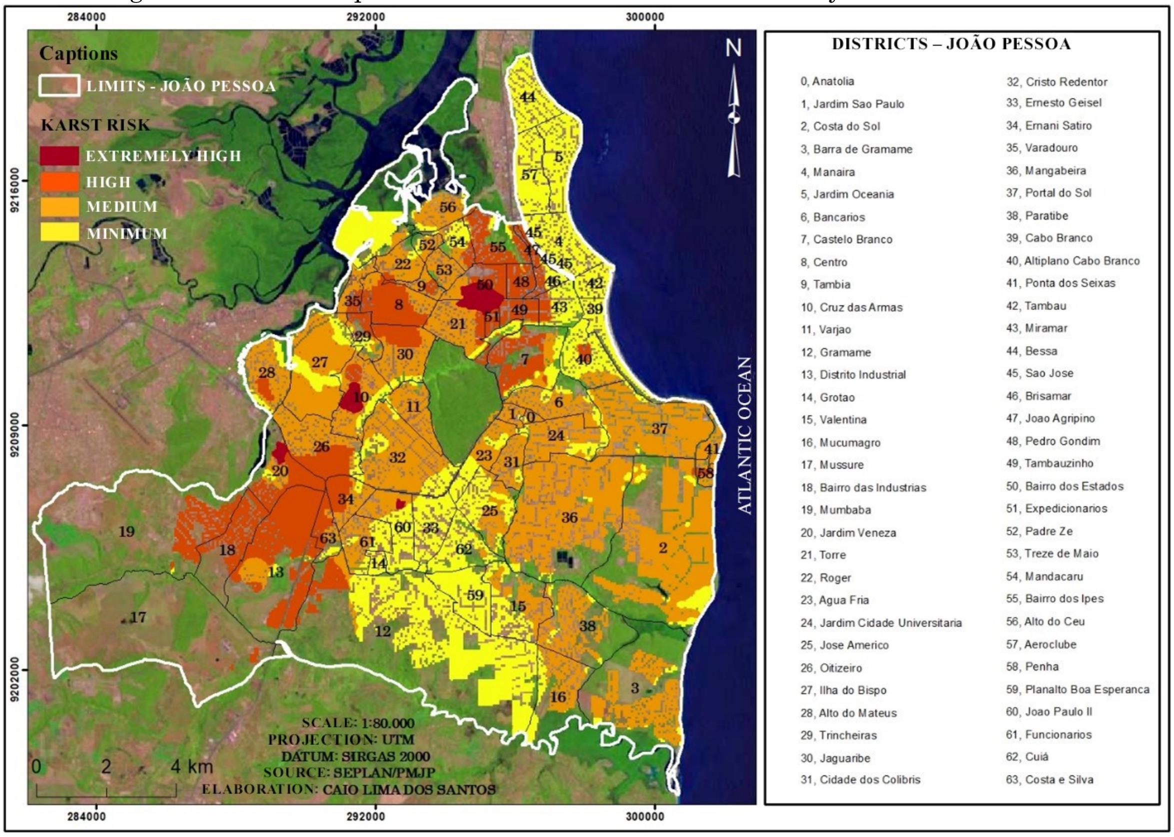
Our study identified 04 (four) cases of burial of closed depressions and posterior urban occupation of these areas (depressions 05, 07, 09, and 12). All of them showed damages in the building structures (Figure 07) – seen as cracks on walls and floor –, in addition to residents reporting recurring events of land subsidence, causing landslide of residences or part of them, thus evidencing the occurrence of land subsidence process in the area. In the case of depression 07, the pond was only partly buried.

Figure 07 – Cracks identified in the buildings were indicated by the arrows on the images. A) depression 05, B) depression 07, C) depression 09, and D) depression 12.

Source: The authors (2021).

Based on the issues described in depressions 03, 05, 07, 09, and 12, these areas were classified as extremely high risk in the risk map (Figure 08) since risk situations were identified in these locations more evidently.

Figure 08 – Risk map associated with karst relief in the city of João Pessoa/PB



Source: The authors (2021).

The risk map (Figure 08) associated with karst processes for the city of João Pessoa results from the overlay of the susceptibility map on the urban registry of the city. We defined 04 (four) risk classes according to the following criteria:

- **Extremely high risk**: Corresponds to the area of closed depressions (03, 05, 07, 09, and 12) mapped in this study with the occurrence of land subsidence process from structural issues in buildings located inside the depressions, in addition to the constant cratering in the soil associated with high-magnitude rainfall events.
- **Elevated risk**: Corresponds to the areas involving high natural susceptibility to karst processes and the remaining mapped depressions, without structural issues identified inside the buildings. These areas are overlaid on the current closed basins.
- **Medium risk**: Corresponds to the areas defined as average natural susceptibility to karst processes. In this context, current karst features do not occur, however, there are some features whose current forms (drainage heads and amphitheaters) reveal the morphodynamical evolution of ancient karst forms.
- **Minimal risk**: Corresponds to the areas involving low natural susceptibility to karst processes. These areas refer to current depositional forms, like river plains and marine regions, since closed depressions do not occur in these geomorphological compartments.

Thereby, the risk map considered only the areas occupied by the urbanization process, defined from the data register of plots provided by the SEPLAN/PMJP (2020), disregarding areas where rural activities prevail. Table 03 presents the number of plots inserted in each risk area mapped.

Table 03 – Number of plots settled in karst risk areas according to the urban registry of city of João Pessoa/PB.

RISK	*Total number of plots*
EXTREMELY HIGH	1,790
HIGH	73,064
MEDIUM	58,320
MINIMAL	60,341
Total	**193,515**

Source: register data granted by SEPLAN/PMJP (2020).

FINAL CONSIDERATIONS

The structural condition represents the prevailing factor for karst depressions to emerge and evolve in the city of João Pessoa/PB. All mapped forms are aligned preferably on the E-W and NE-SW directions, according to the directions of the mapped lineaments in the study area.

The urban growth in the area promoted strong surface alterations, thus representing a prevailing factor in the analysis of risks, in addition to fostering the infiltration of fluids to the subsurface, such as sewage and domestic effluents, which may maximize or trigger the dissolution process of carbonatic rocks, accelerating the creation of underground voids that may manifest superficially during the land subsidence process, thus characterizing a risk situation.

Considering that the city is almost entirely urbanized and that several human activities are maximizing factors for karst processes, it is possible to state that the population of João Pessoa is strongly vulnerable to risk situations that can derive from karst relief development. In addition, phenomena linked to the origin of such forms occur on the subsurface but reflect superficially and affect individuals of all social classes, without restrictions.

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AUTHORS' CONTRIBUTION

All authors made substantial scientific and intellectual contributions to the study. The tasks of conception and design of the study, preparation and writing of the manuscript, as well as critical review were carried out in a group. The first author Caio Lima Dos Santos was especially responsible for the theoretical-conceptual development, data collection and writing of the manuscript. The second author Osvaldo Girão da Silva, for the interpretations and analysis of the data; and the third one Saulo Roberto de Oliveira Vital, for the technical/methodological procedures of the article.