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ORIGINAL ARTICLE

Evaluation of susceptibility for terrain collapse and subsidence in karst areas, municipality of Iraquara, Chapada Diamantina (BA), Brazil

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Abstract

The morphological evolution of the karstic systems is associated with a set of physical and chemical processes, triggered by the dissolution of the rocks, related to percolation of groundwater and surface water, which consequently open underground voids and carve out peculiar forms of relief. Due to environmental and geotechnical aspects, this system is naturally more fragile and vulnerable than other natural systems and, therefore, has increasingly received the attention of the scientific community over the past decades. The objective of the study was to delimit zones with varying degrees of susceptibility for collapses and subsidence of sinkholes in the municipality of Iraquara, Chapada Diamantina (BA), Brazil, and to understand their geological and morphological determinant factors. Geological data, karst phenomenon map, and visual analysis in the field were used to categorize zones with different types of susceptibilities to the nucleation of new sinkholes based on a Hazard Index. This index was defined from the sum of geological hazard factors, lineament density, and sinkhole density. The areas that presented the highest susceptibility for terrain collapse and subsidence corresponded to regions where carbonate rocks outcrop, with high density of photolineaments and 2.62 sinkholes/km^2. Processes associated with terrain collapse and subsidence in karst areas consisted of a combination of various factors, hindering precise predictions. However, zones of different types of susceptibilities to terrain collapse and subsidence can be delimited when the relationships between these processes and their factors are understood. The Hazard Index proposed does not provide quantitative values for the probability of hazard susceptibility, but rather indicates areas that are more susceptible to terrain subsidence and collapse.

Keywords Karst · Carbonate rocks · Chapada Diamantina · Collapse and subsidence · Brazil

Introduction

Karst terrains cover approximately 20% of the Earth's surface and develop mainly in carbonate rocks, evaporative rocks and other, which hold groundwater resources that 22% of the world population directly or indirectly relies upon (Ford and Williams 2007, Huggett 2007). Due to their complex morphology, karst terrains are particularly more fragile and vulnerable to environmental damages in comparison with most natural systems (Elhatip 1995; Zhou 2006; Ford and Williams 2007; Goldsheider and Drew 2007). Moreover, they are also susceptible to terrain collapses. Thus, understanding the properties of this system represents an important tool for the management of groundwater (Galvão et al. 2015) and associated geotechnical risks.

Susceptibility associated with collapse and subsidence issues is more common in karst terrains. This phenomenon may directly affect people's lives and cause severe environmental and economic risks (Sallun Filho 2012; Gutiérrez et al. 2014). Surface bulging may occur either as a result of natural processes or be induced by human activities, especially those related to the overexploitation of groundwater resources (He et al. 2003; Galve et al. 2009a, b). Natural and human processes mainly differ regarding the rate at which subsidence begins, with considerably faster rates observed

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in situations of direct anthropogenic interference (Lei et al. 2001; Galvão et al. 2015).

Terrain collapse and subsidence in karst areas are usually influenced by various natural and/or human factors: (1) degree of karstification; (2) increase of water input in the soil (rain water, floods, pipe leakages, irrigation, among others); (3) water level reduction (due to paleoenvironmental changes, groundwater extraction, and tectonics); (4) water damming; (5) epikarst erosion and carving; (6) underground excavations; (7) vegetation removal; (8) distance from faults and fractures; and (9) soil thawing (Hu et al. 2001; He et al. 2003; Zhou 2006; Galve et al. 2009a, b; Keqiang et al. 2009; Cooper and Gutiérrez 2013; Gutiérrez et al. 2014; Galvão et al. 2015). Catastrophic collapses directly over cavities occur in less than 1% of cases. In most reports, remobilization of unconsolidated cover occurs towards the interior of caves, bulging the surface (Ford and Williams 2007).

Several cases of collapse and subsidence events in karst areas have been reported around the world, for example in Tangshan, China (Hu et al. 2001), in the Ebro Valley, Zaragoza, Spain (Galve et al. 2009a, b), and in Sango, Tennessee, USA (Siska et al. 2016). In Brazil, the municipalities of Lapão and Itaetê (Bahia), Mairinque and Cajamar (São Paulo), Sete Lagoas and Lagoa Santa (Minas Gerais), Almirante Tamandaré and Bocaiuva do Sul (Paraná), and Teresina (Piauí) are examples of areas where geotechnical processes led to countless environmental and material damages (Silva 1998; Pereira 1998; Santos 2008). However, the distribution and probability of occurrence of new collapse and subsidence phenomena represent an important gap in knowledge for most of these municipalities.

Geological and geomorphological characterization and spatialization of information about known events are important actions towards the mitigation of risks associated with collapse and subsidence events in karts terrains, to analyze areas with highest probability of new occurrences (Gutiérrez et al. 2008). Susceptibility maps represent the probability of sinkholes either occurring or not in specific areas (Galve et al. 2011). The purpose of delimiting zones in these types of maps is to express the various levels of nucleation of new sinkholes, which represents an important tool for the management of land use and occupation and of water resources (Hu et al. 2001; Galvão et al. 2015; Siska et al. 2016).

Founded in 1962, the municipality of Iraquara, which was the object of the study, is located in a region with high density of underground galleries (Auler and Ferrant 1996; IBGE 2016). The variety of geoforms, associated with disorderly growth and lack of urban planning, has promoted high geotechnical risks to the municipality. The objective of the paper was to delineate zones with varying degrees of hazard susceptibility, which result from the collapse and subsidence of sinkholes, in the municipality of Iraquara, Bahia, Brazil. To do so, a new method was proposed associating lithology, photolineament density and sinkhole density, and summarized in the Hazard Index. This knowledge is paramount for the protection of the physical environment and territorial development, which should be applied as a subsidy for elaborating a land use and occupation master plan.

Site description

Iraquara is located in the state of Bahia, Brazil, 340 km west from Salvador, the state capital (Fig. 1a). According to the last national census, this municipality presents a population of 25,279 inhabitants (IBGE 2017), distributed over an area of 991 km^2. Demographic growth was estimated at approximately 10% between 2010 and 2016 (IBGE 2016). Urban occupation is mainly observed in the central portion of the municipality (Fig. 1a). Studies conducted based on satellite images showed that an occupation boom occurred in the region in 2006 (Fig. 1b).

The main economic activities are limited to tomato, oleaginous plants and *umbu* crops, and to cave tourism. The region is located within one of the most expressive landscape sites of Brazil, the Chapada Diamantina, where nature tourism represents an important economic activity. For Auler and Ferrant (1996), the gallery networks that exist in the region compose one of the most relevant speleological sites in the country, with 99 cavities recorded so far (CANIE 2017), or 0.12 caves per km^2. This is possibly the location with the highest density of underground galleries per unit of area in Brazil.

Geologically, the area is located within the central panorama of the state of Bahia. Its evolution model follows an aulacogen structural pattern (Souza et al. 1993) called Western Chapada Diamantina Thrust and Fold Belt. In this region, Mesoproterozoic siliciclastic lithostratigraphic unit outcrops are represented, from base to top, by the Tombador, Caboclo, and Morro do Chapéu formations, composing the Chapada Diamantina Group, and a thick Neoproterozoic carbonate–pelite sequence that composes the Una Group (São Francisco Supergroup), where the karst terrains found in Iraquara are developed. This sequence lies discordantly upon meta-sediments of the Chapada Diamantina Group and is composed, from base to top, of the Bebedouro and Salitre formations. Covering this set of rocks are outcrops of Cenozoic detrital covers, which are related to successive erosion cycles that sculpted the relief (Misi 1979; Bonfim et al. 1985; Pedreira et al. 1987; Souza et al. 1993, 2002; Pedreira 2004).

The Salitre Formation is represented by the Nova América and Jussara units. The Nova América unit is composed of calc-siltite, dololutite, dolarenite, and algal mudstone, deposited in an intertidal to subtidal environment with periodical exposure. On the other hand, the Jussara unit is

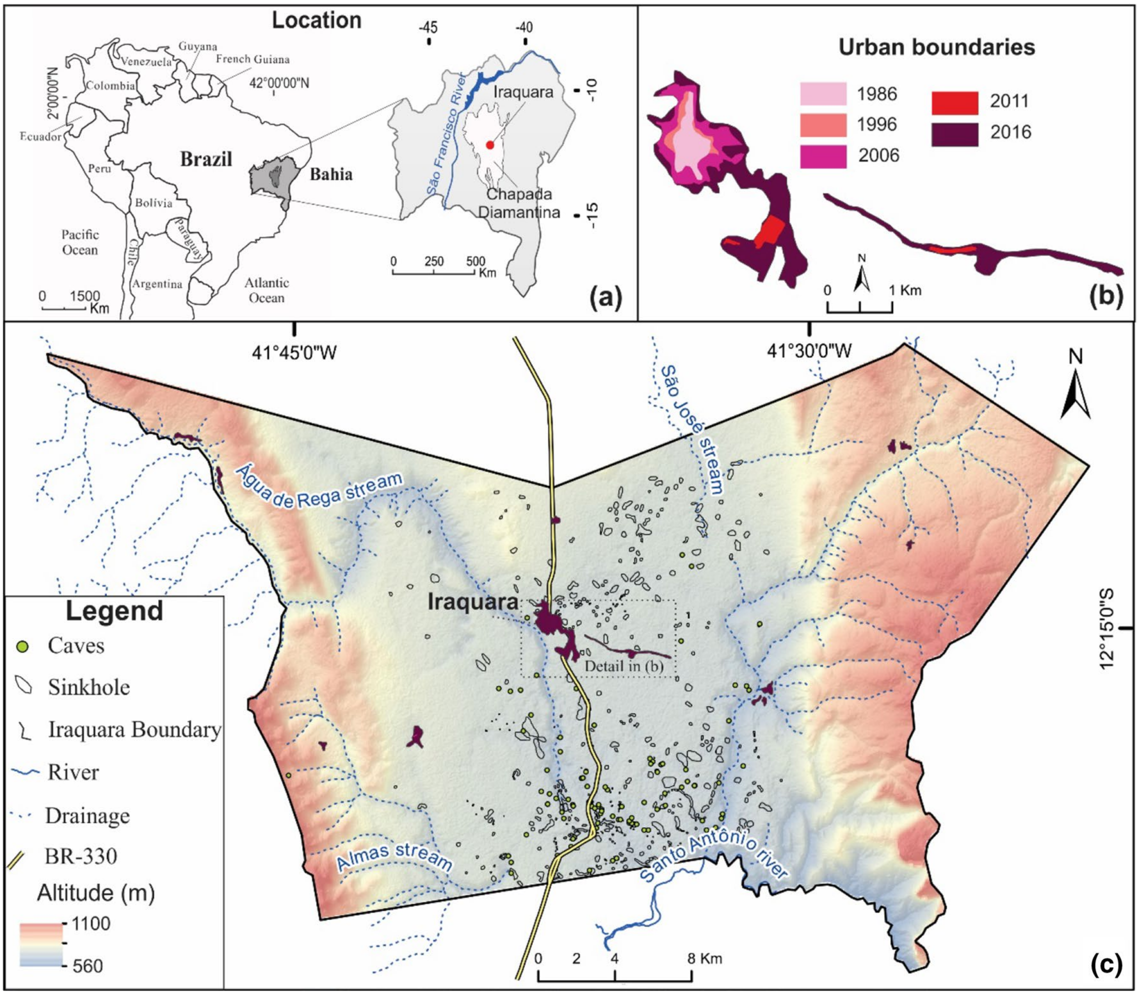


Fig. 1 **a** Location of the study area, in geographic coordinates; **b** urban occupation growth of the municipality of Iraquara, between 1986 and 2016, defined using images from the Landsat satellite; and **c** digital elevation model defined from an ASTER image, with resolution of 30 m

composed of oolitic calcarenites, which are often oncolitic, deposited in a subtidal environment, and, locally, in an intertidal to supratidal environment (Pedreira 2004).

Regarding geomorphology, Iraquara can be divided into two domains: (1) mountainous region, where metasediments of the Chapada Diamantina Group outcrop, with topography ranging between 800 and 1200 m, and slope varying between 8 and 30%; and (2) karst plateau, where morphological features composed of smoothly sloped and wavy ramps predominate, with slopes varying between 0 and 12% (Fig. 1c).

Karst depressions correspond to a set of sinkholes or uvalas that are concentrated along stretches with NW–SE preferential orientation and, subordinately, N–S orientation, occupying 1.64% of the total area of the municipality. In this region, karst depressions can be classified into two groups (Cruz Junior 1998): (1) collapse sinkholes, which correspond to enclosed depressions, with steep profiles; and (2) suffosion sinkholes (Ford and Williams 1989), represented by smooth-profile depressions associated with slow subsidence caused by the removal and infiltration of detrital covers (Fig. 2).

Materials and methods

Three datasets were used to define the hazard susceptibility model associated with collapses in Iraquara. These included geological data, a karst phenomenon map, and visual analysis in the field. Lithology, lineament density, and karst feature density maps were elaborated from these data. Maps were later integrated using Hazard Index map algebra. These methods are described as follows.

Elaboration of basemaps

Geological data comprised: (1) lithological map (1:100,000), elaborated from the IBGE/SEI (2003) database; and (2)

Fig. 2 **a** Collapse sinkhole possibly associated with overexploitation of groundwater and use in tomato crops (See detail in a1); since the collapse an installation and exploration of a tubular well 200 m from the site occured; **b** suffosion sinkhole (Ford and Williams 2007)

lineament density map (Fig. 3a), produced using the "Line Density" tool of ArcMap 10.1 software. Lineaments were delimited by aligned crests, valley bottoms, and drainages, according to the interpretation of shadowed relief images which were produced based on azimuths 0°, 90°, 180°, and 270°.

A karst phenomenon map was developed to build a broad cartographic inventory. The map was built on the extraction of geoforms from aerial photography analysis at a scale of 1:60,000. Aerial photographs were then scanned and vectored in the software ArcMap 10.1. The sinkhole density map consisted of an interpolation of central points (unit of sinkhole) using the "Density" tool of the ArcMap 10.1 software (Fig. 3b).

A class distribution analysis was conducted to define patterns regarding sinkhole and fracturing indexes. This analysis consisted of extracting the values of the previously mentioned indexes from an equidistant sampling mesh of 150 m for lineage density (Fig. 3a1), and 85 m for the sinkhole density map (Fig. 3b1). These values were taken from the extraction of points from the lowest cells of raster images (pixel) using the "Conversions Tools" of the ArcMap 10.1 software. Indexes were divided into three classes: (1) low, for values below the mean, minus standard deviation (σ); (2) high, for values above the mean, plus standard deviation; and (3) medium, for values between intervals 1 and 2 (Fig. 3).

Hazard model associated with terrain collapse and subsidence in karst areas

The purpose of this model was to divide the study area into sub-regions with various collapse or subsidence hazard susceptibilities. Three factors were used to create the hazard model based on Galve et al. (2008), Hu et al. (2001), Galvão et al. (2015), and Siska et al. (2016): (1) lithological; (2) fracturing density; and (3) sinkhole density. Hazard factors and their attributes are summarized in Fig. 4, according to their degree of influence on hazard susceptibility. The Hazard Index (HI) comprises the sum of the previously mentioned factors (Fig. 4).

The lithological hazard factor was based on the rocks mapped in the field and their relationships with the number of occurrences of sinkholes per square kilometer. Thus, three categories were defined regarding this hazard factor: (1) areas where the outcrop carbonate rocks from the Salitre Formation received a hazard score of "10"; (2) carbonate rocks covered by unconsolidated sediments that received a score of "5"; and (3) siliciclastic rocks from the Chapada

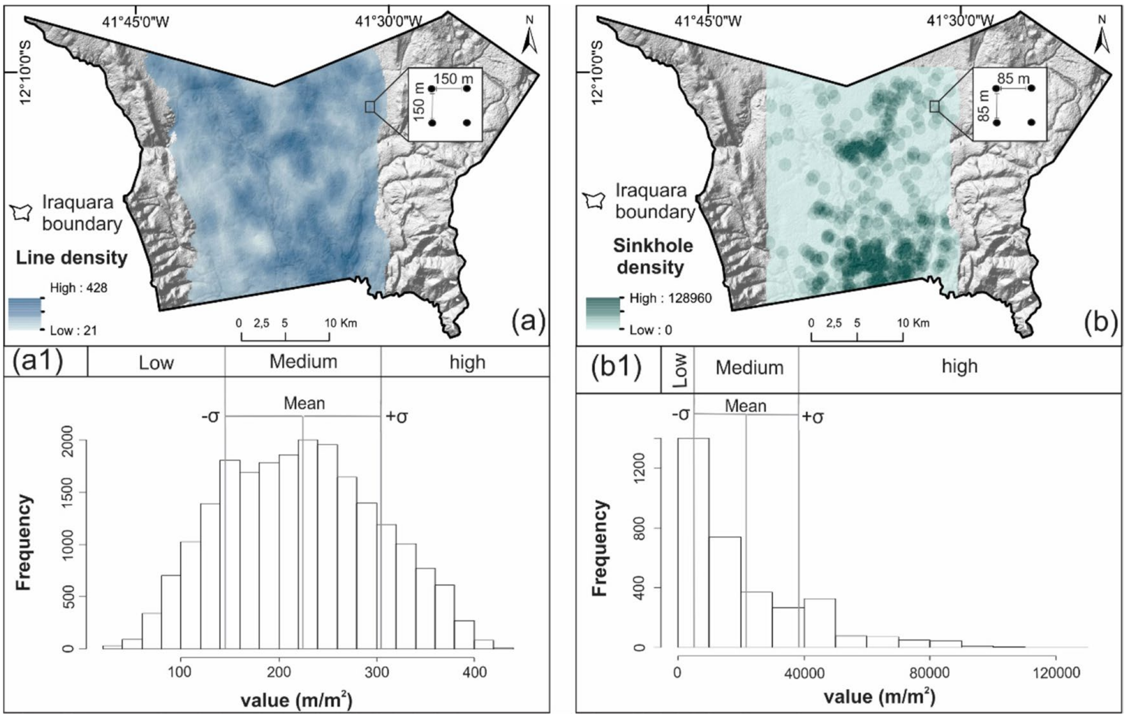
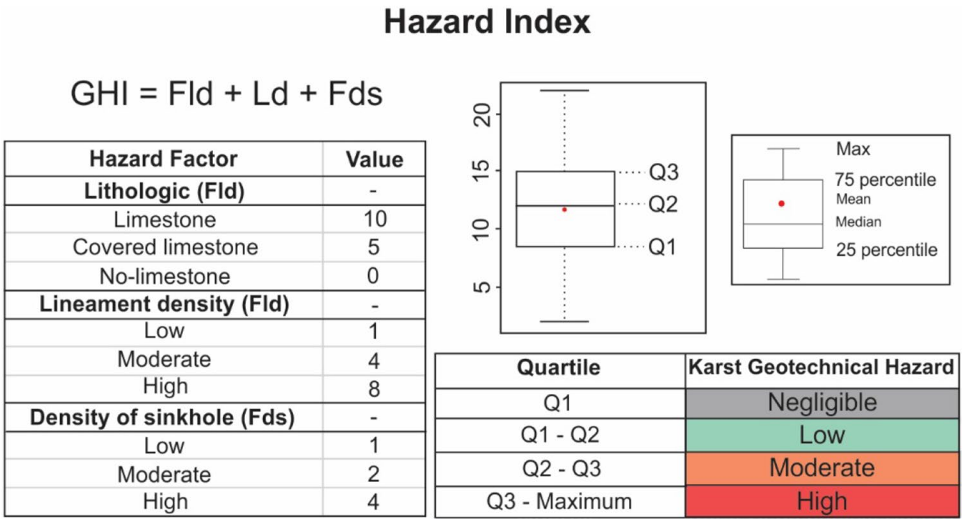


Fig. 3 **a** Photolineament density map extracted from a raster image; (a1) class distribution histogram regarding lineament density and relationship with the degree of Hazard Index; **b** sinkhole density map, elaborated from aerial photographs at a scale of 1:60,000; and (b1) class distribution histogram regarding sinkhole density and relationship with the degree of Hazard Index


Hazard Index

GHI = Fld + Ld + Fds

Hazard Factor	Value
Lithologic (Fld)	-
Limestone	10
Covered limestone	5
No-limestone	0
Lineament density (Fld)	-
Low	1
Moderate	4
High	8
Density of sinkhole (Fds)	-
Low	1
Moderate	2
High	4

Quartile	Karst Geotechnical Hazard
Q1	Negligible
Q1 - Q2	Low
Q2 - Q3	Moderate
Q3 - Maximum	High

Fig. 4 Hazard Index (HI) calculated based on lithological factors, lineament density, and sinkhole density. The box plot exemplifies the method used to separate hazard degree: negligible for the first quartile (Q1); low between Q1–Q2; moderate between Q2–Q3; and high for scores above Q3

Diamantina Group and Bebedouro Formation that received a hazard score of “0”.

The same principle was used to quantify the hazard factor of lineament density. Therefore, three classes were determined regarding the fracturing density hazard factor (Fig. 4). The hazard factor associated with sinkhole density is summarized in three categories: high, medium, and low, attributing scores of 1, 2, and 4, respectively. This factor reflects the degree of terrain surface instability and also favors the coalescence of these superficial karst features, forming uvalas in areas where the number of sinkholes per unit of area is high.

The scores calculated based on the HI (Fig. 4) resulted in dimensionless values. Thus, a descriptive statistical analysis was conducted to evaluate the empiric distribution of data and establish hazard intervals, based on all possible combinations of the degree of hazard for terrain collapse and subsidence, calculated through the HI equation (Fig. 4). Quartiles (the separatrix measurement that divides the data sampled into four different groups—each one presenting 25% of data) of the possible HI scores were divided on an Excel spreadsheet. The relationships between the calculated quartiles and the HI associated with collapse or subsidence of the karst relief were thus determined.

Results

Results consisted of a geologic map, factors associated with terrain collapse and subsidence, and the Hazard Index.

Lithology

From a lithological point of view, the study area can be divided into three domains: (1) siliciclastic rock domain; (2) carbonate rock domain; and (3) Cenozoic unconsolidated cover domain. The siliciclastic rock domain corresponds to diamictites, sandstones, mudstones and conglomerates at the Bebedouro Formation and Chapada Diamantina Group, distributed along the W and E extremities (Fig. 5), occupying approximately 47.9% (Fig. 6) of the area of the municipality (IBGE/SEI 2013).

The carbonate rocks correspond to limestone and dolomite of the Salitre Formation are located in the central portion of Iraquara, occupying approximately 36.6% of the area (IBGE/SEI 2013). Petrographically, the carbonate rocks of the region present an extremely low primary porosity. However, when present, porosity is associated with the process of calcite dolomitization. The effective permeability of the aquifer is limited to secondary porosity (faults and fractures) and the formation of tertiary porosity (cavities) (White 1999, 2002).

Recent unconsolidated sediments cover these units. This cover is indiscriminately distributed over the municipality, occupying approximately 19.6% of its area (IBGE/SEI 2013).

Hazard factor associated with terrain collapse and subsidence

The hazard factor associated with lithology (Fig. 7a) was divided based on the number of sinkholes per unit of area (km^2) of the lithologies exemplified in Fig. 5. In areas where carbonate rocks of the Salitre Formation outcrop, 1.13 sinkhole units occurred per square kilometer (km^2). However, under unconsolidated sediment units, there was a considerable reduction in the number of sinkholes per km^2, six times lower than the exposed karst. No sinkholes were mapped

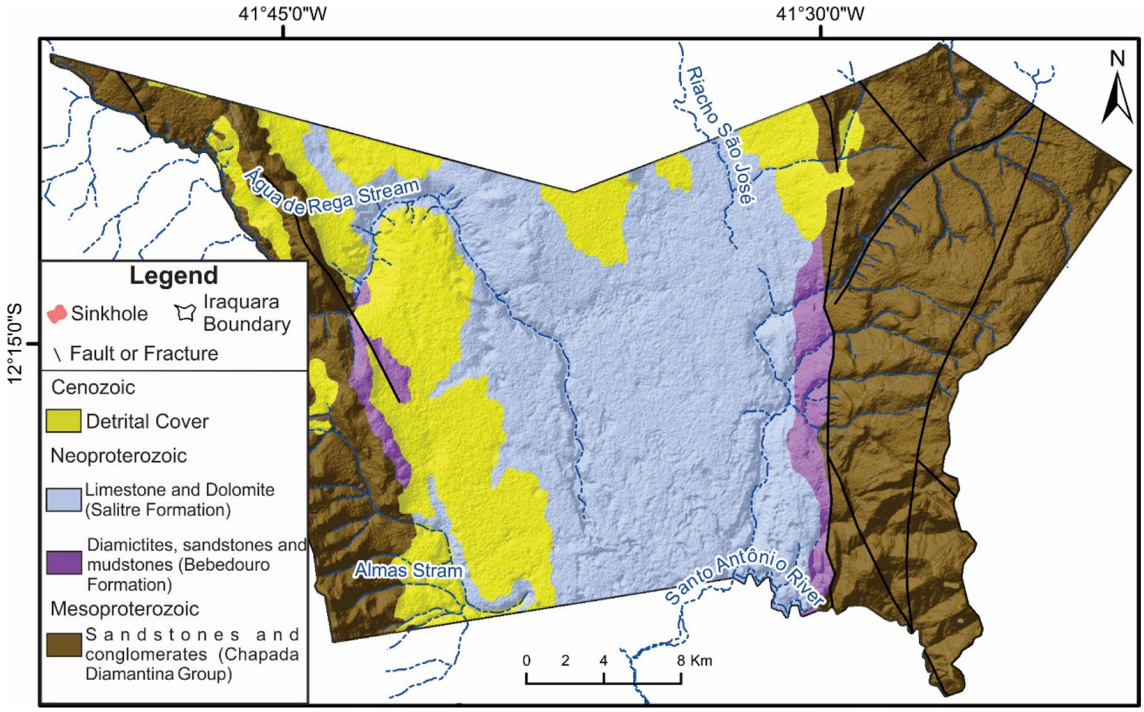


Fig. 5 Geologic map of the municipality of Iraquara. The siliciclastic rocks of the Bebedouro Formation and Chapada Diamantina Group occur in the W and E portions of the municipality; the carbonate rocks of the Salitre Formation outcrop in the central portion of the area; Cenozoic detrital covers occur indiscriminately (IBGE/SEI 2013)

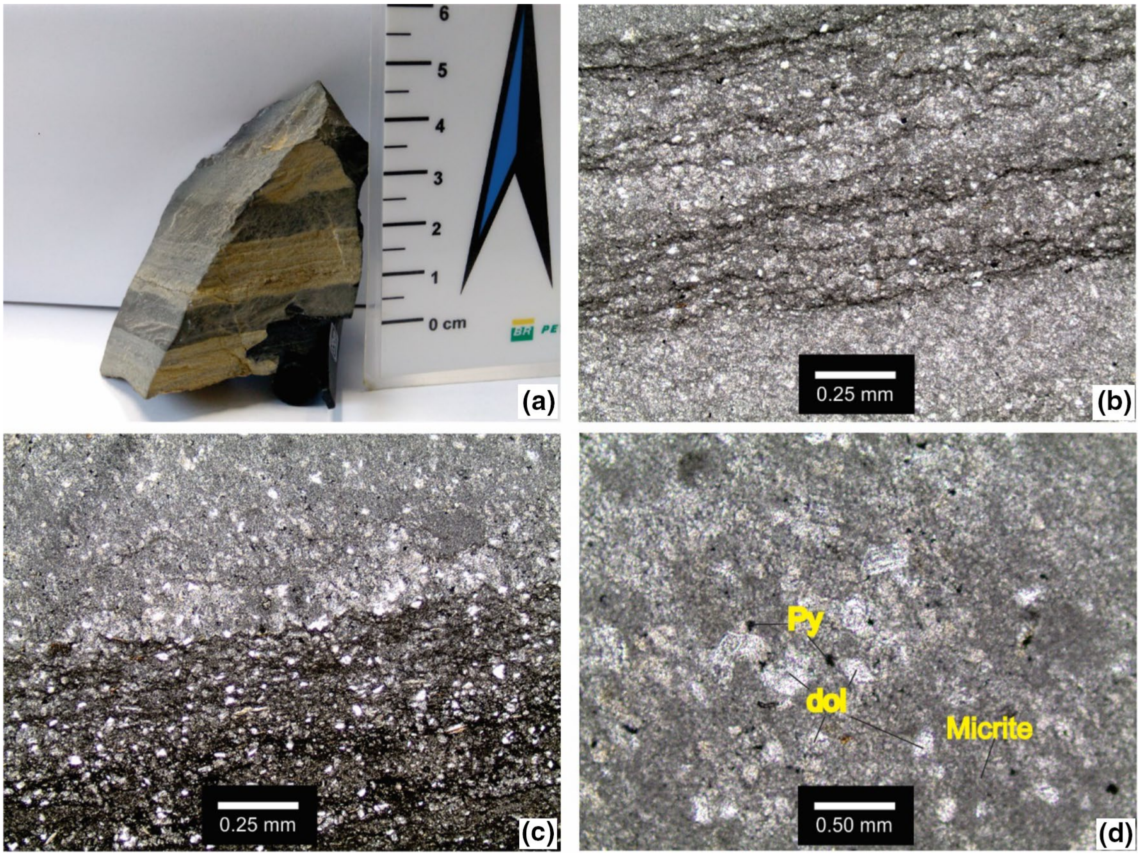


Fig. 6 **a** Cryptoalgal mudstone of the Nova América Formation, deposited in a supratidal environment; **b** petrographic slide, under plane polarized light and ×10 objective, showing levels of rock dissolution (in black) enriched in organic matter (OM); **c** dolomitized algal mudstone detailing the contact of the OM-rick mudstone overlapped by carbonate mud; **d** detail of micrite dolomitization, under plane polarized light and ×20 objective

over the siliciclastic rocks of the Chapada Diamantina Group and Bebedouro Formation.

Photolineaments possibly consist of foliations, fractures, faults and interactions between stratification planes and the surface. These relief features can be partially masked by the presence of sedimentary covers (Cheema and Islan 1994). The lineament density map (Fig. 7b) showed that they were heterogeneously distributed over the area of the municipality. However, the largest unit of high photolineament density was observed in the southern portion of the study area.

The unit of low lineament density occupied 17.9% of the area susceptible to surface bulging. This region presented 0.35 sinkhole unit per km^2. In turn, the moderate photolineament density unit occupied approximately 63.8% of the area subject to terrain collapse and subsidence, with 0.67 sinkhole unit per km^2. Finally, the unit of high lineament density occupied approximately 18.3% of the area subject to collapse and subsidence, with 2.4 sinkhole units per km^2 mapped (Fig. 7b). This analysis demonstrated a direct correlation in the region between photolineament density and the presence of sinkholes.

The geologic hazard factor associated with sinkhole density (Fig. 7c) showed two regions that presented the highest concentrations of sinkholes in Iraquara. The first was located in the central–southern portion of the municipality, while the second was in the central–northern portion, where part of the town is located. In most karst areas, the evolution of the system is directly related to superficial processes, and the characterization of exokarsts is one of the main resources to understand underground karsts (Ford and Williams 2007). Thus, a larger network of surface sinkholes suggests more evolved subterraneous karsts and, therefore, higher susceptibility to collapse and subsidence in these areas (Zhou et al. 2003; Gao et al. 2005; Kemmerly 2006).

Hazard Index associated with terrain collapse and subsidence

The Hazard Index (Fig. 8) was defined through the sum of the geologic hazard factors (Fig. 7a), lineament density (Fig. 7b), and sinkhole density (Fig. 7c). The area that was classified as having high hazard susceptibility (in red)

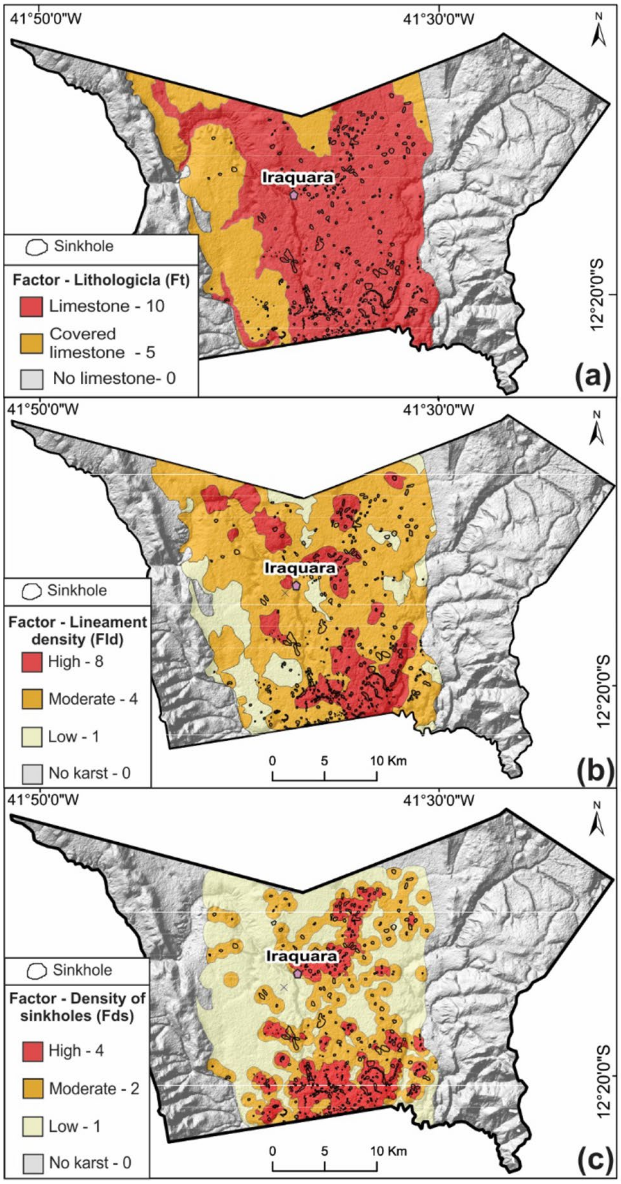


Fig. 7 **a** Hazard factor associated with the lithologies found in the region, summarized in three classes: carbonate rocks, carbonate rocks covered by unconsolidated sediments, and non-carbonate rocks; **b** distribution of classes of the hazard factor associated with the density of lineaments; and **c** distribution of classes of the hazard factor associated with the spatial distribution of sinkholes. Regions that presented a high number of lineaments coincided with those with high number of sinkholes

occupied approximately 13% of the area of the municipality, where 2.62 sinkholes per km^2 occurred. The moderate risk portion (in orange) occurred over 16.7% of the area of the municipality, with 0.775 sinkhole per km^2. In turn, the low-risk region (in yellow) occupied 17.4% of the municipality of Iraquara, where there was 0.15 sinkhole per km^2. Finally, the gray portion of the map corresponds to siliciclastic rocks of the Chapada Diamantina Group and Bebedouro Formation, where no sinkholes occur.

Discussion

The results of the present study provided an expressive perspective regarding the distribution of collapse and subsidence areas in karst reliefs, improving the understanding of their causes in the municipality of Iraquara. This discussion will provide interpretations regarding the nucleation and development of sinkholes.

The risk model associated with terrain collapse and subsidence reported in the study does not correspond to the possibility of collapse and subsidence events in quantitative terms. The model indicates areas that are more susceptible to being affected by relief collapsing processes. This knowledge represents an important tool in land use and occupation management of the region, where areas with lower susceptibility to surface bulging and consequent higher use potential can be suggested, considering only the risk related to terrain collapse and subsidence.

According to Salles (2017), the potentiometric surface in the area suggests a flow that follows local topography, with main NW–SE direction. In the map proposed by this author, no anomalies were observed in the potentiometric surface that could be associated with subsidence and collapse processes in the municipality. However, the map considered only wells that were officially registered in the database of the Water Resource and Environmental Engineering Company of the State of Bahia (CERB) and, therefore, may not represent the real situation of the region.

Field observations showed that terrain subsidence processes may be unleashed with groundwater overexploitation (Fig. 2), since the removal of water from underground cavities may reduce the support provided by the walls of the massif, leading to terrain instability. This fact was observed by Galvão et al. (2015) in a similar study conducted in an urban karst aquifer in the municipality of Sete Lagoas/MG, and by He et al. (2004) in the karst aquifer located in the province of Guizhou (China), who analyzed mechanisms that induce surface collapse in the region. Moreover, groundwater exploitation may increase the gradient and ability to transport surface sediments towards the interior of underground cavities, leading to subsidence, formation of suffosion sinkholes, and accelerating abrasion processes. Therefore, future studies should take groundwater exploitation into consideration, using data that reveal the real situation of the region, providing greater consistency to the Risk Index proposed in the present study.

Results showed that areas with high susceptibility scores corresponded to regions where carbonate rocks outcrop and present high photolineament densities. The latter consist of

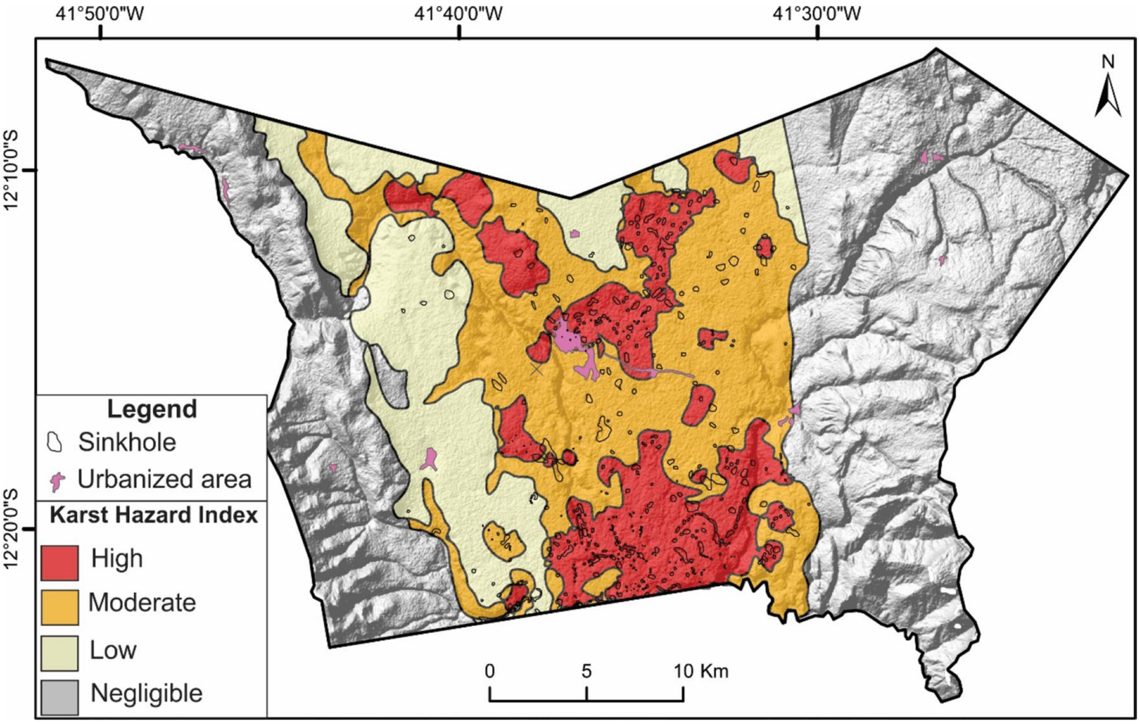


Fig. 8 Distribution of classes of the risk model, sinkholes, and the urbanized area of the municipality. The town area, located in the central portion of the map, is established on units that presented high to moderate risk associated with collapse and subsidence of the area. However, the settlements of Iraquara are located in areas of low to no risk associated with terrain collapse and subsidence

the intersection between fault planes, fractures and rock bedding planes and the terrain surface—interpreted as local discontinuities of the rocky massif. The presence of sinkholes was favored in regions that presented high photolineament densities possibly because of the association with higher permeability and secondary porosity of rocks. Thus, authigenic acidic water percolation is favored in these regions, accelerating the process of void opening and rock karstification. A similar fact was observed by Hu et al. (2001) in the municipality of Tangshan (China), where these authors observed high probabilities for the nucleation of new sinkholes near active fault zones.

In addition, high rock permeability may facilitate, over time, the lixiviation and transport of unconsolidated material over rocks towards the interior of karst ducts, forming depressions (suffosion sinkholes) on the relief. This process occurs gradually and slowly, but can progress faster due to human interference. However, even when the process occurs slowly and gradually, it can cause countless material losses, as observed in the reports by Pereira (1998), Silva (1998), Galve et al. (2008), and Santos (2008).

A close relationship was observed between index factors associated with sinkhole density (Fig. 7c) and photolineament density (Fig. 7b). Areas that presented high sinkhole density could be related to regions with higher development of tertiary porosity, forming a more evolved underground drainage network (Gao et al. 2005; Kemmerly 2006). This would consequently lead to a higher percentage of empty spaces in the rocky massif. This fact presents a close cause and effect relationship with photolineament densities and evolution of kart systems, increasing the degree of risk associated with terrain collapse and subsidence in karst areas.

The data listed and discussed in the study allow the understanding that the nucleation of surface collapses in the municipality of Iraquara may also be associated with: (1) the occurrence of subsurface discontinuities; (2) carbonate rock dissolution; (3) degree of karst evolution and underground voids; and (4) the presence of sedimentary cover over carbonate rocks; locally, the process may also be associated with (5) groundwater exploitation. The risk associated with groundwater removal is not static. It can vary depending on the level of exploitation of aquifers, and the number and proximity of wells. Therefore, poor water resource management can aggravate the risk associated with the formation of collapse or subsidence sinkholes, since it can either reduce the support of walls inside rocky massifs or increase the gradient and ability to transport sediments towards the interior of voids.

This integrated and low-cost analysis produced satisfactory results for the comprehension and spatialization of terrain collapse and subsidence in the municipality of Iraquara. These analyses can be extrapolated to other karst regions where there is low groundwater exploitation. The disadvantages of this approach consist of not considering the relationship between sinkhole nucleation and groundwater removal and soil thickness over carbonate rocks.

Conclusion

A Risk Index and the zoning of areas that present potential for terrain collapse and subsidence were proposed based on the analysis of geological, lineage density, and sinkhole density data in the municipality of Iraquara. The results obtained were effective regarding the comprehension and spatialization of risk areas. This information can support territorial planning and preventive urban planning, indicating high-priority zones to implement corrective measures, delimiting land use, occupation, and preservation in Iraquara.

The susceptibility associated with terrain collapse and subsidence phenomenon is understood in the study as the result of the combination of various factors (geological, structural, karst characteristics, groundwater circulation and use), which makes it difficult to securely anticipate where and when terrain collapse or subsidence will occur. However, when the relationships among these factors are understood, it is possible to delimit zones with varying levels of susceptibility to surface collapsing.

Satellite image analysis showed that the demographic boom in the municipality of Iraquara occurred recently, possibly beginning in 2006. An increase in groundwater resource exploitation in the region may locally accelerate the processes of terrain collapse or subsidence. Therefore, it is paramount to elaborate a management plan for groundwater use.

Based on the results obtained, some actions can be taken to avoid losses and damages related to surface bulging: (1) avoid new constructions in areas that present high risk; (2) control the number of tubular wells dug in areas that present moderate to high risk; (3) control large-scale irrigation to reduce the input of extra water in the system; and (4) promote educational workshops to raise public awareness of the risks associated with terrain collapse and subsidence and how to act in case of catastrophic events.

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