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Intrinsic vulnerability assessment, using the EPIK Method, of the fissure-karstic aquifer present in the Lagoa Santa karstic region, Minas Gerais, Brazil

Avaliação da vulnerabilidade intrínseca, utilizando o Método EPIK, do aquífero fissural-cárstico presente na região cárstica de Lagoa Santa, Minas Gerais, Brasil

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ABSTRACT
This paper presents an intrinsic vulnerability analysis performed in the Lagoa Santa Karst Environmental Protection Area (EPA), north of Belo Horizonte, Minas Gerais, Brazil. This region contains important karstic and fissure-karstic aquifers, essential water sources for urban, industrial and agricultural uses. Classifying the area into contamination vulnerability classes provides a basis for sustainable aquifer management by competent regulatory agencies, ensuring water availability for present and future populations. The area was analyzed using the parametric system EPIK, which utilizes specific geological, geomorphological, and hydrological variables to segregate the region into contamination vulnerability classes. Because this method was originally developed in Switzerland, a temperate climate region, adapting it to the tropical karstic region was necessary for this study. Consequently, intrinsic vulnerability maps comparing the original and modified EPIK methods are presented, illustrating the distribution of respective vulnerability classes across the study area. Notably, the very high vulnerability class represents 10% of the total area (49.8 km^2), corresponding to sites featuring very thin soil profiles and/or where outcrops and dolines occur. Results suggests this method is effective; however, the protective cover parameter necessitated adaptation due to tropical climate conditions. In the original method, classes are defined using a broad soil thickness interval (0-200 cm). Applying these originals intervals to the study area classified most of the region into a single class, significantly reducing the method's classification capability. Therefore, changing parameter intervals to P1: 0-1.6 m, P2: 1.6–8 m, P3: 8–16 m, and P4: >16 m was required to match local conditions.

RESUMO
Este artigo apresenta a análise de vulnerabilidade intrínseca realizado na Área de Proteção Ambiental (APA) Carste Lagoa Santa, ao norte de Belo Horizonte, Minas Gerais, Brasil. A região contém importantes aquíferos cársticos e cárstico-fissurais, fontes essenciais de água para usos urbanos, industriais e agrícolas. Classificar a área em classes de vulnerabilidade à contaminação fornece base à gestão sustentável desses aquíferos pelos órgãos reguladores, garantindo disponibilidade hídrica às populações presentes e futuras. A área foi analisada através do sistema paramétrico EPIK, que, mediante variáveis geológicas, geomorfológicas e hidrológicas específicas, segrega a região em classes de vulnerabilidade à contaminação. Como este método foi desenvolvido na Suíça, clima temperado, foi necessário adaptá-lo à região cárstica tropical deste estudo. Consequentemente, são apresentados mapas de vulnerabilidade intrínseca comparando o método EPIK original e modificado, mostrando distribuição das respectivas classes na área. Notavelmente, a classe de vulnerabilidade muito alta representa 10% da área total (49,8 km2), correspondendo a locais com perfis de solo delgados e/ou onde ocorrem afloramentos e dolinas. Os resultados sugerem que esse método é altamente eficaz; entretanto, o parâmetro de camada de proteção exigiu adaptação devido às condições climáticas tropicais. No método original, são definidas utilizando um amplo intervalo de espessura do solo (0-200 cm). Aplicando esses intervalos à área, a maior parte da área foi classificada em classe única, reduzindo a capacidade discriminatória do método. Portanto, alterar os intervalos para P1: 0-1,6 m, P2: 1,6-8 m, P3: 8-16 m e P4: >16 m, foi necessário para representar as condições locais.

1. INTRODUCTION

The study area, located north of the Belo Horizonte metropolitan region, capital of the state of Minas Gerais, has been an important field of archaeological, cultural and landscape research (Vianna *et al.*, 1998 *apud* De Paula, 2019). Groundwater is the primary supply for the municipalities overlying the aquifer. In these areas, water is used mainly for agriculture, animal feeding, industry, and urban supply. Several natural factors such as the type of recharge (autochthonous or allochthonous) or the degree of karst network development, contribute to the vulnerability of the aquifers, increasing the susceptibility of groundwater systems to contamination and potentially affecting water quality and reservoir supply.

The geomorphological development of the karst makes each system unique, and the understanding of its evolution considers studies of surface and groundwater circulation conditions. Karstification has as its main agent the chemical dissolution of the carbonate rocks, being governed mainly by the compositional difference, the presence of primary and secondary sedimentary structures and the fracturing directions, which promote and or change the porosity and permeability of the medium (White, 2003).

The conscientious management of the territory, the use of the soil, its mineral and water resources must initially pass through extensive studies of the region. Considering the underground flow, which is more complex and unknown, these studies should be even more thorough, because due to its isolation and large volume, small alterations can have catastrophic effects at the regional level.

Intrinsic vulnerability is defined as a function of the geological, hydrogeological, and hydrological properties of a system and independent of the properties of a specific contaminant. In contrast, specific vulnerability considers the properties of a particular contaminant or group of contaminants in addition to the intrinsic vulnerability of the area (Zwahlen, 2003).

Parametric vulnerability assessment systems use selected parameters as indicators of vulnerability, overlaid on maps that combine specific physical features that affect vulnerability, often giving a numerical score to produce some form of vulnerability index, relative or absolute (Vrba; Zaporozec, 1994; NRC, 1993).

Among the parametric systems there are several methods for the evaluation of intrinsic vulnerability, some for application in any type of aquifer such as: AVI (Von Stempvoort *et al.*, 1992), DRASTIC (Aller *et al.*, 1987), SINTACS (Civita *et al.*, 1997) and GOD (Foster, 1987; Foster *et al.*, 1988); and others developed specifically for karstic aquifers, especially the EPIK method (Doerfliger; Jeannin; Zwahlen, 1999) and the COP method (Vias *et al.*, 2002, 2006).

The EPIK method was made for karstic environments in Switzerland's mountains in temperate climate, disregarding dense vegetation, for example (Ford; Williams, 2007 *apud* Pereira *et al.*, 2019). The EPIK method was development exclusively to karst aquifer and emphasize the vulnerability of cavities (Zupo, 2024). Another factor for the use of this method was the wide range of factors that it makes available for analysis

As this method was developed in Switzerland, a temperate climate region, it was necessary to adapt it to the tropical karstic region. As a result, the intrinsic vulnerability maps of the original and modified EPIK method are presented for the study area, which segment the area into their respective vulnerability classes.

The study aimed to map the intrinsic vulnerability of aquifers to identify areas naturally more susceptible to contamination and requiring priority in protection and environmental measures The resulting vulnerability map supports groundwater protection land-use planning decisions by guiding management strategies.

2. CHARACTERIZATION OF THE STUDY AREA

The study region has an area of 505 km2 and includes the Environmental Protection Area (EPA) Karst Lagoa Santa and extending beyond its boundaries to the north and west (Figure 1). It is located 35 km from Belo Horizonte, in the northern sector, encompassing part of the metropolitan region of the state capital. The region is occupied by large properties involved in agribusiness, mining operations and residential condominiums. There is also the Tancredo Neves International Airport, located in the municipality of Confins.

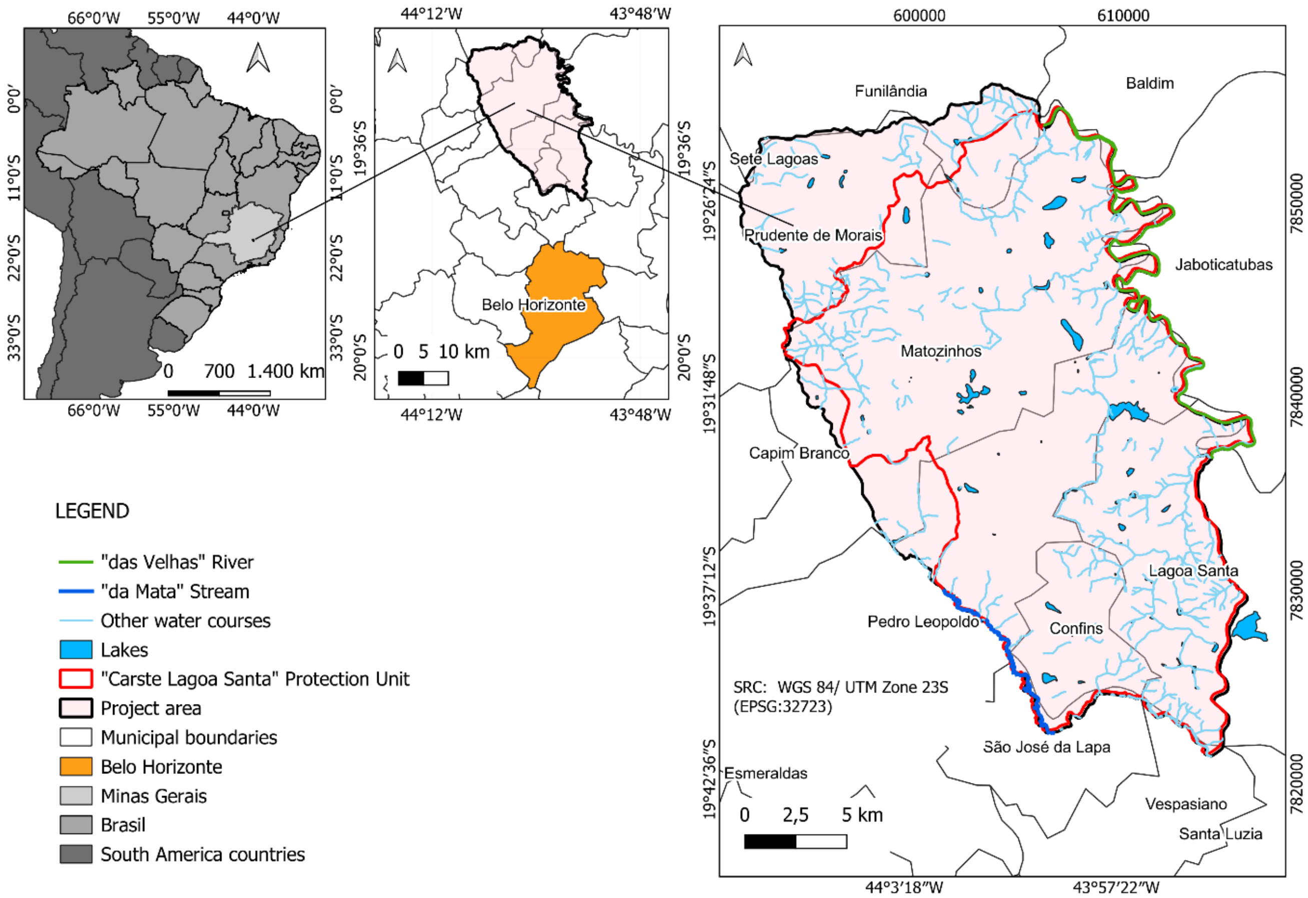

Figure 1. Location Map of the Study Area with delimitation of EPA Karst Lagoa de Santa. Source: Authors (2026).

According to Köppen's climate classification (1936), the region corresponds to the Tropical Humid (Aw) type, with a dry winter and a predominantly hot summer. Two well-defined seasons occur: one from October to March, being humid and hot; and the other from April to September, dry and relatively cold. According to the weather station closest to the study area, the Sete Lagoas station (code A569), operated by the National Institute of Meteorology (INMET), the mean annual rainfall is 1283 mm (1961 to July 2016), the mean annual maximum temperature is 28.5°C and the mean annual minimum temperature is 15.9°C.

The native vegetation of the area is the Cerrado, with sparse plants and trees of variable heights, which can reach up to 8 m, with twisted trunks and coriaceous or hairy leaves. This biome is found only in remnants, and the region has been greatly altered by agribusiness and mining and urbanization processes. The Decidual Seasonal Forest or "Dry Forest" occurs associated with the limestone massifs and has many lianas and bushes containing thorns. There is also the Semideciduous Seasonal Forest, which occurs in dolines and around massifs; and along drainages, it is common to find the presence of well-developed riparian forest (Tuller *et al.*, 2010).

The EPA Karst Lagoa Santa is located within the federal watershed of the São Francisco River and more specifically in the state watershed of Velhas River. There are few surface drainages in the area, since karstification favors the groundwater flow. Thus, the water flow is predominantly underground, and its regional base level is the Velhas River, and the surface runoff occurs on a smaller scale, characterized by a drainage network of low density (Viana; Tavares, 1998).

In the study region, typical karstic geomorphology dominates, presenting several rock masses of large dimensions and intensely fractured, as well as dolines, uvalas, blind valleys, limestone walls, caves, recesses, among other structures. This domain occurs throughout the central area and overlies the limestones. Another geomorphological domain occurs in the marginal limits of the area and in the southeast portion, where pelitic sedimentary rocks predominate. This presents an undulated, hilly, and lowered relief. Still, in the drainages it is common to find detrital alluvial sediments, constituting the fluvial terraces (Shinzato, 1998).

The EPA exposes numerous classes of soil, predominantly the dark red latosols and, subordinately, cambisols and dark red podzolic. These, in general, are characterized by the hegemony of components of silt and clay granulometry, are well drained, deep and have good porosity and permeability (Shinzato, 1998).

The study area is situated on the southeastern border of the São Francisco Intracratonic watershed, in the southern portion of the Craton São Francisco. The stratigraphy of the area is composed of a gneissic-migmatitic basement underlain by basal units of the Bambuí Group (Ribeiro *et al.*, 2003). Figure 2 shows the geological map of the study area.

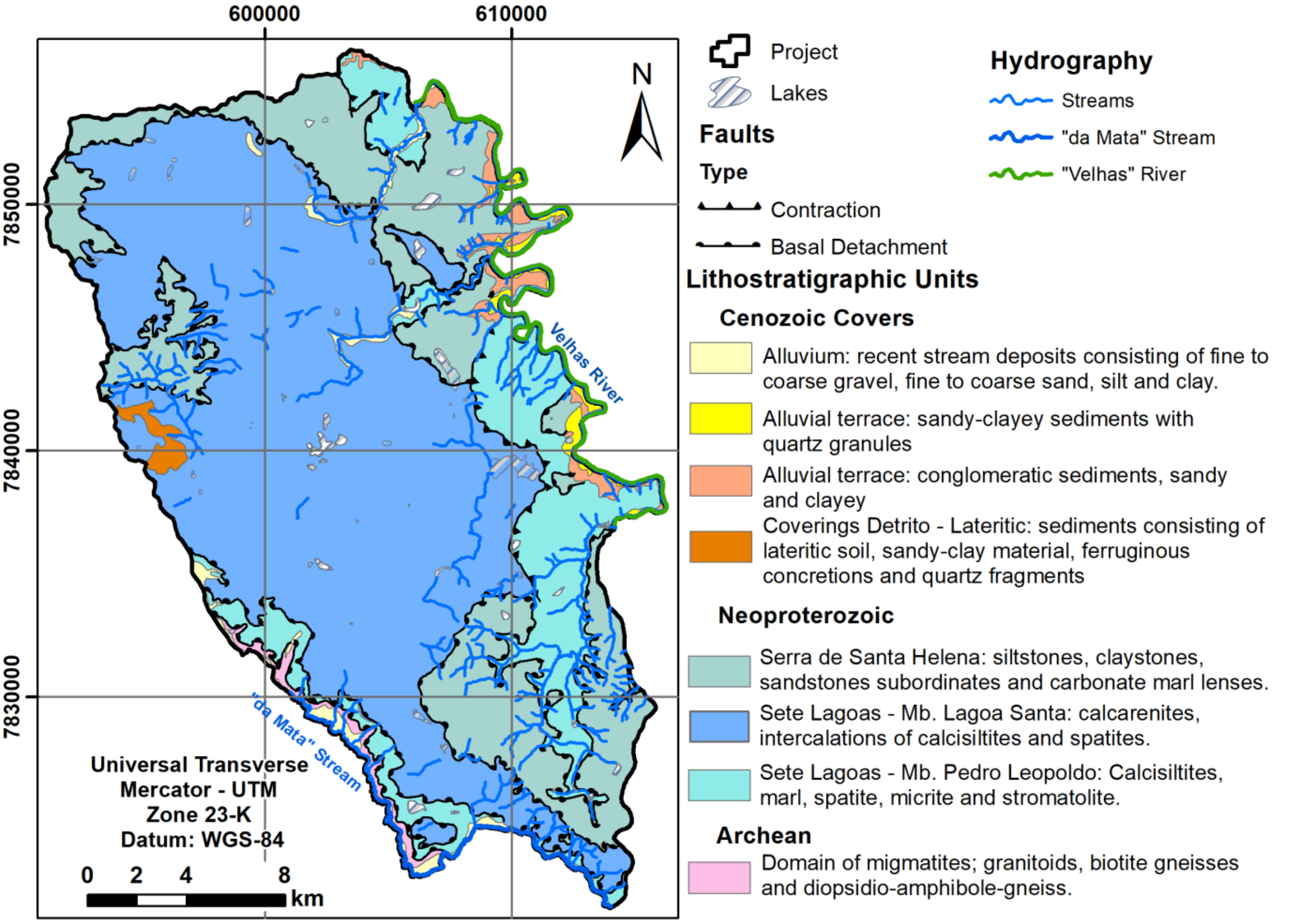

Figure 2. Geological map of the studied area. Source: Ribeiro *et al.* (2019).

The Belo Horizonte Complex presents a granite-gneissic-migmatitic composition, with textural and structural patterns varying from banded, strongly foliated to incipient and isotropic rocks (Ribeiro *et al.*, 2003). This unit outcrops only in some strips to the west and south of the area, where it is uplifted, and the watershed is shallower.

In the studied region, the basal unit of the Bambuí Group corresponds to the Sete Lagoas Formation divided into two members. The Pedro Leopoldo Member, at the base, is composed of calcissiltites; microspatites/spatites; micrites; subordinately, very thin calcarenites; marls and protoderivative milonites. It occurs in the eastern and southwestern extremes of the studied area and presents a thickness of about 150 m. The Lagoa Santa Member overlaps the Pedro Leopoldo Member and is formed by calcarenite, calcisiltite, spatite/microspatite, breccia, stromatolites and protoderived milonites (Ribeiro *et al.*, 2003). This presents thickness of around 100 m, outcropping throughout the central-western portion of the study area Ribeiro *et al.* (2019).

The Serra de Santa Helena Formation occurs overlying the Sete Lagoas Formation and in this formation siltstones and argillites predominate, and, more rarely, carbonate sediments in the form of lenses of different dimensions, sparsely distributed and corresponding to very fine marls and calcarenites (Ribeiro *et al.*, 2003). This formation occurs in the northeast, southeast and northwest portions of the study area as small shapeless bodies, representing remnants of a differentiated and very intense erosion. The thickness of this unit reaches values ranging from a few cm to 200 m (Magalhães; Silva, 2018).

The Cenozoic covers are represented by detrital-lateritic covers and alluvial deposits. The detrital-lateritic covers are composed of fine gravel, sand, silty-clayey material and limonitized portions. These occupy about 1% of the area, occurring in an elongated and irregular band in the western portion of the study area. Their thickness is variable, generally greater than 2 m. Alluvial deposits occupy 5% of the area (De Paula, 2019) and are divided into recent alluvial deposits, which are found associated with current drainages, and alluvial terraces, which are older and lie below the recent deposits, and are commonly found in the vicinity of the Velhas River. The composition of alluvial deposits encompasses gravels, sands, clays, and silts (Ribeiro *et al.*, 2003).

2.1. Hydrogeology

According to De Paula (2019), the hydrogeology of the area is divided into four hydrostratigraphic units: the fissural crystalline aquifer, the karstic-fissural Sete Lagoas aquifer, the Serra de Santa Helena aquitard, and the granular cover aquifer. The following paragraphs explain this division in more detail.

The crystalline aquifer occurs within the gneissic-migmatitic complex. It is a confined aquifer in most of the area, where it is overlain by the metasedimentary rocks of the Bambuí Group and, in the small outcropping area to the south, it constitutes an unconfined aquifer. It has fissure-type porosity, in which groundwater flow occurs through discontinuities, mainly along fracture planes resulting from the tectonic activity in the region.

The most important and representative aquifer in the region is related to the Sete Lagoas Formation, being of the karstic-fissure type, due to its predominantly carbonate composition with pelitic intercalation and tectonic influence. It occurs in the limestones of the Lagoa Santa Member, which is intensely karstified, and in the Pedro Leopoldo Member, which is less karstified and where the well-developed groundwater flow occurs mainly through fractures and along bedding planes. In the karst compartment, the modal value found for hydraulic conductivity was 10^{-3} m/s and in the karstic-fissural compartment it was on the order of 10^{-7} m/s (De Paula,2019). Permeability in karst aquifers depends primarily on fractures and dissolution conduits, which are strongly influenced by rock dissolution. These openings may range from millimeters to hundreds of meters in size (White, 2002, 2003 *apud* De Paula 2019). The presence of well-developed dissolution conduits increases hydraulic conductivity by providing rapid groundwater flow, resulting in a higher hydraulic conductivity in karst aquifers than in karst-fissural aquifers. It is an unconfined aquifer in most of the study areas and semi-confined in the portions where it is overlain by the Serra de Santa Helena aquifer.

The metapelites of the Serra de Santa Helena Formation are an aquifer with fractured porosity, associated with the rock discontinuity planes (fractures and faults). These rocks may function more as recharge zones for carbonate aquifers than as a productive aquifer, although hydrogeological investigations would be required to confirm this hypothesis.

The cover units correspond to the presence of an aquifer with granular-type porosity. This type of aquifer is unconfined and, in general, presents low groundwater potential. Its main characteristic is that it functions as a recharge zone for the underlying aquifers and is exploited through cisterns and wells, usually for domestic supply.

According to Pessoa (2005), the circulation conditions in karst-fissure aquifers are determined by the dissolution capacity of the carbonate rocks and their fracture density. The primary porosity of carbonates does not classify them as aquifers. However, because of the interconnection between fractures and rock stratification planes, there is a significant increase in conductivity in these zones.

According to Shuster and White (1971), the differentiation between fissure and karst systems is related to the groundwater circulation system, which is represented by laminar flow in fractures, and in the latter, by turbulent flow in conduits. In the latter, water circulates in irregular channels of high hydraulic conductivity, contrasting with the low conductivity of the adjacent rock. Because of these characteristics, the discharge usually occurs at a large spring.

Sinkholes, dolines, spring, and upwellings allow direct groundwater connection to surface drainage, which increases recharge efficiency, but also increases aquifer vulnerability.

3. MATERIALS AND METHODS

The EPIK method was first applied in Switzerland, within the zone of influence of springs used for public water supply in the municipality of St-Imier (Doerfliger; Jeannin; Zwahlen, 1999). It was the first method developed specifically for mapping the intrinsic vulnerability of karst aquifers.

Based on specific geological, geomorphological, and hydrological factors, the intrinsic vulnerability index is evaluated using four parameters: *Epikarst (E), Protective Cover (P), Infiltration Conditions (I), and Karst Network Development (K)*. The Protection Index is obtained by Equation1 and multiplies each parameter by its respective weight. These weights were defined after several empirical tests during the development of the method.

Equation 1: Protection Index: (P_{Ind})

$$P_{Ind} = (\alpha.Ei) + (\beta.Pi) + (\lambda.Ii) + (\delta.Ki)$$

$$where\ \alpha = 3, \beta = 1, \lambda = 3\ and\ \delta = 2$$

Thus, the result of the equation allows the classification into four vulnerability classes according to Doerfliger, Jeannin and Zwahlen (1999). The very high vulnerability class considers an index less than 20. The high vulnerability class presents an index between 20 and 24. The moderate vulnerability class corresponds to an index greater than 25. Finally, the low vulnerability class also considers an index greater than 25 but requires the parameter Protective Cover as P4, representing the highest protection scenario.

The Epikarst Parameter (E) represents the degree of epikarst evolution with its respective degree of permeability at the surface and subsurface. These zones are indirectly characterized by geomorphological features that can be easily mapped. Table 1 details the criteria for this classification.

Table 1. Attribute classes of the Epikarst (Doerfliger; Jeannin; Zwahlen, 1999).

Epikarst	Index	Grade	Karst morphological features
Highly developed	E_1	1	Caves, sinkholes or dolines, outcrops with high fracturing.
Moderately developed	E_2	3	Intermediate zones in the alignment of dolines, dry valleys. Outcrops with medium fracture.
Small or absent	E_3	4	No Karst morphological phenomena. Low density of fractures.

Source: Authors (2026).

The Epikarst (E) map was made entirely from geological data of previous studies in the area, using ArcGIS 10.3 software, analyzing and compiling these data (Figure 3 a). A more conservative analysis was always chosen, assigning a higher vulnerability score whenever there was uncertainty.

Amaral (2018) defined the karstic depressions in the study area by means of geoprocessing, remote sensing, and field surveys for the verification of these features. From this study, the delineation data of rock outcrops were also adopted.

To evaluate the fracture index of the outcrops delineated by Amaral (2018), point description tables from Ribeiro *et al.* (2016) and Magalhães and Silva (2018) were compiled. For outcrops that were not visited during fieldwork, their lithology was evaluated, already mapped and refined by several studies Ribeiro *et al.* (2003), Vieira (2015), Ribeiro *et al.*, (2016), Lima, Fonseca and Matinaga (2017), Magalhães and Silva (2018) and Andrade and Amorim (2018); were evaluated, which contributed to the definition of the degree of fracturing, since the Pedro Leopoldo Member in its eastern portion is described as weakly karstified, unlike the Lagoa Santa Member. The presence of cavities in these massifs, obtained from cave mapping by Canie (2020) was also considered. The doline alignment zones were obtained by creating “buffers” around lineaments that interconnected these structures. The lineaments were obtained from SRTM image geoprocessing, and the buffer width of each lineament was set equal to the width of the interconnected dolines.

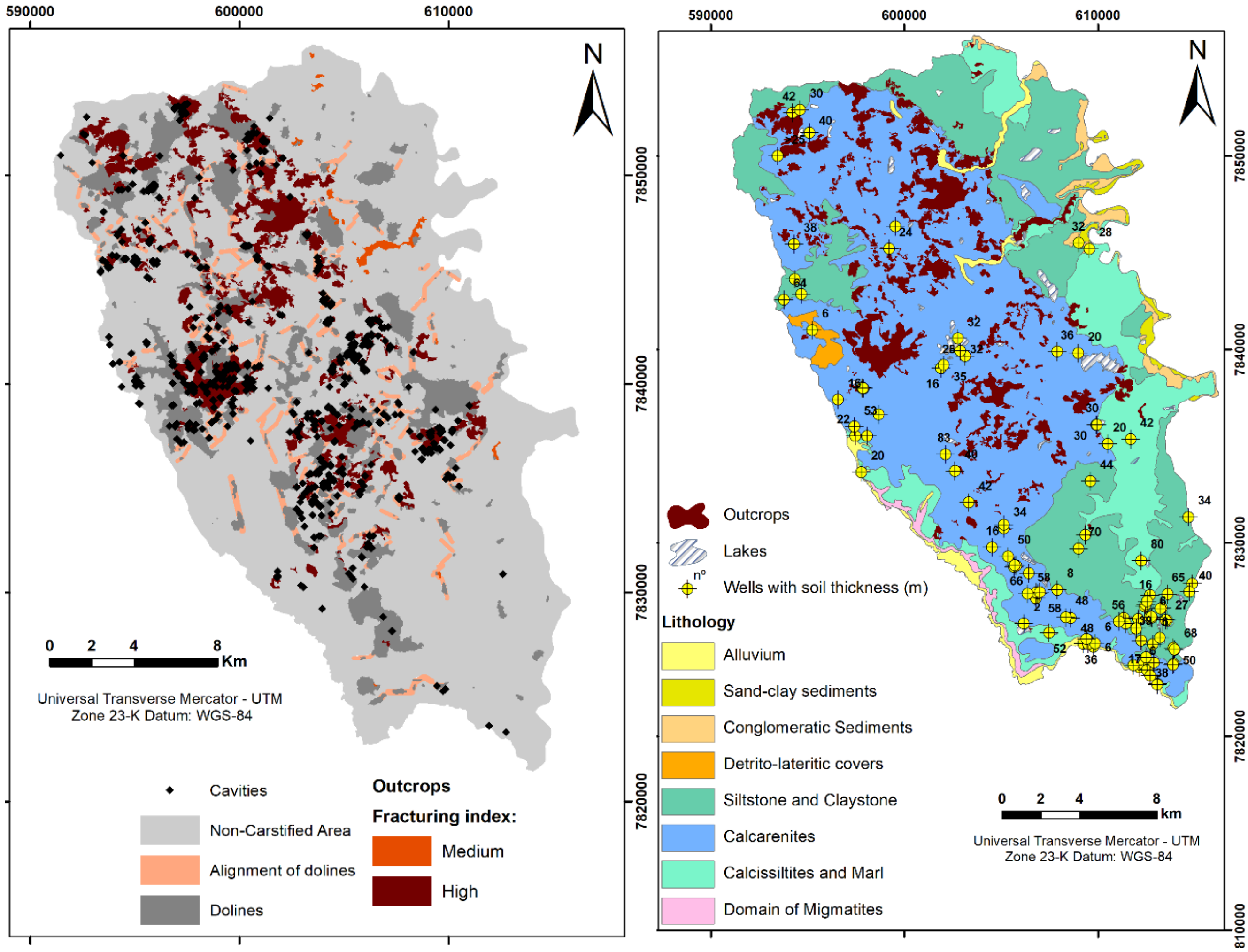

Figure 3. a: Karst morphological features – Database for Epikarst Map; **b:** Soil thickness and lithology - Database for protective cover map. Source: Authors (2026).

Protective Cover (P) integrates soil and other geological coverings such as quaternary deposits and other non-karstic layers. The upper unconsolidated zone covering the aquifer is commonly considered one of the most important attributes in groundwater vulnerability assessment. It potentially has an important attenuation capacity for several types of contaminants (Zaporozec, 1985), depending on the specific characteristics of these materials.

In particular, the soil thickness is strongly related to the water residence time and is an important property when assessing groundwater vulnerability. In the EPIK method, this parameter assumes that thinner soil provides less protection for the aquifer, as there is less soil available for water to infiltrate before reaching the groundwater.

As a first approach, the method suggests considering the thickness of the protective cover as a basic parameter and its hydraulic conductivity (Doerfliger; Jeannin; Zwahlen, 1999), distinguishing two scenarios, one of high and one of low permeability of the geological layers covering the limestone (Table 2).

The information about the thickness of the protective covers of the karstified rocks was obtained from existing wells in the area, registered with government water resources agencies **(Supplementary data I)**. The cataloged data were then superimposed on the geological map of the area and critically analyzed, considering the lithological characteristics of the mapped materials and the description of the drilling profiles of the tube wells. At the end of this analysis, consistent data from 105 well profiles were obtained (Figure 3 b).

As expected, the soil thickness values far exceed the maximum of 8 m established by the method. It is important to consider that this method was developed in Switzerland, where weathering processes are less intense than humid tropical areas, resulting in thinner and less developed soils. Therefore, the EPIK method was adapted to tropical context, and the details are presented in the following sections.

Table 2. Attribute classes of the Protective cover (Doerfliger; Jeannin; Zwahlen, 1999).

Protective cover	Index	Grade	Characterization	
			A. Soil lying directly on limestone or on some high permeability layers.	**B. Soil lying on low permeability geological layers.**
Absent	P1	1	0 – 20 cm of soil	0–20 cm of soil on layers that have a thickness of less than 1 m
↓	P2	2	20 – 100 cm of soil	20–100 cm of soil in layers that have a thickness of less than 1 m
	P3	3	100 – 200 cm of soil	<100 cm of soil or >100 cm of soil and >100 cm of layers of low permeability
Present	P4	4	> 200 cm of soil	>100 cm of soil and thick detritus layers of very low hydraulic conductivity (point-information needs to be checked) or >8 m of clay and clayey silt.

Source: Authors (2026).

Infiltration Conditions (I) considers the type of recharge from the karstic aquifer, not including recharge in terms of quantity. Diffuse and concentrated recharge have different vulnerability inferences. Four classes of infiltration are defined and can be seen in Table 3.

Surface runoff tends to concentrate on the flow, which results in higher vulnerability. Steep slopes and poor vegetation also exacerbate this problem because it is assumed that there is more runoff that will infiltrate into the low-lying areas.

To produce the infiltration conditions map, the slope map was generated using geoprocessing techniques applied to 12.5 m resolution ALOS PALSAR images (JAXA, 2016) of the study area. The drainage network and watersheds were obtained from De Paula (2019) while the sink points were obtained from Teodoro *et al.* (2019). The karstic depressions data, as well as the Epikarst map, were obtained from the work of Amaral (2018). The land-use for cultivation or pasture was manually vectorized in ArcGIS based on visual interpretation of Landsat satellite imagery provided by the Google Earth platform, supported by extensive project area knowledge acquired over three years of field activities.

Table 3. Attribute classes of Infiltration conditions (Doerfliger; Jeannin; Zwahlen, 1999).

Infiltration conditions	Index	Grade	Characterization
Concentrated	I_1	1	Perennial or temporarily losing streams – perennial or temporarily stream feeding a swallow hole or a sinkhole (doline) – water catchment areas of these above-mentioned streams, including artificial drainage system.
↓	I_2	2	Water catchment areas of streams in I1 (without artificial drainage system) with a slope greater than 10% for cultivated areas and 25% for meadows and pastures.
	I_3	3	Water catchment areas of the I1 stream (without artificial drainage system) whose slope is less than: 10% for cultivated areas and 25% for meadows and pastures. Low relief areas collecting runoff water and slopes feeding those low areas (slope higher than: 10% for cultivated sectors and 25% for meadows and pastures).
Diffuse	I_4	4	The rest of the catchment.

Source: Authors (2026).

All these data were analyzed together for the definition of the infiltration index assigned for each of the watersheds, based on the valuations proposed by the EPIK method for the infiltration conditions parameter (Figure 4 a).

The index I_1, which represents concentrated infiltration, was attributed to areas delimited by watersheds that present water flows that flow into sinkholes that direct the water flow to the deep aquifer, according to studies carried out with tracers by Teodoro (2020). The other sinks analyzed in this study showed connectivity of the non-deep aquifer or did not get concise data on connectivity, showing a less concentrated connectivity with the deep aquifers, which have higher vulnerability.

The indices I_2 and I_3, which represent an intermediate infiltration, presented difficult separation based on the proposed factors, because these regions and the cultivated areas are widespread among the pastures because they are used as input for livestock. There are also some properties that have their area occupied by occasional eucalyptus plantations. Still, the areas with a slope greater than 25% are almost exclusively delimited by the occurrence of rock outcrops. Therefore, it was not possible to attribute index 2 to any area, because in proportion, in the watershed delimitations, there are more water collection areas whose inclination is less than 10% for cultivated areas and more than 25% for meadows and pastures.

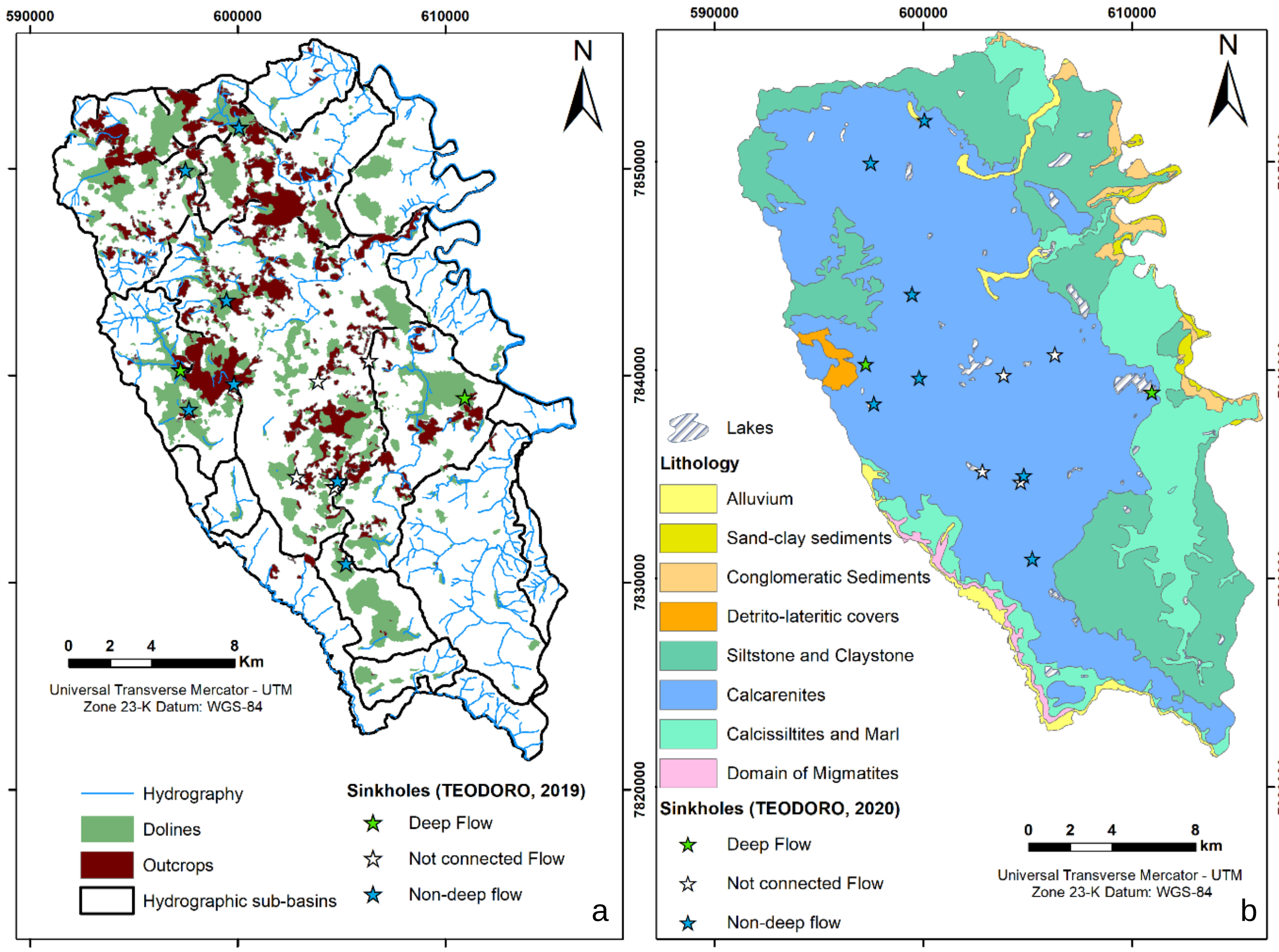

Figure 4. a: Hydrography and infiltration features – Database for Infiltration Conditions Map]; **b:** Sinkholes and lithology – Database for Karst Network Development Map. Source: Authors (2026).

The I_4 index, which shows diffuse infiltration, was attributed to the rest of the area that has its water courses directed on the surface towards the main drainages that delimit the area to the east and west/south, respectively, Velhas River and "da Mata" Stream.

The **Karst Network Development parameter (K)** and its degree of organization play an important role in the speed of water flow and thus in vulnerability. A karst network - or cave system - is a network of conduits with openings greater than 10 mm in diameter or width. This size is the minimum effective opening at which turbulent flow develops under natural conditions (Doerfliger; Jeannin; Zwahlen, 1999). The network can be well developed and connected, depending on the karstic systems considered (Table 4).

According to Doerfliger, Jeannin and Zwahlen (1999), three main types of methods can be applied to evaluate this attribute and its classes, depending on data availability. These methods are short-term discharge analysis; long-term discharge analysis and testing with artificial tracers.

Table 4. Attribute classes of Karst network development (Doerfliger; Jeannin; Zwahlen, 1999).

Karst network	Index	Grade	Characterization
Well-developed Karst network	K1	1	Presence of a well-developed Karst network (network with decimeter to meter sized channels that are rarely plugged and are well-connected).
Poorly developed Karst network	K2	2	Presence of a poorly developed karst network (small conduits network, or poorly connected or filled network, or network with decimeter or smaller sized openings).
Mixed or fissured aquifer	K3	3	Presence of spring emerging through porous terrain. Non-karst, only fissured aquifer.

Source: Authors (2026).

In this work, we chose to use the artificial tracer testing method, where flow velocity values, obtained through artificial tracer tests, can identify, and characterize the karst network. The transit velocity is calculated from the first arrival time or the average peak time. This speed depends on the hydrodynamic conditions and the development of the karst network. If the average transit velocity coming from a sinkhole (usually connected to the karstic network) is higher than 15 m/h in dry stages and 75 m/h in the wet period, it means that a karstic network is present. Lower velocities obviously do not imply the absence of a karstic network.

The assignment of the indices of this parameter was performed by the dye tracer test method carried out by Teodoro (2020), who found, in addition to the water interconnections described in *Infiltration Conditions (I)* section, the aquifer volumes in the investigated conduits, which ranged from 1512.8 m^3 to 38,246.4 m^3. This method also inferred the diameters of the conduits, which ranged from 0.63 m to 2.40 m, from the measurement of the flows at the injection and monitoring points, the residence time, and the percentage of tracer mass recovered. The average apparent velocities calculated for the water flow in the routes evaluated ranged from 8.90 x 10^{-3} m/s to 4.49 x 10^{-2} m/s and, considering the sinuosity factor of the route, from 1.34 x 10^{-2} m/s to 6.74 x 10^{-2} m/s, which shows the high velocity of the flows. These values, as proposed by the EPIK method, point to a well-developed karstic network.

The tests conducted by Teodoro (2020) were in regions where the Lagoa Santa Member outcrops predominantly, as shown in Figure 4 b, which is characterized by a purer limestone rock. Thus, the geological mapping of the region was a second weighting factor, where an intermediate level of karstic development was attributed to the Pedro Leopoldo Member, which is lithologically less pure, with a lower degree of karstification than of the Lagoa Santa Member in the areas bordering the study region. The other lithologies are not karstic, receiving the lowest score in this parameter. Thus, the Lagoa Santa Member was classified as K1, the Pedro Leopoldo Member as K2 and other lithologies (non-karst lithologies) as K3.

3.1. Modifications of the original method

As already foreseen and noted, during the making of the protective cover map, the method should undergo modifications for application in tropical karst, since this method was elaborated for karst areas in a temperate climate.

Therefore, the first modification was the adaptation of the parameter protective cover. Therefore, the table of indexes for this parameter had its values modified, considering the conceptual model used to formulate the EPIK method and the hydrogeological model performed by De Paula (2019).

In the construction of the EPIK method (Doerfliger*;* Jeannin; Zwahlen, 1999) the conceptual model of a karst aquifer includes a network of conduits of high hydraulic conductivity and small volume. This layer called the Epikarst, also called the “subcutaneous zone” is an immediate, highly fissured underground zone due to dissolution and pressure release of the rock near the ground surface. According to the authors, this epikarstic layer would present a depth of up to 10 m, even in tropical areas. However, comparing this definition to De Paula's (2019) hydrogeological model, we see that this thickness is much greater.

De Paula (2019) defined two aquifer compartments for the area: an upper, more karstified one, called the karstic compartment in the interval contained between elevations 638 and 716 m; and a lower compartment, called the karst-fissure, installed at elevations lower than 638 m. In the karstic compartment the modal value found for the hydraulic conductivity was 10^{-3} m/s and in the karst-fissure compartment, of the order of 10^{-7} m/s.

To redefine the intervals of Protective cover, the ratio between a maximum thickness of epikarstic zone considered in the original EPIK method in tropical area (10 m) and the maximum thickness of the upper zone of high permeability defined by De Paula (2019) for the study region (78 m) was calculated. The calculated ratio (7.8) was rounded to 8 and used to multiply the original intervals, according to Table 5.

Table 5. New attribute classes of the Protective cover (Modified to Doerfliger; Jeannin; Zwahlen, 1999).

Protective cover	Index	Grade	Characterization: A. Soil lying directly on limestone or on some high permeability coarse detritus layers.	Characterization: B. Soil over low permeability lithologies
Absent	P1	1	0 – 1,6 m of soil	0 – 1,6 m of soil on layers that have a thickness of less than 8 m
	P2	2	1,6 – 8 m of soil	1,6 – 8 m of soil over layers less than 8 m thick
	P3	3	8 – 16 m of soil	< 8 m of soil or > 8 m of soil and > 8 m low-permeability layer
Present	P4	4	> 16 m of soil	> 8 m of soil and thick layer of debris with low hydraulic conductivity or > 64 m of clay or silty clay

Source: Authors (2026).

Thus, the data from the 105 well profiles were analyzed again and a division into the two soil types was possible. Figure 5-a shows the delimitation of type A soils, i.e., deposited directly over limestone or layers of high permeability. Figure 5-b shows the delimitation of type B soils, corresponding to soils overlain by layers of low permeability. The soil thickness data were valued according to parameters (P1 to P4) and interpolated by IDW, with power exponent of 2 and output raster resolution of 12,5 m. method, generating the assignment of classes for the protective cover. This is a widely used local and deterministic interpolator in geoprocessing to convert point data into raster.

Another necessary change was the modification of the weights assigned to each parameter, because in the original method the most important factors were the epikarst and the infiltration conditions, followed by the karstic development and last, least relevant, the protective cover (see Equation 1). However, in tropical regions, due to strong weathering, the soil layer covering the aquifer is a major factor in mitigating groundwater contamination (Souza, 2020). As stated by the authors of the method, "The choice of these weighting factors and of the values assigned to the different classes of each attribute is empirical" (Doerfliger; Jeannin; Zwahlen, 1999). Therefore, different weighting combinations were evaluated based on the hydrogeological characteristics described by De Paula (2019). The resulting vulnerability maps were compared, and these weights were chosen because they provided the most consistent representation of the study area. This approach follows the empirical nature of the EPIK method proposed by Doerfliger, Jeannin and Zwahlen (1999) and considers the findings of Souza (2020).

For karstic development an intermediate weight was maintained, and the other factors were reduced to weight 1, because its impact in the tropical environment is not as expressive as in the temperate environment, given the development of these structures and their filling with sediments and vegetation. Thus, the weights were then rearranged in the direction from higher to lower protection (Equation 2): Protective Cover (weight 3), Karstic Network Development (weight 2), Epikarst (weight 1) and the Infiltration Condition (weight 1).

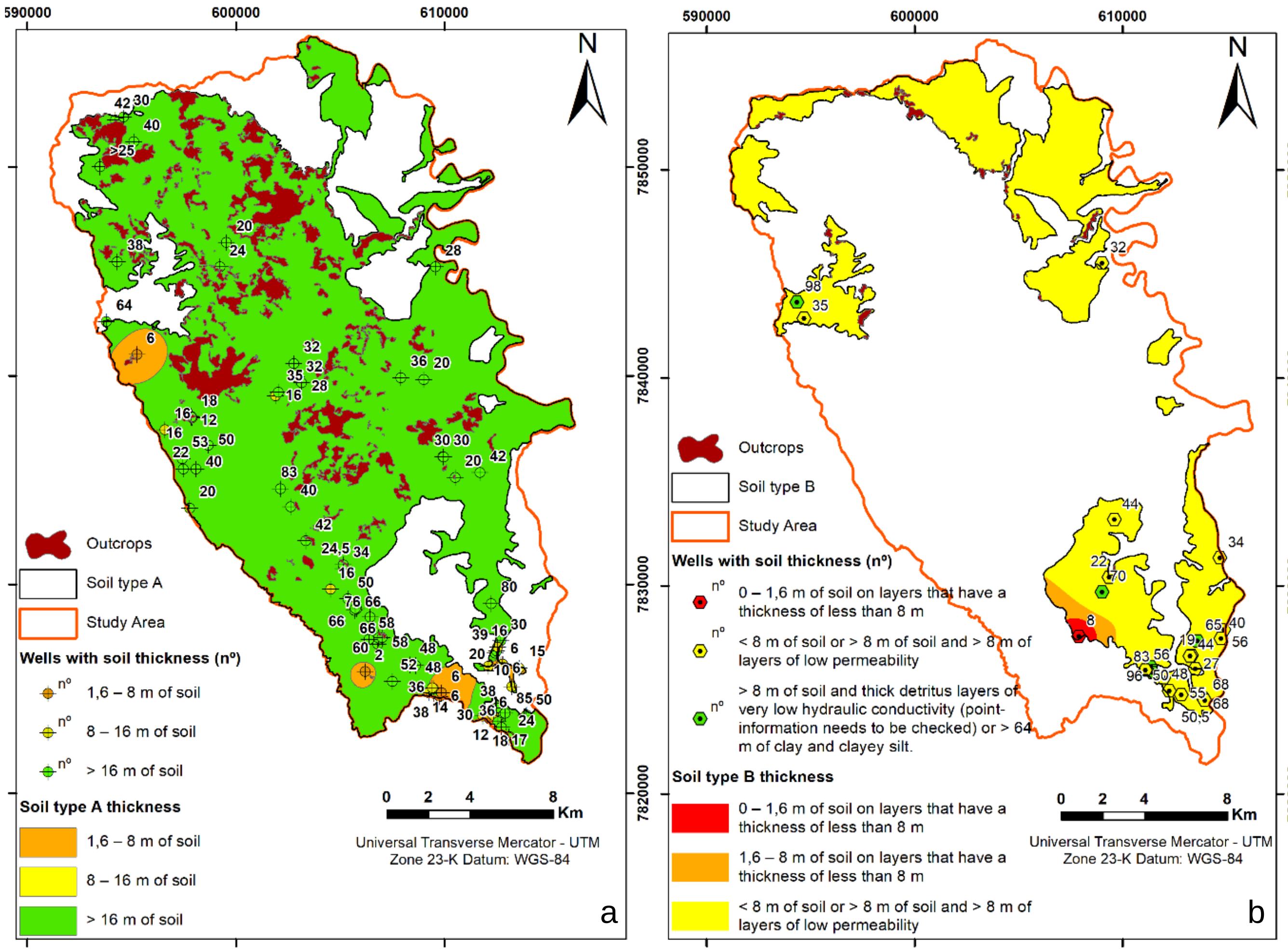

Figure 5. Database for modified protective cover map (a: Soil type A; b: Soil type B). Source: Authors (2026).

Equation 2: Modified Protection Index (MP_{Ind}):

$$MP_{Ind} = (\alpha.Ei) + (\beta.Pi) + (\lambda.Ii) + (\delta.Ki)$$

$$where\ \alpha = 1,\ \beta = 3,\ \lambda = 1\ and\ \delta = 2$$

As a result of these modifications, the minimum and maximum values of the vulnerability classes also changed, leading to the proposal of new interval values for each class for correlation with the original method. The new valuation can be seen in Table 6.

Table 6. Modified Vulnerability classes for the EPIK method.

Value	Vulnerability classes
$MP_{Ind} < 15$	Very High
$15 \leq MP_{Ind} \leq 19$	High
$MP_{Ind} > 19$	Moderate
$MP_{Ind} > 19$ with P4	Low

Source: Authors (2026).

The vulnerability class thresholds were proportionally adjusted according to the new MP_{Ind} range resulting in the modified weighting scheme. The original EPIK classification criteria were maintained, including the requirement that only areas classified as P4 (highest protective cover) could be classified as Low vulnerability.

The Intrinsic Vulnerability Classification map by the modified EPIK method was obtained after the transformation of the four specific maps (Epikarst - E, protective cover - P, Infiltration conditions - I and Karst Network

Development - K) to raster format. Thus, the values of their attributes could be summed according to Equation 2, using the map algebra feature available in the ArcGIS software, generating, using the formula, the aquifer protection indices, and the regions of greatest vulnerability.

4. RESULTS

4.1. Application of the original method

First, the maps of the four parameters proposed by the EPIK method (Epikarst - E; Protective cover - P; Infiltration conditions - I and Karst Network Development - K) are presented below. It is worth mentioning that the range of colors shows the vulnerability of the region, the red color being assigned to the most vulnerable areas, gradually changing to orange, yellow and reaching the green color, which illustrates the less vulnerable areas (Figure 6 a).

The predominance of the E3 class (approximately 74% of the study area) indicates that most of the region presents limited epikarst development, which reduces the contribution of this parameter to aquifer vulnerability. In general, well-developed karst areas present greater susceptibility to contamination due to the presence of fractures and dissolution process that generate conduits. The E1 class (22% of the area) is concentrated in the center and north, where Lagoa Santa Member occurs, consisting of purer and more karstified metalimestone, which favors infiltration pathways. The remaining 4% corresponds to E2 class, representing moderately developed karst conditions. These areas are associated with doline alignments and by some massifs in the east, west and south regions. The application of the original intervals of Protective Cover parameter did not allow an adequate differentiation of vulnerability classes, since most of the study areas presented soil thickness values greater than maximum limit established by the method. Therefore, the application of the original classification in tropical karst context seems to be limited, which indicates the need for adjustments to better reflect local conditions.

This difference is related to the characteristics of tropical environments, where higher temperatures, humidity and rainfall promote intense chemical weathering process, favor development of thicker weathering profiles over carbonate rocks. Among the 105 well analyzed profiles, all showed considerable soil thickness, ranging from a minimum of 10 m to maximum of 100 m, as shown in Figure 3 b.

Thus, except for the regions with rocky outcrops, which correspond to 46.19 km² or 9%, all the rest of the area (458.81 km²) was classified as P4 - Protective Cover Present, with a score of 4 (Figure 6 b). The method distinguishes in two cases (see Table 2), according to the presence of geological layers that cover the limestone and their hydraulic conductivity, admitting a maximum thickness of 2 m for soil deposited immediately over the limestone and >8 m when underlain by layers of low permeability.

For the parameter Infiltration Conditions an area of 79 km², or 16% of the studied area, was evaluated as having concentrated infiltration, index I1 with grade 1 – Figure 7 a. This area corresponds to two sub- watersheds that contain deep flow sinks, respectively named Palmeiras, to the west, and Samambaia, to the east. An area of 200 km² (40%) was classified as intermediate infiltration, with EPIK index I3 and grade 3. This is in the central region of the area, where the other mapped sinks occur, with non-deep flow or where it was not possible to assess connectivity. The rest of the region contains 225 km² (44%), where diffuse infiltration is observed, with an I4 index and grade 4, and whose surface drainage flows into the Velhas River to the east or into the “da Mata” Stream to the west and south.

As for the development of the karstic system, a region of 276 km², 55%, was designated as well developed, corresponding to the K1 index, with grade 1 (Figure 7 b). This is concentrated throughout a north-south strip in the area, where the Lagoa Santa Member outcrops. In 72 km², 14%, a poorly developed area was identified, being attributed the K2 index, with grade 2, with appearances in scattered portions, correlated to the Pedro Leopoldo Member, a more impure metalimestones. And in an area of 155 km², 31%, that corresponds to fissured or mixed aquifers, present in the extremities of the region, located under coverings and in the gneissic-migmatitic complex, the K3 index was assigned, with grade 3.

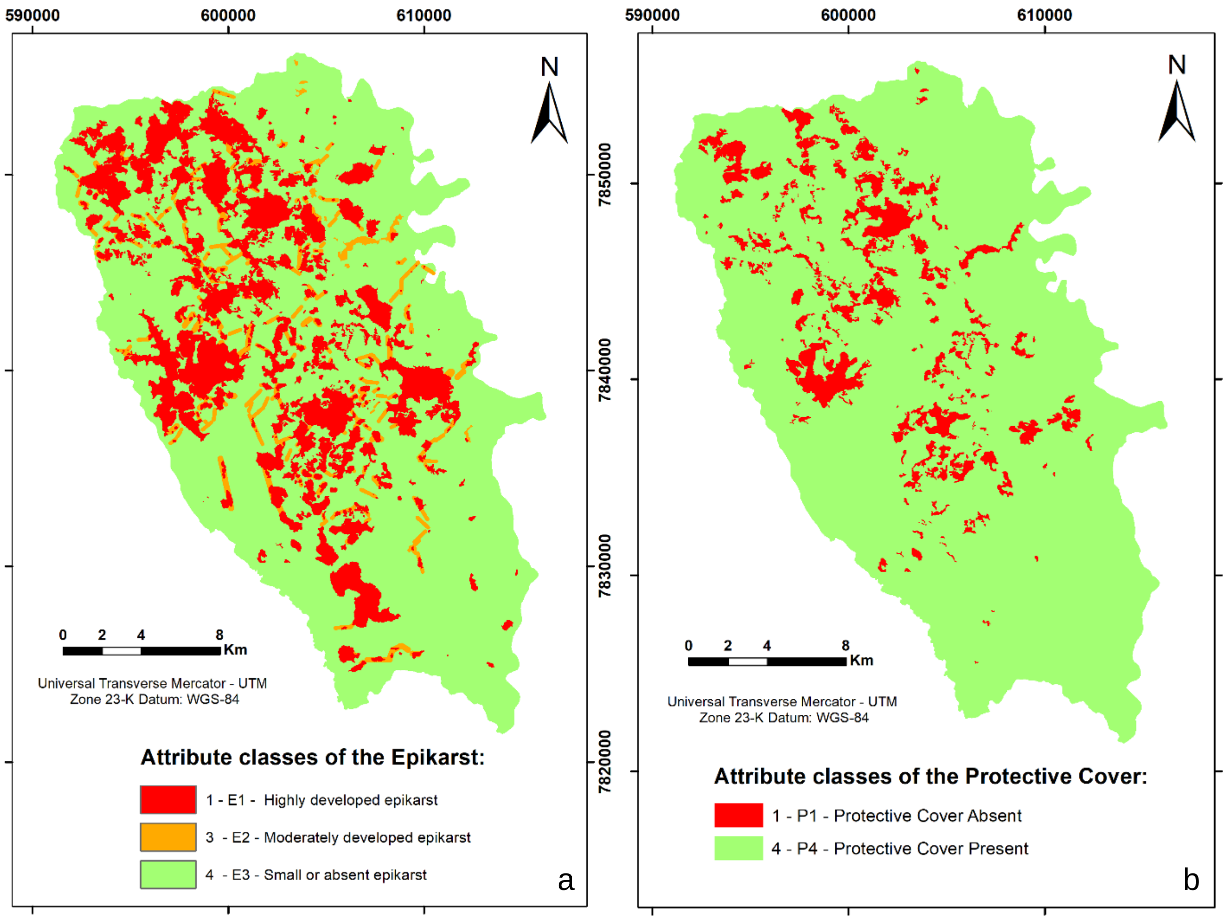

Figure 6. a: Epikarst Resulting Map; **b:** Protective Cover Resulting Map. Source: Authors (2026).

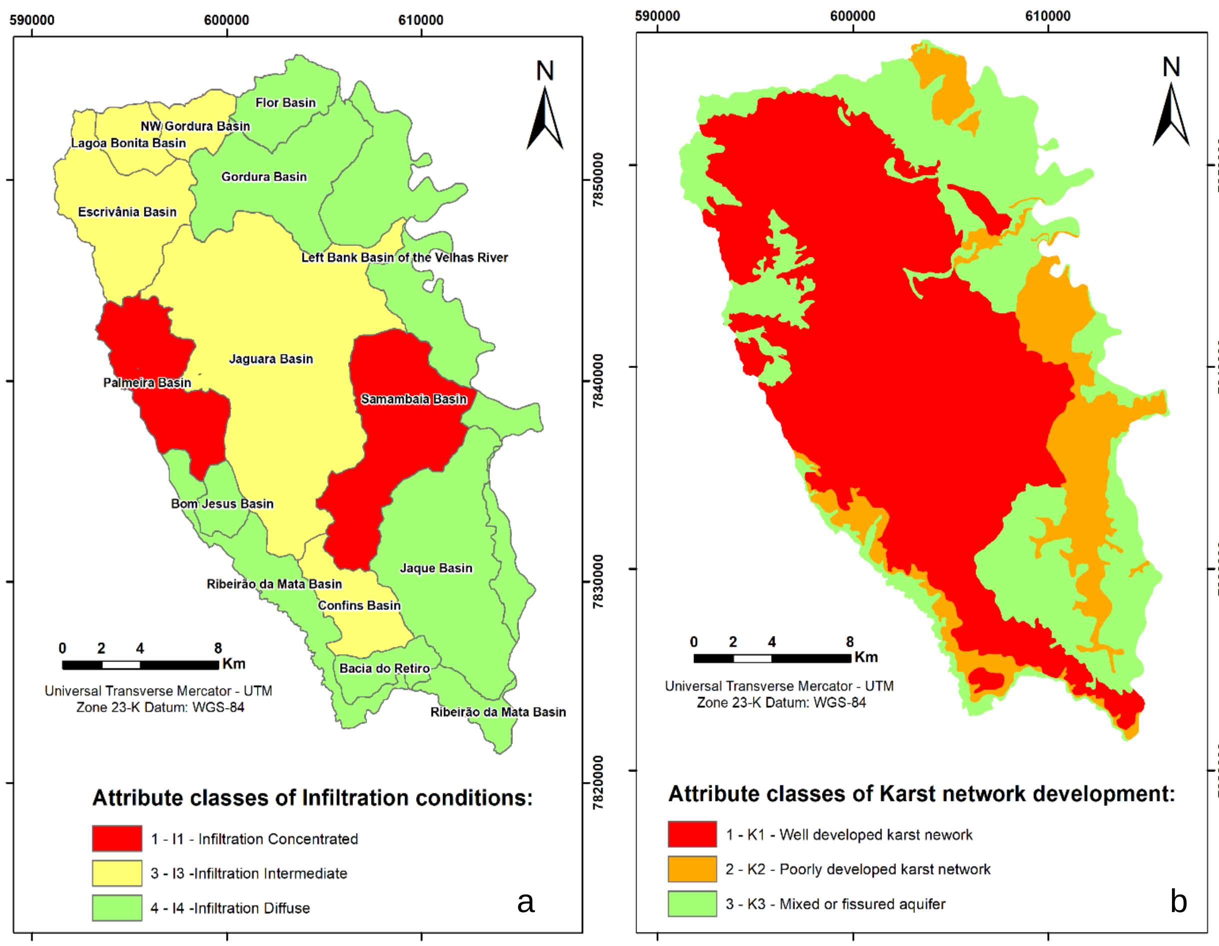

Figure 7. a: Infiltration Conditions Resulting Map; **b:** Karst Network Development Resulting Map. Source: Authors (2026).

The final map of Intrinsic Vulnerability Classification by the EPIK method is shown in Figure 8.

For the very high vulnerability class an area of 98 km² was mapped, corresponding to 19% of the total area, the high vulnerability class represents an area of 78 km² (15%). The moderate vulnerability class has very low representativeness, with only 0.7 km² and 0.14%, demonstrating the non-adherence of the application of the unchanged method to the tropical karstic region. Finally, the low vulnerability class refers to the rest of the region, with 327 km² (65%).

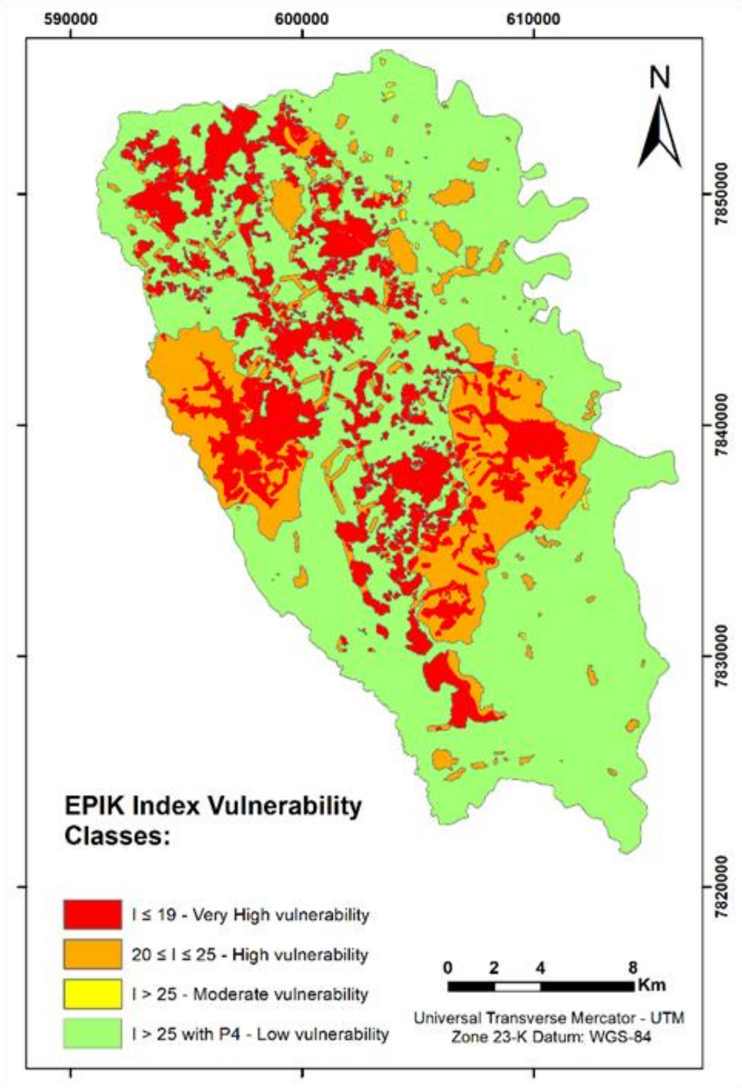

Figure 8. Vulnerability classes map of the EPIK Method. Source: Authors (2026).

The final map shows that the central area, where the limestone outcrops and dolines occur and where the purest and most karstified lithological member is found, were classified as having the very high vulnerability index. The dolines and massifs located in the diffuse infiltration watersheds are classified by the high vulnerability index. In addition, the lineaments between dolines in these diffuse infiltration watersheds were assigned to the high vulnerability class.

Another notable factor that increases the vulnerability of the eastern and western areas of the map is the presence of concentrated infiltration watersheds identified in the Infiltration Condition map. These areas receive the high vulnerability index, as well as the areas corresponding to the alignment between dolines, in the Epikarst map, in the intermediate infiltration watersheds of the infiltration map.

It is also possible to observe the influence of the karstic development map, especially in a massif present in the south of the map, which divided into high vulnerability and very high vulnerability. This division results from the proposed classification, into highly and moderately developed karstic system, corresponding to the lithological division between the Lagoa Santa and Pedro Leopoldo members.

4.2. Application of the modified method

After changing the range of soil thickness for each index of Protective Cover, adapting it to the tropical karst, the sum of the two soil types was made, and the resulting map of this modified factor was obtained. Due to the aquifer coverages, this was able to portray the vulnerability in a more gradual way, as can be seen in Figure 9.

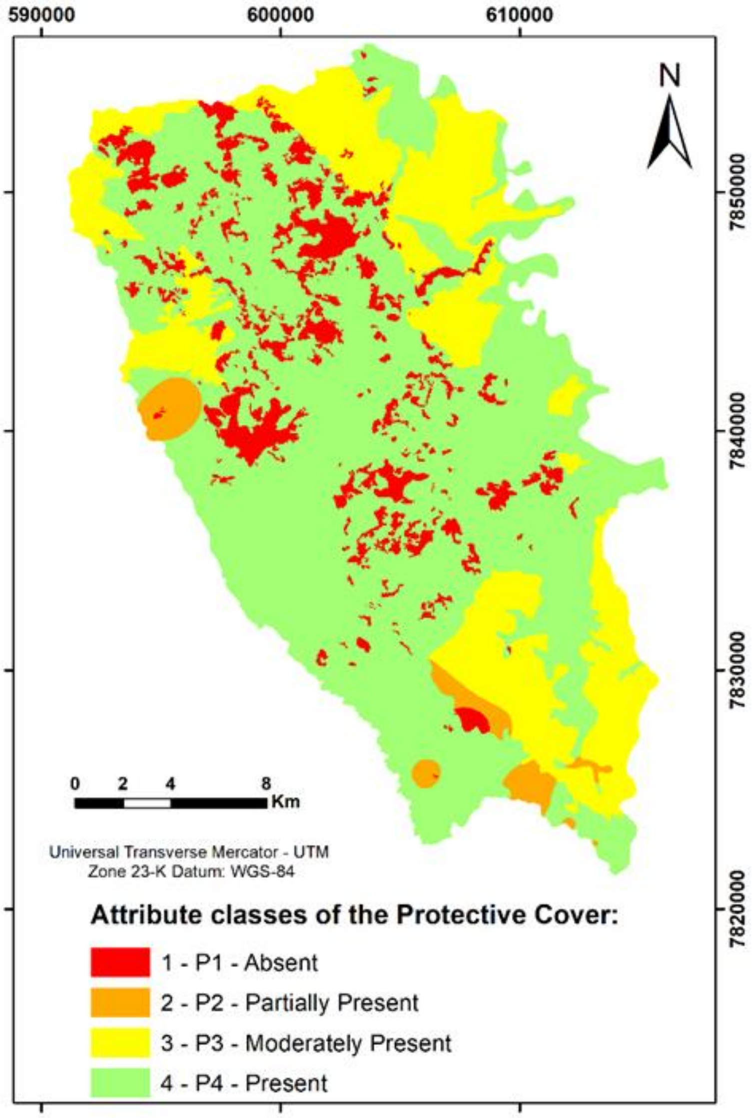

Figure 9. Modified Protective Cover Resulting Map. Source: Authors (2026).

In this map, the P1 index, which designates an absent protective cover, corresponds to 9.4% of the area, with 47.17 km², and is concentrated in the region of rock mass outcroppings. The P2 index - layer of protection partially present, occupies only 2.6% of the area (13.33 km²) and is associated with the interpolation of the wells with less soil thickness. Another 23.5% (117.83 km²) of the area corresponds to the P3 index - moderately present protective cover, concentrated in the regions where the pelitic formation outcrops. Finally, the P4 index - protective cover present, covers the remaining 64.5% of the area or 323.75 km².

And the map of Intrinsic Vulnerability Classification by the modified EPIK method, obtained by Equation 2 and classified based on Table 6, can be seen in Figure 10.

The low vulnerability class predominates covering 46% (231.5 km²) – compared to 64,9% (327.7 km²) with the original method - of the studied area. The moderate vulnerability class in 23% (115.8 km²) of the total area – 0,1% (0,7 km²) with the original method -, and the high vulnerability class in 21% of the area (104.7 km²) – 15,4% (78 km²) with the original method. Finally, the very high vulnerability class represents an area, equivalent to 10% (49.8 km²) – 19,4% (98 km²) with the original method (Figure 11).

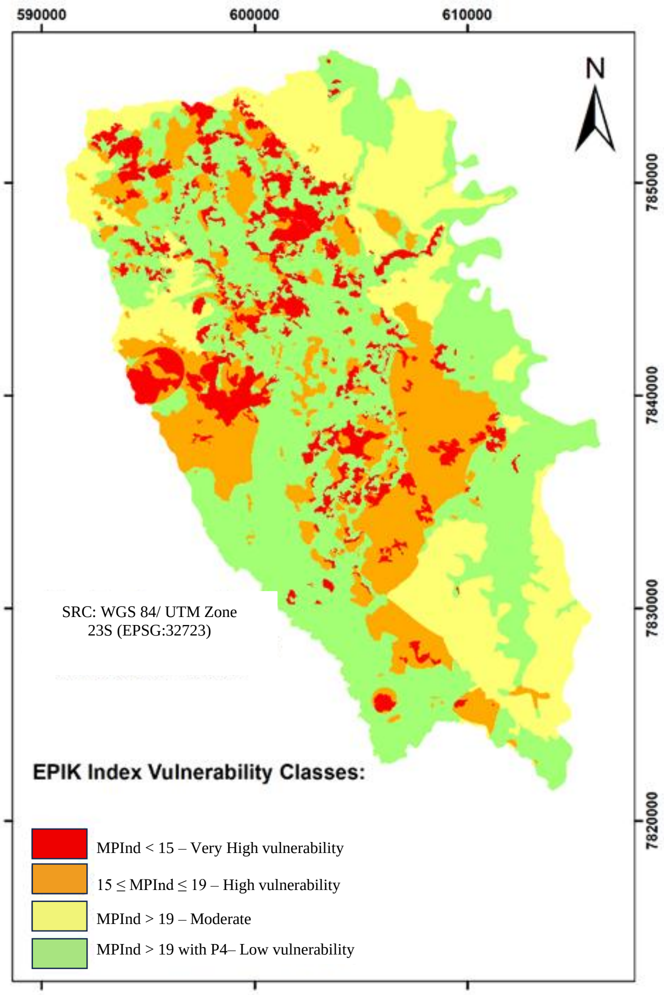

Figure 10. Vulnerability classes map of the Modified EPIK Method. Source: Authors (2026).

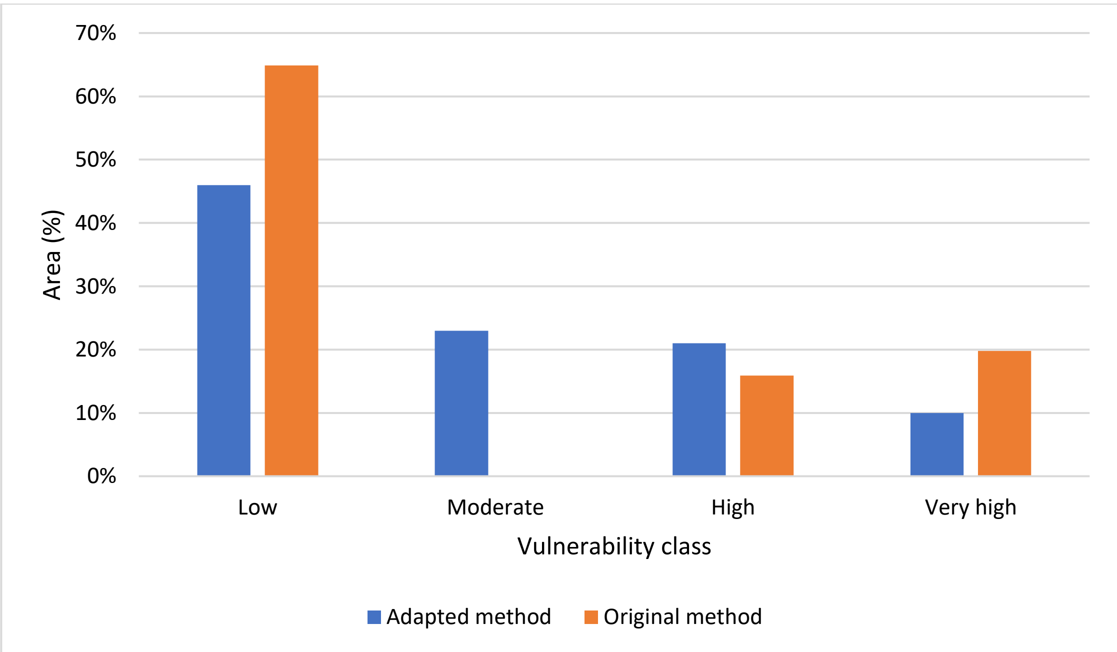

Figure 11. Comparison of the spatial distribution of vulnerability classes between the original and adapted methods. Source: Authors (2026).

The areas of very high vulnerability are localized and correspond to places with very thin soil profiles. It is important to highlight that the central portion of the study area, where the outcrops and dolines occur, was classified as having very high or high vulnerability. This high index also occurs in the more continuous portions to the east and west of the map, which is attributed to the concentrated infiltration, typical of the watersheds of the Palmeiras and Samambaia creeks. This is justified by the fact that both watersheds contain sinks, which are zones of direct recharge and deep flow directed toward to the Jaguara stream watershed and the Velhas River.

One of the main differences between the original and the modified methods is the increase in the area classified as having moderate vulnerability, especially the index of the moderately present protective cover (P3). This index, P3, was only possible to obtain after modifying the soil thickness intervals of the Protective Cover (P) parameter.

The groundwater quality reported by Cardoso (2019) is consistent with the results of the modified EPIK method and provides indirect validation of the proposed adaptation. This author performed analyses of the physicalchemical parameters of potability in water from deep wells and karstic emergences in this region. He found that none of the samples were contaminated by anthropic agents, revealing that the area presents good protection capacity, despite intense human occupation and various land uses. These results indicate that the soil thickness is one of the most crucial factors in attenuating contamination of aquifers by surface agents.

It is observed that the EPIK method is quite effective in valuing the intrinsic vulnerability of the karstic environment, because it still considers unique aspects of this system, for having been developed especially for this environment.

It is still important to emphasize that the EPIK method is exemplary in the way it analyzes its attributes, because even though it is a parametric method, that is, it assigns numerical scores to produce some form of vulnerability index, it allows the analyst greater freedom in the study. In other words, the study becomes more singular, more specified for the area in question, being very subjective in several aspects. On the other hand, the analyst must have great knowledge about the region studied and great availability of data, because this method requires a robust database to be feasible in its application.

Finally, in general, there was a reduction in the area classified as extreme vulnerability (very high and very low vulnerability) and an increase in intermediate classes. Also, this modification represents better the hydrological reality of the area, being more representative of hydrogeological characteristics of the area.

5. CONCLUDING REMARKS

The application of the EPIK method in tropical karst context highlighted the influence of local hydrogeological conditions on the representativeness of the aquifer’s intrinsic vulnerability. The tropical environment significantly influences the application of the EPIK method, since the ranges specified in the original method for the Protective Cover parameter – may result in the classification of nearly all regions into a single category. It is important to analyze each parameter in every area under study, given that the method was designed for temperate regions. Thus, if characteristics are observed that fall outside the ranges or classify them into a single category, it is necessary to adjust the ranges. It is advisable to conduct water quality tests to verify whether the estimates derived from the methodology align with reality, as was the case in this study. In this instance, the greater soil thickness contributes to good aquifer protection. In this way, it is possible to effectively analyze which areas deserve greater attention and urgency in public policy. It is important to have methods that map the intrinsic vulnerability of karst environments, precisely due to the unique nature of their formation

It is also important to note that these modifications were developed based on the Lagoa Santa karst and should be analyzed before being applied to other areas. If necessary, adjustments should be made to the weights and intervals, while preserving the logic of the classification.

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