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Integrated estimation of groundwater resources vulnerability in the urban core of Visconde de Mauá (RJ): application of geophysical methods in the Serra da Mantiqueira environmental protection area and implementation of an adapted methodology

Estimativa integrada de vulnerabilidade dos recursos hídricos subterrâneos no núcleo urbano de Visconde De Mauá (RJ): aplicação de métodos geofísicos na APA Serra da Mantiqueira e implementação de metodologia adaptada

Estimación integrada de la vulnerabilidad de los recursos hídricos subterráneos en el núcleo urbano de Visconde de Mauá (RJ): aplicación de métodos geofísicos en el Área de Protección Ambiental de la Serra da Mantiqueira e implementación de una metodología adaptada

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Abstract: This study aimed to assess the natural vulnerability of groundwater resources through the adaptation of the EKv methodology, combined with physical characterization of the soil and geophysical techniques (GPR, electrical resistivity, and magnetometry), applied in a site lacking pre-existing local hydrogeological data, in Visconde de Mauá–RJ, Brazil. The EKv method considers the thickness (E) and vertical permeability (Kv) of the unsaturated zone, enabling an integrated analysis of the aquifer's natural protective capacity. The results indicated three vulnerability classes: medium in Campo do Centro (EKv = 7), medium in Praça da Igreja (EKv = 5), and high in Lote-10 (EKv = 8).
Keywords: Groundwater, EKV Method, Ground geophysical, Environmental Protection Area.

Resumo: Este estudo teve como objetivo avaliar a vulnerabilidade natural dos recursos hídricos subterrâneos por meio da adaptação da metodologia EKv, associada à caracterização física do solo e técnicas geofísicas (GPR, Eletrorresistividade e Magnetometria), aplicadas em área sem dados hidrogeológicos locais preexistentes, em Visconde de Mauá–RJ. A metodologia EKv considera a espessura (E) e permeabilidade vertical (Kv) da zona não saturada, permitindo uma análise integrada da capacidade natural de proteção dos aquíferos. Os resultados indicaram duas classes de vulnerabilidade: média no Campo do Centro (EKv = 7), média na Praça da Igreja (EKv = 5) e alta no Lote-10 (EKv = 8). Os baixos teores de argila, as estruturas geológicas favoráveis à percolação vertical e a reduzida espessura da zona não saturada foram fatores determinantes à limitação da capacidade de atenuação natural. A presença de contatos litológicos, foliações sub-horizontais e fraturas acentuam o risco de contaminação por promoverem fluxos preferenciais. A abordagem integrada demonstrou eficácia na definição de zonas críticas de vulnerabilidade, mesmo diante das restrições da metodologia EKv. A associação com métodos geofísicos elevou a acurácia das estimativas e contribuiu para a análise espacial pormenorizada da subsuperfície, fornecendo subsídios mais consistentes para avaliação de vulnerabilidade de recursos hídricos subterrâneos.
Palavras-chave: Água subterrânea; Método EKV; Geofísica terrestre; Área de Proteção Ambiental.

Resumen: Este estudio tuvo como objetivo evaluar la vulnerabilidad natural de los recursos hídricos subterráneos mediante la adaptación de la metodología EKv, asociada a la caracterización física del suelo y a técnicas geofísicas (GPR, resistividad eléctrica y magnetometría), aplicadas en un área sin datos hidrogeológicos locales preexistentes, en Visconde de Mauá–RJ. La metodología EKv considera el espesor (E) y la permeabilidad vertical (Kv) de

Author Contributions according to the CRediT Taxonomy

AAF: conceptualization; project administration; investigation; methodology; data curation; formal analysis; software; validation; visualization; writing – original draft; writing – review & editing; resources. DMB: supervision; validation; writing – review & editing; methodology; formal analysis; conceptual guidance and technical-scientific support. AAOJ: supervision; validation; writing – review & editing; methodology; formal analysis; technical guidance; critical revision and quality control. MSS: investigation; methodology; formal analysis; validation; writing – review & editing; resources; technical support in field acquisition; assistance in data processing and critical revision of the geophysical interpretation framework.

la zona no saturada, lo que permite un análisis integrado de la capacidad natural de protección de los acuíferos. Los resultados indicaron dos clases de vulnerabilidad: media en el Campo do Centro (EKv = 7), media en la Praça da Igreja (EKv = 5) y alta en el Lote-10 (EKv = 8). Los bajos contenidos de arcilla, las estructuras geológicas favorables a la percolación vertical y el reducido espesor de la zona no saturada fueron factores determinantes en la limitación de la capacidad de atenuación natural. La presencia de contactos litológicos, foliaciones subhorizontales y fracturas acentúa el riesgo de contaminación al favorecer flujos preferenciales. El enfoque integrado demostró eficacia en la delimitación de zonas críticas de vulnerabilidad, incluso frente a las limitaciones inherentes a la metodología EKv. La asociación con métodos geofísicos incrementó la precisión de las estimaciones y contribuyó a un análisis espacial detallado del subsuelo, proporcionando bases más consistentes para la evaluación de la vulnerabilidad de los recursos hídricos subterráneos.
Palabras clave: Aguas subterráneas; Método EKv; Geofísica terrestre; Área de Protección Ambiental.

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Conflict declaration
Nothing to declare.

1 INTRODUCTION

The assessment of aquifer vulnerability in mountainous and protected areas is gaining increasing relevance across many countries, particularly in light of growing anthropogenic pressures and climate change (DAO et al., 2024). Beyond their primary role in water supply, aquifers serve as critical providers of ecosystem services essential to environmental stability and human well-being. Among these services, notable emphasis is placed on supporting surface ecosystem, such as forests and wetlands, that rely on groundwater contributions to regulate local climate conditions and sustain biodiversity. (GRIEBLER; AVRAMOV, 2015).

The situation is exacerbated by the lack of efficient water collection and treatment systems, which significantly heightens the risk of groundwater contamination and compromises its quality for both human consumption and economic activities (BAIG et al., 2023). In an effort to address existing knowledge gaps and introduce novel methodological approaches, international studies such as Hilberg (2016), in mountainous regions of the Swiss Alps, employed abiotic and biotic natural tracers in fractured hard-rock aquifers. This research incorporated the use of partial CO_2 pressure and calcite saturation in spring waters to simulate capture and flow dynamics. Moreover, it conceptualized hard-rock aquifers as natural habitats, utilizing biological communities to infer hydrodynamic conditions with the goal of developing a comprehensive hydrogeological model.

Similarly, in a study by Zhao et al. (2022) on a remote island, a solute transport model was developed based on the local subsurface flow field. This model integrated sampling data and pollution source detection to simulate contaminant migration and assess groundwater pollution risks.

In Brazil, the conditions of access, distribution, and the factors linked to the vulnerability of water resources vary significantly across regions, depending on each area's natural characteristics, the management models in place, demographic indicators, and water use strategies. A pivotal event highlighting these disparities was the water crisis that impacted the southeastern region, particularly the state of Rio de Janeiro, beginning in 2014. The 2014–2015 period was marked by a sharp decline in reservoir levels, severely affecting the Paraíba do Sul River Basin, which supplies a large portion of both Rio de Janeiro and São Paulo states. The critical situation, however, was attributed to a confluence of factors, most notably high demand and deficits associated with water pollution. (MARQUES; ROCHA; FORMIGA-JOHNSSON, 2020; COSTA; BENASSI, 2015; CEIVAP, 2024).

In tourist-intensive regions with high seasonal population fluctuations, such as the urban clusters of the Visconde de Mauá district, located in the municipality of Resende in southern Rio de Janeiro state, this demographic dynamic significantly exacerbates water stress. In such contexts, water demand often surpasses natural availability, exerting substantial pressure on both surface and groundwater resources. This scenario also increases system vulnerability, contingent on regional land use practices and human activities, particularly regarding groundwater extraction and quality (COSTA, 2024).

Given the scarcity of subsurface hydrogeological data, especially due to the absence of registered wells in the SIAGAS (Groundwater Information System), the development of alternative methodologies for assessing natural aquifer vulnerability becomes imperative. This study, therefore, proposes an adaptation of the EKv method, originally developed by Auge (1995), to address key methodological gaps in data-scarce regions. The EKv technique, which relies on the parameters of thickness (E) and vertical permeability (Kv) of the unsaturated zone, demonstrates applicability to fractured aquifers even in the absence of piezometric data, by integrating geophysical methods and laboratory testing for indirect parameter estimation.

The proposed approach is particularly relevant for supporting environmental assessments in protected areas and informing conservation strategies for groundwater resources, especially in regions experiencing land use intensification and tourism-driven expansion, as observed in Visconde de Mauá. Accordingly, this work aims to evaluate the natural vulnerability of regional groundwater through the adapted EKv method, incorporating laboratory analyses and three distinct geophysical techniques to enhance and refine understanding of subsurface hydraulic dynamics.

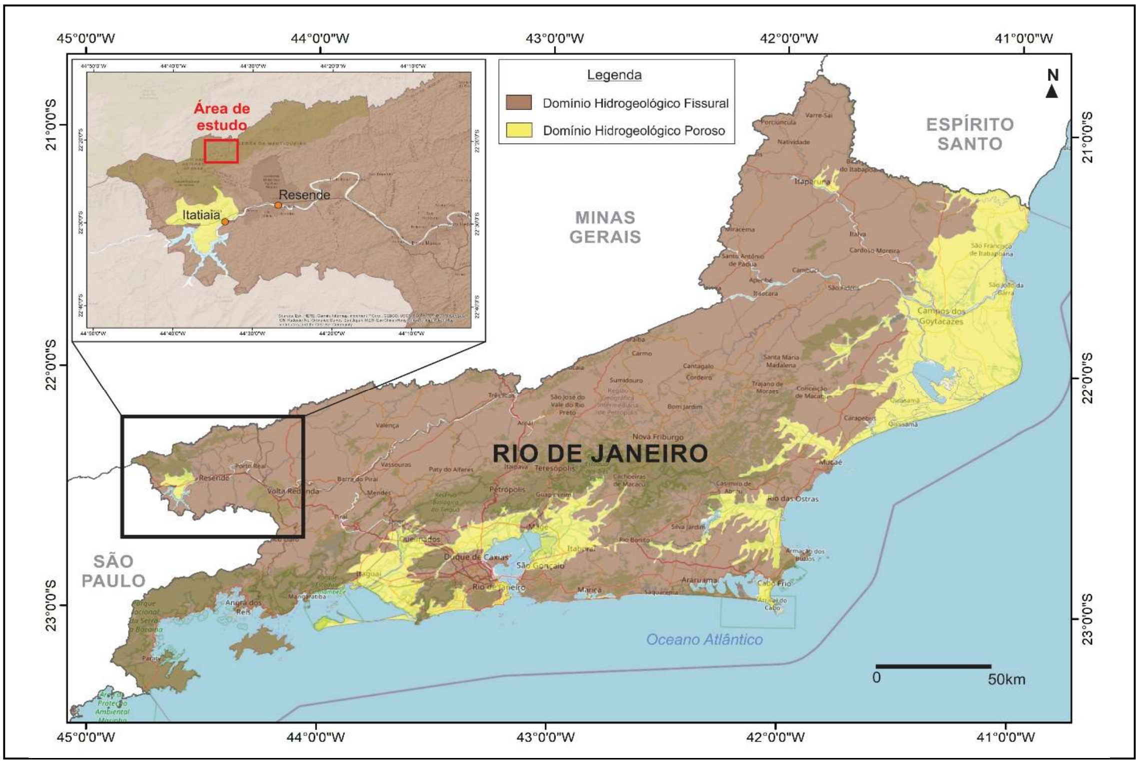
2 STUDY AREA LOCATION

The study area encompasses the urban core of the Visconde de Mauá district, located within the municipality of Resende in the southern region of Rio de Janeiro state. This area borders the municipality of Bocaina de Minas, in the neighboring state of Minas Gerais. Approximately 23.68% of Resende's territory falls within the Serra da Mantiqueira Environmental Protection Area, and Visconde de Mauá is entirely contained within this protected zone (AGEVAP, 2018).

The state of Rio de Janeiro encompasses two main hydrogeological domains: fissured and porous. Fissured aquifers, typical of crystalline rock formations, are widely distributed across elevated terrains such as the Serra da Mantiqueira. In these geological settings, groundwater flow occurs primarily through fractures and fault zones, with permeability governed by the frequency and aperture of the fractures. In contrast, porous aquifers are associated with higher groundwater storage capacity due to the elevated porosity and permeability of their lithological units.

Visconde de Mauá lies within the fissured hydrogeological domain (Figure 1), characterized by limited porosity and permeability. In such systems, groundwater flow is localized and discharge rates range from 3 to 10 m³/h (IBGE, 2015). Fissured aquifers are predominantly recharged by precipitation, with secondary contributions from surface water infiltration. Due to their restricted storage and flow capacity, these aquifers are especially vulnerable to climatic variability and land use pressures.

Figure 1 - Map of the hydrogeological domains of the state of Rio de Janeiro.



Source: Prepared by the authors, based on IBGE (2021).

The region is distinguished by the high heterogeneity and ecological integrity of its natural ecosystems, coupled with an economic matrix predominantly structured around ecotourism and adventure tourism activities. The population of the Visconde de Mauá district is estimated at 1,523 inhabitants (INEA, 2018), with fluctuations due to the seasonal nature of tourism, marked by a significant increase during peak periods. The area is predominantly mountainous, with elevations ranging from 1,200 to 2,000 meters above sea level. The native vegetation is primarily composed of Atlantic Forest and high-altitude grasslands (MAIA, 2013).

The prevailing climate is classified as Cwa under the Köppen system, characterized by a humid subtropical regime with dry winters and hot summers (EMBRAPA, 1992). The average annual precipitation is 1,571.5 mm, and the mean annual air temperature hovers around 19.1°C (KÖPPEN, 2024). The region lies within the Médio Paraíba do Sul Hydrographic Region (RH-III), specifically the Upper Rio Preto micro-basin, and its hydrography is largely composed of small streams and rivers.

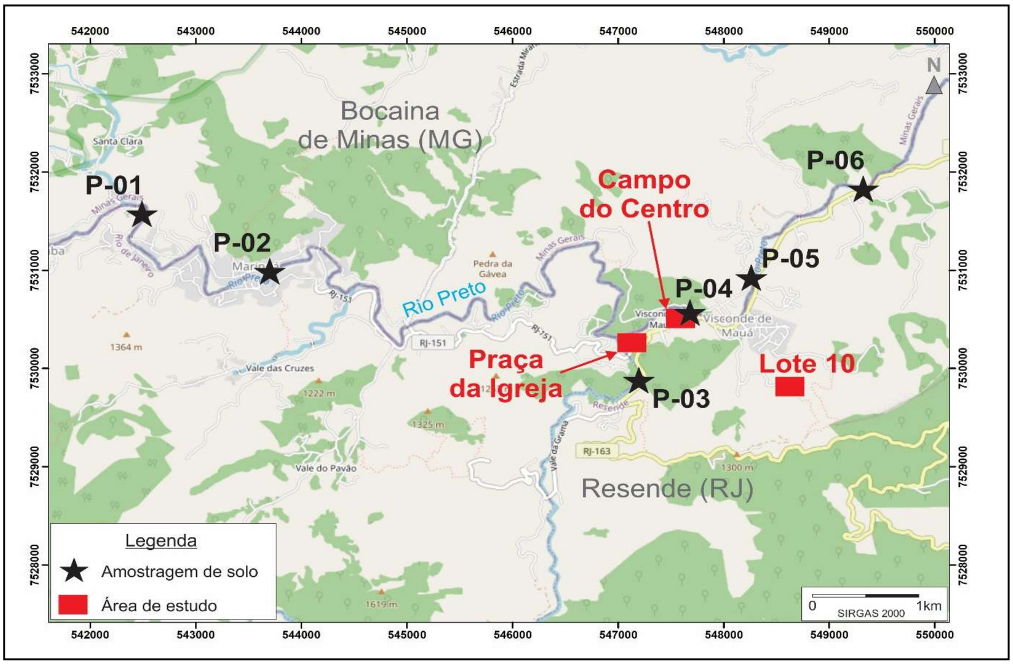
The Rio Preto, the main watercourse, extends for 224 km, originating at 2,787 meters in the Agulhas Negras highlands, in the municipality of Itatiaia-RJ. After merging with the Paraibuna River, its waters flow into the Paraíba do Sul River (OLSZEVSKI et al., 2011; INEA, 2018).

Regional soils are mainly Cambisols, Latosols, and Litholic Neosols, with varying textures that influence the vulnerability of subsurface water resources (IBGE, 2021). The dominant lithologies consist of gneisses, paragneisses, and granites, whose fractures and faults may either channel or restrict subsurface water flows and serve as zones for groundwater storage (IBGE, 2021).

The hydrogeology of Visconde de Mauá is shaped by the geology and morphology of the Mantiqueira Mountain Range. The local geological framework is dominated by igneous and metamorphic rocks, primarily granites and gneisses from the Mantiqueira Complex, formed under Precambrian tectonic conditions (IBGE, 2015). These lithologies govern the development of fractured aquifers, where porosity and permeability are primarily controlled by tectonically induced fractures and faults. Such aquifers possess limited storage capacity, restricted water circulation, and are highly susceptible to climatic variability and land use pressures.

For the purpose of applying the groundwater vulnerability assessment methodology, three sites located within the urban core of the Visconde de Mauá district were selected: Campo do Centro, Praça da Igreja, and Lote 10 (Figure 2). Regarding soil sampling, collections were performed along the banks of the Rio Preto, both upstream and downstream of the study area, in order to more accurately characterize selected pedological parameters within this sector of the region (Figure 2 and Table 1).

Figure 2 - Location of the three study areas, located in the urban center of Visconde de Mauá.



Source: Prepared by the authors, based on IBGE (2021).

Table 1 – Sample collection points

Point	X	Y
P-01	542529	7531556
P-02	543703	7530954
P-03	547204	7529908
P-04	547743	7530578
P-05	548278	7530870
P-06	549320	7531830

Source: Authors.

3 METHODOLOGY

An integrated analysis of laboratory testing and geophysical data was employed to adapt the EKv method for assessing the natural vulnerability of aquifers, with this approach applied in the district of Visconde de Mauá, Resende-RJ, Brazil. This adaptation represents a significant advancement for sensitive and protected regions, where invasive procedures such as drilling are prohibited, and where commonly used vulnerability assessment methods, such as DRASTIC (Depth to water table; Refilling rate; Aquifer type; Soil and sediment type; Topography; Impact of perched water; Conductivity) and GOD (Groundwater hydraulic confinement; Overlaying strata; Depth to groundwater table), are unsuitable due to their reliance on complex preliminary data, which is often unavailable.

Similarly, the AVI (Aquifer Vulnerability Index) method uses parameters closely aligned with EKv, as both emphasize the unsaturated zone thickness and vertical permeability as core factors (VAN STEMPVOORT; EWERT; WASSERNAA, 1992). However, EKv was chosen due to its simplified index structure, better qualitative applicability, and compatibility with geophysical data integration.

The adaptation of the EKv method to fractured aquifers involved:

i) geophysical surveys using a) Ground Penetrating Radar (GPR); b) Electrical Resistivity; and c) Magnetometry;

ii) estimation of the Unsaturated Zone Thickness (E) based on geophysical data;

iii) determination of Vertical Permeability (Kv), defined through laboratory analysis of soil samples collected in the field;

iv) calculation of the Vulnerability Index using E and Kv values, based on the vulnerability index tables from Auge (2004), which define values ranging from 2 (low vulnerability) to 10 (high vulnerability).

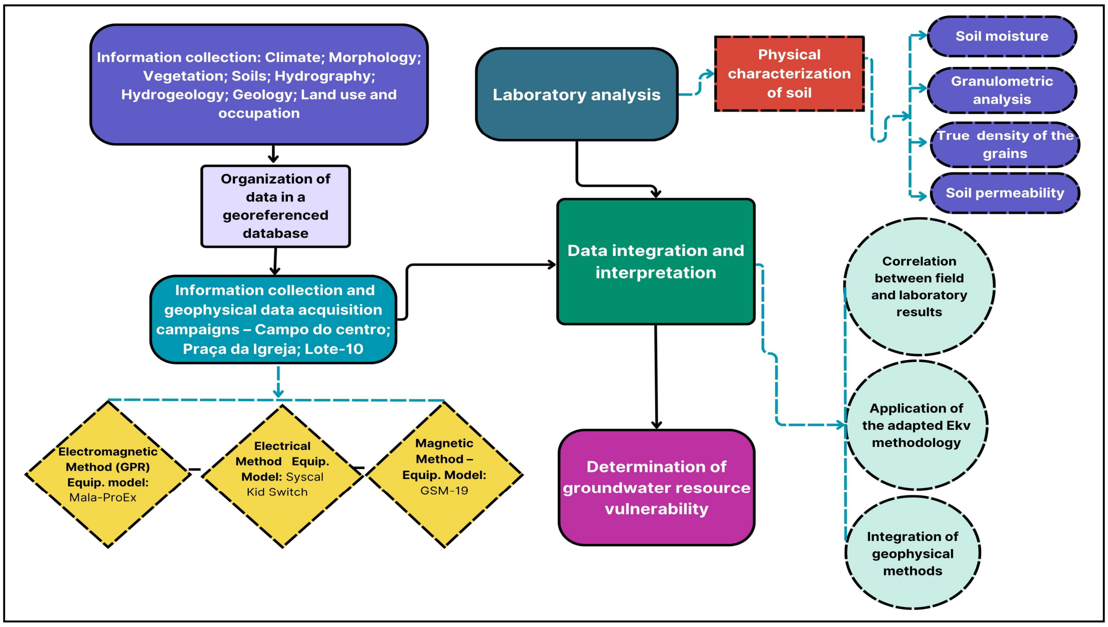
While the EKv method offers considerable advantages in terms of simplicity and applicability in data-scarce contexts, its adaptation to fractured aquifers and integration with geophysical methods requires careful consideration of uncertainties and limitations that may affect result accuracy.

A key limitation concerns the reliability of unsaturated zone thickness (E) estimates derived from geophysical methods in soils with high water saturation or strong textural heterogeneity. Although GPR provides high vertical resolution, its performance is limited in electrically conductive materials such as saturated clays or highly moist soils, where signal attenuation compromises penetration and reflector clarity (ANNAN, 2005; DAVIS & ANNAN, 1989). Under such conditions, accurately delineating the saturated/unsaturated interface may require calibration and validation using direct data, such as borehole profiles or infiltration tests.

Additionally, the vertical and lateral lithological heterogeneity typical of fractured aquifers can undermine the representativeness of laboratory-derived vertical permeability (Kv) data. Point soil samples generally fail to capture the structural and textural variability of the porous or fractured media at depth, leading to discrepancies between laboratory values and actual in situ conditions (FITTS, 2012).

To mitigate such uncertainties, the research was conducted in four stages: literature review, fieldwork, laboratory analysis, and data integration, as outlined in the following flowchart and description:

Figure 3 – Procedures for analyzing the natural vulnerability of groundwater resources.



Source: Authors.

The initial phase comprised the collection of data concerning climate, morphology, vegetation, soils, hydrography, hydrogeology, geology, and land use/land cover, which were consolidated into a georeferenced database to guide subsequent fieldwork activities.

The following stage entailed field campaigns involving in situ instrumentation and measurements across three areas of the urban core in Visconde de Mauá: called Campo do Centro, Praça da Igreja, an

Lote-10. Soil samples were collected, and terrestrial geophysical surveys were performed using Electrical, Electromagnetic, and Magnetic methods. All geophysical instruments were provided by the Laboratory for Mineral Exploration of the Geology Faculty (LEXMIN/FGEL/UERJ).

The Electromagnetic method was implemented through Ground Penetrating Radar (GPR) using a Mala ProEx system with 50 MHz and 100 MHz antennas. Survey lines and sampling points matched those of the electrical and magnetic methods. Data processing was carried out using GroundVision and Reflex2DQuick software, with filtering applied to remove noise and enhance horizontal features.

The Electrical method employed a Syscal Kid Switch system configured in a dipole-dipole array with 24 electrodes and nine investigation levels. Data were processed using Prosys II and Res2DInv software.

For the Magnetic method, a GSM-19 magnetometer was used with 5 m spacing between measurement points. Diurnal variation corrections were performed using GemLink, and maps of the Total Magnetic Field and Analytical Signal Amplitude were generated via Geosoft Oasis Montaj.

A formal weighting model for method prioritization was not adopted. Instead, an integrated qualitative approach was applied, giving precedence to the method offering the highest local reliability.

The third, laboratory phase included analysis and determination of soil physical parameters such as moisture content, grain size distribution, specific gravity, consistency limits, and permeability. Six residual soil samples (0–20 cm depth) were collected after removing surface vegetation, branches, and rocks. Soil moisture was measured using the gravimetric method (oven-drying method), following ABNT NBR 6457/2016.

Particle size analysis was by the Soil Mechanics Laboratory at UERJ's School of Engineering using a complete sedimentation-based characterization test to enhance precision for fine fractions. Specific gravity was determined using the pycnometer method (ABNT NBR 6458:2016), aimed at assessing soil behavior under compaction and permeability conditions.

The Liquid Limit was determined via the Casagrande cup method, as per ABNT NBR 6459/2017, while the Plastic Limit followed ABNT NBR 7180/2016 standards.

Permeability tests involved measurements at 10, 20, 30, and 40-second intervals over a 0.01 m^2 infiltration area. Calculations employed a formulation derived from Darcy's Law, as expressed in Equation 1.

$$K= (Q \times L) / (A \times \Delta H \times t) \qquad (1)$$

Where:

Q - Water flow rate (m^3/s);

L - Length of the flow path (m);

A - Infiltration area (m^2);

ΔH - Hydraulic head difference (m);

t - Infiltration time (s).

The final stage encompassed the integration of data from previous phases and the validation of the EKv methodology, adapted through the application of geophysical techniques, to assess the vulnerability of groundwater resources within the study area.

Originally proposed by Auge (1995), the EKv method adopts a qualitative framework designed to evaluate the natural protection capacity of subsurface water resources. This is achieved through analysis of two key parameters: (i) the contaminant transport velocity across the thickness of the unsaturated zone to the water table or the top of the saturated zone, referred to as E, and (ii) the vertical permeability of the geological materials, denoted as Kv.

Both parameters are assigned vulnerability indices ranging from 1 (indicating lower vulnerability) to 5 (indicating higher vulnerability), as detailed in Tables 2 through 6.

The final values are derived from the convergence of individual parameter indices—specifically, the sum of E and Kv, based on Tables 2 (E), 3 and 4 (Kv). These aggregated values are then applied according to the criteria established in Table 5. Ultimately, the resulting vulnerability indices are categorized in accordance with the classification system outlined in Table 6.

Table 2 – Thickness of the unsaturated zone (E).

Meters	Index
>30	1
>10 a 30	2
>5 a 10	3
>2 A 5	4
<2	5

Source: AUGE (2004).

Table 3 – Unsaturated zone permeability (Kv).

Meters per day	Index
$<1.10^{-3}$	1
$>1,10^{-3}$ a 0,01	2
>0,01 a 1	3
>1 a 50	4
<2	5

Source: AUGE (2004).

Table 2 – Parameters associated with vulnerability índices

Index	Kv (m/d)	Soil texture	Vulnerability
1	< 0,001	Clay and silty clay	Very Low
2	0,001 a 0,01	Silt and clayey silt	Low
3	0,01 a 1	Silt and sandy silt	Medium
4	1 a 50	Very fine to silty sand, fine sand and medium to coarse sand	High
5	50 a 500	Medium and coarse sand, sandy gravel and gravel	Very High

Source: AUGE (2004).

Table 3 – EKv Indices.

E + Kv	Vulnerability
1	Very low
2-4	Low
5-7	Medium
8-10	High

Source: AUGE (2004).

Table 6 – Vulnerability Classes.

KV	**1**	6	5	4	3	2
	2	7	6	5	4	3
	3	8	7	6	5	4
	4	9	8	7	6	5
	5	10	9	8	7	6
		5	**4**	**3**	**2**	**1**
		E				

Source: AUGE (2004).

4 RESULTS

4.1 Soil physical parameters

The physical parameters of the soil, such as granulometry, true density of the grains and average moisture, determined at the six sampling points indicate the presence of predominantly sandy loam and loamy sand soils. The results of the analyses of the collected samples, with their respective textural compositions (sand, silt and clay) and consistency limits to designate the permeability of the soils and assess the natural vulnerability of the aquifers, are summarized in Table 7.

Table 4 – Soil granulometry and true density of the grains.

Point	X	Y	% sand (up to 0,075mm)	% de silt (between 0,075 and 0,005mm)	% clay (less than 0,005mm)	Average humidity (%)	True density of the grains (g/cm^3)
P-01	542529	7531556	76	17	7	7,00	2,644
P-02	543703	7530954	73	18	9	9,00	2,646
P-03	547204	7529908	70	16	14	7,37	2,683
P-04	547743	7530578	71	22	7	8,56	2,682
P-05	548278	7530870	84	13	3	5,26	2,683
P-06	549320	7531830	69	20	11	8,36	2,728

Source: Authors.

Sampling points P-01 through P-06 exhibited a predominance of sand (ranging from 69% to 84%), with lower proportions of silt and clay. This sand-rich composition indicates higher soil permeability, facilitating water infiltration and aquifer recharge. However, it also suggests increased vulnerability to contamination due to the accelerated transport of pollutants. Point P-05, with the highest sand content (84%), implies more efficient water infiltration, yet lower protection against contaminants. An exception is point P-03, which shows a higher clay fraction (14%), resulting in lower permeability. This reduced infiltration rate minimizes the risk of contamination.

Overall soil moisture ranged from 5.26% to 9.0%. Point P-05 recorded the lowest moisture content, indicating reduced water retention or drier conditions. Points P-04 and P-06 showed higher moisture levels, suggesting greater water retention capacity. Nevertheless, aquifer vulnerability is more strongly linked to soil permeability, primarily governed by sand content, than to moisture alone. Despite their higher moisture content, points P-04 and P-06 still have high sand percentages (71% and 69%, respectively), enabling rapid infiltration and potentially increasing contamination risk, particularly if surface pollutants are present.

Soil texture (Table 8), based on the relative proportions of sand, silt, and clay at points P-01 to P-06, was classified using the USDA (United States Department of Agriculture) Textural Triangle. Results indicate that most soils are sandy loam, except for P-05, which is classified as loamy sand.

Table 5 – Soil texture and consistency limits.

Point	Texture	Liquidity Limit (ABNT NBR-6459)	Plasticity Limit (ABNT NBR-7180)
P-01	Sandy loam	NL	NP
P-02	Sandy loam	NL	NP
P-03	Sandy loam	NL	NP
P-04	Sandy loam	NL	NP
P-05	Loamy sand	NL	NP
P-06	Sandy loam	NL	NP

Legend: NL (Non-Liquid); NP (Non-Plastic).

Source: Authors.

Studies in other regions with similar environmental characteristics support these findings. Research by Kalaoum et al. (2020) in the municipality of Queimados, Rio de Janeiro, identified high vulnerability to contamination in areas with sandy soils, using the GOD method for vulnerability assessment. In the same way, investigations by Chrispim (2016) in urban areas of Manaus (Amazonas), employing the DRASTIC method, detected elevated vulnerability in regions dominated by sandy soils, emphasizing the significance of soil texture in determining susceptibility to contamination.

With regard to consistency limits, all sampled soils were classified as “Non-Liquid” (NL) and “Non-Plastic” (NP). This lack of plasticity indicates a low clay content, rendering the soils poorly cohesive and with limited water retention capacity. Soils exhibiting these textural and plasticity characteristics tend to be highly permeable, especially those classified as loam sand, such as at point P-05, resulting in higher infiltration rates and, consequently, greater susceptibility to subsurface water contamination. Although sandy loam soils exhibit some cohesion, they still maintain high permeability, which can enhance aquifer recharge but also promote the downward transport of contaminants into underlying strata.

4.2 Soil permeability

In constant head permeability tests, the following parameters were utilized:

Initial weight: 18.485 kg;

Final weight: 19 kg;

Water column height: 1,49 m;

Infiltration times: 10, 20, 30 and 40 seconds;

Volume of infiltrated water: 22, 43, 64 and 83 ml;

Surface area = 0,01 m².

The observed infiltration rates were 2.20 mL/s, 2.15 mL/s, 2.13 mL/s, and 2.075 mL/s corresponding to the infiltration times of 10, 20, 30, and 40 seconds, respectively. These values exceed 0.1 mL/s, indicating good soil permeability.

Considering Darcy's Law and incorporating the length of the soil column traversed by the water (L) and the hydraulic head difference (ΔH), permeability was determined using Equation 2:

$$K = \frac{Q\ x\ L}{A\ x\ \Delta H\ x\ t} \tag{2}$$

Where:

Q - Water flow (m³/s);

L - Length of the water flow path (m);

A - Infiltration area (m^2);

ΔH - Difference in hydraulic head (m);

t - Infiltration time (s).

The calculation yielded an infiltration rate of 0.01793 m/day.

The extrapolation of vertical permeability (Kv), determined in laboratory tests using samples collected from P-04 in the area designate as Campo do Centro, to other evaluated locations (Praça da Igreja and Lote-10), constituted a methodological decision based on the validation framework of the EKv method. This approach integrates geophysical and laboratory data under conditions constrained by operational and informational limitations. This methodological alignment of soil permeability was feasible only in Campo do Centro, which was therefore selected as the reference site for the calibration and validation of the proposed method, based on the similarities of conditions and results of the granulometric characterization tests. Consequently, the extrapolation of Kv to Praça da Igreja and lote-10 is supported by integration empirical data, spatial geophysical coherence, and the exploratory-methodological nature of the research, sustain consistency with the principles of the EKv method and its adaptations for data-limited contexts.

Studies in other regions of Brazil corroborate the observed natural vulnerability of aquifers in areas with sandy and sandy-loam soils, as identified in the study sites of Visconde de Mauá, Rio de

Janeiro. The research by Miranda et al. (2015) in the Coxim River Sub-Basin, located in Mato Grosso do Sul, compared the GOD and EKv methods for assessing the vulnerability of unconfined aquifers. Their findings demonstrated that areas characterized by sandy soils and high permeability exhibit greater susceptibility to groundwater contamination.

Equaly, Bezerra et al. (2017), in Juazeiro do Norte, Ceará, performed a vulnerability assessment of a zone within the alluvial area of the Riacho dos Macacos, employing the EKv method. The results indicated a classification of moderate vulnerability, which was primarily attributed to the predominantly sandy soil composition and the presence of a shallow water table.

4.3 Geophysical profiles

The geophysical surveys conducted using Electrical, Electromagnetic, and Magnetic methods in three sites located within the urban core of Visconde de Mauá, namely Campo do Centro, Praça da Igreja, and Lote-10, yielded data regarding the composition, properties, and subsurface conditions of the underlying materials. Each geophysical profile extends over a surface length of 120 meters, reaching a maximum investigation depth of 16 meters.

4.3.1 Profile of the Campo do Centro

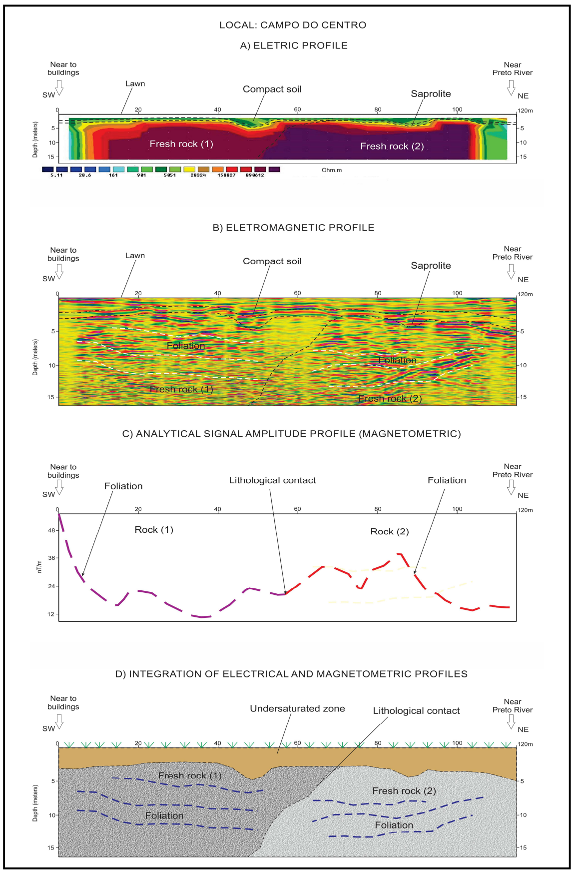
The analysis of geophysical profiles from the "Campo do Centro" reveals a stratigraphic configuration consisting of a compacted soil cover with a maximum thickness of 4 meters, overlying a weathered rock layer (saprolite) up to 1 meter thick, which in turn rests upon fresh bedrock characterized by a pronounced sub-horizontal foliation (Figure 3).

The two unsaturated zone layers lie above competent bedrock, which exhibits irregular surfaces, distinct physical properties (e.g., grain size distribution, mineralogy), and very high resistivity, indicative of low porosity and high mechanical strength. Geophysical signatures by the diferents methods suggest the presence of a lithological contact between 40 and 70 meters along the profiles, inferred from the occurrence of a more conductive zone and shifts in analytical signal amplitude.

The surface compacted soil exhibits low porosity and permeability, acting as a partial barrier to contaminant infiltration. However, its retention effectiveness is constrained by the underlying saprolite, which may facilitate fluid percolation.

Below the saprolite, the lithological contact serves as a preferential conduit for groundwater flow, with flow transmissivity governed by the orientation and connectivity of structural features. Well-connected fracture zones can significantly increase subsurface water vulnerability, particularly in regions where surface cover is thin or discontinuous (SANTOS, 2008). Therefore, in areas where the unsaturated zone consists of materials with low retention capacity, contamination vulnerability is heightened (FEITOSA *et al.*, 2008). Likewise, other researchs on factors associated with aquifer vulnerability indicates that the hydraulic conductivity of saprolites can vary greatly, and may limit or facilitate flow, due to factors such as mineralogy and degree of weathering (BONGA, 2014; DEWANDEL *et al,* 2011; CUSTÓDIO; LLAMAS, 2001).

Figure 4 – Geophysical profiles in the designated area of Campo do Centro: A) Electric; B) Electromagnetic (GPR); C) Magnetic (Analytical Signal Amplitude) and D) Interpretative profile.



Source: Authors.

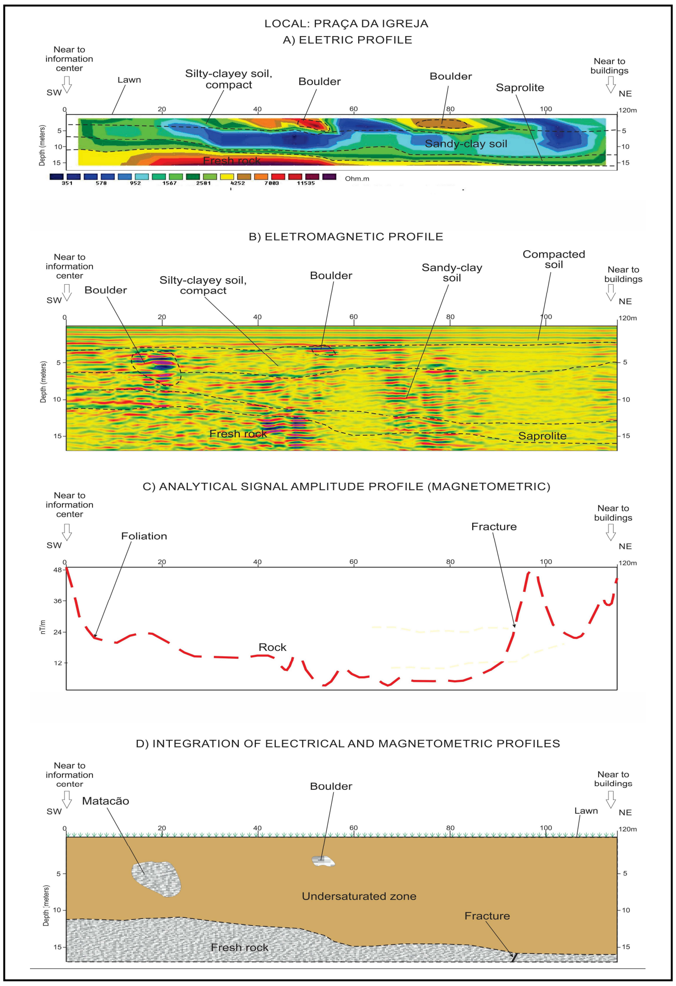
4.3.2 Praça da igreja profile

Geophysical profiles indicate an unsaturated zone, reaching depths of up to 16 meters, composed of a cover of silty-clayey to sandy-clayey soil with boulders immersed in the sediments, overlying a layer of saprolite up to 3 meters thick. Below the saprolite, there is a fractured and competent bedrock, with a slightly flattened surface and dip to NE (Figure 5).

The substrate’s heterogeneity, primarily due to the presence of boulders within the upper sediments, disrupts soil permeability, alters infiltration dynamics, and affects subsurface flow behavior. The underlying saprolite promotes water percolation, a characteristic that can increase vulnerability to contamination, particularly within recharge zones and along geological structures that influence groundwater storage and flow. The combination of sand-clay soils and saprolite suggests high infiltration capacity and low water retention potential within the unsaturated zone.

In analogous environments, geophysical methods have proven effective for aquifer characterization and vulnerability assessment. For instance, Dewandel et al. (2011) integrated geological, hydrodynamic, and geophysical investigations to elucidate the relationship between weathering processes and hydrogeological properties near geological discontinuities, producing a conceptual model that emphasizes the integration of geophysical and hydrogeological data in water resource management. In the same way, Eyankware and Aleke (2021) employed Vertical Electrical Sounding (VES) to delineate fracture zones, aquifer protection capacity, and groundwater potential in Nigeria's Benue Valley, identifying 66% of aquifer units as having low contamination vulnerability, while 31% presented high risk.

Figure 5 – Geophysical profiles in the designated area of Praça da Igreja: A) Electric; B) Electromagnetic (GPR); C) Magnetic (Analytical Signal Amplitude) and D) Interpretative profile.



Source: Authors.

4.3.3 Lote -10 profile

Geophysical profiling reveals a compacted soil cover up to 2 meters thick, overlying a saprolite layer of up to 1 meter, followed by fractured bedrock exhibiting pronounced foliation and a planed surface morphology (Figure 5). The central portion of the electrical resistivity profile (approximately between 40 and 80 meters) indicates a low-resistivity zone, suggestive of increased moisture content or mineralogical alteration. This anomaly is interpreted as being associated with a fracture zone and/or conductive materials that provide preferential pathways for groundwater flow. In this crystalline rock environment, the overlying layers, characterized by distinct hydraulic properties, such as compacted soil and saprolite, as well as the fracture identified in the geophysical profiles, condition the aquifer's natural attenuation capacity and its protection against surface-derived contaminants.

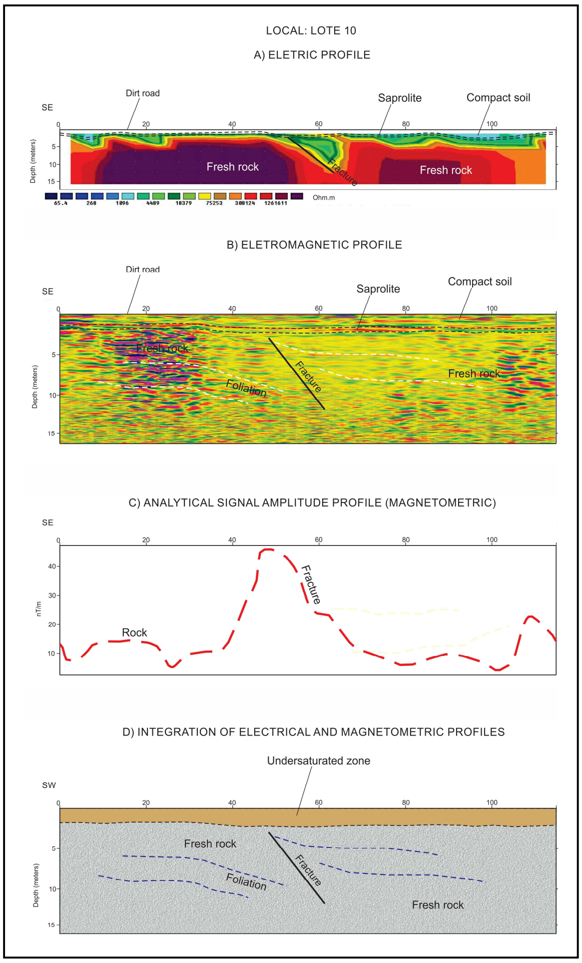
The electromagnetic profile highlights inclined reflections and discontinuities, such as foliations (planar structures) and consistent with the electrical data, a central fracture within the radargram. This fracture coincides with the low-resistivity zone in the electrical profile. Horizontal, continuous reflections at the profile edges indicate a relatively homogeneous geological structure, consistent with unweathered bedrock.

The amplitude of the analytical signal reaches a significant peak in the central region, corresponding to the fracture previously identified by other methods. The low amplitude at the edges further reinforces the

presence of a homogeneous and magnetically unaltered rock substrate.

Thus, the geophysical investigation in Lote-10 reveals the predominance of competent rock substrate with associated foliation and fracturing, characteristics that facilitate the storage and movement of groundwater. The central fracture, which connects the surface to the rock substrate, represents a preferential flow pathway and increases the potential for groundwater contamination. Therefore, periodic hydrogeochemical monitoring is recommended, together with the implementation of recharge protection zones, particularly in the areas considered most vulnerable.

Figure 6 – Geophysical profiles in the designated area of Lote-10: A) Electric; B) Electromagnetic (GPR); C) Magnetic (Analytical Signal Amplitude) and D) Interpretative profile.



Source: Authors

4.4 EKv indices combined with pedological and geophysical characterization

4.4.1 Campo do Centro

At the Central Field site, a compacted soil layer (0–4 m) overlain by a thin saprolite horizon (4–5 m) rests atop unweathered bedrock exhibiting sub-horizontal foliation. The limited thickness of the natural attenuation zone (5 m), combined with the soil's moderate permeability, significantly constrains the subsurface water's natural protection capacity. Ground Penetrating Radar (GPR) data reveal a geological contact that facilitates vertical percolation pathways, effectively establishing rapid hydraulic connectivity between the surface and deeper saturated zones.

The loam sand soil, characterized by a high sand fraction, exhibits low structural cohesion and high permeability, which promotes rapid water infiltration. Therefore, its limited capacity for contaminant retention due to poor adsorption properties further elevates the vulnerability of underlying aquifers to surface-sourced pollutants.

The irregular bedrock surface and marked foliation also condition the infiltration dynamics and groundwater flow regimes. When applying the EKv methodology, the unsaturated zone, estimated at 5 meters thick, corresponded to a thickness index (E) = 4. A value of Kv = 3 was derived from an infiltration rate of 0.01793 m/day, resulting in an EKv index = 7 and a classification within the “medium vulnerability” category.

Although the final classification according to the EKv matrix is “medium”, the integrated analysis points to several structural and textural characteristics that amplify the environmental risk:

i. The low clay content and the absence of plastic properties indicate limited capacity for retention and filtration of contaminants.

ii. Geological features, such as sub-horizontal foliation and lithological contacts, serve as preferential pathways for the vertical transport of pollutants.

iii. The reduced thickness of the attenuation zone shortens the residence time of the water, thus restricting the natural processes of physicochemical and biological purification.

Collectively, these factors suggest that the natural resilience of the aquifer system is low, although the EKv matrix assigns it a moderate vulnerability rating.

4.4.2 Praça da Igreja

At Praça da Igreja, geophysical profiles show a soil cover ranging from silty-clayey to sandy-clayey textures, with boulders embedded in their matrices. This composition suggests a structure of low to moderate permeability, indicative of an average capacity to delay the infiltration of contaminants. Below this layer, a zone of saprolite up to 3 meters thick overlies a fractured bedrock with a gently leveled surface.

Based solely on the proportions of sand, silt and clay, the soil was classified as sandy loam. However, the infiltration rate measured during the permeability tests was 0.01793 m/day. According to the EKv methodology, this corresponds to a Kv index = 3, falling within the “medium permeability” class (0.01 to 1 m/day) and typically associated with silty and silty-sandy soils, considering factors such as compaction, organic matter content and soil structure.

The application of the EKv matrix, which integrates the E index (thickness of the unsaturated zone) and the Kv index (permeability of the unsaturated zone), resulted in a final EKv score = 5, classifying the site as medium vulnerability.

The thicker unsaturated zone, reaching up to 16 meters, can slow the migration of contaminants to the saturated zone. However, the presence of fractures in the bedrock can serve as preferential pathways for water and dissolved substances, potentially increasing the risk of aquifer contamination. Thus, the moderate vulnerability classification attributed to Praça da Igreja is consistent with its geopedological and geophysical context, reflecting a balance between natural protective barriers and factors that favor preferential flow.

4.4.3 Lote-10

In Lote-10, analysis of the subsoil profiles revealed a layer of compacted topsoil approximately 2 meters thick, overlain by 1 meter of saprolite, followed by fresh fractured bedrock with pronounced foliation. From a hydrodynamic point of view, the infiltration rate of 0.01793 m/day, corresponding to a Kv index = 3, indicates medium permeability, consistent with silty-sandy materials, according to the EKv classification matrix. In this context, the thickness of the unsaturated zone (E) was estimated at 2 meters, assigning it an E = 5 index. The combination of these two parameters results in an EKv score of 8, categorizing the site as highly vulnerable.

This classification is consistent with the specific conditions of the site, since the thinness of the unsaturated zone reduces the residence time of potential contaminants and the natural attenuation capacity of the system. Furthermore, the presence of fractures in the bedrock provides preferential flow pathways, facilitating the rapid migration of contaminants into the groundwater system.

This scenario creates an environment conducive to accelerated percolation and significantly reduces the natural protection mechanisms of the aquifer, thus consolidating the high vulnerability classification, despite the inherent limitations of the EKv index. The integrated approach of existing data, laboratory tests and geophysical techniques (electrical, electromagnetic and magnetic), greatly increased the spatial resolution, analytical accuracy and provided a more robust basis for assessing groundwater vulnerability. Although the EKv method is limited by its reliance on only two variables, its effectiveness benefits mainly when complemented by detailed geophysical data detailing the structure and behavior of the subsurface.

Table 9 presents the consolidated results for the three areas assessed.

Table 6 - Results of the Natural Vulnerability Assessment Based on the EKv Methodology

Area	Unsaturated Zone Thickness (m)	Infiltration Rate (m per day)	Index E	Index Kv	EKv	Vulnerability Class (EKV)	Refinement of Results
Campo do Centro	5	0,01793	4	3	7	Medium	Although classified as medium vulnerability, it presents low resilience due to the structure (geological contact) favorable to the transport of contaminants.
Praça da Igreja	16	0,01793	2	3	5	Medium	The greater thickness of the unsaturated zone provides a longer residence time for water, but the fracture of the rock compromises protection.
Lote-10	2	0,01793	5	3	8	High	High vulnerability, with shallow topsoil and rapid percolation pathways due to foliation and fracture in the rock.

Source: Authors.

5 CONCLUSIONS AND RECOMENDATIONS

The results obtained throughout this research demonstrate the high potential of the EKv methodology — adapted and integrated with geophysical data and pedological analyses — as a strategic tool for land use planning in groundwater recharge zones, particularly in environmentally sensitive areas, such as the Visconde de Mauá region (RJ). By enabling spatially differentiated identification of aquifer vulnerability to contamination, the method has proven effective in supporting decisions related to environmental licensing, Ecological-Economic Zoning (ZEE) and land use compatibility.

The proposed adaptation of the EKv methodology successfully incorporates data from geophysical techniques (electrical, electromagnetic and magnetic) and permeability values determined in the laboratory, despite the inherent limitations associated with point extrapolation. The sensitivity of the method highlights that even small variations in the E and Kv parameters are sufficient to alter vulnerability classifications and reinforces the importance of continuous calibration and carefully planned sampling strategies.

Although the EKv indexes classified two areas (Campo do Centro and Praça da Igreja) as medium vulnerability and one area (Lote-10) as highly vulnerable, the combined analysis of geological, pedological and structural attributes indicated important limitations in the natural protection capacity of aquifers. The main vulnerabilities detected include the reduced thickness of the unsaturated zone, the presence of fractures and subhorizontal foliations that promote preferential vertical flow and soils with low cohesion and limited capacity to retain contaminants.

In view of the results and its applicability, the adapted EKv methodology is recommended as a complementary tool to the National System of Conservation Units (SNUC) in Brazil, especially in Environmental Protection Areas (APA), where conflicts between conservation and human use are recurrent. This approach is particularly suitable for fostering participatory monitoring practices, since soil sampling, profile interpretation and certain geophysical readings can be performed with basic technical training. This approach supports local water governance and increases community engagement, essential components of integrated water resource management and effective environmental conservation.

Furthermore, this adapted methodology is scalable to other regions with complex lithological characteristics, especially where the presence of fractures and variability in soil layer thickness can impact aquifer recharge and contamination risk. Its applicability in areas with limited or no data sets makes it a highly recommended alternative for hydrogeological assessments in environmentally sensitive areas, such as conservation units or buffer zones.

REFERENCES

AGAFONKIN, Volodymyr. *Classificação climática de Köppen para os municípios brasileiros*. [S.l.]: [s.n.], [2025]. Available at:
<https://koppenbrasil.github.io/>. Accessed on Jan. 26, 2025>.

AGEVAP. Associação Pró-Gestão das Águas da Bacia Hidrográfica do rio Paraíba do Sul. *Plano de manejo e Web SIG da APA da Serra da Mantiqueira.* 342p. Paraná, 2018.

ALLER, L.; BENNETT, T.; LEHR, J. H.; PETTY, R. J.; HACKETT, G. *DRASTIC:* a standardized system for evaluating ground water pollution potential using hydrogeologic settings. Ada, OK: U.S. Environmental Protection Agency, 1987. (EPA/600/2-87/035). 252 p.

ALMEIDA, D. L.; BENASSI, R. F. Crise hídrica e de energia elétrica entre 2014-2015 na região Sudeste. *Revista Hipótese*, Bauru, v. 1, n. 2, p. 65–76, 2015. Available at:
<https://revistahipotese.editoraiberoamericana.com/revista/article/view/37>. Accessed on Jan. 2, 2025.

ANNAN, A. P. *Ground penetrating radar*: principles, procedures and applications. Ontario: Sensors & Software Inc. Canadá, 2005.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. *NBR 6457:* Solo – amostras de solo – preparação para ensaios de compactação e ensaios de caracterização. São Paulo: ABNT, 2016.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ABNT NBR 6458:2016 — Grãos de pedregulho retidos na peneira de abertura 4,8 mm — Determinação da massa específica, da massa específica aparente e da absorção de água. Rio de Janeiro: ABNT, 2016.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. *NBR 6508:* Grãos de solos que passam na peneira de 4,8 mm – determinação da massa específica. São Paulo: ABNT, 2016.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. *NBR 6459:* Solo – determinação do limite de liquidez. São Paulo: ABNT, 2017.

AUGE, M. Vulnerabilidad de acuíferos. Revista Latino-Americana de Hidrogeologia, n. 4, p. 85-103. 2004

BAIG, F.; SHERIF, M.; SEFELNASR, A.; FAIZ, M. A. Groundwater vulnerability to contamination in the Gulf Cooperation Council region: a review. *Groundwater for Sustainable Development*, v. 23, 2023. Art. 101023. DOI:
<https://doi.org/10.1016/j.gsd.2023.101023>.

BEZERRA, C. O.; CUSIOLI, L. F.; SANCHES, F. M.; QUESADA, H. B.; BELUCI, N. C. L.; MONTAVANI, D.; PINTO, M. R.; LEITAO, J. I. R.; ALMEIDA, J. R. F. Determinação do índice EKv: avaliação da vulnerabilidade ambiental de uma área aluvial do Riacho dos Macacos em Juazeiro do Norte – Ceará. *Águas Subterrâneas*, [S. l.], v. 31, n. 5, 2017. Available at: <https://aguassubterraneas.abas.org/asubterraneas/article/view/29051>. Accessed on Apr. 19, 2025.

BONGA, C. S. J. *Prospecção geoelétrica de água subterrânea no Fontão, Angeja-Portugal*. 2014. Dissertação (Mestrado em Geomateriais e Recursos Geológicos) – Departamento de Geociências, Universidade de Aveiro, Aveiro, 2014.

CEIVAP – COMITÊ DE INTEGRAÇÃO DA BACIA HIDROGRÁFICA DO RIO PARAÍBA DO SUL. Segurança hídrica no Estado do Rio de Janeiro. Revista Pelas Águas Digital, ed. 14, 2023. Available at: <https://ceivap.org.br/revista_digital/ed14/seguranca-hidrica-no-estado-do-rio-de-janeiro>. Accessed on: Fev. 14, 2025.

COSTA, M. V. T. da. *Impactos ambientais associados ao turismo nos distritos de Maromba e Maringá – RJ – região de Visconde de Mauá – RJ:* estudo de caso sobre o Rio Preto. 2024. Dissertação (Mestrado em Geografia) – Programa de Pós-Graduação em Geografia, Universidade do Estado do Rio de Janeiro, Rio de Janeiro, 2024.

CHRISPIM, Zélia Maria Peixoto. *Análise da vulnerabilidade e caracterização hidrogeoquímica dos aquíferos livres rasos da parte emersa da Bacia Sedimentar de Campos*. 2016. xxvii, 320 f.: il. Tese (Doutorado em Engenharia Civil) – Universidade Estadual do Norte Fluminense Darcy Ribeiro, Centro de Ciência e Tecnologia, Laboratório de Engenharia Civil, Campos dos Goytacazes, 2016.

CUSTÓDIO, Emilio; LLAMAS, Manuel Ramón. *Hidrologia subterrânea*. 2. ed. Barcelona: Omega, 2001. 1200 p.

DAO, Phuong Uyen; HEUZARD, Arnaud Guillaume; LE, Thi Xuan Hoa; ZHAO, Jing; YIN, Ran; SHANG, Chii; FAN, Chihhao. The impacts of climate change on groundwater quality: a review. *Science of the Total Environment*, Amsterdam, v. 912, n. único, p. 169241, 2024. ISSN 0048-9697. DOI: <https://doi.org/10.1016/j.scitotenv.2023.169241>.

DAVIS, J. L.; ANNAN, A. P. Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy. *Geophysical Prospecting*, Oxford, v. 37, n. 5, p. 531–551, 1989. ISSN 0016-8025. DOI:<https://doi.org/10.1111/j.1365- 2478.1989.tb02221.x>.

DEWANDEL, Benoît; LACHASSAGNE, Patrick; ZAIDI, Faisal K.; CHANDRA, Subash. A conceptual hydrodynamic model of a geological discontinuity in hard rock aquifers: example of a quartz reef in granitic terrain in South India. *Journal of Hydrology*, Amsterdam, v. 405, n. 3–4, p. 474–487, 2011. ISSN 0022-1694. DOI:<https://doi.org/10.1016/j.jhydrol.2011.05.053>.

EMBRAPA. Empresa Brasileira de Pesquisa Agropecuária. Normais climatológicas: 1961-1990. Brasília, DF: Embrapa, 1992. Available at: <https://www.cnpf.embrapa.br/pesquisa/efb/clima.htm>. Accessed on Oct. 14, 2024.

EYANKWARE, M.; ALEKE, G. Investigação geoelétrica para determinar zonas de fratura e vulnerabilidade do aquífero no sul do Vale de Benue, no sudeste da Nigéria. *Arabian Journal of Geosciences*, [S.l.], v. 14, n. 2259, 2021. ISSN 1866-7511. DOI:<https://doi.org/10.1007/s12517-021-08542-w>.

FEITOSA, Fernando Antônio Carneiro (Coord.); MANOEL FILHO, João (Coord.); FEITOSA, Edilton Carneiro; DEMETRIO, José Geilson A. *Hidrogeologia:* conceitos e aplicações. 3. ed., rev. e ampl. Rio de Janeiro: CPRM; Recife: LABHID, 2008. 812 p. ISBN 978-85-7499-061-3. Available at: <https://rigeo.sgb.gov.br/handle/doc/14818>. Accessed on Feb. 11, 2025.

FITTS, Charles R. *Groundwater science*. 2. ed. Waltham: Academic Press, 2012. 692 p. ISBN 978-0-12-384705-8. Available at: <https://shop.elsevier.com/books/groundwater-science/fitts/978-0-12-384705-8>. Accessed on Dec. 21, 2025.

GRIEBLER, Christian; AVRAMOV, Maria. *Groundwater ecosystem services*: a review. Freshwater Science, Chicago, v. 34, n. 1, p. 355–367, mar. 2015. ISSN 2161-9549. DOI: <https://doi.org/10.1086/679903>.

HILBERG, Sylke. Revisão: traçadores naturais em aquíferos de rocha dura fraturada na parte austríaca dos Alpes Orientais — abordagens anteriores e perspectivas futuras para a hidrogeologia em regiões montanhosas. *Hydrogeology Journal*, [S.l.], v. 24, n. 5, p. 1091–1105, maio 2016. ISSN 1431-2174. DOI: <https://doi.org/10.1007/s10040-016-1395-x>.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE). *Mapeamento de recursos naturais: base contínua de geologia do Brasil – escala 1:250.000*. Rio de Janeiro: IBGE, 2021. Available at: https://www.ibge.gov.br/geociencias/informacoes-ambientais/geologia/15822-geologia-1-250-000.html. Accessed on Mar. 17, 2025.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE). *Mapeamento de recursos naturais: base contínua de pedologia por municípios – escala 1:250.000*. Rio de Janeiro: IBGE, 2021. Available at: https://www.ibge.gov.br/geociencias/informacoes-ambientais/pedologia/10871-pedologia.html. Accessed on Mar. 17, 2025.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE). *Mapa hidrogeológico da Região Sudeste – escala 1:1.800.000*. Rio de Janeiro: IBGE, 2015. Available at: https://geoftp.ibge.gov.br/informacoes_ambientais/geologia/levantamento_hidrogeologico_e_hidroquimico/mapas/regionais/sudeste_hidrogeologico.pdf. Accessed on Mar. 21, 2025.

INSTITUTO ESTADUAL DO AMBIENTE (INEA). *Atlas dos mananciais de abastecimento público do Estado do Rio de Janeiro:* subsídios ao planejamento e ordenamento territorial. Coordenação geral: Silvia Marie Ikemoto; coordenação executiva: Patrícia Rosa Martines Napoleão. Rio de Janeiro: INEA, 2018. 464 p. ISBN 978-85-63884-24-4.

KALAOUM, Jaqueline; SILVA, Jonathas Batista Gonçalves; AQUINO, Otávio Eurico de; PINHO, Camila Ferreira; PEREIRA, Marcos Gervasio; GOMES, João Henrique Gaia. Mapeamento da vulnerabilidade do sistema de aquífero do Distrito Industrial do Município de Queimados (RJ) utilizando a metodologia GOD. *Revista em Agronegócio e Meio Ambiente*, Maringá, v. 13, n. 3, p. 1069–1090, 2020. DOI:<https://doi.org/10.17765/2176-9168.2020v13n3p1069-1090>.

MAIA, Sergio Wright. Governança ambiental e instituições no desenvolvimento sustentável: o caso de Visconde de Mauá. 2013. 278 f. Dissertação (Mestrado em Planejamento Urbano e Regional) – Instituto de Pesquisa e Planejamento Urbano e Regional, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 2013.

MIRANDA, Ciomara de Souza; MIOTO, Camila Leonardo; LASTORIA, Giancarlo; GABAS, Sandra Garcia; PARANHOS FILHO, Antonio Conceição. Uso de sistemas de informação geográfica

(SIG) na modelagem da vulnerabilidade de aquífero livre: comparação entre os métodos GOD e EKv na bacia do rio Coxim, São Gabriel do Oeste, MS, Brasil. *Geociências*, São Paulo, v. 34, n. 2, p. 312–322, jun. 2015.

OLSZEVSKI, Nelci; FERNANDES FILHO, Elpídio Inácio; COSTA, Liovando Marciano da; SCHAEFER, Carlos Ernesto Gonçalves Reynaud; SOUZA, Eliana de; COSTA, Oldair Del'Arco Vinhas. Morfologia e aspectos hidrológicos da bacia hidrográfica do rio Preto, divisa dos estados do Rio de Janeiro e de Minas Gerais. *Revista Árvore*, Viçosa, MG, v. 35, n. 3, p. 485–492, maio/jun. 2011. ISSN 0100-6762. DOI: <https://doi.org/10.1590/S0100-67622011000300011>.

SANTOS, Cristovaldo Bispo dos. *Avaliação hidrogeológica do alto da bacia do rio Jiquiriçá, BA*. 2010. 190 f. Tese (Doutorado em Geologia) – Instituto de Geociências, Universidade Federal da Bahia, Salvador, 2010. Available at:
<https://rigeo.cprm.gov.br/handle/doc/375>. Accessed on Mar. 05, 2025.

VAN STEMPVOORT, Dale; EWERT, Lee; WASSENAAR, Leonard. *AVI*: a method for groundwater protection mapping in the Prairie Provinces of Canada. Saskatoon: Environmental Sciences Division, National Hydrology Research Institute, 1992. Prairie Provinces Water Board Report, 114.

ZHAO, Xiaoning; WANG, Daqing; XU, Haoli; DING, Zhibin; SHI, Yue; LU, Zhao; CHENG, Zijian. Groundwater pollution risk assessment based on groundwater vulnerability and pollution load on an isolated island. Chemosphere, Oxford, v. 289, p. 133134, fev. 2022. Available at:
https://doi.org/10.1016/j.chemosphere.2021.133134. Accessed on Apr. 27, 2025.