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Integration of hydrochemical analysis with aerial geophysics to understand the hydrodynamics around Lagoa da Confusão, in Tocantins, Brazil

Integração de análise hidroquímica à geofísica aérea para entendimento da hidrodinâmica no entorno da Lagoa da Confusão, Tocantins, Brasil

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Abstract: Aerial geophysics, stable isotopes and hydrochemical data analysis were used to understand the dynamics of water flows and the characteristics of surface and groundwater in the surroundings of Lagoa da Confusão - State of Tocantins, Brazil, in order to contribute for a better management of water resources in the area assumed to be an overgrown karst and to subsidize actions to protect the environment. Aerial geophysical data showed three typologies: carbonate rocks, diverse metasedimentary rocks and laterites. Numerous parallel lineaments were identified, including large faults, in the preferential N-S and E-W directions, and subordinately, 45ºNE and 45ºNW, which showed strong control in the surface drainage network. It is interpreted that the Lagoa da Confusão is located on a carbonate substrate. The isotopic and hydrochemical analyzes indicate the occurrence of the karstification process in the study area, in which the chemical and isotopic composition of water is altered by the water-rock interaction and dissolution of carbonate rocks, as it is further evidenced by the occurrence of caves and sinkholes (ipucas).

Keywords: Karst; Stable isotopes; Geophysics.

Resumo: Geofísica aérea regional, isótopos estáveis e análises de dados hidroquímicos foram utilizados para o entendimento da dinâmica dos fluxos hídricos e conhecimento das características das águas superficiais e subterrâneas do entorno da Lagoa da Confusão – Estado do Tocantins, Brasil, com o objetivo de contribuir para uma melhor gestão dos recursos hídricos da área pressuposta como um carste encoberto e subsidiar ações de proteção ao meio ambiente. Dados geofísicos aéreos, evidenciaram três tipologias: rochas carbonáticas, rochas metassedimentares diversas e lateritas. Foram identificados inúmeros lineamentos paralelos, incluindo falhas de grande extensão, nas direções preferenciais N-S e E-W e, subordinadamente, 45ºNE e 45ºNW, que mostram forte controle na rede de drenagem superficial. Interpreta-se que a Lagoa da Confusão está assentada sobre substrato carbonático. As análises isotópicas e hidroquímicas indicam a ocorrência do processo de carstificação na área de estudo, na qual a composição química e isotópica da água é alterada pela interação água-rocha e dissolução das rochas carbonáticas, o que é ainda evidenciado pela ocorrência de cavernas e dolinas (ipucas).

Palavras-chave: Carste; Isótopos estáveis; Geofísica.

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1. Introduction

Water, when of good quality and abundant, is a strategic element for the economic, environmental, and social development of any region. Understanding the mechanisms that influence temporal and spatial changes in water distribution is crucial for effective resource management (BINET et al., 2017), with water resource management (surface and/or groundwater) being one of the main challenges in the society today (BORBA et al., 2021).

In this context, in the northern region of Brazil, an area with fertile soils and abundant water, a series of lagoons associated with the river system of the mid-course plain of the Araguaia River occurs (PEREIRA; MORAIS, 2012), in the municipality of Lagoa da Confusão in the state of Tocantins, one of the most productive agricultural regions in the world and characterized by conflicts over various water uses.

The development of agricultural activities has increased the demand for water to meet irrigation needs, and consequently, triggered various environmental problems that can deteriorate the quality of water resources in the region. Agricultural activities, in addition to using a large amount of water, have the potential to contaminate the environment. Therefore, understanding the mechanisms of water recharge and flow is of fundamental importance for sustainable water resource management (MELO et al., 2017).

A peculiar characteristic of the region is the presence of "ipucas," which constitute natural forest fragments, seasonally flooded, inserted in the vegetal physiognomies of clean fields or floodplains in the Cerrado Biome (TOCANTINS, 2008). According to Nascimento and Morais (2012), ipucas present geomorphological features similar to dolines, typical of karst landscapes, which due to their material composition and hydrological context, are susceptible to collapse.

Therefore, the existence of a karst system is presumed in the area, evidenced by the regional lithological coverage of limestone outcrops, corresponding to the Tocantins Group, and by the presence of underground drainage within cavities found, as well as evidence of limestone dissolution/erosion (OLIVEIRA, 2014), with Lagoa da Confusão and several dolines (ipucas) in the region characterized as resulting from the dissolution of limestone rock.

The protection of karst aquifers is a major challenge, as they represent an important source of drinking water; however, they are considered one of the most vulnerable aquifers to contamination (ZHANG et al., 2014; CHEMSEDDINE et al., 2015). Their complex porosity structures and the heterogeneity of hydrogeological characteristics are the main reasons that hinder the assessment of vulnerability to contamination of karst water resources and the development of pollution modeling and control studies (GUO et al., 2016).

Since rocky outcrops are scarce in the area due to the thick sediment cover, an alternative to assess the rock substrate is the use of Geophysics. This field of Geosciences studies the Earth indirectly, based on the measurement of its physical properties (e.g., magnetism, density and electrical properties), its distribution and natural or induced physical fields (KEAREY et al., 2002). It demonstrated good results in similar regions (e.g., CARNEIRO; BARBOSA, 2008; REIS et al., 2012; CARDOSO et al., 2018).

In this sense, for understanding the dynamics of karst aquifers, as assumed in this work, several methodologies using stable isotopes of oxygen, deuterium, and carbon were applied in various parts of the world, providing significant results for understanding groundwater flow and recharge processes (EINSIEDL et al., 2009; DELBART et al., 2014; MANCE et al., 2014; OZYURT et al., 2014). The use of stable environmental isotopes has contributed to the understanding and solution of hydrogeological problems, such as determining pollution sources, identifying salinization mechanisms in groundwater, defining recharge areas, determining aquifer interactions as well as the velocity and direction of water flows (DIAS, 2016).

Since the particular characteristics of the study area and the extensive use of water resources to support activities in the vicinity of Lagoa da Confusão, and considering that water resources are susceptible to being impacted by these activities, this study aimed to integrate geophysical and hydrochemical analyses to understand hydrodynamics in the area through the processing and interpretation of aerial geophysical data, striving at a regional analysis with the use of hydrochemical and isotopic analyses to understand the dynamics of surface and groundwater in order to contribute to better water resource management.

2. Methodology

2.1. Study area

The study area is located in the middle portion of the Araguaia River basin, within the sub-basin of the Urubu River, in the municipality of Lagoa da Confusão, at coordinates 10° 48' 08" south latitude and 49° 3' 59" west longitude. The municipality has an area of 10 564.66 km^2 and an estimated population of 15 228 inhabitants (IBGE, 2022).

The area has a humid climate with moderate water deficiency during the dry season (May-October), an average annual precipitation of 1750 mm and an average annual temperature of 28°C. The soils in the region are mostly Plinthosols and Gleysols. The favorable climatic conditions and fertile soils make the region one of the main agricultural producers in the state of Tocantins, Brazil.

The geology of the area consists of Neoproterozoic basement rocks of the Baixo Araguaia Supergroup, composed of meta calcarenites, phyllites, slate, metargillite, meta-sandstone, and subordinate quartzites (PEREIRA; MORAIS, 2012) of the Couto Magalhães Formation, Tocantins Group. These rocks are covered by decameter-thick layers of Quaternary sediments. Around the Lagoa da Confusão there are three limestone hills aligned in the SW-NE direction, topographically prominent in the surrounding Quaternary plain.

Lagoa da Confusão is situated within the geomorphological units of the Bananal Plain and Araguaia Depression. The Bananal Plain is a deposition belt characterized by a combination of flat areas with low altitudes and sedimentation caused by periodic floods. It has a surface cover predominantly of low-permeability clay soil and features anastomotic drainage, paleo drainage marks, abandoned channels, and circular lagoons (BRASIL, 1981). The Araguaia Depression is characterized by a vast lowered surface, with gently dissected relief, prevailing convex forms, and a strong presence of tabular interfluves (MARTINS et al., 2006).

In the municipality, the irrigated agriculture sub-project Lagoa da Confusão was implemented, which is part of the Javaés irrigation project. Its objective is to allow for the cultivation of two crops per year (main and off-season) by constructing dams for sub-irrigation, which impounds water from the river and raises the water table in the productive area (NOLÊTO JÚNIOR, 2005; OLIVEIRA, 2014).

Furthermore, the Lagoa da Confusão is located in an area of transition between the Cerrado and Amazon biomes, mainly presenting Cerrado phyto physiognomies, with rich biodiversity and a high degree of endemism (SIMON; PENNINGTON, 2012).

2.2. Methodological procedures

In order to assess the bedrock, magnetic and radiometric geophysical methods were employed. Magnetometry investigates variations in the magnetic field of the Earth due to the heterogeneous distribution of magnetized rocks. Radiometry examines lateral contrasts in surface rocks by detecting variations in isotopes through gamma-ray emissions (e.g., uranium ^{238}U, thorium ^{232}Th, and potassium ^{40}K) (e.g., TELFORD et al., 1990).

The geophysical data were obtained from the Geological Survey of Brazil (CPRM) and are part of the Conceição do Araguaia Project database (LASA, 2012). In magnetometry, corrections were applied for the International Geomagnetic Reference Field (IGRF) and diurnal variation as well as the data were processed in the frequency domain. In radiometry, corrections were made for background cosmic radiation, and maps were generated separately for each radioelement channel. The geophysical software used for processing and lineament rose diagrams generation were Oasis Montaj 9.8.1 (GEOSOFT/SEEQUENT, 2020) and GeoRose 0.3.0 (YOUNG TECHNOLOGY INC., 2020), respectively.

Groundwater samples were collected from production wells (P1 to P5 and P9) and surface water from the Lagoa da Confusão (P6), as well as two points along the Urubu River (P7 and P8), totaling 9 sampled locations (Fig. 1). The selection of sampling points considered obtained authorization for sampling, accessibility, availability of lithological and construction profiles of wells, in addition to the geographical distribution within the study area.

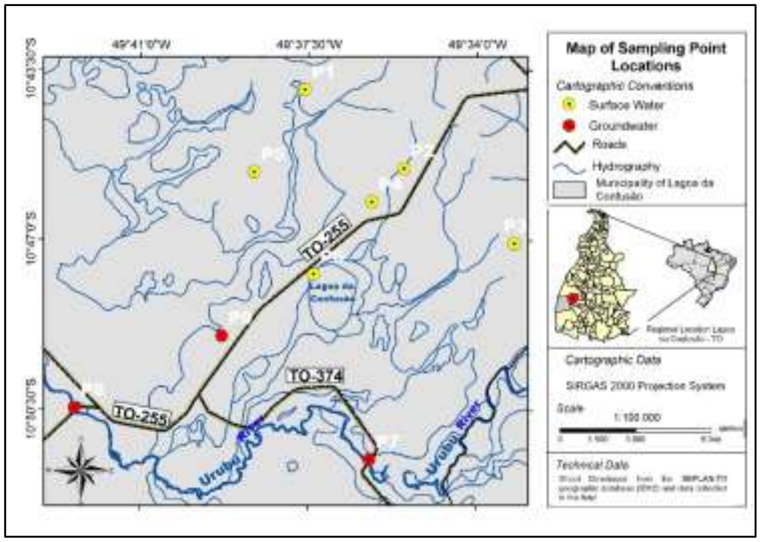

Figure 1 – Location of the sampling points around the Lagoa da Confusão. Source: Author (2021).

The sampling was conducted following the methodology established for water collection and storage by the Environmental Company from the São Paulo State (CETESB, 2011), and it included only samples collected during the dry season (October 2016), when there is no direct connection between surface and groundwater through sinkholes due to seasonal floods in the study area.

In the field, temperature, conductivity, total dissolved solids (TDS), and pH were measured. In the laboratory, turbidity, color, chloride concentration, carbonates, nitrites, nitrates, calcium, magnesium, manganese, iron, total hardness, calcium hardness, magnesium hardness, and alkalinity, potassium, sulfate, and sodium were measured. The analyses followed the methodologies established by the "Standard Methods for the Examination of Water and Wastewater" (APHA, 2005).

For the classification of groundwater chemical types according to the dominant ionic content resulting from water-rock interaction, the Piper triangular diagram was elaborated using the QualiGraf software (FUNCEME, 2016).

Sampling for isotopic analysis of oxygen-18, deuterium, and dissolved inorganic carbon in surface and groundwater was performed following the procedures recommended by the International Atomic Energy Agency (IAEA, 2002). The samples were collected in amber-colored glass containers to prevent light penetration and sealed with stoppers to prevent evaporation and the entry of gases causing isotopic fractionation. Isotopic analyses were performed using a Picarro L2130i Ringdown-CRDS cavity ring-down spectrometer and processed using LIMS for Lasers software at the Stable Isotope Laboratory of the Geochronological Research Center at the University of São Paulo (CPGeo-USP).

The laboratory analysis procedures followed the following methods: Deuterium-hydrogen ratio D/H (BRAND et al., 1996); O^{18}/O^{16} ratio (EPSTEIN; MAYEDA, 1953); C^{13}/C^{12} ratio of dissolved inorganic carbon - DIC (CRAIG, 1957).

The hydrogen isotope analysis followed the method proposed by Brand (1996), with the extraction of hydrogen from water in a reaction with metallic chromium at 850°C under vacuum, generating H_2 gas. For the determination of the deuterium-hydrogen ratio, aliquots of 1.0 µl were injected into a reactor, where the chromium oxidation reaction and H_2 release occurred. The oxidation reaction can be visualized in Equation 1:

$$3H_2O + 2\,Cr \rightarrow Cr_2O_3 + 3H_2\ (850^\circ C) \qquad \text{(Equation 1)}$$

After the reaction, the H_2 was inserted into the mass spectrometer and analyzed to determine the isotopic ratios H/D and referenced to a standard gas of H_2 itself. In order to determine the O^{18}/O^{16} ratio, the equilibrium technique of the CO_2-H_2O reaction, described by Epstein and Mayeda (1953), was used, given by Equation 2:

$$H_2O^{18} + CO^{16}O^{16} \leftrightarrow H_2O^{16} + CO^{18}O^{16} \qquad \text{(Equation 2)}$$

The reaction occurs at a temperature of 25.0 ± 0.1 °C for at least 8 hours. After the reaction, the CO_2 produced in the equilibrium of the reaction is extracted and analyzed in a mass spectrometer, where readings are taken to determine the O^{18}/O^{16} ratios.

The values of the D/H and O^{18}/O^{16} ratios were obtained using secondary standards of international reference with known isotopic composition VSMOW (Vienna Standard Mean Ocean Water), prepared by the International Atomic Energy Agency in Vienna, Austria (IAEA, 2002).

The variation in the isotopic ratio of the samples relative to the standard is expressed as the difference between the ratio measured in the sample and the ratio of the standard, using the delta (δ) per mil (‰) notation, as seen in Equation 3.

$$\delta\ {}^{\circ}/_{\circ\circ} = \frac{R_{sample} - R_{standard}}{R_{standard}} \times 10^3 \qquad \text{(Equation 3)}$$

For the interpretation of the behavior in the isotopic composition of surface and groundwater, the local curve was obtained and compared with curves obtained from Brasília (LOUSADA et al., 2011), the Amazon (SOUZA et al., 2015), and the Global Meteoric Water Line (CRAIG, 1957).

In order to determine the isotopic ratio of dissolved inorganic carbon δ^{13}CCID, a Gas Bench II system coupled to a gas-phase mass spectrometer was used. The sample preparation consists of inserting 7 drops of orthophosphoric acid into a helium-vented Exetainer vial (100 mL/min for 5 min).

Then, 05 mL of water was introduced to convert dissolved inorganic carbon-DIC into dissolved and gaseous CO_2. To obtain isotopic equilibrium between dissolved CO_2 and gaseous CO_2, approximately 18 hours were required.

Finally, the CO_2 was extracted through a chromatographic system, where the gas was introduced into the mass spectrometer to determine the δ^{13}CCID isotopic ratio relative to the international reference standard V-PDB (Vienna Pee Dee Belemnite).

The variation in the isotopic ratio of ^{13}C of the samples is also calculated relative to the standard and expressed in δ^{13}C (‰), as shown in Equation 4, with the analytical error ε of the measurements on the order of 0.05‰.

$$\delta^{13}C^{\circ}/_{\circ\circ} = \frac{{}^{13}C/{}^{12}C_{\,sample} - {}^{13}C/{}^{12}C_{\,standard}}{{}^{13}C/{}^{12}C_{\,standard}} \times 10^3 \qquad \text{(Equation 4)}$$

3. Results and discution

3.1. Geophysics

In the Total Field map (Fig. 2-a), an E-NE-oriented feature is observed, passing through the Lagoa da Confusão, as well as features in the N-S, SW-NE, and SE-NW directions. In the dy and dx maps (Figs. 2-b and 2-c), several parallel features are present in the E-W and N-S directions, respectively, as well as features oriented SW-NE. In the dz map (Fig. 2-d), the entire addressed structural framework appears at a shallow crustal level. In the ASA map (Fig. 2-e), directional faults are discriminated, and three distinct magnetofacies, M1, M2, and M3, related to their respective magnetization ranges, in nT/m, are delineated: between 1.85 and 6.66; between 6.66 and 14.82; and between 9.36 and 19.91. Additionally, zones indicating abrupt and well-defined changes from one magnetofacies to another are observed.

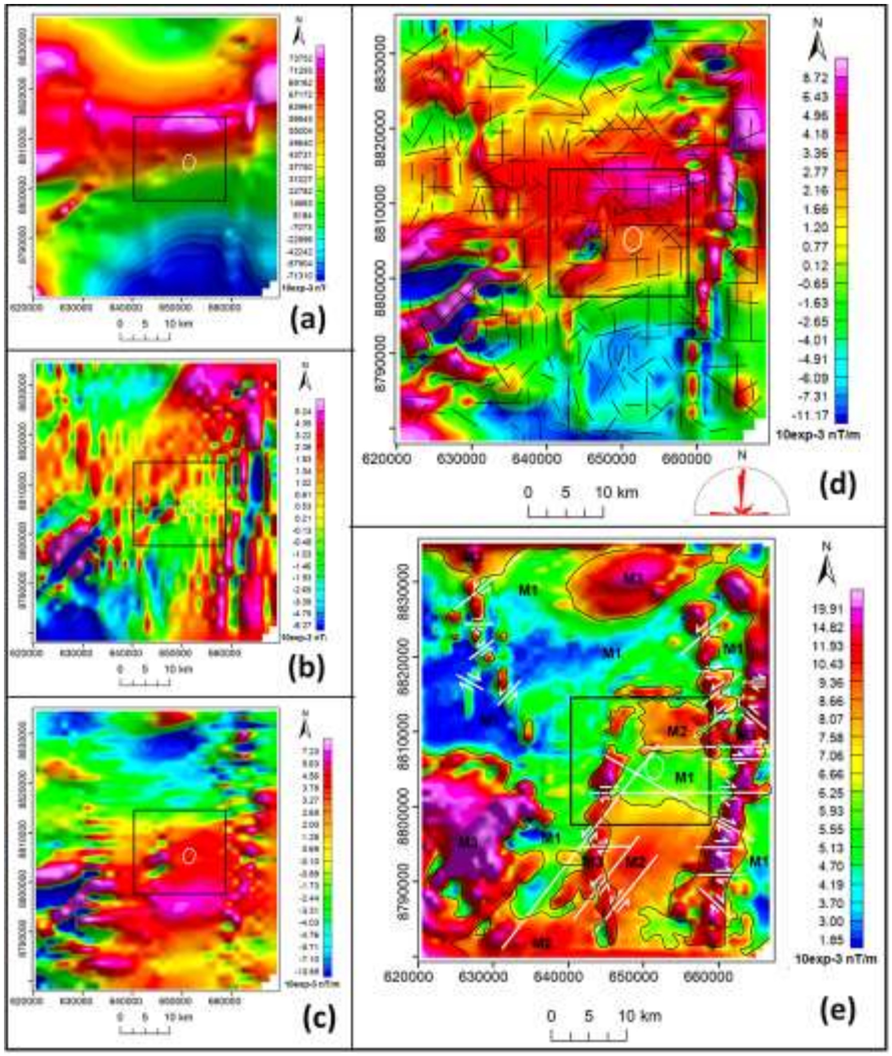

Figure 2 – Magnetic maps with discrimination of the study area (black rectangle) and Confusão Lagoon (white delineation): a) Total Field; b) Horizontal Gradient dx; c) Horizontal Gradient dy; d) Vertical Gradient dz with an overlay of interpreted general magnetic lineaments; e) ASA with an overlay of magnetofacies M1, M2, and M3, and interpreted faults.
Source: Author (2021).

In the ^{238}U channels map (Fig. 3-a) and ^{232}Th (Fig. 3-b), it is possible to discriminate the variation of gamma radiation in well-defined areas, allowing the delineation of five distinct radiofacies (R1, R2, R3, R4, and R5). The ^{40}K channel map is presented in Fig. 3-c, and the quantitative values of the radioelements in each radiofacies are presented in Table 1.

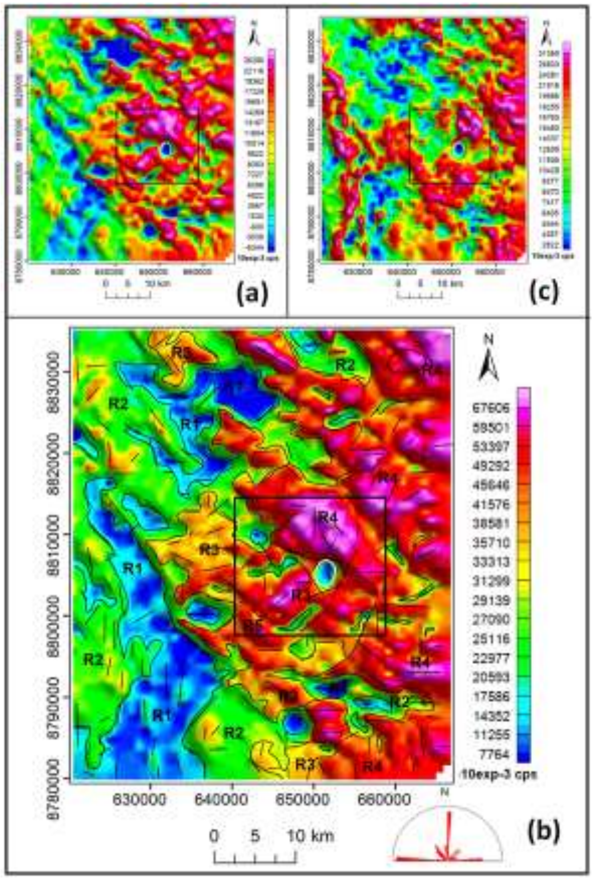

Figure 3 – Radiometric maps: a) ^{238}U Channel; b) ^{232}Th Channel with an overlay of radiofacies and interpreted radiometric lineaments; c) ^{40}K Channel.
Source: Author (2021).

Table 1 – Quantitative values of the radioelements in each radiofacies.

Radiofacies	**Radioelement content in cps**		
	^{238}U	**^{232}Th**	**^{40}K**
R1	>-6344 e <1630	>7764 e <17586	>2522 e <31369
R2	>1630 e <8353	>17586 e <29139	>7417 e <11506
R3	>8353 e <26286	>29139 e <67606	>11506 e <31369
R4	>15691 e <26286	>45646 e <67606	>7417 e <31369
R5	>15691 e <26286	>45646 e <67606	>24381 e <31369

Source: Author (2022).

The rose diagrams of magnetic and radiometric lineaments show a similar distribution of the main lineament directions: N-S, E-W, N45ºE and N45ºW. This implies that the subsurface structural framework in the bedrock interpreted through magnetometry exhibits continuity on the surface as interpreted from the radiometric maps. Figure 4 compares the geophysical interpretations of the bedrock substrate with the distribution of the investigated points and with the regional distribution of dolines.

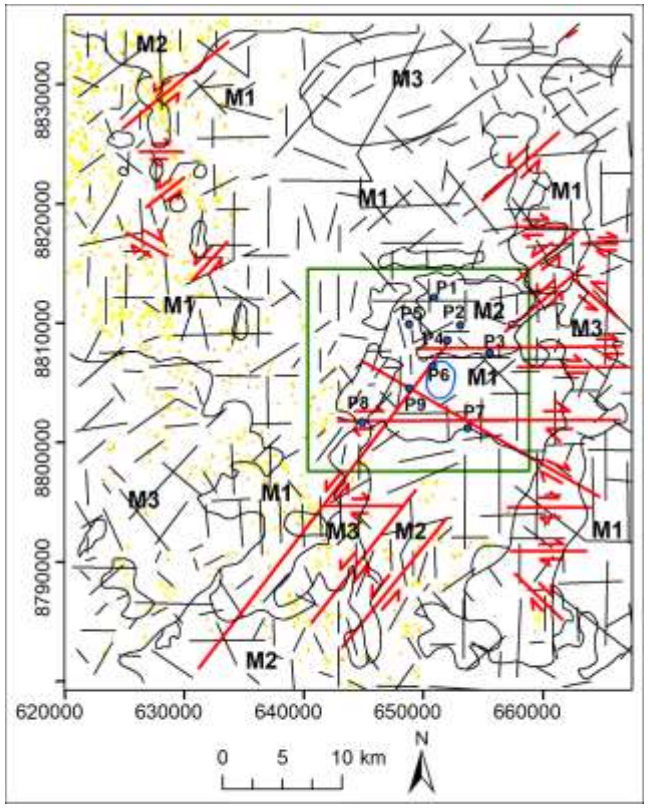

Figure 4 – Map showing the distribution of general magnetic lineaments (black lines); magnetofacies (black outlines); interpreted faults (in red); ipucas (regional distribution - yellow dots); points investigated for isotopic data acquisition (blue dots), and Lagoa da Confusão (blue outline).
Source of ipucas locations: https://oscarepaezm.github.io/morfometria/.

Based on the geological map of the Santa Terezinha Sheet, and data from well logs in lithological profiles from the Groundwater Information System (SIAGAS), the magnetofacies are interpreted as follows:

M1: Rocks with the lowest magnetization values, related to carbonate rocks of the Couto Magalhães Formation;

M2: Rocks with intermediate to high values, related to metasedimentary rocks, including carbonates, with variable iron content from the Couto Magalhães Formation;

M3: Responds to the highest magnetization values, related to ferriferous lateritic coverings.

Based on the Santa Terezinha Sheet and data from Martins et al. (2005) regarding the surface lithological constitution of the study area, the interpretation of radiofacies is as follows:

R1: Alluvial deposits. Sometimes, linear features are observed (Fig. 5) where the lowest anomaly (in blue) is surrounded by a higher one (in green), interpreted as river courses and alluvial plains.

R2: Araguaia Formation (easy alluvial terraces).

R3: Araguaia Formation (easy alluvial terraces) with an accumulation of sediments with higher ^{232}Th content, indicating they were generated by the Couto Magalhães Formation in the northeast and southeast portions of the maps.

R4: Couto Magalhães Formation. It is related to the clayiness of the metasedimentary rocks that capture ^{232}Th, and also to the clasts of ^{232}Th minerals composing the rocks.

R5: Laterite, justified by the composition of detritus of ^{232}Th minerals.

The zones indicating abrupt changes in magnetofacies can be interpreted as shear zones. Lagoa da Confusão is located in their domain and M1, in a structural low. The dominance of R3 in the E-W oriented strip where the lagoon is situated implies coverage by sediments from the Couto Magalhães Formation.

The outcrops of the Couto Magalhães Formation, especially in the M2 domain, to the north of the lagoon, have their boundaries coinciding with the shear zones, implying the formation of the structural highs in the area. In other portions of the map, rock coverings are lateralized, related to the M3 response, which also contributes to shaping the relief highs.

In Figure 4, it is observed that points P1, P2, P3, and P4 are in the M2 domain, which, due to lithological diversity, exhibit variation in iron content (Table 2), with P2 standing out as having the highest values among all investigated points. P8 also presents a high iron concentration, indicating the transition from the M2 to M3 domain, recording the lateralization process and consequent relative and progressive iron concentration. In the other points, concentrations are lower because they are in the M1 domain, and iron is related to mobilization by the structural framework.

The concentrations of HCO_3^-, Ca^{2+} and Mg^{2+} (Table 2) vary due to the proportion of the mixture of groundwater with surface water. Large-scale faults (Fig. 2) pass through most investigated points (P3, P4, P6, P7, P8, and P9), implying a high contribution of groundwater circulating through the carbonate bedrock and percolating through these structures. However, P4 and P9 have the lowest concentrations due to a higher proportion of surface water. P2 has the highest concentration of HCO_3^-, as the proportion of surface water is minimal, and the extension of a large-scale fault-oriented SW-NE passes through this point, mobilizing highly concentrated groundwater, also considering the contribution of the carbonated part of the M2 domain, which occurs with the other points of this domain that present average (P1 and P3) to high values (P7, which is in the transition between M1 and M2). Points P5 (which presents the second-highest value) and P6 are located in M1, where medium to high concentrations are justified by the contribution of the carbonate substrate itself and the structures.

Regarding ipucas, in Figure 2, it is observed that the highest density is located in the M1 domain and follows the same trends 30ºNW and N-S, from the northwest end to the central-southern portion of the map, fitting into the structural lows in the shear zones. Subordinately, some are in the M2 domain. Therefore, as both domains include carbonate rocks, it is implied that the control on the genesis and evolution of ipucas is related to the rock substrate, which may impose greater control than sediment covers on which they are seated. Additionally, the structural framework exerts a strong control on the regional distribution of ipucas.

3.2. Hydrochemistry

The results of the hydrochemical and isotopic analyses of samples collected around Lagoa da Confusão can be seen in Table 2.

Table 2 – Physicochemical parameters and isotopic analyses of $\delta^{18}O$, δD, d and $\delta^{13}CCID$ of groundwater (P1-P5 and P9) and surface waters (P6 to P8) around the Lagoa da Confusão.

Points	P1	P2	P3	P4	P5	P6	P7	P8	P9
pH	7.13	8.1	7.45	5.97	7.12	7.08	7.46	7.18	5.93
Color (UH)	3.7	1.4	0.8	0.2	1.7	4.3	4.7	6.9	0.2
Turbidity (UNT)	5.42	2.31	2.05	2.1	4.36	3.42	5.49	1.35	1.88
STD (mg/L)	31	141	60	9	81	7	34	6	3
CE (µS/cm)	113.2	275	126.6	20.6	252	27.9	71.4	14.4	7.9
Total Hardness (mg/L de CaCO3)	17	80	28	20	81.3	10	10	10	12
Ca^{2+} (mg/L)	5.88	24.28	9.6	2.8	27.2	2.02	1.84	1.04	1.6
Mg^{2+} (mg/L)	2.7	13.54	4.47	4.18	13.15	1.94	1.98	2.18	2.53
K^+ (mg/L)	0.86	2.07	1.58	0.33	0.87	0.76	1.04	0.74	0.47
Na^+ (mg/L)	1.16	4.46	6.11	0.46	2.72	1.05	2.01	1.09	0.46
HCO_3^- (mg/L)	34.6	165.4	68	14	94	46	38.6	5.4	2
Cl^- (mg/L)	2.62	3.83	1.55	3.47	3.62	1.17	1.28	1.06	2.13
SO_4^{2-} (mg/L)	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
NO_3 (mg/L)	0.5	0.2	0.1	0.5	0.1	0.4	0.1	0.1	0.2
Fe (mg/L)	0.04	0.6	0.2	<0.01	<0.01	0.05	0.01	0.18	<0.01
$\delta^{18}O$	-3	-3.7	-3.98	-3.51	-3.75	5.33	0.16	0.5	-3.09
δD	-14.6	-19.4	-21.2	-18.3	-19.3	27.5	0.3	2.1	-16.1

d	9.4	10.2	10.6	9.8	10.7	-15.1	-1	-1.9	8.6
$\delta^{13}C_{CID}$	-15.55	-13.7	-18.85	-16.69	-13.45	-18.22	-12.52	-20.55	-18.69

Source: Author (2021).

The electrical conductivity showed an average of 101.0 µS.cm, ranging from 7.90 to 275.0 µS.cm. The sum of the levels of all mineral constituents present in water given by the measurement of total dissolved solids (TDS) had an average value of 41.33 mg/L, classifying the waters of the area as fresh.

Regarding pH, the waters tend to be slightly acidic, presenting a pH close to neutrality, with values ranging from 5.93 to 8.10, with an average of 7.05 for the analyzed points. Hardness values expressed by the calcium carbonate content (mg/L of CaCO3) ranged from 10.0 to 81.30, classifying the waters of the region as soft or moderately hard.

Calcium concentrations for groundwater varied from 1.60 to 27.20 mg/L and are directly related to the chemical-mineralogical characteristics of the region. For surface waters, calcium concentrations ranged from 2.02 to 1.04 mg/L. Magnesium concentrations ranged from 1.94 to 13.54 mg/L, with magnesium being an element that presents similar dynamics to calcium with differences in precipitation ease.

The main compound in the sampled waters is bicarbonate ion, which originates from the dissolution of CO_2 present in the aquifer rocks or rainwater, with a variation from 2.00 to 165.40 mg/L.

Furthermore, concerning hydrochemical characteristics through the Piper diagram (Fig. 5), there is a predominance of calcic or magnesian bicarbonate waters. It is observed in the diagram that the waters have similar bicarbonate concentrations, with the predominance of ionic species of HCO_3^-, Ca^{2+}, and Mg^{2+} in the hydrochemistry of the waters in the area.

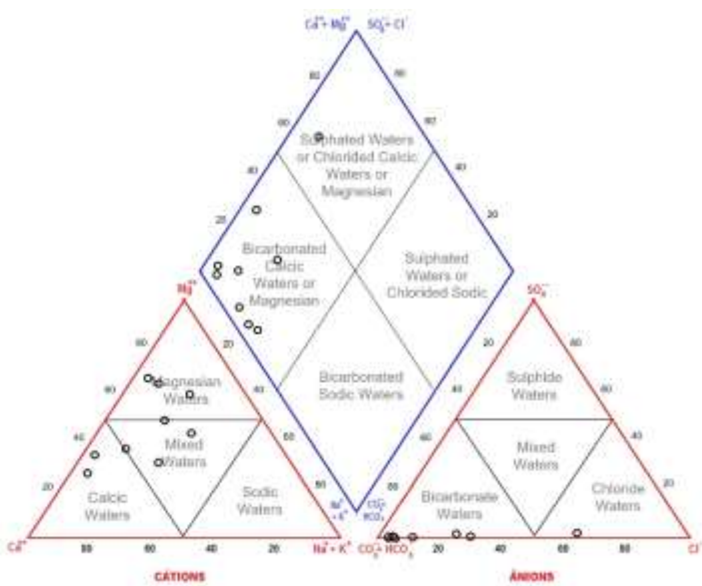

Figure 5 – Classification of the sampled waters studied with the Piper Diagram.
Source: Author (2021).

The δD values of the groundwater samples analyzed around the Lagoa da Confusão varied between -14.6‰ (P1) and -21.2‰ (P3), and the δ18O values between -3.0‰ (P1) and -3.98‰ (P3). From the analysis of the δD and δ18O results, it is possible to elaborate the trend line of the isotopic results of the area (Figure 6).

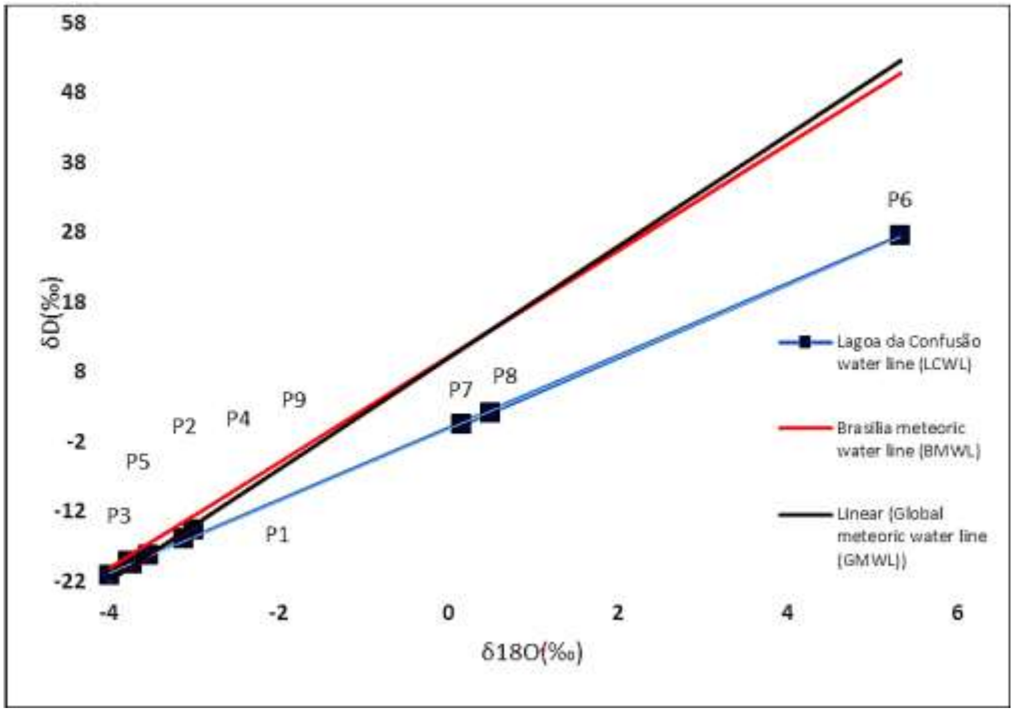

Figure 6 – Variation of the isotopic signal of $\delta^{18}O$ and δD around Lagoa da Confusão. The Local Water Line (LCWL) compared to the Global Meteoric Water Line (GMWL) and the Global Meteoric Water Line of Brasilia – BMWL.
Source: Author (2021).

The slope of the isotopic trend line in the vicinity of Lagoa da Confusão was 5.15, hence indicating that groundwater did not undergo significant evaporation during the infiltration process, originating from precipitation infiltration in recharge areas. The isotopic composition of surface waters collected in the Urubu River (P7 and P8), and especially in Lagoa da Confusão (P6), demonstrates significant evaporation, as expected.

The correlation between $\delta^{18}O$ and δD is common in karstic aquifers and suggests rapid recharge (rapid percolation process) from precipitation to groundwater through karstified carbonate substrates, therefore, indicating that groundwater is of meteoric origin (ARAGUAS; DIAZ TEIJEIRO 2005; AL-CHARIDEH 2012; QIBO et al., 2016).

The isotopic values obtained for surface waters were higher than those for groundwater. For these waters, the samples analyzed in the Urubu River yielded values of 0.16‰ $\delta^{18}O$ and 0.3‰ δD (P7), as well as 0.5‰ $\delta^{18}O$ and 2.21‰ δD (P8). In the Lagoa da Confusão (P6), values of 5.33‰ $\delta^{18}O$ and 27.5‰ δD were obtained.

The values of deuterium excess (Tab. 2) ranged from 9.4‰ to 10.7‰ for groundwater and from -15.1‰ to -1.0‰ for surface waters. The values obtained for groundwater in the area indicate that aquifer recharge waters originated from precipitations formed by atmospheric water vapors that have not undergone successive evaporation processes.

The values of the isotopic ratio of dissolved inorganic carbon (δ^{13}CCID) in the vicinity of the Lagoa da Confusão were predominantly negative and ranged from -20.5‰ to -13.4‰, with an average of -16.5‰. According to Villaneuva et al. (2016), negative values of dissolved inorganic carbon indicate a greater contribution of carbonate dissolution processes by H_2CO_3.

4. Final considerations

The results of the geophysics confirmed that the Lagoa da Confusão is seated on a karstic substrate. In addition, the numerous lineaments, including extensive faulting, the position of the lagoon in a shear zone, and the inflection in its contour imply that the genesis of the lagoon is related to the combined action of the structures passing through the bedrock with the karstification process. This action is also interpreted in the regional distribution of sinkholes.

The hydrochemical study identified that the main element present in the waters sampled around the Lagoa da Confusão, an area heavily impacted by the advance of irrigated agriculture, is bicarbonate ion, originating from the dissolution of CO_2, which is present in the soils of recharge areas or in rainwater, with the predominance of ionic species containing HCO_3^-, Ca^{2+} and Mg^{2+}.

The study of stable isotopes allowed for the identification of the presumed karstic characteristics in the area and an understanding of the dynamics of water flows through knowledge of the isotopic characteristics on the surface and groundwater in the region.

The flow dynamics and residence time indicated by the isotopic composition of the waters are closely related to the karstic characteristics of the region. The values of the isotopic ratio of dissolved inorganic carbon (δ^{13}CCID) were predominantly negative, thus indicating a greater contribution of carbonate dissolution processes by H_2CO_3.

The study proved to be valid by contributing to the hydrogeological characterization of the area and verifying that the chemical composition of the waters is altered by water-rock interaction and dissolution of carbonate rocks. The results highlight the vulnerability of the area, as aquifer waters have a rapid recharge with their dynamics controlled by the limestone formation, which contributes to rapid percolation with high flow rates and little time for filtration, potentially facilitating the transport and reducing self-purification of pollutants.

However, it is suggested that local geophysical sections orthogonal to the main directions of the interpreted lineaments be conducted in order to understand the structural framework around the lagoon in detail. In this manner, together with other data (e.g., from drilling, and well data), it will be possible to discuss its evolutionary model in depth.

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