Brazilian Journal of Geophysics
Brazilian Journal of Geophysics 41 (2023), 1, 1–25
Brazilian Geophysical Society
ISSN 2764-8044
DOI: 10.22564/brjg.v41i1.2199

GROUNDWATER LEVEL VARIATION ANALYSIS USING HYDROGEOPHYSICAL METHODS IN AN AREA OF CAMPO SUJO IN CERRADO, CHAPADA DOS VEADEIROS REGION, GOIÁS

Gustavo Xavier Vilarinho[1*], Welitom Rodrigues Borges[1], Marcelo Henrique Leão Santos[1], Rodrigo de Almeida Heringer[2], Luciano Soares Cunha[1], Rafael Silva Oliveira[3], Thiago Lima Mendes[1], Rafael de Oliveira Xavier[3], and Larissa da Silveira Verona[3]

[1]Universidade de Brasília - UnB, Geoscience Institute, Brasília, DF, Brazil
[2]Universidade Federal de Santa Catarina - UFSC, Geology Department, Florianópolis, SC, Brazil
[3]Universidade Estadual de Campinas - Unicamp, Department of Plant Biology, Campinas, SP, Brazil

*Correspondent author e-mail: vilarinho.gx@gmail.com

ORCID 0000-0003-0915-6629
ORCID 0000-0002-5158-1947
ORCID 0000-0002-2173-4885
ORCID 0000-0001-7035-606X
ORCID 0000-0003-3134-7245
ORCID 0000-0002-6392-2526
ORCID 0009-0001-8197-0492
ORCID 0000-0002-1691-1162
ORCID 0000-0002-3476-9868

ABSTRACT. Cerrado's campo sujo areas have been one of the main focuses of anthropic occupation in the Chapada dos Veadeiros region, Brazil's Central Plateau, as they are easily accessible flattened areas with less dense vegetation. They are usually associated with wetlands representing excellent water reservoirs and groundwater recharge zones. The environmental characterization and analysis of water level variation are essential to investigate the impacts of human occupation. Hydrogeophysics represents one of the main subsurface research tools due to its easy application and efficiency in identifying the water level, with emphasis on Ground-penetrating radar (GPR), and electrical resistivity tomography (ERT). An analysis of GPR sections with 200, 400, and 900 MHz frequency antennas associated with the resistivity model was carried out to identify structures, and map the groundwater level. The overlapping data compose a hydrogeophysical model with good correlation to direct measurements of water level in a monitoring well, and soil horizons mapped in a trench. The GPR proved to be efficient in mapping the water level, mainly about to the survey with a 400 MHz antenna, shown as a horizontal reflector associated with attenuation portions of the reflection signal, registering in profile the lowering of the water level from 1.68 m in May to 3.35 m in August. The resistivity model showed a good correlation with the variations between the mapped soil horizons. The analysis shows that constructing a hydrogeophysical model is an excellent alternative for identifying the water level, and characterizing the shallow subsurface by applying non-invasive techniques. The study area represents a preserved area of campo sujo, and the research data can be used for comparison with future surveys, in addition to representing a base hydrogeophysics methodology that showed promising results for the physiographic characteristics of the area, which can be replicated in regions of similar geoenvironmental aspects.

Keywords: hydrogeophysics; aquifer; GPR; DC resistivity; savanna

INTRODUCTION

Monitoring groundwater level variation and water dynamics in the subsurface has been the focus of several studies, and represents an essential tool for applications in environmental analysis, such as in the study of contaminant propagation (Oostrom et al., 2016; Arora & Mohanty, 2017; Wan et al., 2018), water infiltration, flow, runoff, and contamination (Robinson et al., 2008; Allaire et al., 2009; Tran et al., 2016), groundwater level variation analyses, and availability and management of water resources (Costall & Harris, 2018; Abiye et al., 2018), among others. In this context, some techniques were developed in order to improve this type of survey, with emphasis on hydrogeophysical methods.

Hydrogeophysics has become one of the main tools for investigating the shallowest zones of the subsurface, both for the saturated region and the vadose zone (Rubin & Hubbard, 2005; Binley et al., 2015). It stands out about traditional direct analysis methods since these have limitations, such as higher costs, and difficulties in deeper analyses, and surveys of broader scales, as they generally consist of a point sampling. Also, the measurements, and data from the survey can be influenced by changing the study environment, as they are invasive techniques. On the other hand, hydrogeophysical techniques are non-invasive. They have good sensitivity related to moisture present in the soil, in addition to more practical field surveys, and reaching greater depths and broader horizontal scales (Binley et al., 2015). Authors such as Zhou et al. (2001); Braga (2006); Deiana et al. (2008), Kirsch (2009), Saintenoy & Hopmans (2011), Arora et al. (2016) and Zhu et al. (2022) point to hydrogeophysical techniques as efficient means to identify horizontal structures such as water level, besides making it possible to determine minor variations in the volumetric content of water in the soil.

In this sense, the present study deals with the verification of the variation of the water level in the subsurface using hydrogeophysics as an investigation tool in an area under the domain of a campo sujo in the Cerrado biome located in the region of Chapada dos Veadeiros, state of Goiás, Central Brazil. The campo sujo typical of the Brazilian Cerrado is generally associated with wetlands, and represents true ecological sanctuaries for the local fauna and flora. They are environments that have an intrinsic connection with the moisture present in soils during a long period of the year, also they are usually next to watercourses located in veredas environments. Therefore, they represent excellent reservoirs with water availability for the local fauna during the dry and rainy seasons. They are essential groundwater recharge zones in addition to feeding watercourses due to their high surface runoff rate (Sano et al., 2008; Lima, 2011; Haque et al., 2018; Latrubesse et al., 2019). These areas are susceptible to anthropogenic changes as they have a very shallow groundwater level, and their ecosystem depends on this moisture presence.

Over the past four decades, the Cerrado has been one of the biomes with the highest rate of degradation worldwide, with a high conversion rate of land use for agriculture, cattle run, and human occupation (Shiki & Ortega, 1997; Sano et al., 2008). Fields and wetlands cover about 20% of the Brazilian territory, and their coverage has been drastically reduced (Junk et al., 2014; Rosolen et al., 2015), which affects the natural water storage in several ecosystems. The Chapada dos Veadeiros region represents one of the most significant extensions of preserved Cerrado in the Brazilian territory, located northeast of the state of Goiás (ICMBio, 2021). There is a significant concern about the degradation of the biome in this region because it represents a barrier against the advance of the agricultural frontier (Rodriguez et al., 2018), the number of subdivisions close to the areas of the Cerrado's campo sujo and campo limpo has grown uncontrollably. These areas have smooth to slightly undulating relief, and generally, there are not many rocky blocks on their surface, which makes them the main targets of this occupation.

Due to its ecological importance, there is a huge need to encourage the protection of these Cerrado areas. It is believed that geoenvironmental characterization studies, and monitoring groundwater level variations are essential to support this incentive, and help define the significant impacts of these areas. Therefore, hydrogeophysics proves to be an excellent research tool for the case. A network of studies considers the verification of the water level in the subsurface with the application of hydrogeophysical methods. However, the surveys are usually entirely objective, and are carried out based on the area's specific physical and environmental characteristics (Moreira et al., 2021; Casagrande et al., 2021; Furlan et al., 2021). In this sense, there are no records of the application of these techniques for the campo sujo environment object of the present study, which was carried out on a local scale.

Therefore, there is a need to define a methodology for acquiring geophysical data focusing on mapping the groundwater level and characterizing the subsurface, taking into account the physiographic characteristics of the study area. The potential results represent the possibility of applying this methodology to several places in the Chapada dos Veadeiros mesoregion. It is an environment with geological, pedological, and vegetation aspects that are typical and recurrent in extensive areas of this portion of the Cerrado of Goiás.

STUDY AREA LOCATION

The study area (Fig. 1) is located in Alto Paraíso de Goiás municipality, in the northeast region of the state of Goiás (GO), inserted in the area of the Chapada dos Veadeiros National Park (CVNP), a place that protects one of the main concentrations of preserved Cerrado in Brazil. It is located 23 km from the center of Alto Paraíso de Goiás, and 2 km south of the Rio Preto River, one of the main rivers in the region.

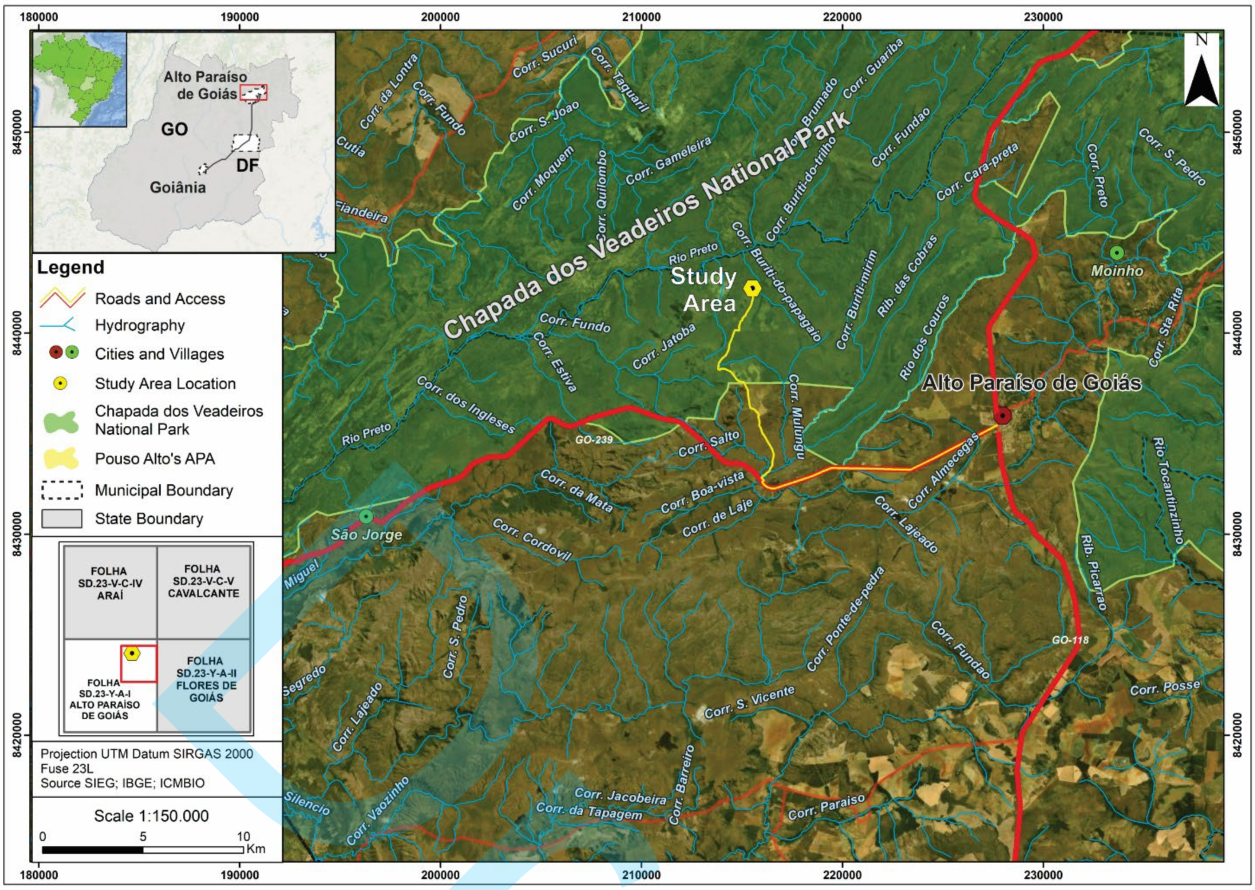

Figure 1 – Location map of the study area indicating the access from Alto Paraíso de Goiás by the yellow line.

GEOLOGICAL SETTING

The study area is located in the geological context of the Traíras Group, a component of the Veadeiros Supergroup, inserted in the Brasília Fold Belt - FB, which corresponds to a Neoproterozoic orogen with more than 1100 km in length, a component of the Tocantins Province. The FB is arranged north-south with vergence to the east, towards the São Francisco Craton. The deformation of the FB occurred from the collision between the São Francisco, Amazonian, and Paranapanema cratons (Pimentel, 2016), known as Brazilian orogenesis (Pimentel et al., 1999). During the tectonic evolution of the FB, there was a process of continental rifting at the end of the Paleoproterozoic, which resulted in the sedimentation of rocks related to the Veadeiros Supergroup, composed of the Paranoá (Campos et al., 2013), Araí and Traíras Groups (Martins-Ferreira & Campos, 2017).

The Traíras Group rocks have a maximum deposition age of 1543 ± 31 Ma, and their formation is related to the evolution of an intracontinental basin environment of the SAG type (Martins-Ferreira & Campos, 2017). It is divided into formations:

(I) Boqueirão: composed of calciferous siltstones interdigitated with quartzites interspersed with carbonaceous material, in addition to an upper unit composed of quartzites and phyllites with marble lenses;

(II) Rio Preto: composed of medium pure quartzites, well selected, with subordinate occurrences of meta conglomerates;

(III) Rosário: composed of pelites made of dark to gray and greenish metasiltstones; psammopelites composed of white quartzites, with granulometry ranging from fine to medium; and a psammo-pelitho-carbonated sequence, with the presence of carbonaceous levels, and eventually, dolomitic meta limestone lenses. The Rosário Formation is the thickest, and represents a marine transgression, which allowed the development of a shallow marine platform with mixed sedimentation characteristics (Tanizaki et al., 2015).

In the study area, the Traíras Group is represented by yellowish to reddish and greenish metasiltstones, and meta rhythmites in the relief's most flattened and eroded portions. A macroscopic description mainly comprises feldspars, quartz, biotite, and muscovite. They present sub-horizontal preserved S0 foliation with a smooth dip in the northwest (NW) direction. There are also white to yellowish micaceous quartzites of fine to medium grain size, interspersed with metasiltstones composing the tops of hills and slopes. They all belong to the Rosário Formation (Martins-Ferreira & Campos, 2017).

STUDY AREA CHARACTERIZATION

The study area corresponds to Cerrado's campo sujo environment (Fig. 2A) in contact with a vereda environment (Fig. 2B), where an affluent watercourse of the Rio Preto River is located. The predominant vegetation comprises spaced small and medium-sized tree-shrubs among the undergrowth vegetation composed of herb plants that cover almost all the soil in the region.

The campo sujo present in the area is characterized by the presence of "murundus" (Fig. 2C), which refers to micro reliefs of 1 m to 1.5 m in height, in which the development of Cerrado parks with higher and thicker bushes. The murundus correspond to characteristic convex elevations, which vary on average from 0.1 to 1.5 meters in height, and from 0.2 to more than 20 meters in diameter. According to Oliveira-Filho (1992), the origin of the murundus is linked to the activity of termites, whose terrain elevations were formed from the construction of their nests, and erosion and degradation after numerous generations of termite generation in a long process of succession.

An extensive area of soft-wavy characterizes the landscape to wavy relief between altitudes 1180 and 1190 m, intersected by high hills with tops at altitudes higher than 1300 m. The vereda is fitted in a U-shaped valley, and is at an elevation of 1179 m. The region is located in the High Rio Preto Dissected Plateau - 1C geomorphological compartment (Martins-Ferreira & Campos, 2017).

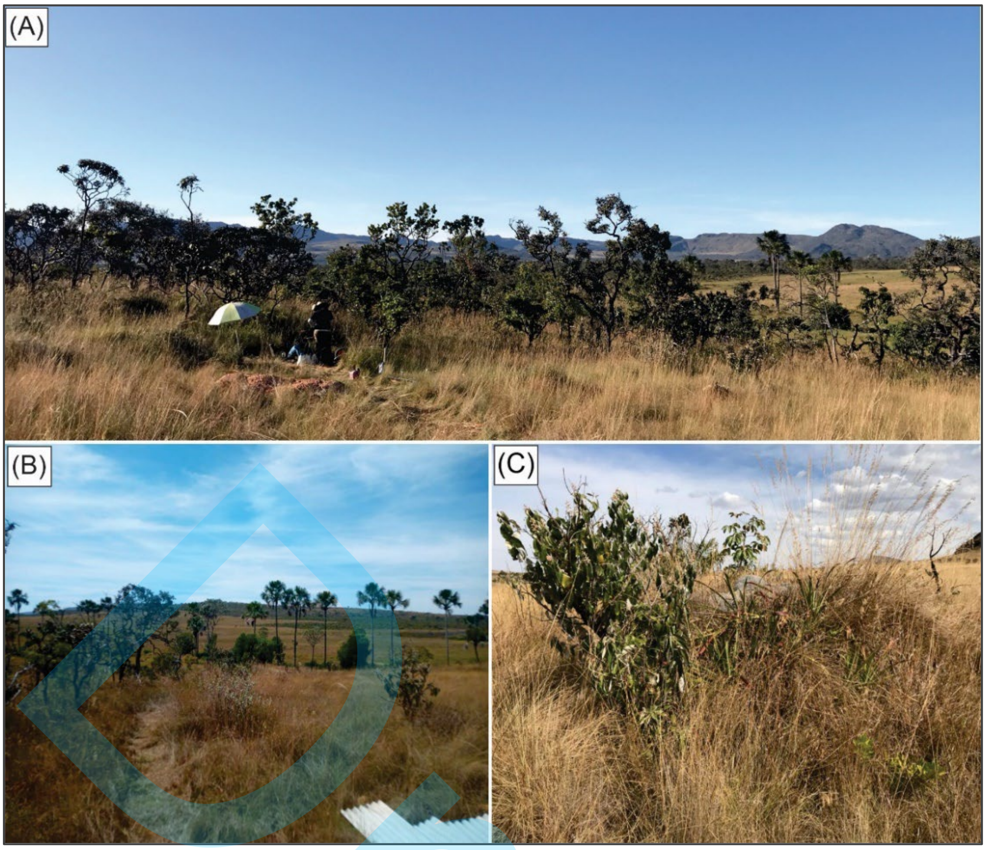

Figure 2 – Records of the study area. (A) it is possible to identify aspects of the vegetation with the presence of small, medium-sized shrubs among the herbaceous plants; (B) the tributary watercourse of the Rio Preto River located in the eastern portion of the area; (C) the micro-relief aspect of the murundu with the development of bush-trees on its surface.

METHODS

The work methods used in this research are related to the description of the physical environment characteristics of the study area, and the stages of acquisition, processing, and modeling of geophysical data. There were restricted possible paths for walking in the study area, so as not to interfere with analyzes of biomass collection (focus of other studies that were being carried out in the area), the geophysical data acquisition profile was oriented in the azimuth direction 180° (South), and is 30 m long (Fig. 5A and 5B). The Ground-penetrating radar (GPR) surveys were carried out on May 19, 2022 (field stage C01), with a precipitation rate of 4 mm for 2022, and an average precipitation for the last 10 years of 38.7 mm, and August 09, 2022 (field stage C02) with average precipitation of 0.12 mm for the last decade, and 0 mm in 2022 (Fig. 3). The resistivity survey was carried out only in August (C02) since the soil was supersaturated in the first stage, making applying this method impracticable.

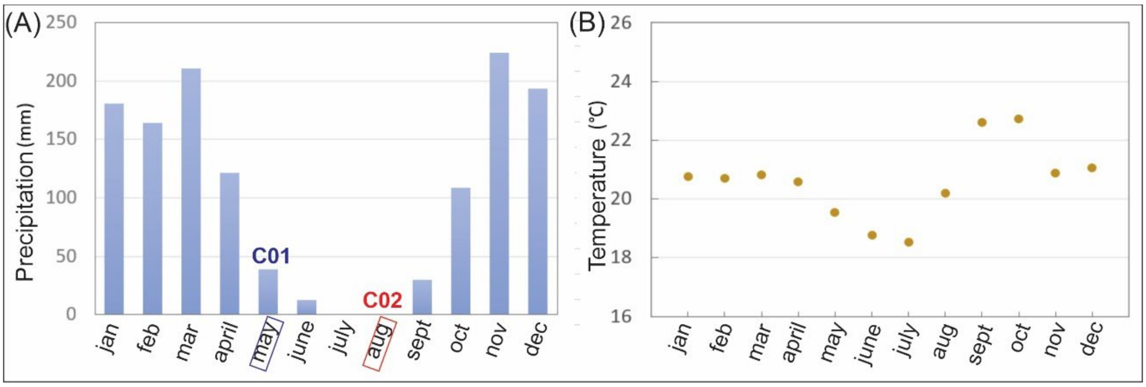

Figure 3 – (A) Monthly averages of precipitation values (mm) and B: temperature (°C) in relation to the period from 2012 to 2022 recorded at the meteorological station of Alto Paraíso de Goiás (A024). BDMEP data source – INMET, 2022.

The characterization of the study area was based on a detailed mapping of the geomorphology, phytophysiognomy vegetation domain, geology, and pedology in the field. Firstly, an aerial photogrammetric survey was carried out from the overflight of the area with the VANT Mavic 2 Pro Drone (DJI) to construct a digital elevation model with high image resolution, and a better definition of contour lines. Then, the characteristics of the Cerrado's campo sujo environment were described as the predominant relief type and the geological mapping, based on verifying the main lithotypes and structures present. After that, the type of soil present in the most superficial layer down to the saprolite horizon was described, observed from the opening of a trench measuring 1.5 m wide x 1.5 m long x 2.0 m deep. A physical analysis of three samples corresponding to the depth intervals 0 – 5 cm, 5 - 15 cm, and 15 - 30 cm was made to characterize the most superficial soil layer. Finally, after installing the monitoring well, the water level was checked during the two field stages (May and August).

Drone Photogrammetry – Topography Model

Due to the unavailability of detailed topographic maps in the study area, it was decided to carry out a topographic survey using aerial photogrammetry with VANT Mavic 2 Pro, which made it possible to insert the topography information in the geophysical sections based on the detailed topographic model. The topography, coupled with the geophysical sections, helps interpret the signal distribution along the sections since it allows direct association with the relief of the terrain studied. For greater accuracy in the aerial photogrammetric survey, a fixed station associated with the collection of control points used in the post-processing image was used. From this survey, it was possible to generate an orthomosaic and a digital elevation model (Fig. 4) to extract the contour lines, so it was possible to plot the height values along the geophysical sections.

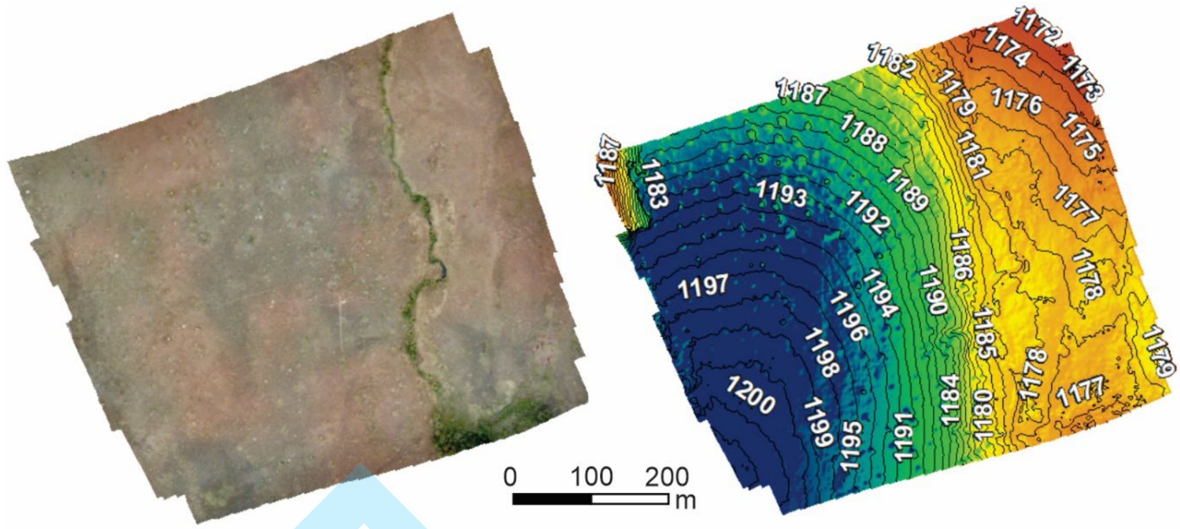

Figure 4 – Orthomosaic and Digital Elevation Models generated for the study area, with the extraction of contour lines at every 1 m of elevation difference.

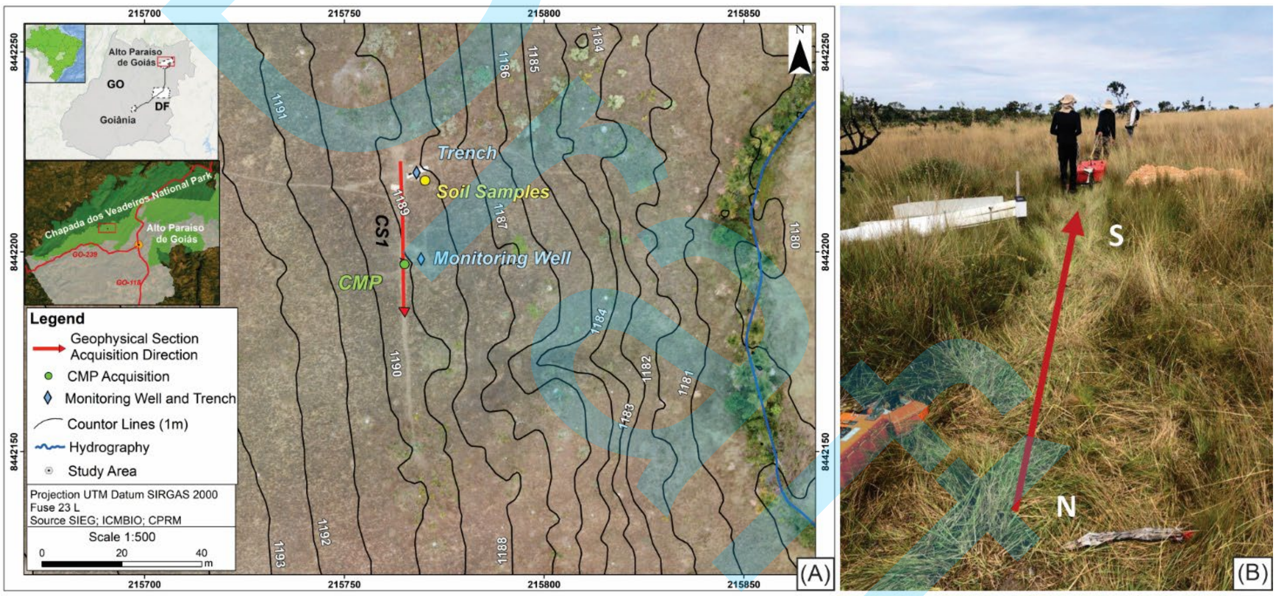

Figure 5 – (A) The location map of the study area indicates the location and acquisition direction along the section. Blue icons, the yellow circle indicate the monitoring well, the trench, and the CMP acquisition point, by the green circle indicate the soil sample collection point. (B) Record of acquisition section looking north to south.

GPR

Concerning the GPR method, 200 MHz, 400 MHz, and 900 MHz frequency antennas were used on the same path in standard offset sections. At 24 m from the section, a common midpoint (CMP) velocity sounding was carried out with 80 MHz shielded antennas to determine the propagation velocity of waves on the ground. The acquisition of the CMP type was carried out along a 20 m long section, with the acquisition of the data collecting points every 10 cm of displacement of the antennas, until completing the total 20 m of the survey. The GPR system used in the field was the SIR 3000, manufactured by GSSI.

The acquisition depths of the GPR data can be defined using the average velocities of direct electromagnetic waves on the ground, calculated from the analysis of the CMP sections by the similarity analysis method (Fig. 6). The velocity models were obtained from the adjustment of the reflectors corresponding to the wave propagation on the ground, discriminating the signal from the reflected waves. Then, the coherence models related to the velocity spectra were generated, indicating the maximum coherence locations for each CMP section acquired during May (C01) and August (C02).

At first, the propagation velocity of direct waves in the air was calculated, resulting in 0.3 m/ns. The propagation velocity of direct waves in the ground was calculated, which resulted in 0.066 m/ns in May (C01), and 0.101 m/ns in August (C02).

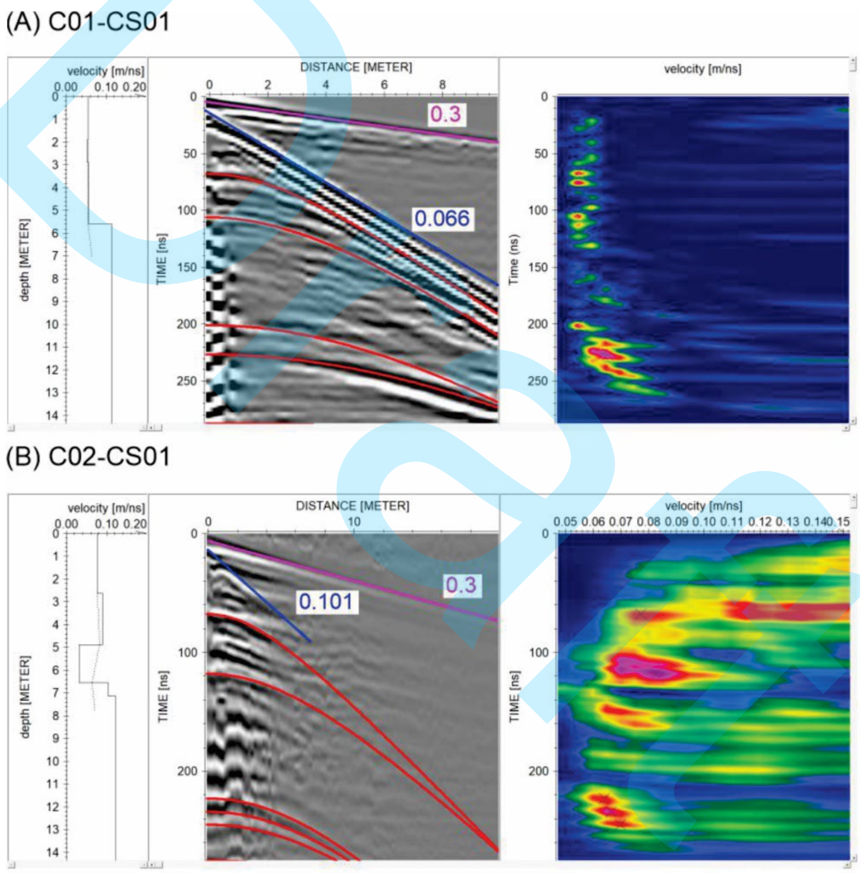

Figure 6 – Analysis of propagation velocity of electromagnetic waves from the CMP for the study area. The figures show the velocity models, followed by the velocity-sounding section with the main identified events, and the semblance analysis showing the most coherent velocity for each period. (A) May (C01). (B) August (C02).

It is observed that there was an increase in the speed of propagation of direct electromagnetic waves in soil for the acquisition in August, which indicates the influence of the presence of drier soils, in which the pores previously filled with moisture were filled by air, which increases the resistivity, and facilitates the propagation of the electromagnetic wave.

The propagation velocity values defined from the analysis of the CMP sections were used in processing the GPR data to have the reflectors' depth closer to reality. The processing was carried out in the software ReflexW Version 7.5.8 (Sandmeier Geophysical Research), from which it is possible to adjust the time zero of all radargrams, in addition to filtering random noise (bandpass filters), filtering instrumental noise, application of gains and migrations, insert of topography, among others (Fig. 7).

The acquisition parameters for the 200 MHz frequency antenna were defined as a T_rate of 100 KHz, range value of 300 ns and 1024 samples, for the 400 MHz frequency antenna, the range was defined at 150 ns and 1024 samples, and for the 900 MHz frequency antenna, the range value of 100 ns, and 2048 samples.

The processing workflow is as follows:

- Data Acquisition;
- Raw Data Importing with conversion of the raw file type for reading in the ReflexW software;
- Static Correction, in which it is possible to remove the wave signals propagated in the air, leveling 0 m of acquisition depth to 0 m of the walking surface;
- Time Cut (ns), cut in the depth of reading to remove signals at greater depths that do not have a good resolution;
- Subtract Mean Dewow and Header Gain values archived in data acquisition to viewing the raw archive without amplification of the time-variant;
- Application of the Gain Function to emphasize the amplitudes of the reflected signal, resulting in a radargram with less noise, and better resolution;
- Simple migration (Diffraction Stack) based on the wave propagation velocity to redistribute the reflections to their original points closer to reality since data without migration sometimes represents a pseudo location that does not portray the real location of the reflections;
- Plotting the Topography information of the walking profile, bringing the section closer to the actual situation of the study environment, which helps interpret subsurface information.

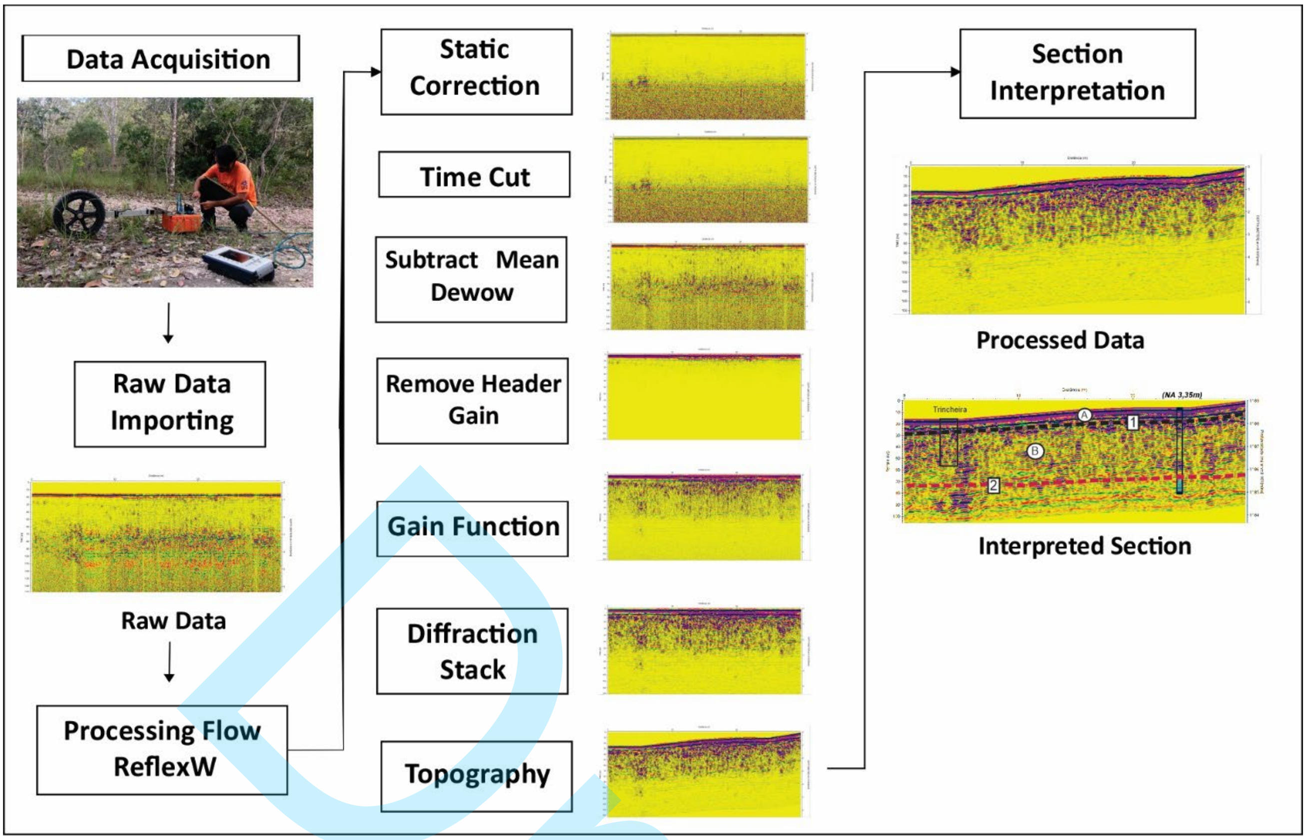

Figure 7 – Workflow for the GPR method, from data acquisition in the field, through filtering and processing in the ReflexW software, and then the interpretation of the radargram with the identification of mapped interfaces and inferred groundwater level.

DC Resistivity

For the electrical resistivity tomography (ERT) technique, the data were acquired on the same walking profile, with an azimuth direction of 180°. The arrangement used was the Dipole-Dipole, using 51 electrodes for each acquisition and spacing between the electrodes of 0.5 m of distance, resulting in a 25-meter acquisition section. The equipment used was the SYSCAL PRO (IRIS Instruments), powered by a 12 V battery.

The modeling workflow with resistivity data was carried out in the Prosys II and III (IRIS Instruments), and RES2DINV (Aarhus Geosoftware) software. It occurred according to the following order (Fig. 8):

- Data Acquisition and conversion of files into extension .bin containing the resistivity information recorded about each electrode;
- Data filtering in the Prosys III software to remove points with very high contact resistivity values or tending to infinity, as well as the negative values recorded, and points where there was no data reading;
- Filtering carried out in the extension file .dat by the RES2DINV software, which allows viewing the distribution of points purchased in a 2D pseudo-section, and allows to remove of noisy

points;

- Definition of model blocks arrangement, and deviation limitation by the minimum square method;
- Data inversion in an apparent resistivity pseudo-section measured and calculated, generating the inverse resistivity model section. From this inverse model, it is possible to emphasize or soften signs to improve the investigation. For the inversion of geophysical data, the refinement model was used;
- Interpretation of the geoelectric section has been made, considering the resistivity values domains and structures related to the direct data recorded in the field, such as the water level in the monitoring well, and the superficial pedological characteristics observed in the open trench.

In concern to the acquisition parameters for the geoelectric section, the total number of data levels generated is 32, with 503 measured data points. The total number of model blocks is 430. Regarding to the data filtering process, it's important to highlight the presence of electrical contact resistance values between 80 and 100 Ohm.m in some electrodes mainly in the southern portion of the section, even taking precautions to reduce these values. Therefore, there was a loss of points since the equipment does not allow the increase in the value of the electric current, which would occur for the acquisition of these points.

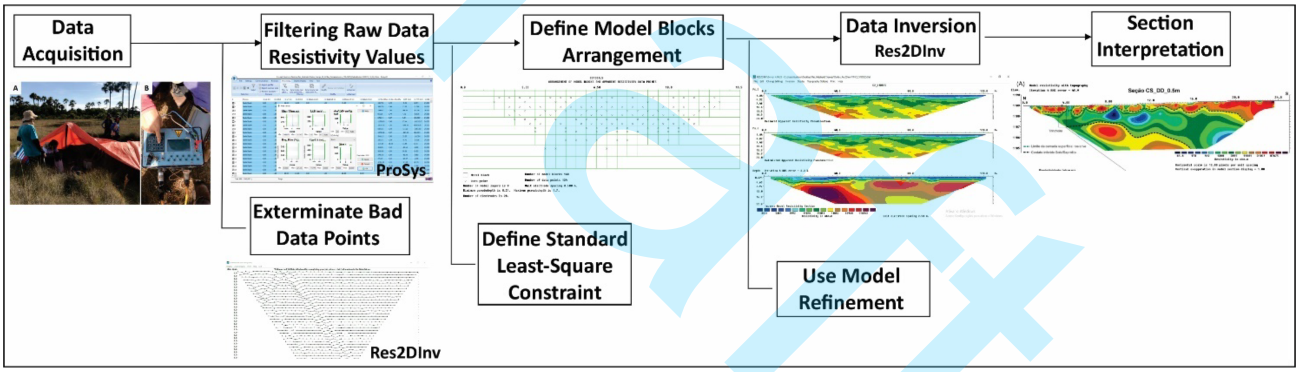

Figure 8 – Workflow for the resistivity method from field data acquisition, through data filtering in Prosys II, III and RES2DINV softwares, then reversing data in pseudo sections and interpretation of the geoelectric section defining domains, and inferring the level of water in subsurface.

RESULTS

Soil Description

The surface soil layer in the study area corresponds to a yellow to orange sandy-silt soil with ferruginous concretions (Fig. 9A). In some places, these concretions have thick levels of up to 10 cm (Fig. 9B and 9C). The surface soil layer was wet in May, and dry in August. According to the EMBRAPA Brazilian Soil Classification System (Santos, 2018), it corresponds to a domain of Petric Concretionary Plinthosol, which covers a vast region close to the study area.

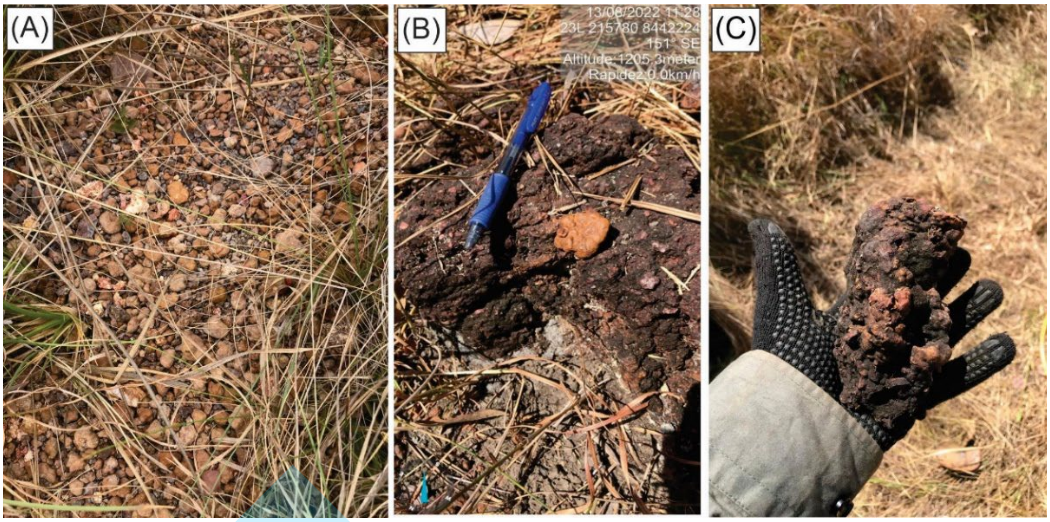

Figure 9 – (A) Gravel aspect of the plinthite surface layer of soil in the study area, composed of concretions and laterites. (B) Block of laterite about 15 cm thick, common in the lower portions of the area. (C) Fragment of laterite about 8 cm thick, common in the highest portion.

Soil samples were collected at 0-5 cm depth intervals, 5-15 cm, and 15-30 cm under the same point, in August (C02). The three samples have a high concentration of thick fraction from 39.77% to 40%, which refers to the presence of lateritic gravel. The samples from the two most superficial levels have gravel texture, with a higher concentration of clay in the upper layer at the thin fraction. The sample collected in the deepest interval showed a much higher concentration than the others, composing 73.69% of the thin fraction. A higher concentration of silt in the intermediate layer composing 40.25%, as observed in Table 1.

Table 1 - Physical analysis results of soil samples collected in the study area.

Sample	Gravimetric Moisture in the Collection	Coarse Fraction (> 2mm) in the Total Sample	Fine Fraction Composition			Texture Group
			Clay	Silt	Sand	
	(%)	(%)		(%)		
CS1_Am1_5cm	2.74	39.77	19.26	32.1	48.64	moderately gravelly
CS1_Am1_15cm	0.61	35.8	12.58	40.25	47.18	moderately gravelly
CS1_Am1_30cm	5.26	40	15.79	10.52	73.69	moderately sandy gravelly

From the characterization of the soil profile exposed in the trench (Fig. 10), four soil horizons were identified. The first horizon, A, has a thickness of 50 cm, and is pink to yellow, sandy silt, characterized by many lateritic concretions from 1 to 5 cm in diameter. It corresponds to the predominant concretionary plinthosol domain in the region. Horizon B represents a poorly developed layer of orange soil, 30 cm thick, marked by an abrupt transition with horizon A, which corresponds to a more compacted silt soil, and has a small amount of gravel up to 2 cm in diameter. It is possible to identify some structures corresponding to a possible foliation. This profile's contact between horizons A and B coincides with the observed moisture level at 50 cm deep. Then the 50 cm thick horizon C1 is present, which differs from the upper horizon due to the smaller amount or practically absence of concretions and gravel, its color is red to pink, and the geological structures are more preserved. It is possible to notice the presence of incipient foliation. Finally, horizon C2 occurs from 1.3 m deep, representing the saprolite composed of an altered reddish metasiltstone with preserved horizontal structures corresponding to the S_0 rock foliation.

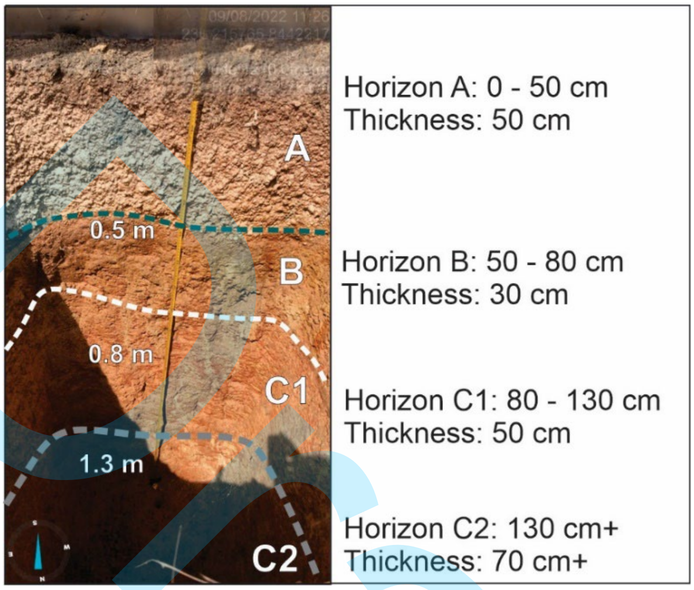

Figure 10 – Soil profile exposed in a trench in the study area, indicating the separation of the different horizons observed A, B, C1 and C2 and their respective thicknesses.

Water Level Measurement

The direct measurement of the water table level (WT) was performed during the two field stages, from the check of a monitoring well installed by the research team of the University of Campinas (UNICAMP), which is building a network of monitoring wells in the Chapada dos Veadeiros region, and in partnership allowed to record the water level during geophysical data acquisitions. The monitoring well was manually opened with a manual auger, and its interruption occurred due to the rock's bolder presence, which made it impossible to continue drilling. The well is installed at a distance of 4 m along the acquisition section, it has 4 m deep, and the water table depth measures recorded were 1.68 m in May and 3.65 m in August.

GPR Sections

GPR sections are shown in Figure 11, which shows the comparison between the two stages of acquisition (May and August) for the three different frequency GPR antennas. It is possible to note the presence of two layers separated by the different reflection patterns, the most superficial layer (A) has a thickness between 0.5 m and 0.7 m, and it covers the first direct waves in the reflected soil, with intense horizontal signal amplitudes.

Its contact with the lower layer (B) is marked by the reflector (1) constant throughout the section, between altitudes 1188.5 and 1188 m. It follows the slope of the surface relief. Around this reflector, it is possible to observe attenuations in the image of the reflection patterns, more evident in sections C02-CS1-200 MHz and C02-CS1-400 MHz (Fig. 11B and 11D) and C01-CS1-200 MHz (Fig. 11A). Layer (B) has smoother reflection patterns, and attenuates its signal. The reflectors are horizontal, and follow the slope of the relief. Observing the presence of occasional parable reflectors distributed at different depths is possible.

A second horizontal reflector (2) is inserted in the layer (B), has a low amplitude signal, and occurs between the altitudes of 1187 and 1187.6 m for the sections acquired in May (C01), and between 1185.5 and 1185, 9 m for sections purchased in August (C02). This reflector coincides with the direct measures of the water level recorded on the monitoring well from 1.68 m in May to 3.35 m in August, indicated at a distance of 24 m of the sections.

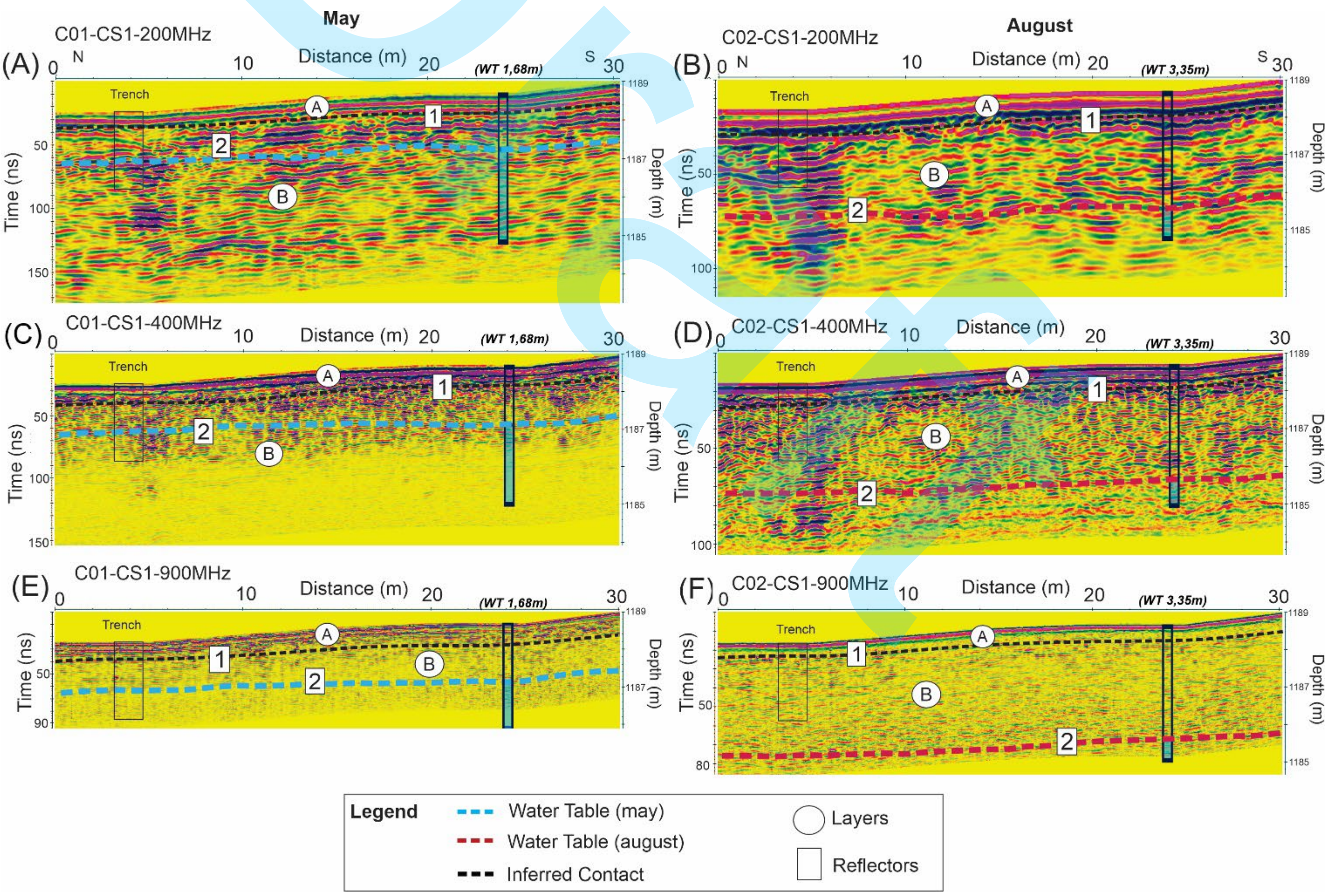

Figure 11 – GPR sections. In (A), (C), and (E) are the sections acquired with the 200 MHz, 400 MHz, and 900 MHz antennas, respectively, in May (C01). In (B), (D), and (F) are the sections acquired in August (C02). The blue and red lines indicate the inferred water table level (WT). The monitoring well is indicated in 24 m of the section, with the direct measurement of WT in blue. The trench is indicated

by the verticalized rectangle 3.65 m from the section.

Resistivity Model

From the electrical resistivity inversion model (Fig. 12), purchased in August, even with an elevated RMS error value of 45.9, due to the high electrical contact resistance values at its lateritic soil horizon, it is still possible to correlate with the direct measurements and soil characterizations observed in field activity. It is possible to bound the presence of a first resistive, horizontal, and superficial layer, with thicknesses between 0.5 m and 1 m, with resistivity values greater than 3,000 Ohm.m. This layer becomes thicker at the end of the section but may represent an edge effect on geophysical inversion. The contact with the lower layer is well marked between depths 1188.5 m and 1188 m, has sinuosities throughout the section, but is preferably horizontal.

The second layer is more conductive, with resistivity values between 500 and 1,000 Ohm.m, has between 1 and 2 m thickness, occurring between the depths 1188.5 and 1186 m, and tends to become deeper from 12 m in the section. It has high conductivity rounded cores, with values between 60 and 200 Ohm.m, located between 8 and 12 m from the section, at depths 1188.5 and 1187.5 m. At this layer, depending on the geometry of the anomalies in the region, north dipping south, there is the possibility of being a recharge aquifer zone. This is pointed out in the resistivity model by the flow arrows which indicate the inferred recharge zone flow direction north dipping south.

The lower portion of the section is marked by the presence of a resistive layer, with values exceeding 10,000 Ohm.m, which occurs from 1187 m. It is preferably horizontal but goes deeper from the 12 m horizontal distance of the section. Its contact with the upper layer is close to the bottom of the trench, indicated in the distance of 3.65 m of the section at 2 m depth.

For this section, the resistivity values were verified from the surface down to 2 m deep at the location where the trench is situated. The distribution of these values is indicated in Figures 12B and 12E, where it is possible to observe a direct correlation between alternation in resistivity values, and variations in soil horizons, indicated in Figures 12C and 12D. It shows a restricted high resistivity value in the more superficial portion, corresponding to the soil horizon A, down to 0.5 m deep, followed by a more conductive domain along the horizons B and C1, until contact with horizon C2 at 1.3 m deep, which indicates an increase in the resistivity values.

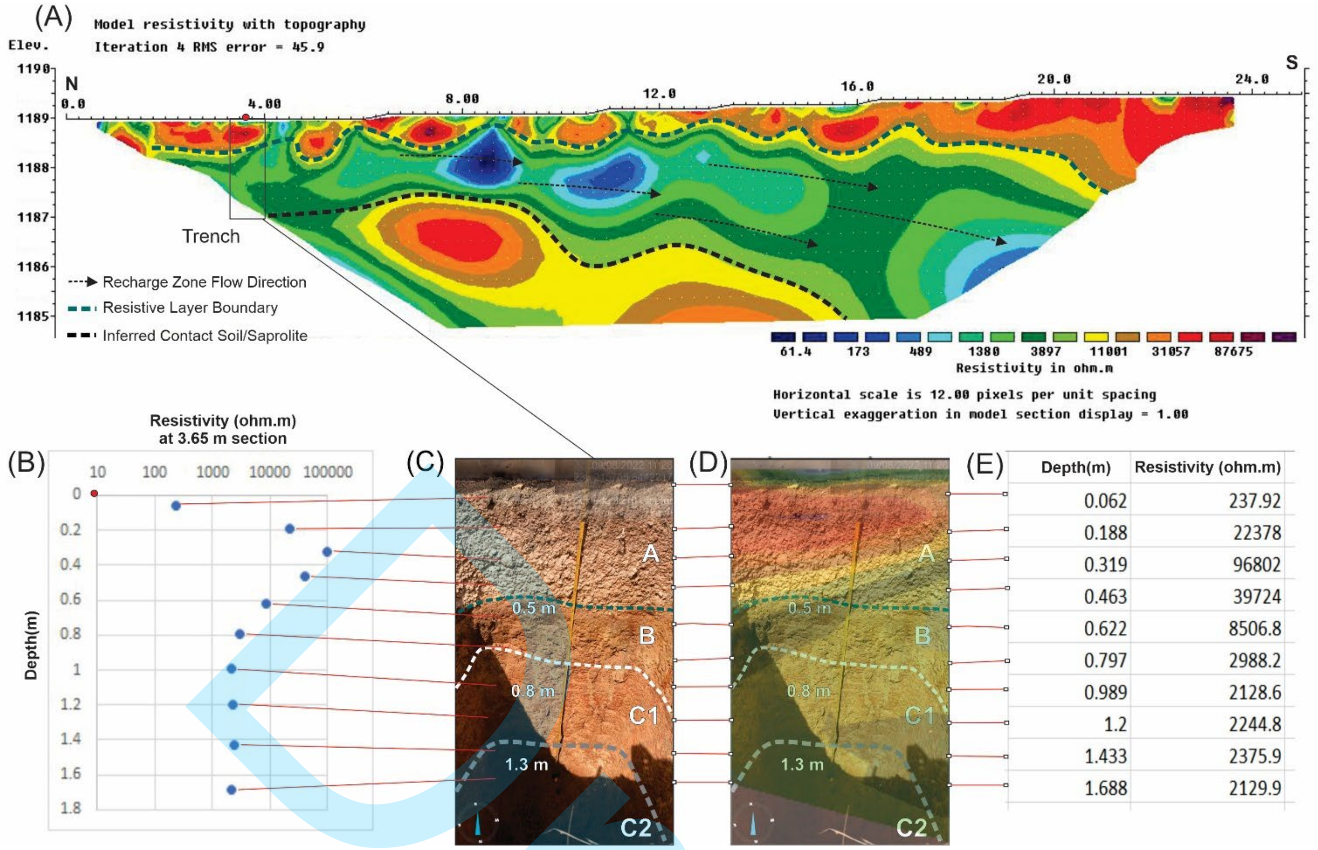

Figure 12 – (A) Section resistivity model (dipole-dipole with 0.5 m spacing between electrodes). (B) Distribution of depth resistivity values acquired at point 3.65 m of the section. (C) and (D) Direct correlation between soil horizons exposed in the trench, and the inverse section overlapping the soil profile. (E) Quantitative values of resistivity measures in depth at 3.65 m of the section.

HYDROGEOPHYSICAL CORRELATION

From the analysis of the results, the GPR section and resistivity model interpretation were correlated with direct water level measurements recorded in the monitoring wells, and observations of soil profiles present in the trench in a hydrogeophysical correlation model. The interpreted hydrogeophysical correlation is represented by Figure 13, which corresponds to the overlap of the resistivity model with the 400 MHz antenna GPR section acquired in August. The hydrogeophysical model has the location of the trench soil profile, plotted at a 3.6 m distance in section, and the monitoring well at 24 m.

The first mapped interface corresponds to the shallow 0.5 m deep, represented by a resistive layer in the geoelectric section, with resistivity values higher than 3,000 Ohm.m, in the GPR section. This first superficial level corresponds to the more precise signals of reflection. It is characterized by well-defined horizontalized high amplitude patterns, identified as a layer (A). Its lower limit is evidenced by the reflector (1), which indicates the contact between the different reflection patterns observed between layers (A) and (B). In the soil profile, horizon A corresponds to the first 0.5 m depth. It is yellowish to pink soil, sandy-silt gravel, with many lateritic concretions from 1 to 5 cm in diameter. It has an abrupt transition to horizon B, which coincides with the reflector (1) seen in the GPR section, at 0.5 m deep.

This contact is indicated in Figure 13 by the yellow dotted line. High resistivity values for this first layer may be associated with the number of laterites on the shallowest subsurface horizon, the petric plinthosol concretionary soil.

Then it is possible to observe a second layer in the geoelectric section, more conducive with resistivity values between 500 and 1,000 Ohm.m. It has between 1 and 2 m thickness, and has high conductivity rounded cores, with values between 60 and 200 Ohm.m. At this same region, it was identified in the GPR section a layer (B), which has more intense reflection patterns with signal attenuation in the upper zone, between 0.5 and 1 m deep, marked by the gray dotted line in Figure 13. In the lower zone, from 1 to 2 m deep, reflection patterns are softer, horizontalized, and follow the relief surface's slope. Regarding the soil profile, between 0.5 and 0.8 m deep is present horizon B, representing a poorly developed soil layer, with higher silt concentration, and more compacted, with lower amounts of concretions, and some incipient structures corresponding to a possible rock foliation. Horizon (B) is followed by horizon C1, between 0.8 and 1.3 m deep, which differs from the upper horizon due to the smaller amount or practically absence of concretions, is pinker, and the structures are more preserved.

The presence of the reflector (2) is also noted inserted in the layer (B) identified in the GPR section, between 1.5 and 1.7 m deep along the sections acquired in May (C01). It represents a reflector well marked, horizontalized, with a low amplitude reflector signal, which coincides with the direct measurement of the water level recorded in the monitoring well at 1.65 m deep. This reflector is indicated in Figure 13 by the blue dotted line.

From 2 m deep, a more resistive layer is observed in the geoelectric section, with resistivity values exceeding 10,000 Ohm.m. At this depth, it is possible to notice a reflector in the GPR section that marks the transition between the upper portion, with more intense reflection patterns in layer B, and the lower region in which these signs are weakened, indicated in Figure 13 by the black dotted line. This contact can be observed in the soil profile at 1.3 m deep, which marks the contact between the horizons C1 and C2. Horizon C1 represents the saprolite, developed from a changed red to yellow metasiltstone, with more preserved sub-horizontal foliation structures, while horizon C2 corresponds to even more preserved metasiltstone than in C1. Regarding the geological context, the present metasiltstone is correlated to the Rosary Formation rocks, which belong to the Traíras Group (Martins-Ferreira & Campos, 2017).

Finally, for the GPR sections acquired in August (C02), the reflector (2) between the depths of 3.2 and 3.4 m along the sections has been identified, which coincides with the direct measurement of the water level in the monitoring well in August at 3.35 m deep. This reflector is indicated in Figure 13 by the red dotted line.

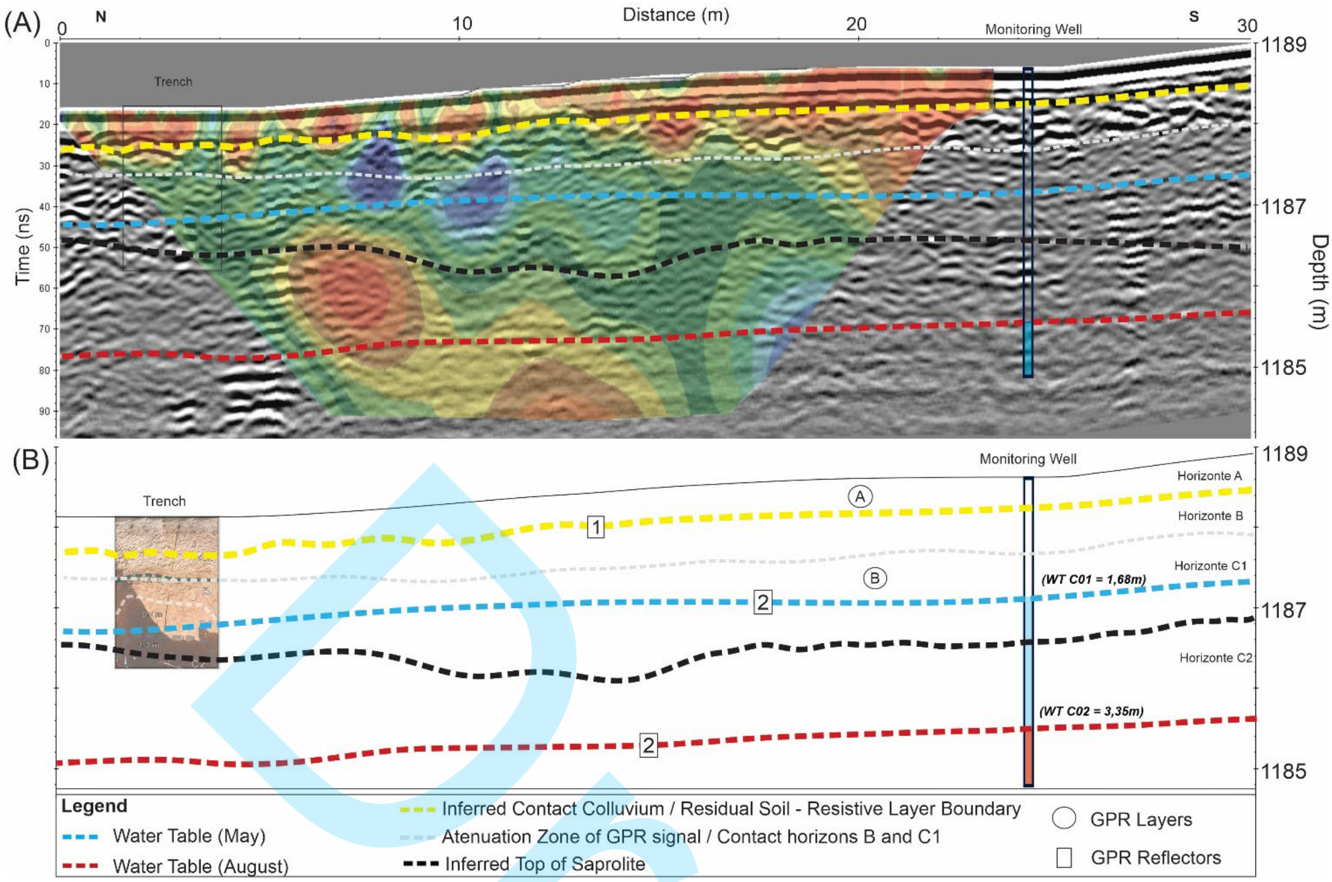

Figure 13 – Hydrogeophysical correlation between GPR and a geoelectric section for the study area. (A) Overlapping geophysical sections indicate interpreted reflectors, contacts, and structures. (B) Profile of hydrogeophysical interpretations, indicating the location of the soil profile exposed in the trench, with the center at 3.65 m of the section, and the monitoring well at 24 m distance, with water levels measured in May (C01) in blue and in August (C02) in red.

CONCLUSIONS

The results of this research show that applying hydrogeophysical techniques allows for obtaining relevant information about the subsurface. The application of data acquisition techniques had particularities, such as the difficulty in reducing the contact resistances in the lateritic plinthosol soil, the problematic coupling of electrodes in the portions of thin and very wet soil, the presence of vegetation in the sections that compromise the coupling of the ground GPR antennas, mainly the 200 MHz and 400 MHz ones, factors that influenced the quality of the signals observed in the geophysical sections. Despite being more practical methods for application, good planning, and knowledge about the environmental conditions and context of the study area are necessary for more efficiency during acquisitions. Also, the occurrences of these particularities reinforce the importance of using different arrangements and acquisition antennas to have better data reading coverage, and to cover possible "gaps" of acquisition from overlapping sections.

The proposed objectives for the present work were achieved. The variation of the water level in the subsurface referring to the records in May and August was well evidenced by the analysis of the acquisitions with the GPR method. A characteristic that guided us to identify the water level region was the attenuation of the signals in the GPR sections, which is generally related to humidity, and marks a contrast with the aerated zone, which was confirmed by comparing the attenuation zone with the direct measurements of the water level in the monitoring wells that coincide. The punctual reflectors observed correspond to rock blocks and saprolite dispersed in the subsurface. Still, it was possible to test, and compare the results obtained from different frequencies of GPR antennas.

The interpretation of the GPR section overlapped by the resistivity model composing the hydrogeophysical model showed a direct correlation between the alternations of the reflection pattern signals, and the resistivity domains values variations, which reflected directly the physical characteristics mapped, such as the changes between structures, features, and soil horizons described in the pedological profile. The geoelectric data indicates a presence of a zone of aquifers recharge at the second layer, more conductive, in which it is possible to infer the recharge zone direction flow, from north dipping to south. The presence of lateritic concretions at the surface characterized by the predominance of a concretionary petric plinthosol formation, defined as horizon A, was well defined as a shallow resistive layer present in the resistivity model, corresponding to the high resistivity related to ferruginous concretions. The interface between soil and saprolite, composed of altered metasiltstones from the Rosário Formation, was well evidenced in the GPR sections, and by the abrupt variation in resistivity values. The lowering of the water level was approximately 1.7 m referring to May to August, and could be observed in the GPR sections by the presence of a horizontal, and well-defined reflector, mainly in the acquisitions with the 200 MHz and 400 MHz.

It is noted that the GPR method proved to be very efficient for interpreting features in the shallow subsurface, with a high resolution of reflection signals. The ERT method was beneficial for observing the contrasts between different soil horizons, mainly concerning the soil and saprolite interface. Thus, it is concluded that acquiring data with GPR antennas of different frequencies for this type of study is essential for a subsurface analysis with greater precision and reliability. For more precise control of this variation in groundwater level throughout the seasons, it would be interesting to apply hydrogeophysical techniques more frequently, for example, every month, to compose an annual variation model. Still, it is indicated that new electrical arrangements be tested with the electrodes inserted in an ionic solution.

The present study shows an efficient alternative for identifying the subsurface water level by applying non-invasive hydrogeophysical techniques. Furthermore, it was possible to show the application of methodologies that can serve as a basis for areas with similar geoenvironmental characteristics, which are recurrent in the vicinity of the study area, and represent a vast domain in the Chapada dos Veadeiros region. The study area represents a preserved area of campo sujo, and its data can be used as a basis for future surveys or comparisons with similar areas in the process of anthropic occupation. In this way, attention is called to ensure the preservation of these environments, and it is believed that geoenvironmental characterization studies and analyses can contribute to its preservation.

ACKNOWLEDGMENTS

The authors would like to thank the project by the Research Support Foundation of the State of Goiás (FAPEG) Hydrogeological-geophysical characterization of water infiltration into the soil in preserved cerrado vegetations and areas burning by fire in northeast goiano (Public Call 04/2021 - Solutions for Nature Conservation in Northeast Goiás) for financing field work, equipment, and computer softwares. We would like to thank the Postgraduate Program in Applied Geosciences and Geodynamics (PPGGAG) and the Applied Geophysics Laboratory (LGA) of the Institute of Geosciences (IG) at University of Brasilia (UnB) for the infrastructure, geophysical equipment, vehicles and computer programs. To the Laboratory of Soil Physics of the Faculty of Agronomy and Veterinary Medicine (FAV) of UnB for characterizing the soils. The research teams at the Institute of Biology at the University of Campinas (UNICAMP) and the University of Exeter (UK) for their support with infrastructure and access to field areas. The junior company Phygeo (UnB), ICMBio (PNCV), the PREVFOGO brigade members, the NGO Berço das Águas, the Cerrado de Pé Organization, for the partnership with data, logistics, and support during field data acquisition. Also, to Inuit space and Taiuá Ambiental for accommodation.

REFERENCES

Abiye, T., K. Masindi, H. Mengistu and M. Demlie, 2018, Understanding the groundwater-level fluctuations for better management of groundwater resource: A case in the Johannesburg region, Groundwater for Sustainable Development, Volume 7, 2018, Pages 1-7, ISSN 2352-801X, doi: 10.1016/j.gsd.2018.02.004.

Allaire S. E., S. Roulier and A. J. Cessna, 2009, Quantifying preferential flow in soils: A review of different techniques. J Hydrol 378:179–204, doi: 10.1016/j.jhydrol.2009.08.013

Arora, B. and B. P. Mohanty, 2017, Influence of spatial heterogeneity and hydrological perturbations on redox dynamics: a column study. Procedia Earth Planet Sci 17:869–872, doi: 10.1016/j.proeps.2017.01.046

Arora, B., N. F. Spycher, C. I. Steefel, S. Molins, M. Bill, M. E. Conrad, W. Dong, B. Faybishenko, T.K. Tokunaga, J. Wan, K. H. Williams and S. B. Yabusaki, 2016, Influence of hydrological, biogeochemical and temperature transients on subsurface carbon fluxes in a flood plain environment. Biogeochemistry 127:367–396, doi: 10.1007/s10533-016-0186-8

Binley, A., S. S. Hubbard, J. A. Huisman, A. Revil, D. A. Robinson, K. Singha and L. D. Slater, 2015, The emergence of hydrogeophysics for improved understanding of subsurface processes over multiple scales. Water Resour Res. 2015 Jun,51(6):3837-3866, doi: 10.1002/2015WR017016. Epub 2015 Jun 15. PMID: 26900183, PMCID: PMC4744786.

Braga, A. C. D. O, 2006, Métodos da eletrorresistividade e polarização induzida aplicados nos estudos da captação e contaminação de águas subterrâneas: uma abordagem metodológica e prática. ii, 121 f. Thesis (livre-docência) - Universidade Estadual Paulista, Instituto de Geociências e Ciências Exatas, 2006. http://hdl.handle.net/11449/116123.

Campos, J. E. G., M. A. Dardenne, F. H. Freitas-Silva and M. A. C. Martins-Ferreira, 2013, Geologia do Grupo Paranoá na porção externa da Faixa Brasília. Braz. J. Geol. 43(3): 461-476, doi: 10.5327/Z2317-48892013000300004

Casagrande, M. F. S., L. M. Furlan, C. A. Moreira, F. T. G. Rosa and V. Rosolen, 2021, Non-invasive methods in the identification of hydrological ecosystem services of a tropical isolated wetland (Brazilian study case), Environmental Challenges, Volume 5, 100233, ISSN 2667-0100, doi: 10.1016/j.envc.2021.100233.

Costall, A. R. and B. Harris, 2018, Rapid Estimation of Volumetric Groundwater Recharge in the Vadose Zone via Ground Penetrating Radar, ASEG Extended Abstracts, 2018:1, 1-7, DOI: 10.1071/ASEG2018abP091.

Deiana, R., G. Cassiani, A. Villa, A. Bagliani and V. Bruno, 2008, Calibration of a Vadose Zone Model Using Water Injection Monitored by GPR and Electrical Resistance Tomography. Vadose Zone Journal, 7(1), 215. 2008, doi: 10.2136/vzj2006.0137.

Furlan, L. M., V. Rosolen and C. A. Moreira, 2021, The interactive pedological-hydrological processes and environmental sensitivity of a tropical isolated wetland in the Brazilian Cerrado. SN Appl. Sci. 3, 144, doi: 10.1007/s42452-021-04174-7

Haque, A., G. Ali and P. Badiou, 2018 Hydrological dynamics of prairie pothole wetlands: Dominant processes and landscape controls under contrasted conditions. Hydrological Processes, v. 32, n. 15, p. 2405-2422, doi: 10.1002/hyp.13173

ICMBio - Instituto Chico Mendes de Conservação da Biodiversidade. 2021. Plano de Manejo do Parque Nacional da Chapada dos Veadeiros. Ministério do Meio Ambiente - MMA. Brasília, DF, Brazil. Available on: <https://www.gov.br/icmbio/pt-br/assuntos/biodiversidade/unidade-de-conservacao/unidades-de-biomas/cerrado/lista-de-ucs/parna-da-chapada-dos-veadeiros/arquivos/Plano_de_Manejo_9730998_PM_VERSAO_FINAL_PNCV_2021_10_01_versao_final_pos_portaria.pdf>. Access on: November 21, 2022.

Junk, W. J., M.T.F. Piedade, R. Lourival, F. Wittmann, P. Kandus, L.D Lacerda and J. Schöngart, 2014, Brazilian wetlands: their definition, delineation, and classification for research, sustainable management, and protection Aquatic. Conserv., 24 (2014), pp. 5-22, doi: 10.1002/aqc.2386

Kirsch, R., 2009, Groundwater Geophysics: A Tool for Hydrogeology. Berlin, Germany. Springer, 556p, doi: 10.1007/978-3-540-88405-7

Latrubesse, E., E. Arima, M. Ferreira, S. Nogueira, F. Wittmann, M. Sversut Dias, F. Dagosta, M. Bayer, 2019, Fostering water resource governance and conservation in the Brazilian Cerrado biome. Conservation Science and Practice, doi: 10.1111/csp2.77

Lima, J.E.F.W., 2011, Situação e perspectivas sobre as águas do Cerrado. Ciência e Cultura 63, 27-29. http://dx.doi.org/10.21800/S0009-67252011000300011

Martins F.A.L., 1999, Análise faciológica e estratigráfica do Paleo-Mesoproterozoico: Seqüência Araí no Parque Nacional da Chapada dos Veadeiros, Goiás. 1999. Master Dissertation, Instituto de Geociências, Universidade de Brasília, DF, Brazil, p. 137.

Martins-Ferreira, M. A. C. and J. E. G. Campos, 2017, Compartimentação geomorfológica como suporte para estudos de evolução geotectônica: aplicação na região da Chapada dos Veadeiros, GO. Revista Brasileira de Geomorfologia, v.18, número 3. 18(3): p. 501-519, doi: 10.20502/rbg.v18i3.1119

Moreira, C.A., V. Rosolen, L. M. Furlan, R. C. Bovi and H. Masquelin, 2021, Hydraulic conductivity and geophysics (ERT) to assess the aquifer recharge capacity of an inland wetland in the Brazilian Savanna, Environmental Challenges, Volume 5, 100274, ISSN 2667-0100, doi: 10.1016/j.envc.2021.100274.

Oliveira-Filho, A. T., 1992, Floodplain “murundus” of Central Brazil: evidence for the termite-origin hypothesis. Journal of Tropical Ecology, Cambridge, v. 8, n. 1, p. 1-19, 1992, doi: 10.1017/S0266467400006027

Oostrom, M., M. J. Truex, G. V. Last, C. E. Strickland and G. D. Tartakovsky, 2016, Evaluation of deep vadose zone contaminant flux into groundwater: Approach and case study. J Contam Hydrol 189:27–43, doi: 10.1016/j.jconhyd.2016.03.002

Pimentel M.M., R. A. Fuck and N. F. Botelho, 1999, Granites and the geodynamic history of the Brasília Belt, central Brazil: a review. Lithos 46:463-483, doi: 10.1016/S0024-4937(98)00078-4.

Pimentel, M. M., 2016, The tectonic evolution of the Neoproterozoic Brasília Belt, central Brazil: a geochronological and isotopic approach. Brazilian Journal of Geology, v. 46, n. 1, p.67-82, jun. 2016. http://dx.doi.org/10.1590/2317-4889201620150004.

Robinson, D. A., C. S. Campbell, J. W. Hopmans, B. K. Hornbuckle, S. B. Jones, R. Knight, F. Ogden,

J. Selker and O. Wendroth, 2008, Soil moisture measurement for ecological and hydrological watershed-scale observatories: A review. Vadose Zone J., 7:358–389, doi: 10.2136/vzj2007.0143

Rodriguez, R. G., B. R. Scanlon, C. W. King, F. V. Scarpare, A. C. Xavier and F. F. Pruski, 2018, Biofuel-water-land nexus in the last agricultural frontier region of the Brazilian Cerrado, Applied Energy, Volume 231, 2018, 1330-1345, ISSN 0306-2619, doi: 10.1016/j.apenergy.2018.09.121.

Rosolen, V., D. A. Oliveira and G. T. Bueno, 2015, Vereda and Murundu wetlands and changes in Brazilian environmental laws: challenges to conservation Wetl. Ecol. Manag., 23 (2015), pp. 285-292, doi: 10.1007/s11273-014-9380-4

Rubin, Y. and S. S. Hubbard, 2005, Hydrogeophysics, 523 pp., Springer, N. Y, doi: 10.1007/1-4020-3102-5

Sano, S. M., S. P. Almeida and J. F. Ribeiro, 2008, Cerrado: ecologia e flora. 2 v. Brasília, DF, Brazil: Embrapa Cerrados.

Santos, H. G., 2018, Sistemas Brasileiro de Classificação de Solos. 5. ed. Brasília, DF, Brazil: Embrapa.

Saintenoy, A. and J. W. Hopmans, 2011, Ground Penetrating Radar: water table detection sensitivity to soil water retention properties. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 2011, 4, pp.748-753, doi: 10.1109/JSTARS.2011.2171920

Shiki, S., J. F. G. Silva and A. Ortega, 1997, Agricultura, meio ambiente e sustentabilidade do cerrado brasileiro. Centro de Documentação e Pesquisa Socioeconômica, Departamento de Economia e Departamento de Geografia da Universidade Federal de Uberlândia MG, Brazil.

Tanizaki, M. L. N., J. E. G. Campos and M. A. Dardenne, 2015, Estratigrafia do Grupo Araí: registro de rifteamento paleoproterozoico no Brasil Central. Brazilian Journal of Geology, 45(1): 95-108, doi: 10.1590/23174889201500010007

Tran, A. P, B. Dafflon, S. S. Hubbard, M. B. Kowalsky, P. Long, T. K. Tokunaga and K. H. Williams, 2016, Quantifying shallow subsurface water and heat dynamics using coupled hydrological-thermal-geophysical inversion. Hydrol Earth Syst Sci 20:3477–3491, doi: 10.5194/hess-20-3477-2016

Wan, J., T. K. Tokunaga, W. Dong, K. H. Williams, Y. Kim, M. E. Conrad, M. Bill, W. J. Riley and S. S. Hubbard, 2018, Deep unsaturated zone contributions to carbon cycling in semiarid environments. J Geophys Res Biogeosci 123:3045–3054, doi: 10.1029/2018JG004669

Zhou, Q. Y., J. Shimada and A. Sato, 2001, Three-dimensional spatial and temporal monitoring of soil water content using electrical resistivity tomography. Water Resources Research, 37(2), 273–285.

https://doi:10.1029/2000wr900284.

Zhu,W., S. Zhao, Z. Qiu, N. He, Y. Li, Z. Zou and F. Yang, 2022, Monitoring and Analysis of Water Level–Water Storage Capacity Changes in Ngoring Lake Based on Multisource Remote Sensing Data. Water 2022, 14, 2272, doi: 10.3390/w14142272.

Vilarinho, G.X.: contributed to conceptualization, investigation, coordination of field activities, data acquisition, processing and modeling in software, writing original draft preparation and review; **Borges, W.R.:** contributed to conceptualization, methodology, GPR software, validation, formal analysis, supervision, project administration, and final review; **Leão-Santos, M.H.:** contributed to conceptualization, methodology, Resistivity software, investigation, supervision, project administration, funding resources acquisition, and final review; **Heringer, R.A.:** contributed to field data acquisition, methodology, processing, and modeling in software and review; **Cunha L.S.:** contributed to the indication and characterization of the study area, the environmental Cerrado's characteristics, the acquiring field data, investigation and review; **Oliveira, R.S.:** contributed to the acquiring field data, processing and modeling data, software, methodology, investigation, and review; **Mendes, T.L.:** contributed to field data acquisition, methodology, investigation, and review. All authors read and agreed to the published version of the manuscript. **Xavier, R. O.:** Contributed to the implementation of test wells and trenches for measuring hydrological and pedological data in the field, monitoring water table variables, defining the study area and review. **Verona, L. S.:** Contributed with the phytophysiographic characterization of the study area, field data acquisition, investigation and review.