



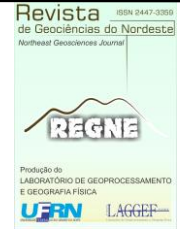
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## Electrical Resistivity method applied to the temporal variation of the groundwater level of the Alter do Chão aquifer, in Santarém, Pará.

*Método da Eletrorresistividade aplicado à variação temporal do nível freático do aquífero alter do chão, em Santarém, Pará.*

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**Abstract:** Based on the observation of permanent floods near the Federal University of Western Pará, this study aimed to verify the fluctuation of the water table level in the free aquifer of the Alter do Chão Formation and the possible relationship with permanent flooding in the research area. In the study area, the techniques of Vertical Electrical Sounding and Electrical Profiling Technique were applied. The measurements of the vertical electrical soundings made it possible to identify the most superficial layer, associated with the soil, with an average thickness of 1.42 m and apparent resistivity of  $\cong 1000\Omega\text{m}$ ; a 2nd underlying layer, with an average thickness of 10.91 m and a highly resistive anomaly ( $\cong 4600\Omega\text{m}$ ); and a 3rd layer, at a depth of 12.34 m, in which there is an abrupt drop in resistivity ( $\cong 300\Omega\text{m}$ ). Vertical Electrical Sounding was carried out 5 times in the same location, from December 2017 to June 2018, allowing the correlation of the water table level variation with rainfall in the same period. Results indicate oscillation in water level of the Alter do Chão Formation unconfined aquifer in 7 m, during the studied period. Electrical Profiling Technique made it possible to associate the highly resistive anomaly of the 2nd layer with the Matura Lateritic Cover, which is the main cause of flooding in the investigated area.

**Keywords:** Alter do Chão Aquifer; Electrical Resistivity Method; Temporal Variation.

**Resumo:** A partir da observação de alagamentos permanentes nas proximidades da Universidade Federal do Oeste do Pará, este estudo teve como objetivo verificar a oscilação do nível freático do aquífero livre da Formação Alter do Chão e a possível relação com os alagamentos permanentes da área de pesquisa. Na área de estudo foram aplicadas as técnicas da Sondagem Elétrica Vertical e do Caminhamento Elétrico. As medidas das sondagens elétricas verticais permitiram identificar a camada mais superficial, associada ao solo, com espessura média de 1,42 m e resistividade aparente de  $\cong 1000\Omega\text{m}$ ; uma 2ª camada subjacente, com espessura média de 10,91 m e uma anomalia altamente resistiva ( $\cong 4600\Omega\text{m}$ ); e uma 3ª camada, aos 12,34m de profundidade, em que há uma queda abrupta da resistividade ( $\cong 300\Omega\text{m}$ ). A Sondagem Elétrica vertical foi realizada por 5 vezes no mesmo local, no período de dezembro de 2017 a junho de 2018, permitindo a correlação da variação do nível freático com a pluviosidade no mesmo período. Os resultados indicam oscilação do nível d'água do aquífero livre da Formação Alter do Chão no período estudado em 7 m. O Caminhamento Elétrico possibilitou associar a anomalia altamente resistiva da 2ª camada à Cobertura Laterítica Matura, a qual é a principal causa dos alagamentos na área investigada.

**Palavras-chave:** Aquífero Alter do Chão; Método da Eletrorresistividade; Variação Temporal.

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## 1. Introduction

Data from IBGE (2019) indicate that, in recent decades, the North Region has undergone an intense process of population expansion in urban centers, with an increase in occupancy from 27% in 1940 to 74% in 2010. of the country, the disorderly growth and the lack of infrastructure policies, together with the historical occupations close to watercourses, caused the Brazilian urban environment to be impacted by floods and inundations (SILVA E CABRAL, 2014). In Santarém, SEMINFRA - Municipal Infrastructure Secretariat reported that, in 2016, of the 673 km of existing streets, only 31% were paved. This condition, added to the local lithology and the period of intense rainfall in the region, makes it difficult for the hydrogeological system of the free aquifer of the Alter do Chão Formation to recharge through adequate drainage, causing flooding in public roads and obstructing traffic in some points. from the city.

The object of study of this work started from the observation of a permanent flooding point in the vicinity of UFOPA - Campus Tapajós and the City Hall's attempts to solve the problem by filling up the area, which in a few days would again present high levels of saturation until water accumulated in the surface again. Groundwater comprises a phase of the hydrological cycle, consisting of the portion of water precipitated by rainfall that infiltrates below the surface of the Earth and fills the pores, intergranular voids, fissures and fractures of soils and rocks, groundwater level (WT) of aquifers is directly linked to the local rainfall regime. In the Amazon this variation is intense, given that the periodicity of the seasons is not regular as in other parts of the country. According to the Weather Spark website, in Santarém (PA), the climatic average of precipitation between the periods from 1980 to 2016 characterizes two seasons a year: the so-called "Amazonian winter" with heavy rains and an average duration of 5.7 months., starting at the end of December and extending until the "Amazon Summer", which has an average of 6.3 months of prolonged drought and starts in June.

Therefore, understanding the hydrogeological system requires the development of studies that help in understanding the dynamics of water table oscillation, not only for its use in the direct and most common form (water exploitation), but also in its indirect form, contributing to other areas of application, especially in Geotechnics, as in all engineering work, knowledge of the position of the water table prevents potential problems.

UFOPA, with just over 10 years of creation, is in the process of consolidating its physical infrastructure. Among the Campi, the Tapajós unit is the area that holds the largest number of projects for the construction of buildings, laboratories and paving. The contribution of geophysics in geotechnics and hydrogeology is already widely used in several studies, with emphasis on those focusing on the mapping of the water table (CASTRO, 2018; OLIVA E CHANG, 2007; SILVA et al., 2011; MARCELINO et al., 2005). Among the various methods, the Electrical Resistivity (ER) method stands out, with its Vertical Electrical Sounding (VES) and Electrical Profiling Technique (EPT).

The present study aimed to: I) verify the oscillation of the water table level of the unconfined aquifer of the Alter do Chão Formation, in an unpaved access road to UFOPA – Campus Tapajós, during the transition from the regime of maximum drought and maximum precipitation, through the ER method, using the VES technique; II) better understand the lateral upward behavior of the saturated zone and its possible relationship with the permanent flooding of the research area, through the EPT; III) contribute with other lithological information that will help in the development of future projects of local infrastructure.

## 2. Methodology

### Study Area

This work was developed in the municipality of Santarém-PA, microregion of the same name and mesoregion of the Lower Amazon. It is located at the confluence of the Tapajós and Amazon rivers and is located about 800 km from the state capital, Belém. The UFOPA Tapajós campus is located in the urban center of the city, in the Salé neighborhood, without number. Access to the campus is via Rua Vera Paz, which is partially paved. The study area (Figure 1) where this research was carried out includes the unpaved part of the 426 m long street, which has an intense flow of trucks and is the only access to the Petrobrás supply tanks, at Companhia DOCAS do Pará (Porto from Santarém).

The region has a hot and humid tropical climate, according to the climate classification based on the Köppen method. with an average air temperature between 25 ° C and 28 ° C, an average relative humidity of 86%. The rainfall regime varies greatly during the year. Due to the fact that the air temperature presents little variability, the climatic characterization is done basically in function of the distribution of its precipitation. Rainfall is the meteorological element that presents the

greatest annual variability, where its annual average values oscillate around 1920 mm. and another less rainy one, which extends from July to November, according to (JACINTO et al, 2006).

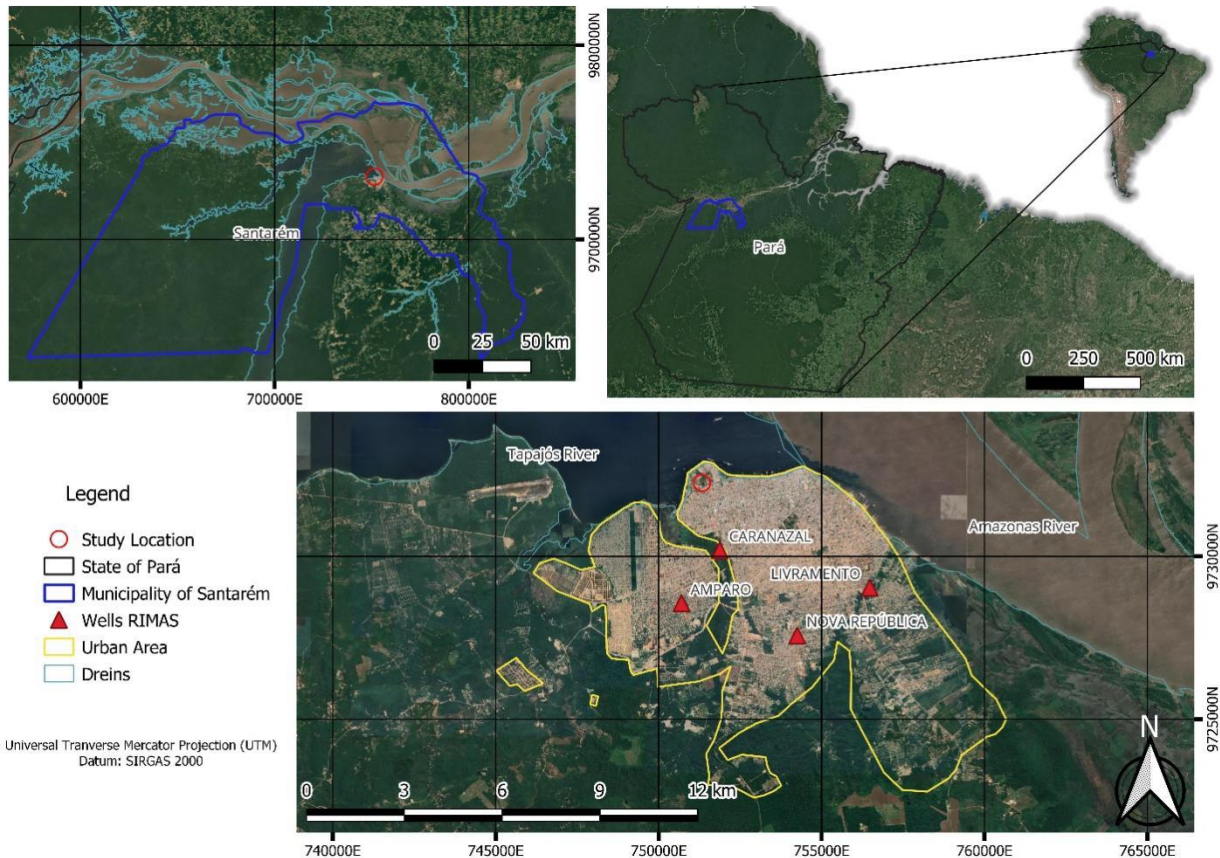


Figure 1 – Location of the study area in the municipality of Santarém (PA) and the respective RIMAS wells used in this work.

Source: Authors (2023).

Rua Vera Paz was the target of this project's study, since it presented the ideal logistical conditions, due to the fact that it is not paved and due to the occurrence of flooding in the rainy season (Figure 2A). When locating the geophysical alignments, we verified the occurrence of lateritic outcrops along the street (Figure 2B). This type of occurrence is common in soil formation in Brazil, mainly due to intense precipitation throughout the year, which influence the process of chemical alteration of minerals and leaching. Soil maturation is more easily achieved, with a high hydrogen ion concentration in the soil, with a consequent increase in chemical alteration by hydrolysis and facilitated conditions for the transport of solutions in its interior, allowing the removal of soluble elements and the accumulation of insoluble ones. Mainly oxides (oxides, hydroxides and hydrated oxides) of silicon, aluminum and iron are formed. The latter are products of the alteration of silicates and other primary minerals by chemical weathering, and may occur in their amorphous or crystalline form, such as, for example, the minerals gibbsite, hematite and goethite (FASSBENDER, 1975).



Figure 2 – (A): Location of permanent flooding on Rua Vera Paz in front of the access guardhouse to the UFCPA Campus Tapajós; (B): Outcrop of ferruginous concretion along the geophysical alignment with detail for Laterite sample.

Source: Authors (2023).

### Regional Geological Context

According to the information provided by the CPRM - Geological Service of Brazil, in the State Geological Map (VASQUEZ et al., 2008), the research area is located in the Amazon Basin. The basin, intracratonic, occupies an area of about 500,000 km<sup>2</sup>, in an E-W direction strip that follows the Amazon River valley (Figure 3A). It is bounded by the Arch of Purus to the west, which separates it from the Solimões Basin; by the Arco de Gurupá to the east, which separates it from the Foz do Amazonas Basin; by the Guiana Shield to the north; and by the Central Brazil Shield to the south (CAPUTO, 1984; CUNHA et al., 2007).

The Proterozoic substratum under which the Phanerozoic sedimentary package of the basin developed is represented by metamorphic rocks belonging to mobile bands, plus an older central nucleus, called Central Amazonia Province (CORDANI et al., 1984), consisting essentially of granitic rocks. The 5,000 m of sedimentary filling present a stratigraphic framework with two important megasequences: the Paleozoic, cut by dikes and sills of Julio-Triassic diabase; and the other sedimentary Mesozoic-Cenozoic (CUNHA et al., 1994).

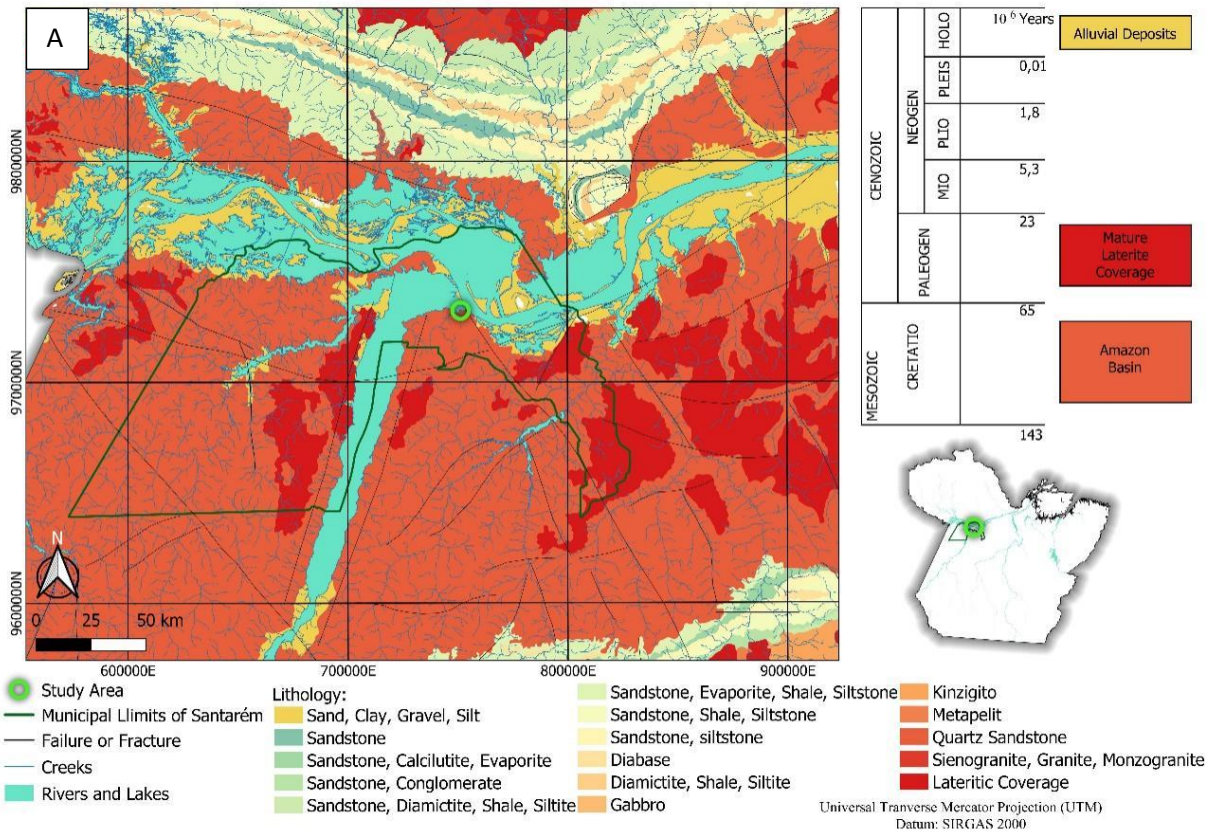
Formalized by Caputo et al (1971), the Alter do Chão Formation consists of a thick pack of sandstones interspersed with layers of pelites and, to a lesser extent, conglomerates (TANCREDI, 1996). The sandstones are fine to medium, reddish-brown and variegated, clayey, kaolinitic, and cross-bedding. The pelites, represented by siltstones and claystones in varying proportions, are red and variegated, solid or laminated (CAPUTO et al., 1971). According to (DAEMON, 1975), the deposition environment of this layer is the high-energy fluvial to the lacustrine-deltaic. In some facies of the deposits of the Alter do Chão Formation, marine influence is indicated in the western portion of the Amazon Basin (ROSSETTI E NETO, 2006).

The Matura Laterite Coverage is a superficial cover, of Cenozoic age, related to the South American Plane Surface (KING, 1956), which consists of plateaus, formed between the Upper Cretaceous and the Paleogene, which form the current relief (COSTA et al., 2005). In the state of Pará, this unit is well represented in the northeast portion, over the Ipixuna and Itapecuru formations, and along the Amazon river channel, over the Alter do Chão Formation. In addition, the occurrences of the Serra dos Carajás region, on several lithostratigraphic units, stand out. According to Costa (1991), the use of the designation Matura Lateritic Cover characterizes the laterite as more evolved, with a complete profile, constituted by the horizons (arranged from the base to the top): transitional pale, clayey, bauxitic and/or phosphate and ferruginous crust.

The Alluvial Deposits represent the unconsolidated clastic sediments of the current alluvial plains of the main water courses, which basically constitute channel deposits (point bars and channel bars) and flood plains. The Alluvial Deposits can reach up to tens of kilometers in length and width, like the Amazon River, whose alluvial plain is more expressive. Its morphology is typical of sedimentary plains associated with the fluvial system, which are, in general, constituted by sandy

to clayey sediments, with levels of gravel and organic matter, unconsolidated to semi-unconsolidated (VASQUEZ E ROSA-COSTA, 2008).

According to Tancredi (1996), the Santarém region is located in the central area of the Amazon Basin, where the Alter do Chão Formation is outcropping. Such lithology, deposited in a continental environment during the Cretaceous, in a layer 600 m thick, is composed of sandstones, siltstones, claystones and conglomerates. The Quaternary alluvial deposits, which partially cover the Alter do Chão Formation, are composed of clays, silts, sands and gravels. The thickness of these alluvial deposits, in the municipality, is estimated at 20 m in the lower courses of the igarapés and thicker in the alluvial plain of the Amazon River. In the State of Pará, along the channel of the Amazon River, over the Alter do Chão Formation, the occurrence of lateritic cover also stands out. For this work, a schematic chronostratigraphic column of the outcropping structures in the municipality of Santarém (Figure 3A) was made, with the aim of assisting in the geological interpretation of geophysical surveys.



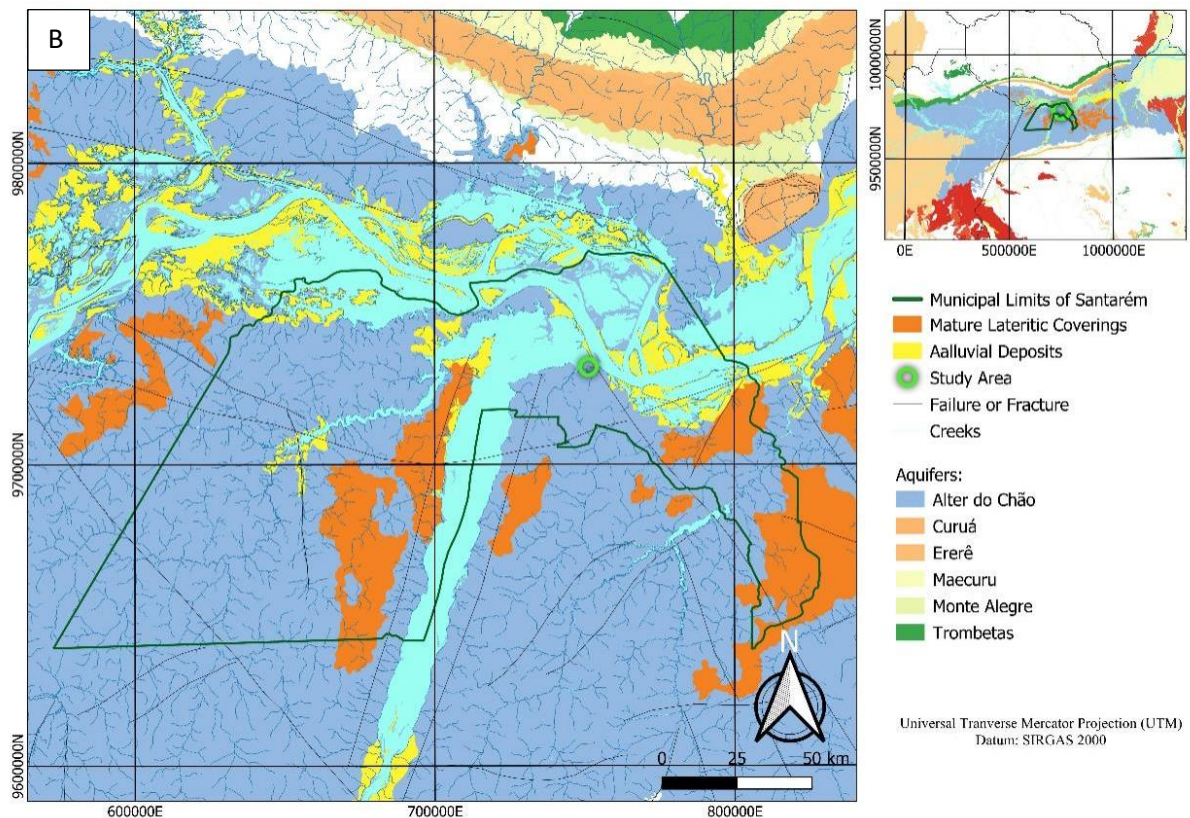


Figure 3 – (A) Geological map of the municipality of Santarém (CPRM, 2019) and schematic chronostratigraphic column of the study area; (B) Hydrogeological map of the municipality of Santarém  
Source: (CPRM, 2019).

### Local Hydrology and Climatology

The hydrogeological distribution in the Santarém region is controlled by lithology, geomorphology and rock structure. The Alter do Chão aquifer (Figure 3B) comprises a hydrogeological system with free and confined aquifer properties and is inserted in the Dominant Hydrographic Region of Amazonas (ANA, 2005 apud CPRM, 2012). Tancredi (1996), in his doctoral thesis at the Federal University of Pará (UFPA), carried out detailed studies on the Alter do Chão Aquifer in the city of Santarém, where he also developed the registration of wells in the urban perimeter and adjacent areas.

The greatest depth recorded for these wells at the time was 258 m, with the hydrogeological data being complemented with information from two oil drillings in the region: the first, in Alter do Chão, with a depth of 527 m; and the second in Belterra, 603 m deep. The data obtained through a hydrogeological inventory indicated an average thickness of 50 m for the free aquifer and 430 m for the confined aquifer, consisting of a sequence of sandy layers, with varying permeability and thickness and intervals separated by aquicludes and/or aquitards consisting of strata clayey clays of small thicknesses between 44 m and 80 m deep (TANCREDI, 1996).

The knowledge of meteorological variables is of paramount importance for climate studies of a region, such as, for example, the maintenance of climate balance. The behavior of rainfall in the Amazon region has been the subject of investigation, given that the periodicity of the seasons of the year is not regular as in other parts of the country, in addition to having enormous relevance for the climatology of South America, mainly due to its effect in the regional hydrological cycle (FIGUEROA E NOBRE, 1990).

Data from Santarém were obtained by compiling data during the period of application of electrical resistivity method. Available free of charge on the website of the National Institute of Meteorology (INMET). As a reference for monthly precipitation, the climatological normal (INMET, 2021) of conventional station 82246 – Belterra (Figure 9B) was used.

Monthly rainfall data for the period August 2017 and July 2018 were obtained from the automatic weather station A250 – Santarém (INMET, 2021).

According to Silva et al. (2013), the analysis of the rainfall index in the region of Santarém (PA) between the years 1969 and 2010 pointed out that the three months with the highest rainfall were February, March and April, while September, October, November and December were the most representative of the season corresponding to the “Amazon Summer”. The annual rainfall average of the series was 2318.69 mm. Thus, the “winter” presents more intense rains, starting at the end of December and extending until the “summer”, the dry period.

### Compiled direct data

Currently there are 519 wells registered by the Geological Survey of Brazil in the municipality of Santarém-PA. Of these, 515 are cataloged in the Groundwater Information System (SIAGAS) and 04 in the Integrated Groundwater Monitoring Network (RIMAS). Despite the huge number of SIAGAS wells, the data entered into the system does not have the same reliability as the wells registered by RIMAS, as these are monitored during drilling and regularly monitored by CPRM. Thus, the wells used as a parameter for analyzing the local lithology in this study are restricted to the 4 that have a complete descriptive profile (Figure 4).



Figure 4 – Geological profiles of the 04 wells, close to the study area, used for analysis of the local geology. The green demarcations determine the dynamic level oscillation.

Source: (RIMAS/CPRM, 2019).

The lithological analysis of the set of 4 wells (Figure 4) indicated, on average, a soil with a thickness of 8 m and a second layer with an average thickness of 36 m. The lithofacies present are made up of fine to coarse sand; however, in the Amparo well, the second layer had a certain clay content. The Nova República and Caranazal wells presented, in their fourth lithological layer, a coarse to conglomeratic sand composition, starting at a depth of 60 and 46 m, respectively. The Amparo and Livramento wells had their fourth layer starting at a depth of 21 and 48 m, in that order, composed of sandy to sandy-silty clay.

### Geophysical Survey

The geophysical surveys were carried out using the RD-1000A resistivity meter, manufactured by GEOTEST, and the SUPERSTING R8-IP resistivity meter. The GEOTEST set consists of an RD 1000 TX transmitter unit, connected to two 60 Ah batteries in series, totaling 24 V; and an RD 1000 RX receiving unit, powered by eight nickel hydride batteries (NI-

MH), size AA of 1.2 V. In the field, stainless steel electrodes and four coils were used, each with 500 m of wire electric 16 AWG; and the SUPERSTING R8-IP resistivometer, manufactured by Advanced Geosciences, Inc.-AGI, consisting of the transmitter unit, the switch box (Switch Box) and 04 multi-electrode cables totaling 280 meters in length, with 8 channels and 56 electrodes, and powered by a single 150 Ah, 12 V battery.

Field work was carried out from December 2017 to June 2018. The survey consisted of: 6 geophysical alignments, being: 1 electrical path (EC), with a length of 270 m; and 5 Vertical Electric Soundings (SEVs), with AB/2 opening of 100 m (SEV), and carried out on the dates of 12/01/17 (SEV\_01), 02/01/2018 (SEV\_02), 03/02/2018 (SEV\_03), 05/02/2018 (SEV\_04) and 06/26/2018 (SEV\_05), respectively. The spatial distribution of the investigated 1D and 2D geoelectric profiles and all references are shown in Figure 5. The coordinates and depth specifications are shown in Table 1.

Table 1 – Geographic coordinates of the geophysical techniques employed.

	Latitude	Longitude
EPT	Start: 2°25'14,88"S Final: 2°25'10,06"S	Start: 54°44'25,19"W Final: 54°44'16,89"W
VES	2°25'12,79"S	54°44'25,26"W

Source: Authors (2023).

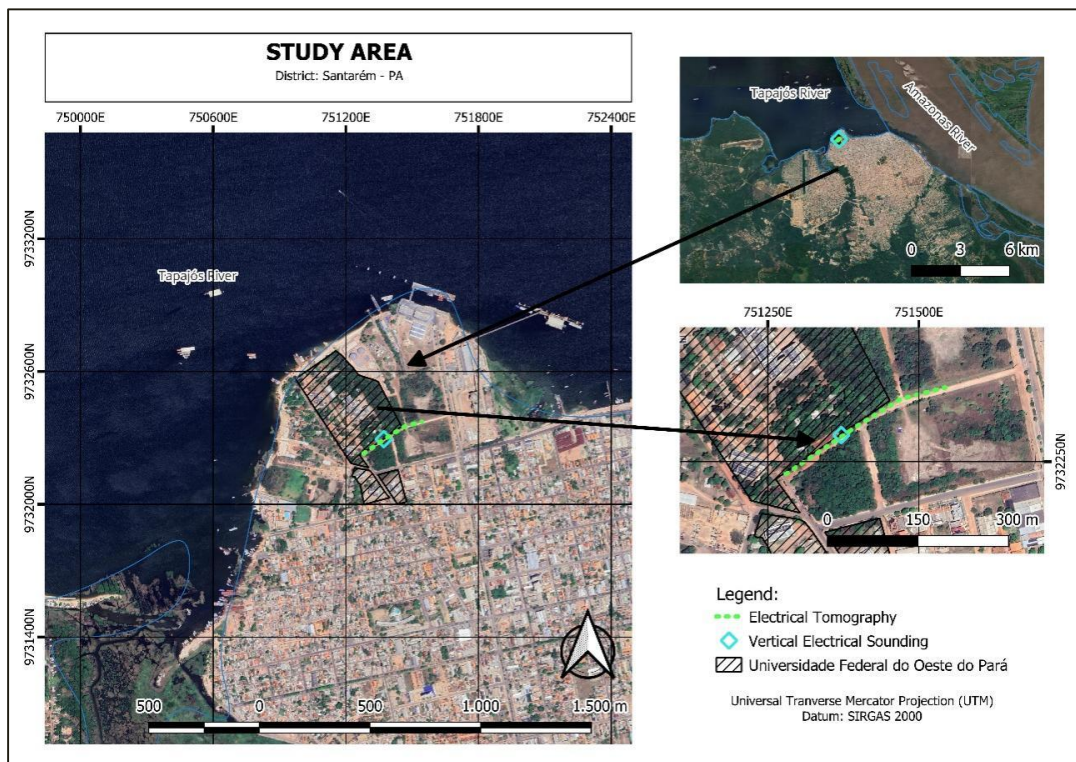


Figure 5 – Map of the location of the UFOPA Tapajós campus and the locations of the geophysical surveys, with emphasis on the EC profile and the punctual demarcation of the five SEVs carried out.

Source: Authors (2023).

### Electrical Resistivity Method

The different materials that make up the Earth's surface and subsurface (soil and rocks) have different physical characteristics, which have already been extensively studied and known in the scientific community. Among them, the



ability of materials to conduct electric current, known as electrical conductivity and its inverse, electrical resistivity, stands out. Different soils and rocks present contrasting values of resistivity and, despite the great variability of this capacity, the different materials can be identified by this property that underlies the electrical resistivity method. The main mechanism of electrical conduction by subsurface materials is ionic or electrolytic conduction. In this mechanism, the current flow occurs through ions present in the interstitial fluids in the pores of soils and rocks. In some cases, electronic conduction also occurs in materials that have free electrons, as is the case with metallic materials and metallic sulfides.

The direct current electrical resistivity method usually works with two current electrodes (A and B) and two potential electrodes (M and N), all fixed on the soil surface. A potential differential is applied between electrodes A and B and, as a result, a direct electric current travels through the ground. The current value is measured and recorded. The M and N electrodes are used to measure the potential difference that is established in the ground and associated with the traveling current. It is worth mentioning that the soil already has a natural electrical potential, called spontaneous potential, which must be subtracted from the measurement between the M and N electrodes. M and N, it is possible to calculate an apparent electrical resistivity value, named as such because it is measured in a heterogeneous and anisotropic medium depending on the arrangement of electrodes (ORELLANA, 1972; DOBRIN, 1981; TELFORD ET AL., 1985; PARASNIS, 1986).

The two most common methods for measuring electrical resistivity as a means of investigating the subsurface are: punctual information, with values taken vertically (Vertical Electrical Soundings - SEV) and two-dimensional information (Electrical Profiling Technique - EPT) with measurements taken vertically and horizontally.

### Vertical Electrical Sounding Technique – Schlumberger Arrangement

The Vertical Electric Sounding technique (allows to measure resistivity variations in depth in the medium, punctually (Figure 6). It consists of injecting an electric current into the ground through two electrodes (A and B) and measuring the potential difference in two receivers (M and N), also nailed directly to the ground. Through this current, the potential variation, the distance between the current injection points and potential measurements, the apparent resistivity of the medium is calculated, using Equation 1 (BHATTACHARYA AND PATRA, 1968).

$$\rho_a = k \frac{\Delta V}{I} \quad (1)$$

Where:

$\rho_a$  = Apparent resistivity (Ohm.m)

K = Geometric factor for the arrangement used (m)

$\Delta V/I$  = Electrical resistance (Ohm)

The geometric factor used in this work, proposed by BHATTACHARYA AND PATRA (1968), for this type of arrangement, is given by Equation 2.

$$k = \frac{2\pi}{\left(\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}\right)} \quad (2)$$

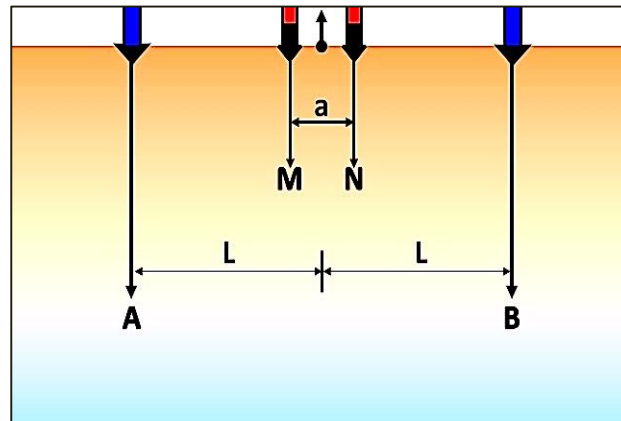


Figura 6 – Schlumberger field arrangement of the SEV technique. The letters “L” and “a” represent, respectively, the ever-increasing distances between the current electrodes and the distance that remains the same between the potential electrodes. The letter “O” represents the central point of the SEV.

Source: (Adapted from Braga, 2016).

As the distance between the AB current electrodes increases, the total volume of the investigated subsurface also increases, allowing deeper and deeper layers to be reached. Successive results will be exclusively linked to variations in resistivity in relation to depth. The use of logarithmic curves to represent the interpretation of field data is justified by allowing the variations of the representative geoelectric structures to be highlighted and by reducing the theoretical calculations for tracing the model curves used in the interpretation.

The current flows in the medium radially, the greater the distance between the current injection points, the greater the investigated depth. This depth is defined as theoretical and follows the  $AB/4$  ratio (BRAGA, 2016). In the Schlumberger arrangement (Figure 5) the current electrodes are moved over the investigation line with an increasing distance (L) while the potential ones are fixed to the ground at a distance (a) obeying the ratio of  $MN \leq AB/5$ .

The Vertical Electrical Soundings data were processed in the IPI2WIN Software, distributed by Geoscan-M Ltd., Moscow, Russia. The RMS approximation error (root-mean-square) uses the method of least squares, being calculated by measuring the distance between the apparent resistivity curve and the generated synthetic curve. (SIQUEIRA NETO et al, 2019).

### Electrical Profiling Technique – Dipole-Dipole Arrangement

The dipole-dipole arrangement was adopted for the acquisition of electrical path data. This arrangement is characterized by having spacing between the centers of the dipoles (AB and MN), which vary along the surveyed line. For each level of investigation (theoretical depth) a certain surface dipole spacing is adopted. Other peculiarities of the dipole-dipole arrangement are that the distances between the current electrodes A and B are equal to those of the potential electrodes M and N.

Normally, measurements are performed at various depths of investigation, that is,  $n = 1, 2, 3, 4$  and  $5$ , assigned at the intersection of the lines departing from the center of AB and MN with angles of  $45^\circ$  degrees (Figure 7). At each measurement point, the dipoles are displaced by a distance equal to “X”. The data obtained are plotted at positions  $n = 1, 2, 3, 4$  and  $5$ , and interpolated, generating a pseudosection of apparent resistivity. Equation 3 is used to calculate apparent electrical resistivity.

$$\rho_a = K \frac{\Delta V}{I} \quad (3)$$

$$K = 2\pi \cdot G \cdot X \quad (4)$$

$$G = 1 / [(1/n) - (2/n+1) + (1/n+2)] \quad (5)$$

Where:

$\rho_a$  = Apparent resistivity (Ohm.m)

$K$  = Geometric factor for the arrangement used (m)

$\Delta V/I$  = Electrical resistance (Ohm)

$G$  = multiple of the dipole distances (usually  $n = 1,2,3,4,5$  e  $6$ )

$X$  = distance displaced by dipoles (m)

$\pi = 3,1415$

$\Delta V$  = electrical potential difference (mV)

$I$  = electric current (mA)

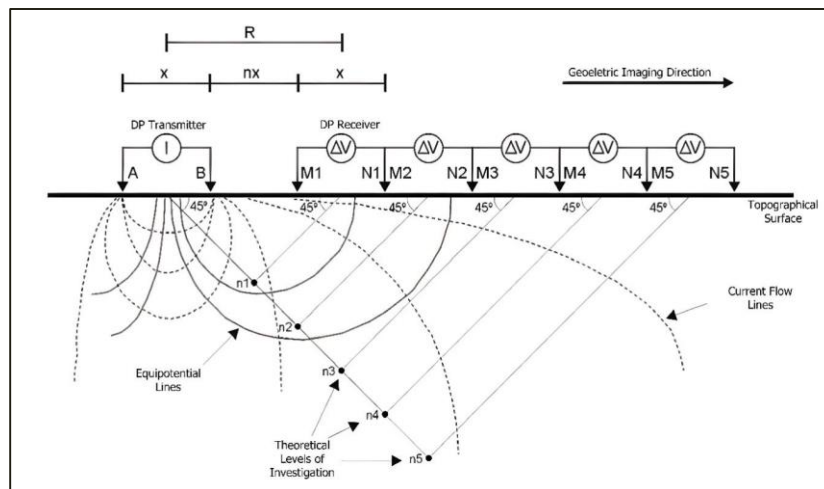


Figure 7 – Dipole-dipole field arrangement scheme used in CE. The dotted lines represent the current flow lines and the full lines the equipotential lines. The letter “n” represents the theoretical levels of investigation (n1 to n5). The letters “x” and “nx” represent the distance between the transmitting electrodes A and B, and the distance between the transmitting dipole and the receiving dipole.

Source: (Siqueira Neto E Elis, 2016).

The development of 2-D electrical imaging equipment was accompanied by the development of specific computer software to represent this type of measurement, such as RES2DINV (LOKE E BARKER, 1996a; 1996b). This software inverts the set of measurements, that is, it allows the construction of a subsurface geoelectric model, whose response reproduces, in the best possible way, the measurements obtained. This geoelectric model is subsequently interpreted based on the geological/hydrogeological/pedological model that best fits the studied area. In this study, the dipole-dipole arrangement with spacing between electrodes of 5 m was used, thus obtaining 19 theoretical levels of investigation

### 3. Results

#### Vertical Electrical Sounding (VES)

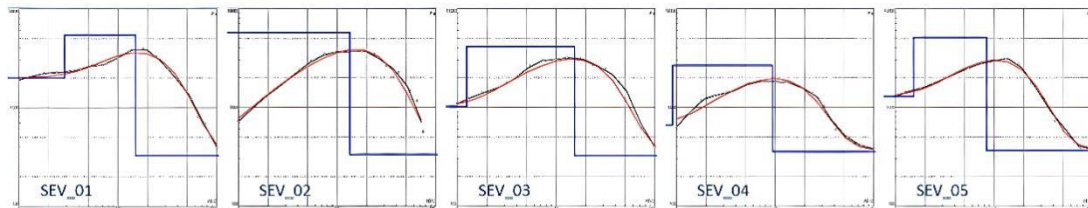
Figure 8 shows the model resistivity curves for each SEV performed. In vertical electrical drilling 01 (SEV\_01) the processed geoelectric model was divided into three layers. The first layer had a resistivity of 2000  $\Omega$ m and a thickness of

2.89 m. The second layer had a significant increase in apparent resistivity, reaching a value of approximately 5500 Ωm, with a depositional column of 12.10 m. At 14.99 m depth, the resistivity showed an abrupt drop in value, falling to the order of 330 Ωm, it was not possible to determine the thickness of this last layer due to the theoretical depth limit established in the investigation (50 m). In SEV\_02, the processed geoelectric model was divided into three layers. The unsaturated zone extended to a depth of 13.53 m and was divided into two parts, the first with a resistivity of 449 Ωm and a thickness of 0.53 m and the second with a resistivity of 5671 Ωm and a thickness of 13.00 m. The last layer, at 13.53 m, showed a resistivity drop of 332 Ωm.

In SEV\_03, the processed geoelectric model maintained the layer pattern of previous drillings. The first layer had a resistivity of 1016 Ωm and a thickness of 1.25 m. The second layer showed a slight drop in resistivity when compared to previous collections (4089 Ωm), with a depositional column of 14.10 m. At a depth of 15.35 m, the resistivity showed an abrupt drop in value, falling to 323 Ωm. Like the others, it was not possible to determine the thickness of this last layer, due to the theoretical depth limit established in the investigation. In SEV\_04, the processed geoelectric model was divided into three layers. The unsaturated zone had its thickness record more superficial than past measurements (9.54 m) and was also divided into two parts: the first with a resistivity of 658 Ωm and a thickness of 0.91 m; and the second layer with a much lower value than the measurements collected previously, but with the same highly resistive pattern of 2665 Ωm and thickness of 13.00 m. The last layer, at 9.45 m, showed a drop in resistivity to 332 Ωm.

The last collection, SEV\_05, had the processed geoelectric model also divided into three layers. In this collection, the data again showed a pattern close to the initial collections. The first layer had a resistivity of 1289 Ωm and a thickness of 1.54 m. The second layer presented a value of approximately 5100 Ωm, but with a smaller thickness (6.58) m. At a depth of 8.39 m, the resistivity showed an abrupt drop in value, dropping to the order of 363 Ωm.

Figure 9A shows the water table depths observed in each SEV and Figure 9B shows monthly rainfall data and the climatological normal for the period from August 2017 to July 2018 obtained from a meteorological station close to the study area. Analyzing the five VESs and the respective periods in which they were analyzed, it is possible to correlate the rise in the water table level with the increase in precipitation over the months, ranging from 15 m deep in SEV\_01 in the month of December 2017, when the precipitation was ~180 mm and 8.39 m at SEV\_05 in June 2018, when precipitation was ~340 mm, marking a variation of approximately 7 m in the water table.



Geoelectric Layers (RMS 6,7%)	SEV_01 (01/12/17)			SEV_02 (01/02/18)			SEV_03 (02/03/18)			SEV_04 (02/05/18)			SEV_05 (26/06/18)		
	ρ	h(m)	d(m)	ρ	h(m)	d(m)	ρ	h(m)	d(m)	ρ	h(m)	d(m)	ρ	h(m)	d(m)
1 <sup>a</sup>	2000	2,89	2,89	449	0,53	0,53	1016	1,25	1,25	658	0,91	0,91	1289	1,54	1,54
2 <sup>a</sup>	5439	12,10	15,00	5671	13,00	13,50	4089	14,10	15,40	2665	8,54	9,45	5107	6,85	8,39
3 <sup>a</sup>	327	-	-	332	-	-	323	-	-	355	-	-	363	-	-

ρ = Apparent resistivity      h = Layer thickness      d = Depth

Figure 8 – Modeled resistivity curves of the 5 VESs executed in the study area and their respective geoelectric layers. Source: Authors (2023).

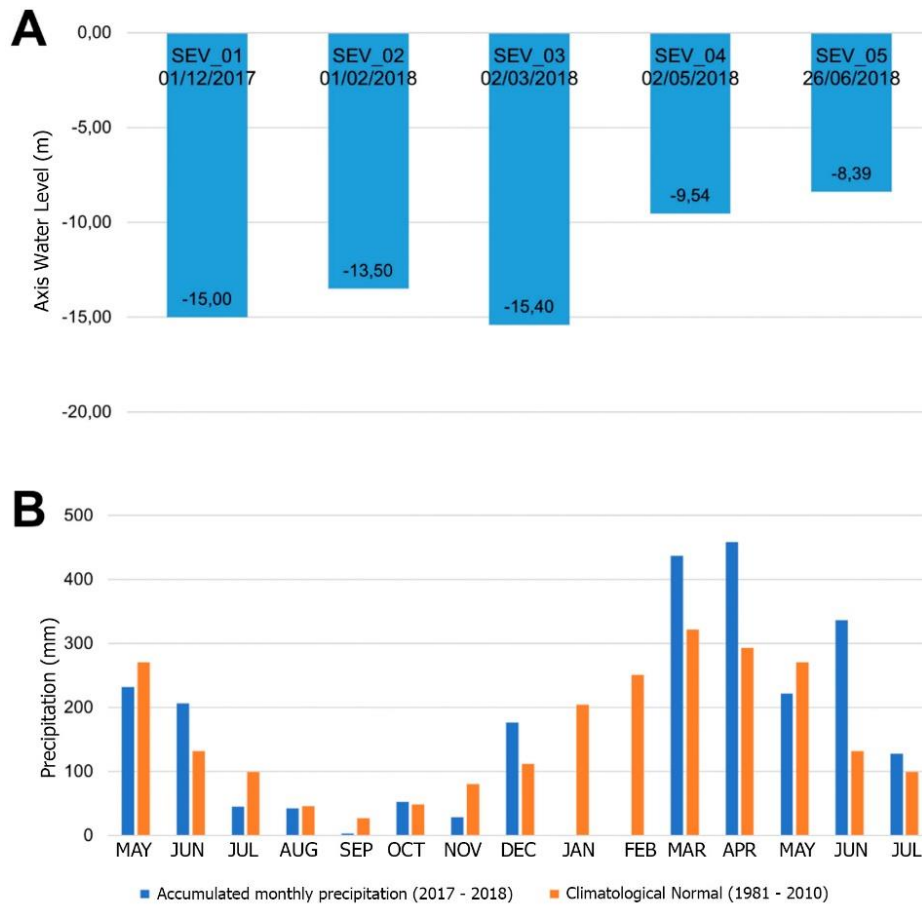


Figure 9 – (A) Variation of the water table level of the free aquifer (Fm. Alter do Chão) from December 2017 to June 2018; (B) Variation of monthly rainfall in the region of Santarém and climatological normal of the conventional station closest to the study area (Belterra).

Authors (2023).

### Electrical Profiling Technique (EPT)

Considering that SEVs 01, 02, 03 and 04 registered a high resistivity in the 2nd layer of investigation, on June 16, 2018, it was decided to add to the work one more technique (EPT) to investigate whether the anomaly registered it was punctual or extended along the entire length of the sounding opening line. The geostatistical construction of isovalues interpolated by the software modeled a profile with a depth of 52.80 m, with 19 levels of depth for an opening line of 270 m.

Analyzing the quantitative data (Figure 11) the initial records of apparent resistivity started at a depth of 0.85 m, not being possible to indicate values of the electrical behavior in the layer above this level and which was associated with the soil in the SEVs. The profile indicated a highly resistive layer that was registered at the beginning of the EPT investigation line (starting from the Security Cabin), extending horizontally for more than 135 m and presenting resistivity of order superior to 5000  $\Omega\text{m}$ ; however, this value gradually decreased beyond the VES site. At that point, the approximate thickness of the layer was 11 m. From this depth onwards, the apparent resistivity dropped to around 300  $\Omega\text{m}$ , maintaining the value pattern recorded in the VES collected previously and marking the beginning of the interface between the unsaturated and saturated zone.

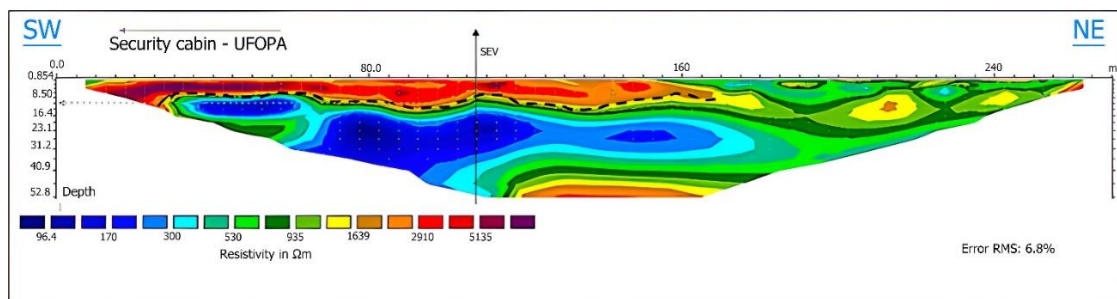


Figure 10 – Geoelectric modeled section of the study area with highlighted demarcations of the SEV location, direction of the UFOPA security cabin and dotted line representing the base of the lateritic cover layer.

Source: Authors (2023).

#### 4. Discussions

Comparing the data from VESs 01, 02, 03, 04 and 05 (Figure 8), it was possible to correlate the 1<sup>st</sup> layer with the soil, due to its small thickness (average of 1.42 m) and high resistivity, associated with the high compaction of the because it was the only access for trucks to the fuel sheds of Companhia DOCAS do Pará (Port of Santarém). SEVs 02 and 04 showed a lower resistivity in this layer because, in the 06 days prior to their collection, there was heavy rain in the municipality, with the weekly rainfall recorded at 186 mm and 57 mm (HIDROWEB, 2019), respectively, therefore saturating the layer pedology in the following days. At the end of the 05 drillings, this layer had its average thickness estimated at 10.91 m. The interface with the greatest depth between the unsaturated and saturated zone occurred on March 2, 2018 (15.40 m) and the smallest interface was on June 26, 2018 (8.39 m), as shown in Figure 9B.

The second layer showed a high resistivity pattern that was maintained in the first 04 SEVs performed, so it was decided to add a second technique to the work, the EPT, to verify whether the anomaly recorded was punctual or extended laterally. This resistive anomaly was later associated with the lateritic cover that outcrops in the study area, which is called the Matura Lateritic Cover superimposed on Fm. Alter do Chão (Figure 3B), which in the region occurs in association with the channel of the Amazon River.

The study area is close to the bank of the Tapajós river. Therefore, the surge may be related to an old floodplain or to the natural rainfall of the locality. The formation of this cover comes from the intense process of leaching by chemical weathering, which develops in tropical to humid temperate climates, and which contains nutrient-poor soil with a high residual concentration of Fe and Al hydroxides. The behavior of WT rising and falling, added to the high residual concentration of these poorly soluble hydroxides, leads to the formation of a very compacted crust, highly resistive, very resistant to erosive agents, which acts as an “impermeable lens”, locally giving the reservoir the behavior of an aquitard. That is, the infiltration of water from rain is difficult, generating accumulations of water on the surface, as occurs in the permanent flooding of Rua Vera Paz, in the rainy season.

It was not possible to determine the column depth of the saturated zone due to the established maximum theoretical depth of investigation (50m). Using the correlation made with the geological description of the Caranazal well and the data available in TANCREDI (1996) as a hydrogeological parameter, it was possible to associate this layer with the unconfined aquifer of Alter do Chão, with its water level varying by 7.0 m between the Amazonian “summer” and “winter” transition periods in the studied area - these, delimited by the study of the monthly rainfall variation in the region of Santarém.

#### 5. Final Considerations

The results showed that the ER Method, using the VES and EPT with the analysis of monthly precipitation in the Santarém region, satisfactorily met the main objective of the investigation, which aimed to verify the WT oscillation of the unconfined aquifer of the Alter do Chão Formation during the transition period between the Amazonian “summer” and “winter”. The study also allowed a better understanding of the rising behavior of the saturated zone and the relationship with the permanent flooding of Rua Vera Paz.

The second geoelectric layer, highly resistive, is possibly associated with a lateritic cover, which is associated with the Matura Lateritic Cover, due to the presence of outcrops present in the study area. With the EPT survey it was found that this geoelectric layer extends laterally along the entire profile, it was also found that its thickness varies along the study line. Because it is a thick layer of low permeability, it behaves like an aquifuge, preventing water from infiltrating into the

unconfined aquifer, thus characterizing a perched aquifer close to the surface, with accumulation of water that rises to the surface generating recurrent flooding on Rua Vera Paz.

Therefore, it is concluded that the Matura Laterite Coverage is the main cause of the flooding of the road, however, it was not possible to state whether the origin of its occurrence in the study area is the result of rainfall or if it was also related to periods of flooding in the area by the Tapajós River, given that this layer was not described in the geological profiles of the wells registered in RIMAS. It is suggested the collection of soil samples with an auger and the creation of trenches to study the pedological horizons and with that to be able to better understand the laterization of the soil and its associated processes. And as for the variation in the water table, it is suggested the association of direct data from wells to the data already collected with geophysics so that there is a way to compare them, ideally collecting data over the same period of the study.

## References

- Alvares, C. A., Stape, J. L., Sentelhas, P. C., Gonçalves, J. D. M., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, 22(6), 711-728. DOI: 10.1127/0941-2948/2013/0507
- Bhattacharya, P. K.; Patra, H. P. (1968). *Direct current geoelectric sounding*. New York: Elsevier Publishing Company, p. 134.
- Braga, A. C. O. (2016). *Geofísica aplicada: Métodos geoeletricos em hidrogeologia*. São Paulo: Oficina de Textos, p. 81.
- Caputo, M.V.; Rodrigues, R.; Vasconcelos, D.N.N. (1971). *Litoestratigrafia da Bacia do Amazonas*. RENOR – Petrobras. 92 p. (Relatório interno).
- CAPUTO, M. V. (1984). *Stratigraphy, tectonics, paleoclimatology and paleogeography of northern basins of Brazil*. Tese (Doutorado). Califórnia: Universidade da Califórnia.
- CASTRO, B.C. (2018). *Uso de Resistividade Elétrica Em Investigação Geotécnica: O caso De Palmas-TO*. Tese de Doutorado, Publicação G.TD-142/18, Departamento de Engenharia Civil, Universidade de Brasília, Brasília, DF, 298 p.
- Cordani, U.G., Brito Neves, B.B. De B., Fuck, R.A., Thomaz Filho, A., Cunha, F.M. B. (1984). Estudo preliminar de integração do Pré-Cambriano com os eventos tectônicos das Bacias Sedimentares Brasileiras. *Revista Ciência-Técnica-Petróleo*. Secção Exploração de Petróleo. Rio de Janeiro: Petrobrás/Cenpes/Sintep, Publicação n. 15, pp.70.
- Costa, M.L. (1991). Aspectos geológicos dos lateritos da Amazônia. *Revista Brasileira de Geociências*, v. 21, n. 2, p. 146-160. DOI: 10.25249 / 0375-7536.1991146160
- COSTA, M.L.; HOEHN, H.; FARACO, M.T.L.; CHOQUE, O.J. (2005). O Jade Araguaia. *Contribuições à geologia da Amazônia*. Manaus: SBG-Núcleo Norte. v. 4, p. 230-235.
- CPRM – Serviço Geológico Brasileiro (2012). *Relatório Diagnóstico: Aquífero Alter do Chão no Estado do Pará – Bacia Sedimentar do Amazonas*. V. 7, p. 19. RIMAS - Rede Integrada de Monitoramento das Águas Subterrâneas.
- Cunha, P. R. C. et al. (1994). *Bacia do Amazonas*. Boletim de Geociências da Petrobras, Rio de Janeiro, v. 8, n.1, p. 47-55.
- Cunha, P. R. C., Melo, J. H. G., Silva, O. B. (2007). *Bacia do Amazonas*. Boletim de Geociências da Petrobras, 15(2), 227-251.
- Daemon, R.F. (1975). Contribuição à datação da Formação Alter do Chão, Bacia do Amazonas. *Revista Brasileira de Geociências*, v. 5, n. 2, p. 78-84.
- Dobrin, M.B. (1981). *Introduction to Geophysical Prospecting*. International Student Edition, 630p.
- Fassbender, W.H. (1975). *Química de suelos; con énfasis en suelos de América Latina*. Ed. IICA. San José de Costa Rica.

- Figueroa, S.N.; Nobre, C.A. (1990). *Precipitations distribution over Central and Western Tropical South America*. Climanálise - Boletim de Monitoramento e Análise Climática, v. 5, n.6, p.36-45.
- IBGE – Instituto Brasileiro de Geografia e Estatística. (2019). *Séries históricas e estatísticas: Taxa de Urbanização*. Disponível em: <<https://seriesestatisticas.ibge.gov.br/default.aspx?op=busca>> Acesso em: 12 maio
- Jacinto, A. I.; Simas, M. T. M.; Bianchi, R.; Oliveira, K. N.; Rech, C. M. C. B. (2006). *Aspectos físicoterritoriais e atrações turísticas do município de Santarém, Pará*.
- King, L.C. (1956). A geomorfologia do Brasil Oriental. *Revista Brasileira de Geografia*, v. 18, n. 2, p. 147-165.
- Loke, M.H.; Barker, R.D. (1996a). *Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method*. Geophysical Prospecting, 44, pp 131-152.
- Loke, M.H.; Barker, R.D. (1996b). *Practical techniques for 3D resistivity surveys and data inversion*. Geophysical Prospecting, 44, pp 499-523.
- Marcelino, T. H.; Shiraiwa, S.; Borges, W. R.; Filho, P. N.; Raiter, F. (2005). *GPR para a verificação do nível d'água subterrânea em transição Floresta Amazônica e Cerrado*. ACTA AMAZÔNICA – INPA, Vol. 35 (3), p. 367 – 374, Manaus, AM.
- Oliva, A.; Chang, H. K. (2007). *Mapeamento do lençol freático no município de Rio Claro (SP) empregando a técnica de Sondagem Elétrica Vertical*. - São Paulo, UNESP, Geociências, v. 26, n. 1, p. 27-34.
- Orellana, E.S. (1972). *Prospección geoelectrica en corriente continua*, Paraninfo, Madrid, 523p.
- Parasnis, D.S. (1986). *Principles of Applied Geophysics*. Chapman and Hall, New York, 4th Ed., 402 p.
- PORTAL HIDROWEB – *Séries Históricas das Estações* – Inventário de Estações da Agência Nacional das Águas (ANA). Disponível em: <[http://www.snirh.gov.br/hidroweb/publico/medicoes\\_historicas\\_abas.jsf](http://www.snirh.gov.br/hidroweb/publico/medicoes_historicas_abas.jsf)>. Acesso em: 10/06/2019.
- Rossetti, D.F.; Neto, R.G. (2006). *First evidence of marine influence in the Cretaceous of the Amazonas Basin, Brazil*. Cretaceous Research, p. 1-16.
- SEMINFRA – Secretaria de Infraestrutura de Santarém, G1 SANTARÉM. *Falta de planejamento de vias em Santarém provoca alagamentos*. Disponível em: <<http://g1.globo.com/pa/santarem-regiao/noticia/2016/06/falta-de-planejamento-de-vias-em-santarem-provoca-alagamentos.html>>. Acessado em: 12 de junho de 2019.
- Silva, A. C.; Dourado, J. C.; Moreira, C. A. (2011). *Aplicação da eletrorresistividade na caracterização do meio hidrogeológico na cidade de Ji-Paraná (RO)* - São Paulo, UNESP, Geociências, v. 30, n. 4, p. 641-650.
- Silva, A. F.; Mitsuya, M.; Silva, R. (2013). *Análise do índice pluviométrico da região de Santarém (PA), entre 1969 e 2010*. Trabalho apresentado em evento - 65º Reunião Anual da SBPC, Recife (PE) – Brasil.
- Silva, P. O.; Cabral, J.J.S.P. (2014). Atenuação de Picos de Vazão em Área Problema: Estudo Comparativo de Reservatórios de Detenção em Lote, em Logradouros e em Grande Área da Bacia. *Revista Brasileira de Recursos Hídricos - RBRH*, Porto Alegre, v. 19, n. 2, p. 7-18.
- Siqueira Neto, A.C., Elis V.R. (2016). Characterization of an experimental cell in a municipal solid waste landfill using 2-D electrical profiling technique. *Brazilian J. Geophys.* 34, 559-570
- SIQUEIRA NETO, A.C.; BARROS, A.C.S.P.C.; SOUZA, L.G. (2019). Mapeamento hidrogeológico e estudo da vulnerabilidade do Aquífero Itapecuru utilizando sondagens elétricas verticais na fazenda Alta Floresta II, Tailândia-PA. Livro: *Contribuições à Geologia da Amazônia - Volume 11*, 21-35.
- TANCREDI, A.C.F.N.S. (1996). *Recursos hídricos subterrâneos de Santarém*. 153 f. Tese (Doutorado) - Centro de Geociências, Universidade Federal do Pará, Belém.
- Telford, W.M.; Geldart, L.P.; Sheriff, R.E. (1990). *Applied Geophysics*. Cambridge Univ. Press. 2nd edition, 770 p.



---

Vasquez, M. L.; Rosa-Costa, L. T. (2008). (Org.). *Geologia e recursos minerais do estado do Pará*: texto explicativo. Belém: CPRM.

Vasquez, M. L.; Sousa, C. S.; Carvalho, J. M. A. (2008). (Orgs.) – *Mapa Geológico e de Recursos Minerais do Estado do Pará*. Escala 1:1.000.000 – Programa de Geologia do Brasil (PGB), Integração, Atualização e Difusão de dados da Geologia do Brasil, mapas Geológicos Estaduais. CPRM – Serviço Geológico do Brasil, Superintendência Regional de Belém.