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Subsurface evaluation for aquaculture ponds in the Amazon Region

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ABSTRACT: Few Brazilian rural landowners are aware of the technology available to survey the subsoil of terrains earmarked for aquaculture operations. This study evaluated subsoils of Monte Alegre (area 1) and Montenegro 3 (area 2) aquaculture zones in the geographic region of Bragança (Amazon region, northern Brazil), and the adequacy of these areas for aquaculture. Ground Penetrating Radar, electrical conductivity measurements, and sedimentological analyses were applied to evaluate the subsoil of fish farms. Apparent conductivity values recorded by the Electromagnetic Induction (EMI) in area 1 indicated possible presence of clayey soils. Excavation analysis and sedimentological samples (sand) from this site confirmed the inadequacy of the terrain. The EMI tool in area 2 indicated possible presence of clayey soils. Geophysical and sedimentological results from the site confirmed its suitability. These geophysical tools are recommended for evaluating prospective aquaculture sites, given their capacity to provide reliable data on the subsoil characteristics , which is essential to guarantee the success and sustainability of aquaculture operations.

Keywords: ground penetrating radar, electrical conductivity meter, fish-farming pond, sedimentological analysis.

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INTRODUCTION

Aquaculture provides a potentially valuable income source for many smallholders, landowners, and the associated communities (Tapader et al., 2017). Aquaculture is a rural activity focuses on the production of different aquatic organisms and it is growing in importance around the world. Aquaculture is an important productive sector in Brazil, which has grown 56 % over the past 12 years (Senar, 2018a; Calixto et al., 2020; MAPA, 2022).

Installations required for fish production – either ponds or net enclosures – represent the principal investment of any aquaculture operation. However, costs of construction of ponds or implantation of other structures may vary considerably according to factors such as site characteristics (climate, topography, type of soil, vegetation cover, and drainage requirements), configuration of infrastructure, and methods employed to install the operation. These costs can nevertheless be minimized by adequately planning the different stages of the installation process (Rodrigues et al., 2013).

Appropriate location selection is essential to ensure the success of aquaculture operations (Hadipour et al., 2014). Soil quality and topography of the terrain are important considerations for installing fish-farming ponds and should be evaluated systematically to ensure the terrain is adequate for this use. Adequate site assessment may reduce environmental risks related to natural resources conservation, such as Areas of Permanent Preservation (APPs), which can not legally be occupied or used to install fish ponds or other infrastructure (Senar, 2018b).

Adequate aquaculture areas require specific conditions (Jamandre and Rabanal, 1975; Adisukresno, 1982; Hechanova, 1982), and soil quality is fundamental, since ponds must be excavated in substrates with reduced permeability that can form stable banks (Senar, 2018b). Geophysical methods provide a non-destructive alternative for a high-performance, low-cost, and time-effective assessment of terrain subsurface. These methods have been widely used for surveying deep substrates, and electromagnetic techniques, in particular, can be applied to the assessment of relatively shallow subsoil environments (Zajícová and Chuman, 2019).

Two methods – Ground Penetrating Radar (GPR) and Eletromagnetic Induction (EMI) – have been employed widely for the collection of field data to evaluate soil types and hydrological properties of a terrain (e.g., Minet et al., 2013; Doolittle and Brevik, 2014; Liu et al., 2016; Campos et al., 2019; Pena and Oliva, 2019; Zajícová and Chuman, 2019; Benedetto et al., 2020; Chira et al., 2023). Geophysical tools provide important data on terrain subsoil characteristics, such as its stratigraphy, lithology, top of the water table, bedrock, depressions, and faults (Davis and Annan, 1989; Kearey et al., 2002; Jol, 2009; Utsi, 2017; Souza and Gandolfo, 2018).

Geophysics provides an investigative approach that contribute important information to guide decision-making on the implantation of aquaculture installations (Nunes et al., 2019; Pena and Oliva, 2019; Chira et al., 2023; Emmanuel et al., 2023). In the communities of Ugono-Abraka and Agbarha-Otor, in the region of the Niger delta, in Nigeria, Emmanuel et al. (2023) assessed the terrains of two earthen fish ponds (one existing, and the other, planned) using geophysical methods of electrical resistivity and induced polarization, combined with the analysis of soil samples to estimate infiltration coefficients of the soil, and potential for water infiltration.

This study applied GPR and Electromagnetic (EM34-3) tools and sedimentological analyses to evaluate the conditions of the rural areas of Monte Alegre and Montenegro 3 (geographic region of Bragança, northern Brazil) to verify their suitability for the construction of fish farming ponds, and thus contribute to the development of successful aquaculture facilities in this region. The GPR was chosen because this method is very sensitive to the presence of clay in the subsoil, especially if this layer is wet, which attenuates the electromagnetic signal. Furthermore, the use of GPR in conjunction with the EM34-3 tool can be very useful for pond excavation, as the locations attenuated in GPR can be corroborated by the conductivity zones measured with the electrical conductivity meter, as observed in the work of Pena and Oliva (2019), who successfully applied these tools to select suitable sites for fish-farming operations in the towns of Tracuateua and Augusto Corrêa (Northern Brazil).

MATERIALS AND METHODS

Study area

This investigation focused on two distinct areas located in the geographic region of Bragança (IBGE, 2017), which is part of the northeastern Pará region, in northern Brazil (Figure 1). Area 1 is a fish farm located in the Monte Alegre aquaculture production zone (1° 12’ 22.62” S, 46° 47’ 44.82” W). Area 2 is also a fish farm located in Montenegro aquaculture production zone 3 (1° 19’ 24.37” S, 46° 50’ 57.81” W) (Figure 1). The municipality of Bragança covers an area of 2,124.734 km^2 and has an estimated population of 123,082 inhabitants (IBGE, 2022).

Exposed upper Cenozoic deposits found in the region of Bragança encompass three stratigraphic successions, limited by regional unconformities, which are designated depositional sequences A–C. Sequence A corresponds to the Pirabas Formation and lower Barreiras Formation, which date to the upper Oligocene/lower Miocene. Sequence B includes the intermediate portion of the Barreiras Formation, which corresponds to the middle Miocene. Sequence C includes the Pliocene deposits, the youngest of which are considered to be post-Barreiras sediments (Rossetti, 2001, 2003). Quaternary sedimentation includes siliciclastic sands from the Miocene and muds from the Barreiras Formation (Rossetti, 2001). The base of the Quaternary sedimentation is represented by facies of fluvial sands and pre-Holocenic gravels deposited in the Neogene-Paleogene (Souza Filho et al., 2009).

Bragança coastal plain, in the municipality of Bragança, extends from Maiaú Point to the mouth of Caeté river, covering a total area of 1,570 km^2 and is located within the Cretaceous Bragança-Viseu coastal basin (Souza Filho and El-Robrini, 1996). This plain has three distinct morphological domains – the alluvial plain, the estuarine plain, and the coastal plain (Souza Filho 1995; Souza Filho and El-Robrini 1995).

Climate of the Bragança region, according to Köppen classification system, is Am2 type, that is, hot and humid with an intense rainy season from January to May (Souza Filho and El-Robrini, 1996; Magalhães et al., 2006), and a prolonged dry (or less rainy) season from June through December. Ambient temperatures vary little over the course of the year in the Bragança region (Costa et al., 2016), with means of 25.2–26.7 °C, minima of 20.4–22.0 °C, and maxima of 29.8–32.8 °C, and constantly high relative humidity, ranging from 77 to 91 %.

Bragança region is dominated by the northeasterly trade winds, particularly between December and May, when these winds may blow up to 8–9 m s^{-1} (Pereira et al., 2013). During the rest of the year (June–November), southeasterly and easterly winds are also common, in addition to the northeasterlies (Monteiro and Pinheiro, 2004).

Methodology

Steps of the employed procedures in the present study are shown in figure 2.

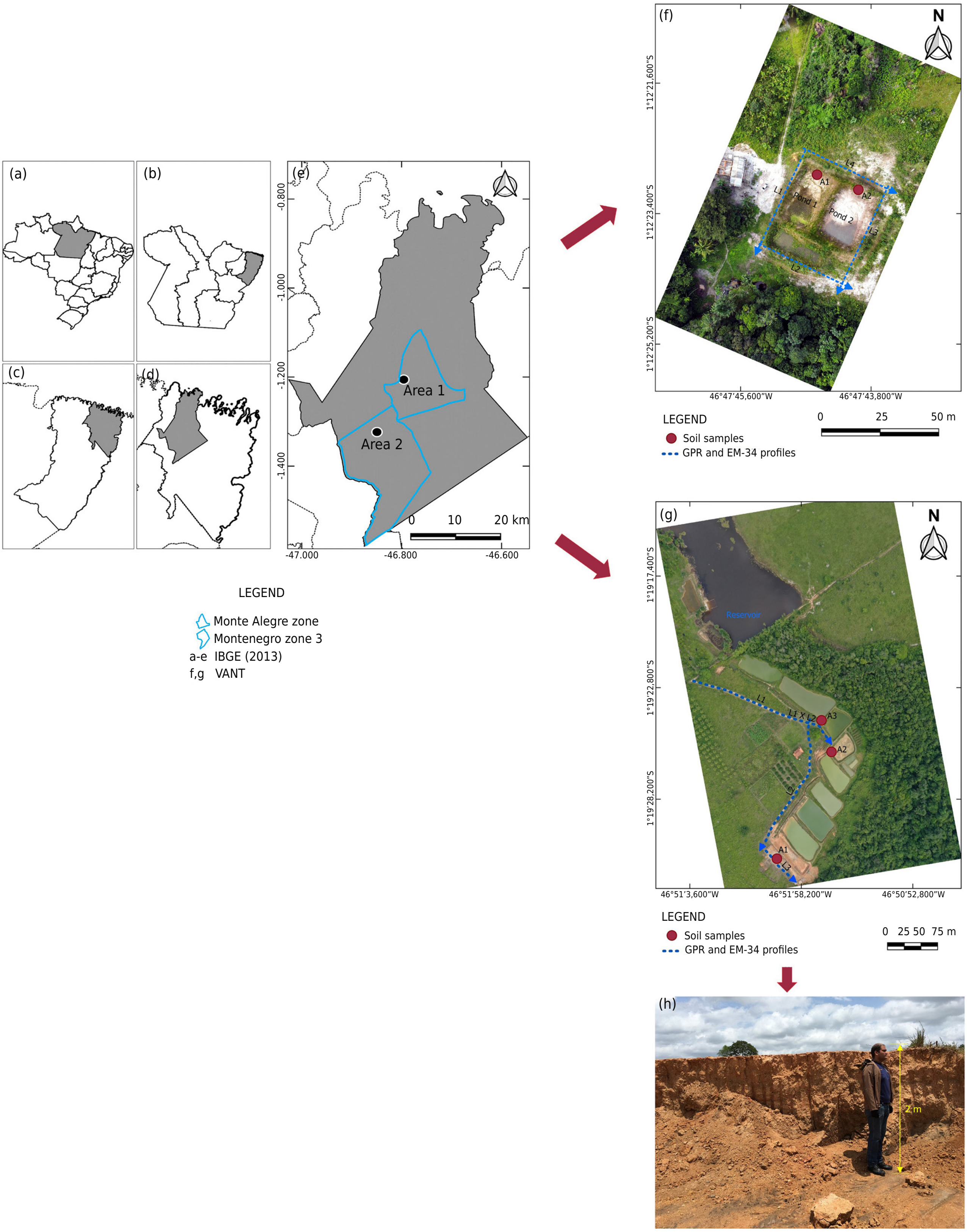

Figure 1. Study area showing (a) Brazil, (b) Pará State, (c) Intermediate Geographic Region of Castanhal, (d) Geographic Region of Bragança, (e) the municipality of Bragança, (f) the location of the fish farm in Monte Alegre aquaculture zone (area 1), (g) location of the fish farm in Montenegro aquaculture zone 3 (area 2) and (h) *Latossolo Amarelo* (Oxisol) profile.

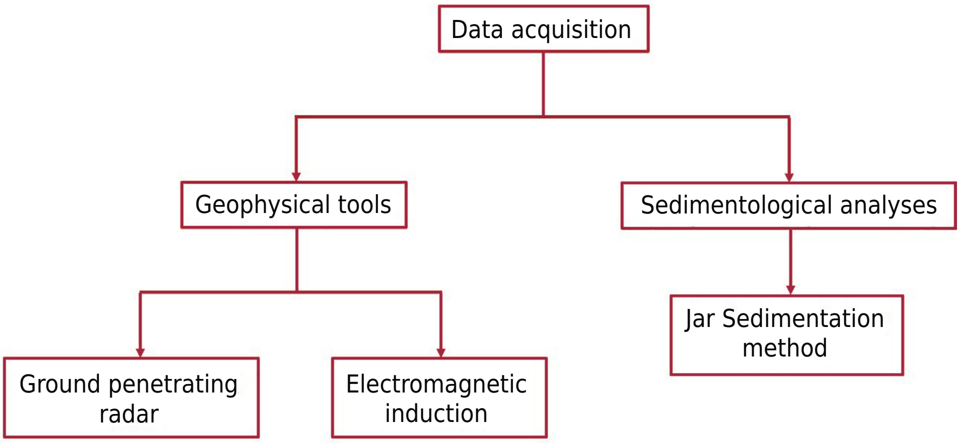

Figure 2. Flowchart of the sequence of adopted procedures in this study.

Data acquisition

To define the potential of the study areas for the implantation of fish-rearing ponds, the geophysical data were collected during the region's two principal seasons (2020-2022), that is, the dry season months of October 2020 and June 2021, and the rainy season months of March 2021 and February 2022.

Geophysical tools

Ground Penetrating Radar

Ground Penetrating Radar (GPR) is a non-destructive electromagnetic method that provides a rapid, practical, and versatile approach to data collection, processing, and interpretation. In addition, GPR has the advantage of being easily operated and highly portable, with a wide range of applications, including aquaculture. It can also be used with both high and low-frequency antennas.

Even so, GPR does have some disadvantages, such as the loss of resolution and range of the equipment due to the shielding or attenuation of the electromagnetic signal in environments with high levels of free ions, as in the case of saltwater, the presence of humid clay substrates or electrically conductive soils, although in practice, other types of soil may also be inadequate, such as agricultural land that combines fertilizers with high humidity. Obviously, in this case, it is necessary to take into account the implications of the humidity of the soil or the presence of subterranean waters during the application of the GPR. Sands containing salt, for example, also hamper the application (Utsi, 2017). There are also limitations in relation to the depth of penetration through geological materials (e.g., Davis and Annan, 1989; Porsani, 2008; Duarte et al., 2012; Romero-Ruiz, 2021; Pradipta et al., 2022a).

Ground Penetrating Radar (GPR) data were collected with a GSSI SIR 3000 apparatus, 200 and 400 MHz antennas, and time window intervals of 100-300 ns. In area 1, four distinct profiles, one (L1) of 50 m in length, and three (L2–L4) of 45 m (Figure 1), were surveyed 64 times. In area 2, three profiles (L1: 195–200 m; L2: 140–170 m; L3: 55 m, Figure 1) were surveyed 34 times. In both areas, the electromagnetic pulses were marked at 5-m intervals.

The data were processed with the Reflexw software, version 8.5.8. and following the sequence (Annan, 1996; Reis Jr. et al., 2014; Sandmeier, 2018; Bacha et al., 2021; Delgado et al., 2022; Gomes et al., 2023): (i) data editing (ii) static correction, (iii) temporal filtering, (iv) gains varying in time, (v) removal of the background noise, and (vi) time-to-depth conversion. The hyperbole overlap method was applied to determine the propagation velocity of the electromagnetic wave. Propagation velocity used in the time-depth conversion were 0.1 m ns^{-1} (area 1) and 0.07 m ns^{-1} (area 2), respectively.

Electrical conductivity

Eletromagnetic Induction (EMI) is a rapid, low-cost method for the assessment of the electrical conductivity and apparent resistivity of terrain at varying depths. Other advantages include the ease with data can be acquired, the versatility of the apparatus in the field, and the potential for the survey of large areas in a short period (e.g., Moreira et al., 2007; McNeill, 1980). The principal disadvantage of this method is the interaction between the electromagnetic field generated by the equipment and metallic structures such as high-tension power lines (McNeill, 1980). This type of interaction generates values of apparent conductivity much higher than the actual ones. In area 2, the EMI survey was suspended near an electric fence to avoid recording false values of conductivity or apparent resistivity.

Geonic Ltd. Electrical conductivity meter (EM34-3) was used to obtain the apparent conductivity data, which were measured in mS m^{-1}. The EM34-3 operational system has two dipole modes: the Horizontal Dipole (HD), in which the coil axes are arranged vertically, and the survey depth is approximately 0.75 times the interval between the coils, and the Vertical Dipole (VD), in which the coil axes are arranged horizontally, and the survey depth is approximately 1.5 times the interval between the coils. As mentioned above, the Tx-Rx coils can be arranged at intervals (10, 20, and 40 m, respectively).

Under ideal conditions, then, it is possible to investigate depths in the HD mode (approximately 7.5, 15, and 30 m), and in the VD mode (approximately 15, 30, and 60 m) (McNeill 1980). As the existing ponds in the two study areas are 1–2 m deep, we prioritized the data obtained in the HD mode with the coils spaced at intervals of 10 m (McNeill, 1980). The EMI data were collected along the same profiles as the GPR, and in the same direction.

Sedimentological analyses of the soil samples

Rodrigues et al. (2013) recommends the detailed investigation of sites earmarked for installing fish farms, either through digging trenches or by drilling probes with an auger, to collect soil samples from different depths. This sampling should be conducted throughout the planned area to determine whether the characteristics of the local soils are adequate for the construction of ponds, embankments, and dykes. This investigation of the subsoil profile should extend to at least 0.60 m below the bottom of the planned ponds.

In the present study, the subsurface lithology was determined using a rapid field test. For this, 2000-mL soil samples were collected using an auger and 1.5-m deep trenches. Samples were labeled prior to the analysis, which had five steps: the samples were dried in an oven at 80 °C for 24 h to standardize their humidity; two subsamples of approximately 1000 mL of the soil were placed in two transparent 2-L jars (Jar Sedimentation method); samples were then ground up with a rod to eliminate the air trapped in the soil and record the volume of the material in the container; 1500 mL of water was added to each container to homogenize the soil and dissociate all the particles present in the sample; and after decanting for 24 h, the particle units (clay, silt, sand) are determined and measured. All the samples were analyzed in duplicate, and we used the mean lithological composition for each sample studied here.

Successful implantation of fish-rearing ponds may depend on the soil quality and the terrain topography (Boyd, 1995; Senar, 2018b; Basudha et al., 2019; Catuxo et al., 2021). These authors recommend that the soil be impermeable, with at least 20 % clay, while the sum of the percentages of clay and silt should be at least 45 %, to minimize water loss by infiltration, for which clayey or loamy soils are ideal. The soils most appropriate for the construction of ponds are poorly permeable, with a medium texture (~30–40 % clay), which ensures the construction of more stable embankments. Soils with a high clay content tend to crack when exposed to the sun, causing leaks or infiltrations (Rodrigues et al., 2013).

RESULTS

Study area 1

A chaotic zone was identified in profile L3 (Figure 3a) between approximately the 29 and 53 m markers, while some small faults are visible in this profile. A high amplitude horizontal reflector was identified at a depth of 7 m, which may represent the top of the water table in this area. Informal interviews with local well diggers confirm that the top of the local water table is located at a depth of 6–10 m. Similar features were observed in profile L1 (Figure 1), which is parallel to profile L3, with a chaotic zone between approximately the 12 and 29 m markers, and the reflector at a depth of 7 m. Similar features were also recorded in profiles L2 and L4 (Figure 3b), which are parallel to each other and perpendicular to profiles L1 and L3.

There is presence of areas with low EM impedance contrast, between 0 and 10 m (profile L3, Figure 3a), and between 5 and 34 m (profile L4, Figure 3b), probably due to the predominance of clay in this area. The plot of the apparent conductivity recorded during the electromagnetic survey with the EM34-3 electrical conductivity meter is shown in figure 4. Apparent conductivity values recorded in area 1 were 900–1070 mS m^{-1} in June, 2021. These values correspond to a theoretical depth of 7.5 m, and indicate the presence of clayey (humid) soil (Davis and Annan, 1989; Telford et al., 1990; Reynolds, 2011).

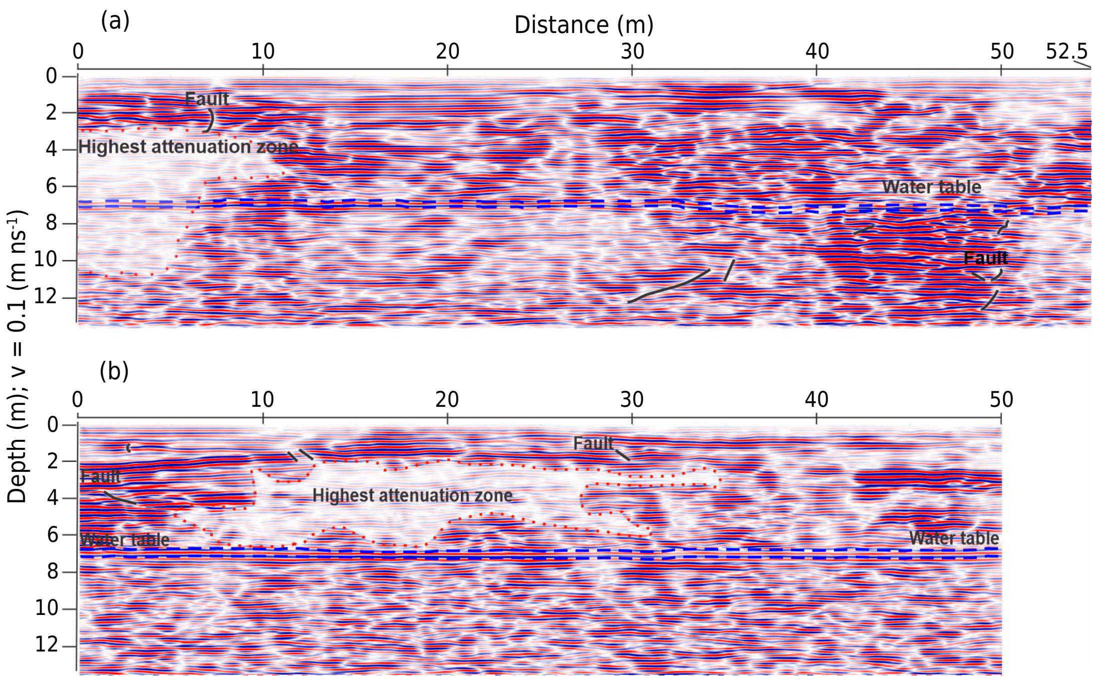

Figure 3. FGPR profiles using a 200 MHz antenna (dry season, June 2021): a) profile L3, with a 300 ns time window and b) profile L4, with a 300 ns time window.

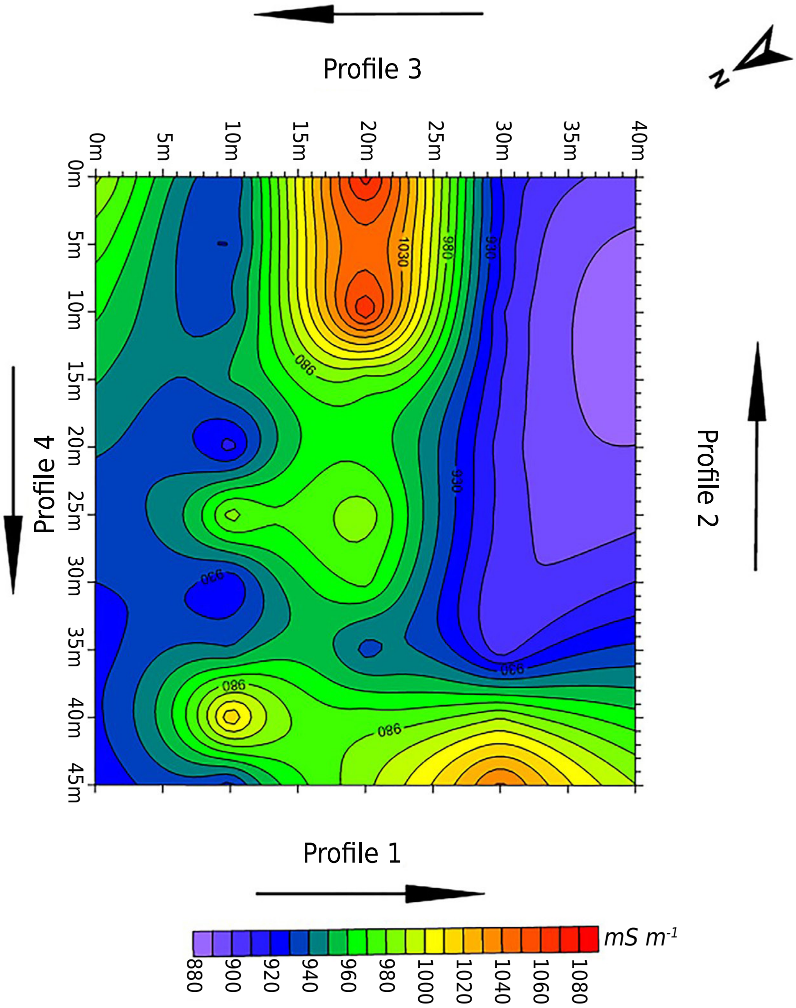

Figure 4. Map of apparent conductivity recorded during the dry season (June) of 2021, based on the HD obtained by the cable antenna with coils spaced at 10 m intervals.

At a depth of approximately 1.5 m, two soil samples collected from this area revealed a predominantly sandy (92.73–100 %) composition (Table 1).

Study area 2

Profile L1 (Figure 5a) identified a sequence of normal faults with small slips between the 0 and 120 m marks and at a depth of 3.5 m, which are probably anchored in plastic clayey layers. This profile has a horst and graben-type structure, with an extensive tectonic regime.

Electromagnetic signals of profile L1 have varying amplitudes, with the GPR signature of the rocky substrate being composed of parallel and subparallel reflectors with low reflection zones in which the electromagnetic signal is absent at depths of approximately 1.4–2.5 m and near 4.2 m. Reflectors similar to energy-dispersive hyperbolas were also identified and may represent underground pipes that are part of the fish pond installations. A 140 m-long electric fence was observed at the beginning of this profile. Profile L1 (Figure 5a) revealed a continuous, high-amplitude reflector at a depth of between 4.48 and 4.62 m, which represents the top of the local water table.

Profile L2 (Figure 5b) revealed a similar sequence of normal faults with small slips between the 40 and 140 m marks. This profile is almost perpendicular to the previous one. This

Table 1. Sedimentological analysis of the soil samples collected in area 1

Sample	Sand	Clay
	g kg^{-1}	
A1	1,000	-
A2	927.3	72.7

sequence is probably anchored in plastic clayey layers, and the profile structure was similar to that of profile L1, with a horst and graben pattern within an extensive tectonic regime. The electromagnetic signal amplitude in this profile also varies substantially, with parallel and subparallel reflectors and reduced continuity. Reflectors similar to energy-dispersive hyperbolas were also detected here, as in profile L1, and once again, the top of the local water table was identified at the same depth.

Profile L3 (Figure 5c) revealed a depression approximately 35 m long between the 20 and 55 m marks. This profile is almost perpendicular to profile L2. The same structural features noted in the previous two profiles were observed again here, i.e., normal faults with horsts and graben, with larger slips between the 35 and 55 m marks. As before, the amplitude of electromagnetic signal varied considerably, with well-marked parallel, subparallel, and divergent reflectors, with a low reflection zone, which may be clayey. We also observed a semi-graben within the area of the depression. As in the previous profiles, the top of the water table was revealed at a similar depth here.

Inductive electromagnetic surveys were also conducted using an EM34-3 geophysical tool to integrate the different geophysical tools for the description of the geological characteristics of the rocky substrate. This survey was based on the apparent conductivity collection of data, measured in mS m^{-1}. Two almost perpendicular EM profiles (L1 and L2) were surveyed with measuring stations placed at intervals of 5 m. The apparent conductivity pseudo-sections were obtained for each profile (Figures 6a and 6b).

Apparent conductivity was not measured in the direction of profile L3 because of another electric fence in this area. As electromagnetic devices are extremely sensitive to electromagnetic noise and interference, such as electrical installations, high-tension transmission lines, and metallic objects in the subsoil (Souza and Gandolfo, 2018), this profile was not surveyed to avoid possible false readings.

Pseudo-section L1 revealed three different zones of high anomaly (Figure 6a): 1–14th stations (dark red zone), 15–18th stations (dark red zone), and 21–38th stations (red, dark red, and orange zone). Pseudo-section L2 also revealed three different zones of high anomaly (Figure 6b), between the 5–11th and 17–29th stations (red and orange, zone 1), the 19–21th and 22–29th stations (dark red, zone 2), and in the 1–29th stations (dark red, zone 3).

In general, the rocky substrate had a high conductivity, of the order of 900-1523 mS m^{-1}. As verified in loco, the apparent conductivity values recorded in area 2 indicate the presence of generally clayey soils (Davis and Annan, 1989; Telford et al., 1990; Reynolds, 2011).

Three soil samples (A1, A2 and A3) were collected from this study area at a depth of approximately 1.5 m (Figure 1 and Table 2). Organic matter derived from the decomposition of vegetation was detected here. Soil sample analysis from this site indicated the presence of two layers, one of clay (top) and the other of ferruginous sandstones (bottom), that characterize the Barreiras Formation of the region. The soil has a medium texture, with a 39.2–65.3 % clay content, which is appropriate for constructing fish farming ponds (Rodrigues et al., 2013).

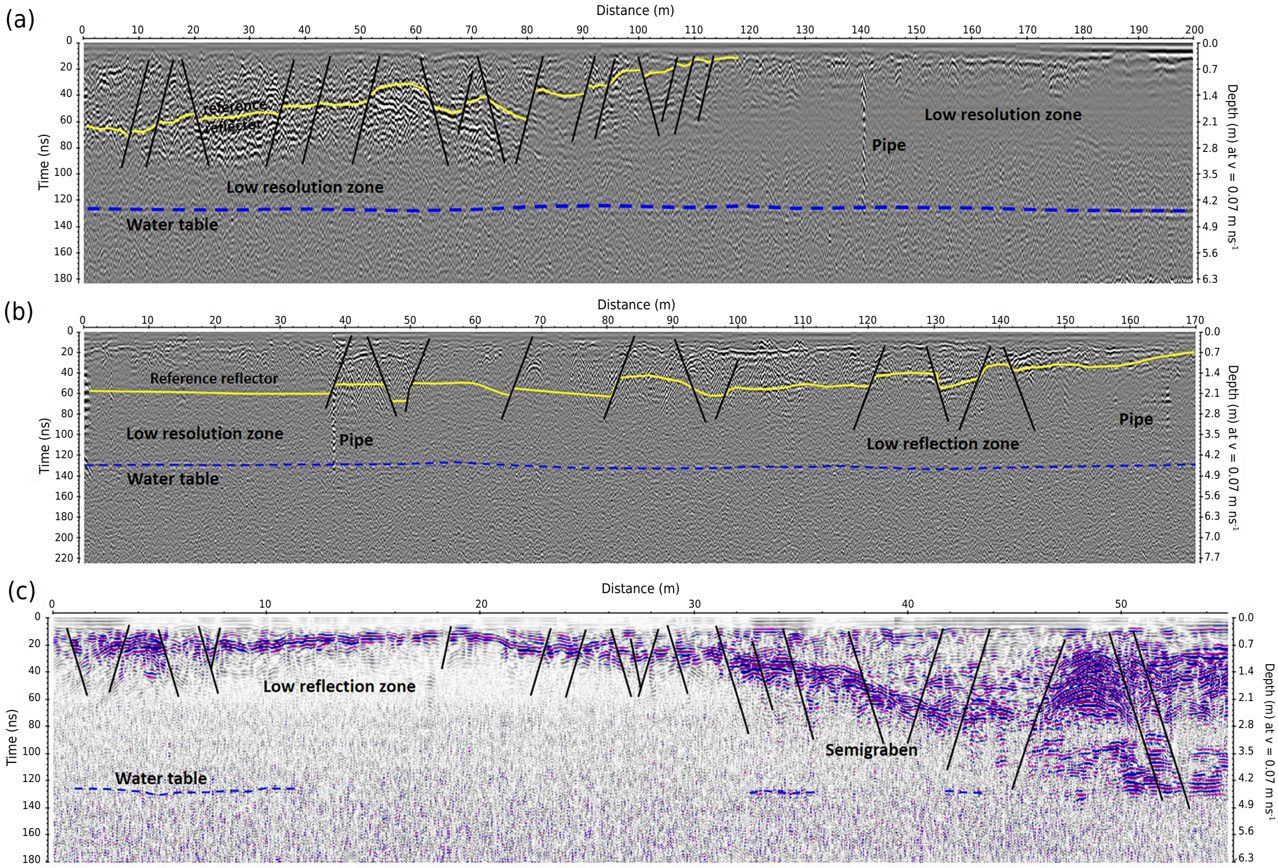

Figure 5. The GPR profiles obtained with the 200 MHz antenna: (a) L1 (200 ns range), (b) L2 (250 ns range), and (c) L3 (200 ns range). This survey was conducted in October 2020.

DISCUSSION

Study area 1

Lithological characteristics identified in this area were consistent with those of a well excavated in the Monte Alegre aquaculture zone, where the local formation is Barreiras Formation (Neogene period) of the Miocene-Pliocene epochs, which is composed mainly of sandy soil up to 2 m deep (Siagas, 2022). The soil of the terrain surveyed in study area 1 is inadequate for the installation of fish farming ponds, based on Senar (2018b), Basudha et al. (2019), and Boyd (1995). Sandy soils identified at the site (Figure 1f) would be subject to seepage and would be unable to retain the water in the ponds to ensure fish rearing.

Study area 2

Data from Siagas (2022) and information obtained from local well diggers confirm the existence of a local water table in this area, the top of which is located at a depth of approximately 4-6 m. Lithological characteristics identified in the study area were corroborated by the information obtained from wells excavated in the Montenegro aquaculture zone 3, where the local formation is the Barreiras Formation (Neogene) of the Miocene-Pliocene epochs, which is composed of ferruginous sandstones, and fine to medium silty and clayey sands (Siagas, 2022).

Sedimentological analysis of the soil samples confirmed the lithological description derived from parameters of apparent conductivity obtained by the conductivity meter (EM34-3), i.e., the soil conditions at the study site are appropriate for the construction

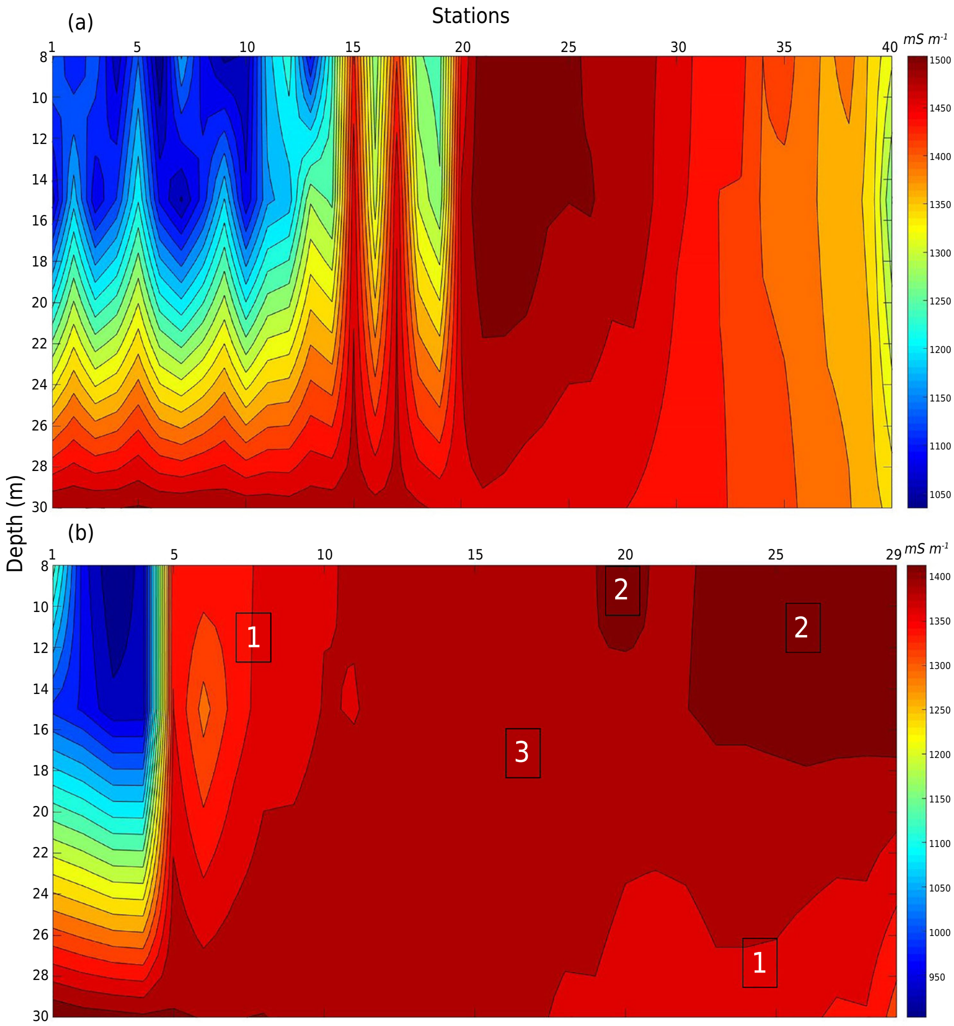

Figure 6. Pseudo-sections of apparent conductivity corresponding to (a) profile L1 surveyed during the rainy season (March) of 2021 and (b) profile L2 surveyed during the rainy season (March) of 2021, based on the HD obtained by the cable antenna with coils spaced at 10 m intervals.

of fish ponds, based on the recommendations of Senar (2018b), Basudha et al. (2019) and Boyd (1995). These results also confirmed this terrain is suitable for installing more ponds, which led to the installation of a new pond (November 2020). Soils of the study areas (municipality of Bragança, Pará) are characterized as *Latossos Amarelos* (Ferralsols or Oxisols) (Figure 1h) (Embrapa, 2016; Santos et al.,2018; Brasil et al., 2020).

In both study areas, the radargrams revealed the presence of attenuated zones in subsurface. Attenuation of electromagnetic wave signal in electrically conductive soils (with a high clay content) is one of the limitations of GPR, which is restricted to relatively shallow depths, where the presence of geological material restricts its penetration (e.g., Davis and Anna, 1989; Porsani, 2008; Duarte et al., 2012; Romero-Ruiz, 2021). To bypass this limitation, Porsani (2008) recommends using complementary sources of geological and geophysical data, i.e., applying an integrated approach, which combines methods to complement and confirm the parameters obtained by the GPR. Santos et al. (2014) evaluated soils of Conceição do Araguaia municipality (Pará, Brazil), and concluded *Argissolos* are the most adequate for the construction of excavated ponds, followed by *Latossolos* (Ferralsols or Oxisols), which, despite their medium texture, tend to be relatively porous. By contrast, *Plintossolos*, which have a loamy-sandy texture, tend to be resistant to percolation, while *Gleissolos* tends to remain saturated for most of the year.

Table 2. Sedimentological analysis of the soil samples collected in area 2

Sample	Sand	Clay
	g kg^{-1}	
A1	607.6	392.4
A2	426.8	573.2
A3	346.9	653.1

Several studies have considered electrical conductivity to be one of the important parameters for quality evaluation of soils earmarked for agriculture and aquaculture operations (e.g., Saraswathy et al., 2016; Tapader et al., 2017; Shafi et al., 2021; Ali et al., 2023; Chandran et al., 2023). Pena and Oliva (2019) evaluated two other sites in northeastern Pará with similar topographic characteristics to those of the present study area (flat terrain near bodies of water). One area is the future site of an aquaculture research center in the municipality of Augusto Corrêa, while the other was an established fish farming operation in the municipality of Tracuateua. The authors used the GPR and EM34-3 tools to describe the subsoil of terrains destined for the implantation of aquaculture ponds. In both locations, the EM data recorded apparent conductivity values that indicated the presence of clayey subsoils (Davis and Annan, 1989).

For soils of fish farms located in Noakhali, Bangladesh, considering the age of the ponds, Tapader et al. (2017) recorded high electrical conductivity (334.8 mS m^{-1}) in the new ponds, excavated within the preceding five years, in comparison with the older ponds, more than five years old (130.6 mS m^{-1}). The authors concluded that this conductivity favored the installation of the aquaculture ponds. By contrast, Gul et al. (2015) recorded electrical conductivity of up to 290 mS m^{-1}, which was considered to be within the favorable range, although the mean value was 221 ± 143 mS m^{-1} for all the experimental ponds. In Bragança, northeastern Pará, Brazil, Chira et al. (2023) used GPR and sedimentological analyses to evaluate the subsoil of sites earmarked for installing fish farming ponds. Electromagnetic signal was attenuated in some parts of the radargrams, probably due to clay and moisture in the soil. Sedimentological analyses confirmed the predominance of sandy-clayey soils, with a mean clay content marginally above the 20 % threshold recommended for fish farming ponds.

Few rural landowners in Pará – in particular in the geographic region of Bragança (Brazil) – are aware of the technology available to survey the subsoil of terrains earmarked for aquaculture operations. This has compromised the success of aquaculture operations for a number of different reasons, ranging from inappropriate decision-making on the type of terrain and aquaculture system to the construction of inadequate installations. While reliable data on the structure of the subsoil are essential to the success of any aquaculture project, the high costs of obtaining such data, not only in terms of the financial costs of data acquisition, laboratory analyses, and the processing of the results, can be prohibitive (Pena and Oliva, 2019).

In our study, direct and indirect methods were applied to cross-reference the data collected, thereby increasing the reliability of the results. The indirect electromagnetic methods used here were Ground Penetrating Radar (GPR) and Electromagnetic Induction (EM34-3), which were combined with sedimentological analyses, a direct approach to the diagnosis of the characteristics of the subsoil of the two aquaculture sites indicated by the municipal government of Bragança, in Pará state, Brazil. These analyses results indicated that the analytical tools employed in the surveys produced satisfactory data to evaluate sites earmarked for aquaculture installations. The combination of these tools permitted the systematic description of the terrain and the establishment of a database that provides an essential reference for the reliable selection of terrains for aquaculture operations in the study region.

Geophysical survey methods applied satisfactorily in this study can also be applied in other areas, such as sustainable agriculture, archaeology, and hydrology. Geophysical methods together with remote sensing is also an important tool for precision agriculture (Pradipta et al., 2022 a,b). Near-surface geophysical tools have been applied extensively in soil management and assessment. This study highlighted the application value of geophysical tools, such as GPR, EMI, and Electrical Resistivity Imaging (ERI), for the development of sustainable agriculture.

CONCLUSIONS

Ground Penetrating Radar (GPR) provided information on subsoil structures in fish farms. This tool identified a high-amplitude horizontal reflector in both study areas, which may be associated with water table. In study area 1, the GPR allowed, besides identifying the possible water table at 7 m, we identifoed areas of signal attenuation, probably due to clay and moisture in the terrain. In study area 2, normal faults with small slips, horsts, grabens, and a depression with semi-grabens and an extensive tectonic regime were identified. These features appeared to be anchored in plastic clayey layers. Apparent conductivity values recorded in area 1 indicated presence of a clayey subsoil. In area 2, by contrast, apparent conductivity values indicated soils are predominantly clayey. Sedimentological analyses, local excavations, and data from wells in this area confirmed the subsoil lithology identified by the electrical conductivity meter.

Geophysical data integration, existing excavations examination, and sedimentological samples showed the terrain in study area 2 is suitable for the installation of new ponds. Moreover, we showed the effectiveness of geophysical methods employed in the surveys to diagnose subsoil of terrains earmarked for aquaculture operations. The combined application of the two geophysical tools (GPR + EM34-3) allowed the compilation of valid and complementary data on subsoil that provided a reliable database for the description of local subsoils of the study sites earmarked for the installation of fish farming ponds.

DATA AVAILABILITY STATEMENT

The data are available on request from the corresponding author.

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