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GROUNDWATER THROUGH GEOPHYSICS: REVIEW AND EXAMPLES

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ABSTRACT. Geophysics, when applied to the study of groundwater, is commonly used in searching for rocks, structures or geological environments that can allow the extraction of water. It can also be used to estimate physical aquifer characteristics (porosity and permeability); to indicate water potability parameters, such as the degree of salinity or the presence of contamination by polluting chemicals; and also to give information on the contaminant transport and ecosystem sustainability. These applications are discussed here, and examples of the use of geophysics in the main geological environments of occurrence of groundwater are also presented. The objective of this article is to review the available methods and demonstrate the importance of the application of Geophysics in the groundwater study.

Keywords: hydraulic conductivity; permeability; transmissivity; freshwater-saltwater interface.

INTRODUCTION

Water, indispensable for life, can be found in two natural sources: surface and underground. Surface water is found in rivers, lakes, streams, bays and oceans, while groundwater occurs in the geological layers below the Earth's surface. From the amount of fresh water that exists on the surface and in the subsurface to a depth of 1000 m, more than 95% is groundwater (Rebouças, 1980).

The safe use of surface water as a source of domestic supply of a city requires a lot of care that involves good planning and administration, as well the control of water quality. This demands a lot of resources and reflects in a high price to be paid by the consumer of water.

An alternative to the supply of water, more effective and less expensive, is to also use groundwater withdrawal of geological layers through wells.

There are at least seven major reasons for the use of groundwater (Rebouças, 1980):

- The water for the population and industries is presented free of pathogens, turbidity and color, eliminating the costly purification processes required by surface water.
- The water is more protected from contaminants or pollution.
- The water presents very large volumes as compared to the volumes stored in surface.
- The water is difficult to get radiochemical contamination and of great strategic importance in the issue of national security, considering the different possibilities of atomic catastrophes or act of terrorism.
- There is no great loss by evaporation, being little affected by drought problems.
- At the level of public supply, allows installment of investments to the extent that the demand evolves.
- It can constitute the main or supplementary source of domestic and industrial supplies.

In the study of groundwater, the rocky subsurface materials can be classified as: Aquifers, aquicludes, and aquifuges.

Aquifers are the subsurface materials provided with sufficient porosity and permeability to produce the necessary water supply. The permeability of the aquifer is typically higher than 10^{-2} darcy.

The materials which do not transmit water at velocities sufficient to provide appropriate supply quantities are called aquicludes. Such materials have low permeability (less than 10^{-2} darcy).

Materials that are not able to provide or absorb water, by not having interconnected voids, are classified as aquifuges. These materials have very low permeability or no permeability (less than 10^{-4} darcy), although they may contain a large number of pores.

Basic concepts on groundwater can be found in De Viest (1969); Custodio and Llamas (1976); Freeze and Cherry (1979); Singhal and Gupta (1999); Alfaro et al. (2006); Feitosa et al. (2008); Manzione (2015); Woessner and Poeter (2020); Clutter et al (2022); and Fetter and Kreamer (2022).

GROUNDWATER ENVIRONMENTS

Groundwater occurs in two main types of geological environments: in the sedimentary basins which house large thicknesses of sediments and sedimentary rocks, and in the basement areas where igneous and metamorphic rocks outcrop or are covered by a small thickness of sediments (Figure 1).

In sedimentary basins, groundwater can be found in aquifers consisting of unconsolidated sediments (sands, gravels) or sedimentary rocks (sandstones, limestones, dolomites), occurring in the form of extensive layers or lenses, or even in the form of paleochannels.

In the basement areas, the major amount of water is normally found in fractures that cut intrusive rocks, basaltic flows or metamorphic rocks. Water can also be extracted from zones of alteration of these rocks or from paleovalleys embedded in them.

In the sedimentary environment, groundwater is stored in the pores of rocks. Therefore, higher porosity rocks and sediments are those with the greatest potential for the extraction of water for supply. However, the existence of high porosity does not necessarily imply that the rock can be exploited as an aquifer. It is necessary, in addition to the large amount of water, that it can easily be removed from the rock.

The ability of a rock or sediment to easily yield the water easily is measured by its hydraulic conductivity or its permeability. Thus, there are rocks and sediments that have high porosity (contain large amount of water) and high permeability (easily yield the water) as unconsolidated sands and sandstones; but there are also rocks and sediments that have high porosity and low permeability (yield the water with difficulty) as clays and shales. Table 1 shows porosity values for various types of rocks and sediments.

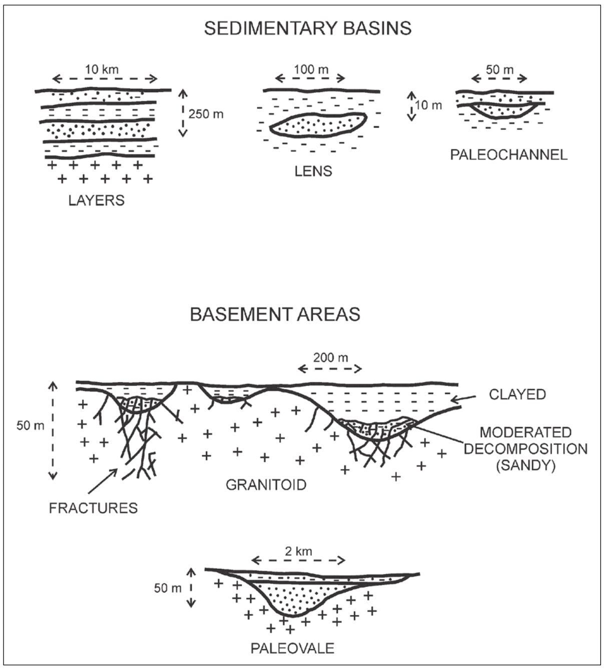

Figure 1: Geological environments of groundwater occurrence.

The hydraulic conductivity and the permeability are defined respectively by:

$$K = \kappa \frac{dg}{\nu} \qquad \kappa = C d^2, \tag{1}$$

where K is the hydraulic conductivity, κ the permeability; d the fluid density; g the gravity; and ν the fluid viscosity.

The permeability described by the expression on the right is a function of the medium, where is a constant which depends on the roundness and arrangement of the grains and the rock compaction, and the average grain diameter in the rock. The speed with which a fluid runs through a medium depends on the hydraulic conductivity and the hydraulic gradient, being expressed by the negative of the product of these two quantities. Table 2 shows values of permeability and hydraulic conductivity for some types of rocks and sediments.

Rocks with permeability values below 10^{-4} darcy are considered impermeable. Permeability values are considered low between 10^{-4} and 1 darcy; medium, between 1 and 102 darcy; high, between 102 and 104 darcy; and very high, above 104 darcy (Benedini, 1976).

Hydraulic transmissivity (m^2/s) is the amount of water that can be transmitted horizontally across the thickness of the aquifer. Its value is calculated by the expression

$$T = Kh, \tag{2}$$

where K is the hydraulic conductivity and h the thickness of the aquifer.

Table 1: Porosity of sediments and rocks (Freeze and Cherry, 1979).

Material	Porosity (%)	Material	Porosity (%)
Gravel	25 - 40	Sandstone	5 - 30
Sand	25 - 50	Limestone	0 - 20
Silt	35 - 50	Dolomite	0 - 20
Clay	40 - 70	Shale	0 - 10
Fractured basalt	5 - 50	Fractured crystalline rock	0 - 10
Karst limestone	5 - 50	Dense crystalline rock	0 - 5

Table 2: Hydraulic conductivity (K) and permeability (κ) of rocks and sediments (Freeze and Cherry, 1979).

Material	K (m/s)	κ (darcy)	Material	K (m/s)	κ (darcy)
Permeable basalt	$10^{-7} – 10^{-2}$	$10^{-2} - 10^{3}$	Shale	$10^{-13} - 10^{-9}$	$10^{-8} - 10^{-4}$
Fractured igneous and metamorphic rocks	$10^{-8} - 10^{-4}$	$10^{-3} - 10$	Marine Clay	$10^{-12} - 10^{-9}$	$10^{-7} - 10^{-4}$
Limestone and dolomite	$10^{-9} - 10^{-6}$	$10^{-4} - 10^{-1}$	Silt	$10^{-9} - 10^{-5}$	$10^{-4} - 1$
Sandstone	$10^{-10} - 10^{-6}$	$10^{-5} - 10^{-1}$	Sand	$10^{-6} – 10^{-2}$	$10^{-1} - 10^{3}$
Unfractured metamorphic and igneous rocks	$10^{-14} - 10^{-10}$	$10^{-9} - 10^{-5}$	Gravel	$10^{-3} - 1$	$10^{2} - 10^{5}$

GEOPHYSICAL RESPONSE

The success of Applied Geophysics as detection tool depends on several factors, among which stands out the contrast between the physical properties of the object being investigated and the environment that surrounds it. Thus, an object with density greater than 5 g/cm^3, for example, may have a good chance of being detected within the geological environment where the rocks have density values rarely exceeding 3 g/cm^3. Although the contrast of physical property is very important, another factor that should be highlighted is the concentration of the object within the volume of material sampled during the geophysical measurements. For this reason, despite gold having very high density and electrical conductivity compared to the host rock, geophysical measurements do not allow directly detecting this mineral because its concentration in rocks is generally less than 50 ppm. The concentration thus controls the contrast in physical properties in the sampled volume. The lower the concentration, the lower the contrast, independent of the absolute value of the physical property of the object of research and the lower the contrast, the more difficult becomes the direct detection through geophysical measurements. For a contrast to be perceived by Geophysics, the concentration should not be less than 1% (10,000 ppm).

The presence of water in the pores of the rock causes changes in some of its physical properties, like, for example, the electrical conductivity and the density. The presence of water also affects the speed at which seismic waves and electromagnetic waves propagate in the rocks. Still, the groundwater prospecting is an indirect application, that is, it is not the physical properties of water that are directly researched and that respond to the geophysical methods. Table 3 shows physical property values and the propagation velocity of seismic waves for various types of rocks and sediments.

The theory of geophysical methods employed in the exploration of groundwater is described by Astier

(1975); Orellana (1982); Telford et al. (1990); Luiz and Silva (1995); Kearey et al. (2009); and Reynolds (2011).

Groundwater prospecting with geophysical methods allows seeking rocks, structures or geologic environments that may allow water extraction. Geophysical methods can also be used to:

a) Estimate the physical characteristics of aquifers, as porosity, permeability, and transmissivity (Benedini, 1976; Griffiths, 1976; Kelly, 1977; Kosinski and Kelly, 1981; Niwas and Singhal, 1981; Ponzini et al., 1984; Marinho and Lima, 1997; Yadav and Abolfazli, 1998; Hagrey and Müller, 2000; Lima and Niwas, 2000; Niwas and Lima, 2003; Lu and Sato, 2007; Soupios et al., 2007; Nascimento and Lima, 2013; Neves and Luiz, 2015; Díaz-Curiel et al., 2016; Omeje et al., 2022).

b) Specify some of the parameters for water quality as, for example, the degree of salinity (Hagrey and Müller, 2000; Benkabbour et al., 2004, Dhakate et al., 2015; Hasan et al., 2019; Shah et al., 2022) or contamination by chemical and organic pollutants (Buselli et al., 1990; Costa and Ferlin, 1992; Costa et al., 1995; Benson et al., 1997; Sauck et al., 1998; Aquino and Botelho, 2001; Nunes and Luiz, 2006; Laureano and Shiraiwa, 2008; Baessa et al., 2010; Bahia et al., 2011; Cunha and Shiraiwa, 2011; Naik, 2017; Marques et al., 2018; Guireli Netto et al., 2020).

Geophysical methods can also provide information about the direction of groundwater flow (Schiavone and Quarto, 1984; Carvalho Junior, 1997; Braz et al., 2000; Neves, 2002; Neves and Luiz, 2003; Bai et al., 2021; Kukemilks and Wagner, 2021) and the volume of water present in aquifers (West and Sumner, 1972; Van Overmeeren et al., 1997; Legchenko et al., 2018; Lähivaara et al., 2019).

While electrical (resistivity tomography - ERT and soundings - VES) and electromagnetic methods (time domain – TDEM and frequency domain - FDEM) are the most widely used in studies of groundwater, seismic methods and gravimetry can also provide good results, as shown in Eaton and Watkins (1970); Hobson (1970); West and Sumner (1972); Zehner (1973); Van Overmeeren (1975); Van Nostrand (1976); Carmichael and Henry, Jr. (1977); Stewart (1980); Ali and Whiteley (1981); Van Overmeeren (1981); Kobayashi (1982); Allis and Hunt (1986); Haeni (1986); Steeples and Miller (1990); Holman et al. (1999); Murty and Raghavan (2002); Mota and Monteiro dos Santos (2006); Adeoti et al. (2012); Azaiez et al. (2021).

The main applications of geophysics in the groundwater exploration and the recommended methods in these applications are:

- Determining the limits and thickness of a sedimentary basin - resistivity, seismic (refraction and reflection), gravimetric, and magnetic methods.
- Determination of the lateral extent and thickness of layers - resistivity and seismic (refraction and reflection) methods.
- Location of palaeochannels and paleovalleys - resistivity, induced polarization, ground penetrating radar (GPR), seismic (refraction and reflection), and gravimetric methods.
- Location of fractures - inductive electromagnetic methods (EM).
- Determination of the top of the water table - resistivity, GPR, and seismic refraction methods.
- Determination of the contact between freshwater and saltwater - resistivity, inductive electromagnetic, and GPR methods.
- Study of the movement (flow direction) of water - spontaneous potential method.
- Study of the variation in permeability - induced polarization (IP) method.
- Estimates of porosity - resistivity, seismic refraction, and radiometric methods (in measurements inside wells and at the surface of the ground for the first two methods and inside wells in the case of radiometric).
- Estimates of permeability - resistivity method (in measurements inside wells and at the surface of the ground).
- Estimates of the content of dissolved solids (salts) - resistivity method (in measurements inside wells).

Despite Geophysics providing a lot of information on groundwater prospecting, worldwide, 96% of spending on geophysical exploration between 1976 and 1990 were made in the demand for oil, while from the remaining 4%, 49% was devoted to mineral prospecting, 4% for groundwater prospecting, 18% to civil engineering, and 1% to environmental protection (Luiz and Silva, 1995). The remaining 28% was spent on research (15%), Oceanography (9%) and geothermal prospecting (4%) (Luiz and Silva, 1995). Currently, it seems that these percentages were little changed.

Next, it is presented examples of applications of Geophysics in the groundwater prospection.

POROSITY, TRANSMISSIVITY AND HYDRAULIC CONDUCTIVITY ESTIMATES

The porosity of the rocks can be estimated from electrical resistivity values through the empirical relationship called Archie-Winsauer Formula. In the case of saturated, non-argillaceous formations, this formula is

$$\rho_r = \rho_a a \emptyset^{-m} \tag{3}$$

where r is the resistivity of the rock saturated with water; a the resistivity of the water; $\emptyset$ the rock porosity; and a, m are empirical parameters respectively related to the texture of the rock and the cementing. The parameter a ranges from 0.6 (sedimentary rocks) to 3.5 (tuffs and volcanic lavas); while the parameter m ranges from 1.3, for weakly consolidated sediments, to 2.3, for rocks with well cemented grains (Keller, 1970).

Some typical values of a and m are (Keller, 1970): a = 0.88 and m = 1.37 for detrital rocks weakly cemented with porosity ranging from 25 % to 45 % and tertiary age (sands, sandstones, and some limestones); a = 0.62 and m = 1.72 for moderately cemented sedimentary rocks, with porosity ranging from 8 % to 35 % and generally mesozoic age (sandstones and limestones); a = 0.62 and m = 1.95

for well cemented sedimentary rocks with a porosity between 5 % and 25 % and age usually paleozoic; a = 3.5 and m = 1.44 for highly porous volcanic rocks (20 % to 80 %); a = 1.4 and m = 1.58 for rocks with less than 4 % porosity (igneous rocks and metamorphosed sedimentary rocks).

As a first approximation, using a = 1 and m = 2, it is produced small errors in the estimates when porosity is between 10 % and 30 % (Keller and Frischknecht, 1966).

Porosity can also be estimated from the velocity of the waves obtained in seismic refraction surveys. In consolidated, saturated, non-argillaceous formations, it is useful the formula given by Wyllie (Astier, 1975):

$$\frac{1}{V} = \frac{\emptyset}{V_a} + \frac{(1-\emptyset)}{V_m} \tag{4}$$

where V is the velocity in the medium; $\emptyset$ the porosity; V_a the velocity in water (1450 m/s); and V_m the speed in the rock matrix. According Astier (1975), satisfactory results are generally achieved using the following values for V_m: 6000 m/s in sandstones, 6400 m/s in limestones and 7000 m/s in dolomites. On the other hand, in consolidated, saturated, argillaceous formations, the expression becomes (Astier, 1975):

$$\frac{1}{V} = \frac{P_{arg}}{V_{arg}} + \frac{\emptyset}{V_a} + \frac{1 - P_{arg} - \emptyset}{V_m} \tag{5}$$

where Parg is the percentage of clay in the rock and Varg the velocity in the clay(about 2000 m/s).

To estimate the hydraulic transmissivity, it is necessary to combine the expression (2), which defines the transmissivity, with the defining expression of the transverse electrical resistance (R) of a layer given by (Orellana, 1982):

$$R = \rho h, \tag{6}$$

where ρ is the electrical resistivity of the layer and h its thickness. From this combination, it results

$$T = K\frac{R}{\rho} \tag{7}$$

If in a given area K/ρ in an aquifer remains constant, representing the logarithm of the transmissivity (obtained in wells in the area) versus the logarithm of the transverse resistance calculated from vertical electrical soundings (made close to the wells where the transmissivity values were obtained) establishes a linear relationship between transmissivity and transverse resistance. Thus, when performing electrical soundings elsewhere in the area, it is possible to estimate the transmissivity and hydraulic conductivity at these points, without the need to drill a well. Moreover, it is possible to identify the areas of greatest transmissivity of the aquifer to indicate locations of drilling.

MAPPING OF AQUIFER LAYERS IN A SEDIMENTARY BASIN

Figure 2 shows a geoelectric section constructed from the lateral correlation of models arising from the interpretation of Vertical Electrical Soundings (VES) conducted with the resistivity method. The geophysical survey was conducted in the town of Bom Jesus do Tocantins, southern of the state of Pará, Brazil. On the section, there is an indication of two possible aquifer layers: a shallower (layer 4) one, starting at a depth of 20 m, and a deeper (layer 6), with the top deeper than 100 m. The indication of the aquifer layers was based on the correlation of the section with additional information obtained in a near shallow well and field observations.

Another example of the mapping of potential aquifer layers in a sedimentary basin is shown in Figure 3. The figure presents the results of gravimetric and seismic refraction data obtained on the same profile. The survey was conducted at the Indian Wells

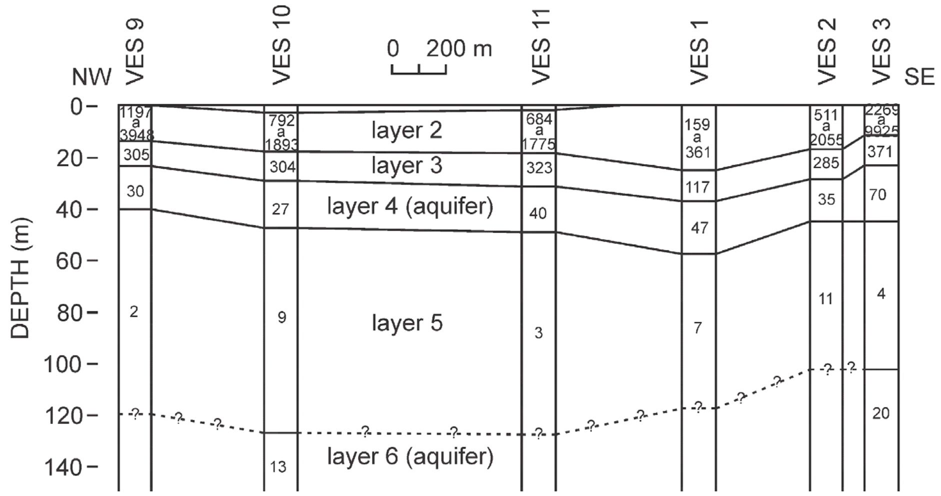

Figure 2: Geoelectric section constructed from models resulting from the interpretation of VES conducted in Bom Jesus do Tocantins, southern Pará, Brazil. The layers 4 and 6 were indicated as aquifers. The values in the columns represent the resistivity in ohm.m (adapted from Alves and Luiz, 2001).

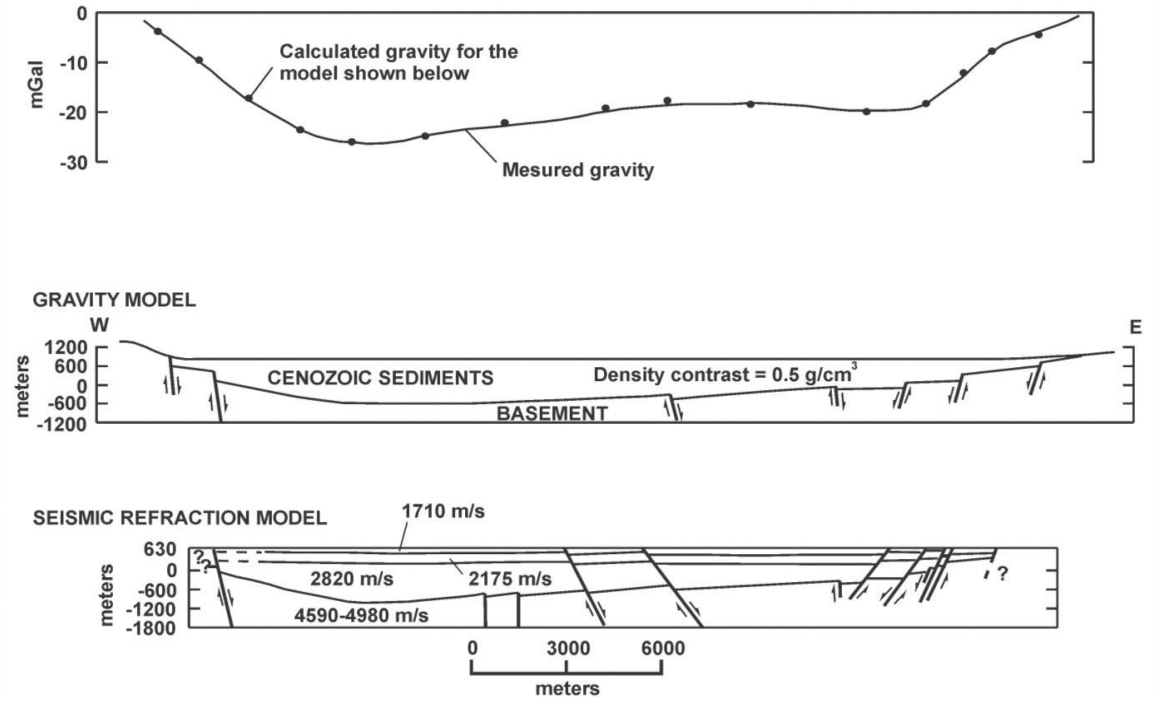

Figure 3: Interpretative models from gravimetric and seismic refraction measurements obtained on profile conducted in Indian Wells Valley, California, USA (Eaton and Watkins, 1970).

Valley, California, USA. The upper part of the figure shows the measured values of the gravity field (solid line) and the gravity values calculated (points) for the subsurface model shown in the middle part of the figure. At the bottom of the figure, it appears the subsurface model obtained from the seismic refraction data. It is observed in the seismic model that the sedimentary layers and the basement are characterized by the velocity of propagation values interpreted for the seismic wave. We note, comparing the two models, that they are very similar, although the model obtained from gravimetry is less detailed than the seismic model, because it can only discriminate the basement and a package of sediments resting on it, without distinguishing the different sediment layers.

More examples of the application of geophysical mapping of aquifer layers can be found in Lima (1990); Souza and Luiz (1994); Harari (1996); Barbosa Junior and Alves (2013); Mendes et al. (2014); Nazifi and Lambon (2021); and Fadakinte (2022).

LOCATION OF FRACTURES IN BASEMENT

In regions where there is little thickness of sedimentary material, the amount of groundwater which can be removed from the subsoil is usually very low. Appreciable quantities of groundwater may, however, be drawn from fractures of basement rocks that lie just below the sedimentary material.

These fractures have been successfully located by applying the inductive electromagnetic methods. Figure 4 illustrates this kind of application. The survey was conducted along streets in the town of Canaã dos Carajás, south of the state of Pará, Brazil, with measurements taken at intervals of 50 m. It is shown in the figure measurements of the in-phase and quadrature components made with the Slingram horizontal loop (HLEM) system Max-Min for three frequencies (110 Hz, 880 Hz and 3250 Hz). The position of the fractures is indicated by arrows in the figure.

Other examples of application of geophysics in the basement environment are described by Lima and Medeiros (1988); Medeiros and Lima (1990, 1991); Cavalcante et al. (2001); Souza Filho et al. (2006); Lima (2010); Oliveira (2011); Sousa and Luiz (2012); Nascimento et al. (2013); Chandra et al. (2019); and Deep et al. (2021).

FRESHWATER-SALTWATER INTERFACE IN COASTAL AQUIFERS

On the seacoast area, saltwater infiltrates into the continent, positioned beneath the fresh groundwater. The knowledge of the depth of the interface that separates these two waters is important to indicate the maximum depth that a catchment well should reach to not attain the salt water. This is a problem that has been satisfactorily solved with the aid of electrical resistivity and inductive electromagnetic methods, and the GPR. In Figure 5, it is shown the application of the electrical resistivity method by VES to delineate the surface that separates saltwater from freshwater in Ilha Comprida, municipality of Iguape, state of São Paulo, Brazil. On the left the figure shows the results obtained in 3 VES and on the right the location of the VES and the interpreted saltwater-freshwater contact.

Figure 6 shows a resistivity section where it was possible to identify the freshwater-saltwater interface. The interface was estimated using the Archie-Winsauer Formula. The section was obtained in a resistivity profile held in the Village of Algodoal, northeastern Pará, Brazil.

Other works involving the mapping of the freshwater-saltwater interface are presented by Arora and Bose (1981); Lima and Macedo (1983); Cavalcanti Neto (1986); Goldman et al. (1991); Silva (1991); Aquino et al. (1998a, b); Pereira et al. (2003); Land et al. (2004); De Mio et al. (2005); Dias et al. (2007); Hasan et al. (2017); Correia et al. (2019); and Hasan et al. (2019).

SEPARATION OF FRESHWATER AQUIFER FROM SALINE AQUIFER

The resistivity values obtained on aquifers with brackish water and on clayed aquifers with freshwater are very similar. Both the brackish water and the presence of clay cause the resistivity decreases. To separate these effects, Roy and Elliott (1980) used the method of induced polarization, which normally produces high values in the presence of clay and low in the presence of brackish water. Figure 7 illustrates this application of the method of induced polarization. In the figure, a comparison is made between the measurements obtained in the VES with the methods of resistivity and induced polarization. In Figure 7 (a), it is shown VES performed on an aquifer with brackish water: the resistivity is less than the threshold 100 Ω.m and the induced polarization less than the limit of 3 ms. In Figure 7 (b), the VES were performed on a clay aquifer with freshwater: the resistivity is close to the limit of 100 Ω.m and the induced polarization above the threshold value of 3 ms.

IDENTIFICATION OF SANDY ZONES IN A WELL

During the drilling of a well for groundwater extraction, samples of the material being cut are collected. The purpose of this sampling is to identify the most promising zones for the exploitation of water (usually the sandy zones in a sedimentary basin). Often, the limits of the sandy zones are difficult to be determined based only on the sampled material; furthermore, the clay intercalations in the sandy zones can also be difficult to recognize. These problems can be easily solved by logging the well with geophysical measurements. The demarcation of the boundaries of the sandy zones supplied by the geophysical logging helps in the accurate placement of filters for water catchment.

Basics of well profiling (or well logging) applied to groundwater can be found in Keys (1970, 1989) and Nery (2008, 2013).

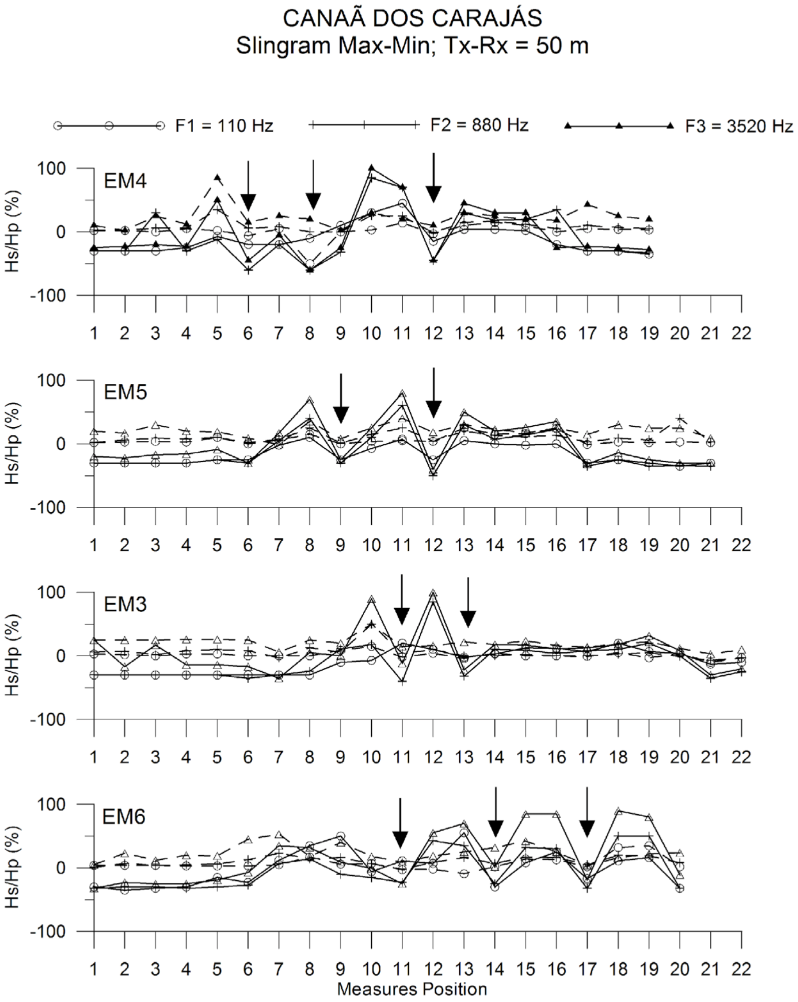

Figure 4: Mapping of fractures with the electromagnetic Slingram HLEM system in Canaã dos Carajás, south of the state of Pará. The position of the fractures are marked by arrows. The solid lines represent the in-phase component, while the dashed lines represent the quadrature component (adapted from Alves and Luiz, 2001).

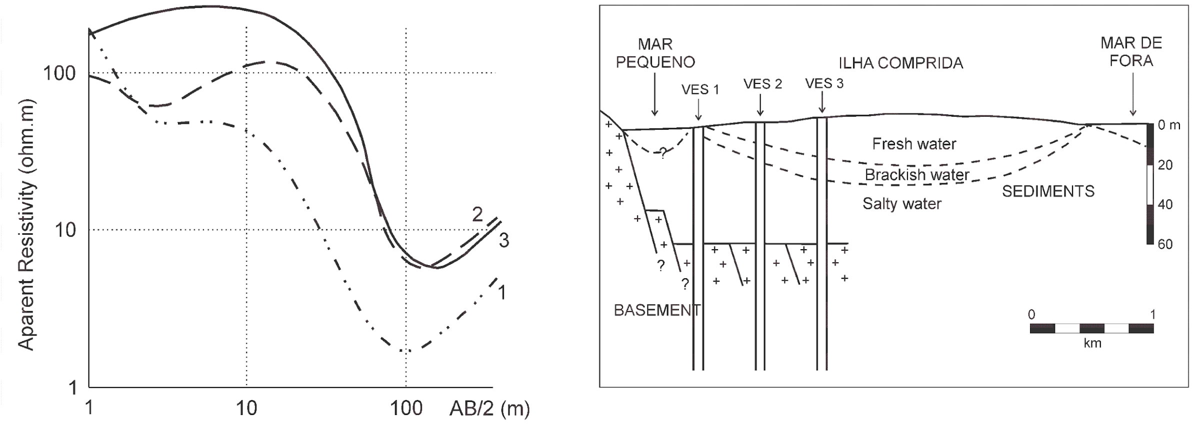

Figure 5: Determination of the freshwater-saltwater interface in Ilha Comprida, municipality of Iguape, São Paulo, Brazil (adapted from Davino et al., 1980).

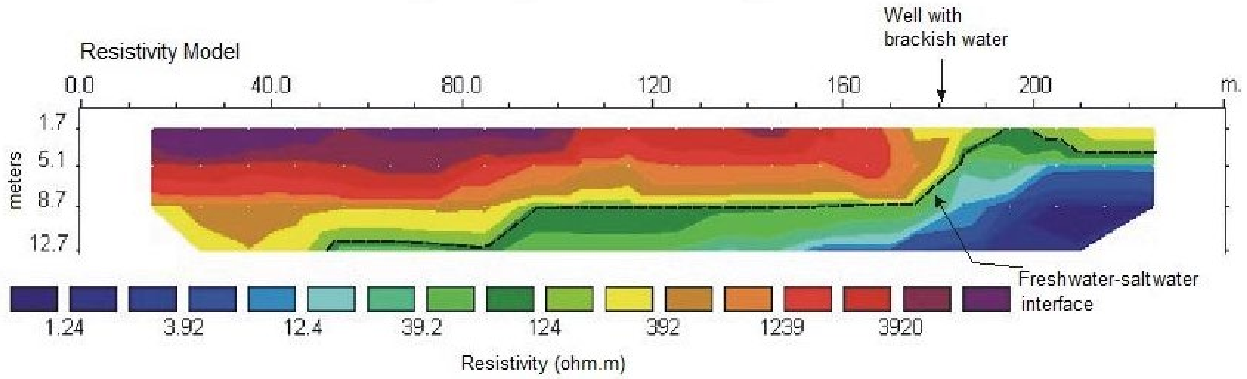

Figure 6: Resistivity section conducted in Algodoal, northeastern Pará, Brazil. The interface separating freshwater from saltwater is represented by the dashed line (adapted from Luiz et al., 2001).

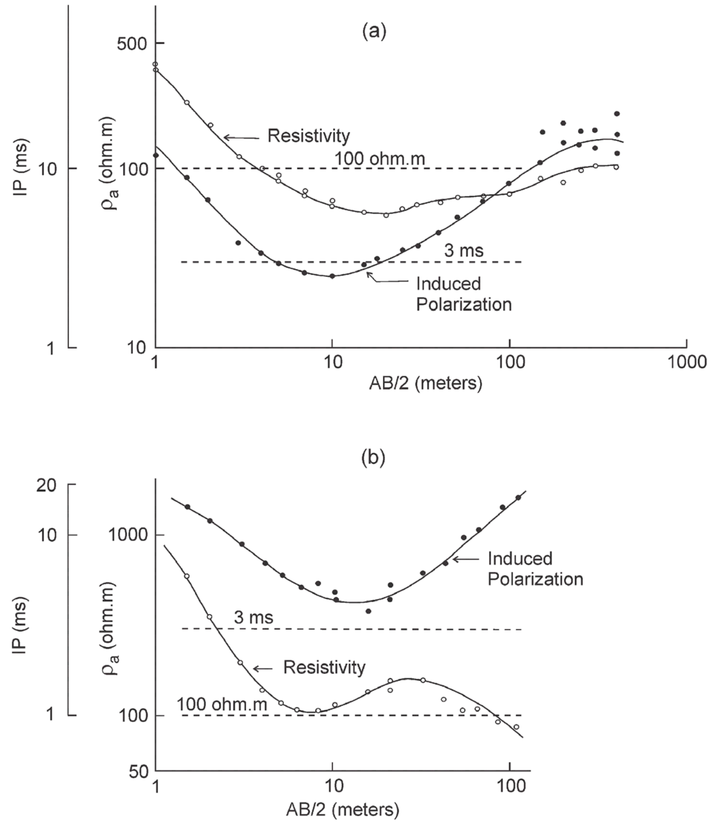

Figure 7: Comparison between VES measurements obtained with the methods of resistivity and induced polarization to separate aquifers with brackish water from clay aquifers with freshwater (Roy and Elliott, 1980).

In Figure 8, it is represented part of the data collected during the geophysical profiling of a well drilled in the metropolitan region of Belém, state of Pará, Brazil. In the well, it was "run" electrical resistance (ER), spontaneous potential (SP), and Gamma Ray profiles. The correlation between the three profiles allowed the identification of three sandy zones, which are potential aquifers for water extraction. These zones are highlighted by the symbols I, II and III. The position of the zones was identified by associating low values of the gamma ray counts (cps - counts per second) with high values of electrical resistance and low values of spontaneous potential. This association characterizes the presence of sandy zones, as opposed to the high values of gamma rays, low values of electrical resistance and high values of spontaneous potential that are produced by clay zones.

The characterization of sandy zones in wells and the lateral correlation for defining aquifer layers is presented by Lima and Ribeiro (1982); Keys (1989); Souza and Luiz (1994); and Freimann et al. (2014).

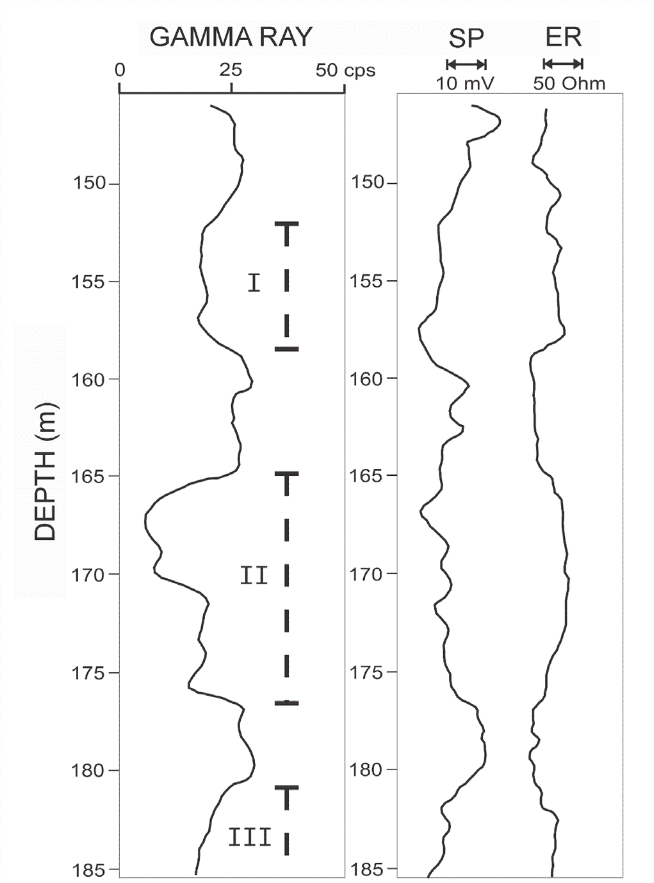

Figure 8: Logging of well drilled for groundwater extraction in a sedimentary basin environment. SP = spontaneous potential, ER = electrical resistance. The sandy areas are highlighted by the dashed lines with the symbols I, II and III.

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