ACTA
AMAZONICA

http://dx.doi.org/10.1590/1809-4392202400942

GEOSCIENCES | ORIGINAL ARTICLE

Lithological characterization of the Alter do Chão Aquifer using geophysical well logging in Manaus, Amazonas, Brazil

Bruno Silva de SOUZA[1], Raphael Di Carlo Silva dos SANTOS[1]*, Cintia Rocha da TRINDADE[2], Renata de Sena SANTOS[2], Ila Morais de BRITO ROCHA[3], Diogo Pena REZENDE[4]

[1] Universidade Federal do Amazonas, Av. Rodrigo Octavio 1200, Coroado I, 69067-005 Manaus, AM, Brazil

[2] Universidade Federal do Oeste do Pará, Rua Vera Paz, s/n (Unidade Tapajós), Salé, 68040-255 Santarém, PA, Brazil

[3] Secretaria de Estado de Educação do Amazonas, R. Waldomiro Lustoza 250, Japiim II, 69076-830 Manaus, AM, Brazil

[4] Transpetro S.A., Rua Henrique Valadares 28, 17º andar, Centro, 20031-030 Rio de Janeiro, RJ, Brazil

* Corresponding author: raphaelsantos@ufam.edu.br

ABSTRACT

Groundwater is a resource of high economic, strategic, and social value, and its sustainable management relies on accurate subsurface characterization. The Alter do Chão Aquifer, the primary groundwater source in Manaus, Amazonas, Brazil, represents the saturated portion of the Alter do Chão Formation and serves as the main reservoir of the Amazon Basin and one of the most significant aquifers in the country. Despite its importance, geological characterization of the aquifer is often constrained to data from isolated well points, limiting the spatial resolution and continuity of subsurface models. This study focuses on lithological characterization derived exclusively from well log data. Geophysical logging from 15 wells – utilizing gamma ray, spontaneous potential, and electrical resistivity profiles – was interpreted to differentiate between sandstone and claystone lithologies, supplemented by drilling mud samples. The interpreted data were used to generate a 3D block model in Datamine Studio RM, representing 26.96 km³ of rocks (77.6% sandstones and 22.4% claystones) through 126,720 parent cells, each measuring 250 x 250 x 5 m. The block model delineates lithological zones (upper, middle, and lower) extrapolating well locations. The model shows general agreement with existing 2D geological mapping and stratigraphic correlations, underscoring the need for integrating geophysical datasets to enhance subsurface characterization of the Alter do Chão Aquifer.

KEYWORDS: spontaneous potential, resistivity, gamma ray, block model, modeling

Caracterização litológica do aquífero Alter do Chão utilizando perfilagem geofísica de poços em Manaus, Amazonas, Brasil

RESUMO

A água subterrânea é um recurso de alto valor econômico, estratégico e social, e sua gestão sustentável depende de uma caracterização precisa do subsolo. O Aquífero Alter do Chão, principal fonte de água subterrânea em Manaus, Amazonas, Brasil, representa a porção saturada da Formação Alter do Chão e é o principal reservatório da Bacia Amazônica, sendo um dos aquíferos mais significativos do país. Apesar de sua importância, a caracterização geológica do aquífero frequentemente se limita a dados de pontos de poços isolados, restringindo a resolução espacial e a continuidade dos modelos de subsuperfície. Este estudo foca na caracterização litológica derivada exclusivamente de perfis de poços. Perfis geofísicos de 15 poços – utilizando raios gama, potencial espontâneo e resistividade – foram interpretados para diferenciar litologias de arenito e argilito, com suporte de amostras de lama de perfuração. Os dados interpretados foram usados para gerar um modelo de bloco 3D no software Datamine Studio RM, representando 26,96 km³ de rochas (77,6% arenitos e 22,4% argilitos) por meio de 126.720 células parentais, cada uma com dimensões de 250 x 250 x 5 m. O modelo de blocos delimitou zonas litológicas (superior, intermediária e inferior) extrapolando as coordenadas dos poços. O modelo converge com mapeamentos geológicos 2D existentes e correlações estratigráficas, destacando a necessidade de integração de conjuntos de dados geofísicos para aprimorar a caracterização da subsuperfície do Aquífero Alter do Chão.

PALAVRAS-CHAVE: potencial espontâneo, resistividade, raios gama, modelo de blocos, modelagem

CITE AS: Souza, B.S.; Santos, R.D.C.S.; Trindade, C.R.; Santos, R.S.; Brito Rocha, I.M.; Rezende, D.P. 2025. Lithological characterization of the Alter do Chão Aquifer using geophysical well logging in Manaus, Amazonas, Brazil. *Acta Amazonica* 55: e55gs24094.

INTRODUCTION

Aquifers are defined as saturated permeable geological units that can transmit significant amounts of water under common hydraulic gradients and are often called by their stratigraphic names (USGS 1986). They are of particular importance because they store water, generally with high standards of potability, traditionally considered as a natural resource of high economic, strategic, and social value (Freeze and Cherry 1979; Duarte 2006; Gleeson *et al.* 2012; Taylor *et al.* 2013; MacDonald *et al* 2014; Agostinho *et al.* 2020). In Manaus city, Amazonas state, Brazil, there is a large availability of subsurface water, and its exploitation has been intense for practical and economic advantages regarding its capture (Sophocleous 2002; Bakker 2003; Foster and Chilton 2003; Silva and Silva 2007; Famiglietti *et al.* 2011; Gleeson *et al.* 2012; Scanlon *et al.* 2016; Barbosa *et al.* 2020).

The Alter do Chão Aquifer is the source of groundwater in Manaus and is the main reservoir of the Amazon Basin and one of the most important aquifers in Brazil, classified as very productive, porous, unconfined to semi-confined (Carvalho and Montenegro 2017). It is approximately 290 m thick, with a zone of the first 50 m composed of clayey lithotypes, superimposed on a zone between 50 m and 290 m composed of sandy and sandy-clayey lithotypes, with good potential for groundwater transmission (Souza and Verma 2006). It belongs to the Amazon intracratonic Basin, which is located between the Guiana Shield to the north, and Central Brazil Shield to the south, with an area of approximately 500,000 km² (Silva *et al.* 2003), containing predominantly siliciclastic rocks, essentially Paleozoic, intruded in the Mesozoic by diabase dikes and sills reaching a maximum thickness of 5000 m (Caputo 1984). The aquifer is hosted by the Alter do Chão Formation, considered one of the last Phanerozoic depositional sequences of the basin, of Upper Cretaceous-Paleogene age, initially defined as being composed of reddish sandstones, mudstones, conglomerates and intradeformational breccias, traditionally attributed to fluvial and lacustrine/deltaic systems (Daemon 1975; Mendes *et al.* 2012). The unit is approximately 200 m thick and is mostly sandy-clayey and sandy, locally clayey and clayey-sandy (Soares *et al.* 2016). In addition, reddish silicified horizons called "Manaus Sandstone" are also found, defined as silcretes (Albuquerque 1922) – paleosols, saprolites or silicified sediments (Dixon 2013). Between the cities of Manaus, Presidente Figueiredo and Itacoatiara, in the state of Amazonas, the formation may be in discordant contact at the top with Miocene-Pliocene rocks (Guimarães *et al.* 2014) of the so-called Novo Remanso Formation by erosion surfaces and/or by ferruginous and immature lateritic crusts, and at the base significant discordant contacts with Paleozoic units can be found (Soares *et al.* 2016).

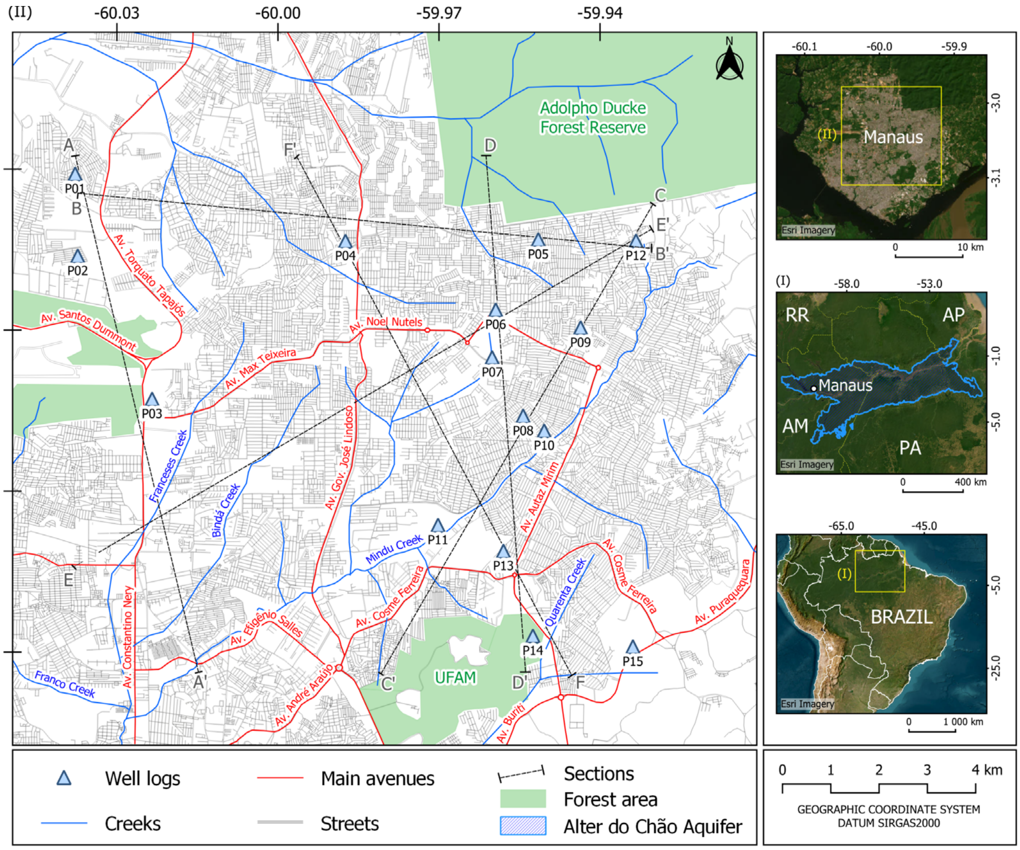
Geological and hydrogeological information is extremely relevant for the study of aquifers, but they represent generalizations and do not have clear spatial connotation, especially when treated in three dimensions (Luiz 2022). For this kind of representation and understanding to be possible, subsurface data with good accuracy and feasibility are required. The most common direct method for shallow subsurface investigations is rotary drilling, which consists of using a motorized set, with perforating action given from combined penetration and rotation forces, which act with cutting power on the rock, allowing the collection of continuous and cylindrical samples. However, this type of method requires high financial investment, making it difficult to use on large scale investigations.

In this context, geophysical surveys represent a more viable alternative, as they usually have lower operating costs for data acquisition and interpretation of subsurface (Liu 2017). These types of surveys are often used in aquifer assessment and mapping, although its main products are 2D stratigraphic columns and profiles (Lai *et al.* 2024). It is also possible to use these data to generate 3D products using geological modeling tools, which consist of a computerized representation of lithologies, structures, rock chemistry and/or physical properties on or below the surface of the planet (Fallara *et al.* 2006; Mallet 2008). Geological modeling is performed through point sampling based on geological and geostatistical knowledge to define continuities, aiming to minimize assumptions and associated errors (Haldar 2018; Justino 2018). From the database input and processing, it is possible to insert georeferenced boreholes in a 3D environment, which allows the generation of block models, data estimation (with geometric and geostatistical methods), classification and cubing (Madsen *et al.* 2022).

This study aimed to generate a 3D lithological characterization of the Alter do Chão Aquifer in the city of Manaus, using geophysical logs from 15 wells as the primary data source. The objective was to enhance the understanding of the aquifer's three-dimensional structure through the application of mining-oriented tools.

MATERIAL AND METHODS

The study area is located in the urban region of Manaus, capital of the state of Amazonas, Brazil, on the western edge of the Alter do Chão Aquifer, encompassing approximately 115 km² and inserted in the context of the Amazon intracratonic sedimentary basin (Figure 1). The 15 wells (Table 1) were selected from Souza (2005), who used the database of the Geophysics Department of Federal University of Pará. The wells hold depths between 145 m and 220 m, and they were logged in JPG image format, requiring georeferencing and digitalization to vectorize the profile curves and extract the numerical values, with the objective of later use in the database.



Fonts: Brazilian Institute of Geography and Statistics (IBGE); National Water and Sanitation Agency (ANA).

Figure 1. Map of the study area in Brazil showing the location of the Alter do Chão Aquifer in Brazil, of the city of Manaus within the aquifer area, and of the study area within the urban extension of Manaus. The main map shows the location of the 15 well log coordinates (blue triangles) used to generate the 2D sections (A-A', B-B', C-C', D-D', E-E', F-F') of the aquifer block model in the city. All coordinates are in geographic format (SIRGAS2000 datum). The abbreviations RR, AM, AP, and PA refer to the states of Roraima, Amazonas, Amapá, and Pará, respectively.

Table 1. Coordinates, maximum depth and type of data available from each of the well logs used for lithological characterization of the Alter do Chão Aquifer in the city of Manaus, Amazonas, Brazil. Datum: SIRGAS 2000. **SP** = spontaneous potential; **GR** = gamma rays; **ER** = electrical resistivity.

Well	Longitude	Latitude	Depth (m)	Data
P01	60°02′15″.994W	3°00′03″.314S	210	SP; GR
P02	60°02′14″.274W	3°00′58″.352S	220	SP; GR; ER
P03	60°01′24″.396W	3°02′34″.323S	190	SP; GR; ER
P04	59°59′14″.714W	3°00′48″.376S	190	GR; ER
P05	59°57′05″.375W	3°00′47″.344S	180	SP; GR; ER
P06	59°57′33″.926W	3°01′34″.470S	145	SP; GR; ER
P07	59°57′36″.334W	3°02′06″.461S	200	SP; GR; ER
P08	59°57′15″.523W	3°02′45″.675S	160	SP; GR; ER
P09	59°56′36″.996W	3°01′46″.509S	200	SP; GR; ER
P10	59°57′01″.419W	3°02′55″.650S	190	SP; GR; ER
P11	59°58′12″.624W	3°03′58″.944S	200	SP; GR; ER
P12	59°55′59″.846W	3°00′48″.204S	190	SP; GR; ER
P13	59°57′28″.766W	3°04′16″.315S	190	SP; GR; ER
P14	59°57′08″.987W	3°05′13″.244S	190	SP; GR; ER
P15	59°56′01″.910W	3°05′20″.468S	200	SP; GR; ER

For georeferencing, the QGIS software (version 3.26.3) was used, with the function "Georeferencer" applied on the location map of Souza (2005), which contains the position of the logged wells. Then, for digitization, the well images were imported into GeoGebra Classic software (version 6.0.752) and inserted into a standard scale, whose values were extracted by adding points along the curves of the profiles. To generate the vectorized profiles from the extracted numerical data, bivariate graph customization in Microsoft Excel 2022 software was used, with depth represented by the Y axis, and geophysical measurements on the X axis.

Geophysical well logging

The geophysical gamma ray (GR) logs show the natural radioactivity of a formation emitted due to the presence of the isotopes thorium (Th^{232}), uranium (U^{235}) and potassium (K^{40}) in the minerals of crystalline and sedimentary rocks (Nery 2008). Thus, granitoid rocks, due to the presence of minerals formed by incompatible elements (among them, the isotopes mentioned above), and clayey sedimentary rocks, due to the presence of clay minerals rich in K, are classic examples that refer to high counts of gamma rays, in the same way that gabbroic rocks and quartz sandstones are examples that generally refer to low counts (Evans and Goodman 1941).

Electrical resistivity (ER) logs show the signal of the resistivity of rock packages induced by the application of an electric current (Nery 2013). It is a property influenced by porosity, permeability, mineralogy, interstitial fluids and salinity of rocks (Braga 2016). These logs can be used in stratigraphic distinction, mainly between sandy materials, generally moderately resistive, and clayey materials, which usually have low resistivity (Chopra *et al.* 2022). Therefore, resistivity indicates how compact a rock layer is, and a layer with low resistivity can indicate the presence of porous water reservoir rocks (Feitosa *et al.* 2008).

Spontaneous potential (SP) logs show electric potential differences naturally generated in the borehole wall due to the interaction between drilling mud and formation water (Nery 2013), being yet another indicator of the porosity of the rock package, in addition to the salinity characteristics of the fluid that fills these pores (Chopra *et al.* 2022). The SP anomalies are mainly associated to changes in lithology and/or salinity of the drilling fluid, meaning that positive SP values indicate higher permeability, while negative or zero values suggest lower permeability.

The drilling mud samples of wells P01 to P08 (Figure 1) presented sandstones, claystones and limestone, but only well P04 presented limestone exclusively at the depth of 200 m. For *a priori* model refinement we assumed that only sandstone and claystone lithologies occur in the wells and we applied the following interpretation to these two lithological types (Figure 2): because of the high concentration of K^+ in its mineral structure and its low permeability, claystone generally shows high gamma ray counts, low resistivity, and spontaneous potential curves without inflections, while sandstone, due to the predominance of quartz in its structure, its high porosity and permeability, and its interstitial freshwater content, generally shows low gamma ray counts, high electrical resistance, and spontaneous potential curves with large inflection amplitudes (Nery 2008, 2013). Mixed lithologies, or those with structural complexity and variability in interstitial fluid salinity, can exhibit distinct behaviors. Therefore, interpreting the most reliable profile and critically assessing the preliminary information are essential steps in the evaluation process.

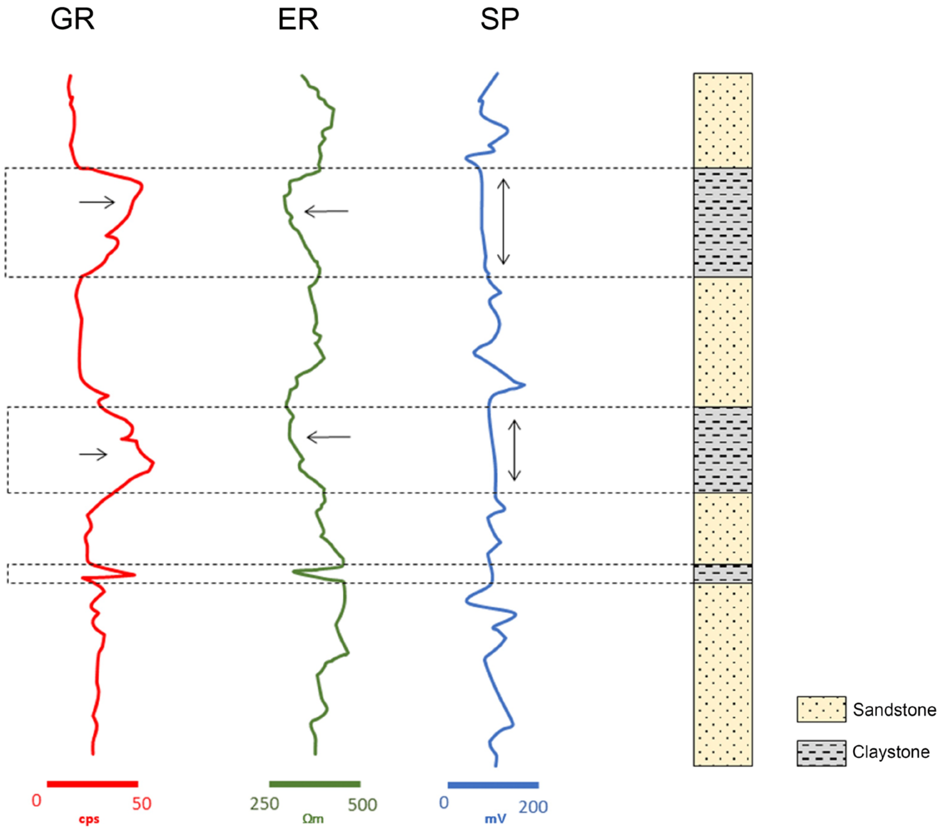


Figure 2. Interpretations adopted for claystone and sandstone lithologies in the geophysical logging of 15 wells in Manaus, Amazonas, Brazil. **GR** = gamma rays (red line); **ER** = eletrical resistivity (green line); **SP** = spontaneous potential (blue line). The signal patterns correspond to typical sandstone and claystone lithology (stratigraphic column on the right) responses. High GR values and low ER values indicate claystone layers, while low GR values and high ER values indicate sandstone layers. SP is related to permeability, meaning that positive SP values indicate higher permeability, while negative or zero values suggest lower permeability.

Data base construction, interpretation and characterization

To perform the geological modeling, once the geophysical logging of the well data was interpreted (Figures 3, 4 and 5), it was necessary to assemble it into a database so that the software could understand the spatial arrangement of the information. Our database had 14 columns and by 5693 rows, totaling 79,702 information fields.

During modeling, it is indispensable to carry out the stepwise processing of the database to reduce bias, outliers, and to regularize the sample intervals. It is important to normalize the sample intervals to standardize the database and to weigh the processing demand for model generation, which increases with sampling detailment. The method used to perform this regularization is called "compositing", and consists of grouping or ungrouping the samples according to specific lengths defined by the modeler, weighing the influence of the data from each previous interval on the current one by the average (Datamine 2016). We determined a 5-m regularization, which was assumed to be balanced between the computational demand needed to generate the model and the compatibility with the original interpretation.

For this model, the prototype's delimitation is tied to the location of the wells (Table 2), and the block dimension was 250 x 250 x 5 m for the X, Y and Z axes of the coordinate grid, respectively, considered compatible with the lens structuring of the model built in the creation stage. The model had 48 blocks on the X axis, 40 on the Y axis, and 66 on the Z axis, totaling 126,720 parent cells.

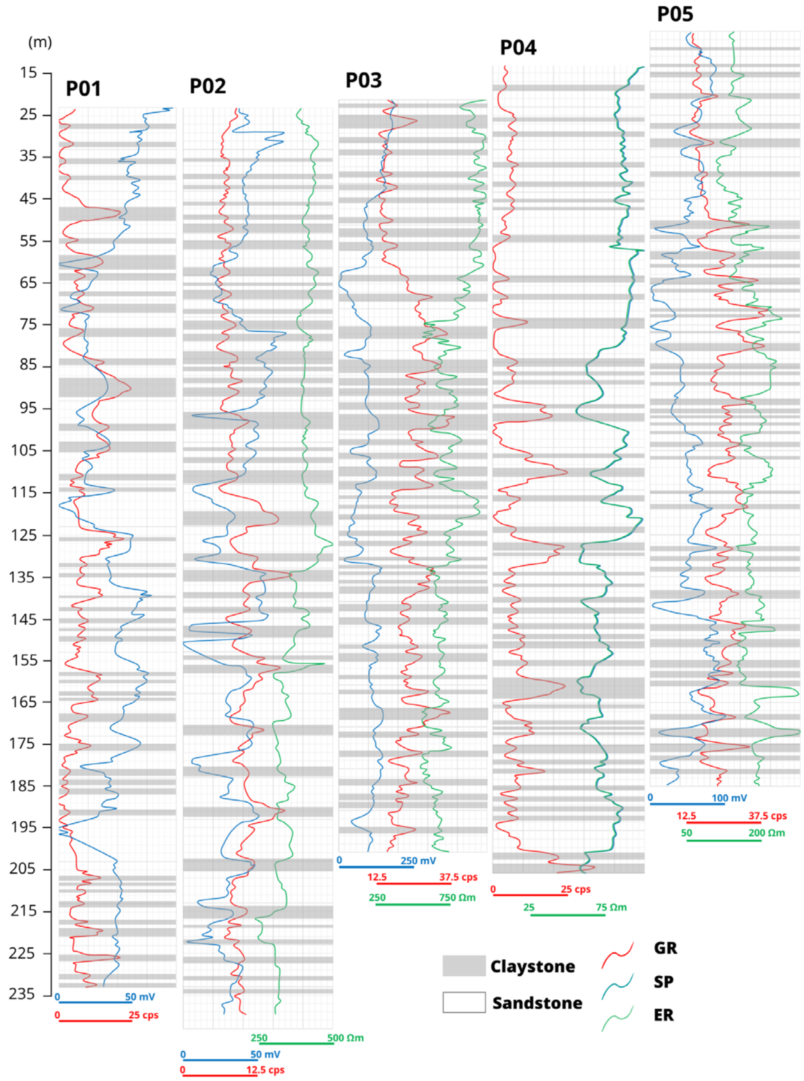


Figure 3. Geophysical logs of the wells P01 to P05 shown in Figure 1, in the north and east of the city of Manaus, Amazonas, Brazil interpreted by Souza (2005). The vertical axis indicates the depth of the wells. Gray bars indicate interpreted zones of claystone and white bars zones of sandstone. **SP** = spontaneous potential; **GR** = gamma rays; **ER** = electrical resistivity.

Finally, the database was submitted to a blocking procedure, which consists of filling the model with blocks in regions limited by open or closed wireframes to spatially represent a mass and assign localized characteristics, storing any information from the rock that can be measured or estimated (Datamine 2016). The blocks represent the fundamental unit of the model, with dimensions defined by the prototype, but they can be further divided into sub-cells, in order to achieve greater adhesion. For our model, the blocks were defined from the topographic surface, filling in the -Z direction, and were assigned to the sandstone lithology, which represents the entire package of tabular layers described in the Alter do Chão Formation (Souza and Verma 2006; Soares *et al.* 2016). Then the lens wireframe was blocked, with internal fill, and the blocks were assigned to the claystone lithology.

Table 2. Vertices of the geometric solid (prototype) that spatially limited the volume of the block model of the portion of the Alter do Chão Aquifer in Manaus, Amazonas (Brazil). UTM coordinate system: Datum: SIRGAS 2000; UTM zone: 21S.

X (meters)	Y (meters)	Z (meters)
162273.568E	9667836.031S	150
173862.904E	9658117.014S	150
162273.568E	9658117.014S	150
173862.904E	9667836.031S	150
162273.568E	9667836.031S	-175
173862.904E	9658117.014S	-175
162273.568E	9658117.014S	-175
162273.568E	9667836.031S	-175

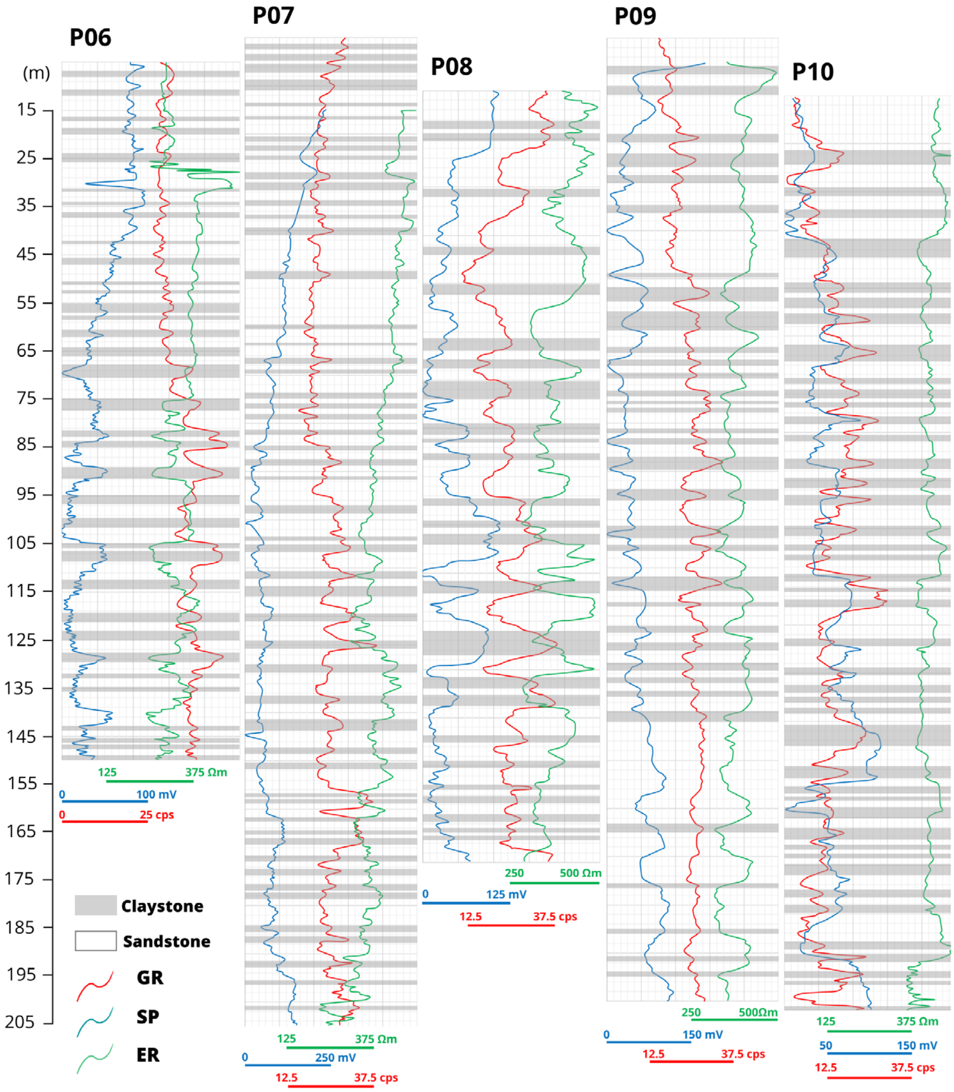


Figure 4. Geophysical logs of the wells P06 to P10 shown in Figure 1 in the eastern region of Manaus, Amazonas, Brazil interpreted by Souza (2005). The vertical axis indicates the depth of the wells. Gray bars indicate interpreted zones of claystone and white bars zones of sandstone. **SP** = spontaneous potential; **GR** = gamma rays; **ER** = electrical resistivity.

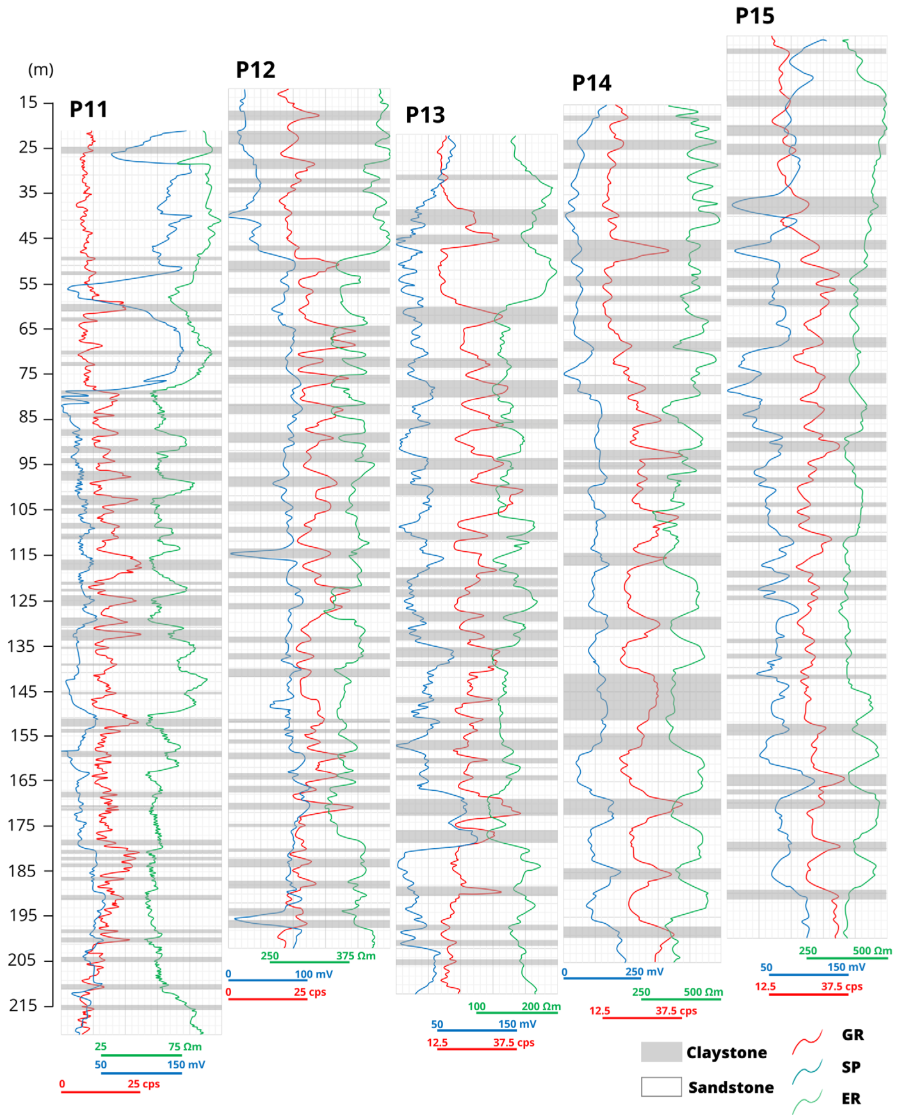


Figure 5. Geophysical logs of the wells P11 to P15 shown in Figure 1 in the southern region of Manaus, Amazonas, Brazil interpreted by Souza (2005). The vertical axis indicates the depth of the wells. Gray bars indicate interpreted zones of claystone and white bars zones of sandstone. **SP** = spontaneous potential; **GR** = gamma rays; **ER** = electrical resistivity.

RESULTS

The lithological block model (Figure 6), represented approximately 27 km^3 of rocks, of which 77.6% were sandstone and 22.4% claystone. The 3D manipulation tools made it possible to visualize slices, geological sections, and lithological stacks in any direction within the model boundaries.

Internal sections of the model (Figure 7) are outlined across the city plan in Figure 1. Each section is divided into upper, middle, and lower zones based on the lithological interpretation, which will be further detailed in the discussion section. Each zone has different depths according to the lithological characterization of each section. Section AA' is positioned in the western portion of the model, encompassing wells P01, P02, and P03, and featured a thick sandstone package (50 m) at more superficial levels to the west, as well as clayey lenses of low lateral continuity less than 10 m thick. In the center and east of AA', the characteristics were reversed, with thick sandstone packages (75 to 100 m) at the base of the model, at levels below -100 m, while the clayey lenses were thicker (up to 15 m) and had lateral continuity.

Section BB' is in the northern portion of the model, encompassing wells P01, P05, and P12, presenting sandstone packages up to 50 m thick at more superficial levels throughout the entire lateral extent, with clayey lenses up to 15 m thick, continuous to the east, mainly from the -50-m level downward. In the center, there was a high proportion of sandstone between 25 m and -75 m, due to the thinning of the clayey lenses in the vicinity.

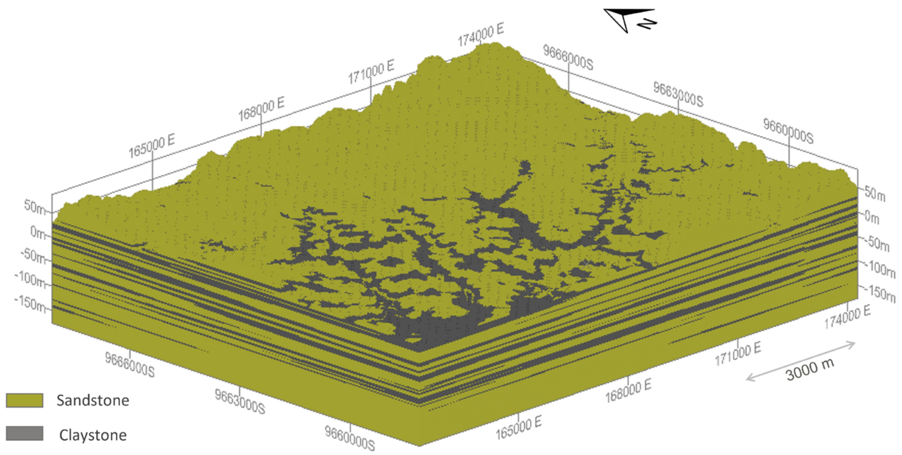


Figure 6. 3D block model of the Alter do Chão Aquifer in Manaus, Amazonas (Brazil), indicating the geometry and depth of the claystone and sandstone layers. Green blocks indicate sandstone layers, and gray blocks claystone layers. The model shows that outcroppings of claystone are concentrated in the southwestern part of the modeled area, while the northeastern part has a higher topography and predominance of sandstone outcrops.

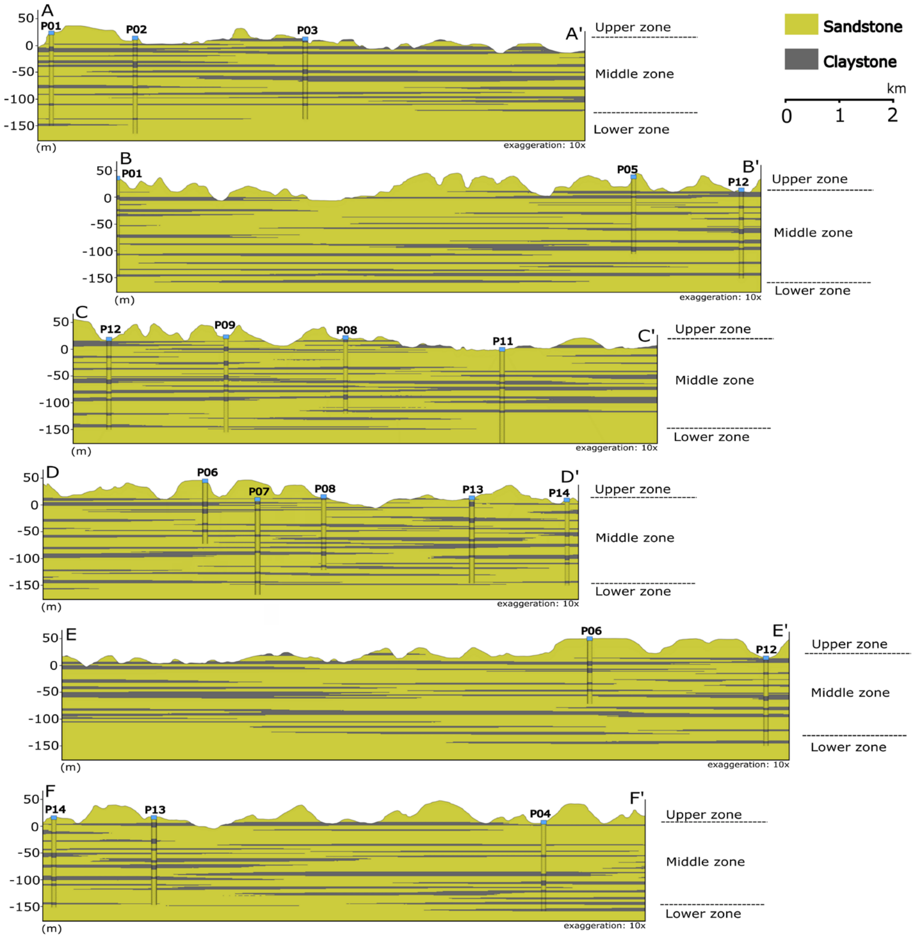


Figure 7. Bidimensional distribution of claystone and sandstone layers in cross sections of the modeled portion of the Alter do Chão Aquifer in Manaus, Amazonas (Brazil). The disposition of the cross sections is shown in Figure 1 (lines A-A', B-B', C-C', D-D', E-E' and F-F'). The Y-axis represents elevation in meters above sea level. In all sections there is a predominance of claystone lenses. Profiles B-B' C-C', D-D' and E-E' show high topography associated with sandstone outcropping. Profile A-A' shows claystone outcropping associated with low topography.

Section CC', in the southeastern portion of the model, encompasses wells P08, P09, P11, and P12, and featured sandstone packages up to 50 m thick at more superficial levels, mainly to the west. Between 25 m and -125 m, there was a large proportion of clayey lenses, up to 10 m thick and with high lateral continuity. To the east, especially around well P11, these lenses thickened and concentrated between the -25 m and -100 m, separating two large upper and lower sandstone packages.

Section DD', the eastern part of the model, encompasses wells P06, P07, P08, P13, and P14, featuring sandstone packages up to 50 m thick at more superficial levels, mainly in the midwest. The clayey lenses had very high lateral continuity and regularity throughout the section, with the sandstone zone appearing only from -150 m down.

Section EE' diagonally crosses the area from southwest to northeast, encompassing wells P6 and P12. The eastern portion featured more superficial sandstone packages up to 50 m thick, whith a more regular and continuous distribution at greater depths, with thinner clayey lenses. There are no wells in the western portion, which had its structure extrapolated based on correlation with wells in the vicinity, and presented a more superficial clayey zone between 50 m and -100 m, with thick and continuous lenses, and a large underlying sandstone package.

Section FF' also crosses the modeled area diagonally, but from southeast to northwest, encompassing wells P4, P13, and P14, and presented the same superficial sandstone package up to 50 m thick shown in previous sections, associated with topographic variations. To the west, there was a higher proportion of clayey lenses at shallower depths, with a thick sandstone package at the base between -100 m and -200 m. To the east, the pattern was reversed, with sandstone packages at the top between 75 m and -75 m, and a higher proportion of the clayey lenses below.

DISCUSSION

Our modeled layers are compatible with those interpreted by Souza (2005) with a depth misfit of at least 50 cm, with the emergence of a more superficial sandy zone that occurs because of the inclusion of topographic data. Additionally, the model shows only two lithologies instead of all lithologies described in the Alter do Chão Formation. Sandstone and claystone are major lithologies and thick compared to thin layers of conglomerates and pelites, and the block model could perform vertical and horizontal geometry estimates only for layers thicker than 5 m due to computational limitations. The drilling mud samples, however, did not present conglomerates. Clay lenses presented long lateral continuity generated during implicit modeling. This continuity is similar to the interpretation of Soares *et al.* (2016), who proposed tabular layers of sandy-clayey lithotypes interspersed with continuous lenses of pelites. In this sense, the 3D block represents an advance in the interpretation of the geometry of the aquifer, as it considers the correlations of the wells in all areas, opposed to interpretations restricted to two dimensions.

Qualitatively, it is possible to discriminate three depth zones in the block model that corroborate the aspects of the subdivision proposed by Soares *et al.* (2016). These zones (upper, middle and lower zone) occur at varying depths throughout the profiles are indicated for each cross section in Figure 7. The depths of the zones vary across sections due to differences in the spatial distribution of lithologies. The upper zone is characterized by the presence of packages up to 50 m thick with limited lateral continuity. These packages are attributed to sandstones because the implicit modeling algorithm associates this zone to the predominant lithotype of the Alter do Chão Formation due to the lack of lithological data and scarce information of minor lithologies. The attribution of sandy lithotypes in supporting the relief is a peculiar characteristic of the model, which deviates from the most accepted conception for the development of undulating reliefs, since sandstones are more easily eroded (Ostanin *et al.* 2017; Migón 2021). However, the presence of silicified packages, called Manaus Sandstone (Albuquerque 1922), which are more resistant to erosion, may explain the occurrence of these packages. Another possibility is the lateritization of impure sandstones as means of supporting the relief (Costa 1991). This zone also suggests the existence of a superficial reservoir, which is consistent with the good water production in relatively shallow wells drilled in the region (Rocha and Horbe 2006). The average flow rate for this zone is 78.72 $m^3 h^{-1}$ and the average depth of water table is 27.65 m (Duarte *et al.* 2019). For comparison, deep wells in Manaus have a flow rate of more than 100 $m^3 h^{-1}$, average specific capacity of 5.55×10^{-4} $m^2 s^{-1}$ and transmissivity of 1.3 x 10-3 $m^2 s^{-1}$ (Silva and Bonotto 2000).

The middle zone is approximately 100 m thick, with intercalations of tabular sandstone layers and continuous mudstone lenses, closer to the interpretation proposed by Soares *et al.* (2016). This zone is defined by continuous lenses that can be correlated over long distances, with the existence of extensive confined or semi-confined aquifers, separated by aquicludes (clay lenses).

The lower zone is approximately 75 m thick and is characterized by a continuous and thick package interpreted as sandstone. It represents the greatest storage potential among the interpreted zones, due to thickness and lateral continuity. Furthermore, the deep occurrence of sandstones and the association with a model of overlapping continuous lenses characterize the zone with low vulnerability to contamination (Costa *et al.* 2022). However, this zone may be associated, at some point, with the underlying Nova Olinda Formation (Souza 2005), which presents potentially contaminating evaporites (Pita *et al.* 2018).

In addition to the geomorphological interpretation of the proposed zones, it is also possible to draw a parallel with the scenarios predicted by Saraiva (2017). Based on numerical modeling, the latter author predicted a dramatic decrease in the hydrostatic column of the Alter do Chão Aquifer in the central urban region of Manaus, with progressive drying up of cells as early as 2020 and throughout 2025, 2035 and 2065 in the most pessimistic scenario. Our sections EE' and FF' intercept the portion of the aquifer studied by Saraiva (2017). Our model shows a predominance of sandstone in these sections, which may have good recharge potential, indicating less influence of geological conditions on the lowering of the water table proposed by Saraiva (2017). Thus, our results support the claim by Saraiva (2017) that the proposed water table depletion would be owed exclusively to anthropic and climatic factors.

Regarding the integrity of our model, although the Alter do Chão Formation presents mixed sandy-clayey layers, silicified lenses (Manaus Sandstone), conglomerates, and even the occurrence of diabase sills from the Penatecaua magmatism (Moreira *et al.* 2023; Maia and Marmos 2010), most of these are subordinate to sandstones and pelites with local occurrences that do not suit the scale of our study. Furthermore, the analysis of the generated sections reveals that most contain claystone lenses, typically less than 5 m thick, extending into areas beyond the wells. This pattern is expected, as the implicit model seeks the best fit within the percentage of extrapolation allowed, possibly reflecting the continuity of this lithology from neighboring wells. Similarly, the model assumes a continuous rock package, despite the ruptile neotectonic structures associated with the Alter do Chão Formation (Costa *et al.* 1996; Queiroz 2020), because structural data are not included in the block model. The use of more wells in a more regular grid for inserting microlayers also tends to improve the lithological characterization. Additionally, seismic/electric tomography may corroborate the direct lithological characterization of the wells, refining the lithological interpretation of the block.

CONCLUSIONS

Our results further evidence that geological modeling from geophysical logging data is a pertinent method in the evaluation of the Alter do Chão Aquifer, proving to be compatible with the results obtained by 2D mapping and numerical modeling. From the generated model, three lithological zones were identified along the depth of the aquifer. The upper zone, formed by the initial 50 m, between the elevations of 75 and 25 m, is composed ofpure sandstone layers with limited lateral continuity due to the topography. The middle zone is approximately 100 m thick, between 25 and -125 m, and presents intercalations and interdigitations of thick sandstone strata (10 to 50 m) and claystone lenses (up to 15 m), both with high lateral continuity. The lower zone is approximately 75 m thick, between -125 and -200 m, and is composed of a sandstone package with sparse thin claystone lenses and low lateral continuity. For recommend that further studies address the discrimination of mixed lithologies and use the generated block model for data estimation using geostatistical methods to assist in quantitative spatial assessments of the Alter do Chão Aquifer in Manaus, as well as the integrated interpretation with other geophysical methods.

ACKNOWLEDGMENTS

The authors acknowledge the Datamine Universidades program for providing the license and training in the software used in the research.

REFERENCES

Albuquerque, O.R. 1922. Reconhecimento dos vales do Amazonas. *Boletim do Serviço Geológico de Minas* 3: 1-84.

Agostinho, L.L.F.; Santos, D.A.V.; Façanha, J.C.R.F. 2020. A água e o seu valor econômico: uma análise sobre os conflitos e as diferentes formas de acesso à água. *Revista Opinião Jurídica* 18: 110-134.

Bakker, K. 2003. From state to market?: The transformation of water-users' associations in Spain and implications for modern water policy. *Geoforum* 34: 359-373.

Barbosa, I.N.B. De C.; Carneiro, C.D.R.; Carvalho, A.M. De; Miguel, G.F. 2020. Conhecer e conservar aquíferos: como torná-los visíveis? *Terrae Didatica* 16: 1-13.

Braga, A.C.O. 2016. *Métodos Geoelétricos em Hidrogeologia*. Oficina de Textos, São Paulo, 159p.

Caputo, M.V. 1984. Stratigraphy, tectonics, paleoclimatology and paleogeography of northern basins of Brazil. Doctoral thesis, University of California Santa Barbara, USA, 586p. (https://repositorio.ufpa.br/jspui/handle/2011/8961).

Carvalho, C.R.; Montenegro, S.M.G.L. 2017. Hydrogeological characterization of the Alter do Chão aquifer, Amazon region, Brazil. *Hydrogeology Journal* 25: 453-468.

Chopra, P.; Papp, É.; Gibson, D. 2002. Geophysical well logging. *Geophysical and Remote Sensing Methods for Regolith Exploration* 144: 105-115.

Costa, M.L. 1991. Aspectos geológicos dos lateritos da Amazônia. *Brazilian Journal of Geology* 21: 146-160.

Costa, J.B.; Ruth L.; Borges, M.; Paranhos, R.; Júnior, F.; Costa, M.; *et al.* 1996. Neotectônica da Região Amazônica: Aspectos tectônicos, geomorfológicos e deposicionais. *Revista Geonomos* 4: 23-44.

Costa, M.; Gomes, M.; Nascimento, S.A. 2022. Vulnerabilidade de aquíferos à poluição: uma revisão metodológica. *Revista de Geociências do Nordeste* 8: 60-76.

Daemon R.F. 1975. Contribuição à datação da Formação Alter do Chão, bacia do Amazonas. *Revista Brasileira de Geologia* 5: 58-84.

Datamine. 2016. *The Datamine Guide to Predictive and IA modeling.* (https://www.datamine.com/datafix/guides/predictive-and-ai-modelling). Accessed on 05 Jan 2024.

Dixon, J.C. 2013. Pedogenesis with respect to geomorphology. In: Shroder, J.F. (Ed.). *Treatise on Geomorphology*. Academic Press, London, p.27-43.

Duarte, A.A.A.M. 2006. O valor econômico e estratégico das águas da Amazônia. Doctoral thesis, Universidade Federal do Pará (UFPA), Brazil, 187p. (https://repositorio.ufpa.br/jspui/handle/2011/8278?locale=en)

Duarte, M.L.; Costa, H.S.; Silva, T.A.D.; Santos, M.V. 2019. Vulnerabilidade natural à contaminação do aquífero Alter do Chão na área urbana de Manaus, Amazonas, Brasil. *Revista Monografias Ambientais* 18: e7.

Evans, R.D.; Goodman, C. 1941. Radioactivity of rocks. *Bulletin of the Geological Society of America* 52: 459-490.

Fallara, F.; Legault, M.; Rabeau, O. 2006. 3-D integrated geological modeling in the Abitibi subprovince (Quebec, Canada): Techniques and applications. *Exploration and Mining Geology* 15: 27-41.

Famiglietti, J.S.; Lo, M.; Ho, S.L.; Bethune, J.; Anderson, K.J.; Syed, T.H.; Swenson, S.C. 2011. Satellites measure recent rates of groundwater depletion in California's Central Valley. *Geophysical Research Letters* 38: L03403-L-03407.

Feitosa, F.A.C.; Filho, J.M; Feitosa, E.C.; Demetrio, J.G.A. 2008. *Hidrogeologia: Conceitos e Aplicações.* CPRM, Rio de Janeiro, 812p.

Foster, S.S.D.; Chilton, P.J. 2003. Groundwater: The processes and global significance of aquifer degradation. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 361: 1867-1880.

Freeze, A.R.; Cherry, J.A. 1979. *Groundwater*. Prentice-Hall Inc, New Jersey, 624p.

Gleeson, T.; Wada, Y.; Bierkens, M.F.; Van Beek, L.P. 2012. Water balance of global aquifers revealed by groundwater footprint. *Nature* 488: 197-200.

Guimarães, J.T.F.; Nogueira, A.C.R.; Silva Júnior, J.B.C.; Soares, J.L.; Alves, R.; Kern, A.K. 2014. Palynology of the middle miocene-pliocene Novo Remanso Formation, central Amazonia, Brazil. *Ameghiniana* 52: 107-134.

Haldar, S.K. 2018. *Mineral Exploration: Principles and Applications*. Elsevier, Berlin, 334p.

Justino, L.B. 2018. Quantificação de Incertezas de Modelagem em Modelos Estruturais Dinâmicos. Doctoral thesis, Universidade Federal de Itajubá (UNIFEI), Brazil, 215p. (https://repositorio.unifei.edu.br/xmlui/handle/123456789/1849).

Lai, J.; Su, Y.; Xiao, L.; Zhao, F.; Bai, T.; Li, Y.; *et al.* 2024. Application of geophysical well logs in solving geologic issues: Past, present and future prospect. *Geosciences Frontier* 15: 101779-101812.

Liu, H. 2017. *Principles and Applications of Well Logging*. Springer, Berlin, 370p.

Luiz, J.G. 2022. Groundwater through geophysics: review and examples. *Brazilian Journal of Geophysics* 40: 59-74

Maia, M.A.M.; Marmos, J.L.M. 2010. *Geodiversidade do Estado do Amazonas*. Serviço Geológico do Brasil, Manaus, 275p.

MacDonald, A.M.; Bonsor, H.C.; Taylor, R.G. 2014. Quantitative maps of groundwater resources in Africa. *Environmental Research Letters* 9: 104002-104009.

Madsen, R.B.; Høyer, A.S.; Andersen, L.T.; Møller, I.; Hansen, T.M. 2022. Geology-driven modeling: a new probabilistic approach for incorporating uncertain geological interpretations in 3D geological modeling. *Engineering Geology* 309:1-25.

Mendes, A.C.; Truckenbrodt, W.; Nogueira, A.C.R. 2012. Análise Faciológica da Formação Alter do Chão, (Cretáceo, Bacia do Amazonas) próximo à cidade de Óbidos. Pará, Brasil. *Revista Brasileira de Geociências* 42: 39-57.

Mallet, J.L. 2008. *Numerical Earth Models*. EAGE Publications, Houten, 148p.

Migón, P. 2021. Sandstone geomorphology – Recent advances. *Geomorphology* 373: 107484.

Moreira, G.; Ernesto, M.; De Min, A.; Marzoli, A.; Machado, F.B.; Vasconcellos, E.M.; *et al.* 2023. Paleomagnetism of the Penatecaua magmatism: The CAMP intrusive rocks in the Amazonas Basin, northern Brazil. *Physics of the Earth and Planetary Interiors* 342: 107075.

Nery, G.G. 2008. Perfilagem geofísica aplicada a água subterrânea. In: Feitosa, A.C.; Manoel Filho, J.; Feitosa, E.C.; Demetrio, J.G.A. (Eds.). *Hidrogeologia: Conceitos e Aplicações*. CPRM, Rio de Janeiro, p.459-505.

Nery, G.G. 2013. *Perfilagem Geofísica em Poço Aberto – fundamentos básicos com ênfase em petróleo*. Sociedade Brasileira de Geofísica, Rio de Janeiro, 222p.

Ostanin, I.; Safonov, A.; Oseledets, I. 2017. Natural erosion of sandstone as shape optimization. *Scientific Reports* 7: 17301.

Pita, R.C.; Júnior, G.C.; Rosário, F.F.; Silva, M.L. 2018. Sistema aquífero Alter do Chão a oeste da cidade de Manaus (AM): Processos hidrogeoquímicos, origem da salinidade e relações com aquíferos adjacentes. *Geologia USP: Série Científica* 18: 273-296.

Queiroz, M.S. 2020. Evidências de neotectônica na bacia hidrográfica do Mindu - Manaus – Amazonas. *Revista Tocantinense de Geografia* 9: 130–142.

Saraiva, M.A. 2017. Avaliação da sustentabilidade do uso da água do Aquífero Alter do Chão na zona urbana de Manaus. Master´s dissertation, Universidade Federal do Amazonas (UFAM), Brazil, 73p. (https://tede.ufam.edu.br/handle/tede/6262).

Scanlon, B.R.; Reedy, R.C.; Faunt, C.C.; Pool, D.R.; Uhlman, K. 2016. Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona. *Environmental Research Letters* 11: 035013.

Rocha, L.C.R.; Horbe, A.M.C. 2006. Contaminação provocada por um depósito de lixo no aquífero Alter do Chão em Manaus-AM. *Acta Amazonica* 36: 307-312.

Silva, A.J.P.; Lopes, R.C.; Vasconcelos, A.M. 2003. Bacias sedimentares paleozóicas e meso-cenozóicas interiores. In: Bizzi, L.A.; Schobbenhaus, C.; Vidotti, R.M.; Gonçalves, J.H. *Geologia, Tectônica e Recursos Minerais do Brasil.* CPRM, Rio de Janeiro, p.55-85.

Silva, M.L.; Bonotto, D.M. 2000. Caracterização hidrogeoquímica na Formação Alter do Chão, Município de Manaus (AM). *Águas Subterrâneas* 2000 (supl): 1-20.

Silva, M.L.; Silva, M.S.R. 2007. Hidrogeoquímica das águas subterrâneas da cidade de Iranduba (AM), Brasil. *Caminhos de Geografia* 8: 87-96.

Soares, E.A.A.; Wahnfried, I.; Dino, R. 2016. Estratigrafia de subsuperfície da sequência sedimentar cretácea-neógena das regiões de Manaus e Itacoatiara, Amazônia Central. *Geologia USP: Série Científica* 16: 23-41.

Sophocleous, M. 2002. Interactions between groundwater and surface water: the state of science. *Hydrogeology Journal* 10: 52-67.

Souza, L.S.B. 2005. Mapeamento de Aquíferos na cidade de Manaus (AM) - utilizando perfilagem geofísica de poço e sondagem elétrica vertical. Master´s dissertation, Universidade Federal do Pará (UFPA), Brazil, 85p. (https://www.repositorio.ufpa.br/jspui/handle/2011/5847).

Souza, L.S.B.; Verma, O.P. 2006. Mapeamento de aquíferos na cidade de Manaus/AM (zonas norte e leste) através de perfilagem geofísica de poço e sondagem elétrica vertical. *Revista Brasileira de Geologia* 19: 111-127.

Taylor, R.G.; Scanlon, B.; Döll, P.; Rodell, M.; van Beek, R.; Wada, Y; *et al.* 2013. Ground water and climate change. *Nature Climate Change* 3: 322-329.

USGS. 1986. *Aquifer-Nomeclature Guidelines*. US Geological Service. (https://www.usgs.gov/publications/aquifer-nomenclature-guidelines). Accessed on 05 Jan 2024.

RECEIVED: 11/04/2024
ACCEPTED: 19/04/2025
ASSOCIATE EDITOR: Ingo Wahnfried

DATA AVAILABILITY: The data that support the findings of this study are available, upon reasonable request from the corresponding author [Raphael Di Carlo Silva dos Santos]. The dataset is not publicly available because it was generated through a partnership with the Datamine Universities program. The disclosure and access to this data are governed by the terms outlined in the collaboration agreement.

AUTHOR CONTRIBUTIONS:
SOUZA, B.S.: Data curation, Formal analysis, Investigation, Software, Validation.
SANTOS, R.D.C.S.: Data curation, Formal analysis, Investigation, Writing – review & editing.
TRINDADE, C.R.; SANTOS, R.S.: Investigation, Methodology.
BRITO ROCHA, I.M.: Investigation, Methodology, Writing – review & editing.
REZENDE, D.P.: Writing - original draft.