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Assessment of the natural vulnerability of underground aquifer aiming at the hierarchization of locations for the implementation of water supply and sanitary sewage systems in the municipality of Ananindeua/PA

Avaliação da vulnerabilidade natural de aquíferos subterrâneos visando à hierarquização de locais para implantação de sistemas de abastecimento de água e esgotamento sanitário no município de Ananindeua/PA

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ABSTRACT

The methodologies for determining aquifer vulnerabilities are currently used as tools to support proposals for the groundwater protection, associated to water management resources and planning and territorial ordination activities. In this context, the objective of this present work is the vulnerability assessment of an aquifer system of interest located in the municipality of Ananindeua, the state of Pará. To this end, the following activities were executed: survey and systematization of pertinent information to existing wells in the municipality of Ananindeua-PA; determination of the constituent parameters of the GOD method and the hydrogeological values of hydraulic conductivity and hydraulic transmissivity; extrapolating the pertinent information for all the interest area aiming the spatialization of homogeneous zones by degree of vulnerability e, finally, the hierarchization of locations for the implementation of water supply systems. With the completion of this present work, it was verified that most part of the area of interest has an aquifer system classified as unconfined, mixed lithological extracts and distance from the top to the water table less than 20 meters. These information, associated with the pattern of land use and occupation, based on the study of hydrogeologic values, enables the subsidy for decision-making regarding the most appropriate allocation of preventive investments with basic sanitation infrastructure, in order to minimize or nullify the associated risks of contamination in the referred area. However, to a better support for an efficient decision-making from the public managers and the actions of other social actors involved in the use and management of groundwater in the locality, it must be provided other information and complementary studies.

Keywords: Water resources planning and management; Natural vulnerability of aquifer systems; Land use and occupation; Investments in basic sanitation.

RESUMO

As metodologias de determinação da vulnerabilidade de aquíferos são atualmente utilizadas como ferramentas de auxílio às propostas de proteção das águas subterrâneas, associadas às atividades de gestão de recursos hídricos e de planejamento e ordenamento territorial. Nesse contexto, este estudo teve como objetivo a avaliação da vulnerabilidade natural de sistema aquífero subterrâneo de interesse localizado no município de Ananindeua, estado do Pará. Para tal, foram executadas as seguintes atividades: levantamento e sistematização de informações pertinentes aos poços existentes no município de Ananindeua/PA; determinação dos parâmetros constituintes do método GOD e das grandezas hidrogeológicas condutividade hidráulica e transmissividade; extrapolação das informações pontuais para toda a área de interesse visando à espacialização de zonas homogêneas por grau de vulnerabilidade e, por fim, a hierarquização de áreas de interesse para implantação de sistemas de saneamento básico. Com a realização do presente estudo, verificou-se que a maior parte da área de interesse possui sistema aquífero enquadrado como não confinado, extratos litológicos mistos e distância do topo ao nível freático menor do que 20 metros. Essas informações, associadas ao padrão de uso e ocupação do solo na localidade, embasado pelo estudo das grandezas hidrogeológicas, permite o subsídio à tomada de decisão quanto à alocação mais adequada de investimentos preventivos com infraestrutura de saneamento básico, a fim de minimizar ou anular os riscos associados de contaminação na referida área. Entretanto, para melhor subsídio à eficiente tomada de decisão dos gestores públicos e das ações dos demais atores sociais envolvidos no uso e no gerenciamento das águas subterrâneas na localidade, deve-se ter o aporte de outras informações e estudos complementares.

Palavras-chave: Planejamento e gestão de recursos hídricos; Vulnerabilidade natural de sistemas aquíferos; Uso e ocupação do solo; Investimentos em saneamento básico.

INTRODUCTION

Water is an indispensable component for life and is a widely discussed element in its different aspects. Groundwater, in particular, is an important source for agricultural, industrial, and domestic uses and is considered the largest liquid freshwater reservoir on the planet (Denizman, 2018). Therefore, the study of groundwater is essential to identify the natural vulnerability of aquifer systems.

The vulnerability of an aquifer system depends on its physical properties, as well as its sensibility to natural impacts and those caused by human beings. The idea of vulnerability is based on the fact that the physical context of the aquifers offers a certain degree of protection to groundwater against contaminations from different sources and, therefore, some areas are more vulnerable to contamination than others.

Thus, groundwater vulnerability is the tendency or likelihood of contaminants to reach the groundwater system after their introduction at the surface (Fannakh & Farsang, 2022). The American Society for Testing Materials (1996), defines the vulnerability of groundwater as the ease in which a given contaminant can reach the water located underground or an aquifer under certain conditions related to the aquifer characteristics (lithology, porosity, etc.), to the area (land use, topography, etc.) and the contaminant (viscosity, density, etc.).

According to Li et al. (2021) groundwater pollution has dire consequences, as it can negatively affect human health, environmental quality, and socioeconomic development. About this, Lisbôa et al. (2016) emphasizes that the contamination of aquifers has been monitored and studied in order to obtain better knowledge aimed at communicating to the user and, especially, to decision makers, as a management tool, with a view to protecting groundwater resources.

Within the concept of contamination risk, it should be noted that there is a difference between vulnerability and risk, considering that the vulnerability exists regardless of the presence of the contaminant. Thus, it is possible to exist an aquifer with a high vulnerability index, but without risk of contamination in case there is no significant contaminant load, despite the vulnerability index being low (Leitão et al., 2003; Milek et al., 2014).

According to Madroñero et al. (2022), to face the increasing contamination of aquifers by anthropic activities, vulnerability assessment is one of the fundamental requirements to generate guidelines, strategies and policies to prevent and minimize groundwater contamination. Thus, the methodologies for determining aquifer vulnerability are currently used as tools to support proposals for groundwater protection, associated to water resources management and territorial ordination.

Among the known methodologies is DRASTIC (Aller et al., 1987), a useful tool for assessing groundwater vulnerability because its application is integrated with GIS and uses available or estimated data. Another method is SI (Ribeiro, 2000), an adaptation of DRASTIC, developed to assess aquifer vulnerability at large and medium scales. However, the use of some methods becomes unfeasible due to the lack of necessary data, obtaining, only the type of underground contaminant, the depth, the degree of consolidation and the lithological characteristics of the aquifer (Foster & Hirata, 1988).

For this reason, in the present work, the use of the GOD Method is proposed to assess the aquifer natural vulnerability in the region of interest due to its easy application and to the fact that the hydrogeological data which are required by other systems were not directly available, similar conclusion to that of Lisbôa et al. (2016), which enables the use of the methodology even in situations where there is no wealth of hydrogeological information.

Therefore, from the application of the GOD Method and the study of complementary physical parameters, it is possible to characterize the natural vulnerability of any aquifer systems of interest, providing good management and better use of underground water resources, as well as the most appropriate allocation of potentially polluting undertakings (Ferreira et al., 2017) and priority areas for investments in basic sanitation projects and works (Barros et al., 2021), in order to minimize or eliminate the risks of contamination.

Groundwater pollution is mainly attributed to human activities, such as the discharge of untreated effluents and chemicals from industries and the excessive use of fertilizers and pesticides in agricultural activities (Akhtar et al., 2020). For ANA (Agência Nacional de Águas e Saneamento Básico, 2018), the greatest concern is concentrated in free aquifers, especially in areas where the freshwater zone is thin and the water level is shallow, as is the case of the city of Ananindeua, where the Barreiras aquifer is located, which points out a high natural vulnerability.

Studies prove the fragility of this aquifer, especially when related to problems in the sanitation system. Ribeiro (2019) found that the exploitation of the aquifer is not adequate, since it presents strong evidence of contamination by septic tanks, indicating that the consumption of these waters could lead to health problems for the population. While, Freddo Filho (2018) identified that the presence of areas with high and extreme vulnerability has a positive correlation with areas that present higher nitrate indices.

In this context, the present work aims to map and evaluate the natural vulnerability of the aquifer system of interest located in the municipality of Ananindeua, Pará state. This mapping is fundamental to support actions to ordering the use and occupation of land in the aquifer area, serving as reference for decision-making by the environmental agencies of the states and municipalities, as well as to guide the planning of sanitation agencies (Agência Nacional de Águas e Saneamento Básico, 2014).

MATERIAL AND METHODS

The methodological strategy used to achieve the objectives of the study involves the following steps: (1) Survey and systematization of relevant information to existing wells in the municipality of Ananindeua/PA; (2) Determination of the GOD Method constituent parameters and the magnitudes of hydraulic conductivity and transmissivity; (3) Extrapolation of specific information for the entire area of interest in order to spatialize homogeneous zones by degree of vulnerability; and (4) Hierarchization of areas of interest for the implementation of basic sanitation systems.

Study area

As the study area of this research, a neighborhood belonging to Ananindeua, which is a Brazilian municipality in the state of Pará, was selected. Located in the Metropolitan Region of Belém, it is the second most populated municipality in the Pará State and the third in the Amazon Forest Region. Its population is estimated at 540.410 inhabitants (Instituto Brasileiro de Geografia e Estatística, 2021).

Initially considered a dormitory city, it has shown considerable development in recent decades due to the urban expansion of the municipality of Belém. Its emancipation to the status of municipality took place in the 1940s, and in the 1970s the construction of the first housing complex called New City began, part of the federal housing program under the responsibility of the Housing Company of the State of Pará (*Companhia de Habitação do Estado do Pará – COHAB*), being completed with nine housing developments.

The insular area of Ananindeua is located north of the city, and is composed of nine (09) islands. It is formed by numerous rivers, especially the Maguari, and boreholes, especially the Bela Vista and Marinhas, as well as streams.

According to the Trata Brasil Institute, which periodically conducts surveys on the conditions of basic sanitation in the 100 most populous municipalities in the country, Ananindeua occupies the 95th position in the ranking, covering only 33.80% of the population with a public system for drinking water supply and 30.18% with a public system of collection and treatment of sewage (Instituto Trata Brasil, 2022).

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Thus, due to the low coverage of water supply and sewage services, most of the households in Ananindeua have shallow wells and septic tanks as alternative solutions, and sometimes they are relatively close. Therefore, there is a risk of compromising the quality of the water used by these households by the waste that percolates from these pits, posing a threat to public health in the locality.

In this context, the adopted study area was the Cidade Nova neighborhood due to the high concentration of water wells present in the neighborhood and registered in the Groundwater Information System (SIAGAS), as illustrated in Figure 1.

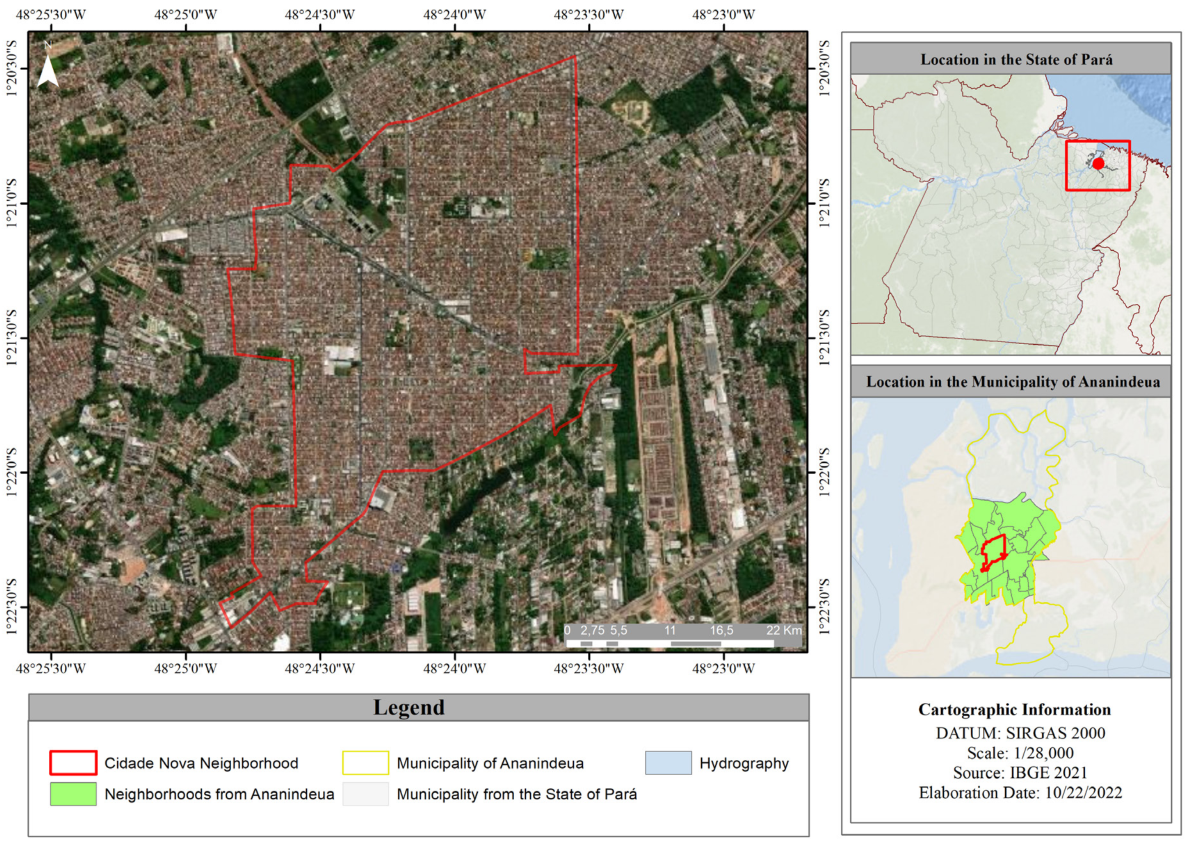

Figure 1. Geographical location of the Cidade Nova neighborhood, municipality of Ananindeua/PA, study area adopted in the research.

Table 1. Determination of "Occurrence of Groundwater " (Parameter "G").

Confinement Degree	None	Ascending Flow	Confined	Semi-confined	Non-confines (Covered)	Non-confined
Code	0	1	2	3	4	5
Score	0	0	0.20	0.40	0.60	1.00

Table 2. Determination of "Lithology of Vadose Zone and Confining Layers" (Parameter "O").

Well	Clay Sandy Soil	Sandy Soil	Thin Sand	Very Thin Sand	Medium Sand	Thick Sand	Clayey Sand
Thickness (meters)							
Score	0.525	0.625	0.60	0.55	0.65	0.70	0.525

Research stages

Because of its simplicity and low technical data requirements, the GOD method is the most suitable method for assessing the natural vulnerability to contamination of surface aquifers (Barriers, Post-Barriers and Recent Cover) (Agência Nacional de Águas e Saneamento Básico, 2018). Its three constituent parameters are:

a) Groundwater occurrence, where values are obtained within a range of 0 to 1;

b) Overall aquifer class, in terms of consolidation degree and lithological features, leading to a second point on the scale of 0.4 to 1.0;

c) Depth to groundwater table, which will define the third point on the scale of 0.6 to 1.0.

After the survey and the systematization of the information, the parameters "Groundwater Occurrence" (free, confined or semi-confined), "Litology of the Flooded Zone and Confining Layers" and the "Depth of the Groundwater" (thickness of the flooded zone) were crossed simultaneously for each well registered in the System, in order to then, according to the GOD Method, classify the degree of vulnerability of the aquifer in the study. All the parameters have the same level of importance. Therefore, the vulnerability index is determined as the multiplication of the values obtained in each factor.

To determine the Degree of Aquifer Confinement (Parameter "G"), it is necessary to describe in which type of aquifer the well is in, according to Table 1:

In addition, to measure the influence of lithology on the natural vulnerability of the aquifer (Parameter "O"), it must be added the values of layer thickness for their respective soil types (Table 2):

Finally, to determine the depth from the top to the water table (Parameter "D"), it is necessary to pay attention to the corresponding column; according to Table 3.

Next, in Figure 2, all the constituent parameters of the GOD Method are gathered.

In addition, other physical parameters that might be determined using as complement the application of the GOD Method are the hydraulic conductivity and hydraulic transmissivity.

The hydraulic conductivity is defined as the measure of the water resistance to movement through a porous medium (Poehls & Smith, 2009) or as the measure of the ease with which an environment transmits water (Fitts, 2002). Its physical meaning is defined by the volume of liquid that flows perpendicularly to an amount of area of a porous medium under the influence of a unitary hydraulic gradient (Delleur, 1999). It is a function of both characteristics of the environment, such as porosity, size, distribution, shape and arrangement of particles (Feitosa & Manoel Filho, 2000), as the characteristics of the fluid, such as specific gravity and kinematic viscosity (Fetter, 2001).

Table 3. Determination of "Groundwater Depth" (Parameter "D").

Depth to Groundwater	Score
> 50m	0.60
50 ⊢ 20m	0.70
20 ⊢ 5m	0.80
5 ⊢ 0m	0.90
Special Case	1.00

At the same time, transmissivity is a hydrogeological parameter that corresponds to the ability of an environment to transmit water. It can be defined as the amount of water that flows through the vertical section of the aquifer when the hydraulic loading from one unit is reduced and represented in square meters per day (m^2/day) or square centimeters per second (cm^2/s). The transmissivity is calculated through the product of the hydraulic conductivity by the thickness of the aquifer.

From the vulnerability determination for exactly each surveyed well, information will be extrapolated to the entire area of the aquifer of interest system by the use of the Inverse Distance Weighted (IDW) complement from the ArcGIS geoprocessing software and statistically, in a representative way, enabling the spatialization of homogenic zones by vulnerability degree.

According to Cordeiro et al. (2016), this complement enables the construction of a raster layer which every value of each cell is determined by the weight of the linear combination of a set of points, assuming that the variable value loses its importance as it moves away from a point. With this method the interpolated values do not result from a simple linear variation between two points with distinct values, but from a variation dependent of the influence that it is intended to give to the points.

Finally, from this spatialization, in a platform which uses geographical information systems (GIS), the areas of interest from the Ananindeua-PA municipality will be hierarchized for the implantation of Water Supply and Sanitary Sewage Systems,

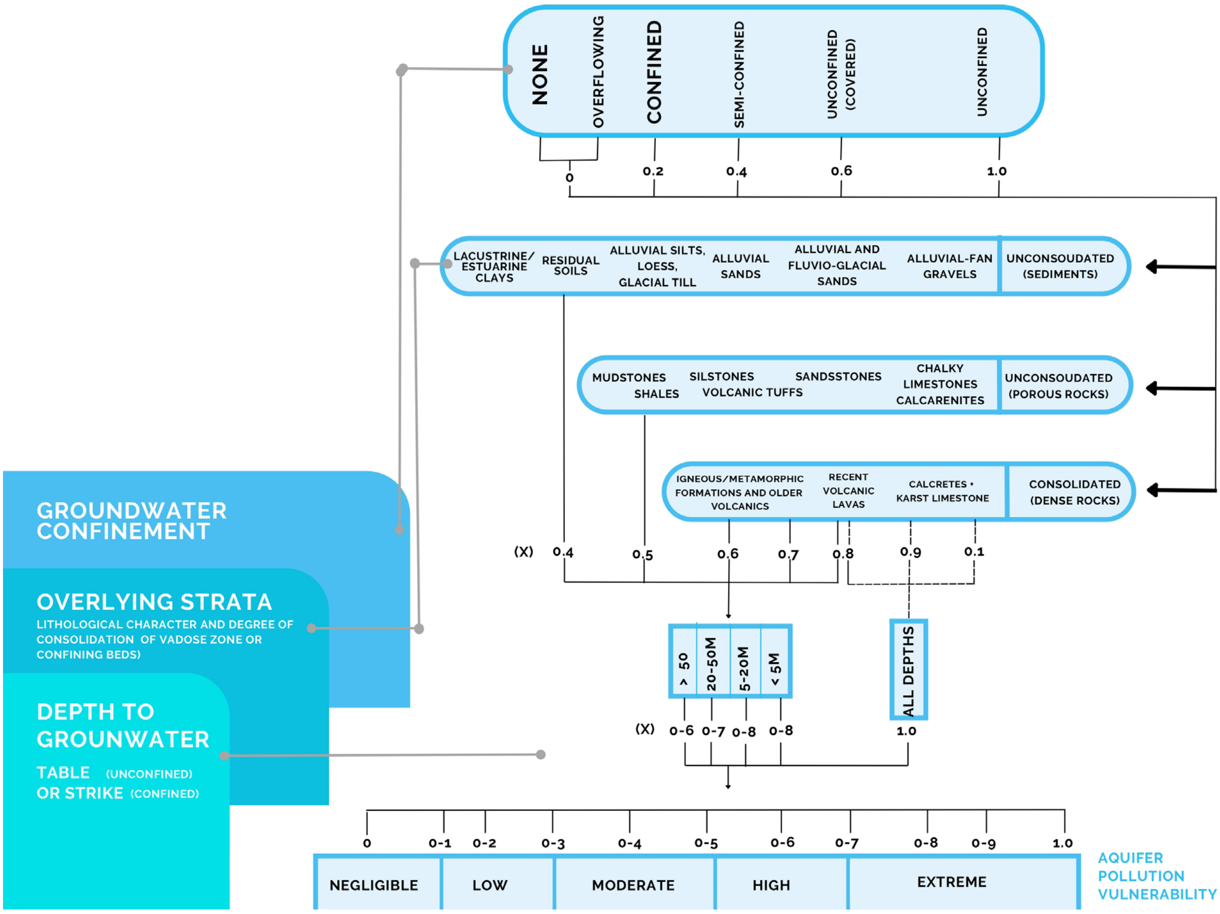

Figure 2. The GOD Method for vulnerability assessment.
Source: Foster & Hirata (1988).

aiming at improving the local environmental quality and ensuring efficient decision-making by public managers and actions from other social actors involved in the use and management of groundwater.

RESULTS AND DISCUSSIONS

The hydrogeological study of the region identified the qualitative impairment of practically all waterways and the most superficial aquifers, where the main potential sources of groundwater pollution correspond to gas stations, cesspools, cemeteries, and garbage dumps (Serviço Geológico Brasileiro, 2002).

According to ANA (Agência Nacional de Águas e Saneamento Básico, 2018), the aquifer systems identified in the region are formed by Tertiary-Qaternary sedimentary rocks that lie on a substrate of probably Cretaceous age. These systems are individualized in aquifers that comprise recent covers (alluvium, colluvium and eluvium), unconsolidated deposits identified as post-Barreiras and sedimentary rocks of the Barreiras and Pirabas formations.

The Barreiras System is made up of less thick aquifer layers that are interspersed with impermeable to semi-permeable layers, with sandy reservoirs in certain places. The Pirabas System, in turn, comprises thick aquifer layers enclosed by impermeable to semi-permeable layers. Well and logging data indicate succession with frequent recurrence of sandy and clay layers.

According to the Groundwater Information System (SIAGAS) database, a total of 132 wells are registered. However, due to the minimum data required for the use of the GOD Method, it was possible the application for 128 of these wells.

Furthermore, it is observed a concentration of the surveyed wells in the center-south portion of the study area. Then, in the extrapolation of the hydrogeological information, it will be more representative in the referred areas with a larger cluster of points of interest. Figure 3 presents the map referring the Degree of Aquifer Confinement (G).

Based on the G-parameter, three different categories were obtained regarding the degree of confinement of the analyzed aquifers, namely: *Unconfined*, *Semiconfined* and *Confined*. Ducci et al. (2023) states that unconfined aquifers, where only the lower boundary is an impermeable layer while the upper boundary is characterized by high permeability, are more vulnerable to anthropogenic pollution than confined aquifers.

Considering the wells surveyed, 123 wells are classified as Unconfined, 04 (four) wells are classified as Confined and only 01 (one) well is classified as Semiconfined. Thus, it can be observed in Figure 4 that the area classified between 0.601-0.700 refers to the wells in greater quantity, i.e., those whose aquifer is of the Unconfined type. Moreover, the vadose zone can act as an efficient filter against urban storm water runoff bacteria during the infiltration of storm water runoff (Voisin et al., 2018).

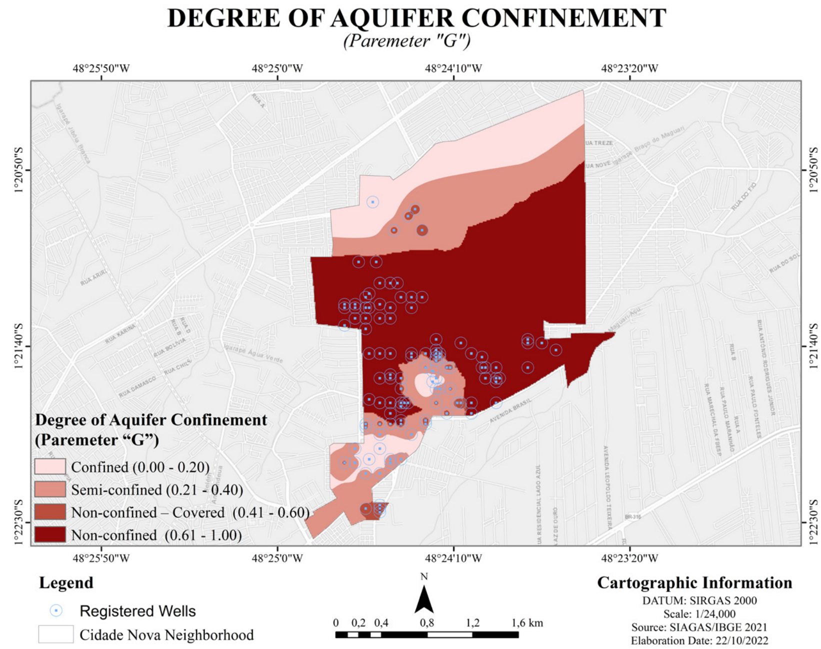

Figure 3. Degree of Aquifer Confinement (G) in the study area.

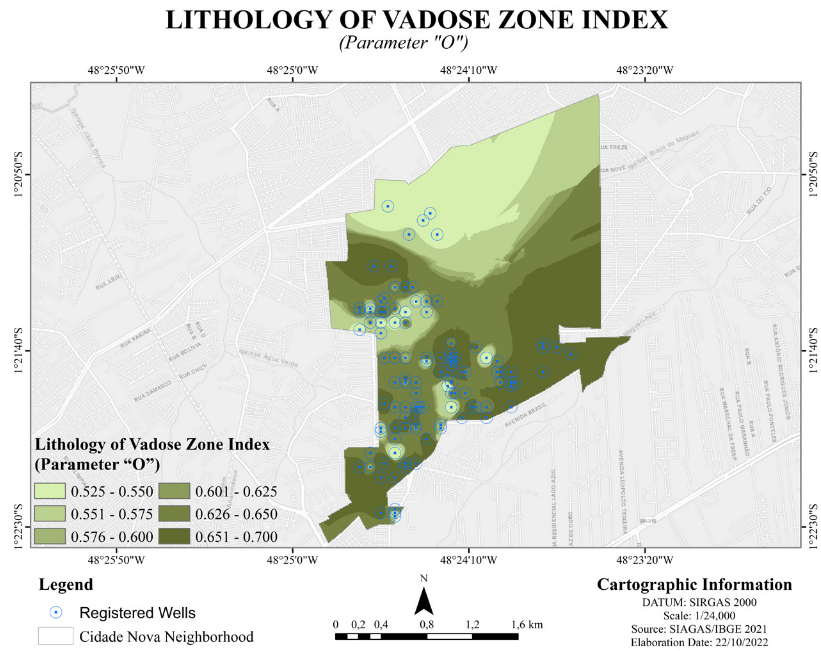

Figure 4. Lithology of the Aquifer Vadose Zone (O) in the study area.

As shown in Figure 4, the areas between 0.525-0.600 are representative of the lithology types “clayey soil, clayey sand and very fine sand”, and the remaining areas represent the lithology type “coarse sand”. According to Rodrigues (2015) in sandy soils there is a high permeability which facilitates the flow of water, while in clayey soils the opposite occurs, because in clay the water flow is much more complex. Therefore, this type of soil is more subject to infiltration of contaminants, making the water table vulnerable.

The parameter D is shown in Figure 5. In the quantitative and qualitative analysis it is observed a small variation regarding the distance from the top to the water table in the study area: 86 wells were classified between 5 to 20 meters (score 0,80, according to Table 3), while 41 wells presented depth under 5 meters according to the method classification (score 0,90, according to Table 3).

As per the vulnerability map (Figure 6), it was possible observed that the areas in which the wells characterized as confined and semiconfined are found, and lithology of the types of clay and clayey sand are also the places where the deepest wells are located, and they are characterized as *Insignificant* and *Low* vulnerability areas. However, Diniz Filho et al. (2015) note that the semi-confined aquifer and the low vulnerability of the aquifer will not guarantee its total protection, because very persistent and mobile contaminants may percolate vertically and reach the deeper semi-confined portions, and a diffuse contamination process may be created.

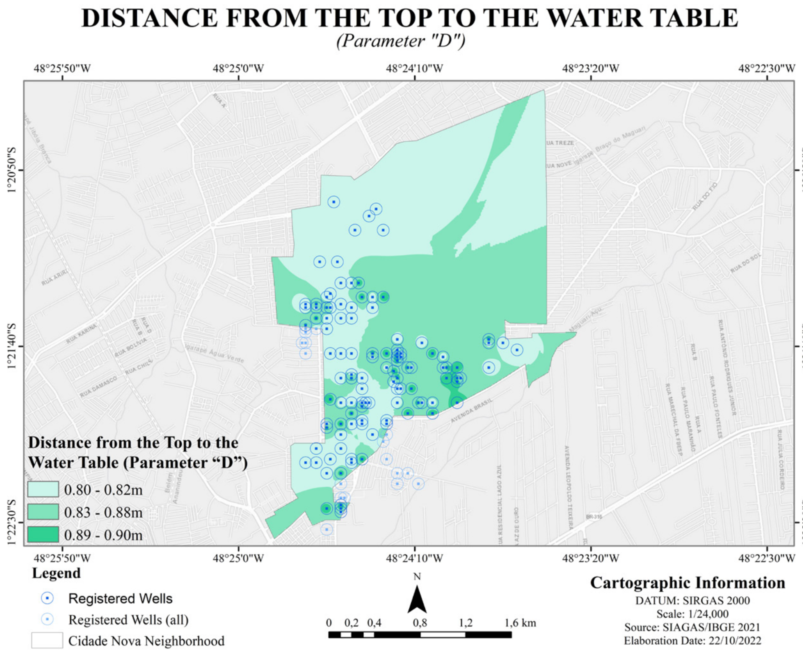

Figure 5. Distance from the top to the Water Table (D) in the study area.

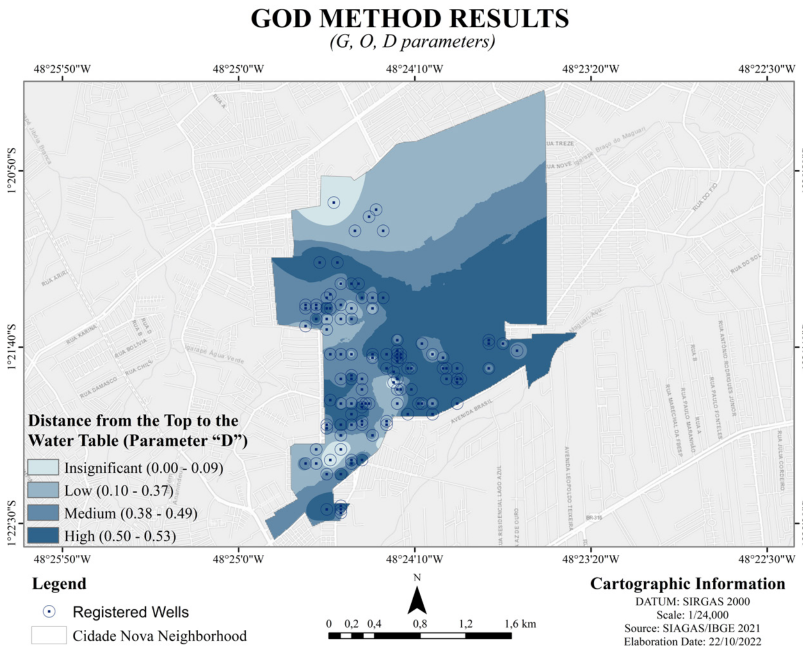

Figure 6. Vulnerability Map according to the GOD Method in the study area.

Meanwhile, areas characterized as *Medium* vulnerability, in general, presented aquifers of the type of free, lithology of types of medium sand, thin and very sand (preponderantly) and clayey sand soil (to a lesser extent), as well as the distance from the top to the water table between 5 and 20 meters. In fact, pollutants can more easily pass through permeable rock and contaminate groundwater (Mester et al., 2021).

Furthermore, it is observed that the *High* vulnerability areas present the same features of confinement degree and lithology as the *Medium* vulnerability areas, being distinguished from the last ones due to the parameter D; where the distance from the top to the water table in these areas was a maximum of 5 meters.

From the hydraulic conductivity map (Figure 7), it can be seen that this parameter varies from 0.45 to 43.63 meters/day, with the high score showing the largest volume of water able to flow through the porous medium and, low score, the volume decreases.

The results found for hydraulic conductivity can be compared with lithology map (Figure 4). Thus, it is observed that the areas where it is possible to find lithological extracts predominantly of the sandy type (medium, thin and very thin) are also the areas that present some of the highest values of hydraulic conductivity – between 20 and 26 meters/day, the which is justified by the greater capacity for greater percolation in this extract than in clayey extracts.

Aquifer transmissivity (Figure 8) was characterized, with variations from 1.40 to 260 m^3/day. Aquifers with higher water transmission capacity in porous media are identified by the value of 110-260 m^3/day, while lower values (1.4-100 m^3/day) represented lower water transmission, a result similar to that of hydraulic conductivity, since these parameters are related.

Finally, after the individual study of the parameters of the GOD method, in order to infer the danger of contamination associated with the use and occupation of the soil in the study area, the Map was generated if Figure 9. This activity was carried out considering the statement by Mimi & Assi (2009), who point out that the land use and occupation is the main factor for defining the danger of contamination of an aquifer system.

According to Ahmad et al. (2021) the quality and quantity of groundwater resources are affected by land use/land cover dynamics, particularly the increasing urbanization coupled with high household wastewater discharge and decreasing open lands. Analyzing Figure 9, it is possible to verify that the existing uses on the site are Residential (preponderant), Commercial/Services, Institutional, and, in addition, the existence of green areas.

It is noticeable that the residential use, in areas classified as to natural vulnerability in the *Insignificant* or *Low* categories, presents a small risk of associated contamination considering that, as previously discussed, these areas have, in a preponderant way, confined or semi-confined aquifer, lithological extracts of types of clay and sandy clay and greater distances from the top to the water table.

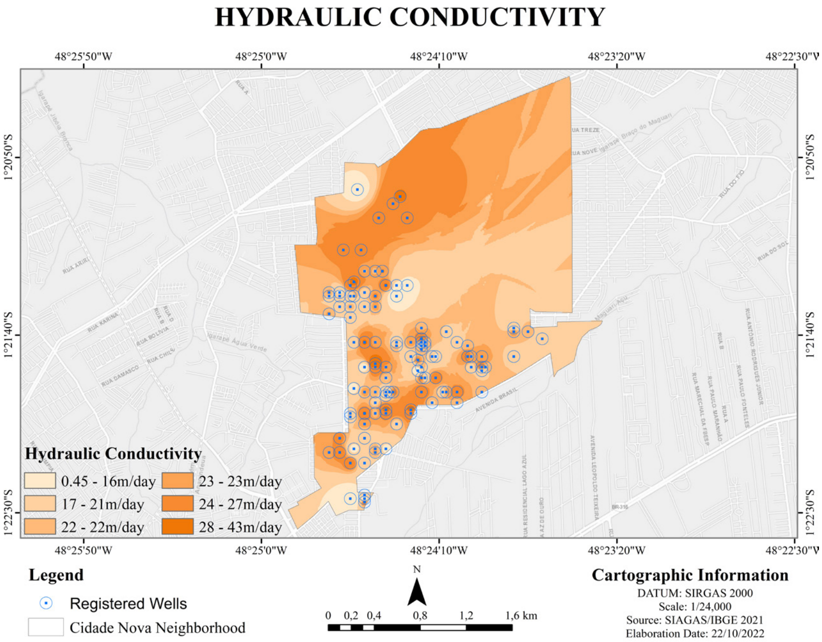

Figure 7. Hydraulic Conductivity in the study area.

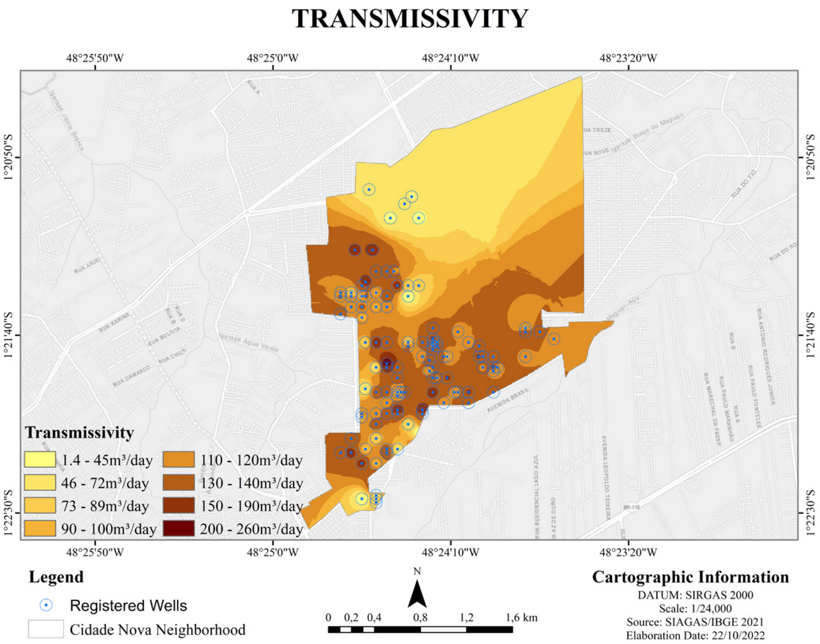

Figure 8. Transmissivity in the study area.

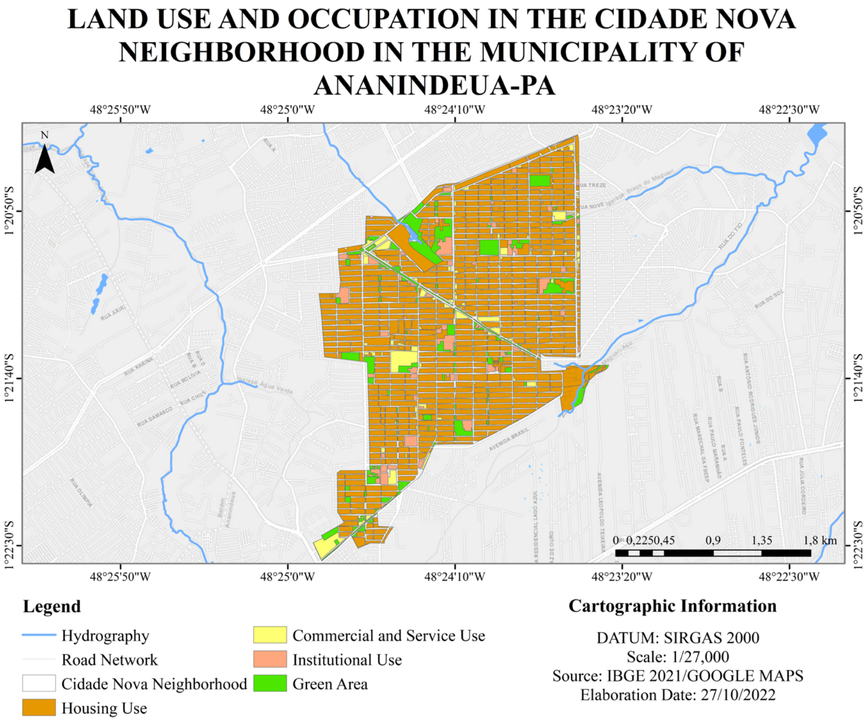

Figure 9. Land use and occupation in the study area.

However, in locations with majoritarian residential use which presents natural vulnerability of aquifers classified as Medium or High and/or with commercial, services and institutional uses, it is found an increased risk of associated contamination. Also, direct discharge of domestic wastes, industrial discharge, leakage from the septic tank, and poor farm waste management is the intrusive groundwater contamination source (Chen et al., 2018).

Thus, it is of great importance that these areas, aiming the decrease of contact of polluting charges with aquifers, must be prioritized on the planning for Water Supply and Sanitary Sewage Systems; focusing on minimizing the risk of contamination by improving coverage indicators and effective service with basic sanitation infrastructure.

The main measure to control contamination is the regularization of the sewage treatment system, ensuring that this effluent does not make its way into the storm drain system. In addition, Talabi & Kayode (2019) consider that an effective prevention plan should take into consideration the following points: waste disposal, hazardous materials, stormwater, management practices, storage tanks and pipes, small- and medium-scale businesses, monitoring wells, and water policy formulation.

It should be noted that the location of these developments in areas of low or insignificant vulnerability does not imply the absence of associated risk of contamination, just as their presence in areas of medium or high vulnerability does not necessarily imply the occurrence of contamination. In this way, preventive measures must be taken for its protection, associated with pollution control as a whole, defining quality criteria starting with the establishment of Guiding Values (Companhia Ambiental do Estado de São Paulo, 2023).

CONCLUSIONS

The application of the GOD method and the use of the ArcGIS software geoprocessing tool to extrapolate the specific hydrogeological information to the whole study area aimed at the subsidy decision-making regarding the planning and management of water resources in the locality.

In this sense, it was found that most of the Cidade Nova neighborhood, located in the municipality of Ananindeua, state of Pará, has an aquifer system classified as *Not Confined*, mixed lithological extracts - ranging from predominantly clayey to mostly sandy - and distance from the top to the water table less than 20 meters.

This information, associated with the pattern of land use and occupation in the area, also based by the study of the hydrogeological quantities of *Hydraulic Conductivity* and *Transmissivity*, are applicable for a better management and use of underground water resources, as well as for the most appropriate allocation of preventive investments with basic sanitation infrastructure in order to minimize or nullify the associated risks of contamination in that neighborhood.

However, it must be provided other information and studies to ensure efficient decision-making by public managers and the actions of other social actors involved in the use and management of groundwater in the locality.

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