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Natural vulnerability of aquifers and the potential contamination of groundwater resources in the State of Acre

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Abstract: Aquifers are strategic reservoirs for any territorial unit, as they serve as future use. However, they must be adequately protected from potential polluting loads, whether of anthropogenic or industrial origin. Such actions depend on policies promoted by the government and the conditions of urban settlements on aquifers, thus instituting them a condition of vulnerability. In this sense, the present study aims to analyze the natural vulnerability of the Rio Branco aquifer, located in the city of the same name, in the state of Acre. For this, we used the GOD - G (Groundwater occurrence), O (Overall aquifer class), D (Depth to groundwater table) methodology as well as the geoprocessing techniques to evaluate the natural vulnerability of the aquifer. The study identifies that the Rio Branco aquifer presents a high degree of vulnerability (0.6) with the application of the methodology. And in this sense, it also comes to propose and contribute to efficient public policies within the territorial planning of the city as a way to minimize the direct impacts on this important subsurface reservoir.

Key words: aquifers; vulnerability; negative impacts

1 Introduction

Groundwater is very important for the balance of the dynamics of water infiltration and flow, and for many years it has served as a reservoir for future demands and implications for an imminent water shortage (FRANCO et al., 2018). Silva et al., (2017) mentions that the underground spring is one of the most important reserves for the water supply and in most cases does not require treatment for its consumption due to the natural filtration process of the subsoil.

Aquifers are characterized as a sufficiently permeable geological layer or formation capable of storing and transmitting water in quantities that can be used as a source of supply for different uses (IRITANI and EZAKI, 2008). Aquifers are classified according to their hydraulic characteristics, confinement or pressure from the bordering surface; they can be free or confined. Regarding the aquifers mentioned above, Faracine (2013, p. 5) states that in the case of a free (or phreatic) aquifer, the saturated zone has direct contact with the unsaturated zone [...] the water that infiltrates the soil crosses the unsaturated zone and directly recharges the aquifer. According to the same author, the confined aquifer is limited at the top and bottom by layers of rock with low permeability (such as clay, shale, massive igneous rock, etc.). The aquifer is subjected to a higher pressure than atmospheric pressure due to a confining layer above it, which is also saturated with water. Thus, the water level has the pressure to reach a height above the top of the aquifer, but is prevented by the confining layer (FARACINE, 2013, p.6).

Both aquifers are subject to natural vulnerability, exposed by their general characteristics. The concept of vulnerability can be understood according to Foster (1988) as the set of intrinsic characteristics of the strata between the saturated zone and the ground surface, which determine their susceptibility to suffering the adverse effects of a contaminant load. The ASTM (American Society for Testing Materials) defines vulnerability in groundwater as the ease at which a contaminant can migrate into the groundwater.

In urban areas exposed to population growth, surface and groundwater are prone to changes in their physical, chemical and biological characteristics due to the input of substances from anthropogenic activities (GOMES et al, 2018). The concern with the maintenance of aquifers is the irregular occupation of adjacent areas since the lack or absence of planning can lead to irreparable environmental liabilities with the reduction of their recharge zone, pollution by toxic contaminants from agriculture and the lack of recurrent basic sanitation in Amazonian cities, being corroborated by Borges et al (2017) who stated that as a result of urbanization, industrial development and agricultural expansion, aquifers are increasingly exposed to contamination, damaging the quality of this resource.

In the state of Acre we have the "Rio Branco Aquifer", which, according to Mello Jr and Marmos (2006 p. 42), is of the confined draining type, covering in the studied region an area of around 122,460,000m², occurring between 2 and 10 meters deep with a thickness varying between 1 and 8 meters. This characteristic applies to the semi permeable layer above the aquifer and the permeable layer below it, formed by intercalated sedimentary packages of the Solimões Formation (TNs). This material would have been deposited from the Pliocene to the Pleistocene (1.75 m.y. and 0.01 m.y.) with an area of 905,000 km² located in the Brazilian sector of the Marañon-Ucayali-Acre Basin (MILANI; THOMAZ FILHO, 2000 p.429).

With this in mind, the aim of this study was to assess the vulnerability of the Rio Branco aquifer using the GOD methodology (G - groundwater occurrence; O - overall aquifer class; D - depth to groundwater table). This type of assessment is of great importance for guiding environmental management mechanisms in the face of anthropogenic activities (BROLLO et. al., 2000).

The aquifer is largely located in the city's second district and in this area you can still see irregular urban occupation and a lack of basic sanitation. This is exacerbating the imminent environmental impact on this water reservoir.

2 Material and methods

2.1 Characterization of the study area

The city of Rio Branco, capital of the state of Acre, has a growing urbanization rate, receiving a population mainly from the interior of Acre and from other regions of the country. The city is divided into seven regional municipal zones distributed in two large districts (SCHMINK and CORDEIRO, 2008).

According to IBGE (2017), Rio Branco has a population of approximately 380,000 inhabitants, making it the sixth largest city in the northern region of Brazil. Its territorial area is 9,222.58 km², making it the fifth largest municipality in the state and with 44.90 square kilometers accounting for 0.49% of the city's circumference.

Most of the neighborhoods of the city were occupied irregularly, by "invasions" or subdivisions without the consent of the government. In this sense, Franco et al., (2018) argued that the occupation occurred by actions of clandestine settlements that did not have public equipment and infrastructure. Without proper territorial organization, the neighborhoods were growing. And due to the lack of an internal water network, many residents began drilling wells, either in Amazonas models or cacimbão models in order to have access to water. Another problem was the construction of black pits in the occupied lots, which in many cases were associated with contamination of the water level, potentiating diseases of water circulation such as Hepatitis A, Giardiasis, Amebiasis and Leptospirosis.

In order to understand the dynamics of the aquifer, it is important to understand the general characteristics surrounding it, including the soil, which, according to Melo Jr et al (2010), has clay, silty clay and sandy clay. These characteristics are present in practically the entire second district of the city.

The second district has 17 neighborhoods (Fig. 1), some of which are older and others more recent, and settled on the area of the Rio Branco aquifer.

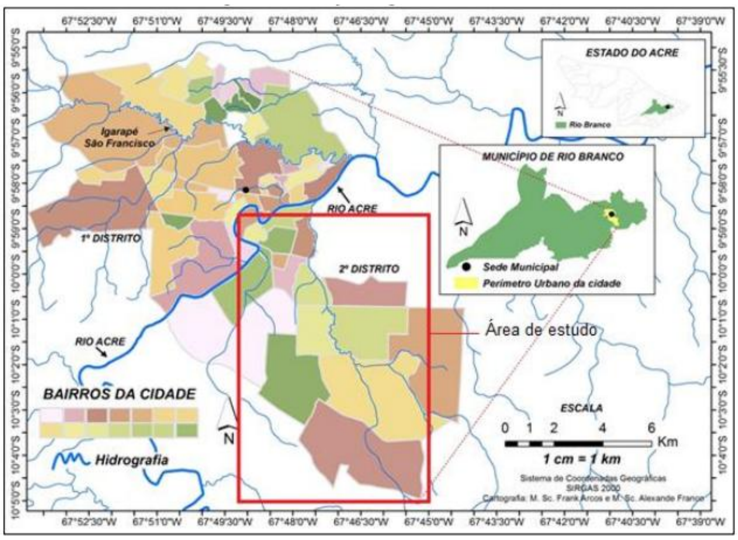

Fig. 1. Geographical location of Rio Branco

Source: UCGeo (2011); PMRB (2013). Organized by the authors (2019).

Problems caused by the lack of a sewage system, the construction of cesspits without proper regulation, urban sprawl and public works without proper planning all have the potential to contaminate groundwater. This has been extremely common in the urban core of the city of Rio Branco, especially in the neighborhoods of the second district, where it is notorious for unplanned horizontal growth.

2.2 Operational research procedures

To assess the vulnerability of the Rio Branco aquifer, the information was organized into three stages:

The first was a bibliographic and documentary survey of the vast literature on the subject, such as books, magazines and technical reports in the field.

In the second stage, an expedited field survey was carried out in the study area as a way of observing the nuances related to the aquifer. The on-site survey was carried out in two phases: the first between 2014 and 2015 to assess water quality. At this stage, we selected eight (08) wells that were previously used by Melo Jr et al 2010 and seven (7) resulting from research by Franco et al (2018), totaling 15 wells in order to establish the metric parameters for analysis. The second was to observe the general characteristics of occupation over the aquifer (allotments created, public works, public bodies installed) in 2019, as well as the lack of sewage systems in the neighborhoods.

In the third stage, the GOD methodology was applied and integrated with the analysis of the aquifer's vulnerability to the risk of pollution. The acronym has meaning in the first letter of the parameters: G (groundwater occurrence), O (overall lithology of aquifers), D (depth to groundwater table). The methodology was developed by the "World Health Organization" (GUIGUER; KOHNKE, 2002 p.5) and, according to the authors, it is a methodology whose main advantage lies in its ease of use and the fact that it uses the most important parameters, such as the depth of the water table, lithologies of the vadose zone and confining layers and the condition of the aquifer (Id. p.12).

This method was chosen for application due to the small number of parameters that enabled better analysis of the data at the soil-water interface. The parameters for assessing vulnerability using the method were proposed in three phases, both of which are interdependent: the degree of confinement, the occurrence of cover extracts and the distance from groundwater. The risk of pollution is defined by Foster and Hirata (1988) as the danger of deterioration in the water quality of an aquifer due to the actual existence of a potential pollutant around it.

The GOD scale index varies between 0 and 1, with the minimum qualifying as insignificant vulnerability and the maximum as extreme. This index is determined by the product of the values obtained in the factors resulting from the phases applied in the assessment (Fig. 2) and with the use of GIS and geostatistical tools, the distribution and, later, the IV (Index of Vulnerability) of the aquifer were carried out.

Among the most varied methodologies for determining the vulnerability index of aquifers, Luiz et al., (2017 p. 756) used R statistical software and its extensions where the spherical, exponential, Gaussian and linear models were evaluated in order to define the best fit from the application of the semivariogram function. However, Guiguer and Kohnke (2002 p.1) tested three methodologies to assess vulnerability, namely DRASTIC, AVI and GOD.

According to Borba et al. (2016 p. 87) after carrying out a study to determine the SI (susceptibility index) using a methodology for this purpose, they concluded that the techniques and use of geoprocessing and geostatistics "proved to be an important tool for delimiting areas with greater and lesser susceptibility to contamination."

In this sense, Foster and Hirata (1988) point out that the vulnerability of aquifers is expressed through the following factors: a) attenuation capacity, resulting from physical-chemical retention (absorption) or reaction of pollutants and b) accessibility of pollutants to the saturated zone. For Hirata and Fernandes (2008, p. 405), [...] the vulnerability of groundwater to contamination can be defined as a function of a set of physical, chemical and biological characteristics of the unsaturated zone and/or bordering aquitard which, together, control the arrival of the contaminant in the aquifer.

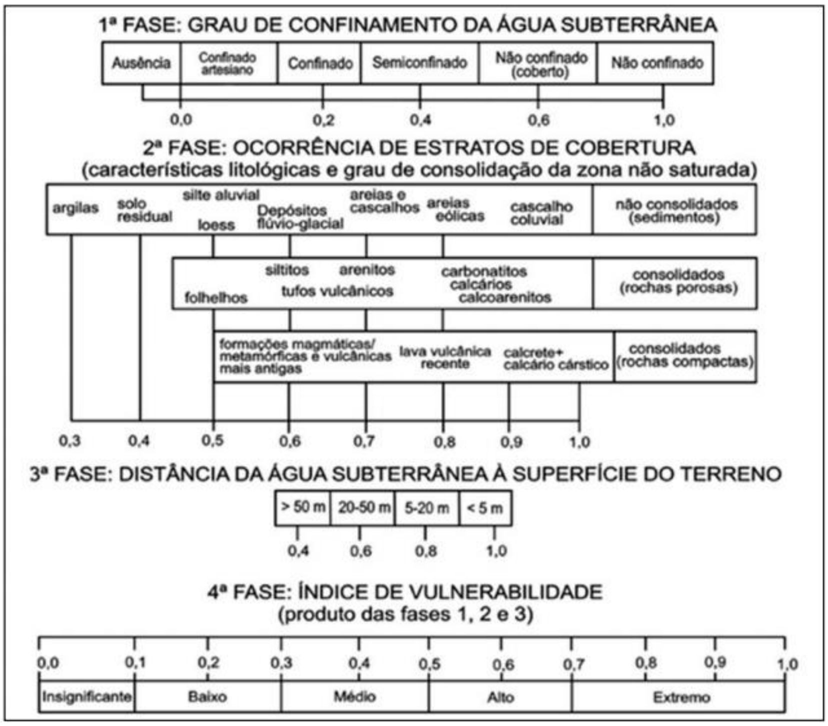

Fig. 2. Stages for determining the vulnerability index using the GOD methodology

Source: Foster et al, (2006). Adapted by the authors (2019).

In this context, vulnerability is understood as the susceptibility of aquifers to be affected by contaminant loads of anthropogenic origin (FEITOSA and MANOEL FILÃO, 2008). Table 1.

Table 1. Vulnerability classes

Vulnerability classes	Corresponding definition
Extreme	Vulnerable to most contaminants with rapid impact in many contamination scenarios.
High	Vulnerable to many contaminants (except those that are strongly adsorbed or rapidly transformed) in many contamination conditions.
Moderate	Vulnerable to some contaminants, but only when continuously discharged or leached.
Low	Vulnerable only to conservative contaminants, in the long term, when continuously and widely released or leached.
Insignificant	Presence of confining layers without significant vertical groundwater flow (percolation).

Source: FOSTER et al, (2002, p. 19)

The vulnerability classes are relevant for measuring the degree of natural vulnerability of the aquifer and indicating the susceptibility of the groundwater body to contamination.

Vulnerability can be represented in the form of maps, allowing management bodies to better evaluate development proposals combined with pollution control and groundwater quality monitoring (RIBEIRO et al., 2011). This contributes to the creation of appropriate and efficient public policies.

3 Results and discussion

The state of Acre, as a territorial unit of the Amazon region, has potentially privileged water characteristics; rainfall is abundant and is very important for any type of analysis. Rainfall corresponds to annual averages of over 1,000 mm (MACÊDO et al 2013). This contributes to recharging the aquifers. Rainfall contributes to the rise and fall of the water table in aquifers, i.e. during periods of abundant rainfall, the Rio Branco aquifer rises closer to the surface, while during periods of drought, the level drops further from the surface. From this perspective, we have different depths for each well according to its location.

The Rio Branco aquifer has the lithological characteristics of a semi-confined aquifer, as it lies between a clay-sand layer at the bottom and one composed of fine sand at the top, also known as a confined drainage aquifer. In the area studied, it is between 2 and 10 meters deep and varies in thickness between 1 and 8 meters (MELO JR; MARMOS, 2006). This type of aquifer is one in which at least one of the boundary layers is semi-permeable, allowing flows to enter or exit (MELO JR et al, 2010).

There is a certain ease of entry of pollutant loads, for example, into groundwater bodies with this type of characteristic. Based on the information mentioned above, it is possible to establish the vulnerability index of the Rio Branco aquifer using the GOD method (table 2).

Table 2. General characteristics: application of the GOD method to wells monitored in the Rio Branco aquifer

Neighborhoods	Wells	G Type of water occurrence	O Lithology of the aquifer	D Depth of water table*	Indices	Degree of vulnerability
Seis de Agosto	P1	Semiconfined - degree of confinement - analytical index 0.4	Holocene alluvium (QHa)- sedimentary deposits of the Solimões Formation (TNs)- characteristic grade - 0.6	4**	0.6	High
Taquari	P2			4**	0.6	High-extreme
Areial	P3			6**	0.66	High-extreme
Belo Jardim - I	P4			7**	0.66	High-extreme
Santa Inês	P5			8**	0.66	High-extreme
Santo Afonso	P6			9**	0.66	High-extreme
Santa Helena	P7			6**	0.66	High-extreme
Praia do Amapá	P8			5**	0.6	High
Ramal Bom Jesus	P9			2***	0.66	High-extreme
Ramal Benfica	P10			3***	0.66	High-extreme
Vila da Amizade	P11			4***	0.66	High-extreme
Major Mendonça	P12			2***	0.66	High-extreme
Rodovia Ac-01	P13			3***	0.66	High-extreme
Cidade Nova	P14			4***	0,66	High-extreme
Cidade Nova	P15			5***	0.6	High

Source: MELO JR et al (2006; 2010); Franco et al, (2018). Org: The authors.

1. Note: * Variable by period of the year (Nov./Apr. - rainy season and May/Oct. - dry season) ** Sampling was carried out during the dry season of the year. *** Sampling took place during the year's rainy season.

At least 14 neighborhoods in the second district of Rio Branco were analyzed (Seis de Agosto, Taquari, Areal, Belo Jardim - I, Santa Inês, Santo Afonso, Santa Helena, Praia do Amapá, Ramal Bom Jesus, Ramal Benfica, Vila da Amizade, Major Mendonça, Rodovia Ac-01 and Cidade Nova).

Among the observations extracted from the study, it can be verified that (Table 2), regardless of the period of the year analyzed, rainy or dry, both show potential contamination for the Rio Branco aquifer and, in this specific case, it is inferred that the natural vulnerability is high to extreme, since its characteristics are "sensitive" to the polluting load of anthropogenic activities, occurring as a result of:

a) type of water occurrence, in this case as mentioned, semi-confined with an index of 0.4; b) aquifer lithology, holocene alluvium and an index of 0.6; c) depth of the water table, variable according to its location, but generally between 2 and 9 meters deep.

Thus, the vulnerability index for the Rio Branco aquifer ranged from high to high-extreme (Fig. 3).

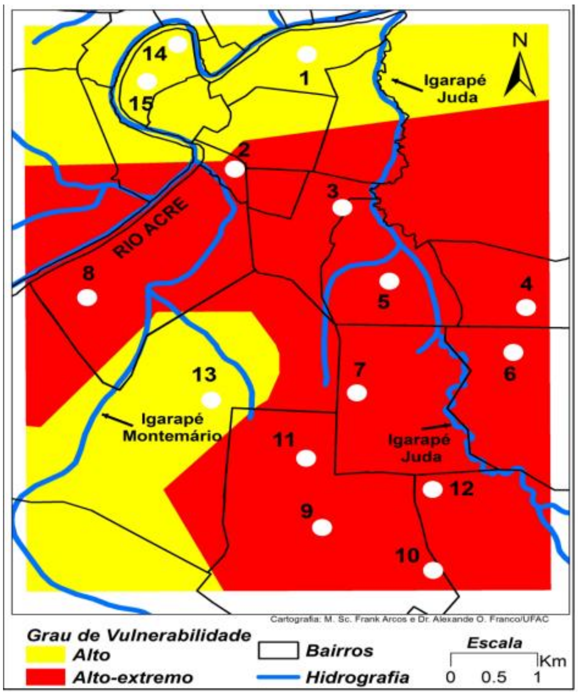

Fig. 3. Areas of vulnerability of the Rio Branco aquifer

Source: Authors (2019)

We can see in the cartogram (Fig. 3) that all the neighborhoods have a certain vulnerability, that the vulnerability of the yellow neighborhoods (Taquari, Areial, Belo Jardim, Santa Inês, Santo Afonso, Santa Helena, Ramal Bom Jesus, Ramal Benfica, Vila da Amizade, Major Mendonça and part of Cidade Nova) and the red neighborhoods (Seis de Agosto, Praia do Amapá) and part of Cidade Nova is greater.

Drawing up the vulnerability map is one of the stages on which groundwater management and protection activities can be based, guiding environmental and territorial planning professionals in the creation of studies to monitor the risks of contamination and water quality, with the subsequent definition of areas to protect and control the use of groundwater (RIBEIRO et al, 2011, p. 100).

It is worth mentioning that, according to Melo Jr et al (2010), the DRASTIC2 method mentioned a natural vulnerability between medium and high for the site, whereas today, almost 10 years after the analysis, the natural vulnerability by GOD is between high and very high (extreme). Despite the different methods, the information converges and highlights the increased vulnerability of the aquifer in question.

In this sense, the aquifer is notoriously vulnerable to many contaminants with rapid impact on many contamination conditions (FOSTER et al, 2002). This perspective clearly indicates the potential impact on the aquifer. The proximity of the phreatic depth has a positive aspect in terms of water collection and a negative aspect that can contribute to the ease of contamination from anthropogenic pollutant loads.

The characteristics of the aquifer combined with irregular occupation, the lack of public policies, poor planning in the construction of wells and, above all, potential pollution loads can undoubtedly interfere with the quality and dynamics of the water in the aquifer in question.

3.1 Irregular occupations and the lack of public policies

Irregular occupation throughout the history of the city of Rio Branco is a risk factor for the aquifer. This is because people occupy a plot of land and then a house without the slightest housing conditions, because there will be no water available in the short term, and often for long periods without a water and sewage system. Irregular land occupation and the absence of legal regulatory mechanisms jeopardize the natural quality of groundwater (RIBEIRO et al., 2011), eventually contributing to pollutants entering aquifers.

The concern is still mainly due to the lack of planning in public policies capable of investing in this area. A reflection of this is the lack of sewage systems throughout the city. According to data from the Sanitation Ranking (INSTITUTO TRATA BRASIL, 2019), the city was 74th in 2017, and a year later, in 2018, the situation worsened, dropping to 90th place. It was a deficit of 16 positions and a percentage of only 22% of the population served. This is even worse in the neighborhoods of the city's second district, as most of the occupation took place through land invasions. These invasions or irregular occupations have resulted in the construction of privy houses close to the wells without the slightest concern, as well as other waste.

This leads to a series of problems related to drinking contaminated water from mines, wells, spouts, or using mineral water from contaminated sources.

3.2 Contaminants and poorly planned wells

Occupation without proper planning brings different problems to society, and with regard to surface and groundwater, this is a silent risk factor. In Rio Branco, as mentioned above, the lack of a sewage system, whether due to irregular occupation or not, increases the potential for contamination.

The most common contamination is related to loads of physiological waste related to coliforms. Corroborating the prospect of contamination of aquifer water, according to Franco et al (2018), a good number of local wells have evidence of contamination by total and fecal coliforms.

Note: 2 A method for analyzing the natural vulnerability of aquifers, where five parameters are analyzed (D - depth to groundwater); R - aquifer recharge (recharge); A - aquifer characteristic; S - soil media; T - topography). 3 Regional name for a black pit. It is a small house with a hole underneath where the individual performs his physiological needs.

The analysis shows that although the Rio Branco aquifer is of great importance to the city and its population as well as a strategy for supplying the city, the actions and occupations of land use give us the dimension of little concern on the part of the public authorities and the population. The main causes of pollution of the aquifer are the lack of a sewage system in most of the houses in these neighborhoods, and its fate is directly thrown into the River Acre or thrown into streams, black pits. In addition, vegetation on the aquifer is also removed for the construction of new houses (FRANCO et al., 2018, p. 10).

Other polluting sources are household oils, detergents and soap, as they can interfere with the quality of water consumed in wells, especially those close to these contamination.

Other potential sources of pollution include:

a) fuel stations - contamination from fuel station waste. These waste products, such as fuel, are highly polluting and degrade aquifers. Taking into account the neighborhoods of the second district and their gas stations, it is important to constantly monitor them as a way of avoiding impacts. It is important to carry out studies on the potential impacts of fuels on the aquifer in question.

b) handling and disposal activities - inadequate handling and disposal of raw materials. These include car washes, mechanics and oil changes. In many of these places, waste is disposed of on the ground or in holes that have been built to store it irregularly, so that it percolates into the ground more quickly.

c) poorly planned wells - Poorly planned or poorly constructed wells next to cesspits become pathways for pollutants to reach the groundwater directly. It is more susceptible to contamination.

d) polluted watercourses - The second district has seen increasingly clear contamination and pollution of surface watercourses, such as the Almoço stream, which cuts through the Vila Acre neighborhoods (Benfica branch, Bom Jesus branch, Vila da Amizade), the Judia stream (Vila Acre, Seis de Agosto, Santo Afonso, Belo Jardim), the Monte Mário stream (Amapá), which contribute to infiltration into the aquifer. This makes it difficult to artificially recharge aquifers with non-compatible water quality.

e) irregular landfills - These are found throughout the neighborhoods mentioned, especially in vacant lots where everything from dead animals to wrecked cars can be found.

This situation is a notorious problem, as Ferreira (2019) mentions, where this condition suggests that domestic wells for water collection by the inhabitants of Rio Branco constitute a health risk for the people who drink this water, that is, there are significant loads of waste being made available to the aquifer, especially in the densest places that present the greatest vulnerability.

4 Final considerations

It is important to mention that although vulnerability is higher than that in other parts of the city, for example, in the first district, although densely populated and on the same lithology (Solimões Formation), there are few studies. And it is therefore necessary to develop management models for urban and environmental planning, which consist of appropriate ways of minimizing environmental impacts within the city and, consequently, on groundwater.

According to the results obtained by the GOD method, the study area is notoriously vulnerable to negative impacts due to the characteristics of the local aquifer. The methodology used, given its flexibility, especially in assigning weights and determining parameters, is essential for obtaining the IV and the risk to which the aquifer is subject.

Susceptibility to contaminants is a problem that is increasingly present in the aquifer and, among the causes observed, are the increase in irregular allotments on the site, urban expansion without planning, public and private construction often without due respect for the environment, as well as low investment in basic sanitation.

With regard to problems related to vulnerability, the planning of occupations over the aquifer must be taken into account, otherwise the geological environmental and, above all, natural conditions of this resource could be compromised. According to the work of Franco et al. (2018), subsurface water is polluted in several neighborhoods in the city. This demonstrates the need for state and municipal authorities to invest resources in monitoring the quality of groundwater, in works that enable better urban, social and environmental planning in the second district of the city of Rio Branco. If this doesn't happen, the increase in diseases related to poor water quality is potentially dangerous in the short and medium term.

To this end, research into areas that are sensitive to contamination, such as aquifers in urban areas, should be improved in terms of the applicability of techniques and procedures in the Acre region, in order to propose them to the constituted authorities, for example, the environmental secretariats at state and municipal levels, with the aim of raising awareness of the problems and acting with effective solutions in urban and environmental planning.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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