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Determination of the groundwater vulnerability index in Novo Hamburgo (RS)

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ABSTRACT
The municipality of Novo Hamburgo is located in the metropolitan region of Greater Porto Alegre (RS) and has a high consumption of water from underground springs. Because of this, it is important to analyze the natural vulnerability of this aquifer. For this, the GOD index was used to analyze, because this index has parameters that are easy to acquire, namely: type of aquifer, lithology of the layer above the saturated zone and depth to the top of the saturated layer. For the municipality, 84 wells were found registered in the SIAGAS database, from which the index data were acquired. Of these wells, 81 are in the lower class and 3 are in the middle class of the index. Based on the GOD index, the municipality does not have areas with natural vulnerability to high aquifer contamination, however, it is recommended to carry out studies that relate the index to land use in the municipality.

Keywords: GOD index, Aquifer, Groundwater.

INTRODUCTION

The study of groundwater has become of potential interest both to the academic community and to society. Due to the growth in demand for this good for the most diversified uses, in addition to human consumption and thirst. The intense use of surface water resources has saturated this asset, either by the reduction of its springs, as well as by the contamination of the waters. Because of this, groundwater is a viable option due to its relatively easy access to this commodity, its good quantity and quality (Foster & Hirata, 1988). On the other hand, for the removal of this asset, it is necessary to build a deep well, as this is an engineering work, it requires some care and rules for the preparation of these.

The elaboration of a deep well without a prior study can cause problems, both in its construction in areas without water, as well as in problems in water collection and problems in the coating and sealing. The latter can end up leaving local groundwater susceptible to external contaminants, as these can come into contact with the waters due to carelessness in the construction of wells (Foster et al, 2006; Kemerich et al, 2011).

In addition, other factors are also important in the analysis of groundwater susceptibility, such as soil type, rock substrate and water depth. These and other attributes are identified and analyzed for the construction of a well, and these same attributes are classified in the groundwater vulnerability study.

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The analysis of groundwater vulnerability is of great importance to identify in which areas there is greater potential for contamination, this study is also important because the identification of more susceptible areas can delimit the use of surface soil, being important in the management of cities. Among the types of analysis, there are groundwater vulnerability indexes, where analysis parameters are delimited, each parameter has classes, and these are calculated in order to indicate the level of vulnerability of the region to contamination (Foster & Hirata, 1988).

Among the most well-known indexes is the GOD index, this index calculates the intrinsic vulnerability of the aquifer, that is, it does not take into account land use; It has three calculation parameters, which are easy to acquire, which makes the GOD index widely used in the country (Foster et al, 2006).

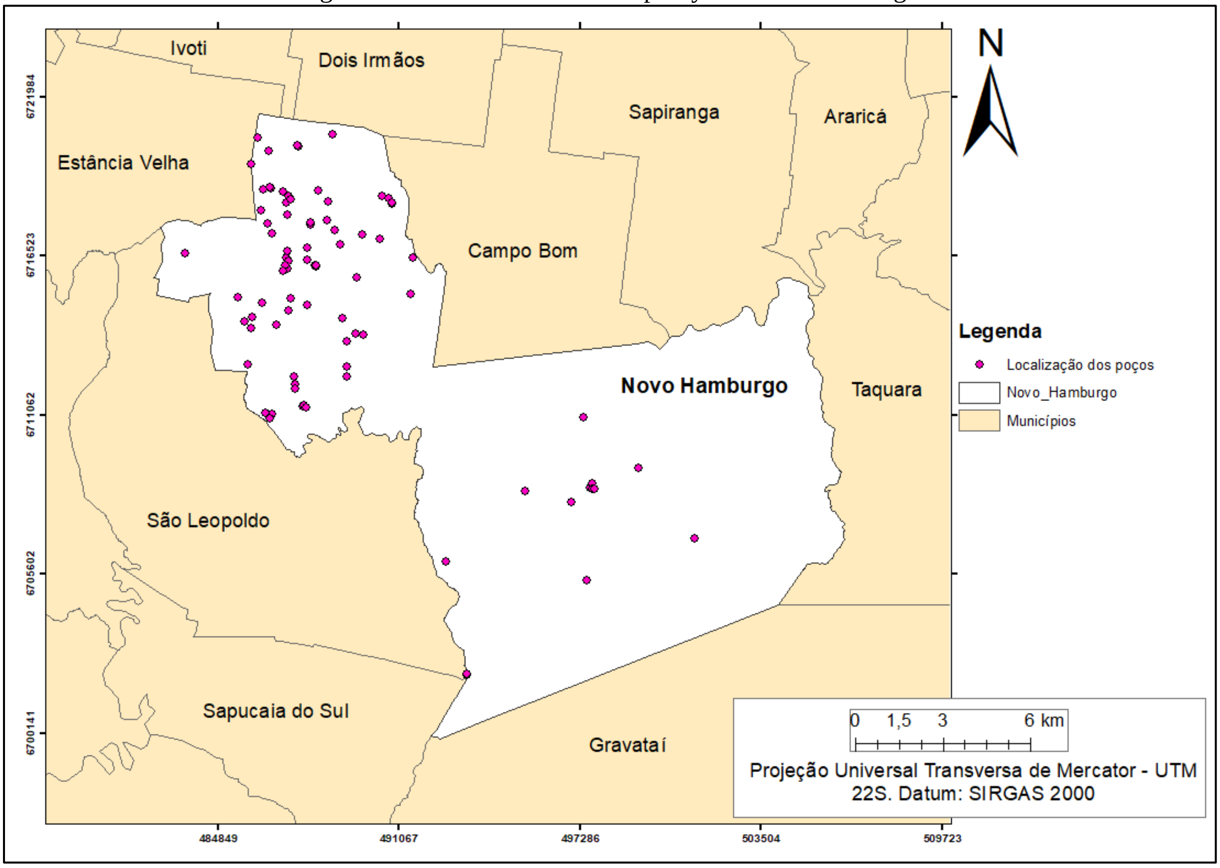
The municipality of Novo Hamburgo, in Rio Grande do Sul (RS), has a high consumption of groundwater, with 84 wells registered (SIAGAS, 2024). The municipality is located 40 km from the capital, Porto Alegre, with a total area of 222,536 km² and a population of 227,646 inhabitants, where water consumption has different sources, such as the water distribution network, collection wells and others (CENSO, 2022; IBGE cities, 2024).

Because of this, this study aims to classify the vulnerability of groundwater in the municipality of Novo Hamburgo (RS) through the GOD index. In order to indicate whether the municipality has a natural vulnerability to contamination, this study may facilitate decision-making about land use, avoiding regions where intrinsic vulnerability is greater.

FIELD OF STUDY

This municipality is located in the metropolitan region of Porto Alegre, located to the north at the base of the Plateau (figure 1, location of the municipality of Novo Hamburgo). It has a total area of 222,536 km² and an urban area of 56.85 km², with a population of 227,646 people, with a population density of 1,022.96 inhabitants/km², according to the 2022 census (IBGE Cidades, 2024).

Figure 1 - location of the municipality of Novo Hamburgo



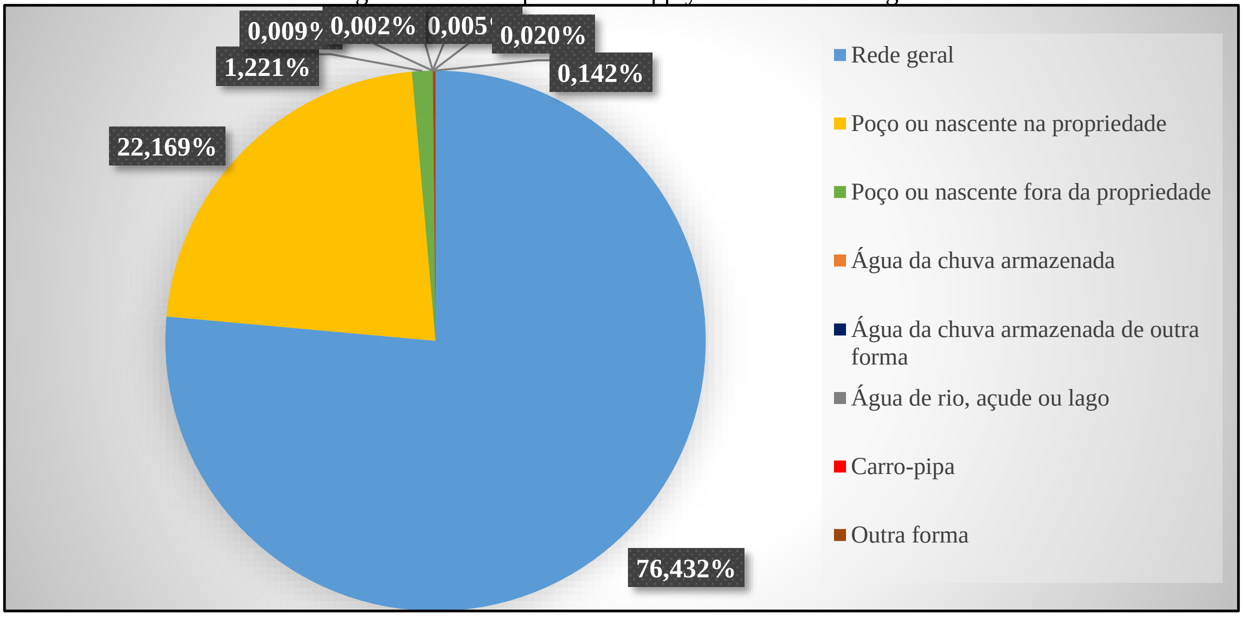
Data source: IBGE (2024), SIAGAS (2024). The author.

The municipality has a sanitary sewage system of 92.1% due to the general sewage system and septic tank (in 2010). It has its territory with 990 ha for crops, 2,891 ha for livestock, 782 ha for woods or forests, 106 ha for silviculture and 18 ha for agroforestry systems; with 66 ha of irrigated area. It has a volume of treated water of 27,031 m³ per day, with 72,921 units of establishments supplied (out of a total of 83,303 households), according to the census (2017) [IBGE Cidades, 2024].

The municipality has an autarchy, since 2008, called COMUSA – Water and Sewage Services of Novo Hamburgo, whose objective is to manage the supply of drinking water and treatment of municipal cloacal sewage. Water is collected from deep wells at three points and at one water collection point the source of water is the Sinos River. According to the municipality, it serves 98% of the municipality's urban area (COMUSA, 2023).

As of the 2010 Census, the form of water supply is from the general network in 61,458 households, 17,826 with a well or spring on the property, 982 households with a well or spring outside the property, 4 households with stored rainwater, 2 households with water from a river, dam or lake, 7 households with rainwater stored in another way, 16 households have water from tanker trucks and 114 have another form of supply (IBGE Cidades, 2024) [figure 2, municipal water supply in Novo Hamburgo].

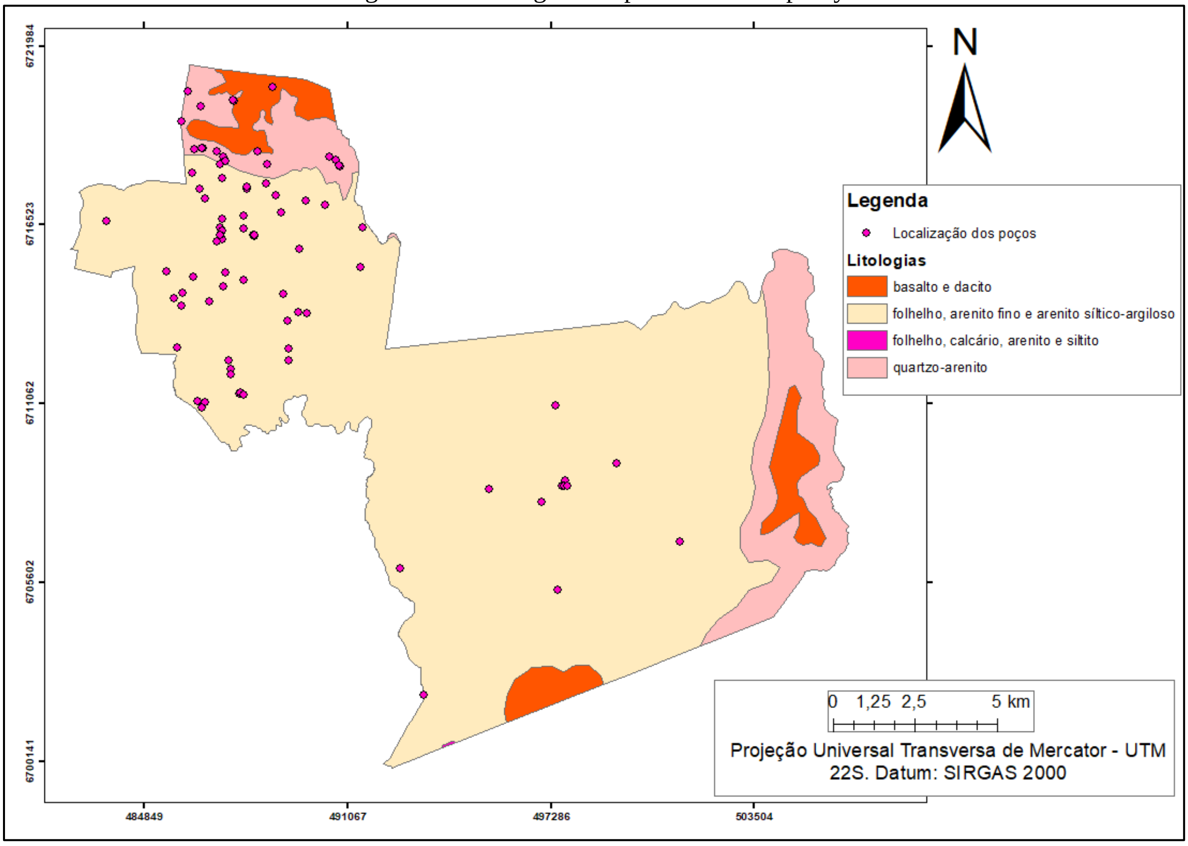
Figure 2 - Municipal water supply in Novo Hamburgo



Data source: IBGE Cidades (2024). The author.

The lithologies found in Novo Hamburgo, according to the mapping of the Geological Survey of Brazil, are mainly sandstones and basalts, with layers of shales, limestone and siltstones, in addition to the occurrence of dacites (figure 3, lithological map of the municipality), of the Serra Geral, Botucatu, Pirambóia and Passa Dois Formations.

Figure 3 - Lithological map of the municipality



Data source: SBG (2020), SIAGAS (2024), IBGE (2024). The author.

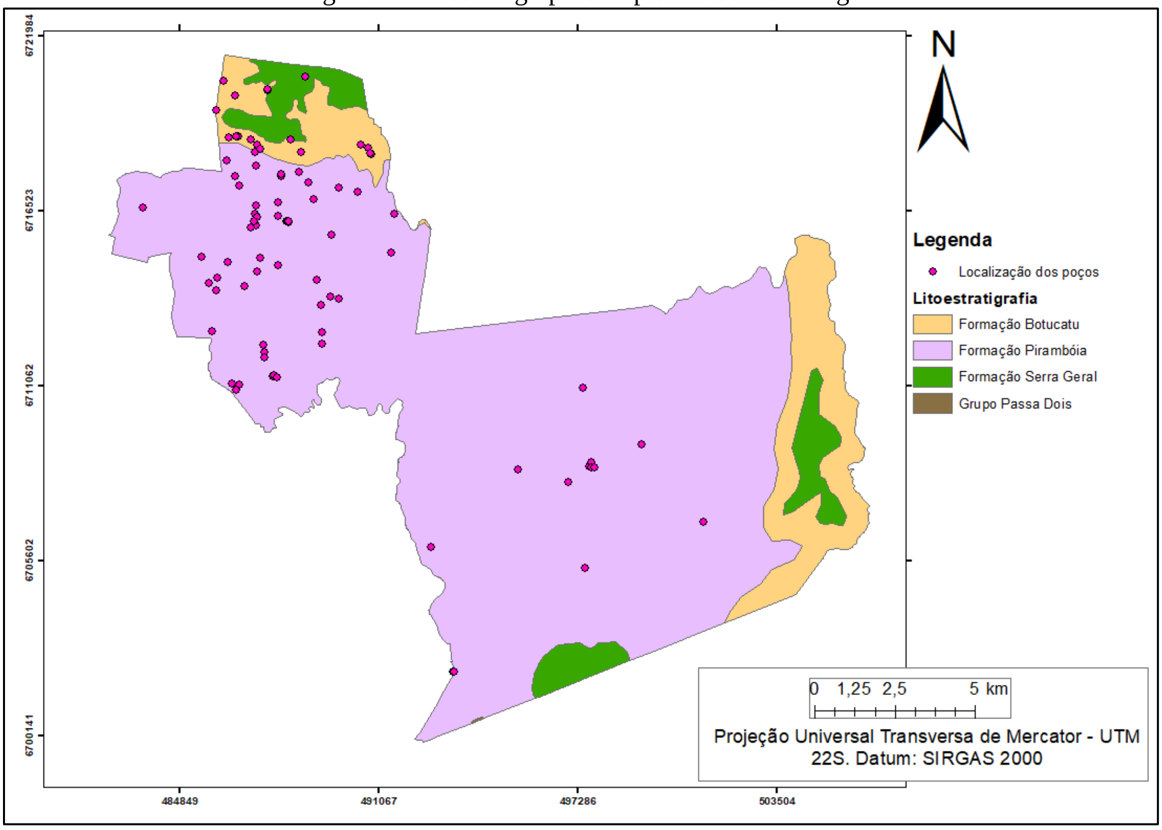
The Serra Geral Formation, with rocks of volcanic origin from the Lower Cretaceous, with the Gramado facies, with basaltic flows of 132 million years, fine granular to medium, melanocratic, while the Caxias facies range from intermediate to acidic, rhyodacites, 131 million years old, mesocratic (SBG, 2009 and Scherer *et al*, 2000).

The Botucatu Formation of aeolian origin, from the Lower Cretaceous, appears interspersed with basalts, as well as, at their base, these sandstones have high sphericity with well-rounded grains, having fine to thick sandstones with small to large cross-stratification (SBG, 2009 and Scherer *et al*, 2000).

The Pirambóia Formation, of the Upper Permian, of predominantly aeolian origin, with facies of dunes and aqueous interdunes, cut by facies of temporary fluvial channels. The sandstones of this formation range from fine to conglomerate, sometimes having interstitial clays, with secondary regrowth of quartz (Caetano-Chang and Wu, 2003; Fúlfaro, Suguio, 1974).

The Passa Dois Group is made up of the Estrada Nova and Irati Formations, of Permian age. The Irati Formation has predominantly shales and associated limestones. The Estrada Nova Formation has limestones interspersed with siltstones and fine sandstones (Fúlfaro, Suguio, 1974) (figure 4, lithostratigraphic map of Novo Hamburgo).

Figure 4 - lithostratigraphic map of Novo Hamburgo



Data source: SBG (2020), SIAGAS (2024), IBGE (2024). The author.

Regarding hydrogeology, the Geological Survey has the hydrogeological map of the state of Rio Grande do Sul, prepared by Machado and Freitas (2005), in which the region has the aquifer systems: Botucatu / Pirambóia and Serra Geral II Aquifer System (figure 5, municipal hydrogeological map).

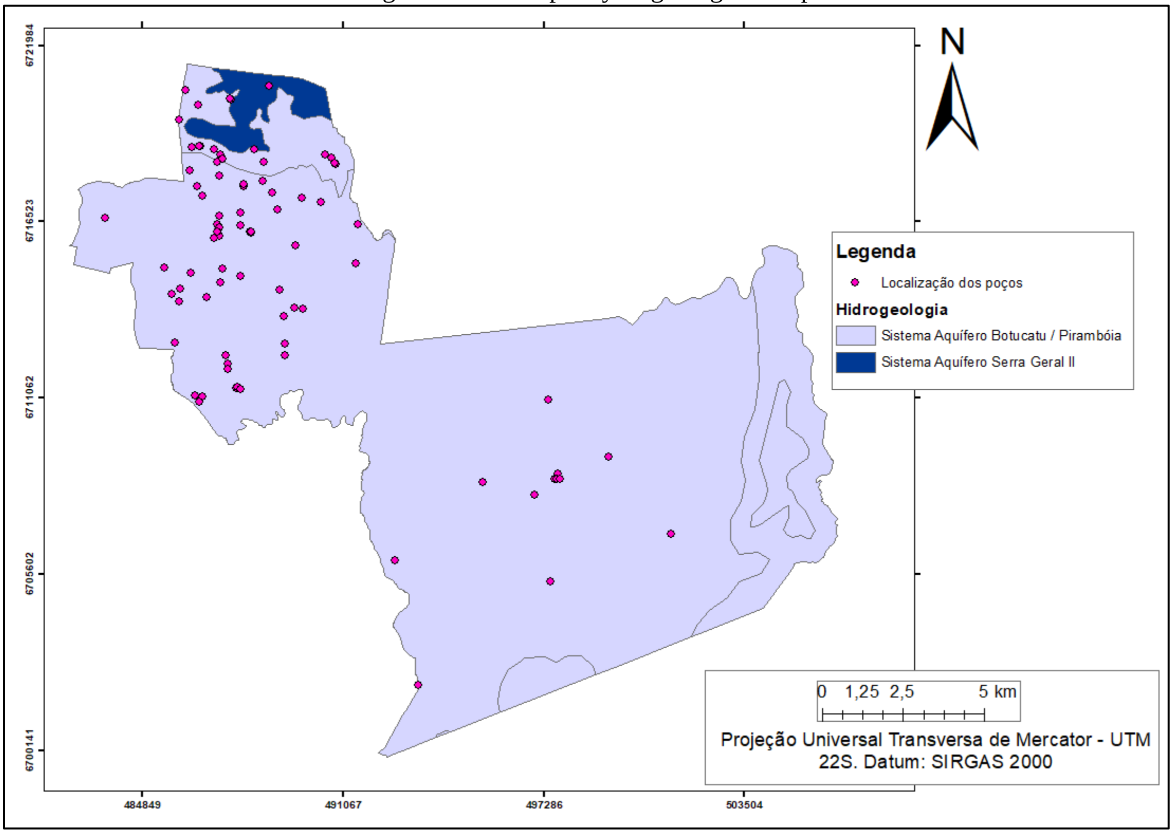
The Serra Geral II Aquifer System has lithology of fractured rhyolites, rhyodacites and basalts, the specific capacity is less than 0.5 m³/h/m, however, in areas where there are sandstones at the base or there is a lot of fracturing, there may be values higher than 2 m³/h/m.

The Botucatu/Pirambóia Aquifer System has medium, pink sandstones with topo-structural conditions generally unfavorable for water storage. It also has fine to very fine sandstones and reddish sandstones with a high clay content. With specific capacities that rarely exceed 0.5 m³/h/m (Machado and Freitas, 2005).

The municipality of Novo Hamburgo is located directly on the Pirambóia Hydrostratigraphic Unit, which is predominantly sandy, but fine-grained and clayey. Because of this, this aquifer has medium to poor capacity, but generally with good quality water. The further north, towards the municipality of Ivoti, the hydrogeological characteristics change. However, in the region of the valleys, where Novo Hamburgo is located, the outcrops of the aeolian sandstones are observed (Machado and Freitas, 2005).

The potentiometric map prepared by Machado (2005) for the compartmentalized Guarani aquifer system (SAG) indicates that it is confined in the region. The Guarani Aquifer System for the state of Rio Grande do Sul is confined by the volcanic lithologies of the Serra Geral Hydrostratigraphic Unit. The Botucatu Hydrostratigraphic Unit is the one with the largest distribution of confined area, with flows sometimes exceeding 500 m³/h; It has average specific capacities between 0.5 and 2 m³/h/m. The Botucatu/Pirambóia system has waters with low salinity (MACHADO, 2005).

Figure 5 - Municipal hydrogeological map



Data source: SBG (2020), SIAGAS (2024), IBGE (2024). The author.

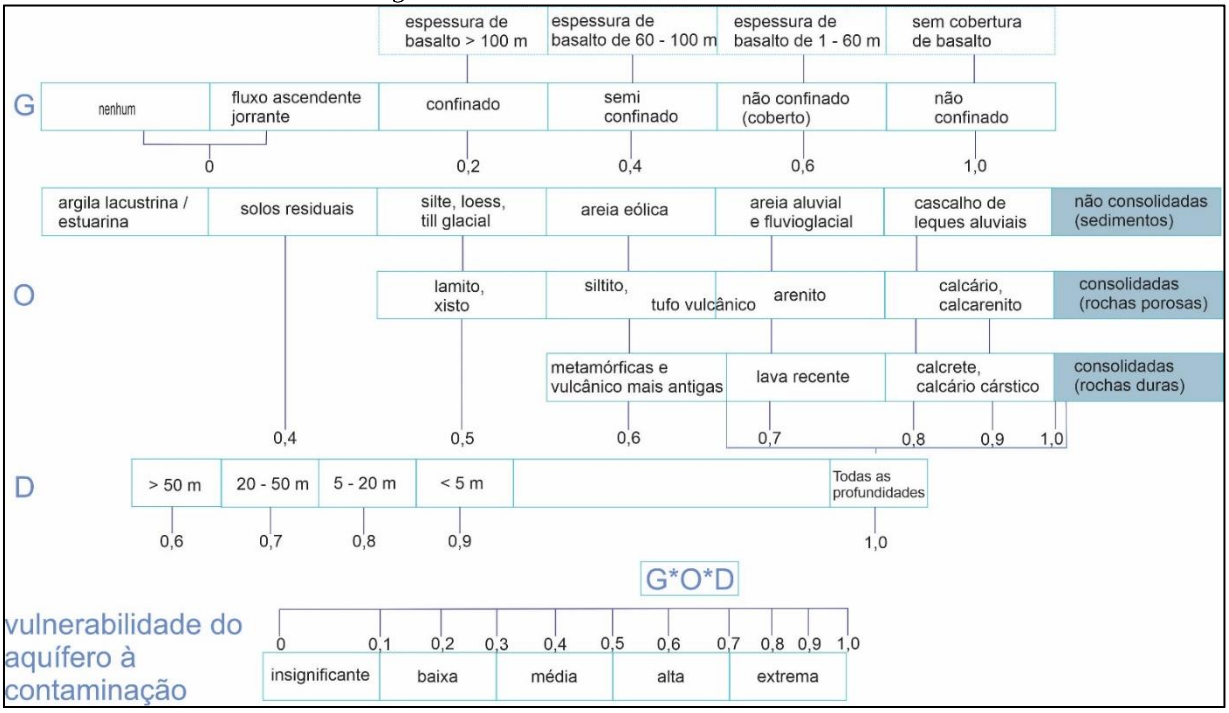
VULNERABILITY INDEX

The GOD index was developed by Foster (1987), Foster and Hirata (1988) and Foster et al (2006), where the Brazilian reality was considered, where the acquisition of parameters is difficult, with many wells without data (Foster et al, 2006). It aims to analyze vulnerability to intrinsic contamination, based on three parameters. These are:

- G Groundwater occurrence: Each well has a type of occurrence. This parameter can be free, covered, semi-confined, confined, or gushing.
- The Lithology of the overlying: Classifies the lithology in the layer above the saturated zone, or the layer above the top of the aquifer, the parameters can vary between sediments, sedimentary rocks, igneous and metamorphic rocks.
- D Depth of groundwater: This parameter is the distance to the saturated zone or to the aquifer ceiling. It varies from water upwelling to depths greater than 50 meters.

Each parameter receives a score, which will be multiplied and classified according to the vulnerability classes (figure 6, characterization of the GOD index).

Figure 6 – Characterization of the GOD index



Adaptado de Foster et al (2006)

RELATED WORKS

Löbler *et al* (2014) used the GOD for the municipality of Nova Palma (RS), where the Serra Geral Aquifer System (SASG) and the Guarani Aquifer System (SAG) occur, the latter is in confinement and free; and this municipality is supplied by these waters. Of the area, the majority are in the medium and high vulnerability classes, however, the value of the extreme class is significant. The areas with the highest levels of vulnerability are located near rivers and flooded areas. The authors considered the basaltic flows as sealants of the SAG water, however, for this, it is important to analyze the billing of the igneous rocks and how they interact with the aquifer.

The GOD analyzes natural vulnerability and does not take into account land use; however, the authors indicated that most of the projects are in the highest classes of aquifer vulnerability, Löbler *et al* (2014) highlight the importance of developing inspection plans for the municipality in order to prevent possible contamination.

Reginato & Ahlert (2013) studied fractured aquifers and the natural vulnerability index, using the GOD and DRASTIC methods. For both indices, the moderate and low vulnerability classes were the majority; There are few discrepancies between the two indexes. For this study, the authors established a value of the G parameter of the GOD of 0.5 (between semi-confined and covered) since the aquifer is basaltic and thick; However, due to fractures and faults in the rocks, it is not advisable to consider it as a confined aquifer.

Brito & Reginato (2018) related GOD and POSH to the Master Plan for Urban and Environmental Development of Porto Alegre, where the value of GOD is average in most of the area, however, POSH is high in most of the area. For the authors, this does not indicate a risk of contamination, but reinforces the importance of inspection so that potentially polluting enterprises do not occur irregularly.

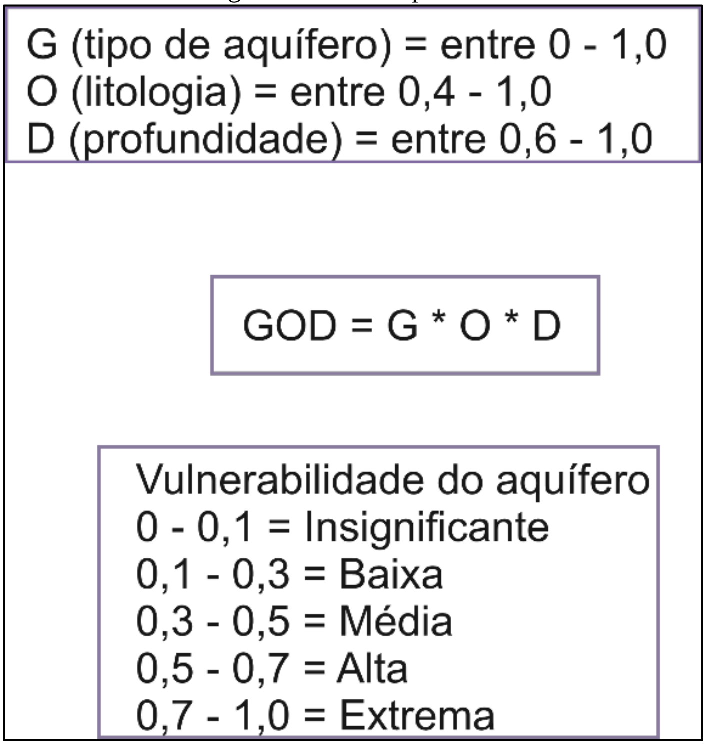
Kemerich et al (2011) conducted the GOD for a neighborhood with a cemetery, where they paid attention to the fact that they found excavated wells and springs, whose water withdrawal is insignificant, but which may end up being contaminated; in the same way, they found irregular wells, being a risk to the quality of the spring.

In the same sense, Foster *et al* (2006) mention that the GOD method underestimates the vulnerability of fractured aquifers, although they ponder the difficulty in acquiring more parameters for calculating vulnerability indices. The authors also note the fact that land use alters other factors and that it is essential to pay attention to the activities carried out on the surface. Also, pay attentionto overexploitation and how this can vary the depth of the water table.

METHODOLOGY

For the calculation of the GOD index, elaborated by Foster *et al* (2006), as can be seen above, the three parameters were acquired from the SIAGAS well registry, a database fed by the Geological Survey of Brazil - SBG. The index was calculated for each well, in a table format in *the Office Excel software*, where each of the three parameters used receives a specific score – each one ranging from 0 to 1 – and then the three scores are multiplied, generating a final value that can vary from 0 to 1 (Figure 7 – expression GOD).

Figure 7 - GOD Expression



Source: Prepared by the authors (2022).

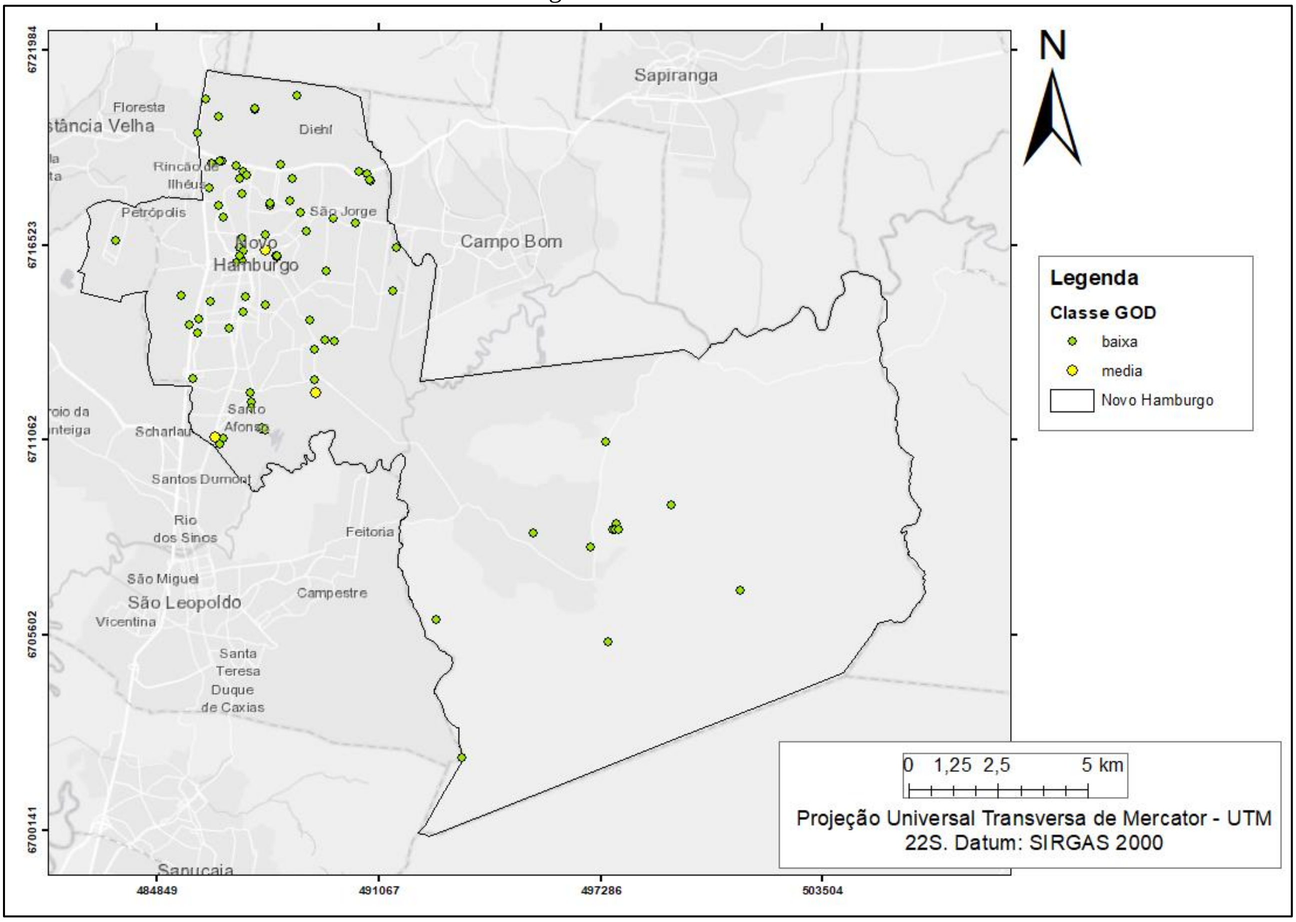
After the organization and calculation of the index, the spreadsheet with data from the wells and coordinates was saved for insertion of the results in a Geographic Information System (GIS) environment, using the *ArcGis* 10 software. The data on the territorial network were taken from the IBGE website, in the geosciences, organization of the territory, and territorial networks tab. Data on soils, geology and hydrogeology were taken from the digital repository, maintained by the Geological Survey of Brazil. All these data were saved as *a shape file* for insertion into the *ArcGis* 10 software.

To analyze the spatial distribution of the GOD index, the input data (well coordinates and total value) were used to generate the GOD index map. The results were compared with the data that are already entered into the database from visual analysis.

DEVELOPMENT

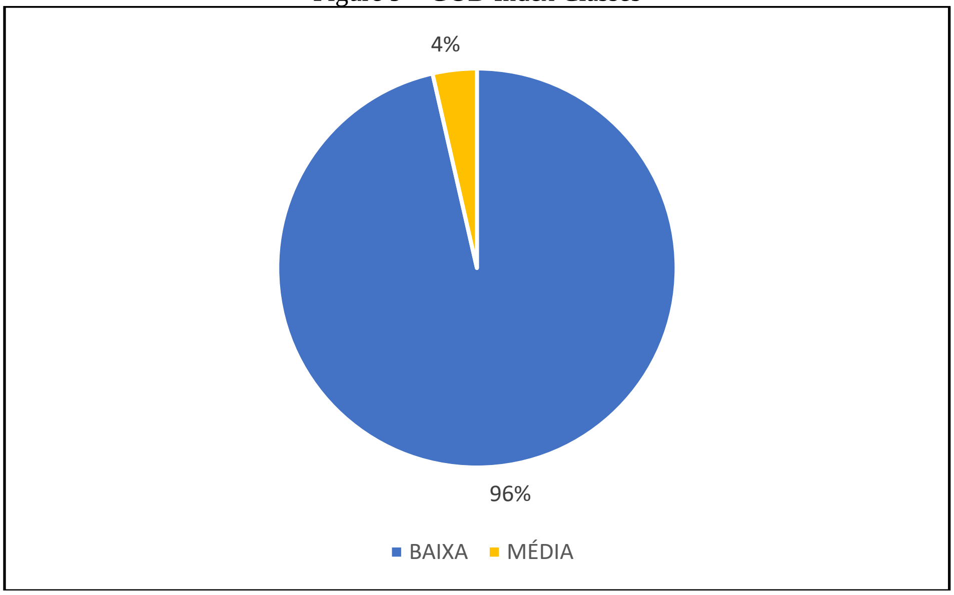
The municipality has 84 wells registered on the groundwater research platform, maintained by the SGB, of which all have constructive and geological data. Of these wells, 14 are in the rural area of the municipality, while the rest are in the urban headquarters. The values of the GOD Index showed spatial variation, and two classes were observed: low and medium. Of the GOD classes, the middle class was found in 3 wells, with the majority, from 81 wells, with the lower class (figure 8 – GOD index and figure 9 – GOD index classes).

Figure 8 – GOD Index



Data source: SIAGAS (2024), IBGE (2024). The author.

Figure 9 – GOD Index Classes

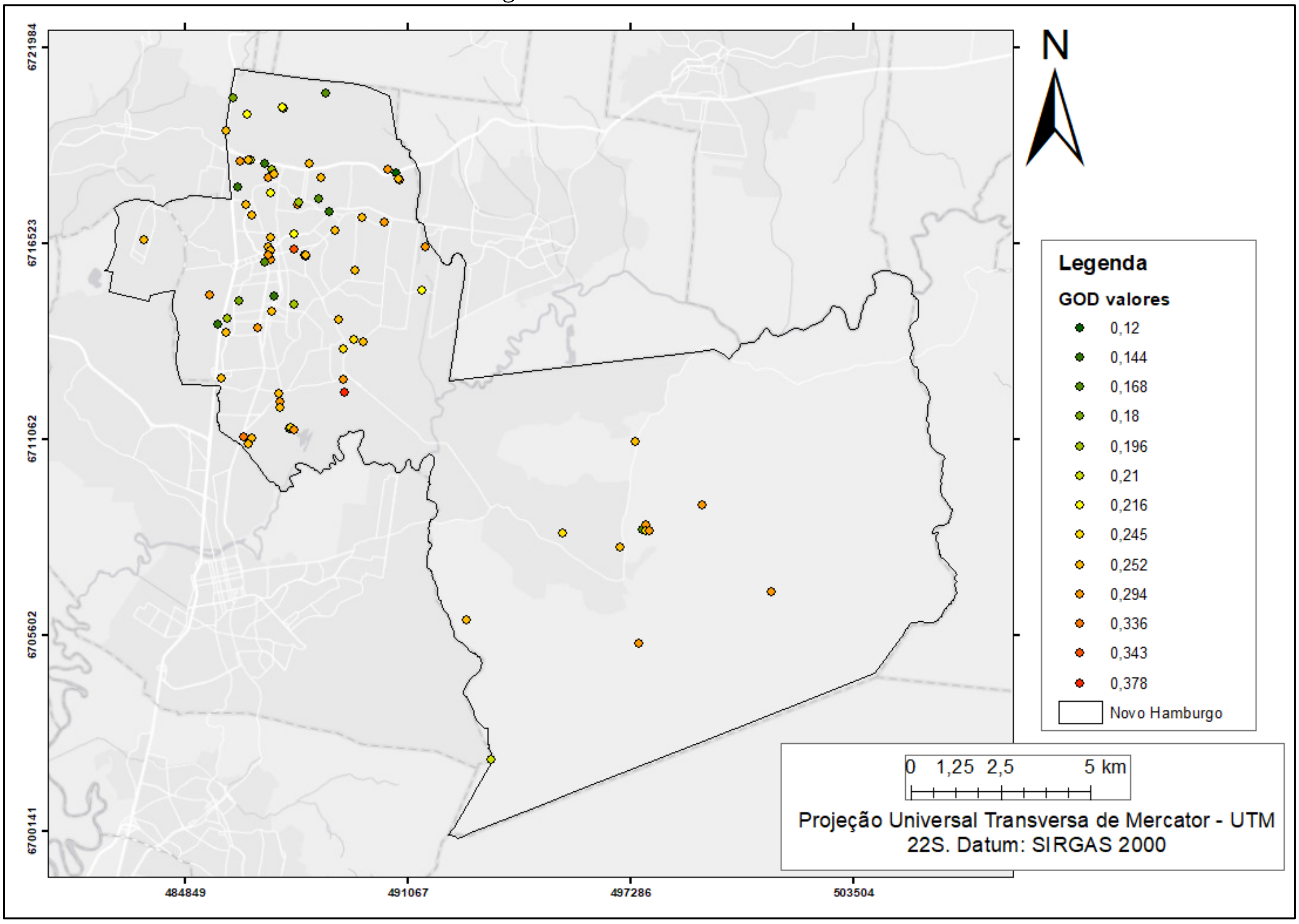


Data source: SIAGAS (2024). The author.

Of the GOD index values, 5 wells have a value of 0.144; 7 wells with a value of 0.168; 3 wells have a value of 0.18; 4 wells have a value of 0.196; 2 wells have a value of 0.21; 5 wells have a value of

0.216; 5 wells with a value of 0.245; 30 wells have a value of 0.252; 19 wells have a value of 0.294; finally, 4 wells have unique values, being the well with the lowest value, 0.12, and the wells with the highest values, 0.336, 0.343 and 0.378, respectively (figure 10 – GOD values in the wells).

Figure 10 – GOD values in wells



Data source: SIAGAS (2024), IBGE (2024). In-house elaboration

Regarding the spatial distribution, it was found that the wells with medium vulnerability class are found in the municipal urban area, while the lower class is dispersed throughout the territory.

The lower class is located in both the urban and rural headquarters. With depths ranging from 20 meters to more than 50 meters. As for lithologies, it is found from clayey, sandy, clay and clay-silty soils, the lithology of the vadosa zone predominantly of sandstone and lithology of the non-vadosa zone mostly of sandstone, but there is occurrence of basalt, siltstone, clay and shale.

The middle class is concentrated in urban areas, one in the downtown neighborhood, another in the Santo Afonso neighborhood, and the third in the Rondônia neighborhood. With depths ranging from 2 to 22 meters. Lithologies of sandstone and basalt, with the lithology of the zone being of sandstone and in 1 basalt pit.

Hydrostratigraphy belongs, for the most part, to the Botucatu/Pirambóia Aquifer System, with two low-class wells belonging to the Serra Geral II Aquifer System. Regarding the local geology, the wells are found in the lithostratigraphic units Botucatu Formation, with 15 wells, Serra Geral Formation with 2 wells and the rest in the Pirambóia Formation, 67 wells. Of the wells with higher GOD values, the three are found in the Pirambóia Formation and Botucatu / Pirambóia Hydrostratigraphic Unit.

Unlike the study by Löbler *et al* (2014), the GOD index for Novo Hamburgo has lower vulnerability classes, identifying a typical valley area with more sandstone layers. However, as with the cited authors, the importance of analyzing the projects in the region is rectified, as well as the elaboration of inspection plans for the municipality in order to prevent possible contamination of groundwater.

As for the uses of groundwater, 56 wells are intended for industrial use, 21 wells for personal use, 5 wells for municipal supply and 2 wells for leisure. Of the 14 wells in the rural area, 1 is intended for leisure, 4 for industrial use and the rest for personal supply, 9 wells. In the urban headquarters, most of the registered wells are for industrial use, with 52 wells. 1 well in the urban headquarters for leisure, the 5 wells for urban supply and 12 wells for personal use.

The wells that are in the middle class of the GOD index, are found with industrial use for the well, while the lower class has all the other uses mentioned. As for the owners, 3 wells are registered by the company that manages the municipal sanitation system, COMUSA, 2 wells registered by the company Capital A Gestão de Transportes Industriais LTDA, 2 wells registered with the Feevale University Center, 2 wells associated with the Nova Via Consortium, 2 wells in the Kunz Forms industry, 2 wells linked to the ACL unit 1 environmental development foundation, 3 wells registered in the name of the industry Irmão Machini and CIA LTDA, 2 wells registered in the metallurgical company Daniel and 2 wells registered in the industry Calçados Beira Rio SA. Finally, 4 wells are registered in the name of the Hamburg County Condominium and another 4 registered in the name of the same individual.

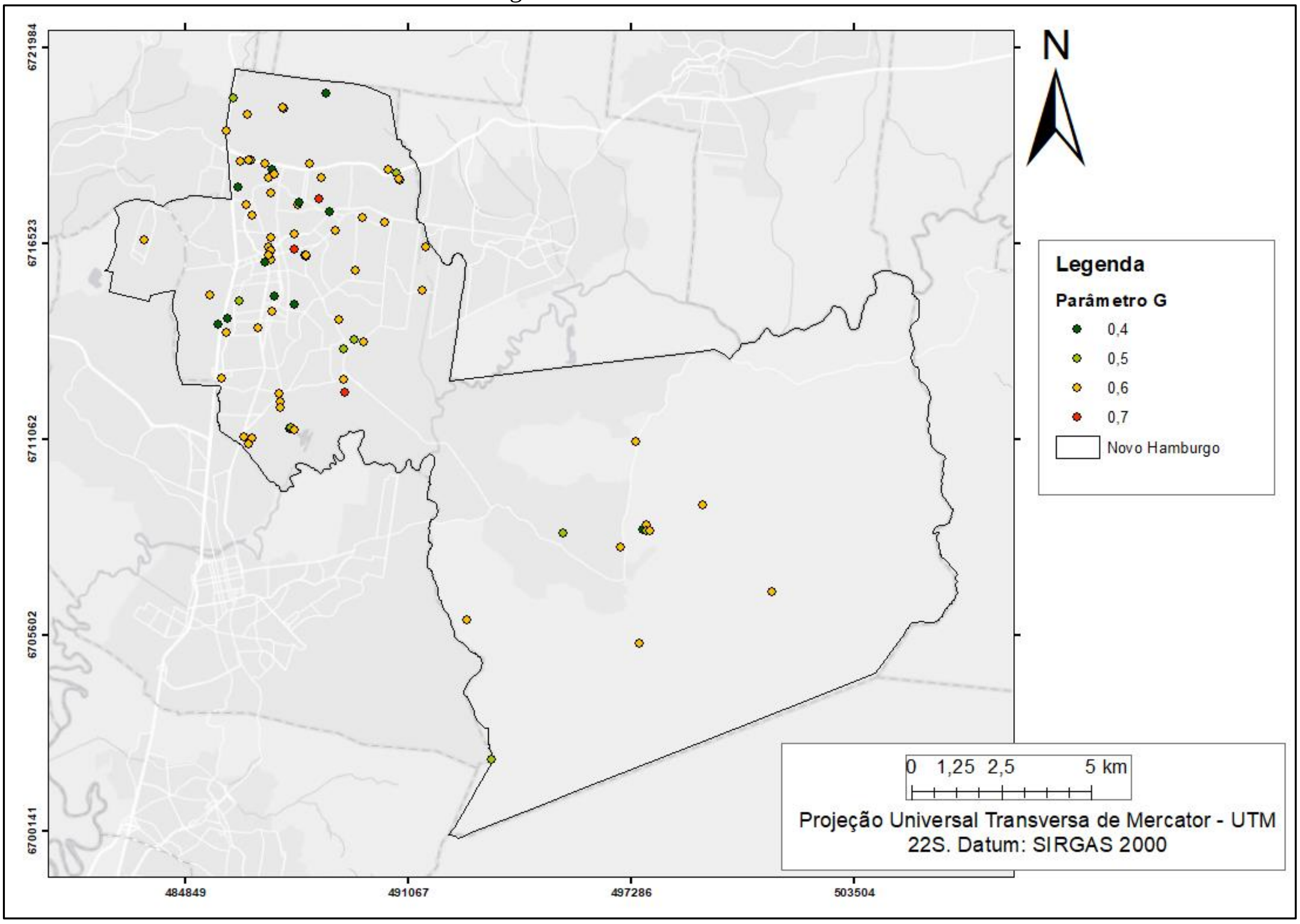
Of the remaining 56 wells, they have different owners, 15 of which are individuals, for personal use and leisure, the rest for industry, among them: footwear and leather industries, paints, plastics, chemicals, metals, injected and food industries, as well as metallurgical workshops, automotive mechanics, construction companies, agricultural enterprises, food distributors, shopping centers, hospitals, hotels and schools.

One of the two wells, which is located in the Serra Geral Unit, is supplied by COMUSA, while the other is registered as industrial use by the Corium Química Ltda. industry. Of the 4 wells linked to individuals, all are in the rural area, while the other 4 linked to the Condominium, these are in an urban area, located on Avenida Doutor Maurício Cardoso, Jardim Mauá neighborhood, neighborhood with the most expensive real estate prices in the city.

Regarding the parameters for determining the GOD, parameter G (type of groundwater occurrence) is mostly found in the Botucatu/Pirambóia Aquifer System, with parameter values ranging from 0.4 to 1 (Figure 11 - Parameter G of the GOD), based on the relationship between the depth of the water level, the lithology of the aquifer and non-aquifer layer. 14 wells have a value of 0.4 of the parameter, 11 wells have a value of 0.5 of the parameter, 56 wells have a value of 0.6 of the parameter, and 3 wells have a value of 0.7 of the parameter.

The three wells without basaltic cover, unconfined and little sandstone cover – parameter 0.7, these are in the urban area, of these, 2 wells are in the middle class and one in the lower class, which is covered. Of the wells that are in the Serra Geral II Aquifer System, one has parameter G semi-confined and the other is covered.

Figure 11 – GOD G-Parameter



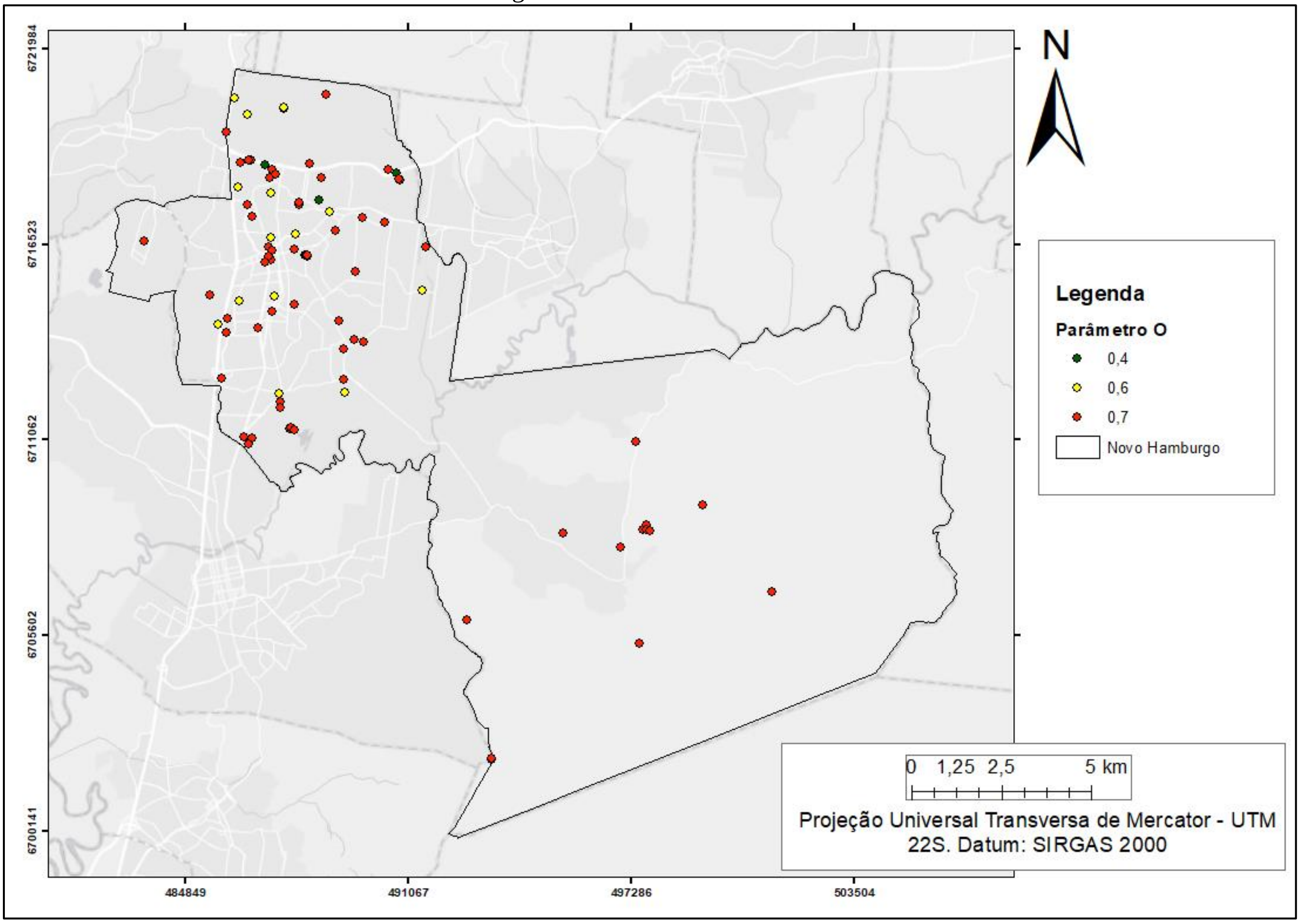
Data source: SIAGAS (2024), IBGE (2024). In-house elaboration

The parameter O (unsaturated zone lithology) varied between 0.4 and 0.7 in the parameter, with 3 wells with residual soils, 15 wells with siltstone rocks, volcanic rocks and basalt thickness between 60 and 100 meters and 66 wells with sandstones. Of the wells registered, only two are in the Serra Geral II

Aquifer System, these wells have thick basalt cover, but are with sandstone rock – parameter 0.7, both wells have GOD in the lower class and are located in the urban headquarters.

The three wells with residual soils are located to the north of the municipality, all three have a GOD value in the lower class. The dominant lithology is sandstone, both in the layer above the saturated zone as well as in the saturated layer (figure 12 – Parameter O of the GOD).

Figure 12 – GOD Parameter O

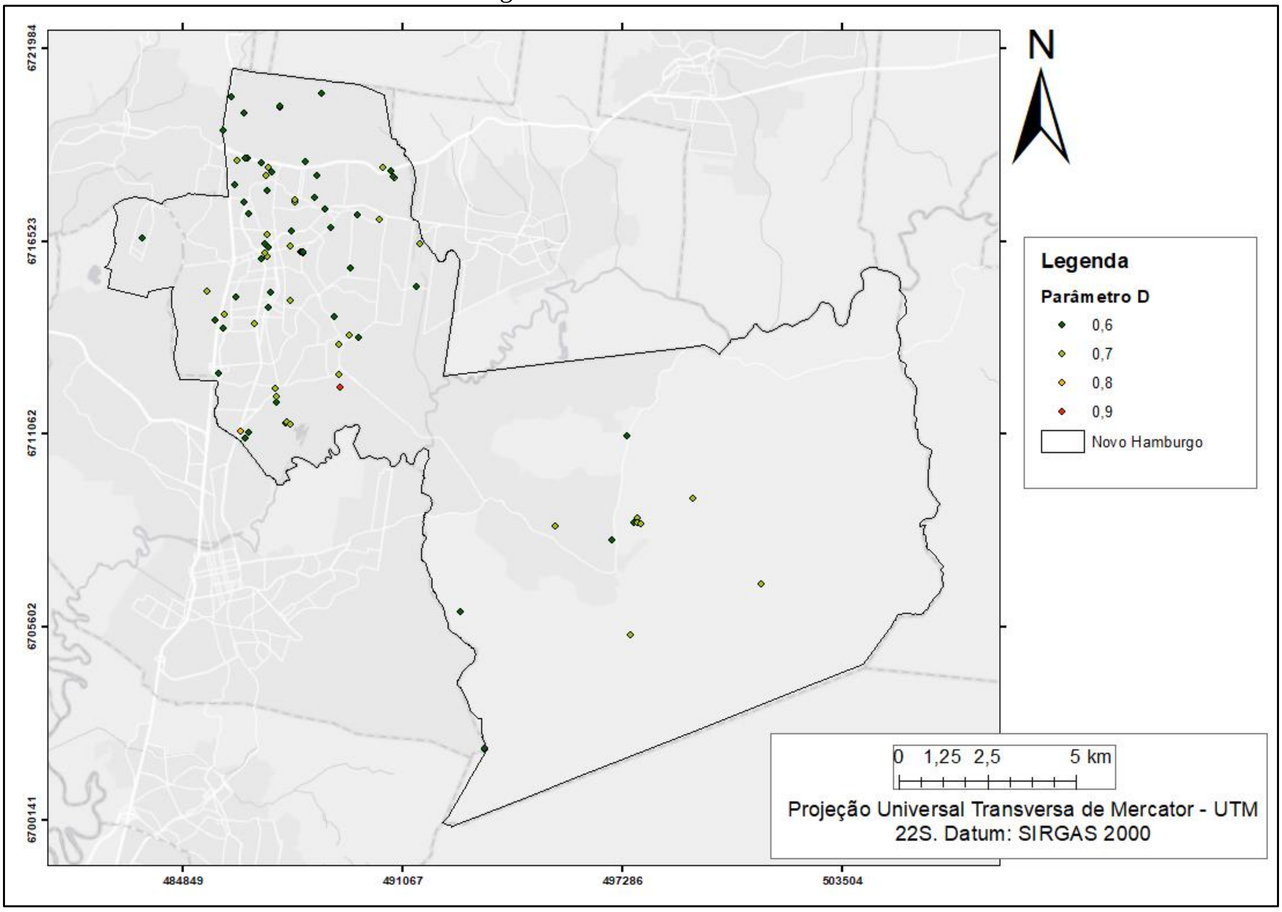


Data source: SIAGAS (2024), IBGE (2024). In-house elaboration

Parameter D (depth to the top of the aquifer) ranged from 0.6 to 0.9. Only one well has a depth of less than 5 meters - parameter 0.9, a well has a depth between 5 and 20 meters - parameter 0.8, 31 wells have a depth between 20 and 50 meters - parameter 0.7, and, finally, 51 wells have a depth above 50 meters - parameter 0.6.

Of the shallower well, this one has the middle class of the GOD index. Of the wells that are in SASG II, both have depths greater than 50 meters deep (figure 13 – Parameter D of the GOD).

Figure 13 – GOD Parameter D



Data source: SIAGAS (2024), IBGE (2024). In-house elaboration

What can be seen, at first glance, is the absence of null values and maximum values for the three parameters of the GOD index. It is also observed that there is little variation in the classes of the index, with the lower class being predominant and, subordinately, the middle class. It is observed that there is not much variation in the lithology, both in the vadosa zone and in the layer above this zone, parameter O. Parameter G, type of aquifer, has a variation, but not relevant to change the class in the region.

Parameter D, depth, is the one that produces the greatest variation, and this parameter is the determinant for the class. The three wells with the middle class have the lowest depths, and it is from the depth that the highest values of the parameter are related. It is identified that the municipality has wells with great depth, most of them with depths above 20 meters.

It is also identified that the municipality has most of the wells for industrial use, and some of these industries with high pollutant risk. The municipality, according to the IBGE (2022 Census) has 18,808 properties with supply through wells, however, through the SIAGAS database, only 21 wells are registered for use in personal supply. Kemerich et al (2011) also emphasize that the use of water tanks and other types of water withdrawal considered insignificant can have a high risk of contamination, as well as the execution of irregular wells.

Only one well is found to be dry, this one was drilled for personal use, in the rural area of the municipality. The wells are grouped in the municipal headquarters, they are not uniformly arranged throughout the territory, which can lead to an overload in the consumption of this good.

With the data from the GOD index, it is indicated that the municipality does not have areas with great aquifer vulnerability, however, this is determined by the depth of the wells. Wells with shallower depths may reflect greater vulnerability, and due to sandstone lithologies, wells are intrinsically more susceptible (Foster *et al*, 2006).

FINAL THOUGHTS

The municipality of Novo Hamburgo has 84 wells registered in the SIAGAS database. Based on the result obtained by the GOD index, the municipality has 81 wells in the lower class and 3 wells in the middle class. Based on the GOD index, the municipality does not have areas with natural vulnerability to high aquifer contamination.

However, it is important to note that the index classes were closely intertwined with the high drilling depths of the wells. Because of this, it is important to analyze the area of natural vulnerability and the relationship with land use, as some developments may result in greater vulnerability, especially in areas where the predominant lithologies are sandstones, porous rocks that infiltrate more efficiently.

An incongruity is also identified in the recorded data, because based on a survey by IBGE Cidades, the municipality has a much higher number of residences supplied by groundwater than that registered in the SIAGAS database. The lack of these data may be due to shallow wells with insignificant use not requiring granting, however, this high value can interfere with the system in general, even more so if they are located in a dense way in the region.

Another issue that should be paid attention to is the great demand for groundwater consumption, from a large withdrawal of water from deep wells, which can lead to a lowering of the aquifer, up to an unsustainable use of it. Because of this, it is suggested to analyze the lowering of deep wells, as well as a study with the identification of water tanks and other types of shallow wells, in order to calculate the consumption of this groundwater, as well as the way in which these works were prepared, for the identification of possible sources of contamination.

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