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Papers

Vulnerability to Anthropogenic Pollution in the Dunas/Barreiras Aquifer System from the Metropolitan Region of Natal

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Abstract
Traditionally, groundwater has been considered protected by the subsurface. However, the disposal of stable pollutants in favorable infiltration zones can generate contamination of the hydric resource, jeopardizing the health of the population. To tackle 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. The present study aims to evaluate the vulnerability to anthropogenic pollution in aquifers of the Metropolitan Region of Natal (MRN). In this research, the GODS (Groundwater hydraulic confinement, Overlaying strata, Deph to groundwater and Soil type) method was used, proposing a vulnerability calculation through the multiplication of four geological and hydrological parameters, which are: degree of hydraulic confinement, the occurrence of the underlying substratum, distance to the groundwater level, and type of soil. Tools from a Geographic Information System (GIS) were used. The results show that most of the territory is in a low vulnerability level with 39.75%, in moderate level with 24.26%, followed by very high vulnerability level with 14.7%, 10.68% with high level, and 10.61% insignificant level. The research contributed to highlighting how the intrinsic characteristics of the Dunas-Barreiras aquifer in the Metropolitan Region of Natal, allow the transport of pollutants to the water table in some areas such as in the coastal zone and in the lower portions of the river basins.

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INTRODUCTION

In Brazil, there are 181 underground potential aquifers, from which a large part of the underground water is extracted by tube wells. It is estimated that there are more than 2.5 million tube wells in the country, responsible for the extraction of 17,580 million m³ of water per year (ANA, 2010). Several sectors use groundwater, with the main uses being domestic supply (30%), agriculture and livestock (24%), urban public supply (18%) and multiple supply (14%), industrial (10%) and others (4%) (HIRATA et al., 2019). The exploitation of aquifers ensures water security for millions of people in Brazil, from small villages to large urban centers; groundwater represents the main available resource for vulnerable populations, especially in arid and semi-arid regions (- ANA, 2020).

In semi-arid regions, groundwater is a vital local and regional resource with a high demand for use and consumption by humans (KHAIR et al., 2019; LAVOIE et al., 2015), which has been contaminated by the increasing urbanization process, industrial development, and agricultural activities (WANG et al., 2012; REGO et al, 2021), resulting from the spillage or leakage of toxic substances (oils and fats, sewage, hydrocarbons, chemical waste, etc.) seeping in, over-exploitation of aquifers, putting at risk their recharge and normal functioning, inadequate maintenance of well extraction systems, biological contamination of groundwater by malfunctioning septic systems or leaks in the sewage system, disposal, sealing or urbanization in aquifer recharge areas, deficiency in the sanitation system, urban sprawl, and especially nitrate contamination of domestic water (VASCONCELOS et al, 2018); the latter is aggravated by the expansion of the agricultural borders, the use of agrochemicals and the discharge of untreated domestic water into the soil (REGO et al., 2021). All this generates an overload of sewage systems (PALMIOTTO et al., 2018), besides affecting the way populations sustain themselves and aggravating the health issues of the population (BANA E COSTA et al., 2014; FORMAN, 2008; DE ASSIS et al., 2020).

One of the regions in the Brazilian Northeast that has been presenting the aforementioned problems is the Metropolitan Region of Natal (ANA, 2012). In that region, the Barreiras aquifer, together with the Dunas aquifer, accounts for about 65% of the population's supply for public and private uses due to the need for a water source, imposed by its climatic conditions (CPRM, 2003; PINHEIRO et al., 2018). In combating the effects of drought, this increased use was not conducted through planning grounded in territorial knowledge ANA, 2012; GARCIA et al., 2018), resulting in consecutive nitrate contaminations and health emergencies in urban and peri-urban regions (ANA, 2012; PINHEIRO et al., 2018; SANTOS et al., 2018). Unfortunately, the contamination of the water resource is an imperceptible process and, in some cases, irreversible one that, for the developing countries, has a high cost and time requirements that can limit efforts to improve their conditions (YU et al., 2010).

In the struggle to effectively reduce groundwater contamination, the assessment of aquifer vulnerability constitutes one of the important pillars in the management of the groundwater resource in a region; furthermore, groundwater contamination vulnerability maps have been increasingly used to support the environmental management plans of governmental and non-governmental agencies (BAALOUSHA, 2011; LINHARES et al., 2014). The vulnerability of the aquifer to contamination represents the intrinsic characteristics that determine its susceptibility to be adversely affected by an imposed pollutant load (MITJAVILA; BRUNO, 2011). Groundwater vulnerability assessment is a useful tool that can help track sensitive areas, which can be affected by potentially harmful sources (LI et al., 2016), besides representing a preventive tool that allows determining, a priori, the natural protection capacity of aquifers and distinguish which areas need mitigating and/or reductionist measures to the danger of contamination in the face of anthropic intervention (REGO et al., 2021).

The vulnerability assessment practices can be based on overlay analysis of geological and hydrogeological information layers in Geographic Information System - GIS (CHEN et al., 2006); (WANG et al., 2012; ZHANG et al., 2012; LI et al., 2016). The effectiveness of these methods depends directly on the quality of the data needed to define the parameters involved (MATZEU et al., 2017). However, there are innovative alternatives that, in the absence of preliminary information, and due to the simplification of the parameters, work very well in systematizing the mapping of aquifer vulnerability (PIZZOL et al., 2015). This can be an important basis for decision-making, such as territorial planning and groundwater monitoring (WANG et al., 2012).

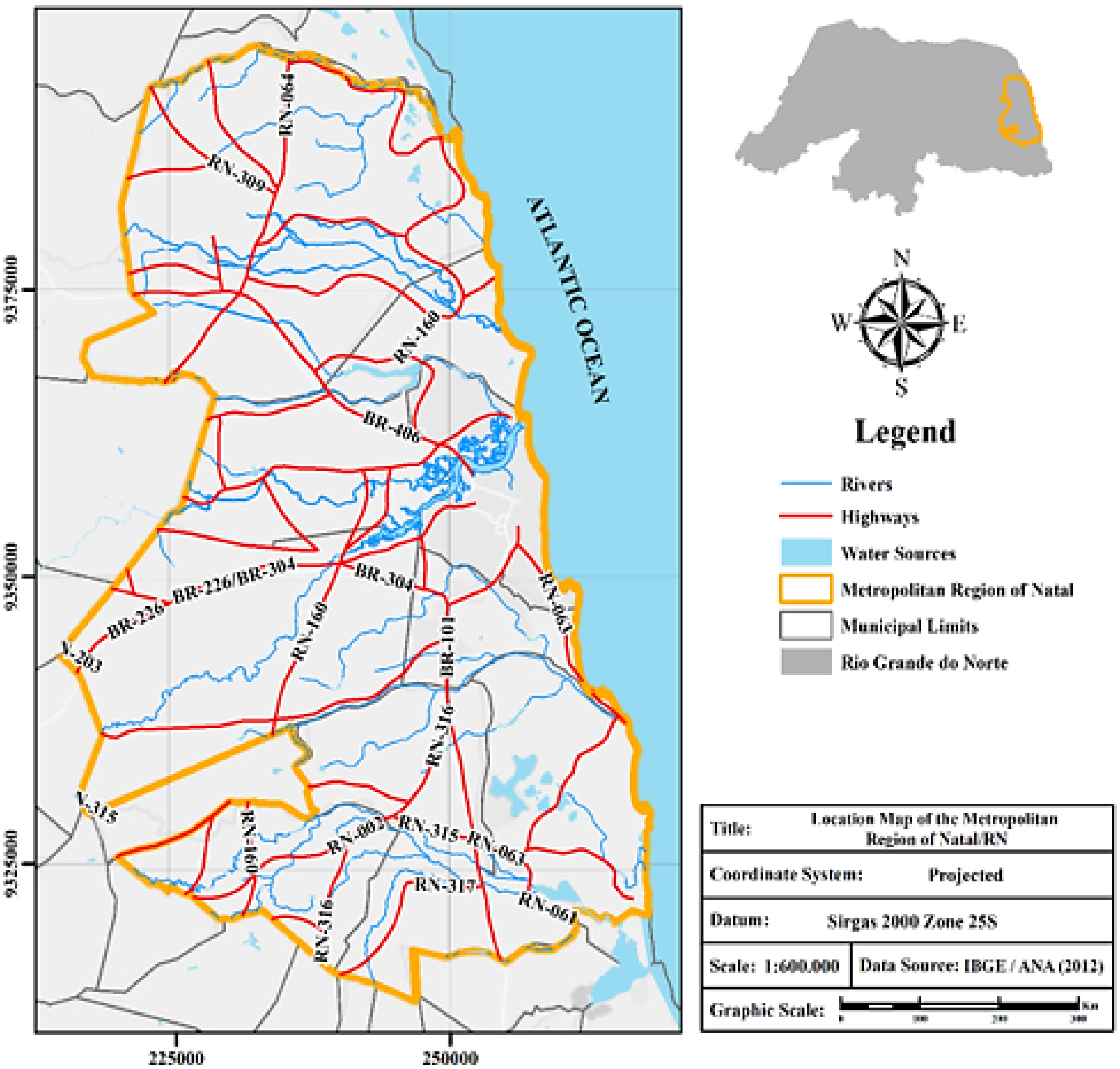
Undoubtedly, a viable alternative for the study of aquifer vulnerability is the GODS (Groundwater hydraulic confinement, Overlaying strata, Deph to groundwater and Soil type), methodology, devised by Foster et al. (2002), which is widely used in Latin America due to its good performance, lower cost, and greater ease of obtaining the necessary information (GAVIRIA; BETANCUR, 2010); this methodology basically evaluates two components of vulnerability: the hydraulic inaccessibility of the pollutant and the capacity of self-purification of the unsaturated zone. In this assessment, four geological and hydrological parameters are overlaid on a Geographic Information System model: degree of hydraulic confinement, the occurrence of the underlying substrate, distance to the groundwater level, and the type of soil.

Considering the above, the objective of this research is to evaluate the vulnerability to anthropogenic pollution in aquifers of the Metropolitan Region of Natal - RN, through the overlay of geological and hydrogeological information layers in a Geographic Information System model - GIS, obtaining the aquifer's vulnerability map to contamination. This aims to obtain an initial diagnosis of vulnerability to improve planning and territorial management, in this case, with emphasis on aquifer protection. Given the above, the following hypothesis was established: if there are geological and hydrogeological conditions in the study area that favor the entry of anthropic pollutants, there is a high intrinsic vulnerability to groundwater contamination.

MATERIAL AND METHODS

The current research was developed in the Dunas - Barreiras aquifer system, considered as a unique system because it presents a hydraulic connection by vertical downward drainage. It is a generally continuous aquifer, with free hydraulic behavior, of Quaternary and Tertiary age, which can locally be semi-confined. It is also composed of unconsolidated to semi-consolidated, sandy-clayey to silty-clayey sediments, and fine to coarse-grained sandstones in the dune cover, locally with conglomeratic fractions, of variegated color (CPRM; 2003). This system covers most of the surface of the Metropolitan Region of Natal (MRN), capital of Rio Grande do Norte, a state in northeastern Brazil, which is located in the microregion of the Eastern Coast of the State of Rio Grande do Norte. It has an area of 2,724 km^2 and integrally includes the municipality of Natal, the state capital, and thirteen other municipalities, which are Ceará-Mirim, Extremoz, São Gonçalo do Amarante, Macaíba, Parnamirim, Monte Alegre, São José de Mipibu, Nísia Floresta, Monte Alegre, Vera Cruz, Maxaranguape, Ielmo Marinho, Bom Jesus, Arês, and Goianinha (PREFEITURA MUNICIPAL DE NATAL, 2019) (Figure 1). The population of the MRN totals more than 1.3 million inhabitants, with 90% residing in urban areas (IBGE, 2010). For insufficient data the municipalities of Vera Cruz, Maxaranguape, Ielmo Marinho, Bom Jesus, Arês and Goianinha were excluded from the research.

Figure 01 - Study area: Metropolitan Region of Natal (MRN).



Source: The Authors (2022).

Vulnerability to anthropogenic pollution in the aquifers of MRN - RN

To obtain the vulnerability map, the GODS methodology was used (JARRÍN et al., 2017) which is based on the principles of Foster and Hirata (1988); this methodology proposes a multiplicative vulnerability model of hydro geological and geological information layers (Table 1), which takes into account the following parameters: the degree of hydraulic confinement, based on the aquifer structure (G); the occurrence of the underlying substrate, based on the lithological characteristics (O); the distance to the groundwater level, based on the depth of the water level (D); and finally, the incorporation of a new parameter in the methodology, the soil type, based on the texture (S). This last parameter shows the amount of water and air it holds and the speed with which a substance penetrates and passes through the soil.

Table 01 - GODS method parameters.

Parameter	***Significance***	***Based on***
G	Degree of hydraulic confinement	Aquifer type (structure).
O	Occurrence of underlying substrate	Lithological characteristics: consolidation, fracture, porosity and permeability.
D	Distance to groundwater level	Depth of water level in free aquifers or depth to confined aquifer ceiling.
S	Soil type	Texture and organic matter content

Source: Foster and Hirata (1988).

In addition, it was necessary to obtain the registration of the wells in the MRN. The necessary information was obtained from the Agência Nacional de Águas (ANA), which is the federal agency responsible for the implementation of Brazilian water resources management, in its report "Hydrogeological studies for the guidance of groundwater management in the Metropolitan Region of Natal (2012)"; the geological and hydrogeological data were obtained from the Serviço Geológico do Brasil (CPRM), is a public company, linked to the Ministry of Mines and Energy. Its mission is to generate and disseminate geoscientific knowledge, and the Instituto Brasileiro de Geografia e Estatística (IBGE), is a public agency of the Brazilian federal statistical administration.

This system allowed to estimate the final GODS integrated aquifer vulnerability index (IVGODS), applying the following equation.

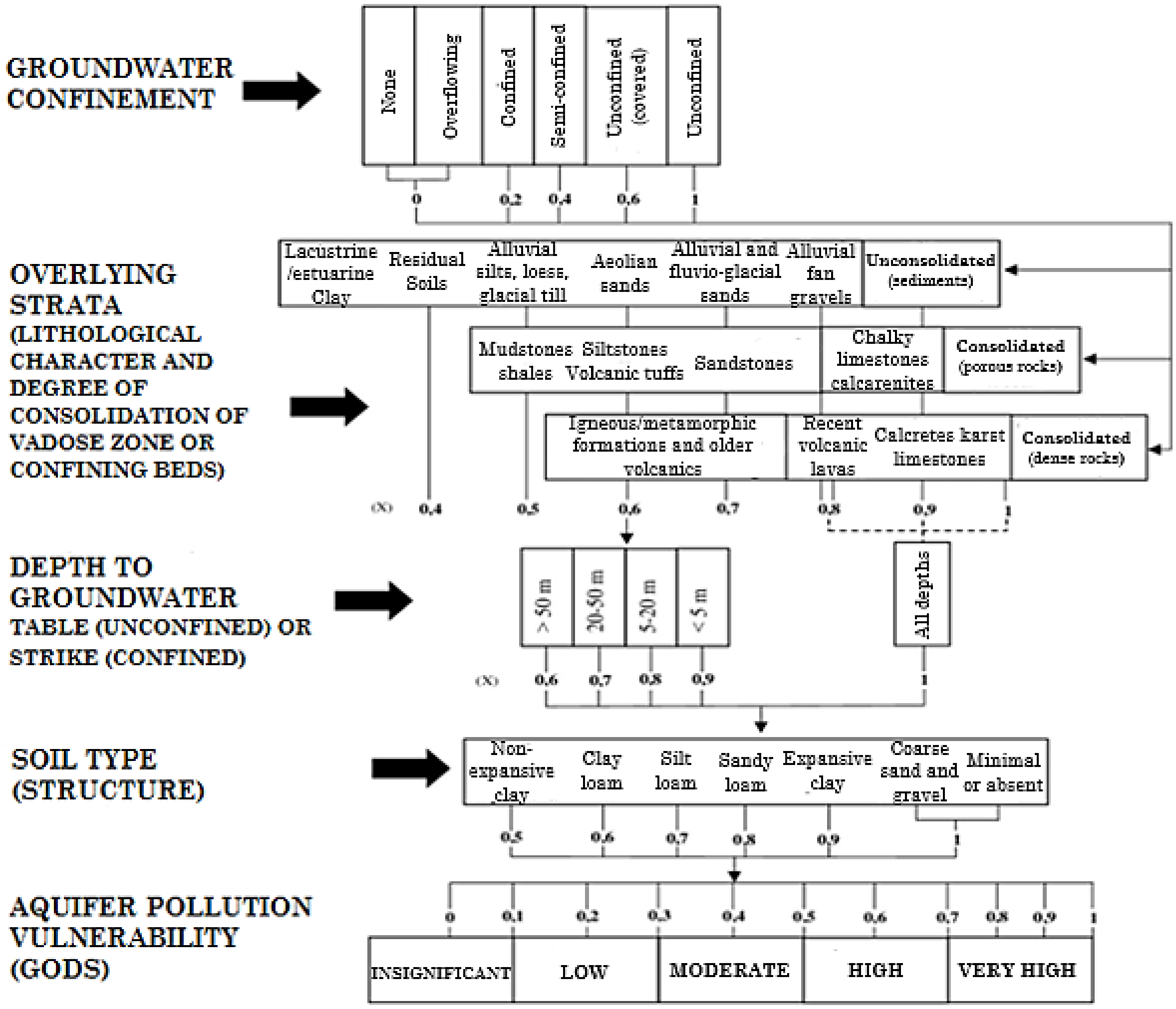
IVGODS=G*O*D*S (Equation 1)

Based on this equation, a series of steps established by Foster and Hirata (1988) were performed to find the vulnerability of the study aquifer, which are as follows:

- Identify the degree of hydraulic confinement of the aquifer and assign it an index on a scale from 0.0 to 1.0.
- To specify the characteristics of the substrate that covers the saturated zone of the aquifer and assign it an index from 0.4 to 1.0.
- Estimate the distance to the water level in free aquifers or the depth to the ceiling in confined aquifers and assign an index between 0.6 and 1.0.
- Determine the soil type and assign an index on a scale of 0.5 to 1.0.

To give weight to the parameters that make up the equation, the modified scheme proposed by Foster et al. (2002) was used (Figure 2), where the weighting of the indices of each parameter is found according to the characteristics of the study area.

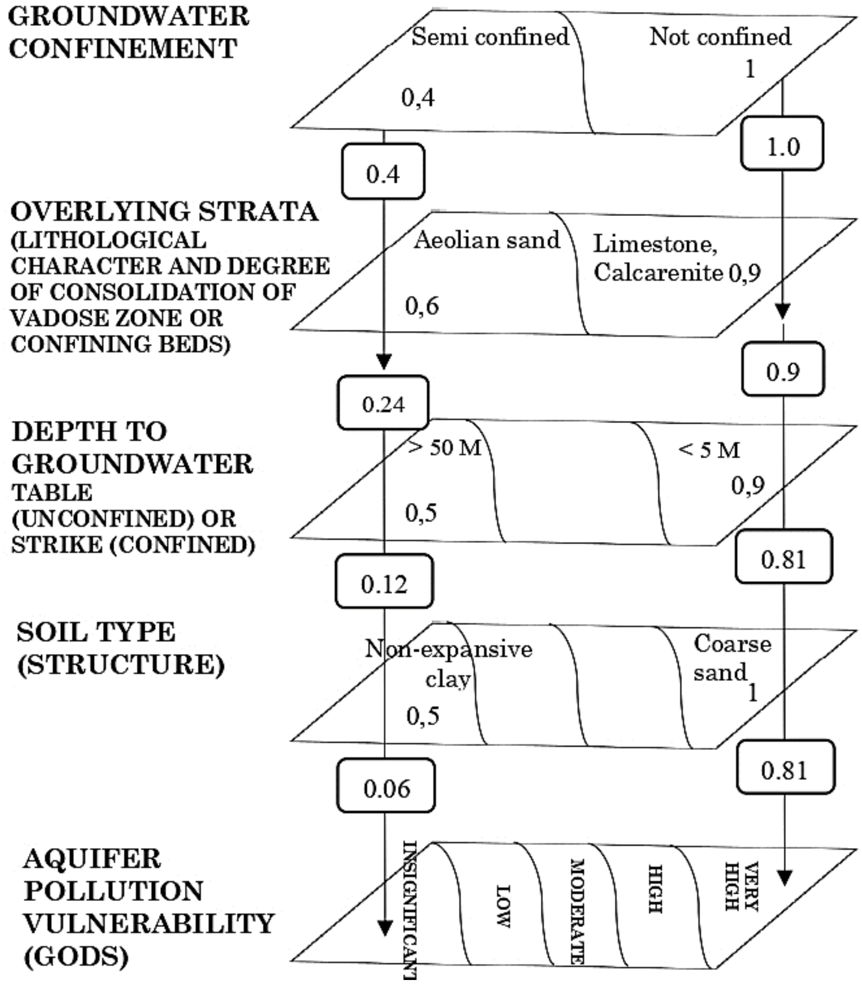
Figure 02 - GODS method for assessing aquifer contamination vulnerability.



Source: adapted from Jarrín et al. (2017)

Finally, to convert equation 1 into an algebraic map expression a Geographic Information System (GIS) environment was required using ArcGis 10.5 software (Student License) from ESRI company and create an overlay of the geological and hydrogeological information layers (Figure 3).

Figure 03 - Procedures adopted in the construction of the vulnerability map based on the GODS method.



Source: The Authors (2022).

Using the ArcGIS 10.5 software, a very efficient geotechnology tool in the area of geoprocessing and Digital Image Processing (DIP), a table was created with the data obtained and the necessary information for the analysis of the vulnerability index by the GODS method was defined. This information was inserted in vector format with shapefile extension. For this, it was necessary to perform a conversion processing to transform these shapes into raster files; the typologies of the information layers of each parameter were converted from alphanumeric data to vectorial and, later, into matrix; for this, the principle of map algebra was required. Once each parameter was obtained in a raster file, a final analysis was needed, which consisted of using the raster calculator (Raster Calculator) to generate a new vulnerability classification (Table 2) into null, insignificant, low, moderate, high, and very high. The map was made on a scale of 1: 600,000.

Table 02 - Vulnerability classes of the GODS methodology.

Vulnerability Class	Corresponding Definition	Vulnerability Index
Insignificant	Presence of confining layers in significant vertical groundwater flow (percolation)	0,0 - 0,1
Low	Vulnerable only to long-term, conservative contaminants when continuously and extensively discharged or leached.	0,1 - 0,3
Moderate	Vulnerable to some contaminants, but only when continuously discharged or leached.	0,3 - 0,5
High	Vulnerable to many contaminants (except those that are strongly adsorbed or rapidly transformed) under many contaminant conditions.	0,5 - 0,7
Very high	Vulnerable to most contaminants with rapid impact in many contamination scenarios.	0,7 - 1,0

Source: Adapted from Foster et al. (2002)

RESULTS AND DISCUSSION

Intrinsic vulnerability in the aquifers of the Metropolitan Region of Natal

Concerning the calculation of intrinsic vulnerability in the aquifers of the Metropolitan Region of Natal, using the GODS methodology, the parameter G (degree of confinement) was taken for the whole territory as unconfined, for being the predominant category; however, semi-consolidated sediments were found in some areas, which expresses changes in storage and permeability conditions.

The parameter O (occurrence of underlying strata) (Figure 4) was taken based on data from ANA (2012); the well profiles of the study area were divided into 04 (four) distinct types: sandstone/clayey sandstone, unconsolidated eolian sand, sandy loam, and clay loam. This procedure innovates in the interpretation and allows the identification of nuances of the characteristic of the parameter "O", with a predominance of a consolidated lithology (97.01%) and an unconsolidated lithology (2.99%). Regarding the unconsolidated lithology, 2.99% are unconsolidated eolian sands present in the eastern part of the study area (dunes or paleodunes). On the other hand, in the consolidated lithology we found a predominance of porous claystone-type rocks with 60.7%, present mainly in the western zone; and porous sandstone/clayey sandstone rocks with 21.72%, in a smaller proportion porous sandy claystone-type rocks with 7.66% and metamorphic hard rocks of the crystalline basement with 6.93%. The more conservative classification of the strata of the unsaturated zone in the area of the dunes was adopted due to the hydrodynamic characteristics of these deposits (such as high hydraulic conductivity), which are important components for the recharge of the Barreiras aquifer, which, in the same way that it helps to recharge the aquifer, is extremely vulnerable to the infiltration of contaminants. The heterogeneity of the sediments of the Formação Barreiras (Barreiras formation) mainly in its upper portion, also conditions the occurrence of semiconfinement in certain places, such as in the south of Natal and Nísia Floresta.

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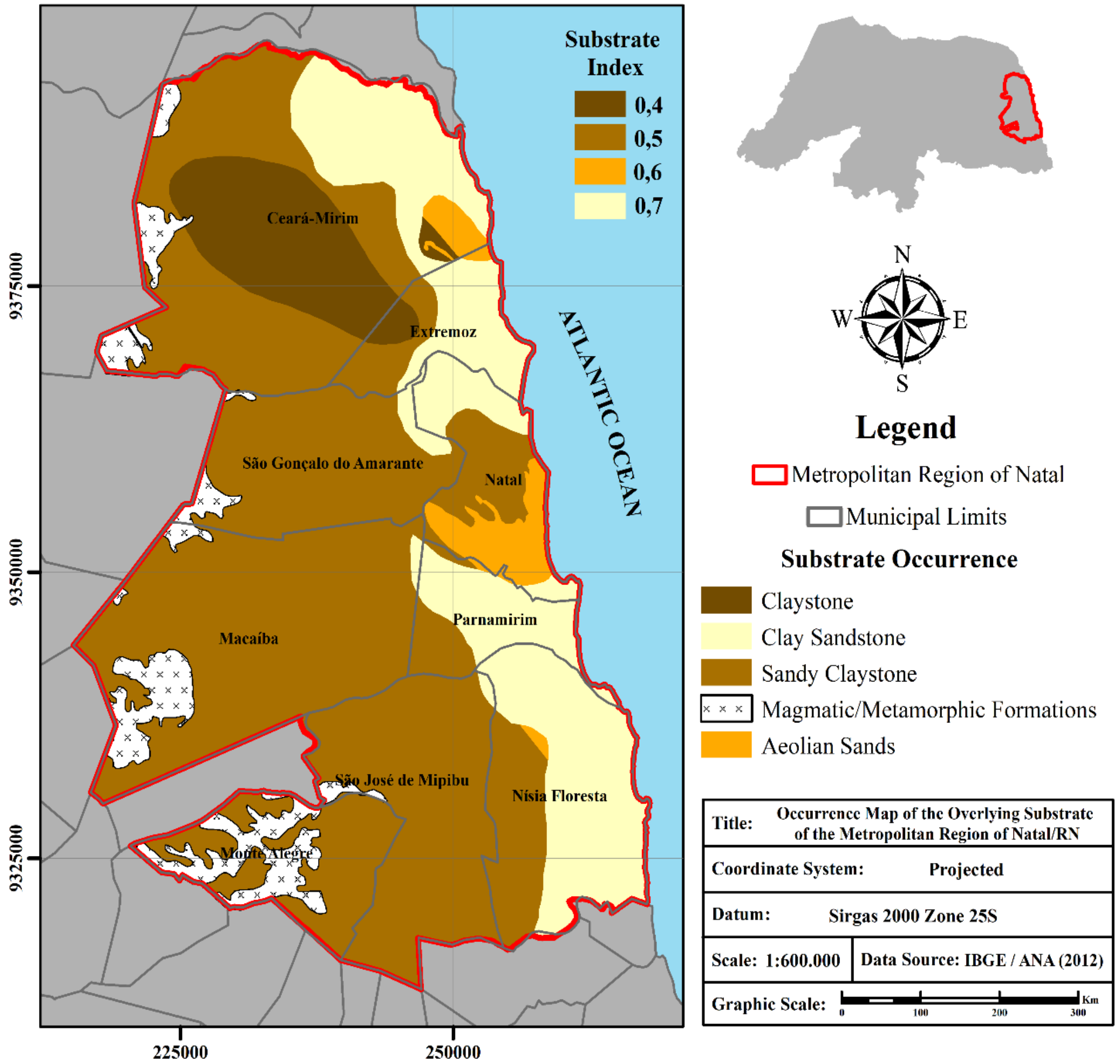
Figure 04 - Parameter O. Occurrence of underlying strata in the MRN aquifers.



Source: The Authors (2022).

For the parameter D (distance to the water table level) (Figure 5), it was verified that the largest percentage of underground water is in the depth of 5 - 20 meters with 45.26%, followed by depths of 20 to 50 meters with 29.3%, < 5 meters 14.67% and 10.76% with an unknown depth. Being a free aquifer system, it is verified that the thickness of the unsaturated zone decreases from the topographic heights towards the valleys of the main drainages in the area, mainly in the lower and middle courses, constituting discharge sites. There is also a decrease in the thickness of the unsaturated zone near the western limit of the study area, which coincides with the limit of the basin itself and where the cretaceous sediments or the crystalline basement outcrop. In the valleys of the main rivers and near the coast the depth of the unsaturated zone is between 5 and 20 meters, analogous to the western part, mainly in the central region, where the thickness of the Barreiras formation is reduced. In the south zone of Natal, on the coast of the municipality of Parnamirim, where the dune fields are, and in the central zone of Macaíba, the depth of the unsaturated zone has values above 20 to 50 meters, similar to the northern part of the municipality of Ceará-Mirim.

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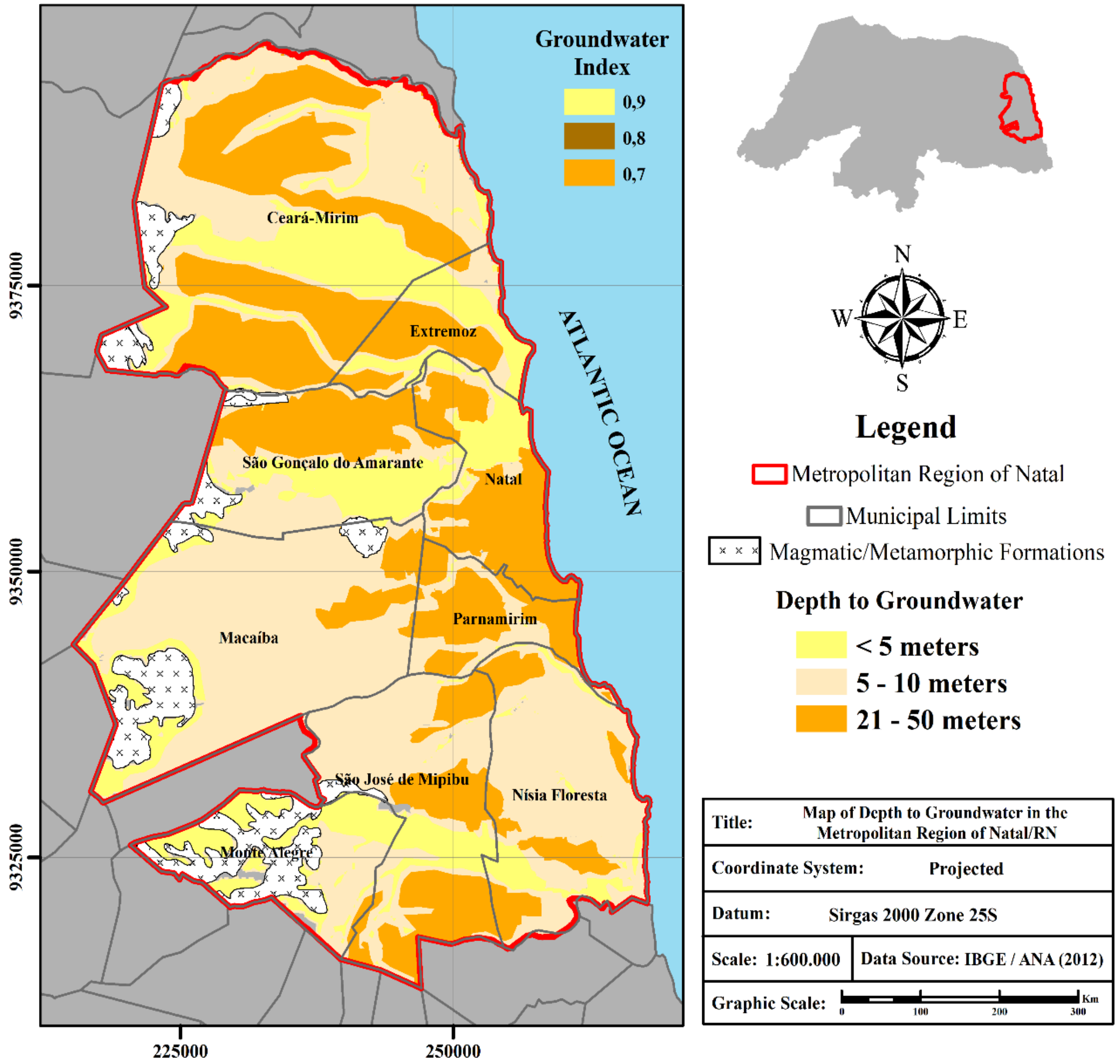
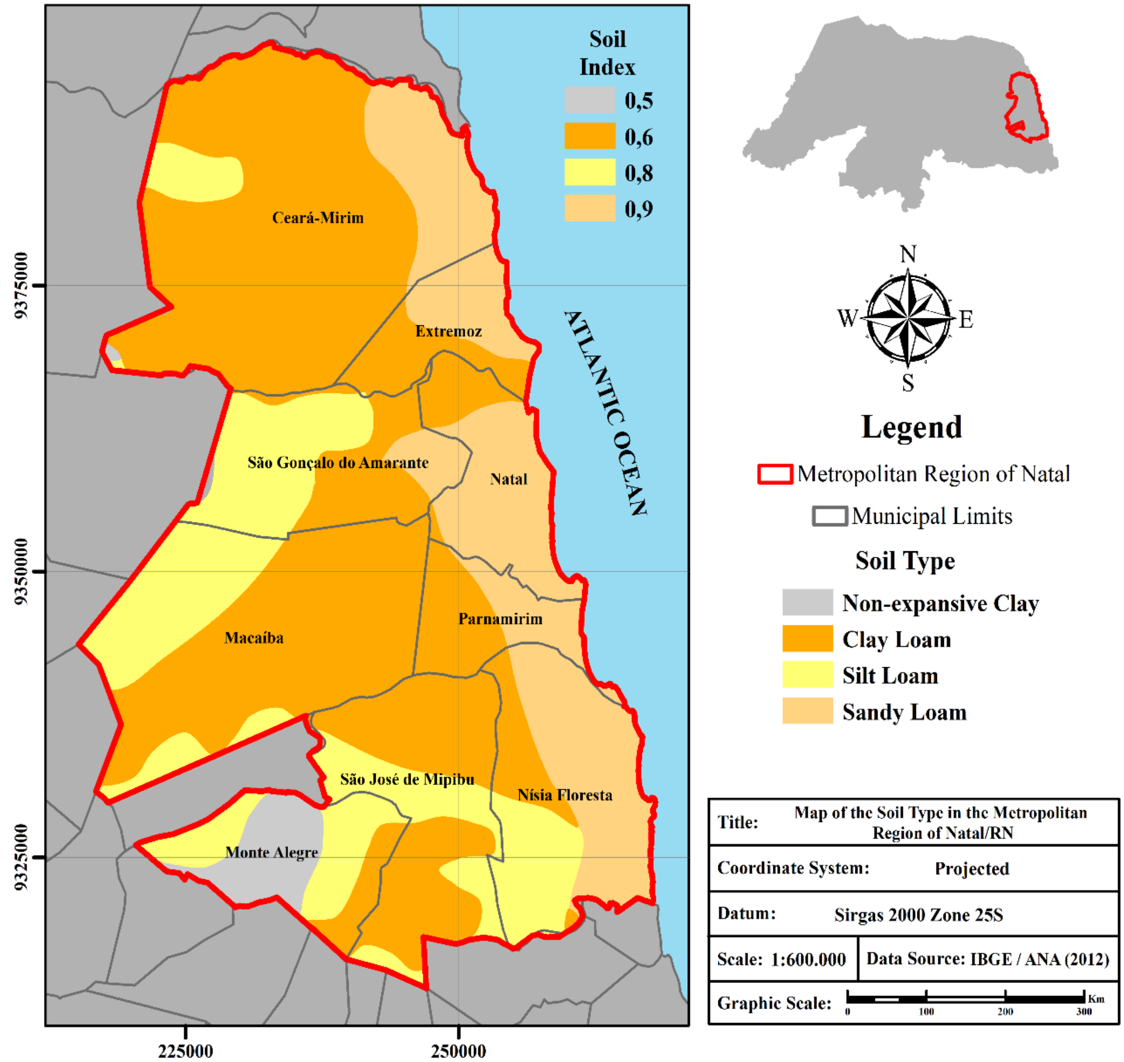
Figure 05 - Parameter D. Distance to groundwater level in the MRN aquifers.



Source: The Authors (2022).

Finally, parameter S (soil type) (Figure 6), shows that the largest percentage of soil area has a loamy-clay texture with 54.05%, followed by a silty-loamy texture with 21.93%, a sandy-loamy with 21.19%, and a non-expansive clay with 2.83%.

Figure 06 - S parameter. Soil type (texture) in the MRN aquifers.

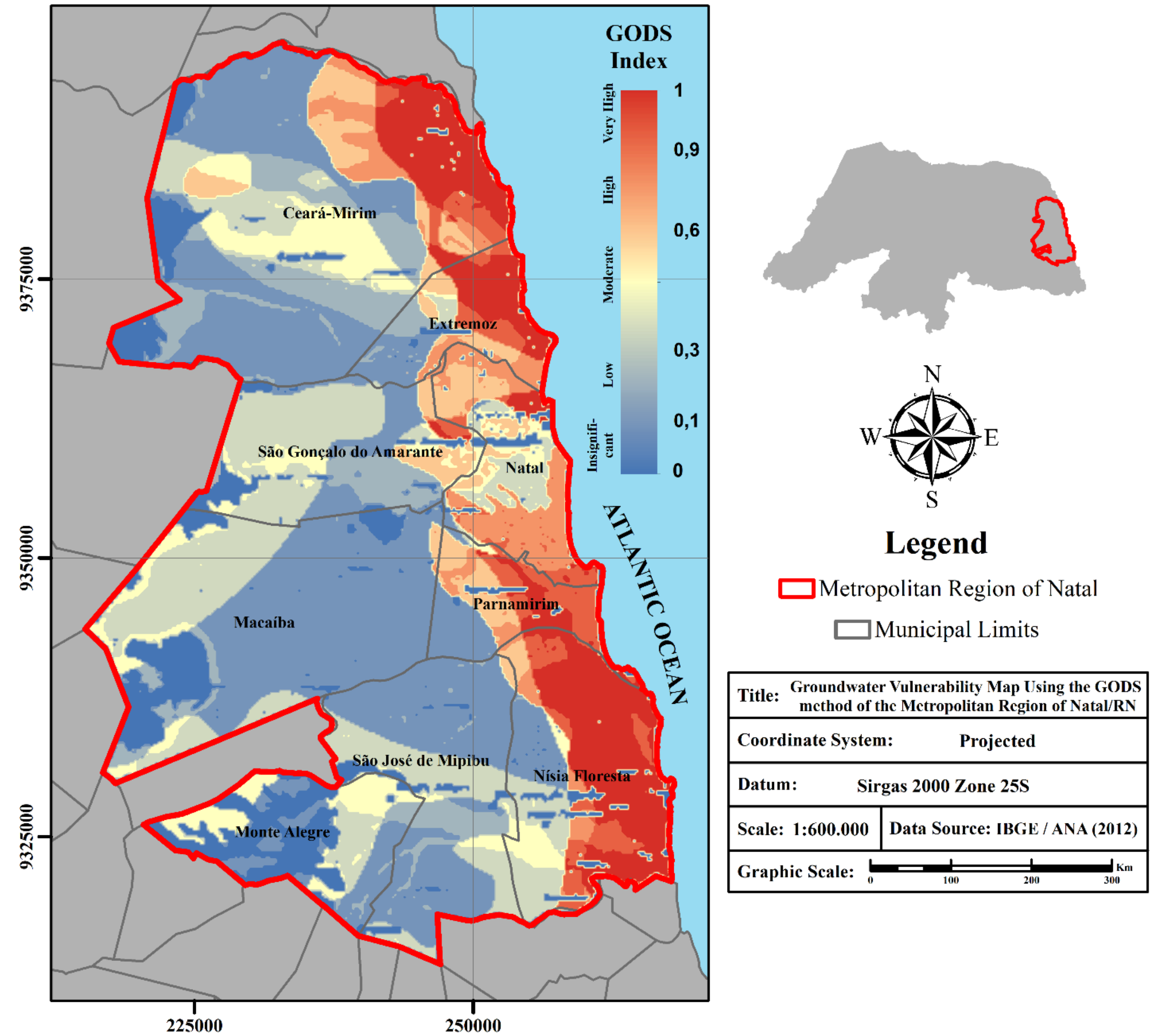


Source: The Authors (2022).

From the product of these 04 (four) parameters, it was possible to generate the map of intrinsic vulnerability to contamination of aquifers in the NMR, as shown in Figure 7. In most of the study areas, it was determined that the vulnerability is at a low level with 39.75% and moderate level with 24.26%, followed by very high vulnerability level with 14.7%, high with 10.68%, and insignificant with 10.61%. The highest very high and high vulnerability indices are associated with the occurrence of predominantly sandy and sandy-clay strata, with a depth of the unsaturated zone less than 5 meters. These situations occur mainly along the coast, at the front of the runoff to the ocean, and in the lower portions of the watersheds. Ratifying what was said by Rego et al. (2021), coastal zones are highly vulnerable because they contain areas where the aquifer is free, that is, where the layer immediately above the aquifer is formed by an aeration zone with a predominantly sandy texture, which is intended to store water temporarily, but where pollutants infiltrate at a faster rate. In these aquifers, there are also static levels that do not exceed a depth of five meters.

The moderate and low vulnerability indices are associated mainly with the topographic highs, and the middle and upper portion of the watersheds, where the water level is deeper in relation to the surface and, consequently, the thickness of the unsaturated zone is greater.

Figure 07 - Map of intrinsic vulnerability index to contamination in the aquifers of MRN



Source: The Authors (2022).

It was also possible to determine the level of vulnerability of each municipality as presented in Table 3. The highest levels of vulnerability occur in the municipalities of Nísia Floresta, Extremoz, Natal, Parnamirim, and Ceará Mirim, mainly due to a large amount of sand in the soil composition, in which the physical characteristics such as good infiltration capacity and low compaction of solid particles collaborate in the process of conduction of contaminants to the water table. Another factor of the high vulnerability of these regions is the height of the phreatic surface in relation to the ground level since the wells are considered shallow, with depths of less than 20 meters; it is also indicated that these sites are vulnerable to many contaminants, except those strongly absorbed or transformed. The lowest levels of vulnerability are found in the municipalities of Monte Alegre, Macaíba, São José do Mipibu, and some areas of the municipality of Parnamirim since they have both sandy and clay soils, and a depth of groundwater greater than 20 meters; this increases the hydraulic inaccessibility of the aquifer and pollutants take a longer time to pass from the unsaturated zone to the saturated zone. This vulnerability indicates that in these locations only a few contaminants can reach the saturated zone of the aquifer when they are continuously discharged. On the other hand, the municipalities that present moderate vulnerability are Macaíba, Monte Alegre, São José do Mipibu and some areas of São Gonçalo do Amarante.

Table 03 - Results of vulnerability level in the municipalities of MRN

Municipality	% Vulnerability level				
	Insignificant	Low	Moderate	High	Very high
Ceará Mirim	7,33	48,78	17,95	12,07	13,88
Extremoz	4,14	27,09	4,92	22,01	41,83
Natal	7,13	1,31	26,74	53,72	11,10
São Gonçalo do Amarante	8,63	30,31	51,45	7,68	1,94
Parnamirim	4,72	25,83	1,47	29,59	38,38
Nísia floresta	6,72	10,16	18,27	6,27	58,58
São José do Mipibu	5,54	66,72	26,93	0,81	0
Macaíba	14,85	57,01	27,44	0,70	0
Monte Alegre	39,57	27,01	33,41	0	0

Source: The Authors (2022).

The intrinsic characteristics of the Dunas-Barreiras aquifer system show that the level of vulnerability of some areas is at a very high level because their geological and hydrogeological conditions can allow the transport of pollutants up to the water table, as is the case in the coastal zone and in the lower portions of the hydrographic basins. In addition, in these areas, and especially in the municipalities of Natal, Nísia Floresta, Parnamirim, Extremoz, and Ceará Mirim, the greatest anthropic activities occur, such as tourism, agriculture, urban and periurban development, cattle-raising, among others, which would allow a greater risk of groundwater contamination.

Poorly constructed or abandoned wells are important focuses of contamination of the aquifer because they allow the direct infiltration of contaminants from the surface to the saturated zone.

In regional recharge zones, the contamination of the aquifer can cause great impacts because, depending on the characteristics of the underground flow and the contaminant, it can be conducted to deep portions of the aquifer.

Confirming what Linhares et al. (2014) said, vulnerability assessments allow the establishment of protocols for the creation of favorable conditions for groundwater protection and appropriate land use, prioritizing specific protection areas and monitoring strategies for the local free aquifer. In this way, it contributes to decision-making on land use and occupation for the preservation of the environment, and maintenance of the quality of life of the population that depends on groundwater.

CONCLUSIONS

The intrinsic natural characteristics in the aquifers of the MRN give it mostly moderate vulnerability with 63.48% and high level with 11.87%. However, there is also an important coverage of very high vulnerability with 11.75%, located mainly along the coast, at the outflow front to the ocean, and in the lower portions of the watersheds.

The moderate and low vulnerability rates are mainly associated with the topographic highs and in the middle and upper portion of the watersheds, where the water level is deeper relative to the surface and consequently pollutant transport can be absorbed before reaching the water table.

The water bodies cannot be classified within a vulnerability classification (because they are not geological formations), but it is possible to determine the chemical quality of their waters so that the imposed pollutant load will be that which predominates in the danger of contamination of the aquifers.

The integration process of hydrological and geological data associated with the vulnerability map of the aquifers through the GODS method, in a Geographic Information System, shows a mechanism that has a positive response to contribute with the knowledge of the underground hydric resources in the Metropolitan Region of Natal.

There are several methodologies to qualify vulnerability and allow its mapping in different scales, most of them developed for free aquifers. The choice of one or another method depends on several factors, among which are: dissemination and comprehensiveness of the methodology, available information, its evaluation, and validation of the results.

The GODS method has as major advantages the simplicity of its operation and the small number of parameters needed for its use; for this reason, its application is optimal in developing countries where information collection is expensive.

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AUTHORS' CONTRIBUTION

Felix David Rivera Madroñero is the main author, he compiled the necessary information for the development of the research results, analyzed the data obtained, concluded the work, and wrote the article. Felipe Silva de Oliveira processed the data in Geographic Information Systems. Raquel Franco de Souza and Júlio Alejandro Navoni wrote and corrected the article.