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INTRINSIC VULNERABILITY TO NATURAL CONTAMINATION OF THE AQUIFER IN THE METROPOLITAN REGION OF SALVADOR – STATE OF BAHIA, BRAZIL

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Abstract

The objective of this work is to elaborate a thematic map of the intrinsic vulnerability of the aquifer in the Metropolitan Region of Salvador (RMS), which constitutes the first step for the assessment of the danger to contamination and protection of the groundwater quality. For this, the GOD (FOSTER; HIRATA, 1998) methodology was used. In the RMS, four vulnerability patterns were found: negligible, low; moderate and high. The GOD method clearly showed the natural vulnerability to contamination, however, it involves simplifications in hydrogeological information, which requires attention when reclassifying, processing the data and interpreting the results.

Palavras-chave: Underground; Impact; Susceptibility.

VULNERABILIDADE INTRÍNSECA À CONTAMINAÇÃO NATURAL DO AQUÍFERO NA REGIÃO METROPOLITANA DE SALVADOR – ESTADO DA BAHIA, BRASIL

Resumo

O objetivo deste trabalho é elaborar um mapa temático da vulnerabilidade intrínseca do aquífero na Região Metropolitana de Salvador (RMS), o qual constitui o primeiro passo para a avaliação do perigo a contaminação e proteção da qualidade da água subterrânea. Para tanto, foi utilizada a metodologia GOD (FOSTER; HIRATA, 1998). Na RMS foi encontrado quatro padrões de vulnerabilidade: desprezível, baixa; moderada e alta. O método GOD mostrou claramente a vulnerabilidade natural à contaminação, porém, o mesmo envolve simplificações nas informações hidrogeológicas, o que requer atenção no momento da reclassificação, tratamento dos dados e interpretação dos resultados.

Keywords: Subterrâneo; Impacto; Susceptibilidade.

VULNERABILIDAD INTRÍNSECA A LA CONTAMINACIÓN NATURAL DEL ACUÍFERO EM LA REGIÓN METROPOLITANA DE SALVADOR – ESTADO DE BAHÍA, BRASIL

Resumen

El objetivo de este trabajo es elaborar un mapa temático de la vulnerabilidad intrínseca del acuífero en la Región Metropolitana de Salvador (RMS), que constituye el primer paso para la evaluación del peligro de contaminación y la protección de la calidad del agua subterránea. Para esto, se utilizó la metodología GOD (FOSTER; HIRATA, 1998). En el RMS, se encontraron cuatro patrones de vulnerabilidad: insignificante, bajo; moderado y alto. El método GOD mostró claramente la vulnerabilidad natural a la contaminación, sin embargo, implica simplificaciones en la información hidrogeológica, lo que requiere atención al reclasificar, procesar datos e interpretar resultados.

Palabras-clave: Bajo tierra; Impacto; Susceptibilidad.

1. INTRODUCTION

Aquifers are suffering a great threat of pollution due to industrial development, urbanization and agricultural activities. The growth of the urban population is an aggravation for the contamination of aquifers, mainly through septic tanks, gas stations and final destination of waste (TUCCI, 2003). However, in industry, waste would be released in the soil and in agriculture, the expansion of agricultural frontiers would encourage the use of chemical products causing the contamination of surface and underground water resources.

The need arose for the implementation of theoretical, conceptual and methodological bases that clarified the dynamics of the environment, being seen as a system, comprising the various entities that compose it, analyzing its organization, spatial structure, functionality, interaction and hierarchy.

From this need, a line of research related to the implementation of socioeconomic activities emerged that assesses the probability of the occurrence of an impact (positive or negative, social or natural), with changes and spatial and temporal interrelations, called vulnerability (CHRISTOFOLETTI , 2002, DAUPHINE; PROVITOLO, 2013; EGLER, 1996; ZWAHLEN, 2003).

In hydrogeology, this line of research is related to vulnerability to aquifer contamination, with emphasis on the pioneering investigations of Albinet (1963, 1970), LeGrand (1964), Margat and Albinet (1965), Margat; Monition; Ricour (1967; 1968) and Margat (1968). These works establish the basic concepts of assessing vulnerability to aquifer contamination, considering it as a preventive tool, which allows determining the natural protection capacity of aquifers and distinguishing which areas need mitigation and / or reductionist measures to the danger of contamination in the face of anthropic intervention. To this end, these authors focus on the dangers and threats of contamination, contextualizing the environment.

A map of vulnerability to aquifer contamination is the first step in assessment the danger, creating mechanisms for the management and control of water resources and protecting their quality (FOSTER et al., 2002), however, their reliability depends on the scale elaboration of the work.

In the Metropolitan Region of Salvador (RMS), there are occurrences of fractured and porous aquifers from crystalline and sedimentary rocks derived from the stratigraphic units of the Salvador-Esplanada Complex, Rio Real Complex, Barreiras Group, São Sebastião Group, Ilhas Group, Brotas Group, Almada Group and coastal deposits. These aquifers are conditioned by different tectonic structures (fractures and faults), different porous dimensions, specific hydrochemical and hydrodynamic behavior (NASCIMENTO; BARBOSA, 2020).

In this context, the objective of this work is to elaborate the thematic map of intrinsic vulnerability of the aquifer in the Metropolitan Region of Salvador (RMS) through the GOD method. The GOD method has conceptual simplicity using accessible parameters. With this, it is intended that the cartographic product allows to know the susceptibility to contamination of the aquifer, demonstrating the different degrees of vulnerability and the suggestion of patterns.

1.1. Characterization of the study area

The Metropolitan Region of Salvador (RMS) is composed of thirteen municipalities: Camaçari, Candeias, Dias D'Ávila, Itaparica, Lauro de Freitas, Madre de Deus, Mata de São João, Pojuca, São Francisco do Conde, São Sebastião do Passé, Salvador (capital of the State of Bahia), Simões Filho and Vera Cruz (Figure 1). In 2018, IBGE (Brazilian Institute of Geography and Statistics) estimated in 2018 a total population of 3.899,533 inhabitants in the RMS distributed for an area of 4.339,109 km².

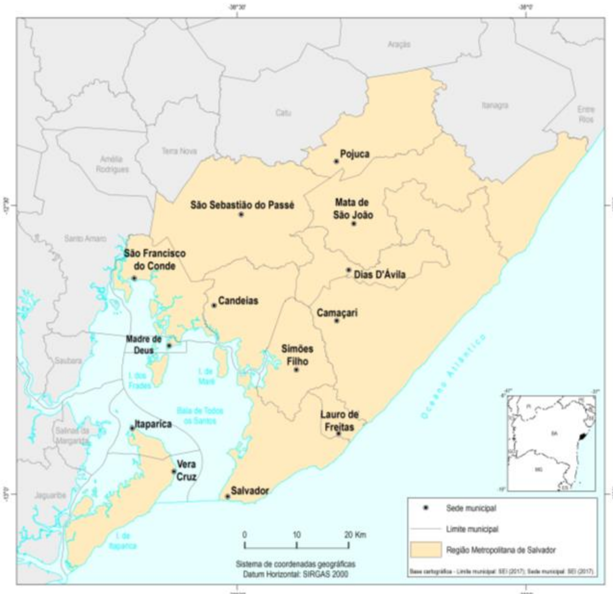

Figure 1 - Location of the Metropolitan Region of Salvador. Most municipalities in this region occupy coastal areas with the exception of Pojuca, São Sebastião do Passé and the western portion of Mata de São João. Source: Authors (2019).

The Metropolitan Region of Salvador is located on the São Francisco Cráton structural province. The eastern portion of the RMS is formed by the landscape unit Salvador Esplanada - Rio Real (serr), composed of crystalline rocks. In this unit, there are convex relief forms, resulting from heterogeneous dissection. In the case of pedology, the soils of the Salvador Esplanada - Rio Real unit tend to have a medium clay texture in the south and, in the north, it has some level of sand. This characteristic is related to the pluviometric distribution in the geographic space. The southern area of the unit rains an average of 1.900 to 2.000 mm per year, whereas the one located in the north, rains 1.500 to 1.700 mm per year, according to the Superintendency of Economic and Social Studies (SEI, 2003).

The Ilhas - São Sebastião (iss) landscape unit constitutes sedimentary rocks of lacustrine and marine origin, through the emergence of the rift basin in Bahia de Todos os Santos and is located on the west coast and in the central portion of the RMS. The rocks of this landscape unit were deposited at similar geological ages, but in the southern portion, they were subjected to greater weathering compared to the northern portion. This was due to sea level fluctuations over time. This dynamic gave rise to retouched buried pediplans in the north and coastal plateau in the central east portion. However, the predominant shapes in the unit in question are convex hills. The soil texture of the Ilhas - São Sebastião landscape unit is clayey, related more to the source material than to the rainfall index of this area, 1.300 to 1.700 mm per year (SEI, 2003).

The Brotas - Almada (ba) landscape unit consists of coastal and lagoon deposits, more precisely at the edges. It is formed by sedimentary rocks and quartz sand with some level of clay. It is possible to find reliefs with convexities, mainly in the central portion of the unit, as a result of heterogeneous dissection. On the edges, there are plains, subsequent to accumulation processes. The soils from the Brotas - Almada unit have a clay texture, while the soils in the deposits tend to be more sandy. Although it rains 1.900 to 2.000 mm per year (SEI, 2003) in the area in question, the soils with a sandy texture have an incipient relationship with the climate and a close connection to the source material and the position in the landscape.

The Barreiras landscape unit (b) is composed of sediments of fluvial and marine origin, poorly consolidated or unconsolidated. The shapes corresponding to this unit are the coastal plateau, fruits of homogeneous or differential dissection and the retouched buried pediplans. The texture of the soils varies between clayey and sandy. In areas where there is the presence of the Barreiras unit and rainfall around 1.900 to 2.000 mm per year (SEI, 2003), soils tend to be more clayey, while in areas where this index decreases to 1.200 to 1.500 mm per year (SEI, 2003), the soils have an average clayey texture.

Also, in the easternmost part of the RMS coast, there is the coastal deposits landscape unit (dl) consisting of quartz sand with some clay levels. The dunes, plains and terraces make up the geomorphology of these deposits and the soils are predominantly sandy, having a greater relationship with the source material. The pluviometric index varies between 1.900 to 2.000 mm per year in the south and 1.500 to 1.700 mm per year in the north (SEI, 2003). These descriptions are shown in Figure 2.

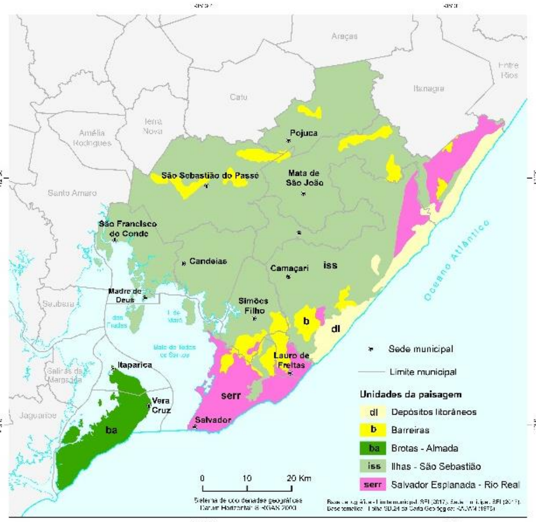

Figure 2 - RMS Landscape Units. The RMS is located on the crystalline basement and there are sedimentary rocks and some coastal deposits. Source: Authors (2019).

2. METHODOLOGY

The method of vulnerability to aquifer contamination is based on the risk of contamination, which can be defined as the probability of aquifers being contaminated by anthropic actions, in concentrations above the permitted values for water quality and potability standards (ZAPOROZEC, 2002). Thus, the risk of its contamination corresponds to the interaction of:

a) Quantity of contaminants from human activities and;
b) Vulnerability to contamination of the aquifer, natural result of the intrinsic characteristics of the natural environment.

The GOD parametric method was developed by Foster (1987) and improved to meet the conditions of Latin American countries by Foster and Hirata (1988). It consists of ranking hierarchical indices relative to the extreme or low intrinsic vulnerability of the aquifer, based on groundwater recharge mechanisms and the natural ability to mitigate contaminants, varying according to geological conditions. As the authors emphasize the recharge mechanisms, attention should be to accounting for fractures and other rock heterogeneities, as they can favor preferential flow, being a crucial factor for increasing vulnerability according to Bartolomeu (2012).

This method is based on the analysis of the three variables that compose it, with values from 0,0 to 1,0 being attributed to each parameter analyzed. The closer to 0, the less vulnerable you are, and the closer to 1 the greater your chance of contamination. The variables are:

a) Groundwater occurrence: identification of the type of containment of the aquifer, reflecting its level of contact with the terrestrial surface, being classified as free, free (covered), confined, semi-confined or squirt, with indexing in an interval of 0,0 to 1,0. Information on hydraulic confinement was extracted from geospatial data from wells, provided by SIAGAS (Sistema de Informações de Águas Subterrâneas). From there, they were interpolated using the IDW (Inverse Distance Weighting) algorithm in order to seek an approximate reality in relation to the representativeness of the confinement. The justification for using the IDW is that it "explicitly implements the assumption that things that are closer to each other are more similar than those that are more distant" (JAKOB and YOUNG, 2006);
b) Overall aquifer class: indexation of the cover strata, located above the aquifer's saturation zone, refers to the degree of consolidation and the type of lithology, with values between 0,4 to 1,0. This stratum conditions the time taken to move the contaminants and the various attenuation processes. For this, geology data provided by CPRM (Companhia de Pesquisa de Recursos Minerais) were used to reclassify the coverage strata using the reclassify algorithm;
c) Depth to groundwater: estimate of the depth of the water table, with values between 0,4 to 1,0. This parameter corresponds to the distance that the contaminant will have to travel to reach the saturated zone of the aquifer. It is important to highlight that for carbonate rocks its value is constant and equal to 1.0. Depth data was also acquired from SIAGAS and the IDW algorithm was used to represent it.

To perform the calculation of the vulnerability index by the Geographic Information System (GIS), it is first necessary to collect the data and transform it. For that, SIRGAS 2000 is adopted as a datum.

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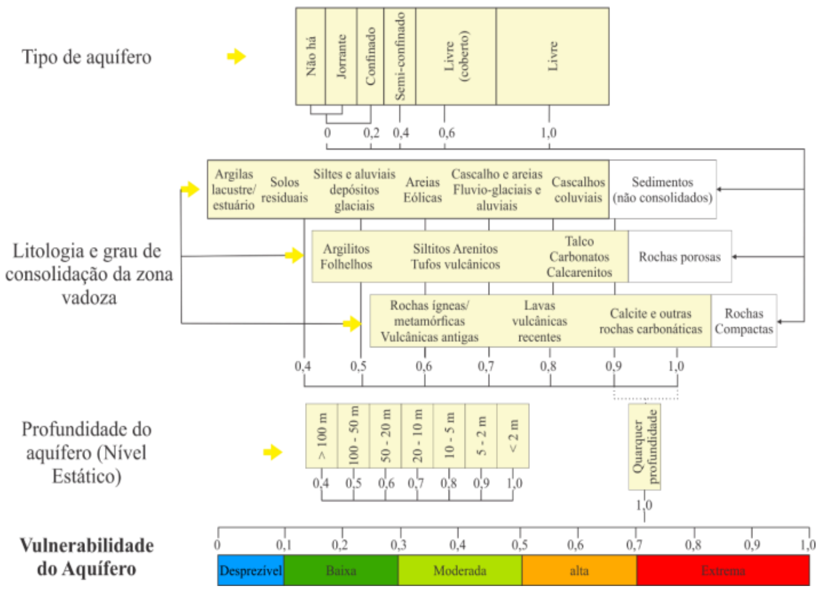

Figure 3 - Diagram of the GOD method. With the three data acquired, a reclassification is made on them using the parameters established in the diagram. Source: Adapted from Foster et al., (2002).

In a GIS environment, after reclassifying them, they are transformed into raster files, thus being formed by pixels. Each pixel or set of them corresponds to the reclassification from the diagram (Figure 3). Therefore, in the confinement raster, a pixel has an index of 0.2, whereas in the lithology raster there is a pixel with an index of 0.5 and finally, in the aquifer depth raster there is a pixel with an index of 0.4. The multiplication of these pixels, in the raster calculator tool, is called map algebra (Figure 4) and would result in the index 0.0, which corresponds to a negligible vulnerability (Figure 4) to aquifer contamination.

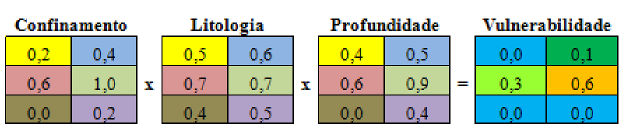

Figure 4 - Map algebra. The multiplication of indices generates a new raster, in this case, the vulnerability to aquifer contamination. Source: Authors (2019).

Foster et al. (2002), calls the final product of this method of integrated vulnerability map, since each analyzed vulnerability category is clearly and consistently defined, making it possible to establish some practical definitions to assist in territorial management and planning, as shown in Table 1.

Table 1 - Practical definition of the vulnerability classes. Source: Foster et al. (2002).

Rank	Index	Practical definition
Extreme	0,7 – 1,0	Vulnerable to many pollutants, impacting rapidly in various contamination scenarios.
High	0,5 – 0,7	Vulnerable to many pollutants, except for those with little mobility or persistence.
Moderate	0,3 – 0,5	Vulnerable to some pollutants and only when continuously released to the source.
Low	0,1 – 0,3	Vulnerable only to contaminants conserved for long term conservation and when released continuously.
Negligible	0,0 – 0,1	Confined layers in vertical downward flow not significant.

3. RESULTS AND DISCUSSION

Aquifers can be classified according to the water pressure in the overlapping layers and also according to their water transmission capacity (FEITOSA; FILHO; CARNEIRO; DEMETRIO, 2008).

In the RMS, as shown in Figure 5, it is possible to find a free aquifer in the extreme eastern portion. On the coast, there is a free (covered) and semi-confined aquifer. In the most continental zone, there is a confined aquifer, however, there is also the occurrence of a free (covered) aquifer. Feitosa, Filho, Carneiro and Demetrio (2008) understand that the recharge areas of confined aquifers correspond to free aquifers, where excess rainwater can penetrate through infiltration.

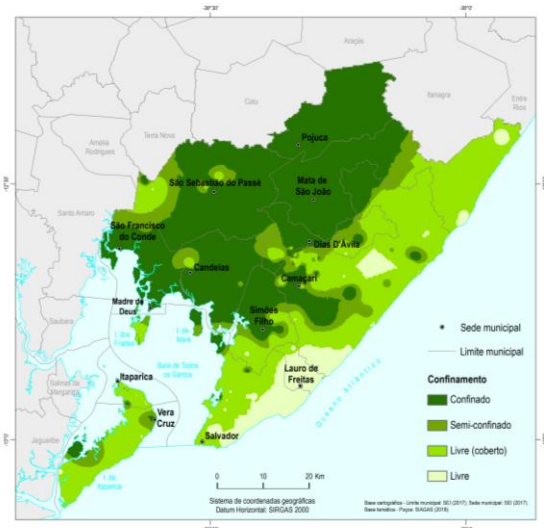

Figure 5 - Degree of confinement. When entering the continent, the aquifer becomes confined, differently coastal areas. Source: Authors (2019).

The vadose zone is also called the unsaturated or aeration zone (MANFRON; THOMÉ, 2012) is the part of the soil partially filled with water and where the phenomenon of filtration occurs. Therefore, this phenomenon is related to lithology, mineral composition, grain size distribution and the degree of compacting of sediments or rocks (FEITOSA; FILHO; CARNEIRO; DEMETRIO, 2008). Thus, the areas of impermeable or poorly permeable aeration are a barrier to the penetration of pollutants into the aquifer. The permeable zones allow the aquifer to be recharged, however, this characteristic allows the rapid diffusion of pollutants or contaminants (MANFRON; THOMÉ, 2012).

In the coastal areas of the RMS, there are very little consolidated materials with a large number of macropores, which correspond to the coastal deposits. In these areas, it is also possible to find swamp and mangrove deposits, which are poorly consolidated, but have a large amount of micropores. In the more interior areas, sedimentary materials with clayey texture occur, however, more consolidated. In the coastal areas there are crystalline rocks, corresponding to a material with a high degree of consolidation (Figure 6).

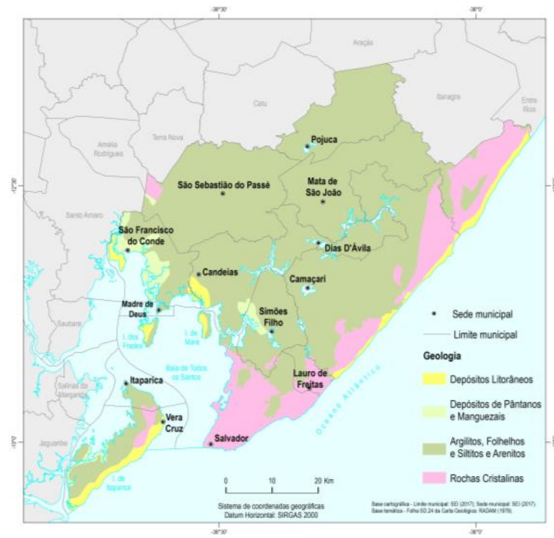

Figure 6 - Degree of consolidation of the vadose zone. The least consolidated materials are found in coastal deposits, mangroves and sedimentary rocks. Crystalline rocks have a higher degree of consolidation. Source: Authors (2019).

Static level is the depth of the water level in relation to the upper limit of the well (CPRM, 1998). This level can vary on a temporal scale and is conditioned by the amount of rain and the degree of consolidation of the vadose zone. In coastal areas, the static level varies between 2 and 10 meters in depth. In the continental areas of the RMS, the static level is between 10 and 50 meters deep (Figure 7).

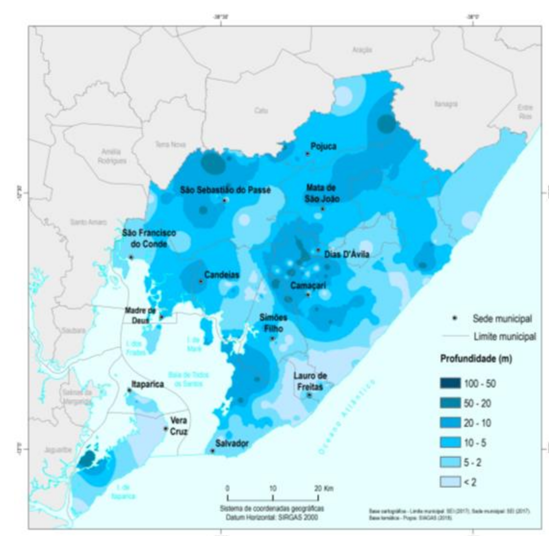

Figure 7 - Depth of the static level. In coastal areas, where the rainfall index is higher, there are less deep static levels. Otherwise, it occurs in continental areas. Source: Authors (2019).

The natural vulnerability to aquifer contamination was found from the multiplication of the parameters that make up the GOD method and resulted in four patterns: negligible, low, moderate and high vulnerability.

The areas of the aquifer that indicate negligible vulnerability are mostly north of the RMS. In this area, three main factors are related to each other: geology, which provides little permeability of contaminating liquids in the area of sand, creating an obstacle to the penetration of pollutants or contaminants in the aquifer; the presence of a confined aquifer, which may have one or two impermeable boundary layers, and the depth of the static level, which will allow a longer time for the displacement of the pollutants allowing their oxidation.

The set of characteristics of the negligible vulnerability of the aquifer, also characterize the areas where low vulnerability occurs. However, in this situation, it is possible to verify some aspects that may provide a greater vulnerability to contamination: the presence of a semi-confined and free (covered) aquifer and; less depth at the static level.

Areas of moderate vulnerability occur behind coastal areas. These have free (covered) aquifer, shallow depth of the static level and geology that produces greater permeability.

High vulnerability is verified in coastal areas and there are 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 aims to temporarily store water however, they infiltrate pollutants with greater speed. In these aquifers there are also static levels that do not exceed five meters in depth.

Finally, the result from the GOD methodology that shows the vulnerability to the natural contamination of aquifers, can be analyzed in Figure 8.

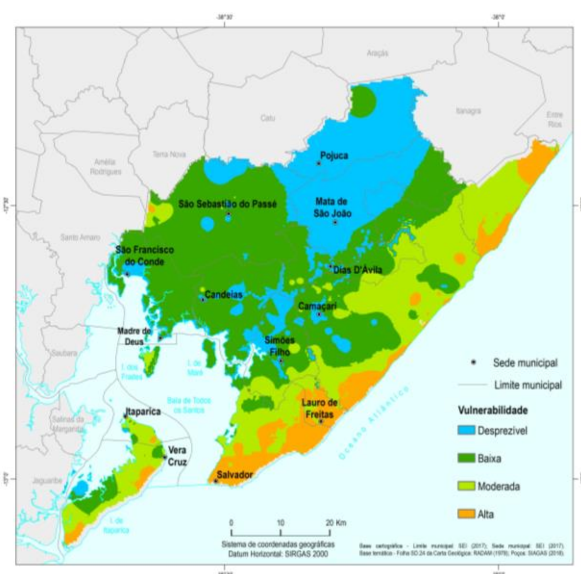

Figure 8 - Intrinsic vulnerability of aquifers in the RMS. The areas most vulnerable to contamination are coastal areas, whose material is predominantly sandy, the amount of rain is greater, the static level is less and the aquifer is free. Source: Source: Authors (2019).

4. FINAL CONSIDERATIONS

The GOD method clearly showed the natural vulnerability to aquifer contamination in the RMS intrinsically associated with lithology, the distinct porous dimensions of the substrates that compose it and the depth of the static level, consequently differentiating the hydrodynamic behavior of the aquifer.

As this method involves simplifications in hydrogeological and geological information, it is necessary to pay attention when reclassifying, treating and interpreting the results. In addition, water depth data were used to prepare the map and as they vary in time and space, it is necessary to update this information as well as the vulnerability map.

The choice of a particular methodology depends on the amount of information available and this technique uses data that is relatively easy to acquire, therefore, it can be used for initial prognoses as a support to environmental management and is geared towards regional studies, because , does not consider anthropic and contaminating activities as a factor that may increase vulnerability.

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