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ANALYSIS OF NATURAL VULNERABILITY TO GROUNDWATER CONTAMINATION: COMPARISON BETWEEN THE GOD AND DRASTIC METHODOLOGIES

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Abstract

Water is an essential natural resource to all forms of life; however, antropic activity, population increase and urbanization are changing the quality of shallow springs and making them unavailable for certain uses. Groundwater emerges as alternative to complete or even replace surface water; however, it is essential to have control over antropic activities so they would not contaminate aquifers. Thus, the aim of the present study is to compare the DRASTIC and GOD methods applied to the Vacacaí-Mirim River basin, in Rio Grande do Sul State. Both methods recorded vulnerability classes between insignificant an external, with higher prevalence of moderate (DRASTIC) and high (GOD) vulnerability. The GOD method held 89.91% of the vulnerability in 2 classes (moderate and high), whereas the DRASTIC one recorded 66.15% in these same classes. The DRASTIC method presented the highest class vulnerabilities in the study site. This outcome regards more consistent results and similar to parameters recorded in the field. Nevertheless, GOD is simpler due to the number of variables necessary for its application. It is important highlighting the importance of applying these methodologies to provide subsidies for decision-making by water resource managers.

Keywords: Aquifer, Hydrogeology, Susceptibility to contamination.

ANÁLISE DA VULNERABILIDADE NATURAL À CONTAMINAÇÃO DA ÁGUA SUBTERRÂNEA: COMPARATIVO ENTRE A METODOLOGIA GOD E DRASTIC

Resumo

A água é um recurso natural imprescindível para todas as formas de vida, porém, atividades antrópicas, aumento populacional e urbanização estão alterando a qualidade dos mananciais superficiais, tornando indisponível para determinados usos. Surge como alternativa para complementar ou até mesmo substituir o uso da água superficial a água subterrânea, porém, e necessita-se de um controle para que atividades antrópicas não venham a contaminar o aquífero. Nesse sentido, esse estudo tem por objetivo comparar os métodos DRASTIC e GOD na bacia hidrográfica do Rio Vacacaí-Mirim, no estado do Rio Grande do Sul. Ambos os métodos tiveram suas classes de vulnerabilidade entre insignificante e extrema, com maior predominâncias da vulnerabilidade média (DRASTIC) e alta (GOD). O método GOD concentrou 89,91 % da vulnerabilidade em 2 classes (Média e alta), já o DRASTIC apresentou 66,15 % nessas mesmas classes. Assim, o DRASTIC, na área de estudo apresentou, uma maior variabilidade das classes, indicando resultados mais consistentes, e com parâmetros obtidos a campo. Porém, o GOD é mais simplificado pelo número de variáveis necessárias para sua aplicação. Assim, destaca-se a importância da aplicação dessas metodologias para fornecer subsídios para tomadas de decisões para gestores dos recursos hídricos.

Palavras-chave: Aquífero, Hidrogeologia, Susceptibilidade a contaminação.

ANÁLISIS DE LA VULNERABILIDAD NATURAL A LA CONTAMINACIÓN DEL AGUA SUBTERRÁNEA: COMPARACIÓN ENTRE LA METODOLOGÍA GOD Y DRASTIC

Resumen

El agua es un recurso natural esencial para todas las formas de vida, sin embargo, las actividades humanas, el crecimiento de la población y la urbanización están cambiando la calidad de las fuentes de agua superficial, haciéndolas no disponibles para ciertos usos. Es una alternativa para complementar o incluso sustituir el uso de las aguas superficiales a las aguas subterráneas, sin embargo, y las necesidades es un control para que las actividades humanas no vienen a contaminar el acuífero. En este sentido, este estudio tiene como objetivo comparar los métodos GOD y DRASTIC en la cuenca del río Vacacaí-Mirim, en el estado de Rio Grande do Sul. Ambos métodos tenían sus clases de vulnerabilidad entre insignificante y extrema, con un mayor predominio de vulnerabilidad media (DRASTIC) y alta (GOD). El método GOD concentró el 89.91% de la vulnerabilidad en 2 clases (media y alta), mientras que DRASTIC presentó el 66.15% en estas mismas clases. Por lo tanto, DRASTIC, en el área de estudio, presentó una mayor variabilidad de clase, lo que indica resultados más consistentes y con parámetros obtenidos en el campo. Sin embargo, GOD se simplifica por la cantidad de variables requeridas para su aplicación. De este modo, se pone de relieve la importancia de la aplicación de estas metodologías para proporcionar información para la toma de decisiones para los administradores de los recursos hídricos.

Palabras-clave: Acuífero, hidrogeología, susceptibilidad a la contaminación.

1. INTRODUCTION

Many activities developed on the surface of the planet present the potential to contaminate natural resources due to population and industrial growth. Thus, Guo, Kuai and Lio (2019) have mentioned that such a growth is associated with severer environmental issues such as air pollution, water pollution and shortage, desertification and soil pollution.

With respect to water resources, surface water spring contamination, mainly caused by liquid waste discharge without proper treatment, impairs the consumption of certain uses, because they turn to groundwater in order to fulfil gaps in public supply. However, if groundwater is inproperly explored, it can become a severe environmental issue.

Accordingly, there are studies about hydrogeological matters that aim at promoting the appropriate management of these resources (Terra et al., 2016; Borba et al., 2016a, 2016b; Ribeiro et al., 2017; Silva et al. 2017; Rosa et al., 2019; Favaretto et al., 2020; Ncibi et al. 2020). The objective of these studies is to identify the areas mostly susceptible to contamination, based on the analysis of a whole range of parameters.

Among the main tools used to point out the areas mostly adequate to the development of potentially polluting activities, there are the methodologies to estimate the natural vulnerability of aquifers to contamination. These methodologies often need information about assays carried out in the field, or in laboratoty environment, or, yet, they need information available in databases of governmental agencies.

The DRASTIC (***D****epth to water,* ***R****echarge,* ***A****quifer media,* ***S****oil media,* ***T****opography,* ***I****mpact the vadose zone, hydraulic* ***C****onductivity of the aquifer*) method stands out among a whole set of existing methodologies described by Aller et al. (1987), such as GOD (***G****roundwater confinement,* ***O****verling strata,* ***D****epth to groundwater*) and POSH (***P****oluent* ***O****rigin and its* ***S****urcharge* ***H****ydraulic*), which were proposed by Foster et al. (2002; 2006). Besides these methods, Ribeiro (2005) has recently modified the original DRASTIC method (Aller et al., 1987), he removed two variables (***R****echarge,* ***A****quifer media,* ***S****oil media,* ***C****onductivity of the aquifer)* and added the LU (*Land Use*) parameter to it. This method is known as Susceptibility Index (SI), which is much used in research carried out in Portugal - POR.

The DRASTIC method involves several types of methods aimed at estimating aquifer vulnerability to contamination. The aim of the current study was to compare the DRASTIC (Aller et al., 1987) and GOD (Foster et al., 2002; 2006) methods applied to Vacacaí-Mirim River basin, in Rio Grande do Sul State.

2. METHODOLOGY

2.1. Study site

Vacacaí-Mirim River basin is located in Central Rio Grande do Sul State, between latitudes 29º 36’ 55”S and 29° 39’ 50”S, and longitudes 53º 46’ 30”W and 53° 49’ 29”W. It covers the total area of 1,145.7 km² (CASAGRANDE, 2004). The basin extends through three great geomorphological partitions that present different morphological and geological features: Planalto Region, Planalto Rebordo and Central or Peripheral Depression.

The river springs are located in Planalto Region, at altitude ranging from 300m to 480m, which is similar to that formed by volcanic events (Jura-cretaceous) that have covered Paraná Sedimentary Basin, at the Mesozoic, with the presence of basalt and sandstone “intertraps”. The region is featured by the presence of river dissection work on Planalto surface. Draining has dendritic pattern, V-shaped or flat-bottomed valleys.

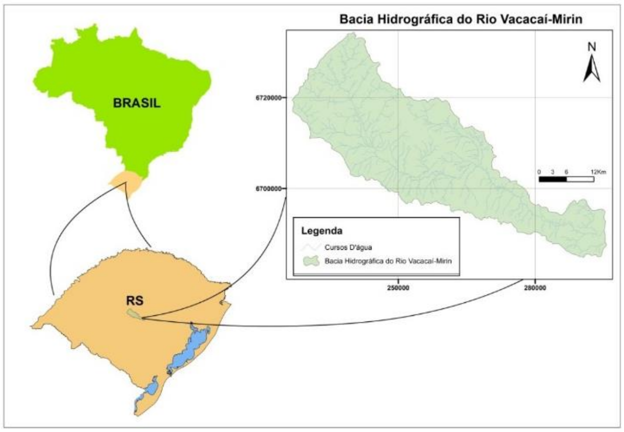

Figure 1 – Location in VAcacaí-Mirin River Basin. RS. Source: Kemerich et al. (2014).

Planalto Rebordo area is located on the transition between Planalto and Central Depression. Its topography is featured by abrupt cliffs, by drenage flowing towards the Central Depression and by dendritic pattern with remarkable V values. The Central Depression or Peripheral area is formed by sedimentary rocks from Paraná River basin that date back to the Paleozoic and Mesozoic (Triassic); they are localy coated with recent Cenozoic sediments (floodplains). The topography is more or lesser flat and slightly wavy, with round-shaped hills (Casagrande, 2004).

Based on Köppen's classification, climate in the basin area is of the Cfa type; subtropical, with well-distributed rainfall throughout the year. Based on the Brazilian Soils Classification (EMBRAPA, 2018), the prevailing soils in Planalto Region were RED-YELLOW ARGISSOLS associated with Eutrophic LITHOLIC NEOSOLS in some locations; Planalto Rebordo presented LITHOLIC NEOSOLS and ARGILUVIC CHERNOSOLS; Central Depression has PLANOSOLS and ARGILÚVICOS CHERNOSOLS (CASAGRANDE, 2004). Natural vegetation in Planalto and Planalto Rebordo is mainly formed by subtropical forest and the Peripheral Region mostly presents natural forage. The presence of isolated small and big-sized forest remnants is common in the field (SEPLAN, 1986).

2.2. Vulnerability estimates carried out through the GOD system (Foster et al., 2002; 2006)

Information available at the webpage of *Sistema de Informações de Águas Subterrâneas* (SIAGAS), which is fed by *Companhia de Pesquisa de Recursos Minerais (CPRM) do Serviço Geológico do Brasil,* is available at http://siagasweb.cprm.gov.br/layout/.

Vulnerability was found based on the product of variables G (Degree of groundwater confinement), O (Occurrence of cover extracts) and D (Distance from the water table). Thus, vulnerability was classified as insignificant (values between 0 and 0.1), low (0.1 to 0.3), moderate (0.3 to 0.5), high (0.5 to 0.7) and very high (0.7 to 1.0).

Figure 2 shows the example of GOD system application (Foster et al., 2002; 2006) in Vacacaí-Mirin River Basin, RS.

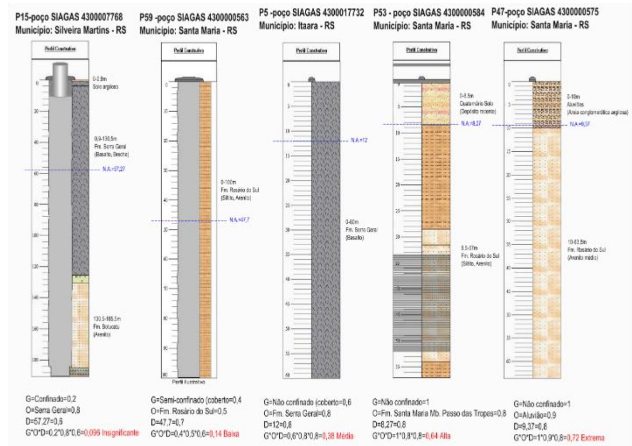

Figure 2 – Example of GOD application (Foster et al., 2002; 2006) at the study site. Source: Kemerich et al. (2013).

2.3. Vulnerability estimates through the DRASTIC method (Aller et al., 1987)

Vulnerability determination through the DRASTIC method followed the proposition by Aller et al. (1987). Values concerning variables D (Deepening the water level), R (Recharge), A (Aquifer material), S (Soil type), T (Topography), I (Influence of vadose zone) and C (soil water conductivity or vadose zone) are shown in Tables 1 (variables D, R and T), 2 (variables A and S), 3 (variable I) and 4 (variable C).

Information about the seven parameters necessary to estimate natural vulnerability to contamination were collected in different databases. Parameter D was obtained in the database of *Sistema de Informações de Águas Subterrâneas* (SIAGAS). Variable R derived from values proposed by Hausmann (1995), and A came from Hentges (2009). Variable S was acquired in soil maps of Rio Grande do Sul State - elaborated by Streck et al. (2008).

Topographies (T) were obtained in images of the *Shuttle Radar Topography Mission* (SRTM), at special resolution of 30m (USGS, 2004), which is available at http://earthexplorer.usgs.gov/. Variables I and A were determined based on Lopes da Silva (2015), who crossed information in geological maps by Hentges (2009), Filho et al. (2013) and in SIAGAS' database.

Table 1 - Parameters D, R and T of the DRASTIC index (ALLER et al., 1987) and their respective scores. Source: Adapted from Aller et al. (1987).

Parameters					
D		**R**		**T**	
Depth (m)	**Score**	**Recharge (mm/year)**	**Score**	**Topography (%)**	**Score**
< 1.5	10	< 51	1	0 - 1	10
1.5 – 4.5	9	21 – 102	3	1 - 6	9
4.5 – 9.0	7	102 – 178	6	6 - 12	5
9.0 – 15.0	5	178 – 254	8	12 - 18	3
15.0 – 22.5	3	< 254	9	> 18	1
22.5 – 30.0	2				
> 30.0	1				

Table 2 - Parameters A and S and their repective scores. Source: Adaped from Aller et al. (1987).

Parmeters				
A			**S**	
Aquifer nature	**Score**	**Usual**	**Soil Type**	Score
Solid shale	1-3	2	Thin or absent	10
Metamorphic / igneous rock	2-5	3	Gravel	10
Weathered metamorphic / igneous rock	3-5	4	Sandy	9
Glacial Till	4-6	5	Peat	8
Layered sandstone, limestone and sequential shale	5-9	6	Aggregated and / or altered clay	7
Massive sandstone	4-9	6	Sandy marl	6
Massive limestone	4-9	8	Marga	5
Sand and gravel	4-9	8	Marly silt	4
Basalt	2-10	9	Marly clay	4
Carsified limestone	9-10	10	Garbage / dung	2
			Disaggregated and non-expandable clay	1

Table 3 – Parameter I and its respective score. Source: Adapted from Aller et al. (1987).

I		
Vadose zone	**Score**	**Usual**
Confining layer	1	1
Silt / clay	2-6	3
Shale	2-5	3
Limestone	2-7	6
Lined limestone, sandstone and shale	4-8	6
Sand and gravel with significant silt and clay	4-8	6
Igneous / metamorphic	4-9	6
Sand and gravel	2-8	4
Sand and gravel	6-9	8
Basalt	2-10	9
Karstic limestone	8-10	10

Table 4 – Parameter C and its respective score. Source: Adapted from Aller et al. (1987).

Infiltration rate (mm/year)	Score
< 51	1
51 - 102	3
102 - 178	6
178 - 254	8
>254	9

Based on variable weighing, as shown in the tables above, the DRASTIC index was calculated through Equation 1. Variables followed by lowercase letter ‘p’ correspond to the score, as described in the classification shown in Tables 1 to 4.

$$DRASTIC = (Dp*5) + (Rp*4) + (Ap*3) + (Sp*2) + (Tp*1) + (Ip*5) + (Cp*3)$$

Thus, the vulnerability index calculated through the DRASTIC method (Aller et al., 1987) is classified as Low (values between 26 and 71), Moderate (71 to 126), High (126 to 180) and Very High (180 to 226). Figure 3 shows the example of DRASTIC method application (Aller et al., 1987) in the Vacacaí-Mirim River Basin, RS.

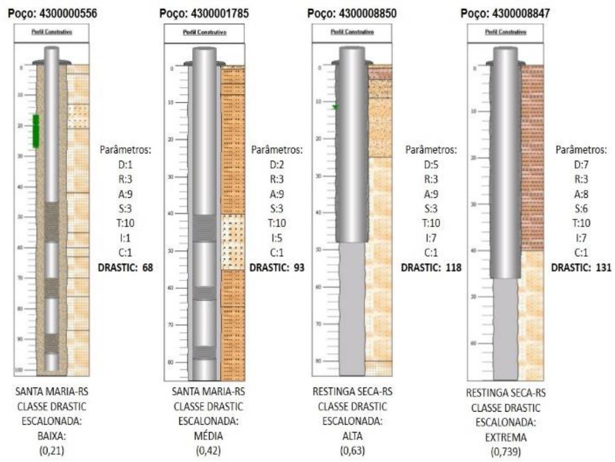

Figure 3 – Application of the DRASTIC methodology (Aller et al., 1987) in Vacacaí-Mirin River Basin, RS. Source: Built from CPRM (2016).

3. RESULTS AND DISCUSSION

Figure 4 depicts soil thickness in Vacacaí-Mirin River Basin, RS. It can be seen that soil thickness changes from less developed soils, such as neossols, to well-developed soils presenting thick clayey layers, such as argisols (STRECK et al., 2008). Soil depth in the basin ranged from 0 meters (outcrops and / or neossols) to 162 meters due to the presence of clay-type soils recording mean thickness of 11.33 meters.

The highest thickness values were concentratetd in the central zone of the basin, where vulnerability classes were classified based on the GOD methodology – which ranged from low to high, given the prevalence of moderate vulnerability class – and on the DRASTIC methodology - classes have ranged from low to high, but the high class has prevailed. It is important highlighting that the methodologies applied to Vacacaí-Mirin River Basin presented similar results in the region; however, there was prevalence of different classes. The shallowest soil depths were in compliance with higher GOD vulnerability values, since the DRASTIC method favored the prevalence of low and moderate classes.

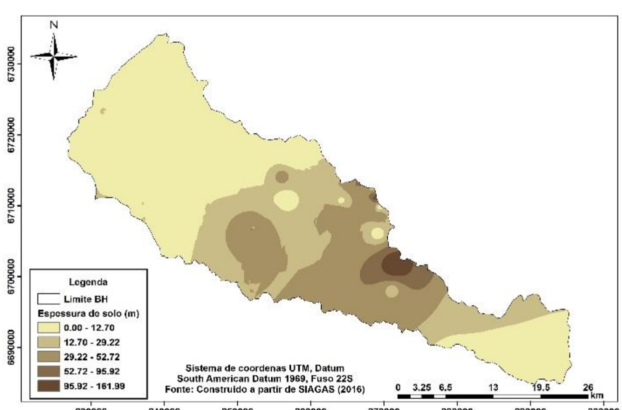

Figure 4 – Soil Layer Thickness in Vacacaí-Mirin River Basin, RS. Source: Built from CPRM (2016).

Of the total basin area (1,153.83 km²), 0.74 km² (0.06 %) was classified as insignificant vulnerability area; 197.21 (17.09 %) of the West region is located in low vulnerability area; 502.56 km² (43.56 %) of the South, Central and West regions were located in moderate vulnerability areas; 260.68 km² (22.59 %) of the Central and West regions were in the high vulnerability area; and 192.64 km² (16.70 %) of the Northeast region was classified as very high vulnerability area. The high and moderate classes have prevailed, they were observed in 66.15 % of the study site. Vulnerability calculated through the DRASTIC method reached 66.15 % (Figure 5).

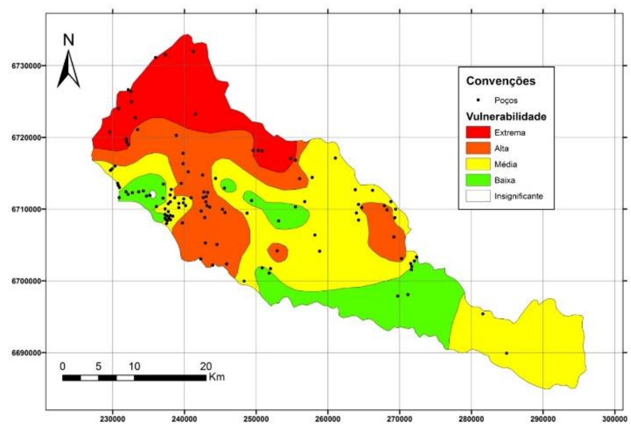

Figure 5 – Vulnerability estimates calculated through the DRASTIC method (Aller et al., 1987). Source: Authors

The comparison to the GOD methodology showed increased rate of insignificant vulnerability areas, since GOD presented 1.24% of low vulnerability area (5.04%), but the moderate vulnerability presented added rates, since GOD methodology presented 24.63% of its area in this classification. Low vulnerability, in its turn, recorded 1/10th of the total, because GOD presented 62.28% of the area within such a classification. The same was observed in the very high vulnerability (6.81%), as depicted in Table 1. Figure 6 shows vulnerability through the GOD system (Foster et al., 2002; 2006), which led to the prevalence of moderate and high classes, similar to results recorded through the DRASTIC method. However, through the GOD method, these classes were observed in 89.91% of the basin area.

Borba et al. (2019) and Fernandes et al. (2019) have assessed Serra Geral Formation in the region and found prevalence of insignificant to low vulnerability classes in Boa Vista das Missões and Marau counties, respectively. Such a fact can be related to the presence of highly clayey soil and the formation of an impermeable layer that prevents contaminants (generated on the surface) from reaching the groundwater (Borba, 2019).

On the other hand, Terra et al. (2016) have found prevalence of low, moderate and high vulnerability classes in São Sepé County, which is located in Vacacaí-Mirin River Basin (FEPAM, 2005), in the limit of the study site. This outcome is similar to that of the study site, where the occurrence of Moderate and High classes have prevailed due to the application of both methods.

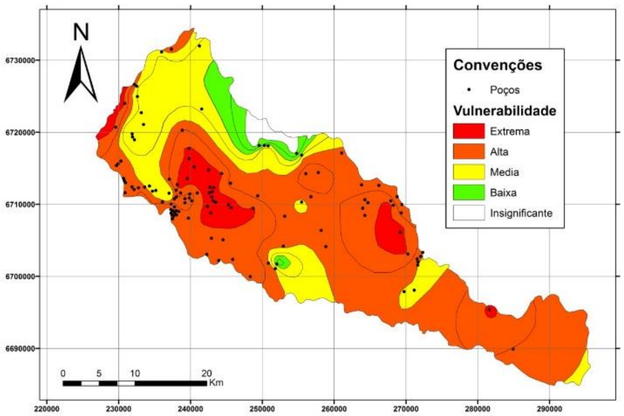

Figure 6 – Natural vulnerability to groundwater contamination calculated through GOD method (Foster et al., 2002; 2006). Source: Authors.

Table 5 depicts the comparision between the GOD and DRASTIC methodologies in Vacacaí-Mirin River Basin.

Table 5 – Comparison between the GOD and DRASTIC methodologies in Vacacaí-Mirin River Basin. Source: Authors.

Vulnerability						
GOD (Foster et al., 2002; 2006)				**DRASTIC (Aller et al., 1987)**		
	Sites			**Sites**		
Classes	%	ha	km^2	%	ha	km^2
Very High	6.81	7,860.00	78.60	16.70	19,264.46	192.64
High	62.28	71,855.00	718.55	22.59	26,067.61	260.68
Moderate	24.63	28,422.00	284.22	43.56	50,256.22	502.56
Low	5.04	5,814.00	58.14	17.09	19,720.97	197.21
Insignificant	1.24	1,432.00	14.32	0.06	74.04	0.74
Total	100.00	115,383.00	1,153.83	100.00	115,383.30	1,153.83

Table 6 shows the results obtained from the application of these two methods in studies carried out in other Brazilian regions.

Table 6 – Results obtained by other authors who had used the GOD (Foster et al., 2002; 2006) and DRASTIC methods (Aller et al., 1987). Source: Authors.

Reference	**Hidrogeology**	Vulnerability classes	
		DRASTIC	**GOD**
Cutrim e Campos (2010)	Aquiclude Ponta Grossa, Furnas Acquifer Systems, Furnas Ponta Grossa Transition	-	Insignificant to high
Medeiros et al. (2011)	Pernambuco - Paraíba Aquifer System	-	Insignificant to very high
Pinheiro et al. (2015)	Aquicludes, porous and fissure aquifers	-	Insignificant to high
Cardoso (2010)	Study carried out in Portugal	Low to high	Insignificant to high
Monteiro et al. (2008)	Barreiras Aquifer	Low and moderate	-
Duarte et al. (2014)	Study carried out in Portugal	Low to very high	-
Reginatto e Alhert (2013)	Serra Geral Aquifer System	Low to High	Low to moderate
Zanetti et al. (2014)	Aquifer from the Rio Claro Formation	Very high to high	Moderate to very high
Alves et al. (2009)	Free and fractured aquifers	Low to very high	-
Rosenberger et al. (2013)	Bauru, Serra Geral and Guarani Aquifer	Low to high	Low to high

The DRASTIC method uses larger number of parameters than GOD; it presented a map with greater spatial variability with vulnerability class switch in small or closer areas (neighbor). The GOD method needs smaller number of parameters; it presented smaller class spatial distribution in the study site. This condition was also found by Siclerio and Verginatto (2011), who found the presence of uniform conditions in the study site. Map representation also represented the occurrence of the same vulnerability class in expressive areas. It was possible observing that vulnerability classes did not change, but the prevalence of the larger classes was different. Both methods presented the same classes but in different portions of the watershed.

It is important highlighting that the GOD methodology (Foster et al., 2002; 2006) does not need field information. It can influence information validation. On the other hand, based on the DRASTIC method (Aller et al., 1987), it is necessary having displacement and sample collection in different spots of the watershed; some of the samples must be collected and analyzed in laboratory environment. DRASTIC prolongues asessment conduction time and increases financial costs; however, it allows the local and regional observation of some variables.

4. FINAL CONSIDERATIONS

The application of the DRASTIC and GOD methodologies enabled estimating aquifer natural vulnerability to contamination in Vacacaí-Mirin River basin. The DRASTIC method was more reliable, since there was greater spatial variability of classes in the basin area; however, recharge parameters and the influence of the vadose zone presented limitations in the estimates - it made it necessary setting a rigorouos planning. With respect to GOD, it was simpler, but presented values close to 90% of the area in only two vulnerability classes (high and moderate). There was similarity in the insignificant class rates in both methods. This outcome showed that DRASTIC is more sentitive to the variables given the weighing difference and the necessary number of parameters.

The methods used in the estimates of aquifer natural vulnerability to contamination emerged as important tools to help environmental management in decision-making processes. It is worth pointing out the application of these methodologies as tool aiming at acquiring lisences to install ventures with the potential to generate contaminants. However, it is suggested to carry out assays in the field in order to validate information about class vulnerability through the application of different methods.

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