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Artigos

Assessment of the vulnerability to contamination of fractured aquifers based on DRASTIC method: the influence of the lineament density

Vulnerabilidade à contaminação de aquíferos fraturados com base no método DRASTIC: a influência da densidade de lineamentos

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Abstract

Vulnerability map is an effective tool to assess and identify the areas that are most susceptible to groundwater contamination, and can aid in the planning and management of municipal groundwater. These maps can help decision-making regarding land use and cover, pointing out proper sites to rural and/or urban sprawling but also highlighting restrictions for groundwater withdrawal. This paper aims at evaluating the influence of the lineament density (DRASTIC-LD) and the influence of the land use and cover, along with the lineament density, (DRASTIC-LDLU) in the classification of the vulnerability of the Serra Geral Aquifer System. The DRASTIC approach was modified by adding the lineament density. The DRASTIC-LD method showed high (70.73%), moderate (17.04%) and very high (12.17%) vulnerability. The DRASTIC-LDLU method presented high (55.35%), extreme (19.65%), very high (14.66%) and moderate (10.31%) vulnerability. Lineament density and land use and cover had a significant influence on the vulnerability classification. The spatial distribution of vulnerable zones was quite similar to those obtained by applying the original DRASTIC model. However, a significant increase in vulnerability was observed across the study area when the lineament density parameter was added, followed by an even greater vulnerability when the lineaments were inserted together with land use land cover. Inserting these two parameters together provides a more accurate result of vulnerability in fractured aquifers, as it is a more faithful representation of the reality of this system.

Resumo

Os mapas de vulnerabilidade são uma ferramenta eficaz para avaliar e identificar as áreas mais suscetíveis à contaminação das águas subterrâneas, auxiliando no planejamento e gestão das águas subterrâneas municipais. Esses mapas podem ajudar na tomada de decisões sobre o uso e ocupação do solo, indicando locais adequados para expansão rural e/ou urbana, e também destacando as restrições para a retirada de água subterrânea. Este trabalho tem como objetivo avaliar a influência da inclusão do parâmetro densidade de lineamentos (DRASTIC-LD) e do uso e cobertura do solo, juntamente com a densidade de lineamentos (DRASTIC-LDLU), na classificação da vulnerabilidade à contaminação do Sistema Aquífero Serra Geral. O método DRASTIC-LD enquadrou 70,73% da área como de vulnerabilidade alta, 17,04% moderada e 12,17% muito alta. Já com método DRASTIC-LDLU, 55,35% da área foi classificada como de vulnerabilidade alta, 19,65% extrema, 14,66% muito alta e 10,31% moderada. A inserção dos parâmetros densidade de lineamento e uso e cobertura do solo apresentou influência significativa na classificação de vulnerabilidade. A distribuição espacial das zonas vulneráveis foi bastante semelhante àquelas obtidas pela aplicação do modelo DRASTIC original. No entanto, observou-se um aumento significativo da vulnerabilidade em toda a área de estudo quando foi inserido o parâmetro densidade de lineamentos, seguido de uma vulnerabilidade ainda maior quando os parâmetros densidade de lineamento em conjunto com o uso e cobertura do solo foram adicionados. A inserção desses dois parâmetros juntos fornece um resultado mais preciso da vulnerabilidade em aquíferos fraturados, pois é uma representação mais fiel da realidade deste sistema.

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1. INTRODUCTION

In the northeast of the state of Rio Grande do Sul, southern Brazil, groundwater is associated with two aquifer systems: the Serra Geral Aquifer System (SGAS), inserted into the volcanic rocks of the Serra Geral Formation, and the Guarani Aquifer System (GAS), a granular aquifer confined by the Serra Geral Formation, which consists of volcanic rocks with an acid and basic composition, associated with the sedimentary rocks of the Botucatu Formation (REGINATO; AHLERT, 2013). Groundwater from these systems is often used for public supply and for the development of industrial and rural activities (REGINATO; AHLERT, 2013; BORTOLIN *et al.*, 2014).

Technical and financial limitations make it difficult to remediate contaminated groundwater, thus protecting these resources is a more viable solution. Vulnerability maps can identify areas that are susceptible to contamination, being a useful tool for groundwater decision-making (HIRATA & FERNANDES, 2008; REGINATO; AHLERT, 2013). The vulnerability to contamination of an aquifer is defined as its susceptibility to being adversely affected by an anthropogenic pollution load. The degree of confinement, the water table depth, the hydraulic conductivity and the characteristics of the material covering the saturated zone are relevant aspects for the assessment of the vulnerability of an aquifer (HIRATA; FERNANDES, 2008).

Among the existing assessment methods, the most widely used is the overlap and index, through which the protective effect of the covering layers, above the water table, are expressed in a semi-quantitative way, assigning weights to different parameters according to their importance in protecting groundwater (FRIND *et al.*, 2006). The DRASTIC index method (ALLER *et al.*, 1985) is widely used, and due to its flexibility, several authors have made changes to its original version, inserting new parameters such as land use and cover and lineament density (UMAR *et al.*, 2009; AWAWDEH; JARADAT, 2010; ALAM *et al.*, 2014; JENIFER; JHA, 2018; MAQSOOM *et al.*, 2020; SALIH; AL-MANMI, 2021). Other studies have changed the weights and loads recommended by the original method through the application of different techniques, such as Fuzzy logic and Analytic Hierarchy Process (AHP) (CHEN; FU, 2003; THIRUMALAIVASAN *et al.*, 2003; TORKASHVAND *et al.*, 2020).

The groundwater flow in the SGAS is conditioned by the presence of fractures, crossing and connection of lineaments (REGINATO, 2003). The quality of the water in this system is related to these structures, because they interfere with the velocity of the groundwater flow, acting as the main transport path for the contaminant (SARIKHANI *et al.*, 2014; JENIFER; JHA, 2018). Therefore, regions that have a higher density of lineaments can also have a higher potential for contamination. The inclusion of lineaments in hydrogeological studies makes the result of the model more accurate, portraying more precisely the assessment of the vulnerability in fractured aquifers (AWAWDEH; JARAD, 2010).

Few studies on the vulnerability of fractured aquifers use the density of lineaments as a parameter for the calculation of the DRASTIC index. Studies such as those by Mendonza & Barmen (2006), Awawdeh & Jaradat (2010), Abdullah *et al.* (2015) and Jenifer; Jha (2018) included the lineament density parameter in order to verify their degree of influence in assessing the vulnerability. Most of them observed an increase in the percentage of classified areas with a greater degree of vulnerability in their analysis, concluding that the insertion of the lineaments resulted in a more accurate representation of the pollution potential associated with highly fractured areas. But on the other, Abdullah *et al.* (2015) concluded that lineaments had little influence on vulnerability to contamination and attributed this discovery to the low density of lineaments in the area of study.

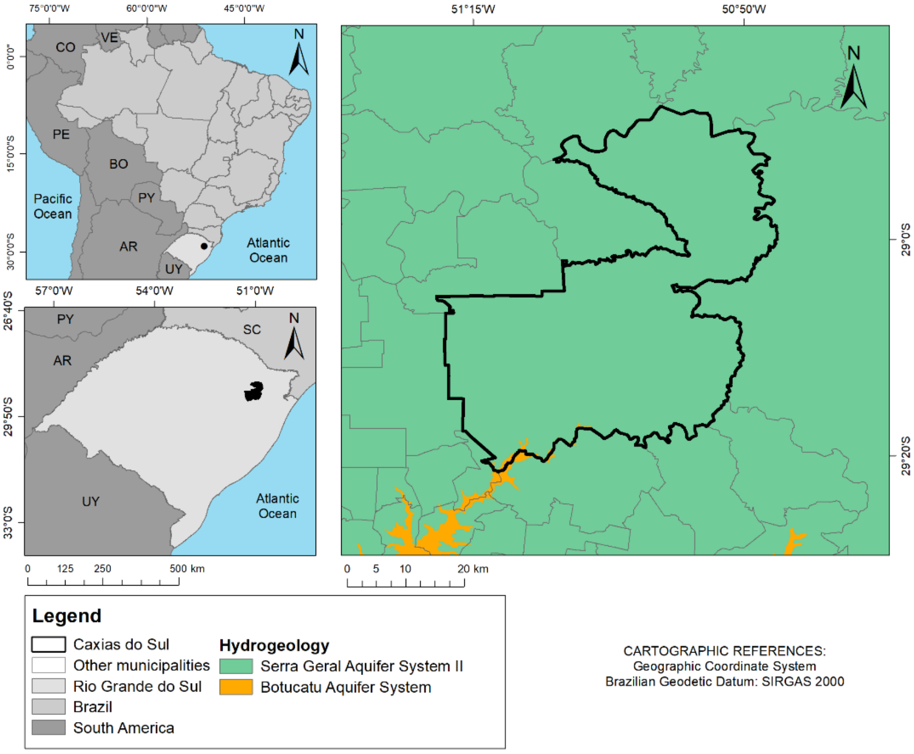
Along with runoff, groundwater is responsible for feeding the creeks that supply water to the city of Caxias do Sul, as well as supplying the industrial and rural sectors of this municipality (VARGAS *et al.*, 2018). Taking into account the fissural characteristics of the aquifer and the importance of this system to the environment and the economy of more than half a million people, this study aims at evaluating the influence of the lineament density in the classification of the natural vulnerability to contamination of the SGAS.

2. AREA OF STUDY

Caxias do Sul is located in the northeast region of the State of Rio Grande do Sul, Brazil, between the geographical coordinates 51°18’00”W – 50°42’00”W and 29°20’00”S – 28°48’00”S. It has an estimated population of 510,906 inhabitants (IBGE, 2019). This study site is in the geological framework of the Paraná Basin that holds the São Bento Group. This group includes the Guará and Botucatu sedimentary Formations and the Serra Geral volcanic Formation. The Serra Geral Formation consists of volcanic flows of tholeitic and andesibasalts at the base and volcanic flows with acid composition in the upper portion (ROISENBERG; VIERO, 2000) and vitrophyres from the Várzea do Cedro Facies (CPRM, 1998). The Gramado unit consists of basalts and andesibasalts, with a dark gray and brown color, set in volcanic packages of less than 30 meters thick. At the Caxias unit, it is commonly found riodacites and rhyolites, presenting light gray, greenish gray and bluish color, set in volcanic packages of about 50 meters (REGINATO; AHLERT, 2013).

The city of Caxias do Sul is located predominantly in the Serra Geral Aquifer System II - SGAS II (Figure 1). SGAS is a fissural aquifer, associated with the volcanic rocks of the Serra Geral Formation, developing along discontinuities and fractures. The circulation of water in this system is related to the tectonic structure (fractures, intersections and connections of the lineaments) and to the primary structure of the rock (volcanic breccia, vesicular and amygdaloid zones). Due to its strong anisotropy, this aquifer is characterized by variable flow rates and, generally, low values of specific capacity and transmissivity (REGINATO, 2003).

Figure 1 - Location and hydrogeology of the study area.



3. METHODS

The assessment of the vulnerability to contamination of the SGAS was carried out by applying the DRASTIC original method (ALLER *et al.*, 1985) and modifications of this model: (1) through the insertion of the lineament density parameter (LD) and (2) the land use and cover, along with the lineament density, parameter (LDLU). DRASTIC is based on the analysis of seven parameters: water table depth (D), recharge (R), aquifer media (A), soil type (S), topography (T), impact of the vadose zone (I) and hydraulic conductivity (C). For each of these parameters it is assigned a weight "w_j", which varies from 1 to 5, and a class, which receives "r_j" rating, varying from 1 to 10 (Table 1), thus generating a vulnerability index (Equation 1). The weights of each parameter are determined in relation to each other, according to their relevance to the vulnerability of the aquifer, where the higher the value, the greater the significance to pollution. The class "r" is established based upon the interpretation of data on the physical media of the area of study and based upon reference values.

$$\mathrm{VI} = \sum_{j=1}^{7} (w_j \ x \, r_j) \qquad (1)$$

Where: VI is the vulnerability index, w is the weight, r is the classification and j each of the seven DRASTIC parameters.

The data used in the model were selected from wells registered in the Serviço Autônomo Municipal de Água e Esgoto – SAMAE of Caxias do Sul and in the Sistema de Informações de Águas Subterrâneas – SIAGAS (CPRM, 2018). The survey and interpretation of the geological, pedological and topographic maps, and climatic data were based respectively on information/data/publications from CPRM (2010); Embrapa (2006), Streck (2008) and Santos *et al.* (2011); Jaxa (2011); Agritempo (2018). The recharge (R), aquifer media (A), topography (T), soil type (S) and material from the vadose zone (I) parameters were extracted from Gomes *et al.* (2021). Water table depth (D) was determined through the interpolation of the water level data of 884 wells, using the Radial Basis Function with Tension (RBF) method, applied with the Geostatistical Analyst tool from ArcGIS 10.6 Software (RIBEIRO *et al.*, 2021). The hydraulic conductivity (C) parameter was replaced by transmissivity, due to discontinuities and strong anisotropy of fractured aquifers. According to Maia and Cruz (2011) and Borges *et al.* (2017), transmissivity has a strong correlation with hydraulic conductivity, thus justifying its use. To obtain this parameter, the Cooper Jacob method (1946) was applied using data from 127 wells, processed in Aquifer Test 2016.1 Software (SCHLUMBERGER, 2018). Through the interpolation of these data, the transmissivity map was obtained using the CoKrigagem interpolator with the Geostatistical Analyst tool of the ArcGIS 10.6 Software (RIBEIRO *et al.*, 2021).

The refinement of the natural vulnerability indexes was carried out with the insertion of the lineament density parameter and the land use and cover parameter. The lineaments, drawn on the scale 1:450.000, were extracted from the work of Lisboa (2003). The lineament density of the region was calculated using the LineDensity tool from the ArcGIS 10.6 Software. The map of land use and cover was obtained from MapBiomas (2019), referring to the year 2018. This map was generated from the pixel-by-pixel classification of images from the Land sat satellite, presented in a matrix format (30 x 30 m). For the location of the current study, data related to the Atlantic Forest Biome were used.

The weights, classes and class ratings used to calculate the DRASTIC vulnerability index are shown in Table 1. The classes and class ratings were selected based on previous studies carried out at the SGAS (REGINATO, 2003; REGINATO & AHLERT, 2013; BORGES *et al.* 2017). The line density and land use/land cover parameters had their weights and classes determined based on the study of Jenifer & Jha (2018).

Table 1 - Weights assigned to DRASTIC parameters, their classes and class ratings

Parameter	Symbol	Weight	Class	Rating
Depth to the water table	D	5	0 – 2	10
			2 – 5	9
			5 - 10	7
			10 – 17	5
			17 – 26	3
			26 – 34	2
			> 34	1
Recharge (mm)	R	4	301,13	7
			354,90	8
Aquifer media	A	3	Sandstone	6
			Basalt	8
Soil (infiltration rate)	S	2	Moderate	6
			Low	3
			Very Low	2
Topography (%)	T	1	0 - 2	10
			2 – 6	9
			6 – 12	5
			12 – 18	3
			> 18	1
Impact of vadose zone (aptitude for waste disposal)	I	5	Proper	1
			Regular	3
			Restricted	6
Transmissivity (m^2/h)	C	3	0 – 0,133	1
			0,133 – 0,493	2
			0,493 – 1,458	4
			1,458 – 5	6
			> 5	8
Lineament density (km/km^2) *	LD	5	0 – 0,15	6
			0,15 – 0,5	7
			0,5 – 1,0	8
			1,0 – 1,6	9
Land use/land cover*	LU	5	Forest formation	0
			Forest plantation	0
			Grassland	0
			Farming	9
			Urban infrastructure	7
			Exposed soil	8
			Water resources	0

Source: modified from Jenifer & Jha (2018)

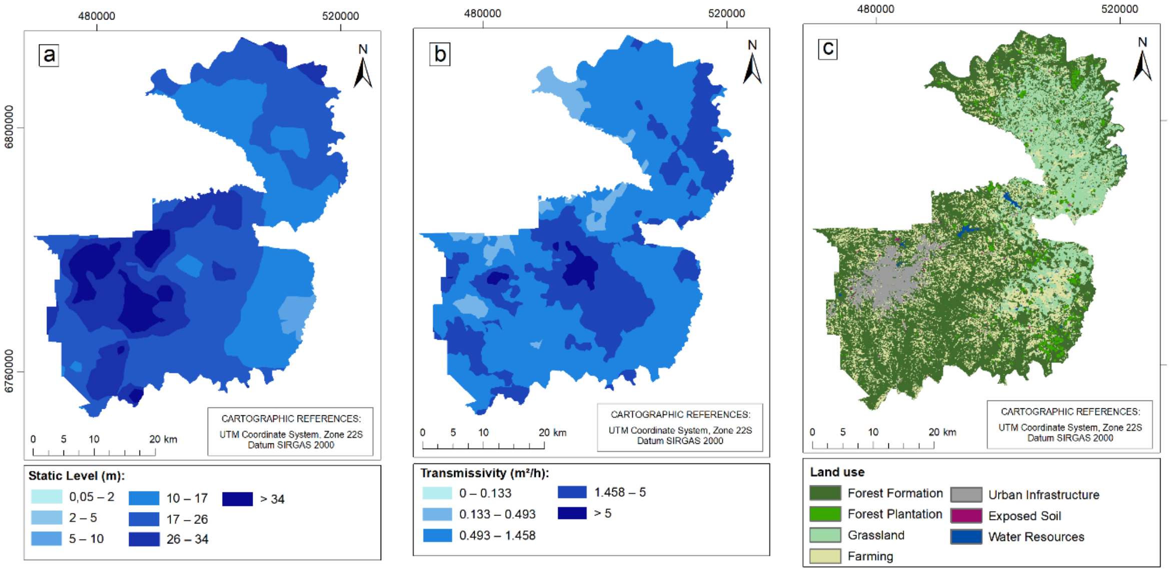
The integration of the parameters for obtaining the vulnerability index was performed by map algebra using the ArcGIS 10.6 Software. Two vulnerability maps were generated, one adding only the lineament density (DRASTIC-LD) and the other adding the lineament density with land use and cover (DRASTIC-LDLU). Aller *et al.* (1987) separate the indices into seven classes: Insignificant (< 79), Very Low (80 - 99), Low (100 - 119), Moderate (120 -139), High (140 - 159), Very High (160 - 179) and Extreme (> 180).

4. RESULTS AND DISCUSSION

4.1. Determination and analysis of the vulnerability parameters

The maps of water table depth (D), transmissivity (C), and land use/land cover (LU) were extracted from the work of Ribeiro *et al.* (2021) and are shown in Figure 2. The static level (Figure 2a) varies from 0.05 to 162.11 m in Caxias do Sul, with a predominance of the range of 17 to 26 m (45.93%) (RIBEIRO *et al.*, 2021). The smallest depths (less than 10 m) were observed in the east and southeast region. Whilst the greatest depths (greater than 26 m) were identified in the western portion of the city. As for the transmissivity parameter (Figure 2b), the same authors identified variation from 0.005 to 22 m²/h, predominating the range from 0.493 to 1.458 m²/h.

Figure 2 - (a) Water depth (D); (b) Transmissivity (C); (c) Land use/land cover (LU)



Source: Ribeiro *et al.* (2021)

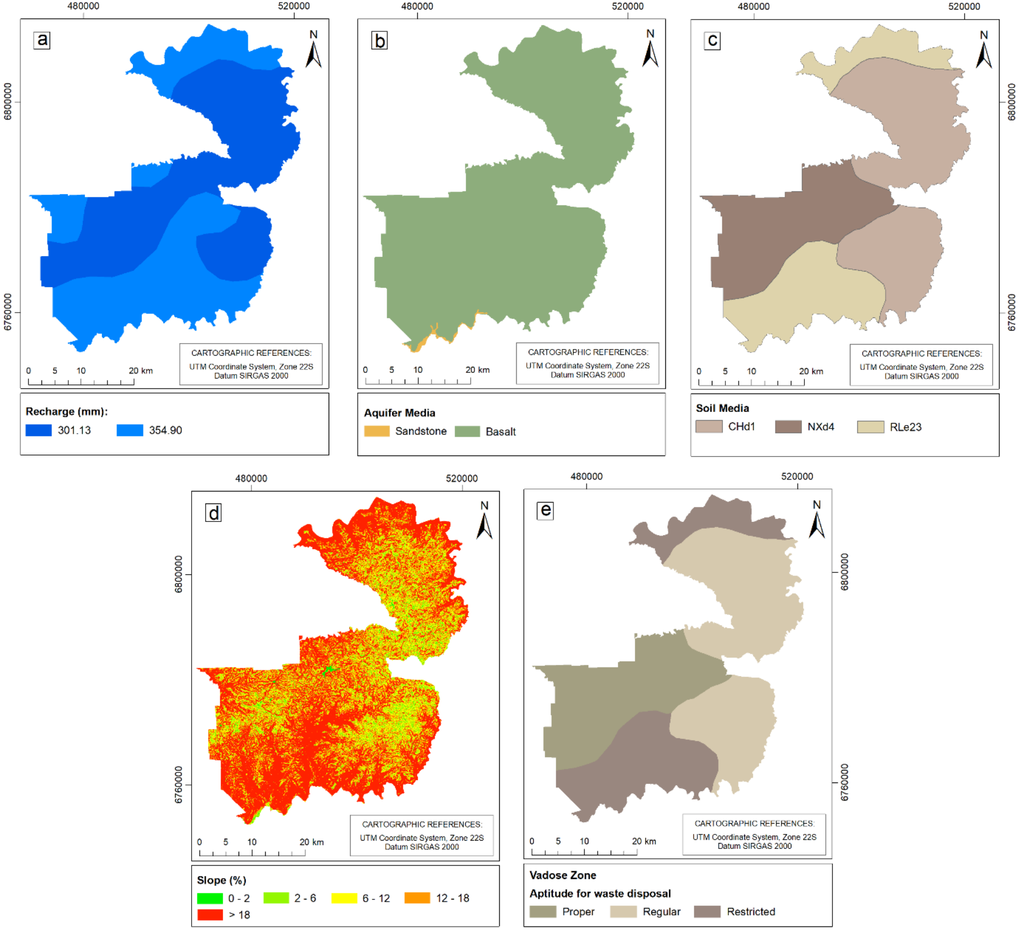
In relation to land use/cover (Figure 2c), Ribeiro *et al.* (2021) identified a predominance of forest formation (57.72% of the area of study), followed by agriculture (20.13%) and grassland formation (18.73%). A greater potential for groundwater pollution occurs in rural areas occupied with agriculture and livestock ranches, as they increase the movement of water and contaminants through the vadose zone (JENIFER; JHA, 2018).

The maps with recharge (R), aquifer media (A), soil media (S), topography (T) and vadose zone (I) were extracted from the work developed by Gomes *et al.* (2021). The recharge estimate (Figure 3a) was obtained by applying the water-budget method, through which the authors identified a recharge of 354.9 mm/year in 53.3% of the area (855.26 km²) and 301.13 mm/year in 46.7% of the area (749.35 km²). To define the aquifer media (Figure 3b), Gomes *et al.* (2021) used the geological map of the site (CPRM, 2010), where almost the entire municipality is formed by outcrops of the Serra Geral Formation (99.5%) and the remainder by the Botucatu Formation (0,5%).

To elaborate the map of the soil media (Figure 3c), Gomes *et al.* (2021) classified the types of soil based upon their infiltration capacity. The authors identified soils with low (42.24%), moderate (29.1%) and very low (28.66%) infiltration capacity. The slope (Figure 3d) of the area presents a variation from flat regions (0%) to sites where it is higher than 18% (Gomes *et al.*, 2021). To elaborate the map of the impact on the vadose zone, the authors classified the area according to its capability of receiving waste disposal, and identified three classes: regular (42.24%), suitable (29.1%) and restricted (28.66%).

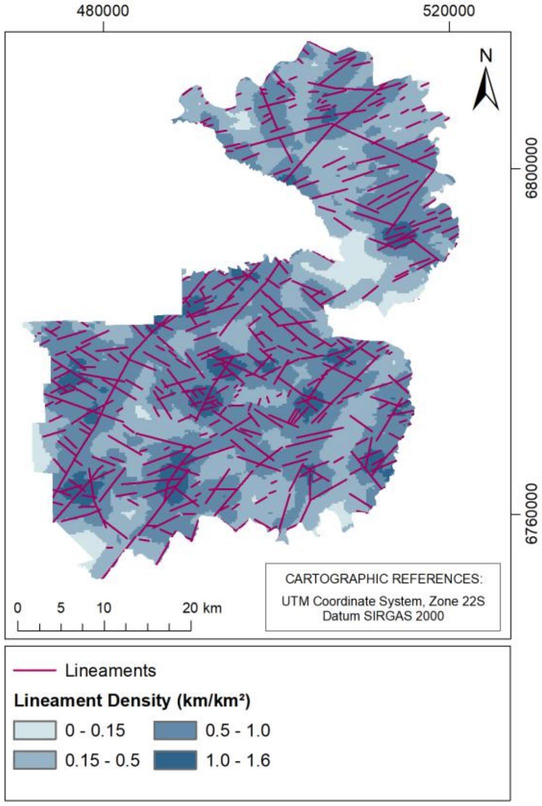
In the lineaments density map (Figure 4), it can be observed that in 54.15% of the area prevails the range of 0.5 to 1.0 km/km², followed by the range 0.15 to 0.5 km/km² (34.12%), 1.0 to 1.6 km/km² (7.48%) and 0.0 to 0.15 km/km² (4.25%).

Figure 3 - (a) Recharge; (b) Aquifer media; (c) Soil media; (d) Topography (T); (e) Vadose zone



Source: Gomes *et al.* (2021)

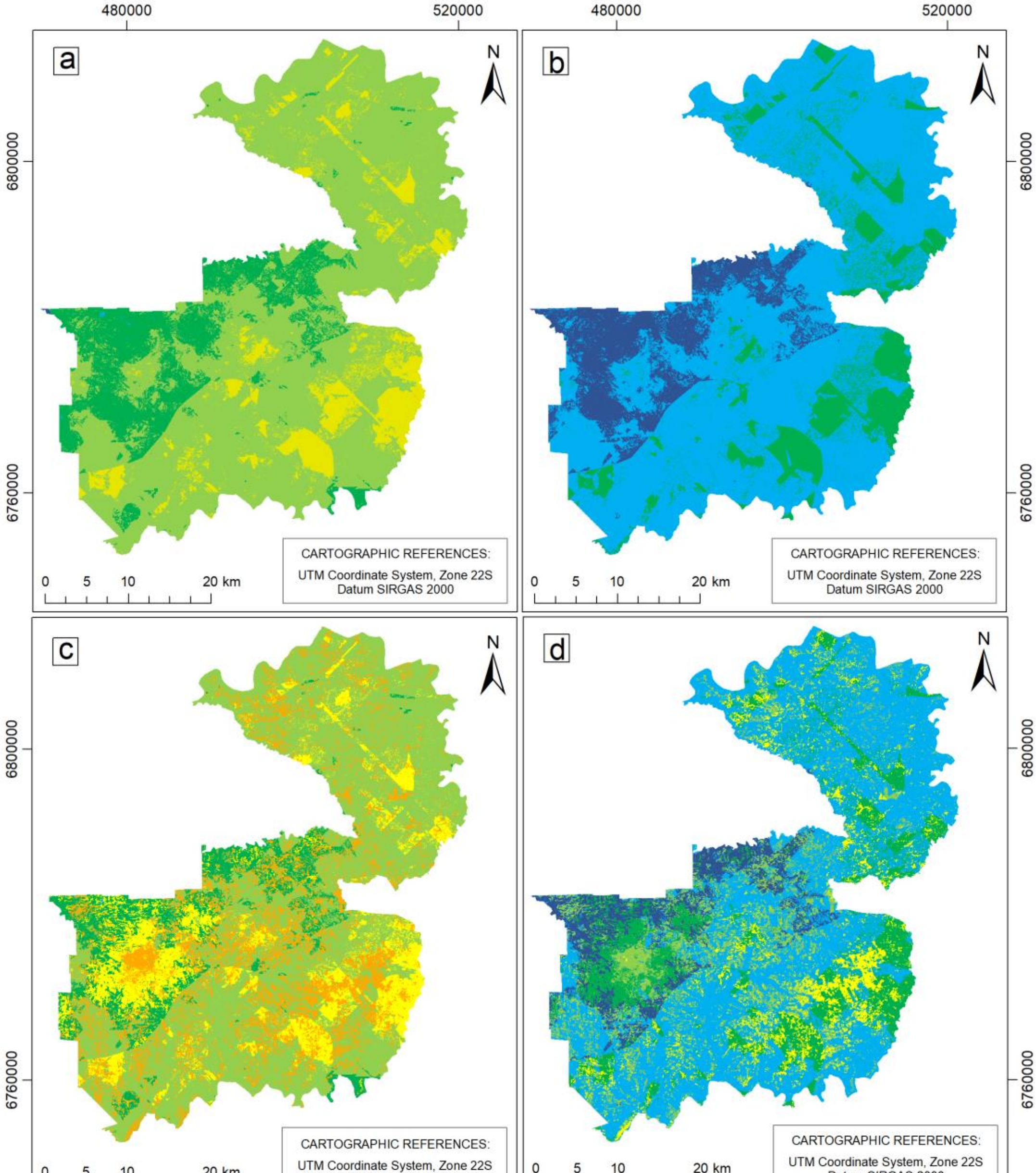
Figure 4 - Lineament density map



4.2. Constitution of the vulnerability of SGAS II

The product from the modified DRASTIC is represented in Figure 5, where it is depicted the results obtained by applying map algebra to the set of parameters selected from Gomes *et al.* (2021), Ribeiro *et al.* (2021) and based upon the lineaments density (Figure 4). Figure 5a presents the vulnerability when the lineament density (LD) is added to the algebra, along with the parameters extracted from the aforementioned authors. In Figure 5c, it is shown the vulnerability map with the insertion of LU (RIBEIRO *et al.*, 2021) and LD. Figure 5b (original DRASTIC) and Figure 5d (DRASTIC-LU), obtained from Riberio *et al.* (2021), were added to this study in order to provide a comparative analysis with the results acquired from the modification of the original DRASTIC. Table 2 shows the percentages and corresponding areas of the vulnerability classes for the applied methods.

Figure 5 - SASG vulnerability maps: (a) DRASTIC-LD; (b) original DRASTIC*; (c) DRASTIC-LDLU; (d) DRASTIC-LU*



Source: (*) Extracted from *Ribeiro et al.* (2021).

Table 2 - Vulnerability classes generated by applying the original DRASTIC and the modified ones

Class/Method		Original *	LD	LU*	LDLU
Insignificant	km²	0,002	-	0,001	-
	%	0,0001		0,00008	
Very Low	km²	226,39	-	133,51	-
	%	13,86		8,17	
Low	km²	1143,28	0,548	888,33	0,340
	%	70,02	0,03	54,40	0,021
Moderatea	km²	263,08	278,31	279,78	168,38
	%	16,11	17,04	17,13	10,31
High	km²	0,07	1154,63	197,09	908,54
	%	0,004	70,73	12,07	55,35
Very High	km²	-	198,73	133,77	239,30
	%		12,17	8,19	14,66
Extreme	km²	-	0,163	0,332	320,81
	%		0,01	0,02	19,65

(*) Extracted from Ribeiro *et al.* (2021).

The vulnerability index (VI) of the study area, with the addition of only LD (Figure 5a), covered 5 vulnerability classes: low, moderate, high, very high and extreme. In 70.73% of the area, the vulnerability is high, in 17.04% it is moderate and in 12.17% very high. The occurance of the lower and extreme classes sum up as little as 0.04% of the municipality area.

Comparing these results with the ones in Ribeiro *et al.* (2021), where the original DRASTIC was applied, there is an increase of approximately 5% in the area classified as moderate, changing from 263.08 km² to 278.31 km² (Table 2). It is also observed that the insignificant and very low classes are no longer present in the map generated with the DRASTIC-LD method. Instead, the very high and extreme vulnerability classes were added. Vulnerability maps are an important auxiliary tool for identifying areas naturally sensitive to human activities, so the 5% increase in areas classified as moderate vulnerability and the emergence of higher vulnerability classes constitutes a significant change for municipal planning.

There is a great similarity in the spatial distribution of the vulnerability zones in the maps generated with the original DRASTIC and the one that was modified by adding LD. However, the areas previously classified as very low, low and moderate following the original DRASTIC, were respectively classified as moderate, high and very high when using the DRASTIC-LD method.

The insertion of the LD parameter, in the original DRASTIC, resulted in a significant increase in the vulnerability in the city of Caxias do Sul. The lineament density has a great influence on vulnerability due to its high weight, and it is noteworthy that it is attributed a high weight for this parameter because it influences the velocity of the underground flow, and consequently acts as the main transport path for the contaminant (SARIKHANI *et al.*, 2014; JENIFER & JHA, 2018).

The vulnerability map obtained with the insertion of both parameters (Figure 5c), lineament density (LD) and land use and cover (LU), indicated that in 55.35% of the area the vulnerability is high, in 19.65% it is extreme, in 14.66% it is very high and in 10.31% moderate. Comparing these results with the ones obtained by Ribeiro *et al.* (2021) applying the DRASTIC-LU method (Figure 5d), it can be seen great similarity between them.

In the work developed by Ribeiro *et al.* (2021), the insertion of the parameter land use and cover in the DRASTIC model resulted in seven vulnerability classes as shown above in Table 2, with most of the study area classified as low vulnerability (54.40%), followed by the classes moderate (17.13%) and high (12.07 %). Those authors identified that the areas classified as moderate, high and very high vulnerability are located in regions where land use and cover refers to urban infrasctruture, exposed soil and agriculture. Such land uses reflect a greater potential for aquifer contamination, due to possible sources of pollutants arising from activities carried out in those areas. The authors conclude that the different uses and covers of the land are of great importance in the assessment of vulnerability, since the presence anthropogenic activities increases the potential for contamination of groundwater resources.

However, the vulnerability of the area becomes higher when the lineament density parameter is added in the method. The insertion of the lineament density parameter increased the vulnerability index in both models, such results suggests that this is a relevant parameter in determining vulnerability in fractured media, corroborating Jenifer & Jha (2018).

Analysing the maps of the parameters (Figures 2 and 3) together with those generated by the DRASTIC approach (Figure 5), it is possible to observe that the areas of moderate and high vulnerability are located in regions where the water level is closer to the surface, there is higher recharge and slopes are between 2% and 12%. This can be seen in all four maps presented in Figure 5, where the eastern portion of the maps generally has the higher vulnerability to contamination. There is a great influence of the recharge and the water level on the results, given their high weight. In the maps generated with the DRASTIC-LD and DRASTIC-LDLU, as well as those by Ribeiro *et al.* (2021), it is possible to note the delimitation of the vadose zone (Figure 3e) due to the high weight addressed to this parameter, as evidenced by Gomes *et al.* (2021).

5. CONCLUSIONS

The vulnerability map generated applying the DRASTIC-LD method presented five classes of vulnerability in the area of study, where predominates: high (70.73%), moderate (17.04%) and very high (12.17%). The vulnerability map acquired by the DRASTIC-LDLU method also shows five classes of vulnerability in the study area, predominantly: high (55.35%), extreme (19.65%), very high (14.66%) and moderate (10.31%).

Even though the spatial distribution of vulnerable zones is quite similar comparing with the original method, the insertion of the lineament density parameter evidenced a significant increase in the vulnerability of the study area, resulting in the predominance of the high and moderate classes, which represent respectively 1154 km² and 278 km² of the studied area. These results reflect the importance of this parameter, as the lineaments represent the main transport path of the contaminant and influence the velocity of the underground flow.

An increase in the vulnerability was also noted when the parameter land use and cover was added by the Authors *et al.* (2021), again comparing the results with the original DRASTIC. However, the insertion of the land use and cover parameter, along with the lineament density, resulted in an even more significant increase in the areas of extreme and very high vulnerability. Being the rise in this index, when added to the model the land use and cover, attributed to the agriculture, livestock production and urban infrastructure spread in the area of study, as such activities increase the risk of groundwater contamination.

These results indicate the relevance of these two parameters in assessing the vulnerability of fractured aquifers. As mentioned above, some activities represent a greater potential for groundwater contamination, thus the importance of the insertion of land use and cover in vulnerability assessment. Since the water circulation in fractured aquifers is conditioned by the presence of fractures, the inclusion of the lineament density parameter together with land use and cover provides a more accurate result of vulnerability in fractured environments.

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