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GROUNDWATER VULNERABILITY TO CONTAMINATION IN URBAN AREA – GUARATIBA AQUIFER, RJ

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Abstract

The DRASTIC method a widely applied method for assessing the intrinsic vulnerability of an aquifer based on the parameters: depth, recharge, aquifer type, topography, impact on vadose zone, soil and hydraulic conductivity. However, studies indicate that these parameters alone are insufficient to characterize an aquifer inserted in an urban area. Thus, DRASTICA method was developed with the addition of the anthropogenic impact parameter. This research work presents the study of vulnerability of the Guaratiba aquifer, Rio de Janeiro city, based on the DRASTIC method and its adaptation DRASTICA. The DRASTIC vulnerability map showed three classes, with a predominance of the lower and middle classes with 0.8% of study area high potential vulnerabilities. The DRASTICA vulnerability map shows the influence of anthropic activities, since the high vulnerability class with 5% of the research area. Thus, in the DRASTICA method, it is observed that the presence of high vulnerability in the highest concentrations of nitrate ions and, moreover, lowest nitrate concentration are not present in this respective class. Therefore, it is concluded that for studies of aquifer vulnerability in urban areas, the DRASTICA method is indicated.

Keywords: Vulnerability; Urban área; DRASTICA method.

VULNERABILIDADE À CONTAMINAÇÃO DE AQUÍFERO EM ÁREA URBANA – AQUÍFERO GUARATIBA, RJ

Resumo

O método DRASTIC é um método amplamente aplicado para avaliar a vulnerabilidade intrínseca de um aquífero com base nos parâmetros: profundidade, recarga, tipo de aquífero, topografia, impacto da zona vadosa, solo e condutividade hidráulica. Porém estudos indicam que esses parâmetros são insuficientes para caracterizar aquíferos inserido em área urbana, assim, o método DRASTICA foi desenvolvido com a adição do parâmetro de impacto antropogênico. Este trabalho apresenta o estudo da vulnerabilidade do aquífero Guaratiba na cidade do Rio de Janeiro, com base no DRASTIC e sua adaptação DRASTICA com a utilização de amostras de concentração de nitrato nos poços indicando a qualidade da água subterrânea. O mapa de vulnerabilidade DRASTIC mostrou três classes, com predominância das classes baixa e média enquanto 0,8% da área de estudo apresentaram alto índice de vulnerabilidades. O mapa DRASTICA mostra a predominância da influência das atividades antrópicas, uma vez que a classe de alta vulnerabilidade possui 5% da área de estudo. No DRASTICA, observa-se a presença de alta vulnerabilidade nas maiores concentrações de nitrato e, além disso, as amostras com a menor concentração de nitrato estão ausentes nessa classe. Portanto, conclui-se que, para estudos de vulnerabilidade do aquífero em áreas urbanas, é indicado o método DRASTICA.

Palavras-chave: Vulnerabilidade; Área urbana; Método DRASTICA.

VULNERABILIDAD A LA CONTAMINACIÓN DE ACUÍFEROS EN ÁREA URBANA – AQUÍFERO GUARATIBA, RJ

Resumen

El método DRASTIC es un método ampliamente aplicado para evaluar la vulnerabilidad de un acuífero basado en los parámetros: profundidad, recarga, tipo de acuífero, topografía, impacto de la zona vadosa, suelo y conductividad hidráulica. Sin embargo, los estudios indican que estos parámetros son insuficientes para caracterizar los acuíferos insertados en un área urbana. Por lo tanto, el método DRASTICA se desarrolló con la adición del parámetro de impacto antropogénico Este trabajo presenta el estudio de la vulnerabilidad del acuífero Guaratiba en el ciudad de Río de Janeiro, basada en DRASTIC y su adaptación DRASTICA con el uso de muestras de concentración de nitrato en pozos que indican la calidad del agua. El mapa de vulnerabilidad DRASTIC mostró tres clases, con predominio de las clases bajas y medias, mientras que el 0,8% del área de estudio tenía una alta tasa de vulnerabilidades El mapa DRASTICA muestra el predominio de la influencia de las actividades. antrópico, ya que la clase de alta vulnerabilidad tiene el 5% del área de estudio. En el DRASTICA, la presencia de alta vulnerabilidad se observa en las concentraciones más altas de nitrato y, además, las muestras con la concentración más baja de nitrato están ausentes en este clase. Por lo tanto, se concluye que, para estudios de vulnerabilidad de acuíferos en áreas zonas urbanas, se indica el método DRASTICA.

Palabras-clave: Vulnerabilidad; Área urbana; Método DRASTICA.

1. INTRODUCTION

The urban growth and the population pressure are two main issues to be discussed in water resources management, particullarly in cities located in developing countries (BAIER et al., 2014), at the same time, this resource presentes a important rule to play a strategic and relevant role regarding the survival and sustainability of life (REBOUÇAS, 2002). In picture of this, groundwater presents itself as an important alternative.

The groundwater can be captured in the confined or free aquifer, which is located close to the surface and is therefore more susceptible to contamination. Due to the low cost and ease of drilling, the capture of water from the free aquifer, although more vulnerable to contamination, is frequently used in Brazil (FOSTER, 1993; ASSIS DA SILVA, 1999).

The vulnerability map were considered as essential for protecting groundwater and a valuable tool in environmental management. The term vulnerability in hydrogeology began to be applied intuitively from the 1970s in France (ALBINET; MARGAT, 1970) and more widely used in the 1980s (HAERTLE, 1983; ALLER, 1987; FOSTER and HIRATA, 1988).

The DRASTIC, created by the American Environmental Protection Agency (US Enviromental Protection Agency - EPA), is a method developed to assess the vulnerability of aquifers based on overlapping maps, widely applied and the most used worldwide (ALLER, 1987; ZWAHLEN, 2003). Its development was intended to analyze hydrogeological factors, through parameters that affect the movement of a contaminant load until reaching the water body in depth (ALLER, 1987). More recent studies, however, prove that the vulnerability of the aquifer is influenced by urban occupation, due to the great propensity to contaminate (ALAM et al., 2012).

In the study applied in the Sharon region of Israel, a basically agricultural region, the parameter "land use" was considered. However, afterwards, adaptation started to be applied in regions with urban areas, such as in the Lucknow Region, India (SINGH et al., 2015) in which the anthropogenic impact parameter (A) was inserted and the land use pattern was evaluated.

This work aims to assess the vulnerability to aquifer contamination in an urban area, using the conventional DRASTIC method and its variation, DRASTICA, which includes the anthropogenic impact parameter, using census data added to the land use and occupation map.

This study aims to elaborate and compare the vulnerability maps of the two DRASTIC and DRASTICA methods, evaluating the accuracy through the comparison between the different levels of nitrate concentrations, present in the different classes of vulnerability generated by the sum of respective parameters.

2. ÁREA DE ESTUDO

The Guaratiba aquifer is located in the Rio de Janeiro city, mostly in the Administrative Regions (RA) XVIII and XXVI, between latitude 23° 4'32.19 "S and 22° 52'45,22" S and longitude 43 ° 39'1.54 "O and 43 ° 28'3.61" O, as shown figure 1, Pereira Passos Institute (2016).

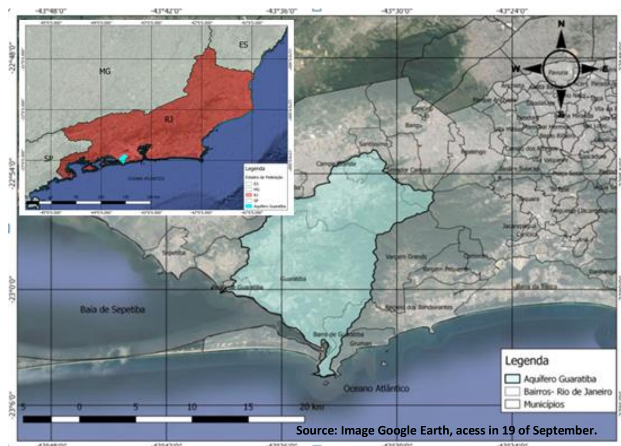

Figure 1 - Study area location Guaratiba Aquifer, Rio de Janeiro. Source: Pereira Passos Institute (2016).

2.1. Physics Aspects

In this chapter, we sought to raise the relevant characteristics for knowledge of the area for the referred study, the following aspects were considered: climate, geology, hydrogeology.

2.1.1. Climate

In the state of Rio de Janeiro the predominance of the semi-humid tropical climate occurs in areas of low altitudes, with emphasis on the metropolitan region of Rio de Janeiro. This area of the State of Rio de Janeiro has an average annual temperature of around 24ºC and with rainy in the summer and dry winters (BASTOS & NAPOLEÃO, 2011). In the area under study, two distinct pluviometric zones were identified, due to the topographic contrast between the lowland and the surrounding slopes: the lowland, with humid summer and dry winter, while the slopes, which surround it, present higher rainfall without a defined dry season (CAMPOS, 1996).

However, Lucena (2010) identified a special case in cities where the climate becomes spatial at a perceptual level due to the action of balance or imbalance in the "urban environmental system", given that the city is an active-passive locus of atmospheric phenomena, called Urban Climate System, which operates in the west of the city.

2.1.2. Geologic Map

The study area had 6 distinct lithotypes. With regard to the mountain regions, the granitic massif of Pedra Branca (granite and granodiorite) is predominant and subordinately exist in the northwest of the study area, the rocks of the Precambrian, called the Rio Negro Unit.

In the lowland stretches, mainly in the central and northern portion of the map, alluviums predominate, constituted of fluvial deposits formed of quite heterogeneous material. South of the study area, close to Sepetiba bay, the unit is composed of organic clay, overlaid with silty-clay layers, which may contain fragments of shells, which shows the presence of the sea during the various transgressions and regressions that occurred in the region (CAMPOS, 1996).

2.1.3. Hydrogeology

Vicente (2009) identified two different types of aquifer systems in the study area: the fissural aquifer system and the intergranular aquifer system. The first consists of crystalline precambrian to tertiary rocks, of metamorphic and igneous origin, with discontinuities that connect, giving the system the ability to store and transmit water. The second, intergranular aquifer system, begins at the base of the mountain ranges that occur in the R.A. of Campo Grande and Guaratiba and extends to the coastal region.

Pires (2016) defined that in fissural aquifers, the wells located next to the northwest direction lines have good hydraulic characteristics, however the lines, in the northeast direction, were identified as the main fractures, with better hydraulic characteristics.

3. MATERIAL AND METHODS

The steps for data collection from bibliographic and cartographic sources served as a basis for the generation of a set of maps that, overlapping, gave rise to the DRASTIC vulnerability map and its adaptation applied in an urban area, DRASTICA.

3.1. DRASTIC data survey and treatment

To generate groundwater vulnerability and risk maps with DRASTIC model. For each parameter a weight (w) is assigned, varying from 1 to 5, according to its importance (Table 1). Each parameter class is evaluated and classified with grades between 1 and 10 (r) defined by Aller et al. (1987).

Table 1 - Weight of DRASTIC parameters. Source: Aller et al. (1987).

Parameters	Acronym	w	i
Depth	D	5	1-10
Recharge	R	4	
Aquifer	A	3	
Soil	S	2	
Topography	T	1	
Impact of the vadose zone	I	5	
Condutivity	C	3	

To apply the DRASTIC index, it is necessary to quantify the vulnerability by adding the rating of the seven weighted hydrogeological parameters (Equation 1) (ALLER, 1987).

$$DI_i = D_wD_r + R_wR_r + A_w A_r + S_w S_r + T_wT_r + I_wI_r + C_wC_r \quad (1)$$

Where:
DI_i = Index DRASTIC;
D_w, R_w, A_w, S_w, T_w, I_w, C_w – weight parameters ; e
D_r , R_r, A_r, S_r, T_r, I_r, C_r – parameters rating.

The first part of this research, then, consisted of collecting the geological, hydrogeological, geomorphological and climatic data used in the DRASTIC method (Table 2).

Table 2 - Database used in the generation of the DRASTIC and DRASTICA vulnerability map of the Guaratiba Aquifer. Source: Author

DRASTIC Parameters	Source/Author/Format	Scale/ Resolution
Depth	1- INEA (2017) 2- Hydrogeological Study of the Cabuçu River, West Zone of the Municipality of Rio de Janeiro- Campos (1996) -Vector	1: 25.000
Recharge	1-Rio Alert System of the City of Rio de Janeiro (2002/2017) - 2- Institute of Meteorology (INMET (2002/2017) 3 Soil Map of the State of Rio de Janeiro- EMBRAPA (2016) 4- IBGE (2010) - wallpaper	3 -1:75.000
Aquifer	Hydrogeological Study of the Cabuçu River, West Zone of the Municipality of Rio de Janeiro- Campos (1996) -Vector	1: 25.000
Soil	Soil Map of the State of Rio de Janeiro - EMBRAPA (2016) - Vector	1:75.000
Topography	DEM Rio de Janeiro City (SMAC, 2016) - Raster	1 m de resolução espacial

Impact	Hydrogeological Study of the Cabuçu River, West Zone of the Municipality of Rio de Janeiro- Campos (1996) -Vector	1: 25.000
Conductibility	1- Hydrogeological Study of the Cabuçu River, West Zone of the Municipality of Rio de Janeiro- Campos (1996) -Vector 2- Geometric Analysis of Lineaments and their Relationship with Groundwater Associated with the Guaratiba Aquifer- RJ Pires (2016) - Vector	1- 1: 25.000
Anthropic Impact	1- Map of Vegetation Cover and Land Use in the municipality of Rio de Janeiro- SMAC (2016) 2- Demographic Census-IBGE (2010)	1:2.000
NO_3	Deep Wells in Campo Grande Guaratiba RA - INEA (2017) - Vector	

In the evaluation of the water table depth parameter (D), the mapping of the Cabuçu River Basin was used, carried out by Campos (1996) based on the recording, in four different annual differences, of the wells and cacimbas used in the study area. Depth data were also collected from wells at the Institute of Environmental Studies - INEA adding 15 wells that ranged from 0.9 to 6m in depth (Table 3).

Table 3 - DRASTIC indexes of depth(D) parameter. Source: Aller et al. (1987).

Water Table Levels (m)	Weight	Rating	DRASTIC
< 1,5	5	10	50
1,5 – 4,6		9	45
4,6 – 9,1		7	35
9,1 – 15,2		5	25

The recharge map (R) was generated based on the data obtained by the Thornthwaite - Mather (T-M) method applied to soil types. To obtain the DRASTIC index, the recharge vary from 1 to 9, weight 4 (Table 4).

Table 4 - DRASTIC indexex of recharge parameters (R).Source: Adapted of Aller (1987).

Recharge (mm)	Weight	Rating	DRASTIC
0 - 51	4	1	4
51,1 - 102		3	12
102,1 - 178		6	24
178,1 - 254		8	32
254,1 - 508		9	36
>508		10	40

To calculate the balance using the T-M method, the total annual rainfall for three stations of the Alert-Rio - Campo Grande, Guaratiba and Grota Funda was used. Temperature data were obtained at Praça Mauá (83743) INMET station, located in the city of Rio de Janeiro with latitude -22.88 ° and longitude -43.18 °, which operated between the years 2002 and 2017.

The study area was also classified into six different types of soil, according to granulometry that varies from clayey, clayey, silty, sandy, loam and sandy (Table 5).

Table 5 - DRASTIC indexes to recharge (R) for Guaratiba Aquifer, calculated trhough T -M . Fonte: Author.

Granulometry	Soil (DRASTIC)	SWS (mm)	Recharge (mm/year)	DRASTIC
Clayey	Clayey	41,25	116,64	24
Very clayey	Clayey			
Medium or clayey	Silty Clay	82,5	116,00	
Medium or clayey / very clayey	Clayey Loam	84	120,27	
Clayey average Sandy / clayey	Sandy Loam	94,5	123,23	
Indiscriminate soil	Loam	117	122,69	
Sand	Sandy	112,5	140,68	

However ,for the urban area, the potential involuntary artificial water recharge was calculated based on the contribution of water from leaks from domestic effluents and the water supply network. In this work, the potential recharge for domestic effluents was based on Von Sperling (2009) as shown in Equation 2.

$$Q_{d(m)} = Pop.\ Q_{pc.}\ R \qquad (2)$$

Where:
$Q_{d(m)}$ - Average domestic sewage flow (m³/day);
Pop - Number of inhabitants;
Q_{PC} - Per capita consumption share (m³hab/day); and
R - Sewage / water return coefficient.

Considering the availability of data and the sanitary conditions of the study area, it was proposed to adapt the calculation of the artificial recharge of domestic effluents by Von Sperling (2009) as shown in Equation 3. Thus, the data aggregated by census sectors were used of the 2010 Demographic Census (IBGE, 2010) referring to the conditions of water supply and sanitation, for the mapping of artificial recharge in the study area.

$$Q_{d(m)A} = Pops\ .\ Q_{PC} \qquad (3)$$

Where:

$Q_{d(m)A}$ - Average domestic sewage flow(m³/day); and
Pops -number of inhabitants with sanitary sewage served by septic tank and rustic pit, and dumped in ditches, or without exhaustion (IBGE, 2010); e
Q_{PC} -Per capita consumption share (m³.hab/day).

The artificial recharge from leaks in the general water supply network was estimated according to Equation 4 defined by Von Sperling (2009).

$$RHAIP_{(ab)} = (Pop._{ab} \, . \, Q_{pc}) \, Ip \qquad (4)$$

Where:
$RHAIP_{(ab)}$ - potential involuntary artificial water recharge from leaks in the supply network (m³T);
$Pop._{ab}$ - number of inhabitants with water supply via general network, IBGE (2010) ; and
Ip - Loss rate, here adopted the value of 28.49% of the volume of water produced according to SNIS (2013).

As the artificial recharge values, the sum of the artificial water recharge from leaks in the supply network and domestic effluents, exceeded the natural recharge values proposed by Aller (1987).

The type of aquifer (A) was based on the Geological Map of the State of Guanabara - DNPM on the scale 1: 50,000 (Folha Santa Cruz, 1965). Campos (1996) applied it to study the aquifer, differentiating two types of sedimentary aquifers: Q1 corresponding to the matrix with the largest clay content and Q2 to the most sandy matrix. To generate the DRASTIC map, rating ranging from 4 to 9 were assigned according to the proposed methodology Aller (1987), multiplied by weight 3, referring to the type of aquifer parameter, as shown in Table 6.

The highest rating (9) was attributed to sandy sediments originating from the sedimentation of the Cabuçu River due to its greater permeability. The intermediate value 6 was attributed to sediments with a characteristic of clayey materials due to the lesser influence of river sedimentation. The lowest rating 4 was related to igneous and metamorphic rocks contained in the study area.

The soil (S) parameter was based on the mapping provided by EMBRAPA (2014) on a scale of 1: 75,000. For the study area, there are a total of twelve soil types, which, aggregated, originated nine classes to which ranging from 1 to 10, weight 2, corresponding to the weight of parameter S (Table 6), were assigned.

For parameter S, chemical characteristics were considered, in particular, the difference between expansive clays (Ta) and non-expansive clays (Tb). Thus, it is considered that expandable clays have greater permeability in certain periods and, consequently, greater vulnerability to contamination (LIMAS, 2008).

As can be seen in Table 7, the values of the DRASTIC indices ranged from 1 to 10. However, as in the urban area the physical characteristics that confer soil impermeability were considered, low permeability values were attributed.

Table 6 - DRASTIC indexes for the type of aquifer parameter (A) for the Guaratiba aquifer, RJ. Source: Adapted from Aller (1987).

Litology	Weight	Range	Rating	DRASTIC
Weathered igneous or metamorphic rock	3	3 - 5	4	12
Layered sandstone, limestone and sequential shale		5 - 9	6	18
Sandy lenses (Cabuçu River)		9	9	27

Table 7 - DRASTIC indexes of the single parameter (S) for the Guaratiba aquifer. Source: Adapted from Aller (1987)

DRASTIC soil	Rating	Weigth	DRASTIC
Tb	1	2	2
absent			
Sandy+ Tb	3		6
Tb + Ta + Sandy	4		8
Ta + silt	5		10
Sandy+ Ta			
Ta	7		14
Sandy+ silte + Ta	8		16
Sandy	9		18

The topography parameter (T) has a weight of 1 in DRASTIC and was obtained from the Digital Elevation Model (DEM) with a spatial resolution of 1 m (SMAC, 2016). From the processing of this model, the slope map classified into five classes was generated, which received indexes between 1 and 10 (Table 8).

The impact of the unsaturated zone, parameter I, from the geological map of Campos (1996), rating between from 4 to 9 were attributed (Table 9).

Tabela 8 - DRASTIC Indexes of topography parameter (T). Source: Aller (1987).

Slope (%)	Weight	Rating	DRASTIC
0 - 2	1	10	10
2 - 6		9	9
6 - 12		5	5
12 - 18		3	3
> 18		1	1

Table 9 - DRASTIC indexes of the parameter with the impact of the vadose zone (I) for the Guaratiba Aquifer. Source: Adapted from Aller (1987).

Vadose Zone	Range	Rating	Weight	DRASTIC
pCgr	2 a 8	4	5	20
pCIIrn				
pCgd				
A- sand and gravel with clay and silt	2 a 6			
Interleaved sand and gravel	4 a 8	6		30
Q – Cabuçu River - Sandy Lenses	9	9		45

The hydraulic conductivity parameter (C), relative to the free aquifer, was developed through the characteristics obtained by the lithological unit map and surveys in the region under study in a permeability test carried out by Campos (1996). While the hydraulic conductivity related to igneous and metamorphic rocks was determined by the density of lineaments in the portion of the fissural aquifer, determined according to the representative values of hydraulic conductivity in the literature, as shown in Table 10 (DOMENICO; SCHWARTZ, 1990).

Table 10 - DRASTIC indexes of the conductivity parameter (C) for fractured rocks. Source: Domenico and Schwartz (1990)

Lithology	Lineaments density (km/km²)	Hydraulic conductivity (m/d)	Rating	Weight	DRASTIC
Fractured Igneous Rock	0-8	$8,64x10^{-3}$	1	3	3
	9-16	$8,64x10^{-2}$			
	17-24	$8,64x10^{-1}$			
	25-32	$8,64x10^{-0}$	2		6
Fractured Metamorphic Rock	0-8	$8,64x10^{-2}$	1		3
	9-16				
	17-24	$8,64x10^{-1}$			
	25-32	$8,64x10^{0}$	2		6

On the other hand, sedimentary deposits, in the parameter conductivity, were considered the granulometry. The rating values ranged from 1 to 8 with weight 3, according to the proposed methodology, which generated DRASTIC indices exposed in Table 11.

Table 11 - DRASTIC indexes according to the hydraulic conductivity in the sediments for the Guaratiba Aquifer. Source: Adapted from Aller (1987).

Lithology classes	Conductivity (m/dia)		Weight	Rating	DRASTIC
	Range	Adopted values			
Sediments Q1 (Sandy sediments with clay)	4,1 - 12,2	7,3	3	2	6
Sediments Q2 (Sandy sediments Interspersed with Gravel and Silt)	12,2 - 28,5	17		4	12
Sandy lenses (Cabuçu River)	40,7 - 81,5	43		8	24

Finally, to apply the DRASTICA method, the parameter referring to anthropic action (A) obtained in the map of vegetation cover and land use in the municipality of Rio de Janeiro (SMAC, 2016) in the scale 1: 2,000, was included, combined with the sectors census of the 2010 Demographic Census (IBGE, 2010) for the calculation of the demographic density of the urban area. The census sectors were hierarchized, according to IBGE (2017), in five classes of demographic density (Table 12). For areas less exposed to human influence, the lowest ratings (1) were assigned, while for areas with the highest density, they reached index 10, which was multiplied by weight 5 (Table 13).

Tabela 12 - Classes de densidade demográfica. Fonte: IBGE (2017).

Density	Tax (hab./km²)
Very High	>500
High	100 a 500
Medium	25 a 100
Low	1 a 25
Dispersion	<1

Table 13 - DRASTIC indices of the anthropic action parameter (A) for the Guaratiba Aquifer. Source: Adapted from Singh et al. (2015).

Land Use	Weight	Rating	DRASTICA
Water Body Urban area - very high density Unoccupied area	5	1	5
Shrubland Forest		2	10
Agriculture Urban area- dispersed density		5	25
Urban area- low density		7	35
Urban area- medium density		8	40
Urban area- high density		9	45
Urban area- very high density		10	50

3.2. Application of the DRASTIC Method

As the DIi value is the sum of values according to the degree of importance, it does not have a unit, so it must be evaluated when compared to other studies whose parameters and weights were applied in a similar way. The final DRASTIC vulnerability index for indices between 26 and 226 (ALLER, 1987). Mello Junior (2008) suggests that the vulnerability values are divided into four classes: low, medium, high and very high (Chart 2).

The anthropogenic impact parameter of the DRASTICA method is incorporated into the rest of the parameters contained in the DRASTIC method, as shown in Equation 5.

$$Di\text{-}Ai = DIi + A_c\, A_w \quad (5)$$

Where:
A_c and A_w - represent the rating and weight corresponding to the anthropogenic impact parameter.

For the DRASTICA method, the classes are similar to the DRASTIC index, however with the rescheduling of the intervals, since the inclusion of the eighth parameter raised the DRASTIC indexes (Table 14).

Table 14 - Vulnerability Scale of the DRASTICA Method. Source: Adapted from Mello Junior (2008).

Scale	DRASTIC Index	DRASTICA Index
Very High	180-226	220 – 280
High	126-180	156 - 220
Medium	71-126	86 - 156
Low	26-71	31 - 86

3.3. Evaluation of DRASTIC and DRASTICA

For the calibration of both the DRASTIC method and the DRASTICA method, the nitrate concentration of samples from ten wells (Table 15) located in the study area was used. The samples were collected by INEA between the years 2011 and 2017 and showed good spatial distribution.

Buffers with a radius of 500 m were created around each sample and, in order to verify the relationship between the vulnerability index and the nitrate concentration, the areas of the vulnerability classes were calculated based on the overlap with the DRASTIC and DRASTICA maps.

Table 15: Location of wells with nitrate samples, Aquifer Guaratiba, RJ. Source: INEA (2017).

Wells		Geographic coordinates	
No.	mg/L	Longitude	Latitude
1	0,58	O 43°33’21”	S 22° 54’ 11”
2	0,196	O 43° 31’ 59”	S 22° 53’ 44”
3	2,53	O 43° 36’ 23”	S 22° 57’
4	1	O 43° 36’ 37”	S 22° 57’ 27”
5	0,03	O 43° 32’ 3”	S 22° 58’ 53”
6	2,5	O 43° 36’	S 22° 57’ 55”
7	0,75	O 43° 33’ 32”	S 22° 55’ 24”
8	0,01	O 43° 34’ 9”	S 22° 59’ 4”
9	7,65	O 43° 34’ 32”	S 22° 53’ 25”
10	0,1	O 43° 32’	S 22° 53’ 36”
11	0,07	O 43° 32’ 54”	S 22° 59’ 39”

4. RESULTS

4.1. DRASTIC parameters

The depth of the water table in the study area varied between 1.5 m and 9 m and showed high indexes of parameter D, between 35 and 50, due to the weight 5 assigned.

The indicators corresponding to the artificial and natural recharge, parameter R, showed values between 4 and 40, also high due to the weight 4 attributed to this parameter. The natural recharge was generated based on rainfall and granulometry. The area of greatest vulnerability was contained in the urban area and reached a DRASTIC index above 28, as it also included artificial recharge.

The parameter A map, referring to the type of aquifer, was derived from geology and presented DRASTIC values between 12 and 27, considered intermediate due to the weight 3 attributed to this parameter. The igneous and metamorphic rocks showed less vulnerability, while the sedimentary portion of the aquifer showed an intermediate value due to its physical characteristics. The portion of greater river sedimentation energy was attributed greater vulnerability.

The parameter S, referring to the type of soils, was derived from the pedology map and classified in vulnerability values between 2 and 18, considered low due to the weight 2 assigned to this parameter.

The parameter T map, referring to topography, was generated based on the slope and presented indexes between 1 and 5, very low values, due to the weight 1 assigned to this parameter.

The map of parameter I, referring to the impact of the vadose zone, was derived from the geological map and presented vulnerability indices that varied from 20 to 45, high values due to the weight 5 attributed to this parameter.

The map of parameter C, conductivity of the aquifer with weight 3, originated from the geological maps and the vulnerability indices, which varied between 3 and 24.

The Anthropic Impact map, parameter A, derived from land use and cover showed values between 5 and 50. The smallest ones were attributed to the class of soil cover with dense vegetation, while to the urban area the highest values were attributed, mainly in places higher occupation density.

4.2. Vulnerability Map for DRASTIC and DRASTIC Aquifers

The Guaratiba Aquifer DRASTIC vulnerability map showed values that ranged between 43 and 156 distinguished in three vulnerability classes. The area of high vulnerability, corresponding to 0.8% (1.3 km2) of the study area, was caused by the influence of strong energy sedimentation in the main channel of the Cabuçu River basin (Table 16). The region has thicker sediments, thus providing high hydraulic conductivity and higher artificial recharge values.

On the DRASTICA vulnerability map, the index ranged between 53 and 208 and is represented by the three vulnerability classes (low, medium and high), with an increase in the area of the high vulnerability class at the expense of low and medium vulnerability. The class of high vulnerability grew towards the urban area.

Table 16 - DRASTIC and DRASTICA area vulnerability classes of the Guaratiba Aquifer, RJ. Source: Author.

Classes	DRASTIC	Area		DRASTICA	Área	
		km²	%		km²	%
High	126 - 180	1,3	0,8	156-220	8,4	5,4
Medium	71-126	70,3	45,5	86-156	72,9	47,1
Low	26 -71	83,0	53,7	31-86	73,3	47,4

4.3. Evaluation of vulnerability maps

The ten water samples from wells with nitrate concentration, located in the study area, and used to assess DRASTIC vulnerability maps, did not identify high levels of NO3. As the samples collected come from the deepest fissural aquifer, they are less vulnerable to contamination originating on the surface. Despite the small number of samples, the influence of the Massif da Pedra Branca on the chemical quality of the water is verified, since the wells close to the rock mass showed considerably lower concentrations of nitrate in its composition, corresponding to the wells 5, 8 and 11 (VICENTE et al., 2010).

The three samples, which are located less than 500 m from the high vulnerability class, have the highest nitrate concentrations, between 2.5 and 0.58 mg / L, corresponding to wells 6, 7 and 1, with the exception of wells 3 and 4, which present values in this range, however, are located more than 500 m from the high vulnerability class (Figure 2 and Table 17). Samples of nitrate concentration below 0.2 mg / L, the surrounding area is located exclusively in the middle and low classes of vulnerability, including the area around the lowest concentrations, wells 8 and 5, predominates in the low class vulnerability.

Regarding the evaluation of the DRASTICA method, it appears that all samples have an area surrounding the high vulnerability class, with the exception of wells 5, 8 and 11, which have the lowest nitrate concentrations, up to 0.07 mg / L (Figure 3 and Table 18), and in the first two there is also a predominance of the surrounding area in the low vulnerability class. On the other hand, higher concentrations, above 0.1 mg / L, have a smaller area of surroundings in the class of low vulnerability. Emphasis should be given to wells 4 and 3, as they now have a surrounding area located in the upper class vulnerability and reduced area in the lower class.

Table 17 - Area of the DRASTIC classes in the 500m radius and around the wells with nitrate water, Guaratiba Aquifer, RJ. Source: Author

Wells		Classes – area (%)		
No.	NO_3 - mg/L	Low	Medium	High
8	0,01	70	30	0
5	0,03	62	38	0
11	0,07	3	97	0
10	0,1	25	75	0
2	0,196	39	61	0
1	0,58	9	90	1
7	0,75	0	67	33
4	1	32	68	0
6	2,5	0	87	13
3	2,53	58	42	0

Table 18 - Area of the DRASTIC classes in the 500m radius and around the wells with nitrate water, Guaratiba Aquifer, RJ. Source: Author

Wells		Classes – area (%)		
No.	NO_3 - mg/L	Low	Medium	High
8	0,01	43	57	0,0
5	0,03	57	43	0,0
11	0,07	1	99	0,0
10	0,1	18	36	46
2	0,196	33	26	41
1	0,58	0	68	32
7	0,75	0	16	84
4	1	9	60	31
6	2,5	0	79	21
3	2,53	10	66	24

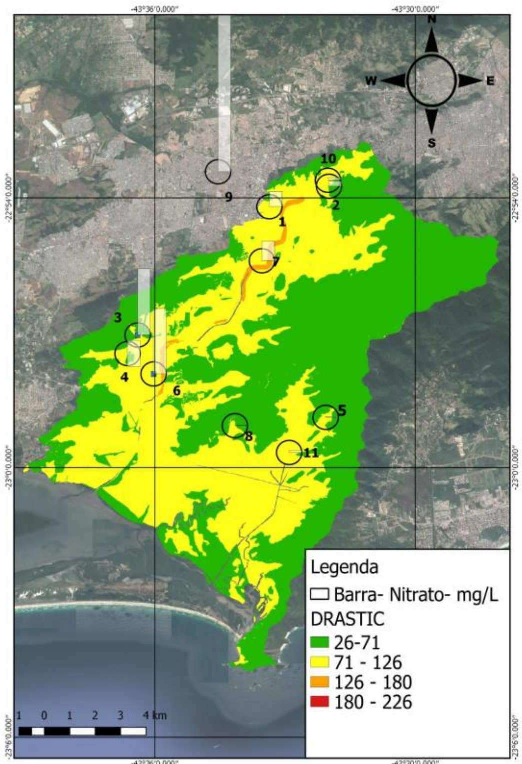

Figure 2 - DRASTIC vulnerability map and wells with water samples, Aquifer Guaratiba, RJ. Source: Author.

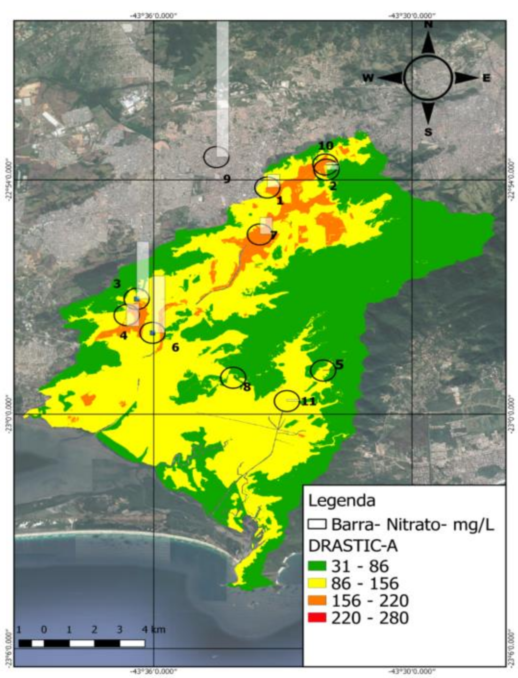

Figure 3 - DRASTICA vulnerability map and wells with water samples, Aquifer Guaratiba, RJ. Source: Author.

5. CONCLUSION

According to the results obtained, the adaptation for DRASTICA vulnerability assessment applied in urban areas is innovative and effective. It includes the anthropogenic impact parameter, which in this work, was characterized by the land use and land cover map adding together with the demographic density, measured through the census sectors. The DRASTICA method has shown advances, because according to the evaluation made with the water samples, the nitrate concentrations of the wells show a spatial pattern of distribution closer to the DRASTICA's vulnerability classes than to the DRASTIC.

The DRASTIC map revealed three classes of vulnerability (low, medium and high) where the influence of the Cabuçu River, due to the depositional environment of high sedimentation energy clearly demarcated by the sandy lenses along the river, which were relevant for the formation of the area of high vulnerability. In the DRASTICA map, three classes of vulnerability were also mapped, however the inclusion of the anthropogenic impact parameter, especially in census sectors with higher occupation densities, was responsible for the highest vulnerability indexes. In addition, the incorporation of the eighth parameter caused the expansion of the high vulnerability class area to the urban area, increasing its extension by five times.

The evaluation based on samples of nitrate concentration, suggests that the area around the samples with the lowest ion concentrations in the groundwater composition, prevails in regions of low and medium vulnerability. This can be seen both in the map generated by the DRASTICA method and in the counterpart generated by DRASTIC.

However, in the DRASTICA method, the presence of high vulnerability is observed in the surroundings of samples with higher concentrations of nitrate ions and, in addition, only the three samples, with lower concentration of nitrate, do not present their surroundings in the respective class.

The analysis of results suggests that studies on the vulnerability of aquifers in urban areas, carried out using the DRASTICA method are certainly recommended. The alteration of the natural characteristics of groundwater, mainly by domestic effluents, allows contamination by nitrate and, thus, can compromise the quality of groundwater, despite the values of the study area still falling within the standards for human consumption.

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