VULNERABILITY OF THE GUARANI AQUIFER IN THE MIDWEST REGION OF RIO GRANDE DO SUL, BRAZIL

VULNERABILIDADE DO AQUÍFERO GUARANI NA REGIÃO CENTRO-OESTE DO RIO GRANDE DO SUL, BRASIL

VULNERABILIDAD DEL ACUÍFERO GUARANI EN LA REGIÓN CENTRO-OESTE DE RÍO GRANDE DO SUL, BRASIL

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ABSTRACT

Knowing groundwater areas of greater natural vulnerability to contamination contributes to taking actions to maintain and preserve groundwater aquifers. The objective of this study was to evaluate the Guarani Aquifer System's natural vulnerability to contamination using the DRASTIC model using information obtained from wells, and to compare differences when using the S (soil) parameter from soil surveys at 1:50.000 and 1:1.000.000 scales. Also, to identify the parameter(s) with the greatest effect on ID-DRASTIC values and propose an ID-DRASTIC estimation equation for the region. The study was carried out in the topographic area of Vila Kramer, municipality of São Francisco de Assis, RS, Brazil. The DRASTIC model identified vulnerable (30%), very vulnerable (61%), and extremely vulnerable (9%) zones. The use of information from soil surveys on the 1:50.000 and 1:1.000.000 scales showed small local variations, having little effect on the modeling of water vulnerability to contamination. Parameter D (unsaturated zone depth) had the greatest effect on ID-DRASTIC values.

Keywords: Soil mapping; Mapping scale; Mathematical modeling; Groundwater contamination; Drastic Index.

RESUMO

Conhecer as áreas de lençóis freáticos de maior vulnerabilidade natural à contaminação contribui para as ações de manutenção e preservação dos aquíferos. O objetivo deste estudo foi avaliar a vulnerabilidade natural do Sistema Aquífero Guarani à contaminação usando o modelo DRASTIC usando informações obtidas em poços, e comparar diferenças ao usar o parâmetro S (solo) de levantamentos de solo em escalas 1:50.000 e 1:1.000.000. Além disso, para identificar o (s) parâmetro (s) com maior efeito nos valores de ID-DRASTIC e propor uma equação de estimativa de ID-DRASTIC para a região. O estudo foi realizado na carta topográfica Vila Kramer, município de São Francisco de Assis, RS, Brasil. O modelo DRASTIC identificou zonas vulneráveis (30%), muito vulneráveis (61%) e extremamente vulneráveis (9%). O uso de informações de levantamentos de solo nas escalas 1:50.000 e 1:1.000.000 apresentaram pequenas variações locais, tendo pouco efeito na modelagem da vulnerabilidade da água à contaminação. O parâmetro D (profundidade da zona não saturada) teve o maior efeito sobre os valores ID-DRASTIC.

Palavras–chave: Mapeamento de solos; Escala de mapeamento; Modelagem matemática; Contaminação da água subterrânea; Índice Drastic.

RESUMEN

Conocer las áreas de agua subterránea con mayor vulnerabilidad natural a la contaminación contribuye a las acciones de mantenimiento y conservación de los acuíferos. El objetivo de este estudio fue evaluar la vulnerabilidad natural del Sistema Acuífero Guaraní a la contaminación utilizando el modelo DRASTIC utilizando información obtenida de pozos, y comparar diferencias al utilizar el parámetro S (suelo) de levantamientos de suelos a escalas 1:50.000 y 1:1.000. 000. Además, identificar el (los) parámetro (s) con mayor efecto sobre los valores de ID-DRASTIC y proponer una ecuación de estimación de ID-DRASTIC para la región. El estudio se realizó sobre el mapa topográfico Vila Kramer, municipio de São Francisco de Assis, RS, Brasil. El modelo DRASTIC identificó áreas vulnerables (30%), muy vulnerables (61%) y extremadamente vulnerables (9%). El uso de información de levantamientos de suelos en las escalas 1:50,000 y 1:1,000,000 mostró pequeñas variaciones locales, teniendo poco efecto en modelar la vulnerabilidad del agua a la contaminación. El parámetro D (profundidad de la zona no saturada) tuvo el mayor efecto sobre los valores de ID-DRASTIC.

Palabras clave: Mapeo de suelos; Escala de mapeo; Modelo matematico; Contaminación de aguas subterráneas; Índice Drastic.

INTRODUCTION

Groundwater is a vital resource for the well-being of humans and aquatic ecosystems, providing nearly half of the world's drinking water (SMITH et al., 2016). Worldwide, aquifers are under threat due to contamination from anthropogenic activities in vulnerable areas (FOSTER et al., 2013; HÉRIVAUX and GRÉMONT, 2019). Changes in groundwater quality are directly related to aquifer vulnerability, including both wells' constructive aspects and land use and occupation (REGINATO and AHLERT, 2013; NEH et al., 2015).

In this scenario, aquifer vulnerability maps are essential to support and guide groundwater protection programs and public policies (VALLE JÚNIOR et al., 2015; HÉRIVAUX and GRÉMONT, 2019). Over the past decades, increasing global awareness of key ecological, hydrological, and economic roles of groundwater bodies has led to studies addressing methodologies for generating quantitative and spatial information on

groundwater vulnerability worldwide (JARRAY et al., 2017; ADNAN et al., 2018; OROJI, 2018; DUARTE et al., 2019; KONG et al., 2019). Sustainable land use is fundamental to watersheds hydrological sustainability and, consequently, necessary to minimize impacts on groundwater (BLANCHARD et al., 2015). Land use and occupation in disagreement with its suitability lead to soil degradation (LEPSCH et al., 2015), impacting water resources (MIGUEL et al., 2014; TIECHER et al., 2017).

Groundwater vulnerability can be defined as the tendency of contaminants to reach a specific position in the groundwater system (BAI et al., 2011; FOSTER et al., 2013). Thus, to maintain aquifers' quality, the use of modeling techniques associated with Geographic Information System (GIS) (DUARTE et al., 2019) is necessary to predict the areas that are most likely to be contaminated by anthropogenic activities (NEH et al. al., 2015). Knowing the areas of greater natural vulnerability to contamination has been an important practice, contributing to actions for underground aquifers maintenance and preservation (REGINATO and AHLERT, 2013; ROSENBERGER et al., 2013; NEH et al. 2015; OUEDRAOGO et al., 2016; HÉRIVAUX and GRÉMONT, 2019), once an aquifer recovery process is slow, difficult and expensive (CUTRIM and CAMPOS, 2010).

Several methods and models have been developed to assess groundwater vulnerability to contamination (FOSTER et al., 2013; VALLE JÚNIOR et al., 2015; HÉRIVAUX and GRÉMONT, 2019). GIS (geographic information system) modeling methods based on hydrogeological factors are commonly used to assess groundwater vulnerability since they are relatively simple to employ, inexpensive, less time-consuming, and generally suitable for application in data scarcity situations (KONG et al., 2019). These include the DRASTIC model developed by the United States Environmental Protection Agency (USEPA) (ALLER et al., 1987). This approach has been employed on a global scale to know areas of greater groundwater natural vulnerability (CUTRIM and CAMPOS, 2010; NEH et al., 2015; OUEDRAOGO et al., 2016; JARRAY et al., 2017; OROJI. 2018; KONG et al., 2019).

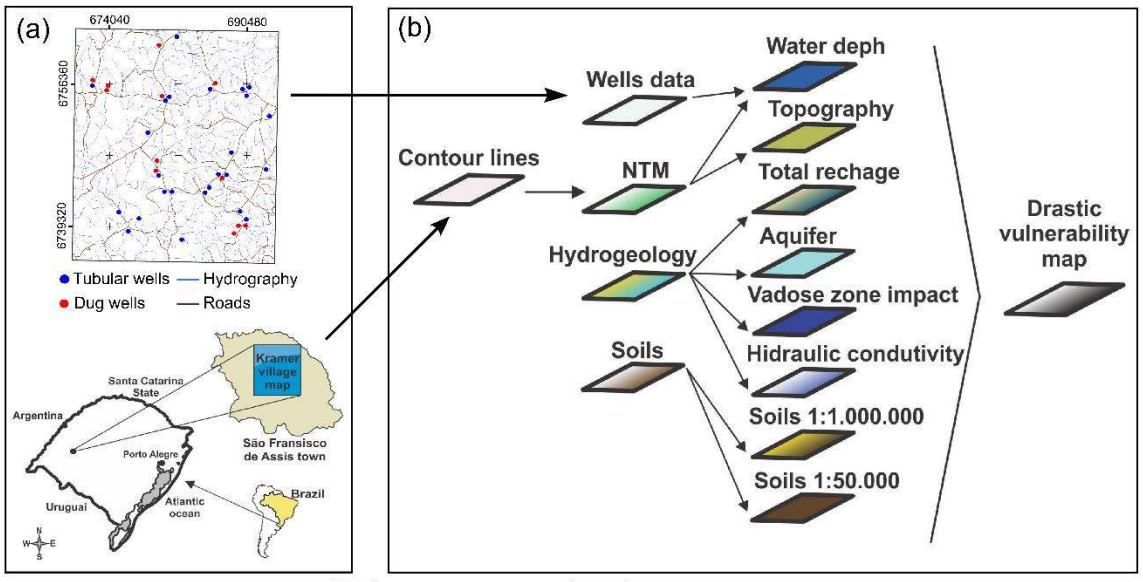
The DRASTIC model determines the aquifers vulnerability index to contamination, called Drastic Index (DI-DRASTIC), for areas larger than 0.4 km² considering seven parameters (ALLER et al., 1987): water level depth (D); aquifer recharge (R); aquifer (A); soil type (S); topography (T); vadose zone impact (I); and hydraulic conductivity (C). However, depending on the study site, it is difficult to obtain the parameters required by the model. Camponogara (2006) used this model for the Guarani Aquifer System (SAG) and stressed the difficulty in obtaining all parameters required by the model, as some of them require intense field activity demanding a higher cost and work time. According to Neh et al., (2015), this method's main disadvantage is the subjectivity factor in values attribution (weights) to factors since field data are often inaccurate, or available on a poorly detailed scale. The S parameter is one of the difficult factors to obtain. In Brazil, for example, most soil surveys are available on a less detailed scale, less than 1:250.000, and are incompatible for watersheds level project evaluations (DALMOLIN et al., 2004). Another factor is the lack of studies evaluating each parameter effect on the DI-DRASTIC value for the Guarani Aquifer System, as the works of Rosenberger et al. (2013), conducted in the Bauru Aquifer System, and Ouedraogo et al. (2016) in Affric.

Given this scenario, there is a lack of studies indicating whether there is a difference in modeling groundwater vulnerability when using the S parameter derived from different sources. Thus, the objective of this study was to evaluate the Guarani Aquifer System's natural vulnerability to contamination using the DRASTIC model with information obtained from wells, and to compare possible differences when using the parameter S from soil surveys at scales 1:50.000 and 1:1.000.000. In addition, to identify the parameter(s) with the greatest effect on DI-DRASTIC values and propose a DI-DRASTIC estimation equation for the region based on highly correlated model parameters.

METHODOLOGY

The study was carried out in the topographic map area of *Vila Kramer* (SH.2-X-D-I-4), prepared by the Brazilian Army Geographic Service Coordination (DSG), on the 1:50.000 scale. The area is located in the municipality of *São Francisco de Assis, Rio Grande do Sul* State, Brazil, between the UTM (Universal Transverse Mercator) coordinates 6762000 and 6736000 m N, and 670000 and 694000 m E, zone 21J, central meridian 57º W Greenwich (Figure 1). The study area is on the Guarani Aquifer System (SAG), an underground water body covering part of Argentina, Brazil, Paraguay, and Uruguay territories, having an accumulated volume of 37.000 km^3 and an estimated area of 1.087.000 km^2.

Figure 1 - Location map of the coverage area of the Vila Kramer topographic map in the Rio Grande do Sul western region, and location of wells registered at CPRM/SIAGAS (a), and work sequence to obtain the DRASTIC model parameters to generate the vulnerability map (b).



The local climate, according to the Köppen classification, is a constantly humid "subtropical mesothermal" Cfah type, with annual precipitation ranging from 1.400 mm to 1.600 mm (HAUSMAN, 1995). The vegetation is composed of forests, native pastures, cultivated pastures, and annual crops. The area relief ranges from 3 to 25% slope. There are three major relief compartments: the Central Depression (consisting of small hills and floodplains); the Southern Plateau slope (with discontinuous levels) and the Plateau (top). The cartographic representation of the area geology was prepared based on the *Rio Grande do Sul* state geological map (CPRM, 2008), and Santiago geological map SH.21-X-D. The information was digitized using the GIS. ArcGIS 9.3 program. The main geological units identified in the area were the sandstones from *Guará* and *Botucatu* Formations (part of the SAG – Guarani Aquifer System) and the volcanic basalt spills from *Serra Geral* Formation (part of the SASG – Serra Geral Aquifer System) (AUZANI et al., 2006).

Data from 39 wells obtained from the Mineral Research and Resource Company/Groundwater Information System (CPRM/SIAGAS) were used. The wells were sequentially identified from P1 to P39, comprising 27 tubular and 12 excavated wells (Figure 1). Information from well, along with geology, topography, and soil data were used to derive the DRASTIC model input parameters. The model determines the relative index of aquifer vulnerability to contamination considering seven parameters (ALLER et al., 1987): water level depth (D); aquifer recharge (R); aquifer (A); soil type (S); topography (T); vadose zone impact (I); and hydraulic conductivity (C). To obtain the D parameter, we used the unsaturated depth variation map, based on data from wells registered at the CPRM/SIAGAS (Groundwater Information System) (Figure 1) and complemented with fieldwork (for wells without the unsaturated zone depth value) and using the sound freatimeter. The R parameter refers to the annual amount of water that infiltrates the soil, and/or rocks into the aquifer. The information from Hausman (1995), which estimated total annual precipitation between 1.400 and 1.600 mm, was used. The A parameter is derived from geological formations and can be associated with aquifer

types (free, confined, and semi-confined), and the information used was obtained from CPRM/SIAGAS.

The S parameter (soil types) was derived from the soil survey of the Vila Kramer topographic map, scale 1:50.000 (FLORES, 2009) (Figure 2a). The comparative test was performed using a 1:1.000.000 soil map (IBGE, 2003) (Figure 2b). The T parameter (topography) was obtained from slope classes. This parameter concerns the probability of a pollutant to flow superficially or remain on the surface long enough to infiltrate (CARVALHO. 2013).

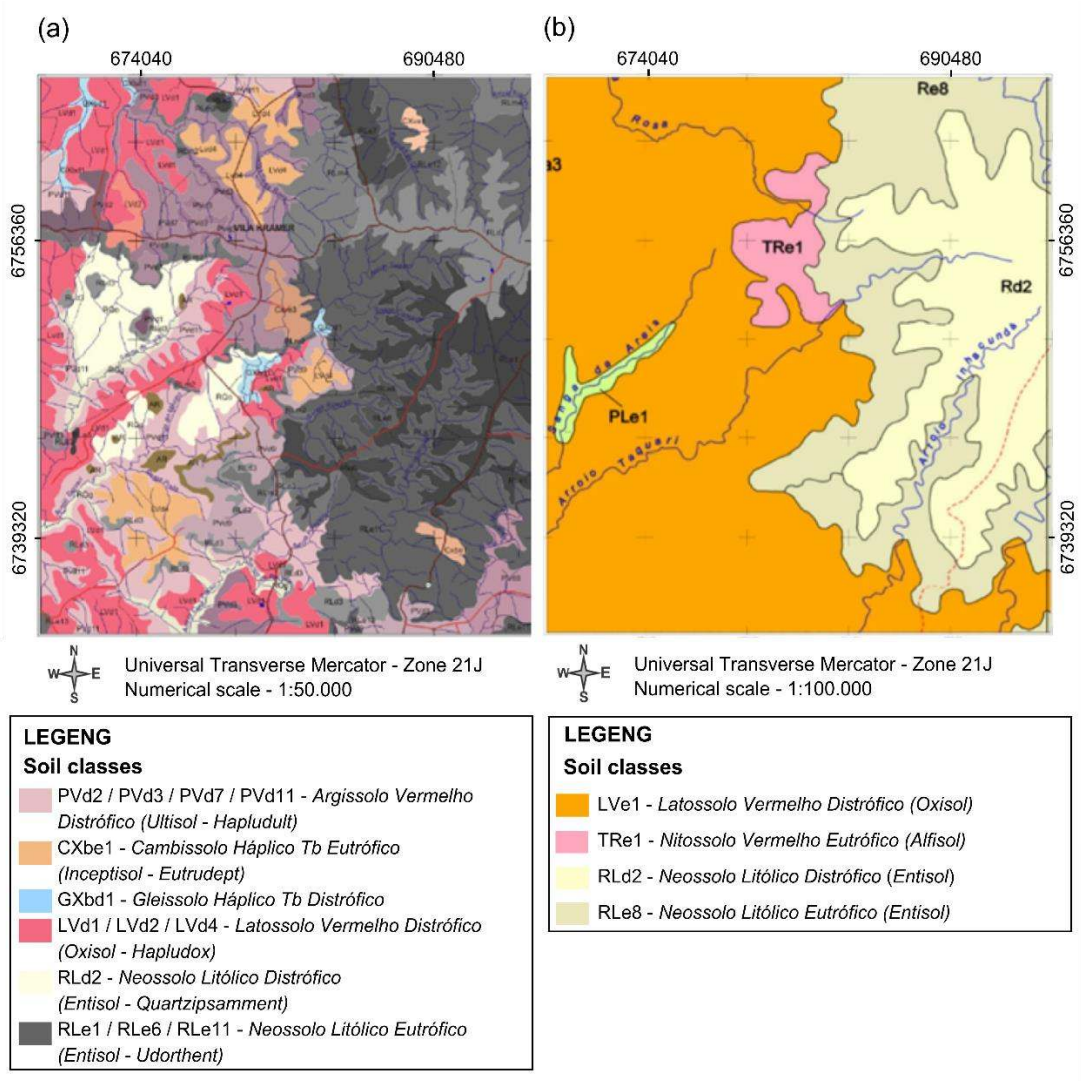
The slope classes were derived from the slope map, which was elaborated according to the methodology proposed by Aller et al. (1987). To make this map, digitization of contour lines and points quoted in Numerical Terrain Model - MNT was performed using the Spring 4.3 software. The I parameter (Vadose Zone Impact) was obtained by identifying the geological formations in the study area (SILVÉRIO DA SILVA et al., 2006). Finally, the C parameter was obtained out of data from Camponogara (2006), who used pumping tests information available from Silvério da Silva et al. (2006).

The DRASTIC Index (DI), which indicates the groundwater vulnerability, is calculated by the DRASTIC model using the weighted mean of the seven values corresponding to the hydrogeological parameters, according to Equation (1) (ALLER et al., 1987). The calculation is based on multiplying the seven parameters by load values "c" and weights "p" according to Aller et al. (1987). The "c" values range from 1 to 10, depending on the range of values and based on the groundwater contamination index, where higher values represent a more sensitive to contamination area. The **"p"** weights range from 1 to 5, with the most significant factor receiving weight 5 and the least significant 1.

$$DI = Dp * Dc + Rp * Rc + Ap * Ac + Sp * Sc + Tp * Tc + Ip * Ic + Cp * Cc \qquad Eq.1$$

where: Dp, Rp, Ap, Sp, Tp, Ip, Cp, Dc, Rc, Ac, Sc, Tc, Ic, Cc correspond to the seven parameters multiplied by the weights “p” and loads “c”.

Figure 2 - Soil map of the Vila Kramer region, 1:50.000 scale (a) and 1:1.000.000 scale (b), used to obtain the S parameter. Soil class according to the Brazilian Soil Classification System (SANTOS et al., 2018) and between parentheses according to Soil Taxonomy (SOIL SURVEY STAFF, 2014).



From the seven parameters analyzed by the DRASTIC model, the DI was calculated taking into account the S parameter derived from the 1:50.000 and 1:1.000.000 soil maps. Then DI was categorized into vulnerability zones (https://engineering.purdue.edu/ABE/engagement) namely: protected area (DI <35), low vulnerability (DI = 35 - 65), vulnerable (DI = 65 - 95), very vulnerable (DI = 95 - 120) and extremely vulnerable (protected area required) (DI>120).

The relationship between the parameters loads of the DRASTIC model with the DI values was evaluated by Pearson's linear correlation analysis ($\alpha = 0.01$). Parameters that best correlated with DI were used in the linear regression analysis to obtain a regression equation for DI estimation. The DI values obtained by the DRASTIC model and estimated by the proposed regression equation were compared using the paired data test (t).

RESULTS E DISCUSSION

The evaluation of the D parameter for the 39 caption wells shows that the assigned loads for intervals closest to the soil surface were higher, resulting in higher depth indexes (ID) (Table 1). More than half of evaluated wells (51.28%) were shallow, with depths ranging from 0 to 10 m, and shallow water levels areas. These areas, and consequently the wells, are the most vulnerable to groundwater contamination due to pollution from inappropriate land use (NEH et al., 2015), especially by agriculture and livestock.

The aquifer recharge parameter (R) was from 51.85 to 103.7 mm year^{-1} with attributed weight 4, and assigned load value equal to 3, resulting in a recharge index (IR) of 12. As higher the water volume reaching the aquifer, the higher the potential to transport pollutants from anthropic activities (NEH et al., 2015). Infiltrating water into the soil/rock will percolate through the subsurface areas, passing through the vadose zone until it reaches the saturated zone. If water is contaminated or carries contaminated sediment it may contribute to pollution of groundwater resources.

The A parameter was classified according to aquifer hydrogeological units, being associated with the confined type aquifer in the Serra Geral Formation, the Botucatu

Formation, and the Guará Formation (SILVÉRIO DA SILVA et al., 2004). This last Formation received the lowest load value 4 compared to the other Formations (Table 1), due to the occurrence of very fine, massive sandstone or siltstone, and composed of fluvial sedimentary rocks and hydrological demeanor with low to moderate permeability (CPRM . 2008). This Formation presented DI = 12, presenting 3 tubular and 2 excavated wells. The Botucatu Formation, with load 6 (Table 1), has a high porosity/permeability ratio and is composed of fine to medium sandstones of wind origin that are easily transported to the subsurface due to the clay fraction absence. This Formation presented the highest index obtained for A parameter (DI = 18) (Table 1), due to the high porosity/permeability of the Botucatu Formation material. This is a porous aquifer, which contains 4 tubular and 4 excavated wells. The Serra Geral Formation, whose assigned load was 5, is composed of the largest number of wells (20 tubular and 6 excavated wells) (Table 1). According to Maciel Filho (1990), this unit permeability is fissural, and water can move relatively easily through fractures attenuating the greater pollution potential (ANWAR et al., 2003). However, this Formation has little water storage capacity, being limited to the fractured space between blocks of massive aphanitic volcanic rock to locally vesicular and amygdaloid with greater porosity.

The T parameter, obtained from the slope map, is important as a function of groundwater recharge since the lower the slope the greater the probability of water infiltration into the soil, as well as contaminants (CARVALHO, 2013; NEH et al., 2015). The slope, represented by the topography factor, has a great influence on the surface contaminants runoff velocity, the hydraulic gradient, and the preferential flow direction, especially in free aquifers (CUTRIM and CAMPOS, 2010). Thus, as more pronounced the relief, the greater the surface runoff and, consequently, subsoil infiltration will be lower, influencing the aquifer recharge and storage (NEH et al., 2015). In the present study, the 0 - 2% slope range represents 5.40% of the area, receiving load 10 (Table 1), and resulting in the highest topographic index. This corroborates the work developed by Carvalho (2013), in which the author states that these places have a high recharge rate

and low surface runoff potential. In these areas, the well's pollution probability may be higher due to the flat slope, where the water infiltration process in the soil/subsoil occurs more intensely.

Table 1 - Parameters depth of unsaturated zone (D), aquifer (A), topography (T) and impact of vadose zone (I) used to determine the vulnerability of SAG by the DRASTIC model.

Unsaturated zone depht (D)				
Intervals (m)	D_p	D_c	Wells	I_D
0 - 1.5	5	10	P5; P13; P14; P19; P21; P25	50
1.5 - 4.6	5	9	P1; P2; P3; P9; P16; P17; P23; P29; P33	45
4.6 - 9.1	5	7	P6; P18; P26; P27; P28.	35
9.1 -15.2	5	5	P7; P8; P20; P39.	25
15.2 - 22.9	5	3	P11; P24; P30; P35; P36	15
22.9 - 30.5	5	2	P10; P12.	10
> 30.5	5	1	P4; P15; P22; P31; P32; P34; P37; P38	5
Aquifer (A)				
Formation: Interval (m)	A_p	A_c	Wells	I_A
Guará: 4-9	3	4	P25; P26; P27; P36; P39	12
Botucatu: 4-9	3	6	P9; P15; P16; P20; P21; P23; P24; P28.	18
Serra Geral: 2-10	3	5	P1 a P8; P10 a P14; P17 a P19; P22; P29 a P35; P37 e P38.	15
Topography (T)				
Slope classes (%)	T_p	T_c	Wells	I_T
0 - 2%	1	10	P12; P15; P25.	10
2 - 6%	1	9	P2; P3; P5; P7; P9 a P11; P16 a P21; P28 a 30; P32; P33; P35; P37 a P39.	9
6 -12%	1	5	P1; P4; P6; P8; P13; P14; P22; P23; P24; P26; P27; P31; P34; P36.	5
Vadose zone impact (I)				
Formation: structure	I_p	I_c	Wells	I_I
Guará: massive sandstone	5	4	P25; P26; P27; P36; P39.	20
Botucatu: massive sandstone	5	6	P9; P15; P16; P20; P21; P23; P24; P28.	30
Serra Geral: fracturated basalt	5	5	P1 a P8; P10 a P14; P17 a P19; P22; P29 a P35; P37; P38.	25

p = weights for each parameters; c = loads for each parameters; I_D = depht of unsaturated zone index; I_A = aquifer index; I_T = topographic index and I_I = vadose zone index.

The largest number of wells is located in the 2 - 6% range there is, representing 56.41% of evaluated wells, with assigned load 9 (Table 1). This interval represents 44.50% of the studied area, is characterized by a soft undulating relief, with the predominance of agricultural and livestock activities. In this slope range, there is a good water infiltration in the soil, and, consequently, of pollutants to the subsurface. The 6 - 12% slope range represented 35.17% of the assessed area, in which 14 wells are inserted. In this area, the relief is undulated and the assigned load was 5. No wells were identified in the 12 - 18% slope ranges neither above 18%. This is since these areas present strongly undulating to mountainous relief with springs likely occurring, which serve for both human and animal supply.

The I parameter is the impact of unsaturated zone, which is found below the soil lower portion, and related to the geological Formation nature. This parameter was classified according to the geological formations in the study area, where loads were attributed according to their variation. This parameter varies according to groundwater depth and soil permeability (ALLER et al., 1987). The water infiltration in the soil lower zones until reaching the aquifer will depend on the original material type present in the vadose zone (ALLER et al., 1987), if it is made up of permeable material it can have a high impact on contaminates movement to underground aquifers (NEH et al., 2015).

The *Botucatu* Formation consists of clean, clay-free sandstones, with excellent selection and degree of particle roundness, receiving the highest load (6) and resulting in the geological Formation highest index (Table 1). This unit presents very porous and permeable rocks (MONTANHEIRO et al., 2011), being subject to greater pollutant movement into the aquifer due to its high porosity/permeability ratio. In this Formation, there are 4 tubular and 4 excavated wells. The excavated wells had a water level variation between 1.34 and 11.14 m deep, while the tubular wells had a wider level variation between 3.35 and 15.6 m (Table 1). The *Guará* Formation, which occurs 5 wells (3 tubular and 2 excavated), consists of fine to conglomerate sandstone with significant silt or clayey matrix (CPRM, 2008), presenting low water infiltration to the subsurface, and

receiving assigned load 4 (Table 1). The *Botucatu* and *Guará* Formations constitute the SAG. In the case of volcanic rocks of the *Serra Geral* Formation, the basalt is massive, with fractures and locally with vesicles and amygdaloids (MACIEL FILHO, 1990; REGINATO and AHLERT, 2013). In this geological formation were observed the largest number of wells (20 tubular and 6 excavated), receiving assigned load 5 (Table 1). Aphanitic basalt, not weathered massifs, are very cohesive rocks, forming a confined aquifer, and making it difficult for pollutants to move.

The values obtained for the C parameter (hydraulic conductivity) in the *Botucatu* Formation sandstones, and the Cenozoic sediments (alluviums), were higher than in the basalts since water percolation occurs more easily due to the higher porosity/permeability ratio (MONTANHEIRO et al., 2011). The weight "p" and load "c" assigned values were, respectively, 3 and 1 for the infiltration coefficient intervals in m day^{-1} of 0 - 4 m day^{-1}, resulting in a hydraulic conductivity index (Ic) equal to 3 (Ic = Cp x Cc). This is according to the Ic values found by Cutrim and Campos (2010), which obtained a hydraulic conductivity of 2.55 mm day^{-1}.

The S parameter took into consideration soil types present in the soil map in the 1:50.000 and 1:1.000.000 scales. Loads were attributed to the different soil classes (Table 2), taking into account attributes such as the rocks particle size composition and/or alteration products, sand, silt, and clay fractions. Soils with a sandy texture have faster and higher water infiltrates than clayey soils. Due to its good permeability, the superficial water reaches underground aquifers more easily, providing greater contaminants transport (ANWAR et al., 2003). The *Argissolo* (Ultisol) has different parameters according to their substrate. The *Argissolo Vermelho Distrófico abrúptico* (PVd3) of sandy/medium texture was the one receiving the highest load value (5) among the *Argissolos* due to its sandy texture in A horizon, medium texture in B horizon, and good water infiltration. The *Argissolo Vermelho Distrófico típico* (PVd7), on the other hand, received a lower load (3) due to the higher clay content (horizon A and B) and, consequently, lower permeability. The PVd11 mapping unit is an association of *Argissolo Vermelho Distrófico*

abrúptico (Arenic Hapludult) soils with sandy/medium texture + *Neossolo Quartzarênico Órtico típico* (Entisol – Quartzipsamment). Due to the sandy texture of these soils, it received load 6. These soils have high infiltration and low inerting power, which makes them very susceptible to carry pollutants into the aquifer.

The *Cambissolo Háplico Tb Eutrófico típico* (Inceptisol – Eutrudept) (CXbe1) with clay texture and Mollic horizon received load 3 and has 2 dug wells and near-surface water level. Due to this soil clay texture and its higher cation exchange capacity (CTC), the ability to attenuate the pollutants' toxic potential, in case of infiltration, is greater. The *Gleissolo Háplico Tb Distrófico típico* (Ultisol – Endoaquult) (GXbd1), with medium texture and plane relief area, presented 1 excavated well and load 4, being a medium-deep soil with a medium texture. The *Latossolo Vermelho Distrófico típico* (Oxisol – Hapludox) (LVd1), with medium texture, received the highest load (4) among the Oxisols, once it is more sandy than the others and, consequently, has a higher permeability, allowing the pollutants passage to the soil subsurface more easily. This soil, although deep and well structured, has low CTC as well as it is susceptible to erosion due to its sandstone original material (STRECK et al., 2018). The other Oxisols of the area (LVd2 and LVd4), due to the clay texture, had an attributed load 3. The *Neossolos Litólicos* (Entisol – Udorthent) (RLe1 and RLd2) occur in single mapping units and also in associations with *Neossolo Litólico* + *Cambissolo Háplico* (Udorthent + Eutrudept) (RLe6 and Rle11), RLe1, RLe6, and RLe11 *Neossolo Litólico* received assigned load 8 (medium texture), and RLd2 assigned load 7 (clay texture). These high assigned loads were due to their shallow soil profiles, which conditions low filtering potential (inertization), resulting in higher Is compared to the other evaluated soils (Table 2).

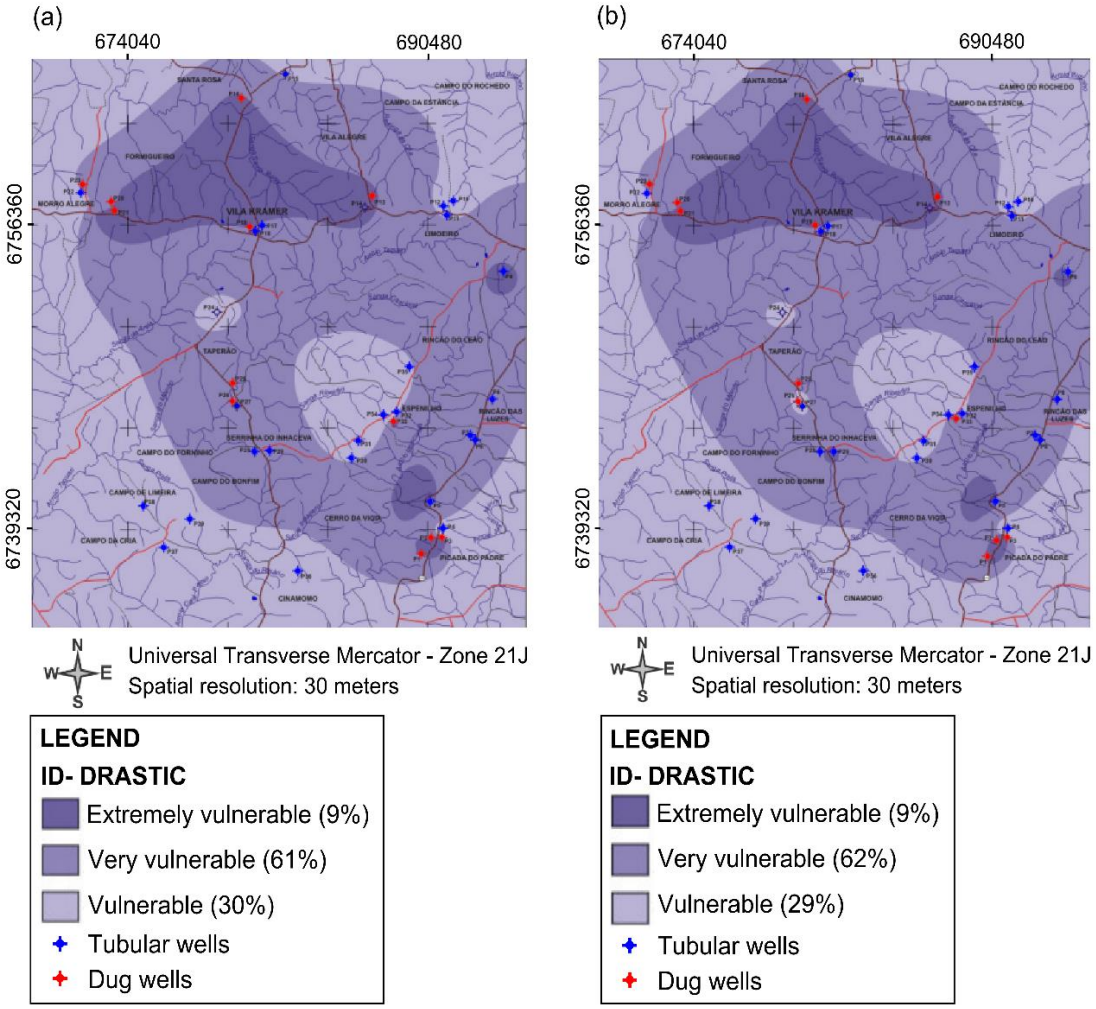
Table 2 - Soil classes of soil surveys on 1:50.000 and 1:1.000.000 scales, respective number of wells, weight (Sp), and assigned loads (Sc), and index for each soil class (Is).

Soil classes or mapping units	Wells	S_p	S_c	I_s
Scale 1:50.000				
PVd2	P22; P23	2	4	8
PVd3	P15	2	5	10
PVd7	P17; P18; P19; P24	2	3	6
PVd9	P28; P29; P39	2	4	8
PVd11	P26; P27; P36	2	6	12
CXbe1	P2; P3	2	3	6
GXbd1	P25	2	4	8
LVd1	P20	2	4	8
LVd2	P21	2	3	6
LVd4	P16; P37; P38	2	3	6
RLd2	P10; P11; P12; P13; P14	2	7	14
RLe1	P5; P6; P7; P9; P32; P33	2	8	16
RLe6	P30	2	8	16
RLe11	P1; P4; P8; P31; P34; P35	2	8	16
Scale 1:1.000.000				
LVd	P15; P16; P20 a P28; P36 a P39	2	4	8
TRe1 = NVe	P17 a P19	2	4	8
RLd2	P2 a P14; P30 a P35	2	7	14
RLe8	P1; P29	2	8	16

The S parameter from the 1:1.000.000 scale soil map. Due to the poorly detailed map scale, only three soil classes were considered (*Latossolos* – Oxisols. *Nitossolos* – Ultisols, and *Neossolos Litólicos* – Entisols). The largest number of wells, representing 53.85% of the total, are in the *Neossolos Litólicos* (RLd. RLe) area, and for wells in RLd was assigned load 7, while for wells in RLe was assigned load 8 (Table 2). Both assigned loads are considered high and were attributed because these soils are shallow, poorly developed, and with no B horizon (STRECK et al., 2018), which provides greater potential for a pollutant to reach the wells (ANWAR et al., 2003; NEH et al., 2015). In the *Nitossolos Vermelho Eutrófico Chernossólico* (NVe) there were 3 wells with assigned load 4. This value was attributed due to the deep, well-drained, very porous, friable, and well-structured soils (STRECK et al., 2018). Thus, it has good permeability, facilitating the water infiltration and percolation, which may or may not contain pollutants.

From the seven parameters analyzed by the DRASTIC model, the DI was calculated considering the three vulnerability zones (vulnerable, very vulnerable, and extremely vulnerable) taking into consideration the S parameter in the 1:50.000 and 1:1.000.000 scales. The DI values ranged from 73 to 133 on the 1:50.000 scale, and 73 to 131 on the 1:1.000.000 scale. The results obtained show for both scales that, approximately 30, 61, and 9% of the total area are vulnerable, very vulnerable, and extremely vulnerable zones respectively (Figure 3a. 3b). It means that most of the area is susceptible to SAG water contamination if land use and occupation occur without prior planning.

Figure 3 - Groundwater contamination vulnerability maps obtained by the DRASTIC model with S parameter on the 1:50.000 (a) and 1:1.1000.0000 (b) scales.



The DI values and percentages of vulnerability zones found in the present study present differences compared to studies performed outside Brazil, especially regarding the minimum DI values, which are reflected in the absence of low vulnerability zones. Adnan et al. (2018) found different minimum and maximum values in a study conducted in Pakistan, where the DI ranged from 47 to 147, and which were divided into zones of low, moderate, and high pollution vulnerability. The final results showed that about 31,

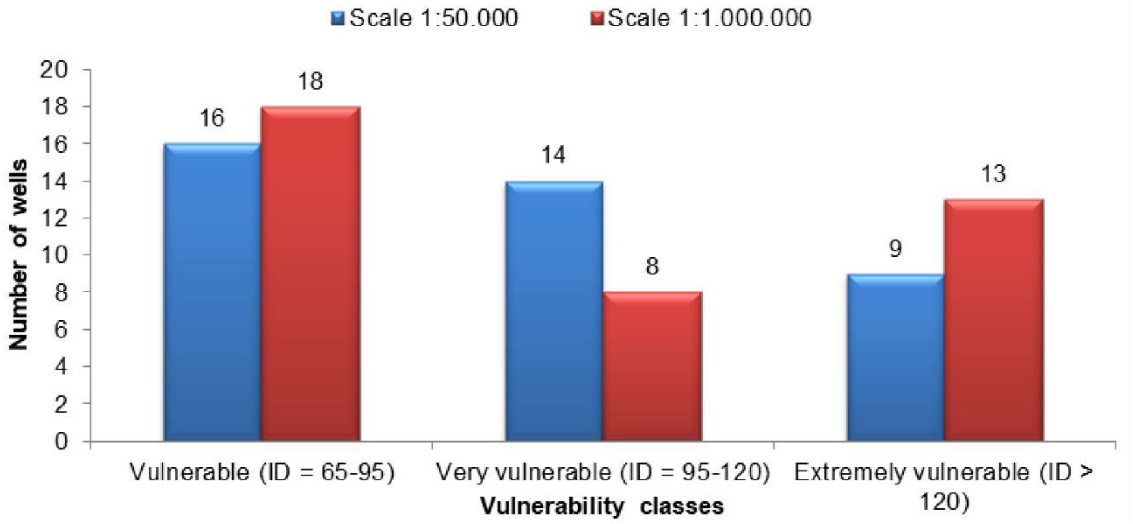
40 and 29% of the area is in low, moderate, and high vulnerable zones respectively. Jarray et al. (2017), analyzing a shallow aquifer in southeastern Tunisia, found DI values ranging from <30 to> 200, and that 48% of the area is in the high-risk zone. Oroji (2018) applied the DRASTIC model to a plain in Iran and found that 15% of the area has very low vulnerability to groundwater contamination, while 34, 29, 15, and 7% have low, moderate, high, and very high vulnerability respectively. Ouedraogo et al. (2016), in Africa, found DI values between 66 and 213, where most of the area was classified into very low and low vulnerability zones due to the absence of significant anthropogenic activities. In a study conducted in Brazil, in the Bauru municipality, São Paulo State, in the SAG and Bauru Aquifer System (SAB), Rosenberger et al. (2013) using the DRASTIC model, report the occurrence of areas with low (30%), moderate (67%) and high (3%) vulnerability, which vulnerability zones proportions are similar to those of the present study (Figure 3).

The vulnerability map generated considering the S parameter in the 1:50.000 scale (Figure 3a) showed that most of the wells were classified in the vulnerable class (ID = 65–95) (Figure 4), all of which were tubular located in the SASG formations (12 wells), and SAG (4 wells). In general, these wells have the deepest water level, and the material consists of fractured or weathered rocks from the SASG, confined and/or sedimentary, containing different sand, silt, and clay proportions. However, the materials thickness and types lead to little water infiltration to the subsurface, making it difficult for pollutants to move. In the very vulnerable class (ID = 95–120), where water infiltration occurs faster due to soil sandy texture, favoring the pollutant movement, there are 14 wells (Figure 4). In the extremely vulnerable class (ID > 120) there are 9 wells, with shallow water levels and strong infiltration conditions, due to the sandy texture and/or shallow soils. Therefore, the area where these wells are located should be considered in all land use and planning processes.

The DI map obtained from the S parameter on the 1:1.000.000 scale (Figure 3b) indicated 18 wells in the vulnerable class, 8 in the very vulnerable class, and 13 in the

extremely vulnerable class (Figure 4). Comparing the wells classification in both scales (Figure 4), it is observed that 4 wells previously classified in the very vulnerable class in the 1:50.000 scale, were classified in the extremely vulnerable class in the 1:1.000.000 scale. On the other hand, another 2 wells in the very vulnerable class on the 1:50.000 scale were changed to the vulnerable class on the 1:1.000.000 scale. This shows that the use of different soil mapping scales affected groundwater vulnerability assessment when considering water catchment wells. However, when compared to the area extension of each vulnerability zone in the two scales of S parameter (Figure 3a. 3b) significant variation was observed. This result is due to the soils mapped characteristics on the 1:1.000.000 scale being analogous to the soils mapped on the 1:50.000 scale, giving similar load values for the S parameter. However, this fact does not diminish the importance of using soil detailed information for DI estimation, especially in regions where soil variation is high, and soil characteristics will be quite different when compared based on maps at different scales (DALMOLIN et al., 2004).

Figure 4 - Number of wells in the groundwater vulnerability DI map obtained with S parameter on 1:50.000 and 1:1.1000.0000 scales.



The linear correlation performed between parameter loads of the DRASTIC model showed that only the D parameter presented a significant correlation (r = 0.950) (Table 3), indicating a greater effect on DI. Such a result is associated with the near-surface static level of most wells (51.28%), which conditioned the areas of the wells framing as very and extremely vulnerable to contamination and corroborating a study by NEH et al. (2015), reporting that near-surface aquifers are more susceptible to contamination. Rosenberger et al. (2013) and Ouedraogo et al. (2016) identified the D, I, and A parameters are the ones with a greater effect on DI.

Table 3 - Pearson linear correlation between the following parameters: unsaturated depth (D), aquifer (A), soil type (S), topography (T), vadose zone impact (I), and the ID.

	Dc	**Ac**	**Sc**	**Tc**	**Tc**	**DI**
Dc	1					
Ac	0.008	1				
Sc	-0.221	-0.250	1			
Tc	0.075	0.156	-0.301	1		
Ic	0.008	1.000**	-0.250	0.156	1	
DI	0.950**	0.221	-0.076	0.157	0.221	1

The linear regression analysis resulted in Equation 2, which showed that the D parameter load has a high predictive power of DI value, with a 90% predictive capacity (adjusted $R^2 = 0.90$), and a standard error from the estimate of 5.52.

$$DI = 75.568 + 4.784 * Dc \qquad Eq.2$$

Equation 2 provided estimates of DI value for the study area, which were compared with values obtained by the DRASTIC model (Equation 1) using a paired "t" test. Results showed that there was no significant difference (t = 0.118) between the values obtained by both equations (Table 4). Thus, in the studied area and/or with similar

environmental characteristics (DRASTIC model parameters), the application of Equation 2 to obtain the DI can be considered, as it only requires the D parameter.

The analysis of aquifers' natural vulnerability to contamination was important for monitoring the catchment by wells in the Vila Kramer region located in the SAG and SASG. This research contributed to identifying the effect of the S parameter scale on the DI, discussing when this factor may be more important for the final result. In addition, the study also generated information for civil society, the watershed Committee, as well as increasing knowledge about the groundwater vulnerability to contamination of SAG and SASG. Information derived from the DI map can serve as a general guideline for planners and decision-makers, supporting regional and local-scale environmental management that will impact continental or even global investment policies by agencies and international authorities.

CONCLUSIONS

The mapping of SAG and SASG aquifers' natural vulnerability to contamination, obtained through the DRASTIC model, identified vulnerable (30%), very vulnerable (61%), and extremely vulnerable (9%) zones.

The use of information from the 1:50.000 and 1:1.000.000 scales of soil surveys showed small local variations in wells, having little effect on the Drastic Index values.

The D parameter (unsaturated zone depth) had the greatest effect on Drastic Index values, reaching a significant correlation of 0.95.

The proposed equation for estimating Drastic Index ($DI = 75.568 + 4.784 * Dc$) for SAG and SASG has potential for use in other areas with similar environmental characteristics to the ones in this study.

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