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ORIGINAL ARTICLE

Groundwater vulnerability assessment in coastal plain of Rio Grande do Sul State, Brazil, using drastic and adsorption capacity of soils

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Abstract Groundwater vulnerability assessment to delineate areas that are more susceptible to contamination has become an important element for resource management and land use planning. The objective of this work was to integrate hydrogeologic data in a geographic information system (GIS) for phreatic groundwater vulnerability assessment of a pilot area from the Coastal Plain of the Rio Grande do Sul State, Brazil, using the DRASTIC method and adsorption capacity of soils. The studied ions were copper, lead, sulfate and phosphate. Using the original DRASTIC method, the vulnerability presented high values, mainly due to the texture of the sediments and the low depths of waters, which favor the accessibility of the contaminants to the groundwaters. DRASTIC with adsorption capacity of soils showed specifics results for each studied ion. Groundwater vulnerability to metals in relationship to anions was lower. These results show that the original DRASTIC method represents better contaminants with high mobility.

Keywords Adsorption · Groundwater vulnerability · DRASTIC · GIS · Brazil

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Introduction

Nowadays, many important aquifers in Brazil and other regions of the world are exposed to the impact of disordered exploitation and inadequate land use, bringing risk to the quality of groundwaters. This stresses the need for strategic planning of the use and protection of these resources. A very important tool for groundwater management consists of vulnerability mapping. The vulnerability concept is implemented by classifying a geographic area with regard to its susceptibility to groundwater contamination because groundwater models often have data requirements that cannot be satisfied in many parts of the world (Knox et al. 1993).

The aim of this project was to assess the phreatic groundwater vulnerability of a pilot area from the Coastal Plain of The Rio Grande do Sul State, Brazil. The GIS technique was used to integrate hydrogeological data obtained in the field, public files and literature. Due to the information gap of area fractured aquifer, only Quaternary aquifers were studied.

One of the most widely used models to assess groundwater vulnerability for a wide range of potential contaminants is DRASTIC (Aller et al. 1987; Evans and Mayers 1990; Secunda et al. 1998; Fritch et al. 2000; Al-Zabet 2002; Al-Adamat et al. 2003; Collin and Melloul 2003; Dixon 2005). DRASTIC methodology was developed in the United States under cooperative agreement between the national water well association (NWWA) and the US environmental protection agency (EPA) for detailed hydrogeologic evaluation pollution potential (Rundquist et al. 1991). This model incorporates the most important hydrogeologic factors that affect the potential for groundwater pollution

(Aller et al. 1987): Depth to water table, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone media, and hydraulic Conductivity. DRASTIC methodology uses four major assumptions: the contaminant is introduced at the ground surface, the contaminant is flushed into the groundwater by precipitation, the contaminant has the mobility of water and the area evaluated is 0.4 km^2 or larger (Aller et al. 1987).

In the soil environment, the mobility and fate of ions is regulated via their portioning between soil and solution (Lee et al. 1998). Anions usually tend to remain dissolved in water, while cations, mainly heavy metals, are retained in soils. Then, to this study was added the soil adsorption capacity in the original DRASTIC method to assess the groundwater vulnerability to different contaminants.

Adsorption is an accumulation of matter at the solid/water interface. It is understood primarily in terms of intermolecular interactions between solute and solid phases (Sposito 1984). The adsorption is influenced by a variety of parameters. The most important ones being pH, type and speciation of ion involved, ion competition, soil composition and aging (Bradl 2004). The soil type and composition plays an important role for ion adsorption. In general, coarse-grained soils exhibit a lower tendency for ion adsorption than fine-grained soils. The most important interfaces involved in ion adsorption in soils are predominantly inorganic colloids such as clays, metal oxides and hydroxides (Bradl 2004). Also, organic colloidal matter of detrital origin and living organisms such as algae and bacteria provide interfaces for ion adsorption (Kerndorf and Schnitzer 1980).

Location of study area

The study area is located in the Viamão District, Rio Grande do Sul State, Brazil (Fig. 1), between longitude 51°00′W and 50°52′30″W and latitude 30°15′S and 30°22′30″S. It represents a pilot area of the Coastal Plain of Rio Grande do Sul State, Brazil, the largest Brazilian Quaternary plain, covering about 33,000 km^2.

Geology

As shown in Fig. 2, the geology of the area is characterized by Precambrian granitoids and Quaternary sediments (eolian and lagoonal deposits). The eolian deposits were formed 400,000 years ago, and are composed mainly of well-rounded, fine to medium grained, red to orange, unconsolidated quartzose sands with variable content of silt and clay matrix (Tomazelli and Villwock 2000). The deposits have maximum thickness of about 120 m.

The lagoonal deposits are composed of many terraces, formed as a result of sea-level oscillations during the Pleistocene. The relative ages among the terraces have influenced the soil formation (Herlinger 2004), mainly in clay content. The lagoonal deposits with paludal deposits favored the development of soils rich in organic matter, named peat in the study area.

Materials and methods

DRASTIC model

The DRASTIC method is composed of two major parts: the designation of mappable units, termed hydrogeologic setting, and the application of a numerical scheme of relative ranking of hydrogeologic factors. DRASTIC helps to evaluate the relative groundwater pollution potential of any hydrogeologic setting (Kim and Hamm 1999).

The original DRASTIC method is based on three components (weight, range and rating) that are expressed numerically. A weight was assigned to each DRASTIC feature in accordance with its relative importance. The weights range from five (most significant) to one (least significant), as shown in Table 1. The range component divides each DRASTIC feature into several classes, or significant media types, which may affect the potential for pollution (Ehteshami et al. 1991). The rating assigns each class a value, based on a scale of one (least contamination potential) to ten (high contamination potential). The DRASTIC index (DI) is calculated by:

$$\mathrm{DI} = D_R D_W + R_R R_W + A_R A_W + S_R S_W + T_R T_W + I_R I_W + C_R C_W, \quad (1)$$

where R is rating, W is weight, D is depth to water, R is net recharge, A is aquifer media, S is soil media, T is topography, I is impact of the vadose zone media and C is hydraulic conductivity. The higher the DRASTIC index the greater the relative groundwater contamination potential. In this method, the ratings are generally chosen subjectively. Then, this approach allows for vulnerability comparison between sites, but it does not offer an absolute measure of groundwater vulnerability.

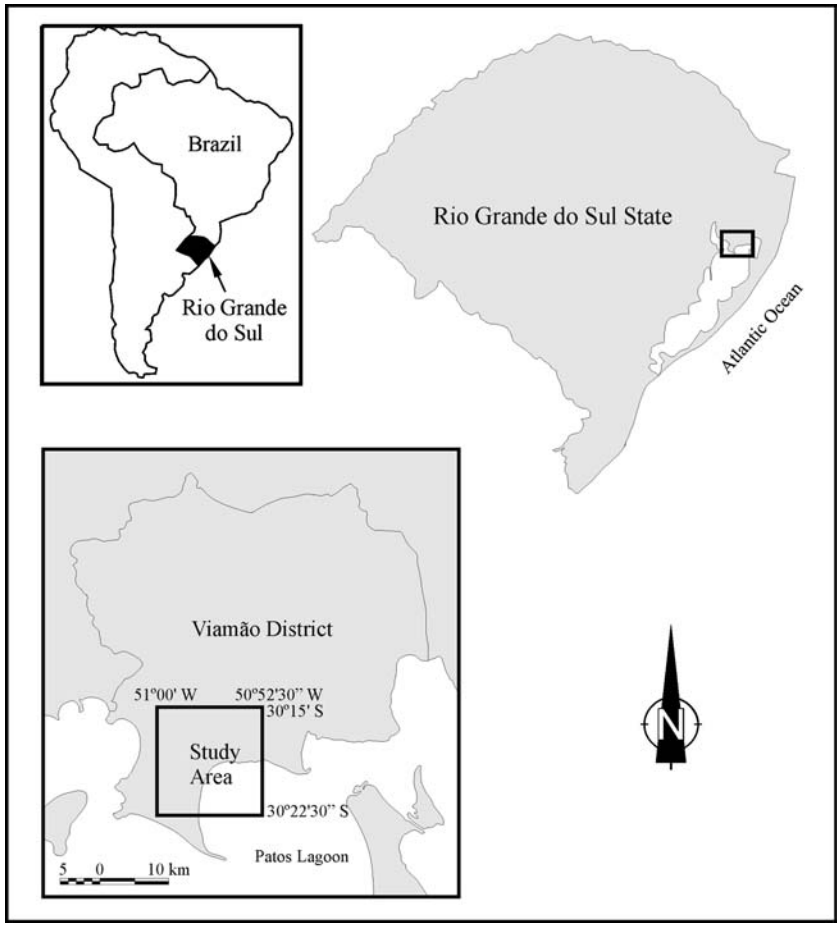

Fig. 1 Location of study area

Data acquisition

The necessary data for the vulnerability evaluation were obtained from public archives, field research and literature data. Data of 38 wells were obtained from public registers (CORSAN—Companhia Riograndense de Saneamento and SEMA/DRH—Secretaria Estadual do Meio Ambiente/Departamento de Recursos Hídricos). Data of 45 wells were obtained directly in field research. The data were used to compose a database with hydraulic and litologic data including wells location, hydraulic conductivity and aquifer and vadose zone media. Three wells were selected to perform slug tests according to Fetter (1994) to determine hydraulic conductivity, based on Hvorslev's equation (1951). The soil and soil adsorption data were obtained from literature (Herlinger and Viero 2006).

Depth to water

Depth to water is an important factor because it determines the depth of material through which a contaminant must travel before reaching the water table in an aquifer and it may help to determine the contact time with the surrounding media. The depth to the water is also important because it provides the maximum opportunity for oxidation by atmospheric oxygen.

The depth to water was obtained from the data of public archives and measurements in field. In the lagoonal deposits, the groundwater depths range between 0 and 1.5 m. In the eolian deposits, the depth was much more variable due to the geomorphologic irregularity. The depths in eolian deposits varied between 0 and 9 m. The ratings for studied ranges of depth to water, according to Aller et al. (1987), are presented in Table 2.

Soil media

Soil media refers to that uppermost portion of the vadose zone characterized by significant biological activity. Soil has a significant impact on the amount of recharge that will infiltrate into the ground and hence on the ability of a contaminant to move vertically into the vadose zone.

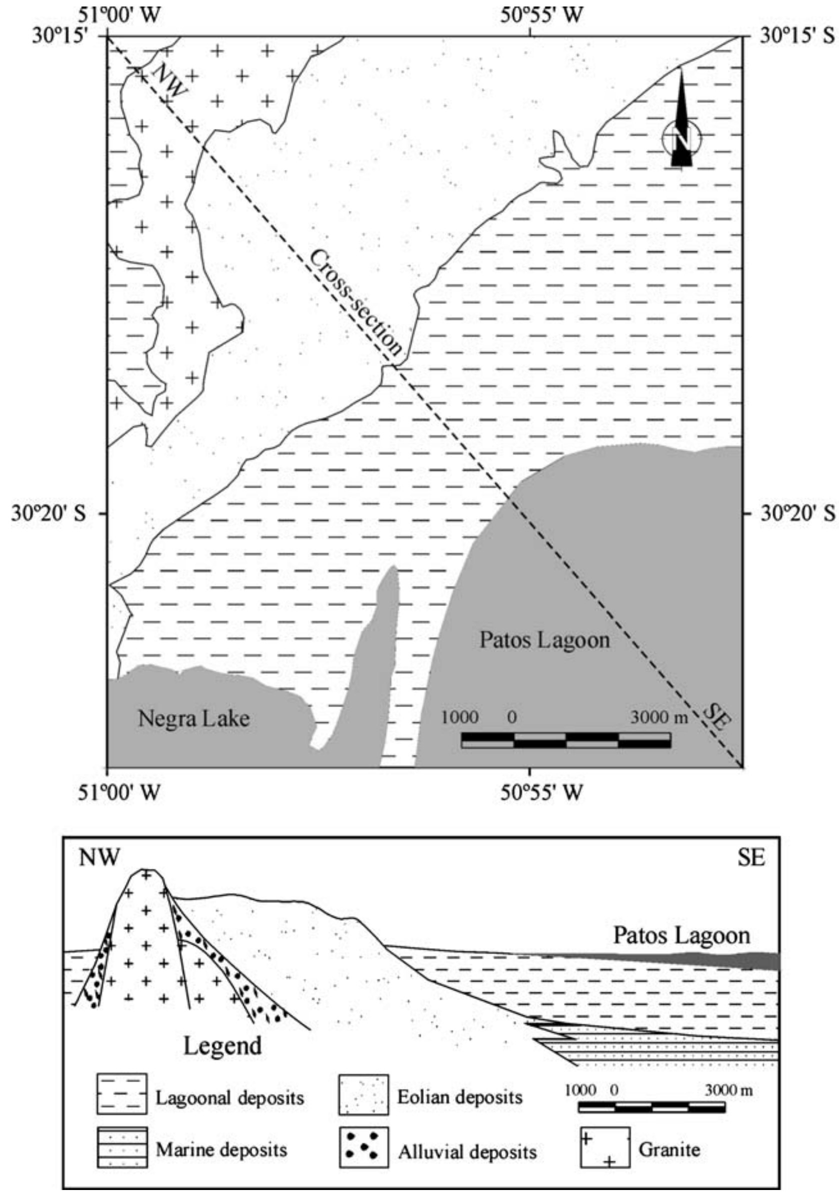

Fig. 2 Hydrogeologic map and cross-section of study area

Table 1 Assigned weights for DRASTIC features (Aller et al. 1987)

Feature	Weight
Depth to water	5
Net recharge	4
Aquifer media	2
Soil media	2
Topography	1
Impact of the vadose zone media	5
Hydraulic conductivity of the aquifer	3

Table 2 Ranges and ratings for depth to water (Aller et al. 1987)

Depth to water (m)	
Range	Rating
0–1.5	10
1.5–4.5	9
4.5–9	7
Weight	5

The textural classification was made in agreement with the system proposed by the Service of Conservation of Soils of the Department of Agriculture of the United States (Soil Conservation Service 1951). Five soils type were described in the area (Fig. 3): peat, fine sand, loamy sand I (rich in clay), loamy sand II (rich in silt) and sandy loam (Herlinger and Viero 2006). Table 3 shows the ratings for soils, according Aller et al. (1987).

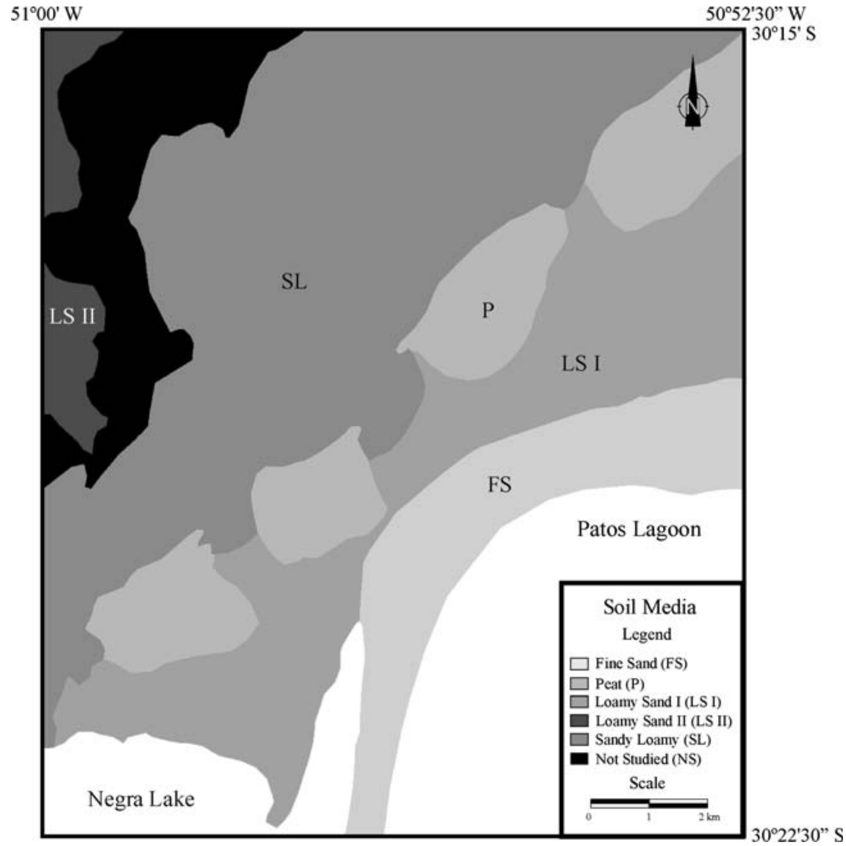

Fig. 3 Soil map

Topography

Topography refers to the slope variability of land surface. Topography helps control the likelihood that a pollutant will run off or remain on the surface in one area long enough to infiltrate.

The slope map was generated from digital elevation model measurements on a base map at a scale of 1:25,000, using the Idrisi Kilimanjaro Software. An extensive plain was observed with slope between 0° and 2° in the areas formed by lagoon deposits. The eolian deposits presented great slope variability. The ratings of slope intervals are presented in Table 4, according to Aller et al. (1987).

Net recharge

The primary source of groundwater is typically precipitation, which infiltrates through the surface and reaches the water table. This recharge water is thus available to transport a contaminant vertically to the water table and horizontally within the aquifer.

The original method considers absolute values for annual recharge. Due to the lack of information, this feature was modified. A procedure was adopted that assesses the relative recharge potential from a combination of slope, soil permeability and rainfall (Piscopo 2001), which are the main processes controlling recharge. The slopes in the study area were derived from the digital elevation model and classified according to criteria given in Table 5. Using the USDA Permeability Key (2005), the soil permeability was classified into three classes: high, moderate to high and moderate (Table 5). The annual average precipitation was about 1,300 mm (Zurita and Tolfo 2000).

Finally, both layers, soils and slope were added together with the annual average rainfall. The recharge potential was then calculated by Eq. 2. The results showed two classes of relative recharge in area: high and very high (Table 5):

$$\text{Recharge value} = \text{slope} + \text{rainfall} + \text{soil permeability} \quad (2)$$

Aquifer media

Aquifer media refers to the consolidated or unconsolidated rock which serves as an aquifer. An aquifer is defined as a subsurface rock unit which will yield sufficient quantities of water for human use. The route and path length which a contaminant must follow are

Table 3 Ranges and ratings for soil media (Aller et al. 1987)

Soil media	
Range	Rating
Fine sand	9
Loamy sand	8
Peat	7
Sandy loam	6
Weight	2

Table 4 Ranges and ratings for topography (Aller et al. 1987)

Topography	
Range	Rating
0–2	10
2–6	9
6–12	5
12–18	3
>18	1
Weight	1

governed by the flow system within the aquifer. The path length is an important control in determining the time available for attenuation processes.

The aquifer media was determined from the wells lithological logs registered in public files. These data indicated that all studied Quaternary aquifers are formed by unconsolidated sands. According to Aller et al. (1987), these aquifer types receive range 8 (Table 6).

Impact of vadose zone media

The vadose zone is defined as that zone above the water table which is unsaturated or discontinuously saturated. The type of vadose zone media determines the attenuation characteristics of the material below the typical soil horizon and above the water table.

The vadose zone media was defined from litologic data of wells and literature. In the plains, the texture of the vadose zone was defined as loamy sands, fine sands and clays underlying the peat soils (Süffert 1998). In eolian deposits the vadose zone is formed mainly by loamy sands. The ratings for vadose zone media are shown in Table 7, according to Aller et al. (1987).

Hydraulic conductivity

Hydraulic conductivity refers to the ability of the aquifer materials to transmit water, which in turn controls the rate at which groundwater will flow under a given hydraulic gradient. The rate at which the groundwater flows also controls the rate at which a contaminant moves away from the point at which it enters the aquifer.

The hydraulic conductivity was defined from field tests and wells data. The average hydraulic conductivity in the eolian deposits was from 2×10^{-2} to 5×10^{-2} m/h. In lagoonal deposits the values were between 5×10^{-2} and 8×10^{-2} m/h. Table 8 shows the weights of the studied values, according to Aller et al. (1987).

Adsorption capacity of soils

In this study, data of adsorption capacity of soils of sulfate, phosphate, lead and copper were used. The area soils had variable adsorptive capacity for the different ions (Herlinger and Viero 2006). Lead had the largest value in all soil units. Sulfate had values close to zero, while copper and phosphate showed intermediate values (Table 9).

Considering the influence of adsorption in mobility of pollutants, in this work was defined the feature adsorption, with weight equal to five. Equation 1 was modified and Eq. 3 was established. The minimum value of adsorption was close to zero and the maximum was 18.43 mmol/g. Considering the distribution of the results, the ratings shown in Table 10 were established,

$$\mathrm{DI} = D_R D_W + R_R R_W + A_R A_W + S_R S_W + T_R T_W + I_R I_W + C_R C_W + N_R N_W, \quad (3)$$

where N is adsorption.

Table 5 The recharge ratings and weightings for the study area (Piscopo 2001)

Recharge							
Slope		Rainfall		Soil permeability[a]		Recharge value	
Slope (%)	Factor	Rain (mm)	Factor	Range	Factor	Range	Rating
<2	4	>850	4	High	5	9–11 (very high)	8
2–10	3			Moderate–high	4	7–9 (high)	5
10–33	2			Moderate	3		
Weight							2

[a] Soil permeability is based on USDA (2005)

Table 6 Ranges and ratings for aquifer media (Aller et al. 1987)

Aquifer media	
Range	Rating
Sands	8
Weight	3

Table 7 Ranges and ratings for impact of vadose zone media (Aller et al. 1987)

Impact of vadose zone media	
Range	Rating
Fine sand	9
Loamy sand	8
Clay	1
Weight	4

Table 8 Ranges and ratings for hydraulic conductivity (Aller et al. 1987)

Hydraulic conductivity (m/h)	
Range	Rating
2×10^{-2} to 5×10^{-2}	4
5×10^{-2} to 8×10^{-2}	6
Weight	3

GIS model

A geographic information system (GIS) is a tool that allows the user to handle large amounts of spatially distributed data by combining a database management system with digital mapping. The ability to analyze and manipulate data in spatial and tabular form makes GIS more powerful than traditional tabular data systems (Lanfear 1989). To perform the groundwater vulnerability assessment within the Idrisi Kilimanjaro Software, a number of individual database files, or map layers, were constructed: topography, soils, depth to water, impact of vadose zone media, aquifer media, net recharge, hydraulic conductivity and adsorption capacity of soils. Each map layer was geocoded and sampled with identical geographic boundaries and spatial cell (pixel) resolution (1 m^2) to facilitate overlay and combination of the layers.

Table 9 Average adsorption of soil units from the study area (Herlinger and Viero 2006)

Soil unit	Average adsorption (mmol/g)			
	PO_4^{3-}	SO_4^{2-}	Cu^{2+}	Pb^{2+}
Sandy loam	6.03	0.14	6.14	11.66
Fine sand	0.11	0.00	4.09	7.83
Loamy sand I	0.00	0.00	3.91	8.03
Loamy sand II	5.47	1.25	4.54	11.29
Peat	3.16	0.00	16.22	18.43

Table 10 Ranges and ratings for adsorption

Adsorption (mmol/g)	
Range	Rating
0–4	10
4–8	7
8–12	5
12–16	3
>16	1
Weight	5

Results

The resulting DRASTIC values calculated using Eq. 1 in this application were between 146 and 203. As the minimum possible DRASTIC index using this equation is 23 and the maximum is 230, this range was divided into seven equal classes. These classes were: (a) 23–55 (no risk), (b) 56–85 (very low), (c) 86–115 (low), (d) 116–143 (moderate), (e) 144–173 (high), (f) 174–202 (very high) and 203–230 (extreme).

The calculated range was ranked based on the classification above as high, very high and extreme as shown in Fig. 4 and Table 11. Table 11 shows that 54.3% of the study area had a high, 35.5% had a very high and 12.2% had an extreme groundwater vulnerability to contamination.

Using Eq. 3, four vulnerability maps were completed, each one considering a specific ion. As the minimum possible DRASTIC index using this equation is 28 and the maximum is 280, this range was divided into seven equal classes. These classes were: (a) 28–64 (no risk), (b) 65–100 (very low), (c) 101–136 (low), (d) 137–172 (moderate), (e) 173–208 (high), (f) 209–244 (very high) and 245–280 (extreme). The groundwater vulnerability to lead, copper, phosphate and sulfate are shown in Figs. 5, 6, 7 and 8, and Table 11 summarizes the area extension for each class of groundwater vulnerability.

Discussion

In this paper, the groundwater vulnerability of a pilot area from the Coastal Plain of The Rio Grande do Sul State, Brazil was assessed employing the DRASTIC method. Eight parameters were used to represent the natural hydrogeological setting: Depth to water table, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone media, hydraulic Conductivity and adsorption capacity of soil. The groundwater vulnerability to pollution using the DRASTIC original

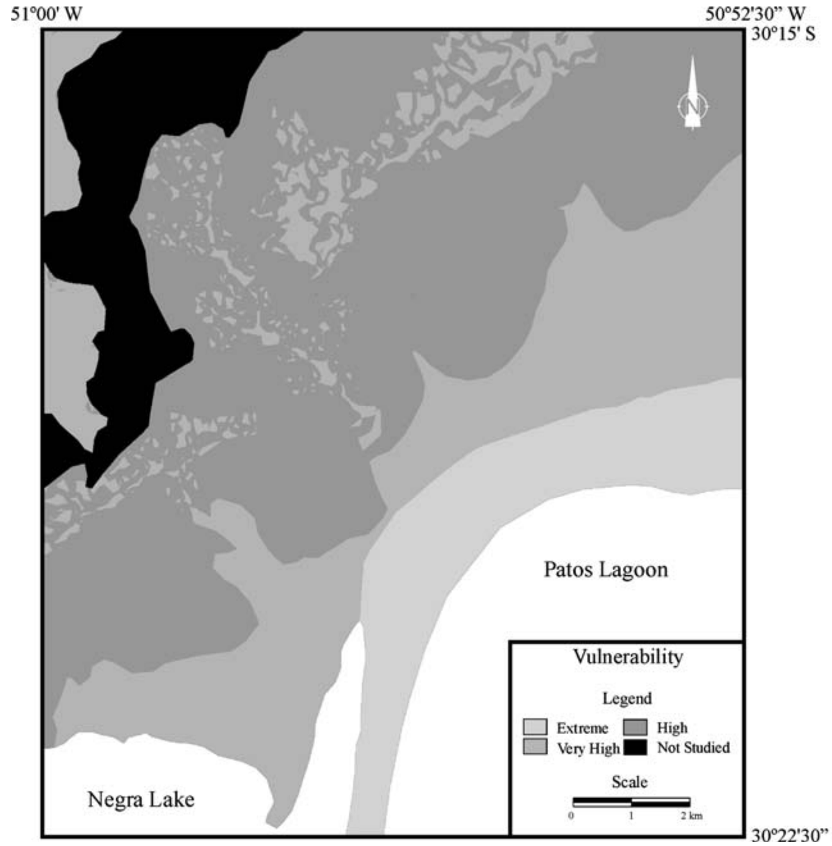

Fig. 4 Groundwater vulnerability map

Table 11 Vulnerability considering the original method and the adapted method

Vulnerability	DRASTIC		DRASTIC–lead		DRASTIC–copper		DRASTIC–phosphate		DRASTIC–sulfate	
	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)
Moderate	–	–	33.3	55.30	16.2	26.93	–	–	–	–
High	54.3	90.27	27.4	45.51	36.1	59.95	38.80	64.41	17.8	29.52
Very high	33.5	55.63	39.3	65.33	34.9	57.92	48.90	81.24	69.9	116.13
Extreme	12.2	20.25	–	–	12.8	21.34	12.30	20.49	12.3	20.49

method indicated high values, mainly due to the sandy texture of the sedimentary deposits, which favors the accessibility of the pollutants to the saturated zone. Besides, the low depths of the waters contribute in an expressive way to the groundwater vulnerability.

The contamination vulnerability maps made with the adsorption parameter indicated significant difference between ions, due to the characteristics of the soils and of the pollutants. The heavy metals, copper and lead, presented high adsorption, mainly in peat soil. The sulfate and phosphate, on the other hand, are not strongly adsorbed by organic matter. The original DRASTIC method considers only the access of the precipitation water to the aquifer. The peat presents high permeability. However, its content of organic matter generates favorable conditions for heavy metals adsorption. To ions with high mobility, the original method shows representative results because the pollutants tend to remain dissolved in the liquid phase. However, to heavy metals, the results of the original DRASTIC method must be used carefully.

Due to high vulnerability when a development application is being prepared, it is important that the impact of the development, on surface and groundwater resources, is assessed. Also the knowledge of these resources and the current groundwater quality is relevant for developers. The potential polluting of groundwater developments should not be allowed within highly vulnerable areas. Where such activities are proposed, significant engineering measures would be necessary to minimize the risks of pollution.

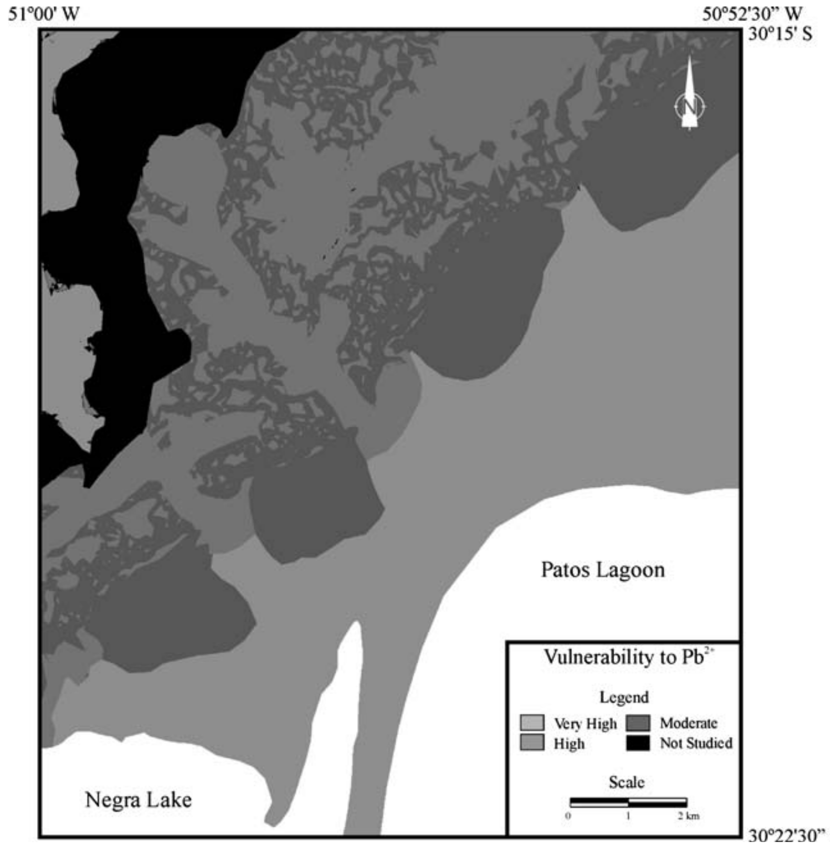

Fig. 5 Groundwater vulnerability to lead map

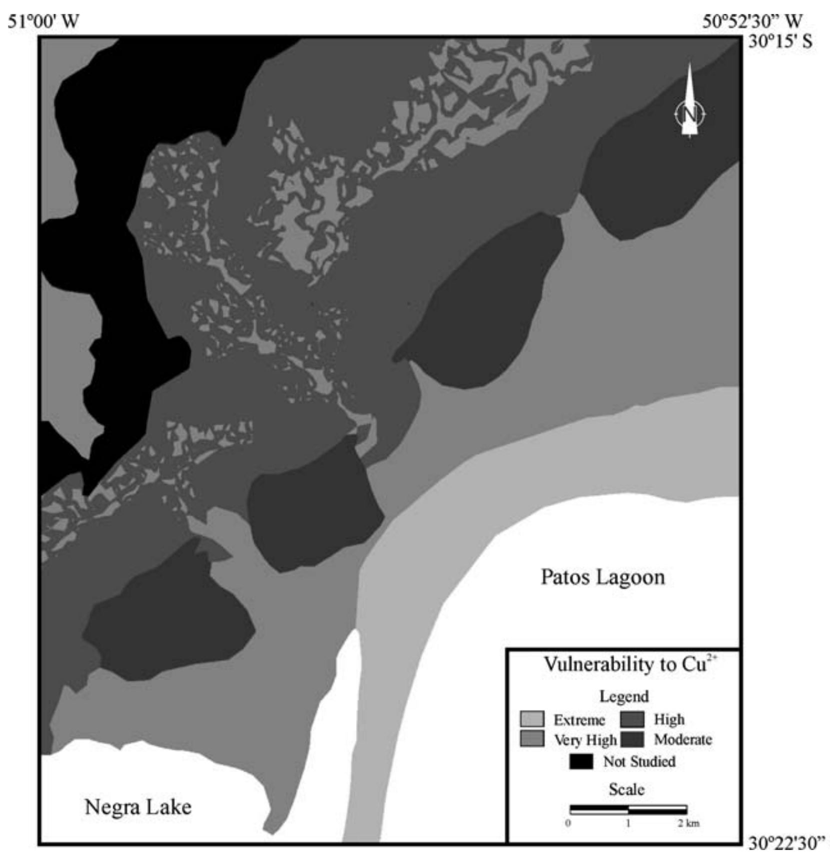

Fig. 6 Groundwater vulnerability to copper map

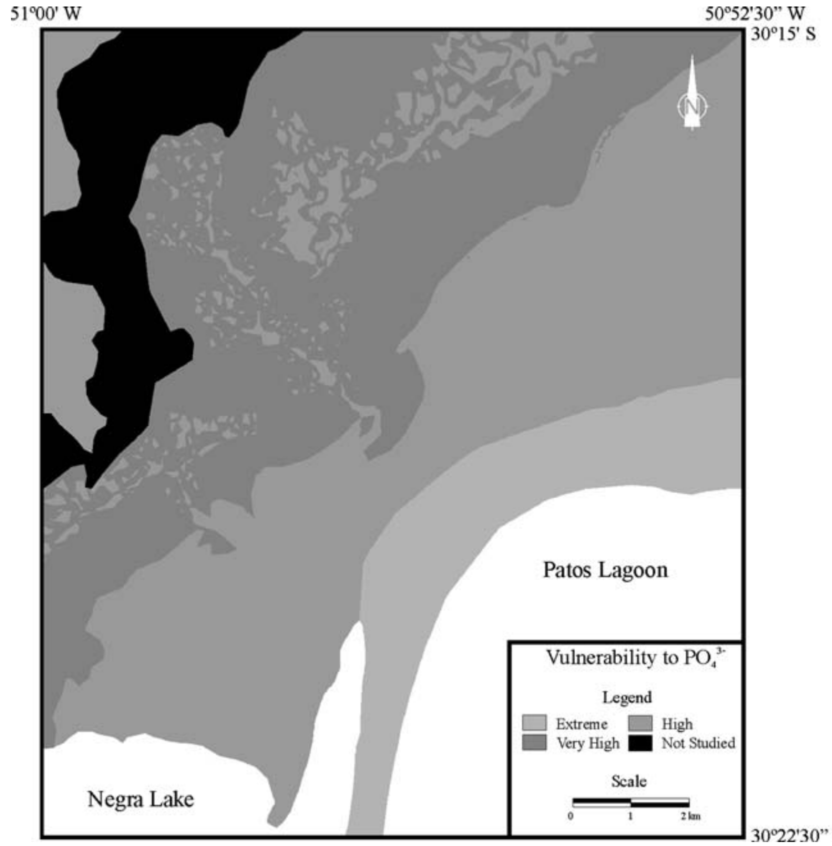

Fig. 7 Groundwater vulnerability to phosphate map

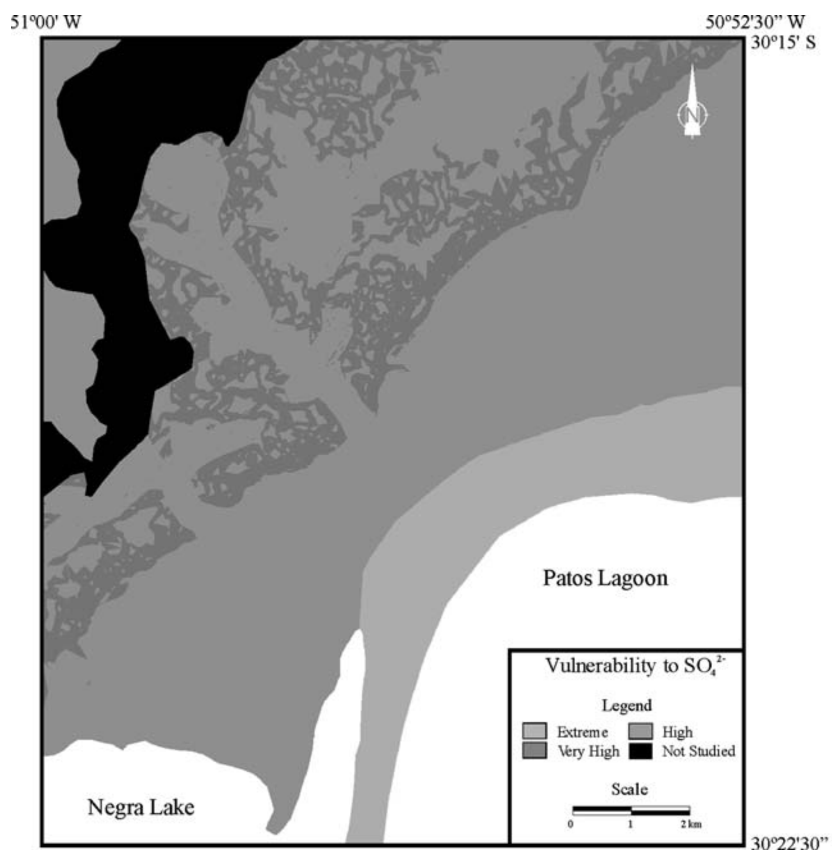

Fig. 8 Groundwater vulnerability to sulfate map

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