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Aquifer vulnerability to pollution: a methodological review

Vulnerabilidade de aquíferos à poluição: uma revisão metodológica

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Abstract: Groundwater 60iferente6060 the largest volume of fresh water available on planet Earth, therefore, it is considered to be na essential resource for humanity's water supply. However, the advance of civilization has contributed to the pollution of aquifers, which has increased the necessity for the remediation and preservation of these systems. Hence, since the 1960s, researchers have been studying the 60iferente60 the vulnerability of aquifers, which has led to na understanding that the degree of vulnerability of na aquifer is associated with a set of physical, 60iferent and biological characteristics of the unsaturated zone and/or from the confining aquitard, which control the arrival of contaminants into the underground system. Simultaneously, delving into this study has been possible thanks to the mathematical approach that has been adopted, enabling the development of cartographic methodologies which delimit vulnerability classes, such as COP, DRASTIC, GOD and AVI. Despite that, these methodologies use formulations with 60iferente physical and geological criteria, resulting in 60iferente maps for the same study 60ife. Considering this particularity, the 60iferent study proposes to introduce a methodological review of the four above-mentioned methodologies, aiming to designate their most appropriate uses in 60iferente geological and geographic environments.

Keywords: Mathematical methods; Methodological review; Vulnerability**.**

Resumo: As águas subterrâneas representam o maior volume de água doce disponível do planeta Terra, por isso, são consideradas um recurso indispensável para o abastecimento humano. Todavia, o avanço da civilização contribuiu para a poluição dos aquíferos, o que ampliou a necessidade de remediação e preservação desses sistemas. Devido a isso, pesquisadores estudam, desde a década de 60, o conceito de vulnerabilidade de aquíferos, proporcinando recentemente o entendimento que o grau de vulnerabilidade de um aquífero está associado a um conjunto de características físicas, químicas e biológicas da zona não saturada e/ou do aquitarde confinante, que controlam a chegada de contaminantes ao sistema subterrâneo. Concomitantemente, o aprofundamento desse estudo foi possível graças ao viés matemáticos adotado, possibilitando o desenvolvimento de metodologias cartográficas que delimitam classes de vulnerabilidade, como o COP, o DRASTIC, o GOD e o AVI. No entanto, essas metodologias utilizam formulações com diferentes critérios físicos e geológicos, resultando em mapas distintos para uma mesma área de estudo. Considerando essa particularidade, este trabalho propõe apresentar a revisão bibliográfica das quatro metodologias citadas, visando indicar a melhor empregabilidade destas metodologias frente aos distintos ambientes geológicos e geográficos.

Palavras-chave: Métodos matemáticos; Revisão bibliográfica; Vulnerabilidade.

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1. Introduction

Groundwater is the largest volume of freshwater available on planet Earth, representing about 10.3 million km³, while lakes and rivers, occupying the second position, accumulate only about 104 thousand km³. In addition, aquifers are susceptible to hierarchy when compared to surface springs, which makes them indispensable for the water supply of homes and manufacturing sectors (BABIKER *et al.*, 2005; REBOUÇAS, 2008).

However, due to the advance of civilization, the indiscriminate environmental pollution and its consequent impact on aquifers, it has become a topic of discussion for environmental researchers and governing authorities, promoting studies and the understanding that groundwater pollution often causes irreversible impacts on the ecosystem (BABIKER *et al*., 2005).

Groundwater pollution can have different origins, yet the most common are related to industrial, domestic, and agricultural activities. The first activity can contaminate aquifers through the disposal of chemical compounds, metals, radioactive elements, leachate, and chemical manufacturing accidents. The second one can pollute through leachate from landfills and garbage, also accidents with septic tanks in sewer systems. Finally, the third activity can pollute through solutes dissolved by rain or irrigation, fertilizers, and pesticides (HIRATA; FERNANDES, 2008).

As aquifer remediation is often expensive and impractical, further studies on the vulnerability and preservation of these systems have become essential, enabling the development of concepts on the subject from studies such as Le Grand (1964), Albinet & Margat (1970), Taltasse (1972), Aller et al. (1987), Bachmat & Collin (1987), Foster & Hirata (1988), VRBA & Zaporozec (1994), Hirata & Fernandes (2008), Cutrim & Campos (2010); and Yu & Michael (2019).

Using definitions proposed by Cutrim & Campos (2010), it is possible to understand that the intrinsic vulnerability of an aquifer is related to the set of physical, chemical and biological characteristics of the unsaturated zone of the system and/or the confining aquitard, which control the arrival of contaminants to the system. The specific vulnerability is related to extrinsic factors, such as a load or a contaminating activity.

One of the methods allied to this study is aquifer vulnerability mapping, which was initially investigated by Le Grand (1964), Seller & Canter (1980), and Cartel *et al*. (1987). Vulnerability mapping is a preventive tool capable of distinguishing the zones of the vulnerability of an aquifer, which enables the analysis of its natural protection ability (HIRATA; FERNANDES, 2008).

Due to technological advances, vulnerability mapping was associated with geoprocessing techniques implemented in Geographic Information System (GIS). This achievement has expanded the capacity for spatial analysis, resulting in reduced work time and increased information accuracy (PAULA; SOUZA, 2011).

Over time, many methods of vulnerability mapping were developed, however, their equations were based on different physical and geological criteria. Because of this, when the same area is studied by different cartographic methods, the maps obtained show zones of different vulnerability.

Considering this particularity, the present study proposes to introduce a methodological review of four methods used in vulnerability mapping, that are, DRASTIC (ALLER *et al*., 1987), GOD (FOSTER; HIRATA, 1988), COP (VÍAS *et al*., 2002; 2006) and AVI (STEMPVOORT *et al*., 1992), aiming to designate their most appropriate use in different geological and geographic environments

2. Methodology

2.1 The COP method

Developed by Viás *et al*. (2002; 2006) based on the premises of the European COST Action 620, the COP method was initially designed for regions with a semi-arid climate, especially in places with low rainfall, in order to assess the vulnerability of karst aquifers (ZWHALEN, 2003; ABDULLAH *et al*., 2020). However, due to its satisfactory results, it has been used in many countries, such as Africa, Cuba, China, Germany, Slovenia, France, Italy, Portugal, and Brazil (NOSSA, 2011).

According to Viás *et al.* (2006) and Nossa (2011), the COP method uses in its calculations three variables with equal weights: (C) concentration of flow, (O) overlying layers and (P) precipitation.

The factor C corresponds to the intensity in which rainwater crosses the unsaturated zone and infiltrates the interior of karst cavities. Thus, this variable represents the influence of infiltration on the vulnerability of an aquifer. This factor is linked to two possible scenarios:

Scenario 1: Situation in which the recharge zones are covered by thin layers of low permeability or are outcropping, favoring concentrated infiltration and resulting in a flow that easily penetrates through the unsaturated zone. The factor (C), in this case, is represented by four variables: the distance from the recharge area to the swallow hole (dh) and to the sinking stream (ds), and the influence of slope (s) and vegetation (v). The slope is subdivided into four classes associated with the presence or absence of vegetation cover, originating the sub-parameter (sv). Factor C is calculated by the expression:

$$\textit{Factor (C)} = sv \times ds \text{ ou } sv \times dh$$

Scenario 2: Situation in which recharge occurs from diffuse infiltration. Factor (C) is subdivided into three factors: surface features (sf), slope (s), and vegetation (v). The surface features (sf) include specific geomorphological forms of carbonate rocks and the presence or absence of overlaying layers, which influence the process of runoff and/or infiltration. Slope and vegetation enter as correlated parameters (sv). The equation to Factor (C) is:

$$\textit{Factor (C)} = sv \times sf$$

The factor O corresponds to the intrinsic protection of the aquifer, which is represented by the texture, lithology and thickness of the layers above the saturated zone. This factor considers that the contaminant attenuation capacity increases proportionally with the increase of the protective layers. To calculate the factor (O), the soil [OS] and lithology [OL] subfactors are applied.

$$\textit{Factor } O = [Os] + [OL]$$

The P factor represents precipitation and the variables that influence the infiltration rate, such as frequency, temporal distribution, duration and intensity of rainfall. These variables determine the role of precipitation in the transport of contaminants from the surface to the aquifer, in which the greater the contaminant transport capacity, the greater the vulnerability of the aquifer. The factor (P) is represented by two subfactors: quantity of precipitation [PQ] and temporal distribution of precipitation [PI].

$$\textit{Factor } P = [Pq] + [PI]$$

Finally, the COP index is calculated by the equation:

$$\textit{COP Indéx} = \textit{Factor } C \times \textit{Factor } O \times \textit{Factor } P$$

Vulnerability classes and values adopted for each factor are presented in Tables 1 and 2.

Table 1 – Vulnerability classes according to the COP method.

Factor C	**Reduction of protection**
0 - 0.2	Very High
0.2 - 0.4	High
0.4 - 0.6	Moderate
0.6 - 0.8	Low
0.8 - 1.0	Very Low
Factor O	**Protection value**
1	Very Low
2	Low
2 - 4	Moderate
4 - 8	High
8 - 12	Very High
Factor P	**Reduction of protection**
0.4 - 0.5	Very High
0.6	High
0.7	Moderate
0.8	Low
0.9 - 1.0	Very Low
COP Indéx	**Vulnerability classes**
0 - 0.5	Very High
0.5 - 1.0	High
1.0 - 2.0	Moderate
2.0 - 4.0	Low

Source: Viás et al. (2006).

Table 2 – Assigned values for each COP method subfactor. Source: Viás et al. (2006).

Factor	Subfactor	Variable	Value	Value
C	Scenario 1: swallow hole recharge area (karst cavities)	Distance to swallow hole (dh)	<500 m	0,0
			500 -1000m	0,1
			1000-1500m	0,2
			1500-2000m	0,3
			2000-2500m	0,4
			2500-3000m	0,5
			3000-3050m	0,6
			3500-4000m	0,7
			4000-4500m	0,8
			4500-5000m	0,9
			>5000m	1,0
		Distance to sinking stream (ds)	<10m	0,0
			10-100m	0,5
			>100m	1,0
		Slope and Vegetation (sv)	≤8%	1,0
			8-31%, high	0,95
			8-31%, low or absent	0,90
			31-76%, high	0,85
			31-76% low or absent	0,80
			>76%	0,75
	Scenario 2: rest of the aquifer area	Karstic features and surface features (sf)	Developed karst, absent	0,25
			Developed karst, permeable	0,50
			Developed karst, impermeable	0,75
			Scarcely developed, absent	0,50
			Scarcely developed, permeable	0,75
			Scarcely developed, impermeable	1,0
			Fissured carbonate, absent	0,75
			Fissured carbonate, permeable	0,75
			Fissured carbonate, impermeable	1,0
			Non karstic terrains, absent	1,0
			Non karstic terrains, permeable	1,0
			Non karstic terrains, impermeable	1,0
		Slope and Vegetation (sv)	≤8%	0,75
			8-31%, high	0,80
			8-31%, low or absent	0,85
			31-76%, high	0,90
			31-76%, low or absent	0,95
O	Soil [Os]	Texture and thickness	Clayey, >1,0m	5,0
			Clayey, 0,5 - 1,0m	4,0
			Clayey, <0,5m	3,0
			Silty, >1,0m	4,0
			Silty, 0,5- 1,0m	3,0
			Silty, <0,5m	2,0
			Loam, >1,0m	3,0
			Loam, 0,5-1,0m	2,0
			Loam, <0,5m	1,0
			Sandy, >1,0m	2,0
			Sandy, 0,5-1,0m	1,0
			Sandy, <0,5m	0,0
	Lithology [OL]	Lithology and fracturation (ly)	Clays	1500
			Silts	1200
			Metapelites and igneous rocks	1000
			Marly limestones	500
			Fissured metapelites and igneous rocks	400
			Cemented or non-fissured conglomerates and breccias	100
			Sandstones	60
			Scarcely cemented or fissured conglomerates and breccias	40
			Sands and gravels	10
			Permeable basalts	5
			Fissured carbonated rocks	3
			Karstic rocks	1
		Confining conditions (cn)	Confined	2,0
			Semi-confined	1,5
			Unconfined	1,0
		Thickness of each layer (m)	<250m	1
			250-1.000m	2
			1.000-2.500m	3
			2.500-10.000m	4
			>10.000m	5
P	Quantity [Pq]	Average rainfall for wet years	>1600 mm/year	0,4
			>1200 e ≤1600 mm/year	0,3
			>800 e ≤1200 mm/year	0,2
			>400 e ≤ 800 mm/year	0,3
			<400 mm/year	0,4
	Intensity [Pi]	Temporal distribution	<10 mm/day	0,6
			≥10 e ≤ 20 mm/day	0,4
			>20 mm/ day	0,2

2.2 The DRASTIC method

Developed at the US Environmental Protection Agency by Aller *et al.* (1987), the DRASTIC method is a tool that assesses the vulnerability of aquifers with various hydrogeological configurations and is widely used in detail mapping (THIRUMALAIVASAN *et al*., 2003).

This method uses seven variables called sub-index i: **D,** depth to water table in meters; **R,** net recharge in mm/year; **A**, aquifer type media; **S,** soil properties media; **T,** topography; **I,** impact of vadose zone; and, **C,** aquifer hydraulic conductivity in cm/sec (THIRUMALAIVASAN *et al*., 2003), described in Table 3.

Aller *et al*. (1987) has assigned values for each sub-index through mathematical calculations, as shown in Table 4. Besides, the method uses a weight system called sub-index p, in which the higher the i sub-index, the greater is its relevance (Table 3).

Table 3 – Assigned weights for each DRASTIC method sub-index i.

Factor	Description	Weight
Depth to water table	It is the depth between the ground surface and the saturated zone. As the depth to water increases, the chances of contamination get lower.	5
Net recharge	It is the amount of rainwater that infiltrates through the ground surface and percolates to the water table. The net recharge represents the vehicle for the transportation of contaminants.	4
Aquifer type	It refers to the material properties of the saturated zone, which controls the attenuation of pollution processes.	3
Soil media	It represents the uppermost portion of the vadose zone, and it controls the volume of the aquifer recharge.	2
Topography	It represents the slope of the land surface. Also, it controls the probability that the contaminant will remain or runoff into the saturated zone.	1
Impact of vadose zone	It is defined as the vadose zone’s material. It controls the passage and the attenuation of the contaminants to the vadose zone.	5
Hydraulic conductivity	It indicates the ability of the aquifer to transmit water. Consequently, it controls the rate at which groundwater flows in the system.	3

Source: Aller et al. (1987).

Finally, the degree of vulnerability of an aquifer is obtained from the equation below and is grouped into vulnerability classes ranging from low to very high (Table 4).

Drastic=D_i D_p+R_i R_p+A_i A_p+S_i S_p+T_i T_p+I_i I_p+C_i C_p

Table 4 – Assigned sub-index weights and classification of vulnerability according to the DRASTIC method.

Depth to water	**Rating**	**Weight**
0 - 1.5	10	5
1.5 - 4.5	9	
4.5 - 9	7	
9 -15	5	
15 - 22.5	3	
2.5 – 30	2	
>30	1	
Net Recharge	**Rating**	**Weight**
<51	1	4
51 -102	3	
102 - 178	6	
178 - 254	8	
> 254	9	
Lithotype	**Rating**	**Weight**
Massive Shale	1 – 3	3
Metamorphic/Igneous	2 – 5	
Weathered Metamorphic/Igneous	3 – 5	
Till	4 – 6	
Bedded Sandstones, Limestones, Shale Sequences	5 – 9	
Massive Sandstone	4 – 9	
Massive Limestone	4 – 9	
Sand and Gravel	4 – 9	
Basalt	2 – 10	
Karst Limestone	9 – 10	
Soil type	**Rating**	**Weight**
Thin or Absent	10	2
Gravel	10	
Sand	9	
Peaty	8	
Shrinking and/or Aggregated Clay	7	
Sandy Loam	6	
Loam	5	
Clay Loam	3	
Garbage, manure	2	
Nonshrinking and Nonaggregared Clay	1	

Hydraulic Conductivity	**Rating**	**Weight**
40.7 – 81.5	8	3
4.1 – 12.2	2	
28.5 – 40.7	6	
12.2 – 28.5	4	
0 -4.1	1	
>81.5	10	
Topography	**Rating**	**Weight**
0 -1	10	1
1 – 6	9	
6 – 12	5	
12 – 18	3	
18	1	
Vadose Zone	**Rating**	**Weight**
Confined layer	1	5
Silt/ Clay	2-6	
Shale	2-5	
Limestone	2-7	
Sandstone	4-8	
Bedded Limestone, Sandstone, Shale, Sand	4-8	
Sand and Gravel with significant Silt and Clay	4-8	
Metamorphic/ Igneous	2-8	
Sand and Gravel	6-9	
Basalt	2-8	
Karst Limestone	8-10	

Source: Adapted from Aller et al. (1987).

2.3 The AVI method

Developed by Stempvoort *et al*. (1992) at the National Hydrological Research Institute of Canada (NHRI), the AVI (Aquifer Vulnerability Index) method is responsible for assessing the vulnerability of aquifers in a simple way, due to the use of few parameters in their mathematical calculations (SANTOS; PEREIRA, 2011).

The main index considered is the hydraulic resistance (C), which reflects the resistance of the vadose zone to vertical flow, that is, the time it takes for contaminants to cross the unsaturated zone (BUSICO et al., 2019). Factor C is obtained by dividing the hydraulic conductivity [D*i*] and sedimentary layer thickness (K*i*) subfactors.

The D*i* factor, named hydraulic conductivity, represents the groundwater flow rate in the system, expressing the velocity at which contaminants move through the aquifer. Thus, the higher the Di of an area, the greater the transport of contaminants, which favors the higher vulnerability of an aquifer (BUSICO *et al*., 2019).

The K*i* factor represents the thickness of the system's sedimentary layer, in which it is considered that higher values of layer thicknesses favor the dilution of contaminants to the aquifer, providing a lower vulnerability of the system. As well as the opposite scenario (ZHONG, 2005).

Lastly, the degree of vulnerability of an aquifer is obtained through the equation below and is grouped into vulnerability classes ranging from low to very high, as shown in tables 5 and 6.

$$C = \sum \boldsymbol{D_i} \,/\, \boldsymbol{K_i}$$

Table 5 – Hydraulic conductivity classes of AVI method.

Hydraulic Conductivity	
Class	Value (m/day)
Low	0,07
Moderately low	0,31
Moderate	1,00
Moderately high	2,25
High	3,75
Very High	5,00

Source: Van stempvoort et al. (1992).

Table 6 – Vulnerability classes of AVI method.

Hydraulic Resistance (days)	**Vulnerability Class**
0-10	Very high
10-100	High
100-1.000	Moderate

Source: Van stempvoort et al. (1992).

2.4 The GOD method

The GOD method, developed in the United Kingdom by Foster (1987), is a tool that assesses the vulnerability of aquifers in a basic way, due to the use of few variables in the mathematical calculations (RIBEIRO et al., 2001; ONI et al., 2017).

In its equation, the method uses three variables with equal weights called sub-index i, namely: Type of Aquifer (G); Lithology and Degree of Consolidation of the Vadose Zone or Confining Layers (O); and Depth to the water table or the confining base of the aquifer (D) (RIBEIRO et al., 2011; GUETTAIA et al., 2017; MFONKA et al., 2018).

The G factor, which corresponds to the type of aquifer, is classified as free, semi-confined or confined. Each type of aquifer influences the number of contaminants coming from the surface capable to penetrate the water table (CUTRIM & CAMPOS, 2010).

Factor O corresponds to the lithology and degree of consolidation of the vadose zone. It influences the transmissivity of contaminants to the aquifer and is intrinsically associated with variations in porosity and/or permeability of rocks. In this regard, Cutrim & Campos (2010) explain that a coarse-grained rock has a lower capacity to attenuate contaminants when compared to a fine-grained rock.

Factor D corresponds to the depth to groundwater level, thus, it also represents the depth that the contaminant will have to travel to reach the saturated zone of the aquifer (CUTRIM; CAMPOS, 2010).

Finally, the degree of vulnerability of an aquifer is obtained through the equation below and is grouped into vulnerability classes, which range from negligible to extreme, as shown in Figure 1 and Table 7.

$$\boldsymbol{GOD = Gi * Oi * D}$$

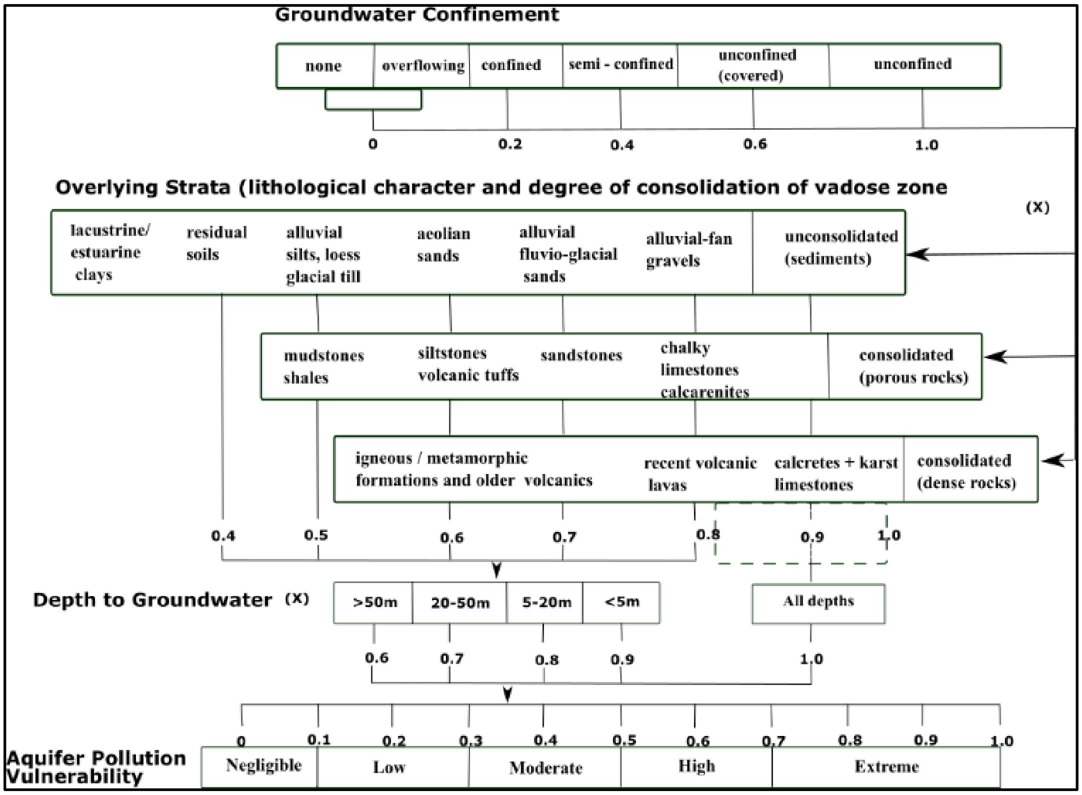

Figure 1 – Vulnerability classes of GOD method.
Source: Adapted from Foster (1987).

Table 7 – Vulnerability classes of GOD method.

Vulnerability Class	Definition
Extreme	Vulnerable to most water pollutants with rapid impact in many pollution scenarios.
High	Vulnerable to many pollutants, except those strongly absorbed or readily transformed.
Moderate	Vulnerable to some pollutants but only when continuously discharged or leached.
Low	Only vulnerable to conservative pollutants in the long term when continuously and widely discharged or leached.
Negligible	Confining beds present with no significant vertical groundwater flow (leakage).

Source: Foster (1987).

3. Results and discussion

To establish comparisons between the presented methods, the works from Vías *et al.* (2006), Kazakis & Voudouris (2011), Fraga *et al.* (2013), and Putranto & Yusrizal (2018) were used.

Viás *et al*. (2006) used the four methods (COP, DRASTIC, AVI, and GOD) to study the vulnerability of two karst aquifers, the Sierra de Líbar and the Torremolinos, in southern Spain. Regarding lithology, the first aquifer is mainly constituted by Jurassic karstified limestone, and the second is constituted by less karstified Triassic marble.

From the cartographic results (Figures 2 and 3), it was concluded that the map obtained through the COP method showed more delimitation of vulnerability classes than the other methods. This happened because COP uses specific variables for karstic aquifers, enabling more satisfactory results in this type of system. However, due to this specificity, its use was not recommended for other types of aquifers. In addition, this method is based on eight variables, therefore, requires a voluminous database, and is normally used on a detailed scale.

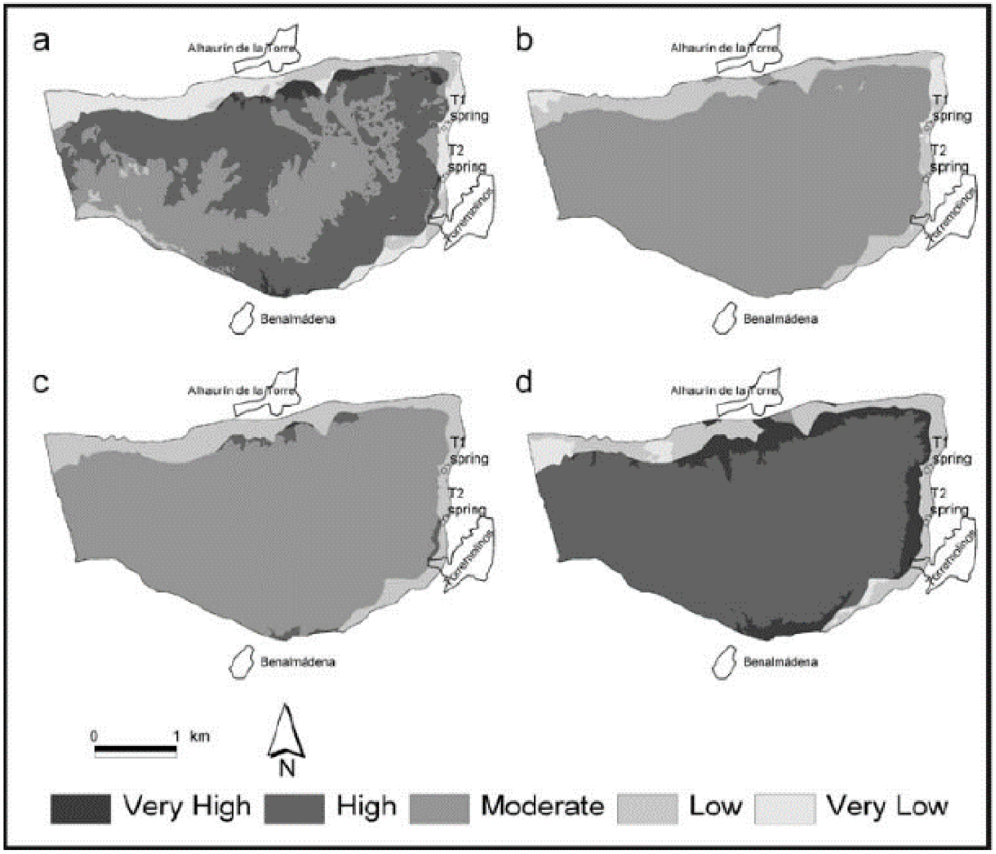

Figure 2 – Vulnerability maps of Torremolinos from COP (a), DRASTIC (b), GOD (c) and AVI (d) methods. Source: Viás et al. (2006)

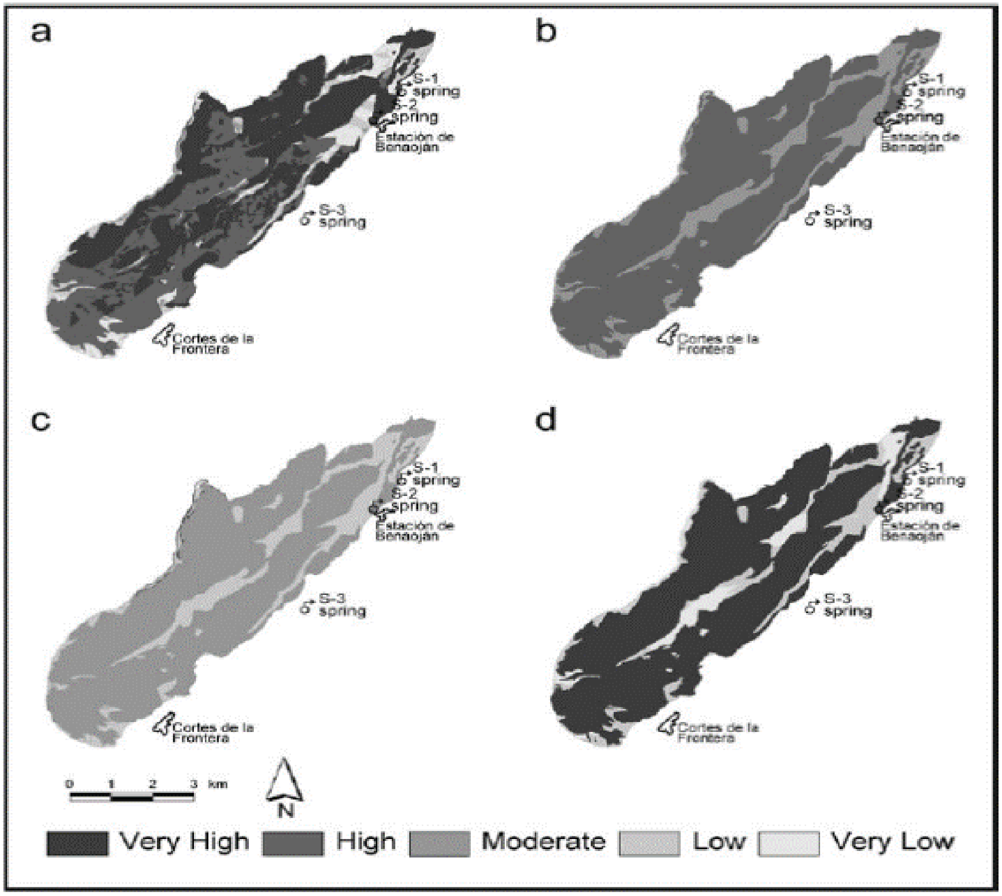

Figure 3 – Vulnerability maps of Sierra de Líbar from COP (a), DRASTIC (b), GOD (c) and AVI (d) methods. Source: Viás et al. (2006).

Fraga *et al*. (2013) used the DRASTIC, AVI, and GOD methods to study the vulnerability of the Sôrdo river basin in Portugal. This basin is mainly constituted by Paleoproterozoic metasediments, covered by alluvial sediments.

From the cartographic results (Figure 4), it was concluded that the map obtained through the DRASTIC method showed more vulnerability class delimitations than the other methods. Such results may be associated with its equation, which is supported by seven variables, that also guarantee greater reliability of results.

Furthermore, Fraga *et al.* (2013) suggest that because it is a method that requires a voluminous database, it is more suitable for detailed scale studies and data availability.

The disadvantages of this method, according to Putranto & Yusrizal (2018), are: *i.* the adopted weight system, considered as a subjective mathematical calculation; *ii.* the difficulty to calculate groundwater recharge, as this variable requires information about evapotranspiration, rainfall, and water runoff; *iii.* doubt about the need to use the topographic parameter in the calculations, since it is not an influential variable in the final result.

The map obtained through the GOD method showed intermediate vulnerability class delimitations when compared to the other maps (Figure 4). This result reflects the simplicity of the math equation, which uses only three variables in its calculation. Because of this, GOD can be adopted for rapid vulnerability diagnoses, urgent environmental decisions, and for regional scales that need little detail.

The disadvantage of the GOD method, according to Putranto & Yusrizal (2018), relies on the fact that it is based only on three parameters, which limits the definition of vulnerability classes, resulting in lower reliability of results.

Finally, the AVI method showed the smallest delimitation of vulnerability classes when compared to the other maps (Figure 4), therefore it is considered the least effective and realistic of the three tools. On the other hand, due to the simplicity of its calculations, which considers only two variables, it was recognized as a tool capable of offering quick diagnoses regarding the vulnerability of an area, which can be used for urgent environmental decisions and for regional scales.

However, according to Putranto & Yusrizal (2018), this method is able to demonstrate a better variation of hydraulic resistance in the results, precisely because it is based exclusively on physical variables.

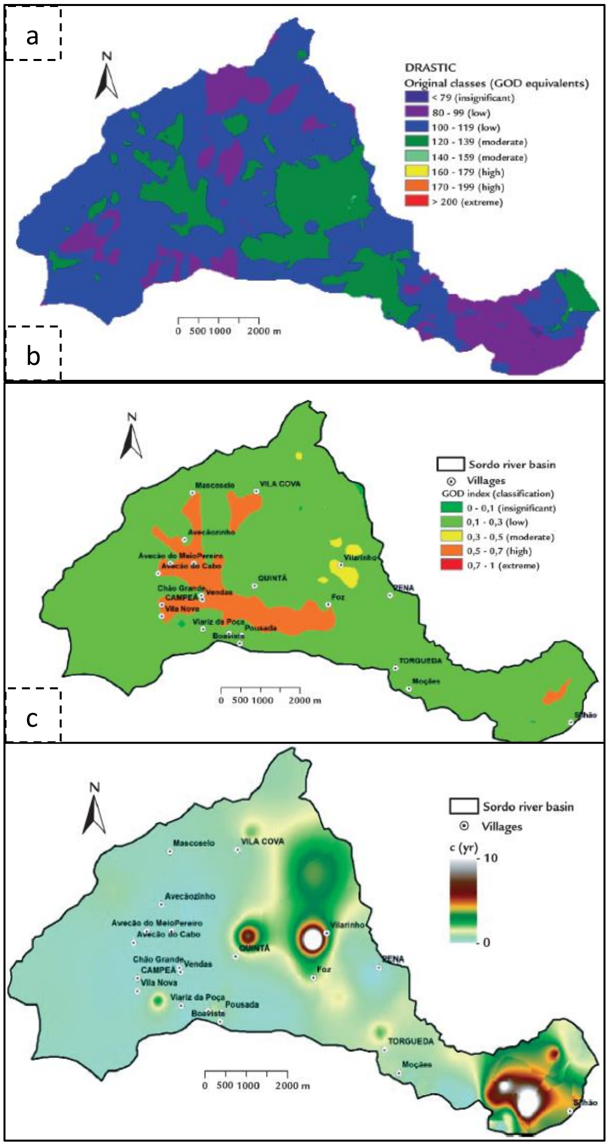

Figure 4 – Vulnerability maps of Sordo river basin, as calculated by DRASTIC (a), GOD (b) and AVI (c) methods. Source: Fraga et al. (2013).

Kazakis & Voudouris (2011) used the DRASTIC, AVI, and GOD methods to study the vulnerability of the Florina basin, which consists mainly of crystalline rocks.

The cartographic results obtained were similar to those of Fraga *et al*. (2003), but besides that, Kazakis & Voudouris (2011) used linear regression analysis to obtain a linear correlation matrix (Table 8).

The matrix obtained between the GOD and DRASTIC methods presented a value above 0.5, because of this, it is possible to suggest an association between them. Kazakis & Voudouris (2011) justified this result by stating that the first method uses three already existing variables in the second equation, and therefore, GOD can be considered a simplified version of DRASTIC.

The matrix obtained between the DRASTIC and AVI methods presented a value below 0.5, so little association between them is suggested. This result was supported by the comparison between the vulnerability maps of these methods, which showed significant differences regarding the delimitation of vulnerability classes.

Table 8 – Correlation matrix of GOD, AVI and DRASTIC methods.

Correlation Matrix	**GOD**	**AVI**	**DRASTIC**
DRASTIC	0.76	0.27	1.00
AVI	0.46	1.00	
GOD	1.00		

Source: Kazakis & Voudouris (2011).

Other researchers have obtained similar results to those already presented, such as Jiménez *et al*. (2004) who used the DRASTIC, GOD, and AVI methods in the study of the Zaachila aquifer in Mexico; Ekwere *et al.* (2017) who used the same methods in the study of the Oban Massif aquifer in Southeast Nigeria; Kemerich *et al*. (2020) who used the DRASTIC and GOD methods in the study of the Vacacaí-Mirim River watershed in Brazil; and Borges *et al*. (2017) who used the DRASTIC and GOD methods in the study of the Serra Geral aquifer in Brazil.

Below is a comparative table showing the main conclusions obtained about the COP, DRASTIC, GOD, and AVI methods (Table 9).

Table 9 – Comparison between COP, DRASTIC, GOD and AVI.

COMPARISON	**COP**	**DRASTIC**	**GOD**	**AVI**
Vulnerability Class Divison	More	More	Intermediate	Less
Reliability	High	High	Moderate	Low
Applicability	Less	Less	More	More
Study scale	Detail scale	Detail scale	Regional scale	Regional scale
Hydrogeology	Karst aquifer	Karst aquifer	Fissured aquifer Porous aquifer	Fissured aquifer Porous aquifer
Budget	High	High	Low	Low
Physical parameters	No	Yes	No	Yes
Hydrogeological parameters	Yes	Yes	Yes	No
Weighting parameter system	No	Yes	No	No

Source: Authors (2021).

4. Final considerations

The COP, DRASTIC, GOD, and AVI methods are used in the study of aquifer vulnerability, being represented from cartographic results that present vulnerability class delimitations, which vary, in general, from very low to extreme.

The COP method was considered more appropriate for studying the vulnerability of karstic aquifers, as it uses specific criteria for this type of system, being able to differentiate the vulnerability classes in a more realistic way. However, due to this specificity, it becomes an inappropriate method for other types of aquifers. Furthermore, due to the need for many variables in its calculation, it is better applied in detail scales and demands a voluminous database for its execution.

The DRASTIC method obtained the best results regarding the delimitation of vulnerability classes in maps of fissured and porous aquifers, precisely due to the use of seven physical and hydrogeological variables. However, due to the need for a lot of data, it was considered a tool with high application cost, more appropriate for detail scales.

The GOD method uses three variables in its calculations, and for this reason, it presented maps with intermediary delimitation of vulnerability classes when compared to the other methods. However, as it is a method with a simple equation, it was considered appropriate for a regional scale and for studies with limited data and/or budget, especially in fissured and porous aquifers.

The AVI method considers two physical variables in its calculations, and for this reason, it presented maps with lesser limits of vulnerability classes when compared to the other methods. However, due to the simplicity of its equation, it can be used at regional scales and in limited studies regarding the availability of data and/or budget, mainly from fissured and porous aquifers.

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