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Exploratory assessment of groundwater vulnerability to pollution in the Sordo River Basin, Northeast of Portugal

Vulnerabilidade de águas subterrâneas à poluição na bacia hidrográfica do Rio Sôrdo - Nordeste de Portugal

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Resumo

O presente artigo pretende demonstrar como se pode fazer um estudo sobre a vulnerabilidade de águas subterrâneas à poluição, utilizando-se métodos diferenciados para o efeito. A análise comparativa entre metodologias e críticas construtivas tive, como base, os estudos realizados na bacia hidrográfica do rio Sôrdo, fonte de fornecimento de água para grande parte da população do nordeste de Portugal. Os métodos aplicados foram o GOD e o AVI, tendo os mapas de vulnerabilidade resultantes do primeiro evidenciado uma bacia de vulnerabilidade predominantemente baixa e os do segundo revelaram-se inconclusivos, ao apresentar uma bacia totalmente de vulnerabilidade extrema. Dessa forma, essa comparação estendeu-se ao método DRASTIC, do qual já haviam sido realizados estudos nessa área, verificando-se que os mapas são idênticos e, predominantemente, de baixa vulnerabilidade, diferenciando-se nos índices de vulnerabilidade máxima da bacia. Concluiu-se que a vulnerabilidade à poluição dos aquíferos da bacia estudada é, sobretudo, baixa, apresentando valores da ordem dos 0-0,3. Considerou-se, ainda, a aplicação do método GOD, a qual foi bem-sucedida, sendo, então, indicada para estudos mais expeditos, aconselhando-se a aplicação do método DRASTIC para estudos mais pormenorizados.

Palavras-chave: Vulnerabilidade de águas subterrâneas, aquíferos, rio Sôrdo, GOD, AVI.

Abstract

Two simple methods of aquifer vulnerability assessment were used in this study: the GOD and AVI methods. The main purpose was to appraise their faithfulness as exploratory techniques, and their applicability to the scale of a small watershed. The study area was the Sordo River Basin (area: 50 km2), located in the Northeast of Portugal. To measure accuracy, model results were compared with vulnerability maps previously obtained for the basin, but using the standard DRASTIC model. Results of the GOD method were a map dominated by class "low vulnerability" where parameter O (overlying strata) imprinted its signature, very similar to the DRASTIC map but with smaller resolution. The method was considered valuable for exploration of *primary factors of aquifer vulnerability (e.g. discrimination between water table and confined aquifers) but not for description of secondary factors (e.g. nuances in the degree of confinement). The application of the AVI method was proven inefficient because the resulting map indicated the presence of a single unrealistic class ("extremely high vulnerability"). The reason was that AVI results are evaluated on a logarithmic scale, which is appropriate for studies at regional scales where the settings are very diverse, but inappropriate for studies on the small watershed scale.*

Keywords: *Groundwater vulnerability to pollution, aquifers, Sordo River, GOD, AVI.*

1. Introduction

Studies on aquifer vulnerability allow delineation of areas at potential risk of groundwater contamination, and thus help in defining criteria for land uses within the target zones of these studies towards prevention of that threat. According to Foster et al. (2002), contamination of groundwater occurs when the load of contaminants on the ground or leachates generated by urban, industrial, agricultural or mining activities are not adequately controlled, and certain components exceed the natural attenuation capacity of subsoil and cover layers.

The studies on vulnerability are mostly based on development of vulnerability maps using indexed methods, and became increasingly and widely used around the world in the last three decades. Examples of this use are the works by Parascandola (1979), Canter et al. (1987), Duijvenbooden and Waegeningh (1987), Lobo Ferreira and Calado (1989), Lobo Ferreira and Cabral (1991), EPA (1991), Carbonell (1993), Foster and Hirata (1993), Vrba and Zaporozec (1994), Lobo Ferreira et al. (1995), Lobo Ferreira (1998) or Sanches Fernandes and Haie (2001).

Among the methods used to evaluate aquifer vulnerability, one can refer the DRASTIC model (Aller et al., 1987) as dominant. This method, hinged on the evaluation of seven hydrologic parameters forming the acronym DRASTIC, is rather effective but requires a considerable amount of information to be applied. For preliminary evaluations of aquifer vulnerability, there is the possibility of using less sophisticated approaches, based on a lesser number of indices. However, the number of studies adopting these simplified techniques is paradoxically small. Two of these methods are the GOD (Foster, 1987) and AVI (Van Stempvoort et al. 1992) models. An extensive survey on the literature shows that authors applying and discussing these techniques are comparatively scarce to those using the DRASTIC model, and that studies using the DOG and AVI models are fairly recent. One can refer Barboza et al. (2007) who studied the GOD vulnerability of a water table aquifer located in Ponta da Fruta, Vila Velha - ES (Brazil), or Santos and Pereira (2011) who applied the AVI method in the classification of aquifer vulnerability in the region of Goytacazes fields (Rio de Janeiro, Brazil). In the cultural region of the fourth colony of Italian immigration in Rio Grande do Sul (Brazil), another GOD vulnerability study was carried out by Vogel (2008), and the Araripe sedimentary basin, Ceará State (Brazil), was also the subject of a study based on the GOD method, but by Tavares et al. (2009). Vulnerability studies based on the GOD or AVI methods could also be found in Canada, like the one by Golder and Monahan (2005), or in Mexico like the one by Ortiz and Castillo (2004) who applied the AVI method in the city of Salamanca. Vulnerability studies based on the comparison of methods are also available. Draoui et al. (2007) compared the methods GOD, AVI, DRASTIC and SINTACS applied to a detrital aquifer in the northwest of Morocco, while Mendoza and Barmen (2006) studied the environmental deterioration of Artiguas river basin in Nicaragua by evaluating vulnerability using DRASTIC and GOD methods.

The purpose of this paper is to present a case study where the results of GOD and AVI methods are compared, and concomitantly to appraise the importance of preliminary evaluation methods in the analysis of aquifer vulnerability. The study area is the Sordo river basin, located in the Northeast of Portugal. This is a small watershed that has already been studied for groundwater vulnerability to contamination by Pacheco et al. (2004), using the DRASTIC method.

2. Characterization of the study area

The Sordo river is a right margin tributary of the Corgo river, which in turn is a tributary of the Douro river. It rises in the Marão mountains and drains a NW-SE oriented hydrographic basin of about 50 km^2 along its course of about 22.4 km from the spring to the mouth area located in the demarcated region of Port wine. Within the basin, altitudes vary from 1300 meters in the spring area to 185 meters in the river's mouth. Topography affects the surface drainage and groundwater flow directions. The basin is well drained and evidences perennial flow. The construction of a hydroelectric dam (1990-1997) for public supply of water and electricity generation has led to a reservoir that serves some municipalities in the district of Vila Real, the capital of Trás-os-Montes and Alto Douro province located in NE Portugal (Figure 1).

The Sordo river basin is located in the largest hydrogeological unit of continental Portugal, the Hesperic Massif also known as Old Iberian Massif or Iberian Meseta. In the western side and eastern edge of the basin, rock outcrops are mostly composed of Palaeozoic metassediments (phyllites, greywackes, quartzites), covered in the flat central area by modern alluvial sediments, whereas in the eastern side they are essentially made of Hercynian granites (Figure 2).

According to Pacheco et al. (2004), fracturing in the crystalline massifs is intense and represented by two dominant systems: the one with NE-SW to NNE-SSW directions and the conjugate with NW-SE orientation. The less important fractures have ENE-WSW and NW-SE orientations. Fracture densities, deduced from analysis of lineaments in aerial photographs, are illustrated in Figure 3.

As regards to soil type, the basin is mostly covered by leptosols and fluvisols, in the flat central area corresponding to the main valley of the basin, and anthrosols in downstream areas (Figure 4).

The urban areas are represented by small spots dispersed thought the basin, occupying a total of about 0.5 km². The fissural aquifers are dominant in the study area and are subject to the fracture extent and orientation, folding characteristics of the metassediments and weathering of outcrops. Locally, the cover deposits may constitute good aquifer systems due to their high permeability and storage capacity. Weathered layers associated with the metamorphic and granitic rocks also originate hydrogeological systems with potential for storage of significant volumes of subsurface waters that serve deeper recharge (Pacheco et al., 2004). Distribution of depths to the water table is illustrated in Figure 5.

As would be expected, these depths are larger in the mountain heights (local recharge areas) and smaller in the valleys (local / regional discharge cells), especially in the flat central area of the basin. Hydraulic properties of the crystalline rocks were studied by Pacheco and Van der Weijden (2007), namely hydraulic conductivity, at the spring watershed scale. Following a method hinged on analysis of spring discharge rates, these authors concluded that hydraulic conductivities

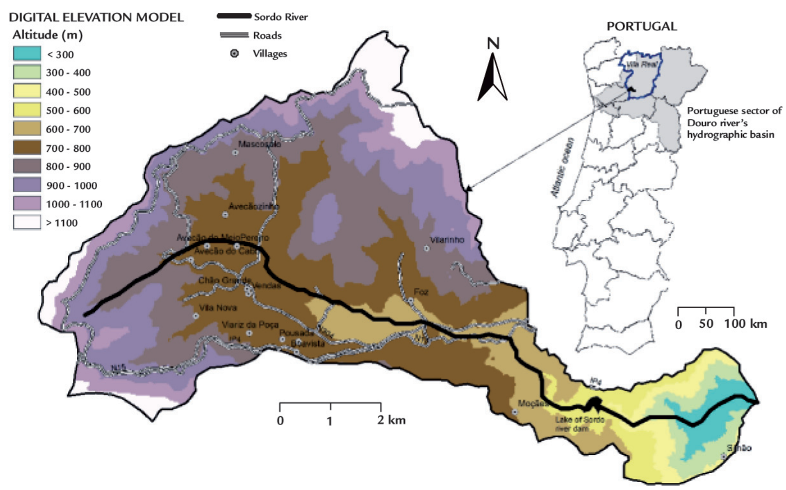

Figure 1
Location and topography of the Sordo river basin.

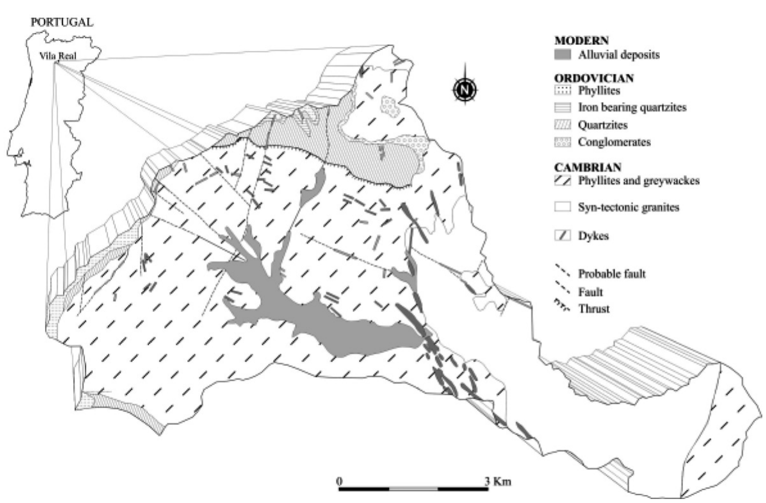

Figure 2
Geologic map of Sordo river basin. Adapted from Pacheco and Alencoão (2006).

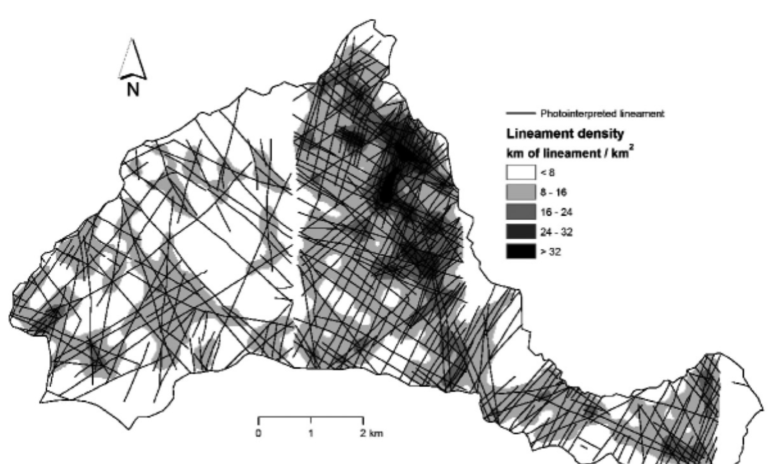

Figure 3
Density of lineaments calculated from lineament projections observed in aerial photographs.

cover three orders of magnitude, varying from a minimum as low as 0.2 m/yr to a maximum of about 420 m/yr, being higher in the metassediments than in the granites (Figure 6).

With regard to climate, temperatures are high in summer, especially in July and August, and low in winter, being the coldest season between December and March; the monthly average temperature of the air varies between 10 and 15°C. The average annual rainfall in the basin varies between 600 and 800 mm/yr, occurring mainly in winter.

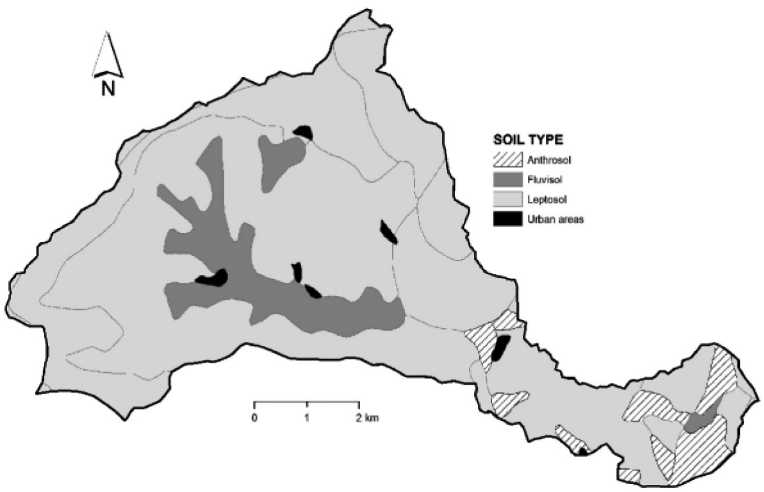

Figure 4
Soil map of Sordo river basin. Adapted from Agroconsultores and Coba (1991).

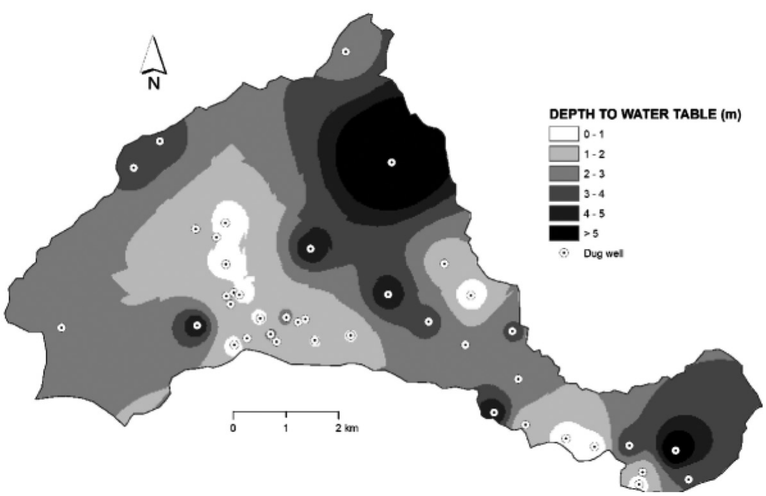

Figure 5
Distribution of depths to groundwater level in the Sordo river basin. Adapted from Carvalho (2009).

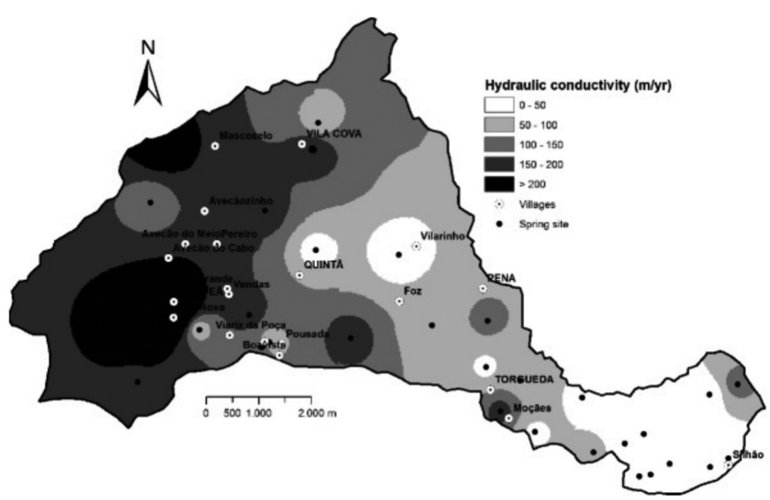

Figure 6
Distribution of hydraulic conductivities within the Sordo river basin, as calculated on the basis of analysis of spring discharge rates by Pacheco and Van der Weijden (2007).

3. Material and Methods

The GOD method was developed by Foster (1987) and Foster and Hirata (1993), the AVI (Aquifer Vulnerability Index) by the National Hydrology Research Institute (NHRI) in Canada (Van Stempvoort et al., 1992). The detailed explanation of these methods is beyond the scope of this paper and can be found in the original publications or elsewhere.

The GOD method is a simple and systematic method used as exploratory approach towards determination of groundwater contamination risk, being the acronym for three attenuator parameters: G (*Groundwater hydraulic* *confinement*) represents the hydraulic confinement of groundwater in the aquifer and is meant to attribute different vulnerabilities to water table, semi-confined or confined aquifers; O (*Overlying strata*) describes the type of materials present in the unsaturated zone above the aquifer, in keeping with their ability to neutralize contaminants; and D (*Depth to groundwater table*) measures the depth to groundwater level, being a proxy to the time that contaminants require to reach the aquifer. In the evaluation of GOD vulnerability, each composing parameter is assigned a value between 0 and 1, where 0 represents minimum vulnerability and 1 represents maximum vulnerability. For example, G parameter will approach 1 if the aquifer is unconfined and will decrease towards 0 if aquifer confinement increases. Parameter O will be low when the unsaturated zone is composed of impermeable or consolidated materials (e.g. clays, relatively fresh granites) and high when that horizon is made of permeable or loose sediments (e.g. clean sands, gravels, karsic limestones). Finally, D parameter will increase as the depth to groundwater level decreases. GOD's vulnerability is the product of composing parameters, the classification of which is in keeping with Table 1.

Table 1
Vulnerability classes of GOD method.

GOD index	Vulnerability class
0 - 0.1	Insignificant
0.1 - 0.3	Low
0.3 - 0.5	Moderate
0.5 - 0.7	High
0.7 - 1.0	Extreme

With regard to AVI method, this quantifies the vulnerability of an aquifer by looking at its hydraulic resistance "c", calculated by the expression (1):

$$c = \sum \frac{d_i}{k_i} = \frac{d_{solo}}{k_{solo}} + \frac{d_{rocha}}{k_{rocha}} \quad (1)$$

where *i* represents a layer of aquifer material, *d* is the thickness of that layer and *k* its hydraulic conductivity.

Hydraulic resistance is a proxy to the flow time of water in its vertical movement across sediment layers of the unsaturated zone above the aquifer. The higher the "c" the lower the vulnerability. In the calculation of "c", hydraulic conductivity and thickness of each layer are based on lithological descriptions and permeability data available in dug well logs. The classification of AVI's vulnerability is in keeping with Table 2.

The GOD and AVI methods determine the aquifer's intrinsic vulnerability because they do not take into consideration the type of contaminant. They can be implemented on a GIS (Geographic Information System) software, as these platforms can easily combine various thematic maps and their databases with analysis of geographical points and their associated information.

Table 2
Vulnerability classes of AVI method.

Hydraulic resistance (yr)	Vulnerability class
0 - 10	Extremely high
10 - 100	High
100 - 1000	Moderate
1000 - 10000	Low
> 10000	Extremely low

The GOD method index

The GOD vulnerability index varies from 0 to 1, in keeping with the classes represented in Table 1. The index is the product of values estimated for the composing parameters: G, O and D, which also vary from 0 to 1. In the present study, the map of G parameter (type of aquifer) resulted from the spatial merging of two auxiliary maps displaying different data. The first map (G1) displays geological information (Figure 2) and was used to delineate water table aquifers (G1 = 1, associated to the cover deposits), separating them from confined to semi confined aquifers (G1=0, associated to the granites and metassediments). The second map (G2) displays information on density of lineaments (Figure 3) and was used to set up the degree of aquifer confinement outside the area of water table aquifers shown in G1 map ($0.2 \le G2 \le 0.6$, increasing in keeping with the lineament density). The map of G parameter (type of aquifer), with values restricted to 0.2, 0.4, 0.6 and 1, was then generated by the function "maximum" of the GIS software, i.e. parameter G is the maximum of G1 and G2 values.

For the O parameter, considering that the outcrops in the basin are represented by alluvial and igneous / metamorphic rocks (Figure 2), the indices were set up to 0.7 and 0.6, respectively.

To obtain the map of D parameter (depth to the water table), depths up to 5 m were attributed the index 0.9 and depths between 5 and 20 m the index 0.8. The depths were measured by Pacheco *et al.* (2004) in 41 dug wells distributed within the Sordo basin, and were reported to vary from 0.2 to 10 m (Figure 5).

The AVI method index

The thicknesses and hydraulic conductivities of layer "soil" (soil's *d* and *k*) were assembled from reports on soil profiles attached to the soil map of Northwest Portugal, produced at scale 1: 100 000 by the Trás-os-Montes and Alto Douro University in cooperation with a private company (Agroconsultores and Coba, 1991; Figure 4). Depending on the soil type, the thicknesses varied between 0.31 (leptosols), 0.78 (cambisols), 1.19 (anthrosols), and 1.41 (fluvisols) meters, whereas hydraulic conductivities ranged between 63.1 (anthrosols from metassediments), 78.4 (anthrosols from granites), 85.6 (leptosols) and 128.3 (fluvisols) m/yr. The thickness of layer "rock" was calculated as the difference between the depth to groundwater level, as reported in Pacheco *et al.* (2004) and illustrated in Figure 5, and the soil's *d*. Negative values were recast to zero. The data on hydraulic conductivity of layer "rock" were gathered from Pacheco and Van der Weijden (2007) who calculated this parameter for a large number of spring watersheds located within the Sordo basin, using a method based on analysis of spring outflows (Figure 6).

4. Results and discussion

Applying the multiplicative formula of GOD methodology to composing parameters (G, O, D), one gets the final vulnerability map (Figure 7). The Sordo river basin displays all classes of vulnerability, except the "extreme". The dominant class describes areas of "low" vulnerability (0.1 to 0.3) which coincide with spots where geology is characterized by igneous and metamorphic rocks. Following the dominant class one finds the areas of "high" vulnerability that coincide with the flat central area represented by alluvial deposits. Finally, Figure 7 shows that classes "insignificant" and "moderate" are scarcely or little represented.

The results indicate that index O (*Overlying strata*) imprints a mark in the final vulnerability map, notwithstanding the presence of very diverse lineament densities (Figure 3), which influences index G, and a relatively wide range of depths to groundwater level (Figure 5) that determines index D. It could be argued that final results also reflect the aquifer hydraulic confinement because the flat central area coincides with areas where G = 1 while the igneous and metamorphic rocks are represented by areas where G ≤ 0.6. However, the effort made in setting up the degree of confinement as a function of lineament density (G values between 0.2 and 0.6) seem to had limited influence in the final results, since the areas with high densities of the N-NE border of the basin (Figure 3), grossly parallel to the contact between the granites and the metassediments (Figure 2), coincide with areas where vulnerability is also high (classified as "moderate") solely in a few small parcels. It could also be argued that depths to groundwater levels are usually smaller in the alluvial deposits than in the igneous and metamorphic rocks (Figure 5), and therefore that the influence of D index is also present in the final results. However, the areas with depths ≤ 2 m of the eastern sectors of the basin do not appear as areas where vulnerability is higher than "low". In view of these arguments, it can be stated that GOD results provide a broad perspective about vulnerability in the Sordo river basin, since they light up primary influences (e.g. separation between confined and semi-confined aquifers; identification broad classes of depths to groundwater level), but fail in describing adequately secondary influences such as degree of confinement.

The calculation of hydraulic resistance according to the AVI methodology leads to the map of Figure 8. A thorough analysis of this map shows that AVI vulnerability classes in the Sordo river basin are limited to class "extremely high" (Table 2), because hydraulic resistances vary between 0 and 10.

This result is mostly explained by the very low thicknesses reported for the unsaturated zone. For example, Figure 5 shows that in some 90% of the basin depths to groundwater level are below 4 m. Considering that leptosols, the prevailing soil type in the basin, are not thicker than 0.4 m, then the unsaturated rock layer above the aquifer would not be thicker than 3.6 m, on average. Under such circumstances, hydraulic conductivities would have to drop below 0.36 m/yr in order to define areas with hydraulic resistances larger than 10 yr, corresponding to AVI vulnerabilities smaller than "extremely high" (Table 2). However, hydraulic conductivities of the rock massifs, although cover three orders of magnitude, are barely that low (Figure 6).

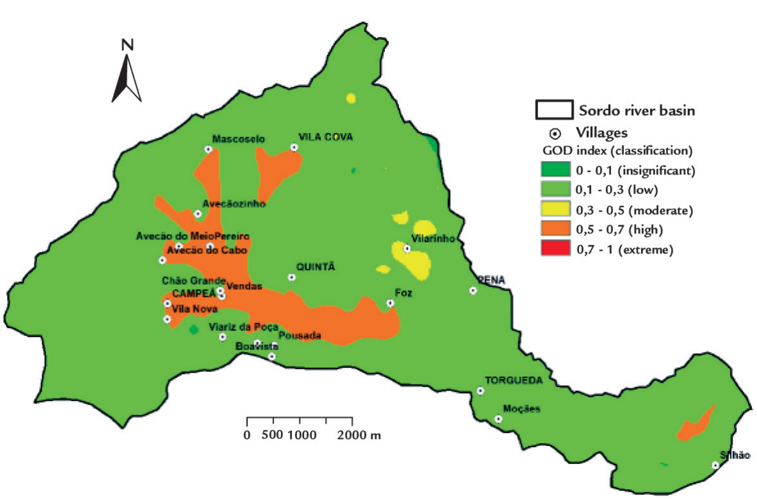

Figure 7
GOD vulnerability map of Sordo river basin.

AVI results are contradictory relative to GOD results, because AVI method describes Sordo river basin as a medium where aquifer vulnerability is extremely high while GOD method states that in a significant part of that basin vulnerability is low. It can be recognized that, being defined as a sum of quotients, AVI vulnerabilities are extremely sensitive to changes in their numerators (*d* values) and/or denominators (*k* values). For example, if *d* and *k* vary in opposite directions across the study area (e.g. one value increases and the other decreases), hydraulic resistances (*c*) will result either very high or very low (bimodal distribution); otherwise *c* values will approach a constant value. A bimodal behavior is adequately illustrated in a study by Golder and Monahan (2005), who reported very high AVI vulnerabilities in a water table aquifer, except where the aquifer was covered by thin lenses of clay, in which case the AVI vulnerabilities resulted very low. On the other hand, the AVI classification scheme is based on a logarithmic scale (Table 2), which means that a limited number of classes will always appear in vulnerability maps unless the quotients *d*/*k* span several orders of magnitude. In the Sordo river basin, where topography changes from steep hill slopes in the mountain tops and flat areas in the main valleys, where different geological settings are present, etc., one would anticipate the incidence of a noteworthy range of *d*/*k* values, but results proved otherwise. Eventually, this is indication that AVI is a method to be used in very complex and diverse set ups, usually encountered at regional or even global scales but not at the scale of a small watershed. In view of these arguments, it is assumed that, for the present case study, AVI results represent an oversimplified description of aquifer vulnerability, and that only GOD results are taken as valuable.

In Figure 9 one plots the DRASTIC map of Sordo river basin. The assessment of vulnerability in this basin using this model started with the work of Pacheco *et al.* (2004), who used CAD and terrain modeling computer programs to do the job. This work was upgraded by Carvalho (2009) and Pacheco (2012) who implemented the model in a GIS software (ArcMap; ESRI, 2007). Although the number of classes in the GOD and DRASTIC models is different, comparison of results can still be made if correspondences between classes are established, for example as in Figure 9.

In this case, it is recognized that classes "insignificant" (DRASTIC < 79) and "extreme" (DRASTIC > 200) are absent from the basin, which is in fair agreement with the GOD results. Areas classified as "moderate" (120 ≤ DRASTIC ≤ 159) include areas identified by the GOD method as being of "high" vulnerability but also accommodates spots of high lineament density that GOD's method kept classified as being of "low" vulnerability. Finally, areas of "low" vulnerability (80 ≤ DRASTIC ≤ 119) correspond in a great extent to areas that GOD's method also identified as belonging to class "low". However, DRASTIC model is able to distinguish among this low vulnerability areas those which are particularly insensitive to aquifer contamination due to their craggy topography (80 ≤ DRASTIC ≤ 99).

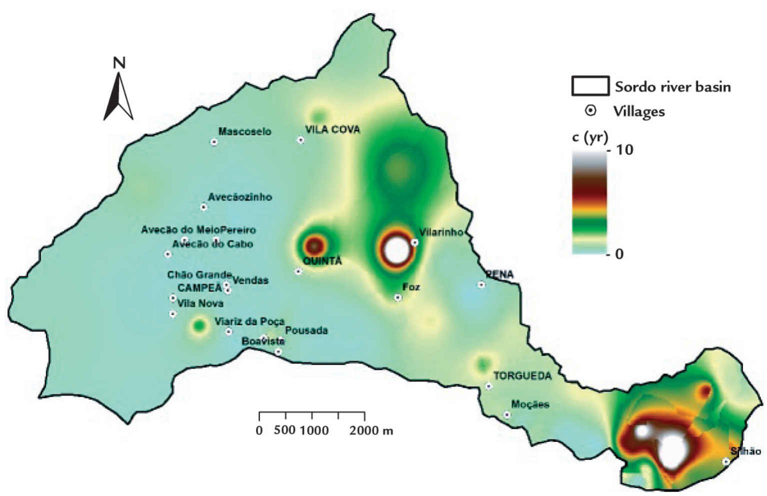

Figure 8
Distribution of hydraulic resistances within the Sordo river basin, as calculated by the AVI method.

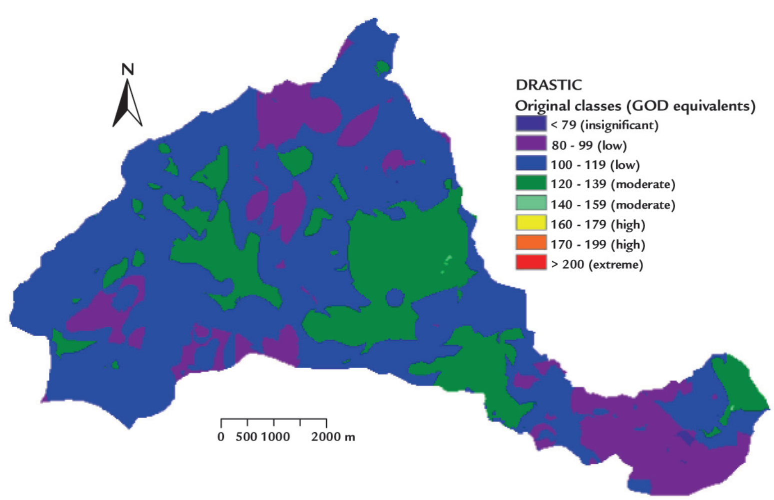

Figure 9
DRASTIC vulnerability map of Sordo river basin.

5. Conclusions

The GOD method allows a rapid perception of factors contributing to a particular class of vulnerability in a specific region, because it hinges on a limited number (three) of parameters. In the Sordo river basin, application of GOD method resulted on a map that covers almost all classes of vulnerability, although being dominated by class "low". It was also observed that parameter O imprints its signature on the final results, and that the method is valuable for exploring primary factors of aquifer vulnerability (discrimination between water table and confined aquifers) but it fails in describing secondary factors (nuances in the degree of confinement). Bearing in mind its simplicity, the GOD method has proven useful when evaluation of vulnerability requires brevity but also reliability so it can be used as an environmental tool for urgent decisions.

At first glance, the AVI method appeared to be simple and fast, with applicability similar to the GOD method but based on different data. However, the shortcoming of being evaluated on a logarithmic scale, in our study manifest in a vulnerability map with a single class, prevented results to be of valuable use. On the other hand, classification of the basin as extremely vulnerable is unrealistic. Nevertheless, it should be mentioned that AVI is one of the simplest vulnerability assessment methods, because it is based on a couple of parameters that are fairly easy to quantify.

The use of DRASTIC model was not in the purposes of this study. However, given the availability of DRASTIC results for the Sordo river basin, comparison of these results with the GOD results was important as a reference. In brief, it was shown that vulnerability maps are identical. The study stresses that DRASTIC is more accurate in detecting nuances in aquifer vulnerability than the GOD, because it stands on a more diverse set of variables, but it also refers the inconvenience of applying the DRASTIC model when data is partially lacking. On the other hand, the GOD method has the advantage of simplicity, but the disadvantage of being unable to produce high resolution vulnerability maps.

6. Acknowledgements

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