Groundwater vulnerability assessment in Portugal

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RESUMEN

Durante la década de los 70's y 80's el mapeo de vulnerabilidad acuífera en Portugal fue basado principalmente en la interpretación de la información geológica en términos de la vulnerabilidad del agua subterránea a la contaminación. En 1987 un método paramétrico para la evaluación de la vulnerabilidad a la contaminación fue introducido por la EPA (el índice DRASTIC). En 1993 Portugal fue el primer estado de la Unión Europea en tener su territorio mapeado usando el índice DRASTIC (1:500,000). Desde entonces varias aplicaciones del índice DRASTIC han sido hechas a diferentes escalas y usando diferentes fuentes de información base. El uso de diferentes fuentes de información, con diferente escala y algunas veces con diferente acercamiento, llevan a diferentes mapas finales de la misma área, como se muestra en este artículo de la península Setúbal, al sur de Lisboa. Siguiendo el desarrollo de diferentes metodologías nuevas para la evaluación de la vulnerabilidad acuífera, basadas en la caracterización de diferentes parámetros, una comparación de los resultados calculados con estas metodologías fue justificable. Con este propósito, una comparación entre los resultados de la aplicación de seis métodos de índices de vulnerabilidad (AVI, GOD, DRASTIC, SI, EPPNA y SINTACS) fue realizada para un sistema acuífero localizado cerca de Evora (Alentejo, Portugal). Al final de este artículo son presentadas conclusiones para futuras investigaciones sobre mapeos de vulnerabilidad.

PALABRAS CLAVE: Agua subterránea, vulnerabilidad, DRASTIC, método de comparación, efectos de escala.

ABSTRACT

During the 70's and 80's groundwater vulnerability mapping in Portugal was based mainly on the interpretation of geological information in terms of vulnerability to groundwater pollution. In 1987 a parametric method for the assessment vulnerability to pollution was introduced by the USEPA (the DRASTIC index). In 1993 Portugal was the first European Union's Member-State to have its territory mapped using the DRASTIC index (1:500,000 scale). Since then several applications of the DRASTIC index, at different scales, and using different sources of base information, have been made. The use of different sources of information, with different scales and sometimes with different approaches lead to different final maps of the same area, as shown in this paper for Setúbal peninsula, south of Lisbon. New methodologies for groundwater vulnerability assessment, based on the characterization of different parameters, led to a comparison of the results. With this aim, a comparison between six vulnerability index methods (AVI, GOD, DRASTIC, SI, EPPNA and SINTACS) was carried out for an aquifer system located near Évora (Alentejo, Portugal). Conclusions for further research on vulnerability mapping are addressed at the end of this paper.

KEY WORDS: Groundwater, vulnerability, DRASTIC, method-comparison, scale-effect.

INTRODUCTION

In February 1991, the groundwater group of the European Community Commission met in Brussels with the purpose of establishing an international agreement on common methodologies for the elaboration of a groundwater resource inventory for all member states. Such an inventory had been made between 1979 and 1981 for all Member States at the time, but it needed to be updated to include new member states. It was decided at the meeting to unify the criteria and procedures used by each member state to evaluate, rank, and map groundwater pollution vulnerability.

GROUNDWATER VULNERABILITY

The term vulnerability has been defined and used before in the area of water resources, within the context of system performance evaluation. Hashimoto and collaborators (1982) present an analysis of system performance, which focuses on system failure. They define three concepts that provide useful measures of system performance (1) how likely the system is to fail is measured by its *reliability*, (2) how quickly the system returns to a satisfactory state once a failure has occurred is expressed by its *resiliency*, and (3) how severe the likely consequences of failure may be measured by its *vulnerability*. This concept of vulnerability defined in the context of system performance may also be used in the context of groundwater pollution if we replace 'system failure' with 'pollutant loading'. The severity of the consequences is measured in terms of water quality deterioration, regardless of its value as a resource. However, the concept of vulnerability has not yet been unambiguously defined in the context of groundwater pollution, and the term has been used to mean different things. Often, the term 'vulnerability to pollution' is used with a composite meaning that would perhaps be better described by risk of pollution.

The authors propose that groundwater vulnerability to pollution be defined, in agreement with the conclusions and recommendations of the international conference on 'Vulnerability of Soil and Groundwater to Pollutants', held in 1987 in The Netherlands (Van Duijvenbooden and Van Waegeningh 1987), as *"the sensitivity of groundwater quality to an imposed contaminant load, which is determined by the intrinsic characteristics of the aquifer"* which are relatively static and mostly beyond human control.

SUGGESTED SYSTEM OF VULNERABILITY EVALUATION AND RANKING

Given the definition of vulnerability, it is important to recognize that the vulnerability of an aquifer will be different for different pollutants. For example, groundwater quality may be highly vulnerable to the loading of nitrates at the surface, originated in agricultural practices, and yet be little vulnerable to the loading of pathogens. Thus, it is scientifically most sound to evaluate vulnerability to pollution in relation to a particular class of pollutant and create specific vulnerability maps. Alternatively, vulnerability mapping could be performed in relation to groups of polluting activities, such as unsewered sanitation, agriculture, and particular groups of industries. As there will generally be insufficient available data to perform specific vulnerability mapping, it is necessary to adopt a mapping system that is simple enough to apply the data generally available, and yet is capable of making best use of those data in a technically valid and useful way. Various of such systems of vulnerability evaluation and ranking have been developed and applied in the past. Some of the systems for vulnerability evaluation and ranking include a vulnerability index, which is computed from hydrogeological, morphological, and other aquifer characteristics in some well-defined way. The adoption of an index has the advantage of, in principle, eliminating or minimizing subjectivity in the ranking process.

Given the multitude of authors and potential users of vulnerability maps in ECC countries, Lobo-Ferreira and Cabral (1991) suggested that a vulnerability index be used in the vulnerability ranking performed for ECC maps.

RECENTLY DEVELOPED GROUNDWATER VULNERABILITY PROJECTS IN LNEC'S HYDRAULICS AND ENVIRONMENT DEPARTMENT

The DRASTIC index, developed by Aller and coll. (1987) for the USEPA (US Environment Protection Authority) has been adopted in the US, Canada, and South Africa. This index has the characteristics of simplicity and usefulness. Several maps of the aquifer systems, hydrogeological parameters, aquifers recharge and the final map of DRASTIC groundwater vulnerability of Portugal, all in scale 1:500,000 were developed in ARC/INFO (the maps were presented in a 1:1,500,000 scale in Lobo-Ferreira and coll. (1995a). In *http://www.dha.lnec.pt/nas/textos/novidades/drastic_e.html*, a one-page map of the DRASTIC index vulnerability assessment of Portuguese groundwater, this map is presented. Several other studies that included DRASTIC groundwater vulnerability assessment, were developed in Portugal following this methodology. Among those studies we find the *"Study for evaluation of the vulnerability of the reception capacity of coastal zone water resources in Portugal. The receiving water bodies: groundwater systems"*, by Lobo-Ferreira and coll. (1995b) should be stood out. This study included an application of the DRASTIC method for all coastal areas of mainland Portugal at the scale 1:100,000.

In *http://www.dha.lnec.pt/nas/textos/novidades/nato97_vulner_internet.html* a vulnerability map at the scale 1:100,000 is presented for the Peniche area, in Portugal's central coastal zone.

During the last five years, *i.e.* 1998 – 2003, Portugal invested about 10 million Euros in the development of 15 River Basin Plans. LNEC's Groundwater Division developed the groundwater component of several of those watershed plans, namely for the Tagus river, the Minho river, the Sado river and the Mira river basins as well as for Western Rivers and for Madeira and Porto Santo Islands. The vulnerability assessment was developed and mapped using a classic method and the DRASTIC index method. Example of those maps (as well as the global map for Mainland Portugal) is available in Internet for the Tagus river basin and for the Minho River Basin:

http://www.dha.lnec.pt/nas/textos/novidades/LoboFerreira_Rio2000.htm

http://www.dha.lnec.pt/nas/textos/novidades/LF_Minho_Interceltic2_colours.html

COMPARISON OF FOUR GROUNDWATER VULNERABILITY ASSESSMENT APPLICATIONS, USING THE DRASTIC INDEX METHOD

The vulnerability evaluation procedure should correspond to a well-defined computation of an index, in order to minimize subjectivity involved in the ranking. Such an index should meet the requirements of being relatively simple, given the limitations of generally available data, while being technically sound and valid for vulnerability classification. An existing index that meets these requirements, is the index DRASTIC. However the outputs of DRASTIC index are strongly dependent on the available information (at different mapping scales) for the assessment and mapping of the seven parameters. This may lead to different regional assessments for the same case study region, making it difficult to select (aiming real world groundwater protection and management) the "real" values. An example of four different assessments for the same case study area (the Setúbal peninsula in Portugal) is presented in Figure 1 to Figure 4. Those assessments have been made under different research contracts, incorporating different DRASTIC parameter value assessments.

COMPARISON OF SIX DIFFERENT METHODS FOR GROUNDWATER VULNERABILITY ASSESSMENT

An application of groundwater vulnerability assessment methods was developed in LNEC during 2002 (Artuso *et al.*, 2002). Six methods have been applied: EPPNA (1998), AVI (Van Stempvoort *et al.*, 1992), GOD (Foster, 1987), DRASTIC (Aller *et al.*, 1987), SINTACS (Civita, 1994), SI (Francés *et al.*, 2001). Due to the paper size it is not possible to describe the methods, but the original comparison between the methods is carried out.

The study area is the gneissic and migmatitic aquifer system of Évora (Alentejo, Portugal). The aquifer is composed mainly of gneisses, migmatites and associates granodiorites and quartzodiorite rocks. Between the gneisses and migmatites, some other meta sediments occur, especially skarns and quartzites.

The aquifer is a classic double porosity system with specific hydraulic interconnecting characteristics: the blocks and fractures. The circulation and the storage of water in this type of aquifer is associated with the alteration layer, with the essential characteristic of a porous media, and a deeper weathered and fractured zone, with the specific characteristic of a double porosity media. The base of the aquifer system can reach 20 to 40 meters, rarely more. Hydrodynamic studies on limited number of wells indicate transmissivity values of 30 to 100 m^2/day.

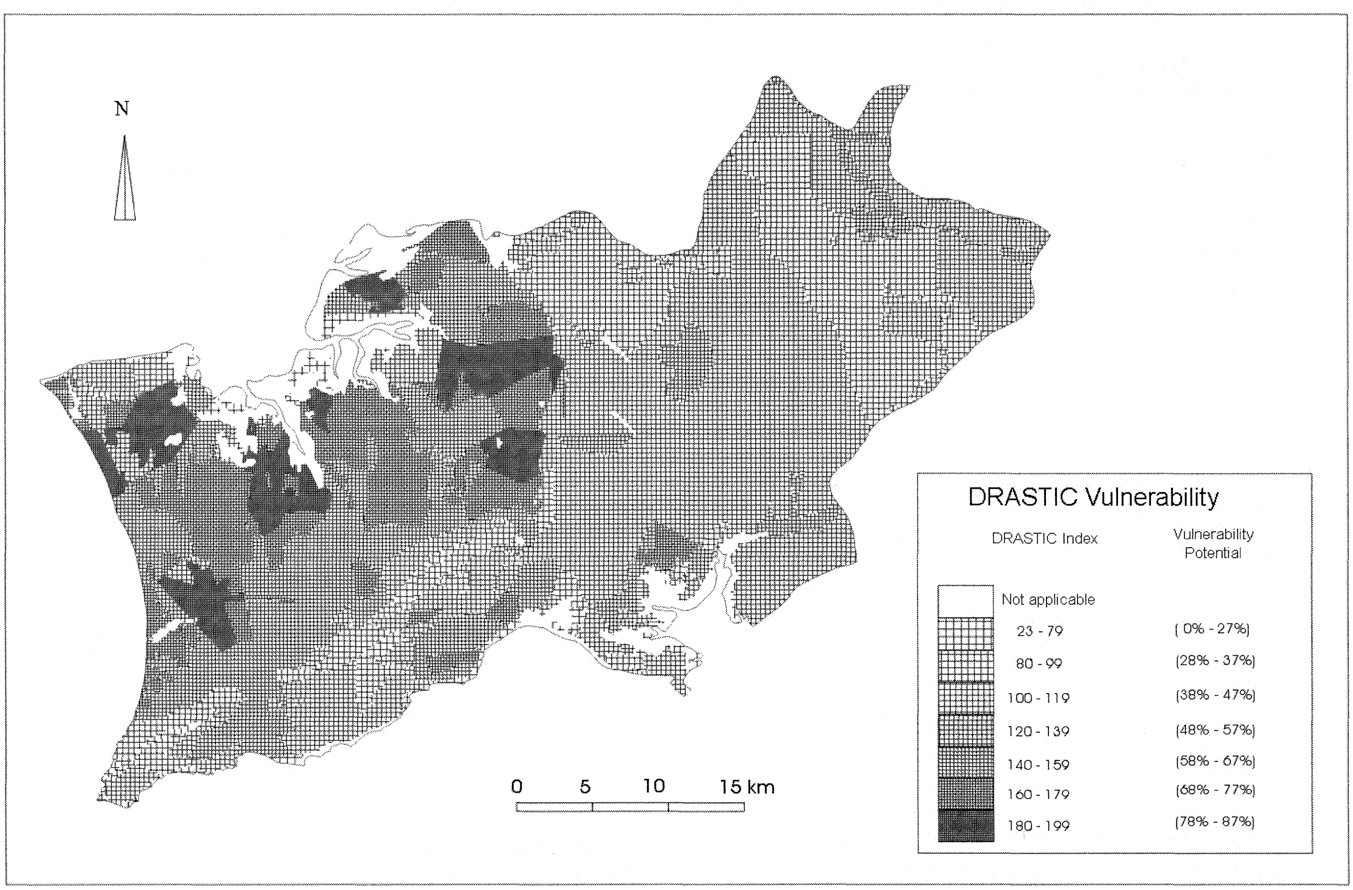

Fig. 1. Vulnerability assessment of Setúbal peninsula, extracted from OLIVEIRA *et al.* (1994) based on the studies developed by LOBO-FERREIRA and OLIVEIRA (1993), originally at a 1:500,000 scale .

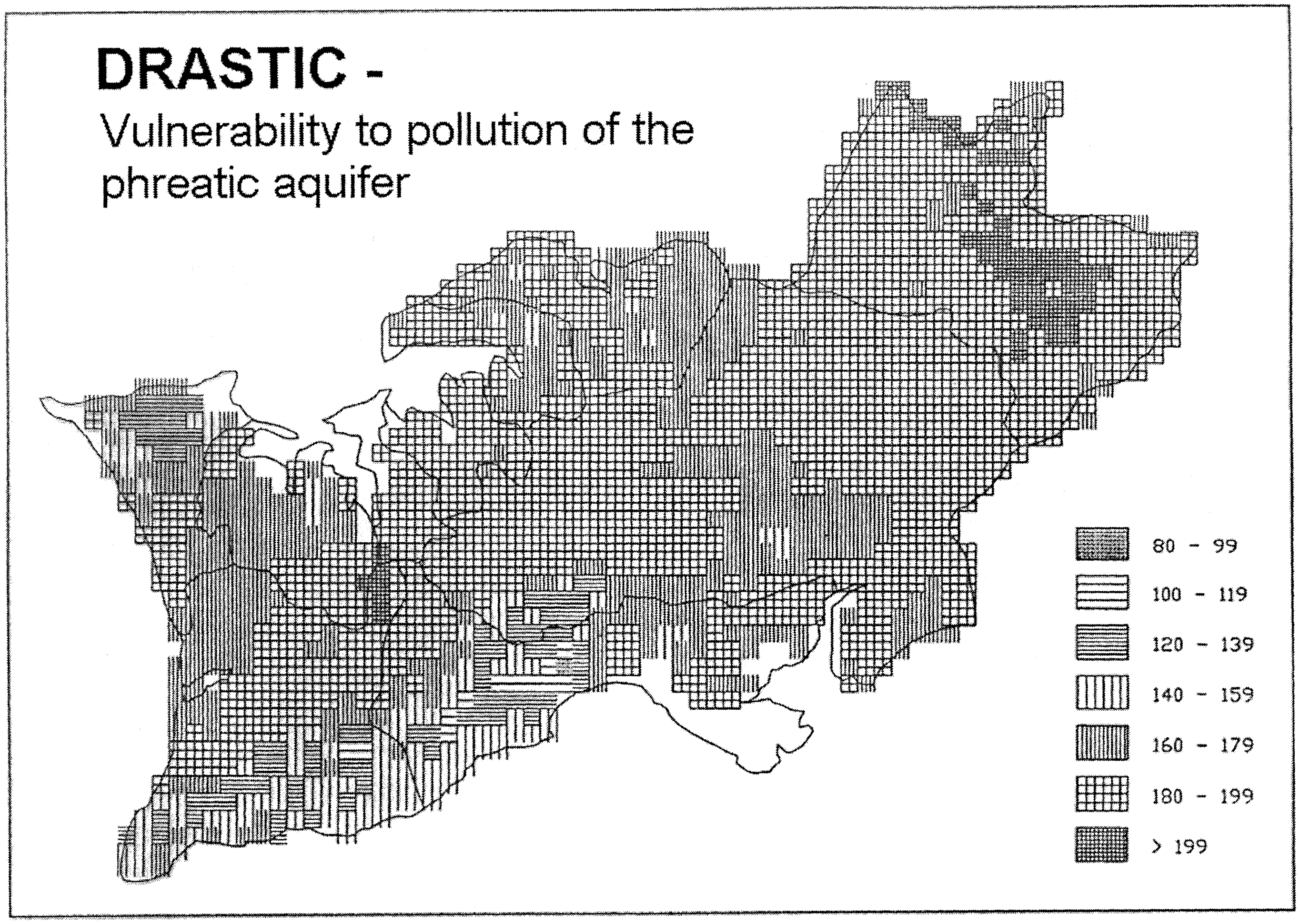

Fig. 2. Vulnerability assessment of Setúbal peninsula, extracted from OLIVEIRA and LOBO FERREIRA (1994), using a model grid of 1 x 1 km².

Table 1

Reclassification of the methods in order to carry out the comparison

Vulnerability	Class	EPPNA	DRASTIC	GOD	AVI	SINTACS	SI
Very high	A	V1, V3	>199	0.7-1	0 to 10	I > 210	85-100
High	B	V2, V4	160-199	0.5-0.7	10 to 100	186 < I < 210	65-85
Intermediate	C	V5, V6	120-159	0.3 – 0.5	100 to 1000	105 < I < 186	45-65
Low	D	V7, V8	<120	0-0.3	> 1000	I < 105	0-45

RECLASSIFICATION TO A UNIFORM CLASSIFICATION OF VULNERABILITY CLASSES

In order to compare the different methods and taking into account that the vulnerability classes defined for each method are different from method to method, all the methods have been reclassified to a uniform classification of vulnerability classes, as shown in Table 1.

This reclassification is somehow a subjective procedure

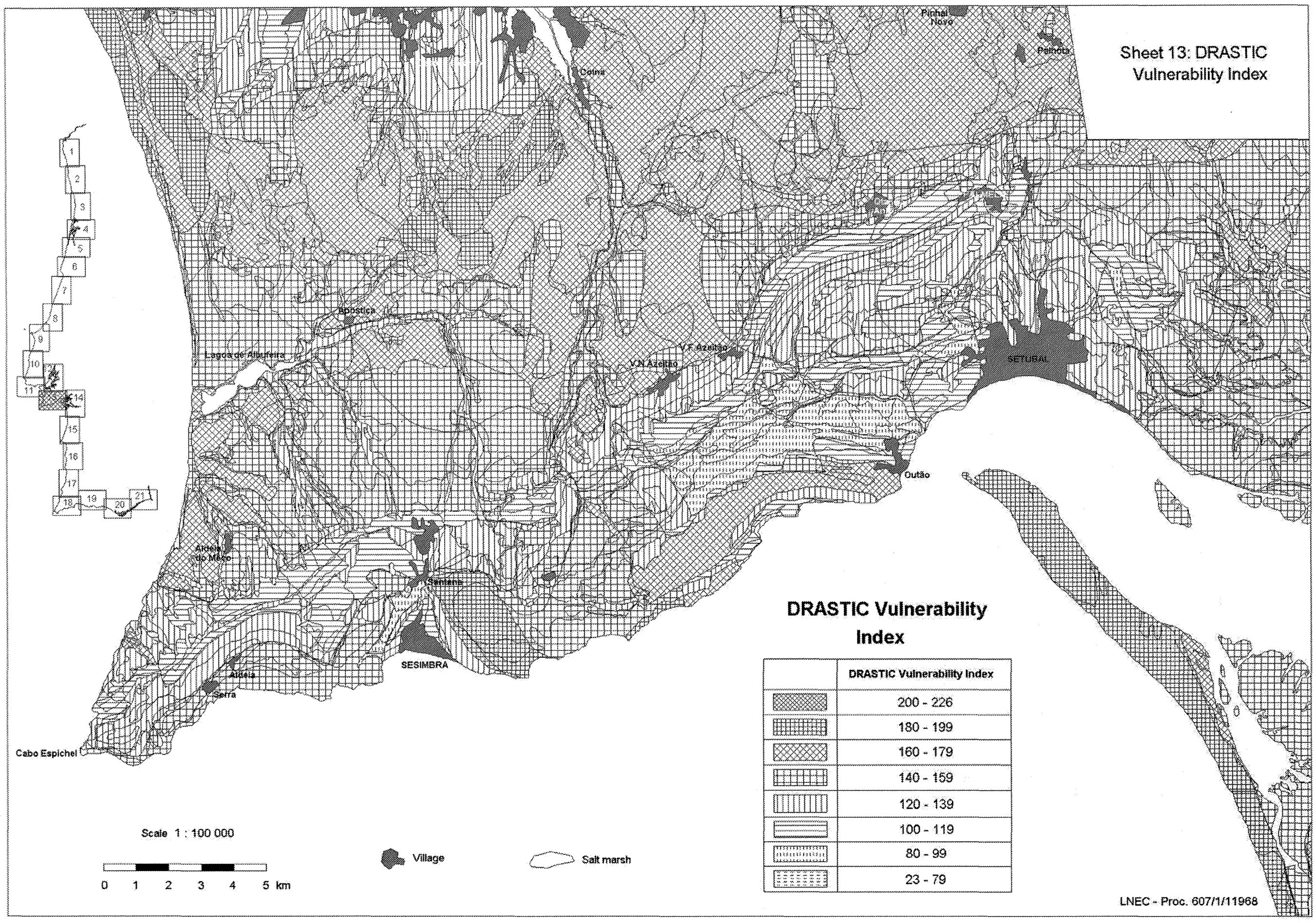

Fig. 3. Vulnerability assessment of Setúbal peninsula, extracted from LOBO-FERREIRA *et al.* (1995b), original scale 1:100,000.

as probably the original assignment of the vulnerability classes in each method also was (at least partially).

Figure 5 shows the results of the application of the different methods to the Évora aquifer system, classified accordingly to Table 1.

The results of the comparison can be consulted in Table 2. Percentages are in relation to the total considered area (254 km^2) where the class is the same or where X/Y represent the percentage of area where column is class X and row is class Y. (*E.g.* B/A means the head of the column is class B and the head of the row is class A). When the differences are of one class (i.e. from A to B, B to C or C to D) this can be due to the subjectivity of the classification or to the fact that the value of one method is near the upper limit of the less vulnerable class and the value of the other method is close to the lower limit of the more vulnerable class. The results of the comparison are as follows:

- the AVI method clearly falls outside the values of the other methods. It is the only method with 100 % of the area in class A;

- SI, SINTACS and EPPNA produce very close results (93-94 % of the area);

- the group SI, SINTACS and EPPNA is different from the DRASTIC method (only 1-6 % of the area is classified in the same way). However this can be due to the fact of the subjectivity of the classification as DRASTIC class D coincides 92-94 % with SI, SINTACS and EPPNA class C. In this way one may state that SI, SINTACS, EPPNA and DRASTIC produce similar results;

- GOD is the closest method to AVI as 90 % of the area is characterised by class B of GOD and class A of AVI;

- DRASTIC is the method that is more distanced from AVI (94 % of the area is DRASTIC class D and AVI class A).

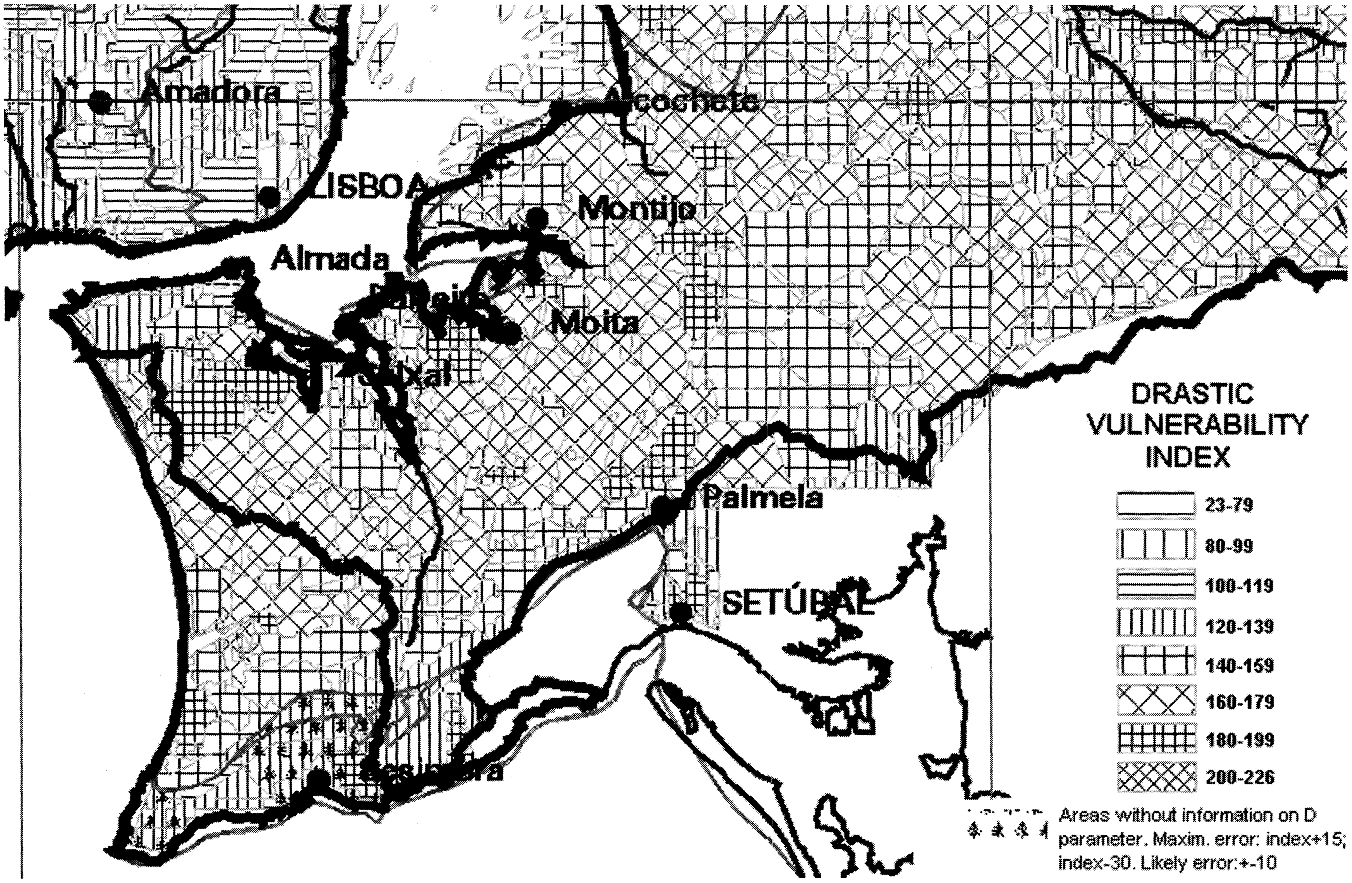

Fig. 4. Vulnerability assessment of Setúbal peninsula, extracted from OLIVEIRA *et al.* (2000), original scale 1:1,000,000.

CONCLUSIONS

As a general conclusion, extractable from Table 2, it is possible to state that for the Évora aquifer system case study area the following order and grouping could be produced (from lower to higher vulnerability): DRASTIC, the group formed by SI, SINTACS and EPPNA (which are very close methods), then GOD and finally AVI.

It should be noted that, for this area, the EPPNA method, that requires much less information, produces results similar to much more complex methods. It is believed that this is mainly due to the fact of the existence of metamorphic and igneous rocks.

It seems that the AVI method is not so much adequate to characterise the groundwater vulnerability of the study area. Based on the studies developed at LNEC, some of them addressed in this paper, and on the studies developed and the conclusions presented by Lobo-Ferreira (2000) this research may conclude stating that: It is important to developed studies aiming the validation of groundwater vulnerability assessment methods, for the DRASTIC method, the computed quantitative results (*i.e.* in terms of index values) and the qualitative values (*i.e.* in terms of "very high", "high", "intermediate", "low" and /or "very low") may be compared with the results of groundwater quality analysis developed for the aquifer systems of Portugal, *e.g.* those available within the Tagus River Basin Water Plan (Oliveira *et al.*, 2000). It would also be important to compare those quantitative and qualitative computed results with others results obtained with different applied research techniques, such as geophysics, *e.g.* the one presented by Andrade-Afonso *et al.* (1998). This author states that geophysical methods permit the delimitation of areas of higher and lower groundwater vulnerability to pollution, by detecting zones of fractures and/or locating and quantifying the thickness of silt strata as well as discontinuities that eventually may occur in those zones.

Table 2

Comparison of the six methods used to characterize groundwater vulnerability to pollution in terms of % of the total area where classes are the same for the different methods or for the classes X/Y, where X stands for the method indicated for the column and Y stands for the method indicated for the row

SAME CLASS	DRASTIC	SI	SINTACS	EPPNA	GOD	AVI
DRASTIC	x	6%	1%	5%	0%	0%
SI		x	93%	94%	11%	0%
SINTACS			x	93%	15%	0%
EPPNA				x	13%	0%
GOD					x	0%
AVI						x

B/A	DRASTIC	SI	SINTACS	EPPNA	GOD	AVI
DRASTIC	x	0%	0%	0%	0%	0%
SI	0%	x	0%	0%	0%	0%
SINTACS	0%	0%	x	0%	0%	0%
EPPNA	0%	0%	0%	x	0%	0%
GOD	0%	0%	0%	0%	x	0%
AVI	0%	2%	5%	3%	90%	x

C/A	DRASTIC	SI	SINTACS	EPPNA	GOD	AVI
DRASTIC	x	0%	0%	0%	0%	0%
SI	0%	x	0%	0%	0%	0%
SINTACS	0%	0%	x	0%	0%	0%
EPPNA	0%	0%	0%	x	0%	0%
GOD	0%	0%	0%	0%	x	0%
AVI	6%	95%	95%	97%	10%	x

D/A	DRASTIC	SI	SINTACS	EPPNA	GOD	AVI
DRASTIC	x	0%	0%	0%	0%	0%
SI	0%	x	0%	0%	0%	0%
SINTACS	0%	0%	x	0%	0%	0%
EPPNA	0%	0%	0%	x	0%	0%
GOD	0%	0%	0%	0%	x	0%
AVI	94%	3%	0%	0%	0%	x

C/B	DRASTIC	SI	SINTACS	EPPNA	GOD	AVI
DRASTIC	x	0%	0%	0%	0%	0%
SI	2%	x	1%	1%	0%	0%
SINTACS	5%	3%	x	5%	0%	0%
EPPNA	1%	2%	3%	x	0%	0%
GOD	6%	86%	85%	87%	x	0%
AVI	0%	0%	0%	0%	0%	x

D/B	DRASTIC	SI	SINTACS	EPPNA	GOD	AVI
DRASTIC	x	0%	0%	0%	0%	0%
SI	0%	x	0%	0%	0%	0%
SINTACS	0%	0%	x	0%	0%	0%
EPPNA	2%	0%	0%	x	0%	0%
GOD	84%	1%	0%	0%	x	0%
AVI	0%	0%	0%	0%	0%	x

D/C	DRASTIC	SI	SINTACS	EPPNA	GOD	AVI
DRASTIC	x	0%	0%	0%	0%	0%
SI	92%	x	0%	0%	0%	0%
SINTACS	94%	3%	x	0%	0%	0%
EPPNA	93%	2%	0%	x	0%	0%
GOD	10%	1%	0%	0%	x	0%
AVI	0%	0%	0%	0%	0%	x

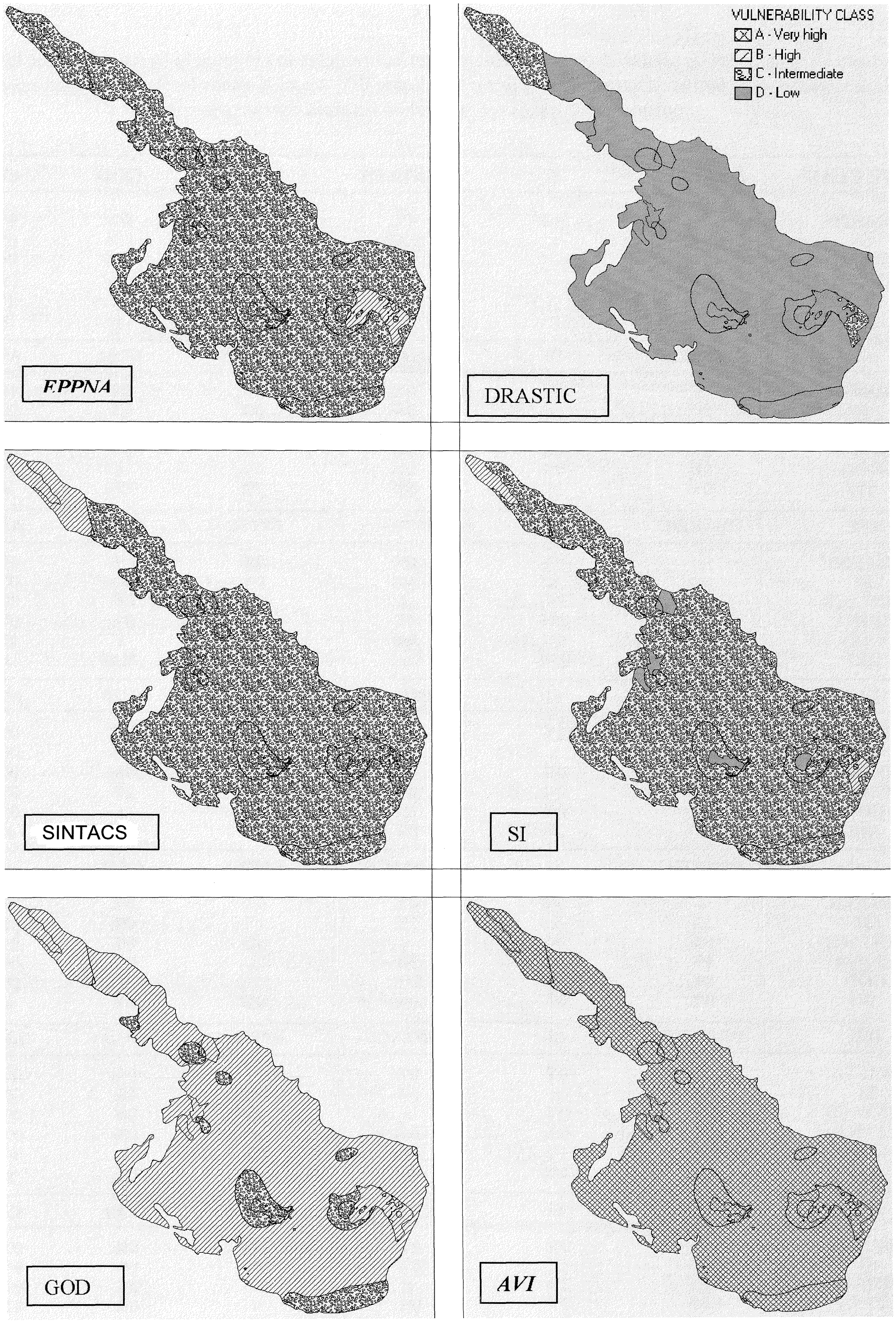

Fig. 5. Application of the different methods to the Évora aquifer system, classified accordingly Table 1.

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