Validity of the vulnerability methods DRASTIC and SI applied by GIS technique to the study of diffuse agricultural pollution in two phreatic aquifers of a semi-arid region (Northeast of Tunisia)

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Abstract: The phreatic aquifer of Oued Guéniche located in the prefecture of Bizerta (northeast of Tunisia) and of the phreatic aquifer of Grombalia located in the prefecture of Nabeul (northeast of Tunisia) have a great economical importance because they are used for irrigation and domestic consumption. They occupy respectively areas of 83 km^2 and 392 km^2. Both aquifers encompass an area comprised mostly of agricultural zones, characterised by an increasing use of chemical fertilizers. Those chemical fertilizers threaten the quality of the ground waters. The study of the vulnerability to pollution of those aquifers was made by applying two vulnerability methods: the generic DRASTIC which is an intrinsic vulnerability method, and the Susceptibility Index (SI) which is a specific vulnerability to agricultural pollution method. This study employed the Geographical Information System (GIS) technology as a system for the acquisition, storage, analysis and display of geographic data. The validity of the two methods to agricultural pollution by nitrates was verified by comparing the distribution of nitrates in the two aquifers with the distribution of the different vulnerability classes. That comparison demonstrated that the SI method is the more valid method in the studied systems.

Keywords: aquifer vulnerability, nitrates, GIS, DRASTIC, SI

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Riassunto: *I due acquiferi studiati sono l'acquifero freatico di Oued Guéniche (governatorato di Bizerta) e l'acquifero freatico di Grombalia (governatorato di Nabeul) situati nel Nord est della Tunisia. Essi hanno una grande importanza dal punto di vista economico poiché sfruttati per l'irrigazione ed il consumo domestico. Questi acquiferi sono localizzati in una pianura prevalentemente adibita all'agricoltura con un utilizzo crescente di fertilizzanti chimici. Occupano rispettivamente superfici di 83 km^2 e 392 km^2 e appartengono a una regione semiarida. Questo studio ha la finalità di verificare la validità del metodo generico parametrico DRASTIC (Aller et al. 1987) e del SI (Riberio, 2000) per la valutazione della vulnerabilità, per il diffuso inquinamento agricolo, essenzialmente a nitrati nelle due aree studiate. L'uso della tecnologia GIS nella valutazione della vulnerabilità dell'acquifero è necessaria poiché il GIS è un sistema per l'acquisizione, l'immagazzinamento, l'analisi e la visualizzazione dei dati geografici. Il Generic DRASTIC è un metodo parametrico che fu sviluppato dall'Agenzia di Protezione Ambientale degli Stati Uniti (US EPA) per la valutazione della vulnerabilità intrinseca verticale del sistema di acque sotterranee a scala regionale.*

SI è un metodo per valutare la vulnerabilità specifica verticale all'inquinamento dovuto all'attività agricola prevalentemente a causa di nitrati. Esso tiene conto delle proprietà dei contaminanti e delle relazioni con i vari componenti della vulnerabilità intrinseca. Il metodo DRASTIC è stato usato con 4 dei parametri iniziali di base mantenuti costanti: la profondità dell'acquifero, la ricarica efficace annuale, l'acquifero medio e la topografia, e ne è stato introdotto uno nuovo: il tipo di terreno di copertura. La validità delle mappe di vulnerabilità derivate dal DRASTIC generico (Aller et al. 1987) e dal SI (Riberio, 2000)per studiare l'inquinamento da nitrati viene verificata nei due acquiferi studiati attraverso la comparazione della distribuzione dei nitrati nell'acquifero e la distribuzione delle classi di vulnerabilità. Tale confronto mostra, nei due acquiferi studiati, che la carta migliore per la valutazione della vulnerabilità a causa dell'inquinamento da nitrati è la quella del metodo SI, con la percentuale di coincidenza, tra la concentrazione dei nitrati e le differenti classi di vulnerabilità , del 70% nel caso dell'acquifero di Oued Guéniche e del 73% nel caso dell'acquifero di Grombalia. La carta del DRASTIC generico mostra una percentuale di coincidenza del 37% nel caso dell'acquifero di Oued Guéniche e del 55% nel caso dell'acquifero di Grombalia. Il metodo DRASTIC è un metodo di vulnerabilità intrinseca che non prende in considerazione né la natura degli inquinanti né i fattori che controllano la vulnerabilità specifica come il fattore dell'uso del suolo. Il comportamento conservativo dei nitrati non permette una corretta valutazione di metodi intrinseci come il DRASTIC, che dà un grande significato alla capacità di attenuazione dei parametri idrogeologici coinvolti. Questi casi studiati mostrano il vantaggio di usare il metodo SI che è stato messo a punto prendendo in considerazione le proprietà chimiche dei nitrati assieme alle esistenti relazioni tra questi inquinanti e i vari componenti considerati nella vulnerabilità intrinseca. In questo specifico metodo di analisi, il parametro uso del terreno permette l'integrazione di specifici fattori per ciascun utilizzo, come l'effetto del riciclo nelle zone irrigate, e quindi permette una migliore sensibilità alle reali condizioni locali.

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Introduction

The underground waters are usually contaminated by pollutants of different natures: biological, chemical or physical. The prevention against the aquifer pollution constitutes an important stage to which scientists are providing an increasing effort specially in studying the aquifer vulnerability. The studied aquifers are the phreatic aquifer of Oued Guéniche (prefecture of Bizerta) and the phreatic aquifer of Grombalia (prefecture of Nabeul) located in the northeast of Tunisia. These aquifers are located in plains used mostly for agriculture caracterized by an increasing consumption of chemical fertilizers. Thus, this study aimed at verifying the validity of the following parametric methods: the generic DRASTIC (Aller et al., 1987) and SI (Ribeiro, 2000) in the assessment of the vulnerability to pollution to diffuse agricultural pollution mainly by nitrates. The first method is an intrinsic vulnerability one; however, the last one is a specific vulnerability to pollution by agricultural pollution. Those methods consist in systems of numerical quotation based on the consideration of different factors affecting the hydrogeological system. The use of GIS technology in the evaluation of aquifer vulnerability is necessary because GIS is a system for the acquisition, storage, analysis and display of geographic data.

The used vulnerability methods

DRASTIC method

DRASTIC (Aller et al., 1987) is a parametric method that was developed by the US Environmental Protection Agency (US EPA) for evaluating the intrinsic vertical vulnerability of groundwater systems on a regional scale. Intrinsic vulnerability is the term used to define the vulnerability of groundwater to contaminants generated by human activities. It takes account of the inherent geological, hydrological and hydrogeological characteristics of an area, but is independent of the nature of human activities. The acronym DRASTIC stands for the parameters included in the method: Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and hydraulic Conductivity of the aquifer. DRASTIC indexes calculated are roughly analogous to the likelihood that contaminants released in a region will reach ground water, higher scores implying higher likelihood of contamination.

The DRASTIC method includes two versions: the generic (or normal) DRASTIC version applied in the case of inorganic pollutants (e.g. in the case of nitrates), and the pesticides DRASTIC version applied in the case of pesticides. The method yields a numerical index that is derived from ratings and weights assigned to the seven model parameters. The significant media types or classes of each parameter represent rating between 1 and 10 based on their relative effect on the aquifer vulnerability. The seven parameters are then assigned weights ranging from 1 to 5 reflecting their relative importance (Tab. 1).

Tab. 1: *Generic DRASTIC parameter weights (Aller et al., 1987)*

Parameter	Weight
D: depth to water	5
R: efficient or net recharge	4
A: aquifer media	3
S: soil media	2
T: topography	1
I: impact of the vadose zone	5
C: hydraulic conductivity of the aquifer	3

The DRASTIC Index is then computed applying a linear combination of all factors according to the following equation :

$$\text{DRASTIC Index} = Dr \cdot Dw + Rr \cdot Rw + Ar \cdot Aw + Sr \cdot Sw + Tr \cdot Tw + Ir \cdot Iw + Cr \cdot Cw$$

where D, R, A, S, T, I, and C are the seven parameters and the subscripts r and w are the corresponding rating and weights, respectively. The DRASTIC index values vary from 23 to 226 in the case of the generic version and fall into 4 classes corresponding to four vulnerability degrees (Tab. 2).

Tab. 2: *Criteria for the evaluation of vulnerability in the DRASTIC method (Aller et al.., 1987)*

Vulnerability degree	Vulnerability index
Low	1 - 120
Moderate	121 - 160
High	161 – 200
Very high	> 200

SI method

SI (Susceptibility Index) method (Ribeiro, 2000) is a vulnerability method for evaluating the specific vertical vulnerability to pollution originated by agricultural activities mainly by nitrates. Specific vulnerability is the term used to define the vulnerability of groundwater to a particular contaminant or group of contaminants. It takes into account of the properties of the contaminants and their relationship with the various components of intrinsic vulnerability.

The DRASTIC method has been used as a base, on which four original parameters have been maintained: depth to water, annual efficient recharge, aquifer media and topography, and a new one has been introduced: the land cover type. The principal types of land use and their assigned ratings provided by a team of Portuguese scientists (Ribeiro, 2000) are shown in Table 3.

Tab. 3: *Main soil occupation classes and correspondant Land Use (LU) values (Ribeiro, 2000)*

Land use class	LU rating
Industrial discharge, landfill, mines	100
Irrigated perimeters, paddy fields, Irrigated perimeters, paddy fields, Irrigated and non irrigated annual culture	90
Quarry, shipyard	80
Artificial covered zones, green zones, continuous urban zones	75
Permanent cultures (vines, orchards, olive trees, etc.)	70
Discontinuous Urban zones	70
Pastures and agro-forest zones	50
Aquatic milieu (swamps, saline, etc.)	50
Forest and semi-natural zones	0

The weight string (Table 4) has been modified in relation to the DRASTIC method. The SI index values measuring the aquifer vulnerability fall into four classes corresponding to four vulnerability degrees (Table 5). The different modifications have been effected taking into consideration the characteristics of common agricultural contaminants, such as the nitrate ion. The following factors were not taken into

Tab. 4: *Weights attributed to SI parameters (varying from 0 to 1, from the less to the most important) (Ribeiro, 2000)*

Vulnerability degree	Vulnerability index
Low	1 - 120
Moderate	121 - 160
High	161 – 200
Very high	> 200

Tab. 5: *Criteria for the evaluation of vulnerability in the SI method (Ribeiro, 2000)*

Parameter	D	R	A	T	OS
Weight	0.186	0.212	0.259	0.121	0.222

consideration: vadose zone media, soil type and permeability of the aquifer media. This last parameter is very difficult to evaluate spatially and it has already taken into consideration in the A parameter (Aquifer media) by the fracturation and granulometry factors. The soil type is indirectly represented by the land use type : "For the purpose of groundwater pollution risk assessment, the soil zone can, in practice, either be allowed for, indirectly when estimating the subsurface pollution load from diffuse sources, or directly in combination with aquifer vulnerability, the resulting categories applying only to diffuse source pollution" (Foster, 1987). Attenuation processes in the soil and vadose zones relative to persistent contaminants are considered by Vrba and Zoporezec (1994) to be of less importance. Foster (1987) also minimizes the vadose zone role: "In the case of persistent mobile pollutants, the unsaturated zone merely introduces a large time-lag before arrival at the water-table, without any beneficial attenuation. In many other cases, the degree of attenuation will be highly dependent upon the flow regime and residence time". In actual fact, besides the cleansing processes, which implicate the degradation of the contaminants, dilution processes are primordial in the vulnerability assessment. They determine the restoration capability of the aquifer, which can also be expressed in terms of residence time (volume of water contained in the aquifer divided by the rate of recharge).

Study areas

Phreatic aquifer of Oued Guéniche

The phreatic aquifer of Oued Guéniche is located in the prefecture of Bizerta (northeast of Tunisia) (Fig. 1). It is situated in a plain between latitudes North 500567.6 and 513208 m and longitudes East 425576.6 and 437778 m (Lambert North Tunisia coordinates) with a total surface of 83 km². The average of thickness of that aquifer is about 30 meters. The main towns and villages in the study area are El Alia, Menzel Jemil, El Khetmine, El Azib, Ejjouaouda, and Daouar Maghraoua. The main rivers crossing the study area are Oued Guéniche, Oued El Azib, Oued El Galaâ, Oued El Hella, Oued Jeddara, Oued El Meleh, and Oued Nechrine. The annual average rainfall varies between 485 and 599 mm and the annual average temperature is about 18 °C (INM, 1985-2005). The water resources of this aquifer have a great economical importance for this agricultural region. In fact, about 1400 wells are currently exploited in the study area and an annual volume of 10.5 million m³ from these wells is used for irrigation (the equivalent of 126.3 mm). The aquifer's area comprises agricultural zones characterised by an increasing use of chemical fertilizers which threatens the groundwater's quality. The identification of the hydrogeological units and subunits as well as the assessment

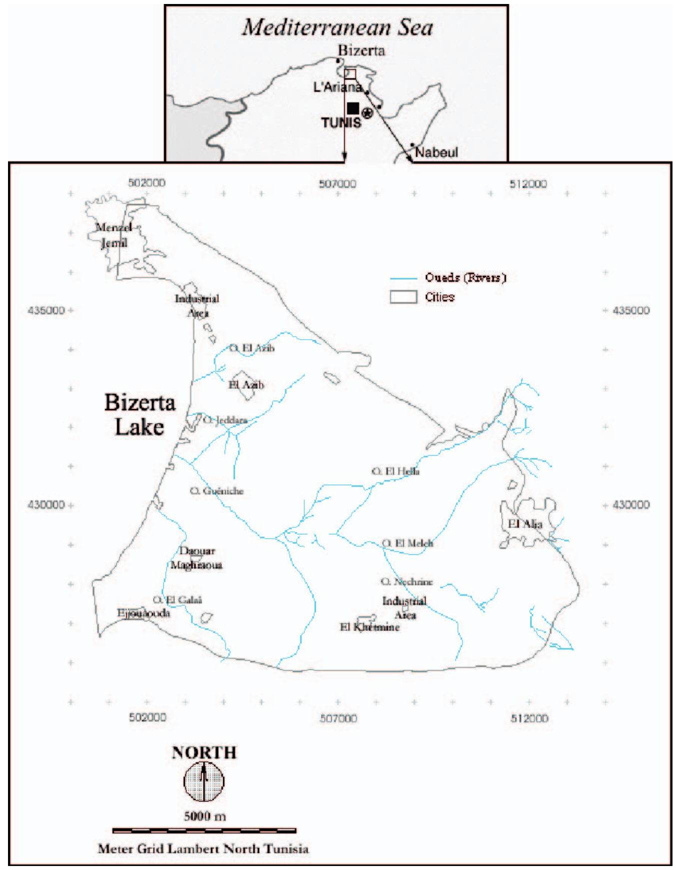

Fig. 1: *The phreatic aquifer of Oued Guéniche*

of the DRASTIC and SI parameters requires a good knowledge of the geology, the hydrogeology, the soil media, the topography, the meteorology and land usage in the study area.

The data used in this study area are taken from different studies: geological (Burollet, 1951 and 1952; El Ghali and Ben Ayed, 2000), hydrogeological (Ennabli, 1966; Haj Ltaief, 1995; DGRE, 2005), geophysical (Ennabli, 1966; Haj Ltaief, 1995), climatic (INM, 1985-2005), pedologic (Le Floc'h, 1959; Gilson, 1995), topographic (OTC, 1981) and land-use (CRDA de Bizerte, 2000) studies.

Phreatic aquifer of Grombalia

The phreatic aquifer of Grombalia covering 392 km² is located in the prefecture of Nabeul (northeast of Tunisia) (Fig. 2). Its is situated in a plain between latitudes North 545432.32 and 565382.32 m and longitudes East 352399.6 and 385249.6 m (Lambert North Tunisia coordinates). The average of thickness of that aquifer located in a Plio-Quaternary sedimentary fill is about 25 meters. The main rivers crossing the study area are Oued Defla, Oued El Jorf, Oued El Bey, Oued Sidi Saïd, Oued Belli, Oued Tahouna and Oued Bezirk. The main towns and villages are Soliman, Soliman plage, Fondouk Djedid, Beni Khalled, Menzel Bou Zelfa, Grombalia, Turki, Nianou and Bou Argoub. The annual average rainfall varies between 356 and 536 mm and the annual average temperature is about 22 °C (INM, 1985-2005). More than 8000 wells are currently exploited in the study area and an annual volume of 90 million m³ is taken from these wells for irrigation (the equivalent of 230 mm). As previously stated, mostly agricultural zones characterised by an increasing use of chemical fertilizers, occupy the study area. The data used in this study area are taken from dif-

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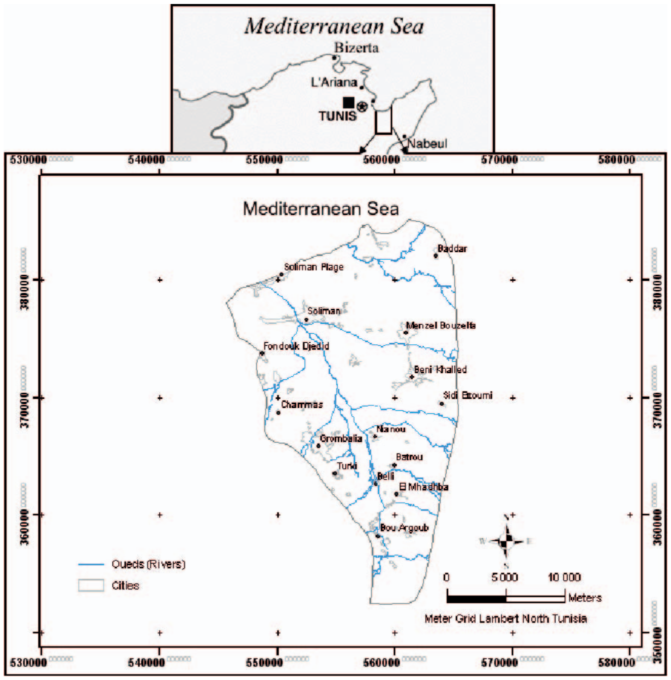

Fig. 2: *The phreatic aquifer of Grombalia*

ferent studies: geological (Schoeler, 1939; Castany, 1948; Ben Salem, 1992), hydrogeological (Ennabli, 1970; DGRE, 2005), climatic (INM, 1985-2005), pedologic (CRDA, 1997, 1998, 1999 and 2000), topographic (OTC, 1981) and land-use (CRDA de Nabeul, 2002) studies.

GIS, an efficient tool for the study of aquifer vulnerability

GIS (Geographic Information System) technology allows a correct and continuous evaluation of the aquifers' potential concerning the exploitation capacity and vulnerability towards the danger of contamination with different pollutants, creating an objective overview. GIS means: Maps (document that contains data and describes hydrogeological events), information that is structured into a Database (information that can be used in the surveillance of the correct exploitation of groundwater) and Correlations between the two types of information: graphical and non-graphical (they are at the base of interpretations, studies, water supply systems design, evaluation and impact on the environment).

In the case of Oued Guéniche aquifer, the software IDRISI ANDES and CartaLinx produced by the Graduate School at Clark University (USA) were used to establish the different thematic maps and to generate the vulnerability to pollution maps. IDRISI ANDES is the industry leader in raster analytical functionality, covering the full spectrum of GIS and remote sensing needs from database query, to spatial modeling, to image enhancement and classification. Special facilities are included for environmental monitoring and natural resource management, including land change modeling and time series analysis, multicriteria and multi-objective decision support, uncertainty and risk analysis, simulation modeling, surface interpolation and statistical characterization. CartaLinx is a spatial data Builder, a digital map development tool that serves as a companion to IDRISI. CartaLinx uses a full topological editor/digitizing system with capabilities for automatically building vector topology; automated generation of polygons and assignment of ID's by means of polygon locators (label points); insertion, deletion, or movement of nodes, arcs or arc vertices; real-time projection/datum transformation of digitizer and GPS input data to meet mapping reference system specifications; feature filtering and extraction to new spatial databases based on feature attributes (filter) or location (clip).

While, in the case of the aquifer of Gromabalia, ArcGIS version 9.2 was used. ArcGIS produced by ESRI, is a complete integrated collection of GIS software products that provides a standards-based platform for spatial analysis, data management, and mapping. At the desktop GIS level, ArcGIS can include: ArcReader, which allows one to view and query maps created with the other Arc products; ArcView, which allows one to view spatial data, create layered maps, and perform basic spatial analysis; ArcEditor which, in addition to the functionality of ArcView, includes more advanced tools for manipulation of shapefiles and geodatabases; or ArcInfo which includes capabilities for data manipulation, editing, and analysis.

Application of the DRASTIC and SI methods in the phreatic aquifer of Oued Guéniche

Application of the generic DRASTIC method

The depth to water map was obtained by interpolating 122 depth to water values homogenously distributed in the study area, recorded in 2005 by the DGRE. The aquifer net recharge was calculated according to the Williams and Kissel method (1991), the most suitable method to the studied area (Hamza et al., 2006). The aquifer media was determined using lithostratigraphic correlations based on the data of electric prospection, of boring logs and of geological maps of the study area (Haj Ltaief, 1995). Six geoelectric sections passing by 13 boring logs distributed in the study area have been established. In addition to these data, the values of hydraulic conductivity of the aquifer (Ennabli, 1966) measured in 9 well distributed localities were used to estimate the aquifer lithology in these localities based on tables giving approximate values of hydraulic conductivity for different lithologic types of the aquifer (Rodrìguez et al., 2001). All these data, as well as the 2005 data of depth to water, permitted to determine the thickness as well as the lithology of the aquifer. The pedologic data was extracted from two sources: the pedologic map at the 1:50.000 scale of the southern border of the lake of Bizerta (Le Floc'h, 1959) and the hydropedologic map (1:12.500 scale) of the area of Menzel Jemil - El Alia (Gilson, 1995). The surface slope map was established using the 4 topographic maps (1:25.000 scale) covering the study area (OTC, 1981). The data of lithology of the vadose zone was extracted as the same way as the aquifer lithology data. Finally, the hydraulic conductivity of the aquifer has been determined referring to the 9 values of hydraulic conductivity already mentioned. Moreover, we used the established map of aquifer lithology as a base to estimate the values of hydraulic conductivity using (Rodrìguez et al., 2001). When all thematic maps had been registered and geo-referenced, they were on-screen digitized to create point, segment, and polygon maps of the different geographical enti ties. The different obtained maps are first classified according to the DRASTIC classification using the IDRISI ANDES Reclass function. Second, by using the Image Calculator function of IDRISI ANDES, each mapped parameter is multiplied by the value of its weight. Third, the seven numerical maps are gathered, hence we obtain a vulnerability index map. The latter is itself classified according to the DRASTIC classes (Tab. 2) to establish the final vulnerability map.

The established generic DRASTIC map (scale 1:50.000) shows three vulnerability classes: low, moderate and high (Fig. 3). The low vulnerable zones occupy 78%, the medium vulnerable zones occupy 21% and the high vulnerable ones occupy less than 1% of the total area.

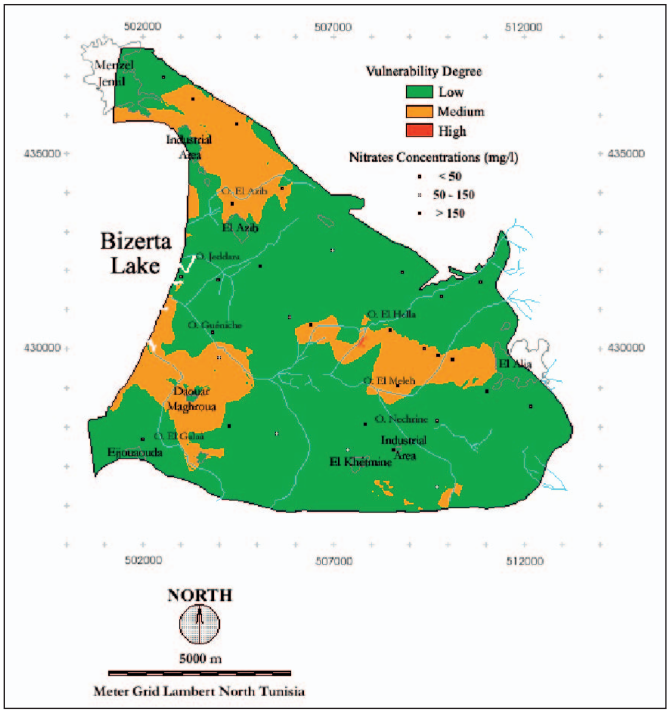

Fig. 3: *Generic DRASTIC vulnerability map of Oued Guéniche phreatic aquifer*

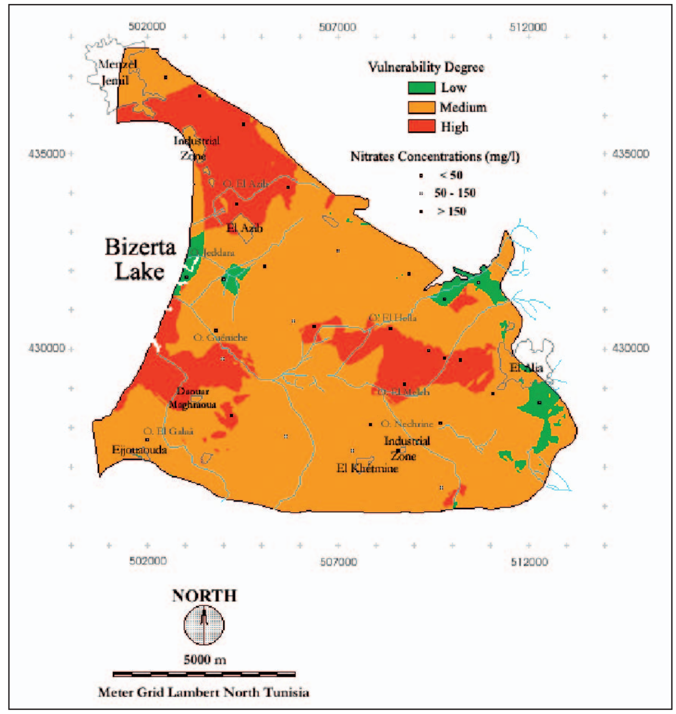

Fig. 4: *SI vulnerability map of Oued Guéniche phreatic aquifer*

Application of the SI method

The four maps related to the parameters depth to water, annual efficient recharge, aquifer media and topography were already prepared in the frame of the elaboration of the DRASTIC map. The preparation of the land use map was based on that of the prefecture of Bizerta (CRDA de Bizerte, 2002). The five thematic maps are classified using the IDRISI ANDES Reclass function. Then, each mapped parameter is multiplied by the value of its weight. Later on, the five numerical maps are gathered to establish a vulnerability index map which is itself classified according to the SI classes (Tab. 5) ending by obtaining the final vulnerability map. The obtained SI vulnerability map (scale 1:50.000) shows three vulnerability classes: low, medium and high (Fig. 4). The low vulnerability zones occupy 4%, the moderate vulnerability zones occupy 75% and the high vulnerability ones occupy 21% of the total area.

Application of the DRASTIC and SI methods in the phreatic aquifer of Grombalia

Application of the generic DRASTIC method

The depth to water map was obtained by interpolating 400 depth to water values recorded in the study area (DGRE, 2005). The aquifer net recharge was calculated according to the Williams and Kissel method (1991). The aquifer media was determined using lithostratigraphic correlations, the 1:50.000 scale geological maps covering the study area: Grombalia (Azzouz, 1971), Menzel Bou Zelfa (Ben Salem, 1977) and Nabeul (Colleuil, 1976) as well as the 2005 depth to water data. The pedologic data was extracted from local studies done by the CRDA of Nabeul (1997, 1998, 1999 and 2000). The surface slope map was established using the 1:25.000 topographic maps covering the study area (OTC, 1981). The lithology of the vadose zone data was extracted as the same way as the aquifer lithology data and the hydraulic conductivity of the aquifer has been deducted referring the map of aquifer lithology using the table established by Rodrìguez et al. (2001) giving the hydraulic conductivity values for different types of aquifer lithology. The different digitized maps are classified according to the DRASTIC classification using the ArcGIS Reclass function. By using the Raster Calculator function, each mapped parameter is multiplied by the value of its weight. Finally, the seven numerical maps are gathered to obtain a vulnerability index map which is classified according to the DRASTIC classes (Tab. 2) to establish the final vulnerability map. The generic DRASTIC map of Grombalia aquifer (scale 1:50000) shows three vulnerability classes: low, moderate and high (Fig. 5). The low vulnerable zones occupy 24%, the medium vulnerable zones occupy 60% and the high vulnerable ones occupy 16% of the total area.

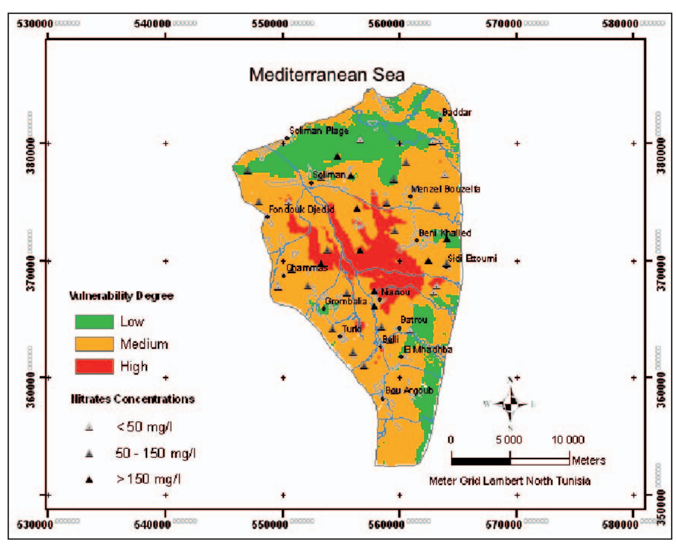

Fig. 5: *Generic DRASTIC vulnerability map of Grombalia phreatic aquifer*

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Application of the SI method

The four maps related to the parameters depth to water, annual efficient recharge, aquifer media and topography were already prepared when DRASTIC map was elaborated. The preparation of the land use map was based on that of the prefecture of Nabeul (CRDA de Nabeul, 2002). The final classified SI vulnerability map (scale 1:50.000) obtained under ArcGIS shows three vulnerability classes: low, medium and high (Fig. 6). The low vulnerability zones occupy 3%, the moderate vulnerability zones occupy 62% and the high vulnerability ones occupy 35% of the total area.

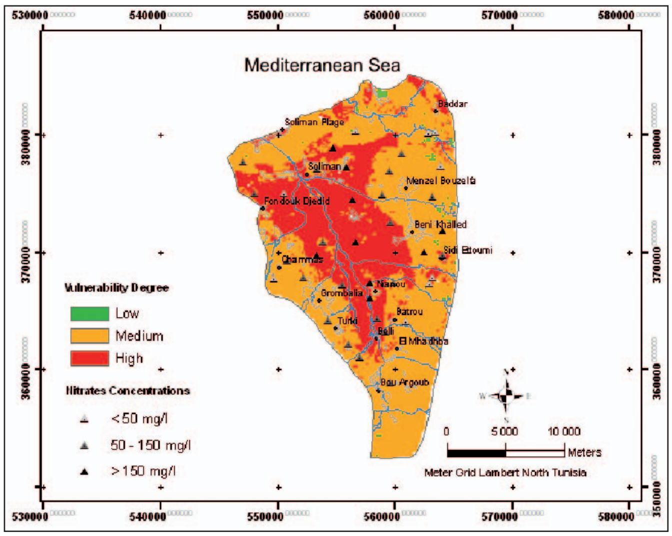

Fig. 6: *SI vulnerability map of Grombalia phreatic aquifer*

Vulnerability to pollution by nitrates, validity of the used methods

The validity of the generic DRASTIC (Aller et al., 1987) and SI (Ribeiro, 2000) methods to the study of pollution by nitrates was verified in the two studied aquifers by comparing the distribution of nitrates in the groundwater and the distribution of the vulnerability classes. Stigter et al. (2006) defined the low nitrate concentrations as the concentrations lower than 50 mg l-1, the moderate ones as the ones between 50 mg l-1 and 150 mg l-1, and the high ones as those larger than 150 mg l-1.

Aquifer of Oued Guéniche

There are 30 available nitrate measures registered in the study area (DGRE, 2005). Based on Table 6, we can deduce that the nitrate concentrations are distributed as follows:

• For the generic DRASTIC map, among the 12 values exceeding 150 mg l-1, 8 values (67% of the values) coincide with the moderate-vulnerability zone, 4 (33% of the values) with the low-vulnerability zone and no one with the high-vulnerability zone. Among the 6 values situated between 50 and 150 mg l-1, only 1 (17% of the values) coincides with the moderate-vulnerability zone and 5 (83% of the values) with the low vulnerability one. Finally, among the 12 values below 50 mg l-1, 10 (83% of the values) coincide with the low-vulnerability zone and only 2 (17%) with the moderate-vulnerability zone;

• For the SI map, among the 12 values exceeding 150 mg l-1, 10 (83% of the values) coincide with the high-vulnerability zone, and only 2 (17% of the values) with the moderate vulnerability one. Among the 6 values situated between 50 and 150 mg l-1, 5 (83% of the values) coincide with the moderate vulnerability zone, and only 1 with the low-vulnerability zone. Finally, among the 12 values below 50 mg l-1, 6 (50% of the values) coincide with the low-vulnerability zone, and 6 others with the moderate-vulnerability one.

Vulnerability to pollution by nitrates, validity of the used methods

There are 38 available nitrate measures registered in the study area (DGRE, 2005). Based on Table 7, we can deduce that the nitrate concentrations are distributed as follows:

- For the generic DRASTIC map, among the 9 values exceeding 150 mg l-1, 3 values (34% of the values) coincide with the high-vulnerability zone, 4 (44% of the values) with the medium-vulnerability zone and 2 (22% of the values) with the low-vulnerability zone. Among the 20 values situated between 50 and 150 mg l-1, 14 (70% of the values) coincides with the moderate-vulnerability zone, 3 (15% of the values) with the low vulnerability zone and 3 with the high vulnerability one. Finally, among the 9 values below 50 mg l-1, 4 (44% of the values) coincide with the low-vulnerability zone and 3 (34% of the values) with the medium-vulnerability and only 2 (22%) with the high-vulnerability zone;
- For the SI map, among the 9 values exceeding 150 mg l-1, 7 (77% of the values) coincide with the high-vulnerability zone, 1 (11% of the values) with the moderate vulnerability one and 1 with the low

Tab. 6: *Coincidence between nitrate concentrations and the different vulnerability classes of the DRASTIC and SI methods, case of Oued Guéniche aquifer*

		Number of high values of $[NO_3^-]$ (> 150 mg/l)	Number of moderate values of $[NO_3^-]$ (stated between 50 and 150 mg/l)	Number of moderate values of $[NO_3^-]$ (< 50 mg/l)
Generic DRASTIC vulnerability map	High Vulnerability	0	8	4
	Moderate Vulnerability	0	1	5
	Low vulnerability	0	2	10
SI vulnerability map	High vulnerability	10	2	0
	Moderate vulnerability	0	5	1
	Low vulnerability	0	6	6

Tab. 7: *Coincidence between nitrate concentrations and the different vulnerability classes of the DRASTIC and SI methods, case of Grombalia aquifer*

		Number of high values of [NO_3^-] (> 150 mg/l)	Number of moderate values of [NO_3^-] (stated between 50 and 150 mg/l)	Number of moderate values of [NO_3^-] (< 50 mg/l)
Generic DRASTIC vulnerability map	High Vulnerability	3	3	2
	Moderate Vulnerability	4	14	3
	Low vulnerability	2	3	4
SI vulnerability map	High vulnerability	7	3	1
	Moderate vulnerability	1	15	2
	Low vulnerability	1	3	6

vulnerability zone. Among the 21 values situated between 50 and 150 mg l-1, 15 (72% of the values) coincide with the moderate vulnerability zone, 3 (14% of the values) coincide with the low-vulnerability zone and 3 with the low vulnerability. Finally, among the 9 values below 50 mg l-1 6 (67% of the values) coincide with the low-vulnerability zone, 2 others (22% of the values) with the moderate-vulnerability and 1 (11% of the values) with the low vulnerability.

Conclusions

The comparative study of the vulnerability maps DRASTIC and SI to the available nitrate measures shows in the two studied phreatic aquifers that the most valid map for the assessment of the vulnerability to pollution by nitrates is the SI map, with a coincidence percentage between the nitrate concentrations and the different vulnerability degrees of 70% in the case of the aquifer of Oued Guéniche and of 73% in the case of Grombalia aquifer. The generic DRASTIC map demonstrates a coincidence percentage of 37% in the case of the aquifer of Oued Guéniche and of 55% in the case of Grombalia aquifer. The DRASTIC method is an intrinsic vulnerability method which do not takes into consideration neither the nature of pollutants nor the factors managing the specific vulnerability as the land use factor. The conservative behaviour of nitrates does not permit a correct vulnerability assessment by intrinsic methods such as DRASTIC, which ascribe a great significance to the attenuation capacity of the involved hydrogeological parameters.

These cases studies show the advantage of using the SI method that take into consideration the chemical properties of nitrates and the existing relations between this pollutant and the various components considered in the intrinsic vulnerability. In that specific vulnerability method, the land use parameter allows the integration of specific factors for each type of land use, such as the recycling effect in irrigation zones, and allows a better sensibility to the real local conditions.

The SI method was verified in many study areas in Portugal (Francés et al., 2002; Ribeiro et al. 2003; Stigter et al., 2006) and in Tunisia (Hamza et al., 2007, Maâlej et al., 2009). However, since the susceptibility index is an empirical method, a better evaluation of the weight of each parameter and a more specific rating of land, taking into account factors as duration, quantity and intensity of fertilizer application in a specific area, will allow obtaining a more accurate result.

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