Comparison between an intrinsic and a specific vulnerability method using a GIS tool: case of the Smar aquifer in Maritime Djeffara (southeastern Tunisia)

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ABSTRACT

The assessment of groundwater vulnerability to pollution has proved to be a useful tool to delimitate zones affected by groundwater contamination. For this reason, development of groundwater vulnerability maps became a useful tool for protecting groundwater resources from pollution. The Smar aquifer belongs to maritime Djeffara (southeastern Tunisia); it is essentially occupied by agricultural areas characterized by an intensive use of chemical fertilizers. The vulnerability mapping was performed by using (i) DRASTIC method (intrinsic vulnerability) that takes into account seven parameters and (ii) Susceptibility Index (SI) method (specific vulnerability) that considers five parameters. The results show that the study area is classified into three classes of vulnerability: low, medium and high for the two methods with an uneven spatial distribution. Most of the study area belongs to the class of medium vulnerability (74% and 46% of the total area for the DRASTIC and SI methods, respectively). Indeed, the validation of DRASTIC and SI models with nitrates values revealed correlation coefficient values of about 61% and 73%, respectively. The comparison between the two methods shows that the SI method is more significant for the study area. Hence, these maps could serve as a scientific basis in groundwater management.

Key words | aquifer, DRASTIC, geographical information system (GIS), Susceptibility Index (SI), vulnerability, Wadi Smar Medenine

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INTRODUCTION

In arid and semi-arid regions, water resources are scarce and considered to be a most important resource although characterized by low rainfall and high evapotranspiration. However, these resources are threatened by water contamination and overexploitation thanks to increasing population and high living standards in most arid countries and the excessive water demands of industries, as well as urban uses and agriculture. These conditions result in some constraints on groundwater uses and management, therefore influencing regional economic development. This concept has been termed 'groundwater vulnerability to contamination' (Yin *et al.* 2012). For this reason, scientists and managers have thought to develop aquifer vulnerability techniques for predicting the most vulnerable areas.

According to Albinet & Margat (1970), aquifer vulnerability was defined as 'the possibility of percolation and diffusion of contaminants from the ground surface into natural water-table reservoirs under natural conditions'. The same authors distinguish two types of vulnerability: specific vulnerability, describing vulnerability as a function of the potential impacts of land uses (LU) and contaminants, and intrinsic vulnerability, describing vulnerability as a function of hydrological factors.

During the past years, the assessment of groundwater vulnerability to pollution has been the subject of intensive research. To estimate groundwater vulnerability, various methods have been developed and are grouped into three types (Vrba & Zaporozec 1994): hydrogeological setting

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methods, parametric methods, and numerical models. Among these methods, we cite a few methods such as GOD (Foster 1987), AVI (Van Stempvoort *et al.* 1993), SINTACS (Civita 1999) and GALDIT (Chachadi & Leitao 2002). These methods can be used to assess soil and predict groundwater contamination in agricultural and industrial areas, considering the different evaluation factors and approaches such as hydraulic parameters and pollution load. The development of these various methods to evaluate the vulnerability of aquifers has usually been achieved by mapping a number of physical parameters using a geographical information system (GIS) environment. Several studies have used GIS techniques including Goodchild (1993), Troge (1994), Sinan *et al.* (2003), and Rebolledo *et al.* (2016), among others.

Several studies of groundwater vulnerability undertaken in semi-arid regions have shown that the factors determining the vulnerability of aquifers are mainly the topography, the LU, the low depth to water and the high permeability of the soil (Saidi *et al.* 2011; Ben Brahim *et al.* 2012). The Smar phreatic aquifer (southeast Tunisia) was classified among the semi-arid regions and characterized by an intensive increase of water demands. In addition to natural factors, the anthropogenic activities are causes of concern for effective sustainable management and water use. Furthermore, the growing contamination problems of phreatic aquifers are considered as an irreversible process (Saidi *et al.* 2011). Indeed, water resources are threatened by overexploitation through irrigation uses and industrial demands.

The main objective of this study is the assessment of the groundwater vulnerability in Smar phreatic aquifer by developing two methods: DRASTIC (intrinsic vulnerability) which evaluates the vulnerability of the phreatic aquifer according to the hydrogeological parameters; and Susceptibility Index (SI) (specific vulnerability) to determine the location of the vulnerable areas according to human activities, especially to evaluate pollution of the phreatic aquifer according to nitrate contamination (agriculture).

STUDY AREA

The study area consists of the Smar phreatic aquifer of Medenine, which is a part of the vast plain of Djeffara (southeastern Tunisia) and covers an area of 590 km^2 (Figure 1). It is limited in the west by Om Ettamer aquifer, in the north by El Fje aquifer, in the east by El Maidher and Bou Hamed aquifers, and in the south by Bir Lahmar aquifer.

It is characterized by an arid to semi-arid climate where mean temperature varied from 30.1°C in summer to 12.4°C in winter during the 1968–2015 period, and the average rainfall is about 91 mm over 33 years (1981–2014), as obtained from the National Institute of Meteorology of Medenine.

The lithology of the study area is dominated by Mio-Plio-Quaternary deposits composed essentially of clay, conglomerate, silt, sandstone, and alluvium. Smar aquifer thickness varies from 65 m in the southwest to 10 m in the northeast.

The piezometric map established for 2014 shows that head values range between 40 m and 110 m (Figure 2(a)). It reveals a general flow direction from the southwest to the northeast showing a mixed relation with Wadi Smar.

The Smar aquifer is characterized by high salinity that exceeds 5 g/L. The lower salinity (1.5 g/L) is located in the center whereas the higher salinity (5.4 g/L) is located in the northeast of the study area (Figure 2(b)). Smar groundwater is threatened by different sources of pollution, such as agriculture and artificial recharges (Steppe Medenine, ONAS). The aquifer is basically recharged by precipitation, water irrigation, and domestic rejections.

TOOLS AND METHODS

Data sources

This study is based essentially on the Regional Commissionership for the Agricultural Development of Medenine 'RCSAD' data, which were completed by piezometric and hydrochemical field measures. The hydrogeological parameters of DRASTIC and SI models were obtained by the data listed in Table 1.

Tools

The tool used in this study is ArcMap 10.1 extension of the GIS. It is designed to capture, store, manipulate, analyze, manage, and present all types of spatial or geographical data. Also, Troge (1994) noted that this computer-based tool has allowed successful integration of water quality variables into a comprehensible format. Consequently, GIS has a great ability to manage a large volume of spatial data from a variety of sources.

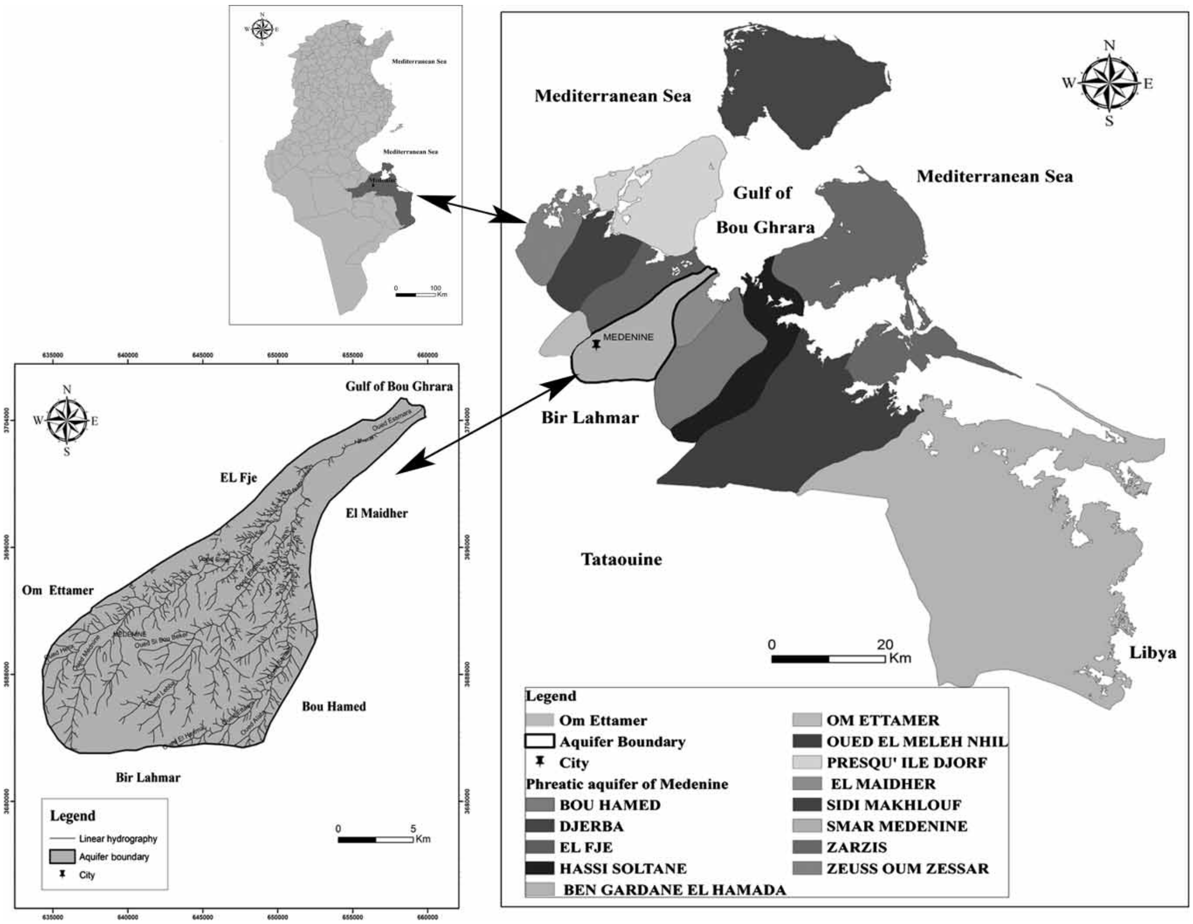

Figure 1 | Location of the study area.

Methods

In the present study, two methods were applied to evaluate the vulnerability assessment of the Smar phreatic aquifer to give an idea about the vulnerable areas taking into account the hydrogeological parameters and to determine the vulnerability caused by anthropogenic activities (agricultural activity developed in the study area). The vulnerability models are elaborated using several data such as those presented in Figure 3.

DRASTIC method

The DRASTIC method is a parametric system method developed by Aller *et al.* (1987) for the US Environmental Protection Agency (EPA). It is one of the most frequently used methods to assess aquifer vulnerability. This method includes several factors that characterize aquifers (US EPA 1985). It is applied in various countries, such as Tunisia (Saidi *et al.* 2011), Morocco (Ettazarini 2006), Palestine (Mimi *et al.* 2012), Portugal (Ferreiro & Oliveira 2004; Pacheco & Sanches Fernandes 2012), among others.

The DRASTIC method uses seven parameters to determine the index number: depth to water (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I), and hydraulic conductivity of the aquifer (C). Each parameter considers a weighting coefficient and a numerical relative rating. The ratings range from 1 (least pollution potential) to 10 (highest pollution potential) according to their relative impact on the pollution potential. Also, each parameter is assigned by a weighting coefficient which varies from 1 to 5 (Table 2), according to their importance in pollution transport outside and within the aquifer. A DRASTIC index (DI) can be obtained by

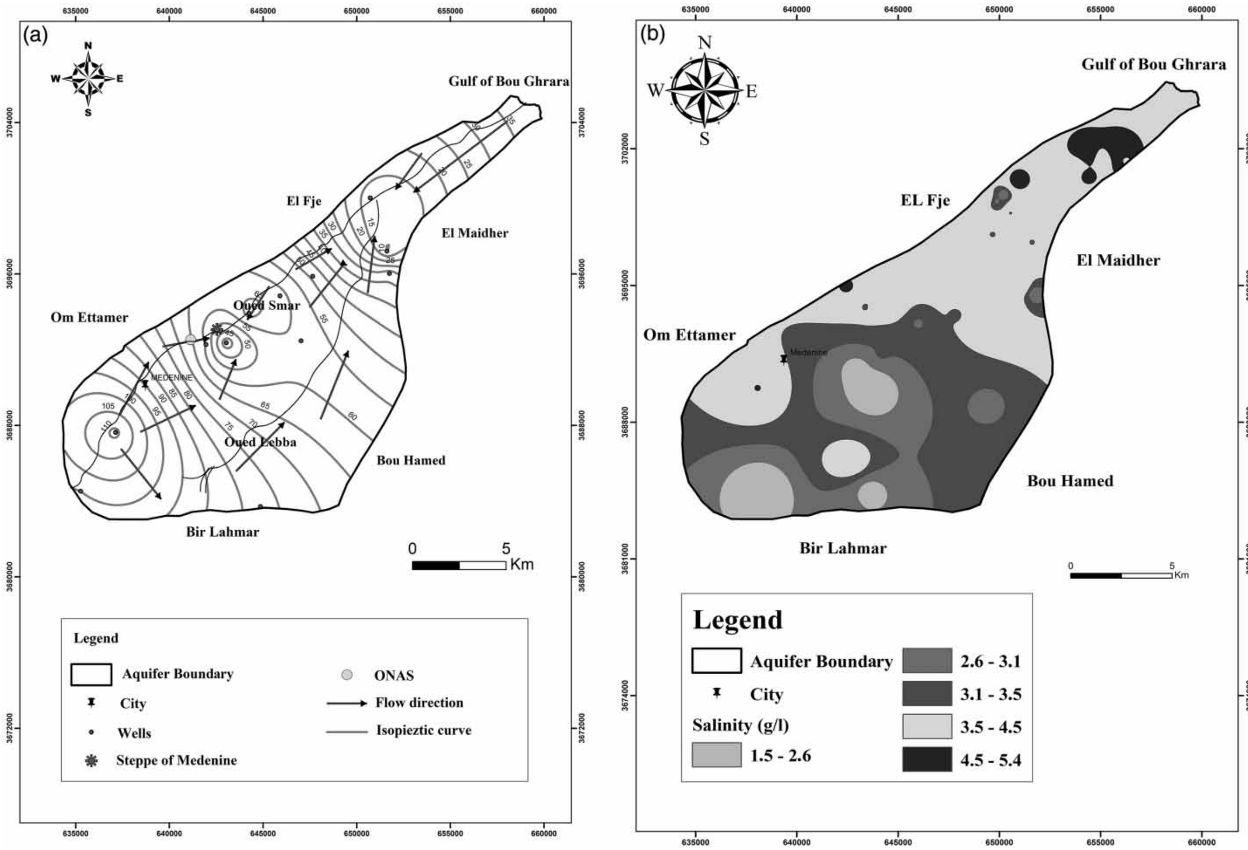

Figure 2 | Piezometric and salinity maps.

Table 1 | Data sources

Parameters	**Data sources**	**Mode of processing**
D	Hydraulic data: from 44 wells and 9 piezometers	Interpolation
R	Rainfall data, from INM Medenine and Landform information, from RCSAD of Medenine	Interpolation
A	Geological logs using borehole data	Interpolation
S	Soil map of the region released by CRDA Medenine	Digitalization
T	Topographic map obtained from CRDA Medenine	Digitalization
I	Geological logs using borehole data	Interpolation
C	Pumping test, transmissivity, thicknesses of the aquifer	Interpolation
LU	Agriculture map for the Smar region performed by CRDA Medenine	Digitalization

applying the following equation:

$$\mathbf{DI} = D_r \times D_w + R_r \times R_w + A_r \times A_w + S_r \times S_w + T_r \times T_w + I_r \times I_w + C_r \times C_w \quad (1)$$

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 (Aller *et al.* 1987). The DI can be divided into four categories (Engel *et al.* 1996): low, moderate, high, and very high (Table 3).

SI method

The specific vulnerability assessment method, SI, was created by Ribeiro (2000) and was developed with the objective of evaluating aquifer vulnerability to diffuse agricultural pollution. It represents an adaptation of the DRASTIC method. This method has been applied to several case studies, for example, in Portugal (Lobo-Ferreira *et al.* 2003).

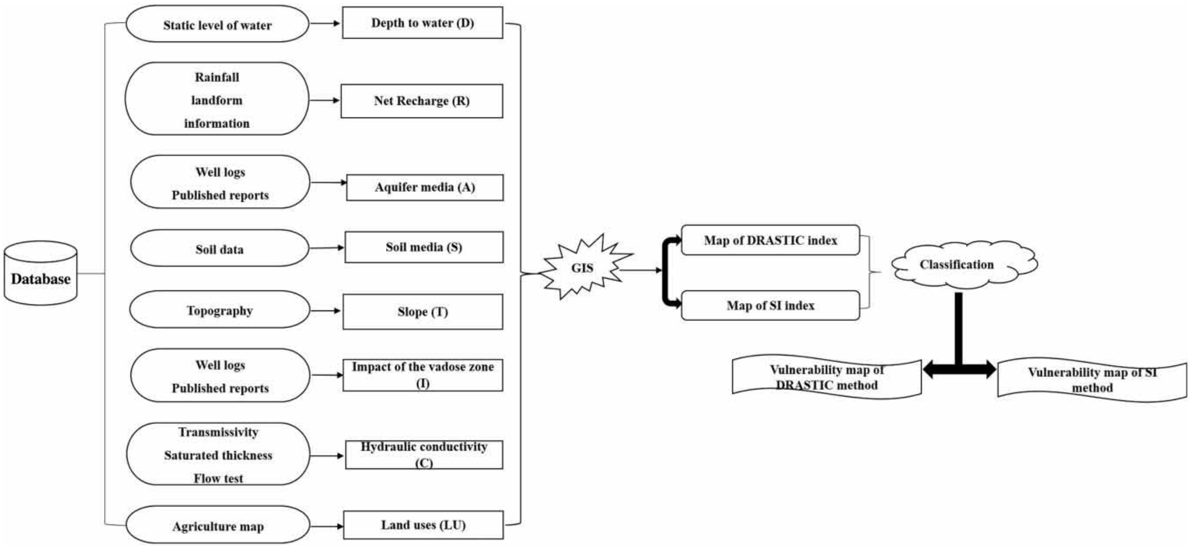

Figure 3 | Model schema for DRASTIC and SI models.

Table 2 | Weight settings of DRASTIC parameters (Aller et al. 1987)

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

Table 3 | Vulnerability classes in the DRASTIC method (Engel et al. 1996)

DI	Pollution susceptibility
>200	Very high
141–200	High
101–140	Medium
23–100	Low

This method evaluates the specific vertical vulnerability to pollution originated by agricultural activities, mainly by nitrates. This method uses five parameters: the first four are used in the DRASTIC method (D: depth to water, R: net recharge, A: aquifer media, and T: topography) and the fifth one considered is the LU parameter.

The SI index can be obtained by applying the following equation:

$$\mathbf{SI} = Dr \times Dw + Rr \times Rw + Ar \times Aw + Tr \times Tw + LUr \times LUw \quad (2)$$

where D, R, A, T, and LU are the five parameters and the subscripts r and w are the corresponding rating and weights, respectively.

The rating system of LU class ranges from 0 to 100 (Table 4). The same as the others, ratings parameters

Table 4 | Main soil occupation classes and their correspondent LU values (Ribeiro 2000)

Land classification	LU (land use factor)
Industrial waste discharges, landfill	100
Irrigated rice fields	90
Caries, shipyards, open-air mines	80
Areas covered artificial, green spaces	75
Permanent crops (vineyards, orchards, olives, etc.)	70
Discontinuous urban areas	70
Pasture and agro-forestry	50
Aquatic environments (saltmarshes, salinas, etc.)	50
Forests and semi-natural zones	0

have been multiplied by 10 to facilitate the reading of results. The affected weight for each parameter is given in Table 5.

The SI index values are distributed among four classes: low, moderate, high, and very high (Table 6).

Determination of DRASTIC and SI parameters

Depth of groundwater (D)

This parameter represents the depth from the ground surface to the first groundwater aquifer. It determines the thickness of material through which infiltrating water must move before reaching the saturated zone. Therefore, the deeper the water levels, the longer time the pollutant takes to reach the groundwater table. The depth to water was established by measuring the groundwater level in 44 wells and nine piezometers located in the Smar watershed.

Net recharge (R)

This parameter corresponds to the rain water and artificial recharge which are available to migrate down to the groundwater. The net recharge is the most important vehicle that transports contaminants to the groundwater. In this study, this parameter was determined by General Direction of Water Resources indexes, where efficient recharge depends on the precipitation percentage and the soil permeability: 6% for high permeability, 4% for moderate permeability, and 2% for low permeability (BougHariou *et al.* 2014). The net recharge of the study area was calculated from the permeability map and the rainfall variation map.

Table 5 | SI parameters and their corresponding weight (Ribeiro 2000)

Parameters	Weights
D: depth to water	0.186
R: net recharge	0.212
A: aquifer media	0.259
T: topography	0.121
LU: land uses	0.222

Table 6 | Vulnerability classes in the SI method

Vulnerability class	Index
Low	<45
Moderate	45–64
High	65–84
Very high	85–100

Aquifer media (A)

This represents the lithology of the saturated zone calculated by the lithology logs. In the present study, we used the Castany equation (Equation (3)) to determine the equivalent permeability of the saturated zone:

$$\mathbf{K_{mh}} = \mathbf{K_{eq}} = (h_1k_1 + h_2k_2 + \ldots h_nk_n.)/H \quad (3)$$

where K_{mh} is the average of the horizontal permeability (m/s), H is the total thickness of the aquifer (m), h_i is the thickness of layer i (m), and k_i is the permeability of layer i (m/s) (Castany 1982).

Soil media (S)

The soil media represents the upper layer of the earth. This parameter indicates the recharge rate that could infiltrate into the aquifer. In this study, the soil parameter was obtained by digitizing the existing soil maps covering the region which were collected from the RCSAD of Medenine.

Topography (T)

This parameter refers to the slope percentage of the land surface. Theoretically, the topography controls the likelihood that a contaminant will run off or rest on the surface in an area long enough to infiltrate. The topography of the study area was determined from the topographic maps obtained from the RCSAD of Medenine.

Impact of the vadose zone (I)

The vadose zone represents the unsaturated zone of subsoil. It influences the percolation of rainfall and surface flow (Aller *et al.* 1987). In this study the equivalent permeability of the material was calculated by using well logs. This parameter was estimated by the Castany equation (Equation (4)):

$$\mathbf{K_{mv}} = \mathbf{K_{eq}} = \mathrm{H}/(\mathrm{h}_1/\mathrm{k}_1 + \mathrm{h}_2/\mathrm{k}_2 + \ldots.\mathrm{h}_n/\mathrm{k}_{n.}) \quad (4)$$

where K_{mv} is the average of the vertical permeability (m/s), H is the total thickness of the unsaturated layer (m), h_i is the thickness of layer i (m), and k_i is the permeability of layer i (m/s).

Hydraulic conductivity (C)

The hydraulic conductivity is defined as the ability of aquifer materials to transmit water and to control the groundwater flow under a given hydraulic gradient. This parameter was calculated by the following equation:

$$\mathbf{K} = \mathrm{t}/\mathrm{b} \quad (5)$$

where K is the hydraulic conductivity (m/s), b is the thickness of the aquifer (m), and t is the transmissivity (m^2/s), measured from the field pumping test data.

LU

The LU parameter plays a very important role in assessing vulnerability. In fact, it intervenes in pollutant infiltration in soil. In this study, this parameter was extracted from the agriculture map covering the Smar watershed obtained from RCSAD of Medenine.

Model validation

Generally, any vulnerability map should be tested and validated. The frequently used validation methods are process simulation method, artificial tracer test, hydrographs, chemographs, the measurement and analysis of chemical elements in groundwater (nitrate concentrations, chloride concentrations, etc.), statistical methods, etc. (Huan *et al.* 2012). In the present study, the selection of chemical method was based on the fact that the study area is contaminated, especially by nitrates, as a result of the high use of rates of nitrogenous fertilizers (agriculture activities).

In order to validate vulnerability models (DRASTIC and SI), a correlation between vulnerability classes and vulnerability indexes and nitrate concentration values have been established. In 2000, Ribeiro stated the highest concentrations were those greater than 150 mg/L, the medium concentrations were those between 50 mg/L and 150 mg/L, and the lower concentrations were those below 50 mg/L (Ribeiro 2000). The nitrate concentration values used in this study were obtained from the RCSAD of Medenine.

RESULTS AND DISCUSSION

The thematic maps representing the depth of groundwater (D), net recharge (R), aquifer media (A), impact of the vadose zone (I), hydraulic conductivity (C), and LU parameters were created by interpolation of the raw data using the interface ArcMap 10.1 and projected in 'WGS 1984 UTM Zone 32N'.

The water depth parameter (D) varies from 5.16 to 49.4 m. The Smar phreatic aquifer shows a low depth of water which makes it more vulnerable to pollution. Five significant intervals of this parameter were identified and assigned by rating varying from 1 to 7 according to Aller *et al.* (1987) (Figure 4(a)). The areas with low water depths are the most exposed and threatened by contamination. In this study, the low depths of groundwater (5.16–23 m) are mainly located at Wadi Smar. The same results were obtained for the second method, SI, except that the rating system was multiplied by 10 to facilitate the reading of the results (Figure 4(a)). The 'D' parameter was assigned to the weights of about 5 and 0.186 to calculate the DRASTIC and the SI models, respectively.

The net recharge values (R) for the study area ranges between a minimum of 3.8 mm/yr and a maximum of 21.3 mm/yr, which were classified into four significant intervals of recharge: the first one varies from 3.8 to 5 mm/yr, the second interval starts with a value of 5 to 10 mm/yr, the third one varies between 10 and 17.5 mm/yr, and the final interval ranges from 17.5 to 21.3 mm/yr. These values of recharge create a significant opportunity for the pollutants to reach the water table and affect the water quality. The assigned ratings for this parameter vary from 1 to 8 for the DRASTIC method and from 10 to 80 for the SI method (Figure 4(b)). We note that most of the study area is characterized by

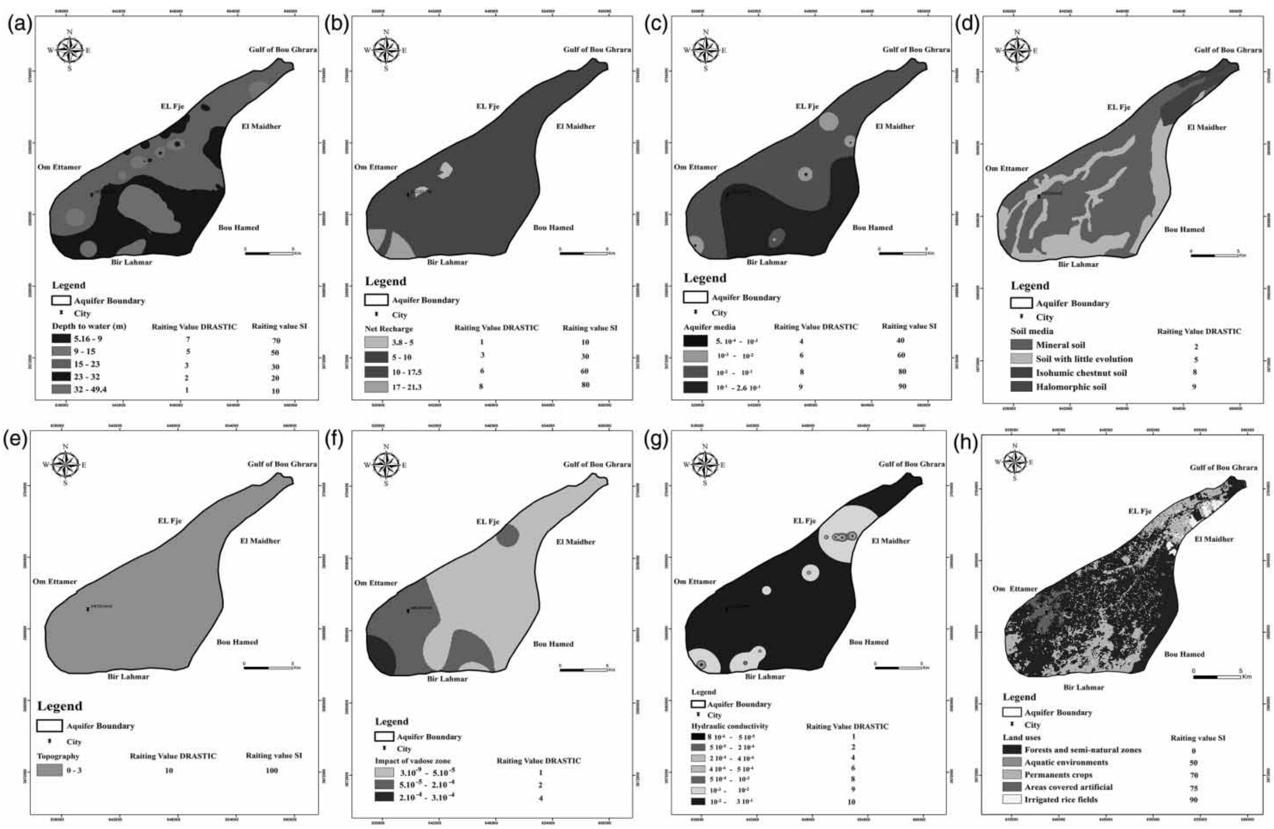

Figure 4 | DRASTIC and SI parameters.

important values of recharge (10–17.5 mm/yr). The most important values of 'R' are located in the northwestern part of the study area, where aquifer vulnerability is high. The net recharge parameter was affected to a determined weight 4 and 0.212 for the DRASTIC and SI methods, respectively.

The established Aquifer media map (A) in the Smar watershed represents especially sand, gravel, sandstone with some proportions of clay and limestone. When the grain sizes are larger, the permeability is higher and the ability of attenuation decreases as well, causing an increase of contamination. This parameter was classified into four intervals; each one was affected by these relative ratings which vary from 4 to 9 for the DRASTIC method and from 40 to 90 for the SI method (Figure 4(c)). The study area is characterized by homogeneous aquifer materials with a dominance of mixed lithology (sand and gravel), located at the Smar Wadi, and gravel lithology at the southwestern area, with ratings of 8 and 9, respectively. This lithology allows a rapid infiltration from the surface and exposes the aquifer to a high risk of contamination. The A parameter will be multiplied by a weight equal to 3 for the DRASTIC method and the most important weight (0.259) for the SI method.

The soil media layer (S) of the study area consists of: (i) mineral soils which are non-evolved soils, formed only by the mineral substance, and occupying a large part of the study area; (ii) soil with little evolution which is material transported and deposited by water, characteristic of alluvial plains, and located at the Smar Wadi; (iii) isohumic chestnut soil with an evolution mainly conditioned by general bioclimatic factors (climate and vegetation); and (iv) halomorphic soil, which is developed at the level of depressions, at the outlets of the watershed where evaporation contributes to the formation of salty soils, especially at the Sebkhat. These soil types were assigned a rating of 2, 5, 8, and 9, respectively (Figure 4(d)). The study area is dominated by the mineral soil which is characterized by the highest rating (9) due to its important permeability. The isohumic chestnut soil, which is located at the outlet of the Smar phreatic aquifer (Sebkhat) is assigned the second most important rate (8). The S will be assigned a weight of 2 in the DRASTIC model.

The topography of the Smar watershed (T) consists of one class (0–3%) since the study area belongs to a low-slope plain (Maritime Djeffara). The study area is characterized by a low percentage of slopes which makes the aquifer more vulnerable because it gives more times for contaminants to infiltrate and reach the groundwater. It was assigned to a rating of 10 and 100 for the DRASTIC and SI methods, respectively (Figure 4(e)). The weights 1 and 0.121 were multiplied in the T parameter for DRASTIC and SI models, respectively.

The map of impact of vadose zone I shows that the area is covered essentially with silt clay and sand gravel. The study area is characterized by some values of permeability varying from a minimum of 3.10^{-9} m/s to a maximum of 3.10^{-4} m/s. These values were classified into three intervals, and each one was affected by these relative rating ranges between 1 and 4 (Figure 4(f)). The main study area belongs to the intervals of medium permeability (3.10^{-9}–5.10^{-5} m/s and 5.10^{-5}–2.10^{-4} m/s).

In the present study, the hydraulic conductivity (C) values range from 8.10^{-6} to 3.10^{-1} m/s. This parameter was classified in seven intervals and each one of them was assigned ratings ranging from 1 to 10 (Figure 4(g)). The highest rating (10) was assigned to the areas with high hydraulic conductivity (from 10^{-2} m/s to 3.10^{-1} m/s) because this zone determines how long a pollutant will travel through it. Areas in black are highly vulnerable (Figure 4(g)). The weight assigned to this parameter is 3 in DRASTIC model.

The LU layer of the study area consists of forests and semi-natural zones, aquatic environments, permanent crops, and areas covered with artificial and irrigated rice fields. Each LU was assigned to a rating ranging from 0 to 90 according to its intervention in the vulnerability assessment (Figure 4(h)). Most of the study area is occupied by some permanent crops which are assigned a rate of 70. The LU parameter will be multiplied by a specific weight 0.222.

The vulnerability map of the DRASTIC method is obtained as a sum of the seven maps mentioned above, after multiplying each map with its standard ratings and weights (Table 7; Equation (1)) by using the raster calculator function of spatial analyst tool in ArcMap 10.1 (Figure 5(a)).

The same procedure was established for the SI method after multiplying each map with its standard ratings and weights (Table 8; Equation (2); Figure 5(b)).

The DRASTIC map represented by Figure 5(a) shows the values of DIs ranging from 91 to 149. Three classes of vulnerability to pollution were distinguished according to their spatial distribution: low, moderate, and high.

- The zones with high vulnerability cover only 8% of the total area of the study area and are mainly distributed in the southwestern part. They are characterized by a high hydraulic conductivity, net recharge, and permeability and consist of mineral soil.

Table 7 | Rate and weight of the DRASTIC parameters

Depth to water (m) (D)		**Net recharge (mm) (R)**		**Aquifer media (A)**		**Soil media (S)**		**Topography (%) (T)**		**Impact of the vadose zone (I)**		**Hydraulic conductivity (m/s) (C)**	
Interval	**R**	**Interval**	**R**	**Permeability classes**	**R**	**Soil classes**	**R**	**Interval**	**R**	**Permeability classes**	**R**	**Interval**	**R**
4.5–9	7	3.8–5	1	Sand, gravel and sandy clay ($5\ 10^{-4}$–10^{-3})	4	Halomorphic soil	2	0–3	10	Confined aquifer ($3\ 10^{-9}$–$5\ 10^{-5}$)	1	10^{-6}–$5\ 10^{-5}$	1
9–15	5	5–10	3	Sand (10^{-3}–10^{-2})	6	Soil with little evolution	5	Weight 1		Sandy clay and sand ($5\ 10^{-5}$–$2\ 10^{-4}$)	2	$5\ 10^{-5}$–$2\ 10^{-4}$	2
15–23	3	10–17.5 17.5–21.3	6 8	Sand and gravel (10^{-2}–10^{-1})	8	Isohumic chestnut soil	8			Sand ($2\ 10^{-4}$–$4\ 10^{-4}$)	4	$2\ 10^{-4}$–$4\ 10^{-4}$	4
23–32	2	Weight 4		Gravel (10^{-1}–$2.6\ 10^{-1}$)	9	Mineral soil	9			Weight 5		$4\ 10^{-4}$–$5\ 10^{-4}$ $5\ 10^{-4}$–10^{-3} 10^{-3}–10^{-2}	6 8 9
32– 50	1			Weight 3		Weight 2						$>10^{-2}$	10
Weight 5												Weight 3	

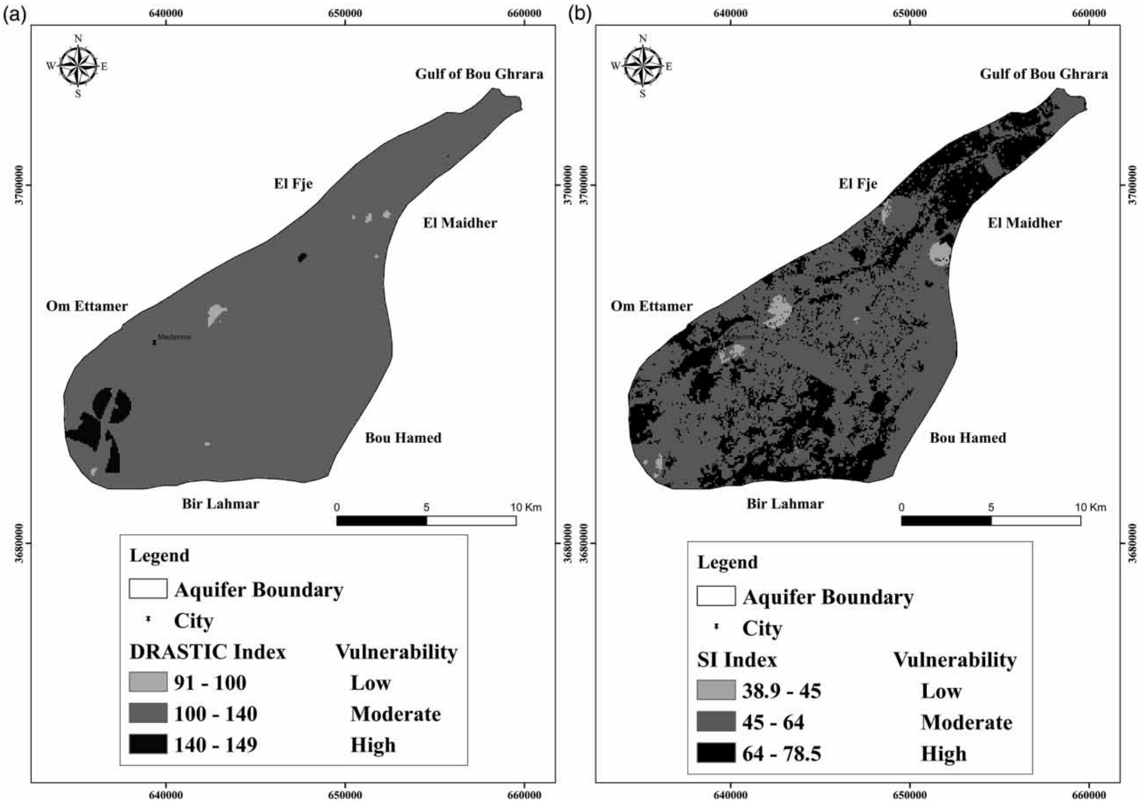

Figure 5 | (a) DRASTIC and (b) SI vulnerability maps.

Table 8 | Rate and weight of the five SI parameters

Depth to water (m) (D)		Net recharge (mm) (R)		Aquifer media (A)		Topography (%) (T)		LU	
Interval	**R**	**Interval**	**R**	**Permeability classes**	**R**	**Interval**	**R**	**Interval**	**R**
4.5–9	70	3.8–5	10	Sand, gravel and sand clay (5 10^{-5}–10^{-3})	40	0–3	100	Forests and semi-natural zones	0
9–15	50	5–10	30	Sand (10^{-3}–10^{-2})	60	Weight 0.121		Aquatic environments	50
15–23	30	10–17.5 17.5–21.3	60 80	Sand and gravel (10^{-2}–10^{-1})	80			Permanent crops	70
23–32	20	Weight 0.212		Gravel (10^{-1}–2.6 10^{-1})	90			Areas covered artificial	75
32–50	10			Weight 0.259				Irrigated rice fields	90
Weight 0.186								Weight 0.222	

- The zones with moderate vulnerability cover 74% of the study area, located mainly in the area characterized by a low depth of water, moderate hydraulic conductivity, moderate permeability, and net recharge. They consist mainly of a mineral soil and soil with little evolution.
- The low vulnerability zones cover 8%, with this distribution being due to the low permeability, hydraulic conductivity, and net recharge. They consist of impermeable materials.

The groundwater vulnerability map resulting from the SI method for the study area is shown in Figure 5(b). It represents the values of SI indexes ranging from 38.9 to 78.5. Three degrees of vulnerability were distinguished: low, moderate, and high. The distribution of these classes is different to the DRASTIC method thanks to the LU parameter that is added to the SI method.

- The high vulnerability areas cover 41.9% of the total area, located in the artificial covered areas in the southwestern, southern, and northeastern parts of the study area; the irrigated rice fields and permanents crops are located in the northeastern part of the study area. The vulnerability of the aquifer is mainly controlled by the high permeability, the important net recharge, and the shallow water depth.
- The moderate vulnerability areas cover 46% of the study area, which are located in the forests and semi-natural zones. Also, these zones are characterized by a moderate permeability of the aquifer, moderate net recharge, and moderate water depth.
- Finally, the low vulnerability zones cover only 12.1%.

In the case of the Smar phreatic aquifer, the validation procedure was established by using 38 values of NO_3^- concentration with values ranging from 15.6 mg/L to 192.3 mg/L and the vulnerability map of the DRASTIC and SI models.

The overlay of the distribution of NO_3^- concentration values '[NO_3^-]' with the DRASTIC and SI vulnerability maps (Figure 6(a) and 6(b); Tables 9 and 10) shows the following.

- Eleven [NO_3^-] are less than 50 mg/L: no one coincides with the low vulnerability class in the SI model, whereas only one value coincides with low vulnerability degree in the DRASTIC model.
- Twenty-two [NO_3^-] range between 50 and 150 mg/L: only seven values coincide with the moderate vulnerability class for the SI model, whereas 21 [NO_3^-] coincide with the moderate vulnerability class in the DRASTIC model.
- Five [NO_3^-] are greater than 150 mg/L: no one coincides with the high vulnerability degree for the DRASTIC model, whereas three values coincide with the high vulnerability degree for the SI model.

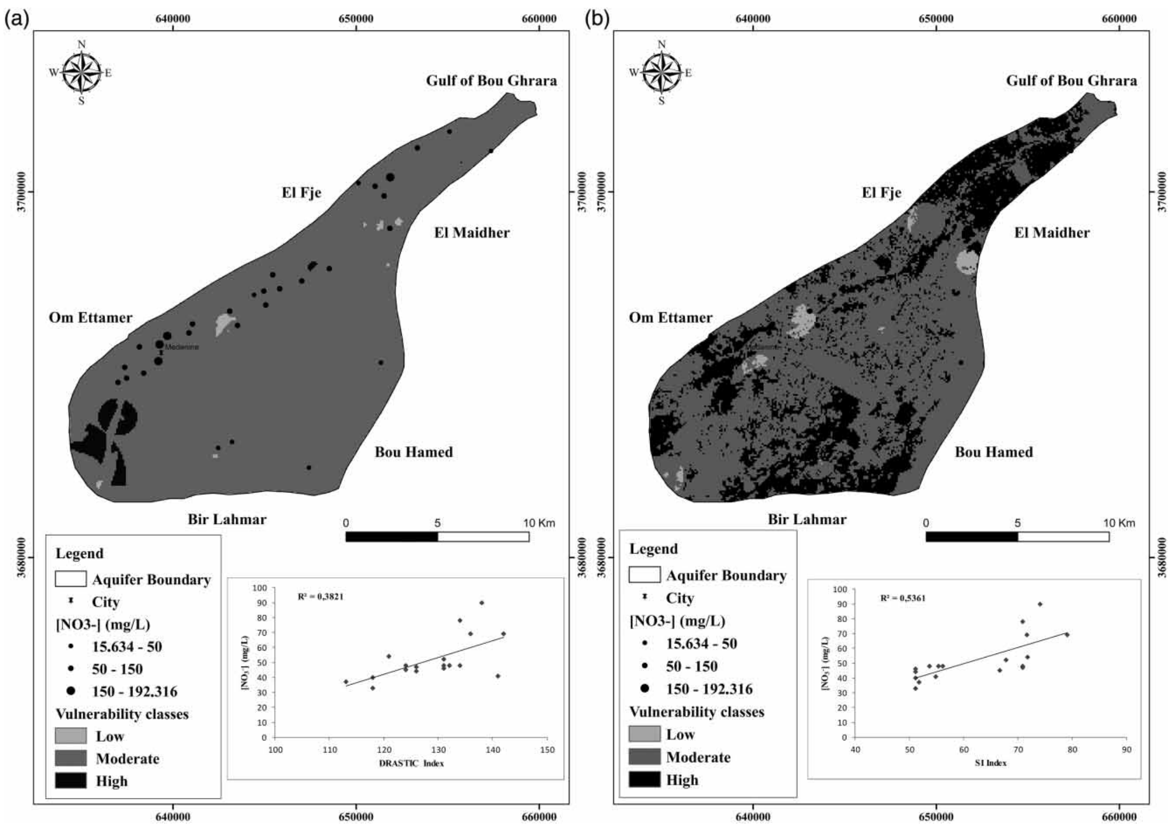

Figure 6 | Overlay between nitrate concentrations and vulnerability classes and indexes: (a) DRASTIC method and (b) SI method.

Table 9 | The coincidence between the vulnerability degree of DRASTIC method and the nitrate concentrations

	Low vulnerability	Moderate vulnerability	High vulnerability
Number of low values of $[NO_3^-]$ (<50 mg/L)	1	10	
Number of moderate values of $[NO_3^-]$ (50 < $[NO_3^-]$ < 150mg/L)		21	1
Number of high values of $[NO_3^-]$ ($[NO_3^-]$ > 150mg/L)		5	

Table 10 | The coincidence between the vulnerability degree of SI method and the nitrate concentrations

	Low vulnerability	Moderate vulnerability	High vulnerability
Number of low values of $[NO_3^-]$ (<50 mg/L)		4	7
Number of moderate values of $[NO_3^-]$ (50 < $[NO_3^-]$ < 150mg/L)	1	7	
Number of high values of $[NO_3^-]$ ($[NO_3^-]$ > 150mg/L)		2	3

Furthermore, the correlation between $[NO_3^-]$ values and DIs (Figure 6(a)) on the one hand and SI indexes (Figure 6(b)) on the other hand shows correlation coefficient values of 61% and 73%, respectively.

The comparison between DRASTIC and SI methods shows that the most significant results are obtained from the SI method. In fact, the vulnerability map from the SI method is similar to the LU map. Indeed, the high degree of vulnerability covers only 8% for the DRASTIC method which increases in the SI method to 41.9% because of the LU parameter that was added in this method. Also, the correlation between the DRASTIC and SI index and the nitrate concentrations shows that the results obtained by the SI method are more significant (61% for DRASTIC model and 73% for SI model).

Finally, we conclude that the SI method is more recommended to this type of environment. It offers a scientific basis to guide stakeholders to make decisions regarding planning and groundwater management.

CONCLUSION

To assess the groundwater vulnerability in the agricultural area of Smar Medenine, two methods were applied: DRASTIC (intrinsic vulnerability method) and SI (specific vulnerability method) by using GIS techniques. Vulnerability study results show that vulnerability degree was presented in three classes: low, moderate, and high for the two methods. The DRASTIC method describes vulnerability according to the attenuation capacity of the hydrogeological parameters. It shows that the moderate vulnerability class covers 74%, against the high vulnerability degree which does not exceed 8%. Nevertheless, the SI approach is more reliable in representing the vulnerability area. In fact, it relates to the intensive anthropogenic soil activities (LU parameter: agriculture, urban areas, industry, etc.). It shows that the moderate vulnerability class covers 45.9% and the high vulnerability degree achieved was 41.9%. These results are more significant because it shows their similarity to the LU map. The DRASTIC and SI vulnerability indexes were correlated with nitrates values for validation. This revealed a significant correlation showing that high values of nitrates occurred in highly vulnerable zones. The correlation coefficient values for DRASTIC and SI models are about 61% and 73%, respectively. Thus, the application of the SI method for diffuse agricultural pollution is considered a good tool for decision support in water exploitation planning and water management in the Smar phreatic aquifer.

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