Validation of two applied methods of groundwater vulnerability mapping: application to the coastal aquifer system of Southern Sfax (Tunisia)

Nabila Allouche, Fatma Ben Brahim, Mona Gontara, Hafedh Khanfir and Salem Bouri

ABSTRACT

The coastal aquifers system of Sfax Agareb Chaffar Mahres (Southern Sfax) located in the central east of Tunisia is well known for population growth and industrial development. These industrial and agricultural developments have led to the degradation of water quality. In this study, DRASTIC and GALDIT models were integrated with geographical information system (GIS) tools, in order to assess the aquifers vulnerability to pollution and the seawater intrusion risk. These methods use different parameters explaining the different results in the vulnerability degrees in the Aghereb–Chaffar–Mahres aquifer system. The vulnerability map to contamination as well as vulnerability to seawater intrusion showed three classes of vulnerability: low, moderate and high, depending on the intrinsic properties. In addition, the risk map showed three risk classes: low, moderate and high depending on hydrogeological characteristics, land use, distance from the coast and human impacts in the majority of the study area. GIS is used to manage, manipulate and analyze the necessary geographical data used in the different vulnerability methods. These maps could serve as a scientific basis for sustainable land use planning and groundwater management in Southern Sfax.

Key words | coastal aquifer, DRASTIC, GALDIT, pollution, risk map, Southern Sfax

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INTRODUCTION

Coastal aquifers serve as a major source of fresh water in many countries around the world, especially in arid and semi-arid zones (Saidi *et al.* 2014). These zones have scarce rainfall resulting in intermittent rivers like at the site of this study, the Sfax–Aghereb–Chaffar–Mahres regions (Southern Sfax). The study site receives low levels of renewable recharge and has experienced an increase in anthropogenic activities, a fact that means the need for fresh water is even more acute. Indeed, water resources are threatened by overexploitation through drinking water, irrigation uses, and so on.

This increased need induces an increase in pumping and the possibility of contamination by salt water, and many wells are saline and have had to be abandoned, particularly those close to the coast. So, recently salinization of the coastal aquifer has become a major constraint imposed on groundwater utilization, and therefore one of the most important water management issues. Hence, it is proposed to delineate the areas which are susceptible or vulnerable to contamination and in particular vulnerable to seawater intrusion.

The concept of groundwater vulnerability was first introduced in France toward the end of the 1960s to create awareness about groundwater contamination (Vrba *et al.* 1994). It can be defined as the possibility of percolation and diffusion of contaminants from the ground surface into the groundwater system. Vulnerability is usually considered to be an intrinsic property of a groundwater system that depends on its sensitivity to human and/or natural impacts (Babiker *et al.* 2005; Ben Brahim *et al.* 2012;

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Celebi & Özdemir 2014; Kharroubi *et al.* 2014; Sherpa *et al.* 2014; Xiaosi *et al.* 2014). Groundwater vulnerability deals only with the hydrogeological setting and does not include pollutant attenuation (Saidi *et al.* 2014).

To this end, two methods were proposed in this study: DRASTIC (Aller *et al.* 1987) and GALDIT (Chachadi *et al.* 2003; Agarwadkar 2005). The DRASTIC method is chosen because it is considered to be the most common method used worldwide for measuring the vulnerability to pollution assessment. GALDIT was selected in order to assess the transmit time of contaminants and to analyze the seawater intrusion state of the aquifer. For vulnerability assessment, a comprehensive investigation program was carried out, including detailed geological, structural, lithological and physico-chemical parameters.

The practical, site-specific purpose of this study is to characterize and to identify the most threatened zones by multidisciplinary data and by mapping the most vulnerable areas. Another goal was to test and compare the two different methods and the resulting maps, and to validate the vulnerability assessments by comparisons with nitrate and chloride concentrations maps. Furthermore, the geographical information system (GIS) technique provides an efficient environment to reach this objective.

STUDY AREA

The study area is located at the central east of Tunisian Sahel with a total surface of 1,899 km^2 (Figure 1). This study concerns three regions (Sfax–Agareb, Chaffar and Mahres) of the Southern Sfax area. These regions are characterized by an arid to semi-arid Mediterranean climate with large temperature and rainfall variations. Average annual rainfall and temperature are about 225 mm and 19.7 °C, respectively (Institut de la Météorologie Nationale (INM) 2012). The increase in the agricultural irrigation return, domestic effluents and intensive pumping has greatly contributed to the contamination of groundwater.

Geologically, this zone is located on an alluvial plain and dominated by Quaternary deposits. The Sfax–Agareb, Chaffar and Mahres areas have relatively stable tectonics

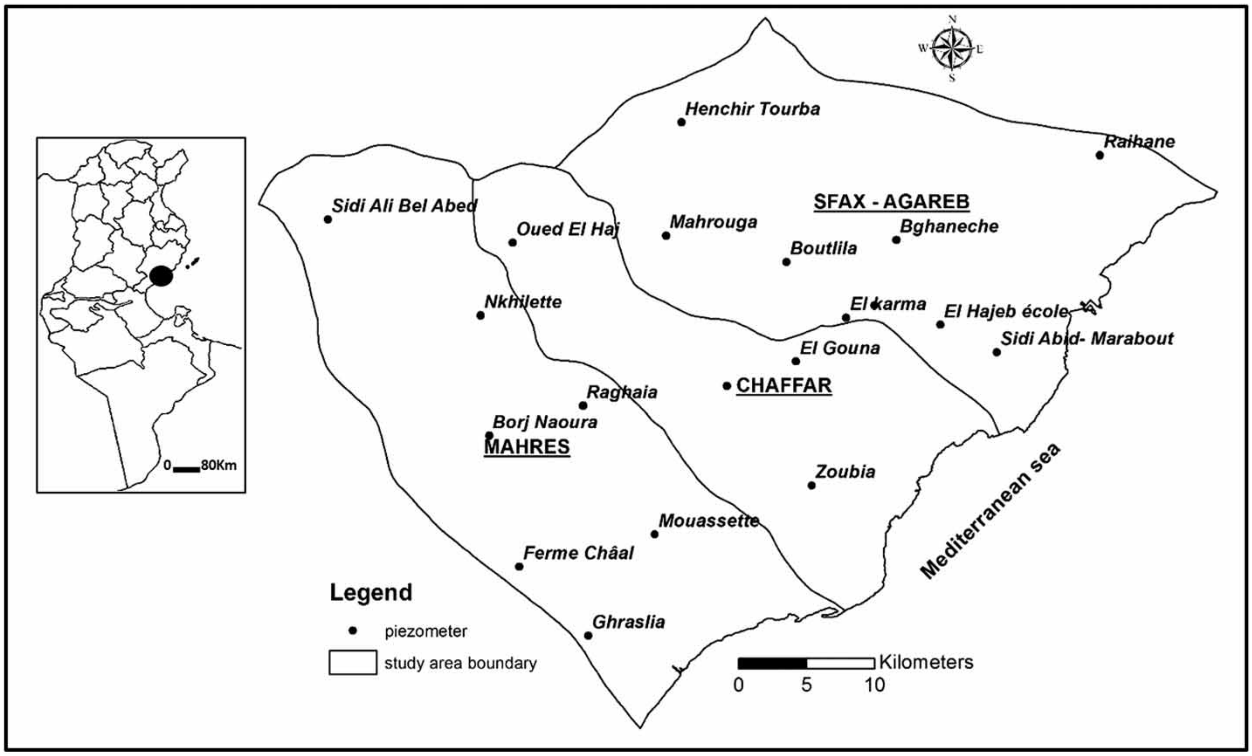

Figure 1 | Location of the study area.

apparent in the tabular sedimentary structure. The Mio-Plio-Quaternary and the Quaternary terrains occupy a large part of the study area (Figure 2); they are considered by current and recent alluvial deposit: conglomerates, gravels, sands, silts, calcareous with high permeability (Maliki 2000; Bouaziz 2002).

The synthetic geological cross section along the three regions presented in Figure 3 shows that the aquifer is composed by clayey sand, sandy clay and sand of Mio-Plio-Quaternary age which extends over the entire basin. The thickness of this aquifer is between 22 and 45 m, and its depth varies between 15 and 55 m. This aquifer is limited to the bottom by a clay layer, representing the aquifer substratum. On the top, heterogeneous clastic materials presented essentially by sand and gravel are encountered, implying a generally permeable aquifer.

The spatial variability of the aquifer lithology results in a lateral variation of the permeability of the aquifer. A large part of the study area is characterized by an average permeability; the highest values trace the beds of rivers and major part of the coastal zone (Figure 4). This event caused a significant natural recharge. The transmissivity was calculated using Porchet tests, performed on wells existing in the study area. These tests allowed the authors to determine the transmissivity value during the drawdown and upwelling. Transmissivity values vary between 5.08×10^{-3} m^2/s in the

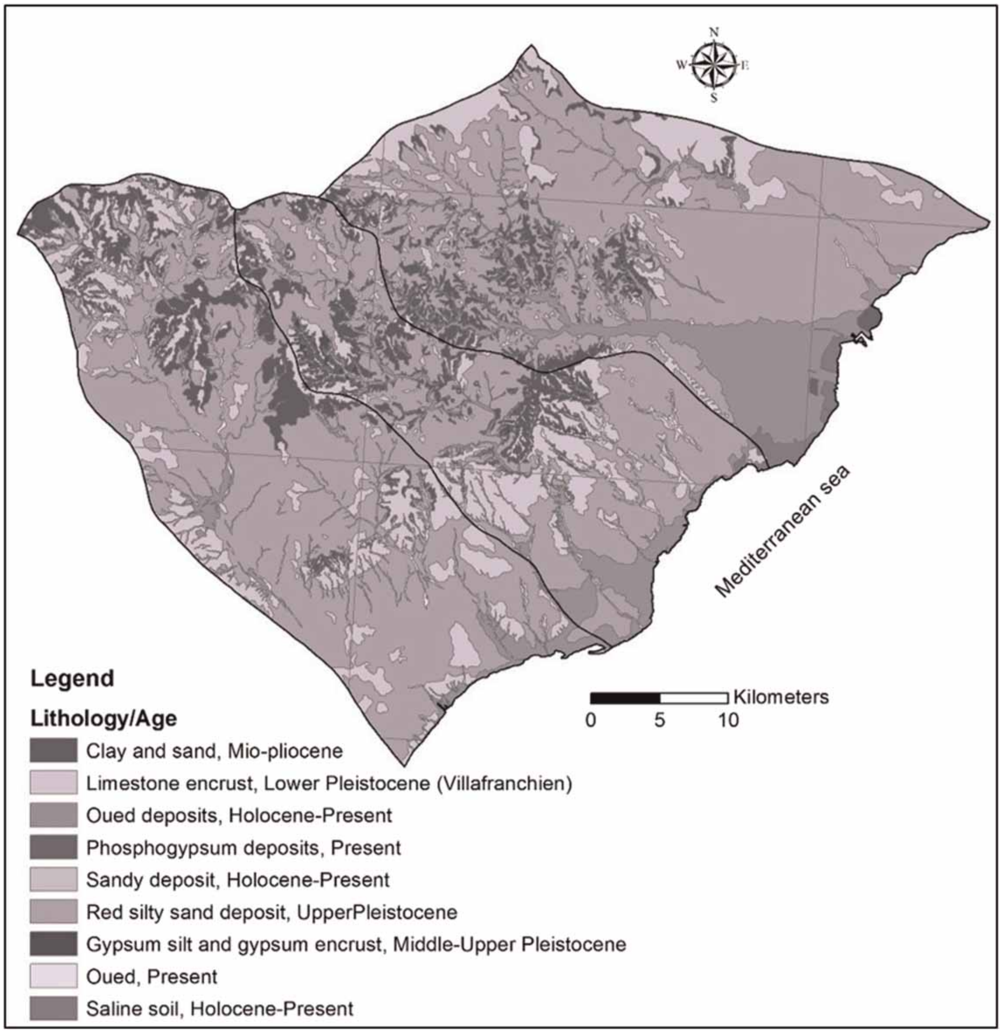

Figure 2 | Geological map of the study area (Allouche 2012).

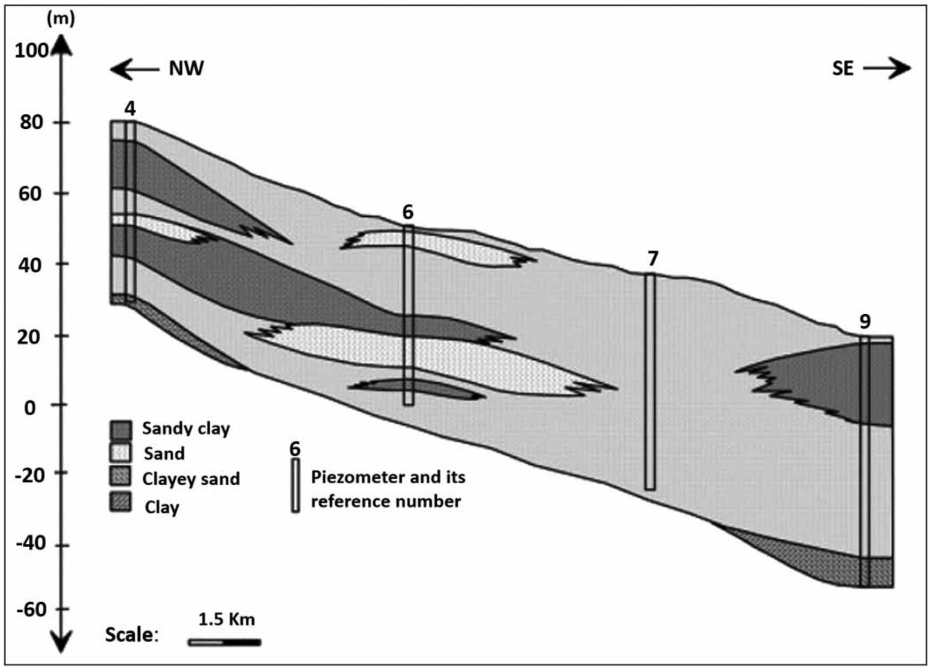

Figure 3 | Lithologic units and geometry of Sfax–Agareb aquifer (Hentati *et al.* 2010).

southern part of the aquifer (piezometer Ghraslia) and 4×10^{-6} m^2/s in the center of the Sfax–Agareb aquifer (piezometer Bghaneche) (Table 1).

From the new piezometric map developed (Figure 5), it can be inferred that the main groundwater flow direction is generally toward the southeast, implying discharge to the Mediterranean Sea, the natural outlet. Nevertheless, the coastal zone of the Sfax–Agareb, Chaffar and Mahres regions appears to be highly influenced by overexploitation because the isopiestic lines show values lower than 0 m. This might be explained by the intensive pumping which tends to be quite important in zones of low piezometric levels (Figure 6).

MATERIALS AND METHODS

The concept of vulnerability to pollution of an aquifer is defined as the intrinsic susceptibility to changes in the quality and quantity of groundwater in space and time, due to natural processes and/or anthropogenic activity (Civita 1994). So, it is necessary to establish vulnerability maps to pollution following the DRASTIC and GALDIT methods.

In this study, the vulnerability assessment is based primarily on the collection of geological, hydrological and hydrogeological data. Secondly, the software of GIS ArcMap10 allows the presentation, assembly, overlay and analysis of various geo-referenced informations.

The DRASTIC method

The DRASTIC method was developed by the US Environmental Protection Agency to evaluate the groundwater pollution potential for the entire USA (Aller *et al.* 1987). It was based on the concept of the hydrogeological setting that is defined as a composite description of all the major geologic and hydrologic factors that affect and control the groundwater movement into, through and out of an area (Aller *et al.* 1987; Saidi *et al.* 2014). The acronym DRASTIC stands for the seven parameters used in the model, which are: depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity (Table 2).

This method generates an index for the pollution potential of groundwater resources (Aller *et al.* 1987; Civita 1994). The DRASTIC index (Di) is the sum of the indices obtained for

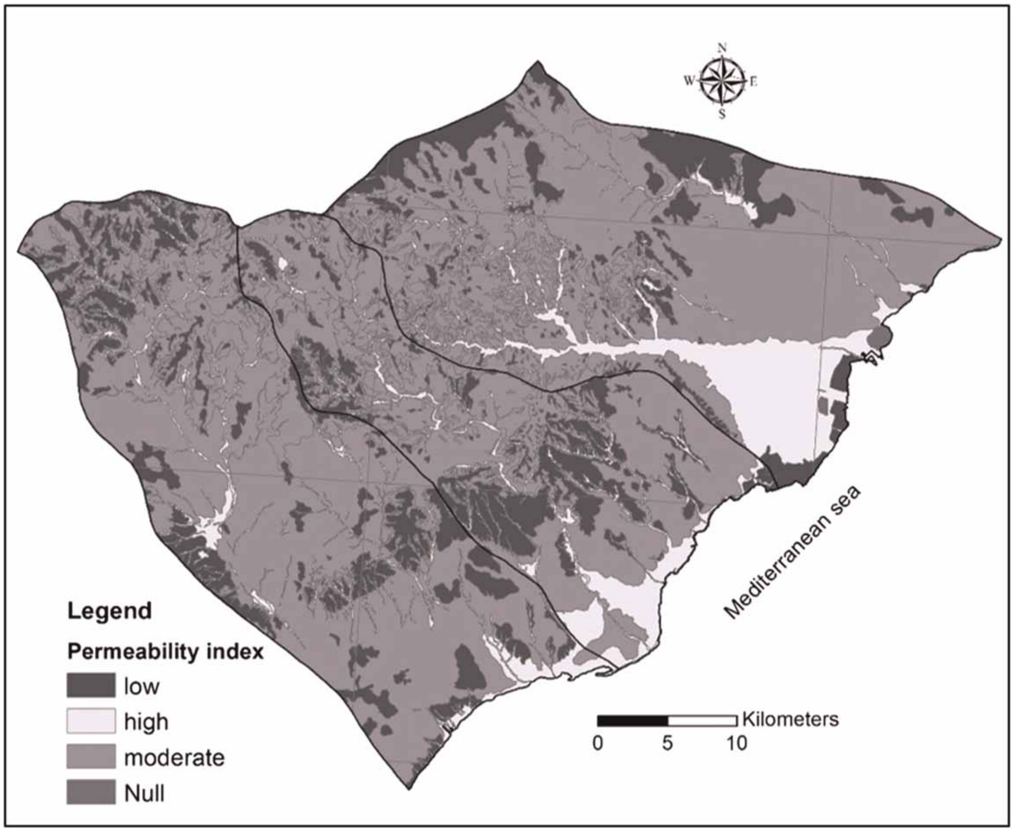

Figure 4 | Permeability index of study area (Commisséria Régional du Développement Agricole (CRDA) du Sfax 2012).

each of the seven parameters, weighted accordingly. Higher sum values represent a greater potential for pollution or a greater vulnerability of the aquifer to contamination (Table 3).

In the DRASTIC method, the characteristics of the environment assigned a numerical value are used as parameters. Each parameter is rated on a scale from 1 to 10 based on their relative effect on the aquifer vulnerability. Then, these parameters are assigned weights ranging from 1 to 5 reflecting their relative importance with respect to each other (Table 4). The Di can be calculated according to the following equation:

$$D_i = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r D_w \tag{1}$$

where D, R, A, S, T, I and C are the seven parameters of the DRASTIC method and the subscripts r and w are the rating and weight, respectively, associated with each parameter.

Depth of groundwater (D) represents the depth from the land surface to the first groundwater aquifer (Witczak *et al.* 2007). It determines the thickness of the material through which the infiltrating water must travel before reaching the aquifer or the saturated zone. Consequently, the depth of the groundwater has a great impact on the degree of interaction between the percolating contaminant and subsurface materials (air, minerals and water) and, therefore, on the degree and extent of physical and chemical attenuation, and degradation processes (Rahman 2008). The distribution of the depth of groundwater parameter (D) was established by subtracting the groundwater level, measured in 29 wells in the Sfax–Aghareb–Chaffar–Mahres aquifer from the topographic elevation in the corresponding cell location (Allouche 2012).

Net recharge (R) is the amount of water from precipitation and artificial sources available to migrate downward to the groundwater. Recharge water is, therefore, a significant vehicle for percolating and transporting contaminants within the vadose zone to the saturated zone. To calculate

Table 1 | Transmissivity index of the study area (Commissériat Régional du Développement Agricole (CRDA) du Sfax 2012)

Piezometer	Transmissivity (m^2/s)
Sfax–Agareb	
Raihane	5.77×10^{-5}
Henchir Tourba	4.59×10^{-4}
El Karma	1.75×10^{-5}
Boutlila	3.41×10^{-4}
Bghaneche	4×10^{-6}
Chaffar	
Ferme Agareb O.T.D	1.06×10^{-3}
Raghaia	1.05×10^{-4}
Zoubia	1.02×10^{-5}
Mahres	
Ferme châal	1.63×10^{-6}
Ghraslia	5.08×10^{-3}
Nkhilette	2.61×10^{-5}
Borj Nouara	1.46×10^{-5}
Mouassette	1.31×10^{-5}

the distribution of the recharge parameter, the water table fluctuations (WTF) method was used. This method estimates groundwater recharge as the product of specific yield and the annual rate of water table rise including the total groundwater draft (Sophocleous 1991). In general, the WTF method was proved to be particularly appropriate when water levels show a quick response in areas with a relatively thin vadose zone (Moon *et al.* 2004), which is the case for the Sfax–Aghareb–Chaffar–Mahres aquifer.

Aquifer media (A) and the impact of the vadose zone (I) represent the lithology of the saturated zone (A) and the vadose zone (I), and are found from well logs. These can influence the vulnerability to pollution, such that, in a weakly permeable aquifer with relatively low recharge rates the vulnerability is low, whereas the more permeable aquifer with greater recharge potential which is exposed at the surface is highly vulnerable and its groundwater is a significant resource.

Soil media (S) considers the uppermost part of the vadose zone and influences the pollution potential. The soil parameter (S) was obtained by digitizing the existing

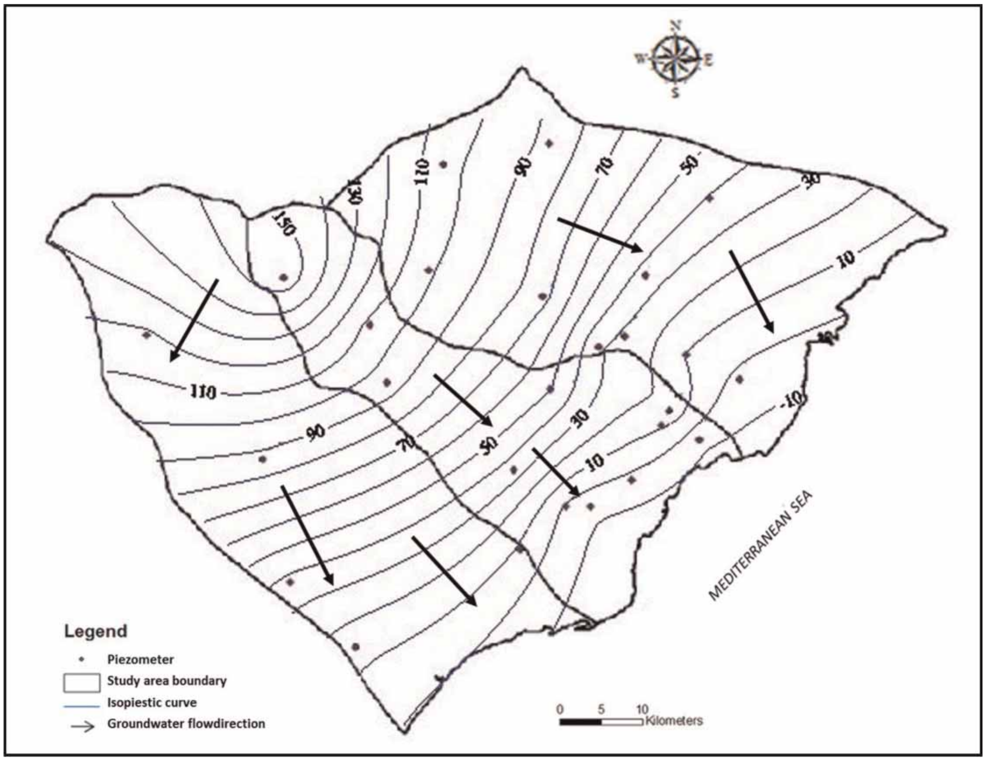

Figure 5 | Piezometric map of the aquifer system in Southern Sfax region (2012).

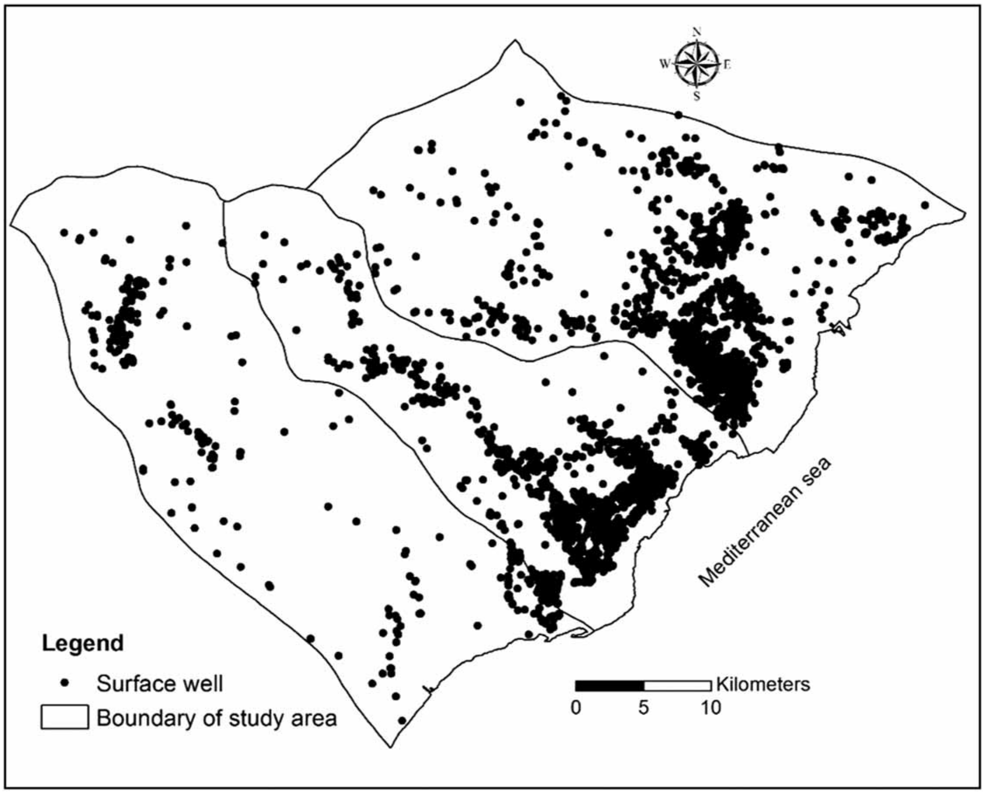

Figure 6 | Location of pumping wells in the study area (2012).

Table 2 | Rank and weight of the seven DRASTIC parameters (Aller *et al*. 1987; modified)

Depth of groundwater *D* (m)		**Net recharge *R* (mm)**		**Aquifer media *A***		**Soil type *S***		**Topography *T* (slope) (%)**		**Impact of the vadose zone *I***		**Hydraulic conductivity *C* (m/s)**	
Interval	***r***	**Interval**	***r***	**Lithology classes of the saturated zone**	***r***	**Soil classes**	***r***	**Interval**	***r***	**Lithology classes of the unsaturated zone**	***r***	**Interval**	***r***
4.5–9	7	50–100	3	Sandy clay	1	Mineral soil	9	0–3	10	Sand with clay	5	3.4×10^{-6}–5×10^{-5}	1
9–15	5	100–180	6	Weight 3		Isohumic chestnut soil	8	3–5	9	Thin sand and clay	6	5×10^{-5}–2×10^{-4}	2
15–23	3	Weight 4				Rendzina Calcareous brown soil	7 6	5–10	5	Sandy gravel	8	2×10^{-4}–4×10^{-4}	4
23–31	2					Soil with little evolution	5	10–15	3	Gravel	9	4×10^{-4}–5×10^{-4}	6
>31	1					Polygene-tic soil	4	15–25	1	Weight 5		5×10^{-4}–10^{-3}	8
Weight 5						Gypsum soil Halomor-phic soil	3 2	Weight 1					
						Urban zones	1					Weight 3	
						Weight 2							

r: rate.

soil maps, with a scale of 1:50,000 acquired from the Regional Agency of Agriculture Laboratory ‘CRDA’, covering the region of Southern Sfax.

Topography (*T*) was represented by the slopes map (1/50,000 scale) covering the study area. The importance of topography in this context is to control the runoff of pollutants.

Table 3 | Evaluation of degrees of vulnerability DRASTIC (Engel *et al.* 1996)

Degrees	Vulnerability index
Low	1–100
Moderate	101–140
High	141–200
Very high	>200

Table 4 | Data sources used for constructing the DRASTIC parameters

DRASTIC parameters	Type of data	Format	Mode of processing data
Depth to groundwater (*D*)	Static level statement of the year 2010 (Allouche 2012)	Table	Interpolation
Rainfall distribution (*R*)	Annual rainfall data during the period 1990–2012 (Institut de la Météorologie Nationale (INM) 2012)	Table	Interpolation
Aquifer media (*A*)	Equivalent permeability taken from well logs (District of the Water Resources (DWR) of Sfax)	Table	Interpolation
Soil type (*S*)	Soil map (agricultural maps obtained from the Regional Agency of Agricultural Development) Commissériat Régional du Développement Agricole (CRDA) du Sfax (2012)	Map	Digitalization
Topography (*T*)	Topographic maps with the 1/50,000: sheets No 81, 82, 89, 90, 97 and 98 (Commissériat Régional du Développement Agricole (CRDA) du Sfax 2012)	Map sheet	Digitalization
Impact of vadose zone (*I*)	Equivalent permeability taken from well logs (District of the Water Resources (DWR) of Sfax)	Table	Interpolation
Hydraulic conductivity (*C*)	Permeability calculated from the transmissivities: taken from the pumping tests (District of the Water Resources (DWR) of Sfax)	Table and map	Interpolation

Table 5 | Score and weight of the GALDIT parameters

	G	*A*	*L*	*D*	*I*		*T*
	Groundwater occurrence	Aquifer hydraulic conductivity	Depth of groundwater	Distance from the coastline	Impact of existing status of seawater intrusion in the area		Thickness of the aquifer
Parameters	Aquifer type	m/day	m	m	Cl^-/HCO_3^-	SO_4^{2-}/Cl^-	m
Weight	1	3	4	2	1		2
Rank							
1		0,086–10	15 <	1,000 <			
2			8–15	800–1,000			
3			5–8	700–800			5–6
4		10–5	4–5	600–700			6–8
5			3–4	500–600			8–10
6			2–3	400–500			10–12
7		15–20		300–400		1.75–2	12–14
8	Leaky confined			200–300		1.5–1.75	14–16
9	Unconfined			100–200		1–1.5	16–20
10	Confined	20 <		< 100	5–27.45	< 1	20 <

Hydraulic conductivity (C) refers to the ability of aquifer materials to transmit water, which in turn, controls the rate at which groundwater will flow under a given hydraulic gradient. The hydraulic conductivity was calculated based on the following equation:

$$K = \frac{T}{b} \tag{2}$$

where K is the hydraulic conductivity of the aquifer (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 (Allouche 2012).

Table 6 | Vulnerability classes according to the GALDIT method (Chachadi *et al.* 2003)

GALDIT INDEX	Vulnerability class
<30	Not vulnerable
50–70	Low
70–90	Moderate
>90	High

The groundwater vulnerability map of Sfax–Agareb, Chaffar and Mahres regions is created by overlaying the thematic maps relating to the seven parameters (classification of Aller *et al.* 1987; Engel *et al.* 1996). These data must be in digital form to facilitate their integration into the GIS. Table 4 summarizes data types, GIS pre-processing and manipulation techniques used to create seven input data layers for the Di.

The GALDIT method

The GALDIT method was developed for the first time during the project 'EU-India INCO-DEV COASTIN' (Michaud *et al.* 2003). This object of this method is to delineate the most vulnerable areas to seawater intrusion. This method is used to evaluate the vulnerability of the Sfax–Agareb–Chaffar–Mahres aquifer to seawater intrusion. It is

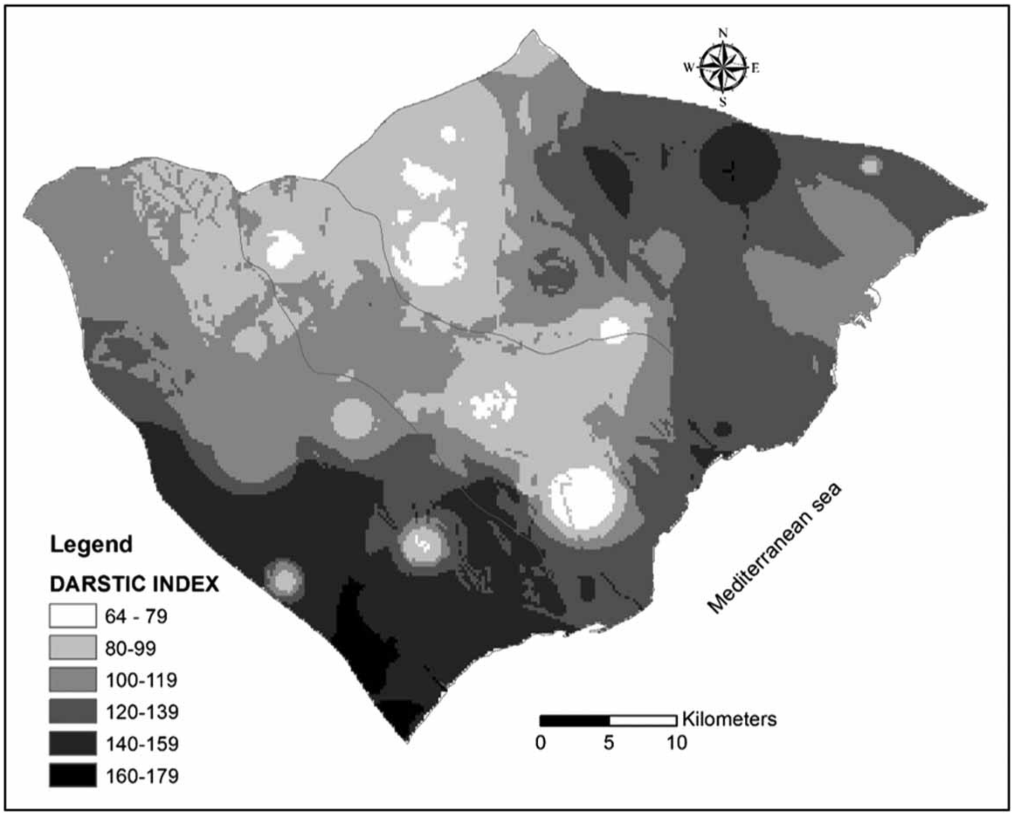

Figure 7 | Di map.

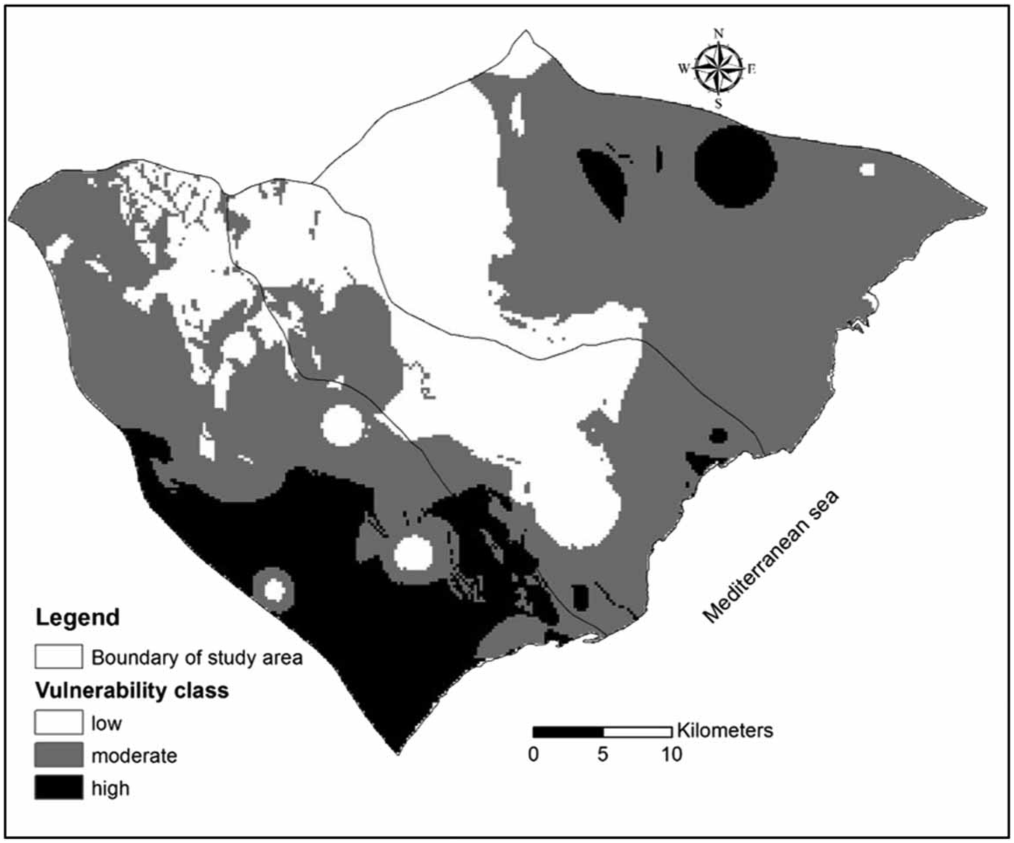

Figure 8 | Groundwater vulnerability map of Sfax-Agareb, Chaffar and Mahres.

chosen because it takes into account the physical characteristics affecting seawater intrusion potential and which are also inherent in each hydrogeologic setting. The most important factors that control seawater intrusion are found to be the following.

Groundwater occurrence (*G*) (aquifer type: unconfined, confined or leaky confined): based on the geological nature, layers can be categorized as confined, unconfined or leaky confined. The type of groundwater occurrence has a high influence on the extent of seawater intrusion. Thus, an unconfined aquifer will be more affected by seawater intrusion than a confined aquifer. Also, the confined aquifer may be more prone to seawater intrusion than a leaky confined aquifer because a confined aquifer is more vulnerable due to a larger cone of depression after pumping, whereas a leaky confined aquifer maintains minimum hydraulic pressure by way of leakage from adjoining aquifers. Hence, the latter has the least susceptibility to saltwater intrusion (Chachadi & Lobo-Ferreira 2005).

Aquifer hydraulic conductivity (*A*) is defined as the ability of the aquifer to transmit water. This parameter has a high influence on the magnitude of seawater front movement; the higher the conductivity, the higher the inland movement of the seawater front.

Depth of groundwater Level above the sea (*L*) represents the level of groundwater with respect to mean sea elevation measured in many points. These samples were emplaced on the aquifer and interpolated using inverse distance weight technique to generate a raster surface. This represents a very important factor in evaluating seawater intrusion because it determines the hydraulic pressure availability to push the seawater front back.

Distance from the shore (*D*): the impact of sea water intrusion generally decreases as one moves inland at right angles to the shore. Data for this parameter can be computed using the topographical map of the study area, the sample points and their emplacement, and the distance measured perpendicular from shoreline.

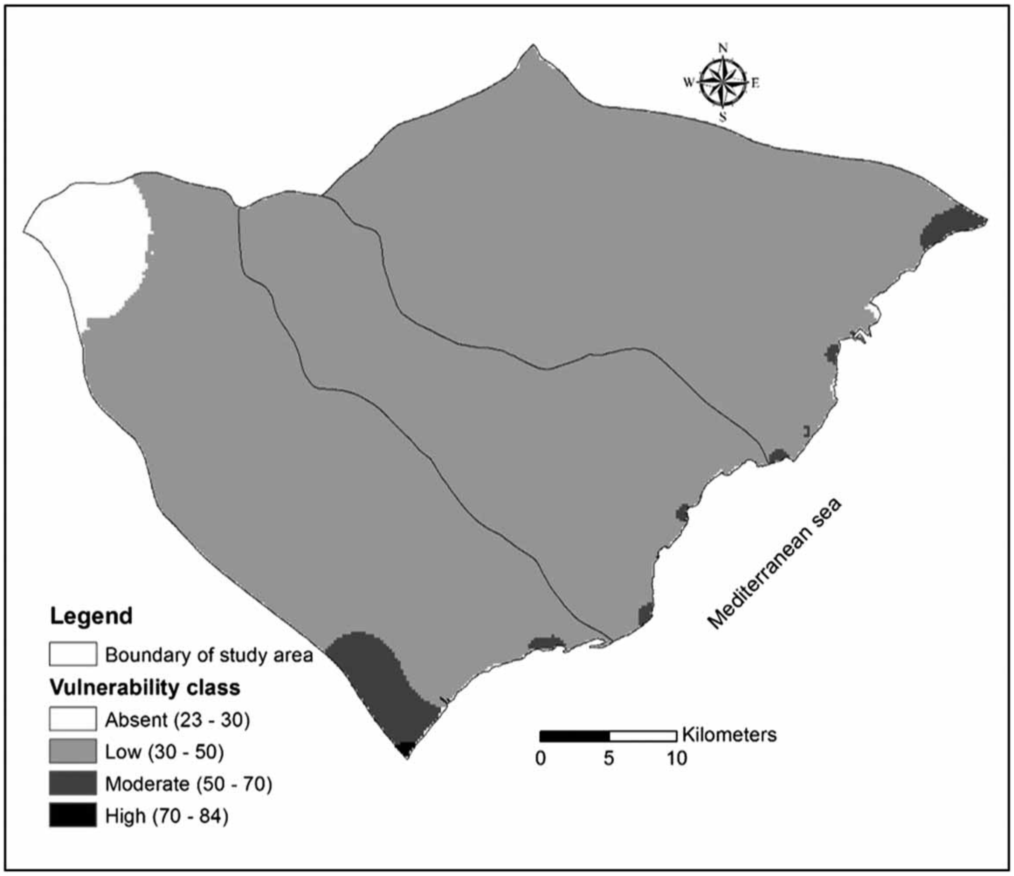

Figure 9 | Vulnerability to seawater intrusion degree according to the GALDIT method.

Impact of existing status of seawater intrusion in the area (I) can be computed using the ratio of SO_4^{2-} /Cl^- (Allouche 2012).

Thickness of the aquifer, which is being mapped (T) plays an important role in determining the extent and the magnitude of seawater intrusion in the coast; the larger the aquifer thickness, the smaller the extent of seawater intrusion and vice versa (Allouche 2012).

Each GALDIT parameter is affected by a relative weight from 1 to 4 and a score varying from 1 to 10, depending on local conditions (Agarwadkar 2005) (Table 5). The GALDIT index is the sum of the indices obtained for each of the six parameters, weighted accordingly (Chachadi & Lobo-Ferreira 2001). It is calculated using Equation (3)

$$\text{GALDIT} = (1\times G) + (3\times A) + (4\times L) + (2\times D) + (1\times I) + (2\times T) \quad (3)$$

where G, A, L, D, I and T are the six parameters of the GALDIT method. Once the GALDIT index is calculated, it is then possible to identify areas that are affected by a potential saline intrusion. This index varies between 13 and 130 and can be classified into four classes according to Table 6.

Using the GALDIT index, it is possible to delineate areas that are more likely to be vulnerable to seawater intrusion than other areas; the higher the index, the greater the seawater intrusion potential (Agarwadkar 2005; Chachadi & Ferreira 2005).

APPLICATION OF THE METHODS

Application of DRASTIC method

According to the range of Aller *et al.* (1987), the DRASTIC vulnerability index was determined by overlying the seven

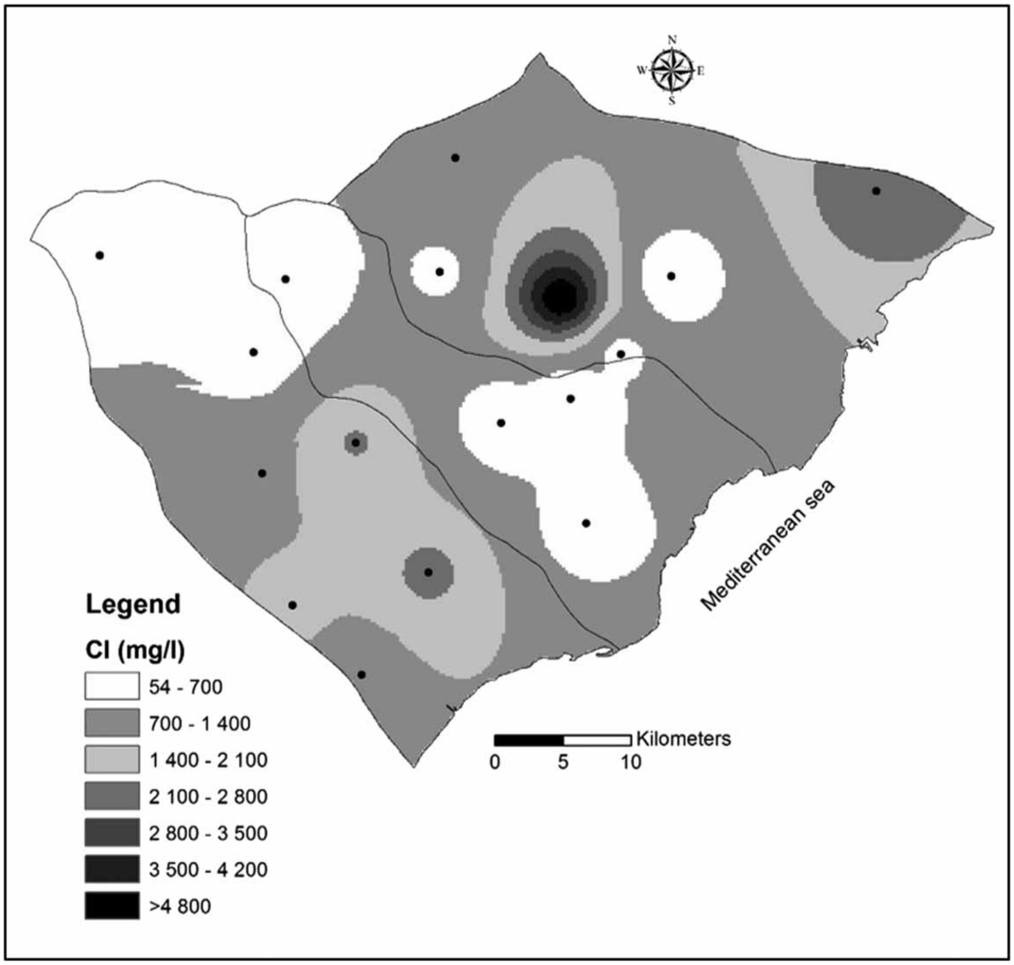

Figure 10 | Cl$^-$ concentration map in Sfax–Agareb, Chaffar, Mahres aquifer system.

thematic layers. All the GIS data coverage is in raster format and values for each overlay are summed in Arc GIS according to the pixel value of each area that resulted from multiplying the ratings with the appropriate DRASTIC weight. The resulting DRASTIC values lay between 64 and 179 (Figure 7). This range is classified on the basis of the above classification as: (1) 64–100, which is assigned low vulnerability; (2) 100–140, which is assigned moderate vulnerability; and (3) 140–179, which is assigned high vulnerability (Figure 8, Table 3).

The North part of the study area and the central part of the Chaffar aquifer are of a low class of vulnerability due to the important depth of water and the low permeability of the vadose zone and the aquifer. Almost all the Sfax–Agareb aquifer with the coastal part of Chaffar aquifer and the north western zone of the Mahres aquifer are characterized by a moderate vulnerability. At these sites, the unsaturated zone and that of the aquifer are moderately permeable. The south western zone of the Mahres aquifer, and other areas like the coast of the Chaffar region and the center of the Sfax–Agareb aquifer are of the highest class of vulnerability. This distribution is explained by the shallow groundwater table (<9 m), a flat topography ($<3\%$), high recharge, a permeable vadose zone and aquifer (made up of sand and gravel lithology) and low capacity to attenuate the contaminants.

Application of GALDIT method

The resulting GALDIT map shows values ranging between 23 and 84. It subdivides the study area into four classes

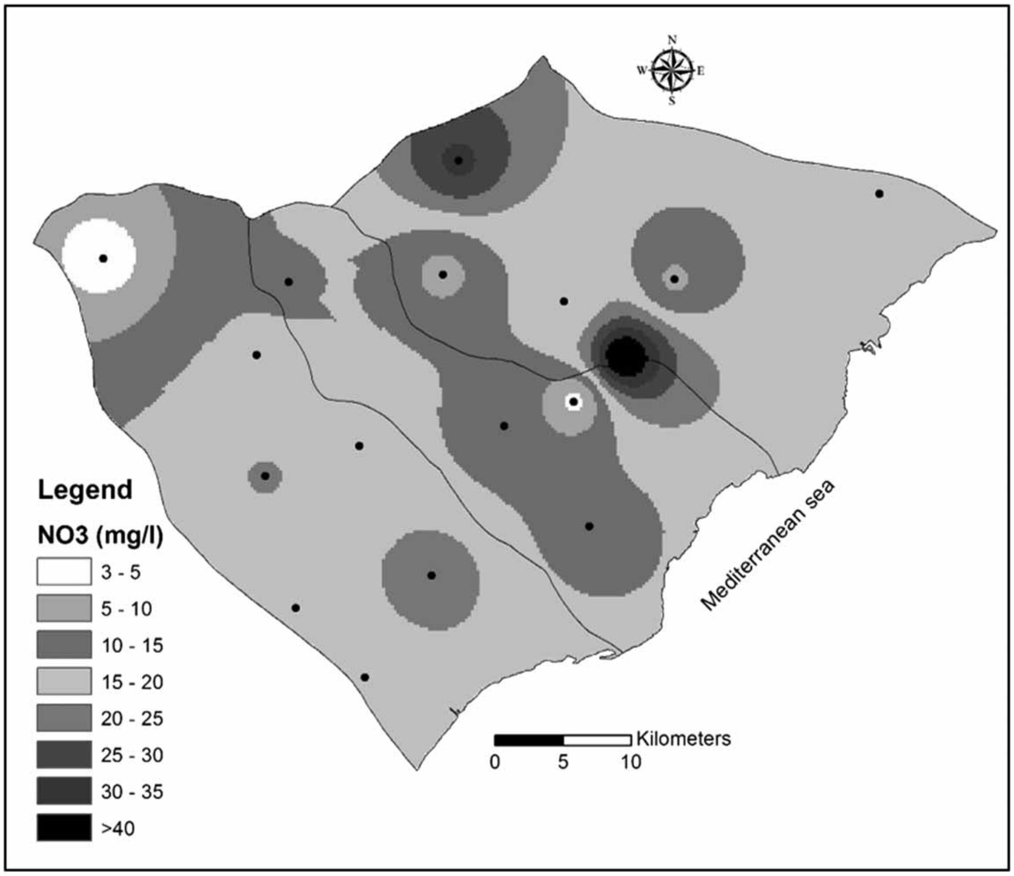

Figure 11 | NO$_3$ concentration map in Sfax–Agareb, Chaffar, Mahres aquifer system.

as indicated in Figure 9. The coastal areas are the most sensitive and exposed to seawater intrusion in relation to other areas. This is due to the high permeability (unconfined aquifer), the high hydraulic conductivity (>20 m/day), the shallow groundwater table (<9 m), the high Cl^- concentration (hence, a low SO_4^{2-}/Cl^- ratio), the thin aquifer (<10 m) and the relatively low distance from wells to the sea (<1,000 m). On the contrary, the low vulnerability class represents a low vulnerability which is attributed essentially to the high depth of the water table, the high distance to the coast and the low aquifer conductivity (Figure 10, Table 5).

The southern part of the Mahres aquifer is highly vulnerable, some areas all along the coast are moderately vulnerable and the remaining areas are characterized by a low vulnerability. So, the vulnerability is different from one zone to another throughout the coastline.

VALIDATION OF THE METHODS

Aquifer vulnerability method requires validation to reduce subjectivity in the selection of rating and to increase reliability (Ramos-Leal and Rodriguez-Castillo 2003).

Nitrate distribution

The spatial distribution of nitrate concentration can be used to validate a groundwater vulnerability assessment. Indeed, 18 wells in the area are sampled, during the year 2012, in order to observe the nitrate contamination of Sfax–Agareb, Chaffar and Mahrès groundwater. Results are presented in Figure 11 and concentrations (expressed as NO_3^-) range from 40 to 143 mg/l with relatively high variability between wells.

The distribution of nitrate shows a relatively high concentration in the south and central of the Sfax–Agareb

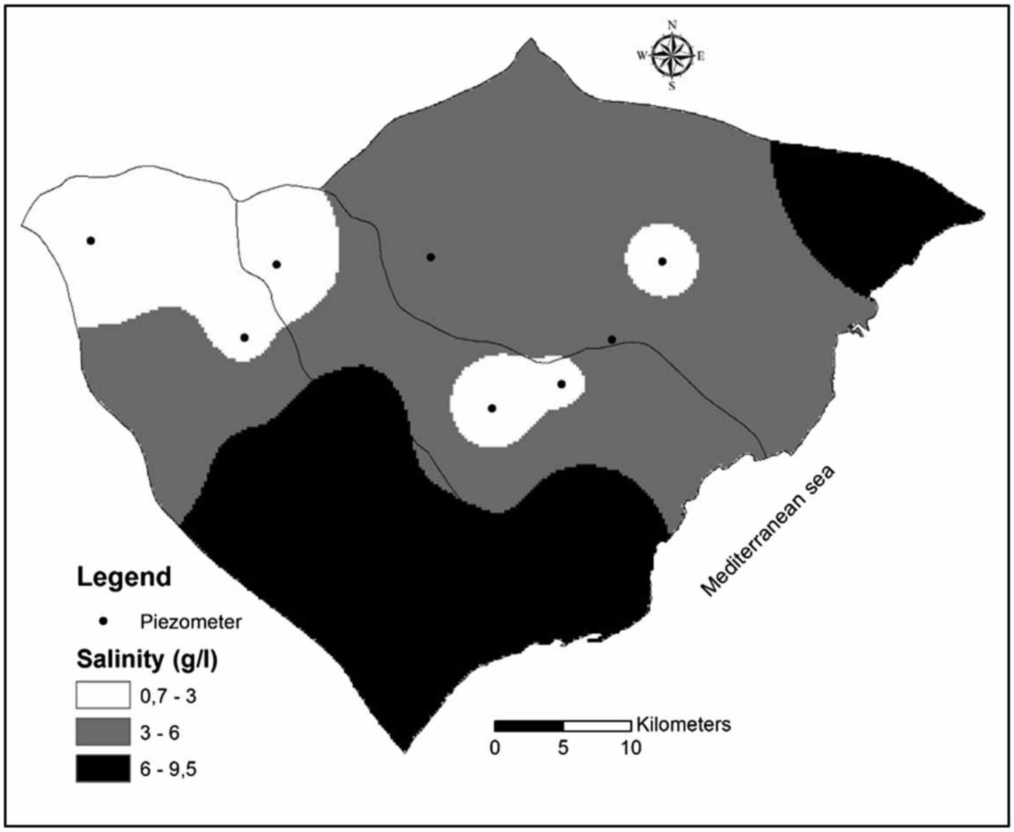

Figure 12 | Distribution of salinity in the aquifer system in the study area.

aquifer (in the Sidi Abid area), which are greater than the recommended limit 45 mg l^{-1} proposed by the World Health Organization (WHO 1998) and also reveals the same tendency reflected in the intrinsic vulnerability index mapping (see Figure 7). The DRASTIC model seems to be suitable to demonstrate that the water resources are threatened by artificial fertilizers (nitrates).

The absence of a sanitation network in the whole region contributes to the nitrification of ground waters according to the process. In addition, the salinity map of the aquifer shows an increasing tendency along the coastal zones (Figure 12). This might be explained by the intensive pumping which tends to be quite important in zones of low piezometric levels.

Development of the risk assessment

In this method, risk assessment includes all activities that consider the possible origins of pollution. The points of potential contamination release are determined with hazard assessment where all possible origins of pollution and likelihood of release are considered (Andreo *et al.* 2005). To attain the risk assessment, we could overlay the hazard map (Figure 13) and the map of anthropogenic activities (Figure 14).

The risk map shows three classes as indicated in Figure 15. The highest class of risk covers 60% of the study area, characterized by high to moderate vulnerability where human activities are concentrated. The moderate class of risk represents nearly 30% of the study area marked by low vulnerability with the presence of anthropogenic activities. These areas characterized mainly the central part of the aquifer. In the upstream part of the aquifer, the absence of anthropogenic activities, placed in low vulnerability zones, implicate a low risk.

These vulnerability and risk classes are too relative: a site with moderate vulnerability or risk does not mean that it is free from groundwater contamination, but it is relatively

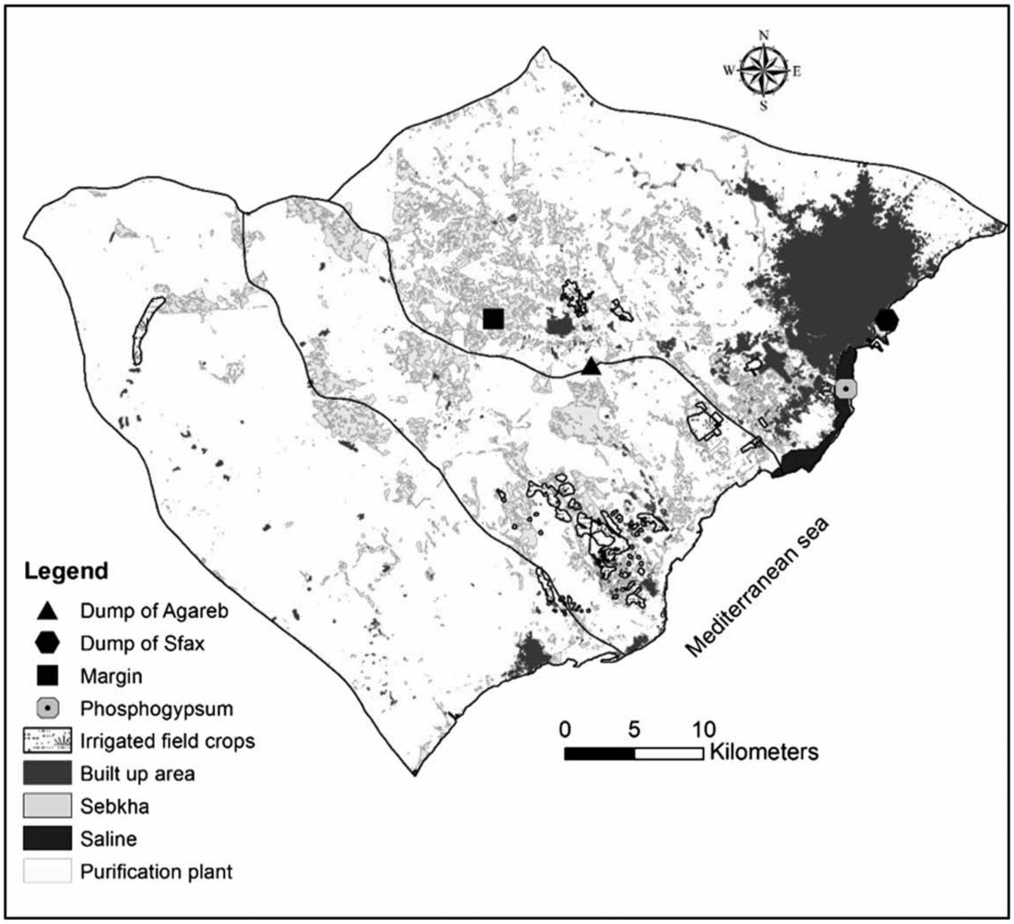

Figure 13 | Hazard map of the study area.

less susceptible to contamination compared to the others. The observation of these maps shows that the best correspondence is observed where there is a high density of wells (high density of information). Thus, to obtain a better validation, other monitoring wells should be analyzed, to cover areas with less data.

DISCUSSION

The main objective of this project was to develop a methodology in order to assess the degrees of risk of the study area in order to facilitate the decision-making in water resource management under geo-scientific aspects. These aspects take into account the importance of the database to support reclassifications, store multiple data and integrate them in a generic model (Ballesteros 2004).

In this respect, the project workflow can serve as a methodological approach to support the sustainable development in developing regions with an arid and semi-arid climate.

Using the DRASTIC and GALDIT methods, the majority of the coastal part of aquifer system of Sfax–Agareb, Chaffar and Mahres presents medium to high vulnerability, which makes it susceptible to pollution and particularly in seawater intrusion. In fact, areas with high vulnerability present high nitrate concentrations. Consequently, GALDIT is validated. But, some areas present a high vulnerability and are localized in the west as far as the coast. This is due to high lithology variation in the region and the integration of chemical analysis in the aquifer vulnerability assessments.

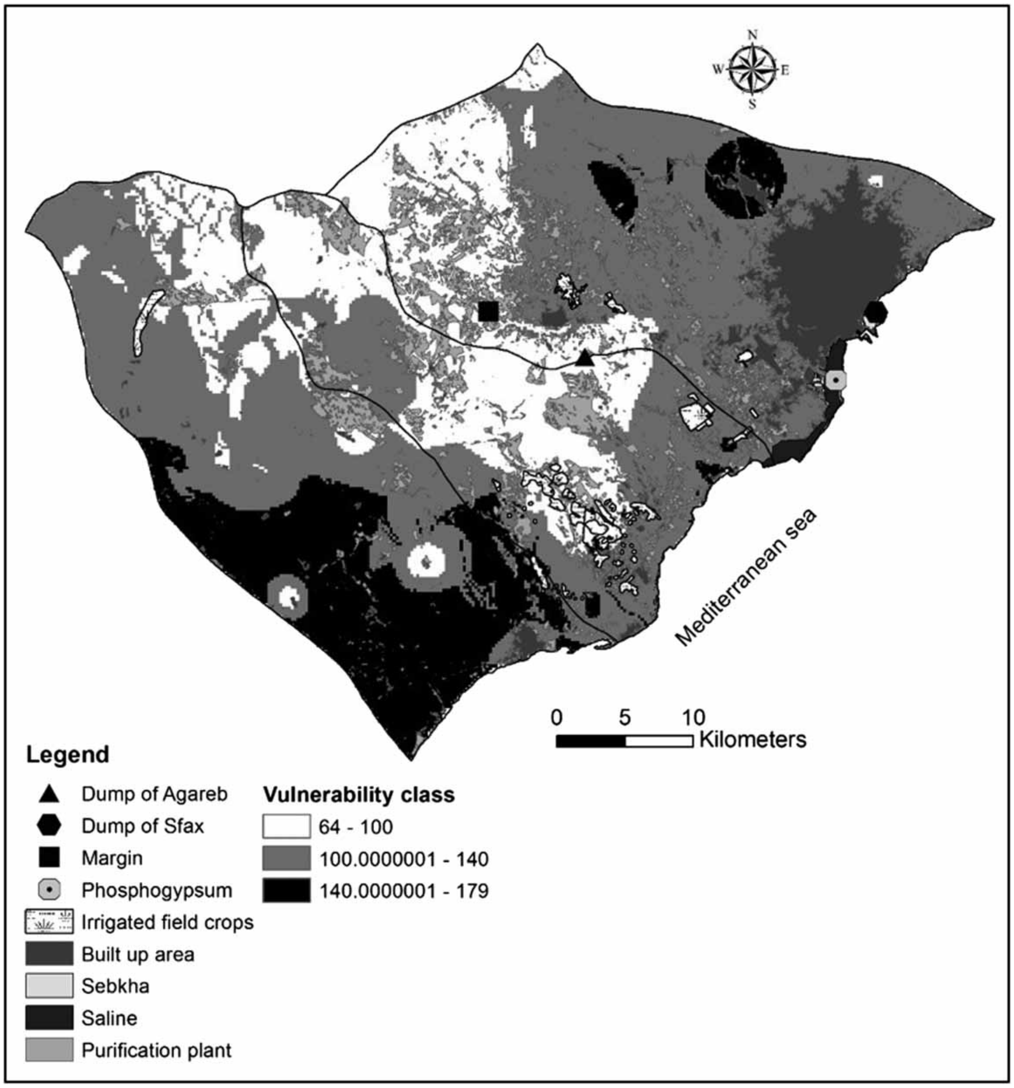

Figure 14 | Location of the various sources of pollution on the vulnerability map.

Perhaps the biggest limitations are the constraints and errors associated with the interpolation technique in all vulnerability parameters.

In this research project, GIS plays an important role as it allows: (1) integration, organization and structuring of the geo-data set; (2) interpolation of a large database to generate different thematic maps of vulnerability and risk evaluations; (3) overlying a variety of maps; (4) assigning weights and rates for each hazard; and (5) calculating the HI, VI and RI indices for each cells using the calculating tool available in the Arc GIS 9.2 software.

Finally, the risk map should be updated because it depends on hazard development and aquifer vulnerability. This procedure is facilitated by the use of GIS and other technologies like remote sensing (Serra *et al.* 2008; Wood 2009; Pelorosso *et al.* 2009).

CONCLUSION

This paper proposes a methodology to assess groundwater vulnerability using different methods and a comparison

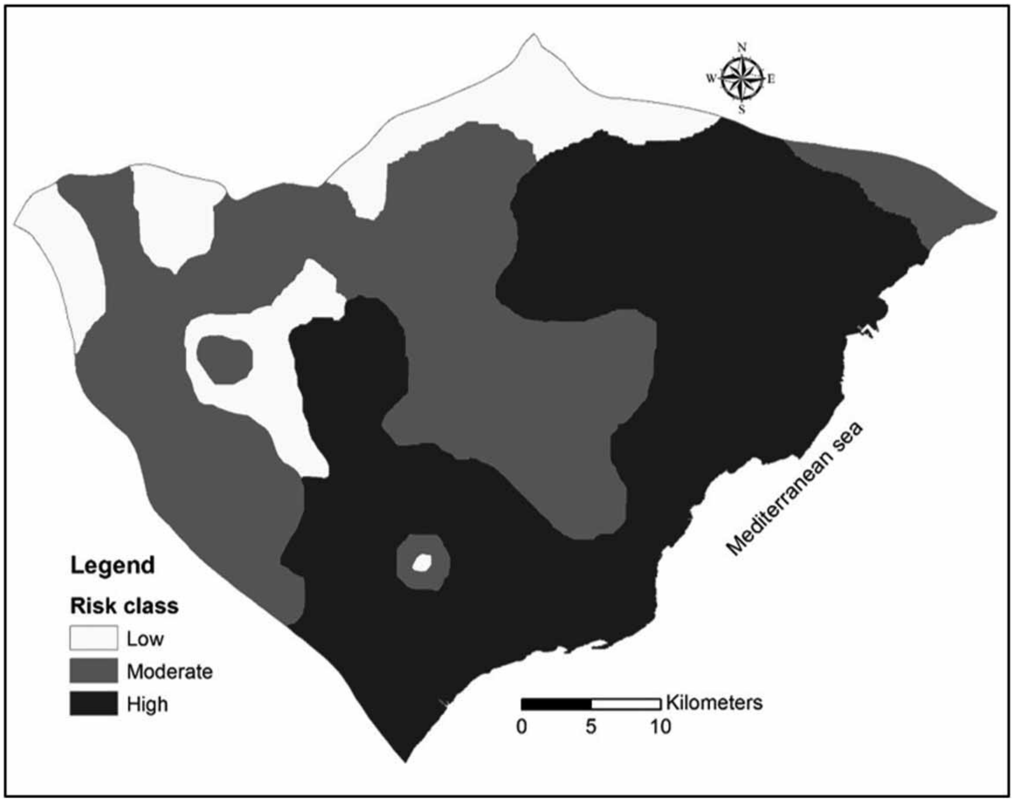

Figure 15 | The risk map made by overlaying the vulnerability and the hazard maps.

was made in order to delineate the most vulnerable zones in the study area. The vulnerability maps of the study area were obtained by combining several parameters (physical, chemical, intrinsic, etc.). The results of the DRASTIC and GALDIT methods are compared and critically examined. Using the spatial distribution of nitrate concentration and the development of the risk assessment in the validation of different methods reveals that reducing the number of parameters is unsatisfactory due to the variety of geological conditions in the study area. Also, the comparison between real weights, calculated by the theoretical weights of DRASTIC and GALDIT methods, permitted a reconsideration of the weights of hydraulic conductivity and the impact of the vadose zone parameters. Using different synthetic documents, in the eastern part of the study area, we should not allow either additional wells or high-risk activities in order to preserve groundwater resource and reduce potential environmental pollution hazard. Consequently, this area should be considered by the managers in order to minimize groundwater contamination by seawater intrusion and anthropogenic activities. However, the southern part of the aquifer will be more suitable for the implantation of potential anthropogenic activities and additional wells for consumption. GIS greatly facilitated the aquifer vulnerability assessment and the implementation of sensitivity analysis applied on different methods (DRASTIC, GALDIT) which otherwise would have been impractical.

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