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Comparison of three applied methods of groundwater vulnerability mapping: application to the coastal aquifer of Chebba–Mellouleche (Tunisia)

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ABSTRACT

The Chebba–Mellouleche Aquifer situated in the eastern coast of Tunisia is known for population growth and industrial development. These industrial and agricultural developments have led to water resources' degradation. So, cartography of the vulnerability seems to be an efficient tool for water resources management. In order to evaluate the vulnerability of the aquifer to pollution, three methods were used: DRASTIC, GALDIT and AVI based on the geographical information system (GIS) tools. These methods use different parameters which explain the different results in the vulnerability degrees in the Chebba–Mellouleche Aquifer. The vulnerability maps show that the coastal part of the study area is the most vulnerable zone. This explains the high similarity between the vulnerability map using the real weights, calculated by sensitivity analysis, and the nitrate distribution one. This reveals the high importance of sensitivity analysis in the validation of the vulnerability methods and in the choice of the suitable method in the decision-making in water protection and management. Also, when comparing the results, it seems that reducing the number of parameters is unsatisfactory due the variety of geological conditions of the study area. GIS is utilized to manage, manipulate and analyse the necessary geographical data used in the different vulnerability methods.

Keywords: Chebba–Mellouleche Aquifer; Geographical information system; DRASTIC; GALDIT; Aquifer vulnerability index

1. Introduction

Coastal aquifers serve as a major source for freshwater supply in many countries around the world, especially in arid and semi-arid zones. These zones have scarce rainfall and resultant intermittent rivers like the site of this study, the Chebba–Mellouleche region. It receives less renewable recharge and has experienced an increase in anthropogenic activities, a fact that creates the need for freshwater even more acute. Indeed, the water resources are threatened by

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overexploitation (drinking water, irrigation uses, etc). Thus, it induces an increase in pumping and the possibility of contamination by salt water, and many wells are saline and have to be abandoned, especially those close to the coast. So, salinization of coastal aquifer has been experienced recently as 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 by the end of the 1960s to create awareness about groundwater contamination [1]. 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 as an intrinsic property of a groundwater system that depends on its sensitivity to human and/or natural impacts [2]. Groundwater vulnerability deals only with the hydrogeological setting and does not include pollutant attenuation.

To this end, three methods were proposed in this study: DRASTIC [3], AVI [4] and GALDIT [5,6].

The DRASTIC method is chosen because it seems that it is the most common method used worldwide for measuring the vulnerability to pollution assessment. AVI and GALDIT are selected in order to assess the transmit time of contaminants and to analyse the seawater intrusion state of the aquifer. In fact, for vulnerability assessment, a comprehensive investigation program was carried out, including detailed geological, structural, lithological and geomorphological mapping, geophysical surveys (electrical resistivity), and physico- chemical parameters.

The practical, site-specific purpose of this study is to characterize and to identify the most threatened zone by multidisciplinary data and by mapping the most vulnerable area. Moreover, a sensitivity analysis has been performed to evaluate the contribution of each parameter to aquifer vulnerability. Another goal was to test and compare the three different methods and the resulting maps, and to validate the vulnerability assessments by sensitivity analysis and

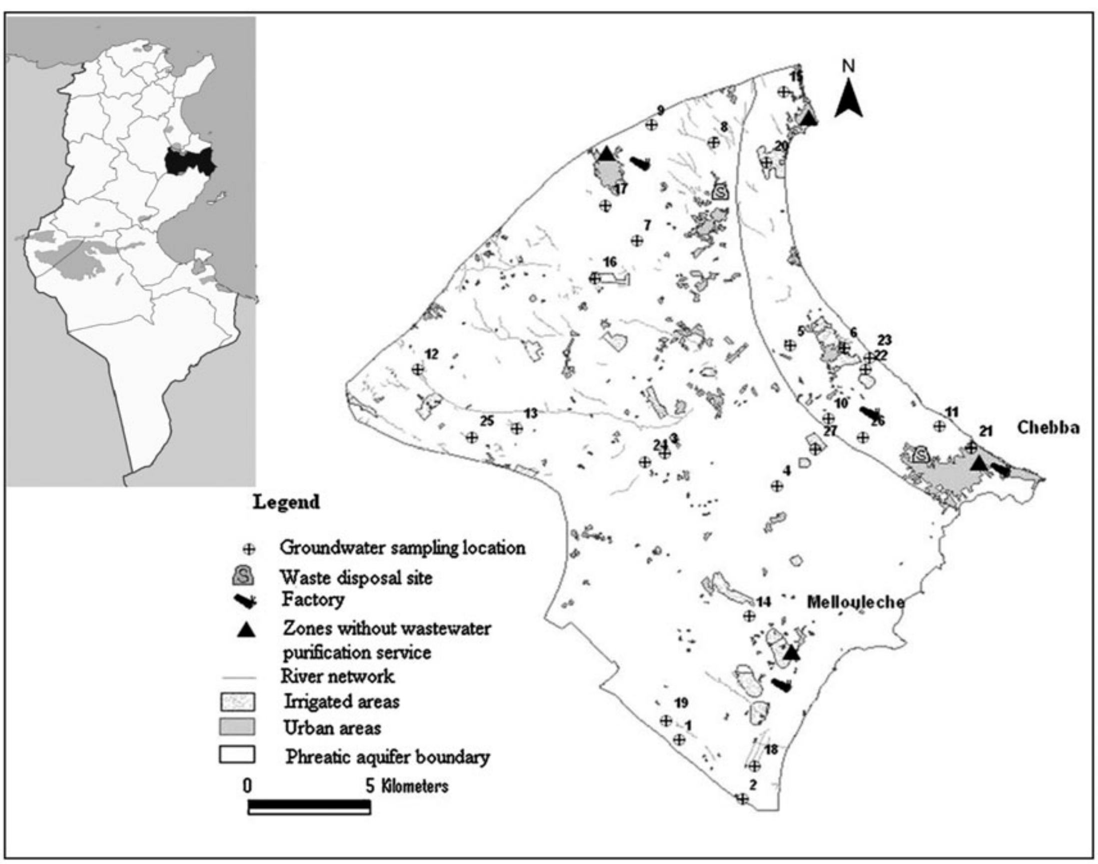

Fig. 1. Location of the study area.

comparisons with nitrate and chloride concentrations maps. Furthermore, the geographical information system (GIS) technique provides an efficient environment to reach this objective.

2. Description of the study area

The study area is located in eastern part of Tunisian Sahel with a total surface of 510 km^2 (Fig. 1). This region has a semi-arid climate, with large temperature and rainfall variations. Averages of annual temperature and rainfall are about 19˚C and 225 mm, respectively. The morphology of the study area is characterized by a wide flatness. The Chebba–Mellouleche coast is one of the major coastal districts of Tunisia and has a coastline of 51 km. The coastal population of this district is around 23,334 inhabitants according to the 2004 census [7].

Geologically, this zone is located on an alluvial plain and dominated by Quaternary deposits. The Chebba and Mellouleche areas have relatively stable tectonics apparent in the tabular sedimentary structure. The coastal part study area is located in the Plio-Quaternary layer system which is constituted mainly by alluvial fan, gravel, sand and clay with high permeability [8].

The aquifer is known for overexploitations, where the demand largely exceeds the exploited water resources of the aquifer, since 1995 (Table 1; [9]). It has an estimated safe yield of 3.24 106 m^3/yr, but annual abstraction by pumping from 4,643 wells stands at 4.28 106 m^3/yr [7]. This fact was confirmed by piezometric and hydrochemical studies. In fact, in coastal zones with high exploitation, it corresponds to piezometric depression and a high salinity level.

Electrical resistivity data have been used to identify the geographical extent of salinization in the Chebba–Mellouleche Aquifer and in particular the coastal part. In fact, when resistivity decreases the salinity increases. The cross-section was established in the study area with the direction southern-west–northern-east. It indicates a low resistivity associated with the areas near the coast (Fig. 2). These low resistivity zones adjoining the coast correspond to the higher chloride concentrations and salinity exceeding 6 g/l, suggesting seawater intrusion [7].

Table 1
Evolution of the abstraction rates in the Chebba–Mellouleche Aquifer [9]

Year	Resources (Mm^3/yr)	Number of wells	Abstraction (Mm^3/yr)
1980	3.24	1,540	2.2
1995	3.24	5,228	3.61
2005	3.24	6,427	4.28

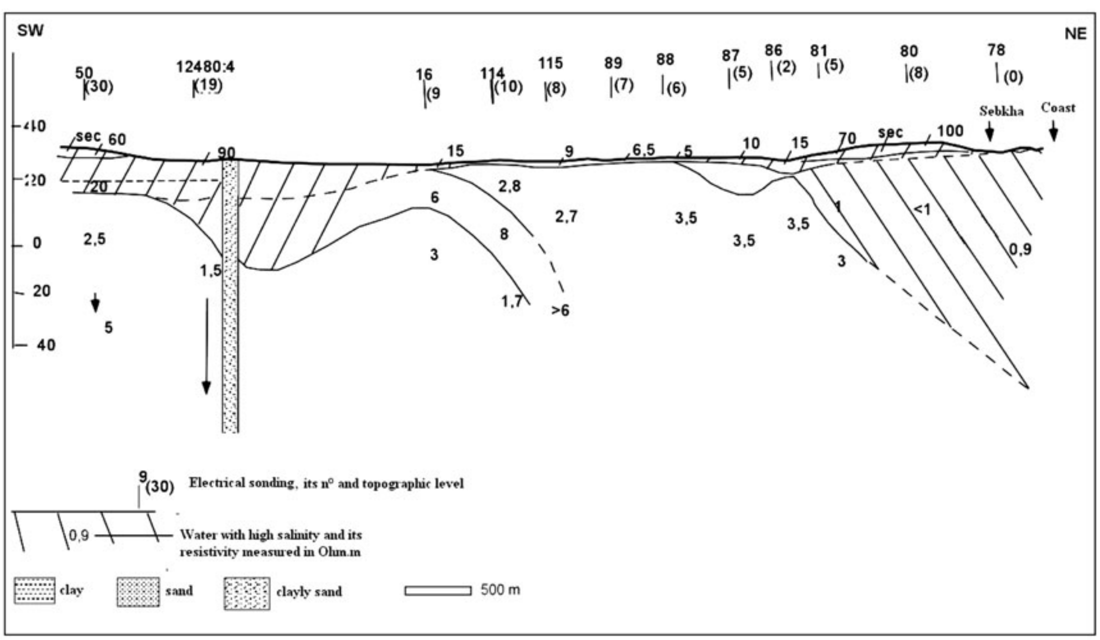

Fig. 2. Geoelectrical cross-section of the study area [7].

Table 2
Rank and weight of the seven DRASTIC parameters [3]

Depth to groundwater table (m) «D»		Recharge (m) «R»		Topography (slope) (%) «T»		Hydraulic conductivity (m/s) «C»		Aquifer lithology «A»		Impact of the vadose zone «I»		Soil type «S»	
I	R	I	R	I	R	I	R	Lithological classes	R	Lithological classes	R	Soil classes	R
2–4.5	9	0.01–0.05	1	0–3%	10	$4\ 10^{-5}$–$8.3\ 10^{-5}$	2	Sand with clay intercalations	1	Confined aquifer	1	Mineral Soil	9
4.5–9	7	0.05–0.10	3	3–5%	9	$4\ 10^{-5}$–$2.5\ 10^{-4}$	4	Clayey sand	2	Clayey sand	2	Isohumic chestnut soil	8
9–15	5	0.10–0.18	6	5–10%	5	$2.5\ 10^{-4}$–$4\ 10^{-4}$	6	Sand, gravel, clay	4	Silty sand	4	Rendzina	7
15–23	3	0.18–0.25	8	10–15%	3	$4\ 10^{-4}$–10^{-3}	8	Sand and gravel	8	Gravel and sand	10	Calcareous brown soil	6
23–32	2	>0.25	9	15–25%	1	Weight 3		Gravel sand	10	Weight 5		Soil with little evolution	5
Weight 5		Weight 4		Weight 1				Weight 3				Polygenetic soil	4
												Gypsum soil	3
												Halomorphic soil	2
												Urbain zones	1
												Weight 2	

I: interval; R: rate.

Table 3
Hydraulic conductivity [13]

Aquifer lithology	Hydraulic conductivity (m/s)
Sand	1.4×10^{-9}
Sandy clay	5.1×10^{-6}
Sand	2.1×10^{-4}
Clay with sand	5×10^{-5}
Thin/moderate sand	1×10^{-3}
Thin sand	6×10^{-4}
Moderate sand	1×10^{-4}
Gravel	1.4×10^{-3}

Chemical composition of groundwater samples shows that it is rich in $SO_4^{2}-$ and Cl^{-}. Consequently, the Chebba–Mellouleche groundwater belongs to the same water type: SO_4–Cl–Ca–Na.

3. Vulnerability mapping

3.1. Overview of the three methods

The three applied methods of groundwater vulnerability assessment are based on different types of information about the soil and unsaturated zone, recharge conditions and aquifer characteristics. This information is categorized into different factors. Their nomenclature differs and they require diverse data sources and high number of parameters (input data) (Tables 2–4).

The vulnerability methods are classified into two approaches: the first one aims to protect groundwater from general pollution using "intrinsic vulnerability" and physical parameters (DRASTIC and AVI methods). The second approach deals with vulnerability to seawater intrusion using physical and chemical parameters (GALDIT).

DRASTIC: The DRASTIC method was developed by the US Environmental Protection Agency to evaluate the groundwater pollution potential for entire USA [3]. 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 [3]. 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).

Depth of groundwater (D) represents the depth from the land surface to the first groundwater aquifer [10]. It determines the thickness of the material through which the infiltrating water must travel before reaching the aquifer or the saturated zone.

Table 4
Weights and rates proposed for GALDIT model of Chebba–Mellouleche Aquifer

Parameter	G	A	L	D	I		T
					Impact of existing intrusion		
	Groundwater occurrence Aquifer type	Hydraulic conductivity m/day	Level above mean sea m	Distance from coast m	Cl^- / HCO_3^-	SO_4^{2-} / Cl^-	Aquifer thickness m
Weights rates	1	3	4	2	1		2
1		0,086–10	15<	1,000 <			
2			8–15	800–1,000			
3			5–8	700–800			5–6
4		10–15	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 unconfined			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<

Consequently, the depth of the groundwater has a great impact on the degree of interaction between the percolating contaminant and sub-surface materials (air, minerals and water) and, therefore, on the degree and extent of physical and chemical attenuation, and degradation processes [11]. The distribution of the depth of groundwater parameter (D) was established by subtracting the groundwater level, measured in 30 wells in Mahdia-Ksour Essaf Aquifer from the topographic elevation in the corresponding cell location.

Net recharge (R) represents the amount of water stored in the aquifer which can control the dilution degree of the contaminant in the aquifer. In order to calculate the recharge parameter, the water table fluctuations method was used. It estimates the groundwater recharge as a product of specific yield and the annual rate of water table rise plus the total groundwater draft [12].

Aquifer media (A) and the impact of the vadose zone (I) represents the lithology of the saturated zone (*A*) and the vadose zone (*I*), which is found from well logs. It can influence the vulnerability to pollution. Thus, in 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 it influences the pollution potential. The soil parameter (S) was obtained by digitizing the existing soil maps, with a scale of 1:50 000 acquired from Regional Agency of Agriculture Laboratory "CRDA", covering the region.

Topography (T) refers to the percent slope of the land surface which was determined directly from the topographic maps (scale 1:50 000) and using 3D analyst extension of Arc GIS 9.3. The importance of topography in this context is to control the runoff of pollutants.

Hydraulic conductivity (C) is defined as 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 Eq. (1):

$$K = t/b$$

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 [7].

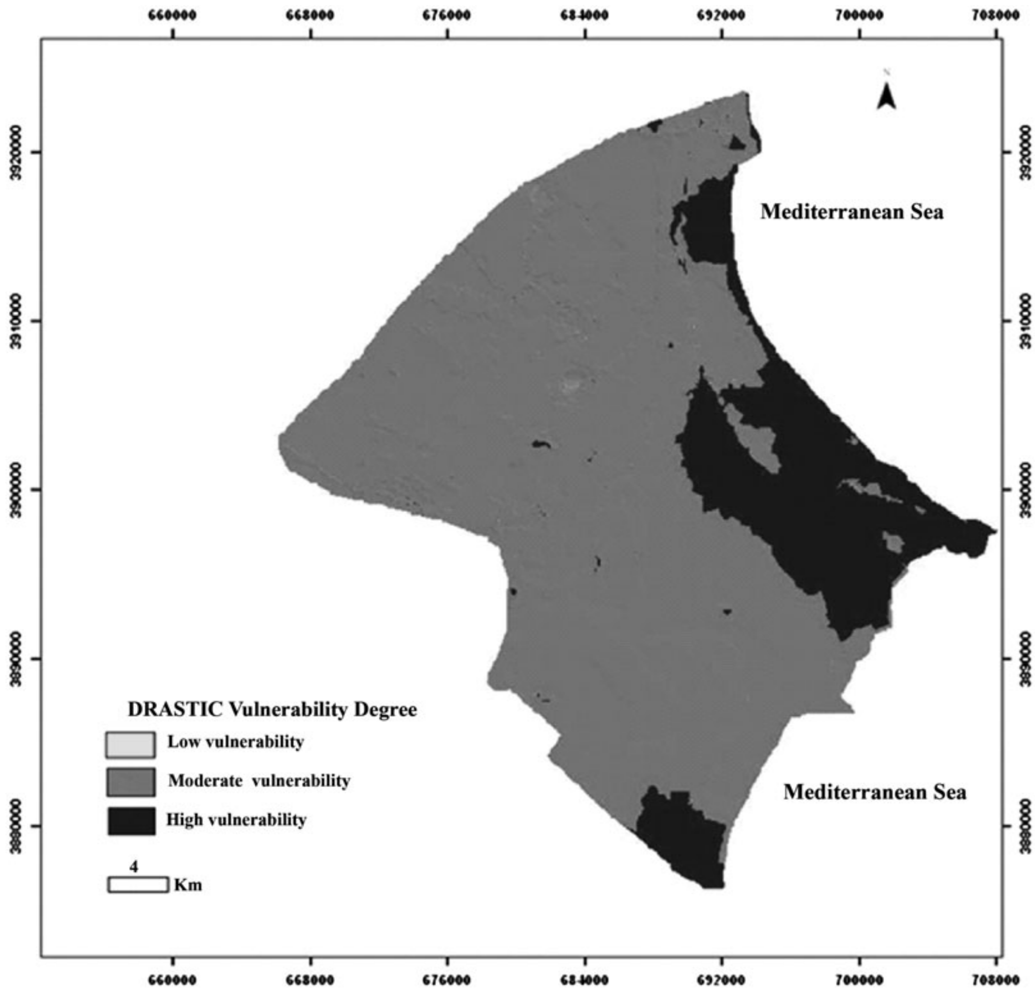

Fig. 3. Aquifer vulnerability according to the DRASTIC method [7].

The model 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 the ranges, which are rated from 1 to 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 (Table 2). The DRASTIC Index (DI) is then computed applying a linear combination of all factors according to the following Eq. (2):

$$\mathrm{ID} = I = D_R D_W + R_R R_w + A_R A_W + S_R S_W + T_R T_W + I_R I_W + C_R C_W$$

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.

AVI: AVI stands for aquifer vulnerability index. The parameter hydraulic resistance C is an estimation of the travel time of a contaminant through the unsaturated zone [4]. The AVI index is calculated by means of the following expression (3):

$$\mathrm{AVI} = 10\,\mathrm{Log}\,(\mathrm{Hr});$$

where Hr is the hydraulic resistance (Table 3; [13])

GALDIT: The GALDIT method is used in the object to delineate the most vulnerable areas to seawater intrusion. This method is used to evaluate the vulnerability of the Chebba–Mellouleche Aquifer to seawater intrusion. It is chosen because it takes accounts into the physical characteristics affecting the 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:

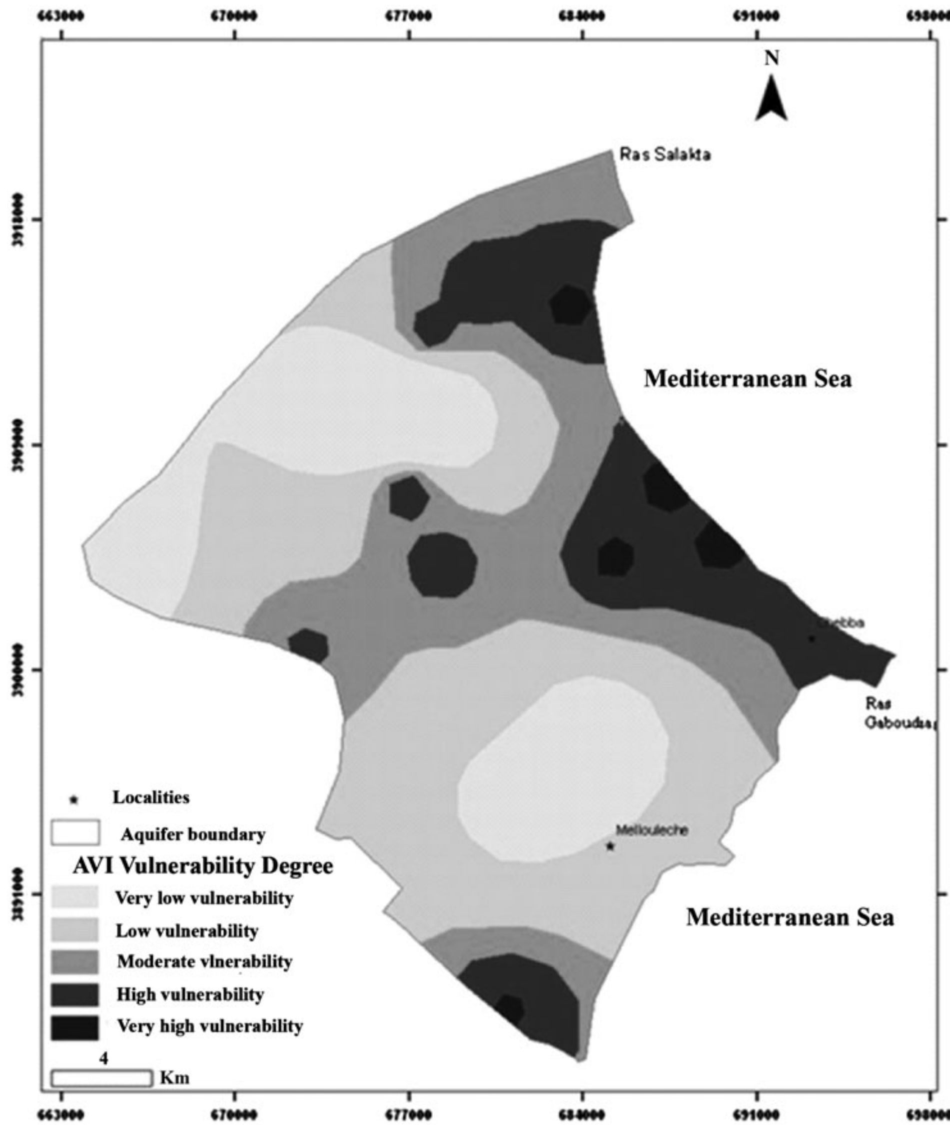

Fig. 4. Aquifer vulnerability according to the AVI method [7].

- Groundwater occurrence (D) (aquifer type: unconfined, confined or leaky confined): Based on the geological nature, layers can be categorized as confined, unconfined or leaky confined. So, 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 one is more vulnerable due to larger cone of depression after pumping, whereas leaky confined maintains minimum hydraulic pressure by way of leakage from adjoining aquifers. Hence, the latter has got least susceptibility to saltwater intrusion [14].
- *Aquifer* hydraulic conductivity (A): It 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 seawater front.
- Depth of groundwater *L*evel above the sea (L): it 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 raster surface. It represents a very important factor in evaluating seawater

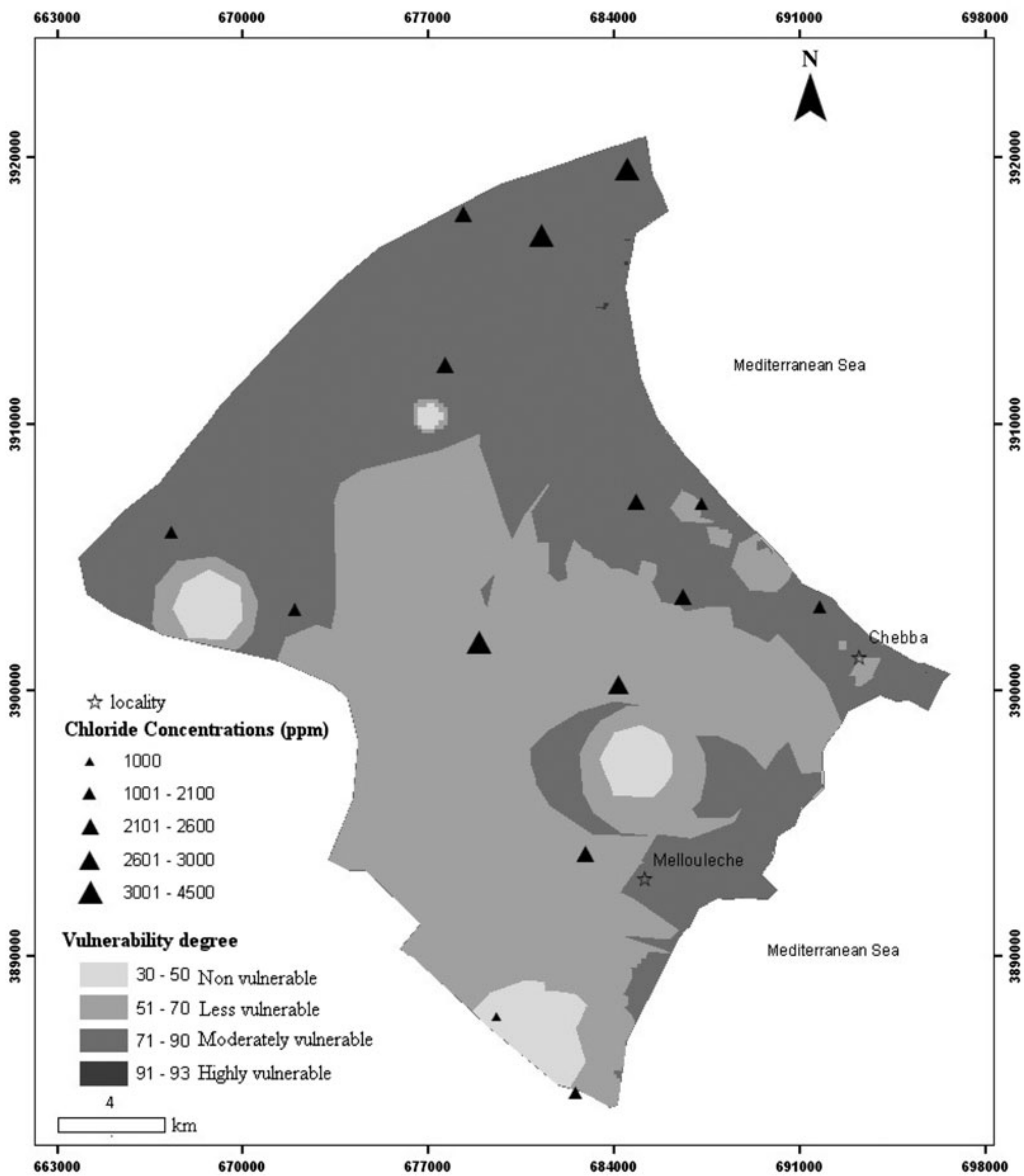

Fig. 5. Vulnerability to seawater intrusion degree according to the GALDIT method.

intrusion because it determines the hydraulic pressure availability to push the seawater front back.

- Distance from the shore (D): the impact of seawater 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.
- *I*mpact of existing status of seawater intrusion in the area (I): it can be computed using the ratio of SO_4^{2-}/Cl^- [7].
- Thickness of the aquifer, which is being mapped (T): it 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 [7].

Each of the six parameters have a predetermined fixed weight that reflects their relative importance to seawater intrusion (Table 4). The GALDIT index is calculated by the following Eq. (4):

$$\text{GALDIT} = 1^{*}G + 3^{*}A + 4^{*}L + 2^{*}D + 1^{*}I + 2^{*}T$$

Using 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 [6,14].

3.2. Application and adaptation of methods

The three resulting vulnerability maps show some similarities as well as notable differences (Figs. 3–5). The DRASTIC map shows three classes as indicated in Fig. 3. The highest class of vulnerability (140–159) covers 25% of the total surface. This is due to the shallow groundwater table (<9 m), a flat topography (<5%), a high recharge, a permeable vadose zone and aquifer (made up of sand and gravel lithology) and low capacity to attenuate the contaminants. The decrease of vulnerability from high to moderate class (index 101–139) in the rest of the zone, except for a small zone (3%) with low vulnerability, is essentially due to a deeper groundwater table at more than 25 m depth (Table 2).

The results of the AVI method confirm those of the DRASTIC method in the fact that the coastal part is the most vulnerable area. But, for this method, in the western part there are both high and low vulnerability classes in the same context. The presence of extreme vulnerability classes is due to the high lithological variations and hydraulic conductivity (Fig. 4).

The GALDIT map shows four classes as indicated in Fig. 5. The highest class of vulnerability covers particularly the north-eastern part and the eastern part of the aquifer (the coast). This is due to the high permeability (unconfined aquifer), the high hydraulic conductivity (>20 m/day), the shallow groundwater table (<8 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 (<1000 m). In contrary, the low vulnerability class presents low vulnerability which is attributed essentially to the high depth of water table, the high distance to the coast and the low aquifer conductivity (Table 4).

4. Validation of the methods

4.1. Sensitivity analysis

The sensitivity analysis, which is carried out in this study, helps to validate and evaluate the consistency of the analytical results and it represents the basis of proper evaluation of vulnerability maps. Using sensitivity analysis, a more efficient interpretation of the vulnerability index can be achieved. For this exercise, many sensitivity tests were used. In this study, the single-parameter sensitivity measure was developed to evaluate the impact of each of the DRASTIC parameters on the vulnerability index [2]. It has been done to compare the weight assigned by the analytical model and the real or the "effective" weight which is computed by the following formula (5):

$$W = ((\text{PrPw})/V) \times 100$$

where W refers to the "effective" weight of each parameter, Pr and Pw are the rating value and weight for each parameter and V is the overall vulnerability index.

The results of the statistical analysis are illustrated in Tables 5 and 6 revealing that the most important parameter in aquifer vulnerability is the hydraulic conductivity when comparing real and theoretical weights using both DRASTIC and GALDIT. The impact of the vadose zone seems to be of low importance in aquifer vulnerability since it has a real weight largely lower than the theoretical one. The other calculated weights demonstrate no significant difference.

Table 5
Comparision between theoretical and real weights for the DRASTIC method

DRASTIC parameter	Theoretical weight	Real or calculated weight
D	5	4.66
R	4	2.4
A	3	5.81
S	2	1.83
T	1	1.95
I	5	3.91
C	3	2.41

Table 6
Comparision between theoretical and real weights for the GALDIT method

GALDIT parameter	Theoretical weight	Calculated or real weight
G	1	1.62
A	3	4.64
L	4	1.65
D	2	1.5
I	1	1.77
T	2	1.76

4.2. Nitrate and chloride distribution

The comparison of the vulnerability maps to those of nitrate and chloride distribution constitute the second method used here for the validation. So, the comparison between the vulnerability profiles (Fig. 6) and the nitrate distribution ones reveal a high similarity observed in the case of the GALDIT using modified or real weights (calculated by sensitivity test). So, the GALDIT method is very suitable to determine the vulnerability of the Chebba–Mellouleche Aquifer.

However, when comparing the different vulnerability profiles to the chloride and nitrate, a similarity is observed in the coast (east) which confirms the contamination of freshwater of the Chebba–Mellouleche Aquifer by seawater intrusion, a fact proved by the geophysical and hydrochemical study (Figs. 5 and 6). This test also confirms the high importance of sensitivity analysis in the validation of the results.

5. Discussion

Using DRASTIC, AVI and GALDIT methods, the majority of the coastal part of the Chebba–Mellouleche Aquifer presents medium to very 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 and AVI are 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.

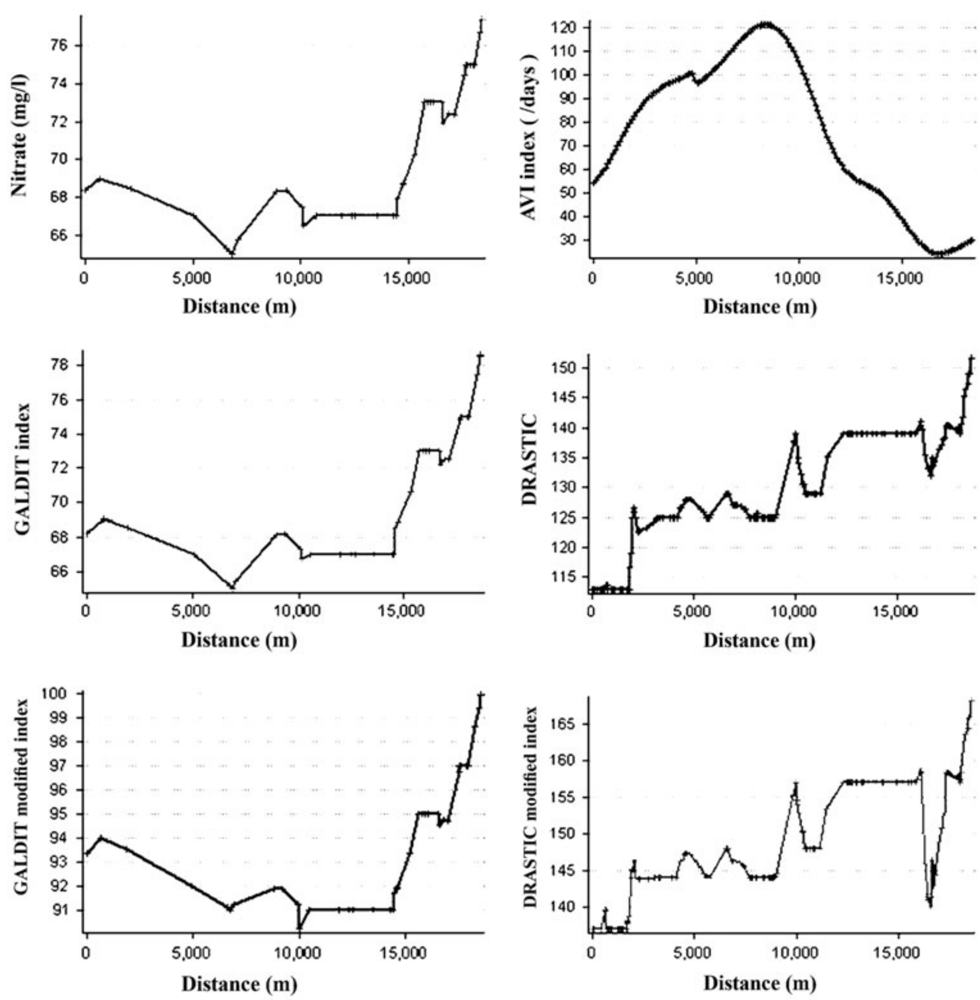

Fig. 6. Comparison between vulnerability profiles using real and theoretical weights and nitrate distribution in the Chebba–Mellouleche Aquifer.

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

6. Conclusion

This paper proposes a methodology to assess groundwater vulnerability using different methods and a comparison was made in order to delineate the most vulnerable zones in the study area. The vulnerability maps of the study area have been obtained by combining several parameters (physical, chemical, intrinsic, etc). The results of the DRASTIC, AVI and GALDIT methods are compared and critically examined. Using the sensitivity analysis 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 sensitivity analysis, and 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 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 could have been impractical.

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