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Guideline for Groundwater Resource Management Using the GIS Tools in Arid to Semi Arid Climate Regions

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1. Introduction

The quality of groundwater is generally under a considerable potential of contamination especially in coastal areas with arid and semi-arid climate like the study area. It is also characterized by intensive agriculture activities, improper disposal of wastewater, and occurrence of olive mills. In addition the intensity of exploitation, often characterized by irrational use, imposes pressures on groundwater reserves. Therefore, there is clearly an urgent need for rapid reconnaissance techniques that allow a protection of groundwater resources of this area.

Groundwater management and protection constitutes an expensive undertaking because of the prohibitive costs and time requirements. To preserve the groundwater resources a simple susceptibility indexing method, based on vulnerability and quality index, was proposed.

The groundwater vulnerability assessment has recently become an increasingly important environment management tool for local governments. It allows for better understanding of the vulnerabilities associated with the pollution of local groundwater sub areas, according to local hydrological, geological or meteorological conditions. The adopted method was specifically developed for groundwater vulnerability DRASTIC method and it is a widely used in many cases of study (Aller et al., 1987; Saidi et al., 2009 and 2011;Rahman, 2008). The DRASTIC model is based on seven parameters, corresponding to the seven layers to be used as input parameters for modeling, including depth to water table (D), recharge (R), aquifer type (A), soil type (S), topography (T), impact of vadose zone (I) and conductivity (C). Vulnerability index is defined as a weighted sum of ratings of these parameters. The quality index calculation procedure, based on the water classification, was introduced to evaluate hydrochemical data.

Therefore the main objective of this study is to propose some water management scenarios by performing the susceptibility index (Pusatli et al., 2009) for drinking and irrigation water. The first objective was to evaluate the susceptibility index. To this end, a combination of both vulnerability and water quality maps has been considered. The second objective was to classify the study area into zones according to each degree of susceptibility and some alternatives to manage the groundwater resources of the Chebba – Mellouleche aquifer were proposed.

A geographic information system (GIS) offers the tools to manage, manipulate process, analyze, map, and spatially organize the data to facilitate the vulnerability analysis. In addition, GIS is a sound approach to evaluate the outcomes of various management alternatives are designed to collect diverse spatial data to represent spatially variable phenomena by applying a series of overlay analysis of data layers that are in spatial register.

2. Study area

The region, object of this study, is the Chebba – Mellouleche aquifer which is situated in the Eastern Tunisia with a total surface of 510 km^2 and a coastline of 51Km (Fig. 1). This region is characterized by a semi-arid climate, with large temperature and rainfall variations. Averages of annual temperature and rainfall are about 19.8°C and 225 mm, respectively (Anon., 2007a). It is known for intensive anthropogenic activities such as industrial and especially agricultural ones which is concentrated in its North east part (Fig. 1).

Both of the aquifer and the vadose zone of the Chebba– Mellouleche region are located in Plio-Quaternary layer system which is constituted mainly by alluvial fan, gravel, sand, silt and clay with high permeability (Saidi et al., 2009). Hence, it results in an easily infiltration of nutrients in the groundwater. The aquifer has an estimated safe yield of 3.24 10^6 m^3/yr, but annual abstraction by pumping from 4643 wells stands at 4.28 10^6 m^3/yr (CRDA, 2005).

The groundwater supply is under threat due to salinisation as salinity measures are generally of 1.5–3 g/l in the majority of the coastal Aquifer, and exceed 6 g/L in the West (Anon., 2007b). For these reasons, a new water management planning is highly required.

3. Methodology

It is noted that an integration of hydrogeological and hydrochemical parameters through the use of the susceptibility index method should be considered as a reliable tool for groundwater quality protection and decision making in this region.

To reach this aim, a variety of GIS analysis and geo - processing framework, which includes: Arc Map, Arc Catalog, Arc Scene and Model Builder of the Arc GIS 9.2 were used (Rahman, 2008).

3.1 Susceptibility index (S_I)

The contamination susceptibility index (S_I) was calculated by considering the product of the vulnerability index (V_I) and the quality index (Q_I) using the following equation (Pusatli et al., 2009):

$$S_I = V_I * Q_I \qquad (1)$$

3.1.1 Vulnerability index (V_I)

In the present study the DRASTIC method, a standard system for evaluating groundwater pollution potential is used. The DRASTIC model is very used all over the world because the input information required for its application is either readily available or easily

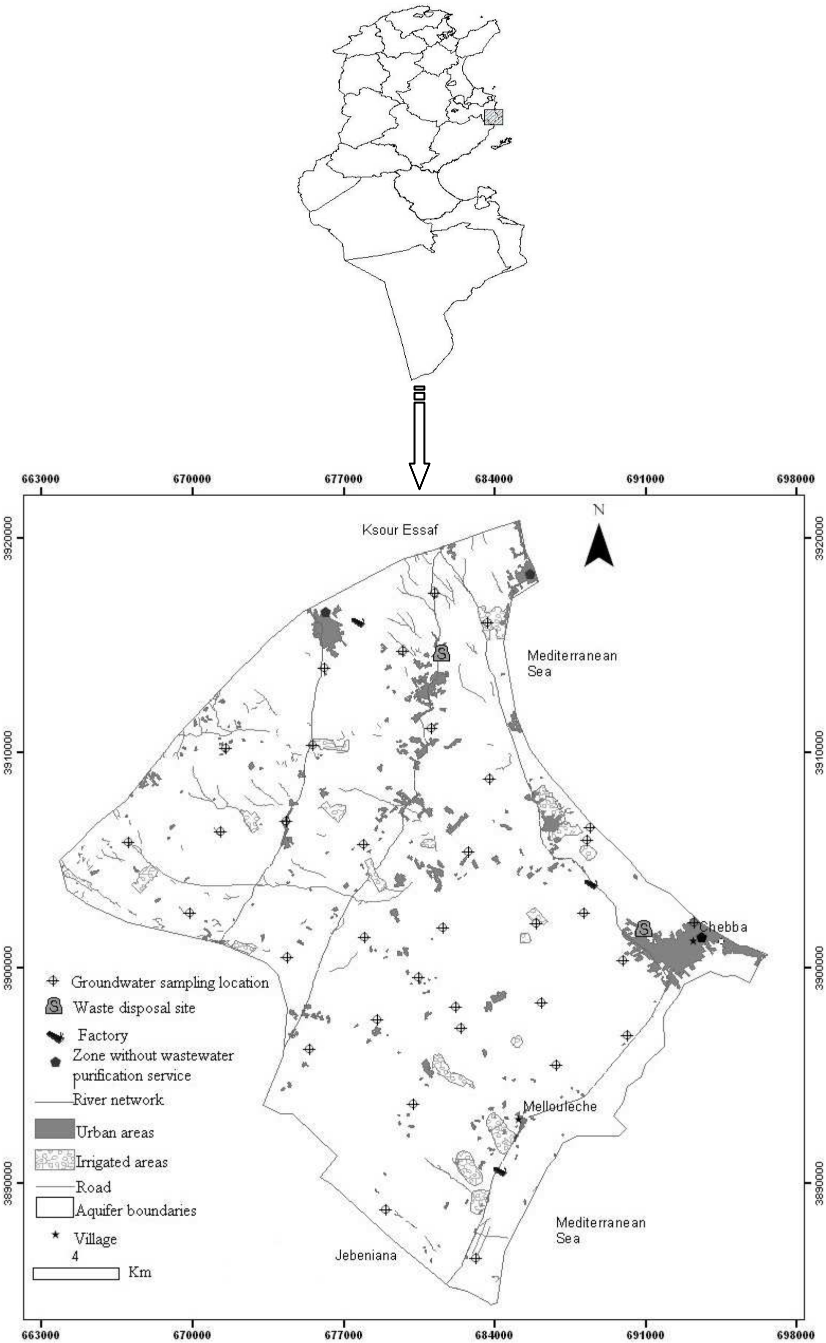

Fig. 1. Location of the study area.

obtained from various government agencies. This model was developed for the purpose of groundwater protection in the United States of America and its methodology is referred as ''DRASTIC.'' This methodology developed as a result of a cooperative agreement between the NWWA and the US Environmental Protection Agency (EPA). It was designed to provide systematic evaluation of GW pollution potential based on seven parameters whose required information were obtained from various Government and semi-Government agencies at a desired scale (Table 1). The acronym DRASTIC stands for the seven hydrogeologic parameters used in the model which are: Depth of water, Net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone and hydraulic Conductivity:

Parameter	Data and Sources	Mode of processing
Vulnerability (V_I) or DRASTIC Parameters		
D	Monthly monitoring of shallow wells in 2007 (Anon., 2007b).	Interpolation
R	Precipitation, Evapotranspiration (Anon., 2007a).	Interpolation
A	Geological information (Bedir, 1995), well logs (Anon., 2007).	Interpolation
S	Soil maps (scale 1:50,000) (Anon., 2008).	Digitalization
T	Topographical maps (scale 1:50000) (Anon., 2008).	Digitalization
I	Analysis of water logs and geological maps (Anon., 2007b).	Interpolation
C	Pumping tests (Anon., 2007c).	Interpolation
Quality index (Q_I)	Chemical composition of water wells samples (Anon., 2007c and Trabelsi, 2008)	Interpolation

Table 1. Data sources of susceptibility index (VI and QI) parameters

Depth to groundwater (D): It represents one of the most important factors because it determines the thickness of the material through which infiltrating water must travel before reaching the aquifer-saturated zone. In general, the aquifer potential protection increases with its water depth. The borewell and borehole data was collected from Mahdia Agricultural Agency.

Net Recharge (R): The net recharge is the amount of water from precipitation and artificial sources available to migrate down 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 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 rate including the total groundwater draft (Sophocleous, 1991).

Aquifer media (A) and the impact of the vadose zone (I): were represented by the lithology of the saturated and unsaturated zones, which is found in well logs (Saidi et al., 2009).

Topography (T): was represented by the slopes map (1/50 000 scale) covering the study area.

Soil media (S): It considers the uppermost part of the vadose zone and it influences the pollution potential. A soil map, for the study area, was obtained by digitizing the existing soil maps covering the region (Anon., 2008).

Hydraulic conductivity (C): It refers to the ability of the aquifer materials to transmit water, which in turn, controls the rate at which ground water will flow under a given hydraulic gradient. The rate at which the ground water flows also controls the rate at which a contaminant moves away from the point at which it enters the aquifer (Aller et al., 1987).

The hydraulic Conductivity was calculated based on the following equation

$$K = T/b, \tag{2}$$

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 tests data.

It is divided into ranges where high values are associated with higher pollution potential. Figure 2 shows the relative importance of the ranges.

Thus, thematic maps representing the D, R, A, I and C parameters were created by interpolation of data used for each one (Table 1). However, the soil type and topography maps are geo-referenced and digitized from different data files (Saidi et al., 2009).

The final vulnerability index is computed as the weighted sum overlay of the seven layers using the following equation:

$$V_I = Dr\,Dw + Rr\,Rw + Ar\,Aw + Sr\,Sw + Tr\,Tw + Ir\,Iw + Cr\,Cw \tag{3}$$

where D, R, A, S, T, I, and C are the seven parameters and the subscripts r and w are the corresponding rating and weights, respectively.

The DRASTIC vulnerability index was determined from multidisciplinary studies as shown in Table 1. The distributed value of each parameter was the rated in each cell of the grid map of 300 m by 300 m cell dimensions. According to the range of Aller et al. (1987), the contamination vulnerability index was created by overlying the seven thematic layers using intersect function of analysis tools in the Arc Map.

3.1.2 Modification of the weights of the DRASTIC method

The “real” weight is a function of the other six parameters as well as the weight assigned to it by the DRASTIC model (Saidi et al., 2011).

In this analysis real or ‘‘effective’’ weight of each parameter was compared with its assigned or ‘‘theoretical’’ weight. The effective weight of a parameter in a sub-area was calculated by using the following equation:

$$W = ((P_r\,P_w)/V_I)*100 \tag{4}$$

where W refers to the “effective” weight of each parameter, P_r and P_w are the rating value and weight for each parameter and V_I is the overall vulnerability index.

3.1.3 Quality index (Q_I)

The quality index calculation is based on the quality classes of ions, which were determined using the concentrations of ions in groundwater at a given location. In this application, we used four classification schemes that are described in the following references: WCCR (1991), Anon. (2003), Neubert and Benabdallah (2003) and WHO (2006). In this classification, the irrigation water quality is classified into five groups with respect to each ion concentration as very good (I), good (II), usable (III), usable with caution (IV) and harmful (V). The classification limits used in this study for the considered parameters are listed in Table 2.

1- Irrigation water classification

Parameters	Irrigation water limits				
	Class I (very good)	Class II (good)	Class III (usable)	Class IV (usable with caution)	Class V (harmful)
EC (µS/cm)	0 – 250	250 - 750	750 - 2000	2000 - 3000	> 3000
Cl (mg/l)	0 – 142	142 - 249	249 - 426	426 – 710	> 710
NO_3^- (mg/l)	0 – 10	10 - 30	30 - 50	50 – 100	> 100
SO_4^{2-} (mg/l)	0 – 192	192 - 336	336 - 575	576 – 960	> 960
Na^+ (mg/l)	0 – 69	69 - 200	200 - 252		> 252

2- Drinking water classification

Parameters	Irrigation water limits				
	Class I (very good)	Class II (good)	Class III (usable)	Class IV (usable with caution)	Class V (harmful)
EC (µS/cm)	0 – 180	180 - 400	400 - 2000	2000 – 3000	> 3000
Cl (mg/l)	0 - 25	25 - 200			> 200
NO_3^- (mg/l)	0 – 10	10 - 25	25 - 50		> 50
SO_4^{2-} (mg/l)	0 - 25	25 - 250			> 250
Na^+ (mg/l)	0 – 20	20 - 200			> 200

Table 2. Water classification (WCCR, 1991; Anonymous, 2003; Neubert et Benabdallah, 2003 and WHO, 2006)

The quality index at a given location can be calculated using the following formulation:

$$Q_I = P(Ci)^2 \tag{5}$$

where summation is overall considered quality parameters (ions). C is the determined class of parameter, i (ion), as an integer number (from 1 to 5) at a given location. The second power of C was used to enhance the effect of poor quality classes in the index (Saidi et al., 2009). In order to determine the chemical composition of the Chebba– Mellouleche groundwater during the irrigation period, 33 samples were collected from wells and analyzed in July 2007 (Saidi, 2011) (Fig. 1). Groundwater samples were taken from 27 wells of the Chebba – Mellouleche Aquifer.

3.2 Water management propositions

The builder model, describing the methodology applied to assess the water susceptibility index, was created using the Arc Tool Box in Arc Map interface of Arc GIS 9.2 (Saidi et al., 2009). Next, it is possible to propose a management plan by overlying the susceptibility index maps for irrigation and drinking water.

4. Results and discussions

4.1 Modification of the DRASTIC weights

The “real” or effective weights of the DRASTIC parameters exhibited some deviation from the “theoretical” weight (Table 3). The depth to groundwater table and the Aquifer media seem to be the most effective parameters in the vulnerability assessment; The depth of groundwater, D, with an average weight of 20.3% against a theoretical weight of 21.7% assigned by DRASTIC and the Aquifer media parameter, A (25.3%) against a theoretical weight of 13%. The net Recharge, R, the hydraulic conductivity, C, and especially the impact of the vadose zone, I, reveal lower “effective” weights when comparing with the “theoretical” weights.

Parameter	Theoretical weight	Theoretical weight (%)	Effective weight (%)				Real weight after rescaling
			Mean	Minimum	Maximum	SD	
D	5	21.7	20,3	5	36	5,92	4.66
R	4	17.4	10,5	3	25	6,32	2,4
A	3	13	25,3	2	41	3.92	5,81
S	2	8.7	8	0	20	3.93	1,83
T	1	4.4	8.5	1	14	2,14	1.95
I	5	21.8	17	5	24	2,87	3,91
C	3	13	10,5	4	17	2,19	2,41

SD: standard deviation.

Table 3. Statistics of single parameter sensitivity analysis and a comparison between “theoretical” weight and “effective” weight.

4.2 Aquifer vulnerability

The vulnerability map shows three classes as indicated in Fig. 3. The highest class of vulnerability (140–159) covers 25% of the total surface. In fact, zones with high vulnerability correspond to the shallow groundwater table (<9 m), a flat topography (<5%), a high recharge and a permeable lithologies of the vadose zone and The Aquifer (made up of sand and gravel lithology). It results in a low capacity to attenuate the contaminants.

The areas with moderate to low vulnerability cover the rest of the study area, characterized by a deep groundwater table (> 25 m), low recharge (>150 mm) and lithology with low permeability (Table 4).

Using real weights, the high vulnerability class covers the whole of the southern part of the study area. It corresponds to the location of the irrigated areas, using intensive fertilizers. So, the utilization of the calculated or real weights can better reflect the pollution state of the study area than using theoretical weights, in groundwater vulnerability assessment. Therefore, the use of real weights in the DRASTIC index shows more similarity when comparing vulnerability degree and nitrate distribution (Figs. 3).

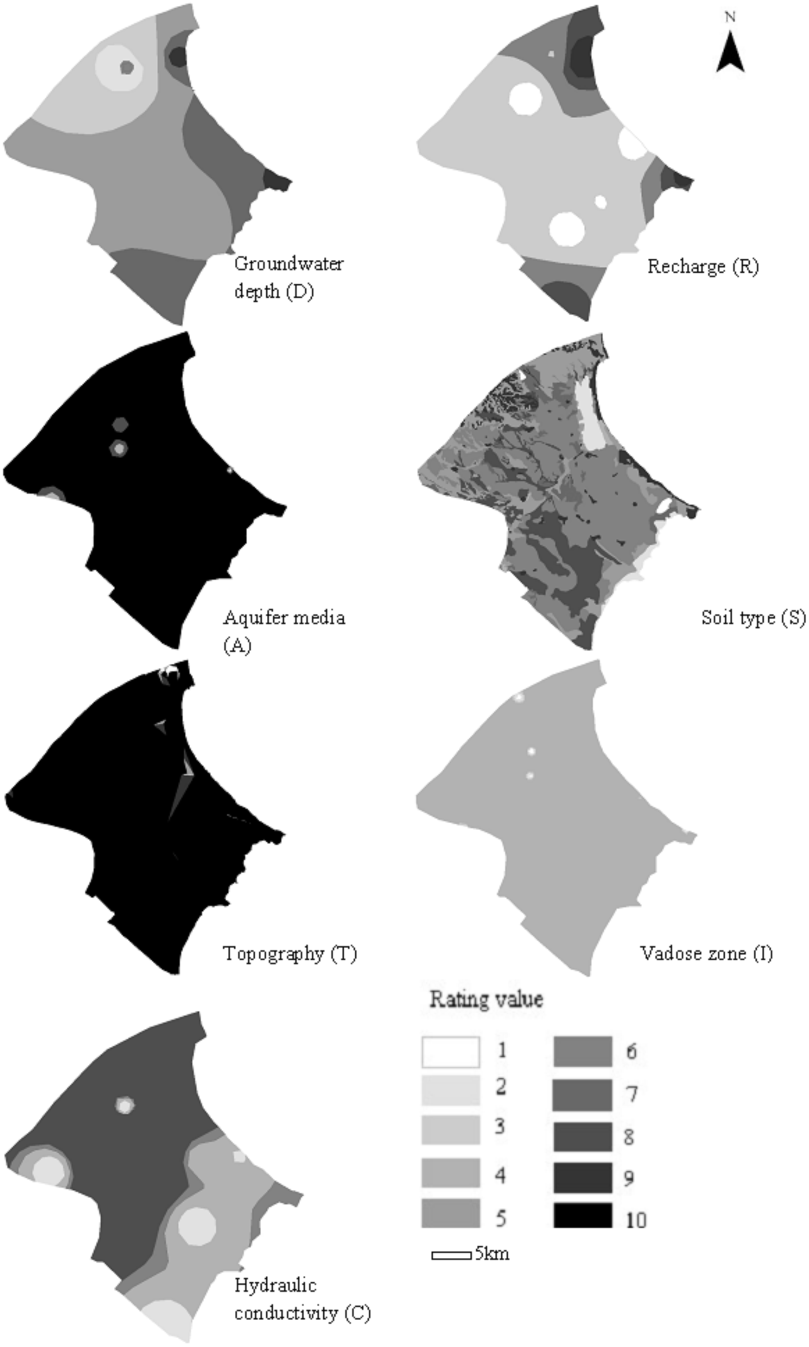

Fig. 2. Seven DRASTIC maps to compute the vulnerability index.

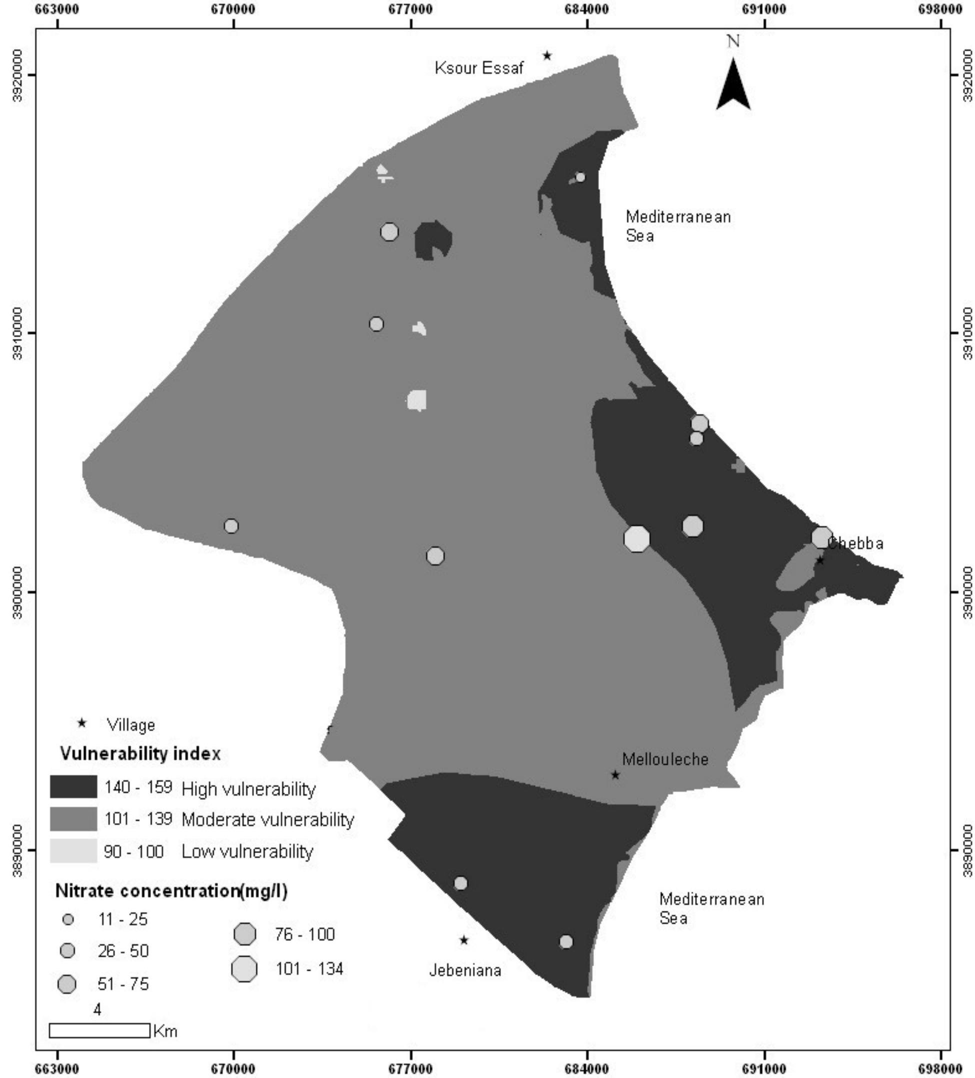

Fig. 3. Groundwater vulnerability and nitrate distribution in the Chebba – Mellouleche Aquifer using DRASTIC method (Saidi, 2011).

4.3 Water quality

Both the drinking and the irrigation water quality present a low quality, especially in the south of the Aquifer (Fig. 5). The main causes are the high permeability of its lithology as well as its localization in the vicinity of an irrigated area with intensive use of fertilizers. There is no similarity between vulnerability classes and water susceptibility classes. Thus, this proves the impact of the irrigation water quality on the aquifer groundwater quality.

Depth of water (m)		Net recharge (m)		Topography (slope) (%)		Hydraulic Conductivity (m/s)		Aquifer media		Impact of the vadose zone		Soil media	
Interval	R	Interval	R	Interval	R	Interval	R	Lithology classes	R	Lithology classes	R	Soil classes	
2-4.5	9	0.01–0.05	1	0-3%	10	$8.3*10^{-5}$ – $4*10^{-5}$	2	Sand and clay	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	Massive clay and sand	2	Sandy clay and calcareous	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 and clay	4	sand and silt	4	Rendzina	7
15-23	3	0.18-0.25	8	10-15%	3			Sandy gravel	8	Gravel and sand	10	Calcareous brown soil	6
23-32	2	>0.25	9					Gravel and Sand	10			Soil with little evolution	5
												Polygenetic soil	4
												Gypsum soil	3
												Halomorphic soil	2
												Urbain zones	1

R; Rank

Table 4. Ranks of the seven DRASTIC parameters (Aller et al., 1987).

For instance, the extreme North East part of the Aquifer has a high and a moderate vulnerability but a high water quality (low index). As a consequence, this area reveals a low water susceptibility index (Fig. 6). Nevertheless, the centre of the Aquifer which presented a low water quality and moderate vulnerability corresponds to a moderate water susceptibility index. This is due to the high permeability in this area which can cause a rapid infiltration of contaminant from the surface to the groundwater. But, in the South east a high vulnerability and a moderate to low water quality and the results are a moderate to low susceptibility index. The main reasons are probably the lithology of unsaturated zone and the comportment of the contaminants, in this area, which need further investigations (Saidi et al., 2009). The comparison between irrigation and drinking water maps show a few differences; the drinking water indexes are stricter than the irrigation ones (Fig. 6).

According to the drinking water susceptibility index map, people can exploit only the Northern part of the Aquifer for drinking uses and for irrigation of sensible plants. This is due to the high capacity of the unsaturated zone to attenuate the contaminant infiltration (made up of silt, clay and sandy clay) and the deep groundwater table in this area (>25 m) (Fig.2).

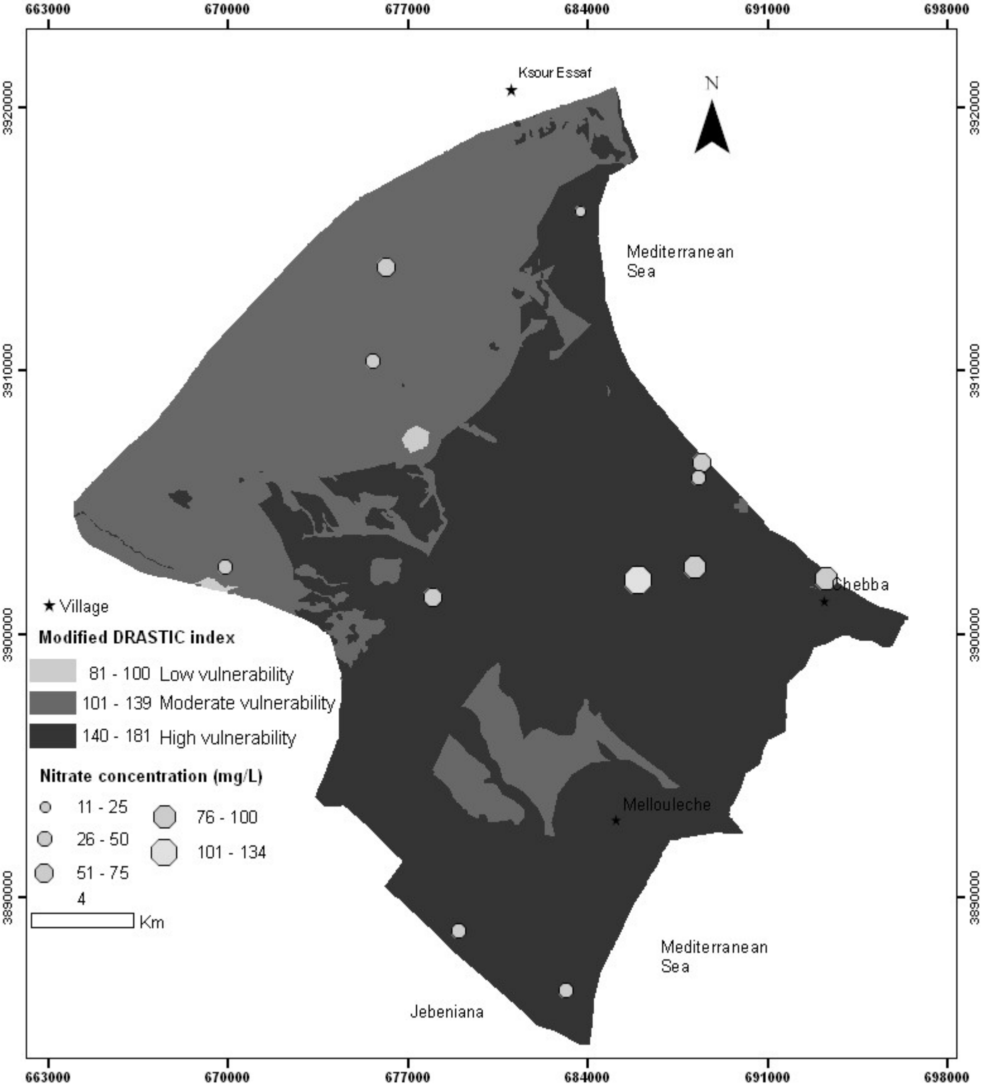

Fig. 4. Groundwater vulnerability and nitrate distribution in of the Chebba – Mellouleche Aquifer using modified DRASTIC method.

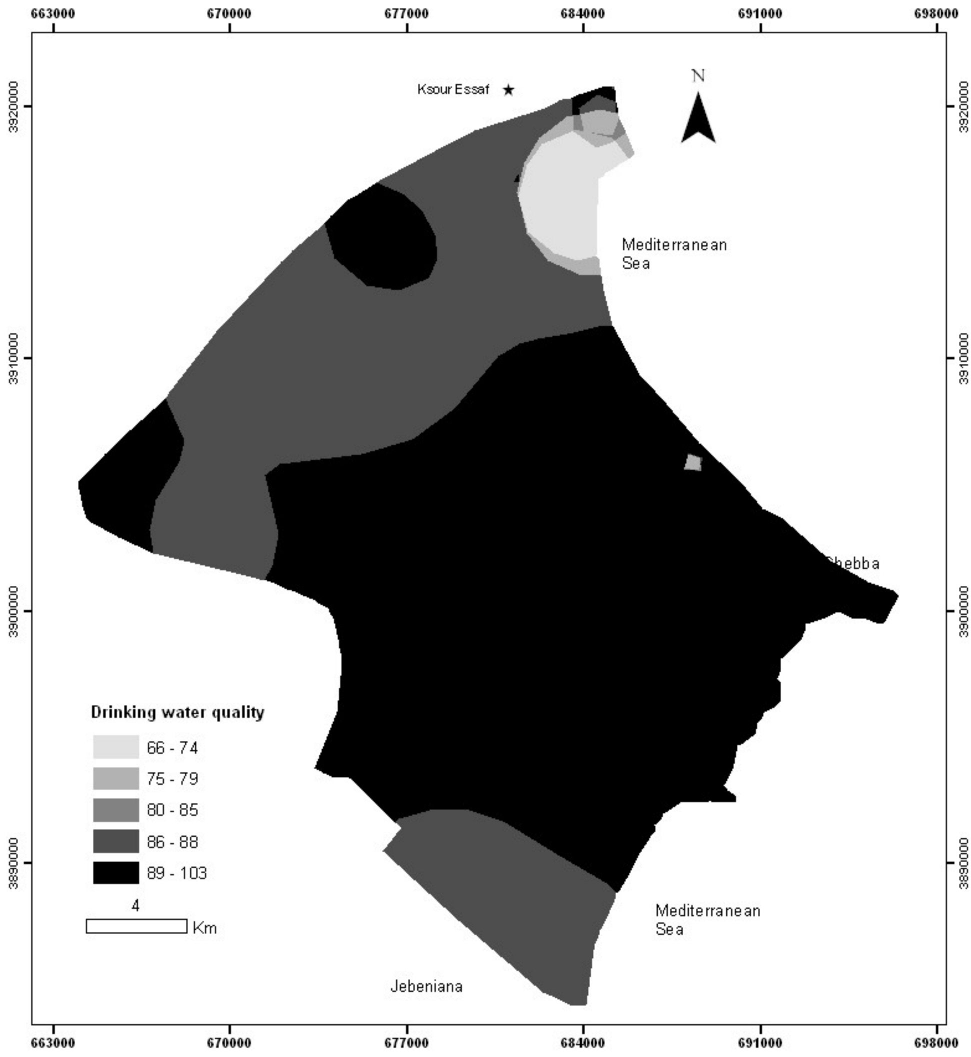

Fig. 5. Drinking water quality of the Chebba-Mellouleche Aquifer (Saidi et al., 2009).

However the Southern part of the study area presents a low water quality because it coincides with a variety of sites and activities which are hazardous to groundwater such as waste disposal sites (which have no technical or geological barrier), industrial estates (which have no proper sewage treatment facilities), agriculture (which applies fertilizers and pesticides abundantly) and fish farming in the vicinity of the coast (where antibiotic and pesticides are used in abundance and imports saltwater increases the salinity in the surrounding area) (Fig.6).

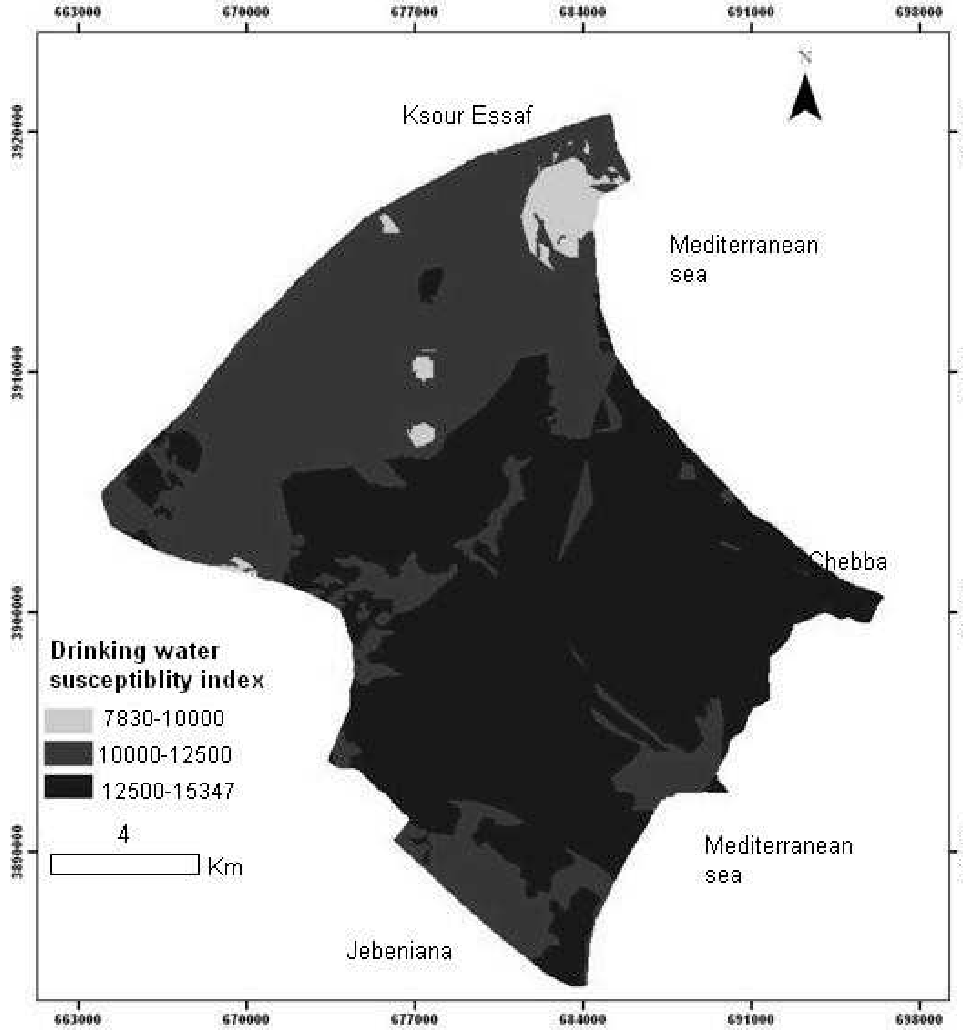

Fig. 6. Drinking water susceptibility index of the Chebba – Mellouleche Aquifer.

The Builder Model, created for the susceptibility indexing assessment, displays and provides a description of the procedures and the geo-processing operations which are used to create the susceptibility index maps (Fig. 7).

So, it can help to retain the main tools for the susceptibility assessment used in this study and facilitate the proposition of a water management schema (Saidi et al., 2009). In fact, a management map was created by overlaying the susceptibility index maps for irrigation and drinking water (Fig. 8).

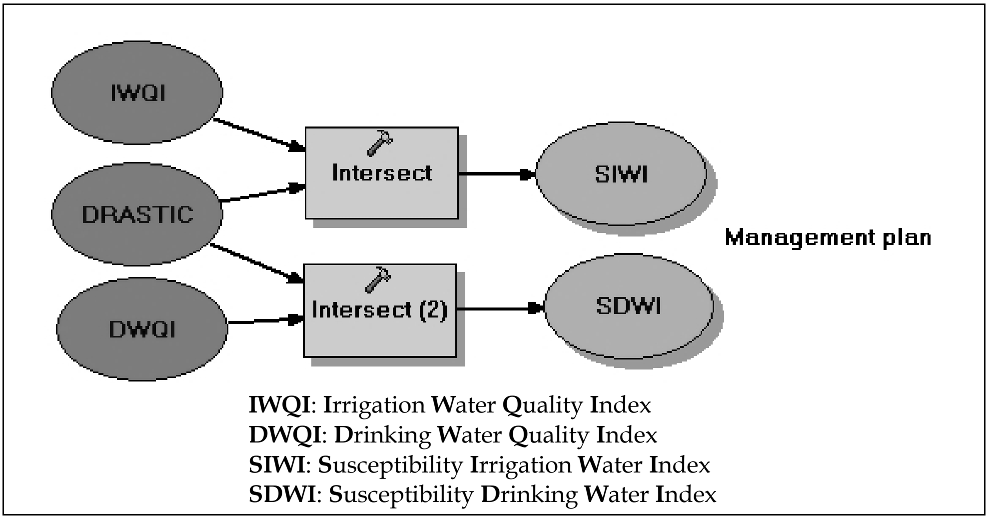

Fig. 7. Builder model for water management (Saidi et al., 2009).

This map shows that: (i) in the north of the aquifer the water can be used for drinking water and for irrigation of the sensible crops (ii) in the Extreme north eastern corner, the water has a high water quality but it represents a high risk since it is near to the coast. So, we should allow additional wells to ovoid seawater intrusion (iii) in the southern part of the study area, we should not allow additional high risk activities in order to obtain economic advantage and reduce environmental pollution hazard. Furthermore, water should be decontaminated before applying to reduce diseases to sensitive plants and should not be utilized for drinking uses.

5. Conclusions

The use of both intrinsic vulnerability data and quality one in a GIS environment proved to be a powerful tool for the groundwater management in arid and semi arid regions like Chebba–Mellouleche. The seven DRASTIC parameters: depth of groundwater, net recharge, aquifer media, soil media, topography, impact of the vadose zone and hydraulic conductivity, were used to calculate the vulnerability of the study area. The results show that groundwater in Chebba – Mellouleche is characterized by four classes as follow: Moderate vulnerability ranked groundwater areas dominated the study area (>52%), which occupy middle of the study area, while (>38%) of the Chebba – Mellouleche aquifer is under high groundwater vulnerability.

The water susceptibility indexes show a low water quality, covering the majority of the study area. Indeed, there is a high similarity between the more hazardous pollution zones and the areas with low water quality. So, these scenarios proposed by this study could be used as a general guide for groundwater managers and planners.

The GIS technique has provided an efficient environment for analyses and high capabilities in handling a large quantity of spatial data. The susceptibility index parameters were constructed; classified and mapped employing various map and attribute GIS functions.

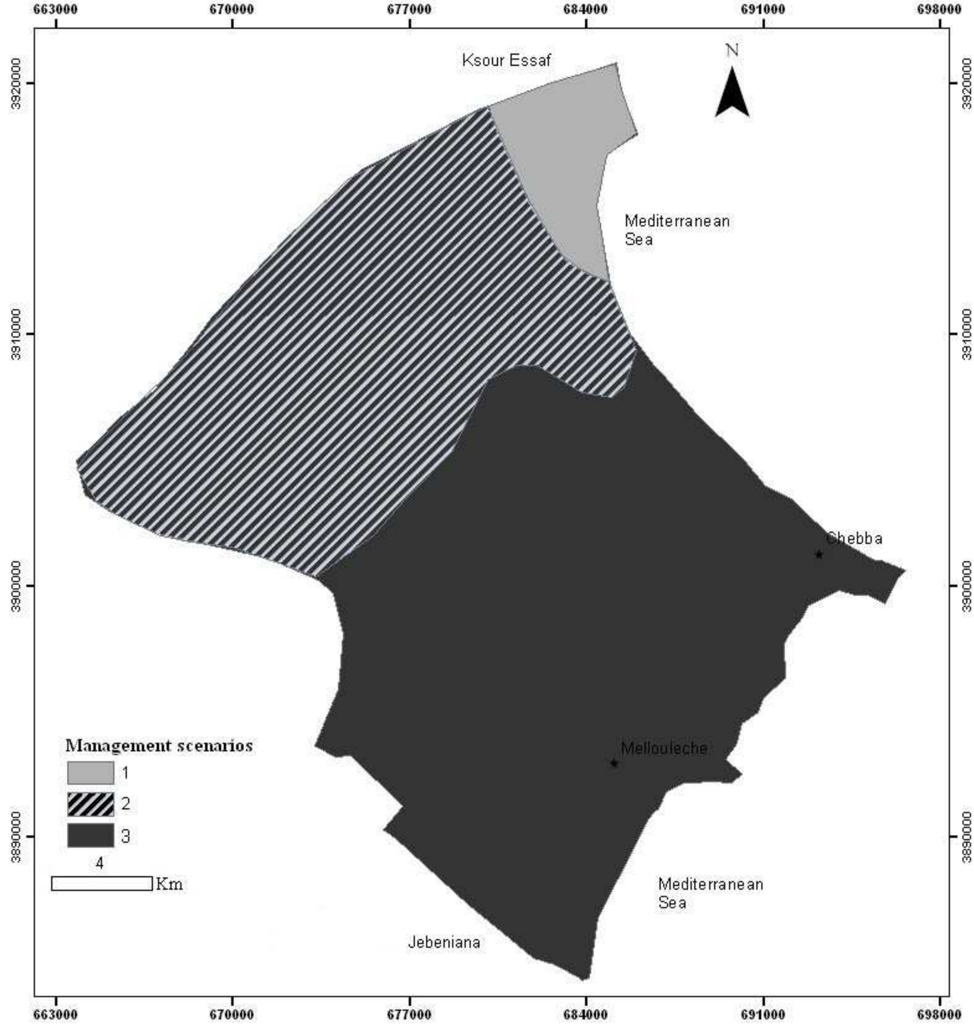

Fig. 8. Groundwater management scenarios proposed in the Chebba – Mellouleche Aquifer.

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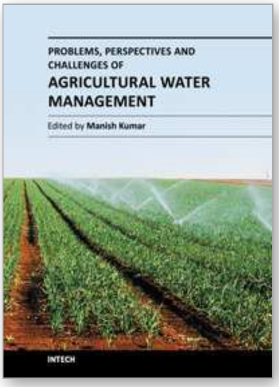

Problems, Perspectives and Challenges of Agricultural Water Management

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Food security emerged as an issue in the first decade of the 21st Century, questioning the sustainability of the human race, which is inevitably related directly to the agricultural water management that has multifaceted dimensions and requires interdisciplinary expertise in order to be dealt with. The purpose of this book is to bring together and integrate the subject matter that deals with the equity, profitability and irrigation water pricing; modelling, monitoring and assessment techniques; sustainable irrigation development and management, and strategies for irrigation water supply and conservation in a single text. The book is divided into four sections and is intended to be a comprehensive reference for students, professionals and researchers working on various aspects of agricultural water management. The book seeks its impact from the diverse nature of content revealing situations from different continents (Australia, USA, Asia, Europe and Africa). Various case studies have been discussed in the chapters to present a general scenario of the problem, perspective and challenges of irrigation water use.

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