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ORIGINAL PAPER

Vulnerability mapping and risk of groundwater of the oasis of Figuig, Morocco: application of DRASTIC and AVI methods

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Abstract Climate change, population growth, and agriculture contribute to a qualitative and quantitative deterioration of groundwater reserves. The protection of natural water resources is crucial, especially in arid areas. The purpose of this paper is to map the vulnerability and risk mapping of a Moroccan aquifer, i.e., the Figuig oasis, using DRASTIC (depth of water (D), net recharge (R), aquifer media (A), soil (S), topography (T), impact of the vadose zone (I), and hydraulic conductivity (C)) and AVI (aquifer vulnerability index) methods. DRASTIC vulnerability maps have been drawn up for 4 years (1995, 2004, 2008, and 2010). Thematic maps were performed by both methods using the geographic information system (GIS). The DRASTIC method was modified in order to take into account the numerous faults. The AVI method allows estimating the transfer of a pollutant from the surface to the water level. Both methods give consistent results, enhancing high, medium, and moderate vulnerability. Risk assessment of groundwater pollution by septic tanks has been achieved by integrating the modified DRASTIC vulnerability map. Three areas with high, moderate, and low risk assessment have been identified and mapped.

Keywords Vulnerability mapping · Groundwater · DRASTIC and AVI models · GIS · Figuig

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Introduction

Vulnerability maps can be used to define the area of potential groundwater pollution. That allows us to avoid areas pollution risk related to anthropogenic activity (waste, industry, agriculture) and thus the main maintenance of ecosystems. Vulnerability is the natural failure to protect groundwater against the threats of pollution, according to local hydrogeological conditions. In other words, the term vulnerability is used to represent the natural features that determine the sensitivity of groundwater to pollution (Aller et al. 1987; Allier et al. 2008). According to the literature, vulnerability may be either specific or intrinsic. The first term takes into account the properties of a contaminant or a group of contaminants. The second term consists of the geological, hydrological, and hydrogeological characteristics of the study area but is independent from the nature of the contaminants. This second term which uses different methods developed by Aller et al. (1987); Foster (1987); Vrba and Zaporozec (1994); and Doerfliger and Zwahlen (1997) has been applied by several authors, for example Chandrashekhar et al. (1999); Gogu and Dassargues (2000a); Gogu and Dassargues (2000b); Daly et al. (2002); Anwar et al. (2003); Gogu et al. (2003); Rahman (2008); and Moratalla et al. (2011).

The oasis of Figuig is located at the eastern extremity of High Atlas (Fig. 1). This region is characterized by an arid climate, with hot summer and cold winter. Surrounded by the High Atlas Mountains, the study area is the site of several water springs used for irrigation, with Tzadert, Tighzert, Tajamalt, and Maghni as the most important. Management of water resources in the oasis of Figuig is not yet resolute, and the number of wells used for irrigation is increasing. The average rainfall between 1935 and 2011 was estimated at 120 mm. The maximum rainfall occurs in October while the minimum in July. Rainfall remains very irregular from one year to another. The Basin of Figuig may undergo two or three brief and violent storms per year, often responsible for

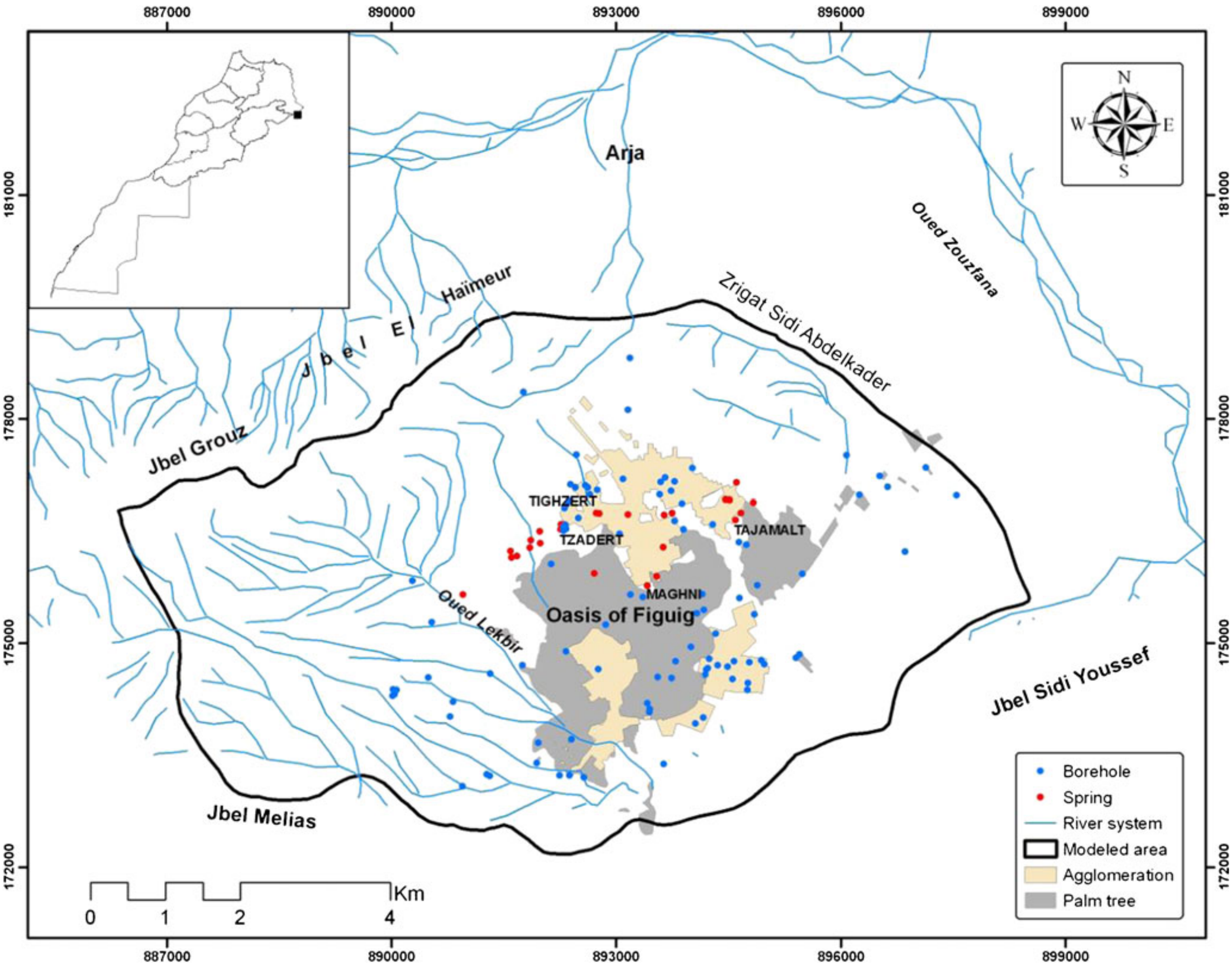

Fig. 1 Study area

flooding. The frequency of drought is also variable, and watercourses are temporary. The calculated temperature between 1937 and 1967 is from −2 to 1 °C in winter (December to February) and 45 to 48 °C in summer (June to August).

Tectonics has been playing a major role in the regional hydrogeology. Structurally, the study area is formed by two main anticlines (i.e., Jbel el Haimeur and Melias-Sidi Youssef). The anticlines are separated by the synclinal of Figuig. Anticlines are formed by Triassic red clays and carbonates of the Lower and Middle Lias. Syncline is composed of Upper Lias limestone, alternations of Bajocian marls, limestones and sandstones. Those Bajocian formations are in contact with Cretaceous sandstones, the unconformity being due to the South Atlas Fault. Quaternary formations (alluvial silts, eolian sands, and travertines) are present on the slopes and in the plains. The faults in the area extend along three main directions, i.e., EW, NE-SW, and NW-SE, and are not observed in the syncline area, covered by Quaternary deposits (Dresnay 1963; Jilali 2009).

We aim to perform a mapping of the intrinsic vulnerability of the oasis of Figuig to detect the areas of high vulnerability and to give recommendations about area managing (i.e., to avoid activity in high vulnerability areas). For this purpose, we apply both the DRASTIC method criteria standardization (Lallemand-Barrès 1994) for establishing pollution vulnerability maps for 4 years (1995, 2004, 2008, and 2010) and aquifer vulnerability index (AVI) method (Stempvoort et al. 1993). In order to reflect fracturing that plays an important role in the groundwater circulation, the DRASTIC method was modified by the addition of the fracturing parameter (F). The high vulnerability is located in the north of the study area (Jbel el Haïmeur and Grouz).

Vulnerability evaluation methods

The DRASTIC method

This method is a part of intrinsic vulnerability evaluation. The method allows determining the index of vulnerability based on seven parameters or seven layers of information.

DRASTIC is an acronym which stands for depth of water (D), net recharge (R), aquifer media (A), soil (S), topography (T), impact of the vadose zone (I), and hydraulic conductivity (C). Each parameter is subdivided into the interval values and is assigned a numerical rating increasing, according to its vulnerability importance. The method requires three steps:

1 Assigning a numeric value or weight (P_j), comprised between 1 and 5, to each parameter, which reflects its degree of influence;
2 To each parameter, a rating value (C_i), ranging from 1 to 10, is associated (Table 1). The lowest value represents the weakest conditions of vulnerability to contamination;
3 A DRASTIC vulnerability index (D_i) is calculated by summing the values of ($C_i \times P_j$) products as follows:

$$D_i = \sum_{j=1}^{7} \left(C_i \times P_j \right).$$

A database was then created on the geographic information system (GIS) integrating. Every vector data was converted into raster format with a very good resolution of 30 m×30 m. The parameters D and C are converted by the inverse distance weighting (IDW) interpolation method.

AVI method

This method uses the hydraulic conductivity (K) and the thickness (b) of the layers overlying the unsaturated aquifer. In order to estimate the hydraulic resistance (c) we use the following equation:

$$c = \sum bi \;\; Ki.$$

This index determines the vulnerability through hydraulic resistance. Indeed, the flow resistance represents the average time of the pollutants to travel from the soil surface to the groundwater reservoir. The hydraulic

Table 1 DRASTIC parameters

Parameters	Ratings	Relative weights
D (depth of water)		5
R (net recharge)		4
A (aquifer media)		3
S (soil media)	1, 2, 3,…, 10	2
T (topography)		1
I (impact of vadose zone)		5
C (hydraulic conductivity)		3

Table 2 DRASTIC and DRASTICF parameterization

Ratings	D×5 (m) 1995	D×5 (m) 2004	D×5 (m) 2008	D×5 (m) 2010	R×4 (mm/an) 1995	R×4 (mm/an) 2004	R×4 (mm/an) 2008	R×4 (mm/an) 2010	A×3	S×2	T×1 (%)	I×5	C×3 (m/s)	F×5
1	>31	>31	>31	>31		0–5		0–5			>18		$1{,}47.10^{-7}$–$4{,}7.10^{-5}$	Free
2	23–31	23–31	23–31	23–31					Clayey marls				$4{,}7.10^{-5}$–$1{,}47.10^{-4}$	
3	15–23	15–23	15–23	15–23	5–10	5–10		5–10			12–18			
4										Sands, clays			$1{,}47.10^{-4}$–$3{,}22.10^{-4}$	
5	9–15	9–15		9–15							6–12			
6					10–18	10–18	10–18	10–18	Limestone, travertine, alluvium, gravel, sandstone, and silt	Alluvium and silt		Alluvium, sandstone, gravel, and limestone		
7				4,5–9										With
8							18–26		Sands, clayey sands			Sands and clayey sands		
9					>26	>26	>26	>26		Sands	2–6			
10									Limestone karst	Soil thin or absent	0–2	Limestone karst		

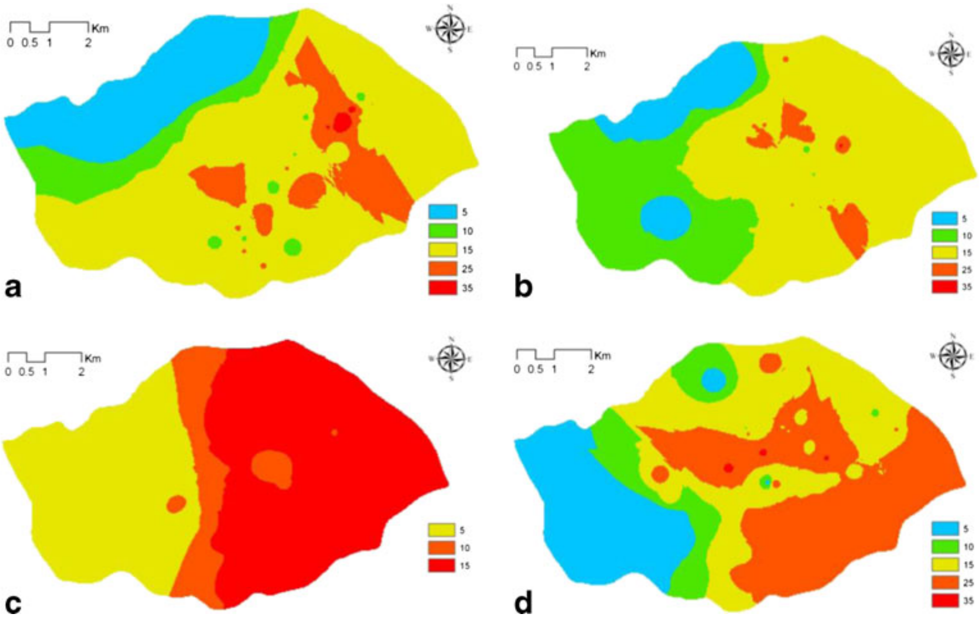

Fig. 2 Groundwater depth index for 1995 (**a**), 2004 (**b**), 2008 (**c**), and 2010 (**d**)

conductivities were evaluated for the different geological formation by several pumping tests (33). The obtained hydraulic resistance values were imported into the GIS, and then converted into a raster format with a resolution of 200 m×200 m.

Results and discussions

The field data (hydraulic conductivity, net recharge, etc.) have been compiled in a database designed on a geographic information system (GIS). This makes it easier to obtain the different thematic maps for each parameter in the DRASTIC method and from interpolation by the AVI method.

Application of DRASTIC standard method

Parameter D

The depth to water level is one of the most important factors in any vulnerability model because it determines the thickness of material through which infiltrating water must pass before reaching the aquifer-saturated zone (Rahman 2008;

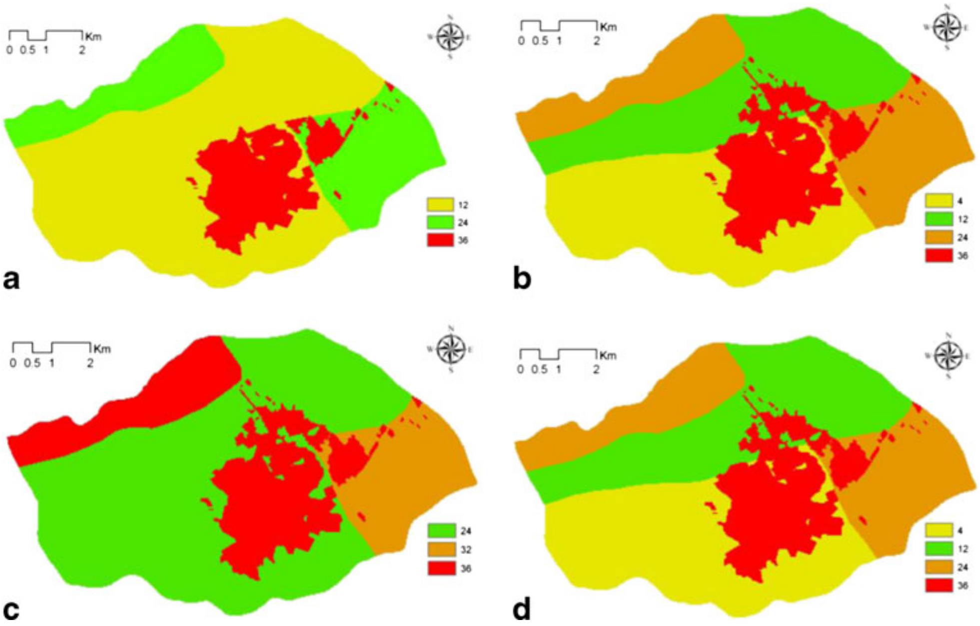

Fig. 3 Recharge index for 1995 (**a**), 2004 (**b**), 2008 (**c**), and 2010 (**d**)

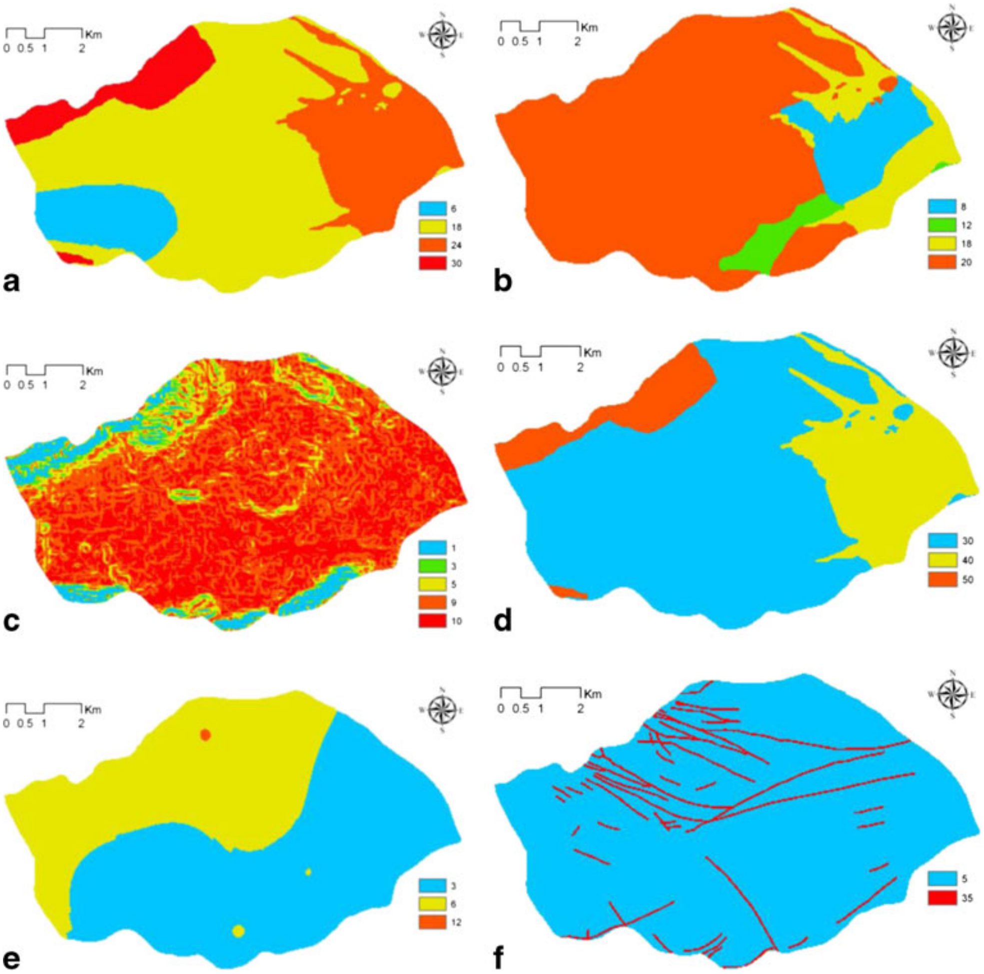

Fig. 4 Aquifer media (**a**), soil media (**b**), topography (**c**), impact of the vadose zone (**d**), hydraulic conductivity (**e**), and Fractures (**f**)

Moratalla et al. 2011). The depth to water level affects the level of interaction between the percolating contaminants and subsurface materials and hence, the degree, the extent, the physical and chemical attenuations and degradation processes (Rahman 2008). The aquifer potential protection increases with the depth to water level.

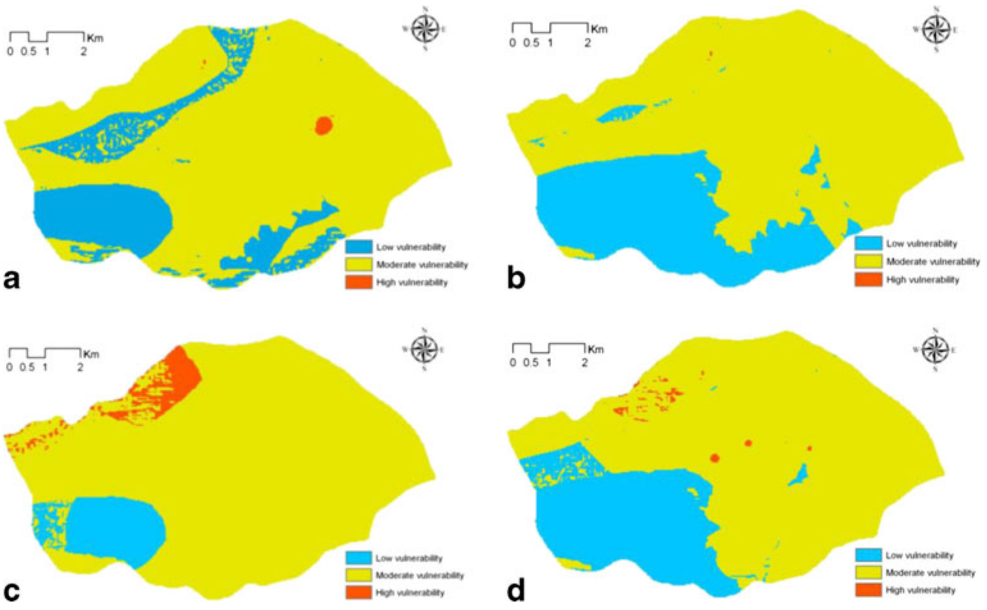

Fig. 5 DRASTIC vulnerability for 1995 (**a**), 2004 (**b**), 2008 (**c**), and 2010 (**d**)

Table 3 Area under vulnerability (DRASTIC) to groundwater pollution in Figuig oasis

DRASTIC index value	1995		2004		2008		2010		Vulnerability zone
	Area (acres)	Area (%)	Area (acres)	Area (%)	Area (acres)	Area (%)	Area (acres)	Area (%)	
<100	1235.07	21.07	1665.90	28.42	514.80	8.78	1477.26	25.20	Low
100–150	4607.19	78.59	4195.62	71.57	5126.22	87.44	4346.91	74.15	Moderate
>150	20.16	0.34	0.90	0.02	221.40	3.78	38.25	0.65	High
Total	5862.42	100	5862.42	100	5862.42	100	5862.42	100	

The water level measurements were undertaken in 2008 and 2010, by a survey of 40 and 104 water points, respectively. For the years 1995 and 2004, the water level is collected, during a survey of 75 (Assou 1996) and 117 (ABHM 2004) water points, respectively. Four maps were obtained by field data interpolation. Five classes were identified (>31, 23–31, 15–23, 9–15, and 4.5–9 m, data in Table 2), converted into scores and then multiplied by the corresponding weight. Map D index is shown in Fig. 2. In general, we note that the most vulnerable areas are located in the central and southern parts of Figuig oasis.

Parameter R

The net recharge is the amount of water, from net or efficient precipitation and from artificial recharge areas, available to migrate down to the groundwater. Transport of contaminants from the vadose zone to the saturated zone is produced through dissolution in the recharge water (Rahman 2008; Moratalla et al. 2011). This parameter is related to some main factors: rainfall, evaporation and evapotranspiration, the hydrological regime, the nature of the geological formations, and the areas of intensive irrigation. In the oasis of Figuig, the irrigation is done by gravity and the discharge of wastewater (agglomeration) into wells may be considered in the recharge of aquifer.

Several authors (Breil et al. 1977; ABHM 2004; Puigserver 2004; Jilali 2009) assessed the values of effective infiltration of about 12 mm/year and the infiltration coefficients between 4 and 12 %. In our case, we take into account the lithology, the irrigation fields, and the discharge of wastewater to subdivide the area into different recharge zones. Karstified and sandy formations are characterized by a coefficient of infiltration of 12 %, clayey and marly formations by 4 to 8 % and irrigation fields, discharge wastewater were calculated (ABHM 2004). The results of 4 years are shown in Fig. 3 and in Table 2. In general, the irrigation fields and wastewater are the most vulnerable areas.

Parameter A

Groundwater flow, contaminant fate, and transport modeling are important components of most aquifer remediation studies. The aquifer media refers to consolidated and unconsolidated rocks, which allow to store and transport the water (Chandrashekhar et al. 1999).

To describe the aquifer media, we first superimposed our field observations on the geological map of the area (Dresnay 1963); then, we integrate boreholes data made by Hydraulic Basin Agency Moulouya (HBAM) with our drilling description during pumping tests. Finally, we reinterpret available geophysical data (CAG 1968; CAG 1974; GéoAtlas 1993; GéoAtlas 2004). Ratings were assigned to the different geological formations, as follows: a value of 2 for clayey marls; 6 for limestone, travertine, silt, gravel, sandstone, and silt; 8 for sand and clayey sand; and 10 for karstified limestone (Fig. 4a, data in Table 2). The attenuation of contaminants in the aquifer depends on the quantity and sorting of fine grains. In general, the higher grain size and large fracture opening in the aquifer give lower permeability and attenuation capacity; therefore, the sensitivity for pollution increases (Anwar et al. 2003). The highest rating was therefore assigned to the coarsest (saturated or unsaturated) media.

Table 4 Area under vulnerability (DRASTICF) to groundwater pollution in Figuig oasis

DRASTICF index value	1995		2004		2008		2010		Vulnerability zone
	Area (acres)	Area (%)	Area (acres)	Area (%)	Area (acres)	Area (%)	Area (acres)	Area (%)	
<100	275.49	4.70	1297.08	22.13	21.87	0.37	1108.44	18.91	Low
100–150	5402.97	92.16	4401.99	75.09	5214.96	88.96	4327.56	73.82	Moderate
>150	183.96	3.14	163.35	2.79	625.59	10.67	426.42	7.27	High
Total	5862.42	100	5862.42	100	5862.42	100	5862.42	100	

Table 5 Difference area% between DRASTICF and DRASTIC methods

	Area% 1995	Area% 2004	Area% 2008	Area% 2010	Vulnerability zone
DRASTICF-DRASTIC	−16.4	−6.3	−8.4	−6.3	Low
	13.6	3.5	1.5	−0.3	Moderate
	2.8	2.8	6.9	6.6	High

Parameter S

The sensitivity of soils to pollution is largely affected by the type and abundance of clay particles, the shrink or swelling potential and grain size. The soil properties control the recharge amount of water infiltrating the ground surface. (Rahman 2008; Moratalla et al. 2011).

A map of S index (Fig. 4b) is derived from both the compiled geological map and from available soil quality information for Figuig oasis (Assou 2001). Four classes (Table 2) were identified with the following ratings: 4 for sand and clays, 6 for alluvial and silt, 9 for sand, and 10 for thin or absent soil.

Parameter T

The topography represents the variation of the slope in a region. A low slope tends to retain water for a longer time than a high slope. A good infiltration (recharge) of water corresponds to an important potential of contamination migration. The degree of groundwater vulnerability (contamination) is higher in areas of low slopes.

A map of T index (Fig. 4c) was prepared from a digital elevation model (DEM) with a resolution of 30 m. The slope from the DEM was extracted using the ArcGis software and clustered in five classes (0–2, 2–6, 6–12, 12–18, and >18 % - Table 2).

Parameter I

The influence of the vadose zone in regard of the aquifer pollution potential is similar to the soil parameter, depending on the permeability and attenuation characteristics. The impact of the vadose zone is complicated, combining the characteristics of the aquifer, the media, and the topography.

The parameter I was prepared like the parameter A. The impact of the vadose zone on the water transport is high if composed by a permeable material. Obtained classes are shown in the Table 2 and Fig. 4d.

Parameter C

Hydraulic conductivity of the aquifer is linked to the transmissivity of its formations. It depends on the intrinsic permeability and the degree of the geological formation saturation. It controls the migration and dispersal of the contaminant, and therefore its concentration in the aquifer. Hydraulic conductivity is calculated from the transmissivity, obtained from pumping tests. The more the hydraulic conductivity increases, the more the aquifer becomes vulnerable to contamination (Table 2 and Fig. 4e).

Maps of vulnerability index for 4 years were obtained by summing the seven layers (Fig. 5). Generally, the maps show a score ranging between 69 and 168. This interval was further clustered into three classes: (1) low vulnerability, (2) moderate vulnerability, and (3) high vulnerability (Table 3 and Fig. 5). The study area covers a total surface of

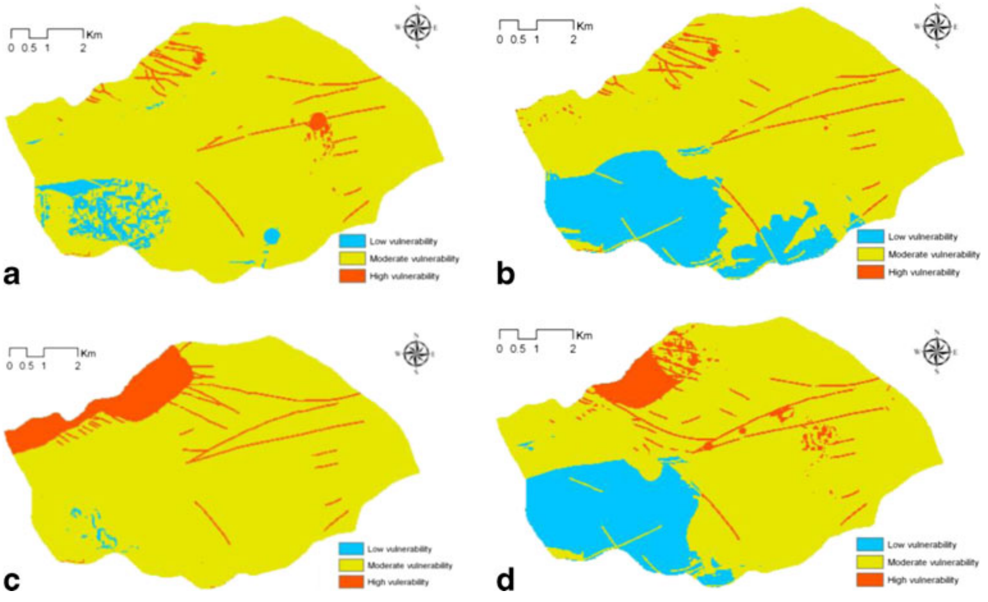

Fig. 6 DRASTICF vulnerability for 1995 (**a**), 2004 (**b**), 2008 (**c**), and 2010 (**d**)

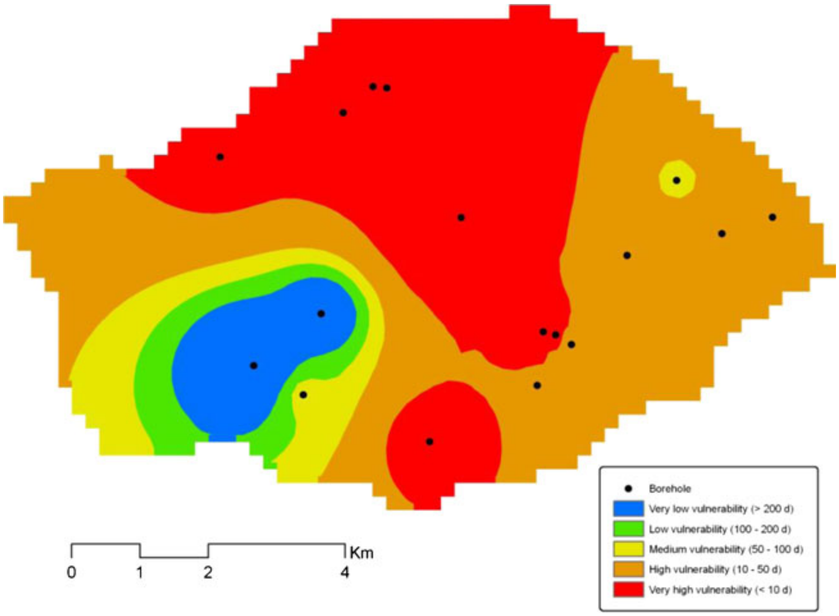

Fig. 7 AVI vulnerability index

5862.42 acres where the value of vulnerability is distributed as follows: 8.8 to 25.2 % (corresponding to a superficies ranging from 514.8 to 1,477.26 acres) have a low vulnerability DRASTIC index ranging between 69 and 100, 71.6 to 87.4 % (corresponding to a superficies ranging from 4,195.62 to 5,126.22 acres) have a moderate vulnerability with a DRASTIC index comprised between 100 and 150, and finally, 0.02 to 3.8 % (corresponding to a superficies ranging from 0.9 to 221.4 acres) have a high vulnerability (150<DRASTIC index<168). The small surface area of high vulnerability is recorded in 2004 over 0.02 % of the total area. This was a dry year with a minimum rainfall level, while the rainy year 2008 points out the biggest surface area of high vulnerability with 3.8 % (Table 3). This means that most of Figuig oasis is characterized by a moderate pollution risk. Though the high vulnerability area represents a very small percentage, it is important to underline that such area indicates the only unique source of drinking water in the region. To take into account this parameter, we have modified the standard DRASTIC method to optimize our results.

Table 6 Area under vulnerability (AVI) to groundwater pollution in Figuig Oasis

AVI Index value (Day)	Area (Acres)	Area (%)	Vulnerability zone
>200	384	6.56	Very low
100–200	284	4.85	Low
50–100	488	8.32	Medium
10–50	2500	42.58	High
<10	2,212	37.69	Very high
Total	5,868	100.00	

Application of the revised DRASTIC method or DRASTICF method

The area with a high vulnerability corresponds to highly fractured karstified zone. The faults represent a groundwater discharge corridor, and also, a favorable area for rainwater infiltration even if the aquifer is deep. To take into account the fracturing, the revised DRASTIC method integrates the DRASTIC vulnerability map and the standard fracturing parameter F, which was derived from the geological map. These fractures correspond to corridors of about 30 m diameter. A rating of 7 was affected to fractured zones and 1 to unfractured zones then the results are weighted of 5 (Table 2 and Fig. 4f).

$$\mathrm{DRASTICF} = \mathrm{DRASTIC} + \mathrm{F}(\mathrm{Rating} \times 5).$$

Results show that the percentage of low vulnerability area has decreased by 16.4 % in 1995, by applying this revised method. In contrast, the areas of moderate to high vulnerability increased by 13.6 % in 1995 and 6.9 % in 2008, respectively (Tables 4 and 5 and Fig. 6).

Table 7 Risk parameterization

Rating	Land use×5
3	Bare land
7	Palm grove
10	Agglomeration

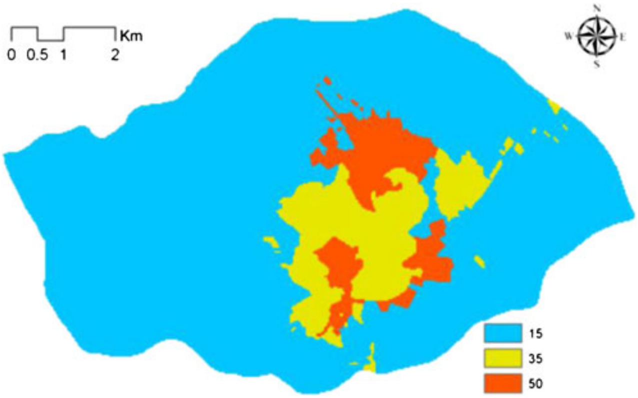

Fig. 8 Land use index

Application of AVI method

The AVI map index is generated by interpolating the calculated values for each borehole (Fig. 7). The AVI index calculated in this study area was reclassified into five classes: (1) very low vulnerability (arrival times >200 days); (2) low vulnerability (arrival times between 100 and 200 days); (3) moderate vulnerability (arrival times between 50 and 100 days); (4) high vulnerability (arrival times between 10 and 50 days); and (5) very high vulnerability (arrival times <10 days) (Fig. 7).

The vulnerability assessment shows that a large part of the area is characterized by a high (42.58 %) or very high (37.69 %) vulnerability (Table 6). The transfer time calculated for the contaminant migration from the surface to the water is considered only if the infiltration process continues and is related to the physical properties of the contaminant.

Risk evaluation

The risk of groundwater pollution is defined as the probability that the aquifer is contaminated to an unacceptable level by activities influencing immediate cover surface (Morris and Foster 2000). This approach uses the interaction between the charge and the concentration of contaminants and pollution vulnerability of the aquifer at such a location. This shows areas of various risk degree and hazard types of groundwater pollution (discharge, industrial zone, culture, etc.).

The assessment of groundwater contamination risk has been achieved by incorporating an additional parameter related to anthropogenic overground activities. The overground covers are clustered into three categories, i.e., bare land, palm, and agglomeration. A rating is assigned to each category according to their degree of impact, then weighted of 5 (Table 7 and Fig. 8). The following equation allows calculating the risk map by integrating the DRASTICF vulnerability map:

$$\text{Risk map} = \text{DRASTICF} + \text{Risk Index}(\text{Rating} \times 5).$$

Generally, the results indicate three areas of risk: high, moderate, and low (Fig. 9). At present, the risk may increase to the West with the expansion of farms and/or North/North East with the agglomeration growing.

The application of vulnerability DRASTIC/DRASTICF and AVI methods to groundwater in Figuig oasis allows to describe the system and evaluate its role in the management of regional groundwater resources. The resulting maps can help to implement strategies to prevent groundwater quality

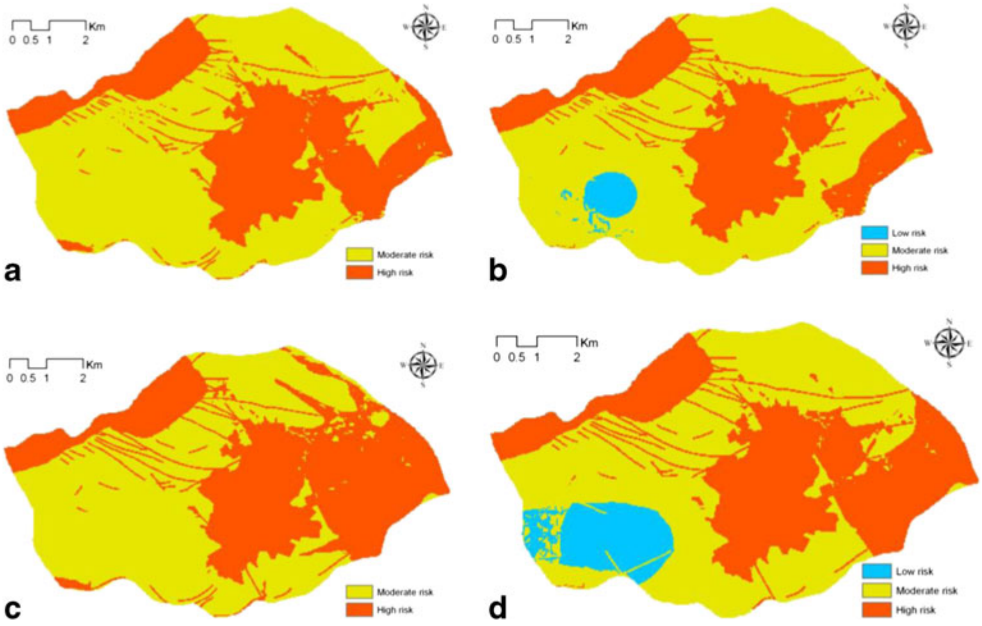

Fig. 9 Risk for 1995 (**a**), 2004 (**b**), 2008 (**c**), and 2010 (**d**)

degradation. The northern region is particularly characterized by high to very high vulnerability and high risk. As this area is the main source or infiltration and drinking water of the oasis, it is crucial to protect against it for any kind of polluting activity.

Conclusions

DRASTIC/DRASTICF and AVI methods were used in combination with a GIS modeling to find out the vulnerability of groundwater to contamination in Figuig oasis. The study shows that the 3.1 (1995), 2.8 (2004), 10.7 (2008), and 7.3 % (2010) of the total study area is under a high vulnerability risk if we use the revised DRASTICF method and 80 % if we use AVI method. The North of the study area (high vulnerability) is the main source of drinking water of the oasis. Therefore, it is important to protect it from any kind of contamination (Jbel el Haïmeur and Jbel Grouz).

Mapping the intrinsic vulnerability cannot alone be decisive on measures to be taken regarding the vulnerability but must be integrated in a comprehensive approach for the protection of groundwater. We propose a revised method adapted to highly fractured area. Our results indicate that the proposed approach is a powerful tool to classify the surface into different zones in regard of water resources protection. The different maps and summarized information may be useful for public, local authorities, and the interveners to raise the level of water resources awareness.

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