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Groundwater vulnerability and risk mapping of the Angad transboundary aquifer using DRASTIC index method in GIS environment

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Abstract The protection and preservation of groundwater resources are compulsory, particularly in the arid and semiarid countries where the waters are scarce. The effects of increasing urbanization, economic development, and agricultural activities, along with the erratic and scarce rainfall, contribute to the quantitative and qualitative deterioration of these resources. This paper attempts to produce groundwater vulnerability and risk maps for the Angad transboundary aquifer using DRASTIC model. The data which correspond to the seven parameters of the model were collected and converted to thematic maps in Geographic Information System environment. The modified DRASTIC map, which is the summation of the DRASTIC index and the network fractures maps, shows two degreed of vulnerability: medium and high. This map is then integrated with a land use map to assess the potential risk of groundwater to pollution in the Angad transboundary aquifer. There are three risk zones that are identified: moderate, high, and very high.

Keywords Water management · Groundwater vulnerability · Pollution · DRASTIC index · Morocco

Introduction

Vulnerability is a construct designed to help planners to protect aquifers as an economic resource. There has not yet been a general agreement on what the strict definition of vulnerability should be (Vrba and Zaporozec 1994), and the term vulnerability has come to mean different things in different contexts. It refers generally to the sensitivity of groundwater to contamination. This concept is based on the assumption that the physical environment may provide some degree of protection to groundwater against human activities. In the interaction with "The risk" concept, it is possible to have high vulnerability but no pollution risk if a significant contaminant load is absent and vice versa.

The Angad plain forms a subsiding basin where the maximum thickness is located at the center (Lahrach 1999), and a flexure divides it into two units: South Angads (260 km^2) and North Angads (200 km^2). The Angad water table is formed by made Plio-Quaternary formations and supported at its base by the impermeable Miocene marls that separate it from the aquifer of great regional importance residing in the Lias dolomite formation. The transition from the South unit to the North one is marked by a softening of the topography and a reduction in the thickness of the marly substratum with thickening of the

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groundwater aquifer in the vicinity of the Angad airport. The resulting morphology of plain shows two basins on both sides of the flexure.

The Angad plain is limited in the north by the dolomitic formations of the Orientals Beni Snassen, in the South by the liasic anticline of Jbel El Hamra, in the West by El Aioun hills and Bou Houria plain, and in the East, the plain is in hydrogeological continuity with Marnia plain in Algeria (Fig. 1).

Methodology

The DRASTIC model was developed by the US Environmental Protection Agency to be a standardized system for evaluating groundwater vulnerability to pollution (Aller et al. 1987; Evans and Mayers 1990). The goal of the model is to identify areas where special attention or protection efforts are warranted.

The model has four assumptions:

1. the contaminant is introduced at the ground surface;
2. the contaminant is flushed into the groundwater by precipitation;
3. the contaminant has the mobility of water; and
4. the area being evaluated by DRASTIC is 0.4 km² or larger.

DRASTIC is an acronym for the most important hydrogeological features which control groundwater pollution: Depth to water, net recharge, Aquifer media, Soil media,

Topography, Impact of the vadose zone media, and hydraulic Conductivity of the aquifer.

The seven parameters cut—in a schematic way—a local hydrogeological unity into its main components, which, in varying degrees, affect the processes of transport and attenuation of contaminants in soil and their transit time.

Each of the hydrogeological factors is assigned a rating from 1 to 10 based on a range of values. The ratings are then multiplied by a relative weight ranging from 1 to 5. The most significant factors have a weight of 5; the least significant have a weight of 1. A Geographic Information System (GIS) is used to compile the geospatial data, to compute the DRASTIC indices, and to generate the final vulnerability map.

For the quantitative parameters: Depth of the water, net Recharge, Topography, and hydraulic Conductivity of the aquifer, the classes are in the form of numerical values ranges, and they do not pose a problem in classifying and assigning ratings to each corresponding class (Table 1). Regarding the qualitative parameters—the aquifer media, soil media, and vadose zone—they may not exactly correspond to what is proposed by the DRASTIC model guide (Table 2). At this moment, we must follow a logical reasoning to determine the appropriate level and thereafter assigned to each class the corresponding range.

The equation for determining the DRASTIC index is:

$$ID = D_r\, D_w + R_r\, R_w + A_r\, A_w + S_r\, S_w + T_r\, T_w$$
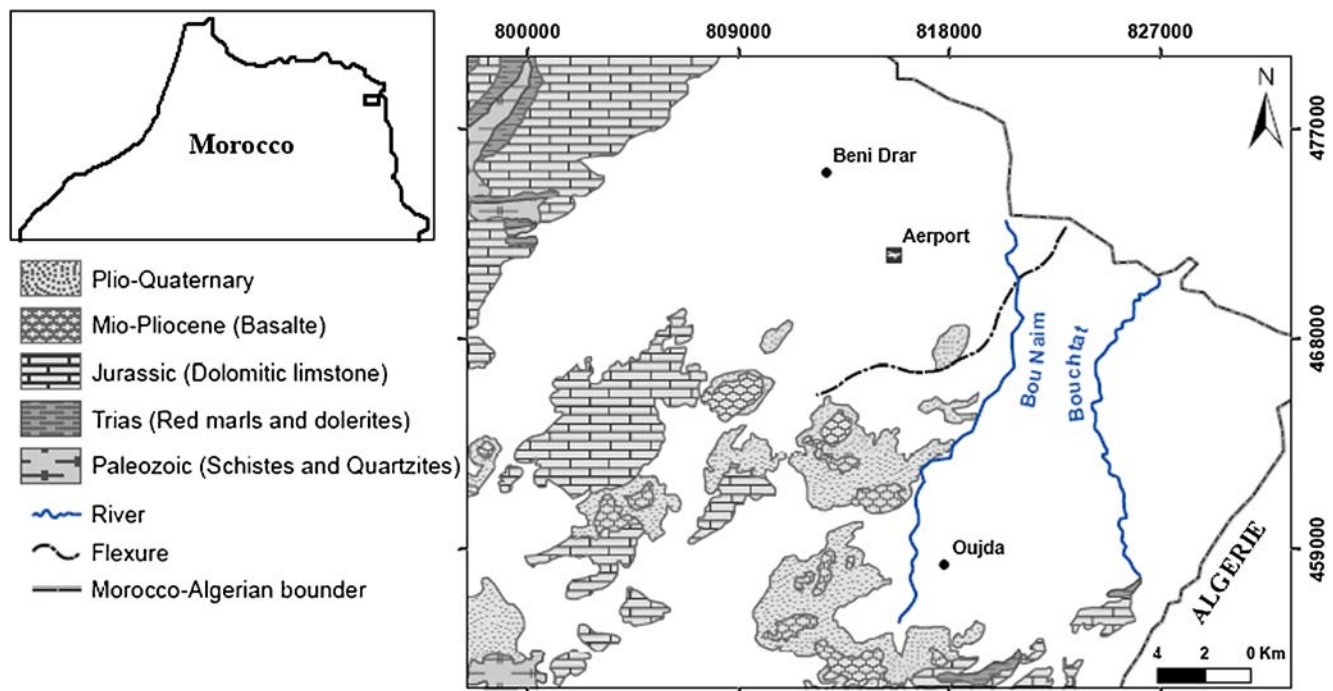$$+ I_r\, I_w + C_r\, C_w \qquad (1)$$

Fig. 1 Localization of the study area

Table 1 The DRASTIC quantitative parameters

DRASTIC quantitative parameters

Rating	Hydraulic conductivity ×3 (m/s)	Net recharge ×4 (mm/year)	Topography ×1 (%)	Depth to water ×5 (m)
10	$>9.5\times10^{-4}$		0–2	0–1.5
9		>250	2–6	1.5–4.5
8	5×10^{-4}–9.5×10^{-4}	180–250		
7				4.5–9
6	33×10^{-5}–5×10^{-4}	100–180		
5			6–12	9–15
4	15×10^{-5}–33×10^{-5}			
3		50–100	12–18	15–23
2	5×10^{-5}–15×10^{-5}			23–31
1	1.5×10^{-7}–5×10^{-5}	0–50	18+	>31

Where D, R, A, S, T, I, C represent the seven hydrogeologic factors,

r   designates the rating and
w   the weight.

The resulting DRASTIC index represents a relative measure of groundwater vulnerability. The higher the DRASTIC index, the greater is the vulnerability of the aquifer to contamination. A site with a low DRASTIC index is not necessarily free from groundwater contamination, but it is less susceptible to contamination compared with sites with high DRASTIC indices.

This work begins by the creation of a database for the quantitative evaluation of vulnerability, including: topography, geology, hydrology, and pedology data. A GIS is used to convert these maps to raster mode. The conversion consists in the fragmentation of a map into a series of pixels with defined size (400×400 m, see Fig. 2). A numerical value is attributed to each pixel. The resulting grid corresponds to a support for the seven DRASTIC param-

eters. Thus, the vulnerability is calculated for each pixel implicating a high resolution. The GIS is also used to generate the groundwater vulnerability map by overlaying the seven thematic maps. Table 3 summarizes the GIS preprocessing and manipulation techniques used to create the seven input data layers for the DRASTIC index.

Result and discussion

The Geographical Information System provides the DRASTIC parameters maps summarized in Table 4 for the transboundary Angad aquifer.

Depth to water (D) This map is obtained from an interpolation of the water depth values (measured in 2007). The Angad water depth varies between 15 and 87 m. An area of shallow depth in the north east of Oujda city is the most vulnerable to pollution as shown in Fig. 3

Table 2 The DRASTIC qualitative parameters

DRASTIC qualitative parameters

Rating	Soil media × 2	Aquifer media × 3	Impact of the vadose zone media × 5
10	Thin or absent, gravel	Karst limestone	Karst limestone
9	Sand	Basalt	Basalt
8	Peat	Sand and gravel	Sand and gravel
7	Shrinking and/or aggregate clay	Massive sandstone, massive limestone	
6	Sandy loam	Bedded sandstone, limestone, shale	Sandstone, limestone, sand, and gravel
5	Loam	Glacial till	
4	Silty loam	Weathered metamorphic/igneous	Metamorphic/ignous
3	Clay loam	Metamorphic/igneous	Shale, silt, and clay
2	Muck	Massive shale	
1	Nonshring and nonaggregated clay		Confining layer

Fig. 2 Grid of Angad transboundary aquifer
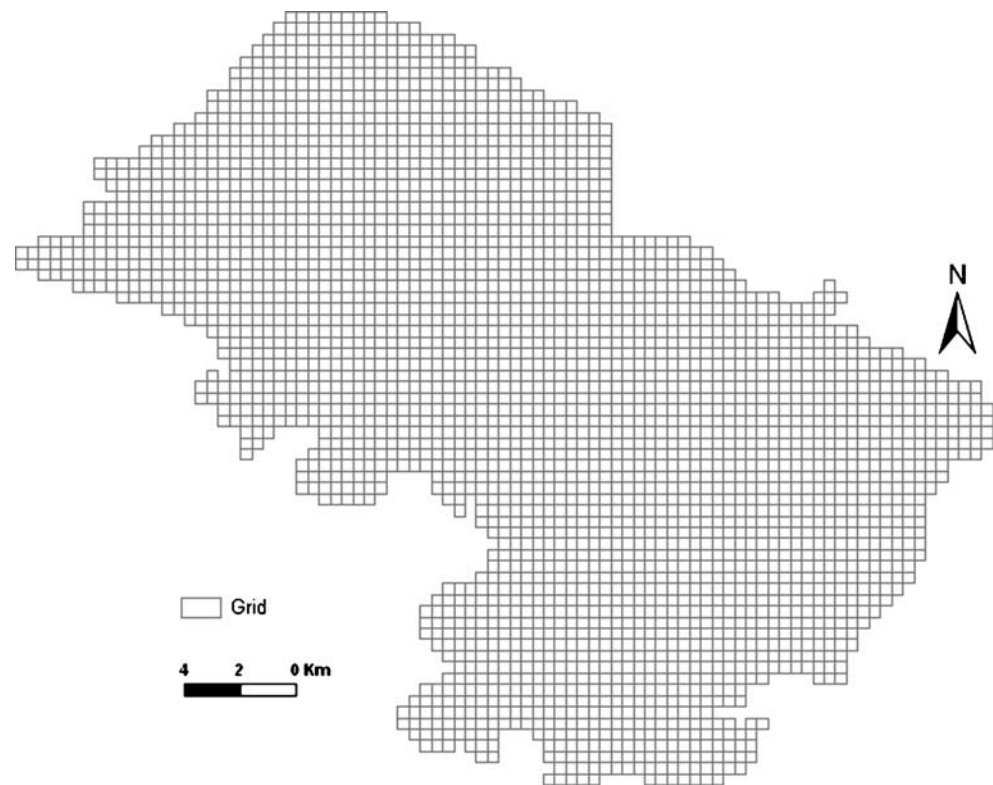
Net recharge (R) This represents an effective recharge or the quantity that reaches the aquifer by the infiltration mechanism in a determined period (annual recharge; in this case). Obviously, the risk of contamination increases with the volume of the infiltrated water. Rainfall data recorded at the meteorological station of Oujda-Angad, within a period of 37 years (1968–2005), were used to establish the hydrologic balance according to the method of Thornthwaite and to estimate the efficient infiltration by Eq. 2:

$$Ie = P - ETR - R \qquad (2)$$

Where:

Ie   efficient infiltration
P   total precipitation

ETR   real evapo-transpiration
R   surface flow.

The net recharge of the Angad groundwater is estimated at 60.70 mm/year (Fig. 4).

Aquifer Media (A) Data from the drilling completed by the Hydraulic Agency of the Moulouya basin allowed the preparation of the aquifer media map. Range and spatial distribution are showed respectively in Table 4 and Fig. 5.

Soil media (S) Data on soil media have been abstracted from the pedologic map (1/75,000) of the Angad plain. Three classes were identified (Fig. 6): rate 1 is attributed to urban soil with a very low rate of infiltration, rate 6 to brown carbonate soils, and rate 8 for isohumic soil.

Table 3 DRASTIC parameters sources and GIS mode processing

DRASTIC parameters	Data and sources	Mode of processing
Depth to water	Piezometric level (2007).	Interpolation
Net recharge	Annual rainfall (1968–2005). *Oujda-Angad meteorological station.*	Interpolation
Aquifer media	Geological map, Data wells. *The hydraulic agency of Moulouya basin.*	Interpolation
Soil media	Soil map. *Provincial office of agriculture.*	Digitalization
Topography	Topographic maps (1/50,000). *Oujda-Zouj Bghal-Ahfir-Beni wkil.*	Digitalization
Impact of vadose zone	Geological map,Data wells. *The hydraulic agency of Moulouya basin.*	Interpolation
Hydraulic conductivity	Transmissivities data taken from the pumping tests. *The hydraulic agency of Moulouya basin.*	Interpolation

Table 4 DRASTIC parameters for the Angad transboundary aquifer

Parameters rating	D×5 (m)	R×4 (mm/y)	A×3	S×2	T×1 (%)	I×5	C×3 (m/s)
1	>31			Urban soil	18+		$1.5×10^{-7}–5×10^{-5}$
2	23–31						$5×10^{-5}–15×10^{-5}$
3	15–23	50–100			12–18		
4							
5					06–12		
6			Loam, conglomerate	Calcareous brown soil		Loam, pebble	$33×10^{-5}–5×10^{-4}$
7			Pebble slightly cemented				
8				Isohumic soil		Sand and gravel	
9			Basalt		2–6	Basalt	
10					0–2		

Topography (T) The surface slope was calculated by using four topographic maps (1/50,000 scale) covering the study area. Then, the slope index was reclassified and converted into grid coverage and multiplied by the topographic weight (Fig. 7).

Impact of the vadose zone (I) Data of unsaturated zone lithology (I) were extracted from the logs and boreholes provided by the Hydraulic Agency of the Moulouya basin. Three classes were identified (Fig. 8).

Hydraulic conductivity (C) This parameter was calculated based on the following equation:

$$k = T/b, \tag{3}$$

Where:

k is the hydraulic conductivity of the aquifer (m/s)

T is the transmissivity (m^2/s), and

b is the thickness of the aquifer expressed in meters
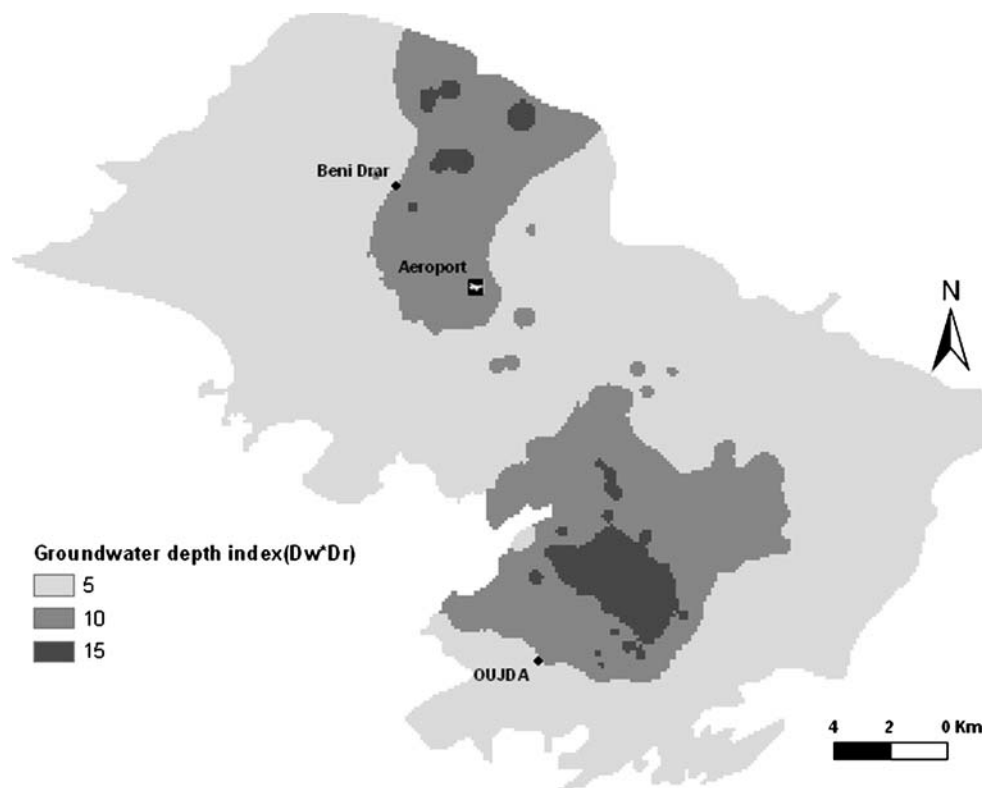
Fig. 3 Depth to groundwater map (2007)
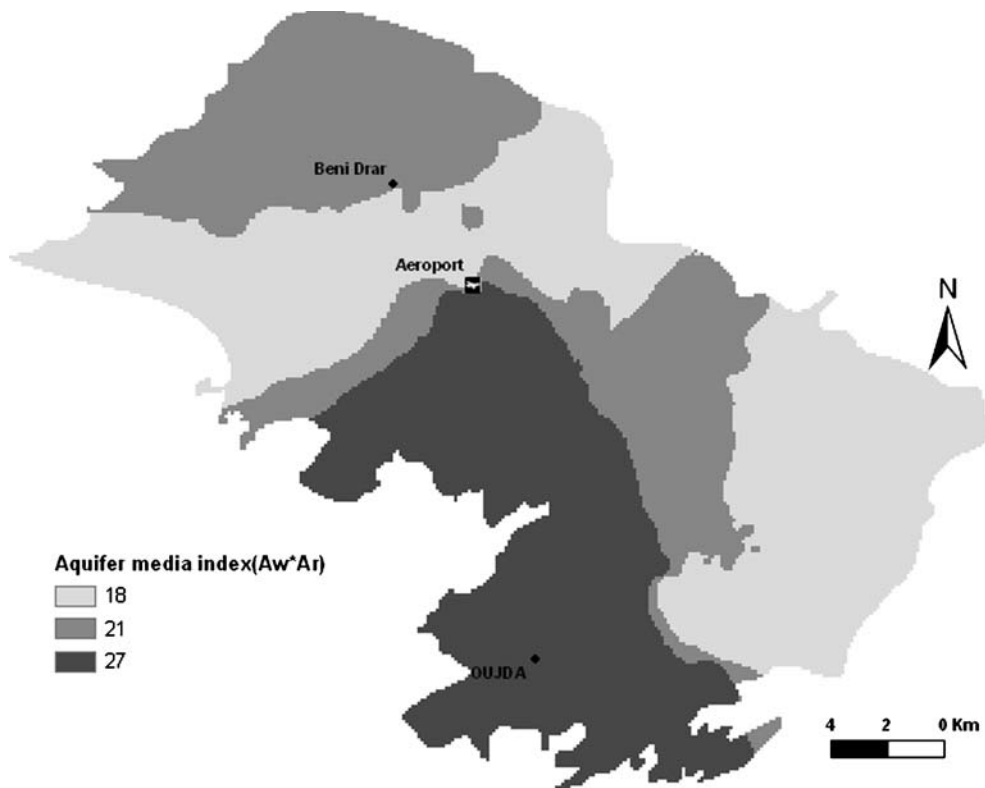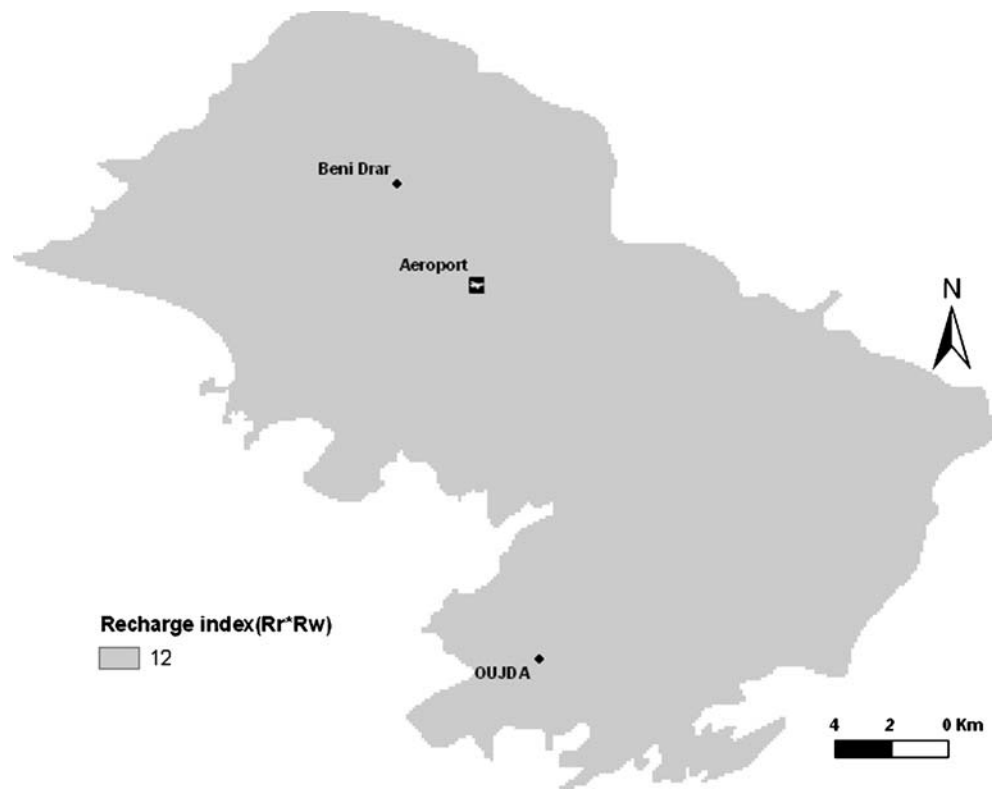
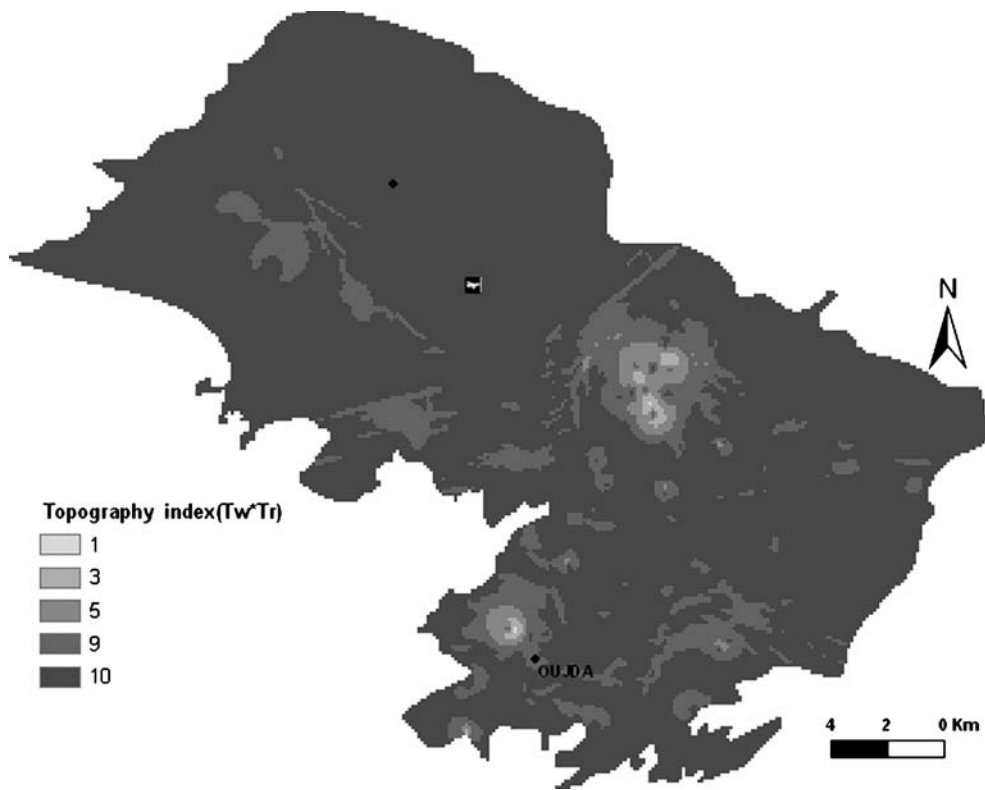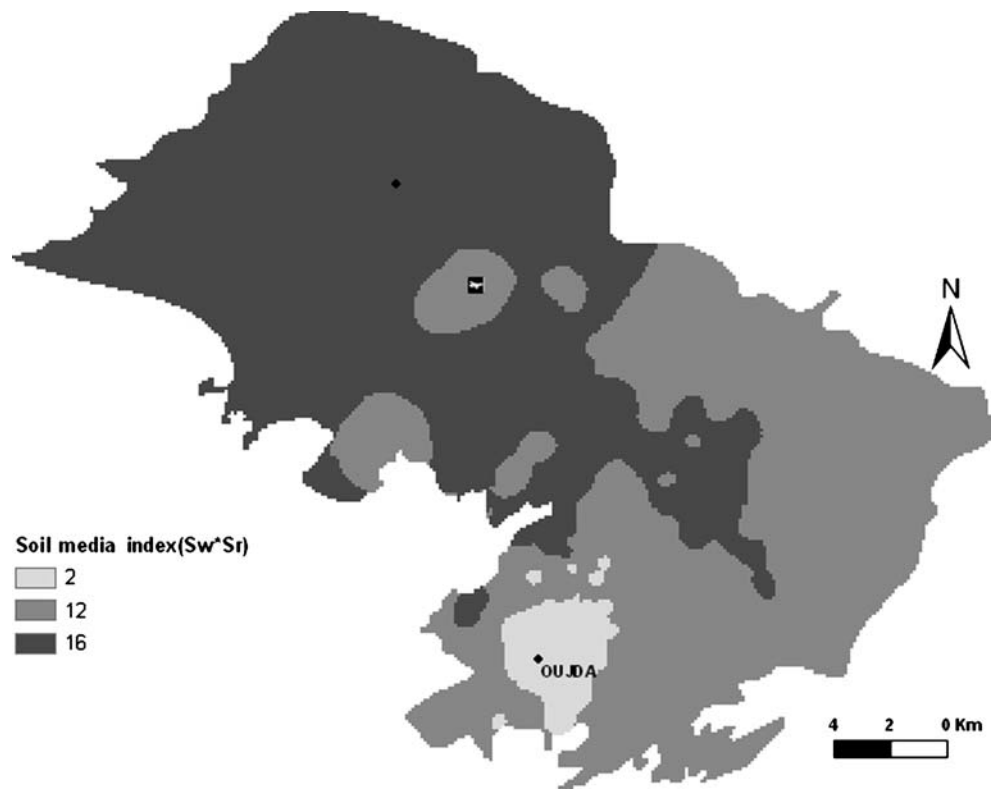**Fig. 4** The recharge map

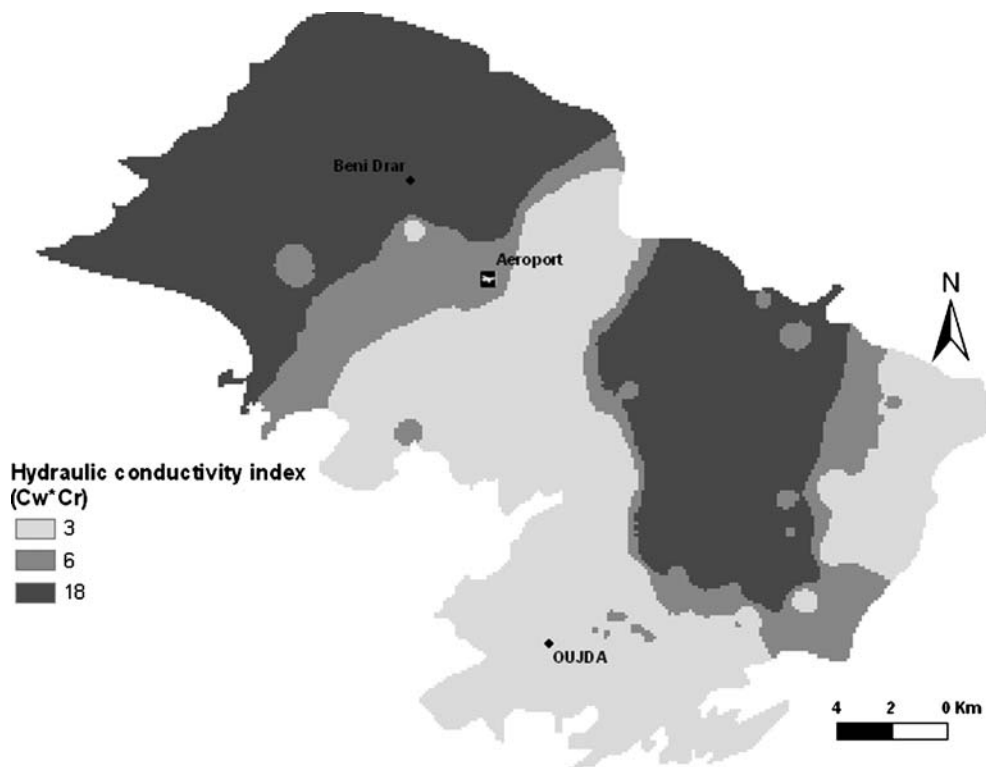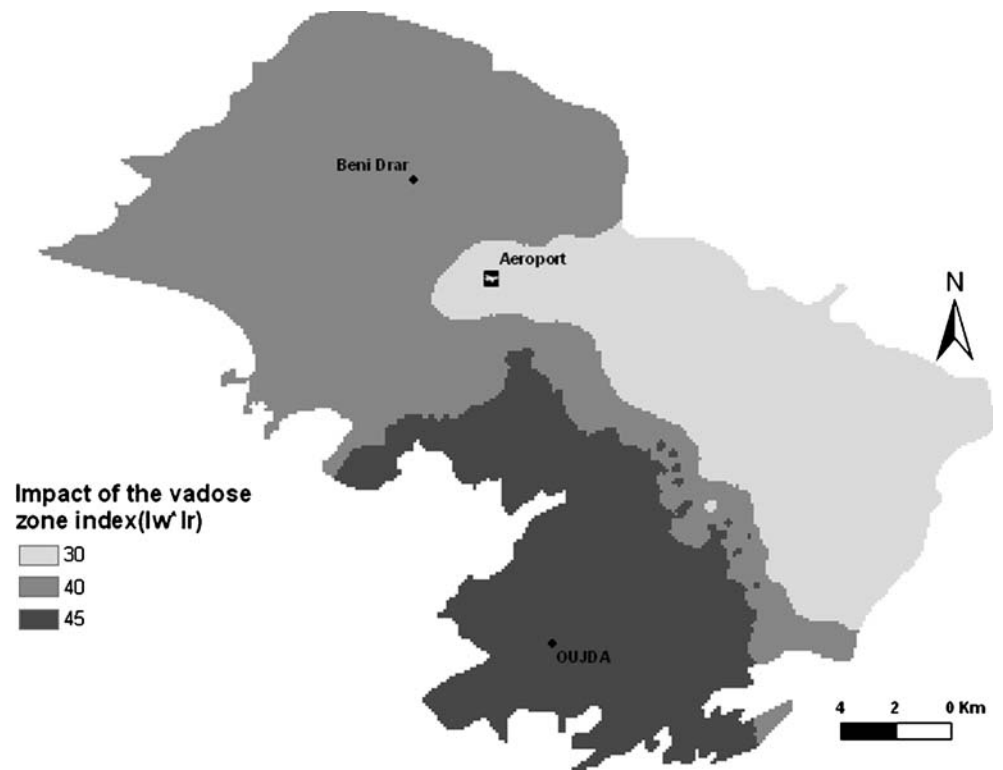**Fig. 5** The aquifer media map

Fig. 6 The soil media map

Fig. 7 The topographic map
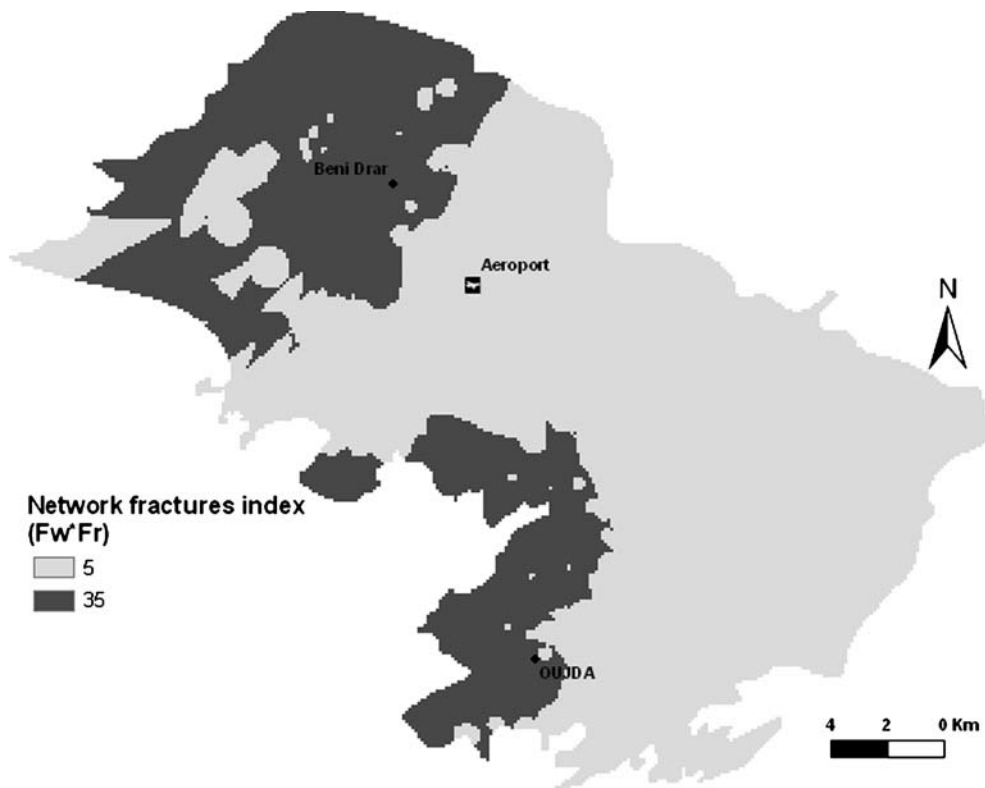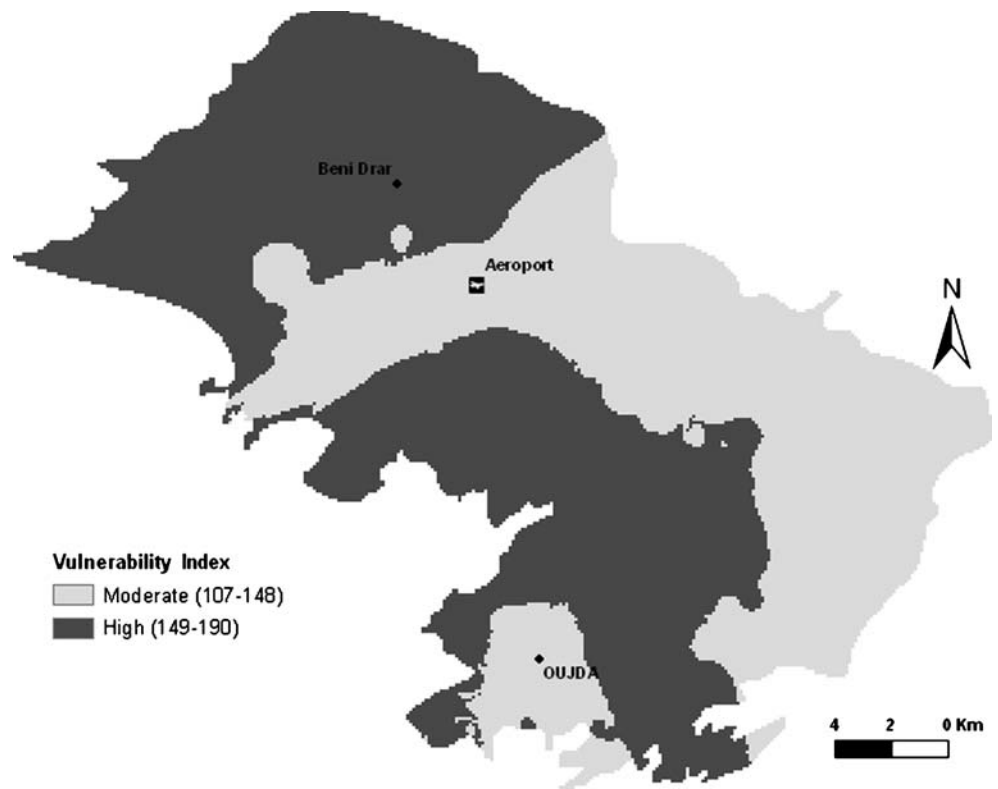
Fig. 8 Impact of the vadose zone map

Fig. 9 The hydraulic conductivity map

Fig. 10 The map of vulnerability to pollution

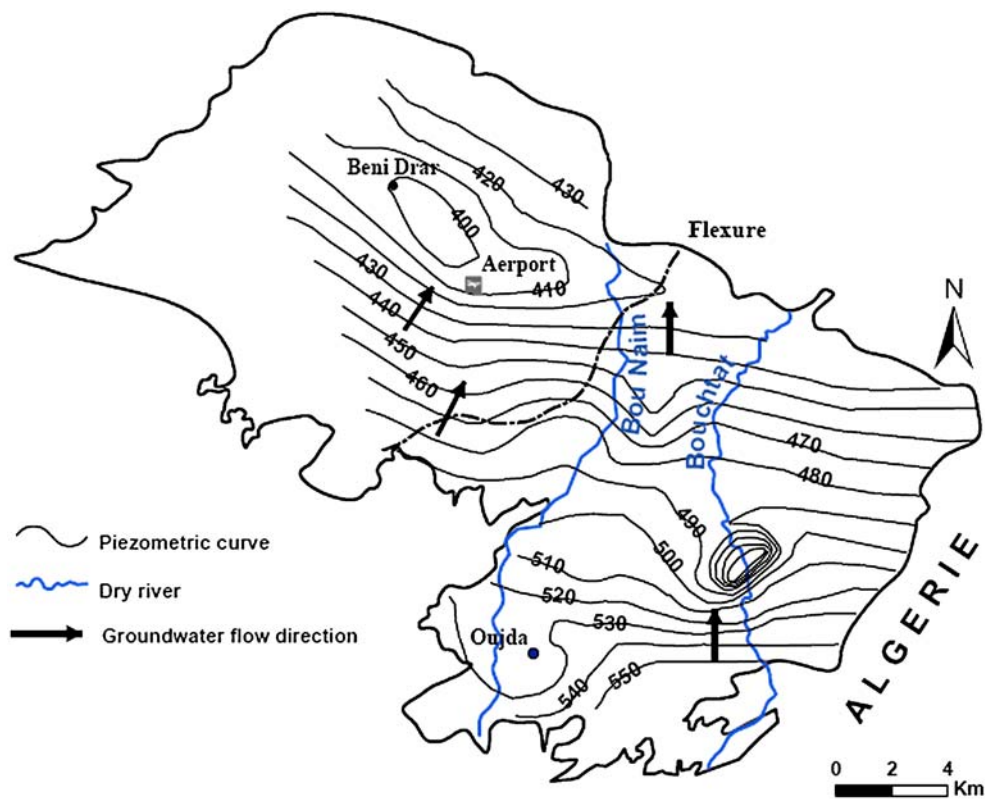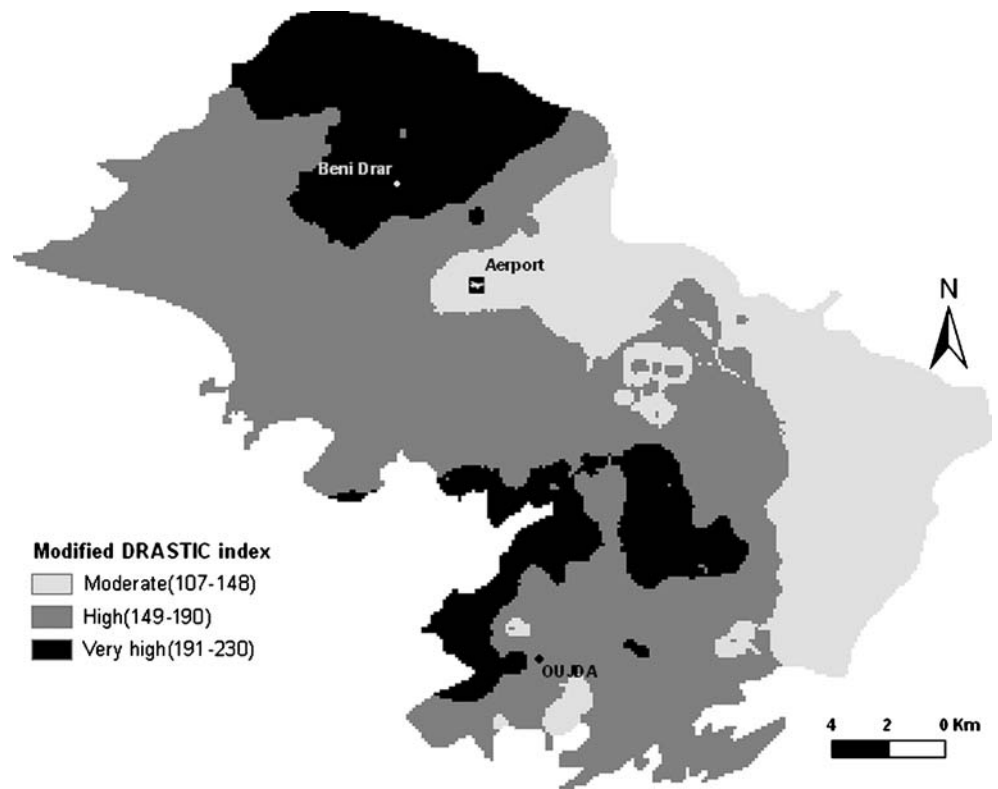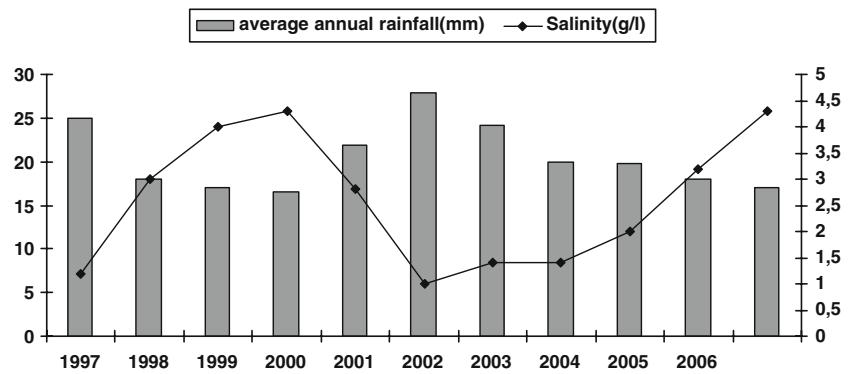Fig. 11 Network fractures distribution

Fig. 12 The modified
DRASTIC index

Modified DRASTIC index
- Moderate(107-148)
- High(149-190)
- Very high(191 -230)

- Piezometric curve
- Dry river
- Groundwater flow direction

Fig. 13 Piezometric map

The resulting map has three classes with ratings ranging from 1 to 6 (Fig. 9).

The DRASTIC index

The integration of the seven maps provides a synthetic map of vulnerability to pollution for the Angad transboundary aquifer (Fig. 10). The minimum possible DRASTIC index using these parameters is 23 and the maximum is 230. This range was divided into five equal classes: absent, low, moderate, high, and very high. The resulting DRASTIC values lay between 107 and 190. This range is classified as follows: 107–148=moderate vulnerability (representing 43% of study area), 148–190=high vulnerability (with 57% of the study area).

Modified DRASTIC index

In this paper, the DRASTIC method was modified responding to certain characteristics of the Angad plain. The depth to water alone does not provide a protection for groundwater against the contaminants infiltration as it is possible that the pollutant may penetrate the aquifer through fractures even if the aquifer is deep (Lee et al. 1998). Following this logic, the modified DRASTIC system is the sum of the original DRASTIC system and the fractures density which is
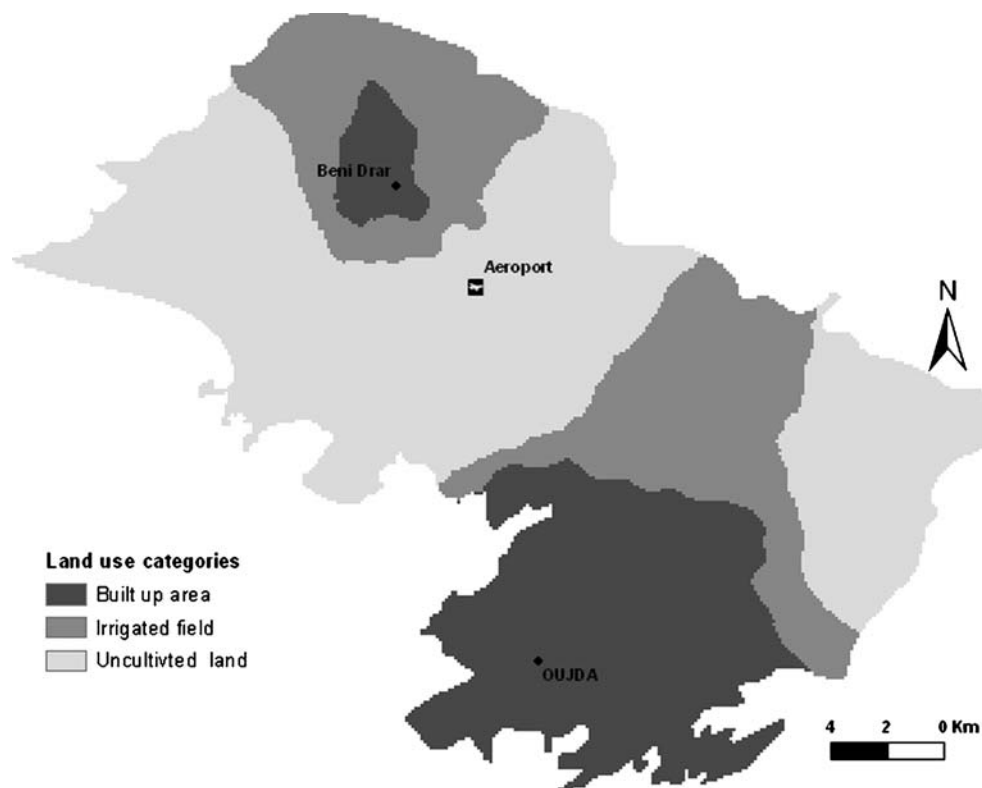
Fig. 15 Land use categories

Table 5 Land use categories

Land use categories	Lr
Built-up area	8
Irrigated field crops	8
Uncultivated land	5
Lw	5

Secunda et al. 1998 in Adamat et al. 2003

obtained by using aerial photographs and geological maps. Higher fractures density values represent a greater potential for groundwater contamination.

Modified DRASTIC index
$$= \text{DRASTIC index} + (\text{Distribution density rating} \times 5)$$
(4)

Figure 11 illustrates the fractures distribution in the Angad tranboundary aquifer which is added to the vulnerability index. The modified DRASTIC map shows three degrees of vulnerability: moderate, high, and very high (Fig. 12).

Deterioration of the Angad transboundary aquifer

In quantitative terms, the piezometric map (June 2007) shows the depression of the Angad water table to the south and north of the Angad plain (Fig. 13). In qualitative terms, the measured salinization reflects the progressive growth of adverse impacts. Both a decrease in groundwater resources and the beginning of a qualitative deterioration are evident (Fig. 14).

Risk evaluation

It is important to make clear the distinction between vulnerability and risk because risk of pollution is determined not only by the intrinsic characteristics of the aquifer (which are relatively static) but also by the existence of potentially polluting activities (which are dynamic factors that can in principle be both changed and controlled; see Ferreira and Oliveira 1997).

To evaluate potential risk, an additional parameter can be integrated into the analysis, which is the land use (Fig. 15). Three categories are used according to the method of Secunda et al. (1998) in Adamat et al. (2003; see Table 5); this map was converted into a raster grid and was multiplied by the weight of the parameter (Lw=5). The resultant grid coverage was then added to the DRASTIC
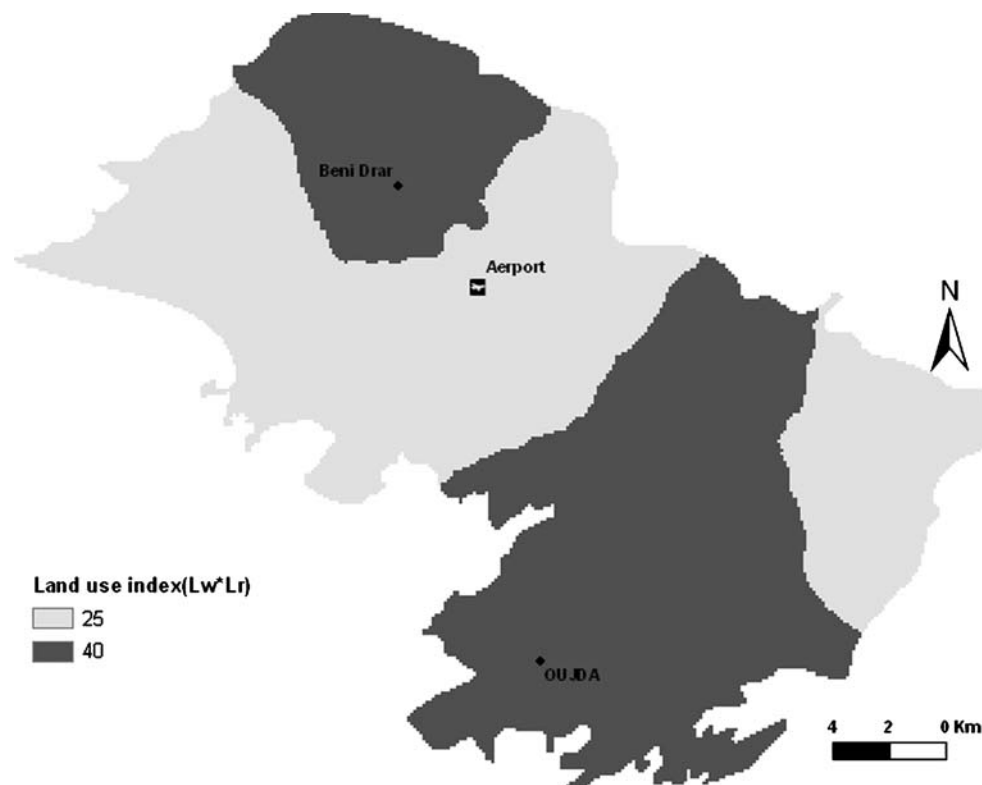
Fig. 16 The map of land use ratings and weight (Lr×Lw)
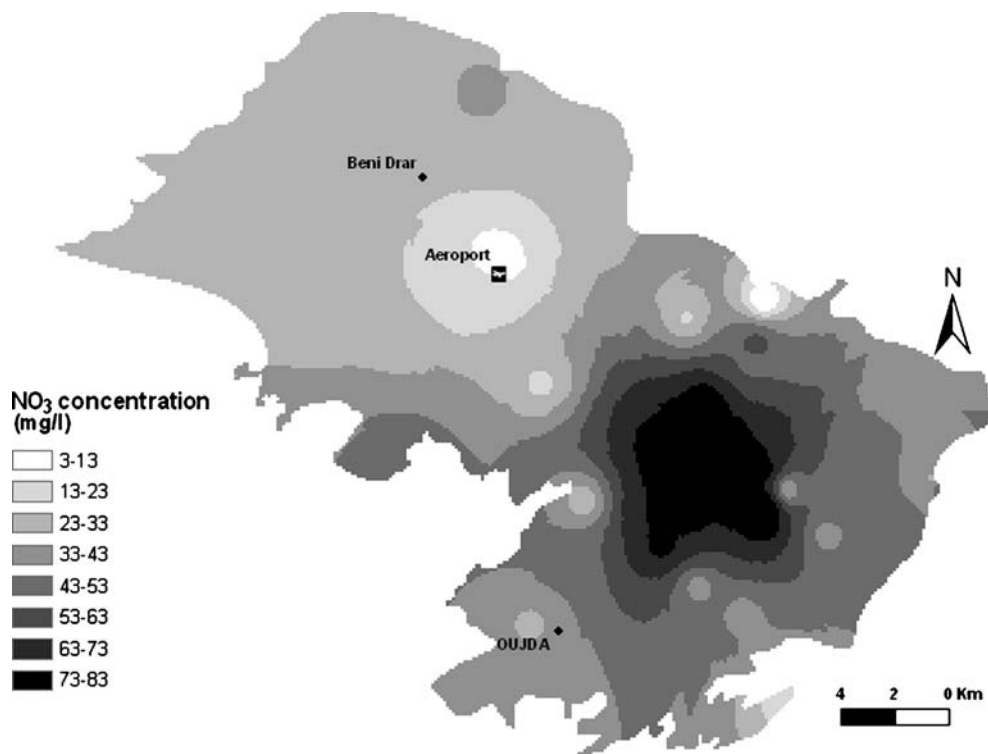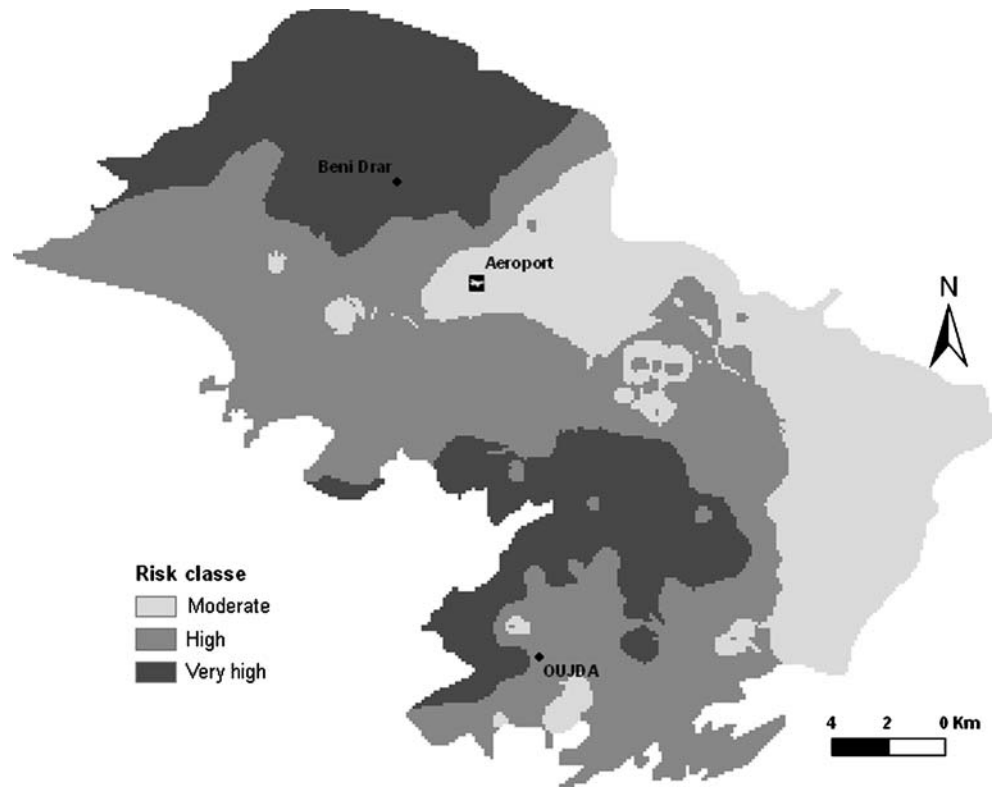
Fig. 17 The risk map

Fig. 18 Nitrate concentration map in the Angad transboundary

index based on the Eq. 5 provided by Collin and Melloul (1998) in Adamat et al. (2003; see Fig. 16)

$$Riskmap = MDI + Lr \times Lw \qquad (5)$$

Where:

MDI   is the Modified DRASTIC index and
Lr×Lw   is the land use index

In the Angad transboundary aquifer, the overexploitation of the groundwater resources, the increasing of urbanization, and the use of wastewater in the irrigation of cultivated land are the main causes of groundwater pollution. The risk map shows three of risk zones: moderate, high, and very high (Fig. 17).

Validation of the intrinsic vulnerability maps

The aquifer vulnerability method requires validation to reduce subjectivity in the selection of ratings and to increase reliability (Ramos-Leal and Rodriguez-Castillo 2003). Nitrate concentrations can be used to validate a groundwater vulnerability assessment. The analyzed water samples show a high concentration of nitrate in the northern-east of Oujda city, corresponding to the discharge of urban wastewater which is used for field irrigation. This high concentration of NO_3 corresponds to both the high and very high vulnerability area and the high and very high risk zones. Results are presented in Fig. 18)

Conclusion

Groundwater vulnerability maps can assist in developing groundwater protection strategies. Areas that are identified as being vulnerable to contamination may benefit from increased groundwater monitoring for pollutants and/or from additional efforts to clean up an aquifer. A risk map is used to assess the potential impact of anthropogenic activities.

In the Angad transborder aquifer, the Modified DRASTIC index was used responding to the study area characteristic; the resulting map was obtained from the summation of the intrinsic vulnerability and the network fractures index. The result shows three degrees of vulnerability: moderate, high, and very high. On the other side, the risk map demonstrates: moderate, high, and very high risk zone.

Nitrate concentrations are used to validate the obtained result. The analyzed water samples show high nitrate concentration in the Northern east of Oujda city corresponding to the urban discharge of wastewater which is used for the field irrigation. These areas correspond perfectly to both high, very high vulnerability and high, very high risk zones. These

results reflect a reality of the Angad water table which is exposed to a different anthropogenic stress.

The application of the DRASTIC approach not only reveals some advantages but also shows some drawbacks. Indeed, the outputs of DRASTIC index depend strongly on the data reliability. This may lead to different assessments for the same case study region. For example, in certain zones, it is not easy to attribute a range to the qualitative parameters because there is no agreement between the nature of the study area and what is already preset in the DRASTIC model list. Other parameters must be considered when using the DRASTIC model, such as the fractures network which is a determining factor. A major drawback of vulnerability and risk mapping is the difficulty to validate the result (Andreo et al. 2005). For this, the elaboration of the risk map must include the potential size and age of infrastructural installations.

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