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ORIGINAL ARTICLE

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Groundwater pollution risk mapping for the Eocene aquifer of the Oum Er-Rabia basin, Morocco

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Abstract Sustainable development requires the management and preservation of water resources indispensable for all human activities. When groundwater constitutes the main water resource, vulnerability maps therefore are an important tool for identifying zones of high pollution risk and taking preventive measures in potential pollution sites. The vulnerability assessment for the Eocene aquifer in the Moroccan basin of Oum Er-Rabia is based on the DRASTIC method that uses seven parameters summarizing climatic, geological, and hydrogeological conditions controlling the seepage of pollutant substances to groundwater. Vulnerability maps were produced by using GIS techniques and applying the "generic" and "agricultural" models according to the DRASTIC charter. Resulting maps revealed that the aquifer is highly vulnerable in the western part of the basin and areas being under high contamination risk are more extensive when the "agricultural" model was applied.

Keywords Vulnerability · Water resources sustainability · DRASTIC · GIS · Morocco

Introduction

In the Moroccan basin of Oum Er-Rabia, of about 35,000 sq.km, the water resources are mainly provided by a multi-layer aquifer system that provides a potential groundwater resource of about 326 million m^3/year among a potential of 4,000 million m^3/year estimated for the global groundwater resources in Morocco. Geological formations of Eocene ages outcrop on an area of 2,300 sq.km and provide an important portion of water resources in the basin. Anthropogenic activities in the region are: mining and industry that are developed due to the existence of one of larger world phosphorite reserves that is the occurrence of Ouled Abdoun. The agriculture in the region is characterized by the production of wheat, barley, and corn in the phosphates plateau north of the basin, but it varies in the Tadla plain where modern methods of irrigation and fertilization are used. Irrigated areas in the phosphate phosphates plateau and the Tadla plain reached 150,000 ha in 1994 (Benbiba and Lakfifi 1994). Since the 1970s, urban centers of the region are in continuous growth. According to the last census of 2004, population in the region reached more than 590,000 inhabitants. The main centers are Khouribga, Oued Zem, Boujaad, El Borouj, Fkih Ben Salah, Qasbat Tadla, and Beni Mellal (Fig. 1). In addition to the increase in groundwater demand, due to the socio-economic development of the region and frequent dryness periods, water resources are threatened by the pollution in zones of anthropogenic activities. Thus, the preservation of water resources quality is necessary for the success of sustainable development programs. It requires management measures based on a preventive strategy. This study constitutes an attempt for the pollution risk assessment that the Eocene aquifer of the Oum Er-Rabia basin undergoes. It uses the DRASTIC method described by Aller et al. (1985) and that has shown encouraging results in the Moroccan region (El Mahmouhi et al. 2003; Ettazarini and El Mahmouhi 2004).

Site presentation

The Oum Er-Rabia basin is between the High Atlas mountains and the Mesetian domain of central Morocco (Fig. 1). The sector of study corresponds to the central part of the basin where the existence of a water table is known to be permanent through Eocene formations. It includes the phosphates plateau to the north and the Tadla plain to the south. The southern limit is marked by the course of the Oum Er-Rabia river. Climatologic data reveal a semi-arid climate to contrasted seasons for the region (Labyed and Genah 1979; Hsissou 1991). Rainfall is relatively important in the east and in zones neighboring the Atlas mountains such as Dcher El Oued (507 mm/year) and Qasbat Tadla (368 mm/year). Annual precipitation decreases from east to west (315 mm in Khouribga) and southwest (211 mm in Ouled Sidi Driss) (Labyed and Genah 1979; Hsissou 1991).

Outcrops are marly and dolomitic limestones of Upper Cretaceous ages, overlain by deposits of a phosphatic complex composed of sandy, calcareous, and flinty phosphorites interbedded with marly and flinty limestones. The basis of the phosphatic complex is marked by a “bone-bed” level of Maastrichtian age, while the summit is characterized by a continuous slab of sandy limestone with *Thersitea* fossils of Lutetian age (Belfkira 1980; Rahhali 1992; Moutaouakil and Giresse 1993). In the south, recent outcrops are constituted of sandy, conglomeratic, and clayey deposits of Mio-Plio-Quaternary. Cretaceous to Eocene layers are slightly undulated and have a weak dip to the south. They plunge under recent deposits of Tadla and their dip remarkably increases (Belfkira 1980; Rahhali 1992; Moutaouakil and Giresse 1993; Ettazarini 2002).

The multi-layer aquifer system of the Oum Er-Rabia basin is composed of four main superposed aquifers that are encouraging to very good hydraulic characteristics. They are from the deeper to the shallower as follows: the Turonian, the Senonian, the Eocene, and the Mio-Plio-Quaternary aquifers (Labyed and Genah 1979; Hsissou 1991; BRGM 1993; Ben Hammou 1995; Ettazarini 2002). The wall of the Eocene aquifer is constituted of bituminous marls in the phosphates plateau, but in the Tadla plain water-bearing limestones of Eocene are in hydraulic continuity with those of the Senonian. The thickness of Maastrichtian-Eocene series increases gradually from the north (40 m in Khouribga) to the center of the basin (100 m in Fkih Ben Salah), and then the thickness changes rapidly to reach 300 m near the High Atlas mountains (BRGM 1993). But in the El Borouj region, Eocene formations are truncated by erosion and outcrops are Senonian limestones.

Piezometric maps of the aquifer show a groundwater flow from the north to the south and southwest. The hydraulic gradient ranges from 0.6 to 0.8% in the phosphates plateau, while it evolves gradually from 0.4 to 0.1% in the Tadla plain (BRGM 1993). Fluctuations of the water table have been observed in survey points south of the basin. They reveal a progressive decline of the water-table level explained by the influence of the pumping used for irrigation (BRGM 1993), but also it is due to the decrease of natural recharge during dryness periods.

Data on the hydraulic transmissivity of the Eocene aquifer are available for 34 test pumpings realized in the region by the DRH “Direction Régionale de l’Hydraulique” of Beni Mellal, actually ABHOR “Agence de Bassin Hydraulique d’Oum Er-Rabia”. Most observation points are grouped in the center of the basin, but the transmissivity varies between 1×10^{-3} and 9×10^{-3} m^2/s, reflecting thus the heterogeneity of the aquifer lithology.

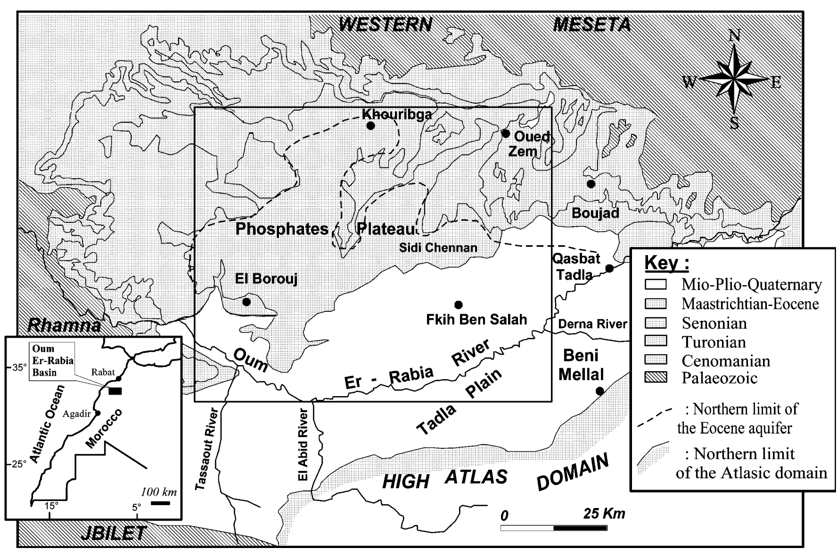

Fig. 1 Location and geological maps of the Oum Er-Rabia basin. *Central rectangle* shows the study area

Hydrochemical characteristics of the Eocene aquifer are variable through the basin. In the north, waters are characterized by a global salinity not exceeding 400 mg/l and a hardness limited to 20°H, while waters from Fkih Ben Salah have salinity values more than 1 g/l and hardness between 20 and 35°H (Ettazarini 2004). In addition, waters of the Eocene aquifer are characterized by raised contents in fluorine that exceed locally 3 mg/l west of the basin (BRGM 1993). This contamination is due to the dissolution of fluorapatite, the main mineral of the phosphorites. The chemical water facie, according to the classification of Piper (1944), reveals a SO_4–Cl–Ca–Mg type to the east and it passes to the HCO_3–Ca–Mg type in the west (Ettazarini 2002). Waters are saturated in carbonate minerals: calcite, dolomite, and aragonite, but are unsaturated in evaporitic minerals: gypsum, anhydrite, and halite (Ettazarini 2004). These observations suggest the existence of water–rock interaction processes and the influence of the carbonated and phosphatic rocks on the chemical properties of groundwater (Ettazarini 2004, 2005). Sustainable development of the region requires the maintenance of the equilibrium between available resources and growing demands. It requires measures of pollution risk estimation to protect the quality and provide the sustainability of water resources. A map of aquifer vulnerability thus provides the possibility to take preventive measures for optimizing procedures of the water resources management.

Methodology of the aquifer vulnerability assessment

The evaluation of the aquifer vulnerability by applying the DRTASTIC DRASTIC method, as described by Aller et al. (1985), consists of evaluating the impact of seven parameters controlling the infiltration of pollutant substances to groundwater. This standardized model uses the information on natural terrain conditions as well as climatic and hydrogeological characteristics of the aquifer to assess the pollution potential (Aller et al. 1985; Deichert and Hamlet 1992; Lallemand-Barrès 1994). The parameters are depth to water (D), net recharge (R), aquifer media (A), soil media (S), topography (T), vadose zone media (I) and hydraulic conductivity (C). Subsection maps showing local information have been elaborated for each parameter using a geographical information system (GIS) technique. A notation from 1 to 10 is attributed to each fragment of a given map according to the DRASTIC charter (Fig. 2). Weights given for parameters correspond to their relative importance to determine the ability for a pollutant to reach the water table. The calculation of the DRASTIC vulnerability index is based on the combination of the seven generated thematic maps as follows:

$$\text{DRASTIC index} = \text{Dr.Dw} + \text{Rr.Rw} + \text{Ar.Aw} + \text{Sr.Sw} + \text{Tr.Tw} + \text{Ir.Iw} + \text{Cr.Cw}.$$

Where r is the notation value (1–10) and w is the weight value for a given parameter (1–5).

Parameters of vulnerability to the pollution

The depth to water (D)

The Eocene aquifer is unconfined in the phosphates plateau and the map of depth to water was obtained from the elevation difference between the topographic surface, digitized from topographic sheets at 1:50,000 scale, and the water surface deducted from the piezometric map for the year 1988 (Ettazarini 2002). But in the Tadla plain, where the aquifer is confined, depth to water is the distance from surface to roof of the aquifer that was determined from drill holes.

The depth to water is changing in the study zone of approximately 3,123 sq.km (Fig. 3). The majority of terrains, 80.56% of the total surface, show depths exceeding 30 m. Depths exceeding 100 m characterize the Tadla plain where Eocene formations are covered by Mio-Plio-Quaternary deposits. Depths lower than 1.5 m are revealed only in the western part of the basin occupying 2% of the total surface. The remainder of the area corresponding to 17.44% shows depths to water between 1.5 and 30 m.

The recharge (R)

The recharge influences the contamination of groundwater guided by infiltration of rainwater in outcrop areas. Climatic data for the period 1975–1991 available from eight meteorological stations were used. The recharge hence was estimated by the efficient rains (ER) and by taking in consideration local conditions of the maximum retention capacity (RUmax) of superficial formations (Ettazarini and El Mahmouhi 2004; Ettazarini 2005).

Four recharge levels were distinguished in the elaborated map (Fig. 3): the northwestern side of Sidi Chennan constitutes the important aquifer recharge zone. This area accounting for 5.3% of the studied surface, receives between 175 and 255 mm/year. The areas receiving between 100 and 175 mm/year mainly follow a NE–SW axis at the basin center, but others are occurring locally in Khouribga region. These zones of medium recharge correspond to 13.7% of the surface study. The remainder of terrains, forming 81% is covered by clayey formations and the recharge is less than 100 mm/year.

Fig. 2 Summary table of the seven DRASTIC parameters used for the assessment of the Eocene aquifer vulnerability in the Oum Er-Rabia basin

Depth to water (m)	Description	0 - 1.5	1.5 - 3	3 – 4.5	4.5 - 9	9 - 15	15 - 22	22 - 30	>30
	Notation	10	9	8	7	5	3	2	1
Recharge (mm/year)	Description	>255	175 -255	100 - 175	50 - 100	<50			
	Notation	9	8	6	3	1			
Aquifer media	Description	Sandstone and sandy limestone	Limestone and dolomite	Marly limestone	Calcareous marl				
	Notation	8	6	4	3				
Soil media	Description	Sandy and stony soils	Soils with weakly differentiated horizons: sandy and muddy soils	Isohumic soils: calcimagnesian soils with calcareous crust	Argillous soils with iron sesquioxides and argilic horizon				
	Notation	9	7	5	3				
Topography slope (%)	Description	<2	2 - 6	6 - 12	12 - 18	>18			
	Notation	10	9	5	3	1			
Unsaturated zone media	Description	Sandstone	Sandy limestone	Limestone and dolomite	Marly limestone	Calcareous marl			
	Notation	8	7	6	4	3			
Permeability (m/s)	Description	$>9.4\ 10^{-4}$	$4.7\ 10^{-4}$ to $9.4\ 10^{-4}$	$3.29\ 10^{-4}$ to $4.7\ 10^{-4}$	$1.47\ 10^{-4}$ to $3.29\ 10^{-4}$	$0.47\ 10^{-4}$ to $1.47\ 10^{-4}$	$<0.47\ 10^{-4}$		
	Notation	10	8	6	4	2	1		

The aquifer media (A)

The saturated zone lithology is deducted from the hydrogeological drilling sections from the DRH (BRGM 1993; Ettazarini 2002). The map of the aquifer media (Fig. 3) shows a progressive evolution from the north to the south: in the Khouribga and Sidi Chennan regions aquifer rocks are dominated by phosphate and sandy limestones that occupy approximately 6.3% of the total studied area. The central part of the basin forming around 59% of areas is dominated by marly and calcareous rocks, while most saturated rocks in the Tadla plain are characterized by limestones and dolomites and account for about 34.7% of the studied surface.

The soil media (S)

The soil distribution in the Oum Er-Rabia basin is digitized from the soils map of Morocco available at a 1:1 million scale. Isohumic sols that occupy 52.65% of the area dominate the studied zone (Fig. 3). They are largely distributed in all parts of the basin. Calcimagnesian soils are also occurring in the basin and cover approximately 16.4% of studied terrains. They are sandy and stony soils in the northern and western parts of the basin. Weakly differentiated soils are representing 16.25% of the surface. They are permeable to semi-permeable soils occurring on a NE–SW axis at the basin center. These soil types are formed on calcareous bedrock widely outcropping in the region. But argillous soils with iron sesquioxides and argilic horizon are equally present in the northern part of the Tadla plain and occupy nearly 14.7% of studied area.

The topography (T)

The topography impact was estimated from the map of slopes that are calculated by derivation from surface elevation. The areas that have slopes between 2 and 6% cover nearly 2.3% of studied surface, while 97.7% have slopes less than 2% reflecting the tabular morphology in the central part of the Oum Er-Rabia basin (Fig. 3). These conditions are favorable for downward transportation of contamination in irrigated areas that are frequent in the Tadla plain.

The vadose zone media (I)

The unsaturated zone conditions are deducted from the hydrogeological drill holes of the DRH (Ettazarini 2002). The vadose zone corresponds to unsaturated rocks that a contaminant solution must pass through to reach the water table. The map of overburden properties (Fig. 3) shows that limestone-marl alternation characterizes the center of the basin. Massive dolomites and limestones occur in the Tadla plain to the south, while sandstone-marl alternation is encountered in the western side of the basin. Sandy and calcareous rocks in the phosphates plateau dominate unsaturated zone. The most permeable overburden is mainly constituted of sandstones. But this area is limited to the south of Khouribga region. The weakly permeable rocks are calcareous marls occurring at the center of the phosphates plateau.

The aquifer permeability (C)

The establishment of the hydraulic conductivity map estimated the aquifer permeability. The transmissivity determined by test pumpings undertaken by the DRH (BRGM 1993) was divided by the thickness of saturated zone based on drill holes data (Ettazarini 2002). The resulting map (Fig. 3) shows a remarkable evolution from northwest to southeast. In the phosphates plateau the permeability of unconfined aquifer exceeds

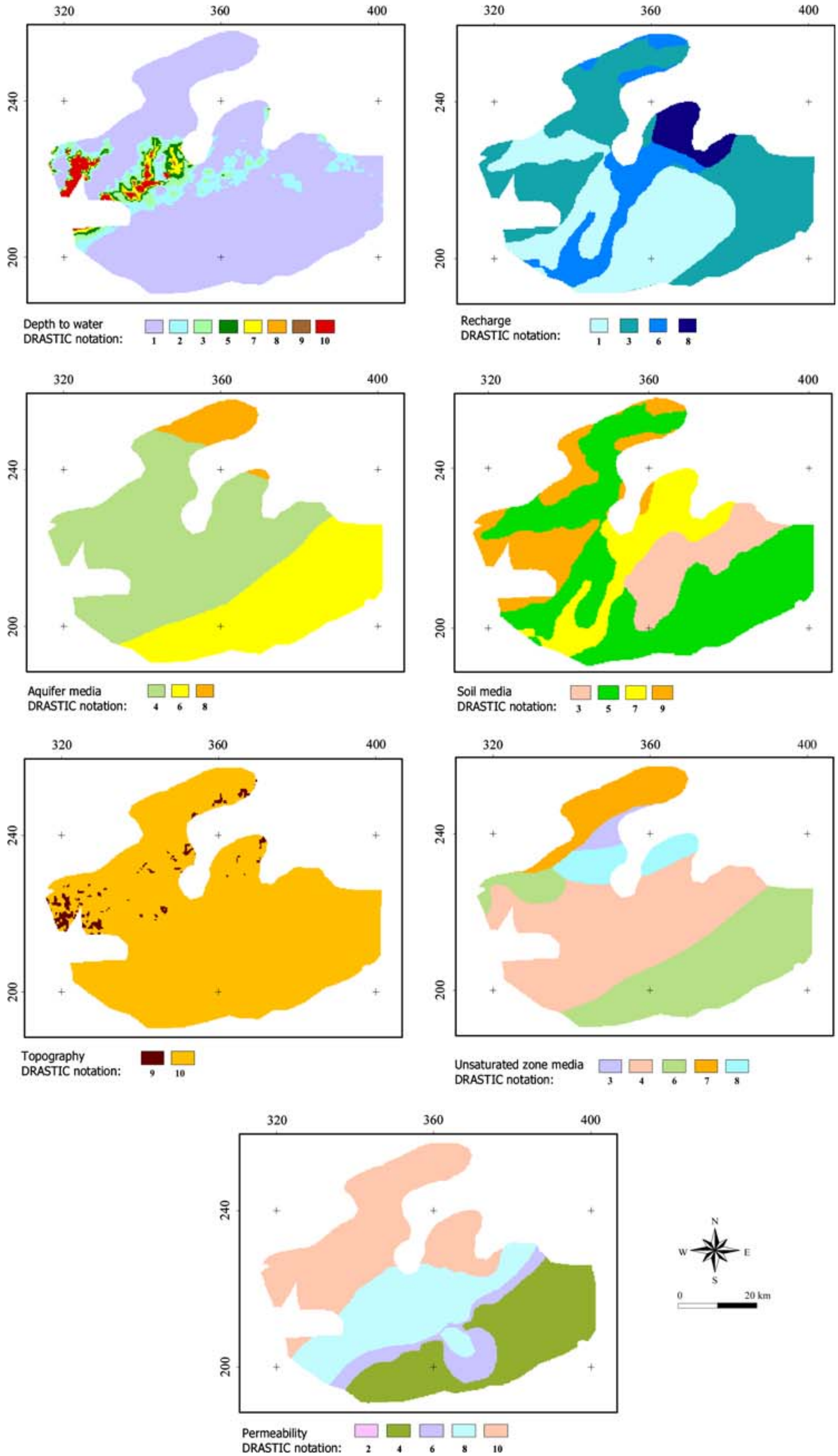

Fig. 3 Rating maps of the different DRASTIC parameters in the Eocene aquifer of Oum Er-Rabia basin

$9.4{\times}10^{-4}$ m/s. The central part of the basin is characterized by a permeability between $9.4{\times}10^{-4}$ and $3.29{\times}10^{-4}$ m/s. But in the Tadla plain the Eocene aquifer becomes confined and its permeability is less than $3.29{\times}10^{-3}$ m/s.

The aquifer vulnerability maps

The vulnerability maps were generated with ArcView Geographical Information System (GIS) software. The resulting maps are based on the ''generic'' and ''agricultural'' models of DRASTIC defined as follows:

$$\text{Generic DRASTIC index} = 5.D + 4.R + 3.A + 2.S + 1.T + 5.I + 3.C$$

$$\text{Agricultural DRASTIC index} = 5.D + 4.R + 3.A + 5.S + 3.T + 4.I + 2.C.$$

According to the ''generic'' model the vulnerability map reveals tree levels of pollution risk that ranges between 69 and 174: higher values of vulnerability index indicating higher contamination potential are encountered in the western part of the basin and north of Sidi Chennan (Fig. 4). These vulnerable zones are covering around 1.5% of studied area. The Eocene aquifer is under lowest risk in the eastern part of the Tadla plain. Other areas of low vulnerability are also encountered in some locations in the phosphates plateau and east of El Borouj region. The global area of low contamination potential covers approximately 60.5% of the total surface, while the remainder of the terrains is under moderate risk potential. The ''agricultural'' model importance resides in the existence of developed agricultural activities and zones where modern irrigation methods and nitrogen-based fertilizers are largely used, notably in the Tadla plain. These conditions suggest that the pollution risk should be estimated with suitable method that gives more importance to soil and topography impacts. According to this second model, the vulnerability index is between 90 and 200 and the distribution of vulnerable zones is similar to the previous model (Fig. 4). But vulnerable zones proportion has increased to 7.3% of global surface. In fact, the aquifer reveals a high vulnerability in some locations in the Khouribga region in addition to the western part of the basin, while low vulnerable zones have shown a decrease to 57.5%. The surface of moderate risk potential occupies about 35.2% of terrains.

Despite the continuous evolution of the DRASTIC method that is increasingly applied in combination with other models such as the ''fuzzy pattern recognition model'' (Zhou et al. 1999; Chen and Fu 2003), the maps resulting from the application of the DRASTIC method, as described in this study, present certain correspondence between the area classification and the quality of groundwater in the Oum Er-Rabia basin. Indeed, groundwater shows contents in sulfates and nitrates exceeding permitted values NE of the studied region, certifying thus the reliability of the used method. Nevertheless, the future attempts to improve the concept of the pollution risk mapping should include the impact of human activities as the real source of threat.

Conclusion

The combination of available climatic and hydrogeological data and the utilization of GIS techniques have allowed the application of the DRASTIC method to assess the potential of pollution risk for the Eocene

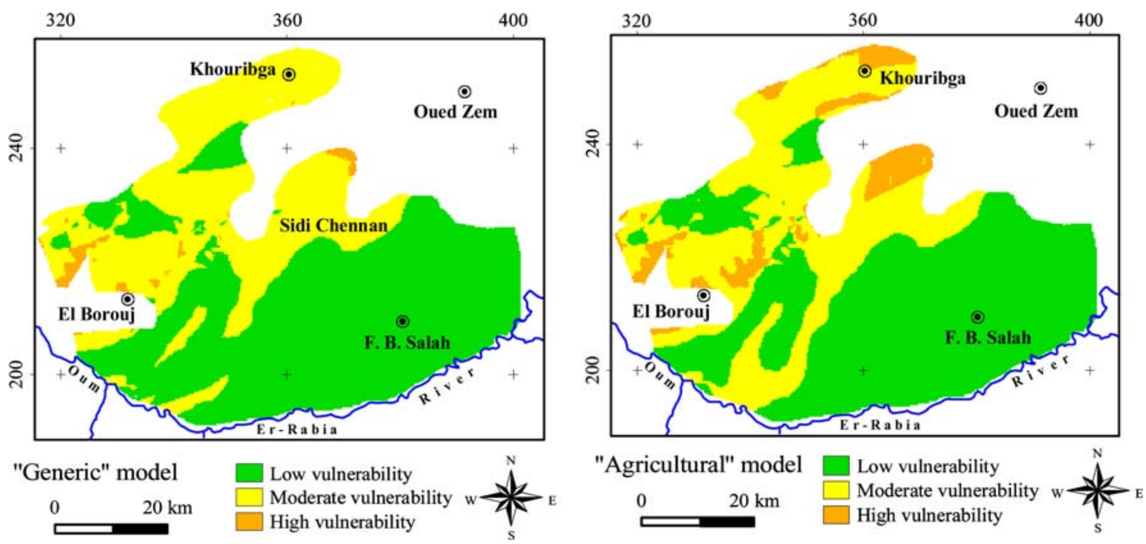

Fig. 4 Vulnerability maps of the Eocene aquifer of Oum Er-Rabia basin, according to ''generic'' and ''agricultural'' DRASTIC models

aquifer in the Oum Er-Rabia basin. Elaborated vulnerability maps thus anticipate areas that are, more than others, threatened by the contamination. The studied aquifer is highly vulnerable in the western part of the basin and the surface proportion of vulnerable zones increases from 1.5% according to the "generic" model to 7.3% when the "agricultural" model is applied. Maps of vulnerability therefore are easy-to-use tools that provide the possibility to take measures of water resources preservation. Points of supervision of the groundwater quality should be localized in vulnerable zones where the pollution threat is the greatest. In addition, the choice of dump-site location should take in consideration the aquifers vulnerability. The use of fertilizers should also to be rationalized and must avoid the degradation of groundwater quality, notably in plains and under absent or weakly differentiated soils.

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