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The combination of the modified DRASTIC and GOD methods for assessing the vulnerability to pollution of the Middle Cheliff aquifer, Algeria

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ABSTRACT

The Middle Cheliff basin (Algeria) is located in an area where groundwater is limited and undergoes excessive withdrawal for water supply, irrigation and industrial purposes. These uses, combined with the scarcity of rainfall, lead to the contamination of the water resources. This study aims to assess the vulnerability to pollution of the Middle Cheliff aquifer by the application of GOD and the modified DRASTIC methods. The use of these methods resulted in the development of two vulnerability maps, which were tested and validated using the distribution of nitrate in the aquifer during May 2012. A comparative study of the two methods based on Kendall's test and the statistical analysis of the different classes of vulnerability revealed that the vulnerability by the modified DRASTIC method is represented by four classes: low, medium, high and very high, with the predominance of the medium class (58.3%). The GOD method also resulted in four classes of vulnerability (low, medium, high and very high), and the medium class is again predominating (74.1%). The analysis of surfaces by classes of both methods revealed that 78.76% of the mapped area has identical indices. The vulnerability maps constitute a tool for water resources management in the Middle Cheliff basin.

Keywords: Alluvial aquifer; Vulnerability; Modified DRASTIC; GOD; Algeria

1. Introduction

In arid areas, groundwater constitutes the major water supply for domestic, agricultural and industrial needs. Environmental concerns related to groundwater generally focus on the impact of pollution and the degradation of quality in relation to human uses, particularly domestic supply. As a result of population growth and industrialization, large amounts of domestic and industrial effluents are discharged in the nearby watercourse, leading to the pollution of groundwater in shallow aquifers [1]. Groundwater vulnerability to contamination, which is a worldwide serious issue [2], is defined as the tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction, at some location above the uppermost aquifer (National Research Council [3]).

Extensive research has been carried out to assess groundwater vulnerability by different methods. The most common methods incorporating the hydrogeological parameters of an aquifer are the DRASTIC index [4,5] and the GOD method [6]. The classic DRASTIC model has been developed basically for studying the unsaturated

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zone of an aquifer. However, instead of assessing only the impact of the unsaturated zone, the modified DRASTIC method is used because it considers the basic hydrogeological parameters that seemed influencing the transport of contaminant from superficial sources to groundwater. This method allows the integration of the impact of fertilization, the type of culture and the agricultural habits. The modified DRASTIC method can be used for agricultural, arid, semi-arid and basaltic regions [2]. This study is carried out in the Middle Cheliff, which is suffering from water scarcity. This area required a large quantity of water not only for farming which is the main activity but also for water supply for a population having an increasing demographic rate.

The Middle Cheliff basin is located in the center of the Cheliff Wilaya (northwestern Algeria), 200 km west of Algiers and about 45 km from the Mediterranean. It extends over an area of 321 km^2 and had a population of about 480,000 as of 2010 [7] (Fig. 1). The climate is semi-arid with annual average rainfall of about 520 mm. The Middle Cheliff contains an important alluvial aquifer exploited mainly for drinking water, irrigation and industrial needs. In recent years, an economic boom, particularly in agriculture, has led to an increased demand for water and resulted in the degradation of water quality [8].

The geological studies [9,10] show that the study area is underlain by two lithologic sequences; the pre-Neogene formations and the Neogene–Quaternary formation (Fig. 2). The pre-Neogene (Lower Cretaceous and Oligocene) formations consist of a thick accumulation of sedimentary rocks unconformably overlying older units. The basin contains three aquifers with different hydrogeological potential (Fig. 3):

- the Upper Miocene limestone, which outcrops along the southern boundary of the valley and lies beneath the alluvium;
- the Pliocene sandstone, which is practically covered by the Quaternary formations and
- the Pleistocene–Quaternary alluvial sediments, which form the embankment of the valley. These sediments include clays and marls with beds of sands, gravels and conglomerates.

This last aquifer, which is the subject of our study, has an average annual water withdrawal of about 15.5 hm^3 [12], of which 64% is for drinking water supply, 31% for irrigation and 5% for industrial purposes (Fig. 4).

The water-table map during low water levels in October 2009 [12] shows that groundwater flow is mainly northeast

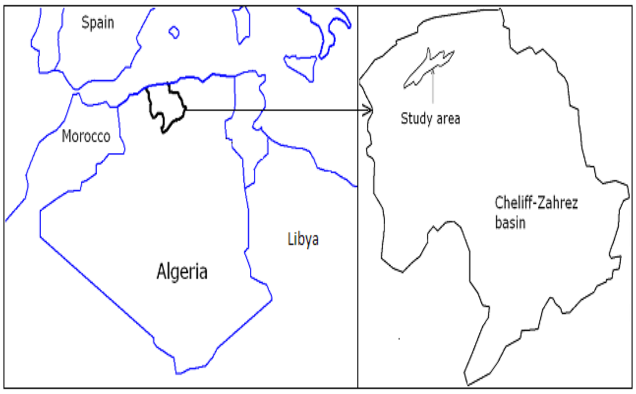

Fig. 1. Situation of study area.

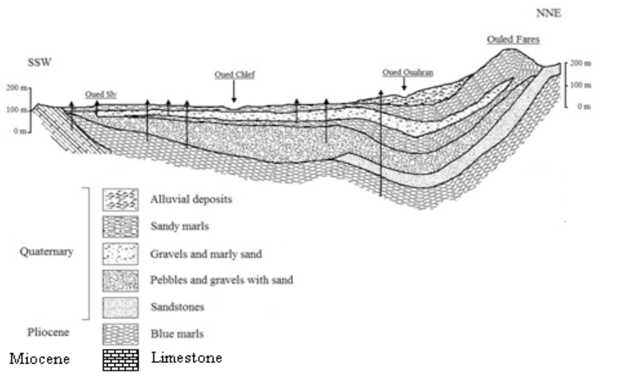

Fig. 3. Geological cross section showing the different aquifers [11].

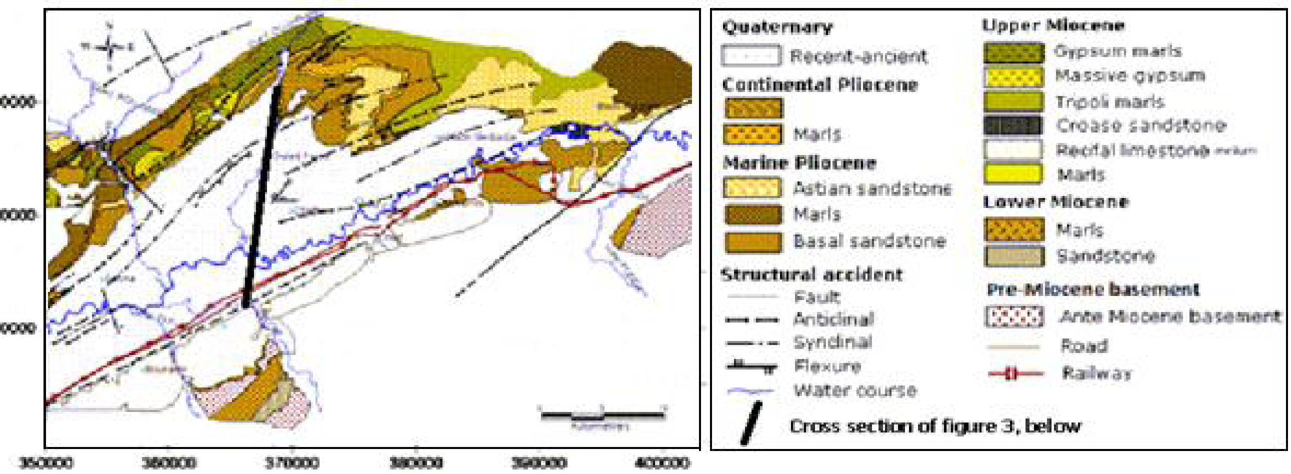

Fig. 2. Geological map of Middle Cheliff basin [9].

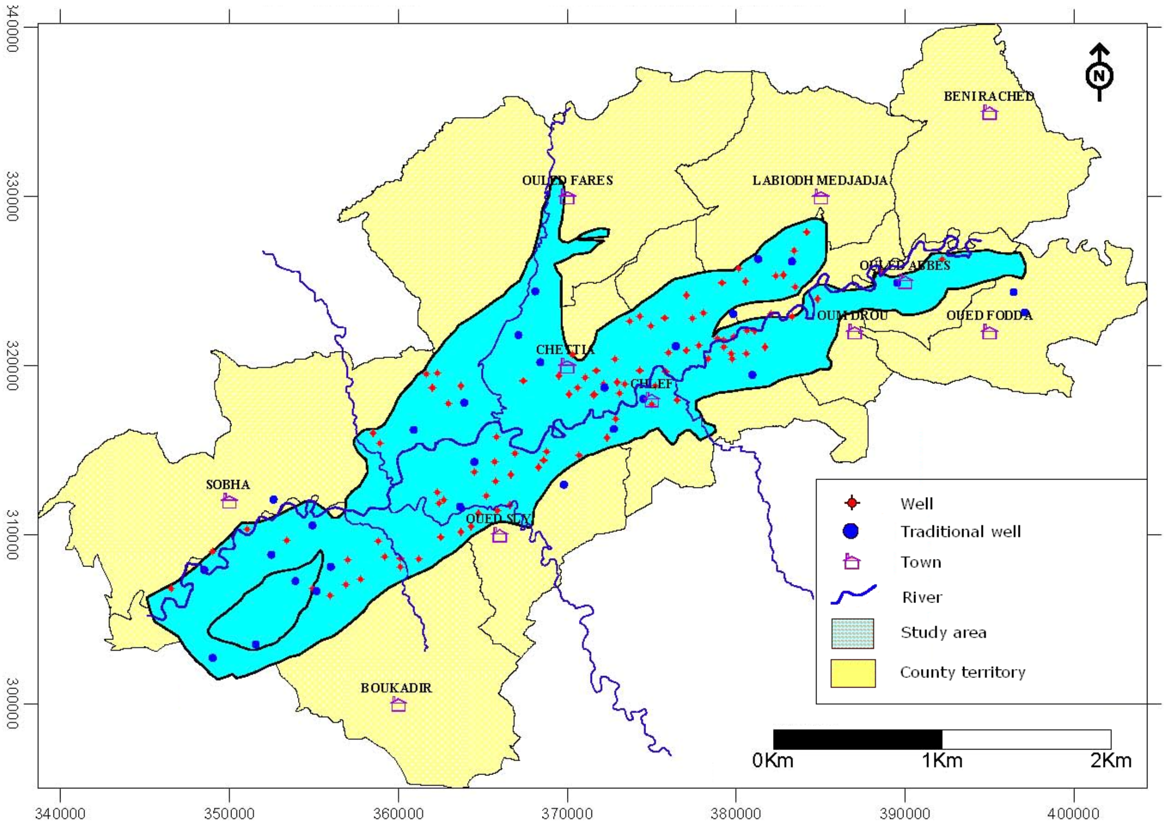

Fig. 4. Sampling sites in the alluvial aquifer [12].

and southwest to the centre of the basin (Fig. 5). The weak recharge does not compensate the aquifer pumping. Nevertheless, some water-level fluctuations are observed in the central part of the area. The high water levels in May 2010 [12] showed almost the same tendency as for October 2009.

2. Materials and methods

The assessment of groundwater vulnerability to pollution depends mainly on the nature, quantity and reliability of the available data [13]. In this study, water samples from 14 deep wells and 61 shallow wells were investigated. The chemical analyses were realized by the ANRH and the ABH-CZ, respectively, the national Agency of Hydraulic Resources and the Cheliff Zahrez Hydrographic Basin Agency.

The assessment of degrees of the intrinsic vulnerability was carried out by applying the modified DRASTIC and GOD methods, taking into account the availability of data related to the required parameters.

2.1. Modified DRASTIC method

Developed for the US Environmental Protection Agency [14], DRASTIC is an acronym created of the first letters of the features used to create the map: depth to the groundwater (D), net recharge (R), and aquifer media (A), soil media (S), topography (T), impact of vadose zone (I) and conductivity of the aquifer (C). These are weighted and ranked, and then are combined to obtain a final ranking value using a groundwater vulnerability algorithm [15]. Each parameter of

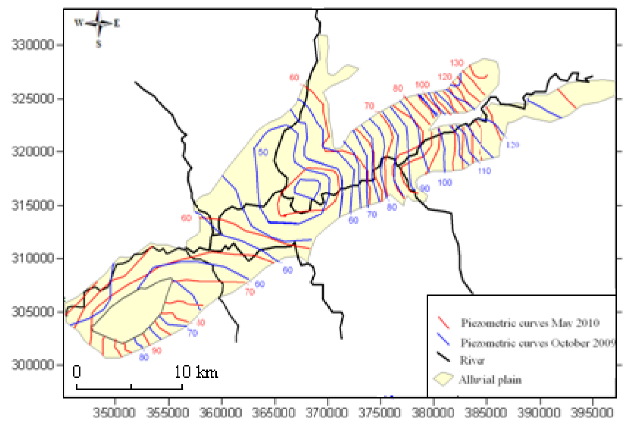

Fig. 5. Water-table map of the alluvial aquifer (October 2009 and May 2010).

this method is divided into intervals with a numerical rating according to its importance in the vulnerability. The modified DRASTIC method, used by Sinan et al. [16], is based on parameters related only to the unsaturated zone, excluding aquifer permeability and lithology. The same notes and weight are considered as those of the DRASTIC method according to Eq. (1):

$$\text{Rev. D} = (\text{Dr} \times \text{Dw}) + (\text{Rr} \times \text{Rw}) + (\text{Sr} \times \text{Sw}) + (\text{Tr} \times \text{Tw}) + (\text{Ir} \pm \text{Iw}) \tag{1}$$

Rev.D, R, S, T, and I represent the modified DRASTIC parameters previously defined, while *r* and *w* represent, respectively, the rating and the weight assigned to each parameter. This method assigns a note from 1 to 10 (Table 1) [17].

2.2. GOD method

A parametric system developed by Foster [6] uses an empirical approach to define aquifer vulnerability with regard to the penetration of pollutant and the attenuation capacity within the unsaturated zone. The approach uses three parameters: the type of aquifer as a function of its degree of containment (*Ci*), the depth of the aquifer (*Cp*) and the lithology of the unsaturated zone (*Ca*) [18]. The ratings assigned to classes of different parameters are ≤1. Mapping the aquifer vulnerability to pollution by this method is operated by the calculation of the GOD index (GI) according to Murat et al. [18] (Eq. (2)):

$$\text{GI} = (Ca \times Cl \times Cd) \quad (2)$$

The ranges of the GI have been implemented in parallel with the vulnerability classes. In general, the GOD indices are divided into five classes of vulnerability, ranging from very low to extreme. The degree of vulnerability increases proportionally with the GI. The classification of the GI map is similar as for the DRASTIC method. For the GOD method, the different classes of vulnerability have been reviewed taking into account the characteristics of the study area. Values from 0 to 1 can be assigned to the parameters (Table 2) [18].

2.3. Statistical calculations and spatial analysis

The comparison of the obtained results by the application of the two methods facilitates the assessment of the vulnerability spatial variations. This comparison has been carried out by the statistical analysis of the surfaces relating to the classes of vulnerability and by the test of concordance and the evolution of the vulnerability indices. The statistical analysis of the surfaces focuses on the number of meshes per class of the maps created using the modified DRASTIC and GOD methods. Nearest neighbor interpolation has been used in the spatial analysis of the modified DRASTIC and GOD parameters. This interpolation selects the closest *n* values to the point of estimation and the partition of the area into polygons. The concordance test involves calculation of the Kendall's *W* coefficient [19], considering the modified DRASTIC method as a reference method. This coefficient measures the degree of concordance of an evaluation between two or more raters having to judge the same phenomenon. This coefficient varies between 0 and 1, and the degree of concordance, which is higher than the *W* coefficient, remains close to 1.

3. Results and discussion

The estimation of the various parameters and their combination resulted in two maps of vulnerability to pollution in the Middle Cheliff aquifer according to each method (Table 3).

Table 1
Attribution of notes for DRASTIC parameters

D (m)	Note	R (mm)	Note	A	Note	S	Note	T (%)	Note	I (m)	Note	C (m/s)	Note
0–1.5	10	0–50	1	Massive shale	2	Thin or absent	10	0–2	10	Silt and shales	3	$1.5 \times 10^{-7} - 5 \times 10^{-5}$	1
1.5–4.5	9	50–100	3	Metamorphic	6	Gravels	10	2–6	9	Shale	3	$5 \times 10^{-5} - 15 \times 10^{-5}$	2
4.5–9	7	100–175	6	Altered sandstone	6	Sands	9	6–12	5	Limestone	3	$15 \times 10^{-5} - 33 \times 10^{-5}$	4
9–15	5	175–225	8	Massive limestone	8	Sandy silts	6	12–18	3	Sandstones	6	$33 \times 10^{-5} - 5 \times 10^{-4}$	6
15–23	3	>225	9	Massive sandstone	6	Silty loam	3	>18	1	Sand and Gravel with passage silt and shales	6	$5 \times 10^{-4} - 9.5 \times 10^{-4}$	8
23–30	2			Sand and gravel	8	Shales	1			Sand and gravels	8	$>9.5 \times 10^{-4}$	10
>30	1			Karstic limestone	10								

Table 2
Attribution of notes for GOD parameters

Aquifer type	Note	Depth (m)	Note	Lithology	Note
None aquifer	0	<2	1	Residual soil	0.4
Artesian	0.1	2–5	0.9	Limon alluvial, loess, shale, fine limestone	0.5
Con-fined	0.2	5–10	0.8	Aeolian sand, siltite, tufa, igneous rock	0.6
Semi confined	0.3	10–20	0.7	Sand and gravel, sandstone, tufa	0.7
Free with cover	0.4–0.6	20–50	0.6	Gravel	0.8
	0.7–1	50–100	0.5	Limestone	0.9
		>100	0.4	Fractured or karstic limestone	1

Table 3
Intervals of vulnerability indices and corresponding classes

Vulnerability indices		Vulnerability classes
Modified DRASTIC	GOD	
<28	0.0–0.1	Very low
20–50	0.1–0.3	Low
50–80	0.3–0.5	Medium
80–110	0.5–0.7	High
110–140	0.7–0.1	Very high

3.1. Vulnerability map by modified DRASTIC method

In order to give more statistical information on the percentage of occurrence of each class of vulnerability, the study area has been divided into a mesh of cells of 542 × 542 m each, following the distribution of different parameters. The resulting grid includes 1,102 cells for a total area of 324.48 km^2. The modified DRASTIC method shows that there are four classes of vulnerability (Figs. 6 and 7):

- The low class, reflecting a weak vulnerability to pollution, covers 22.7% of the mapped area. The weak vulnerability index is due to a relatively impermeable, loamy clay soil in the center of the plain.
- The medium class extends from southwest to northeast and occupies the largest portion (58.3%) of the plain. The medium degree of vulnerability is explained by the lithologic nature of the unsaturated zone, consisting of a mixture of clay, silt and sandy gravels at shallow depths.
- The high class is generally observed in the northwest and northeast of the region of Oued Sly. It represents <6.5% of the study area. The high index of vulnerability may be due to the shallow depth of the aquifer, which ranges between 0 and 15 m with a slope of <2%. The vadose zone is composed of a sequence of clay, sand, pebbles and gravel, facilitating the movement of pollutants.
- The very high class is located in the center-west of the plain to the north of the region of Boukadir and generally follows the trace of the Cheliff stream. This class occupies an area of 12.4%. The shallow depth to groundwater (<9 m) and the low slope (<2%), which promotes infiltration, are the main causes of the very high index value.

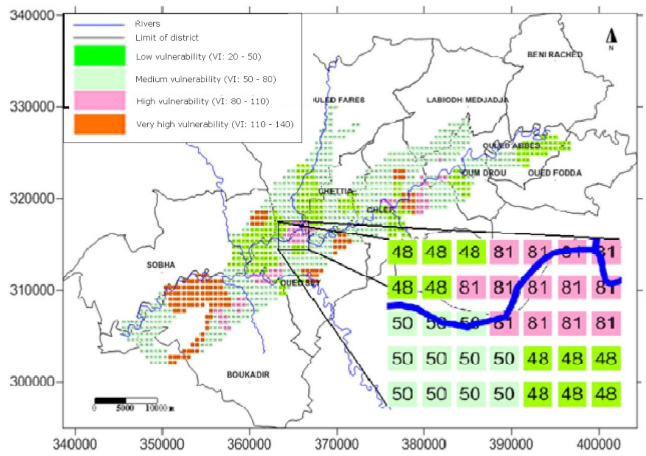

Fig. 6. The aquifer vulnerability to pollution by the modified DRASTIC method.

3.2. Vulnerability map by GOD method

The GOD method results in vulnerability indices ranging between 0.1 and 1.5 and representing four classes, which vary from low to very high (Figs. 8 and 9). The analysis of this map shows the spatial distribution of these classes as follows:

- The low class is located close to the aquifer boundary and occupies 7.8% of the mapped area. The observed weak index of vulnerability is explained by the relatively large depth to water table.
- The medium class occupies a part of the plain extending from south to north and represents the largest proportion of the area (74.1%). The degree of vulnerability is linked to the medium depth of the aquifer and to the vadose-zone lithology, which is composed of alluvial silt with clay interbeds.
- The high class is located in the northwest and the center of the study area (11.1%). The degree of vulnerability is explained by the shallow depth to the water table, which is sometimes at the land surface and the lithology of the vadose zone (clayey sand).
- The very high class occupies 7% of the study area, mainly in the southwest part, with a few isolated blocks in the center and the east. The spatial distribution of this class is explained by the shallow depth to the water table (typically <5 m), the lithology of the unsaturated zone (coarse sand and limestone) and the low slope.

3.3. Validation of the vulnerability maps

The pollution index used in this study is the nitrate (NO_3^-) concentration (mg/L). The selection of this index was because it constitutes the main contaminant generated by

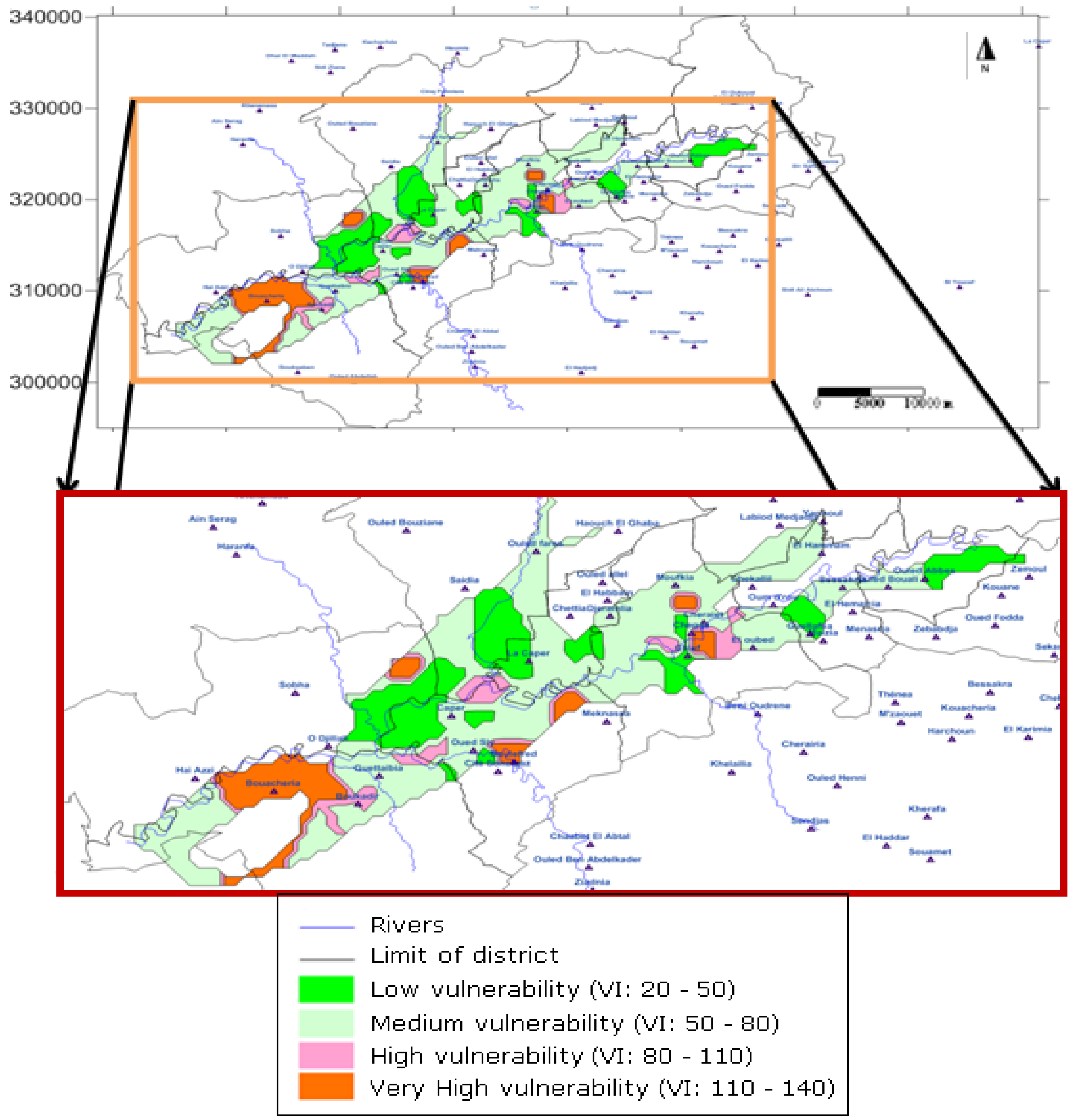

Fig. 7. Map of risk to pollution of the aquifer by the modified DRASTIC method.

human activities in the area of study, and also because it has been considered as a representative indicator of groundwater quality degradation [20]. The high nitrate concentration in the western part is due to in situ surface activity.

The maps established by the modified DRASTIC and GOD methods show that the central and western parts and the boundaries of the plain are the most vulnerable to pollution. However, any map of vulnerability must be tested and validated by measurements and chemical analyses of groundwater [21]. For this purpose, the distribution of nitrate in May 2012 (Fig. 10) was used. The groundwater nitrate concentration in the study area is between 30 and 120 mg/L, and the spatial distribution of this pollutant shows that:

- the relatively low values (<50 mg/L, the WHO guideline for drinking-water quality) coincide with areas of low to medium vulnerability;
- the average concentrations (50–70 mg/L) coincide with the area of medium vulnerability and
- the maximum concentrations of nitrate (>100 mg/L) occur in the western region of the study area, which corresponds to the area of very high vulnerability.

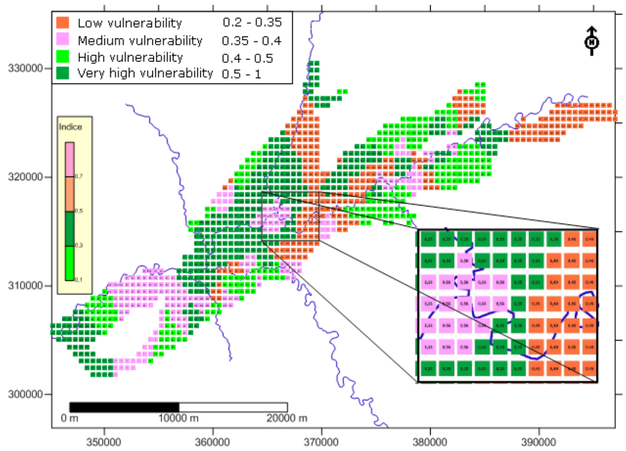

Fig. 8. The aquifer vulnerability to pollution by the GOD method.

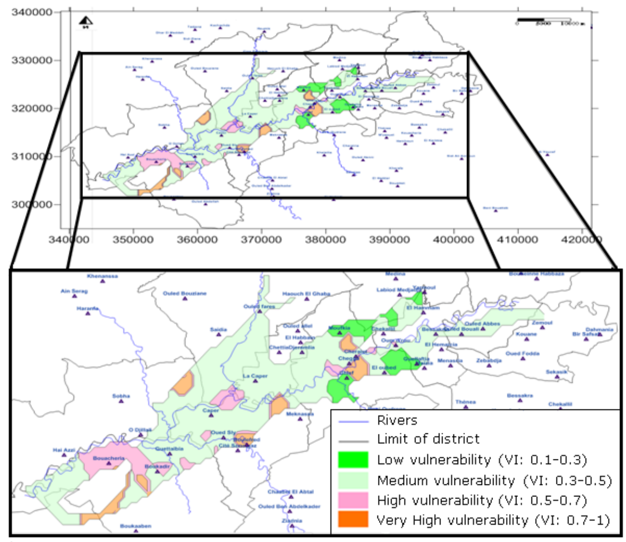

Fig. 9. Map of risk to pollution of the aquifer by the GOD method.

Nitrate concentration generally increases in the aquifer from east to west, which is consistent with the vulnerability maps developed by the two methods.

3.4. Comparison between the two methods of vulnerability assessment

The number of cells by class and method (Table 4) constitutes the basic element of comparison between the two methods of vulnerability assessment. The calculation of Kendall's *W* coefficient yielded a value (0.33) that is positive and therefore interpretable.

The comparison of meshes has been made by subtraction of the two respective vulnerability classes (Table 5). Relative to the modified DRASTIC method, the GOD method tends to underestimate the areas of the extreme classes (low and very high) and overestimate the medium and high vulnerability areas.

By assigning the values 1, 2, 3 and 4 to the different vulnerability classes (low, medium, high and very high, respectively) obtained by the two methods and by crossing those classes, the results given by Table 6 have been obtained. This table shows that the index differences –3, –2, +2 and +3 do not occur in the study area. The index difference of 0 represents the largest portion (78.76%) for the both methods; this confirms the concordance of the two methods as noted by Murat et al. [18].

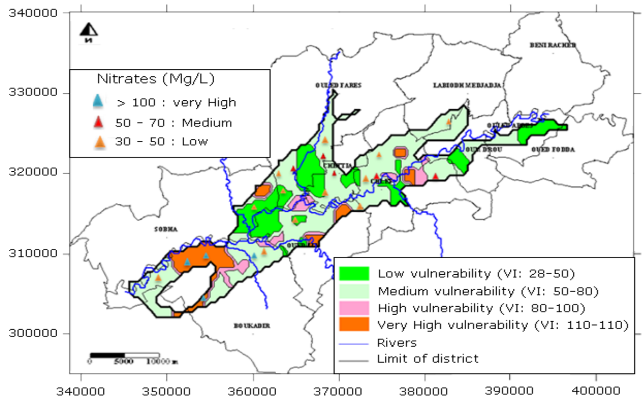

Fig. 10. Distribution of nitrate concentrations (May 2012).

Table 4
Percentages of the vulnerability-class surfaces for modified DRASTIC and GOD methods

Vulnerability classes	Modified DRASTIC		GOD	
	Number of cells	%	Number of cells	%
Low	250	22.7	86	7.8
Medium	643	58.3	817	74.1
High	72	6.5	122	11.1
Very high	137	12.4	77	7.0
Total	1,102	100	1,102	100

Table 5
Comparison of meshes by classes for modified DRASTIC and GOD methods

GOD	Modified DRASTIC				
	Low	Medium	High	Very high	Total
Low	86	0	0	0	86
Medium	164	643	10	0	817
High	0	0	62	60	122
Very high	0	0	0	77	77
Total	250	643	72	137	1,102

Table 6
The surface percentages for differences of indices between the modified DRASTIC and GOD methods

Index difference	–3	–2	–1	0	+1	+2	+3
%	0	0	14.88	78.76	6.35	0	0
Total			14.88	78.76	6.35		

4. Conclusions

Drought and groundwater overuse lead to water excessive pumping inducing the lowering of water table, which in turn tends to increase the vulnerability of aquifers to pollution mainly by return flow of irrigation and wastewater infiltration. This is particularly the case for the Middle Cheliff aquifer of northwestern Algeria. The mapping of the intrinsic vulnerability of this alluvial aquifer by the modified DRASTIC and the GOD methods has resulted in the delineation of four major classes of vulnerability (low, medium, high and very high). The medium class is clearly dominant (58.30% of the study area for the modified DRASTIC method and 74.10% for the GOD method). The modified DRASTIC method seems to be more valid for assessing the vulnerability to pollution, with an agreement of 60% between ranges of observed nitrate concentrations and the different classes of vulnerability vs. 47.2% agreement for the GOD method. Comparison of the obtained classes by the two methods shows that 78.76% of the mapped area is classified equivalently. Although the two maps of vulnerability are relatively close, the modified DRASTIC map seems to better reflect the vulnerability to pollution in the study area. The vulnerability maps should be useful for water resources management in the Middle Cheliff basin.

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