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Assessment of groundwater vulnerability to pollution in an Arid environment

Rabia Slimani[1], Messaouda Charikh[1,2], Mohammad Aljaradin[3]*

[1]Laboratory of Biogeochemistry of desert environments, Faculty of Natural and Life Sciences, Kasdi Marbah University, Ouargla, Algeria
[2]Ouargla Higher Normal School, Algeria
[3]School of Health and Environmental Studies, Hamdan Bin Mohammed Smart University, Dubai, UAE

*Corresponding author's e-mail: ttuetc@yahoo.com

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Abstract: This study focuses on mapping the groundwater's vulnerability to pollution in the region of Ouargla, located in the North-East of the northern Sahara, exposed to potential risks of alteration. By applying the methods (GOD, DRASTIC, and SINTACS), coupled with a Geographic Information System (GIS), we were able to identify a medium to high vulnerability trend. In light of the results recorded, the DRASTIC and SINTACS methods prove to be more suitable for our study region. This makes it possible to highlight the recharge zones and land use as being the most vulnerable in the territory studied. The GOD method presents a strong vulnerability trend over 77.02% of the study area. Such a result is directly related to the depth of the water table. It can therefore be argued that this method is far from being representative of the reality on the ground because of these very heterogeneous characteristics.

Introduction

Water is critical for human systems. Humans have historically implemented water management strategies to utilize water resources to support diverse human activities (domestic, agricultural, and industrial). It provides 50% of drinking water in the world (United Nations, 2022; Qian et al. 2020), and 43% of global consumption for irrigation (Saranya & Saravanan, 2022). Nevertheless, ever-evolving water use patterns have brought about major changes in natural water flows, storages, and quality. These changes pose risks to human health, habitats, ecosystems and their ecosystem services (UNESCO, 2020; Gao et al. 2022).

The quality of groundwater is of particular interest to the international scientific community, which has resulted in a plethora of publications devoted to environmental management and protection (Abunada et al. 2021; Gharekhani et al. 2022). This protection necessitates predicting the risk of pollution threatening this valuable resource by the delimitation of areas likely to be affected by pollution, which are qualified as vulnerable or at risk (Sarkar & Pal, 2021; Gao et al. 2022). In general, the hydrogeological characteristics of a region affect how pollutants interact with one another and migrate through the ecosystem. Therefore, groundwater vulnerability is a result of the interaction between geology and anthropogenic activities, and a spatial knowledge of its distribution is very important in water resource management decision-making (Elzain et al. 2022; Chakraborty et al. 2022; Gao et al. 2022). Thus, mapping groundwater vulnerability has become an essential method for quantifying groundwater resource responsiveness to its surroundings and providing a graphic output for policymaking, planning, and law implementation. The methods for assessing the sustainability of groundwater can generally be divided into three groups: index and overlay, process-based simulation, and statistical modeling methods. The adoption of any one of these methods depends on a number of variables, including the aim and scope of the study, scale, data accessibility, time, cost, and end-user needs. Each of these methods has advantages and a degree of uncertainty (Foster 1987; Goyal et al. 2021). Although process-based simulation models typically take contaminant migration into groundwater systems into account, they have not consistently outperformed the other approaches, frequently because there is not enough information available to mathematically define the processes. To develop statistical correlations between the identified pollution, environmental variables, and land use for vulnerability assessment, statistical modeling methodologies, on the other hand, call for the use of surrogate observations. Therefore, the results of this method can only be used in areas where data is collected and that have similar characteristics that are correlated with the risk of groundwater pollution (Sarkar & Pal, 2021; Chakraborty et al. 2022).

The index and overlay method employs a variety of important factors that have a big effect on controlling groundwater risk in the assessment. These parameters, which frequently represent an aquifer's physical characteristics including water depth and lithology, are mapped from either pre-existing data sets or field data and given subjective numerical values. The rating maps are then spatially integrated to create an output composite map that illustrates the relative vulnerability of a certain location (Foster 1987; Kirlas et al. 2022). This method is frequently used to evaluate vulnerability because it needs less data and provides categorical results. All parameters in basic overlay systems frequently have equal weights. However, in more sophisticated systems, more sophisticated algorithms assign various numerical weights to the parameters based on their contribution to vulnerability. Examples of mostly used models based on the index and overlay approach include DRASTIC, GOD, SINTACS, EPIK, and Aquifer Vulnerability Index (AVI) (Fannakh & Farsang, 2022; Saranya & Saravanan, 2022).

This study which has employed the GOD, DRASTIC, and SINTACS models to comparatively assess the pollution vulnerability of groundwater in the city of Ouargla (Low-Sahara Algerian) is instructive. This region is characterized by a hyper-arid climate and the water shortage is also aggravated by the socio-economic progress which required the mobilization of a great quantity of water from boreholes. The ancestral cultural practice, in particular that of palm dates uses only water from the water table for the irrigation. However, the rapid growth of this huge city has forced the overexploitation of deep aquifer water. The absence of a natural outlet to discharge domestic and agricultural sanitation water terribly threatens its immediate environment and urges researchers to conduct appropriate studies in order to initiate a strategy to combat the degradation of this oasis ecosystem, described as fragile reliefs (Slimani & Guendouz, 2015).

However, there are threats to the water quality in the area due to the increasing use of agrochemicals in crop farming and other unsafe waste disposal practices. Therefore, the generated vulnerability map in this study will aid in educating the populace and the state in establishing land-use policies to effectively manage and protect areas where the groundwater may be highly susceptible to pollution. In addition, it would be a practical, informative tool for developing groundwater resources in the area.

Methodology

Presentation of the study area

Ouargla is part of the Algerian Lower Sahara. It corresponds to a large depression with an area of approximately 990 km^2 and lies between 31°58'02"N latitude and 5°19'37"E longitude, with an average altitude of 134 m (Fig. 1).

From a climatic point of view, it belongs to the arid Mediterranean type. Precipitation is irregular with an annual average of 43.6 mm. The average annual temperature is 23.67°C. With a mean speed of 11.34 m/s, the winds, and notably the sandstorms, have a particularly drying function. The average monthly evaporation is 272.32 mm, and the mean humidity is 40.24%.

Geologically, the study location is composed of sedimentary formations. The Continental Terminal, a continental formation composed primarily of sands deposited and solidified in a hot, semi-arid climate during the Pontian Miocene or Lower Pliocene, was deposited on the Upper Senonian or Middle Eocene flint limestone and marls.

The hydrographic network of the Ouargla basin is sparse and consists of a fossil wadi called Wadi Mya and two functional wadis called Wadi N'sa and Wadi M'zab. All these wadis have a temporary flow (Slimani et al. 2017).

The aquifer system of the Ouargla region is made up of three units: the Continental Intercalary aquifer, the Complex Terminal aquifer, and the groundwater, whose level is often close to the surface, generally between 1 and 2 m, but it can exceed 18 m south of Ouargla or under the reliefs (Slimani & Guendouz, 2015).

Sampling and analysis

Groundwater samples were collected in March 2022 from a monitoring network consisting of 106 sampling points (Fig. 1). The samples were filtered through a Millipore filter (0.45 μm) and then analyzed for nitrate concentration adopting the cadmium reduction method, using a spectrophotometer (Hach, DR 5000).

Soil samples were also collected from 57 sites, covering the whole range of the Ouargla topsoil types. The samples were collected using a 2.5-cm diameter tube. The analyses were carried out at the laboratory of Biogeochemistry of Desert Environments, the University of Ouargla.

All required data examined are interpolated using the inverse distance weighting (IDW) method in ArcGIS 10.8.

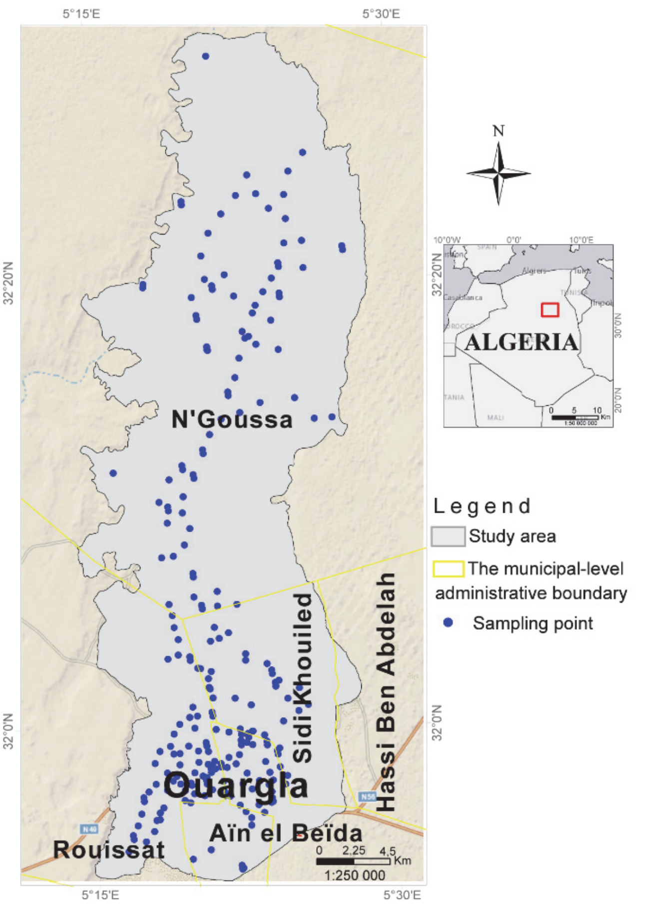

Fig. 1. Location of the study area

Vulnerability method

In this research, the methodological framework for evaluating groundwater vulnerability indices models is shown in Fig. 2.

GOD's method

The GOD method for determining groundwater vulnerability is basically divided into three general categories, namely process method based on simulation, statistical method, and overlapping method.

The GOD method is a simple, practical, and experimental approach that gives a quick assessment of the contamination sources (Foster 1987; Kirlas et al. 2022). The GOD calculates the vulnerability index of aquifers in response to contaminations using four indices, including the type of aquifer (G), lithology of the unsaturated zone (O), and water table depth (D) (Tab. 1). Vulnerability increases with the index and the classification is done in five categories, ranging from 0 to 1 (Fannakh & Farsang, 2022).

The vulnerability index is calculated as follows: $IGOD = G \times O \times D$

DRASTIC's method

This mapping method's purpose is to estimate the potential for groundwater pollution. This method has seven parameters: [D]: Depth to water, [R]: Net Recharge, [A]: Aquifer media, [S]: Soil media, [T]: Topography, [I]: Impact of vadoze zone, [C]: Hydraulic Conductivity of the aquifer (Abunada et al. 2021; El Baba & Kayastha, 2022). It is a matter of designating a numerical value for each parameter from 1 to 5 which will correspond to the weight and which increases according to the importance of the parameter in the estimation of vulnerability (Sarkar & Pal, 2021; Gharekhani et al. 2022). Then, these layers are superimposed to produce a resulting layer where the DRASTIC vulnerability index (ID) will be calculated (Tab. 2). Each of the parameters is associated with a depth varying from 1 to 10, defined according to the intervals of the values (Goyal et al. 2021). The lower depth

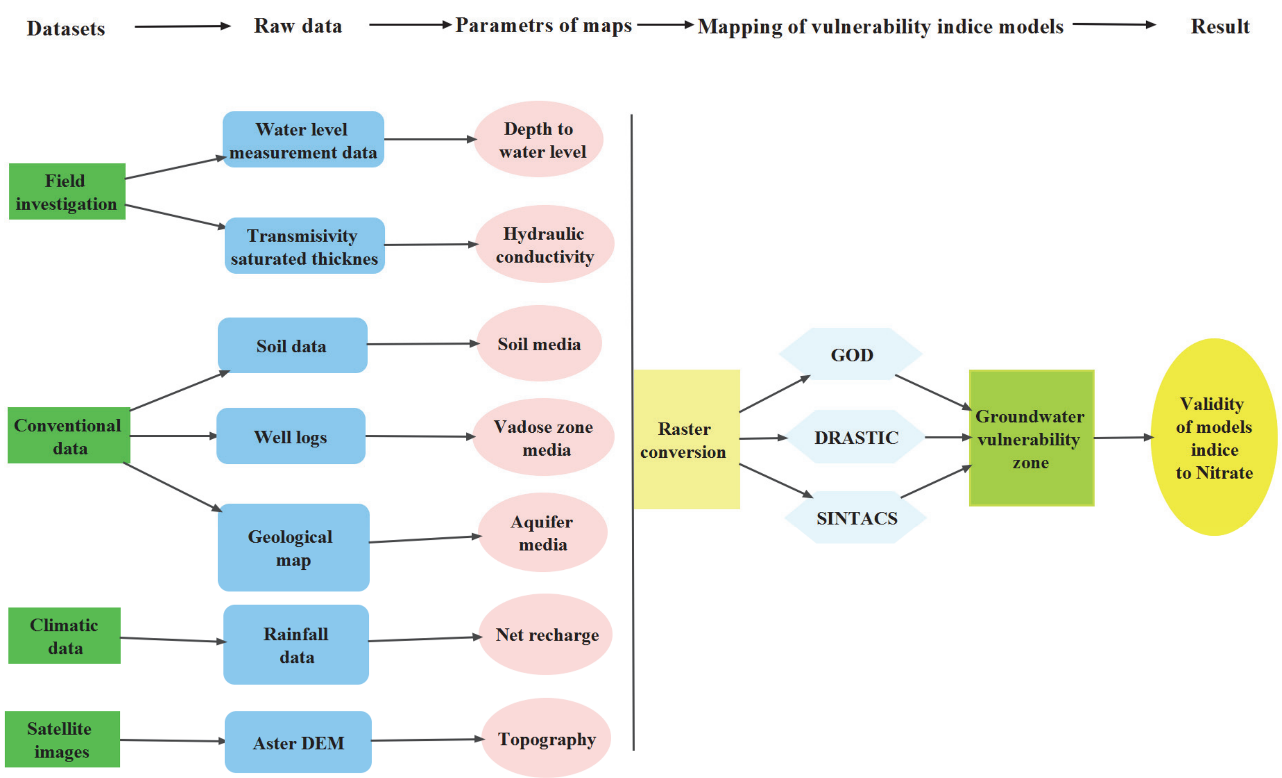

Fig. 2. Study method framework applied in the present work

Table 1. Range and rating values used in GOD model

Type of aquifer (G)		lithology of the unsaturated zone (O)		Depth of Water (D) (m)	
No aquifer	0	Residual soil	0.4	< 2	1
Aquifer confined and artesian	0.1	Alluvial silt, clay, marl, fine limestone	0.5	2–5	0.9
Confined and non-artesian aquifer	0.2	Wind, silt, tuff, igneous rock, and fractured metamorphic	0.6	5–10	0.8
Semi-Confined Aquifer	0.3	Sand and gravel, sandstone, tuff	0.7	10–20	0.7
Aquifer with fairly permeable cover	0.4–0.6	Gravel (colluvium)	0.8	20–50	0.6
Unconfined aquifer	0.7–1	Limestone	0.9	50–100	0.5
		Fractured or karst limestone	1	> 100	0.4

represents conditions of lower vulnerability to contamination (Hamza & Chmit, 2022; Chakraborty et al. 2022).

$$IDRASTIC = D_R \times D_W + R_R \times R_W + A_R \times A_W + S_R \times S_W + \\ + T_R \times T_W + I_R \times I_W + C_R \times C_W$$

Where: subscript R is the rate value and W is the weight assigned to each parameter.

SINTACS's method

The SINTACS method is the Italian version of the DRASTIC method. This intrinsic vertical vulnerability method takes into account the same parameters as the DRASTIC method (Awawdeh et al. 2020). The specificity of this method compared to the DRASTIC method is that it offers five different vulnerability scenarios: normal impact, severe impact, heavy drainage from a superficial network, highly karstified terrain and cracked terrain (Tab. 3). A weight between 1 and 5 is assigned to each parameter, and each parameter is classified into several classes, each of which is associated with a rating ranging from 1 to 10 (Hamza & Chmit, 2022; Kirlas et al. 2022). Unlike the DRASTIC method, the SINTACS method makes it possible to use, at the same time and in different cells, variable weights depending on the situation (Goyal et al. 2021).

Results

Parameters Thematic Mapping

Depth of groundwater (D)

The piezometric map (Fig. 3a) shows that the flow is mainly from south to north. In the area north of N'Goussa assisted by Sebkhet Safioune, the depth of the water table fluctuates

Table 2. Range and rating values used in DRASTIC model

Depth of Water (D) m		Net Recharge (R) mm/yr		Aquifer Media (A)		Soil Media (S)		Topography (T) %		Impact of Vadose Zone (I)		Hyd. Conductivity (C) mm/ day	
0–4.5	10	< 50	1	Massive shale	2	Thin or Absent, Gravel	10	0–2	10	Confining layer	1	< 4	1
1.5–4.5	9	50–100	3	Metamorphic/ Igneous	3	Sand	9	2–6	9	Silty/clay	3	4–12	2
4.5–7.5	8	100–175	6	Weathered/ metamorphic	4	Peat	8	6–12	5	Shale	3	12–30	4
7.5–10	7	175–250	8	Igneous		Shrinking and/or	7	12–18	3	Limestone	6	30–40	6
10–12.5	6	> 250	9	Glacial Till	5	aggregated clay		> 18	1	Sandstone, Bedded	6	40–80	8
12.5– 15	5			Bedded sandstone,	6	Sandy loam	6			Limestone	6	> 80	10
15–19	4			limestone, shale		Loam	5			Sandstone, shale, sand	4		
19–23	3			Massive sandstone,	7	Silty loam	4			and gravel			
23–30	2			massive limestone		Clay loam	3			Metamorphic/ Igneous			
> 30	1			Sand and gravel	8	Muck	2			Sand and gravel	8		
				Basalt	9	Non-shrinking and	1			Basalt	9		
				Karst limestone	10	non-aggregated clay				Karst limestone	10		
weight	5	weight	4	weight	3	Weight	2	weight	1	weight	5	weight	3

Table 3. Weighting scenarios in SINTACS Method

Weighting Scenarios	S	I	N	T	A	C	S
Normal impact	5	4	5	4	3	3	2
Relevant impact	5	5	4	5	3	2	2
Drainage from surficial network	4	4	4	2	5	5	2
Karstic impact	2	5	1	3	5	5	5
Fissuring impact	3	3	3	4	4	5	4

between 0.5 to 2 m. at the South of N'goussa and up to the limit of Bour el Aïcha, it is between 2 m and 4 m.

In the axis of Bour El Haicha / Bamendil, we notice that the level of the water table is submerged compared to the north and varies between 5 and 16 m. for the East of Ouargla agglomeration (between Chott and Aïn el Beïda) we noted that the level of the water table varies from 0 to 1 m. Finally, in the city of Ouargla, the water level of the water table varies between 1 and 3 m in the center of the agglomeration and it does not exceed 2 m on the western periphery.

The hydraulic gradients are well correlated with the topography of the land. The regions in which the water table is the deepest correspond to high points of the topography (Fig. 3a) west of Bour El Aicha, south-east of Sebkhat Safioune and in the extreme north-west of study zone. The shallower points are located southwest of Ouargla, south of Oum er Raneb, northwest of N'Goussa. The shallowest depth was measured near Chott.

The unsaturated zone

This parameter does not represent the same phenomenon for the three methods. In the case of the DRASTIC and SINTACS methods (Bera et al. 2021; Parthasarathy et al. 2022) it is a question of qualifying the environment overcoming the saturated zone of the aquifer, whereas for the GOD method, it is a question of describing this environment according to its degree of consolidation (Fannakh & Farsang, 2022; Saranya & Saravanan, 2022).

The development of the aquifer type map was based essentially on the interpretation and correlation of more than 400 boreholes drilled in the study area (ANRH, 2018; 2022). These correlations show that the aquifer is essentially formed by sandy facies (Fig. 3b). Therefore, the unsaturated zone promotes the movement of pollutants to the water table.

Soil type

The soil types map (Fig. 3c) in the study area was drawn up by digitizing the soil map produced by (Hamdi-Aïssa & Girard, 2000). This parameter is obtained by listing different types of soil according to the soil classes defined by the DRASTIC method.

The study area is made up of sandy-clayey soil, rarely coarse at the south of Ouargla. In the north (N'goussa and Sebkhet Safioune), the sands are rich in gypsum, which becomes dominant at Sebkhet Safioune.

Topography

The topographic coverage of the Ouargla basin is obtained from the digital terrain model (DTM) at 30 meters (Fig. 3d). One of the morphological particularities of Ouargla lies in its low relief, with low slopes of slightly less than 1‰, which is not constant, from which we note the presence of two large sectors (Fig. 3e):

– Low slope areas: South of Bamendil towards Oum er Raneb and after the threshold of N'goussa to the banks of Sebkhet Safioune.
– Medium slope areas: west of the Hamada Pliocene plateau, east of the Erg (Erg Touil and Erg Arifdj) and to the northwest at Hassi el Khefif.

The recharge

In this work, the recharge was calculated using the equation of Williams and Kissel (1991) in (Griffel, 2022). The map obtained showed the existence of three classes of efficient recharge (Fig. 3f). The recharge via the irrigation of Ouargla's palm presents a value of 182.2 mm/year (Charikh et al. 2022). It is useful to specify that the recharge via irrigation presents values that differ according to the localities and the seasons (Slimani & Guendouz, 2015). However, the values were recorded during the winter season between a minimum of 89.67 mm/year at the Beni Ouaguine's palm and a maximum of 249.81 mm/year at the Adjadja's palm. For the summer period, a minimum value of 118.71 mm/year was recorded at the Beni Ouaguine's palm; and a maximum value of 316.86 mm/year at the ITAS's exploitation. The urban area experiences a recharge of up to 128.6 mm/year. The recharge on the sebkha and the Chott areas is varied, from a minimal value of 50 to 250 mm/year on most of the surface up to relatively large values of 262.5 mm/year on Sebkhet Safioune.

It should be noted that the recharge values obtained constitute a regional approximation, the result may vary depending on the quality of the data and the methods used.

The hydraulic conductivity

The resulting map of this parameter (Fig. 3g) reveals a very high uniformity of ratings throughout the territory. The spatial variability of groundwater hydraulic conductivity shows two classes. The first varies between 0.04 and 4 m/d and covers 62% of the total surface. The second oscillates between 4 and 12 m/d, is located in the Chotts and Sebkhas, and covers 38% of the study area.

Aquifer types

For this parameter in the GOD method, it is the degree of confinement, while for the DRASTIC and SINTACS methods, it is the nature of the materials present (Kirlas et al. 2022).

Vulnerability index

The vulnerability index varies from one method to another as shown in the Figure (5.a). It fluctuates between 0.34 and 0.51 for the GOD method, between 127 and 188 for the DRASTIC method, and between 113 and 158 for the SINTACS method. The average index is 0.46, 166.91 and 141.68 for the GOD, DRASTIC and SINTACS method successively.

Presentation of the vulnerability maps obtained

The vulnerability study to water pollution of the groundwater in the Ouargla region indicates potential risks of contamination (Fig. 4). This information is similarly revealed by the three methods used, where two vulnerability categories are distinguished but with different occupancy rates.

GOD method's Vulnerability map

The superposition of the three thematic maps recommended by the GOD method, allowed us to establish an intrinsic vulnerability map whose index varies from 0.1 to 0.7 Based on classification (Kirlas et al. 2022), four categories have been developed (Fig. 5b).

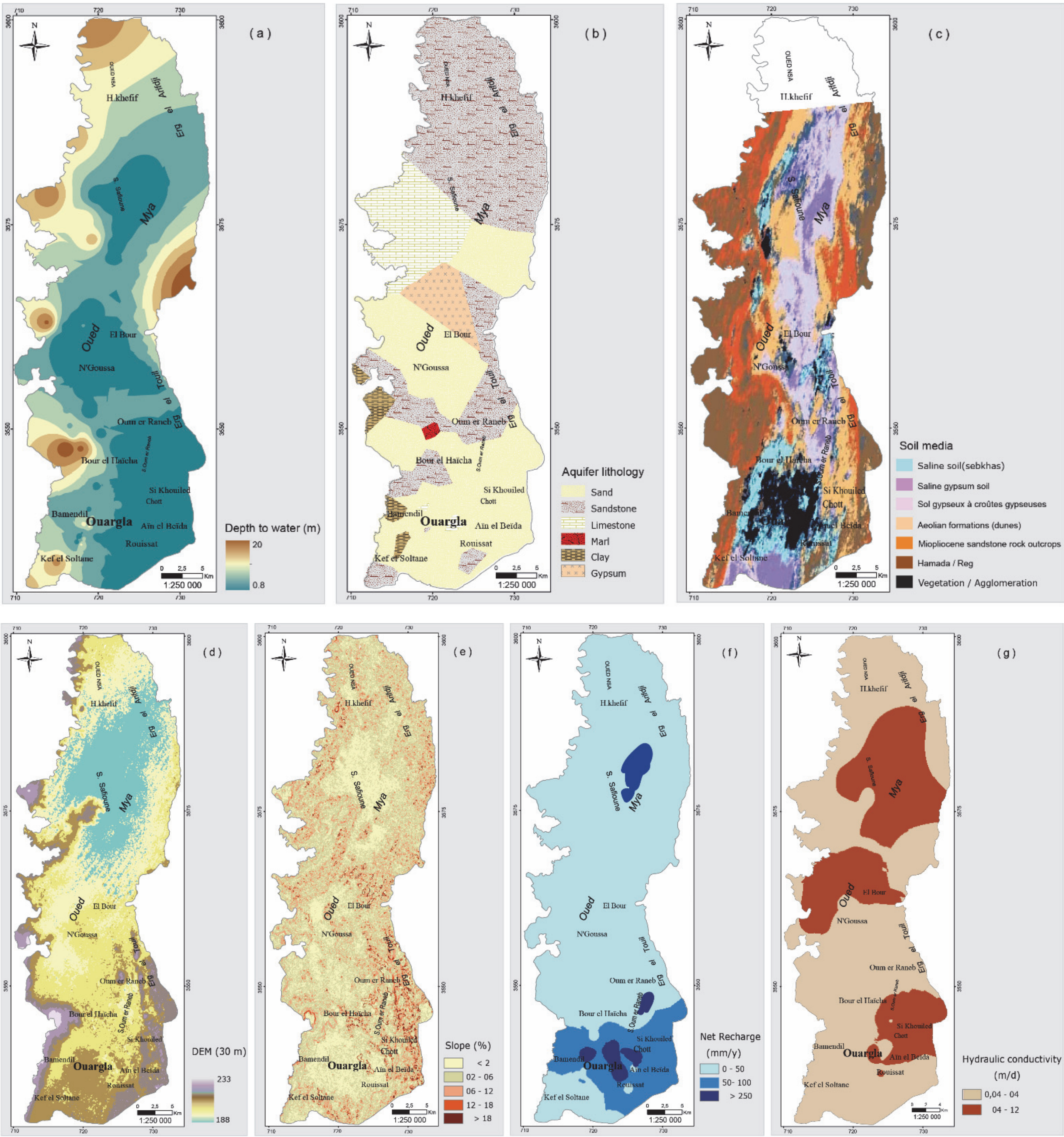

Fig. 3. The thematic maps of method's models parameters: (a) depth to water, (b) aquifer media, (c) soil media, (d) digital terrain model, (e) slope, (f) net recharge, and (g) hydraulic conductivity

- Very low vulnerability category, occupying an area of 17.59%. It is located to the south at Kef Soltane, at the western edge of the basin, to the southeast at Sidi Khouiled, and to the north of Hassi Khefif.
- Low vulnerability category, occupying 36.76% of the study area.
- The moderate vulnerability category occupies an area of 41.83% of the aquifer studied surface. It is located at the level of Ouargla, Oum er Raneb, Rouissat, and N'Goussa.
- The high vulnerability category occupies an area of 3.82% and is dispersed in belts like the sebkhas of Oum er Raneb, Safioune and Chott.

DRASTIC method's Vulnerability map

The DRASTIC vulnerability map presents an index ranging from 89 to 154. Based on classification (Kirlas et al. 2022), three categories of vulnerability are distinguished (Fig. 5b).

– Low vulnerability areas cover an area of 40.34% of the study area. They are located in Kaf Soltan, Bour el Haïcha, and Hassi Khefif.
– Moderate vulnerability areas occupy 38.98% of the total study area. They are located at the downstream end of the basin, in the center, and on the northeast edges. They extend mainly to Sidi Khouiled, N'Goussa, and El Bour.
– High vulnerability areas with approximately 20.68% of the total aquifer surface. They are mainly located in downtown Ouargla, Bamendil, Rouissat, Aïn el Beïda, Chott, Oum er Raneb and part of Sebkhet Safioune.

SINTACS method's Vulnerability map

In Ouargla, the SINTACS method is characterized by three scenarios (normal impact, severe impact, and significant drainage). The use of this method in an urbanized area caused some difficulties.

Particularly in the evaluation of some parameters related to infiltration, the difficulty comes from the fact that the area is highly urbanized. The vulnerability index varies between 100 and 196. The vulnerability map obtained (Fig. 5c) shows the existence of three degrees of vulnerability.

– The low vulnerability zones occupy 15.88% of the total aquifer surface. They are located in Kef Soltane and the northwest of Bour el Haïcha.
– The moderate vulnerability zones occupy 39.07% of the total study area. They occupy the regions of Sidi Khouiled, Bour el Haïcha, N'Goussa, El Bour, and the northern part of Hassi Khefif.
– The high vulnerability zones cover an area of 45.05%. This category concerns the city center of Ouargla, Bamendil, Rouissat, Aïn el Beïda, Chott, Oum er Raneb and Sabkhet Safioune. Most of these areas correspond to urban or agricultural land, which also increases the risk of groundwater pollution. The distribution of these categories is essentially governed by land use (industrial and urban installations, vegetation type, and surface water canalization). This is a factor that influenced the final result as much as the other parameters.

Validation of water pollution vulnerability maps

Several authors (Zhang et al. 2021) have verified the method's validity for assessing vulnerability to pollution based on groundwater chemical data. The assessment validity of the vulnerability to groundwater pollution by the three methods was tested by measuring the nitrate rate (Elzain et al. 2022).

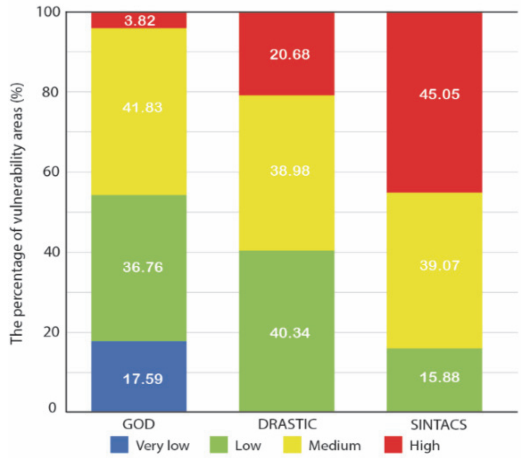

Fig. 4. Percentage of vulnerability class areas (%) by different method

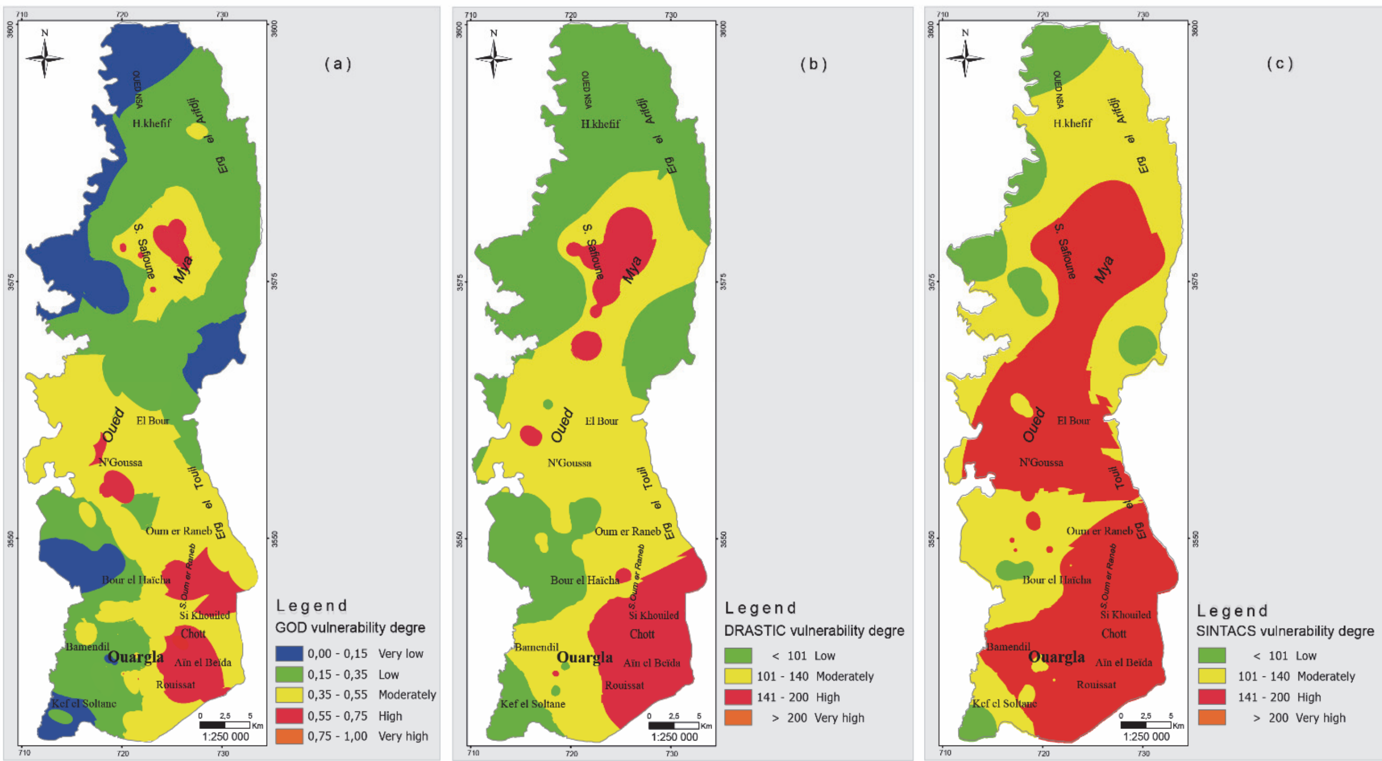

Fig. 5. Vulnerability index maps of (a) GOD, (b) DRASTIC, and (c) SINTACS

These water analyses concern 67 samples distributed equally over the study area. The map resulting from these data (Fig. 6) reveals that the groundwater has a nitrate rate varying from 0.7 to 98.7 mg.l^{-1}. According to Stigter et al. (2006), these concentrations should be classified into two groups. The first group includes low concentrations of nitrates below 50 mg.l^{-1} and the second group contains the highest concentrations. In our case, we identified 41 samples belonging to the first group, while the second contained 26 samples.

The comparison of different vulnerability maps with the nitrate values in the water table's water allowed us to demonstrate that the most valid map for evaluating pollution vulnerability due to nitrates in our region is that given by the SINTACS method, with a coincidence rate of 56.81% between available nitrate concentrations and the different vulnerability classes. The DRASTIC vulnerability map shows a coincidence rate of 32.17%, and a rate of 11.02% for the GOD vulnerability map. Therefore, the areas of high vulnerability (downtown Ouargla, Bamendil, Rouissat, Aïn el Beïda, Chott, Oum er Raneb and Sabkhet Safioune) highlighted in this study deserve special attention for protection.

Discussion

The comparative study, conducted by the GOD, DRASTIC and SINTACS methods, showed that the first method (GOD) gives more detailed information for the representation of vulnerability, since the resulting map consists of four classes; by contrast, the DRASTIC and SINTACS methods give only three classes (Figure 5.b).

Fig. 6. Nitrate concentration in groundwater

Another point worth noting is that the amount of information acquired by the GOD method is not sufficient enough to understand the functioning of aquifer systems in Ouargla because this method uses only three parameters, against seven parameters for the DRASTIC and SINTACS methods. The DRASTIC and SINTACS methods make it possible to obtain finer information at the level of the representation of the vulnerability compared to the GOD method. This finesse in the quality of the information that was obtained and observed between the different methods is exclusively linked to the multiplication of the parameters and the weighting assigned to each of them.

The results indicate that the water table in the Ouargla region is quite threatened by pollution. The same degrees of vulnerability are determined by the three methods used, with different areas, which are the low degree, the medium degree, the high degree and the very high degree except for the very low degree which was not deducted than with the GOD method. The vulnerability map obtained by the GOD method shows that the depth of the water table is the determining parameter of vulnerability because the other parameters are homogeneous throughout the region studied.

The vulnerability classes obtained by the DRASTIC method are substantially identical to those observed by the SINTACS method. The difference in the covering surface obtained between the three vulnerability zones could be justified by the urban occupation and the type of soil. The latter is more important at the level of the SINTACS method, with a rating of 4 against 2 for the DRASTIC method.

These results show that the depth of the aquifer does not reflect their real degree of vulnerability because there are places where the depth of the aquifer is < 1.5m and the aquifer is moderately vulnerable such as the south-east of the region and places where the depth of the water table is average but the degree of vulnerability is high, which is due to the occupation of the soil by the sources of pollution.

Similar results were obtained by Hamza & Chmit (2022) during the study of diffuse agricultural pollution of a semi-arid region (north-eastern Tunisia), by Awawdeh et al. (2020) in Wadi Shueib, (Jordan) and by Bera et al. 2021 and Chakraborty et al. (2022) for the water table of Dwarakeshwar river basin (West Bengal, India).

Conclusion

The study highlights the critical concern of groundwater quality in Ouargla, an arid region experiencing high water table pumping and decreasing rainfall. To accurately assess the intrinsic vulnerability of groundwater to pollution, three methods (GOD, DRASTIC, and SINTACS) were applied, resulting in vulnerability maps that identified four classes for GOD and three classes for DRASTIC and SINTACS. The analysis showed that low vulnerability zones are generally observed in sectors with impermeable sandstone vadose zones, while medium vulnerability zones are found in coarse sands. High vulnerability zones are associated with a shallow water table depth, high recharge, and very permeable soil. Comparing the vulnerability maps with nitrate values showed that the SINTACS model is the most suitable approach for Ouargla's regional conditions, as it considers land occupation, a crucial factor in determining groundwater vulnerability. In contrast, the GOD and DRASTIC methods only consider parameters that affect pollutant movement from soil to the water table and provide relatively homogeneous vulnerability estimates, making it challenging to accurately assess groundwater vulnerability. Therefore, the SINTACS method is recommended for creating aquifer protection zones and making land management decisions.

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