

Determination of Groundwater Vulnerability Using the DRASTIC Method in Ouargla Shallow Aquifer (Algerian Sahara)

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ABSTRACT

Groundwater is the main source for many uses around the city of Ouargla. In this study, the DRASTIC method was used to assess the vulnerability of the groundwater aquifer. Seven hydrogeological parameters of the model (D water depth, R efficient charging, A aquifer type, S soil type, T topography, I unsaturated zone and C hydraulic conductivity) were measured and mapped. The intrinsic vulnerability map of the shallow aquifer, using the DRASTIC method, shows a high to very high vulnerability to pollution; 91.6% of the study area has high vulnerability, 8.4% of it has very high vulnerability. The comparison of the DRASTIC maps with the land use map illustrates that the agglomerations and irrigated areas are the most vulnerable areas to pollution, due to the low depth of the aquifer and the infiltration of significant domestic and irrigation wastewater. The results show that the relationship coefficient between the DRASTIC index and nitrate concentration is $R = 0.73$. This indicates that the groundwater vulnerability mapping by using the DRASTIC method can be applied for sensible groundwater resources management and land-use planning in the study area.

Keywords: Ouargla, shallow aquifer, vulnerability, DRASTIC, land-use.

INTRODUCTION

The region of Ouargla has long suffered from the shallow aquifer water upwelling phenomena. This increase is largely due to the overexploitation of deep aquifers to meet the needs of irrigation and drinking water supply, and the direct discharge into the shallow aquifer of wastewater without treatment. In addition, natural constraints, such as the almost flat topography and the absence of an effective natural outlet, have accentuated the phenomenon of upwelling.

In the investigated area, numerous sources of groundwater contamination have been identified (Zeddouri, 2008; Bouselsal, 2017), such as

the infiltration of domestic wastewater under the settlements and the excessive use of fertilizers in the agricultural areas. These multiple pollutants alter the quality of groundwater, if conditions are favorable. This paper presents a pollution vulnerability assessment using the DRASTIC approach. The aim was to create an effective model for the sustainable management and protection of groundwater resources in the study area.

PRESENTATION OF THE STUDY AREA

The Ouargla basin is located in a depression of Oued Miya (Algerian Sahara), delimited

by UTM coordinates: $X = 710000/730000E$ and $Y = 3\,530000/3600000N$. The surface of the study area (Fig. 1) is approximately 700 km² and it has a population of about 297,696 inhabitants. The climate of the region is Saharan type, characterized by weak and irregular rainfall (62.40 mm/year). There is a significant difference in temperature with a monthly average of about 24.74°C and a very high evaporation (2758.80 mm) (NOM, 2007–2018).

The Ouargla basin is part of the Saharan platform (Busson, 1970; Slimani et al., 2017). The latter is an asymmetric syncline emerged by sediments of several thousand meters, in the center of the basin, ranging from Primary to Quaternary.

At the surface of the investigated area, only Quaternary and Mio-Pliocene geologic layers are visible. The well data show that the geological trainings contain three aquifer layers (UNESCO, 1972; OSS, 2003). These are, from bottom to top (Fig. 2): the intercalary continental (CI) aquifer, the complex terminal (CT) aquifer and the shallow

aquifer. The latter is made up of detrital formations of Quaternary age represented by sands, sandstones and gravels with the presence of gypsum.

The piezometric map established in May 2017 (Fig. 3) shows that the direction of flow of the water table is from South-West to North-East. The isohypses curves are relatively close with a concavity oriented to the South-West; its concavities indicating a surplus of water resulting from the infiltration of wastewater under the city of Ouargla and the infiltration of irrigation water under the agricultural areas (Bour Elhaicha and Ain Moussa).

MATERIALS AND METHODS

DRASTIC model

The DRASTIC method (Aller et al., 1987; Bouselsal et al., 2015) is a method with super

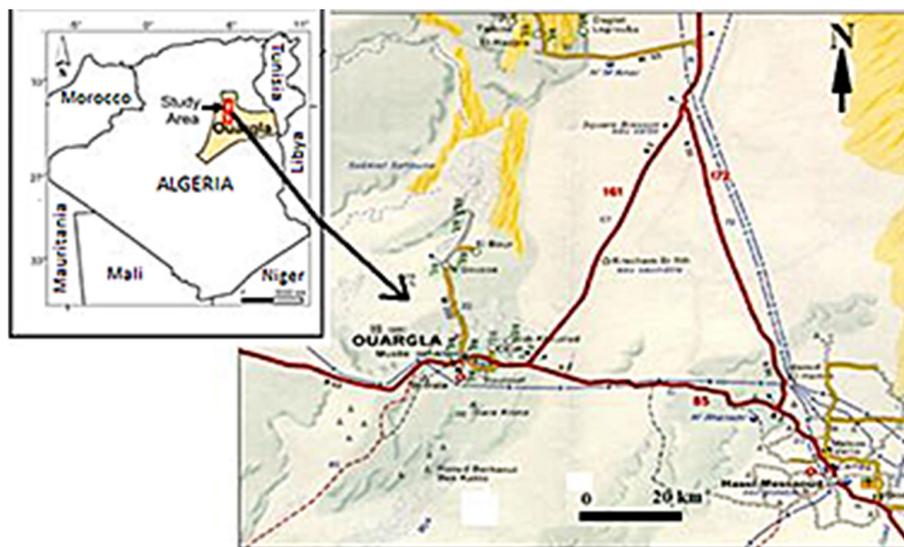


Figure 1. Geographic situation of the study area

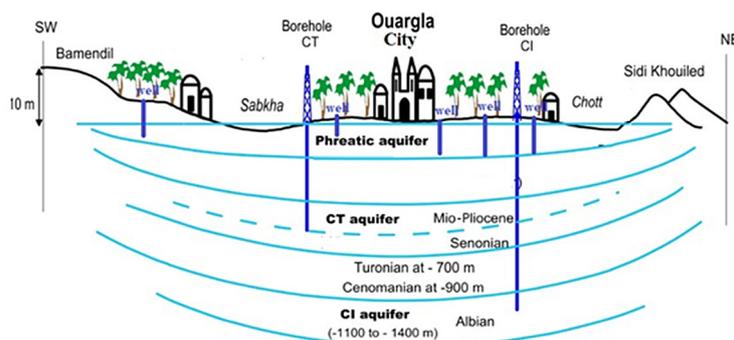


Figure 2. Schematic hydrogeological section of the Ouargla basin

impossible parameters and indices. It was developed by the US Environmental Protection Agency (EPA). The method considers seven parameters to estimate the groundwater vulnerability, namely D (water depth), R (efficient charging), A (aquifer type), S (soil type), T (topography), I (unsaturated zone), and C (hydraulic conductivity) of the aquifer medium.

Each parameter is subdivided into ranges that are assigned different scores on a scale of 1 to 10 (Aller et al., 1987). The weight multipliers vary between 1 and 5, the latter illustrating the importance of the parameter in the contaminant transport and attenuation process (Table 1).

The calculation of the DRASTIC Index (DI) for each hydrogeological unit is obtained by summing the products of each index by its weight, using the following formula:

$$ID = Dp \times Dc + Rp \times Rc + Ap \times Ac + Sp \times Sc + Tp \times Tc + Ip \times Ic + Cp \times Cc \quad (1)$$

Engel et al. (1996) proposed the classification of the vulnerability index values into four classes (Table 2).

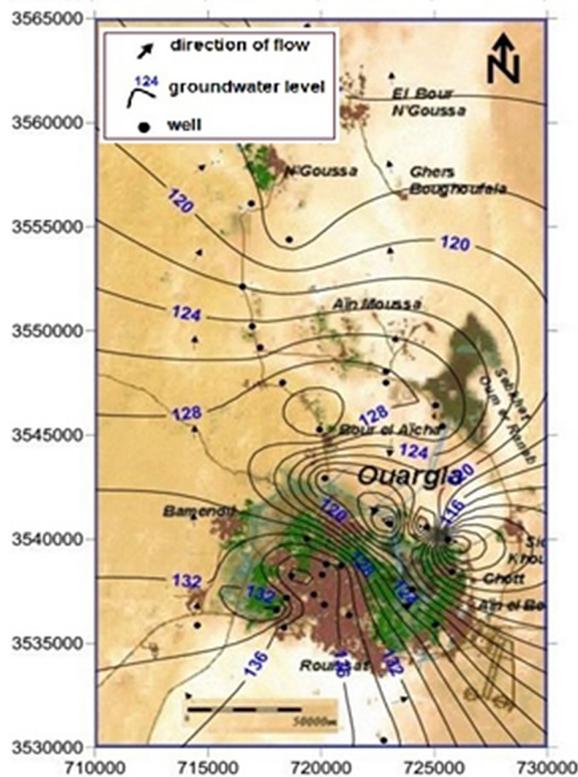


Figure 3. Piezometric map of the Phreatic aquifer

Table 1. Ratings given to the parameters of the DRASTIC method and their weighting (Lallemand-Barrès, 1994)

Parameter	Parameter Value/Types	Ranges	Weights
D Depth to water	>30 m	1	
	30 – 22.5 m	2	
	22.5 – 15 m	3	
	9 – 15 m	5	5
	4.5 – 9 m	7	
	3 – 4.5 m	8	
	1.5 – 3 m	9	
	<1.5 m	10	
R Net recharge	0 – 50 mm	1	
	50 – 100 mm	3	
	100 – 175 mm	6	4
	175 – 225 mm	8	
	>225 mm	9	
A Aquifer media	Silt/Clay	1	
	Shale	2	
	Metamorphic/Igneous	3	
	Sand and gravel with significant silt and clay	4	
	Shale in sequence	6	
	Sandstone	6	3
	Massive limestone	6	
	Sand and gravel	8	
	Basalt	9	
	Karst limestone	10	
S Soil media	Unfissured clay	1	
	Siltyclay	3	
	Limon silteux	4	
	Silt	5	
	Siltysand	6	2
	Clay, aggregates or slopes	7	
	Sand	9	
	Gravel	10	
	Soil slightly thick or absent	10	
	T Topography	>18 %	1
12 – 18 %		3	
10– 12 %		5	
8 – 10 %		7	
6 – 8 %		8	1
2 – 6 %		9	
0 – 2 %		10	
I Impact of vadose zone	Silt and Clay	1	
	Shale	3	
	Limestone	6	
	Sandstone	6	
	Lite limestone, sandstone, shale	6	5
	Sand and gravel with silt and clay	6	
	Sand and gravel	8	
	Basalt	9	
C Hydraulic conductivity	Karst limestone	10	
	$4.7 \cdot 10^{-5} - 4.7 \cdot 10^{-5} \text{ m/s}$	1	
	$4.7 \cdot 10^{-5} - 14.7 \cdot 10^{-5} \text{ m/s}$	2	
	$14.7 \cdot 10^{-5} - 32.9 \cdot 10^{-5} \text{ m/s}$	4	3
	$32.9 \cdot 10^{-5} - 4.7 \cdot 10^{-4} \text{ m/s}$	6	
	$4.7 \cdot 10^{-4} - 9.4 \cdot 10^{-4} \text{ m/s}$	8	
$>9.4 \cdot 10^{-4} \text{ m/s}$	10		

Measures and preparation of the data:

The elaboration of the vulnerability map requires a certain amount of data. According to Table 3, the types of data were obtained from different sources.

Validation Vulnerability map

The aquifer vulnerability method requires validation (Al-Amoush et al., 2010; Bachaer et al., 2017; Leone et al., 2007). To this end, this study used Pearson’s correlation (Fink et al., 1995) to assess the relationship between the DRASTIC model and actual pollution data (nitrate values in water). Indeed, the nitrate values are used as an indicator of anthropogenic pollution when the nitrate concentration exceeds 10 mg/l (Ghazavi et al., 2015).

RESULTS AND DISCUSSIONS

Vulnerability settings

The study of the seven vulnerability parameters was carried out in this work and the results indicate that the water depth is a critical parameter. It defines the width of the materials through which water infiltrates to meet groundwater and reflects the vertical distance between the ground surface and the water table (Rahman, 2008). This parameter is assigned a maximum weight of 5 in the DRASTIC model (Aller et al., 1987). The depth of the aquifer varies between 1.5 and 15 m (Fig. 4), increasing from East to West. According to the DRASTIC classification, there are five depth classes, with scores ranging from 10 to 6.

Next, the results show that recharge of an aquifer can have several origins. Each of these must be addressed separately to estimate recharge (Thomas et al., 2006). These origins are direct contribution by precipitation (effective rainfall), re-infiltration due to irrigation, and urban charging. The water balance of the study

area shows that the easily usable reserve is empty during the eleven months of the year, generated by low precipitation and high evaporation. In this study, the recharge areas were defined from the interpretation of the satellite image and the land-use map. The calculation of urban wastewater recharge was based on water consumption by the population of urban areas and the ratio of water consumed to wastewater estimated at 0.8 (Bouselsal et al., 2015). Irrigation recharge was estimated from the data provided by the Directorate of Agriculture of Ouargla.

As for the effective recharge map (R), it defines two recharge classes (Fig. 5). In Class 1, the recharge is greater than 225 mm. In agricultural areas, it is the result of irrigation water infiltration and in urban areas, it is the result of domestic wastewater and irrigation water infiltration. The score assigned to this class is equal to 9. In Class 2, the recharge is less than 50 mm. This class is represented by desert areas as well as uninhabited and unexploited places. Due to very arid climatic conditions, the recharge is very low or even zero. The score assigned to this class is equal to 1.

The geo-electric section (Fig. 6) shows that the lithology of the aquifer consists of sand and gravel with the presence of gypsum and tuff (limestone concretion) levels in the chotts and sebkhas. The score assigned to this class is equal to 8.

The unsaturated zone is defined by the interface between the ground surface and the piezometric surface of the water table. The core drillings, as well as the piezometer logs (Fig. 7), identified the presence of three classes of geological profiles. The score attributed for this parameter is 8.

Table 2. Vulnerability DRASTIC Class (Engel et al 1996)

Vulnerability class	vulnerability index
low	<100
Moderate	101 to 140
High	141 to 200
Very high	>200

Table 3. Basic data used for the vulnerability calculation

Parameter	Main sources of information
D : Depth to water	A piezometric measurement company may 2017
R : Net recharge	Hydraulic balance Analysis of the land use map
A : Aquifer media	Borehole data analyze Geophysical data
S : Soil media	data from the Directorate of Agriculture Particle size curves established by LTPS
T : Topography	Remote sensing imagery
I : Impact of vadose zone	Geologic map. Borehole data analyze
C : Hydraulic conductivity	The interpretation of pumping tests Data provided by ANRH and LTPS

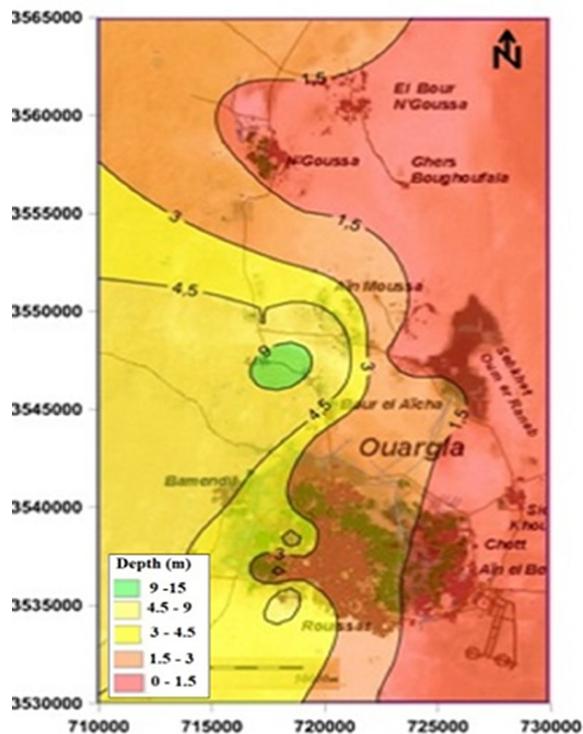


Figure 4. Depth to water level map

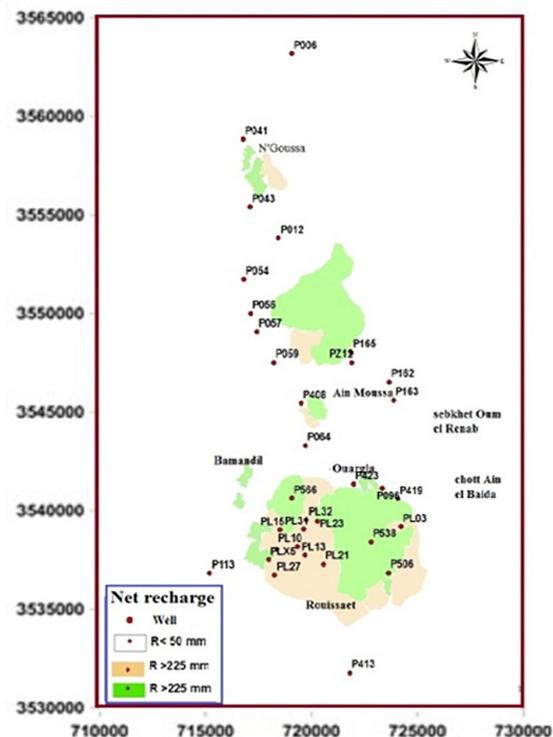


Figure 5. Net recharge map

Class A: This is the most widespread class, representing 75% of the area, where the following can be distinguished:

- a first layer, the thickness of which varies from 1 to 2 m, made up of fine to medium sand slightly gypsum with a consistency of medium compactness;
- a second layer made up of compact clayey sand, the thickness of which varies between 5 and 15 m.

Class B: characterizes the chotts and sebkhas, where the following can be distinguished:

- very salty gypsum crusts whose thickness varies from 1 to 2 m;
- silty sands with a passage of tuff.

Class C: characterizes the slopes of the basin and the Mio-Pliocene plateau, where where the following can be distinguished:

- detrital material consisting of consolidated sandstone (glacis) and gypsum-poor loamy sand, with a thickness greater than 10 m;
- coarse and compact sand.

The amount of recharge and method of pollutant purification is also influenced by the nature and thickness of the soil (Lee, 2003). Soil is the top, weathered layer that supports biological processes. It plays a critical role in determining the amount of water that infiltrates the soil and in controlling the rate at which contaminants pass

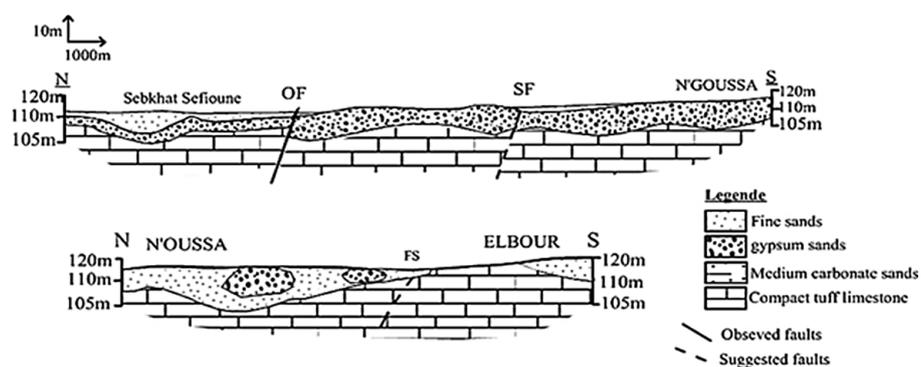


Figure 6. Geo-electric cut through sebkhat Safioune and N'Goussa

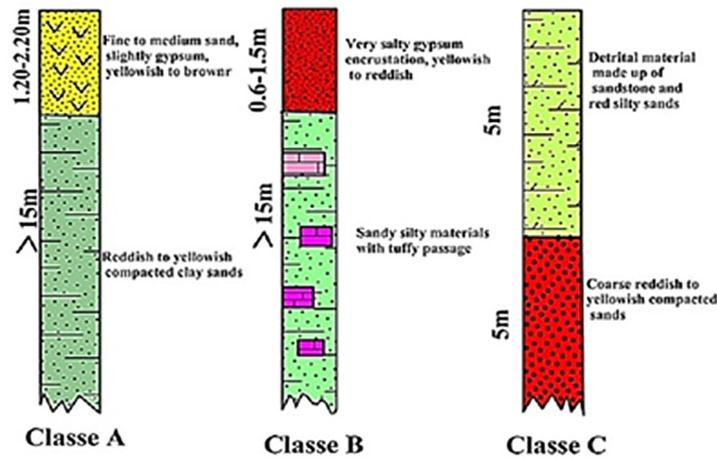


Figure 7. Lithology of the unsaturated zone of Phreatic aquifer

vertically through the vadose region. The description of the constituent soils of the Ouargla region is dominated by sands. The score assigned to this class is equal to 9.

In the DRASTIC model, topography is expressed as slope. In hydrological modeling and water quality research, topography is very important. The low slope retains water for extended periods of time, which promotes water infiltration and thus increases the risk of groundwater pollution (Malik and Shucla, 2019). In this study, the SRTM data was processed in ArcGIS for slope extraction. The slope map established by given values varies between 0% and 18% (Fig. 8); it increases in the eastern part. According to the DRASTIC classification, there are five dominant slope classes, with scores ranging from 10 to 5.

With respect to hydraulic conductivity, it controls the rate of groundwater flow in the saturated zone and thus the rate of migration of a pollutant. The average permeability coefficient of the aquifer based on the data provided by ANRH and LTPS and interpretation of pumping tests ranges from 4.7×10^{-4} m/s to 5.6×10^{-4} m/s. Only one permeability class was determined with a score of 8.

Intrinsic vulnerability

The indices evaluated by using the DRASTIC method (Engel et al., 1996) range from 151 to 208 and thus represent two classes that constitute the current map (Fig. 9). These are distributed as follows:

- very high vulnerability class; it covers 58.8 km² or 8.4% of the area of the study region, it is located in the southeast of the area investigated. In areas with a low water table,

due to upwelling water resulting from water infiltration under built-up areas and agricultural areas to the southeast of the study area;

- high vulnerability class; it occupies an area of 641.2 km² or 91.6% of the total area. This class is located in the rest of the study area, mainly favored by the low piezometric level depth as well as the lithology of the saturated zone and unsaturated zone.

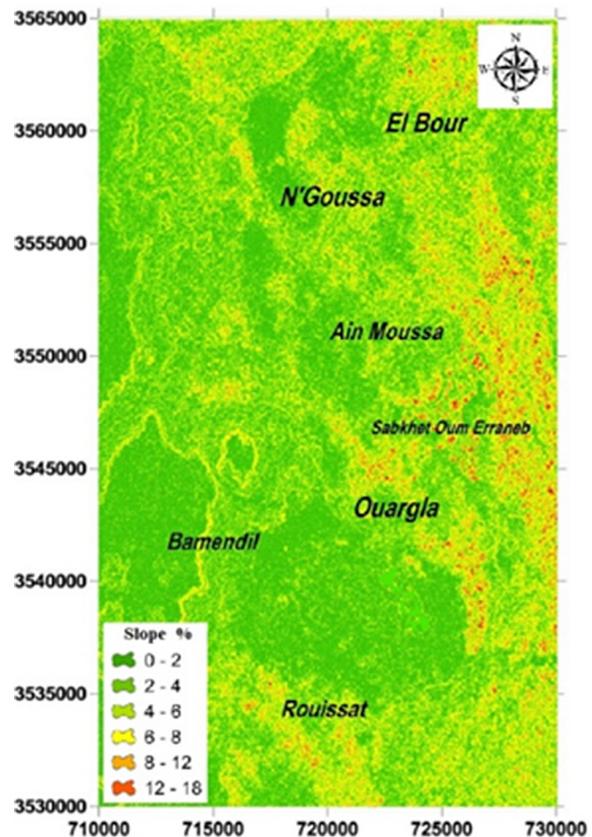


Figure 8. Slope map

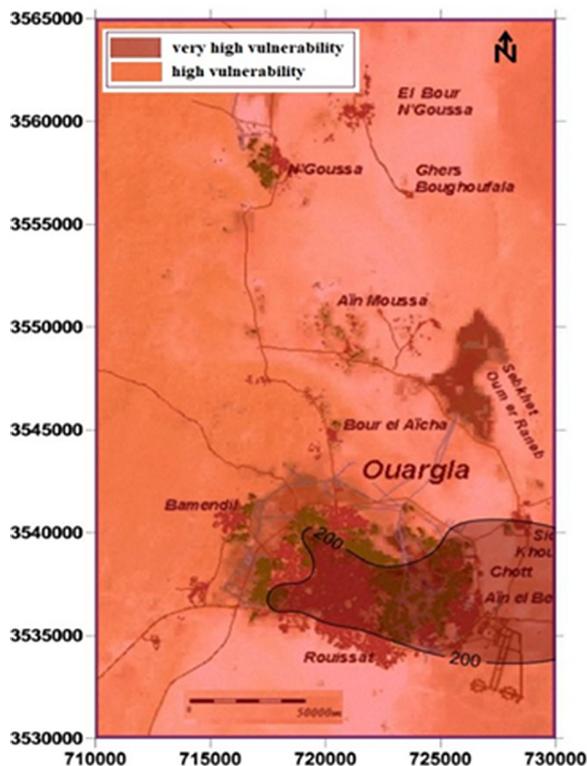


Figure 9. DRASTIC vulnerability map of the Phreatic aquifer

Validation of vulnerability maps

The relationship between the DRASTIC index and nitrate concentrations in groundwater was investigated to verify the effectiveness of the DRASTIC method. Therefore, 33 groundwater samples were collected from the wells located in the investigated areas in June 2019. The distribution of nitrate in the investigated area illustrates the concentration values ranging from 30 to 93 mg/l. The highest desirable limit and maximum allowable limit of nitrate is 50 mg/l (WHO, 2011). The nitrate concentration above 50 mg/l in groundwater is harmful for human consumption. Well locations with high nitrate values are located in agricultural and built-up areas. There are no known geological sources of nitrate in the wells studied, the measured nitrate values indicate contamination of the shallow aquifer by domestic sewage infiltration under the built-up areas and excessive fertilizer use, in agricultural areas. The correlation coefficient between the DRASTIC index and the nitrate values is $R = 0.73$ (Fig. 10). This indicates that groundwater vulnerability mapping by DRASTIC method can be applied for reasonable management of groundwater resources and land-use in the study area.

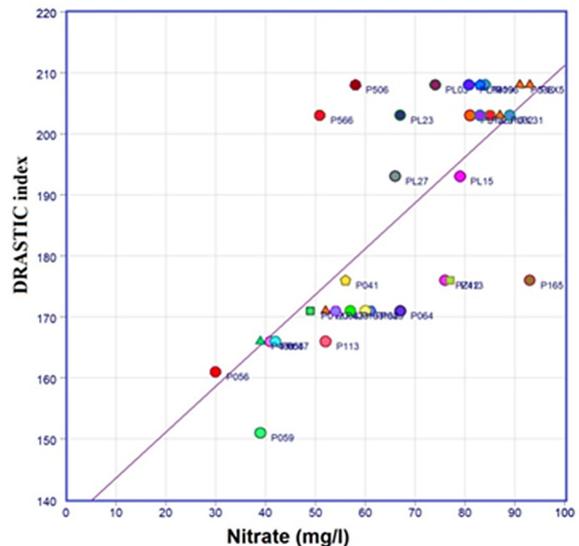


Figure 10. Correlation coefficient between DRASTIC index and nitrate concentration

CONCLUSIONS

The assessment of the vulnerability of the shallow aquifer of the Ouargla basin (Algeria Sahara) to pollution by applying the DRASTIC method reveals a trend of high to very high vulnerability to pollution. The most dominant class is the strong class (91.6%) against 8.4% for the very strong class. The validity of the application of this method to the study of the pollution of the aquifer in question was tested by a measurement campaign of nitrates. It showed a correlation coefficient between the DRASTIC index and nitrate values ($R = 0.73$). This result indicates that DRASTIC groundwater vulnerability mapping can be applied for proper management of the groundwater resources and land-use planning in the Ouargla region.

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