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Sensitivity analysis of groundwater vulnerability maps in the Messaad plateau. South Algerian steppe region.

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ABSTRACT/RESUME

Abstract: *The Messaad plateau is part of the arid zones, located in the region of the South Algerian steppes, with annual precipitation of around 150 mm. This area includes the Barremian aquifer, which plays a very important role in the supply of drinking water and irrigation water. The objective of this work is to assess the vulnerability of groundwater to pollution. The results obtained by the application of the DRASTIC method, show that the areas with high pollution potential are located in the extreme southwest of the watershed, in the south near the Oued Messaad, and in the north at the level of the Ain Naga area. The rest of the area characterized by low to medium vulnerability. The sensitivity analysis after removing one or more maps shows that the vulnerability of groundwater to pollution is largely influenced by the impact of the vadose zone (I), this is confirmed by the single parameter sensitivity analysis , where the effective weight of the impact of the vadose zone (I 29.74%) exceeds the theoretical weight determined by DRASTIC (I 21.7%).*

I. Introduction

Groundwater pollution has been a growing problem in recent years, particularly in arid and semi-arid areas where groundwater is the mainstay of drinking water and agricultural irrigation. Therefore, the development and implementation of technologies that prevent pollution and protect groundwater has become a priority.

Anthropogenic activities are responsible for the disturbance of aquatic environments both quantitatively, through the intensive exploitation of water resources, and qualitatively, through the modification of their physico-chemical properties (inputs of potentially toxic chemicals) [1]. The study area, which is mainly agricultural, is particularly affected by these problems because of its continued development of the agricultural sector. Liquid discharges of domestic origin are discharged directly into the Oued Messaad which runs through the city from west to east. The latter is spread over a distance of 30 km; along its passage, local farmers use it for the irrigation of crops. [2] they showed that the ionic charge of groundwater in the area near the Oued is very high with conductivity values exceeding 4000 µS/cm, the researchers believe that there is a possibility of groundwater contamination. It is therefore necessary to map areas vulnerable to pollution, which makes it possible to better manage the water resource by protecting it from the risk of pollution and therefore limiting it.

Mapping areas vulnerable to pollution is one of the best ways to reduce groundwater pollution. The basic principle of this approach is that land can be divided into zones. Groundwater pollution risk classifications, from low to high, can be assigned based on hydrogeological and/or soil factors. Among the methods available to characterize groundwater vulnerability, we have chosen the DRASTIC method that adapts to the characteristics of our terrain, and it includes several parameters which increase the accuracy of the results, and it also gave good results for some regions in Algeria [3,4,5,6]. A sensitivity analysis was also conducted on the results of this method to assess vulnerability.

II. Materials and methods

II.1. The study area

The plateau of Messaad occupies the Southern part of the central Saharan Atlas, South-East of the Wilaya of Djelfa, it is located 370 km South of the capital of Algiers, 60 km North of the Wilaya of Laghouat, surrounded by the massifs of Djebels: Mergueb, Dj zerga, Tafara and Dj Bou Kahil. (Figure 1). The plateau belongs mainly to the west of the large Melghigh chott basin coded 06, more precisely, in the swallowed part of the sub-watershed of the Oued Demmede coded 06-06. Limited by longitudes 3°13’0,3020’’ and 3°39’8,3384’’ and latitudes 34°4’23,0794’’ and 34°20’31,5612’’.

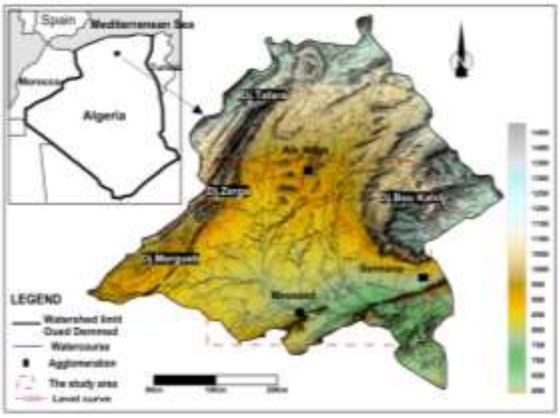

Figure 01. *Status of the study area.*

II.2. Presentation of the DRASTIC method

DRASTIC was developed by the US Environmental Protection Agency [7] is a vertical vulnerability assessment method based on the following seven parameters: water depth (D), recharge (R), aquifer media (A), soil media (S), topography (T), vadose zone impact (I) and hydraulic conductivity (C). Each mapped factor is classified as beaches with an impact on pollution potential, with a typical score of 1 to 10 (Table 1). Weighting multipliers are then used for each factor in order to balance and improve their importance; a numerical value between 1 and 5 reflects the degree of influence of each of these parameters or their weight in the calculation of the indices. The final vulnerability index is a weighted sum of the seven factors. The index values can range from 23 to 226. As with ratings, the higher the index, the higher the intrinsic vulnerability of groundwater. The DRASTIC Index (Di) can be calculated using the following formula:

$$Di=Dn.dp+Rn.Rp+An.Ap+Sn.Sp+Tn.Tp+In.Ip+Cn.Cp$$

P: weighting factor given to each parameter.

n: notation given to each parameter.

Table 1. *Weights, classes and notes of the seven parameters (Lallemand Barèes 1994).*

water Depth Weight 5	**Values (m)**	**Rating**
	0-1.5	10
	1.5-4.5	9
	4.5-9	7
	sept-15	5
	15-22.5	3
	22.5-30	2
	>30	1
Recharge Weight 4	**Values (mm)**	**Rating**
	25.5	9
	17.5-22.5	8
	10.-17.5	6
	05-oct	3
	0-5	1
Aquifer media Weight 3	**Calsses**	**Rating**
	Karstic limestone	10
	Sand and gravel	8
	Solid sandstone	6
	Altered metamorphic	4
	Metamorphic	3
	Massive shale	2
Soil media Weight 2	**Classes**	**Rating**
	Thin or absent	10
	Sands	9
	sandy silts	6
	silts	4
	silty clay	3
	clay	1
Topography Weight 1	**Values %**	**Rating**
	0-2	10
	2-6	9
	6-12	5
	12-18	3
	>18	1
vadose zone Impact Weight 5	**Classes**	**Rating**
	Karstic limestone	10
	Sand and gravel	9
	Sand and gravel with silt and clay	8
	Sandstone	6
	Limestone	6
	Silt and clay	1

	Values m/s	Rating
hydraulic Conductivity Weight 3	$>9,4.10^{-4}$	10
	$4,7.10^{-4}$ à 9,4.10-4	8
	$32,9.10^{-5}$ à 4,7.10-4	6
	$14,7.10^{-5}$ à $32,9.10^{-5}$	4
	$4,7.10^{-5}$ à $14,7.10^{-5}$	2
	$4,7.10^{-7}$ à $4,7.10^{-5}$	1

III. Results and discussion

III.1. Parameter Indices

III.1.1. Depth of water level (D)

The depth of the water table is the distance between the earth's surface and the static level of the water. This is an important factor because it determines the thickness of the material that an infiltrate must pass through before reaching the saturated zone. The deeper the water table, the less likely it is that pollutants will enter groundwater and the less likely it is that pollutants will be transported to the aquifer [8]. For the study area this endpoint was determined during piezometric surveys July 2018. Table 2 provides a summary of the water depth and the water depth indices.

Table 2. *Depth parameter rating and weighting.*

Interval	Dn	Dp	Dn.Dp
0-1,5	10	5	50
1,5-4,5	9	5	45
4,5-9	7	5	35
9-15	5	5	25
15-22,5	3	5	15
22,5-30	2	5	10
>30	1	5	5

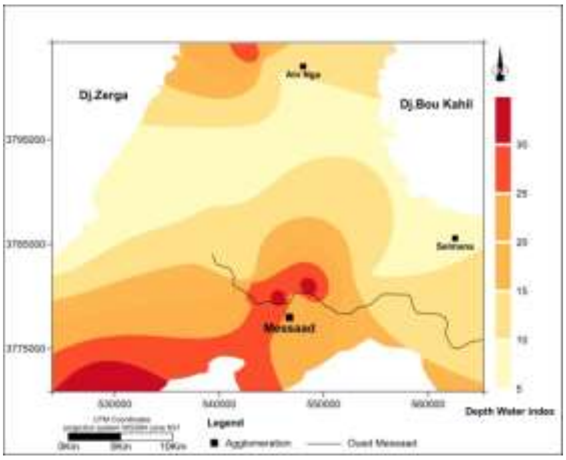

Figure 2. *Groundwater depth index map.*

III.1.2. Recharge (R)

The estimation of the recharge of the aquifer, is important for the calculation of the DRASTIC indices, it is the quantity of water that seeps from the surface to the aquifer. Transfer times from the soil surface to the water table can vary from a few days to a few decades [9].

The calculation of the hydrological balance based on data from the Messaad rainfall station shows that the value of this parameter is 9.8 mm over the entire basin (Table 3).

Table 3*. Rating and weighting of the recharge parameter.*

Interval	Rn	Rp	Rn.Rp
5-10	3	4	12

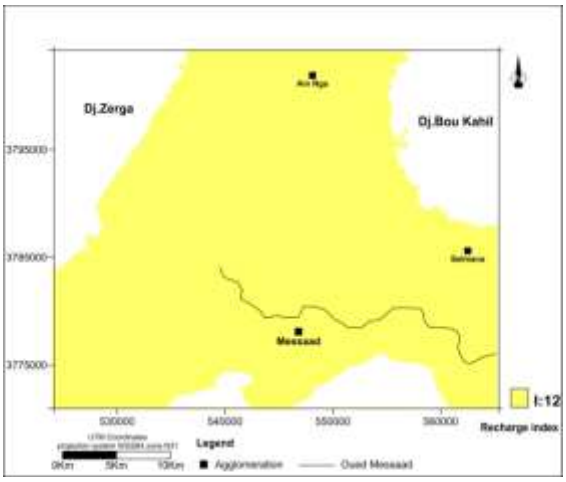

Figure 3. *Effective tablecloth Recharge map.*

III.1.3. Nature of the Aquifer media (A)

This parameter describes the nature of the geological formation of the aquifer. To determine this, we have based on the drilling logs which are the source of the most accurate data. Examination of these data has shown that the Barremian aquifer is mainly composed of sandstone, gravel sandstone and sandstone with intercalation of clay and marl. The indicators corresponding to this parameter were estimated according to the symbol presented in Table 4.

Table 4. *Rating and weighting of aquifer material.*

Calasses	An	Ap	An.Ap
gravel sandstone	9	3	27
sandstone	6	3	18
Sandstone with intercalation of clays and marls and sometimes limestone.	4	3	12

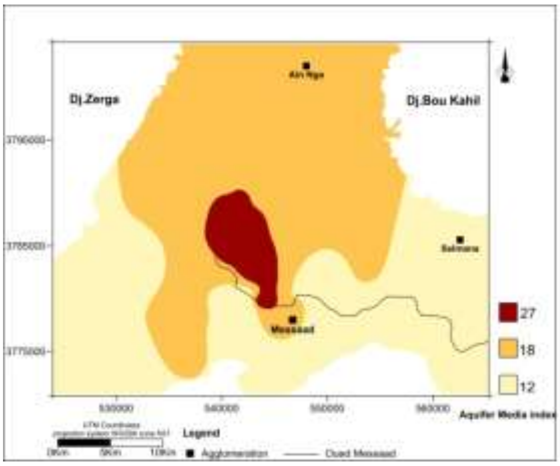

Figure 4. Aquifer Materials Map

III.1.4. Soil media (S)

The soil medium refers to the highest part of the vadose zone characterized by significant biological activity. The soil plays an important role in the amount of recharge that can seep into the soil and thus on the ability of a contaminant to move vertically into the vadose zone. The potential for soil pollution is largely affected by the type of clay present, the potential for clay shrinkage/swelling, and the size of the soil grains. [10] The soil medium in the study area was determined using drill profiles and the soil map [11]. Examination of these data showed that the soil is mainly composed of Conglomerate, Coarse sand and gravel, Clay sandstone, Limestone crust, gypsum clay. Index values were determined according to the classes reported in Table 5.

***Table 5.** Rating and weighting of the nature of the soil.*

Calasses	Sn	Sp	Sn.Sp
Conglomerate	10	2	20
Coarse sand and gravel	8	2	16
Clay sandstone	6	2	12
Limestone crust	2	2	4
gypsum clay	1	2	2

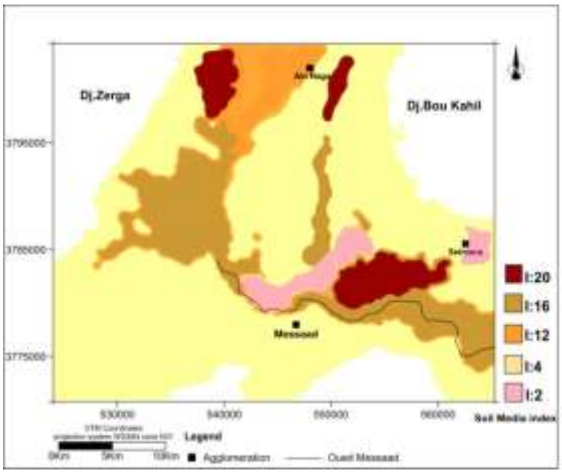

***Figure 5.** Map of soil types of the aquifer.*

III.1.5. Topography (T)

Topography refers to the variability of the slope of the earth's surface. The degree of slope will determine the extent of runoff from pollutants and sedimentation long enough to infiltrate. A digital terrain model (MNT) of the SRTM type was used to extract the slope from the study area, while 70% of the plateau has a gentle slope, (Figure 6).

***Table 6.** Slope factor rating and weighting.*

Classes	Tn	Tp	Tn.Tp
0-2	10	3	30
2-6	9	3	27

III.1.6. Impact of the Vadose zone (I)

The vadose zone is defined as the area above the layer that is unsaturated. Its impact is determined from the lithology of the lands that constitute it. The greater the favourable lithology, the greater the percolation of the contaminants to the piezometric surface [12].

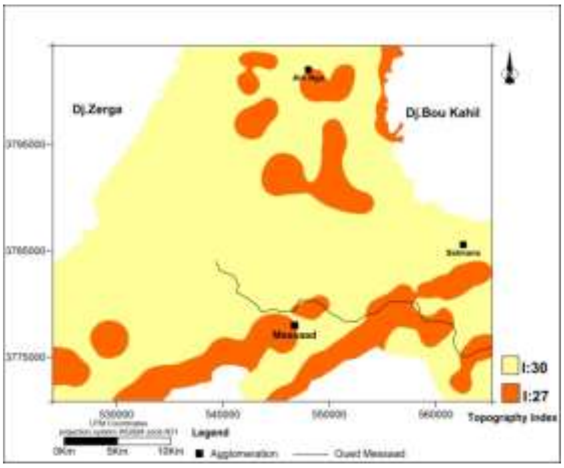

***Figure 6.** Topographic slope map.*

Examination of the different drill logs showed that the vadose zone is composed of gravel, sand and gravel, sandstone, and clay sand. The indicators corresponding to this parameter were estimated according to the symbol presented in Table 7.

Table 7. *Rating and Weighting of the vadose layer.*

Classes	In	Ip	In.Ip
gravel	10	5	50
sand and gravel	9	5	45
sand and gravel with clay	8	5	40
sandstone	6	5	30
clayey sand	4	5	20

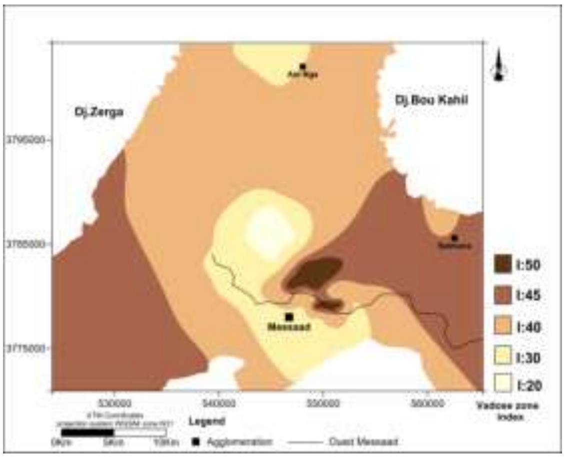

Figure 7. *Vadose Layer Impact Map.*

III.1.7. Hydraulic conductivity (C)

Hydraulic conductivity is important because it controls the rate of groundwater movement in the saturated area, thus controlling the degree and fate of contaminants. The hydraulic conductivity values used in this study were derived from the pumping test data. The indicators corresponding to this parameter were estimated according to the symbol presented in Table 8.

Table 8. *Classes and ratings for permeability.*

Permeability in (10^{-4} m/s)	Cn	Cp	Cn.Cp
0,85 à 1,02	8	3	24
0,4 à 0,85	5	3	15
0,04 à 0,4	3	3	9
<0,04	1	3	3

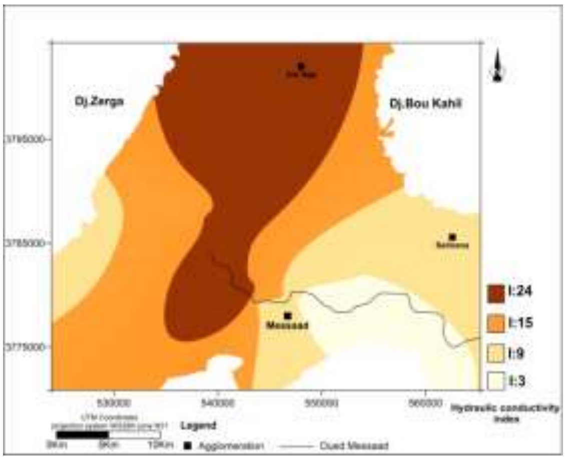

Figure 8. *Map of water table permeability indices.*

III.2. Summary map:

The vulnerability map was obtained from the seven hydrogeological data parameters using the math data surfer 2013 option, the resulting values were classified according to the unsupervised binning method, is a statistical method, which converts the numerical variables in categorical analogues. Equal width and equal frequency are the two unsupervised clustering techniques. In equal width, the algorithm divides the data in k intervals of equal size, while in equal frequency; the algorithm divides the data into k groups with each group containing approximately the same number of values [13]. For both methods, the best way to determine k is to look at the histogram and try different intervals or groups.
The histogram is a graphical presentation of the classes of a statistical variable. Frequency histograms are established by giving the relative frequency of each class in relation to the total number of samples.

$$F = ni / n$$

F: frequency

ni: number of samples in class i, the interval of each class is calculated by the following formula:

$$D = R\ (max\text{-}min) / 5\log n$$

n: total number of samples

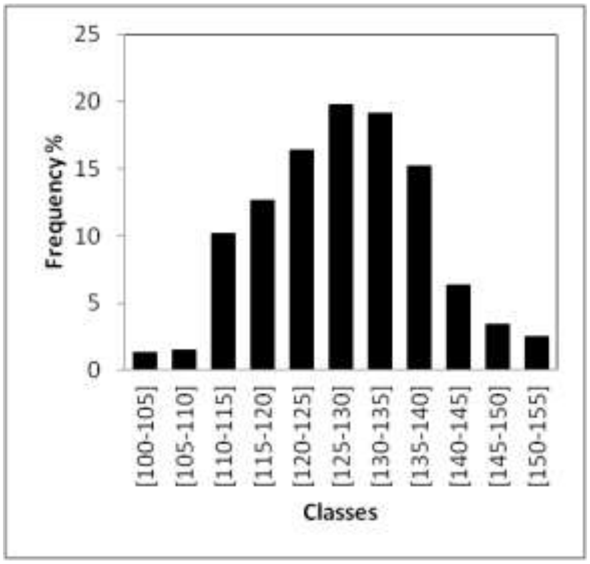

Figure 9. *Histogram of vulnerability index classes.*

This classification allows us to group the vulnerability values as follows:

- 140 < I : high vulnerability.
- 110 < I < 140 : medium vulnerability.
- I<110 : low vulnerability.

Observation of the vulnerability map (Figure 10), shows that the areas with high pollution potential were extreme South West, South at the Oued level, and in the North at the level of the Ain Naga, these areas are characterized by low water depth and high hydraulic conductivity. The weak indices are located in the periphery of the plateau and in the centre, but extend over a limited area. The rest of the area characterized by medium vulnerability.

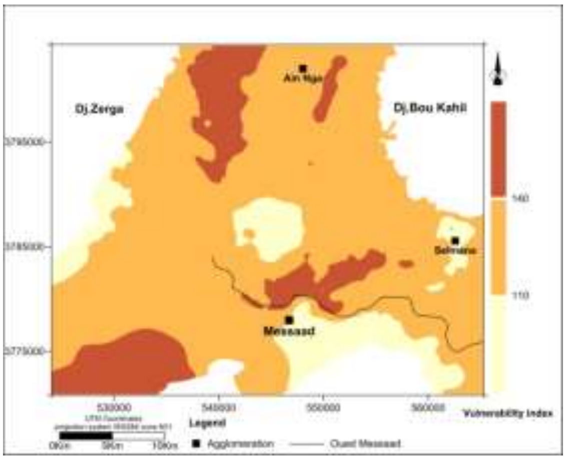

Figure 10. *Groundwater Pollution Vulnerability Map.*

III.3. Sensitivity Analysis

Sensitivity analysis is the study of how the uncertainty of a system's output can be attributed to the uncertainty in its inputs. This involves estimating sensitivity indices that quantify the influence of an input or input group on the output. [14]. The DRASTIC method is characterized by the use of a large number of parameters, which is supposed to limit the impact of errors and uncertainties in the individual parameters on the final results [15]. However, many discussions have been raised in the context of vulnerability assessment, [16][17] these researchers believe that by using fewer parameters, more accurate results can be achieved. Several studies have been published in recent years to highlight the importance of this sensitivity analysis in order to better understand the parameters that affect the index of the vulnerability of water bodies to pollution. [18][14].

There are two types of sensitivity analyses: sensitivity analysis by map deletion defined by [8], and single parameter sensitivity analysis proposed by [20], In this study, a sensitivity analysis was conducted to assess vulnerability by performing both methods.

III.3.1 Map Removal Sensitivity Analysis

This analysis consists of the removal of one or more maps from an aptitude analysis and is defined as follows:

$$S = [|V/N - V'/n|/V]\ 100$$

From where

S: sensitivity measurement.

V: undisturbed vulnerability index (all seven parameters were used to obtain the actual index).

V' is a disrupted vulnerability index (calculated vulnerability index with less stress).

N and n: to calculate V and V' the number of data layers used.

Tables 9 and 10 present the variations in the vulnerability index determined by the map suppression sensitivity analysis after the deletion of one or more layers of DRASTIC parameters. The sensitivity analysis after the deletion of each parameter shows an increased disparity in the vulnerability index, it is found that the parameter of the vadose zone plays an important roll in the determination of the vulnerability index (S 2,57), in theory this parameter is of great importance (weight 5), followed by the parameter of soil media and topography (S 1,52 and S1.42), although these two parameters are considered theoretically less important (weight 2 and 1 respectively). The four parameters of hydraulic conductivity, depth, recharge and the nature of the aquifer medium are the least sensitive of the seven parameters used in the DRASTIC method (S0.99, S0.83, S0.82, S0.35). Based on these results, a sensitivity analysis was performed on the removal of several layers. The vulnerability appears to be very sensitive to the removal of both parameters (vadose zone Impact (I) and Topography (T)).

Table 9. *Map removal sensitivity analysis statistics after removing of each parameter.*

Parameter removed	**Variation index%**			
	Min	**Mean**	**Max**	**SD**
D	0	0,83	1,77	0,39
R	0,48	0,82	1,09	0,12
A	0	0,35	1,08	0,28
S	0	1,52	2,43	0,64
T	0,65	1,42	2,15	0,29
I	0,13	2,57	4,38	0,72
C	0	0,99	2,17	0,65

Table 10. *Map removal sensitivity analysis statistics after removing of several parameters.*

Parameter removed	**Variation index %**			
	Min	**Mean**	**Max**	**SD**
DRSTIC	0	2,08	6,49	1,96
DSTIC	0	3,30	6,46	1,38
STIC	0	3,10	6,11	1,43
STI	0,42	3,72	6,91	1,28
TI	2,16	4,8	7,8	0,97
SI	0	1,49	3,84	0,86

III.3.2. Single parameter sensitivity analysis:

The single parameter sensitivity analysis aims to compare the theoretical weights and the effective weights of the DRASTIC parameters, and is calculated as follows:

$$Wpi = [(Pri \_ Pwi) / V]\ 100$$

Where:

Wpi: effective weight of a parameter.

Pri and Pwi: are the weights and the value of the interval (rating) assigned to this parameter.

V: is the DRASTIC vulnerability index.

The use of the single parameter sensitivity analysis method allows us to verify the results found by the test «Map removal sensitivity analysis». Table 11 shows the difference between the 'effective' and 'theoretical' weight assessments of the DRASTIC method. The most important parameters for assessing vulnerability were the impact of vadose (I:29.74%) and topography (T:22.81%), as their effective weights exceed the theoretical weights determined by DRASTIC (21.7%, 18.2%, respectively). This confirms the results obtained previously. For the remaining parameters, depth D, recharge (R), aquifer medium (A), soil type (S) and hydraulic conductivity (C), the effective weights are less than the theoretical weights assigned to them (Without neglecting their role also in determining the vulnerability of the aquifer).
So for the parameter, the impact of the vadose zone (I), more complete and accurate data are necessary, for a better assessment of the vulnerability to groundwater pollution.

Table 11. *Single parameter sensitivity analysis statistics.*

Parameter		**D**	**R**	**A**	**S**
Theoretical weight		5	4	3	2
Theoretical weight (%)		21,7	17,4	13	8,7
Effective Weight %	Min	3,62	7,72	7,82	0,17
	Mea	11,74	9,34	12,5	5,21
	Max	22,87	11,35	20,76	16,71
	SD	4,94	0,72	2	3,95
Paramètre		**T**	**I**	**C**	
Theoretical weight		1	5	3	
Theoretical weight (%)		4,3	21,7	13	
Effective Weight %	Min	18,2	15,11	1,25	
	Mea	22,81	29,74	8,53	
	Max	27,19	40,57	17,47	
	SD	1,76	4,35	4,1	

IV. Conclusion

The application of the DRASTIC method allowed us to divide our field of study into three zones according to the vulnerability index; One with high vulnerability indices above 140 in the North at Ain Naga, near Oued Messaad and at the extreme South West, the second low-vulnerability zone on the periphery of the plateau and in the centre, the third zone which is characterized by a medium vulnerability with indices between 110 and 140, covering the rest of the study area. The work reveals the importance of using sensitivity analysis to better assess the index of groundwater vulnerability. In our case, the vadose zone and topography play an important role in determining the vulnerability index.

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