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Cartography of intrinsic aquifer vulnerability to pollution using GOD method: Case study Beni Amir groundwoter, Tadla, Morocco

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Abstract

In recent years, the quality of groundwater has deteriorated in several regions of Morocco due to many factors. The main objective of this work is to determine the vulnerability of the water table of the Beni Amir to any form of pollutant introduced from the surface by applying the GOD method (Groundwater occurrence, Overall aquifer class and Depth of water table) coupled with a geographic information system (GIS). The three parameters (the type of aquifer, lithology of the unsaturated zone and depth to the water table) for this method were calculated and mapped using the functions available on ArcGIS, which allowed us to obtain vulnerability indices. These have been classified into five classes of vulnerability: very high, high, moderate, low and no vulnerability. The results show that the highest indicators appear in areas of shallow groundwater and in areas where permeability is important. However the least vulnerable areas are located in areas where the permeability is low and the water table is deeper. The elaborate map can be used as a decision support tool for the protection and the reasonable management of groundwater resources in plain of Tadla.

1. Introduction

The quality of groundwater in some regions of Morocco is generally threatened by a variety of anthropogenic activities [15] [10] [24]. Industrial discharges, uncontrolled landfills [8], irrational use of pesticides and fertilizers [19], as well as domestic releases pose a great threat to the quality of groundwater [5].

Faced with this threat, there is therefore a need to ensure that groundwater resources are of good quality, by protecting them from sources of pollution [21]. Decontamination of groundwater is a very difficult operation, even impossible in the case of diffuse pollution [25].

The assessment of the groundwater vulnerability to pollution remains an essential to ensure an effective and sustainable management of the groundwater by identifying areas [16], which are more likely than others to be polluted By a polluting input from the soil surface [4].

The search for information concerning the risk of groundwater pollution requires taking into account all the factors that are involved in this phenomenon [14].

There is a wide range of methods for assessing the vulnerability of aquifers to pollution [22] [6]. Among the classic methods of developing a vulnerability map there is the GOD method (the type of aquifer "G", the lithology of the unsaturated zone "O" and the depth to the water table"D"), which was Introduced by Foster in England in 1987. This method does not take into account the transport processes in the saturated zone.

This study aims to assess the vulnerability of the Beni Amir groundwater to pollution using the GOD method.

This approach was carried out by the use of GIS software [20], which allowed the acquisition and crossing of the data to calculate the GOD index and to generate the final map of the vulnerability of the groundwater to pollution.

2. The Study Area

The plain of the Tadla is a depression spread over 100 km long and 40 km wide, it is limited by the Middle Atlas in the south and by the plateau of phosphates in the North.

It's part of the Watershed of the Oum Er Rbia river and houses one of the most important irrigated perimeters of Morocco, that of tadla, ranked first in Morocco.

Geologically, the plain presents itself as a vast depression filled with heterogeneous mio-plio-quaternary deposits. Its topography is regular with very low slopes. Soils are characterized by their depth and their balanced texture, but they are poor in organic matter [1].The vast majority of soils are isohumic. The climate is arid to semi-arid with an average annual temperature of 19 ° C. The average annual rainfall is 550 mm.

The plain harbors considerable water resources, the surface waters come mainly from the Oum Er-Rbia river and the underground waters from the deep and phreatic aquifers. The Tadla aquifer system is in the form of a superposition of four main aquifers which are from bottom to top: the carbonate aquifer of the Turonian; The carbonate aquifer of the Senonian; The calcareo-sandy aquifer of the Eocene and the Mio-Plio-Quaternary alluvial aquifers (Beni-Moussa and Beni-Amir groundwater). [3]

The figure 1 shows the delimitation of the Beni Amir groundwater, the subject of this study, which extends under the irrigated perimeter of Béni-Amir and the "Bour" areas, it's limited by the Oum-Er-Rbia river in the south, the main channel of the Béni-Amir to the north and the outcrop limits of the mio-plio-quaternary formations to the east and west.

Its reservoir consists of an alternation of marl-limestones, lacustrine limestones and conglomerates with a thickness generally between 50 and 100 m and decreases in a south-east–north-west direction [7]. The inputs of this water table consist largely of infiltrations of irrigation water which are estimated at 114 Mm3 per year, while infiltrations from rainwater are only 2 Mm3 / year. [2]

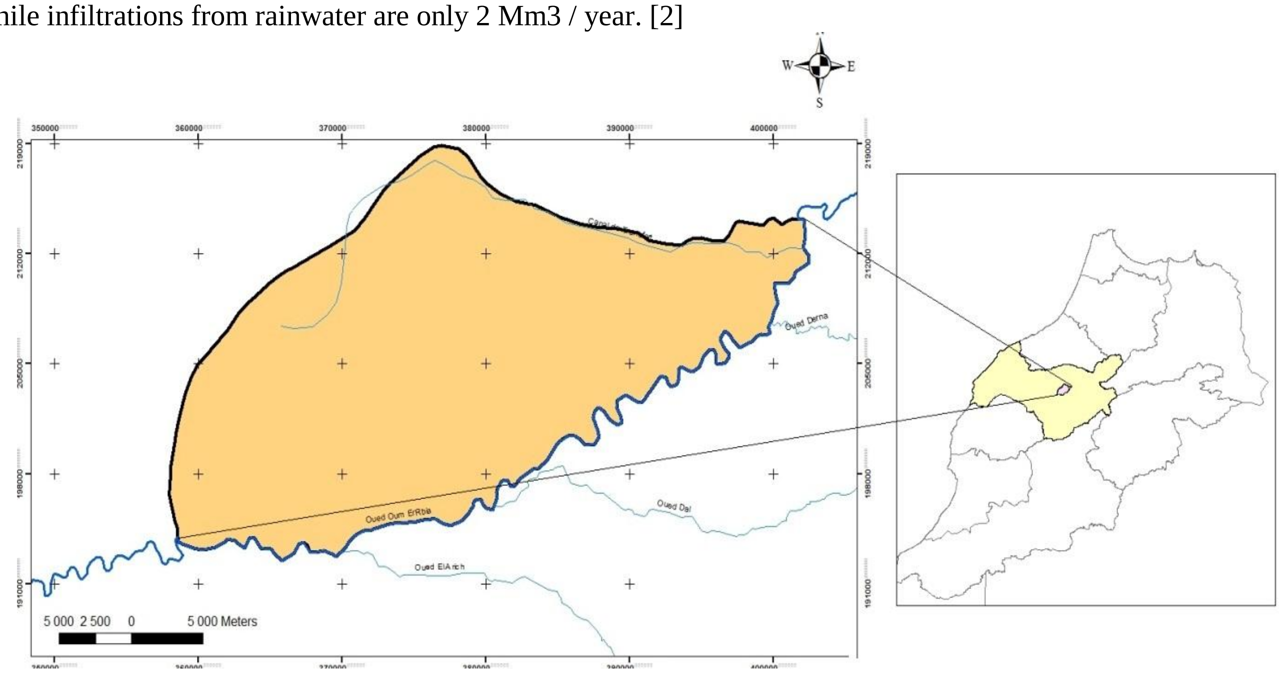

Figure 1: Location map of the study area.

3. Materials and methods

In this work, the GOD method was chosen to assess the vulnerability of groundwater to pollution. It's an empirical approach that assesses the vulnerability using three parameters [3]. The first: Groundwater occurrence (G), lies in the identification of the degree of confinement of the aquifer. The second: Overall lithology of aquifer (O) corresponds to the overall lithology of the aquifer and the third is the Depth to groundwater (D), it's defined by depth to the water table [23].

Although this method uses fewer parameters than other approaches, this does not mean that it's less precise. It is always necessary to compare the different approaches to adopt the method that better characterizes the vulnerability of an aquifer to pollution [3]. Table 1 shows the data collected in order to apply the GOD method.

Table 2 shows that for each parameter, the range of possible values varies from 0 (minimum vulnerability) to 1 (maximum vulnerability). Vulnerability indices are calculated by multiplying the scores assigned to each of the three parameters of the method according to equation (1).

$$IV\,(GOD) = G \times O \times D \qquad \text{Equation (1)}$$

The possible values of the GOD index vary between 0 and 1 and five classes of vulnerability have been defined. Figure 2 illustrates the concept of creating a GOD vulnerability map.

Table 1: Data used for the development of the three layers of GOD parameters

Symbol	Parameter	Data Type	Source of data
G	Groundwater occurrence	Boreholes data	Agency of the Hydraulic Basin of the Oum Er Rbia (ABHOR)
O	Overall lithology of aquifer	Geological map 1/50 000	
D	Depth to water table	Wells Data	

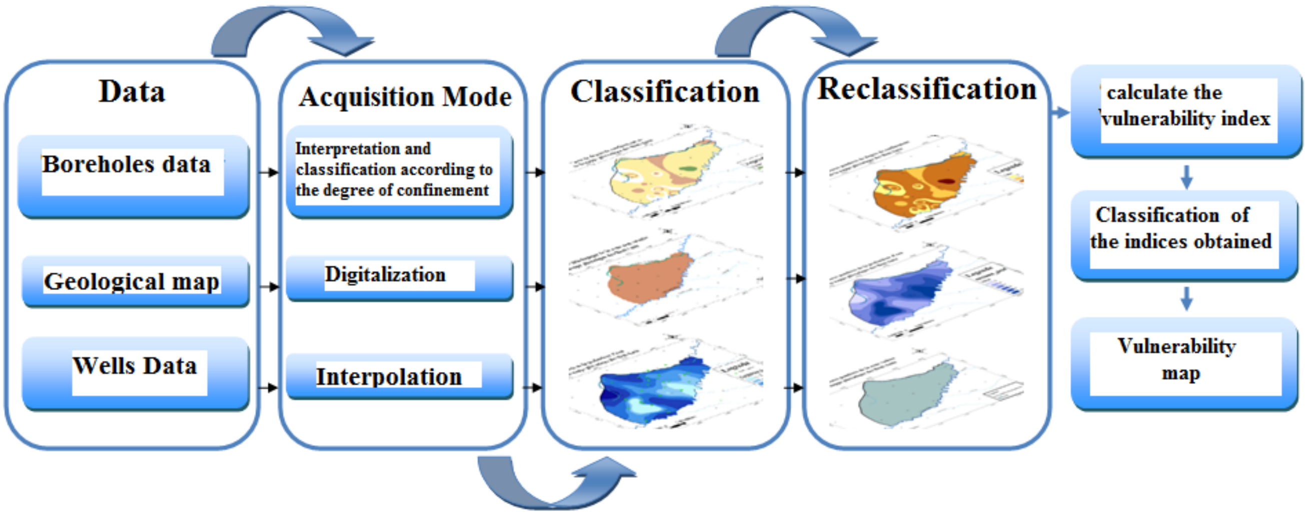

Figure 2: Procedure for developing the vulnerability map using the GOD method.

Table 2: Notes of each parameter [11]

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

To create the vulnerability map, information on materials covering the aquifer, unsaturated zone lithology and depth of groundwater was collected and interpreted from 25 boreholes, 31 piezometers and the geological map at 1 : 50000 of the study area. For the piezometric levels, the highest levels recorded between 2010 and 2015

were chosen to take account of the periods of rising groundwater level, which increases the exposure and vulnerability to pollution.
This approach was applied using the ArcGIS 10.2 software which allowed the transformation of point and vector type data into raster data, the standardization of raster data, the indexing of spatial information , as well as the superposition of the different layers of information.
The problem we encountered was related to the fact that the software only works for integers, so it was necessary to reclassify by multiplying the decimal notes of each parameter by ten to obtain integers, but before superimposing the layers According to equation 1, they are multiplied by 0.1 to obtain final scores between 0 and 1.

4. Results

4.1. Groundwater occurrence

The map of aquifer type was developed by interpreting and correlating between 25 boreholes in the study area.
Figure 3a shows the map obtained after classification according to the degree of confinement, a reclassification of each pixel is then made according to the rating system of the GOD method.
Figure 4a shows the elaborate map which shows that the aquifer is generally surmounted by relatively permeable formations. Therefore, the vadose zone will provide a very fast displacement of pollutants located on the soil surface. Unlike the other methods of assessing pollution vulnerability, the GOD method evaluates this parameter as the degree of confinement of the water table [23].

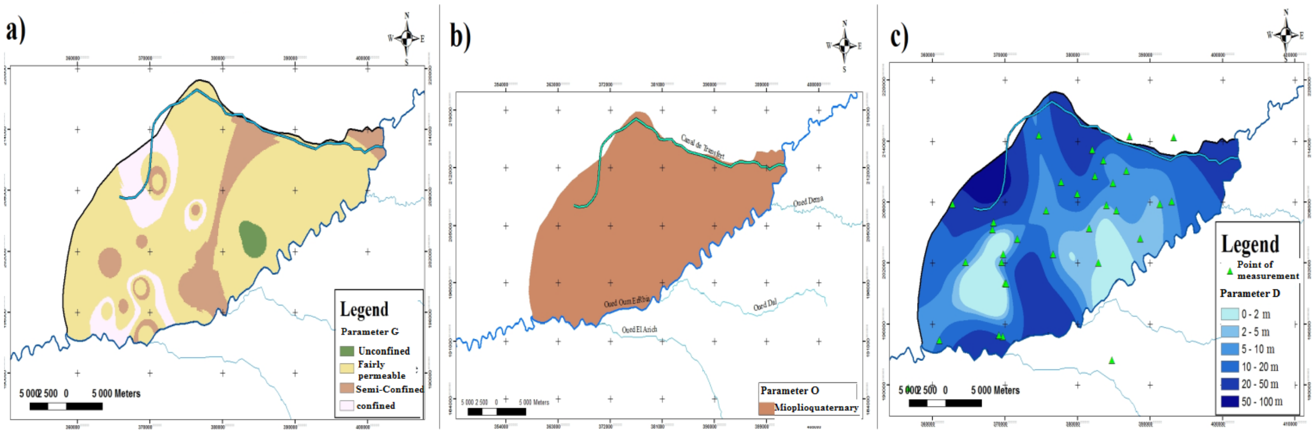

Figure 3: Thematic maps of the Beni Amir groundwater used

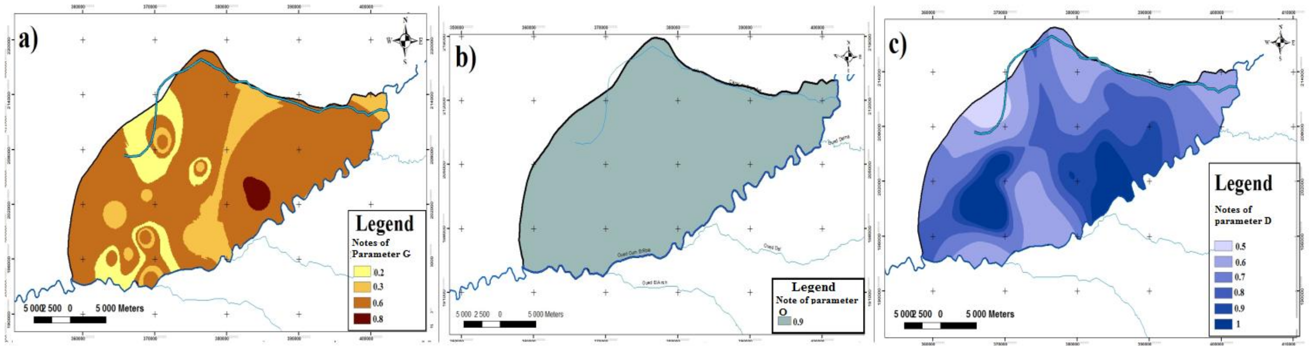

Figure 4: GOD Parameters reclassified

4.2. Overall lithology of aquifer

Figure 3b is the map obtained from the digitization of the geological map 1/50000 of the study area and a conversion to raster mode (Enabling the reclassification according to the rating system of the GOD method).
After reclassification, Figure 4b is the map obtained, it’s shows that the study area contains homogeneous GOD scores throughout the study area. This parameter represents the degree of consolidation of the strata above the water table [23].

4.3. Depth to water table

Figure 3c shows the map of the depth to the water table parameter, which was established from the interpolation of the piezometric measurements using the ordinary Kriging method [13].

After the interpolation of the water levels of the water table, a reclassification of each pixel was then carried out according to the rating system of the GOD method.

Figure 4c is the reclassified map, showing that the depth of the water table decreases gradually from the NW to the SE. The South and SW boundaries are the areas most likely to be contaminated.

The vulnerability index (IGOD) is calculated using equation (1). The values of this index range from 0 to 0.72. They are reclassified according to the classification system of the GOD method shown in Table 3 below:

Table 3: Classes of GOD Vulnerability Index [11].

Vulnerability Index	Class of vulnerability
0	No vulnerability
0-0.1	Negligible
0.1-0.3	Low
0.3-0.5	Medium
0.5-0.7	High
0.7-1	Very High

Figure 5 shows the map of vulnerability to pollution of the Beni Amir aquifer, established using the GOD method, it’s shows the existence of five zones of vulnerability: low, moderate, high, extreme and no vulnerability.

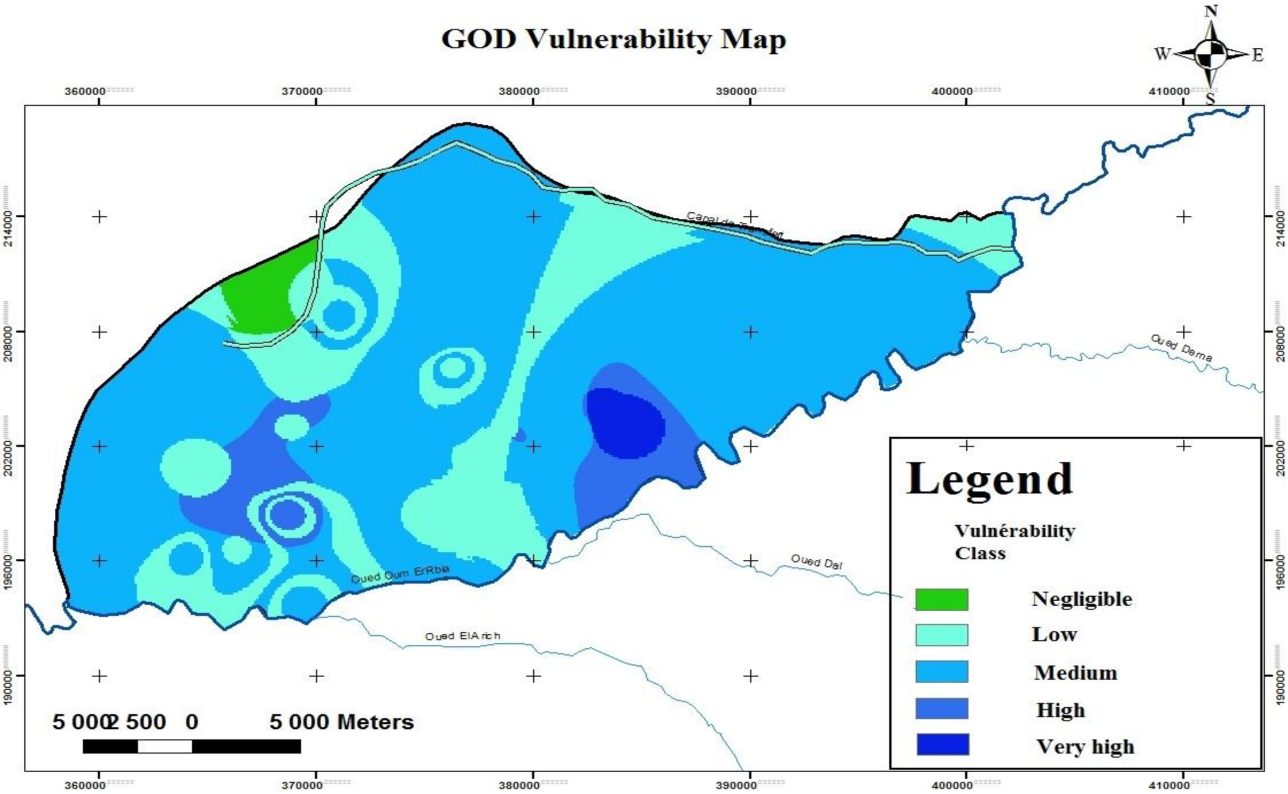

Figure 5 : Carte de vulnérabilité à la pollution de la nappe phréatique des Béni Amir

The analysis of the Figure 6 reveals that low-vulnerability areas account for 24% of the total study area, moderately vulnerable occupy 66%, while high-vulnerability areas occupy 8% (high and extreme) ; They are notably located in the SE and SW of the groundwater. This high vulnerability can be explained by the shallow depth of the water table and its low degree of confinement (semi or unconfined aquifer).

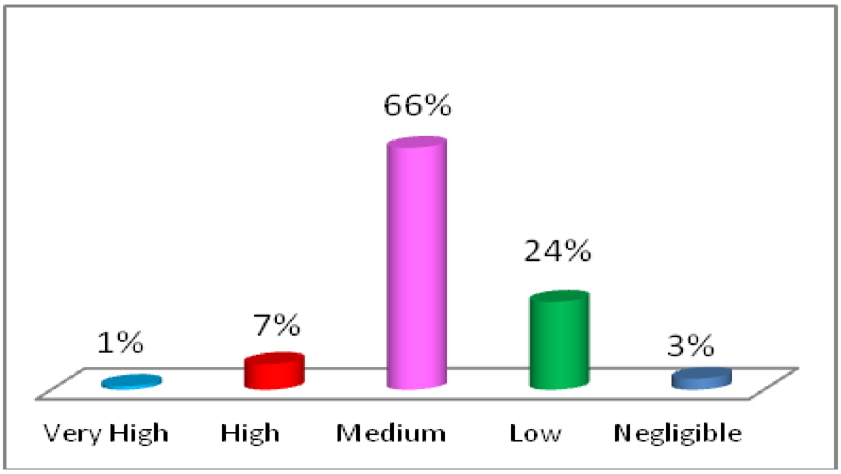

Figure 6: Distribution of the degrees of vulnerability to pollution obtained by the GOD method

5. Discussion

5.1. Statistical analysis

The analysis of Table 4, which presents the averages of the three parameters used to calculate the GOD index, shows that the depth of water "D" and the lithology of the unsaturated zone "O", whose averages are respectively 0.9 And 0.77 are the parameters that most impact the vulnerability of the groundwater to pollution. The type of aquifer "parameter G" (with an average of 0.41) participates in a moderate way to this vulnerability.

Table 4 below also shows that the lithology of the unsaturated zone "O" does not participate in the variations of the GOD index (cv: 0). However, the type of aquifer "G" is a major contributor to changes in the vulnerability index with a coefficient of variation equal to 51.83%. The depth of the water table "D", whose coefficient of variation is equal to 23.12%, represents an average contribution to the change in the vulnerability index.

Table 4 : Summary statistics of the GOD parameters of the Beni Amir groundwater

	G	O	D
Min	0,2	0,9	0,5
Max	0,8	0,9	1
Average	0,41	0,9	0,77
Sd	0,2125	0	0,1780
Cv	51,83%	0,00%	23,12%

5.2. Sensitivity analysis

5.2.1 Test « the map removal sensitivity analysis »

This test is defined by Lodwick and al. (1990) [18] and determines the sensitivity of the vulnerability map to the elimination of one or more parameters, it is calculated by equation 2 below [12]:

$$S = (|V/N - V'/n|/V) * 100 \qquad \text{Equation (2)}$$

- *Where:*

S: measured sensitivity expressed in terms of index of variation
V: undisturbed GOD index
V ': perturbed GOD index.
N: the number of parameters used in the calculation of the index V
N: the number of parameters used in the calculation of the index V '

Table 5 shows the statistical results of the sensitivity analysis performed by the removal each time of a GOD parameter. This test revealed that it is generally the parameter type of the Aquifer "G" with an average variation index of 122.9% which most affects the variation of the GOD vulnerability index. A small variation of the index God of vulnerability is planned during the elimination of lithology of the unsaturated zone "O" and depth to the groundwater table "D", whose averages variation index are respectively: 22.2% and 35.4%.

Table 5: Statistics of the test « Map removal sensitivity analysis »

Parameter removed	Variation index (%)	
	Average	Standard deviation
G	122,9	73,6
O	22,2	0,0
D	35,4	17,5

Conclusions

In this study, a method of scoring system coupled to a GIS was applied to assess the vulnerability to pollution of the Tadla groundwater.
The map established by the GOD method showed that the Beni Amir groundwater is generally of moderate to low vulnerability and that the most vulnerable areas occupy 8% of the total area of the study perimeter.
The statistical analysis and the sensitivity analysis showed that the GOD vulnerability index seems to be sensitive to the elimination of the parameter; type of the Aquifer "G", because of the low scores (the average =0.41) that are assigned to the other parameters. Consequently, the calculation of the vulnerability index from the product of the notes assigned to the parameters; depth to the groundwater and lithology of the unsaturated zone generate higher indices, since the averages of their scores are respectively 0.77 and 0.9. Therefore, caution should be exercised during the determination of the parameter type of the aquifer "G".
The Pollution vulnerability mapping is a powerful tool for identifying high-risk areas of pollution in the study area [9]. In principle, this should be a prerequisite for land-use planning, or at least allow to identify areas where stringent protection measures should be applied.

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