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Sensitivity Analysis and GIS Tools for Groundwater Vulnerability Assessment. (Application in the Middle Chellif Plain, Algeria)

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ABSTRACT

Contamination due to rapid urban development, industrialization, and agricultural sources is increasingly threatening the groundwater resources of the plioquaternary phreatic aquifer of the Middle Western Cheliff. An intrinsic vulnerability assessment was carried out based on the DRASTIC method on parameters involved in the vertical transfer of pollution from the soil surface. The vulnerability maps obtained showed a high extension of areas of medium vulnerability (54%). On the other hand, areas of low vulnerability occupied about 36%. The high and very high vulnerability was mainly related to low water depth values (8% and 2%, respectively). The results of a sensitivity analysis using the two tests—the single parameter sensitivity analysis and the map removal sensitivity analysis—show that every parameter is, without fail, required for the computation of the vulnerability index. The validation of the vulnerability map produced by the DRASTIC method confirmed the evolution of this sensitivity which decreases towards the S.W. of the plain with nitrate concentrations between 30 and 120 mg/L. Planners can use the produced risk maps as tools to make a preliminary choice of priority locations for various forms of environmental sustainability.

Keywords: Vulnerability; DRASTIC method; Sensitivity Analysis; Pollution Middle Cheliff, Algeria.

Análisis de sensibilidad y herramientas SIG para la evaluación de la vulnerabilidad de las aguas subterráneas. (Aplicación en la llanura de Chellif Medio, Argelia)

RESUMEN

La contaminación debida al rápido desarrollo urbano, la industrialización y las fuentes agrícolas amenaza cada vez más los recursos hídricos subterráneos del acuífero freático pliocuaternario del Cheliff medio occidental. En este estudio se llevó a cabo una evaluación de la vulnerabilidad intrínseca basada en el método DRASTIC sobre los parámetros que intervienen en la transferencia vertical de la contaminación desde la superficie del suelo. Los mapas de vulnerabilidad obtenidos mostraron una elevada extensión de zonas de vulnerabilidad media (54%). Por otro lado, las zonas de vulnerabilidad baja ocupaban alrededor del 36%. La vulnerabilidad alta y muy alta estaba relacionada principalmente con valores bajos de profundidad del agua (8% y 2%, respectivamente). Los resultados de un análisis de sensibilidad utilizando las dos pruebas -el análisis de sensibilidad de un solo parámetro y el análisis de sensibilidad de eliminación de mapas- muestran que todos los parámetros son, sin excepción, necesarios para el cálculo del índice de vulnerabilidad. La validación del mapa de vulnerabilidad producido por el método DRASTIC confirmó la evolución de esta sensibilidad que disminuye hacia el S.O. de la llanura con concentraciones de nitrato entre 30 y 120 mg/L. Los planificadores pueden utilizar los mapas de riesgo producidos como herramientas para hacer una elección preliminar de los lugares prioritarios para las distintas formas de sostenibilidad medioambiental.

Palabras clave: Vulnerabilidad; método DRASTIC; Análisis de sensibilidad; Contaminación Medio Cheliff, Argelia.

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1. Introduction

Most agricultural regions of the world are plagued by water pollution. In arid areas, groundwater is the major water supply for domestic, agricultural, and industrial needs. The aquifer of the Middle Chéliff is the only water resource that can be mobilized in the study area. It offers an interesting aquifer potential, and its extension is very important. The preservation of this resource is essential with a participatory and integrated management approach. However, the depletion of aquifer reserves caused by the imbalance between the recharge and extraction of groundwater aggravates the problems related to the pollution of this resource (Haider et al, 2021). Prevention is the most appropriate strategy for groundwater protection (Uzcategui-Salazar & Lillo, 2022). The most widely used methods for assessing vulnerability to aquifer contamination are based on overlay index maps, such as DRASTIC, GOD and AVI. These methods assign weighting and scoring values to hydrogeological features, which introduces some subjectivity in the assessment (Kadkhodaie et al, 2019). Due to population growth and industrialization, large quantities of domestic and industrial effluents are discharged into the nearby river, resulting in groundwater pollution in shallow aquifers (Rahman, 2008).Groundwater vulnerability to contamination, which is a severe problem worldwide (Shirazi et al, 2012) is defined as the tendency or likelihood of contaminants reaching a specified position in the groundwater system after introduction at a location above the uppermost aquifer (NRC, 1993). Groundwater vulnerability mapping can indicate areas more vulnerable to contamination at the planning stage of socio-economic activities (Fritch et al., 2000). Therefore, aquifer vulnerability maps are essential for groundwater management and protection (Zwahlen, 2004). Furthermore, vulnerability maps illustrate different degrees of aquifer sensitivity (Guillaume & Marie, 2015) and provide valuable and necessary information to guide policy choices for the prevention and management of pollution risks to the region's groundwater resources with a view to sustainable management (Ake et al., 2010).

In this work, we consider the problem of vulnerability and pollution risk mapping of groundwater using GIS (Geographic Information System). Our choice was to apply one of the methods of the index mapping category with the weighting of criteria, namely the standard DRASTIC method (Aller et al., 1987) based on parameters that intervene in the vertical transfer of pollution from the soil surface. To assess the effect of each of these parameters on the vulnerability map, a sensitivity analysis was carried out by applying the two tests: "the map removal sensitivity analysis" (Napolitano & Fabbri, 1996) and "the single parameter sensitivity analysis" (Napolitano & Fabbri, 1996).

2. Material and methods

Study area

This study is carried out in the Middle Cheliff, suffering from water scarcity. This area required a large quantity of water not only for farming, the main activity, but also for water supply for a population with 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 (Fig. 1). It extended over an area of 321 km^2 and had a population of about 480,000 as of 2010 (ONS, 2011). The region experiences a semi-arid environment with an average of 520 mm of annual rainfall. A major alluvial aquifer in the Middle Cheliff is used primarily for drinking water, agriculture, and industrial purposes. A recent economic boom, especially in agriculture, has increased the demand for water and degraded the water quality (ABH-CZ, 2004). The pre-Neogene formations and the Neogene-Quaternary formation are the two lithologic sequences that lie beneath the study area, according to geological research (Perrodon, 1957; Mattauer, 1958) (Fig. 2). The pre-Neogene strata (Lower Cretaceous and Oligocene) are made up of a substantial accumulation of sedimentary rocks that are incongruously deposited on top of older levels. Three aquifers with various hydrogeological potentials are present in the basin (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 barrier of the valley. These sediments include clays and marl with beds of sand, gravel, and conglomerates This last aquifer, the subject of our study, has an average annual water withdrawal of about 15.5hm^3 (Chakour & Dahmane, 2012), of which 64% is for drinking water supply, 31% for irrigation, and 5% for industrial purposes (Fig. 4).

In order to have complete coverage of the Middle Chellif plain, a 1/500,000 geological map of northern Algeria was used.

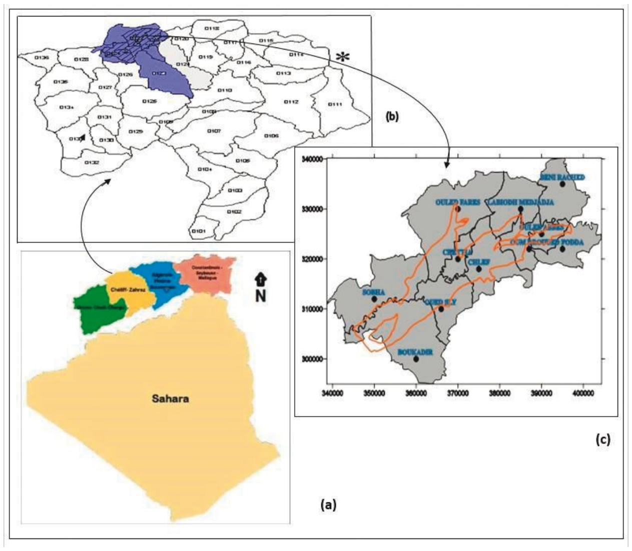


Figure 1. Geographical location map of the study area.

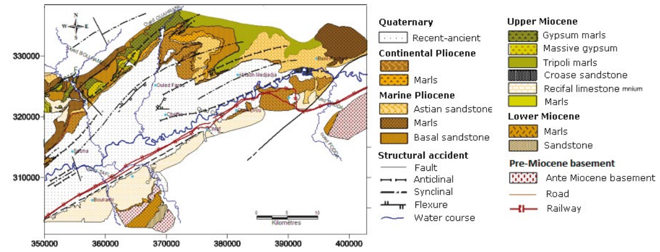


Figure 2. Geological map of the Middle Cheliff basin (Scet- Agri, 1985).

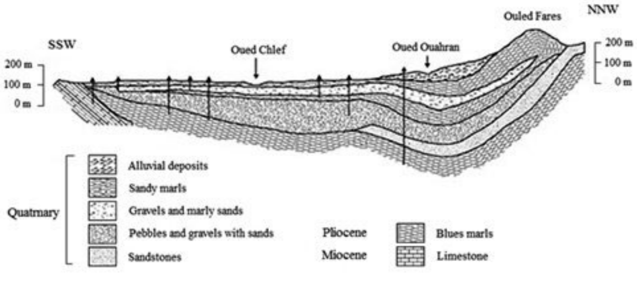


Figure 3. Geological cross section showing the different aquifers (Scet- Agri, 1985).

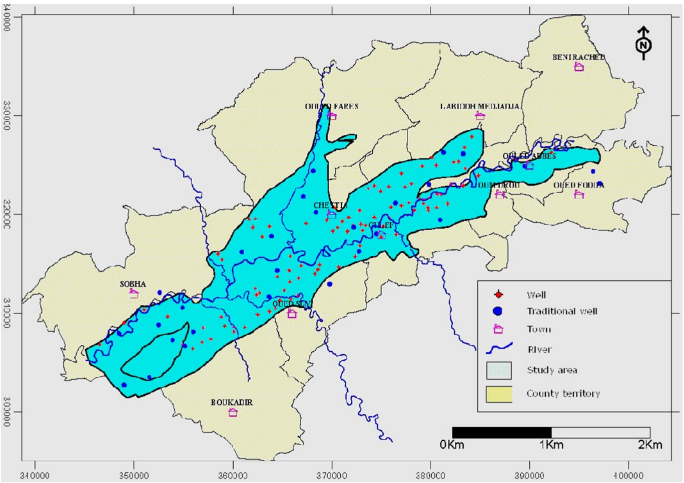


Figure 4. Sampling sites in the alluvial aquifer (Chakour & Dahmane, 2012)

Methodological approach

The type, volume, and dependability of the available data play a major role in determining how vulnerable groundwater is to contamination. (Melloul et al., 2009). This study studied water samples from 14 deep and 61 shallow wells. ANRH and ABH-CZ conducted chemical analyses, respectively, of the National Water Resources Agency and the Cheliff Zahrez River Basin Agency. The assessment of intrinsic vulnerability levels was carried out using the DRASTIC method, considering the availability of data on the required parameters.

DRASTIC method

This technique distinguishes between the vertical susceptibility of a pollution layer at the surface of the earth and its horizontal exposure to pollution that has already reached the layer (Sinan et al., 2003). DRASTIC is the most popular point-counting and matrix evaluation technique (Chen & Fu, 2003) because to its straightforward and basic properties. In addition, the DRASTIC model has been used to estimate the vulnerability of groundwater in other regions of the globe (Zhou et al., 1999).

The DRASTIC approach is a very basic, affordable, multi-criteria method whose parameters are readily accessible and straightforward to analyze. It examines the transfer circumstances under which common pollutants may reach the slick's surface. Developed for the United States Environmental Protection Agency (Andrzej & Kowalczyk, 2007), DRASTIC is an acronym comprised of the initial letters of the characteristics used to create the map: groundwater depth (D), net recharge (R), and aquifer media (A), soil media (S), topography (T), vadose impact (I), and aquifer hydraulic conductivity (C) (C). These are weighted, ranked, and then integrated using a groundwater vulnerability algorithm (Neukum et al., 2008)to get a final rating score. According to the significance of its vulnerability, this approach divides each parameter into intervals with a numerical rating. According to the following equation (1), a DRASTIC index (iD) or vulnerability rating may be derived from these parameters:

$$IDRASTIC = DwDr + RwRr + AwAr + SwSr + TwTr + IwIr + CwCr \quad (1)$$

with:

w and r, respectively, the weight and value of the interval (rating) assigned to each parameter.

The final DRASTIC index ranges from 23 to 226 and is used to quantify the degree of susceptibility of a certain slick region. Because the estimated index (iDRASTIC) is high, openness is crucial. The bigger the value of the DRASTIC index, the more susceptible that portion of the aquifer is to contamination.

Table 1 displays the many data sources used to evaluate the criteria that describe the vulnerability of the alluvial slick of the Western Middle Cheliff plain.

Sensitivity analysis and analysis of the DRASTIC method

Utilizing seven criteria, the DRASTIC technique generates a vulnerability map. Some experts claim that sensitivity to groundwater may be determined without utilizing all of these criteria (Barber et al., 1993 ; Merchant, 1994). Others [10] have claimed that the model's weights and scores are subjective and that, in the lack of experimental data, there is no reason to reject the accuracy of the vulnerability index so produced. To eliminate such uncertainties, a sensitivity analysis of the model was conducted. First, the dependency and variability of the model's parameters will be investigated (Babiker et al., 2005; Rosen, 1994). Then, two sensitivity tests were conducted: "the map removal sensitivity analysis," which was established by Lodwick et al.(1990), and "the single parameter sensitivity analysis," which was provided by Napolitano & Fabbri (1996).

Table 1. Weight and mode of acquisition of the seven parameters of the DRASTIC method.

Parameters	Weight	Data sources
D	5	• Piezometric directory of the Middle Cheliff Plain (DRE-Chlef)
R	4	• ANRH Precipitation and ONM Temperature • AGRI Water Resources-Set (ONID)
A	3	•Drilling cuts in the Middle West Cheliff area (DRE-Chlef) •Geological map of the Middle West Cheliff area (Set AGRI, 1985)
S	2	•Map of the soils of Algeria plain of Cheliff 1:50000 (Boulaine, J 1956) •Map of the Plains of the Middle West Cheliff (ABH-Chlef)
T	1	•Topographic map of the Zahrez Watershed 1:200,000 (DHW-Chlef) •Topographic map of the wilaya of Chlef 1:200000
I	5	•Drilling cuts in the Middle West Cheliff area (DHW-Chlef)
C	3	•Hydrogeological Cup (ABH-CZ) •Drilling report 77.SHYG.18 (D. Pradines, 1977) •STUDY No.33 GE (Schrambach, 1966)

The first test identifies the sensitivity of the vulnerability map by removing one or more layers from the map. The following equation calculates it:

$$S = (|V/N - V'/n|/V) * 100 \quad (2)$$

With:

S is the measured sensitivity expressed in terms of the index of variation.

V is the undisturbed DRASTIC vulnerability index

V' is the disturbing vulnerability index

N and n are the numbers of layers used in calculating the indices.

The "single parameter sensitivity analysis" test was designed in order to evaluate the effect of DRASTIC parameters on the vulnerability index. It compares the actual weights given to input parameters to the theoretical weights. The effective weights are computed using the following equation:

$$W = \left(\frac{PrPw}{v}\right) * 100 \quad (3)$$

With:

W effective weight of a parameter.

Pr and Pw are the weights and the value of the interval (rating) assigned to this parameter.

V is the DRASTIC vulnerability index.

Creation of thematic maps

The DRASTIC method requires seven parameters. The reliability of these parameters depends on the data used for their realization. Several parameters, such as the depth of the water table map, established by kriging using Golden software's Surfer which require a data such as (X,Y,Depth). Other parameters uses a numerical rating system based on the parameterization of the various factors influencing the hydrogeological system of vulnerability. The difficulty of applying DRASTIC method is the limits of the classes and the ratings that are assigned to the different parameters. Indeed, the boundaries of standard classes not often reflect the reality of the study area because these classes may group together different entities.

3. Results and discussion

Vulnerability map by the DRASTIC method

For the Parameter depth of water "D", the depth of the water table is a crucial parameter in the characterization of vulnerability by the DRASTIC method. It is therefore assigned a maximum weight of 5. The depth of the water body in the Middle Western Cheliff aquifer varies from 6 meters in the central zone of the aquifer and in the vicinity of Oued Cheliff to more than 50 meters at the edges of the aquifer (Figure 5a). These values have been classified according to the ranges established in the DRASTIC rating system tables. For the parameter Net recharge 'R,' evaluating the adequate recharge of the water table is often complicated to achieve without prior hydrogeological and hydrological studies. The amount of water infiltrated over the whole study area is between 5 and 10 cm/year (5 cm/year on the edges of the aquifer and 10 cm/year in the significant bed of the wadi) (Scet- Agri, 1985). This figure corresponds to a low partial vulnerability index, i.e., I.R. = 12 (Figure 5b).

For the parameter aquifer environment "A": From the hydrogeological sections obtained by Scet-Agri (1985) and the lithological description of the drill sections, the constituent materials of the saturated zone of the aquifer may be determined (Figure 5c).

For the parameter soil type "S," the pedological study by Boulaine (1959) is the main study carried out in northern Algeria. Therefore, this study covers the whole of our region, which makes it easy to deduce the soil types included in our area (Figure 5d).

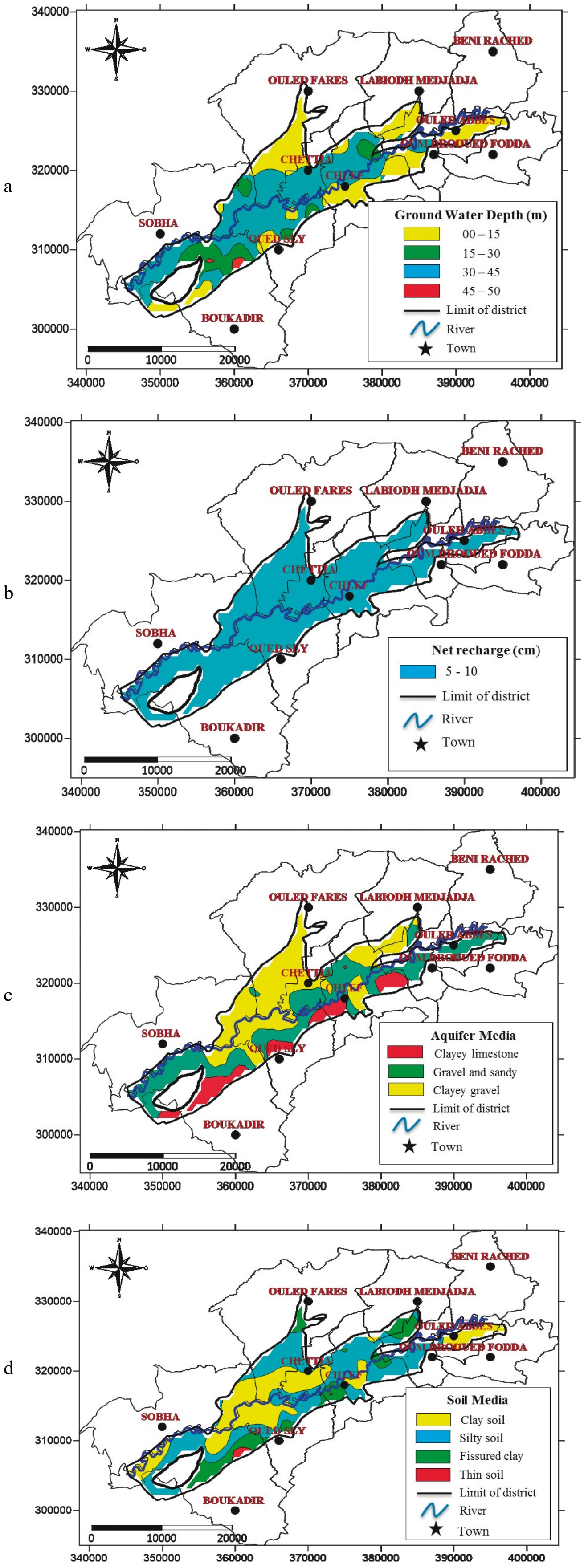
For the parameter Topography "T," The plain of the western middle Cheliff does not represent significant differences in level; nevertheless, a class of slopes was deduced, which means the quasi-totality of the present plain, these fragile slopes included between 0 and 2%, this class is assigned a partial index is equal to 30(Figure 5e)

For the parameter impact of the unsaturated zone "I," as for the "I" parameter, the lithology of the unsaturated zone described by examining the hydrogeological sections carried out, and the boreholes make it possible to distinguish three zones characterized by a different partial vulnerability index (Figure 5f).

For the Hydraulic conductivity "C" This parameter depends on the nature and texture of the materials making up the aquifer. A great deal of work has been done to determine the hydrodynamic characteristics of the limestone aquifer, and the alluvial aquifer through pumping tests carried out in the region. In particular, the work of Pradines in 1977 (drilling report No. 77. SHYG.18) and that of Schrambach in 1966 (study No. 33 G.E.). The results obtained determined permeability coefficients of $6.6 .10^{-5}$ to $1.8 .10^{-5}$ m/s for the limestone water table and $0.6 .10^{-4}$ to $0.05 .10^{-2}$ m/s for the quaternary alluvium water table (El Meddahi, 2009).

The average values thus determined for the region under study allow the DRASTIC rating tables to highlight the different zones, each characterized by a partial iC index (Figure 5g).

The research area has been subdivided into a mesh of cells, each 727 m x 727 m, in accordance with the distribution of various factors in order to provide more statistical data on the frequency of occurrence of each vulnerability class. The final grid consists of 608 cells covering a total of 321.35 km^2. The DRASTIC technique reveals four categories of vulnerability (Fig. 6 and 7).



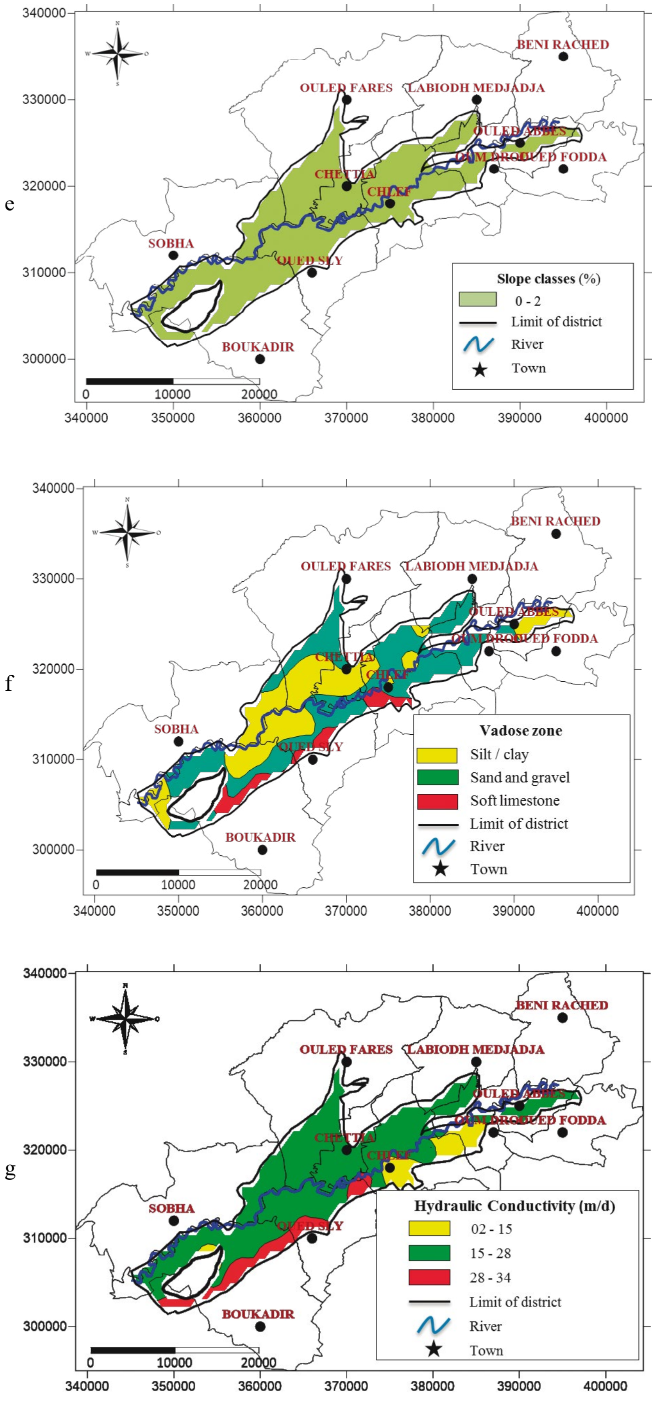


Figure 5. Maps of the seven parameters of the DRASTIC method: A: "D" depth of the water; B: "R" net recharge.; C: "A" aquifer environment; D: "T" map topography; E: "I" parameter impact of the unsaturated zone; "C" hydraulic conductivity; F: The aquifer vulnerability to pollution by the DRASTIC method.

The "low" class reflects a low vulnerability to pollution and represents only 36% of the mapped area. The typical vulnerability index observed results from the relatively high depths and the non-permeable silty clay soil type in the center of the plain.

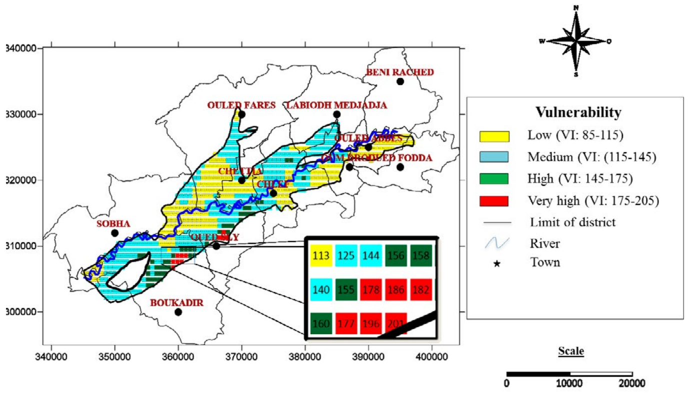


Figure 6. The aquifer vulnerability to pollution by the DRASTIC method.

Table 2. Distribution of the degree of vulnerability according to the DRASTIC method (ABH-CZ, vol 1, 2000)

Vulnerability class	Minimum	Maximum	Area %	Number of cells	Symbol
Low	84	114	36	220	🟨
Medium	114	145	54	331	🟦
High	145	175	08	46	🟩
Very High	175	226	02	11	🟥

The 'medium' class occupies the largest percentage (54%) of the plain, extending from the southwest to the northeast. The medium degree of susceptibility is due to the combination of the lithological composition of the unsaturated layer, which consists of a mixture of silt clay and sand gravel, and shorter depths, resulting in less severe pollution.

The "High and Very high" class is represented by a rate of (8% and 2%, respectively), with the bulk of these two classes being concentrated on the borders of the plain at the interface of the soft limestone nappe (Miocene with lithothamnium), along the Boukadir and Oued Sly area.

These two classes are located along the plain's margins, at the interface of the soft limestone nappe (Miocene with lithothamnium), on the Boukadir and Oued Sly side (Figure 7).

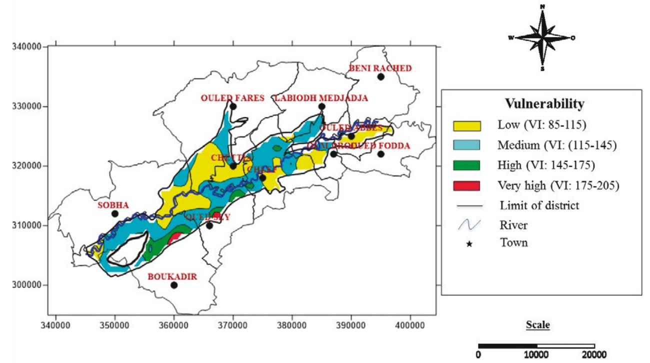


Figure 7. Map of risk to pollution of the aquifer by DRASTIC method.

The very high vulnerability index is due to the combination of the following parameters:

- The overlap of the piezometric surface with the ground surface (depth less than 9m); and the low slope (less than 1%) favors any pollutant's infiltration.
- The lithology of the vadose layer consists of soft limestone, gravel, and coarse sand.

Sensitivity of the DRASTIC model

Table 3 shows the summary statistics of the seven parameters used to calculate the DRASTIC index in the Middle Western Cheliff plain. The analysis of the averages shows that the most significant risk of groundwater contamination in the Middle Western Cheliff plain is favoured by the parameters "aquifer, hydraulic conductivity and depth of the water table" (whose averages are 25.6; 23.2 and 20.5). However, the parameters "recharge and soil" participate with a moderate risk (average is 12), and the parameters topography, impact of the unsaturated zone favour a low risk (average: 10).

The coefficient of variation shows that the major contribution to the variations of the vulnerability index is due to the parameter "impact of the unsaturated zone" (CV: 133.21%). The parameters "Depth, Soil, and Hydraulic Conductivity" show a medium contribution (CV: 66.90%; 38.25% and 30.63%). However, the topography, recharge, and aquifer represent a low to zero contribution to the variation of the vulnerability index (CV: 11.65; 0 and 0).

Table 3. Summary statistics of DRASTIC parameters

	D	**R**	**A**	**S**	**T**	**I**	**C**
MIN	5	12	18	6	10	5	3
MAX	50	12	30	20	10	50	30
MEAN	20.5	12	25.6	12	10	10	23.2
SD	13.76	0.00	2.98	4.56	0.00	13.32	7.13
CV	66.90%	0.00%	11.65%	38.25%	0.00%	133.21%	30.63%

SD: standard deviation; **CV:** coefficient of variation

The" Map removal sensitivity analysis" test

The results of the "Map removal sensitivity analysis" test, based on removing one or more parameters at a time, are shown in Tables 4 and 5.

Table 4 shows the variation in the vulnerability index as a result of removing a single DRASTIC parameter. It is clear that the removal of either parameter results in a considerable variation in the vulnerability index. The parameters "depth, aquifer medium, topography, unsaturated zone, and hydraulic conductivity" are the most responsible index variation (1.20; 1.05; 1.02; 1.55, and 1.07). Vulnerability seems very sensitive to removing the parameters "unsaturated zone" and "depth."

Table 5 presents the variations in the vulnerability index due to the removal of one or more parameters. The removal of layers was based on the map removal sensitivity analysis shown in the table. The layer with a minor influence on the variation of the vulnerability index is preferentially removed. The removal of any parameter shows no trend in the variation index, which means that all parameters are, without exception, necessary for calculating the vulnerability index, as reported in some previous studies (Babiker et al., 2005; Napolitano and Fabbri, 1996).

Table 4. The statistics of the "Map removal sensitivity analysis" test

Removed parameters	**Variation index (%)**		
	Mean	Min	Max
D	1.20	0.17	3.98
R	0.75	0.6	1.39
A	1.05	0.6	2.43
S	0.86	0.6	1.74
T	1.02	0.44	1.56
I	1.55	0.37	3.43
C	1.07	0.6	2.27

Table 5. The statistics of the "Map removal sensitivity analysis" test

Used parameters	**Variation index (%)**		
	Mean	Min	Max
I, D, C, A, T, and S	0.75	0.06	1.39
I, D, C, A, and T	1.93	0.71	3.41
I, D, C and A	3.95	1.99	6.23
I, D, and C	3.34	0.44	7.94
I and D	3.72	0.06	14.29
I	9.29	2.2	20.6

The "Single-parameter sensitivity analysis" test

After the importance of the seven parameters in calculating the vulnerability index was highlighted by the "Map removal sensitivity analysis" test, the objective of applying the "Single-parameter sensitivity analysis" test in this section is to complete and confirm the first results. This test consists of a comparison between the theoretical and practical weights of the parameters. Table 6 shows the results of the test and shows that the parameters "aquifer, soil, topography and hydraulic conductivity" are the parameters that have the most significant influence on vulnerability in the study area, as their average effective weights (21%, 09%, 08%, and 18% respectively) are higher than their theoretical weights, which is all the more reason to look for more detailed information on these four factors.

Validation of pollution vulnerability maps

From the maps obtained by the DRASTIC method, it can be seen that the central-east and the edges of the plain are the most vulnerable areas to pollution. This sensitivity decreases towards the S.W. Validation of these maps is necessary, as any vulnerability map elaborated must be tested and validated by measurements and chemical analysis of groundwater (Ake et al., 2009). For this purpose, the distribution of nitrates in the groundwater from the May 2012 campaign was used (Figure 8).

Table 6. Statistics of the "Single-parameter sensitivity analysis" test.

Parameters	**Theoretical weight**	**Theoretical weight**	**Effective weight %**		
		%	**Mean**	**Min**	**Max**
D	5	21.7%	16	03	38
R	4	17.4%	10	06	14
A	3	13.0%	21	15	29
S	2	8.7%	09	04	15
T	1	4.3%	08	05	12
I	5	21.7%	18	04	35
C	3	13.0%	18	02	28

The nitrate concentrations in the groundwater range from 30 to 120 mg/L. From this distribution, we can deduce that nitrate pollution decreases from the N.E. to the S.W. of the groundwater. The vulnerability map produced by the DRASTIC method confirmed this evolution. Indeed, the zones with average nitrate levels (30 to 70 mg/L) are superimposed on the zones with moderate and low vulnerability indices; the zones with maximum nitrate concentrations (over 100 mg/L) coincide with the zones of high and very high vulnerability.

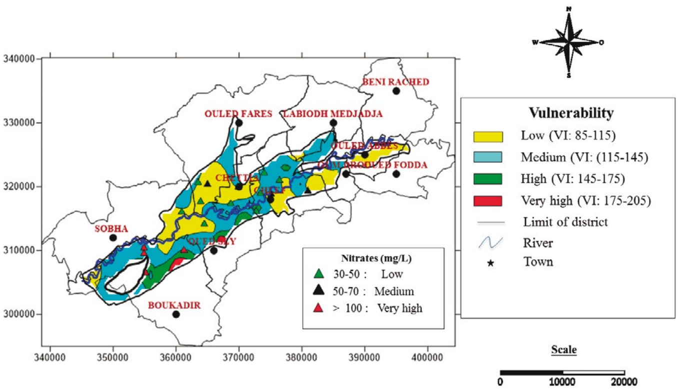


Figure 8. Map of the spatial distribution of nitrate concentrations (May 2012).

Conclusion

Drought and overexploitation of groundwater can lead to excessive pumping, which can cause the water table to deepen, which in turn can increase the vulnerability of aquifers to pollution, mainly through irrigation backflow and seepage of wastewater. This is particularly the case for the Middle Cheliff aquifer in northwest Algeria, which has a semi-arid climate. The mapping of the intrinsic vulnerability of this alluvial aquifer using the DRASTIC method has enabled four main classes of exposure to be defined (low, medium, high, and very high).

The medium class is dominant (54%) in the study area, followed by the low class located in the center of the plain (36%) of the total area. The strong and powerful types (8% and 2%, respectively) of the total area are presented at the Miocene lithothamnium water table interface with high conductivity. The 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.

References

ABH-CZ. (2004). *Cadastre hydraulique du bassin hydrographie du Cheliff – aval du barrage Boughzoul – première partie. Haut et Moyen Cheliff.* Hydrographics Basins Agency Publications: Algiers, Algeria, 62 pp.

Ake, G. K., Kouassi, B. H., Kouadio, D., Dibi, B., Saley, M. B., & Biemi, J. (2009). Contribution des méthodes de vulnérabilité intrinsèque DRASTIC et GOD à l ́étude de la pollution par les nitrates dans la région de Bonoua (Sud-Est de la Côte d ́Ivoire). *European Journal of Scientific Research*, 31(1), 157–171.

Ake, G. E., Kouadio, H. B., Dongo, K., Dibi, B., Kouame, F. K., & Biemi, J. (2010). Application des méthodes DRASTIC et SI pour l ́étude de la vulnérabilité à la pollution par les nitrates (N03-) de la nappe de Bonoua (Sud-Est de la Côte d ́Ivoire). *International Journal of Biological and Chemical Sciences,* 4(5), 1676-1692 https://doi.org/10.4314/ijbcs.v4i5.65557

Aller, L., Bennet, T. J., Lehr, H., Petty, R. J., & Hackett, G. (1987). *DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings.* EPA- 600/2-87-035, Ada, Oklahoma. https://doi.org/EPA-800/2-87-035.

Andrzej, J., Kowalczyk, W. A., & Vrba, J. (2007). *Groundwater Vulnerability Assessment and Mapping.* IAH-Selected Papers, Vol. 11, CRC Publication, London, England, 260 pp. https://doi.org/10.4324/9780203934586

Babiker, I. S., Mohamed, M. A., Hiyama, T., & Kato, K. (2005). A GIS-based DRASTIC model for 409 assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan. *Science of Total Environment,* 345(1-3), 127-140, https://doi.org/10.1016/j.scitotenv.2004.11.005,

Barber, C., Bates, L. E., Barron, R., & Allison, H. (1993). Assessment of the relative vulnerability of 421 groundwater to pollution: A review and background paper for the conference workshop on vulnerability assessment. *Journal of Australian Geology and Geophysics (AGSO),* 14(2-3), 147-154. https://sid.ir/paper/628229/en

Chakour, F. Z., & Dahmane, S. (2012). *Etude de l'évolution piézométrique des eaux souterraines de la nappe alluviale du Moyen Cheliff Occidental.* [Master Thesis, Hassiba Ben Bouali University, Chlef, Algeria.]

Chen, S. Y., & Fu, G. T. (2003). A DRASTIC-based fuzzy pattern recognition methodology for groundwater vulnerability evaluation. *Hydrological Sciences Journal,* 48(2), 211–220. https://doi.org/10.1623/hysj.48.2.211.44700

El Meddahi, Y. (2009). *Contribution à l'étude hydrogéologique des réservoirs aquifères du bassin du Moyen Cheliff.* [Magister Thesis, Hassiba Ben Bouali University, Chlef, Algeria.]

Fritch, T. G., McKnight, C. L., Yelderman, J. C. Jr., & Arnold, J. G. (2000). An aquifer vulnerability assessment of the Paluxy aquifer, Central Texas, USA, using GIS and a modified DRASTIC approach. *Environmental Management,* 25(3), 337–345. https://doi.org/10.1007/s002679910026

Guillaume, M., & Marie, L. (2015). *Étude de la vulnérabilité de l'eau souterraine sur la zone Bécancour (Centre-du-Québec).* Géohydro2011 Conference paper. 7pp

Haied, N., Khadri, S., Foufou, A., Azlaoui, M., Chaab, S., & Bougherira, N. (2021). Assessment of groundwater pollution vulnerability, hazard and risk in a semi-arid region. *Journal of Ecological Engineering,* 22(10), 1-13. https://doi.org/10.12911/22998993/142234.

Kadkhodaie, F., Asghari Moghaddam, A., & Barzegar, R. (2019). Optimizing the DRASTIC vulnerability approach to overcome the subjectivity: a case study from Shabestar plain, Iran. *Arab Journal of Geosciences,* 12(527). https://doi.org/10.1007/s12517-019-4647-y

Lodwick, W. A., Monson, W., & Svoboda, L. (1990). Attribute error and sensitivity analysis of map operations in geographical information systems: suitability analysis. *International Journal of Geographical Information Systems,* 4(4), 413–28. https://doi.org/10.1080/02693799008941556

Mattauer, M. (1958). *Etude géologique de l'Ouarsenis oriental, Algérie.* Algerian Geological Map Survey Publications, No. 17, Algiers, Algeria.

Melloul, A., Boughriba, M., & Boufaida, M. (2009). Etude de la contamination des ressources en eaux souterraines et cartographie de la vulnérabilité d'un aquifère soumis au climat semi-aride méditerranéen: cas de la plaine côtière de Saidia, Maroc. *Sécheresse,* 20 223–231. https://doi.org/10.1684/sec.2009.0183

Merchant, J. W. (1994). GIS-based groundwater pollution hazard assessment: a critical review of the DRASTIC model. *Photogrammetric Engineering and Remote Sensing,* 60(9), 1117-1128.

Napolitano, P., & Fabbri, A. (1996). *Single-Parameter Sensitivity Analysis for Aquifer Vulnerability Assessment Using DRASTIC and SINTACS.* IAHS Publication N°. 235, International Association of Hydrological Sciences, No.2 Vienna, Austria, 559-566. http://hydrologie.org/redbooks/a235/iahs_235_0559.pdf

National Research Council. (1999). *Groundwater Vulnerability Assessment, Contamination Potential under Conditions of Uncertainty*. National Academy Press, Washington, D.C., USA, 210 pp.

Neukum, C., Hötzl, H., & Himmelsbach, T. (2008). Validation of vulnerability mapping methods by field investigations and numerical modeling. *Hydrogeology Journal,* 16, 641–658. https://doi.org/10.1007/s10040-007-0249-y

ONS. (2011). *Annuaire Statistique de l'Algérie, Algérie en quelques Chiffres et données Statistiques.* National Office of Statistics, Algiers, Algeria

Perrodon, A. (1957). Etude géologique des bassins néogènes sublittoraux de l'Algérie nord Occidentale, [PhD. Thesis, Nancy University, France.]

Rahman, A. (2008). A GIS based DRASTIC model for assessing groundwater vulnerability in shallow aquifer in Aligarh, India. Applied Geography, 28(1), 32–53. https://doi.org/10.1016/j.apgeog.2007.07.008.

Rosen, L. (1994). A study of the DRASTIC methodology with emphasis on Swedish conditions. *Groundwater,* 32(2), 278–285. https://doi.org/10.1111/j.1745-6584.1994.tb00642.x

Scet-Agri. (1985). *Hydrologie et bilan des ressources, étude de réaménagement et de l'extension du périmètre du Moyen Cheliff.* Ministry of Hydraulics, Algiers, Algeria.

Shirazi, S. M., Imran, H. M., & Akib S. (2012). GIS-based DRASTIC method for groundwater vulnerability assessment: a review. *Journal of Risk Resources,* 15(8), 991–1011.

https://doi.org/10.1080/13669877.2012.686053.

Sinan, M., Maslouhi, R., & Moumtaz, R. (2003). *Utilisation des SIG pour la caractérisation de la vulnérabilité et de la sensibilité à la pollution des nappes d'eau souterraine, Application à la nappe du Haouz de Marrakech, Maroc.* 2nd FIG Regional Conference, Marrakech,

Uzcategui-Salazar, M., & Lillo, J. (2022). A New Approach to Pollution Vulnerability Assessment in Aquifers Using K-means Analysis. *Environmental Earth Sciences,* 81, 495. https://doi.org/10.1007/s12665-022-10591-7

Zhou, H. C., Wang, G. L., & Yang, Q. (1999). A multi-objective fuzzy pattern recognition model for assessing groundwater vulnerability based on the DRASTIC system. *Hydrological Sciences Journal,* 44(4), 611–618. https://doi.org/10.1080/02626669909492256

Zwahlen, F. (2004). *Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers, COST Action 620, Final Report.* European Commission Directorate-General XII, Science, Research and Development, Report EUR 20912, COST Action 620, Luxembourg, Belgium, 297 pp.