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Assessment of groundwater vulnerability to pollution using DRASTIC and the SI methods: case of the alluvial aquifer in Tadjenanet- Chelghoum laid (East Algeria)

Valutazione della vulnerabilità delle acque sotterranee all'inquinamento mediante i metodi DRASTIC e SI: il caso dell'acquifero alluvionale di Tadjenanet-Chelghoum (Algeria orientale)

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Riassunto

La regione di Chelghoum Laid - Tadjenanet si trova in Algeria orientale, negli altopiani meridionali di Setif, che sono caratterizzati dalla presenza di un acquifero superficiale altamente vulnerabile. La vulnerabilità delle acque sotterranee agli inquinanti è un concetto relativo, non misurabile direttamente. La natura, la qualità e l'attendibilità dei dati utilizzati hanno un impatto importante sulla correttezza della sua valutazione. La sua classificazione si basa solitamente sulla stima di molti fattori più o meno essenziali, come le caratteristiche del suolo e della zona insatura, della zona satura, la ricarica, la topografia e la conducibilità idraulica. La vulnerabilità dell'acquifero all'inquinamento è stata indagata utilizzando due metodi di vulnerabilità intrinseca: DRASTIC e indice di suscettibilità (SI). Il metodo SI costituisce un adattamento del DRASTIC al caso specifico di inquinamento da nitrato. I parametri usati come input sono, tra gli altri, la profondità della falda, il tipo di suolo, la pendenza topografica e la ricarica della falda. La validità dei due metodi applicati per stimare la vulnerabilità ai nitrati è stata verificata confrontando la distribuzione della concentrazione di nitrati con la distribuzione delle diverse classi di vulnerabilità ottenute. Le tecniche SIT sono state utilizzate per implementare questi metodi. Le carte di vulnerabilità create utilizzando il metodo DRASTIC e SI rappresentano la suscettibilità dell'acquifero alla penetrazione e diffusione degli inquinanti nelle falde considerate, a seconda del tipo di terreno e della profondità della falda. Il confronto ha rivelato che la tecnica SI è la più accurata nel sistema in esame. L'elaborazione della carta di vulnerabilità all'inquinamento ha evidenziato un'area di grande vulnerabilità al centro della pianura, dovuta alla fragilità del suolo e alla bassa profondità della falda. Mentre le aree di vulnerabilità media sono al centro e ad est, al margine del Wadi Rhumel, e poi il resto dell'area è leggermente vulnerabile. Le carte di vulnerabilità e di rischio di contaminazione create in questo studio sono strumenti preziosi per la pianificazione ambientale e possono essere utili alla gestione delle risorse idriche sotterrannee, anche in termini predittivi. L'approccio usato in questo caso studio potrebbe essere replicabile ad altre aree, al fine di supportare la gestione delle risorse idriche sotterranee.

Abstract

The region of Chelghoum Laid - Tadjenanet is located in the east of Algeria in the high southern plains of Setif, characterized by a highly vulnerable shallow alluvial aquifer. The vulnerability of groundwater to pollutants is a relative concept, not measurable or dimensional. The nature, quality, and reliability of used data used have a major impact on the correctness of its assessment. Its classification is usually based on the estimation of many more or less essential factors, such as the characteristics of soil and unsaturated zone, the saturated zone, the recharge , the topography and the hydraulic conductivity. The vulnerability of the aquifer to pollution was investigated using two intrinsic vulnerability methods: DRASTIC and susceptibility index (SI). SI method is an adaptation of the DRASTIC specifically design for nitrate-based pollution. The parameters used as input data are, among others, the depth of the groundwater, the soil type, the topographic slope and the groundwater recharge.
The validity of the two methods for assessing the vulnerability to nitrates was established by comparing the distribution of these elements in groundwater with the distribution of the various vulnerability classes.
GIS techniques were used to implement these methods. Vulnerability maps created using the DRASTIC and SI method's depict the potential for pollutants to penetrate and spread in these locations depending on the terrain encountered on the surface and the depth of the aquifer. The comparison revealed that the SI technique is the most accurate in the studied alluvial aquifer. The establishment of the pollution vulnerability map highlighted an area of great vulnerability in the center of the plain, reflected by the fragility of the soil and the shallow depth of the water. While the average vulnerability areas are in the center, and east at the periphery of Wadi Rhumel, the rest of the field is slightly vulnerable. The vulnerability and contamination risk maps created for this study are valuable tools for environmental planning and can be used for predictive management of groundwater resources. This case study suggests that the approach may be applicable to other areas as part of efforts to target groundwater management efforts.

Introduction

In most countries, especially in dry and semi-arid regions, groundwater is the primary supply of freshwater for household, agricultural, and industrial needs. Shallow groundwater is much easier to extract than deep groundwater, but it is susceptible to pollutants and its quality is rapidly affected by natural water-rock interactions and anthropogenic activity (Arzu & Fatma, 2013; Hirata & Bertolo, 2009; Moratalla et al., 2011). As a result, shallow groundwater necessitates extra care and protection.

The plain of Tadjnanet-Chelghoum Laid, with an agricultural vocation, is located in the North East of Algeria where the various water needs are provided by groundwater from the surficial alluvial aquifer.

The groundwater in the alluvial aquifer is usually of high quality because it receives a lot of recharge from the Rhumel wadi. The surface layer of the subsoil characterizing the unsaturated zone is typically composed of clays, sands and gravels, which allow both the groundwater to infiltrate and flow quickly through the pores and the pollutants to travel easily through the unsaturated zone. A minor disturbance caused by natural processes or human activities can significantly alter the chemical constituents and quality of groundwater (Zouhri & Armand, 2021).

It is, therefore, necessary to take it into account to ensure effective water management (Jarray et al., 2017). Indeed the combination of geological, geophysical, hydrogeological, and hydrochemical cartography of the data collected on the ground and their interpretations, can constitute an excellent tool to apprehend the great aquifer potentialities, their spatial distribution, and their degrees of vulnerability to different types of natural pollution or anthropogenic.

Water salinity is primarily a natural origin by dissolving the surrounding formations and anthropogenic by irrational use of forms of nitrogen in agriculture. The presence of terrigenous salt formations could affect water quality.

Increased human activities of the last decades have contributed to the deterioration of groundwater quality in the porous aquifer. Intense agriculture, the absence of aquifer protection zones and the overuse of fertilizers have caused the groundwater to become polluted by nitrate. The protection of the porous aquifer is of utmost importance to sustain the water supply in the study area, whereas a nitrate pollution vulnerability and risk map may constitute the initiation of an integrated protection and management plan. The aim of this study is mainly concerned with the vulnerability to pollution of the alluvial aquifer of Tadjenanet-Chelghoum Laid, which supplies two large populations located along Rhumel wadi. The water from this aquifer has been known in recent times a total degradation due to the presence of many sources of pollution characterizing various domestic and industrial discharges without prior treatment. The study area is mainly made up of agricultural land where the use of fertilizers and pesticides is a common practice.

Material and methods

Geological and hydrogeological settings

The investigated area is part of the western area of the great watershed Kebir Rhumel, which is located in eastern Algeria. The climate in the area is semi-arid, with a wet and cold winter and a hot, dry summer.

The study area is surrounded by mountains of carbonate nature of Cretaceous age characterizing the mountains of Djebel Tnoutit in the South-West and Djebel Grouz in the North-East, and by Eocene carbonate formations forming Djebel Ed Dess in the North West and Jebel Chebka to the southeast. All these formations delimiting the study area constitute a supply limit of the alluvial aquifer.

The topography of the plain is almost flat with a slope not exceeding 2%, and altitudes ranging from 920 to 720 m northwest and southeast. This morphology is monotonous and sometimes interrupted by a few hills scattered across the plain. The area is mainly covered with Neogene-Quaternary formations corresponding to clays, marls, silts, alluviums and limestone (Fig. 1).

From a stratigraphic point of view, the formations encountered are essentially of continental and lacustrine origin. These are mainly red clays, marls, benches of lacustrine limestone, sandstone and conglomerate. The whole has variable thicknesses.

Hydrogeological studies have shown the existence of a shallow aquifer in the Tadjnanet-Chelghoum Laid region located in the alluvial Miocene-Quaternary formations. The aquiclude at the base of the alluvial deposits is composed of clays, marls, and gypsum (CGG, 1973; Khedidja & Boudoukha, 2014). It is an unconfined aquifer whose thickness varies between ten meters on the limits and a hundred meters in the center of the plain. These alluviums have an average permeability of 10-4 m/s (Khedidja, 2016). This aquifer is characterized by a flow converging towards the East, characterized by closed equipotential lines of West-East direction which coincides with the morphology of the bedrock. The spacing of the equipotential lines reflects an average hydraulic gradient of around 3% (Khedidja, 2016) (Fig. 1). The presence of salt formations could have an impact on water quality.

The development of a water balance using the Thornthwaite method in the station of Hammam Grouz for a period of 24 years (1989 to 2012) demonstrates that this location is in deficit, with annual average rainfall and temperature of 374 mm and 16°C, respectively. Actual evapotranspiration accounts for 92% of precipitation, while infiltration accounts for only 1.5% of total precipitation (7 mm) (Khedidja, 2016, O.N.M, 2009). This shows that groundwater recharging is accomplished not only through effective infiltration but also with the presence of a water supply zone from carbonate formations located on the periphery of the study zone.

The physico-chemical analysis of 33 samples distributed over the study area during May 2016 (Khedidja, 2016), allowed us to observe that water chemistry of the alluvial

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aquifer is characterized by a dominant chemical facies of calcium bicarbonate type, with 51% of water samples analyzed, as well as and that nearly 79% of water points have values higher than 50 mg/L. The origin of these chemicals is linked to the water interaction with gypsum in the Triassic and Quaternary formations and dissolution of limestone and dolomite. Only nitrogen compounds have a different origin, which is related to the use of fertilizers (chemical and/ or organic) in agriculture and the decomposition of organic matter.

Methods used in Vulnerability assessment

The assessment of the vulnerability to pollution of the Tadjenanet–Chelghoum Laid alluvial aquifer is made by applying the DRASTIC method and the Susceptibility Index (SI) method that is designed for areas with nitrates pollution (Arfaoui et al., 2022; Aller et al., 1987; Ribeiro, 2000).

The intrinsic vulnerability refers to the natural environmental factors that determine the sensitivity of groundwater to pollution from human activities. The term "specific vulnerability" is used to describe how vulnerable groundwater is to a given pollutant or combination of pollutants, considering the features of the pollutants and their relationships to other intrinsic vulnerability components. (Smida et al., 2010; Schnebelenet al., 2002).

The main crucial importance of vulnerability maps is that their analysis can provide effective information for making informed decisions for water management (Alam et al., 2014).

Although the vulnerability assessment methods used were intended to be used in mapping applications, they were not expressly designed for use in GIS, with their initial applications relying on a manual map overlay and computation procedure (Hosseini & Saremi, 2018 ; Merchant, 1994). GIS methods have been successfully used for assessing groundwater vulnerability because of their ability to retrieve, store, organize, analyze, and present geographically referenced spatial data (Hrkal, 2001; Thirumalaivasan et al., 2003).

The evaluation of the various parameters considered in the DRASTIC and SI methods requires a thorough understanding of the soil and whose combination of geological and geophysical data has enabled us to identify the lithological nature of the saturated and unsaturated zone, the climatic data of the region were used for the calculation of the recharge, the water depth parameter is determined from the piezometric data, the soil type is defined by the analysis of the pedological data. The slope map was extracted from the topographic maps covering the study area (Ray and O'dell, 1993). Finally, the land use map of the study region (Adams & Foster, 1992), allowed us to determine the specific land use map relative to the SI method.

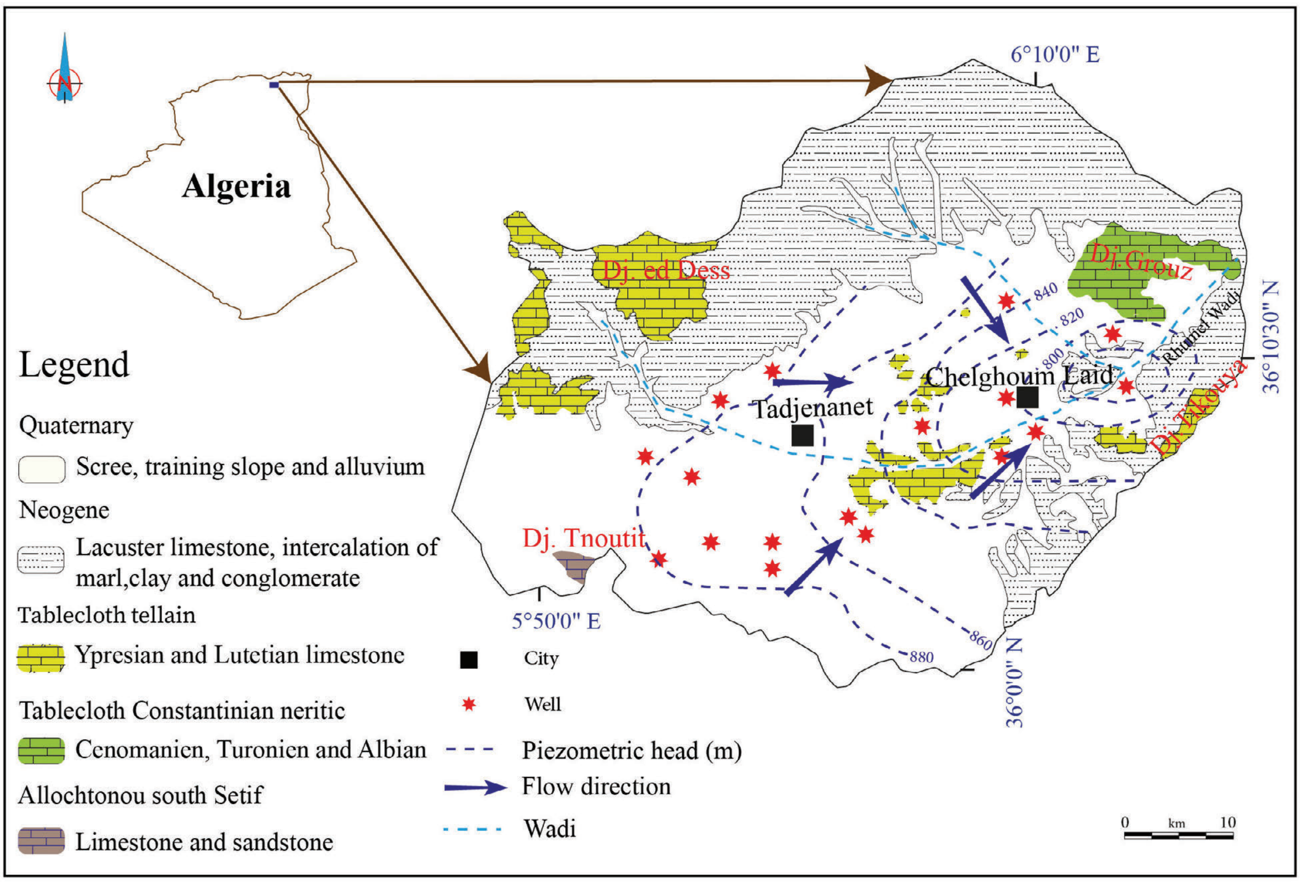

Fig. 1 - Map of the natural conditions of the study area: geology (Vila, 1977) and piezometry (Khedidja, 2016).

Fig. 1 - Carta delle caratteristiche naturali dell'area di studio: geologia (Vila, 1977) e piezometria (Khedidja, 2016).

The selected study area is mainly composed of agricultural land and the use of fertilizers and pesticides are common practices. All the parameters used in the DRASTIC and SI methods have been acquired in the field and require a good knowledge of the geology, hydrogeology, soils, topography, meteorology and land use in the study area. To this end, we used the piezometric data (campaign of April 2016) to determine the depth of the water in the aquifer, as well as the chemistry of the water with respect to the nitrate concentrations.

The data provided by HDT organizations (Hydraulic Direction of Mila) and Direction of agricultural services of Mila are reports on boreholes and wells drilled in the region, map of slopes, soil reports and data hydroclimatological. Finally, the pollution risk map was created by combining all the theme maps that were previously created using GIS (Ariffin et al., 2016).

DRASTIC method

The Environmental Protection Agency (EPA) in the United States developed the DRASTIC approach in 1985 (Aller et al., 1987) to estimate pollution potential and analyze the vertical vulnerability of groundwater using parametric systems. Each parameter is separated into meaningful intervals and given a numerical dimension that increases in proportion to its importance in vulnerability (Aller, 1985). The DRASTIC method is based on seven parameters that determine the vulnerability index's value:

[D]: Depth to water;
[R]: Net Recharge;
[A]: Aquifer media;
[S]: Soil media;
[T]: Topography;
[I]: Impact of vadose zone;
[C]: Hydraulic Conductivity of the aquifer.

Each parameter is divided into classes, with scores ranging from one to ten. The lowest value shows that the environment is less vulnerable to contamination.

The DRASTIC vulnerability index (ID) represents the degree of vulnerability of each hydrogeological unit and is calculated by multiplying the ratings by the weights of the respective parameters (Tab. 1, see next page).

Once the different classes have been defined and their scores have been assigned, the method determines the DRASTIC (ID) index, which makes it possible to characterize the degree of vulnerability of a given sector of the water table. The vulnerability is even more important as the index (Id) calculated is high. This index is defined:

$$ID = (D_R \cdot D_W) + (R_R \cdot R_W) + (A_R \cdot A_W) + (S_R \cdot S_W) + (T_R \cdot T_W) + (I_R \cdot I_W) + (C_R \cdot C_W) \quad (1)$$

Where R is the rate and w is the parameter weight.

The Table 1, in the next page, contains the weights assigned to each of the parameters. The highest weights (5) are attributed to the lithological nature and the thickness of the unsaturated zone. The lowest weights (1 and 2) are attributed to the slope and the lithological nature of the soil, respectively (Tab. 1).

A thematic map is created for each of the seven criteria employed by the DRASTIC method. The zones delineated by a partial vulnerability index of the associated parameter are marked on each of these maps.

The DRASTIC index values obtained represent a measurement of the aquifer's hydrogeological vulnerability; in the conventional form, they range from 23 to 226 (Engel et al., 1996), the results are divided into four categories (Tab. 2).

Tab. 2 - Vulnerability evaluation criteria in the DRASTIC method.

Tab. 2 - Classi di vulnerabilità del metodo DRASTIC.

Vulnerability degree	Vulnerability index
Low	< 101
Moderate	101–140
High	141–200
Very high	> 200

Susceptibility Index

The SI (Susceptibility Index) approach, also known as the susceptibility index method, was created in Portugal by Ribeiro (Ribeiro, 2000; Marín et al., 2015) to account for the behavior of agricultural pollutants, primarily nitrates.

This method considers five parameters, whose four parameters are identical to four parameters already considered in the method DRASTIC: the depth of the water (D), the net recharge (R), the aquifer media (A), and the topographical slope of the land (T).

Ratings assigned to the different classes of these parameters in the DRASTIC method have been retained. The fifth new parameter introduced is the "land use" parameter (LU). (European Commission, 1993) (Tab. 3).

Tab. 3 - Main Land Use classes and corresponding LU values (Ribeiro, 2000).

Tab. 3 - Principali classi di uso del suolo e rispettivi punteggi (Ribeiro, 2000).

Land-use class	LU rating
Industrial discharge, landfill, mines	100
Irrigated perimeters, paddy fields, Irrigated and non irrigated annual culture	90
Quarry, shipyard	80
Artificial covered zones, green zones, continuous urban zones	75
Permanent cultures (vines, orchards, olive trees, etc.)	70
Discontinuous urban zones	70
Pastures and agro-forest zones	50
Aquatic milieu (swamps, saline, etc.)	50
Forest and semi-natural zones	0

Tab. 1 (see next page) - Standards assigned ratings for DRASTIC method parameters and their weights (Aller et al., 1987).

Tab. 1 (vedi pagina a fianco) - Punteggi standard assegnati ai parametri del metodo DRASTIC e relativi pesi (Aller et al., 1987).

Parametres	Ranges (classes)	Ratings	Assigned weight
(D) Depth to Water (m)	+30	1	5
	30 -22.5	2	
	22.5 - 15	3	
	9 - 15	5	
	4.5 - 9	7	
	3 - 4.5	8	
	1.5 - 3	9	
	0- 1.5	10	
(R) Net Recharge (mm)	0 - 5	1	4
	5 - 10	3	
	10 – 17.5	6	
	17.5 – 25.5	8	
	+25.5	9	
(A) Aquifer Media	Massive Shale	2	3
	Metamorphic Rocks	3	
	Weathered Metamorphic Rocks, bedded Sandstones, Limestones	4	
	Shale in Sequence	6	
	Massive Sandstone	6	
	Massive Limestone	6	
	Sand and Gravel	8	
	Basalt	9	
	Karst Limestone	10	
(S) Soil media	Non shrinking Non-aggregated Clay	1	2
	Clayey Silt	3	
	Silty Loam	4	
	Silt	5	
	Sandy Silt	6	
	Shrinking and Aggregated Clay	7	
	Sand	9	
	Gravel	10	
	Thin or Absent	10	
(T) Topography (%)	+18	1	1
	12 - 18	3	
	10 - 12	5	
	8 - 10	7	
	6 - 8	8	
	2 - 6	9	
	0 - 2	10	
(I) Impact of Vadose Zone	Silt and Clay	1	5
	Shale	3	
	Limestone	6	
	Sandstone	6	
	Bedded Limestone, Sandstone, Shale	6	
	Sand and Gravel with Silt and Clay	6	
	Sand and Gravel	8	
	Basalt	9	
	Karst Limestone	10	
(C) Hydraulic Conductivity ($m.s^{-1}$)	4,7.10-5-4,7.10-5	1	3
	4,7 .10-5 -14,7.10-5	2	
	14,7.10-5 -32,9.10-5	4	
	32,9.10-5 -4,7.10-4	6	
	4,7.10-4 -9,4.10-4	8	
	+9,4.10-4	10	

To make the interpretation of the results easier, the values of the ratings ascribed to the classes of the various parameters have been multiplied by ten. As a result, the ratings range from 0 to 100, with the lowest number being the least vulnerable and the highest value is the most vulnerable. The weights assigned to SI parameters range from 0 to 1 depending on the parameter's importance in the vulnerability (Tab. 4).

Tab. 4 - Weights attributed to SI parameters.

Tab. 4 - Pesi attribuiti ai parametri del metodo SI.

Parameters	D	R	A	T	LU
Weights	0.186	0.212	0.259	0.121	0.222

The SI method presents four degrees of vulnerability according to the values of the vulnerability index (Tab. 5). Several studies have shown a good correlation between the areas considered vulnerable by this method and the contaminated areas. (Frances et al., 2001; Ferreira & Oliveira, 2004; Stigter et al., 2006).

Tab. 5 - Vulnerability evaluation criteria in the SI method (Ribeiro, 2000).

Tab. 5 - Classi di vulnerabilità del metodo SI (Ribeiro, 2000).

Vulnerability degree	Vulnerability index
Low	< 45
Moderate	45–64
High	65–84
Very high	85- 100

Results and Discussion

Index thematic maps

For each of the seven parameters used by the DRASTIC method, a thematic map is produced. On each of these maps, the zones characterized by a partial vulnerability index of the corresponding parameter are delimited.

The elaboration of the maps is carried out in the main structure of a Geographic Information System "Arc GIS", which represents a powerful tool of analysis for environmental studies and spatial modeling of natural phenomena, with coordinate system WGS 1984 UTM Zone 30N.

Aquifer depth (D)

The depth of the groundwater is an important parameter, which constitutes a determining factor of vulnerability.

The observation of the said map shows that the lowest index is distributed in the southwestern part near Djebel Tnoutit, with values do not exceed 15, while the most important index is situated in the central and eastern zones of the study area, along the Rhumel wadi, with values from 35 to 45.

Net recharge

Efficient recharge plays a decisive role in the transfer of the water layer from the ground surface to the underlying aquifer.

The results of the water balance show that the value of this parameter is estimated to be 7 mm in the entire study area. The DRASTIC index is around 4 distributed over the entire plain (Fig. 3).

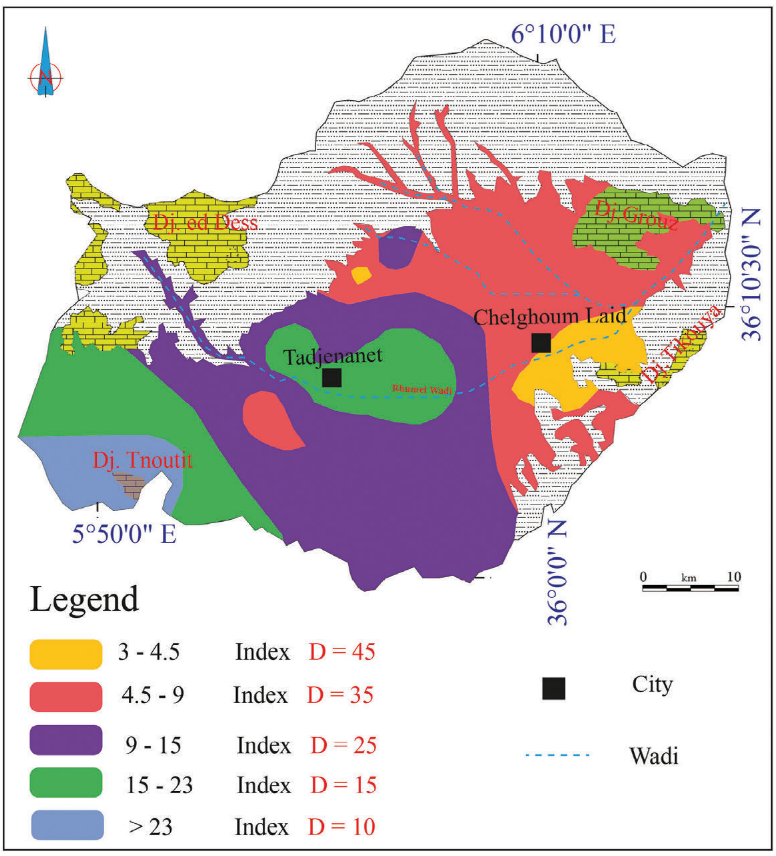

Fig. 2 - Index map: groundwater depth (m).

Fig. 2 - Carta del parametro profondità della falda (m).

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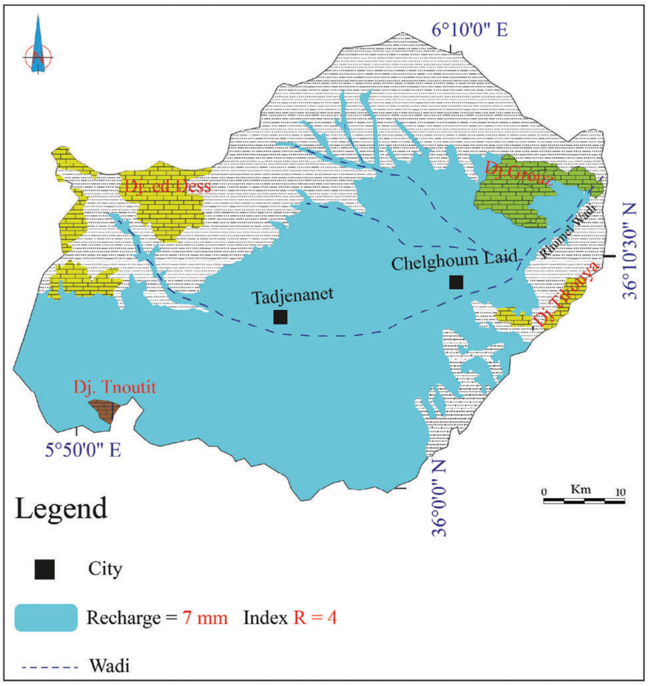

Fig. 3 - Index map: Efficient recharge.

Fig. 3 - Carta del parametro ricarica efficace.

Nature of the saturated zone (A)

This parameter designates the lithology of the aquifer. Identification was based on the logs boreholes and wells intercepting the aquifer.

Examination of the map of material of the saturated zone shows that the most important indices are situated on the periphery of Rhumel wadi and the weakest in the center and east of the study area (Fig. 4).

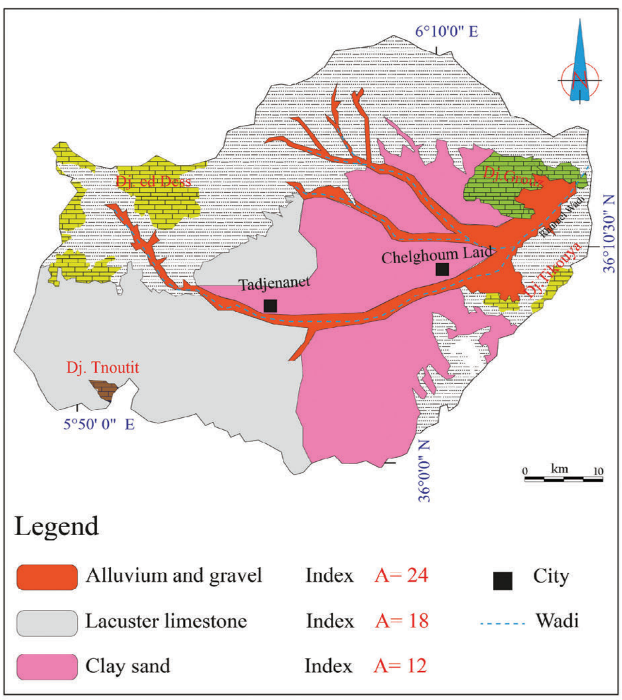

Fig. 4 - Index map: aquifer material.

Fig. 4 - Carta del parametro composizione

The nature of the soil (S)

The nature of the soil surface influences the penetration of pollutants into the aquifer. The more the soil is rich in clay, the more absorption of pollutants is important, and protection of groundwater is high.

Examination of the map of the indices relating to the nature of the soil (Fig. 5) shows that the soil is calcimagnesic type with a coarse texture characterized by a sandy dominance distributed along Rhumel wadi. This type of soil represents a medium vulnerability risk. From the pedological point of view, the soil of a little evolved type of colluvial contribution is distributed at the approach of the massive carbonates surrounded by the region of study represents a high risk of vulnerability. The rest of the field is characterized by more or less clayey soil of fine texture.

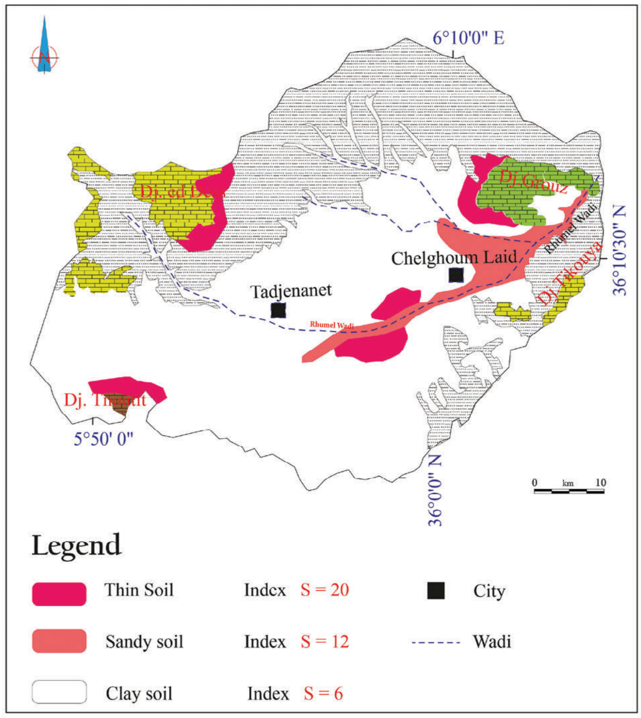

Fig. 5 - Index Map: Type of soil.

Fig. 5 - Carta del parametro: tipo di suolo.

Topography (T)

The steeper the slope of the land, the more water runoff is important, and therefore the groundwater contamination is low. Examination of the index map shows two ranges of the slope. The first varies from 2 to 6% corresponding index (Index T = 9) which occupies most of the plain, while the second varies from 6 to 12%, characterizes the areas of the topographic limit of the study area with index (Index T = 5) (Fig. 6).

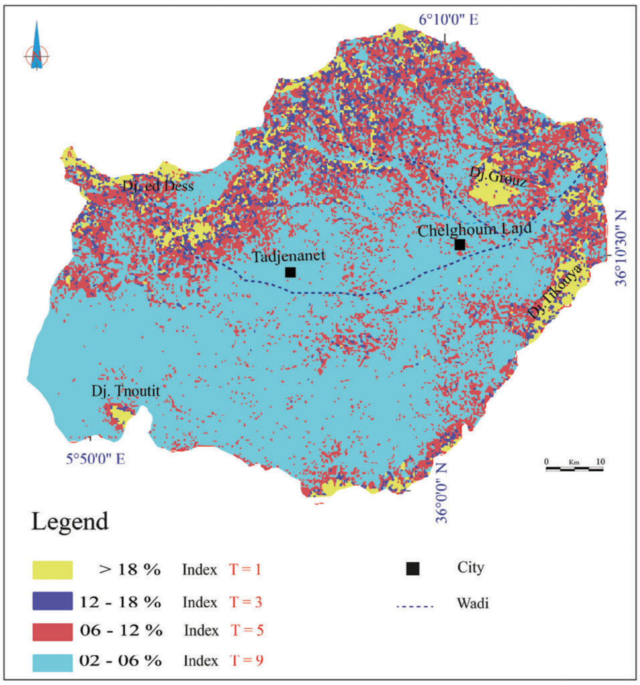

Fig. 6 - Index Map: Slope of the terrain.

Fig. 6 - Carta del parametro pendenza del terreno.

Impact of the unsaturated zone (I)

The impact of the unsaturated zone is considered to be a very important parameter in the application of the DRASTIC method.

According to the index map relating to the impact of the unsaturated zone (Fig. 7), we can see that the central and eastern part of the study area, along the Rhumel wadi, has a very high index (Index I = 30)

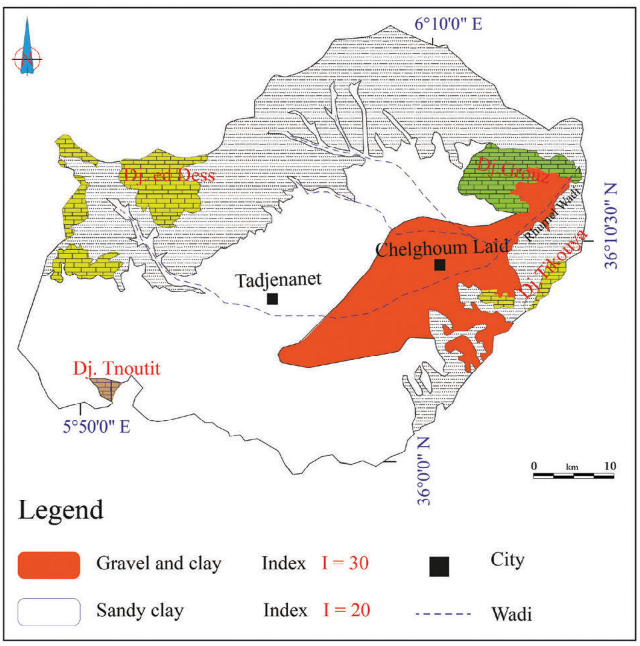

Fig. 7 - Index map: Impact of the unsaturated zone.

Fig. 7 - Carta del parametro composizione della zona insatura.

Hydraulic conductivity

The permeability of the aquifer informs us about the speed of propagation of pollutants in the aquifer.

The permeability map of the aquifer is determined from the transmissivity values measured by the interpretation of the results of pumping tests in the water boreholes implanted in the study region. The analysis of the latter revealed the presence of two zones, the first zone is characterized by a variation in hydraulic conductivity between 10^{-6} and 10^{-5} m/s, which spreads over the southwest part of the study area; this gives a DRASTIC index 3. The second zone is characterized the rest of the ground with hydraulic conductivity values varying between 10^{-5} and 10^{-4} m/s (Fig. 8).

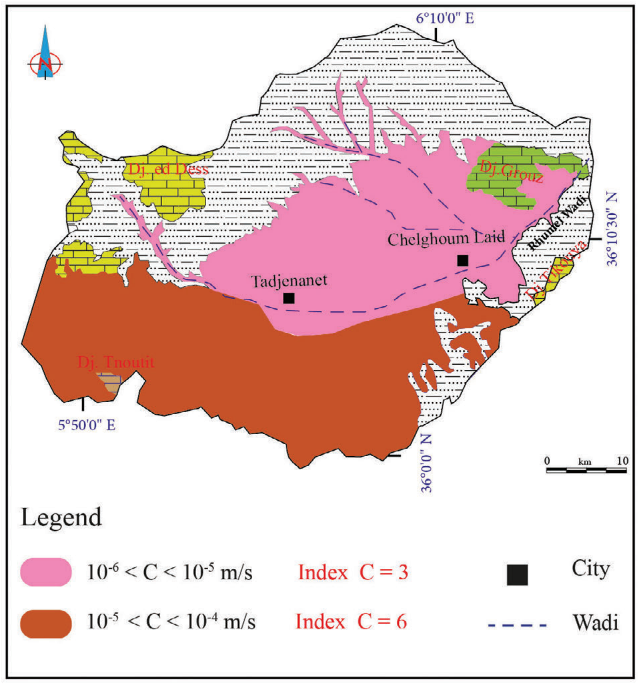

Fig. 8 - Index map: Hydraulic conductivity.

Fig. 8 - Carta del parametro conducibilità idraulica.

Map of synthesis (vulnerability to pollution)

DRASTIC vulnerability assessment

According to the classification adopted by the Quebec Ministry of the Environment (Appelo and Postma, 2004; Aller et al., 1987; Murat et al., 2003), different classes of vulnerability can be distinguished in Table 2.

The examination of the vulnerability map of the studied aquifer (Fig. 9), allowed us to identify ID that varies between 55 and 124, which highlights an aquifer with medium to low vulnerability to pollution.

The zone of average vulnerability occupies the central and eastern part of the study area along the Rhumel wadi, whose vulnerability index varies from 100 to 124, which is mainly due to the shallow depth of the piezometric surface and the nature of the vadose layer. It is situated in areas influenced by agricultural activities and urban waste.

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The low vulnerability zone is situated in the rest of the study area. Its vulnerability index varies from 55 to 100.

These areas are more closely related to the gravelly nature of the soil and the lithological nature of the unsaturated zone with high permeability. It also coincides with shallow water depth, where the depth of the piezometric surface is very low and near to soil surface. In these areas, most boreholes are reserved for water supply and agricultural needs. These areas must be subjected to rigorous control to define adequate protection measures.

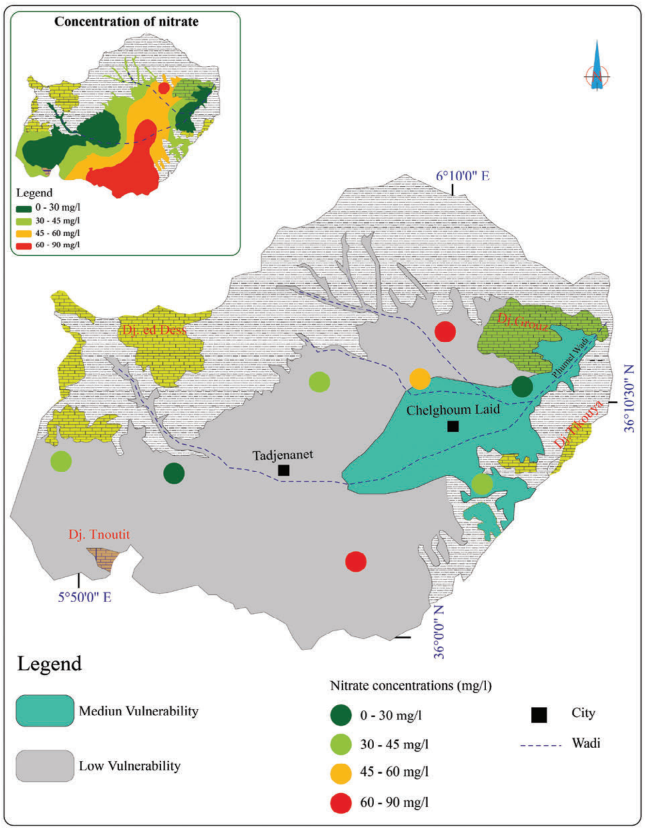

Fig. 9 - Vulnerability map to the pollution of groundwater in the Tadjenanet - Chelghoum Laid alluvial aquifer using the DRASTIC method.

Fig. 9 - Carta della vulnerabilità all'inquinamento per l'acquifero alluvionale di Tadjenanet - Chelghoum Laid, secondo il metodo DRASTIC.

SI vulnerability assessment

The last map from the SI method (Fig. 10) highlights three sectors of low, medium, and high vulnerability.

According to the map, moderate vulnerability zones cover practically the entire surface of the study area, whereas high vulnerability zones stretch from the research area's center to the east along wadi Rhumel. These places characterize large expanses with an intense agricultural vocation, as well as the distribution of urban agglomerations and industrial units. The moderate vulnerability zones are correlated with the highest levels of nitrate contamination. Analysis of the SI map reveals a high vulnerability index resulting from both depth of water in the aquifer and land use (Lallemand-Barrès, 1994; Sinan, 2000; Vrba and Zaporozec, 1994; Ewodo 2017).

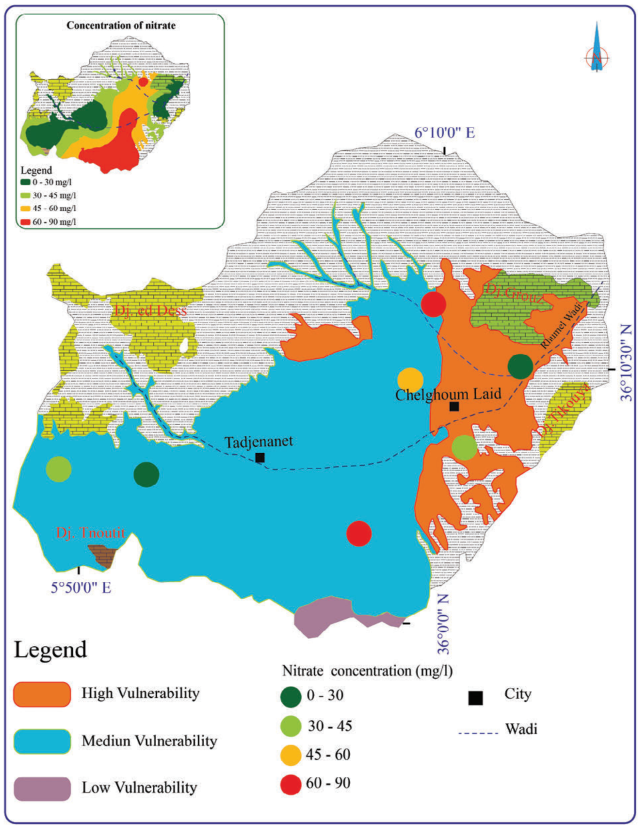

Fig. 10 - Vulnerability map to the pollution of groundwater in the Tadjenanet - Chelghoum Laid alluvial aquifer using the SI method.

Fig. 10 - Carta della vulnerabilità all'inquinamento per l'acquifero alluvionale di Tadjenanet - Chelghoum Laid, secondo il metodo SI.

Validation of vulnerability methods

The aquifer's vulnerability to pollution, determined by the two methods DRASTIC and SI, reveals a trend of low and medium vulnerability. The presence of high nitrate values in the high and medium vulnerability classes shows that the aquifer is likely to be threatened locally by the infiltration of pollutants. In general, this tendency to low and medium vulnerability is followed by that of high vulnerability especially on the periphery of Rhumel wadi, where the depth of the water is close to the surface of the ground, since this zone is marked by a piezometric depression, and has known an intense agricultural use. The DRASTIC method makes it possible to obtain finer information at the level of the representation of the vulnerability that of the map produced by the SI method. The evaluation is more or less uniform, including the breakdown of the map developed by the DRASTIC method, more varied than that of the map produced by the SI method relating to the number of parameters involved in the vulnerability's estimation of each. The SI method is suggested for agricultural areas with extensive use of nitrates, where the accumulation of nitrates in the groundwater is mainly due to its leaching from the soil surface layers (Fusco et al., 2020).

The chemical analysis showed that nearly 79% of water points have values higher than 50 mg/L.

The superposition of the map of nitrate concentrations on the two maps of vulnerability, allowed us to observe that high concentrations of nitrates (greater than 50 mg/L) are coincident with areas of high to medium vulnerability for the SI method and in areas of low to medium vulnerability for the DRASTIC method, with a coincidence rate of 85%, (Thiuone et al., 2017)

When the two pollution vulnerability assessment approaches are compared, the SI method shows a high rate of correlation between high nitrate concentrations and high susceptibility locations. This method considers the features of pollutants and the many components already discussed in intrinsic vulnerability (Ake et al., 2009; Brou et al., 2013), to address a specific vulnerability connected with pollution sources. As a result, it's an evolutionary weakness that's better suited to the research topic (Thiuone et al., 2017).

DRASTIC is not a numerical model to compute nitrate concentrations in aquifers but to predict

aquifer vulnerability classes from very high vulnerability to very low vulnerability with hydrogeological

settings. The application of the two methods for the evaluation of the degree of vulnerability to the pollution of the alluvial aquifer of tadjenanet - Chelghoum Laid, allowed us to note that the DRASTIC method does not take into account the nature of the contaminant and grants a great importance to hydrogeological factors. The case study supports the idea that the SI method was designed to take into account the nature and the property of the pollutant (example nitrates) as well as the LU factor integrates the ground, types of use, allowing the integration of different particular characteristics.

Conclusions

The study of the vulnerability of the alluvial aquifer based on the establishment of the estimation map of the sensitivity of the groundwater aquifer to contamination in general according to the DRASTIC estimation method and the Susceptibility Index revealed an area of high and moderate vulnerability in the plain's east;

This study leads us to conclude that this zone is already contaminated, from which high nitrates contents have been recorded, while the zones with medium vulnerability are situated in the center, in the east on the periphery of wadi Rhumel. The rest of the field has a low vulnerability, whose water depth and thickness of the unsaturated zone become more and more important.

The superposition of the vulnerability maps with the map representing the spatial distribution of nitrate concentrations revealed that the SI method is appropriate for this type of pollutant, with a high coincidence rate of 85 percent between the nitrate concentrations and the different classes of vulnerability. However, the comparison analysis using the DRASTIC and SI methodologies allowed us to conclude that the SI method is the best appropriate for studying the aquifer's susceptibility.

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Author contributions
The authors Khedidja Abdelhamid and Drias Tarek contributed to the design and implementation of the research, to the analysis of the results, and to the writing of the manuscript.
The author Reghais Azzeddine contributed the design of the figures.
All authors read and approved the final manuscript.

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