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RESEARCH ARTICLE

Vulnerability Study by DRASTIC Method for Eocene and Turonian Aquifers in the Tadla Plain

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Abstract

In numerous regions across Morocco, groundwater quality has undergone a significant decline in recent years, primarily due to factors such as agricultural expansion, improper solid waste disposal, and industrialization. This study presents an analysis of the vulnerability of two primary shallow aquifers, namely the Turonian and Eocene.

The vulnerability assessment entails the evaluation of the aquifers' susceptibility to various forms of surface pollution, based on the physical characteristics of their surroundings. Within the Moroccan context, the DRASTIC method, integrated with Geographic Information Systems (GIS), emerges as the most suitable approach. This method involves the processing and analysis of seven factors pertaining to the three soil compartments, encompassing land cover, the unsaturated zone, and the saturated zone.

Each chosen parameter is assigned a weight, reflecting its significance concerning groundwater protection. Notably, the water table's depth and the nature of the vadose zone exert the most substantial influence, followed by factors like recharge. Conversely, topography exhibits minimal impact, with soil type following suit. Lastly, the nature of the aquifer medium and its conductivity carry a moderate degree of influence. Each parameter is further categorized into classes, each defined by a specific rating.

To derive an all-encompassing measure of vulnerability, the weights and scores of these various factors are synthesized through an additive model, yielding the comprehensive "DRASTIC Index." Subsequently, this index is employed to assess the intrinsic vulnerability level of the Turonian and Eocene aquifers by superimposing the seven index maps.

Introduction

Béni Mellal-Khénifra is one of the first agricultural regions of the country. It concentrates 959,000 Ha of functional agricultural area, i.e. around 10% of the useful agricultural area of the Kingdom, of which 212,000 hectares are irrigated, i.e. 22% of the functional agricultural area of the Region and 15% of the irrigated area in Morocco (Regional Center of investment, Beni Mellal-Khénifra Region. 2016).

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According to the Regional Center of investment, Beni Mellal-Khénifra Region, with the aim of improving yield, it provides for a considerable increase in the use of fertilizers and phytosanitary products, offering investors opportunities to set up production units for the production of these elements. To quantify this increase, the needs are:

- Fertilizer: 100,000 tons
- Phytosanitary products: 900 ton

Indeed, these actions will have beneficial returns for the kingdom on an economic scale, which is mainly based on agriculture. But knowing that these fertilizers, or phosphates in general, are composed of trace or major chemical elements that can be a source of environmental pollution, especially for groundwater.

The location of the Ouled Abdoun phosphate deposit at the foot of the High Atlas is known for its strong tectonic deformation, which is reflected by fractures detected at the level of the basin, the most important of which are developed in the form of large faults filled with mixtures of limestone blocks, marl, phosphates, flint...and which are called: disturbances (a phenomenon to which we have devoted a whole chapter).

In addition to these constraints, there are the risks of groundwater pollution linked to the discharge of urban wastewater and agri-food effluents. Thus, the most marked degradation processes in the perimeter of Beni Amir are salinization, sodification, deterioration of the soil structure, and nitrate pollution, the eco-toxicological and health effects of which are not negligible. The latter is due, among other things, to the intensive use of nitrogen fertilizers, with an estimate of about 1800 tons of nitrogen which are leached annually and reaching the Tadla aquifer.

Methodology and Materials

Methodology

To begin this study by the DRASTIC method, the detailed characterization of the hydrogeological units of the territory to be studied is mandatory, in particular, the definition of seven physical parameters which are also at the origin of the name DRASTIC and which intervene in the phenomena of transport and attenuation of contaminants:

- D: Distance to the water table = Depth to the water table = thickness of the unsaturated zone;
- R: Groundwater recharge;
- A: Nature of the aquifer medium (saturated zone);
- S: Soil type;
- T: Slope of the terrain;
- I: Impact of the unsaturated zone (nature of the materials);
- C: Hydraulic conductivity of the aquifer (permeability).

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. Table 1 shows Weights relative to each DRASTIC factor.

A rating ranging from 1 to 10, defined according to ranges of values, is associated with each of the parameters, depending on local conditions; conditions of less vulnerability provide low scores, while those that increase it provide high scores. Tables 1 and 2 present the scores assigned to each DRASTIC parameter, these tables are described in detail in document EPA/600-2-87-035, published jointly by the Environmental Protecting Agency (EPA) and the Natural Well Water Association (NWWA).

$$DRASTIC_{index} = D_pD_n + R_pR_n + A_pA_n + S_pS_n + T_pT_n + I_pI_n + C_pC_n$$

p : Weight

n : Rib

The calculated values of this index reflect the degree of vulnerability, in other words the level of risk of contamination of a groundwater. They range between a minimum of 23 and a maximum of 226, but the majority of these values range from 50 to 200. The risk is proportional to the index.

Table 1: Weights relative to each DRASTIC factor.

Factor DRASTIC	Weight
Distance to the water table = thickness of the unsaturated zone	5
Impact of the unsaturated zone = nature of the unsaturated zone	5
Tablecloth refill	4
Nature of the saturated aquifer environment (saturated zone)	3
Hydraulic conductivity (permeability)	3
Type of soil	2
Topography	1

Table 2: Parameter ratings for the calculation of the DRASTIC index.

Rib	D	R	A	S	T	I	C
	Groundwater depth (m)(1)	**Recharge (mm/year)**	**Nature of the aquifer environment** *(interval of dimension)* (2)	**Soil type(3)**	**Land slope (%)**	**Nature of the vadose zone(4)** *(interval of dimension)(2)*	**Hydraulic conductivity of the aquifer (m/d)**
1	31 and over	0 to 50	0.77	clay	18 and over	Containment layer (1)	0,04 to 4
2	23 to 31		Massive shale (1-3)	Black land			4 to 12
3	15 to 23	4 to 12	Igneous or metamorphic rocks (2-5)	clay loam	12 to 18	• Silt or clay (2-6) • Shale (2-5)	
4			Igneous or metamorphic weathered rocks (3-5)	Silty loam		Igneous or metamorphic rocks (2-8)	12 to 29
5	9 to 15		Till (4-6)	loam	6 to 12		
6		100 to 180	• Beds of sandstone, limestone Beds of sandstone, limestone, and shale (5-9) • Solid sandstone (4-9) • Massive limestone (4-9)	sandy loam		• Limestone (2-7) • Sandstone (4-8) • Beds of limestone, sandstone, and shale (4-8) • Sand and gravel with silt and clay (4-8)	29 to 41
7	4,5 to 9			cracked clay			
8		180 to 250	Sand and gravel (4-9)	Peat		Sand and gravel (6-9)	41 to 82
9	1.5 to 4.5	250 and over	Basalt (2-10)	Sand	2 to 6	Basalt (2-10)	
10	0 to 1.5		Karst limestone (9-10)	Thin soil or rock or gravel	0 to 2	Karst limestone (8-10)	82 and over
Wight	**5**	**4**	**3**	**2**	**1**	**5**	**3**

(1) In confined aquifer conditions, the depth of the aquifer corresponds to the top of the aquifer.
(2) Each material is classified according to the standard rating proposed by the DRASTIC method. It also offers a dimension interval, indicated between () in this table.
(3) Approximately the first meter of deposit from the ground surface.
(4) Underground portion between the ground and the level of the aquifer or between the ground and the top of the aquifer in the case of a confined aquifer.

Database

As we said, to study the vulnerability of the aquifer to pollution, we need a lot of information from several sources, such as reports and existing databases. This information must be well and carefully analyzed so that it is useful if deemed necessary in the field. In our case, the sources of information available are contained in the table 3.

Results

Mapping and vulnerability assessment of aquifers

According to kachi, 2007, to make a reliable study of the DRASTIC method, we need a well-detailed characterization of the hydrogeological units of the study area using exact parameters. We subdivided our study area into regular cells of 2.5 km2. For each parameter, a notation was adopted in the study area. The highest rating corresponds to the highest degree of vulnerability for all the thematic maps that will be established that will allow us to assess the relative degree of vulnerability.

Thematic Map of Criterion D (Depth of the aquifer)

To measure this parameter (D), a campaign of piezometric measurements was carried out in August 2018. These measurements will be used for mapping and assessing the vulnerability to pollution of the

Table 3: Types and sources of information available.

Type of information	Database	Custodian bodies
Geological data	- Geological maps - Log of wells and boreholes - Geophysical data	- Field trips - Universitys - ABHOER - ORMVAT - ONHYM
Soil data	- Facies maps - Well and borehole cross-section data - Soil map of the irrigated perimeter of the Tadla	- Universitys - ABHOER
Hydrological and hydrogeological data	- Piezometry - Hydrodynamic parameters - Refill - PH, T°, Salinity and Electrical Conductivity	- Field trips - Universités - ABHOER
Land use	- Occupancy classes - Sources of pollution	- H.C.P - A.B.H.O.E.R.

aquifer relative to the depth of the aquifer. This parameter, which indicates the depth of the aquifer, is one of the most important parameters (weight = 5) in the mapping and assessment of aquifer pollution (Table 4 and Figure 1).

Based on the D parameter map above, we find that the Eocene aquifer is more or less deep except for the area between Fquih Ben Salah and Dar Ould Zidouh which is the most vulnerable due to its shallow depth. So to pollute this water table, it takes time for the contaminant to get there and travel through its significant depth. The Turonian aquifer is shallower to the west of the Khouribga-Dar Ouald Zidouh line where the polluting power is more or less easy compared to the east, comprising a fairly large aquifer cover which protects the aquifer from pollution.

Thematic map of parameter R (Efficient recharge)

Estimation of regional, or aquifer-scale, recharge is usually sufficient to calculate DRASTIC indices. A single value can therefore often be used for all protection areas. However, the covers vary, the infiltration rates in the basement also vary, and several recharge values will have to be considered. For example, at the abstraction site, and over most of the surface area of the protection areas, the exploited aquifer may be in confined aquifer conditions and appear to have low recharge. On the other hand, the aquifer can preferentially receive its recharge from a small portion of territory upstream, on the intake area of the abstraction, which is in unconfined aquifer conditions. Since the recharge has a significant influence on the calculation of the DRASTIC indices, the use of a recharge calculated using information at the sampling site will induce a significant error on this portion of the territory upstream. The DRASTIC index should reflect the significant vulnerability to contamination of this portion of the territory so that protective measures can be implemented there.

Efficient recharge then is the quantity of water per unit area that infiltrates and joins the aquifer, transporting pollutants from the surface to the groundwater.

Table 4: Dimensions and class retained for the depth parameter (D).

Legend				
Class	Deep	Rating	Weight	Value
I	0 - 1.5	10	5	52
II	1.5 - 4.5	9		45
III	4.5 - 9	7		35
IV	9 -15	5		25
V	15 - 23	3		15
VII	23 - 31	2		10
VIII	>31	1		5

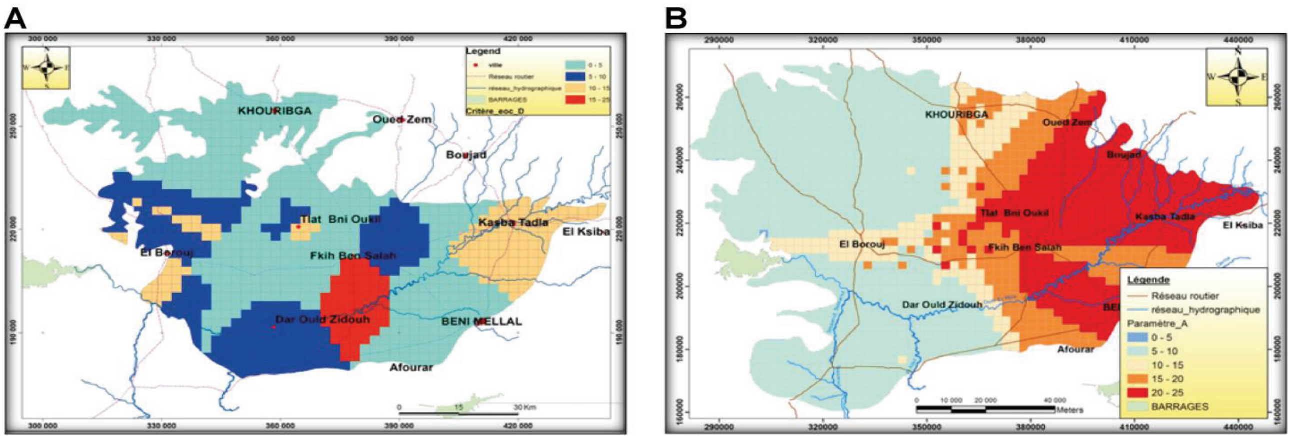

Figure 1 Map of the parameter relating to the depth of A) the Eocene aquifer and B) the Turonian aquifer of the Tadla Plain.

Depending on the nature of the aquifer and the type of climate that characterizes the region, several methods exist to calculate the quantity infiltrated. In our region, groundwater is recharged by the direct infiltration of meteoric waters. The infiltration coefficient, depending on the nature of their coverings, is estimated at 12% (Tables 5,6). Also the precipitations are very variable according to the data of the ABHOER according to the seasons and according to the periods. The evaporation rate is estimated at 150.7 mm/year (Bac) and 181.7 (piche).

The net recharge estimation formula is quoted below:

$$R_{nette} = (P - ETR) \times w = (E + I) \times w$$

- Rnette: Net recharge;
- P: Precipitation in mm;
- ETR: Actual evapotranspiration in mm;
- W: Infiltration coefficient in %;
- E: Runoff in mm;
- I: Infiltration in mm.

Except for a small area in the northwest, all of the two aquifers receive significant recharge from rainwater that reaches the groundwater of the two aquifers. Therefore, their contamination becomes very high (Figure 2).

Thematic map of parameter A (Nature of the aquifer environment)

The texture and the lithological nature, the grain size, the porosity, the permeability of the layers of the aquifer, are the factors which control the circulation and the propagation of a contaminant in the saturated zone. While the migration of contaminants and their

Table 5: Value of equivalent homogenized infiltration coefficient of each lithological unit.

Unité lithologique	Coefficient d'infiltration en %
Neogene (Miocene or marine Pliocene) and Quaternary cover (marl, molasse sandstone, lacustrine limestone, silt and alluvium)	12
Jurassic-Cretaceous internal synclinal basins	12
Secondary and tertiary, tabular or slightly folded cover of the rigid zones of the central Mesetas (Cretaceous and Eocene)	12
Jurassic, tabular or slightly folded cover of the rigid zones of the central Mesetas (dolomites and marl-limestone)	8
Folded secondary of the High Atlas and the Middle Atlas, especially Lias and Jurassic (dolomites, marls and sometimes sandstone)	5
Permo-Trias (Sandstone, conglomerate and red clays)	2
Autunian (conglomerate, sandstone and red clays)	2
Paleozoic and Precambrian (Schists, quartzites, flyschs, granites, etc.)	5
Upper Triassic doleritic basalts	2
Hercynian granites	2

Table 6: Class and ratings retained for R.

Classes	Recharge (cm/year)	Scoring	Weight	Value
I	0 - 5	1		4
II	5 - 10	3	4	12
III	10 - 18	6		24

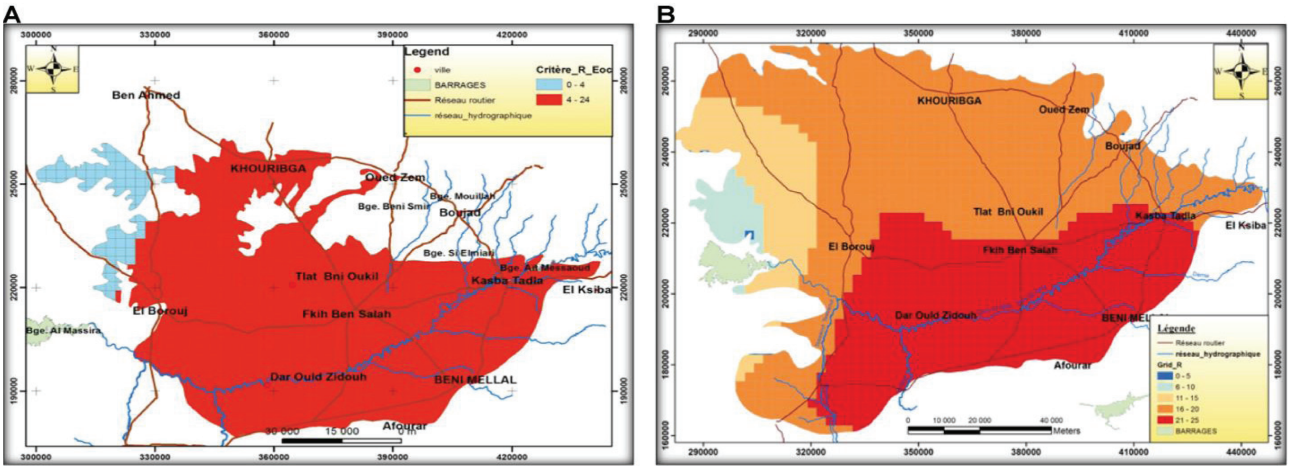

Figure 2 Map of the parameter relating to the effective recharge of: A) the Eocene aquifer and B) the Turonian of the Tadla plain.

dispersion from the point of injection, at the surface, to the saturated zone is guided by the hydraulic conductivity of the aquifer. The hydraulic conductivity map according to Castany, 1982 and Banton, 1997, is obtained by assigning for each lithological class a permeability factor (Table 7, figure 3).

Thematic map of the soil parameter (S)

The soil plays a very important role in the downward transport of the polluting substance to the water table. In fact, the soil by its composition of fine materials (clays, silts and silts) and organic matter, it decreases intrinsic permeability, and delays the migration of contaminants, by physico-chemical processes (adsorption, ion exchange, oxidation, biodegradation (Table 8).

The analysis of the thematic map of criterion S (Figure 4) showed 5 textures: Alluvium and gravel, Limestone and limestone crust, Marly phosphates, Silts and Clays. The richer the soil in clay, the greater the absorption of heavy metals, and the greater the protection of groundwater.

Thematic map of the topography parameter (T)

L'analyse de la topographie permet de connaitre le taux de ruissèlement ou d'infiltration d'un polluant dans la nappe en connaissant la pente. Grace à un modèle numérique de terrain (MNT) qui a été exploité et transformé via un logiciel SIG (Arc Gis) tout en utilisant les extensions « Spatial analyst », « 3D analyst » et « Grid Analyst », nous avons obtenu la topographie de notre secteur d'étude (Table 9, figure 5).

Table 7: Ratings and class retained for parameter A.

Matériaux	Typical rating	Weight	Value
Clay	2		6
Plastic marls	3		9
Phosphate sands + sandy marls	4		12
Marl-limestone	5		15
marly limestone	6	3	18
Phosphated limestone	7		21
Massive limestone	8		24
Conglomerate	9		27
Fractured limestone	10		30

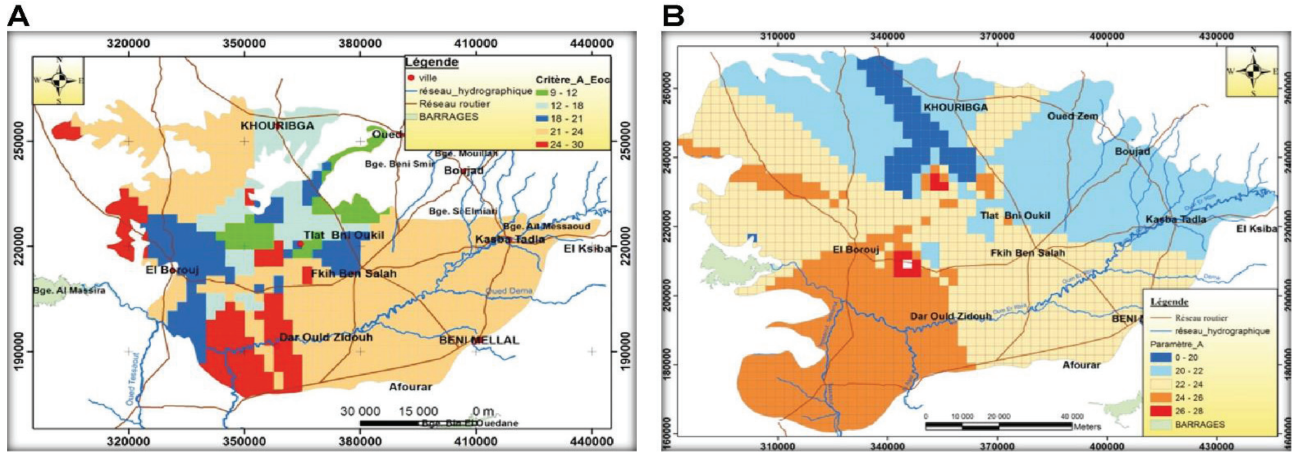

Figure 3 Map of the parameter relating to the nature of : A) of the Eocene aquifer and B) the Turonian aquifer of the Tadla Plain.

Table 8: Dimensions and class retained for parameter A.			
Soil type	**Note**	**Weight**	**Value**
Gravel, conglomerate, Alluvium	10		20
calcareous crust, limestone	9		18
Marl phosphates	6	2	12
Marl phosphates Marl	5		10
Clays	2		4

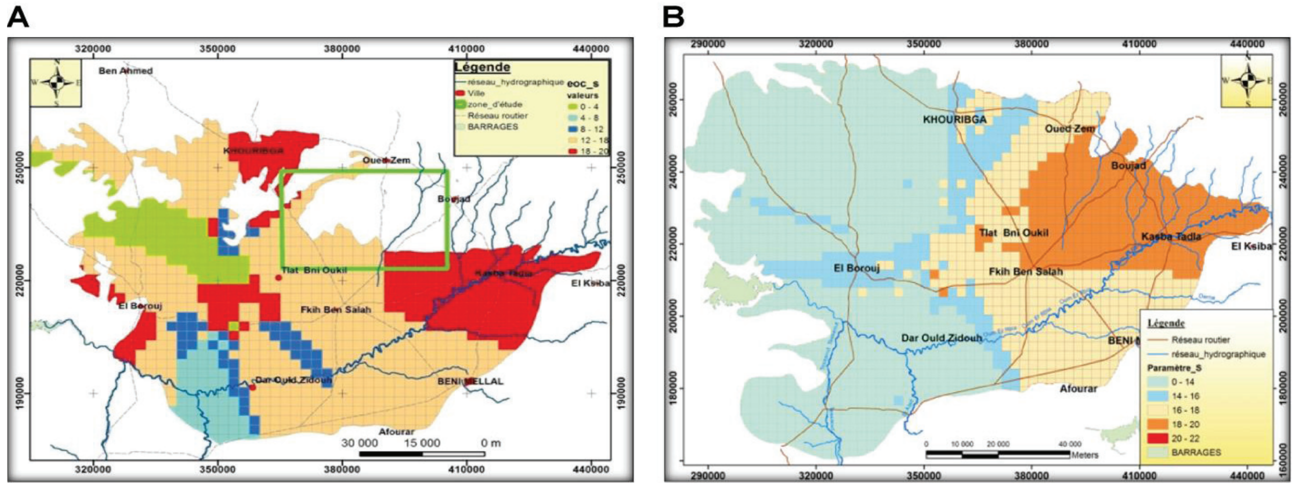

Figure 4 Soil type criterion (S) map of: A) the Eocene aquifer and B) the Turonian aquifer of the Tadla plain.

The lands of the study area are almost sub-horizontal or even have a generally low slope which is between 0% and 6%. The runoff is then absent or weak, which leaves a strong infiltration of contaminating substances towards the groundwater.

Thematic map of the "I" parameter linked to the vadose zone (unsaturated zone)

An unsaturated zone, also called vadose zone, is all the layers of land between the aquifer and the ground. The ability to attenuate and the permeability of these terrains are the main factors influencing the evolution of pollution. The well data available and the results of Hsissou in 1991, as well as data from BRGM version 1993, enabled us to establish an assessment of the vulnerability vis-à-vis the nature of the unsaturated zone (Table 10, , figure 6).

The facies of the unsaturated zone, according to the map above, is generally made up of lacustrine limestones, marl-limestones, alluvial deposits and silts. This heterogeneity, or even the difficulty of limiting the me-polio-quaternary formation, makes

Table 9: Ratings and class retained for the topography parameter (T).

Slope range (%)	Note	Weight	Value
0 à 2	10		**10**
2 à 6	9		**9**
6 à 12	5	1	**5**
12 à 18	3		**3**
> 18	**1**		**1**

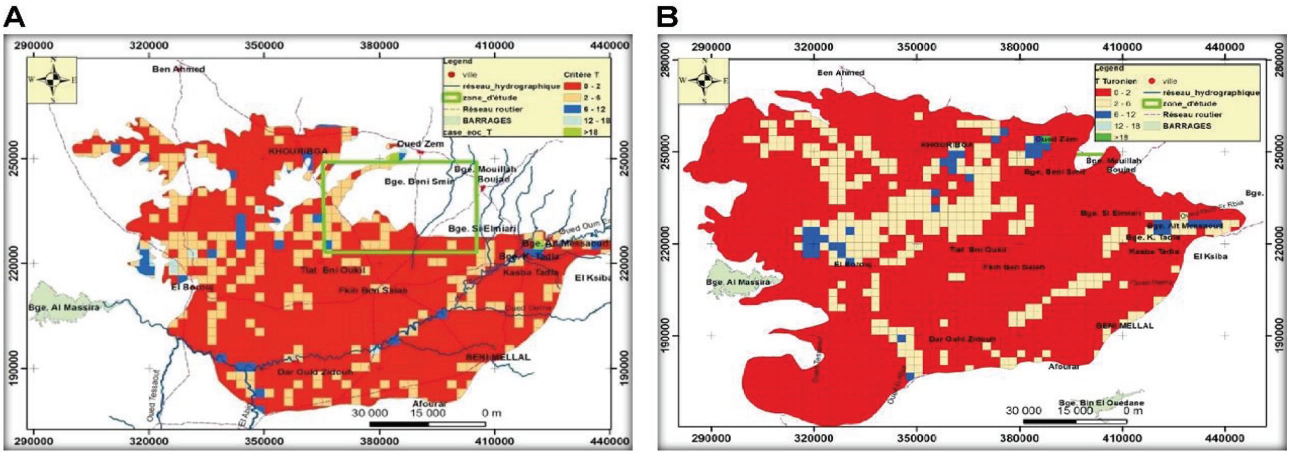

Figure 5 Map of the parameter relating to the topography (T) of the A) Eocene aquifer and B) Turonian aquifer of the Tadla.

the degree of vulnerability of the aquifer very variable in space.

Thematic map of parameter C (Electrical conductivity)

According to Azzi 2014, hydraulic conductivity expresses the ability of geological formations to transmit water with possible pollutants under the effect of a hydraulic gradient up to the saturated zone. Based on the sections of the ABHOER wells and more particularly the lithology and hydraulic conductivity, with the aim of assigning a coast for each lithological class (Table 11).

The analysis of the thematic map of criterion C of the Eocene aquifer, figure 7A shows the presence of 5 permeability ranges according to the lithology, the predominant of which is 18 and 24 and for the Turonian aquifer (Figure 7B) between 18 and 23. The larger this parameter, the greater the pollutant transfer is rapid.

Pollution vulnerability map of the Eocene and Turonian aquifers

The vulnerability index is calculated by a sum of the products (Score * Weight) of the seven DRASTIC parameters (see the calculation formula). The values of the DRASTIC index are classified into four intervals defining four classes from 1 to 4 ranging from the value 75 to the value 183 (Aller et al, 1987) (Table 12).

The calculation of the DRASTIC index of the two Eocene and Turonian aquifers (Figure 8A and B) enabled us to establish pollution vulnerability maps in 4 classes (Table 12).

- Zones with high vulnerability: they are found at the level of the Eocene aquifer, more precisely in the NW, S and SE part. This could be explained by the gravelly nature of the soil, the vadose zone and the aquifer materials which are very permeable. The terrain in this area forms a gentle relief and has a regular and slight dip towards the SW. A strong percolation of water is practically favoured, and this in the absence of runoff, thus contributing to a rise in the water table. The deep drainage of the aquifer by the Oum-Rbia in turn remains very limited due to the direction of the flow of the aquifer which follows the dip of the Plio-Quaternary geological foundations towards the southwest. The proportion of rain infiltration in relation to irrigation inputs does not generally exceed 20% (Belhacene and Chayat, 1992) even for years

Table 10: Coasts and classes retained for the parameter I of the unsaturated zone.

Lithologic nature	Typical rating	Weight	Value
Clay and silt	1	5	**5**
Marls	2		**10**
Limestone	3		**15**
Marl-limestone	4		**20**
Soft sandstone and soft phosphated limestone	5		**25**
Conglomerate	6		**30**
Phosphate sands	7		**35**
Gravels and alluvium	**9**		**45**

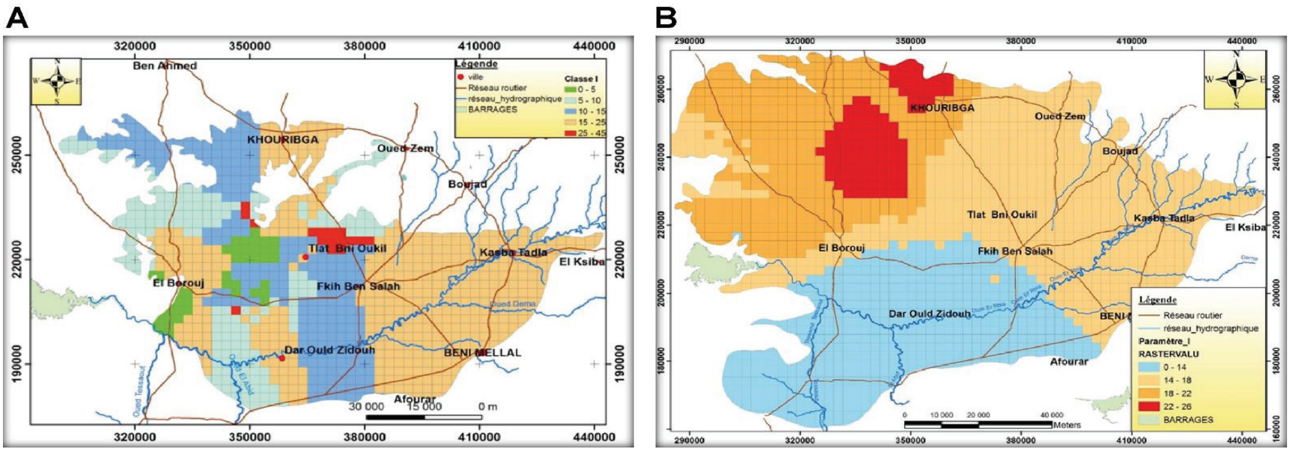

Figure 6 Map of the parameter relating to the unsaturated zone (I) of the: A) Eocene aquifer and B) Turonian of the Tadla Plain.

Table 11: Coast and classes retained for parameter C (Hydraulic conductivity).

Permeability range (in m/s)	Note	Weight	Value
<10-9	1	3	**3**
10-9 – 10-7	2		**6**
10-7 – 10-5	4		**12**
10-5 – 10-3	6		**18**
10-3 – 10-1	8		**24**
10-1 – 10	**9**		**27**

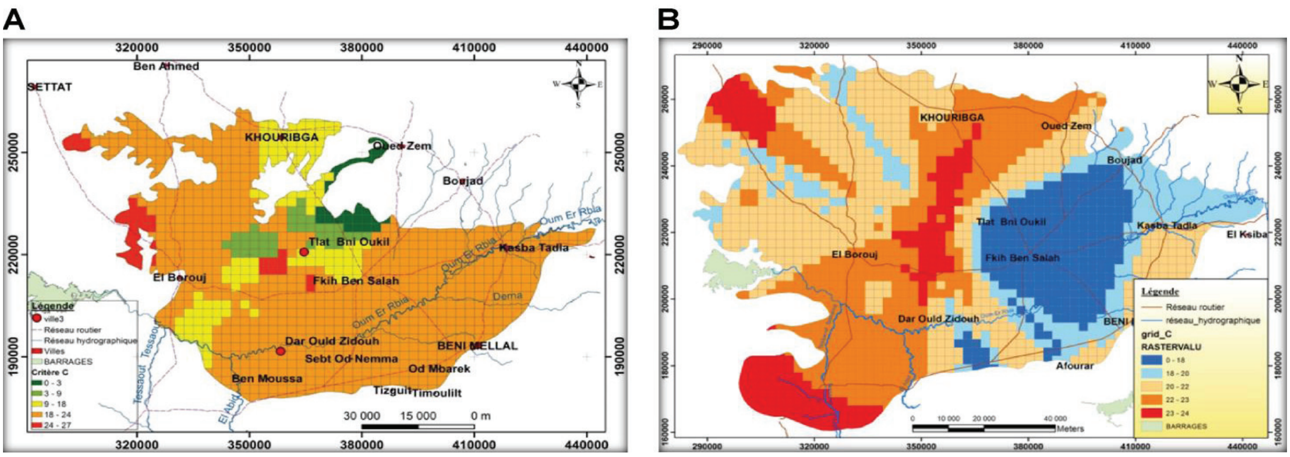

Figure 7 Map of the criterion relating to the Hydraulic Conductivity (C) of the: A) Eocene aquifer and B) Turonian aquifer of the Tadla Plain.

Table 12: Coast and indices retained for the vulnerability map.

Class	Hint	Degree of vulnerability
I	75-85	Very weak
II	85-106	Weak
III	106-121	Mean
IV	121-183	Vulnerable

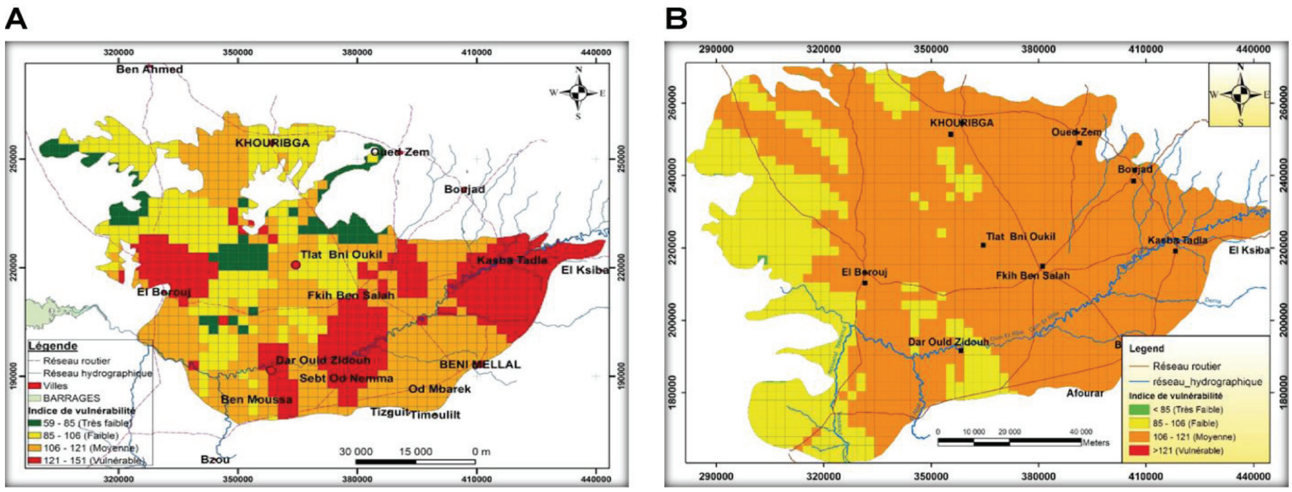

Figure 8 Pollution vulnerability map of the: A) Eocene aquifer and B) Turonian aquifer of the Tadla plain.

with a strong rainfall surplus, groundwater recharge by precipitation seems to mark the evolution of the bathymetry of the aquifer. Also the semi-arid nature of the climate of the plain means that the rains are often in the form of heavy downpours of short duration. These, and in the absence of surface drainage, would contribute to the rise in the piezometric level of the water table.

- Areas of medium vulnerability: highly responded to by a large area of the Tadla plain represented by the two aquifers (Eocene and Turonian). The very low topographic slope which is added to the presence in certain places of large basins favors the infiltration of water. The depth of the piezometric level is a direct function of the recharge rate generated by the infiltration of rainwater and that of springs.

- Zones of low vulnerability: limited in the SW part for the two aquifers with an extension towards the Fkih Ben Saleh zone for the Eocene aquifer. The various parameters acting on the vulnerability to groundwater pollution have intermediate values. The recharge rate is relatively low, and the soil is of the moderately deep iso-humic type.

- Zones with very low vulnerability: they are presented in the map of vulnerability to pollution of the Eocene aquifer. This character is mainly due to the low rate of recharge and the great thickness of the unsaturated zone. The depth of the piezometric level generally exceeds 15 m and the soil facies represented in this zone has a texture thus limiting the rapid infiltration of water.

Conclusion

Our study area is located in an agricultural region, where the use of fertilizers and pesticides is increasing. This constitutes real pollution threats, in addition to irrigation using water of mediocre physico-chemical quality and poor management of drainage water and livestock effluents. To know to what extent the places with the greatest vulnerability constitute a danger for the groundwater resource, a vulnerability study becomes very necessary and important. It is for this purpose that different degrees of vulnerability to groundwater pollution have been defined and a specialized mapping method has been developed to indicate their geographical distribution in the region of the study area.

Overall, the vulnerability indices calculated from the Seven DRASTIC parameters indicate four classes of vulnerabilities:

- Vulnerable (between 121 and 183).
- Moderately vulnerable (between 106 and 121)
- Low (between 85 and 106),
- Very low (between 75 and 85),

The depth of the two more or less deep Eocene and Turonian aquifers has experienced a considerable drop. Indeed, between the year 1990 and 2000 the Eocene water table went from 23 m to 50 m. This decline is mainly due to the development of the pumping technique and the digging of boreholes and the deepening of old boreholes which can sometimes reach the captive aquifers of the Eocene and probably the Turonian. In our study area, the average depth of the Eocene aquifer varies between a minimum value of around 6 m and a maximum value of 90 m. Other similar depths, especially those that vary between 80 and 100 m, have been located south of our study area [1-6].

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