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Assessment of Aquifer Vulnerability to pollution Based on TCR Method: Application to Oulad Ogbane aquifer (Morocco)

Laila Knitar[1], Mina Amharref[1], Abdes Samed Bernoussi[1], Hind Es Saouini[1]
[1]*Geoinformation and Land Management Team (GAT), AbdelmalekEssaâdi University, Faculty of Sciences and Technology, Ancienne Route de l'Aéroport, Km 10, Ziaten. BP : 416. Tangier - Morroco*
Corresponding Author: Laila Knitar

Abstract: *In this study, we address the issue the vulnerability of groundwater to pollution at the aquifer of Oulad Ogbane (Northwest of Morocco). The study has been carried out following the TCR method (Method based on 3 parameters: The transit time (T); The degree of purification (C'p/Cp) and The recharge degree (R'/R) ; the weighting coefficients have been determined by sensibility tests, followed by multiple linear regression analysis performed on sample sources showing significant variations in the applied parameters. The studied aquifer is a vital natural source used for domestic agricultural purposes. The area around it is used primarily for farming, which is characterized by a significant use of chemical fertilizers, which represents, in addition to the discharge effluents, a permanent danger to the quality of groundwater. We have carried out a comparison of results against the results of similar studies done on other neighboring aquifers, which showed an urgent necessity to adapt the weighting coefficients, which change from one area to another, to the particularities of the studied area. Applying the TCR method has allowed for distinguishing high sensibility areas that require special attention in terms of preservation and management.*

Keywords: *Groundwater; Vulnerability; Pollution; TCR; Sensibility tests; Oulad Ogbane (Morocco).*

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I. Introduction

The protection and preservation of natural resources constitute an urgent necessity, especially in countries where these resources are limited. In Morocco, natural water sources are among the weakest in the world, declared the State Secretary in charge of Water. It estimates the potential natural water sources at 700 m³/person/year (22 billion m³/year). In general, it can be said that the quality of the groundwater in the area is good. Thus, mapping the vulnerability of aquifers to pollution represents an efficient tool in limiting and controlling the risks of regression in the quality of such water sources and ensuring the durability of natural resources. A number of methods for determining the groundwater vulnerability have been developed around the world; such as: DRASTIC (Aller et al., 1985), GOD (Foster, 1987), F-DRASTIC (Amharref et al., 2015) going from more complex ones with models that take into account the physical, chemical, and biological processes, to methods that balance between different criteria that affect the vulnerability (Gogu and Dassargues, 1998 b). The choice of using one vulnerability method is made based on many criteria. It is firstly important to determine the type of method to be used, then to determine the method based on both the available and necessary data (Murat, 2000).

In this study, conducted by our research team (GAT) in collaboration with the Regional Office for Agricultural Investment Loukkos (ORMVAL), we are going to adopt the TCR method in order to define the vulnerability of the Oulad Ogbane aquifer to pollution, with the aim of preserving and improving the management of this water source.

The importance of TCR method lies in the fact that it only takes into account the most significant factors for assessing vulnerability by avoiding the redundancy problem associated with the most widely used methods. It has been used for vulnerability mapping of the Gharb plain (Amharref and Bernoussi, 2007) and the R'Mel aquifer (Es Saouini et al., 2014).

1. Vulnerability index and mapping

1.1 Principle and methodology

The notion of vulnerability, which was developed by Margat in the sixties, designates the possibility of the leaking and spreading of polluting substances in the aquifer (Albinet and Margat, 1970). An area is considered vulnerable if a polluting substance enters the water reserve in a big amount at a short time (Amharref and Bernoussi, 2007). In order to estimate the vulnerability of the Oulad Ogbane reserve to pollution, we have chosen to use the TCR method (Amharref et al., 2007), which was successfully used in modeling the vulnerability of the neighboring reserve (R'Mel), (Es Saouini et al., 2014). This is a flexible method that adapts easily to the different conditions. The change we have made concerns the adoption of new Weighting coefficients linked to the specificity of the region. TCR method belongs to the group of parametric methods and depends on three parameters linked to the transfer of polluting substances:

The transit time (T) of a polluting substance in the unsaturated zone (Fig. 1); is the time necessary for a drop of water that has fallen on the soil surface to reach the reserve. That depends on the nature of the crossed layers and the filtration speed.

The degree of purification (C'p/Cp) is the ratio of the concentration of the pollutant substance in the groundwater, C'p, compared to its initial concentration on the surface of the soil, Cp. It is essential for estimating the vulnerability of water sources and often hard to achieve due to the complexity of the infiltration processes that control the movement of the pollutant across the unsaturated area.

The recharge degree (R'/R) is the relation of effective recharge **R'** compared to the potential recharge **R**. It is an index of the degree of water supply in the aquifers that are naturally supplied with water through rain and surface leaking.

The TCR index is the average total of the three parameters according to the following formula (1):

$$\mathbf{Iv = \alpha\ 1/T + \beta\ C'p/Cp + \gamma\ R'/R} \qquad \mathbf{(1)}$$

Where **α, β, γ** represent the affected weights in every parameter according to their relative importance.

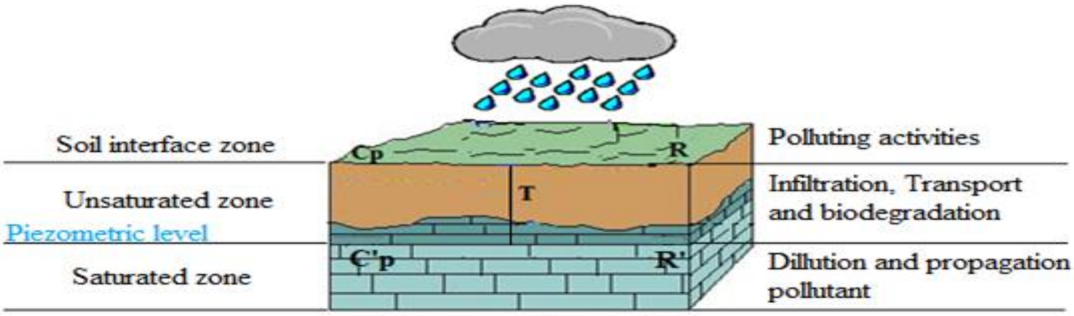


Fig.1 Diagram of groundwater contamination

1.2 Assessment of the R'/R, C'p/Cp and T parameters

The parameters transit time and degree of purification have been analyzed through the filtration speed, the purifying power, and the thickness of the different layers of the covering area (Amharref et al., 2007)

T: the transit time via the covering area, it has been assessed using the filtration speed (Vi) through the different layers of the unsaturated area. The transit time Ti, for a given layer is calculated by: Ti = hi/Vi (hi is the thickness of the crossed layer).

C'p/Cp: the purification degree is the ratio of the concentration of the pollutant substance in the groundwater (C'p) compared to its initial concentration on the surface of the soil (Cp), it is estimated using the purifying power Md of the covering layer, considering that:

$$C'p/Cp = \begin{cases} 1-Md & \text{if } Md < 1 \text{ case of partial purification} \\ 0 & \text{if } Md = 1 \text{ case of total purification} \end{cases}$$

Md and Vi of each layer have been assessed using the empirical method of Rehse (1977).

Table 1 Infiltration rates and purge index of different rocks (Rehse, 1977)

Granulometry	Materials	Purification index	Filtration speed (m/j)
Sediment Mud	Humus, 5-10% humus, 5-10% clay	0,8	0,86
	clay, clay loam, clayey sand, silty clay,	0,5	0,003 - 0,025
	Clayey silt to silt, fine silt	0,4	0,16
	Silt, silty sand, litle silty clayey sand, litly sand	0,22-0,33	0,54 - 4,32
Sediment Sand	Fine to medium sand	0,17	8,23 -10
	Medium to coarse sand	0,1	19,2
	Coarse sand	0,07	27
Sediment Gravel	Silty gravel, rich in sand and clay	0,13	0,72
	Little silty gravel, lots of sand	0,08	144
	Fine to medium gravel rich in sand	0,04	201
	Medium to coarse gravel, litle sand	0,03	480
	Pebble	0,02	4320

R'/R: the recharge degree is the relation between the effective refill R', compared to the partial refill R. it can be estimated using many methods, the most commonly used one is that of water balance. We have established a monthly water balance assessment by the Thornthwaite method.

- **Weighting coefficients: α, β, γ**

In order to assess the values of the elements α, β, γ of the vulnerability index Iv, we have performed sensibility tests followed by multiple linear regression analysis of the index Iv and the three parameters 1/T, C'p/Cp, R'/R (Amharref et al 2007). This analysis was done on sample 11 wells.

II. Application on the Oulad Ogbane aquifer (Loukkos-Morocco)

2.1 Description of the study area

Located in the northwest of Morocco, the Loukkos area extends on around 4771 km^2 and is divided into two sub-basins:

-Dradere Soueire (1041 km^2).

-Loukkos (3730 km^2) includes the Loukkos, Rmel, and Oulad Ogbane aquifers, distributed as shown in the map (Fig.2).

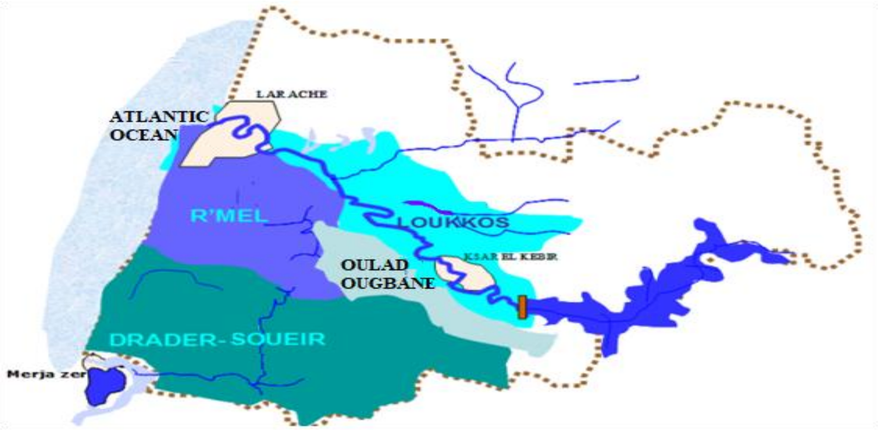


Fig. 2 The main aquifers of the Loukkos Bassin

The Oulad Ogbane aquifer is located in the south-west of the city of Ksar El Kbir. It stretches for about 16 km from the northwest to the southeast over an area of 60 km^2. In administrative demarcation, the reserve is located mainly on the territory of the rural commune of Zouada and partly on the territory of that of Arbaoua.

The reserve circulates within Villafranchian pebbles and gravels whose thickness varies between 40 and 60m. it flows from the south-west towards the northeast before pouring into the alluvial reserve of Oued Loukkos. It also drains into the superficial water currents that cross through it (Oued Dahnoun and Oued Khefacha). The depth of the reserve's surface varies from less than 5 m in the eastern part to more than 15 m/soil in the central and western zones (ORMVAL, internal report, 2007).

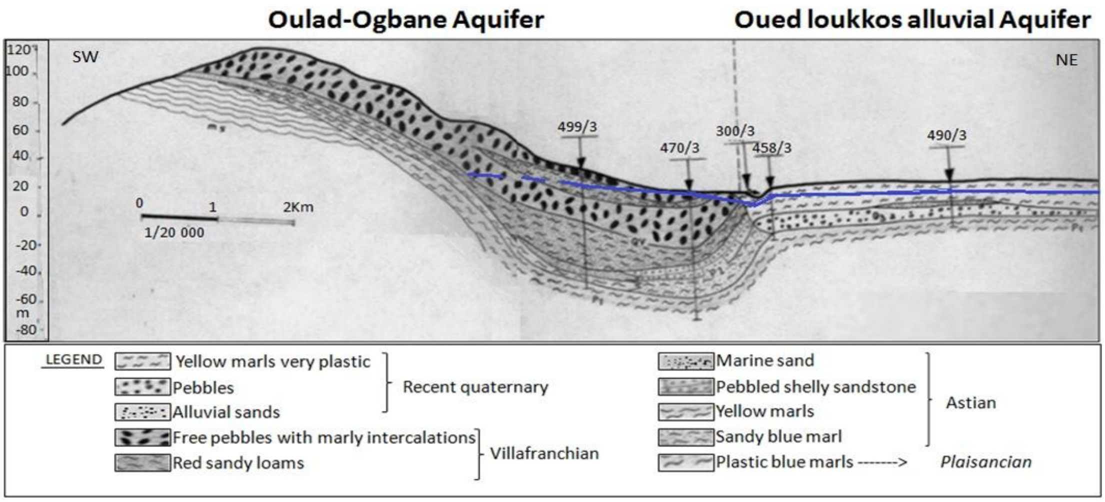


Fig. 3 Hydrogeological profile

2.2 Data related to the study area

The transit time depends on the propagation speed of pollutants, which are themselves conditioned by the nature and organization of components that make up the unsaturated area.

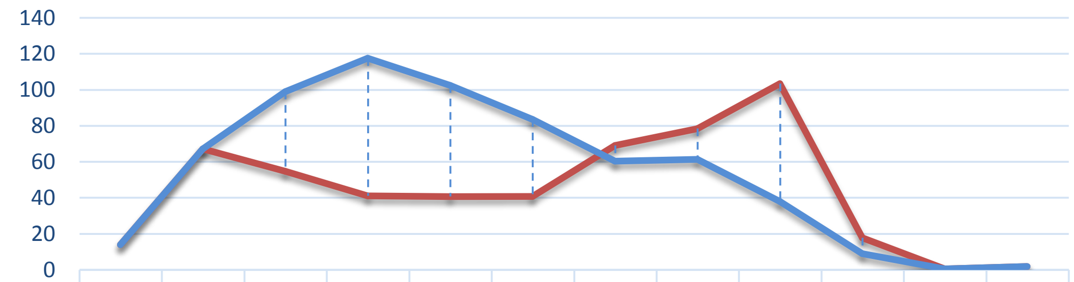
Thus, the rougher the material is, the faster the infiltrated water can move into the water reserve. In contrast, finer sediments increase the residence time of the infiltrated water in the vadose zone. The data collected on the lithological sections of the boreholes, soundings and piezometer tests carried out in the studied area have allowed us to determine the nature and the thickness of the layers constituting the ZNS.

The Oulad Ogbane reserve circulates primarily within pebbles and gravels. These layers contain a clay matrix in the western zones and have sandy intercalations in the central zone. The maximum thickness of the unsaturated zone is about 20 m in the western zones and 1.15 is the value minimum has been recorded in the eastern zone.

The degree of purification parameter depends on the lithological nature of the layers constituting the unsaturated area. This parameter is involved in the trapping of the pollutant. The finer the size of the materials is, the greater is the trapping of the pollutant, which promotes certain physicochemical processes (Absorption, Adsorption ...). The data used to calculate this parameter are those used to estimate the transit time. The purifying power (Md) of each layer was estimated by the empirical method proposed by Rehse (1977).

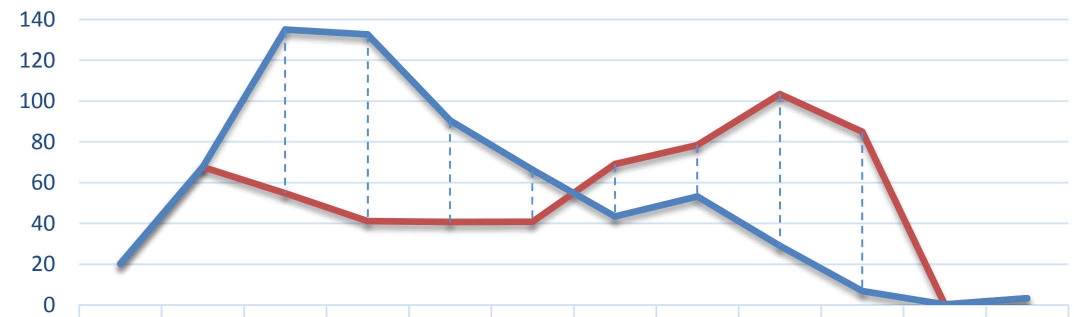
The estimation of **the recharge degree R '/ R** (the ratio of the effective recharge compared to the potential recharge) was carried out according to the Thornthwait method.

For the spatial distribution of rainfall, we have chosen to apply the Thiessen polygon method, based on the use of mediators between the different neighboring stations, this method has revealed three sub-zones related to the closest testing stations. We have noticed that nearly the entire surface of the aquifer is linked to the M'rissa station; the other stations occupy limited parts in the north (Aouamra) and in the south (Arbaoua).



	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG
ETR	13.95	67.21	54.78	41.11	40.7	40.8	69.11	78.44	103.44	17.81	0.53	1.87
P	13.95	67.21	99.00	117.60	102.50	83.60	60.40	61.40	38.00	9.00	0.53	1.87

Fig. 4 Water-balance diagram of the M'RISSA climate station



	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG
ETR	20.19	67.64	54.78	41.11	40.7	40.8	69.11	78.44	103.44	84.95	0.23	3.26
P	20.19	67.64	135.10	132.70	90.50	66.30	43.40	53.20	29.00	6.80	0.23	3.26

Fig. 5 Water-balance diagram of the Aouamra climate station

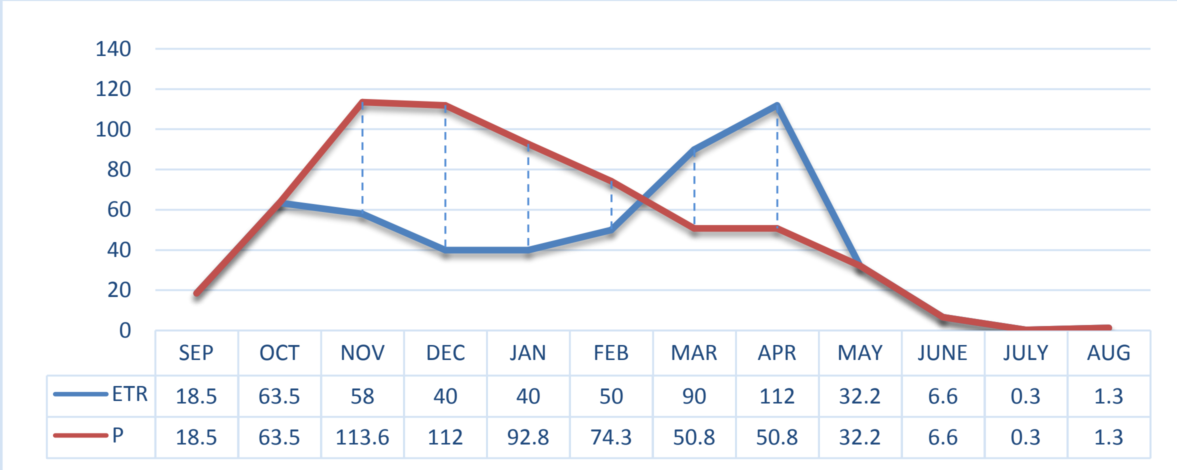


Fig. 6 Water-balance diagram of the Arbaoua climate station

The water assessment results in an average annual recharge of about 125 mm^3 / year, or about 19% of the estimated annual rainfall of 655 mm^3 / year at the M'rissa station, 147 mm^3 / year (22%) estimated at the Aouamra station and 106 mm3 / yr (18.7%) for the Arbaoua station. The results of simulated recharge levels are between 0.19 and 0.22 for all testing points. The change of land use is a main reason for the difference between these three stations.

2.3 Method adjustment: Sensibility test

The weighting coefficients (α, β, and γ) have been determined by sensibility tests followed by multiple linear regression analysis carried out on 11 sample wells (table 2), which represent significant variations in the three parameters. We could calculate the 1/T and C'p/Cp parameters depending on the data of the table below, the infiltration speed, and the purification indexes of the different layers.

Table 2 Data table

N°	X	Y	Z	Depth (m)	Thickness (m)	Soil layers
1688	440,650	496,700	26,53	5,80	0 - 5,8	SandandSilt
1030	442,750	493,350	35,00	20,00	0 - 1 1 - 8 8 - 10 10 - 17 17 – 20	Pebbles Clay Sand and Gravel Pebbled clay Clayey Sand
470	446,000	491,000	15,19	1,15	0 – 1,15	Fine Sand
499	444,975	489,925	35,52	12,70	0 – 2 2 – 12,70	Pebblesand Sand ClayandPebbles
1740	448,050	489,400	15,00	5,00	0 – 1 1 – 2 2 – 5	Sandand Gravel SandandSilt Pebblesand Gravels
1695	449,300	487,850	25,00	19,59	0 – 2 2 – 6 6 – 19,59	Fine Sand Pebbled sandy silt Pebblesand Gravels
1697	448,306	487,750	30,00	10,96	0 – 2 2 – 7 7 – 10,96	Fine Sand Pebbles and Gravels Sandy Pebbles and Gravels
1696	450,100	486,545	20,00	12,95	0 – 12.95	Sandy Pebbles and Gravels
1808	448,500	486,800	36,00	11,85	0 – 11.85	Sandy Pebbles and Gravels
1700	449,505	485,750	20,00	6,80	0 – 6.8	Silty Sand and Gravels

In addition to the sample wells, we have considered a reference well (well number 1111 [sic]: a fictive well of T=1, C'p/Cp=1, R'/R=1). These wells have been organized qualitatively according to an increasing vulnerability, based on the determination of the variation sign of the vulnerability index for two consecutive wells, with the unknown values (Iv_i+1-Iv_i). (Table.3). Based on this order, we have carried out a first analysis of the effect of the variation of the different parameters (1/T, C'p/Cp, R'/R) on the vulnerability. It also seems that the parameter 1/T is the most active on the vulnerability index compared to the other parameters C'p/Cp, R'/R.

Table 3 Classification of control wells

N°Wells	1030	700	499	1695	1700	1688	111	1740	1697	470	1696	1808
1/T	0,00	0,00	0,05	0,18	0,64	0,72	1,00	3,57	3,85	8,33	37,04	40,00
C'p/Cp	0	0	0	0	0	0	1	0,6	0,39	0,83	0,61	0,64
R'/R	0,19	0,19	0,19	0,19	0,19	0,23	1	0,19	0,19	0,19	0,19	0,19
Ranking by order of vulnerability	1	2	3	4	5	6	7	8	9	10	11	12

We then carried out a series of simulations for the different values of α, β, and γ within the interval of [0-1] with a step of 0.1 for each element. Calculated for each combination, the index Iv has allowed us to order the sample wells and to eliminate the combinations that give results that don't conform with the qualitative ordering of those wells. Fig.6 gives a graphic representation of the different combinations.

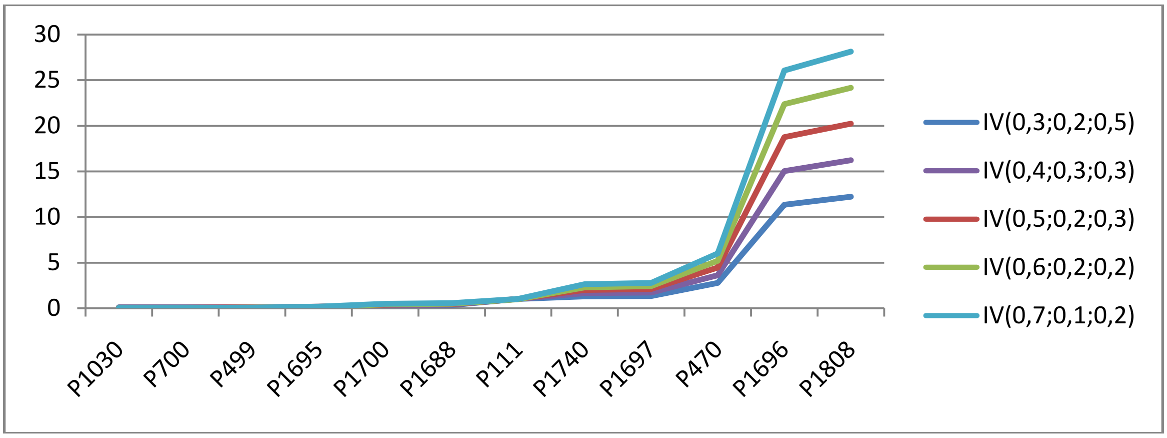


Fig. 7 curves representing Iv for different combinations of weighting coefficients

After that, we calculated an average value of Iv, which is the average of the results obtained by the retained combinations, and that allowed for getting approximate values of Iv for the sample wells (Table 4).

Table 4 Calculation of Iv medium

N° Wells	1/T	C'p/Cp	R'/R	Vulnerability Ranking	Iv medium
1030	0,0004	0	0,19	1	0,0553
700	0,0008	0	0,19	2	0,0555
499	0,0518	0	0,19	3	0,081
1695	0,1764	0	0,19	4	0,1433
1700	0,6369	0	0,19	5	0,3736
1688	0,7194	0	0,23	6	0,4264
111	1	1	1	7	1
1740	3,5714	0,6	0,19	8	1,9668
1697	3,8462	0,39	0,19	9	2,0601
470	8,3333	0,83	0,19	10	4,3961
1696	37,0370	0,61	0,19	11	18,702
1808	40,0000	0,64	0,19	12	20,19

Using these values, we performed a linear regression in order to determine the values of α, β, and γ. The adopted coefficients are:

Iv = 0.5 1/T + 0.21 C’p/Cp + 0.29 R’/R

The obtained equation shows that what conditions the index Iv ($\alpha = 0.5$) most is the factor of transit time and that the purification degree affects it least ($\beta = 0.21$ and $\gamma = 0.29$). These results conform to the preliminary analysis of the variation effect of the different parameters (1/T, C’p/Cp, R’/R) on the vulnerability, realized on the database (Table 2), which represents significant variations of the parameter 1/T, in contrast with the other parameters.

2.4 Mapping and interpreting the vulnerability

The values of the calculated weighting coefficients for the Oulad Ogbane reserve have been determined by sensibility tests followed by multiple linear regression analysis performed on 11 sample wells. The linear combination that estimates the vulnerability index based on the three parameters is approximately: Iv = 0.5 1/T + 0.21 C’p/Cp + 0.29 R’/R. These values look different from those estimated for the reserve of R’mel (Iv= 0.4 1/T + 0.3 C’p/Cp + 0.3 R’/R). Although we are talking here about two neighbor reserves situated within the same climate and have been considered by many previous studies as one aquifer, this difference in coefficients could be explained by the variation observed at many parameters of the two reserves (the nature of the surrounding land, permeability…). (Table 5)

Table 5 Aquifers characteristics

	R’Mel	Oulad Ogbane
Area	$240*10^6$ m^2	$58*10^6$ m^2
Lithology	Sand, SandyMarl and Shell Sandstone	Pebbles and Gravels
Thickness	20 at 100 m	40 and 60 m
Groundwater Depth	5 at 20 m	1 at 20 m
Permeabilites	5.10^{-6} (west and south) $3,5.10^{-4}$ m/s in the center	5 and 6.10^{-5} m/s
Transmissivites	10^{-4} and 10^{-2} m²/s	1,3 and 3.10^{-3} m/s (North)
Productivity	> 2 l/s (10 l/s Aâouamra)	10 and 15 l/s
Total reserve	129 Mm³	32.82 Mm³
Medium Storage Saturated zone	5.10^{-3} $2.58*10^{10}$ m³	$2,3.10^{-3}$ $1.42*10^{10}$ m³
Flow	- From South to Northeast - Towards the Atlantic Ocean in the Northwest	Southwest to northeast

Although the calculated values of weighting coefficients on the level of the Oulad Ogbane reserve differ from those seen at the R’mel one, we observe that the obtained equations show that the factor of Transit Time (1/T) is the one that conditions the vulnerability index most, and that the purification degree and recharge factors are the ones that have the least effect on the index. Bearing in mind that the parameter 1/T depends on the filtration speed of the thickness of the layers that compose the saturated area, it is, therefore, conditioned by the nature of the layers of the vadose zone and the depth of the reserve. The values of this latter are approximately similar in the two reserves and experience a significant variation compared to the other parameters; it is estimated between around 1 and 20 m for the Oulad Ogbane reserve, and between 5 and 20 m for the R’mel one, which explains the dominance of this parameter in the results of the indexes of the two reserves.

Using the TCR method in the mapping of the vulnerability of the Oulad Ogbane aquifer has allowed us to obtain three thematic cards (recharge degree, purification degree, and the reverse of the transit time).
Combining these thematic cards has allowed us to set up an intrinsic vulnerability card (fig. 7) where we distinguish four classes of different vulnerability degrees:

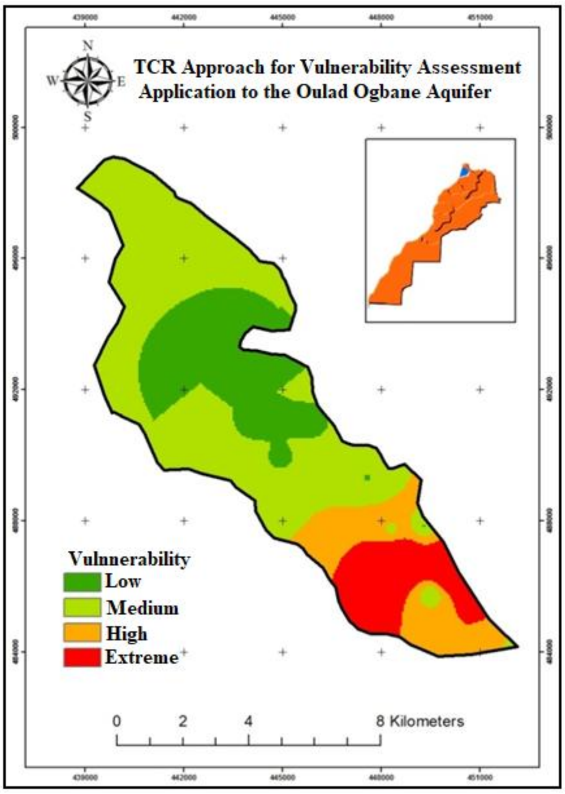


Fig. 8 Vulnerability Map

Areas of low to average vulnerability degrees are located mainly in the northern part of the reserve. The low degree is explained by the combination of significant depth of the 20 m order and the clayish nature of the lithological layers that ensure a significant purification while increasing the transit time of water in the soil.

Areas of strong to extreme vulnerability are located in the southern part of the reserve where there are the unsaturated layers that are constituted mainly of gravel, pebble, and sand. We observe the dominance of average vulnerability areas by 52.09% of the surface of the reserve (Fig. 8). They coincide with less significant depth and layers of mixed lithology, composed of pebble and gravel, with sandy and clayish intercalations. (Vulnerability is an intrinsic property of aquifers, it depends on the characteristics of the environment, it does not include the degree of exposure to the risks of pollution.)

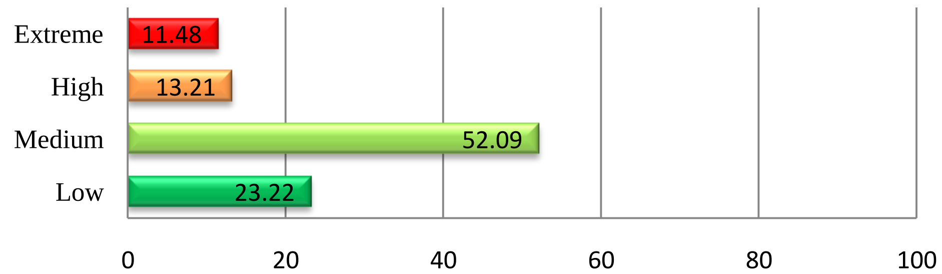


Fig. 9 Distribution of aquifer area according to the degree of vulnerability

III. Conclusion

Applying the TCR method in mapping the vulnerability of the Oulad Ogbane groundwater reserve to pollution has uncovered areas of high vulnerability in the southern part of the aquifer, which occupy about 25% of the reserve's surface. On the other hand, the northern part of the aquifer is characterized by average to low vulnerability degrees.

The weighting coefficients, which were estimated by the sensibility tests, differ from those defined for the R'mel aquifer. This result shows that applying the TCR method with the estimation of the weighting coefficients of the applied parameters change according to the nature of the environment where it is applied.

The analysis of the adopted parameters used by the method and their range of variation, and the weighting coefficientsreveals, in both cases, that the transit time (T) is the one that conditions most the vulnerability index, these results are due to:

1. Variation in the nature of the layers that constitute the unsaturated area of both aquifers.
2. Both reserves are situated at relatively low depths, which are consecutively (between 1 and 20 m) for Oulad Ogbane, and (5 and 20 m) for R'mel.

Finally, we would like to note that the weighting coefficients of the TCR method, which are estimated by sensibility tests, change from one area to another. Therefore, choosing to adopt this method in mapping the vulnerability groundwater requires adapting the weighting coefficients to the characteristics of each aquifer in order to obtain a reliable vulnerability map that represents the particularity of the studied area. Therefore, and in order to ensure the best protection of this source, another study of risks has proven necessary (an ongoing project).

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