CONTRIBUTION TO THE STUDY OF VULNERABILITY OF TERMINAL COMPLEX AQUIFER AND WELLHEAD PROTECTION AREA OF WATER CATCHMENT IN THE VALLEY OF EL-OUED

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Abstract.- *Water is a vital resource for all living things, particularly in arid regions where water scarcity is a problem. Increasing population, pollution and climate changing are the main factors that negatively affect the amount of water on earth and increase water stress. In arid Algerian regions (the Sahara), underground water is basically the only source of water supply for various uses (human, agricultural and industrial). So, its preservation is critical. For this reason, its preservation is vital. The aim of this study is to verify the vulnerability of groundwater to pollution using the WYSSLING method to identify a wellhead protection area in the aquifer of the terminal complex (TC) of the valley of Oued Souf (South-Eastern Algeria). Results obtained using the WYSSLING method and isochronous calculations show that the terminal complex aquifer has low vulnerability and sensitivity to pollution, and that wellhead protected areas vary from one place to another due to geological features of the region and other factors such as water rising.*

Key words: *Groundwater, vulnerability, pollution, WYSSLING method, wellhead protection.*

CONTRIBUTION A L'ETUDE DE LA VULNERABILITE DE LA NAPPE DE COMPLEXE TERMINAL ET LES AIRES DE PROTECTION DES TETES DE PUITS D'EAU DANS LA VALLEE D'EL OUED

Résumé.- *L'eau est une ressource vitale pour tous les êtres vivants, en particulier dans les régions arides où la pénurie d'eau est un problème. L'augmentation de la population, la pollution et le changement climatique sont les principaux facteurs qui affectent négativement la quantité d'eau sur terre et augmentent le stress hydrique. Dans les régions arides algériennes (le Sahara), les eaux souterraines sont la principale et la seule source d'approvisionnement en eau pour divers usages (humains, agricoles et industriels). Donc, sa préservation est essentielle. La présente étude vise à vérifier la vulnérabilité des eaux souterraines à la pollution par la méthode WYSSLING qui permet d'identifier la zone de protection de tête de puits dans la nappe de complexe terminal (CT) de la vallée de l'Oued Souf (sud-est de l'Algérie). Les résultats obtenus à l'aide de la méthode de WYSSLING et des calculs isochrones montrent que les eaux de la nappe du complexe terminal ont une faible vulnérabilité et sensibilité à la pollution, et que les surfaces des aires protégées des têtes de puits varient d'un endroit à l'autre en raison des caractéristiques géologiques de la région et d'autres facteurs tels que la remontée des eaux.*

Mots clés*: Eau souterraine, vulnérabilité, pollution, méthode de WYSSLING, protection des têtes de puits.*

Introduction

All over the world , groundwater provides essential and valuable source of water for drinking water production, agricultural irrigation [1] and industrial processes [2].

In the Algerian Sahara, groundwater is the only resource available for the population's various needs (domestic, agricultural, and industrial) [3]. The inhabitants of Oued Souf valley, like those of other Saharan regions,, used the phreatic aquifer water for agriculture and human consumption before the discovery of petroleum in the Sahara. This water is subsequently thrown back into the wild to reach the phreatic aquifer water again without affecting its piezometric level (this is called: closed system) [4].

The discovery of petroleum led to the finding of deep water aquifers. Also, in light of the rapid increase in demand caused by the rise of the number of inhabitants, the extension of agricultural land and the appearance of industrial activities; authorities resorted to the deep water of the terminal complex(TC) and continental infill (CI) despite their poor quality (salty and/or hot water) [5,6].

The intensive exploitation of these deep and fossil aquifers, which supply the groundwater after their use, caused the aquifer to rise and occasionally outcrop (called: opened system) [4]. The phreatic aquifer receives wastewater from wild settlements in addition to groundwater, making it increasingly polluted and dangerous to human health and the environment [7-9].

With all these risks, the study of the vulnerability of groundwater in the Algerian Sahara became essential to provide for prior protection. For this, several methods are used. Among them, there is WYSSLING method used in our study to determine the degree of weakness of the water and wellhead protected areas of the terminal complex in Oued Souf valley.

1.- Presentation of the study area

El Oued is located 600 kilometers South-East of Algiers in the North of the Algerian Sahara (33° 07′ 00″ N, 7° 11′ 00″ E). It is divided into three distinct zones: The Souf valley, the Oued Rhig valley, and the border region (Taleb Larbi). El Oued has an arid climate with long dry periods, and its water is derived from underground sources. The population of El Oued are mostly farmers. After agriculture, the small and medium enterprises industry plays an important role in people’s lives.

2.- Work plan

To study the vulnerability of terminal complex in El Oued region, we selected six of the 14 existing wells in the southern Souf Valley (fig. 1).

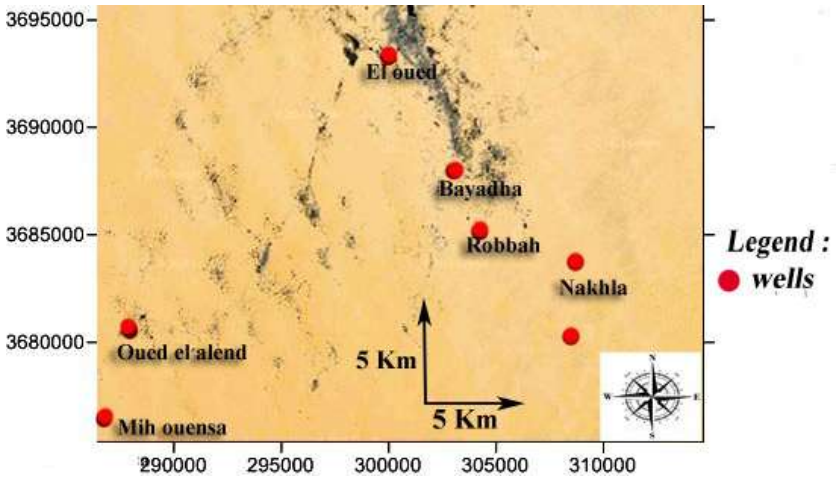


Figure 1.- Universal Transverse Mercator (UTM) coordinates of pumping test sites (satellite map, 2019)

For determining vulnerability, we need a geological section of the catchment. The detailed vulnerability assessment required for using the WYSSLING method needs five criteria:

- The thickness of the unsaturated zone;
- The nature of the unsaturated zone;
- The type of aquifer;
- The permeability of the aquifer; and
- The relationship with the hydrographic network.

The following table I specifies the classes for each of the criteria as well as the weighted scores.

Table I.- Vulnerability Criteria with Weighted Ratings

Prediction of vulnerability in details			
Unsaturated zone thickness	< 15 m $V_1 = 6$	from 15 to 30 m $V_1 = 3$	from 30 to 60 m $V_1 = 0$
Nature of the unsaturated zone	Permeable formations (medium to coarse sands, gravel) $V_2 = 4$	Intermediate permeability formations (clay sands, sandy clays) $V_2 = 2$	Waterproof or very low permeability formations (clays, uncracked base) $V_2 = 0$
Type of groundwater	Free $V_3 = 2$	Semi-captive $V_3 = 1$	Captive $V_3 = 0$
Permeability K of the aquifer	Strong: K> 10^{-3} m/s or aquifer composed of limestones, coarse sands, gravels $V_4 = 6$	Average: K between 10^{-5} and 10^{-3} m/s gold aquifer compound of fine to medium sands $V_4 = 3$	Low: K less than 10^{-5} m/s or aquifer composed of clay sands or low permeability formations $V_4 = 0$
Relationship with the hydrographic network	YES $V_5 = 2$	Unknown or uncertain $V_5 = 1$	No $V_5 = 0$

We get a score of $V = V_1 + V_2 + V_3 + V_4 + V_5$ by adding the weighted scores of each criteria, which ranges from 0 (the lowest vulnerability possible) to 20 (the highest vulnerability possible). The vulnerability class is shown in table II.

Table II.- Relationship between the weighted score and the vulnerability class

$V = V_1+V_2+V_3+V_4+V_5$ (weighted score / 20)	0 to 6	7 to 12	13 to 20
Vulnerability class	Low	Average	Strong

3.- Nearest and further perimeters protection

The most crucial stage in the WHPA program's implementation is the creation of a protected zone around one or more wells[10]. Nevertheless, before proceeding with the method or methods to be used, it is necessary to determine if the required information is available and if it is reliable[11]. In the case where geological and hydrogeological studies have been carried out, or can be done, the extent of the near and far protection perimeters is determined using the transfer time criterion, which leads to isochronous calculations using the WYSSLING method. After that, it is necessary to know:
- The direction and the gradient of the flow (to have a piezometric map),
- The aquifer geometry (its thickness at the level of the catchment),
- The permeability of the aquifer (from a long-term pumping test),
- Transmissivity T, (the product of permeability by wet thickness),
- The aquifer's effective porosity (can be derived directly from a tracing test or from a pumping test, which gives the storage coefficient S. We can consider S to be of the same order of magnitude as effective porosity in free water.
- The average flow of the catchment.

Table III gives the perimeters of free-ground protection.

Table III.- Free-ground protection perimeters, with complete hydrogeological data

Immediate protection perimeter (IPP) Sampling area	Nearest Protection Perimeter (NPP) Protection Zone	Farest protection perimeter (FPP) Zone of Vigilance
A circle with a minimum radius of 15 m	50 days isochronous	200 days isochronous

The calculation of the isochrones (fig. 2) is based on the WYSSLING method, which assumes that the environment is homogeneous.

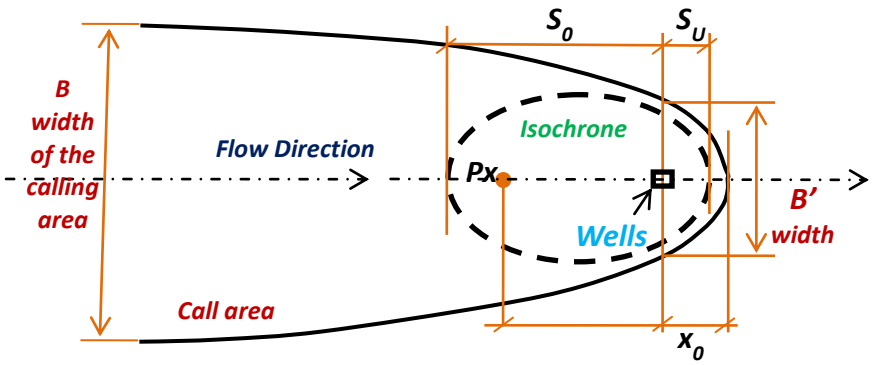


Figure 2.- Determination of the calling area and isochronous by the WYSSLING method (1979)

The capture rate:

$$Q = T.B.i \quad (1)$$

With:
Q = flow of the catchment (m^3/s).
T = transmissivity (m^2/s) = K. e where: K = coefficient of the permeability (m / s) and e = wet thickness of the aquifer (m).
B: is the width of the call front
i = hydraulic gradient (dimensionless) = slope of the water table.
So:

$$Q = T.B.i \Rightarrow B = Q / T.i \quad (2)$$

The calling radius (x0) represented the downstream distance involved in the pumping. All of water molecules included in the call zone will be captured . Outside of the calling zone, all molecules can flow without reaching the capture.

$$x_0 = \frac{Q}{2.\pi.T.i} \quad (3)$$

At the level of the collection B, the width of the call front is half of the total width of the calling area:

$$B' = \frac{B}{2} = \frac{Q}{2.T.i} \quad (4)$$

Now, that we've established the effective transfer speed,

$$U = K.i / \omega \quad (5)$$

With:
ω = effective porosity.

The approximate values of S_0 and S_u, the distances upstream and downstream on the flow axis, respectively, are:

$$S_0 = \frac{L + \sqrt{L(L + 8.x_0)}}{2} \quad (6)$$

$$S_u = \frac{-L + \sqrt{L(L + 8.x_0)}}{2} \quad (7)$$

With: L = U. t

If the flow direction and aquifer nature are known, but the permeability K and effective porosity ω data are missing, it is possible to replace them with the standard values.

4.- Results and discussion

4.1.- Vulnerability estimation

The physical, hydrogeological, operating, and degree of vulnerability characteristics of the six studied catchments are shown in Table IV.

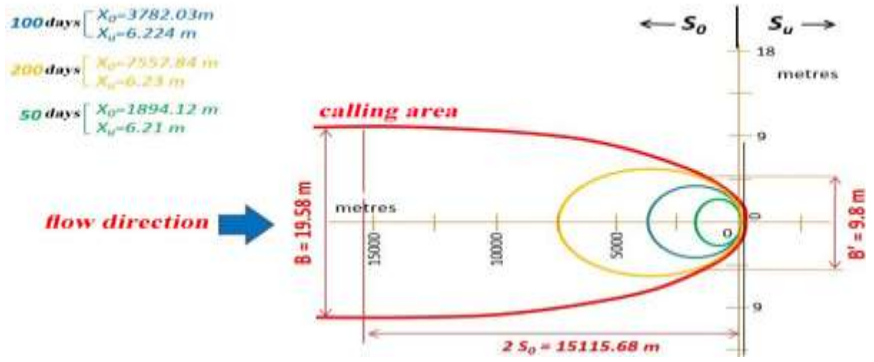
Table IV.- Vulnerability estimation of catchments

Description	Locations					
	El Oued	**Bayadha**	**Robbah**	**Nakhla**	**Oued El Alenda**	**Mih Ouensa**
Type of work:	Drilling	Drilling	Drilling	Drilling	Drilling	Drilling
Diameter (m):	24	24	24	24	24	22
Total depth (m):	278	255	247	255	222	204
Hydrogeology						
Aquifer captured :	Captive	Captive	Captive	Captive	Captive	Captive
Static level:	52.39	46.1	53	47.87	32	34.2
Thickness of the Layer	34	38	36.5	30	56	77
Recovery (nature)	Fine sand dune	Fine whitish sand (dune)	Fine whitish dune sand	Fine sand dune	Yellowish dune sand	Yellowish sand
Aquifer lithology	Fine and medium ferruginous sand	Fine sand, medium to coarse, siliceous with ferruginous grains	Medium sand and ferruginous grains	Medium sand and ferruginous grains	Medium sand and ferruginous grains	Fine to medium ferruginous yellowish sand
Exploitation						
Max usable flow rate	0.037	0.05	0.033	0.04	0.042	0.048
The captured resource	Underground water	Underground water	Underground water	Underground water	Underground water	Underground water
Type of aquifer	Sedimentary basin	Sedimentary basin	Sedimentary basin	Sedimentary basin	Sedimentary basin	Sedimentary basin
Type of Layer	Captive	Captive	Captive	Captive	Captive	Captive
Alluvial aquifer	No	No	No	No	No	No
Hydrodynamic data	Known	Known	Known	Known	Known	Known
Determination of vulnerability						
Geological section	Yes	Yes	Yes	Yes	Yes	Yes
Thickness (UNZ)> 60m?	Yes	Yes	Yes	Yes	Yes	Yes
Result	Low	Low	Low	Low	Low	Low

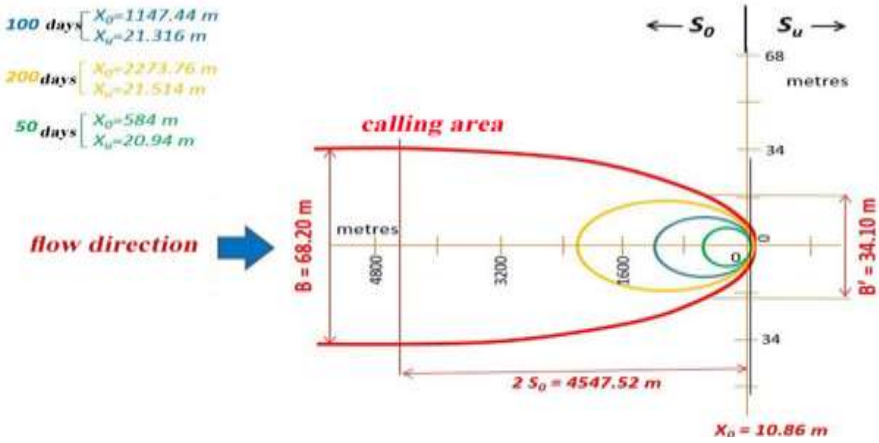
According to table IV, the captured aquifer is captive, well depths range from 204 to 278 m, and operating flows vary between 0.033 and 0.05 m^3/s. As a consequence, the studied catchments are located in low-vulnerability areas.

1.1.4.2.- Isochronous drilling

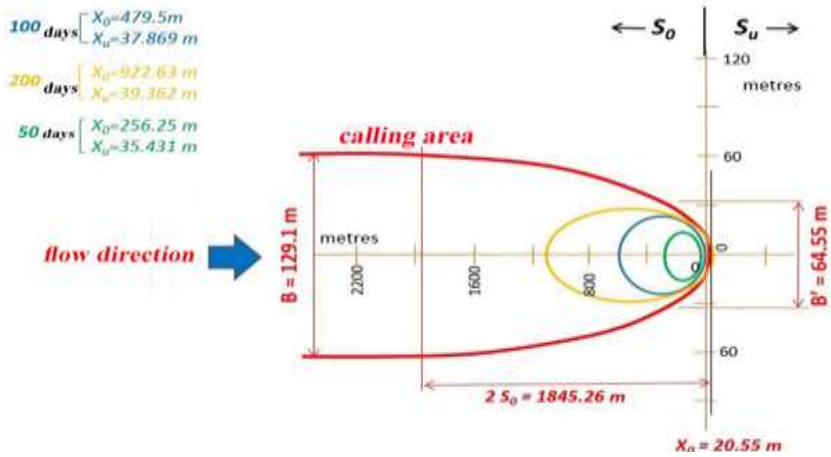
The following figures represent the surfaces of the nearest and the further protection perimeters.



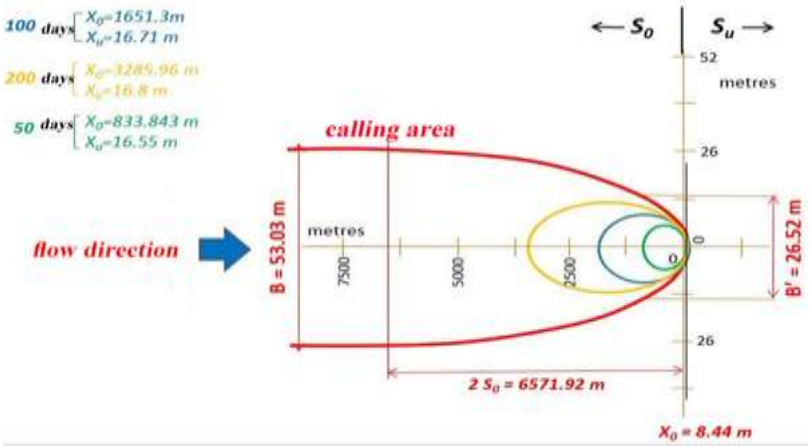
A: El Oued



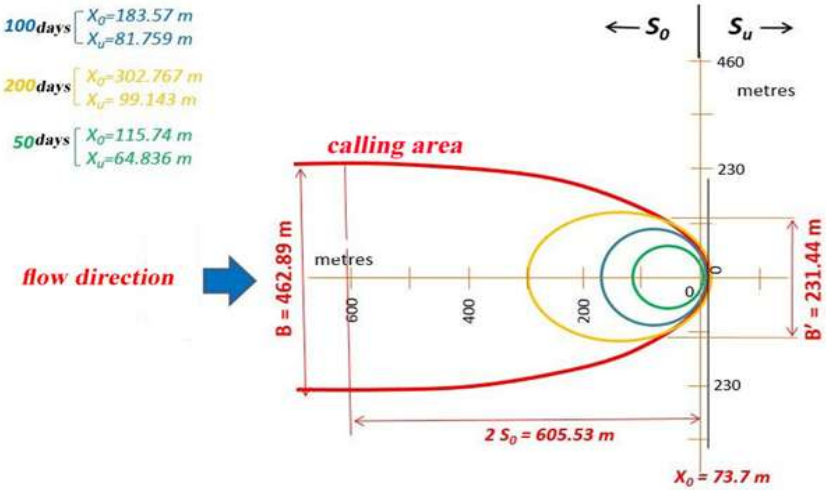
B.Bayadha



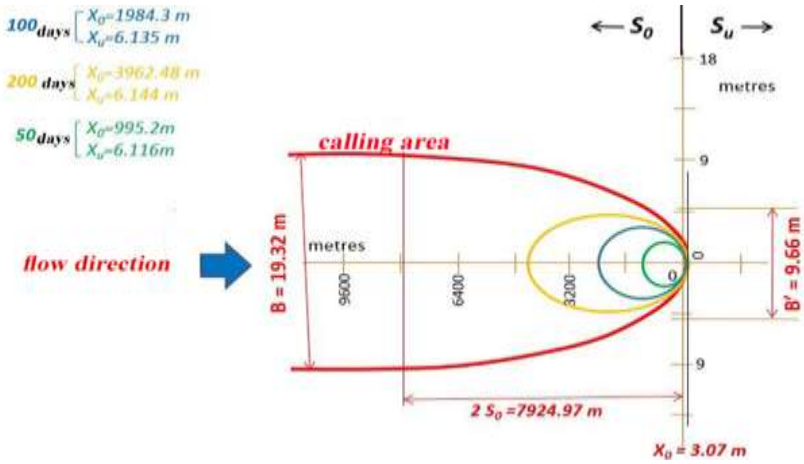
C: Robbah



D: Nakhla



E: Oued El Alenda



F: Mih Ouensa

Figure 3 (A,B,C,D,E,F).- Determination of the calling area and the isochronous

El Oued (A)

According to figure 3-A., the isochrones lines in El Oued at 50 and 200 days indicate a superficies protection perimeter of between 2.8 and 11.2 Ha approximately around the borehole.

Bayadha (B)

Figure 3-B, shows that the nearest protected perimeter in the Bayadha catchmentdefines an area of approximately 0.2 Ha, while that further defines an area of approximately 4 Ha.

Robbah (C)

In the Robbah catchment, figure 3-C. indicates that the surface area of the NPP is 0.03 Ha, while the surface area of the FPP is 0.6 Ha.

Nakhla (D)

Regarding the catchment of Nakhla, figure 3-D. shows that after 50 days, the surface of the protection perimeter is 0.5 Ha. After 200 days, it becomes about 8.4 Ha around the borehole.

Oued El Alenda (E)

In figure 3-E., it is observed that the Oued El Alenda catchment has a nearest protection perimeter of 0.002 Ha and a fares protection perimeter of 0.03 Ha.

Mih Ouensa (F)

In Mih Ouensa, the NPP surface obtained after 50 days is 0.7 Ha, and the FPP surface obtained after 200 days is about 3 Ha around the catchment (figure 3-F).

A simple comparison between the values of the far protection perimeters' areas and the width of the calling area reveals that they have an inversely proportional relationship.

The layout of the isochrones using the Wyssling method allowed to propose protective perimeters for six catchments used fordrinking water supply.

The hydraulic gradient, maximum operating flow and transmissivity are the basic parameters that define the pollutant transfer time to the capture.

Conclusion

The water in El Oued's province comes from underground sources. In recent years, the waters of phreatic aquifer have been extremely polluted and therefore unusable, requiring the use of deep layers of terminal complex (TC) and continental infill (CI).
Because of the increased risk of groundwater pollution and to protect the environment, several methods of assessing the degree of vulnerability can be used to identify the risk of water pollution. We used the WYSSLING method as an example.

The WYSSLING method revealed that the terminal complex's aquifer has a low vulnerability and weak sensitivity to pollution.
We were able to identify wellhead protection area (a remote protection perimeter and a close protection perimeter) due to the WYSSLING study, with the protection distance varying depending to the surrounding characteristics of the well. This study is also

important in order to protect aquifers from pollution.

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