Larhyss Journal, ISSN 1112-3680, n°55, Sept 2023, pp. 41-55

APPLICATION OF THE WYSSLING ANALYTICAL METHOD TO DEFINE THE VULNERABILITY OF THE ALLUVIAL AQUIFER AND THE WELL PROTECTION PERIMETER IN THE ABDI WADI BASIN OF THE AURES MASSIF (ALGERIA)

BENDJERAD M.[1], BOUGHERIRA N.[1], NECHEM D.[2], CHAFFAI H.[1*]

[1] Laboratory of Water Resources and Sustainable Development (REDD), Department of Geology, Faculty of Earth Sciences, Badji Mokhtar-Annaba University P.O. Box 12, Annaba, 23000, Algeria.
[2] Laboratory of Geology, Faculty of Earth Sciences, Badji Mokhtar-Annaba University P.O. Box 12, Annaba, 23000, Algeria.

(*)hichamchaffai@yahoo.fr

Research Article – Available at http://larhyss.net/ojs/index.php/larhyss/index
Received February 9, 2023, Received in revised form August 25, 2023, Accepted August 27, 2023

ABSTRACT

The alluvial aquifer, which is sensitive to atmospheric pollution, is considered the appropriate repository for the activity of bacteria and germs that live in the water. It is therefore favorable to the propagation of bacteria requiring protection from the risks of pollution. The direct source water points that can pollute this water reserve are the wells located in it, and to protect them, the Wyssling method, which is based on the determination of the degree of vulnerability, makes it possible to define the perimeters of protection according to the direction and the zone of contact depending on the distance traveled by the water particles around the point of collection upstream and downstream. The protection perimeters are determined according to the distance traveled by the water during a time indicated by the isochrones of 50, 100 and 200 days. The results show a very high vulnerability equal to 14; the immediate, intermediate and extended protection perimeters are 107, 159 and 239 m upstream and 85, 115 and 152 m downstream, respectively. These distances must be respected to protect catchments from polluting activities that cause the water to lose its natural physico-chemical quality.

Keywords: Vulnerability, Immediate, Intermediate, Extended, Protection zone, Isochrones

INTRODUCTION

Making an effort to protect water resources is a duty and necessary for every person and institution. It depends on scientific and financial capacities because water is the basis of life on the planet. Our research aims to study the vulnerability of the alluvial aquifer close to the surface and the most sensitive to pollution (Chaffai et al., 2006; Seghir, 2014; Djabri et al., 2015; Sedrati et al., 2016; Zegait et al., 2021); it also aims to apply the Wyssling method to delimit the perimeter of protection against various types of pollutants (Wyssling, 1979; BRGM, 2007; Vernoux et al., 2007); there are two types of contaminants: soluble contaminants that dissolve essentially in groundwater and insoluble contaminants (Kollias et al., 2001), increasing demand for groundwater for a different type of supply, a constant increase in the risk of contamination and an intense and, in many cases, excessive population growth (M. V. Esteller et al., 2002; 2005). The phreatic aquifer receives wastewater from wild settlements in addition to groundwater, which makes it increasingly polluted and dangerous for human health and the environment (Amina et al., 2019; Bouselsal et al., 2014; Kadri & Chaouche, 2018). Simple and robust zones, which can be defined according to the vulnerability to pollution of aquifers and wellhead protection zones, must be established (Expósito et al., 2010; Haouchine et al., 2015), indicating which anthropogenic activities are possible and where they can be located, with an acceptable risk for groundwater (Expósito et al., 2010; Foster et al., 2002). There are three protection zones: Immediate, intermediate and extended protection zones; the immediate protection zone is the area around the well in which all activities are prohibited, except those of conservation, maintenance or better exploration of the aquifer; the intermediate protection zone is the area around the immediate protection zone, in which the objective is to protect groundwater resources from microbiological pollution, the extended protection zone; and the area around the intermediate protection zone, in which activities are prohibited or restricted concerning installations capable of polluting groundwater resources with persistent pollutants, such as organic compounds, radioactive substances, heavy metals, hydrocarbons and nitrates (Moinante and Lobo-Ferreira, 2005; Faye et al., 2020). The zones have different restrictions based on fixed distances or transit times (Allwright and Atangana, 2018; García-García and Martínez-Navarrete, 2005; Martínez Navarrete et al., 2008; United States Environmental Protection Agency, 1987; Zeferino et al., 2022). Groundwater protection is an important strategic objective for balanced and sustainable socioeconomic development (Shultz Steven and Lindsay, 1990; Velis et al., 2017; Zeferino et al., 2022). Determining protection zones is the process of preventing water pollution better than treating it, which is very expensive.

HYDROGEOLOGICAL AND STUDY AREA MAP

The study area is a subbasin of Chute-Melghir located in the mountainous region of Aures in northern Algeria in the eastern Saharan Atlas, with a maximum altitude of 2321 m

(Djebel al-Mahmal) and a minimum height of 731 m (Fig. 1). The basin's high altitudes are cold and semi humid in winter and a dry and hot semiarid region in summer. From top to bottom, the basin of the Oued Abdi is the seat of multilayer aquifer systems; the first is the place where the 21 identified wells that are the subject of the study are located and extend (Table 1), i.e., the Quaternary alluvial aquifer and the Miocene alluvial part. All the wells exploit the same aquifer and have depths that vary from 7 to 21 m. They are mainly used for agricultural irrigation and are most likely to be contaminated by various sources; the second is the cracked aquifers of the Lutetian and Oligocene, and finally, it is the calcareous aquifer systems of the Landenian and Maëstrichtian. The bottom of the valley is covered, in the current bed of the Oued, very narrow (10-20 m), by coarse alluvium (sand, gravel and pebbles). The terraces that extend significantly on the right valley, which lend themselves more easily to erosion, are not very extensive in width (20 to 50 m, sometimes 100 m).

The main economic activity in the region is agriculture and livestock. There is also a juice and canning factory in Manaa representing industrial activity. In the construction sector, a dam project is underway in Bouzina in the region of Tagoust. Unfortunately, the aquifer is threatened by the sewer network and random dumps.

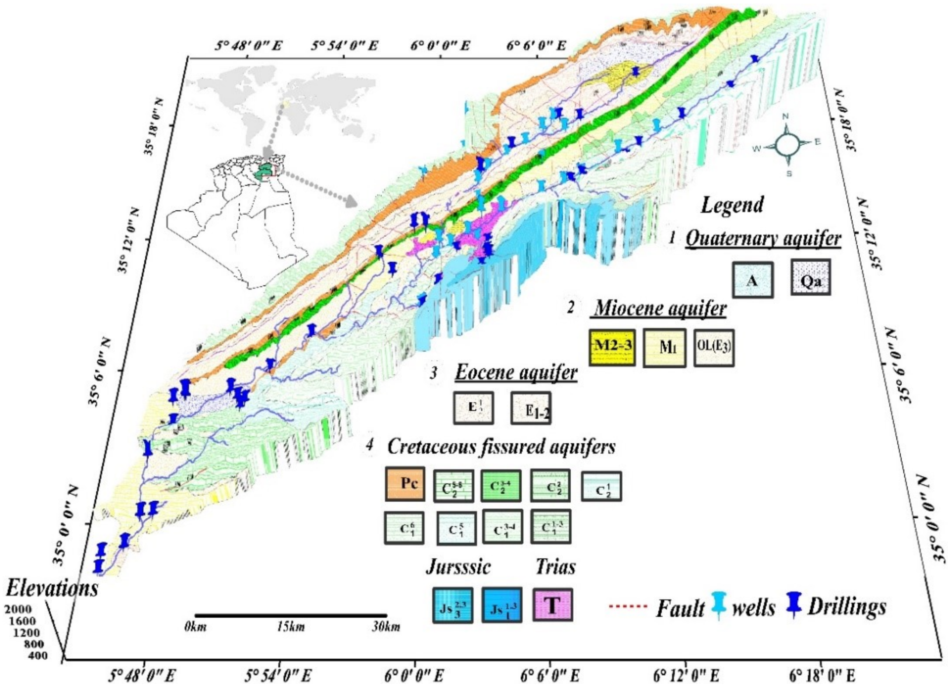

Figure 1: Hydrogeological and study area map of the Abdi Wadi watershed (in Abchiche, 1999; created by Laffitte, 1939; modified by Bendjerad, 2023)

Table 1: Private wells named according to the region implanted

No. and names of wells		
1. Tidjedad	8. Lakoulaai	15. Sennane
2. Ain Zina	9. Ali Oyaha	16. Chir
3. Taher	10. Tagoust El-Beida	17. Nouder
4. Tizogaghine	11. Tagoust ElHamra	18. Akhribe
5. Tifirassin	12. Menaa	19. Theniet emlthena
6. Samer	13. Chelma	20. Idg kadi
7. Oum el Rekha	14. Tigherghar	21. Theniet el abed

GEOLOGICAL DIAGRAM BLOCK

The block is a conceptual model representing the succession of hydrogeological formations identifying alluvium, pebbles, Quaternary scree with a thickness of 15 to 20 meters, sandstones, sand and puddings of the lower Miocene with a thickness of 80 meters, and Eocene limestones (Lutetian and Landenian) with a thickness of 150 meters, aquifers and rocks of the Eocene of the upper Cretaceous by the cracked limestones of the Maestrichtian with a thickness of 360 meters and the Turonian with a thickness of 200 meters (Fig. 2). The sandstones of the Lower Cretaceous and in particular the Albian of the marly sandstone limestones with a thickness of 110 meters, and the Aptian with a thickness of 150 meters, The sandstones, the limestones and the sandstone limestones of the Neocomian with a thickness of 100 meters, as well as the longitudinal accidents along the Oued Abdi.

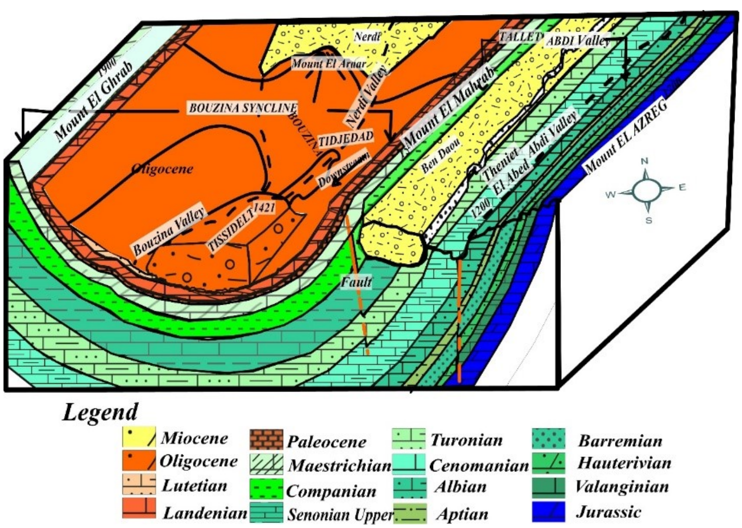

Figure 2: Geological diagram block (in Abchiche, 1999; modified by Bendjerad, 2023)

METHOD

Wyssling's method (1979) makes it possible to establish the isochronous as ellipses in the direction of flow of the layer according to the upstream and downstream distances of transfer time. The first step to achieve the objective of the study is to determine the vulnerability of a water point, which requires at least one geological section to know the different characteristics of the aquifer and then evaluate the weight of each of these properties. After calculating the sum of the values of these weights, the result makes it possible to assess the vulnerability according to the following classification: ($0 < V < 6$) low vulnerability, ($7 < V < 12$) medium vulnerability, and ($13 < V < 20$) high vulnerability. All the steps to be followed are summarized and schematized in the flowchart (Fig. 3). The second step consists of determining the protection perimeter using a mathematical formula according to the Wyssling method, by which the flow time (t) of a drop of groundwater is calculated upstream to downstream according to the direction of flow of the groundwater. The necessary isochronous is thus identified to determine the protection perimeter.

Flow chart

Vulnerability assessment requires having at least one geological section in the studied area. The flow chart (Fig. 3) represents the roadmap for calculating the total values of the hydrodynamic and hydrogeological characteristics of the aquifer. The resulting weight of each feature is a function of the type or degree of influence and contribution to the groundwater reservoir. The final value is classified according to the degree of vulnerability: high, medium and low.

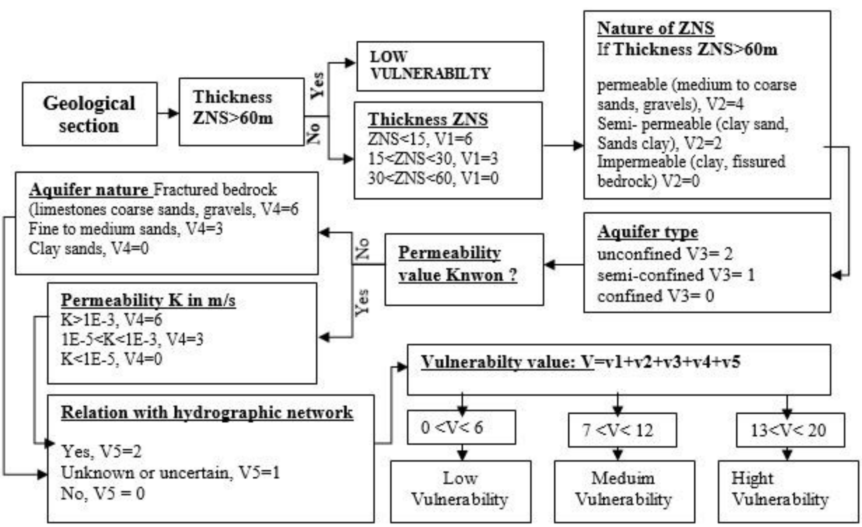

Figure 3: Vulnerability assessment flow chart by Wyssling's method

Vulnerability assessment and determination of isochrones in alluvial aquifers using Wyssling's method

Vulnerability assessment

We explain below which steps we followed:

- Geological log? = yes
- Unsaturated zone thickness (ZNS) > 60 m? = non. The ZNS here has a thickness of 20 m.
- Average thickness ZNS = between 15 and 30 so V1 = 3
- Nature ZNS = permeable (alluvium, stands, gravel): V2 = 4
- The Type of layer = free: V3 = 2
- Is the permeability value of the aquifer known? = 1.4 E-5 m/s V4= 3
- Connection to the hydrographic network = yes: V5 = 2
- A note of vulnerability: V=3 + 4 + 2+ 3 + 2= 14
- Therefore, V is between 13 and 20; this value of vulnerability is high.

The resulting value, equal to 14, indicates a high vulnerability that requires the creation of protection perimeters to protect the wells from pollution.

Determination of isochrones

The isochronous is defined after the determination of the width of the capture zone according to the Wyssling method, where the width of the capture zone (B) is calculated, then the width of the capture zone in the pumping well, and Xo, the capture diameter in succession according to the following formulas (B=Q/T. i) (, B'=B/2), (X_0 = Q/2π.T. i). The intermediate magnitude for t = 50, 100 and 200 days was determined using the formula L (tj) =K.I.t/w. Therefore, the downstream (Su) and upstream (So) distances of the capture from the well to the distance corresponding to the desired time t are identified from the formula So or Su = [±L+√L (L+8X_0)]/2. To calculate the isochronous, the values used are summarized in the tables below according to the following information (Table 2).

Table 2: Summary of information values used

Flow direction	North–East and South–West
hydraulic Gradient i	0.022
Flow velocity u=Ki/w (m/s)	5 E-06 m/s
Permeability k (m/s)	1.4E-05 m/s
Transmissivity	2.08E-04 m^2/s
porosity	6.06%
Flow Q (m^3/s)	0.008 m^3/s

Hydrogeological log

The lithostratigraphic section of the Djebel El-Azreg anticline (Fig. 4), established by M. Bedroune 1998, shows that the thickness of the Quaternary aquifer is 20 m, constituted by the alluvial deposits that fill the valleys of Oued Abdi and Bouzina. It is generally located in the Oued bed. Quaternary groundwater is commonly exploited by wells, and Miocene groundwater is exploited by numerous sources and wells for agricultural needs and servants.

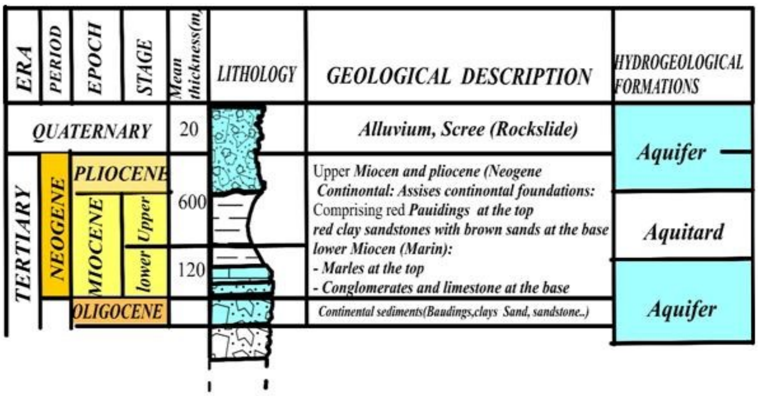

Figure 4: Lithostratigraphic Section of the Djebel El-Azreg (Wadi Abdi) (in Abchiche, 1999; modified by Bendjerad, 2023)

Permeability, transmissivity and porosity

Physical and mechanical tests are carried out at the Bouzina dam laboratory on samples taken from boreholes and wells located at the dam site and in the emergency zone (Fig. 5). The (f04) vertical sounding encounters coarse alluvium up to 10.1 m (sandy loams, sands and pebbles, sometimes blocks), then comes an alternation of conglomerates with beds of red clay sands. The vertical sounding (f05) encounters conglomerates up to 15 m (conglomerates 90%, clays 10%). The average permeability of the alluvial aquifer described according to the Bouzina dam laboratory carried out at depths of 2 and 3 m in the cover colluviums gave permeability values of 1.4×10^{-5} m/s, and the transmissivity calculated according to Darcy's law T=kxb=1.4 E-05 m/s x20 m is equal to 2.8 E-04 m^2/s; b is the thickness of the aquifer, and the porosity identified in the laboratory according to the samples of a particular survey is significantly more porous in the aquifer zone (average 6.06%).

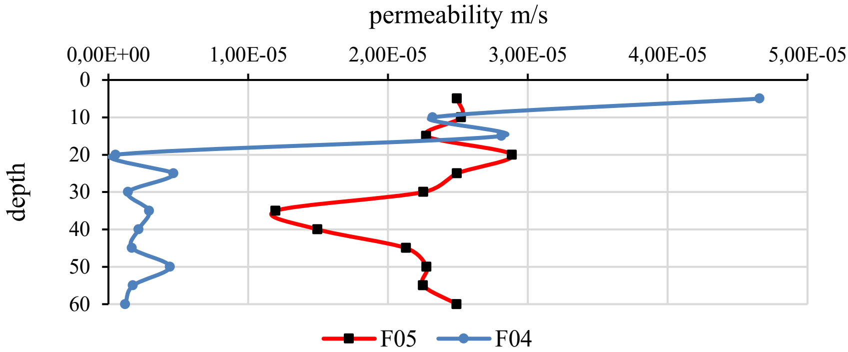

Figure 5: Graph of Permeability Tests

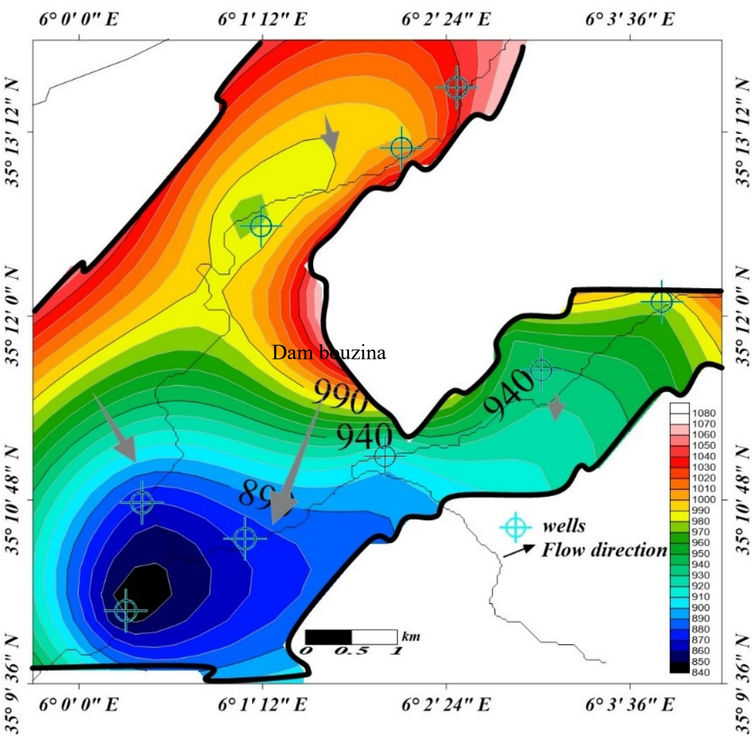

Figure 6: Alluvial piezometric map (by Bendjerad, 2022)

Hydraulic Gradient

The alluvial map translates piezometric levels during the high-water period; it shows an inclined surface, and a flow is directed in two opposite directions toward the two Oueds Abdi and Bouzina in a north–east and south–west direction, where the alluvial plain is located, and the current lines and the direction of flow converge toward the outside. The hydraulic gradient calculated from the piezometric map (Fig. 6) is equal to 0.022. I = dh/l = (1100-920)/8076=0.022

RESULTAT AND DISCUSSION

The protection perimeters were determined and traced after vulnerability assessment according to geology and hydrogeology. The Wyssling method was used to calculate the geometric characteristics of the capture area and the isochronous 50, 100, and 200 days (Table 3). The geological section determined that the aquifer has a thickness of 20 meters, a permeability of 1.4 E-05 m/s measured at the Bouzina dam, a porosity of 6.06%, and an average flow rate of the wells of approximately 0.008 m^3/s.

The transmissivity of the aquifer was determined using the Darcy equation. Since the aquifer was assumed to be homogeneous, the permeability was divided by the aquifer thickness, resulting in a value of 2.80 E-04 m^2/s, and the hydraulic gradient was calculated by measuring the difference between two piezometric curves relative to the distance, as shown in a piezometric map. Taking into account the scale of the map (Fig. 7), the gradient value is 0.022.

The vulnerability of the wells implanted in the study aquifer was assessed by summing the weight values of all the characteristics, resulting in a value of 14. This value falls within the range of 13-20, which is classified as very high vulnerability. It is essential to identify the protection perimeters of the wells to protect the underground water, and this can be done using the Wyssling method, which assumes that the media is homogeneous, first created.

The capture zone was determined by considering the direction of the flow by calculating three main components: the width of capture zone B (1299 m), the width of the capture zone in pumping well B' (649 m), and the distance between the upstream and capture points (twice the upstream distance of capture from the well to the distance corresponding to time t =200 d) (2xS0). To determine the protection perimeters, the axes of the ellipsoids for isochronous 50, 100 and 200 days were calculated. The immediate perimeters are represented in the 50-day isochronous, meaning that a distance of 107 m from the inlet and 85 m from the outlet must be maintained to avoid any direct or indirect danger to the well. The intermediate perimeters are defined by a 100-day isochronous from the upstream 159 m and downstream 115 m axes.

Any activities that could potentially damage the outer part of the aquifer, such as mining, quarrying, or drilling, are strictly prohibited. The 200-day isochronous extended perimeters outline an elliptical area from an upstream axis of 239 meters and a downstream axis of 152 meters, where industrial activities and certain forms of pollution, such as public landfills, are not allowed. The purpose of delimiting these protection perimeters to protect the wells is to protect water from pollution and preserve the health and safety of living organisms.

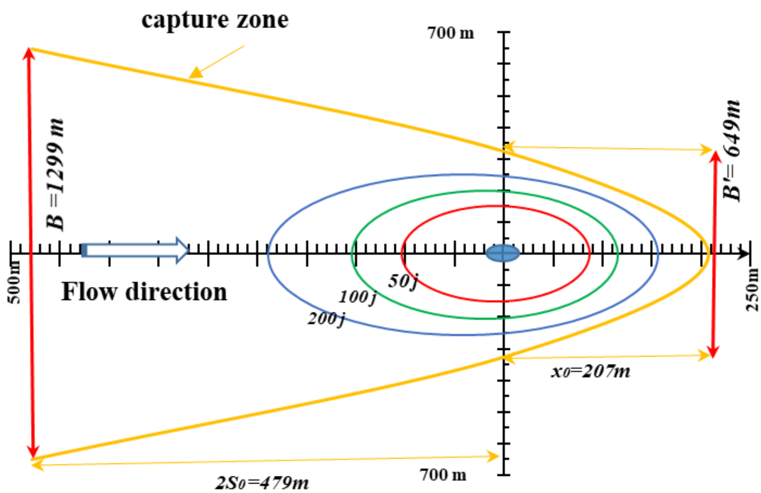

Figure 7: Determination of the capture area and the isochronous 50, 100 and 200 days

Table 3: Aquifer parameters and calculation of the isochronous by the Wyssling method

Isochrone calculation Wyssling's method				
FLOW DIRECTION		NE-SW		
Aquifer parameters				
Aquifer thickness in meters	b			20m
Permeability in m/s	K			1.4E-05 m/s
Transmissivity	T			2.80E-04m^2/s
Hydraulic gradient	I			0.022
Effective porosity	ω			6.06 %
Well flow in m^3/s	Q			0.008 m3/s
The capture zone				
Width of the capture zone	B=Q/ T.i			1299 m
Capture diameter	X0 = Q/2Π.T.i			207 m
Width of the capture zone in the Pumping well	B'=B/2			649m
Effective speed	U=k.i/ ω (m/s)			5 E-06m/s
Isochrones		50 days	100 days	200 days
Intermediate magnitude for t =50, 100 et days.	L(t j)=K.i.t/w	22 m	44m	88m
Upgradient protection distance) m	S0 = (L+ √L(L+8x$_0$)) /2	107m	159m	239m
Down gradient protection distance(m)	Su= (-L+ √L(L+8x$_0$))/2	85m	115m	152m

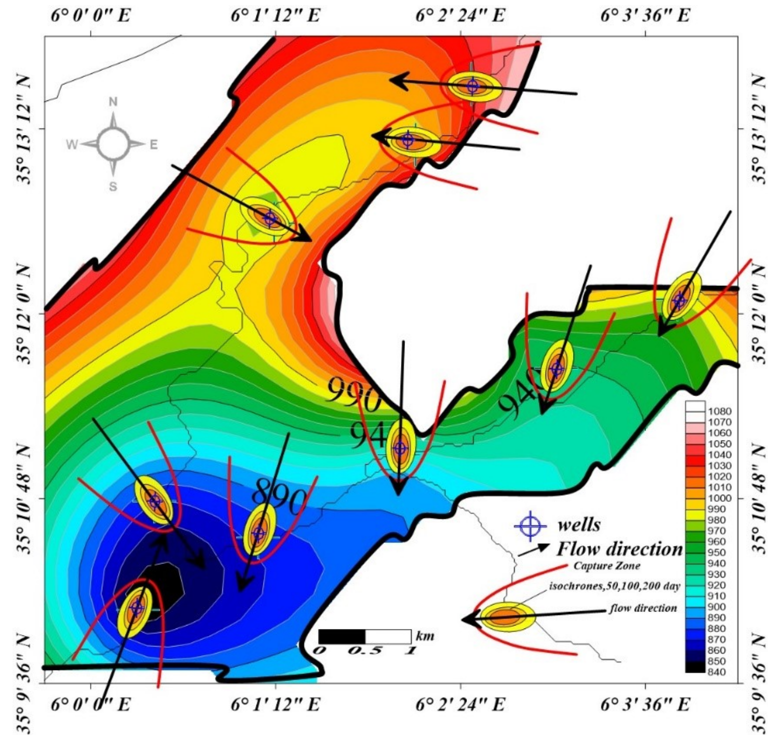

Figure 8: Alluvial piezometric map with isochronous 50, 100, and 200 days (by Bendjerad, 2022)

CONCLUSION

Our research aims to protect the wells integrated into the alluvial aquifer, which is considered an aquifer close to the surface and the most vulnerable to pollution due to its unique geological characteristics, such as permeability and porosity. The Wyssling method was used to assess the vulnerability of the well to pollution by identifying the isochronous zone after determining the boundaries of the call zone resembling the shape of an ellipse, for example, the width of capture zone B, which is equal to 1299 m, the width of the capture zone in pumping well B', which is equal to 649 m, and the capture diameter X0, which is equal to 207 m. For the limits of immediate, intermediate and extended protection, defined according to times of 50 days, 100 days and 200 days, respectively, on the upstream side, according to the direction of flow, the drop in water will take 50 days to reach the catchment point, cutting a distance of 107 m and traveling a distance of 159 m in 100 days and 239 m in a period of 200 days. On the downstream side, it cuts 85 m, 115 m and 152 m with times of 50 days, 100 days and 200 days, respectively. These isochronous zones constitute priority protection zones in which it is forbidden to place pollution sources according to their degree of risk in each zone. The safety of water sources, which is the basis of life, is a paramount necessity and must be protected against all risks.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the laboratory of water resources and sustainable development (REDD) under the aegis of the General Directorate of Scientific Research and Technological Development (DGRSDT), Ministry of Higher Education and Scientific Research or its contribution to the realization of this study. Dedicate this research to the soul of the dearest that I lost, my father, my grandmother and my friends ZM and BS, and to all the victims of the coronavirus in the world.

REFERENCES

ABCHICHE M. (1999). Hydrogeological study of the valley of Oued Abdi and Bouzina, District of Batna, Report, 56 p. (In French)

ALLWRIGHT A., ATANGANA A. (2018). Fractal advection–dispersion equation for groundwater transport in fractured aquifers with self-similarities. European Physical Journal Plus, Vol. 133, Issue 2, pp. 1–20. https://doi.org/10.1140/epjp/i2018-11885-3

AMINA R., LAKHDAR T., KARIMA T., SOFIANE S., EAU P.D., LA D., EL V.D. (2019). Contribution to the Study of vulnerability of terminal complex aquifer and wellhead protection area of water catchment in the Valley of El-Oued, Algerian Journal of Arid Environment, Vol. 9, No 2, pp. 48–57.

BRGM (2007). Délimitation des bassins d'alimentation des captages et cartographie de leur vulnérabilité vis-à-vis des pollutions diffuses – Guide méthodologique – BRGM/RP-55874-FR. http://infoterre.brgm.fr/rapports/RP-55874-FR.pdf

CHAFFAI H., LAOUAR R., DJABRI L., HANI A. (2006). Study of the vulnerability to water pollution of the alluvial aquifer of Skikda: Application of the DRASTIC method, Bulletin of the National Geological Service, Algeria, Vol. 17, No1, pp.63-74. (In French)

DJABRI L., HANI A., CHAFFAI H., HABES S., DJOUAMA M.C. (2015). Study of the vulnerability to pollution a guarantee for the development of an IWRM: case of the alluvial plain of Tébessa, Algeria, Larhyss Journal, No 22, pp. 25-34. (In French)

ESTELLER M.V., ANDREU, J.M. (2005). Anthropic effects on hydrochemical characteristics of the Valle de Toluca aquifer (central Mexico), Hydrogeology Journal, Vol. 13, Issue 2, pp.378–390. https://doi.org/10.1007/s10040-004-0395-4

ESTELLER M.V., DIAZ-DELGADO C. (2002). Environmental effects of aquifer overexploitation: A case study in the highlands of Mexico, Environmental Management, Vol.29, Issue2, pp.266–278. https://doi.org/10.1007/s00267-001-0024-0

EXPÓSITO J.L., ESTELLER M.V., PAREDES J., RICO C., FRANCO R. (2010). Groundwater Protection Using Vulnerability Maps and Wellhead Protection Area (WHPA): A Case Study in Mexico, Water Resources Management, Vol. 24, Issue 15, pp. 4219–4236. https://doi.org/10.1007/s11269-010-9654-4

FAYE MD, BIAOU AC, SORO DD, LEYE B., KOITA M., YACOUBA H. (2020). Understanding Groundwater Pollution in the Sissili Watershed in Burkina-Faso, Larhyss Journal, No 42, p. 121-144. (In French)

FOSTER S., HIRATA R., GOMES D., D'ELIA M., PARIS M. (2002). Groundwater quality protection: a guide for water utilities in Municipal Authorities and Environmental Agencies, World Bank Publication Washington DC, USA.

GARCIA-GARCIA Á., MARTINEZ-NAVARRETE C. (2005). Protection of groundwater intended for human consumption in the water framework directive: Strategies and regulations applied in some European countries, Polish Geological Institute, Special Papers, No18, pp. 28–32.

HAOUCHINE A., HAOUCHINE F.Z., LABADI A. (2015). Assessing groundwater vulnerability using an index-based method. Case of the Sebaou aquifer (Northern Algeria), Larhyss Journal, No 24, pp. 337-349.

KADRI S.R., CHAOUCHE S. (2018). The rising waters in the Souf region: A threat to an oasis ecosystem, Les Cahiers d'EMAM, Studies on the Arab World and the Mediterranean, 30p. (In French).

KOLLIAS P.S., KOLLIAS V., KOLLIAS S. (2001). The protection of aquifers that are subject to land pollution sources, Progress in Water Resources, Vol. 49, pp. 15–24.

LAFFITTE R. (1939). Geological study of the Aurès. Bulletin of the Geological Map Service of Algeria, 2nd series, No 43, 451p. (In French)

MARTÍNEZ NAVARRETE C., GRIMA OLMEDO J., DURÁN VALSERO J.J., GÓMEZ GÓMEZ J.D., LUQUE ESPINAR J.A., DE LA ORDEN GÓMEZ J.A. (2008). Groundwater protection in Mediterranean countries after the European water framework directive, Environmental Geology, Vol. 54, Issue 3, pp. 537–549. https://doi.org/10.1007/s00254-007-0856-x

MOINANTE M.J., LOBO-FERREIRA J.P. (2005). On wellhead protection assessment methods and a case-study application in Montemor-o-Novo, Portugal, The Fourth Inter-Celtic Colloquium on Hydrology and Management of Water Resources, pp. 21–34.

SEDRATI N., DJABRI L., CHAFFAI H. (2016). Evaluating groundwater pollution and assessing the vulnerability: case of massive dune of Bouteldja, Algeria, Journal of biodiversity and environmental Sciences (JBES), pp. 129-136.

SEGHIR K. (2014). Vulnerability to groundwater pollution in the Tébessa-Hammamet region (Eastern Algeria), Larhyss Journal, No 18, pp. 53-61. (In French)

SHULTZ STEVEN D., LINDSAY B.E. (1990). The willingness to pay for groundwater protection, Water resources, Vol. 26, Issue 9, pp. 1869-1875.

VELIS M., CONTI K., BIERMANN F. (2017). Groundwater and human development: synergies and trade-offs within the context of the sustainable development goals, Sustainability science, Springer, Vol. 12, Issue 6, pp. 1007-1017.

VERNOUX J.F., WUILLE UMIER A., DORFLIGER N. (2007). Delimitation of catchment supply basins and their vulnerabilities to diffuse pollution, Final Report, BRGM/RP-55874-FR, France, 72p. (In French).

ZEFERINO J., PAIVA M., CARVALHO M.D.R., CARVALHO J. M., ALMEIDA C. (2022). Long Term Effectiveness of Wellhead Protection Areas, Water, Vol. 14, Issue 7, pp. 1-20. https://doi.org/10.3390/w14071063

ZEGAIT R., REMINI B., BENSAHA H. (2021). Groundwater vulnerability assessment in the M'zab Valley - Southern Algeria, Larhyss Journal, No 48, pp. 211-234.