Larhyss Journal, ISSN 1112-3680, n°27, Sept 2016, pp. 187-203

FACTORS FOR ASSESSMENT OF GROUNDWATER VULNERABILITY IN SEMI-ARID AND ARID ZONES

KERZABI R.[1], MANSOUR H.[2], YOUSFI S.[1], MUDRY J.[3], BENCHAIB A.[4], BENTOUMI M.S.[5]

[1] Laboratoire n° 25 «PRHPM-LE-CT» Département des Sciences de la Terre et de l'UniversFaculté SNV-STU—Université de Tlemcen, Le Nouveau Pôle Universitaire 2ème Tranche, Tlemcen 13000, Algeria.
[2] Laboratoire Géoressources, Environnement et Risques Naturels, Département des Sciences de la Terre, Faculté FSTGAT— Université d'Oran, BP 1524, El M'naouer, Oran 31000, Algeria.
[3] Laboratoire Chrono-Environnement, UMR Université de Franche Comté, 16, Route de Gray, Besançon 25000, France.
[4] Laboratoire des Systèmes Dynamiques et Applications, Département de Mathématiques, Faculté des sciences, Université de Tlemcen, BP 119, Tlemcen13000, Algérie.
[5] NALTIS Communication, rue Derrar Abderrahmne Tlemcen 13000, Algérie.

rachidkerza@gmail.com

ABSTRACT

Aquifer protection from pollution is an important action for a development and wise exploitation of the groundwater resources. In arid and semi-arid zones, rare surface water resources make groundwater the principal source of drinking, industrial and agricultural exploitation water. The idea of this work is to present the different factors participating in natural protection and assessing the groundwater vulnerability in a particular climatic context "arid and semi-arid", so four factors are chosen for vulnerability mapping: lithology, water surface depth, infiltration conditions and effective rainfall. Each parameter is classified to identify a large variability. The vulnerability index is calculated by multiplication of four factor's rating. A pilot site, the ElBayadh syncline is used to test this methodology in terms of typical physical and hydrogeological characteristics. The vulnerability map shows about 75% of the surface pilot site is classified as very high vulnerability. These areas could consequently be protected for future development.

Keywords: groundwater, arid zone, vulnerability, ElBayadh syncline.

INTRODUCTION

The dry areas occupy 41.2 % of earth area (UNDD 2005), among which 7 % are arid and 20 % semi-arid (UNCDD 2011). These zones are increasingly populated because of the mining and petroleum exploitations, and agricultural development. Rare surface water resources make groundwater the principal source of drinking, industrial and agricultural exploitation water. Therefore the human settlements can cluster around these sources, and therefore present an actual threat: overexploitation and pollution considered like irreversible deterioration (Foster and Chilton 2003), so the protection is crucial.

Physical and hydrogeological contexts in the arid and semi-arid zones (scarce vegetative cover, porosity and low thickness of soil, torrential floods, interstice ant fissure permeability…) make aquifers susceptible to pollution in different ways.

Assessment of vulnerability can be the first step towards the protection and sustainable development of this resource. Fortunately, many methods were developed to assess hazards and vulnerability, not only for groundwater resources, but in the wider context of socio-environmental systems affected by global environmental changes (Eakin and Luers 2006). Three basic vulnerability approaches were adopted by scientists (NRC 1993): subjective, physically based and statistical methods but the most popular are the subjective methods which are based on the subjective rating, overlay and index of individual hydrogeological factors (Filippini et al. 2013).

In arid and semi-arid zones, the methods used for mapping vulnerability are limited in number and can require a considerable amount of parameters which is generally discontinuous in the time and space (Table 1). In the present work, we try to highlight and incorporate various factors that describe the hydrogeological system in such zones, using a GIS system.

Table 1: Examples of vulnerability methods used in semi-arid and arid area

Methods used	Countries and region
DRASTIC (Aller et al. 1987)	Algeria, Tunisia, USA, Yemen, Jordan, Turkey
SINTACS (Civita and De Maio 2000)	Algeria
GOD (Foster 1987)	Algeria
PPilK (Tayebi et al. 2010)	Morocco
TCR (Amharref et al. 2001)	Morocco
PI (Goldscheider et al. 2000)	Jordan, Palestinian territories
GLA (Hölting 1995)	Jordan
DRAV-Model (Jinlong Zhou et al. 2009)	China

METHODOLOGY

Various methodologies have been developed to evaluate sensitivity of groundwater to pollution sources and mapping the intrinsic vulnerability of groundwater to contaminants, with many of them use the principal factors controlling vulnerability: the geological, hydrological and hydrogeological characteristics of an area (COST Action 620 2003) *i. e.* recharge, soil, unsaturated zone and saturated zone (Vrba & Civita 1994) (Fig. 1).

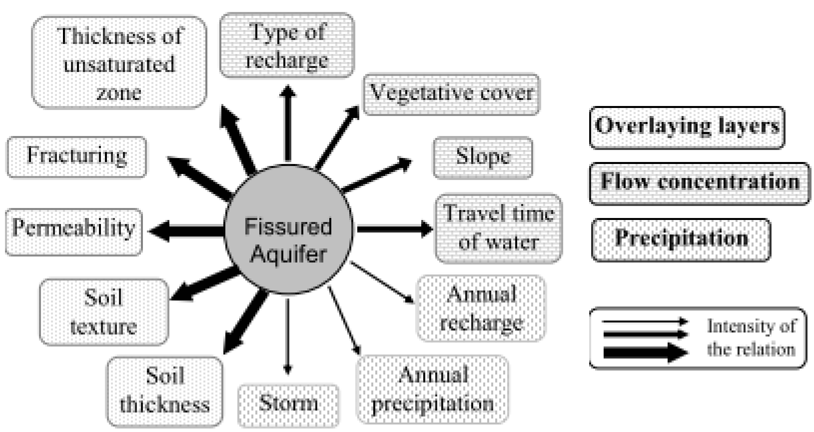

Figure 1 : Influence of main variables and factors on the resource vulnerability of fissured aquifers (Vías et al. 2006).

The main goal of this work is to determine the principal factors involved in the groundwater sensitivity in arid zone. We chose four factors in assessing intrinsic vulnerability: lithology, water surface depth, infiltration conditions and effective rainfall (Fig. 2).

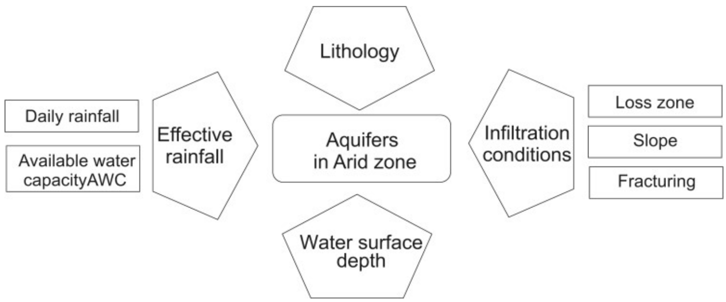

Figure 2 : Factors of evaluation the groundwater vulnerability in arid zone

Lithology factor

The permeability is one of the principal parameters in groundwater vulnerability evaluation (Fig. 1). It is directly connected to lithological characteristics. A comparative application of four methods (COP, DRASTIC, GOD and AVI) provides that the parameters relating to lithology are the most relevant (Vías et al. 2006). The fundamental properties of aquifers (*storativity* and *transmissivity*) are widely related with geological formation nature (Foster & Chilton 2003).

Table 2: Principal geological formations and their rating

Lithology racing	Geological formations
1	**CF**: Consolidated Fissured formations: limestone or dolomitic rocks.
0.9	**UF**: Unconsolidated Formations: alluvial (sand and gravels) and dune formations.
0.8	**SF**: Sandstone Formations with interstice and fracture permeability.
0.6	**DCS**: Depression Consolidated Sediments (sand, clays, cemented conglomerates).
0.4	**MLS**: Marly Limestone and Sandstone rocks which is interlayered with thin marly bands. Very anisotropic formations with medium and irregular productivity.
0.2	**AF**: Anisotropic Formations with interstice permeability. Multilayered aquifers: clay and sandstone alternation; low productivity.
0.1	**MC**: Marls and Clays formations with low permeability (silts, clays, marls).

Infiltration conditions

The amount of recharge depends on factors like topography (slope), soil cover, fracturing, etc. (Margane 2003). The recharge execute by two ways: diffuse or concentrated infiltration in loss zone, swallow holes, doline or dry valley (Dörfliger et al. 2010).

In this work, the availability of the following features helps to classify the infiltration conditions (Table3):

a- Loss zone: it is a preferential infiltration zone, identified in arid zone by a loss of water by fast and concentrated infiltration into the soil from rivers meeting with fracture system. We distributed *rating 1* to these zones. For the left over area we disturbed the sum of fracturing density and slope rating.

b- Fracturing density: The fracturing zones present a significant vertical groundwater flow. Many of vulnerability assessment methods used the density of faults and fracture network parameter; directly (DRASTIC-FM (Denny et al. 2007); PaPRIKA, (Dörfliger and Plagnes 2009)) or indirectly (DRASTIC (Aller et al. 1987); GOD (Foster 1987)).

We use sum of three short distances between each pixel and faults to define the fracturing density (Fig. 3).

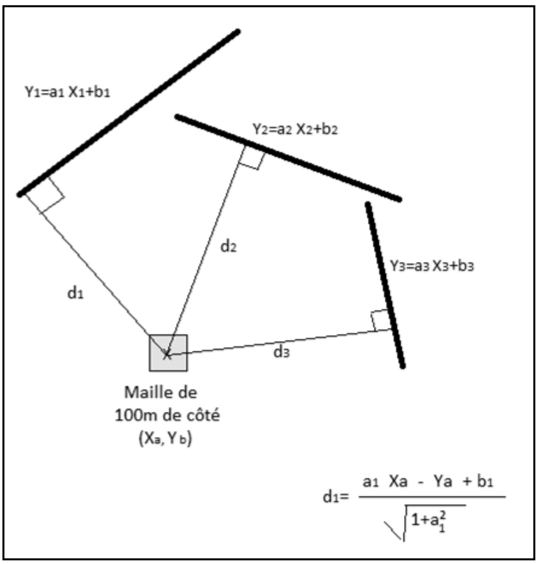

Figure 3: Mathematical function used to determine fracturing density

c- Slope: The topographic slope is an important factor in vulnerability assessment because it determines the amount of surface runoff, the precipitation rate and displacement velocity of the water (Civita and De Maio 2004). The slope ranges between 0 and >18% (in DRASTIC method) and 0 to 30% (in SINTACS method (Civita and De Maio 2000)); both of them attributes a high rating to slight slopes (to areas wherein infiltration can be important).

Table 3: Rating of Infiltration Conditions factor

Loss zone				
Yes			**No**	
			R_S+R_D	
1	**Slope %**	**Rating**	**Fracturing density (Σ 3D [Fault/Pixel](m))**	**Rating**
	0-5	0.45	0-200	0.45
	5-10	0.4	200-400	0.4
	10-15	0.3	400-600	0.3
	15-20	0.2	600-800	0.2
	>20	0.1	>800	0.1

Water surface depth

Depth to the water table, equivalent to the thickness of vadose zone, gives an idea of the distance that a hydro-vectored or fluid contaminant has to travel to reach the saturated zone. Five classes identify this factor (Table 4);

Table 4: Rating of Water Surface Depth factor

Water surface depth	Rating
<2	1
2-5m	0.9
5-15m	0.8
15-30m	0.6
30-45m	0.4
>45	0.1

Effective rainfall factor

In COP method and according to Daly et al. 2002 (in Vìas 2006), Precipitation factor includes the quantity of precipitation and factors which influence the rate of infiltration. The role that the effective infiltration plays in aquifer vulnerability assessment is very significant because of the dragging down surface of the pollutant but also their dilution (Civita and De Maio 2004).

The calculations of effective rainfall in a semiarid area by conventional methods with a monthly or an annual update and the pinpoint data give underestimated values; however, the approach of estimation (Yousfi et al. 2013) has allowed us to calculate the effective rainfall on a daily scale. The method couples two approaches: the spatial and temporal interpolation of rainfall (R), temperature (T), and potential evapotranspiration (PET) data, and the recharge areas should also help to define the infiltration parameters: recharge altitude of the catchment area (z) and soil characteristics (available water capacity (AWC)), specially in semi arid regions where the small thickness of the soil and little biological activity increase the vulnerability of aquifers (Hirata, Bertolo) (Fig. 4).

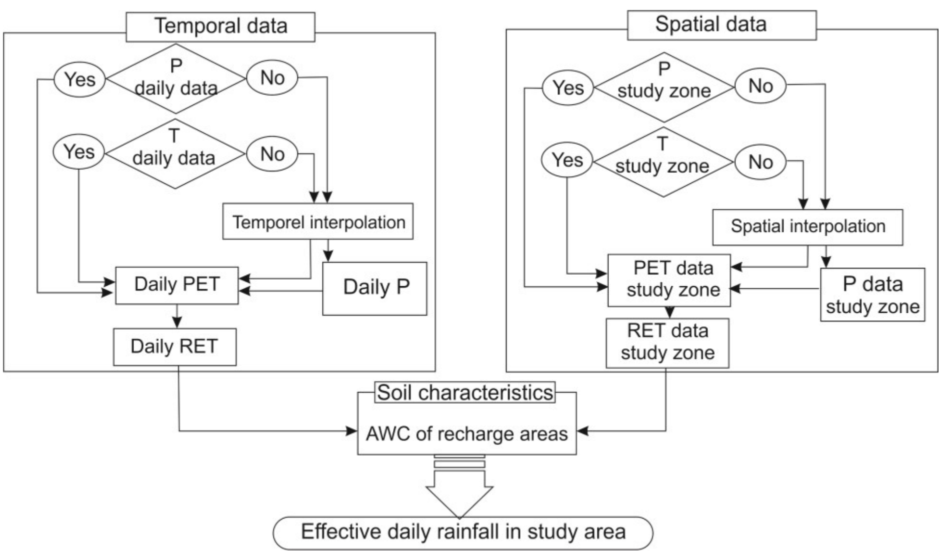

Figure 4: Diagram of Effective daily rainfall estimation method.

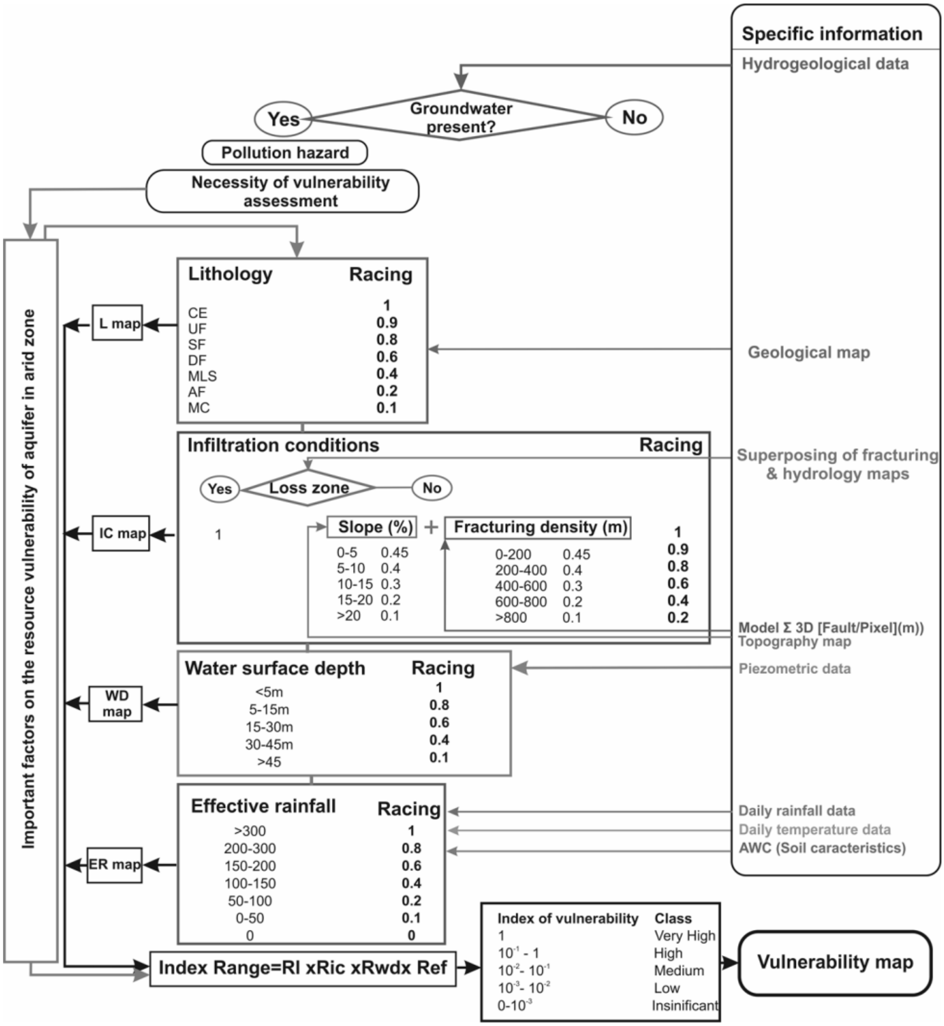

Figure 5: Model used to determine the groundwater vulnerability in arid zone

Application to El Bayadh syncline

The study area is located in extreme west of the Central Saharan Atlas 'Ammour Mountains' (NW Algeria). ElBayadh syncline covers a surface area of around 620 km², with an average rainfall of 320 mm. It is made up of Jurassic sandstone and limestone, Cretaceous sandstone, Tertiary sand claystone and Quaternary alluvium formations (Fig. 6). Most of the formations in the study area are affected by orogenetic movements causing synclines, anticlines and faulting. The study area is dominated by faults of SW-NE direction and strike-slip generally perpendicular to anticlines and synclines direction (Cornet 1952).

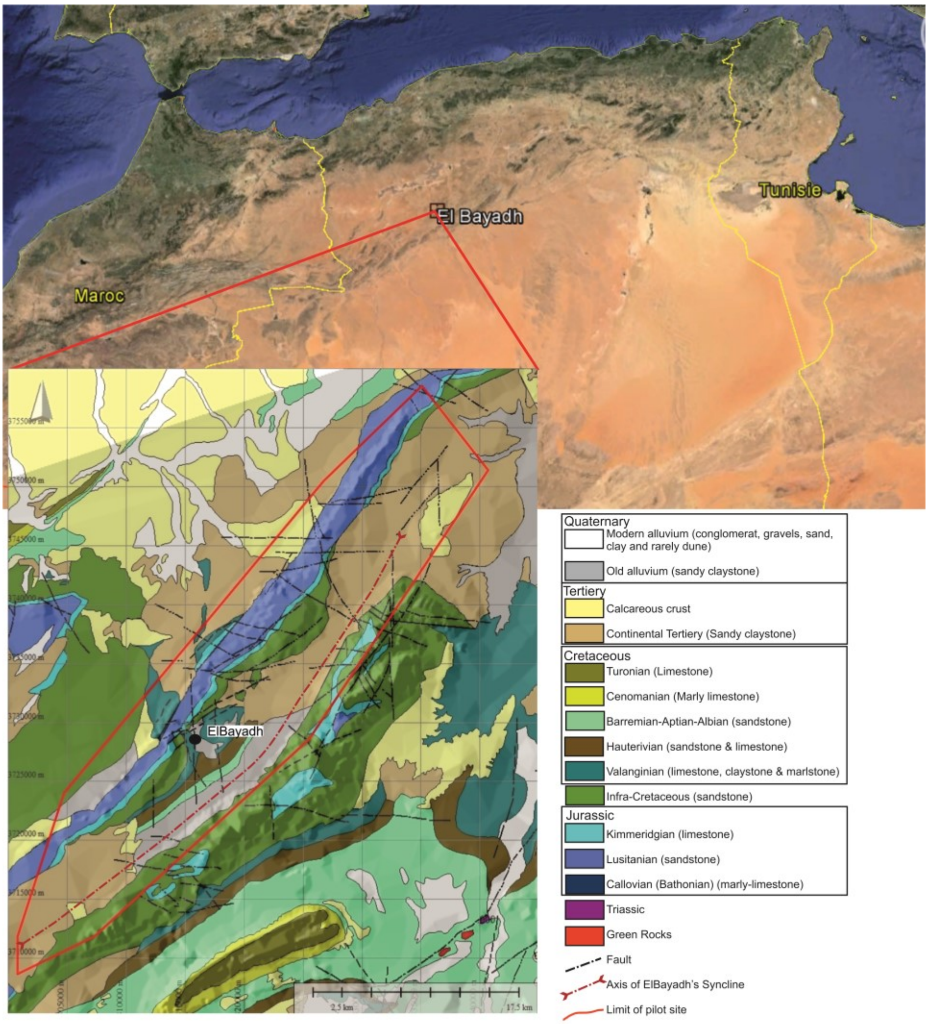

Figure 6: Geographical location and geological map of El Bayadh syncline

El Bayadh's aquifer is considered as a multilayer aquifer, with variable permeabilities (fissured, interstice and mixed). It includes an important aquifer exploited by more than 500 water points. The presence of agricultural activity yields this area strongly threatened by pollution. In this application, we try to assess the ElBayadh aquifer's vulnerability, taking into account the previously described factors and the assessment is limited by availability of piezometric data. Input data used for assessment of aquifer vulnerability were obtained from geological, topography maps, soil study, hydrogeological and climatic data; so different map are executed: lithology, infiltration conditions, depth to groundwater surface, and effective rainfall.

Lithology map: this map represents different ratings and refers to the geological formation of the aquifer in the upper layer, taking account fundamentally their texture and geohydraulic properties. The map was prepared from the geological map (Cornet 1952) and hydrogeological map (ANRH 2008) of ElBayadh and Chellala Dahrania 1/200 000; various formations have different degree of permeability and based on this, a rating is assigned to each of them (Table 5). The map showing lithology map is given in the Fig. 7 a.

Table 5: Lithology rating

Formations	Rating
Old alluvium (sandy claystone)	0.6
Calcareous crust	1
Continental Tertiary (Sandy claystone)	0.6
Barremian-Aptian-Albian (sandstone)	0.8
Hauterivian (sandstone)	0.8
Hauterivian (limestone)	1
Valanginian (limestone)	1
Infra-Cretaceous (sandstone)	0.8
Kimmeridgian (limestone)	1
Lusitanian (sandstone)	0.8
Callovian (Bathonian) (marly-limestone)	0.1

Infiltration conditions map: It is established by coupling three factors: loss zone (R=1: determined by superimposing hydrological and fracturing maps, Cornet 1952 et ANRH 2008), slope map (calculated from topographic maps of ElBayadh and Chellala Dahrania 1/200 000, IGN 1966) and fracturing density map (determined by sum of three short distances between every pixel and fault). Majority of the synclinal surface have a medium rating. The high values occur to loss zones and the proximity of faults, and lower ones are attributed to zones with a high slope (Fig.7 b).

Water surface depth map: To obtain this map, a database had 520 points, it includes location and static piezometry measured in 2003 (B.E.T.G.H. 2003). The depth to the water table ranges from 0.2 to 96 m. The ratings were 0.1 and 0.4 as the ground water table is protected. The depth to water table map is given in the Fig. 7 c.

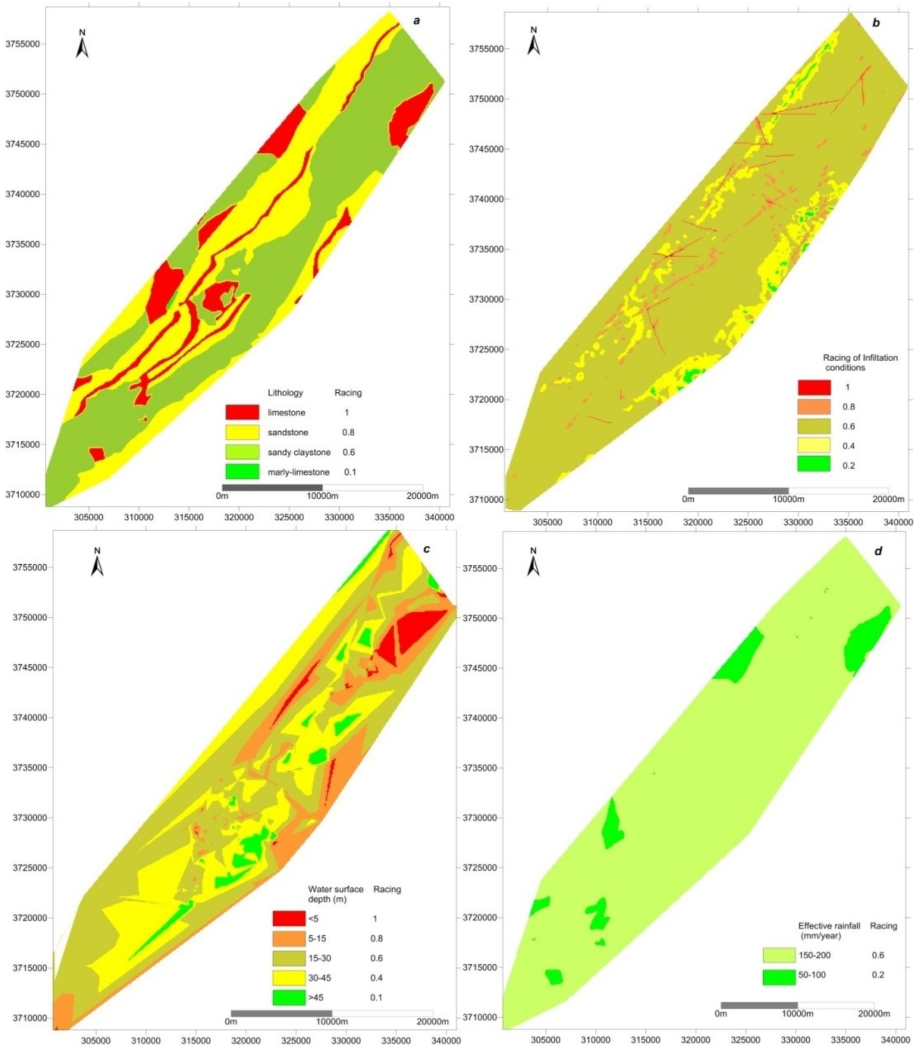

Figure 7: Vulnerability factors maps: a-lithology, b-infiltrations conditions, c- depth to groundwater surface and d-effective rainfall

Effective rainfall map: In the study area precipitation is the unique source of groundwater recharge. The average of annual rainfall, measured in ElBayadh station, for the ten last years, is 323 mm. The effective rainfall has been calculated by daily data of 2009 represent an average year (326 mm) (rainfall, temperature and air humidity) from http://en.tutiempo.net/, taking account of soil textures (Regagba 2012, Pouget 1980) to estimate AWC from Rieul and Ruelle (2003).

Daily potential evapotranspiration (PET) is calculated by Turc expression (Gilli et al. 2004). Flowchart in figure 9 is used to determine the daily actual evapotranspiration (AET) and effective rainfall (ER). The effective rainfall value ranges from 84 to 112 mm and rating value lies in range of 0.2 to 0.4 (Fig. 7 d).

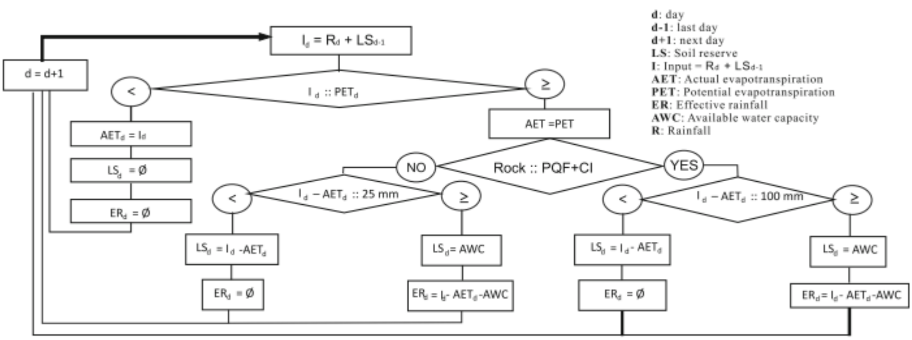

Figure 8: Flowchart enabling calculation of AET and ER (Modified) (Yousfi et al. 2013)

RESULTS AND DISCUSSION

Final groundwater vulnerability map of ElBayadh syncline (Fig. 10), showing a spatial distribution of groundwater vulnerability was based on the different factors maps; the vulnerability index is obtained by multiplication of different rating of lithology, infiltration conditions, water surface depth and effective rainfall.

A large part of study area is highly vulnerable (75.5%), with vulnerability index varies between 0.1 and 1, coinciding with limestone and sandstone outcrops, loss zone and low depth to water surface. This can be explained by the hydrogeological characteristics of formations (high mixed permeability) and soil proprieties (low AWC), thus favoring the infiltration although the steep slope; the case of aquifer that recharges primarily according to altitude (Yousfi

2014). The left over area is moderately vulnerable due principally to lower effective rainfall and higher depth to groundwater surface.

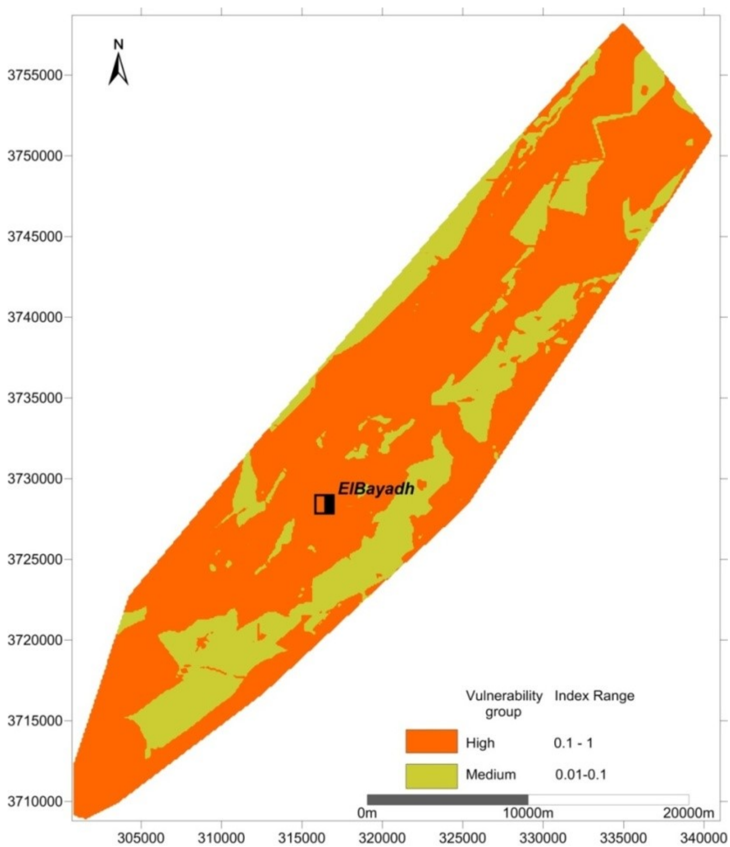

Figure 9: Vulnerability classes obtained with the proposed methodology mapped for the ElBayadh aquifer

CONCLUSION

The goal of this work was to identify the factors influencing the vulnerability assessment, to perform a protection of the precious water resource, in arid and semi-arid zones. The different factors were chosen in terms of dominant physicals and hydrogeological characteristics in these zones. The vulnerability index was calculated by multiplication of four racings of: lithology, infiltration conditions, water surface depth and effective rainfall factors, taking into account a large variability of each of them to include whole possible context in arid and semi-arid zones.

Vulnerability mapping of a pilot site "ElBayadh" syncline displays a high vulnerability for most of study area, explained by weak protection characteristics of aquifer.

This methodology can be successfully applied in an area with basic data available even if they are discontinuous. The obtained vulnerability map can be used as initial protective measurements for the groundwater resource.

This proposition represents a significant step forward in assessing the groundwater vulnerability within aquifers in arid and semi-arid zones but it should be tested in other areas.

REFERENCES

Adams B. et al. (2003): COST Action 620. Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers.. Zwahlen F. Editor-in-chief. Final Report

Aller, L., Bennett, T., Lehr, J. H., Petty, R.J., and Hackett G. (1987): DRASTIC: A standardized system for evaluating ground water pollution potential using hydrogeologic settings. NWWA/EPA Series, EPA-600/2-87-035.

Amharref M., Mania J., Haddouchi B., (2001): Adaptation of an evaluation vulnerability method to groundwater pollution. Proc. of Salt Water Intrusion in Coastal Aquifer: Monitoring, Modeling, and Management. Essaouira, Maroc, 23-25 april. pp. 1-10; www.olemiss.edu/sciencenet/saltnet/swica1/swica1.html.

ANHR, (2008) : Carte hydrogéologique interprétative d'ElBayadh 1/200 000.

ANHR, (2008) : Carte hydrogéologique interprétative de Chellala Dahrania 1/200 000.

B. E. T.G. H., Bureau d'études techniques de géologie et hydrogéologie, Geo-Water, (2003) : Etude géologique et hydrogéologique du secteur ELBayadh.

Civita, M., De Maio M., (2000): Valutazione e cartografia automatica della vulnerabilità degli acquiferi all'inquinamento con il sistema parametrico. SINTACS R5 a new parametric system for the assessment and automatic mapping of groundwater vulnerability to contamination. Pitagora Editrice, Bologna pp.240. Pubbl. n°2200 del GNDCI-CNR.

Civita M., De Maio M. (2004): Assessing and mapping groundwater vulnerability to contamination: The Italian "combined" approach. Geofísica Internacional (2004), Vol. 43, Num. 4, pp. 513-532.

Civita M., (2009): The Combined Approach When Assessing and Mapping Groundwater Vulnerability to Contamination. J. Water Resource and Protection, 2010, 2, 14-28 doi:10.4236/jwarp.2010.21003 (http://www.scirp.org/journal/jwarp).

Cornet A., (1950) : Carte géologique Géryville (ElBayadh) 1/200 000. Service de la carte géologique de l'Algérie.

Cornet A., (1950) : Carte géologique Chott Ech Chergui 1/200 000. Service de la carte géologique de l'Algérie.

Cornet A., (1952) : L'Atlas Saharien Sud Oranais. XIX ème Congrès géologique interne, Alger, Monographies régionales, 51 p, 9 fig, 1 pl.

Daly D., Dassargues A., Drew D., Dunne S., Goldscheider N., Neale S., Popescu C., Zwhalen F., (2002): Main concepts of the "European Approach" for (karst) groundwater vulnerability assessment and mapping. Hydrogeol J 10(2):340–345.

Denny S. C., Allen D. M., Journeay J. M., (2007): DRASTIC-Fm: a modified vulnerability mapping method for structurally controlled aquifers in the southern Gulf Islands, British Columbia, Canada. Hydrogeology Journal (2007) 15: 483–493.

Dörfliger N., Plagnes V. (2009) : Cartographie de la vulnérabilité intrinsèque des aquifères karstiques. Guide Méthodologique de la méthode PaPRIKa. BRGM/RP-57527-FR.

Dörfliger N., Plagnes V., Kavouri K., Balayre S., Paris C., Muet P., Subias C., Marchet P., (2010) : PaPRIKa, une méthode multicritère de cartographie de la vulnérabilité pour une gestion des ressources et des captages en milieu karstique. Exemples d'application dans le Sud-Ouest de la France. Méthodologie pour la caractérisation de la sensibilité des aquifères.

Eakin H. and Luers A. L., (2006): Assessing the vulnerability of social-environmental systems. ANNUAL REVIEW OF ENVIRONMENT AND RESOURCES Book Series: Annual Review of Environment and Resources Volume: 31 Pages:365-394 DOI: 10.1146/annurev. energy. 30.050504.144352.

Filippini M., Gargini A., Gkemitzi A., Kvaerner J., Meeks J., Stumpp C., Różański K., Wachniew P., Witczak S., Żurek A., (2013): Critical review of methods for assessment of vulnerability of groundwater systems. Project of Groundwater and Dependent Ecosystems: New Scientific and Technological Basis for Assessing Climate Change and Land-use Impacts on Groundwater.

Foster S.S.D., Duijvenboden W., Waegeningh H.G. (1987): Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. Vulnerability of Soil and Groundwater to Pollutants. TNO Comm. on Hydro. Research. Hague, Proc. and Inform., 38:69–86

Foster S. S. D. and Chilton P. J., (2003): Groundwater: the processes and global significance of aquifer degradation. Phil. Trans. R. Soc. Lond. B. 358, 1957–1972.

Gilli E., Mangan C. et Mudry J., (2004) : Hydrogéologie, Objets, méthodes, applications. Paris, Dunod.

Goldscheider N., Klute M., Sturm S., Hötzl H., (2000): The PI method– a GIS- based approach to mapping groundwater vulnerability with special consideration of karst aquifers. Zeitschrift fur Angewandte Geologie 46(3):157–166

Hirata R., Bertolo R.,: Groundwater vulnerability in different climatic zones. Encyclopedia of life support systems EOLSS-UNESCO).

Hölting B., Haertle T., Hohberger K.H., Nachtigal K.H., Villinger E., Weinzierll W., Wrobel J.P., (1995) : Konzept zur Ermittlung der Schutzfunktion der Grundwasser uberdeckung. Geol. Jahrbuch, Reihe C, Heft 63, Hannover

Institut Géographique National, (1966) : Carte topographique d'ElBayadh 1/200 000.

Institut Géographique National, (1966) : Carte topographique de Chellala Dahrania 1/200 000.

Margane A., (2003): Guideline for groundwater vulnerability mapping and risk assessment for the susceptibility of groundwater resources to contamination. Vol. 4, Technical cooperation project management, Protection and sustainable use of groundwater and soil resources in the Arab Region. Damascus.

NRC, (1993): Groundwater vulnerability assessment, contamination potential under condition of uncertainty. National Academy Press. Washington DC.

Pouget M., (1980) : Les sols à croûte calcaire dans les steppes algériennes : Quelque aspects morphologiques et esquisse actuelle. Cah. ORSTOM., sér. Pédol., vol. XVIII, nos3-4, 1980-1981: 235-246.

Regagba Z., (2012): Dynamique des populations végétales halophytes dans la région Sud-est de Tlemcen. Aspects phytoécologiques et cartographiques. Thèse de doctorat en biologie, université de Tlemcen.

Rieul L. and Ruelle P.,(2003): Guide pratique irrigation. Centre national du machinisme agricole, du génie rural, des eaux et des forêts (France).

Tayebi A., Jaillet S., Gasquet D., Delannoy J.-J., (2010) : Réflexion Méditerranéenne Pour l'analyse de la vulnérabilité des ressources en eau karstiques, exemple du massif des Béni Snassen orientaux (Maroc), La cinquième session du congrès international Géotunis, L'utilisation des SIG et la télédétection pour le développement durable. Tunis.

UNDDD, (2005) : évaluation des écosystèmes pour le Millénaire de. http://www.un.org/fr/events/desertification_decade/value.shtml

UNCDD (2011): Désertification, une synthèse visuelle.

Vìas J. M., Andreo B., Perles M. J., Carrasco F., Vadillo I., Jimìenez P., (2006): Proposed method for groundwater vulnerability mapping in carbonate (karstic) aquifers: the COP method. Application in two pilot sites in Southern Spain. Hydrogeology Journal 14 (6), 912–925.

Vìas J. M., Neukum C., Hötzl H., Andreo B., (2006): Statistical comparison and control of different vulnerability mapping methods in Bauschlotter Platte aquifer (Germany). Proceedings of the 8 th conference on limestone hydrogeology 2006, Neuchâtel Switzerland. Presses universitaires de Franche-Comté,- ISBN 2-84867-143-2. Goldscheider N., Mudry J., Savoy L. & Zwahlen F. editors

Vrba, J. Civita, M., (1994): Guidebook on mapping groundwater vulnerability., tomo 16, capítulo Assessment of groundwater vulnerability, págs. 3148. International contributions to hydrogeology, Verlag Heinz Heise, Hannover.

Yousfi S., Kerzabi R., Mansour H., Mudry J., (2013): Estimation and condition of groundwater recharge in semiarid zone: example from the Ksour Ridge, NW Algeria. Arabian Journal of Geosciences ISSN 1866-7511 Arab J Geosci DOI 10.1007/s12517-013-1175-z.

Yousfi S., (2014): Étude hydrodynamique et modélisation des écoulements souterrains dans les gouttières synclinales gréseuses du Barrémo-Albo-Aptien d'Aïn Séfra (partie centrale des Monts des Ksour – Atlas Saharien, Nord-Ouest Algérie). Thèse Doctorat Hydrogéologie Univ. – Oran, Sciences de la Terre et de l'Environnement & Univ. de Franche-Comté.