Research Journal of Applied Sciences 3 (7): 500-507, 2008
ISSN: 1815-932X

A GIS Based DRASTIC Model for the Assessment of Groundwater Vulnerability to Pollution in West Mitidja: Blida City, Algeria

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Abstract: Groundwater is an important natural resource for Algeria as the proportion of the people who depend on groundwater for potable water supply is estimated at 60%. As a contribution to the protection of groundwater resource, we mapped areas of groundwater vulnerability to pollution for the alluvial aquifer of the plain of Mitidja within Blida area, Algeria. The method applied to undertake this work is called DRASTIC model, based on the major hydrogeological factors that affect and control groundwater flow: depth to groundwater, net recharge, Aquifer media, Soil media, Topography, Impact of the unsaturated zone and hydraulic Conductivity. These factors are represented by numerical values that lead to a final DRASTIC index. GIS software is used to find out the water vulnerable zones. The study shows that more than 80% of the city's groundwater is under medium to high vulnerability level.

Key words: DRASTIC model, groundwater, vulnerability, GIS technique, Mitidja, Blida, Algeria

INTRODUCTION

The fresh water made up of surface waters, polar glaciers and underground waters account for <3% of our water resources and it is very unequally distributed on a worldwide scale. Also, it is not enough to have water in abundance, but it must be suitable not polluted water because many countries are poor and cannot face the cost requires for a clean up. Pollution of both surface and subsoil waters by, especially, pollutants of anthropogenic origin is currently a concern for several countries.

According to UNESCO as a whole, groundwater provides about 50% of current potable water supplies over the world. In Algeria, the subsoil water constitutes the principal source of drinking water supply, indeed more than 60% water withdrawals come from groundwater (IAH, 2005). Mitidja which is one of the most fertile plains of Algeria contains two important aquiferous tanks exploited to serve Algiers and the surrounding agglomerations including Blida City.

These resources used for the population, industry and the hydro agricultural needs are nowadays threatened by contamination.

In particular, these aquifers are threatened mainly by the intensive use of agricultural chemicals (fertilizers and pesticides), uncontrolled solid waste disposal and significant untreated wastewater discharge into or near surface waters (that recharge the alluvial reservoir), urbanization and accelerated industrialization often carried out in an anarchistic way.

It is thus essential to search for ways to protect and preserve quantitatively and qualitatively these aquifers. In an effort to protect the underground water sources, this study aims to assess and analyze the vulnerability to water pollution of alluvial aquifers in Blida City, Western Mitidja, Algeria. There are several methods available for vulnerability mapping however based on the type, the amount and the quality of data available the present research will be conducted using the DRASTIC model which is also one of the most renowned methods for the vulnerability mapping.

Presentation of the study area: The fertile plain of Mitidja corresponds to a synclinal alluvial basin resulting from a subsidence followed by an active sedimentation by alluvia mainly from the Atlas Mountains. Mitidja is generally divided into three parts: Eastern Mitidja, Central Mitidja and Western Mitijda. Situated in the Western Mitidja, Blida town (36°N, 3°E) the capital city of the province (Wilaya) of Blida is located at the south of Algiers the national capital at approximately 22 km from the Mediterranean Sea. Blida city also called El Boulaïda is characterized by a Mediterranean climate type, very cold in winter and hot in summer with an annual average temperature of 18°C. A twice time destroyed by earthquakes in 1825 and 1867, Blida is an economic, administrative, agricultural trading center. The city extends on 1,696 km^2, the 2/3 of which is mainly occupied by the Atlas Mountains. At the north of the Atlas

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Mountains, the plain oriented within WSW toward ENE direction occupies mainly the North-west part with an average width ranging between 12.5 and 4 km then narrows considerably with a width of 1.25 km at the North-East. Geophysical studies conducted in 1967 revealed the existence of two superimposed aquifers under the plain of Mitidja: the aquifer of Eocene (formed during the tertiary age) and the aquifer of the quaternary alluvia.

- The aquifer of Eocene is a confined aquifer formed by the sandstones and sandy limestones of the Pliocene. Its substratum is composed by the blue marls of the pleostene age and its roof by semi permeable yellow marls named marls of El Harrach. Its average thickness varies from 100-150 m. This aquifer is very deep, generally located between 250 and 300 m below ground in the major part of the plain.
- The alluvial aquifer of the quaternary is mainly composed of sands, gravels and rollers alternating with silts and clays. Apart from the zone of Mazafran, this aquifer is entirely unconfined and based on the yellow marls of El Harrach. Its thickness varies from 100-200 m. Its edge Eastern and Western limit is ensured by the rise of the blue marls of the pleostene. The depth of water table ranges between 4 and 30 m.

As mentioned above the aquifer of Eocene is not only a confined aquifer but also a very deep one, these natural characteristics make it less vulnerable to pollution compared to the phreatic aquifer of the Quaternary. This last aquifer despite the protection that can provide the marl formation at its edges (East and West) a high potential of groundwater pollution predominates. Indeed the natural conditions allow the entry of pollutants through the roof (unconfined conditions, shallow water table). Consequently, the groundwater vulnerability will be evaluated for the aquifer of the quaternary age. This reservoir represents the most important water-bearing formations with a contribution of 295 hm^3 per annum that is approximately 60% of the total volume of the two aquifers.

CONCEPT OF VULNERABILITY

The French, Margat (1968) was the one that first used the term vulnerability in Hydrogeology; thereafter the concept was adopted worldwide (Albinet and Margat, 1970; Haertle, 1983; Aller *et al*., 1987; Foster and Hirata, 1988; Adams and Foster, 1992; Drew and H¨otzl, 1999; Zwahlen, 2003).

Up to date, several propositions have been given by scientists to define groundwater vulnerability, many are quite similar, however there is not any recognized and accepted common definition that has been developed yet.

Daly and Warren (1998), defined groundwater vulnerability as its sensitivity to a contamination generated by human activity applied on the subsurface environment. This sensitivity is function of the geological and hydro geological intrinsic characteristics of the aquifer.

A committee under the National Research Council defined groundwater vulnerability as: the tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer. Based on some considerations the committee states fundamental principles known as groundwater Vulnerability law: First law, all groundwater is vulnerable, second law: Uncertainty is inherent in all vulnerability assessments and third law: there is risk that the obvious may be obscured and the subtle indistinguishable.

Vrba and Zaporozec (1994), the concept of ground-water vulnerability is founded on the hypothesis that the physical environment provides naturally a high or less degree of protection against anthropogenic pollution to groundwater according to the characteristics of this medium. Consequently some lands are more vulnerable to groundwater contamination than others. Vulnerability characterizes a relative, non-measurable and dimensionless property. Besides they first made distinctions between intrinsic vulnerability and specific vulnerability.

COST action 620 (Zwahlen, 2003) defined the two types of vulnerability as follow:

- The intrinsic vulnerability of groundwater to contaminants takes into account the geological, hydrological and hydrogeological characteristics of an area, but is independent of the nature of the contaminants and the contamination scenario.
- The specific vulnerability takes into account the properties of a particular contaminant or group of contaminants in addition to the intrinsic vulnerability.

Intrinsic vulnerability can be considered as invariant in time whereas specific vulnerability (directly related to the sources of pollution) is evolutionary and characterizes only one precise moment. Groundwater vulnerability is not a characteristic that can be directly measured in the field (Gogu and Dassargues, 2000).

Zwahlen (2003), suggested that the concept of groundwater vulnerability is based on an origin-pathway-target model for environmental management (Fig. 1) and mentioned the fact that it is practicable to distinguish between resource and source protection. Resource protection is to protect all of the groundwater, whereas source protection focuses on the protection of a discrete water source.

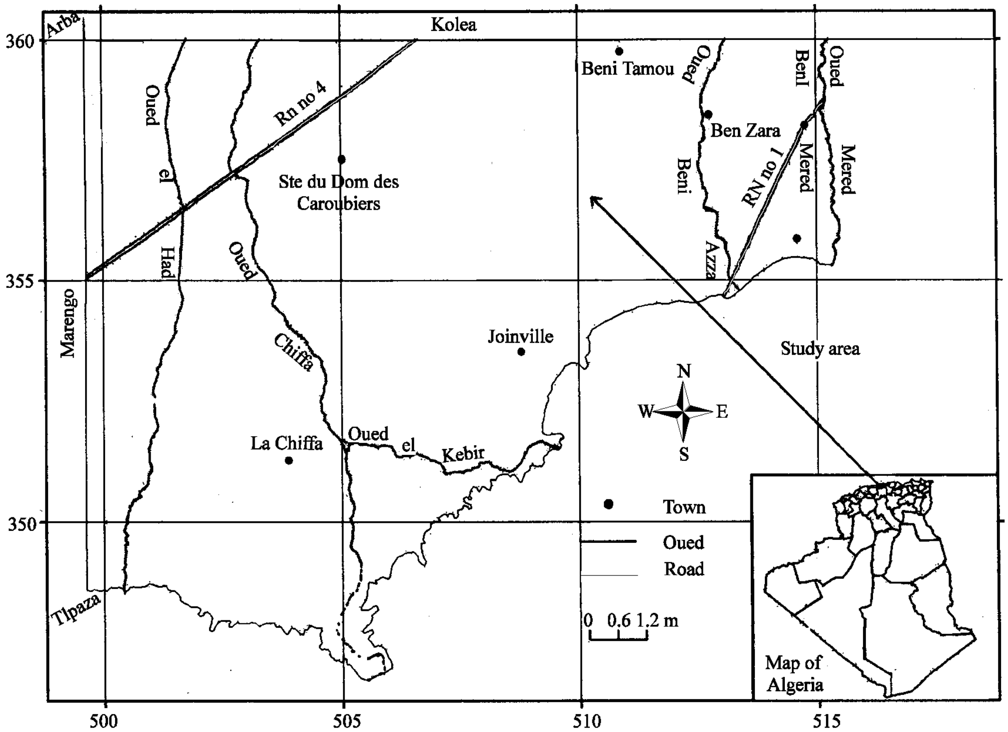

Fig. 1: Location f the study area (IGN, 1959)

Vulnerability assessment is meant to be part of a protection strategy and not to constitute a single tool (Lindström and Scharp, 1995; Foster *et al.*, 2002). Although, in a general way groundwater vulnerability mapping purpose is to protect groundwater resources, these maps could be used for activities such as land use planning, decision-making, groundwater resources management and groundwater quality maintenance.

PARAMETERS DETERMINING GROUNDWATER VULNERABILITY

Aquifer pollution vulnerability refers to the intrinsic characteristics of the aquifer that determine whether it will be adversely affected by a pollutant loading. Within this work, a map will be made for the intrinsic vulnerability, as defined above. The contaminants displacement from the surface towards the water table is not made in a random way. It is a function of the intrinsic properties of each contaminant and the chemical and physical properties of the crossed zone (Fig. 2).

Thus depending on whether, it is about a porous environment; saturated or unsaturated the characteristics of migration are different. Foster and Hirata (1988), Vrba and Zaporozec (1994), enumerate probable processes and mechanism leading to contamination attenuation in different media. The vulnerability of groundwater to pollution depends on a range of criteria which controls the behavior of the pollutants:

- Recharge rates affect the extent and rate of transport of contaminants through the saturated zone.
- Environmental factors such as temperature and water content can significantly influence the potential for biodegradation (degradation of contaminants by microbial transformations).

Criteria related to the soil: The behavior of a soil vis-à-vis to a pollutant is directly related to its properties which control the nature and the quantity of exchanges between the surface and the unsaturated zone. The soil plays a determining role in underground aquatic environments protection, it can have a high potential of fixing and retention due to its much diversified micro-flora and the great number of micro-organisms which it contains.

Properties such as clays content, porosity, texture, thickness, the organic matter content, the redox potential, the vertical permeability, the chemical and mineralogical composition influence pollutants transfer towards the water table. For example clayey soils have a great aptitude to retain or fix the pollutants by adsorption.

Criteria relating to the unsaturated zone: The transport of the pollutant in this zone, depends not only on its

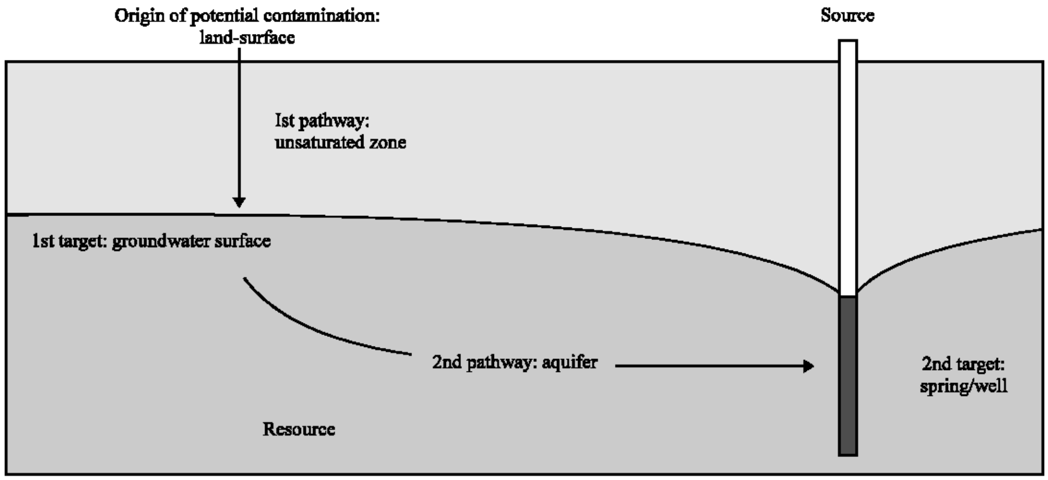

Fig. 2: Source-Pathway-Target model of groundwater vulnerability (Goldschneider *et al*., 2000)

concentration but also on subsoil water flow and the fluctuations of the piezometric surface. The unsaturated zone thickness influence the transfer time (the greater the travel time, the greater the potential for pollutant attenuation) of a contaminant until it reaches the water table. Some physical-chemical reactions which retain, reduce or degrade the pollutant can take place in that zone. Besides, the vertical permeability of the unsaturated zone and its structure are many factors which condition fluids migration towards the saturated zone.

So, the composition within the unsaturated zone can greatly influence transformations and reactions.

Criteria relating to the saturated zone: The underground waters are generally contained in 3 mediums which determine the more or less facility of the pollutant to continue its migration. There are porous, fissured and Karst aquifer. Groundwater is more or less vulnerable depending on the type of aquifer to which it belongs. Indeed a confined aquifer by the presence of impermeable formations has a better protection than an unconfined aquifer.

The depth to the water table can be an important factor because short flow paths decrease the opportunity for sorption and biodegradation, thus increasing the potential for many contaminants to reach the ground water.

Thickness of the aquifer (quantity of reserve): Quantity of water stored in the aquifer determines the dilution conditions of a pollutant introduced into the saturated zone. Dilution is more significant as the flow, the speed or the transmissivity of the aquifer increase.

The flow direction determines likely spaces to be reached by a pollutant once it reached the water table.

Hydrodynamic parameters (transmissivity (T), permeability (K), coefficient of storage (S), hydraulic gradient (I)) determine the migration speed and time of residence of a pollutant in the saturated zone.

APPROACHES TO GROUNDWATER VULNERABILITY ASSESSMENT

There is no absolute method for predicting groundwater vulnerability. An array of methods to estimate aquifers sensitivity to pollution has been developed in the world.

Comprehensive reviews of vulnerability assessment methods can be found in Vrba and Zaporozec (1994), Lindström and Scharp (1995), Gogu and Dassargues (2000), Magiera (2000), Zwahlen (2003) and Hans *et al.* (2004).

They can be classified in three main classes and each one has characteristic strengths and weaknesses that affect its suitability for particular applications.

Overlay and index methods: Based on the combination of maps of specific physical attributes that affect vulnerability (e.g., rate of recharge, topography, soils, depth to water table, etc.) by giving a numerical index or a value to each parameter.

The simplest of these methods weighted equally all the attributes whereas the more quantitative methods assigned different numerical scores and weights to attributes based on their relative importance in contributing to vulnerability and develop a range of vulnerability classes. Data required by these methods are generally more available.

For overlay and Index methods two approaches can be distinguished: hierarchical system method and parametric system method.

- Hierarchical system methods based on the comparison of a given area with the criteria representing the vulnerability conditions of other areas.
- Parametric system methods based on a selection of criteria considered as representative to estimate groundwater vulnerability for a certain area. Each criterion has a range of definite natural variation subdivided in intervals. An index reflecting the degree of sensitivity relating to a contamination is allocated to each interval.

The parametric system methods were classified in three principal groups: matrix systems, Rating systems (e.g., GOD method; Foster, 1987; GLA method; Hoelting *et al.*, 1995) and Point Count Systems Models: PCSM (e.g., DRASTIC method; Aller *et al.*, 1987).

Point Count Systems Models (PCSM) are most relevant with regard to the ground realities as they consider the relative importance of each criterion in relation to the general groundwater vulnerability. Besides they are actually the most recognized and frequently used on the international level (Gogu and Dassargues., 2000).

Process-based simulation models: Require analytical or numerical solutions to mathematical equations that approximate the behavior of contaminants in the subsurface environment. They give an image about the specific vulnerability; predict contaminant transport in both space and time, however, the data they require are infrequently available and must be estimated by indirect means.

Statistical methods: Based on a variable which depends on the contaminant concentration or a probability of contamination. These methods integrate data on known area contaminant distributions and provide characteristics on the probabilities of contamination for the specific geographic area from which the data were drawn. They are useful for groundwater specific vulnerability mapping, can deal with data of varying quality and types.

DRASTIC MODEL

Developed by Aller *et al.* (1987), DRASTIC method is probably the most commonly used of all models for assessing groundwater vulnerability. Indeed the DRASTIC method, has been widely used in the US and also in many parts of the world such as Israel (Melloul and Collin, 1998), Portugal (Lobo-Ferreira and Oliveira, 1997), South Korea (Kim and Hamm, 1999), India (Rahman, 2007), United Arab Emirates (Zabet, 2002) and so on. DRASTIC method is one of the PCSM (Point Count System Model) subgroup and focuses on the intrinsic factors. DRASTIC is an acronym for the seven hydrogeological parameters considered in the method: D: depth of water table from the surface, R: net recharge, A: Aquifer Media, S: Soil Media, T: Topography, I: Impact of the Vadose zone and C: Hydraulic Conductivity of the Aquifer.

In order to assess groundwater pollution potential, numerical ranking is used on the DRASTIC factors. There are 3 significant parts: weights, ranges and ratings.

Weights: Each factor has a fixed relative weight that reflects its relative importance with respect to the others in terms of vulnerability. The values allotted to the weights ranging from 1 given to the least significant factors to 5 allocated to the most significant factors (Table 1).

Ranges: Each DRASTIC factor had been evaluated divided into either ranges or significant media types based on its impact on pollution potential.

Ratings: A value between 1 and 10 is assigned to each DRASTIC factor based on local conditions, this process provide a relative assessment between ranges in each factor. High values correspond to high vulnerability.

The ratings are obtained from tables presented in DRASTIC manual.

The DRASTIC Index (D_i) for the standard DRASTIC method is calculated using the following formula:

$$\text{DRASTIC Index: } D_i = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w$$

where,
r = Rating
w = Weight.

For each parameter evaluated within the study area, a map can be developed by using GIS and the final vulnerability map is obtained by the overlaying of previous individual maps. As the vulnerability index increases pollution potential of groundwater becomes high.

As seen in Table 1, two different systems are available: the standard or normal DRASTIC and the Pesticides or Agricultural DRASTIC. The latter is mainly designated for groundwater vulnerability assessment in areas affected by agricultural usage of pesticides.

Table 1: Assigned Weights for DRASTIC Parameters

Parameters	Standard DRASTIC	DRASTIC pesticides
Depth to water table	5	5
Net Recharge	4	4
Aquifer Media	3	3
Soil Media	2	5
Topography	1	3
Impact of the Vadose zone	5	4
Hydraulic Conductivity	3	2

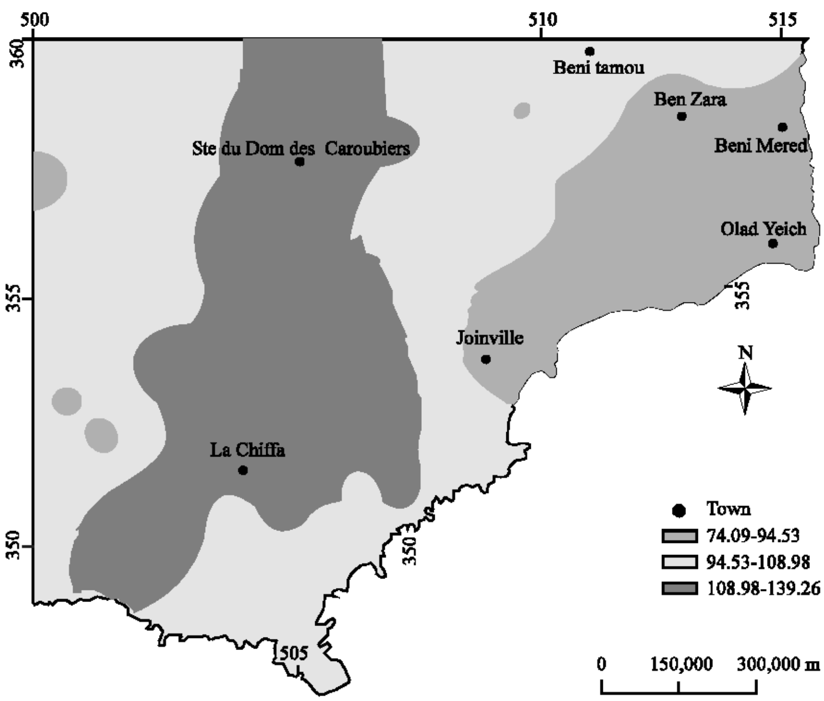

Fig. 3: Groundwater vulnerability zones of Blida city

DATA ACQUISITION

The parameters used by the DRASTIC method have been extracted from the following documents available either at ANRH (National Agency of Hydraulic Resources) or DHWB (Hydraulic Direction) of Blida: Topographic map to 1/50,000 of Blida (N°63-B5-C18); Geophysical map of Algiers (1964); Hydrogeologic Directory of Mitidja (2004); Geologic map to 1/50,000 of Blida and explanatory leaflet (1896); Hydrogeologic map to 1/200,000 of Algiers and explanatory leaflet (1973); Pedologic map to 1/25,000 of the plain of Mitidja (1992);

Rainfall data recorded at the meteorological station of Boufarik within a period of 30 years (1972/73-2002/03); The stratigraphic log of 29 wells and geophysical survey data were used to determine the lithologic composition of the saturated and the unsaturated zone; depth to water measured from 29 wells (Fig. 3).

CONCLUSION

This study employed a GIS based model to determine the vulnerability of GW to contamination in Blida city. This was accomplished using the DRASTIC model. DRASTIC model is a tool for the protection of subsoil waters and their safeguarding. The output map obtained determines the vulnerability of groundwater to pollution in the quaternary alluvial aquifer of West Mitidja in Blida City. The vulnerable zones were classified into three, i.e. low, moderate and high zones (Fig. 2). The extreme DRASTIC index values were 74.09 as minimum and 139.26 as maximum. The results reveal that moderate vulnerability ranked groundwater resources along with high make-up the largest areas of pollution vulnerability in Blida city.

These areas extend from the upper North - East corner of the map to the western edge. The high vulnerability area (blue light) counts a part of Oued chiffa, Oued El Kebir and Chiffa town, this part is centered by the moderate vulnerability zone (dark blue). These classes are found in terrains with high-moderate recharge potential, moderate and shallow watertables, permeable soils. These areas require a particular attention in regard to future land use decisions. Areas of low degrees of vulnerability constitute the smallest area of all the groundwater vulnerability classifications. This zone is mainly located at the Southern East edge of the study area from Jonville to Ben Zara including the towns of Beni Mered and Olad Yaich. This class is characterized predominantly by deep watertable, moderate to significant clay rate within the vadose zone.

The DRASTIC model can be a useful tool for identifying areas vulnerable to pollution, even though it cannot reflect the characteristics of individual contaminants. A large number of contaminant sources and types of pollutants may derive from domestic and industrial activities and agricultural practices. Therefore, an inventory of the types of pollutants and the frequency of their use in the study area help to identify the elements that could harm the groundwater.

The characterization of groundwater vulnerability will not be only useful to identify and delimit zones of high risk of contamination but also offers a base for land use planning.

Therefore, the accuracy of the data in the local area is very important for the assessment, more detailed and robust data will bring better results.

REFERENCES

Adams, B. and S.S.D. Foster, 1992. Land-surface zoning for groundwater protection. J. Institut. Water Environ. Manage., 6 (3): 312-320. London, ROYAUME-UNI.

Albinet, M. and J. Margat, 1970. Groundwater pollution vulnerability mapping. Bulletin du Bureau de Recherches Géologiques et Minières Bull BRGM 2nd Series, 3 (4): 13-22 (in French).

Aller, L., T. Bennett, J.H. Lehr, R.J. Petty and G. Hackett, 1987. DRASTIC: A standardized system for evaluating ground water pollution potential using hydrogeologic settings. U.S. Environmental Protection Agency, Ada, OK, USA, pp: 455. EPA/600/2-87-035.

Daly, D. and W.P. Warren, 1998. Mapping Groundwater Vulnerability: The Irish Perspective. Geological Society, London, Special Publications, 130: 179-190. DOI: 10.1144/GSL.SP.1998.130.01.16. Geological Society of London.

Drew, D. and H. H¨otzl, 1999. The Management of Karst Environments. Chapter 8. In: Drew, D. and H. Hotzl (Eds.). Karst Hydrogeology and Human Activities Impacts, Consequences and Implications, A.A. Balkema, Rotterdam, pp: 259-273.

Foster, S.S.D., 1987. Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. In: van Duijvanbooden, W. and H.G. van Waegeningh (Eds.). Vulnerability of Soil and Groundwater to Pollution, Proceedings and Information No. 38 of the International Conference held in the Netherlands, in 1987, TNO Committee on Hydrological Research, Delft. The Netherlands, pp: 69-86.

Foster, S.S.D. and R. Hirata, 1988. Groundwater pollution risk assessment: A methodology using available data, WHO-PAHO/HPE-CEPIS Technical Manual, Lima, Peru, pp: 81.

Foster, S., R. Hirata, D.M. Gomes, M. D'Elia and Paris, 2002. Groundwater Quality Protection a guide for water utilities, municipal authorities and environment agencies. World Bank Washington, D.C., pp: 116.

Gogu, R. and A. Dassargues, 2000. Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. Environ. Geol., 39 (2): 549-559. DOI: 10.1007/s 002540050466.

Goldschneider N., M. Klute, S. Sturm and H. Hötzl, 2000. The PI method a GIS-based approach to mapping groundwater vulnerability with special consideration of karst aquifers. Z. Angew. Geol., 46 (3): 157-166. Hannover.

Haertlé, T., 1983. Method of working and employment of EDP during the preparation of groundwater vulnerability maps. In: Groundwater in water resources planning, UNESCO. INTER. SYMP, Proc. Koblenz, Germany. UNESCO/IAH/IAHS. II: 1073-1085.

Hans, J.V., T. Heinkele, C. Jahnke and R. Wolte, 2004. Characterization of Groundwater vulnerability to fulfill requirements of the water framework directive of the European Union. Geofisica Internacional 43 (4): 567-574.

Hölting, B., T. Haertlé, K.H. Hohberger, K.H. Nachtigall, E. Villinger, W. Weinzierl and J.P. Wrobel, 1995. Konzept zur Ermittlung der Schutzfunktion der Grundwasserüberdeckung. Geol. Jb. C, 63: 5-24. Hannover. [Translated into English by the Federal Institute for Geosciences and Natural Resources: Concept for the Determination of the Protective Effectiveness of the Cover above the Groundwater against Pollution. Ad-hoc Working Group on Hydrogeology, pp: 28; Hannover].

International Assocation of Hydrogeologists, 2005. Groundwater and poverty reduction in Africa. Issues discussed at the London "GW8" meeting. http://www.iah.org/News/2005/051.html.

IGN (Institut Géographique National), 1959. National Geographical Institute. Topographic map of Blida, Blida/[I.G.N]._1/50,000._Paris:institut géographique national,1959._1f.:illen coul.; 56x77cm. Sheet. N°63-B5-C18. France.

Kim, Y.J. and S. Hamm, 1999. Assessment of the potential for ground water contamination using the DRASTIC/EGIS technique, Cheongju area, South Korea: Hydrogeol. J., 7 (2): 227-235. DOI: 10.1007/s 100400050195.

Lindström, R. and C. Scharp, 1995. Approaches to groundwater vulnerability assessments: A state of the art report no. 3015. Div. of Land and Water Resources report no. 3015, Royal Institute of Technology, Stockholm, Sweden, pp: 77.

Lobo-Ferreira, J.P. and M.M. Oliviera 1997. Groundwater: An Endangered Resource. In: Proceedings of Theme C of the 27th Congress of the International Association for Hydraulic Research, held in San Francisco, USA, Aug. 10-15.

Magiera, P., 2000. Methoden zur Abschätzung der Verschmutzungsempfindlichkeit des Grundwassers [Methods of assessing groundwater vulnerability]. Grundwasser. DOI: 10.1007/s767-000-8357-1, H3/2000 S 103-114.

Margat, J., 1968. Vulnérabilité des nappes d'eau souterraine à la pollution {Vulnerability of groundwater to pollution]. BRGM-Publication 68 SGL 198 HYD, Orléans, France.

Melloul, M. and M. Collin, 1998. A proposed index for aquifer water-quality assessment: The case of Israel's Sharon region. J. Environ. Manage., 54 (2): 131-142. DOI: 10.1006/jema.1998.0219.

Rahman, A., 2007. A GIS based model for assessing groundwater vulnerability in shallow aquifer in Algarh, India. Applied Geogr., 28 (1): 32-53. DOI: 10.1016/j.apgeog

Vrba, J. and A. Zaporozec, 1994. Guidebook on Mapping Groundwater Vulnerability. IAH. International Contributions to Hydrogeology. Verlag Heinz Heise, Hannover, Germany, 16: 131.

Zabet, T.A., 2002. Evaluation of aquifer vulnerability to contamination potential using the DRASTIC method. Environ. Geol., 43 (1-2): 203-208. DOI: 10.1007/s00254-002-0645-5.

Zwahlen, F., 2003. Vulnerability and risk mapping for the protection of carbonate (karst) aquifers, final report (COSTaction 620). European Commission, Brussels, pp: 297.