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WATER RESOURCES AND THE REGIME OF WATER BODIES

GIS based DRASTIC Model for Groundwater Vulnerability Assessment: Case Study of the Shallow Mio-Plio-Quaternary Aquifer (Southeastern Tunisia)[1]

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Abstract—Groundwater is the main source of water in arid regions. Thus, groundwater pollution becomes a major issue due to the increasing contamination, which poses serious and harmful risk to the environment. Groundwater vulnerability maps can be used as a tool to help decision makers to protect groundwater resources from contamination. The vulnerability of the Mio-Plio-Quaternary shallow aquifer (Southeast Tunisia) has been assessed using a DRASTIC model based on Geographic Information System (GIS). The different parameters of the model were collected from several sources and converted into thematic maps using ArcGis©. Each DRASTIC parameter was assigned a weight and rating based on a range of information within the parameter. Groundwater vulnerability map shows a large area (48%) with high risk of pollution. It indicates that the Southern part of the aquifer and the wadi beds are the most susceptible to contamination. The measured nitrate concentration is coherent with the DRASTIC model results.

Keywords: groundwater vulnerability, DRASTIC index, GIS, shallow aquifer, Southeast Tunisia

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INTRODUCTION

Nowadays, sustainable management of water resources, the prediction of the pollution risk and the protection of these resources have crucial importance. Hence, it is essential to safeguard the quality of these resources. Various pollution types appear to predominate in groundwater such as heavy metals, fertilizers, pesticides and other organic chemicals [6]. The leaching of various pollutants through the unsaturated zone and the groundwater zone leads to the contamination of these areas. This process differs from one place to another.

Groundwater contamination can be minimized or even avoided by delineating and monitoring vulnerable areas [23]. Determining how to delineate areas susceptible to contamination is difficult due to many variables that may affect groundwater contamination [10]. The concept of groundwater vulnerability to contamination was introduced in the 1960s in France by [20]. It can be defined as the possibility of percolation and diffusion of pollutants from surface into the groundwater [2, 20]. It deals with hydrogeological setting and does not include pollutant concentration. Several approaches were developed to map aquifer vulnerability [15, 16] such as DRASTIC [3], GOD [11], AVI [24] and SINTACS [9].

The DRASTIC method was developed in the US Environment Protection Agency (USEPA) to evaluate groundwater pollution potential for the entire United States [3]. DRASTIC is an acronym standing for Depth to water; net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone and hydraulic Conductivity. It is an index model designed to produce vulnerability scores by combining several thematic layers. GIS are designed to collect data and produce spatial layers by applying a series of interpolations and overlay analysis.

The Mio-Plio-Quaternary (MPQ) shallow aquifer, which is located in the Southeastern Tunisia, provides a source of water used in agriculture (vegetable farming, olive etc.). Recently, the MPQ waters sampling showed pollution signs. However, the previous geochemical works were focused on the interaction between groundwater and the rock constituting the aquifer [14]. The main sources of nitrate contamination are domestic and industry wastewater effluents.

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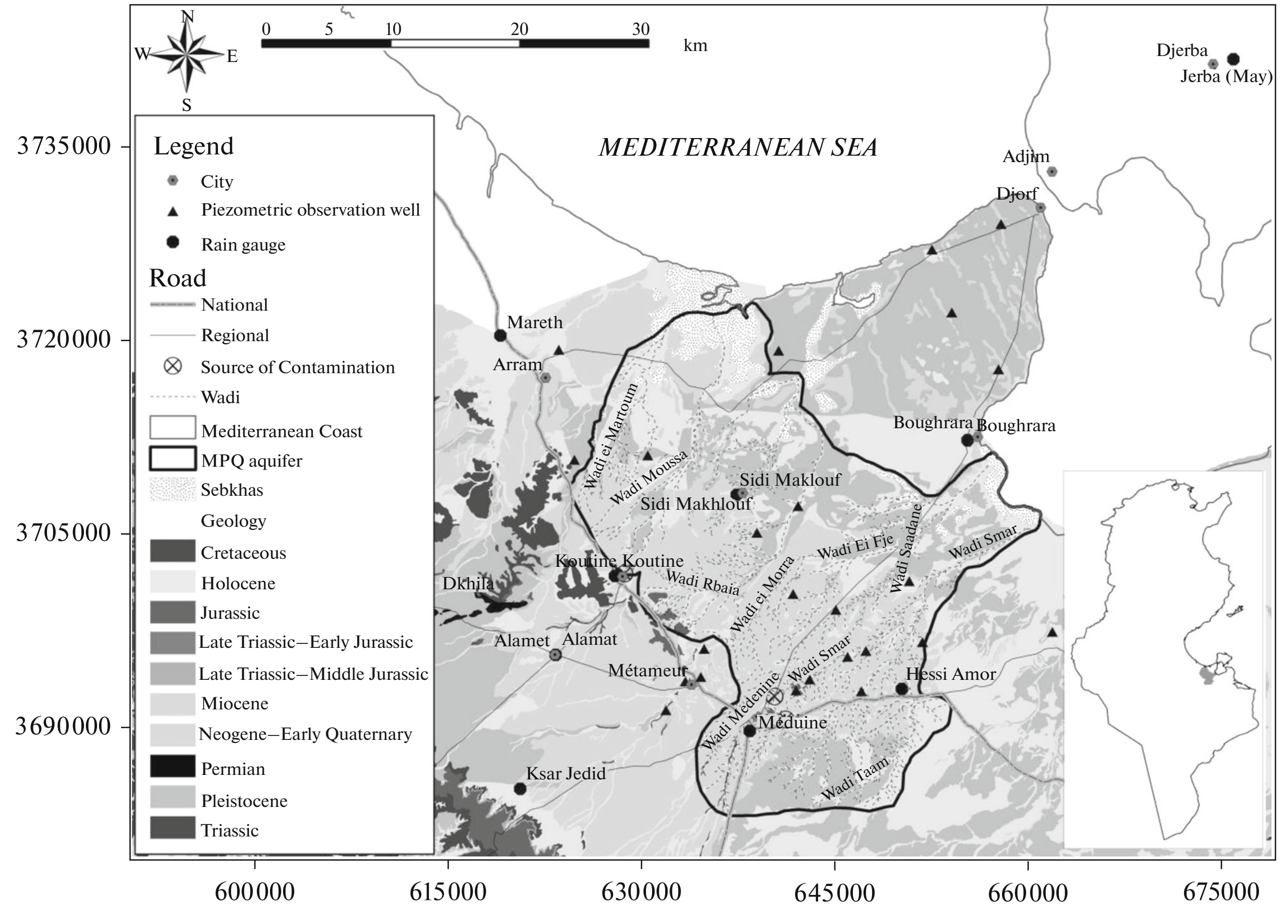

Fig. 1. Location of the study area.

In fact, it is important to identify the areas susceptible to contamination and the source of contamination. We used the DRASTIC model based in a GIS environment to assess the groundwater vulnerability.

The present paper aims to evaluate the MPQ groundwater vulnerability integrating the DRASTIC model into GIS (ArcGis©).

MATERIALS AND METHODS

Study Area

The Mio-Plio-Quaternary aquifer is located in the coastal Jeffara plain, in South-East Tunisia. The plain is characterized by low elevations with a maximum of 100 m asl. The study area (Fig. 1) covers 762.72 km^2 and forms the downstream part of the catchment of several ephemeral streams (wadis), such as wadi Smar, wadi El Fjé, wadi Sidi Makhlouf and wadi Zeuss-Oum Zessar. The climate is arid Mediterranean with an average annual rainfall of 200 mm at Medenine rainfall station.

The southeast of Tunisia is characterized by the presence of alternating marine and continental formations that are the consequence of marine transgressions and regressions throughout the geological history of the northern Sahara [7, 12, 19]. The stratigraphic sequence outcropping in the study area ranges from Triassic to Quaternary (Fig. 1).

It can be divided in three major groups: Mesozoic, Mio-Pliocene and Quaternary sedimentary formations. The MPQ aquifer consists of Quaternary alluvium mainly gravelly. In fact, it is formed by sandy clays and clayey sands of the Mio-Pliocene intercalated with clay pebbles and sometimes disseminated gypsum [26].

The MPQ aquifer is recharged by the rainfall infiltration. The runoff infiltration through the beds of wadis contributes to the aquifer recharge. In fact, the piezometer Smar, located in close proximity to the wadi Smar, shows a groundwater level rise of 1.64 m, following significant rainy events occurred over the period from December 21, 2002 to September 14, 2004 (Fig. 2b). However, others piezometers such as Sidi Makhlouf and Bedoui situated far away from the wadis show an insignificant or null increase (Fig. 2c). The flow direction of MPQ aquifer is towards the Mediterranean Sea (NE). As shown in Fig. 2a, exploitation through pumping increased from 1.45 × 10^6 m^3 in 1980 to 10^7 m^3 in 2010. With increasing abstraction activity, piezometric levels in the MPQ aquifer in the region have fallen at a rate ranging from 0.1 to 0.3 m/year over the last 20 years.

Methods

The DRASTIC model. A DRASTIC model applied in GIS environment was used to assess the MPQ groundwater vulnerability. This model was developed by the US Environment Protection Agency (USEPA) to evaluate groundwater pollution potential [3]. It was successfully used worldwide [1, 4, 6, 15–17, 21, 25] and in Tunisia [5, 13, 21–23] for the groundwater vulnerability studying.

The parameters used in the model DRASTIC are represented by appropriate weights (Table 1). A combination of ratings and weights were assigned to these factors based on how significantly they influenced pollution potential. Each DRASTIC factor was assigned a DRASTIC weight ranging from 1 to 5. It was further assigned a rating, typically from 1 to 10, based on a range of information within the parameter. Higher ratings and weights indicated higher risk of vulnerability. The vulnerability index is calculated as follows [3]:

$$\text{DRASTIC Index}\,(Di) = Dr \times Dw + Rr \times Rw + Ar \times Aw + Sr \times Sw + Tr \times Tw + Ir \times Iw + Cr \times Cw\,, \quad (1)$$

where D, R, A, S, T, I, and C are the parameters depth to water; net recharge, aquifer media, soil media, topography, impact of the vadose zone and hydraulic conductivity, respectively. The subscripts r and w are the corresponding rating and weights.

The DRASTIC model uses a great number of parameters in the vulnerability index calculation in order to guarantee the best representation of the hydrogeological settings. Each parameter index, which is the product of rating and weight, is well defined and used worldwide [3]. This model is relevant and suitable to achieve vulnerability maps on different regions. Data analyses and model implementation were performed using the GIS software (ArcGis©).

Preparation of the Aquifer Vulnerability Map. To establish thematic layers (Fig. 3) of the seven parameters, several types of data were used. Most information was gathered from Tunisian Water Authorities, i.e. Direction des Ressources en Eau (DRE) of Medenine and Commissiorat Régional au Développement Agricole (CRDA) of Medenine. Table 2 shows type, source and usage of collected data.

The depth to water (D) is the vertical distance from the ground surface to the water table [3, 5]. Generally, potential aquifer protection increases with the higher depth of the water. The water table depths were measured from 24 observation wells, in February 2015.

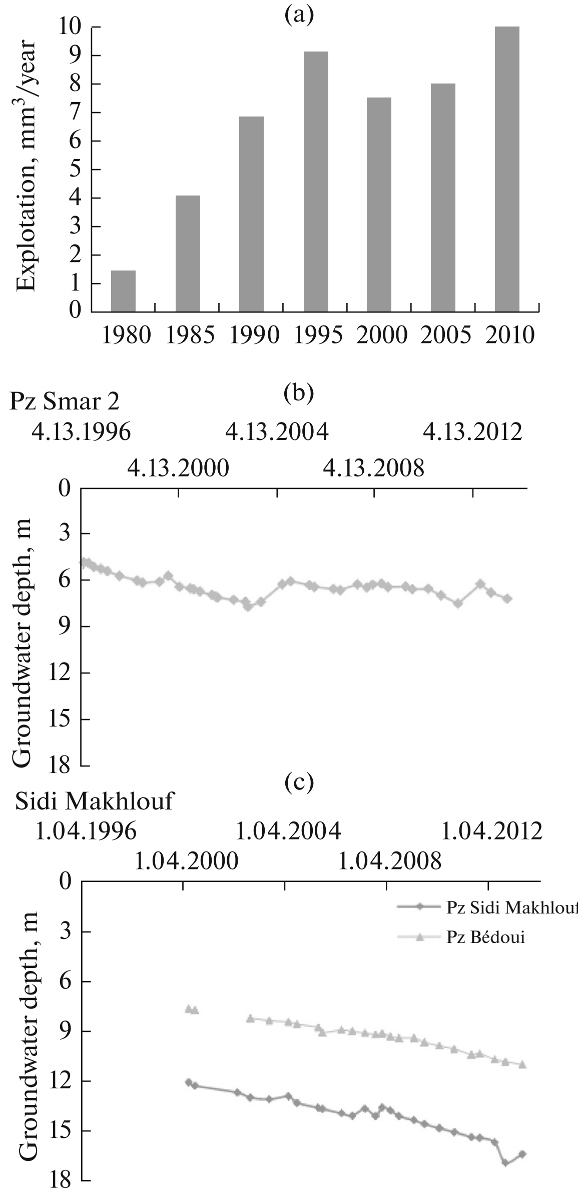

Fig. 2. Evolution of exploitation of shallow aquifers, mm^3/year (a), and evolution of drawdown in three piezometers in MPQ aquifer (b, c).

The ArcGIS Geostatistical Analyst extension of Inverse Distance Weight (IDW) interpolation was applied to interpolate the points and to develop the raster map with a pixel size of 100 m. The IDW technique provided better fitting data, it produced the value ranges found within the data attributes. The depths to the water levels for the MPQ shallow aquifer are classified into six classes: 1.5–4.5; 4.5–9; 9–15; 15–23; 23–31; >31 m.

The net recharge (R) is the quantity of water per unit of land which reaches the aquifer [3]. The main groundwater recharge is the rainfall infiltration. Rainfall data were collected from CRDA-DRE of Mede-

Table 1. The DRASTIC model parameters weights [3]

Factor	Weight
Depth to water	5
Net Recharge	4
Aquifer media	3
Soil media	2
Topography	1
Impact of vadose zone	5
Hydraulic Conductivity	3

nine; these data were available in Alamet, Koutine, Sidi Makhlouf, Ksar Jedid, Medenine, Beni Khedeche, Hessi Amor, Boghrara and Mareth rainfall stations. The interpolation technique has allowed transforming punctual information in a complete coverage of the study area, the isohyets map. Since the MPQ shallow aquifer is unconfined; rating of net recharge is derived from the precipitation amount. Net recharge is classified into two classes: 0.1–0.17 and >0.17 m/year with net recharge rates (R_r) of 6 and 8, respectively.

Circulation and spread of any contaminant into the saturated zone (A) depends on the texture and lithology of the aquifer layers [1]. This is always controlled by the particle size, porosity, permeability and lithology of geological formations. The spatial distribution of reservoir levels of MPQ aquifer shows three lithological classes: Pebble, gravels and alluvium of wadi, sands and loamy clayey sands known as Mio-Plio-Quaternary filling. The permeability of each layer was established by reference to [8]. This parameter is obtained by IDW interpolation of horizontal equivalent permeability of the saturated zone. Horizontal equivalent permeability is calculated as below:

$$K_{\text{eq}} = \frac{\sum_{i=1}^{3} H_i \times K_i}{\sum_{i=1}^{3} H_i}, \tag{2}$$

where K_{eq} is horizontal equivalent permeability (m/s), H_i is thickness of the layer i (m), K_i is permeability of the layer i (m/s), i (i = 1 to 3) is an index related to the lithological classes forming the MPQ aquifer.

The soil parameter (S) represents the influence of soil material on the infiltration. In fact, the soil media layer controls the recharge rate infiltrated into the aquifer. In general, the less permeable the soil, the less contaminant will reach the aquifer [3]. The soil map of the study area was obtained from the CRDA of Medenine. The classification of soils types and theirs ratings are shown in Table 3.

The topography (T) refers to the slope of the land surface. The topography indicates whether a contaminant will run out or will stay on the ground surface to percolate downward, reaching the aquifer [18]. The slope of the study area was obtained from the Digital Elevation Model (DEM). The percent slopes were classified into five classes: 0–2; 2–9; 6–12; 12–18; >18%. Most of the slopes in this study area are in the ranges of 0–12%.

The vadose zone (I) is defined as the fraction between water table surface and the soil surface where the pores are partially saturated with water. The permeability of the vadose zone controls the movement of pollutants and their coming into the aquifer. Most of physicochemical processes taking place in this zone are influenced by its thickness. The infiltration and dispersion of contaminants are guided by the lithological characteristics of the layers that control their paths and trajectory in the subsurface. The spatial distribution of vadose levels of MPQ aquifer shows four lithological classes: Pebble, gravels and alluvium of wadi,

Table 2. Sources of data used for production of hydrogeological parameters of the DRASTIC model

Data type	Source	Format	Scale	Used to produce
Borehole, Piezometer data (water table level)	CRDA, DRE of Medenine	Table, Location map	1 : 100000	D
Annual rainfall (mean)	CRDA, DRE of Medenine	Table	1 : 100000	R
Geology map	Geologic maps (Office National des Mines)	Digital	1 : 100000	A
Soil map	CRDA of Medenine	Digital	1 : 100000	S
Topographic map	Service géographique de l'armée, DEM 30 Tunisie		1 : 100000	T
Hydraulic conductivity, piezometer geological profiles	CRDA, DRE of Medenine			I, A, C

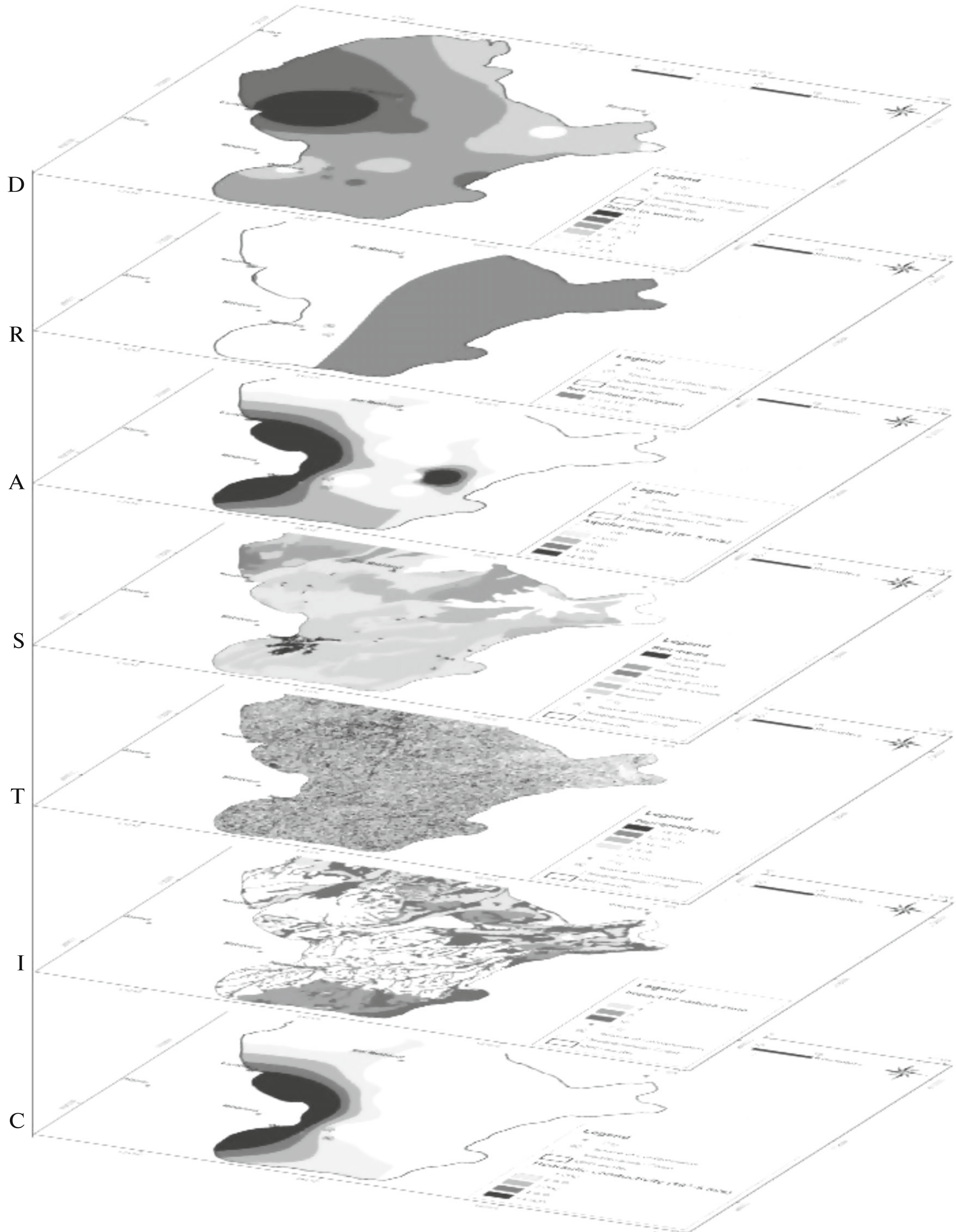

Fig. 3. The seven layers of DRASTIC model.

sands, loamy clays and limestone crust. The permeability of each layer was established by reference to [8].

The hydraulic conductivity (*C*) refers to the ability of the aquifer to transmit water. It controls the migration and dispersion of contaminants. Hydraulic conductivity is obtained by assigning a permeability coefficient for each lithological class [8]. The high conductivity implies generally the aquifer vulnerability. This factor is obtained by IDW interpolation of pie-

Table 3. The type of the soil media and their ratings [3]

Soil class	Rating
Regosols	9
Lithosols, Fluvisols	5
Rendzinas	3
Xerosols	8
Gleysols	2
Solonchak	3
Complex soil units	4
Urban areas	1

zometers hydraulic conductivity data. The spatial variability of hydraulic conductivity in the MPQ aquifer ranges from 10^{-7} to 10^{-1} m/s.

The final DRASTIC map was produced by calculating a weighted sum of the individual aquifer attribute rasters within Conceptual model in ArcGis 10. In fact, the appropriate weight of the seven parameters, referenced to the Table 1, is introduced in the Eq. 1 in order to calculate the DRASTIC index.

Validation of the DRASTIC Model Results. In order to validate the results of DRASTIC model, a nitrate sampling campaign was carried out in 2015 and 24 samples from the MPQ aquifer were collected. covering almost the entire study site. Accordingly, the assessed map is representative of the nitrate concentration distribution in the aquifer.

RESULTS AND DISCUSSION

The spatial distribution of vulnerability classes of the MPQ shallow aquifer (Fig. 4) shows that the highest calculated value was 210 (shown as red) while the lowest one was 72 (shown as pale pink). Based on [3], the highest possible DRASTIC value is 226 while the lowest is 23. The vulnerability map shows five classes of vulnerability: Very low (72–79), Low (79–99), Moderate (99–139), High (139–179), Very high (179–210). It shows that 1% of the total area of the study area has a very high vulnerability index, 48% a high vulnerability, 49% a moderate vulnerability, and 2% of area has low to very low vulnerability.

The highest vulnerability is mainly located in wadi beds and the southern part of the plain. This result is

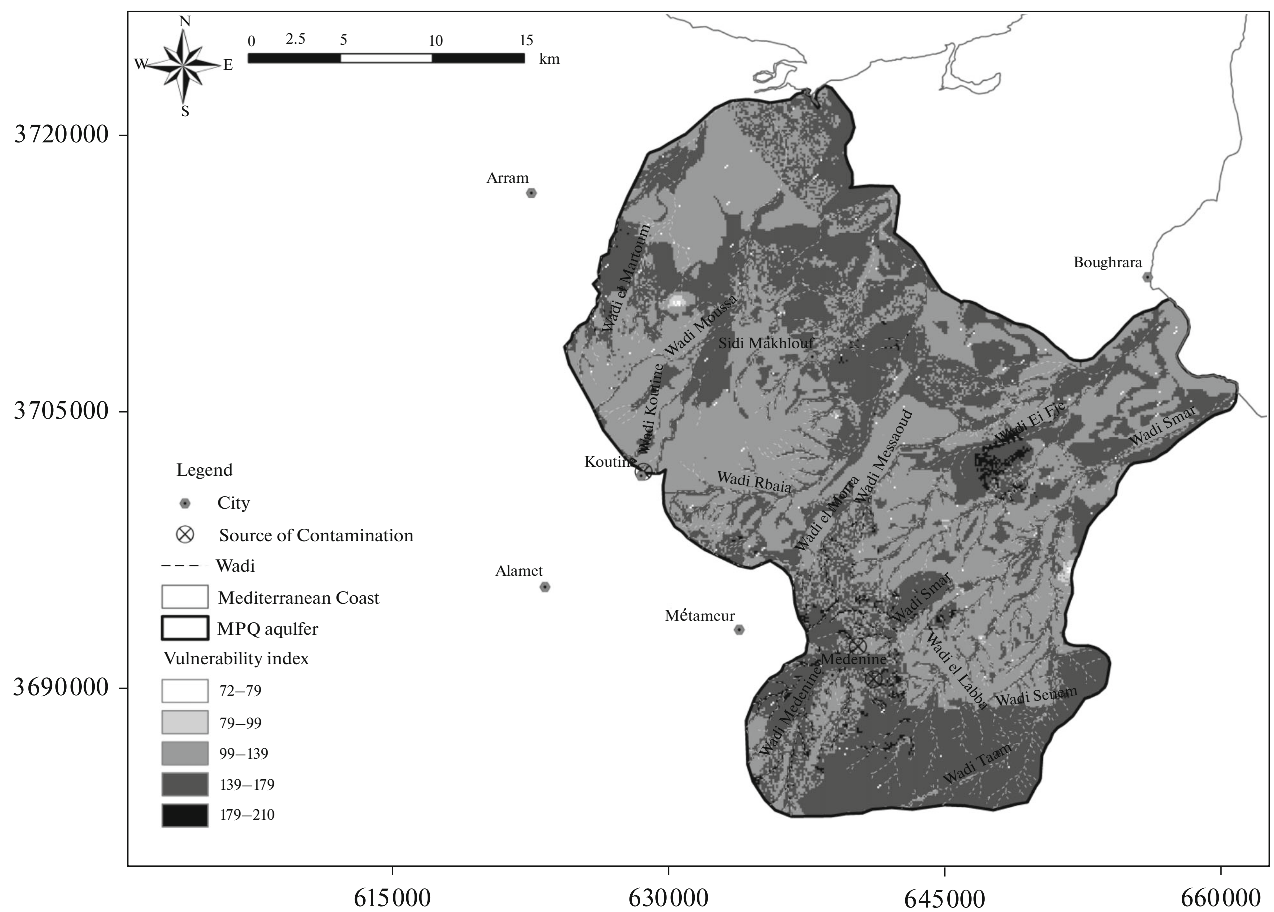

Fig. 4. Vulnerability map of MPQ shallow aquifer.

(a)

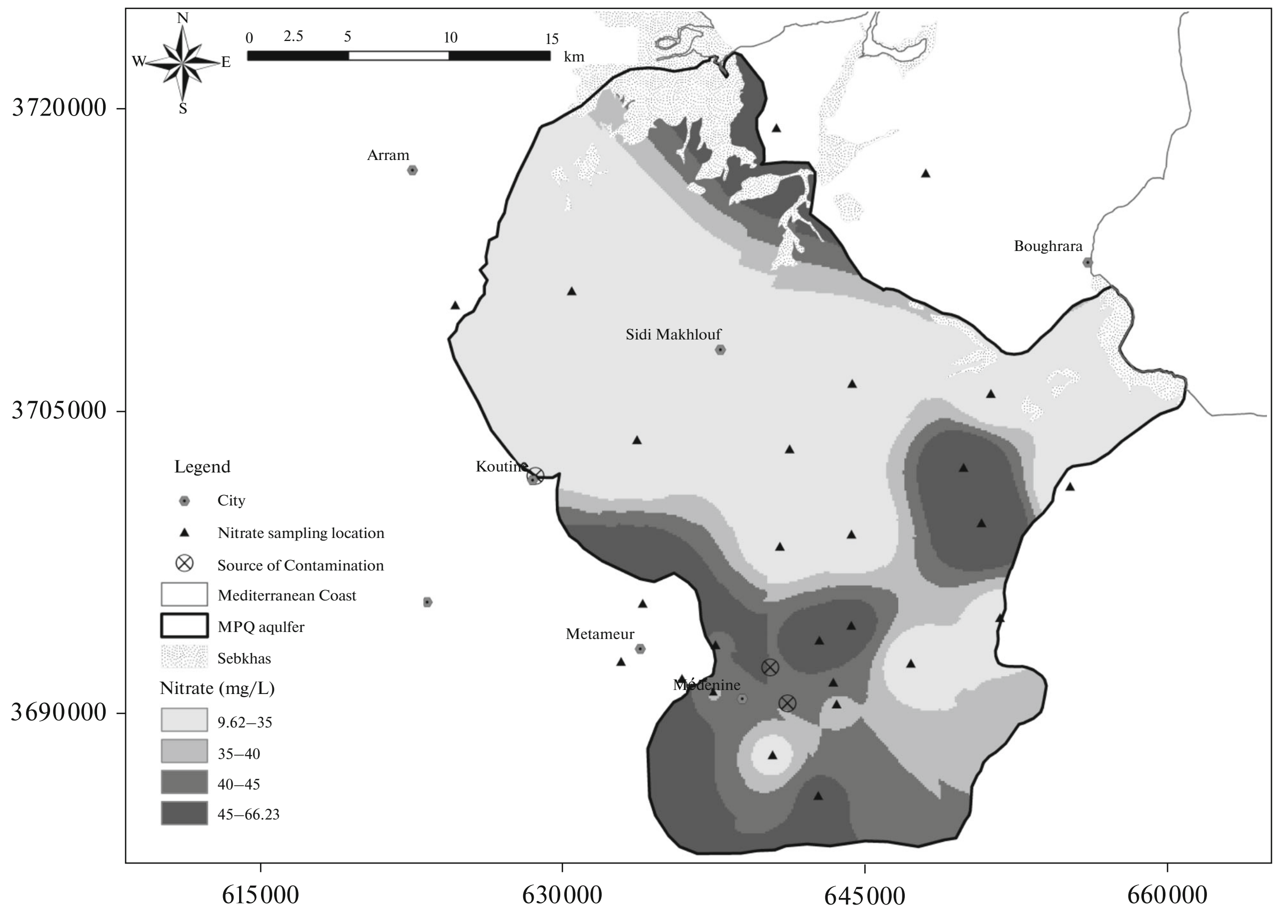

Fig. 5. Nitrates values map: interpolated map (a), bubbles map relating to NO_3 values (b).

explained by the low water table depth and the high permeability of lithological formations in these areas, which consisted of recent alluvial wadi deposits, mainly formed by gravels and pebbles. Areas with moderate vulnerability are localized in the central and the northern parts of the aquifer. Areas characterized by low vulnerability are insignificant. It is noteworthy that the wadis, which constitute the main groundwater recharge area, has the highest index of vulnerability. This is make wadis more susceptible to contamination.

Furthermore, nitrate concentration of MPQ waters was used for validating the DRASTIC model results. The nitrate concentration ranges from 16.52 to 132 mg/L. The nitrate distribution (Fig. 5) shows that the highest concentrations of nitrates are located in the south and southwest part of the MPQ aquifer near the urbanism areas of Medenine, wastewater treatment plant and the Koutine industrial area. The comparison of the nitrate distribution and the vulnerability map shows their concordance over large areas. The obtained results can be considered realistic and representative to the actual situation in the field.

CONCLUSIONS

The groundwater vulnerability in an arid region was assessed using an empirical index DRASTIC model. Seven environmental parameters, prepared in a GIS environment, were used to represent the natural hydrogeological setting of the Mio-Plio-Quaternary shallow aquifer. The DRASTIC aquifer vulnerability map indicated that the Southwestern part of the aquifer and wadi beds are most susceptible to contamination.

The nitrate distribution matches well to the vulnerability map over large areas. The areas showing a high vulnerability index have a high nitrate concentration. These results are frightening since the aquifer is vulnerable over large areas, with a vulnerability index ranging between moderate and high values. Nowadays, sources of contamination are limited to the southwestern part. They may multiply and spread with the population growth and the economic development of the region, threatening the MPQ waters. In order to relieve the MPQ waters pollution, recommendations may be taken into account. Various sources of waste that can affect groundwater such as solid wastes dis-

(b)

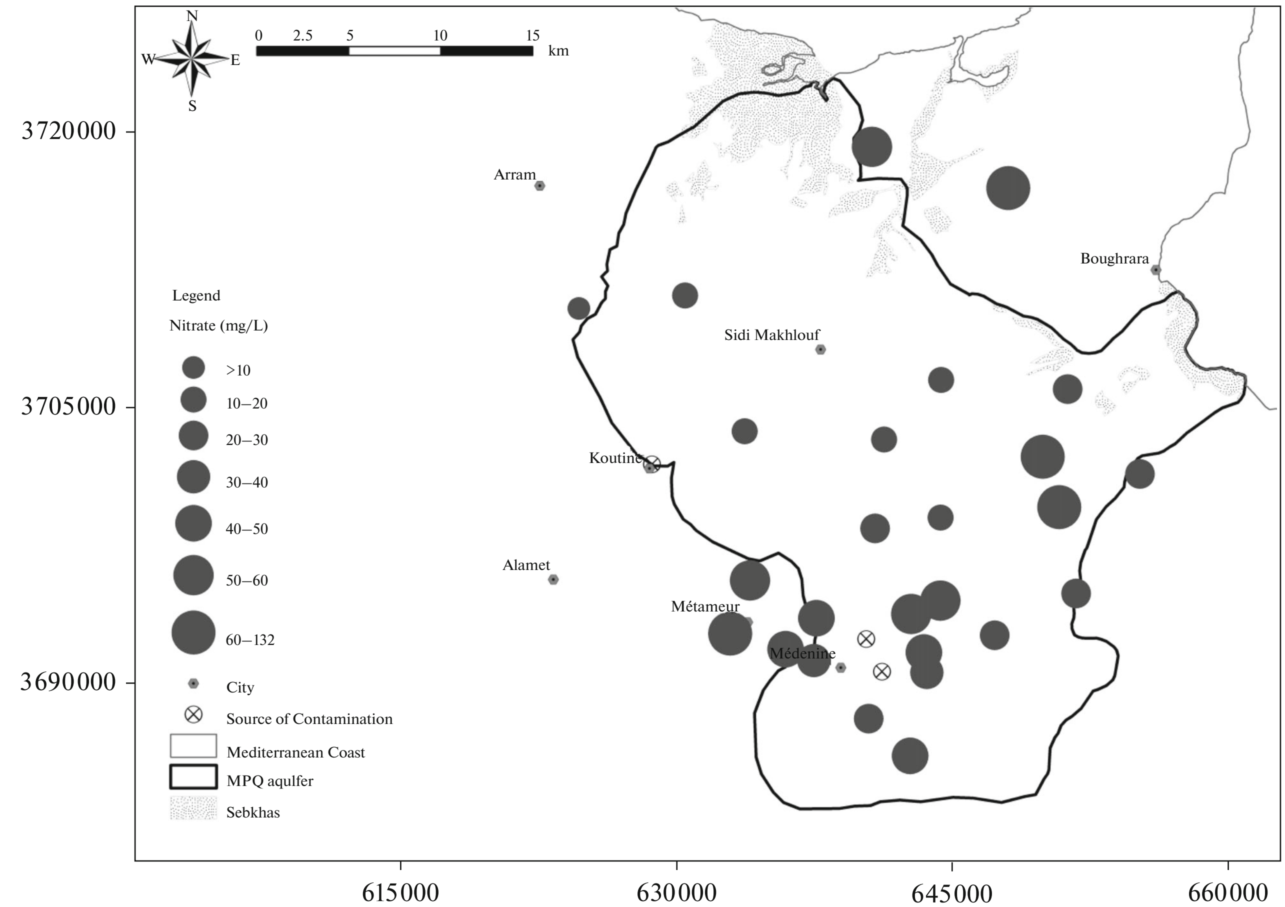

Fig. 5. (Contd.)

charges, wastewater treatment plant, industrial areas, etc. should be reduced. A channel discharging plastic pipes with sizes and diameters suitable for the delivery of wastewater treatment plant to the sea should be planned.

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