Groundwater vulnerability based on GIS approach: Case study of Zeuss-Koutine aquifer, South-Eastern Tunisia

Hanen Jarray*, Mounira Zammouri, Mohamed Ouessar, Fadoua Hamzaoui-Azaza, Manuela Barbieri, Ammar Zerrim, Albert Soler and Houcine Yahyaoui

Resumen

La cartografía de la vulnerabilidad del agua subterránea se utiliza como herramienta de modelado de contaminación y para proteger los recursos hídricos. El acuifero Zeuss-Koutin, que constituye una fuente primordial de agua potable en el sur este de Tunez, esta sometido a una explotación intensiva y amenazado de contaminación debido esencialmente a la zona industrial de Koutine. El agua subterránea circula a través de piedra calcarea fisurada y karstificada. La vulnerabilidad del acuifero se ha evaluado en los acuiferos Zeuss-Koutine utilizando el método SINTACS. Los distintos parámetros del modelo se obtuvieron de distintes fuentes y se hicieron mapas temáticos utilizand ArcGis. A cada parámetro SINTACS se le assigno un peso y una clasificación basados en una amplia gama de información del parámetro. El peso de cada parámetro depende del impacto de la contaminación potencial. El análisis del mapa de vulnerabilidad a la contaminación muestra que la parte sud-este del acuifero y los lechos Wadis son mas susceptibles a la contaminación. Las concentraciones de nitratos medidas en dos campañas de muestreo realizadas en temporades altas y secas en agua son coherentes con los resultados del modelo SINTACS.

Palabras clave: vulnerabilidad de agua subterranea, método SINTACS, SIG, contaminación, acuifero Zeuss-Koutine, sud este de Tunez.

H. Jarray*
Ecole Nationale des Ingénieurs Sfax (ENIS)
Université de Sfax, Route Soukra Km 3.5
1173-3038, Tunisia
*Corresponding author: jarray_hanen@yahoo.fr

M. Zammouri
Faculté des Sciences de Tunis
Université de Tunis El Manar
Campus Universitaire Farhat Hached, 2092
Tunis, Tunisia

H. Jarray
M. Ouessar
A. Zerrim
Laboratoire d'Eremologie et Lutte contre la Désertification
Institut des Régions Arides Médenine (IRA)
4119-Médenine, Tunisia

F. Hamzaoui-Azaza
Unité de recherche Géochimie et Géologie de l'Environnement
Faculté des Sciences de Tunis
Université de Tunis El Manar
Campus Universitaire Farhat Hached, 2092
Tunis, Tunisia

M. Barbieri
A. Soler i Gil
Grup de Mineralogia Aplicada i Geoquímica de Fluids
Departament de Mineralogia, Petrologia i Geologia Aplicada
Facultat de Ciencies de la Terra, Universitat de Barcelona (UB)
C/Martí i Franquès s/n, 08028
Barcelona, Spain

H. Yahyaoui
Commissariat Régional au Développement Agricole (CRDA) de Médenine
4100 Médenine, Tunisia

H. Jarray, M. Zammouri, M. Ouessar, F. Hamzaoui-Azaza, M. Barbieri, A. Zerrim, A. Soler and H. Yahyaoui

Abstract

Groundwater vulnerability mapping is largely used as a modeling tool to delineate areas susceptible to pollution and to protect groundwater resources from this threat. The Zeuss-Koutine aquifer, which constitutes an important source of drinking water in the Southeastern Tunisia, is subjected to an intensive exploitation and threatened by pollution due mainly to the industrial zone of Koutine. The groundwater circulates in fissured and karstified limestone. Aquifer vulnerability has been assessed using the SINTACS method. The different parameters of the SINTACS model were collected from several sources and converted into thematic maps using ArcGis. Each SINTACS parameter was assigned a weight and rating based on a range of information within the parameter. The weight of each parameter depends on the impact of potential pollution. The analysis of vulnerability map to pollution shows that the Southeastern part of the aquifer and the Wadis beds are more susceptible to pollution. The measured nitrate concentrations of two sampling campaigns carried out in high and dry water seasons are coherent with the SINTACS model results.

Key words: Groundwater vulnerability; SINTACS method; GIS; pollution; Zeuss-Koutine aquifer, South-East of Tunisia.

Introduction

Groundwater pollution can be avoided by delineating and monitoring vulnerable areas. Determining the spatial extension of areas susceptible to pollution is difficult given the many variables affecting groundwater pollution (Dixon, 2005). In fact, groundwater vulnerability cannot be directly measured in situ. It is a complex function of large number of parameters related to the soil, the unsaturated zone and the aquifer (Aller *et al*., 1987; Civita, 1990).

Margat (1968) introduced the concept of groundwater vulnerability to pollution in the 1960s in France. It can be defined as the possibility of percolation and diffusion of pollutants from surface into the groundwater (Aller *et al*., 1987; Civita, 1990).

Several approaches were developed in the world for aquifer vulnerability assessment. They include statistical approaches, based on variable related to pollutant concentration or to pollution probability (Zwahlen, 2004), indices methods, based on weighting between various criteria affecting the vulnerability (Gogu & Dassargues, 2000) and models taking into account the physical, chemical and biological processes in the unsaturated zone (Schnebelen *et al*., 2002). The indexes methods such as DRASTIC (Aller *et al*., 1987), GOD (Foster 1987), AVI (Van Stempvoort *et al*., 1993), SINTACS (Civita, 1994), DRISTPI (Jiménez-Madrid, 2013), EPIK (Doerfliger & Zwahlen, 1997), PI (Goldscheider *et al*., 2000) and COP were based on the European approach (COST, 2003). They are well-known worldwide of low cost and the most relevant with regard to field realities because of the consideration of the relative importance of every criterion involved in groundwater vulnerability (Ashokraj *et al*.,

2015; Al-Abadi *et al*., 2014; Neshat *et al*., 2014; Kumar *et al*., 2013; Sener & Davraz, 2013; Saidi *et al*., 2010, Leyland & Witthüser, 2010). The characterization of groundwater vulnerability is regularly a qualitative process; specified intrinsic vulnerability assessment methods present a subjective component that may affect the results (Jiménez-Madrid, 2011). Dissimilarities between the different results of vulnerability methods are a result of the weight and rating attributed to each parameter (Hiscock *et al*., 1995).

Sustainable management of groundwater resources, the prediction of the pollution risk and the prevention against groundwater pollution are important issues, especially in semiarid and arid regions where precipitation are scarce and irregular (Ouessar *et al*., 2006; Khemmoudj *et al*., 2014). In these regions, groundwater resources are the main source for water supply and their prevention from degradation and pollution is vital. Various pollution types such as heavy metals, fertilizers, pesticides and other organic chemicals threaten groundwater (Babiker *et al*., 2005). The karstified and fissured carbonated aquifers are highly vulnerable to pollution due to human activities (Corniello & Ducci, 2000; Corniello *et al*., 2004; Ducci, 2010).

The aim of this paper is to evaluate Zeuss-Koutine aquifer vulnerability using SINTACS method based on GIS. The hydrogeological parameters were mapped and processed to delineate areas susceptible to pollution producing a vulnerability assessment map. The SINTACS model results are compared to measured nitrate concentration of two sampling campaigns carried out in February and June 2015 and representative of high and low water seasons, respectively.

Description of the study area

The Zeuss-Koutine aquifer is located in the coastal Jeffara plain in South-East of Tunisia. The aquifer covers an area of about 820 km^2 (Figure 1). The geographical location of the study area lies in longitudes 10°16´-10°61´E and latitudes of 33°39´-33°75´N. The climate is arid Mediterranean with an average annual rainfall of 180 mm. The southeastern Tunisia is characterized by the presence of alternating marine and continental formations consequences of marine transgressions and regressions throughout the geological history of the northern Sahara (Gabtni *et al*., 2009). The stratigraphic sequence outcropping in the study area ranges from Triassic to Quaternary (figure 1). The groundwater circulates in the carbonate formations of the Jurassic, the Albo-Aptian, the Turonian and the lower Senonian. However, the Jurassic limestones is the main layer with a thickness reaching 120 m (Hamzaoui-Azaza *et al*., 2011). The Zeuss-Koutine aquifer constitutes a multilayered hydrogeologic entity where the relays are available through faults or by vertical drainance (Gaubi, 1988). The hydraulic communication between different layers of the Zeuss-Koutine aquifer is realized through faults of which the Medenine fault is the most important. Currently, this aquifer is subjected to an intensive exploitation and exploited by several wells. The main recharge of Zeuss-Koutine is infiltration of runoff water flowing from Matmata Mountains and local infiltration from several wadis (streams) (Oum Zessar, Zeuss…). The Zeuss-Koutine aquifer provides a source of water for drinking and agriculture use. Since 1962, Zeuss Koutine aquifer has been contributing significantly to drinking water supply of Jerba Island and major cities of Tataouine and Medenine governorates. The pumping of the aquifer started since the 60s and has kept a gradual increase up to present. For example, exploitation flow rates have increased from 206 l/s in 1977 to 277 l/s in 1987, 298 l/s in 1995, 339 l/s in 2004, 589 l/s in 2010 to 623 l/s in 2014. The withdrawals reached 641 l/s in 2014 while the renewable resources are estimated to 352 l/s (DGRE, 2014). The exploitation increase produced a continuous piezometric decline of 0.5 to 1 m/year on average and a possible groundwater pollution by the salty waters of Sebkha in the northeast of the Zeuss-Koutine basin (Gaubi, 1988). The transmissivity of the aquifer varies between 0.055 and 0.2 m^{2}s^{-1} (OSS, 2005).
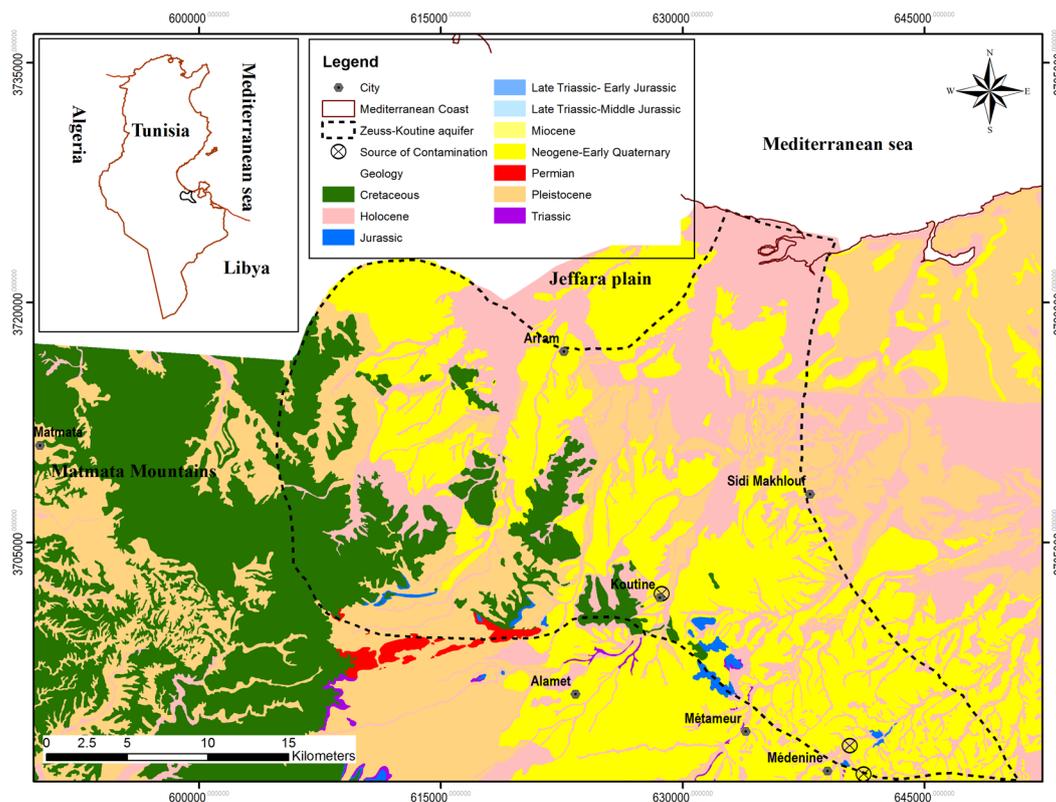
Figure 1. Geologic map of Zeuss-Koutine aquifer (based on Geologic maps: Medenine, Ajim, Mareth, Kirchaou, Matmata and Ghomrassen).

Groundwater flow in the study area is towards the Sebkha Oum Zessar and the Mediterranean Sea (Hamzaoui-Azaza, 2011) (Figure 2). Moreover, groundwater is threatened by pollution. The main source of pollution is the industrial zone of Koutine (milk, soft drinks and juice industries) in the south part of the Zeuss-Koutine aquifer and wastewater effluents in Medenine urban area in the southeastern part of the aquifer. The vulnerability assessment of the Zeuss-Koutine aquifer is a crucial issue in order to prevent groundwater from pollution. We focus on the SINTACS model (Civita, 1990; Civita *et al*., 1999) that has been widely used for any kind of aquifer and especially for karstic and fissured aquifers (Civita *et al*., 1999).

Materials and Methods

The vulnerability assessment approach

SINTACS method is an updated model of US DRASTIC method. It was developed in Italy in the early 1990s in order to adapt the mapping to a larger scale in view of the great diversity of the hydrogeology of Italy (Civita, 1990; Civita, & De Maio, 2004). SINTACS model shows vulnerability index of the study area using seven hydrological parameters, which are the Depth to water S (*Soggiacenza* in Italian), Impact of effective infiltration I (*Infiltrazione* in Italian), Hydrogeologic properties of the aquifer N (*Not Azione del Satoru* in Italian), Attenuation capacity of the soil/sediment cover T (*Tipologia della Copertura* in Italian), Attenuation capacity in the unsaturated zone A (*Carratteri Idrogeologici dell Acquifero* in Italian), Hydraulic conductivity range of the aquifer C (*Conductivity Idraulica* in Italian), and Hydrological role of the terrain slope S (*Acclività della Topographica area* in Italian). To avoid confusion with the depth to water table, we will change the terrain slope designation to SA. Unlike DRASTIC, SINTACS method allows to use, at the same time and in different cells, weighting factors variable according to certain situations. It is more flexible in terms of the indexation and weighting system. The steps followed in the Zeuss-Koutine aquifer vulnerability assessment were data gathering, processing and mapping data using ArcGis, and operating results for the identification of vulnerable areas.
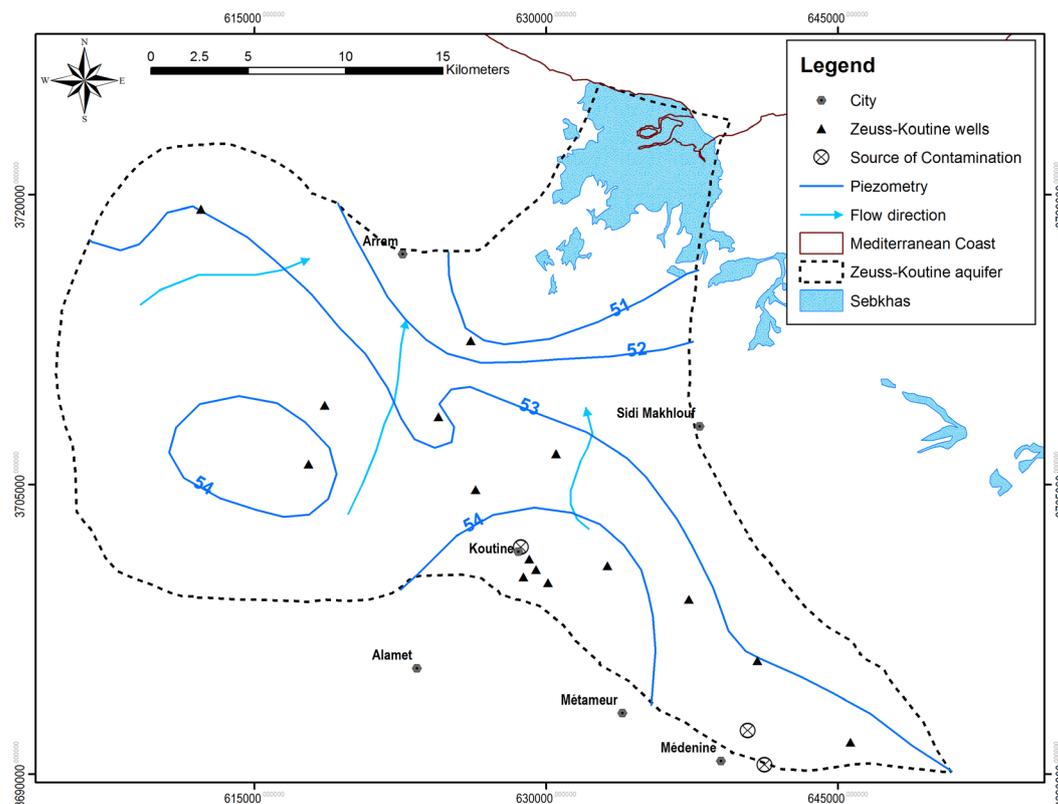
Figure 2. Piezometric map of Zeuss-Koutine aquifer (Hamzaoui-Azaza et al. 2011)

SINTACS vulnerability index (*SI*) is computed using the equation (1) (Civita & De Maio, 1997):

$$SI = S_r \times S_w + I_r \times I_w + N_r \times N_w + T_r \times T_w + A_r \times A_w + C_r \times C_w + SA_r \times SA_w$$

(1)

Where the weighted parameters are: S_w, I_w, N_w, T_w, A_w, C_w and SA_w (Table 1). S_r, I_r, N_r, T_r, A_r, C_r and SA_r are ratings for each of the parameters. The weight of each parameter depends on the impact of potential pollution (Table 1). The SINTACS parameters ratings vary from 1 to 10, where higher values are directly proportional to the degree of vulnerability.

Table 1. The SINTACS model parameter weight's (Civita & De Maio, 2004).

Factor	Weight
Depth to water (S)	3
Impact of effective infiltration (I)	3
Attenuation capacity in the unsaturated zone (N)	3
Attenuation capacity of the soil/sediment cover (T)	4
Hydrogeologic properties of the aquifer (A)	4
Hydraulic conductivity range of the aquifer (C)	5
Hydrological role of the terrain slope (SA)	4

Table 2. Vulnerability classes of SINTACS method

Vulnerability index (SI)	Degree of intrinsic vulnerability
26–80	Very low
81–105	Low
106–140	Medium
141–186	High
187–210	Very high
211–260	Extremely high

The intrinsic vulnerability values indicate the potential pollution in the aquifer. A higher vulnerability index indicates a higher probability of pollution (Civita & De Maio, 1997). The output values vary from 26 to 226. The vulnerability classes are defined using Table 2 (Corniello *et al.*, 2004):

To establish thematic layers of the seven parameters, several types of data were used. Table 3 shows data types, sources and usages.

The depth to water (*S*) is the vertical distance from the ground surface to the water table. Generally, potential aquifer protection increases with the higher depth of the water. The water table depths were measured from observation wells. The Inverse Distance Weight (IDW) interpolation method implemented in the ArcGIS Geostatistical Analyst extension 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 for use in this study since it produced only the value ranges found within the data attributes.

Table 3. Sources of data used for creation of hydrogeological parameter for SINTACS method

Data type	Source	Format	Scale	Used to produce
Borehole, Piezometer data, water table level	CRDA[1], DRE[2]	Table, Location map	1:100 000	*S, A*
Inter annual rainfall (mean)	CRDA, DRE	Table	1:100 000	*I*
Geology map	Geologic maps	Digital	1:100 000	*A*
Soil map	Agriculture map, 2003	Digital	1:100 000	*T*
Topographic map	DEM3 30 Tunisie		1:100 000	*SA*
Hydraulic conductivity, piezometer geological profiles	CRDA, DRE			*N, A, C*

[1]CRDA: Commissariat Régional au Développement Agricole
[2] DRE: Direction de ressources en eau (Tunisie)
[3] DEM: Digital elevation model

The main source of groundwater recharge is rainfall infiltration. Net recharge (*I*) is the quantity of water per unit of land that reaches the aquifer (Aller *et al*., 1987). Rainfall data were collected from CRDA-DRE Medenine rain gauges and interpolated using IDW method; to produce the isohyet map. Since, the Zeuss-Koutine aquifer is unconfined; rating of net recharge is derived from the amount of precipitation.

An aquifer is a geological formation containing water, which can be exploited through wells or sources for domestic, industrial and agricultural usage. Circulation and spread of any pollutant into the saturated zone depends on the texture and lithology of the aquifer layers. This is always controlled by the particle size, porosity, permeability and lithology of geological formations. The parameter *A* was obtained by IDW interpolation of horizontal equivalent permeability of the saturated zone. Horizontal equivalent permeability was calculated using the equation (2):

$$A_{eq} = \frac{\Sigma_{i=1}^{3} H_i \times A_i}{\Sigma_{i=1}^{3} = 1 \, H_i} \qquad (2)$$

Where: A_{eq} is horizontal equivalent permeability (m/s), H_i is thickness of the layer *i* (m), A_i is permeability of the layer *i* (m/s), *i* (*i*=1 to 3) is an index related to the lithological classes forming the Zeuss-koutine aquifer.

The soil parameter (*T*) represents the influence of soil material on the infiltration. The soil layer types indicate the recharge rate infiltrated into the aquifer. In general, the less clay and the smaller the grain size of the soil, the less permeable the soil will be and the less pollutant will reach the aquifer (Aller *et al*., 1987). Taamallah (2003) provided the soil map of the study area. Table 4 shows the classification of soil types and their rating.

Table 4. The type of the soil media and their ratings.

Soil class	Rating
Regosols	9
Lithosols, Fluvisols	5
Rendzinas (Gypsum)	3
Xerosols	8
Solonchak	2
Gleysols	3
Rendzinas (Calcareous)	4
Urban areas	1

Topography (*SA*) refers to the slope of the land surface. The topography indicates whether a pollutant will move or will stay on the ground surface to penetrate into the aquifer (Lynchez *et al*., 1994). The slope (%) of the study area was obtained from the Digital Elevation Model (DEM).

The vadose zone (*N*) is defined as the fraction between groundwater and the surface of soil where the pores are partially saturated with water. The permeability of the vadose zone controls the movement of pollutants and their arrival to the aquifer. Most of the physicochemical processes taking place in this zone are influenced by its thickness. The infiltration and dispersion of pollutants are guided by the lithological characteristics of the layers that control their paths and trajectory in the subsurface.

Hydraulic conductivity (*C*) refers to the ability of the aquifer to transmit water. It controls the migration and dispersion of pollutants. Hydraulic conductivity was obtained by identifying the permeability coefficient for each lithological class (Castany, 1982) and assigning a rating to each interval (Aller *et al*., 1987). The conductivity and the aquifer vulnerability are proportional. This factor was obtained by IDW interpolation of point data.

The final SINTACS map was created by calculating a weighted sum of the individual aquifer attribute raster's within Conceptual model ArcGis.

The nitrate sampling campaigns

Groundwater was sampled from 17 wells of Zeuss-Koutine aquifer for nitrate analysis during February (Humid period) and June (Dry period) 2015. The samples were well spatially distributed. A volume of 5 ml of each sample was filtered at 0.2 µm and was conserved in 10 ml plastic tubes. All samples were stored in ice chests at 4°C and transported to the laboratory where they were analyzed within two weeks. The analyses were performed in the Laboratory of the Department of Crystallography, Mineralogy and Mineral Deposits of the University of Barcelona, Spain. Nitrates concentrations were determined using High Performance Liquid Chromatography (HPLC).

Results and discussion

SINTACS parameters

Figure 3 shows the different thematic maps of SINTACS model realized using ArcGis. The ratings corresponding to each class for the parameters are presented in Table 5.

Figure 3a shows that the Zeuss-Koutine aquifer is divided into two water depth intervals (from 23 to 31 m and >31 m). The lowest water table values have the highest index ($S_r \times S_w = 6$) and located near the discharge area of Sebkhat Oum Zessar.

Impact of effective infiltration (I) map (Figure 3b) indicates that the amount of rainfall received by the aquifer is divided into two intervals from 0.1 to 0.17 m/year and from 0.17 to 0.25 m/year, respectively. The major area of the aquifer belongs to the second interval with an index ($I_r \times I_w = 32$).

The parameter A map (Figure 3c), corresponding to hydrogeological properties of the aquifer, shows the distribution of the horizontal equivalent permeability of the saturated zone. The highest permeability is represented by dark red and reaches 8.7×10^{-4} m/s with $Ar \times Aw = 32$. In fact, the aquifer layers consisting of limestone that has been affected by dissolution producing ridges, fissures, karsts and sinkholes show high permeability values. The lower permeability is about 10^{-5} m/s, this permeability decrease is explained by

the existence of marl and clay layers (Gaubi 1988; Yahyaoui 1998).

Figure 3d shows the soil type distribution. Each soil type has a rating. Regosols have the highest index ($Tr \times Tw = 36$) while the urban areas have the lowest index ($Tr \times Tw = 4$).

Topography of the aquifer (SA) map (Figure 3e) shows that the majority of the Zeuss-Koutine aquifer area has a slope between 0 and 18 %.

The vadose zone (N) map indicates that the wadi beds have the highest permeability value, about 10^{-3} m/s. In fact, wadi beds are formed by gravels, pebbles and sands resulting in high permeability (Figure 3f).

The hydraulic conductivity (C) map shows that the highest values are located in Matmata mountains and in the southeastern part of the aquifer (Figure 3g). This is explained by the existence of fissured and karstified limestones. The hydraulic conductivity of the aquifer reaches 4.45×10^{-3} m/s.
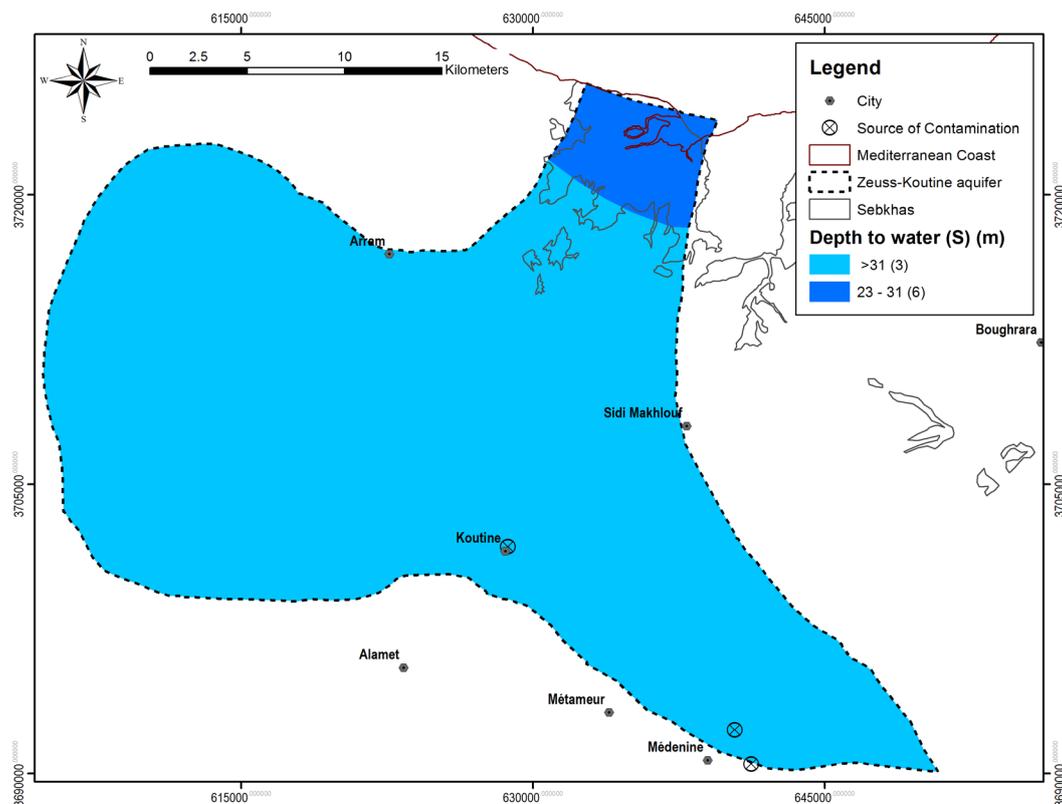
Figure 3. The calculated layers of SINTACS model showing the calculated weight of the different parameters. *(a)* Depth to water (*S*), *(b)* Impact of effective infiltration (*I*), *(c)* Hydrogeologic properties of the aquifer (*A*), *(d)* Attenuation capacity of the soil/sediment cover (*T*), *(e)* Hydrological role of the terrain slope (*SA*), *(f)* Attenuation capacity in the unsaturated zone (*N*), *(g)* Hydraulic conductivity range of the aquifer (*C*).
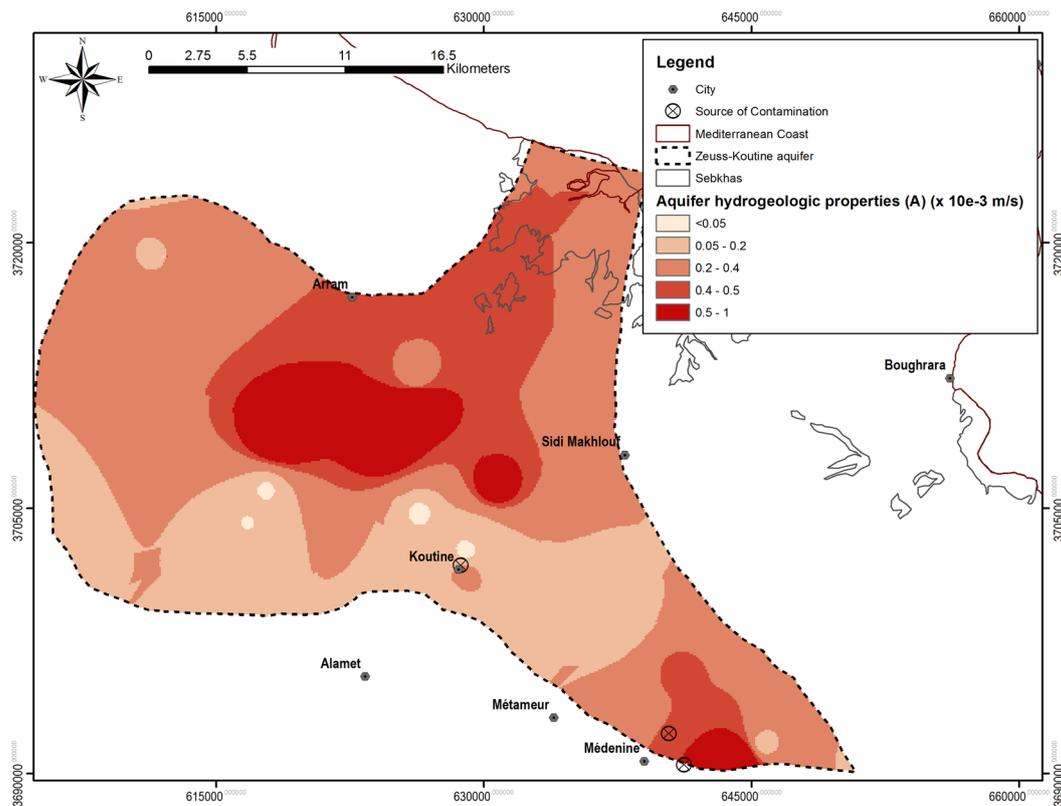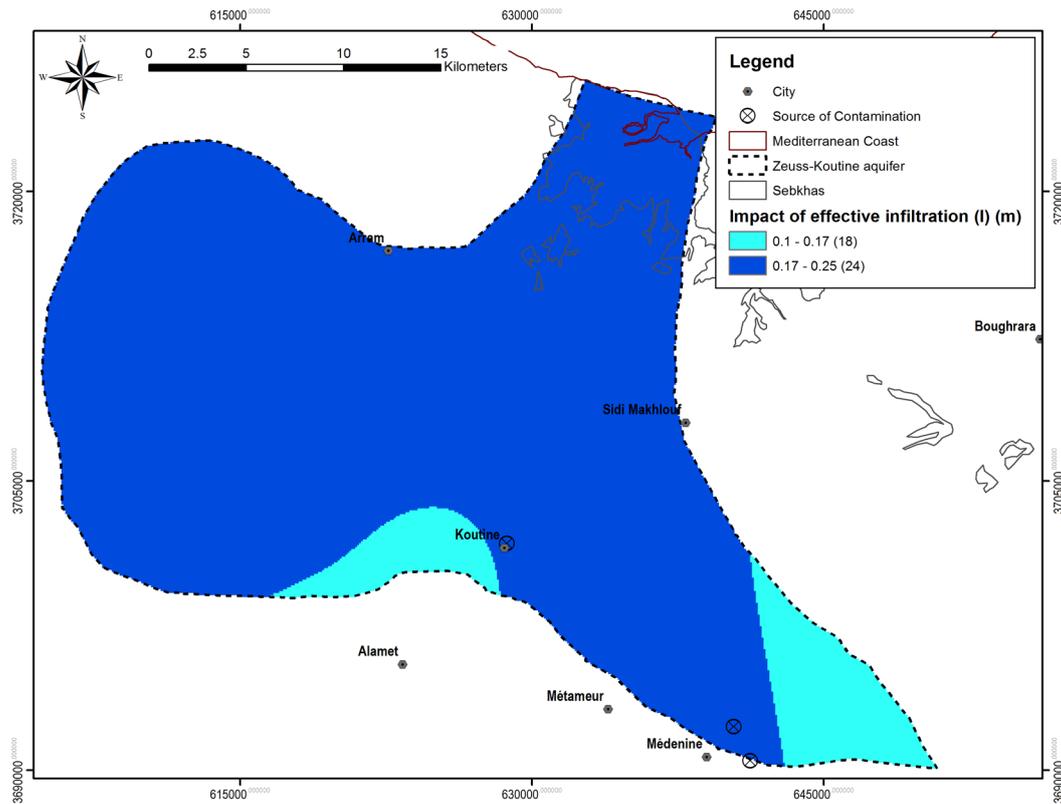
Figure 3b and 3c.
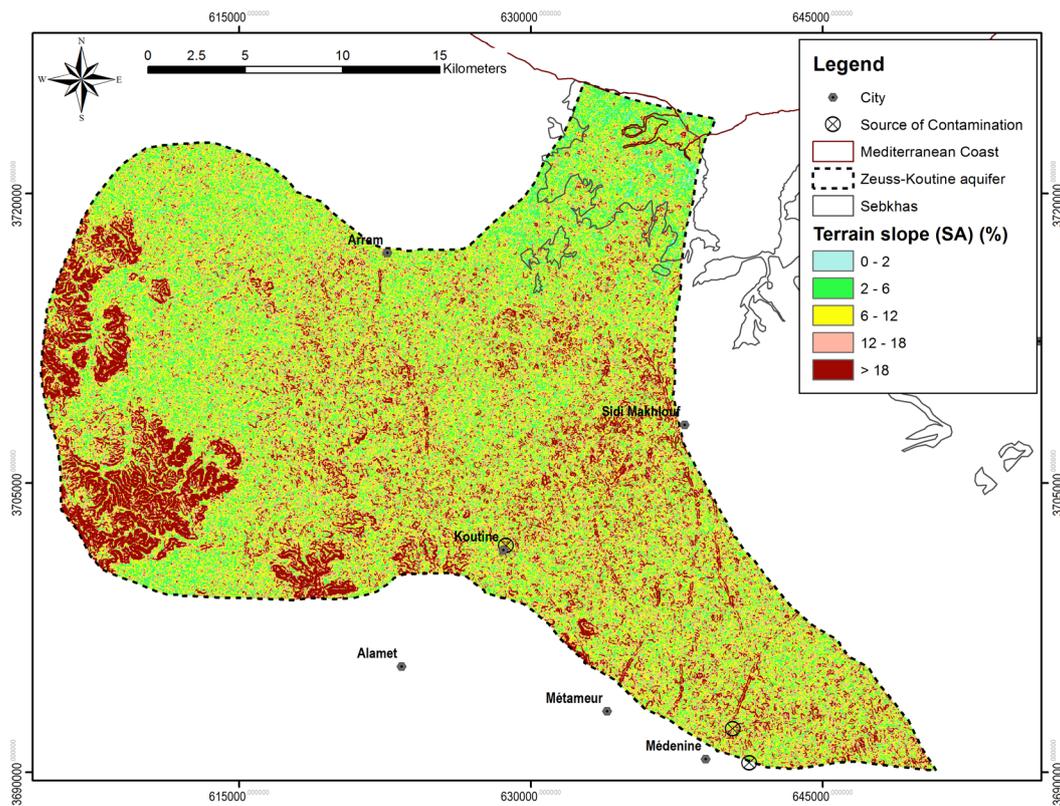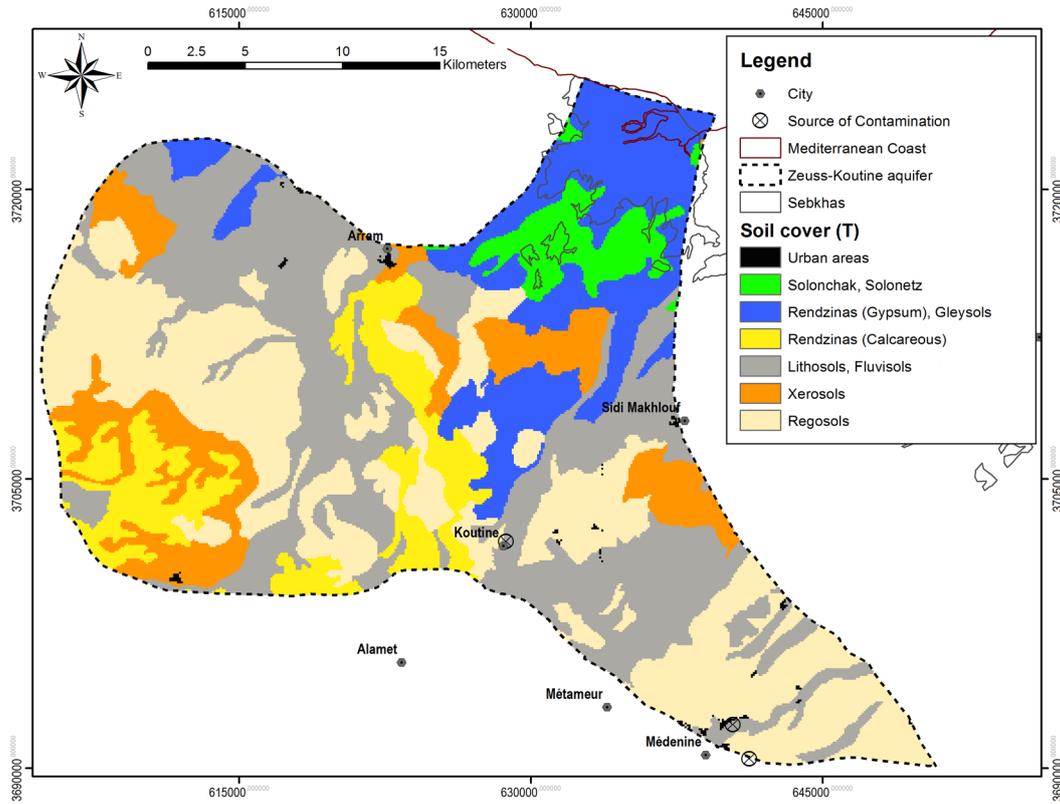
Figure 3d and 3e.
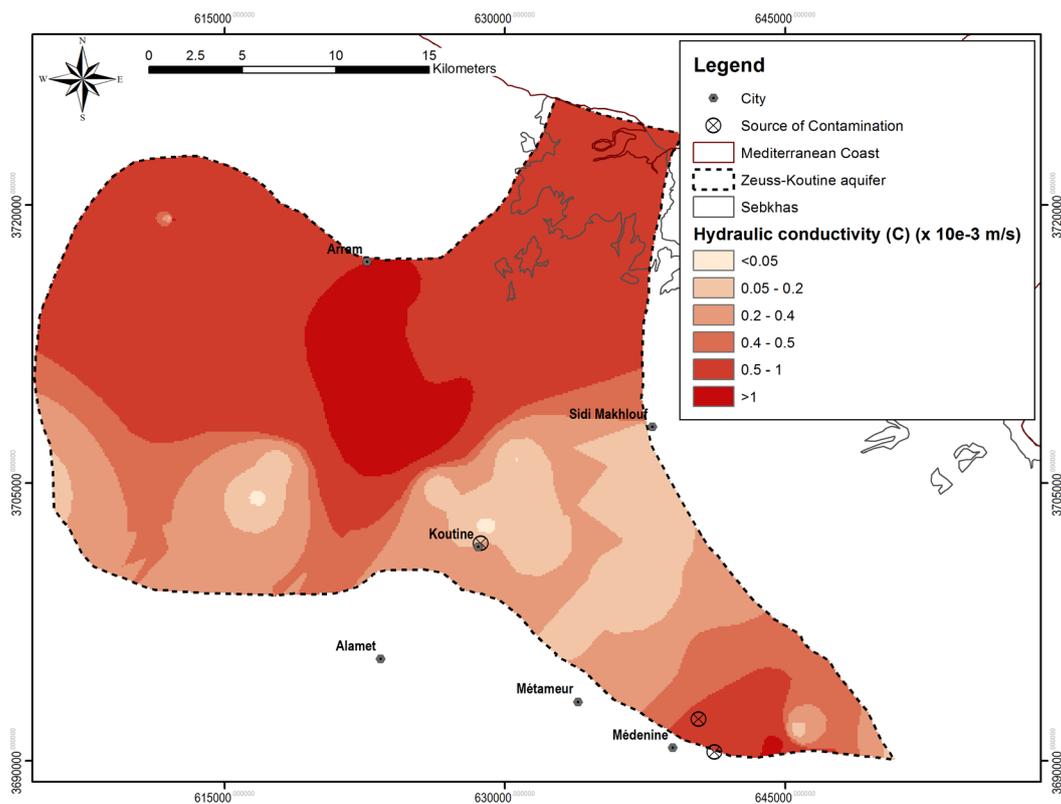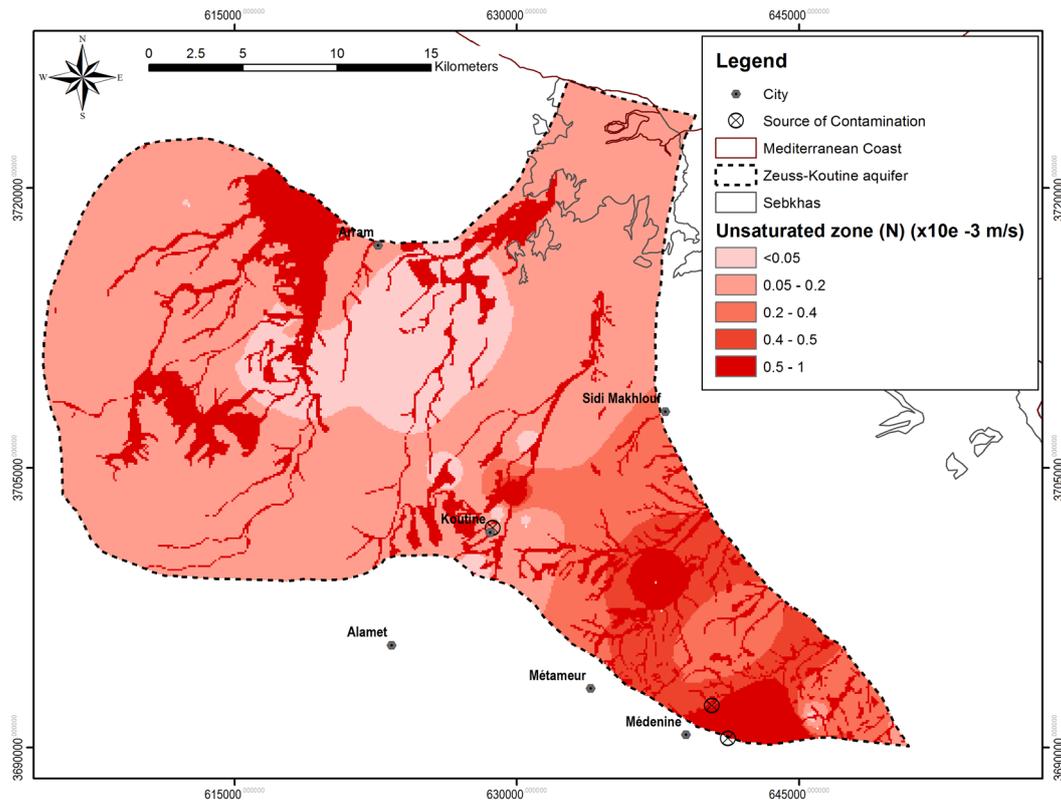
Figure 3f and 3g.

Table 5. Rating values of the vulnerability parameters for the SINTACS method.

S (Depth to water)							
Range (m)	0 - 1.5	1.5 - 4.5	4.5 - 9	9 - 15	15 - 23	23 - 31	> 31
Rating	10	9	7	5	3	2	1

I (Impact of effective infiltration)					
Range (m)	0 - 0.05	0.05 - 0.1	0.1 - 0.17	0.17 - 0.25	> 0.25
Rating	1	3	6	8	9

N (Attenuation capacity in the unsaturated zone)					
Range (10^{-3}m/s)	<0.05	0.05 - 0.2	0.2 - 0.4	0.4 - 0.5	0.5 - 1	>1
Rating	1	2	4	6	8	10

T (Soil parameter)							
Range	Regosols	Lithosols, Fluvisols	Rendzinas (Gypsum)	Xerosols	Solonchak, Solonetz	Gleysols	Rendzinas (Calcareous)	Urban areas
Rating	9	5	3	8	2	3	4	1

A (Hydrogeologic properties of the aquifer)					
Range (10^{-3}m/s)	<0.05	0.05 - 0.2	0.2 - 0.4	0.4 - 0.5	0.5 - 1	>1
Rating	1	2	4	6	8	10

C (Hydraulic conductivity)					
Range (10^{-3}m/s)	<0.05	0.05 - 0.2	0.2 - 0.4	0.4 - 0.5	0.5 - 1	>1
Rating	1	2	4	6	8	10

SA (Hydrological role of the terrain slope)				
Range (%)	0 - 2	2 - 6	6 - 12	12 - 18	> 18
Rating	10	9	5	3	1

SINTACS vulnerability map

Figure 4 shows the spatial distribution of vulnerability classes of the Zeuss-Koutine aquifer. SINTACS map shows that 0.1 % of the total area of the study area has an extremely high vulnerability index, 8.4 % a very high vulnerability, 46.1 % a high vulnerability, 34.8 % a moderate vulnerability, 10.5 % a low vulnerability and 0.1 % a very low vulnerability. The highest vulnerability is located mainly in wadis beds, the southeastern part of the aquifer and the area of Matmata Mountains. In the wadis and Matamta Mountains, the high values are explained by the low depth of the water table and the high permeability of lithological formations consisted in current alluvial wadis deposits (gravels, pebbles…) corresponding to Mio-Plio-Quaternary filling. It is important to note that the recharge area of the Zeuss-Koutine aquifer comprising wadi beds and Matmata Mountains has the highest index of vulnerability (46 % of the total area). In addition, the southeastern part of the aquifer has a high vulnerability index (8.6 % of the total area). This is can be explained by the low depth of water table and the high permeability of the saturated and vadose zone in wadi beds that let water to infiltrate easily. In addition, the low slope allows runoff to stagnate and to infiltrate immediately.

Vulnerability map validation

Nitrate concentration ranges from 0.01 to 34.2 mg/l for the high water season campaign (February, 2015) while it varies between 1 and 61.02 mg/l for the low water season campaign (June, 2015) (Table 6). Results of the two campaigns show an increase of nitrate concentrations from the high water season to the low water season. Nitrate spatial distribution map for the Zeuss-Koutine aquifer (Figures 5a and 5b) indicates that the highest values are located in the southeast of the aquifer near Medenine urban area, in the close vicinity of the Koutine region where industrial factories are implemented and in the extreme West of the aquifer. The nitrate distribution map confirms the vulnerability map results. In fact, urban area and Matmata Mountains region have the highest nitrate values (>20 mg/l).
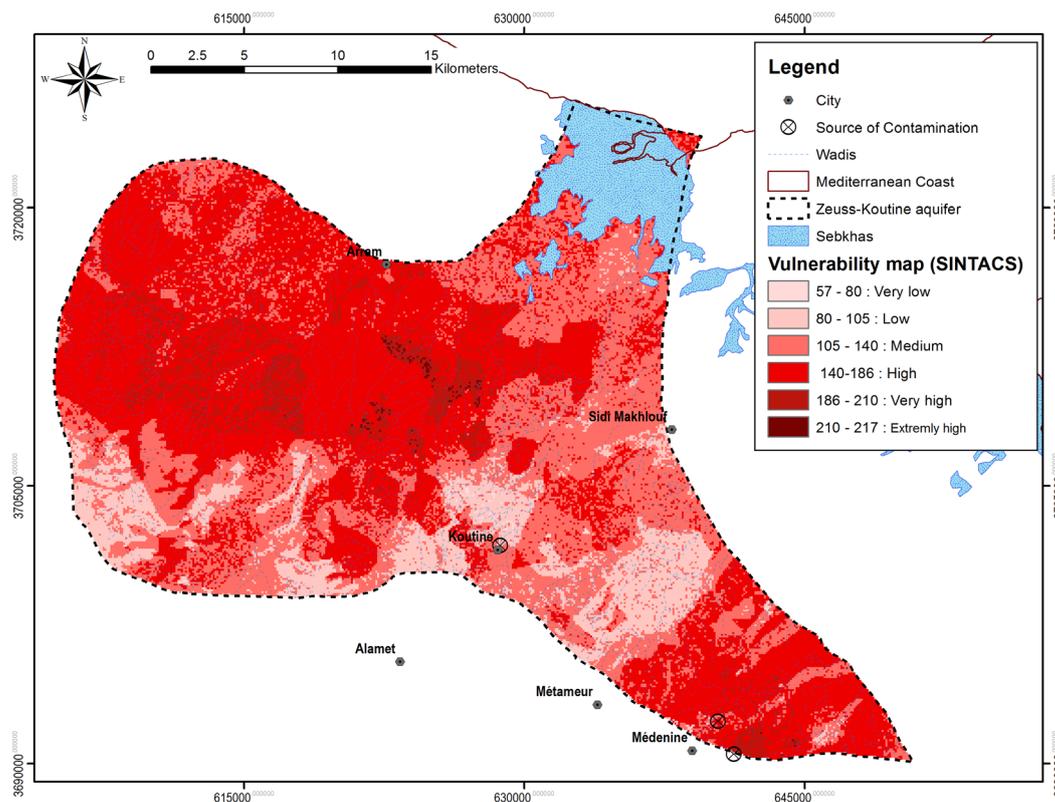
Figure 4. Vulnerability map of Zeuss-Koutine aquifer (SINTACS).

Table 6. Nitrate concentration results of sampled water points.

Sampled points	X (UTM)	Y (UTM)	February 2015 campaign	June 2015 campaign
			Nitrate (mg/l)	
ZK-1	640865	3695888	25.28	24.36
ZK-2	645647	3691676	20.67	18.11
ZK-3	612259	3719252	23.73	23.52
ZK-4	617362	3704685	13.31	**
ZK-5	618628	3709107	15.27	15.02
ZK-6	629480	3700610	34.20	45.52
ZK-7	633148	3700799	28.11	25.31
ZK-8	630095	3699929	0.01	1.00
ZK-9	626379	3704741	3.11	2.67
ZK-10	630513	3706604	6.65	7.60
ZK-11	629139	3701159	33.88	42.63
ZK-12	628102	3702038	26.77	**
ZK-13	626131	3712454	6.65	7.07
ZK-14	624465	3708517	7.21	7.96
ZK-15	637347	3699068	24.24	25.55
ZK-16	628834	3700218	16.50	17.92
ZK-17	617787	3706070	9.33	61.02

** Not analyzed
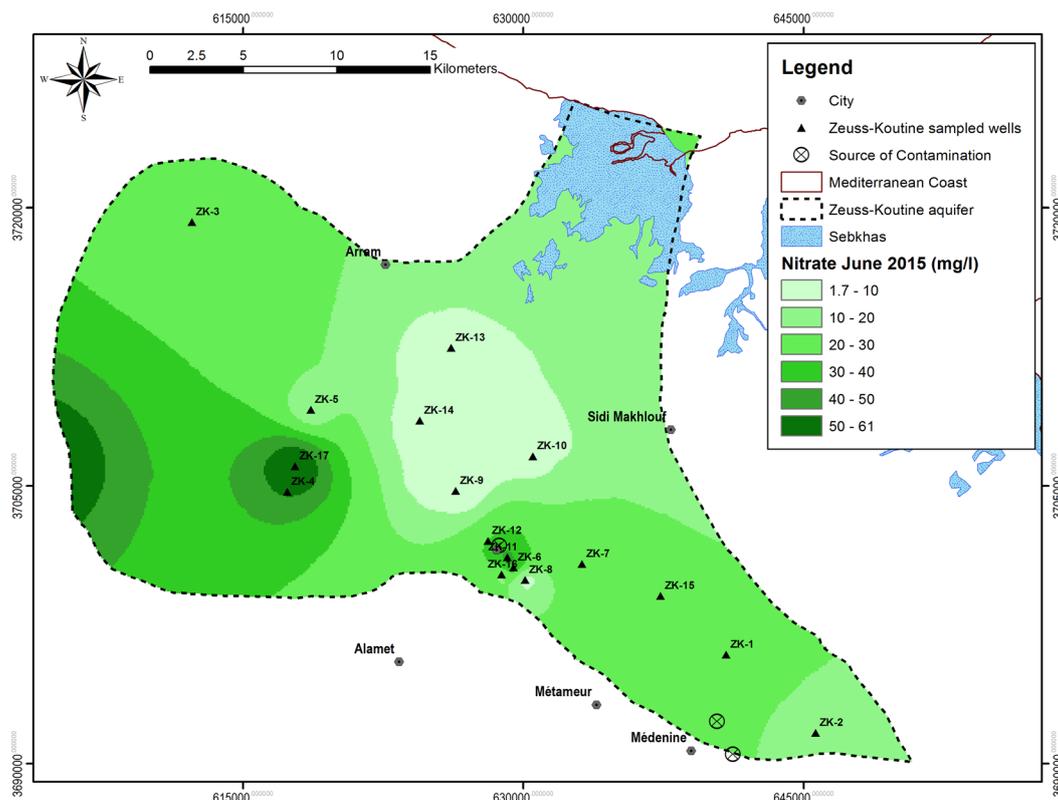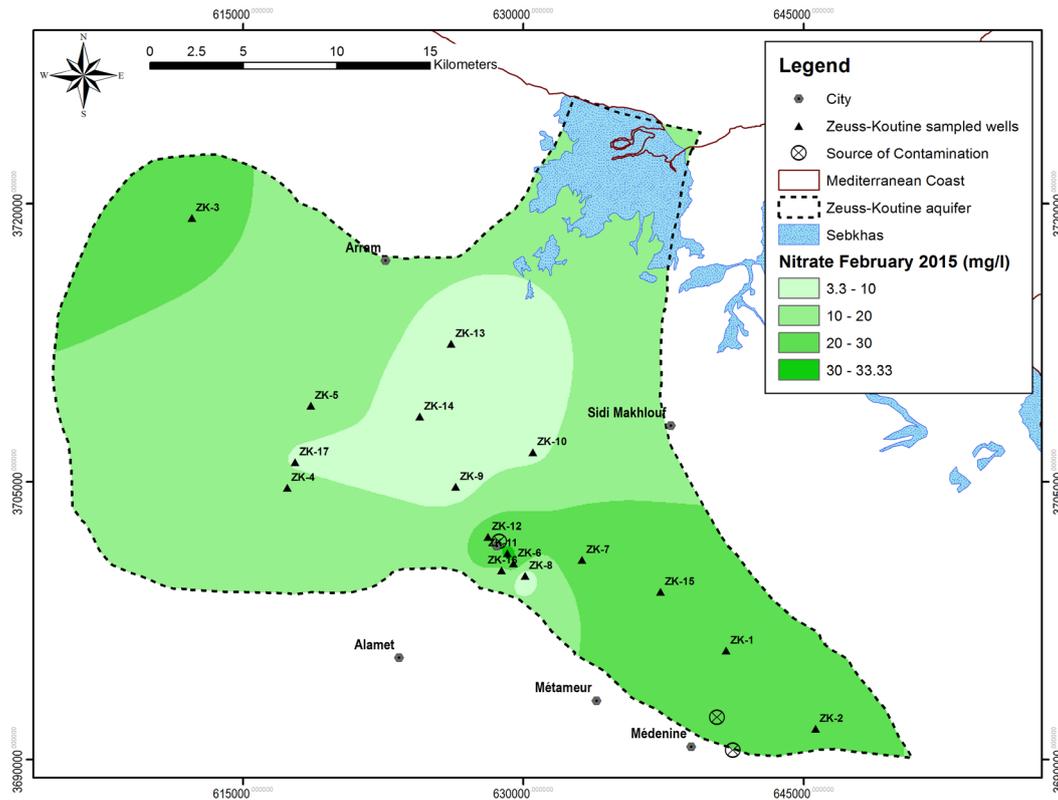
Figure 5. Nitrate concentration distribution in Zeuss-Koutine aquifer in *(a)* February 2015 and *(b)* June 2015.

Summary and conclusion

This study aims to assess groundwater vulnerability in an arid region using the empirical indexes SINTACS models. Seven environmental parameters, prepared in a GIS environment, were used to represent the natural hydrogeological setting of Zeuss-Koutine aquifer. The vulnerability map indicated that wadi beds, urban area and the region of Matmata are more susceptible to pollution where nitrate concentrations are higher than 20 mg/l.

Nowadays, sources of contamination are limited to the southeastern part. They may multiply and spread with the population growth and the economic development of the region, threatening the Zeuss-Koutine waters. In order to relieve the Zeuss-Koutine waters pollution, recommendations may be taken into account. Various sources of waste that can affect groundwater such as solid waste discharges, 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 and industry wastewaters to the sea should be planned.

In order to better exploit the vulnerability map, more detailed information on local conditions and additional hydrologic studies about the studied area are necessary for planners and decision makers to understand the mechanisms of pollution and recharge of the aquifer. Furthermore, in the indexes methods, the concept of groundwater vulnerability deals only with hydrogeological setting and does not include pollutant concentration. This work will be completed by the development of transport model that would enable us to follow the pollutant propagation. This model could be used to investigate some remediation solution like pumping the polluted water by wells located close the pollution source.

Acknowledgements

References

Al-Abadi A.M, Al-Shamma'a A.M., Aljabbari M.H., 2014, A GIS-based DRASTIC model for assessing intrinsic groundwater vulnerability in northeastern Missan governorate, southern Iraq. *Appl Water Sci*., DOI 10.1007/s13201-014-0221-7.

Aller L., Bennet T., Leher J.H., 1987, DRASTIC: A Standardized System For Evaluating Ground Water Pollution Potential Using Hydrogeological Settings. EPA 600/2-87-035.

Ashokraj C., Kirubakaran M., Colins Johnny J., 2015, Estimation of Groundwater Vulnerability using Remote Sensing and GIS Techniques. IJIRST. 1, 9: 2349-6010.

Babiker I.S., Mohamed A.A., Hiyama T., 2005, A GIS based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan. *Sci of the Total Environ*. 345: 127– 140.

Castany G., 1982, Principe et méthodes de l'hydrogéologie.]. Paris: University of Pierre Marie Crue (ParisVI).

Civita M., De Maio M., 1997, SINTACS: un sistema parametrico pernla valutazione e la cartografia della vulnerabilita ´degli acquiferi all'inquinamento. Metodologia et Automatizzazione. Pitagora Ed., Bologna: Itlaia, 191 pp.

Civita M., De Maio M., 2004, Assessing and mapping groundwater vulnerability to contamination - The Italian "combined" approach. *Geofisica internacional*, 43, 4-19.

Civita M., 1990, Legenda unificata per le carte della vulnerabilita dei corpi idrici soutterranei. In: Studi sulla vulnerabilita degli Acquiferi. Pitagora: Bologna.

Civita M., 1994, Contamination Vulnerability Mapping of the Aquifer: Theory and Practice. Quaderni di Tecniche di Protezione Ambientale, Pitagora.

Corniello A., Ducci D., Monti G.M., 2004, Aquifer pollution vulnerability in the Sorrento peninsula,southern Italy, evaluated by SINTACS method. *Geofísica Internacional*, 43, 4, pp. 575-581.

Corniello A., Ducci D., 2000, "Pollution Vulnerability Assessment in Karstic Aquifers: A Case Study of the Matese Mountains," In: O. Sililo *et al*., Ed., 30th International Association of r:Past Achievements and Future Challenges Cape Town, Balkema, Rotterdam, 26 November-1 December 2000, pp. 725-730.

COST (European cooperation in science and technology), 2003, Action 620 – Vulnerability and risk mapping for the protection of carbonate (karst) aquifers. European Commission, Directorate-General for Research, Report EUR 20912, Luxemburg.

DGRE (Direction Générale des Ressources en Eau, Ministère de l'Agriculture), 2014, Rapport annuel d'exploitation des nappes profondes. DGRE, Tunis, 363 pp.

Dixon B., 2005, Applicability of neurofuzzy techniques in predicting groundwater vulnerability: a GIS-based sensitivity analysis. *J of Hydrol*., 309: 17-38.

Doerfliger N., Jeannin P.Y., Zwahlen F., 1999, Water vulnerability assessment in karst environments: a new method of defining protection areas using a multi-attribute approach and GIS tools (EPIK method). *Environ Geol*., 39, 2: 165–176.

Doerfliger N., Zwahlen F., 1997, EPIK: a new method for outlining of protection areas in karstic environment, in: International symposium and field seminar on "karst waters and environmental impacts", edited by: Gunay, G. and Jonshon, A. I., Antalya, Turkey, Balkema, Rotterdam. 117–123.

Ducci D., 2010, Aquifer Vulnerability Assessment Methods: The Non-Independence of Parameters Problem. J. Water Resource and Protection, 2, 298-308 doi:10.4236/jwarp.2010.24034.

Foster S., 1987, Fundamental Concept in Aquifer Vulnerability, Pollution Risk and Protection Strategy. In: W. Van Dui- jvenbooden and H. G. Van Waegeningh, Eds., Vulnerability of Soil and Groundwater to Pollutions. Committee on Hydrogeological Research, Hague, 69-86.

Gabtni H., Jallouli K., Mickuse L., 2009, Deep structure and crustal configration of the Jeffara basin (Southern Tunisia) based on regional gravity, seismic reflection and borehole data: How to explain a gravity maximum within a large sedimentary basin? *J of Geodynamics*. 4: 142-152.

Gaubi E., 1988, Evolution de la piézométrie et de la géochimie de la nappe de Zeuss-Koutine. Tunis: Faculty of Science of Tunis, 63 pp.

Gogu R.C., Dassargues A., 2000, Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. *Environ Geol*., 39: 549–559.

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

Hamzaoui-Azaza F., Ketata M., Bouhlila, R., 2011, Hydrogeochemical characteristics and evaluation of drinking water quality in Zeuss-Koutine aquifer, south-eastern Tunisia: *Environ Monit and Assess*. 174: 283–298.

Hamzaoui-Azaza F., 2011, Géochimie et Modélisation des Nappes de Zeuss-Koutine, des Grès du Trias et du Miocène de Jorf Jerba-Zarzis. Department of Geology, University of Tunis El-Manar, Faculty of Science of Tunis, 262 pp.

Hiscock K.M., Lovett A.A., Brainard J.S., Parfitt J.P., 1995, Groundwater vulnerability assessment: two case studies using GIS methodology. *Q J of Eng Geol*., 28: 179–194.

Jiménez-Madrid A., Carrasco F., Martínez C., Gogu R.C., 2013, DRISTPI, a new groundwater vulnerability mapping method for use in karstic and non-karstic aquifers. *Q J of Eng Geol and Hydrogeol*., 46:245-255.

Jiménez-Madrid A., Carrasco F., Martínez C., Vernoux J.F., 2011, Comparative analysis of intrinsic groundwater vulnerability assessment methods for carbonate aquifers. Q J of Eng Geol and Hydrogeol. 44:361-371.

Khemmoudj K., Bendadouche H., Merabet S., 2014, Assessment of the vulnerability of an aquifer by DRASTIC and SINTACS methods: Aquifer of Bazer – Geult Zerga area (northeast Algeria). E3 Journal of Environmental Research and Management 5: 9. pp. 0169-0179.

Kumar S., Thirumalaivasan D., Radhakrishnan N., Mathew S., 2013, Groundwater vulnerability assessment using SINTACS model, Geomat, *Nat Hazards and Risk*, 4, 4: 339-354.

Leyland R.C., Witthuser K.T., 2010, VUKA: a modified COP vulnerability mapping method

for karst terrains in South Africa. *Q J of Eng Geol and Hydrogeol.*, 43: 107–116.

Lynchez S.D., Reynders A.G., Schulze R.E., 1994, Preparing input data for a national-scale groundwater vulnerability map of southern Africa. Document ESRI94. Strasbourg: ESRI.

Margat J., 1968. "Groundwater Vulnerability to Contamination," Bases de la Cartographie. Doc. 68 SGC 198 HYD, BRGM, Orleans.

Neshat A., Pradhan B., Dadras M., 2014, Groundwater vulnerability assessment using an improved DRASTIC method in GIS. Resour, *Conserv and Recycl.*, 86: 74–86.

OSS (Observatoire du Sahara et du Sahel), 2005, Etude hydrogéologique du système aquifère de la Djeffara tuniso-libyenne. Observatoire du Sahara et du Sahel, Tunisia, 209 pp.

Ouessar M., Taamallah H., Ouled Belgacem A., 2006, Un environnement soumis à des fortes contraintes climatiques. In: Genin D., Guillaume H., Ouessar M., Ouled Belgacem A., Romagny B., Sghaier M., Taamallah H. (eds). Entre la désertification et le développement: la Jeffara tunisienne. CERES, 2006, Tunis, pp: 23-32.

Saidi S., Bouri S., Ben Dhia H., 2010, Groundwater vulnerability and risk mapping of the Hajeb-jelma aquifer (Central Tunisia) using a GIS-based DRASTIC model. *Environ Earth Sci*. 59: 1579–1588.

Schnebelen N., Platel J.P., Le Nindre Y., 2002, Gestion des eaux souterraines en Aquitaine Année 5. Opération sectorielle. Protection de nappe de l'Oligocène en région bordelaise. (ERIC Document Reproduction Service No ED 98-01) 51178).

Sener E., Davraz A., 2013, Assessment of groundwater vulnerability based on a modified DRASTIC model, GIS and an analytic hierarchy process (AHP) method: the case of Egirdir Lake basin (Isparta, Turkey). *Hydrogeol J.*, 21: 701–714.

Taamallah H., 2003, Carte pédologique de la Jeffara. Rapport interne. [Soil Map of the Jeffara. Internal report]. Jeffara project, IRA/IRD, Tunis.

Van Stempvoort D., Ewert Wassenaar L.L., 1993, "Aquifer Vulnerability Index (AVI): A GIS Compatible Method for Groundwater Vulnerability Mapping". *Canadian Water Resour J.*, 18, 1: 25-37.

Yahyaoui H., 1998, Fluctuations piézométriques des principales nappes dans le gouvernorat de Medénine. DGRE-Tunis, 30pp.

Zwahlen F., 2004, (ed.): Vulnerability and risk mapping for the protection of carbonate (karst) aquifers. European Commission, Directorate – General for Research, European research area: structural aspects – COST 620, 279 pp.