Water Resour Manage (2010) 24:921–939
DOI 10.1007/s11269-009-9479-1

Groundwater Recharge Zone Mapping Using GIS-Based Multi-criteria Analysis: A Case Study in Central Tunisia (Maknassy Basin)

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Received: 24 November 2008 / Accepted: 3 July 2009 /

Abstract The groundwater recharge zone mapping often requires a large amount of spatial information and criteria. Geographic information systems are capable of managing large amount of spatially related information, providing the ability to integrate multiple layers of information for multi-criteria analysis. To show the capabilities of GIS techniques for mapping groundwater refill zone in arid area, a study was carried out in the Maknassy basin located in Central Tunisia. This evaluation incorporates historic rainfall data analysis, watershed drainage density, surficial geology and aquifer boundary conditions. The study basin is categorized according to the previous criteria. Multi-criteria analysis is performed to evaluate suitability to the groundwater recharge for each factor, according to its associated weight. The thematic layers were integrated with one another using the weighted aggregation method to derive the groundwater recharge map. The results demonstrated that the GIS methodology has good functionality for mapping groundwater recharge zone.

Keywords Arid area · Groundwater recharge ·
Geographical information systems (GIS) · Weighted segregation method

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1 Introduction

The depletion of groundwater levels is not a new account in Central Tunisia, but one that has continued for at least a decade, whilst annual water demand increase for agricultural and industrial activities. Added to the depletion of groundwater resources, the arid climate aggravates the situation. Even though these resources are scarce, the hydrogeologic system characterization and artificial recharging of aquifers might help to defeat the problem to some extent. The practice of artificial recharging is increasingly emerging as a powerful tool in water resources management (Ma and Spalding 1997). By constructing suitable types of artificial recharge structures, groundwater resources can be augmented (Başağaoğlu and Mariňo 1999). Many agencies have produced papers and reports on the depletion of groundwater levels in Tunisia and the need for artificial recharge of groundwater aquifers (Besbes et al. 1978; Mamou and Kassah 2000).

Surface and sub-surface hydrological features such as lithology, geological structure, drainage density, groundwater flow and boundary conditions of the aquifer system play an important role in groundwater replenishment. But through conventional methods, it is not an easy task to study the hydrogeological basin parameters to identify suitable area for artificial recharge, since many controlling parameters must be independently derived and integrated, which involves additional cost, time and manpower.

Many assessments of groundwater conditions made with remote sensing techniques have been reported (Krishnamurthy and Srinivas 1995; Bastiaansen et al. 1998; Venkata et al. 2008; Chowdary et al. 2009; Jasrotia et al. 2009). Geographic Information System (GIS) techniques have many advantages over older, improved georeferenced thematic map analysis and interpretations (Thapinta and Hudak 2003; Dixon 2005; Martin et al. 2005). Cowen (1988) defined GIS as a decision support system involving the integration of spatially referenced data in a problem solving environment. In addition, unlike conventional methods, GIS methods for demarcation of suitable areas for ground water replenishment are able to take into account the diversity of factors that control groundwater recharge. Thematic map integrated various features derived from data in a GIS environment (Krishnamurthy et al. 1996; Murthy 2000; Saraf and Choudhury 1998; Baker et al. 2001; Henry et al. 2007; Tabesh et al. 2009). However only a limited number of studies have taken the approach of specifically mapping potential artificial recharge zones, and as such there is no integrating of multi-criteria analysis using the weighted aggregation method, associated with GIS techniques to derive the groundwater recharge map. It is a new approach adopted for mapping groundwater recharge zones.

In recent years, a shift in groundwater resources management approaches from the traditional concept towards the new model using the geographical information system utilities can be recognized (Rowshon et al. 2009; Koch and Grünewald 2009; Al-Qudah and Abu-Jaber 2009). The GIS techniques applications in hydrogeological mapping can be almost divided into two parts: hydrological analysis (Patil et al. 2008; Naik et al. 2009) and water resources development (Wu et al. 2008; Chowdary et al. 2009) on the one hand and water quality (Mantzafleri et al. 2009) on the other.

2 Method

2.1 The Study Area

Maknassy basin is located in southern central Atlas of Tunisia (Fig. 1). It constitutes an individualized hydrogeological basin and is underlain by diverse geological formations (Fig. 1). It is edged by anticlines folds initiated during Miocene and Pleistocene compressive phases (Tanfous et al. 2005). Field geological observations allied to boring cuts surveys reveal that the district can be subdivided into three hydrogeological units, namely porous and two fissured formations. The porous formation consists of mio–plio–quaternary sands and gravels deposits that define phreatic aquifer, whereas the fissured formation made of karstic limestone and subdivided in two different unit forms the most interesting aquiferous water resources in this multi-layered aquifer system.

Because the economy of the region is agro-based, the significance of water availability and its management is very important. In order to create sufficient irrigation facilities, attention needs to be focused on groundwater, which is the only viable source of water in such arid area.

2.2 Multi-criteria Evaluation Framework and Geographical Information Management

2.2.1 Data Collection and Processing

One of the most important data to be identified, in groundwater refill study in such arid area, is the water resource to be added to the aquiferous system.

For the long-term average annual precipitation in the study area, Monthly rainfall has been recorded at six meteorological stations since 1971. To assess average water

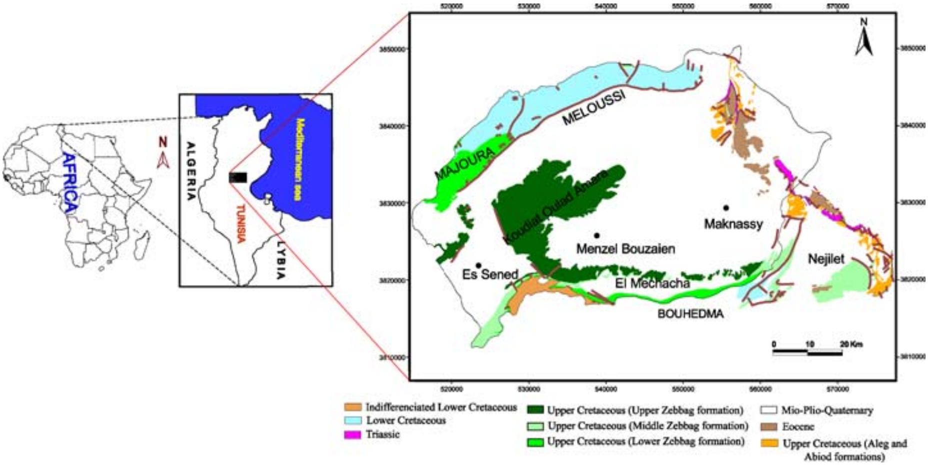

Fig. 1 The location of Maknassy basin with simplified geological map

rainfall, we interpolate precipitations data of the six considered stations during 36 years (from 1970 to 2006).

The Arithmetic average precipitations method consists in calculating arithmetic average precipitations recorded from 1970 until 2006. The rainfall is given by the following formula:

$$\mathrm{Pm} = (\mathrm{Pi})/\mathrm{N} \tag{1}$$

With:

Pm precipitation average,
Pi registered rainfall of every pluviometric station,
N number of pluviometric stations (N = 6),

$$\mathrm{Pm} = (204.7 + 205.5 + 207.25 + 210.2 + 211.5 + 213)/6 = 208.6\ \mathrm{mm}.$$

So rainfall on the hydrologic Maknassy basin is assessed to 208 mm.

To obtain an effective uniform depth of precipitation over the area, it is necessary to apply the Thiessen method (Kopec 1963). This method consists, firstly, in carving the topographic watershed according to the existing pluviometrics stations. After that, a controlled area is assigned to every station. The study basin watershed is subdivided on 6 shaped parts. The surface of each one is determines by planimetry (Fig. 2).

$$\begin{aligned}\mathrm{Pm} = {} & ((211.5\times 2180) + (213 \times 2025) + (207.25 \times 7200) + (205.5 \times 6500) \\ & + (210.2 \times 1750) + (204.7 \times 11200))/30875 = 206.8\ \mathrm{mm},\end{aligned}$$

Either Pm = 207 mm.

Arithmetic average precipitation practice and Thiessen method permit to get very near value. We will consider as value of rainfall the average value gotten by the two methods.

$$\mathrm{Pm} = 207\ \mathrm{mm}$$

In order to calculate the volume of precipitated water (Pw) on the watershed, the rate and area would be multiplied after the units were unified. For the Maknassy basin watershed, the volume of precipitated water would be:

$$\mathrm{Pw} = \text{Precipitation rate (m)} \times \text{Watershed area}\left(\mathrm{m}^2\right) \tag{2}$$

Therefore,

$$\mathrm{Pw} = \left(207/1000\right).\ 1235 \times 10^6 = 256.645 \times 10^6 \mathrm{m}^3 \mathrm{year}^{-1}$$

An integral portion of the above-noted volume of precipitated water falls in the form of rainfall.

Maknassy basin, located in Central Tunisia, has a typical Mediterranean arid climate with mild winters, long, hot, and dry summers, and short autumn and spring seasons. Climatic data (temperature, evaporation, humidity, wind velocity) have been recorded at four meteorological stations since 1984 by National Institute of Meteorology.

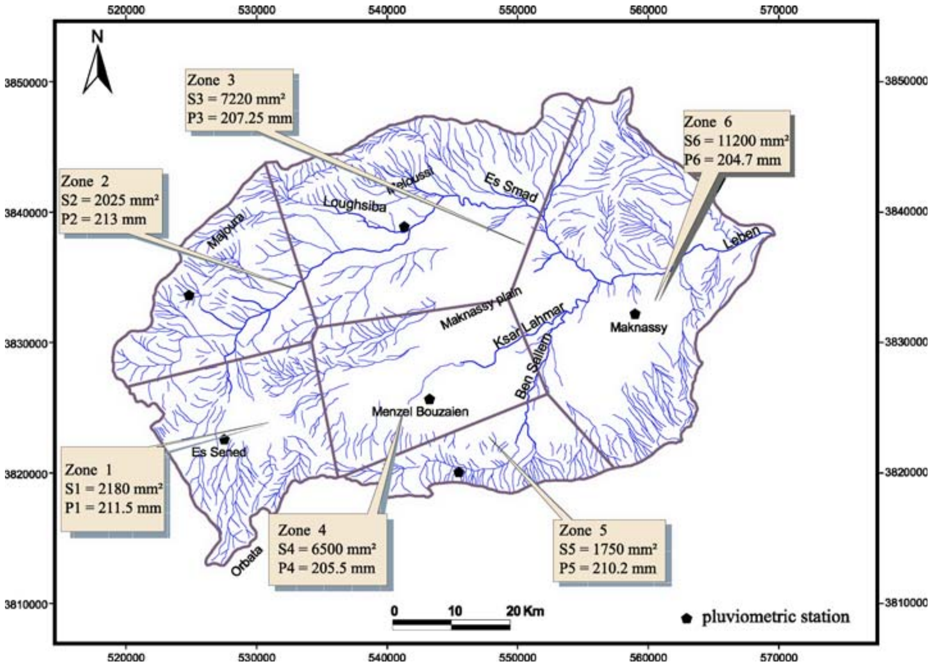

Fig. 2 Localisation map of hydrometric and pluviometric stations and Thiessen method zoning of Maknassy basin water shed (after Chenini et al. 2008)

The Maknassy basin is drained by three watercourses: Oued Leben, Oued Ben Sallem and Oued Ksar Lahmar (Fig. 2). Daily streamflow data is available from four gauging stations, although data collection at each began in different years.

Groundwater balance of Maknassy basin has been attempted in previous work (Chenini et al. 2008). The surface water dripping is estimated at 102.61×10^6 m^3 (40% of total annual rainfall). This aquifer system present a very meaningful recharge faculty (permeability, fracture) using the dripping waters partially mobilized (Chenini 2009).

In Maknassy basin, a historical data study of the rainfall and water balance (Chenini et al. 2008) shows that an important surface water resource of about 11×10^6 m^3/year is not yet totally managed. This important surface water resource motivates the study of the groundwater recharge in this arid region as an integrated water management to increase groundwater reserve and to avoid surface water losses.

Maknassy basin has been subdivided into watersheds. Drainage map and the drainage density map were established. Syntheses of structural acknowledgement, geological field observations and boring cuts correlations have been performed in studied area. These results allow us to specify aquiferous system structure. The orientations of the lineaments have been established. The potential hydrogeologic fractured levels were displayed in a map.

The hydrogeology of Maknassy basin is controlled by the geological setting, morphogenesis of the terrain, distribution of rainfall and the movement of groundwater. Field geological observations allied to boring cuts surveys reveal that the district can be subdivided into three hydrogeological units, namely porous and two fissured formations (Fig. 3).

Pumping tests help in delineating hydraulic characteristics of aquifers and determine boundary conditions (Xaviez et al. 1999). Thus several drawdown and recovery data sets were analyzed and interpreted. The Theis equation (1935), has been applied. Drawdowns vs. time are plotted on a semi_log graph where the slope for one logarithmic cycle (c) of the straight line and the pumping rate (Q) are used to calculate transmissivity using:

$$T = 0.183Q/c$$

The Theis method was applied for recovery data. Furthermore, step drawdown data interpretation based on the Cooper–Jacob graphical method, $s = BQ + CQ^2$, and Rorabaugh's method, $s = BQ + CQ^n$, led to the aquifer loss coefficient B and well loss coefficient C.

Results are presented in Table 1. The transmissivity values obtained reflect the variability of the thickness and the permeability of the aquifer levels. This variability is explained by the well location over the aquifer aerial extent. The important thickness of the phreatic aquifer in the central west part of the study area and the important porosity of the porous media elucidate the increase of the transmissivity. For the deep aquifer, the important thickness of the fractured formation is a possible origin of the transmissivity enhance. If the western Maknassy basin is highly fissured, then Transmissivity will tend to increase from east to west.

The goal of hydrogeologic mapping is to develop a conceptual model from the aquifer geometry and any recharge and barrier boundaries. The hydrogeologic characteristics of surficial materials were gathered. Pumping tests help in delineating quantitative hydraulic characteristics of aquifers. Piezometric map interpretations are accomplished to identify boundary conditions such as groundwater flow direction and presence of recharge or barrier boundaries.

2.2.2 Recharge Mapping Criteria and Weighting

For groundwater resources studies, GIS offers a spatial representation of complex hydrogeologic systems. GIS is capable of incorporating related spatial data into traditional water resources databases in order to present a more comprehensive view

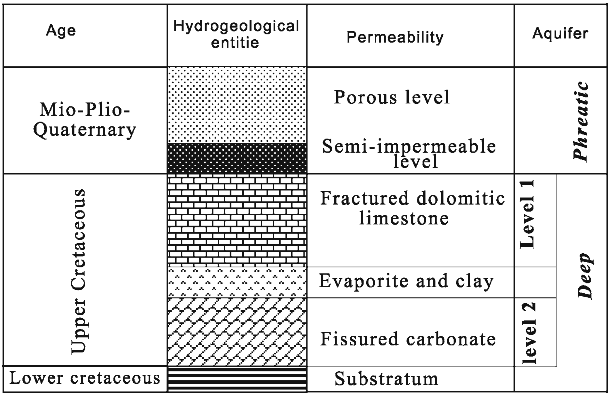

Fig. 3 Hydrogeological model of Maknassy multi layered aquifer system

Table 1 Pumping tests results for the Maknassy basin aquifer system

Well	Q (m^3/h)	B ($m^3h^{-1}10^{-1}$)	Well loss coefficient C	T drawdown (m^2/s)	T recovery (m^2/s^{-1})	Specific capacity ($m^3h^{-1}m^{-1}$)
Shallow aquifer						
1	38.4	0.0056	0.1 10^{-6}	2.4 10^{-3}		109.25
2	60.2	0.054	0.12 10^{-6}	1.5 10^{-3}	1.5 10^{-3}	112
3	18.4	0.036	0.089 10^{-6}	3.2 10^{-4}	3.7 10^{-4}	121.25
4	21.2	0.023	0.11 10^{-6}	2.9 10^{-2}	3.5 10^{-4}	205.3
5	25.2	0.025	0.09 10^{-6}	1.4 10^{-3}	6.5 10^{-4}	90.55
6	19.25	0.027	0.13 10^{-6}	1.5 10^{-3}	1.6 10^{-3}	84.3
7	31.2	0.07	0.075 10^{-6}	1.5 10^{-2}	4.3 10^{-3}	102.78
8	45.3	0.03	0.095 10^{-6}	1.6 10^{-3}	2.8 10^{-3}	89.75
9	50.3	0.042	0.08 10^{-6}	1.6 10^{-3}		115.34
10	23.5	0.022	0.13 10^{-6}	1.3 10^{-3}		120
11	21.67	0.017	0.12 10^{-6}	3.5 10^{-4}		107.45
Deep aquifer						
Level 1						
12	25.33	0.264	0.18 10^{-6}	5.7 10^{-3}	5.5 10^{-3}	109.22
13	43.5	0.0927	0.2 10^{-6}	3.3 10^{-2}		66.87
14	36	0.125	0.21 10^{-6}	1.25 10^{-2}		26.45
15	65.58	0.287	0.17 10^{-6}	4.95 10^{-2}	4.83 10^{-1}	125.22
16	20.1	0.0564	0.21 10^{-6}	1.25 10^{-2}		141.36
17	18.3	0.672	0.195 10^{-6}	3.1 10^{-4}	2.6 10^{-3}	85.45
18	64.6	0.721	0.23 10^{-6}	1.4 10^{-1}		260.3
19	12	0.425	0.2 10^{-6}	1.55 10^{-4}		111.21
20	29	0.312	0.19 10^{-6}	1.1 10^{-2}		25.45
Level 2						
21	48.57	0.628	0.25 10^{-6}	2.1 10^{-2}		59.6
22	30.5	0.282	0.3 10^{-6}	5.1 10^{-3}		113.82
23	42.5	0.335	0.27 10^{-6}	3.4 10^{-4}	3.6 10^{-4}	92.5
24	15	0.79	0.29 10^{-6}	3.5 10^{-4}		75.66
25	19	0.643	0.28 10^{-6}	1.1 10^{-3}	2.2 10^{-3}	89.2

of the target region (Fortes et al. 2005). This integrated view is developed by combining geographic, geologic, and hydrogeologic factors related to the groundwater resource study.

In the first phase of the work a number of thematic maps reflecting factors that directly influence the recharge of groundwater were prepared from data collected. Thematic maps established using GIS technique included: (1) watershed limit, (2) drainage, (3) drainage density, (4) lithology, (5) fractured outcrops, (6) lineament, (7) permeability, and (8) piezometry. The adopted reasoning is used to integrate and analyze the thematic maps and to prepare a map showing areas suitable for artificial recharge of groundwater. By superimposing the drainage network map onto this artificial recharge map and also by taking the outcrops lithology characteristics into consideration, the types of artificial recharge structures suitable for each of the zones were identified. The recharge structures consist of dams in serial disposition in the principle watercourse of the watershed. These structures dimension and orientation depend on the position in the hydrogeological system.

The method used in the study is shown in a flow chart (Fig. 4).

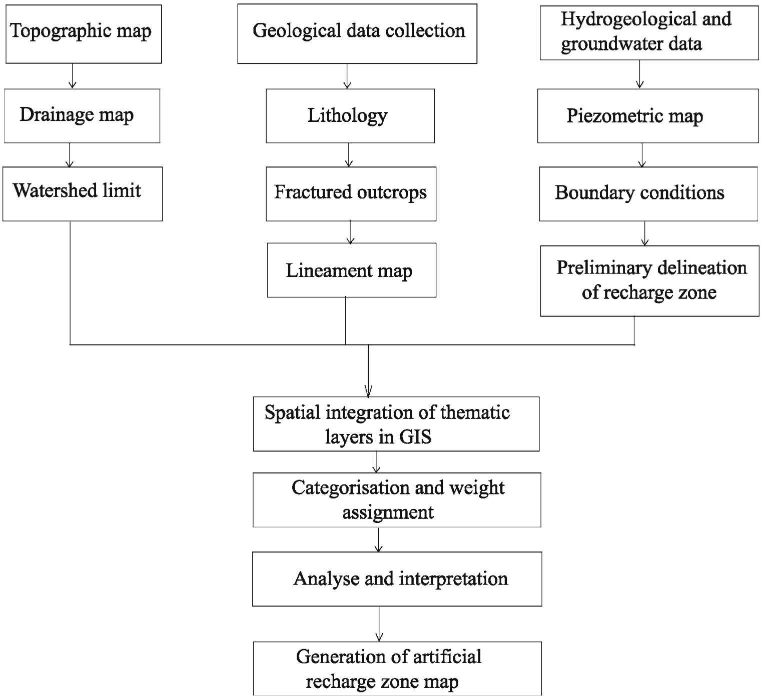

Fig. 4 Chart of the methodology adopted

3 Results and Discussion

3.1 Thematic Maps

Details of thematic maps relevant for demarcation of artificial recharge zones are given in the following subsections.

3.1.1 Watershed Limit and Drainage Density

Watershed limits are important surficial indicators in the search for suitable basin, since each one differs in its areal extent and its outlet. In our study, sub-basin superficies was considered as one of the prime indicators for selection of artificial recharge sites since it is directly related to the superficial water resource considered as the source of water used in artificial refill.

Figure 5 shows the drainage map of the study area with sub-basin demarcation; the drainage density map is given in Fig. 6. The drainage density values were grouped into five categories. In Maknassy Basin, as many as 34 sub-basins were delineated with an interbasinal area (Maknassy plain).

The drainage density, expressed in terms of length of channels per unit area (km/km^2) indicates an expression of the closeness of spacing of channels. It thus provides a quantitative measure of the average length of stream channels within different portions of the whole basin. Drainage density indirectly indicates its permeability and porosity due to its relationship with surface run-off (Krishnamurthy et al. 2000).

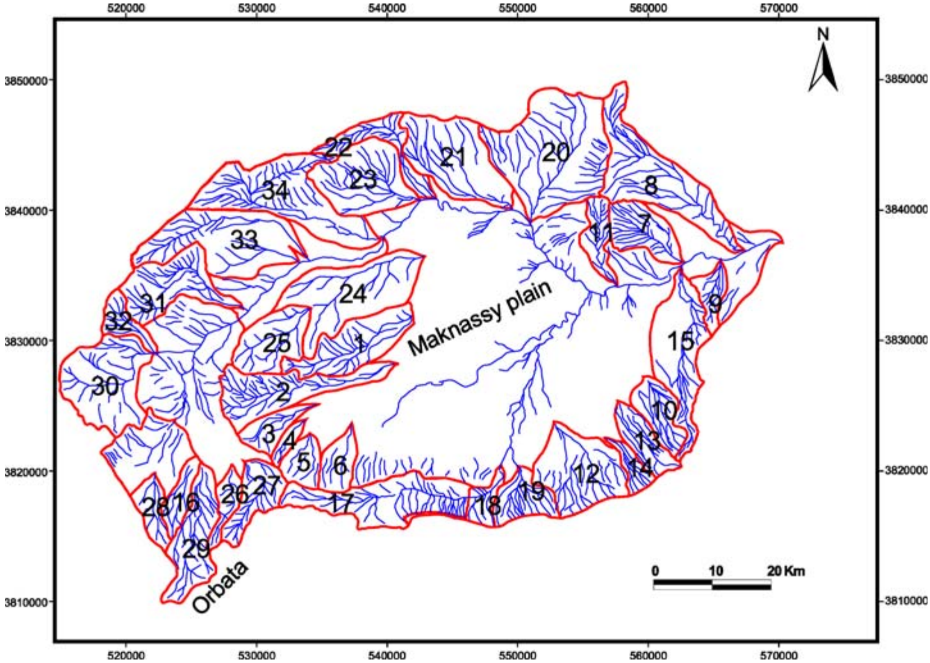

Fig. 5 Drainage map of the study area with sub-basin delineation

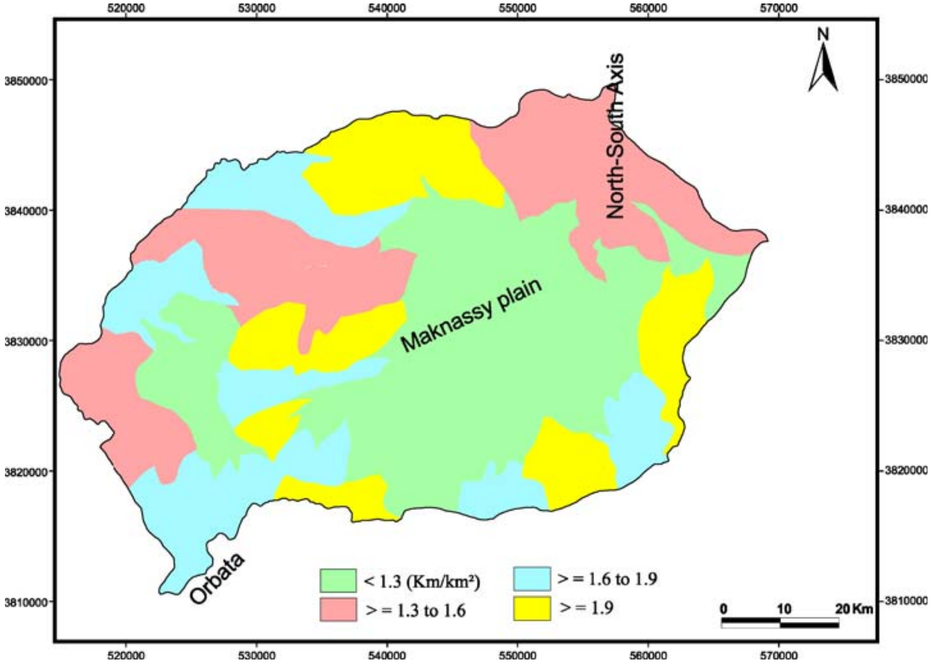

Fig. 6 Drainage density map of the study area

Areas with high drainage density values indicate high surface run-off, hence such areas are to be considered favorable for arresting excessive run-off (Krishnamurthy et al. 2000).

3.1.2 Lithology

The lithological map of the study area (Fig. 1) was prepared using published geological maps and from field observations. This map shows the important outcrops of the fracturated carbonates. Inside these units, the mio–plio–quaternary is heterogeneous because it is composed of sandstone and gravels in different granulometry. Cretaceous formations are all fractured at different scales.

Porous formations constitute the oldest continental quaternary deposits in the study area. The variation in the thickness of mio–plio–quaternary sands and gravels deposits is mainly because of uneven bedrock topography. The thickness of the phreatic aquifer increases eastward of the study area (Chenini 2009), but the aerial extent of this aquifer is restricted because of the mounds surrounding hydrogeological basin. A mean depth of this formation is about 65 m. The porosity of the shallow aquifer is 28% (Illy 1967).

The fractured formations, which occur in the major outcrops of hydrogeological Maknassy basin, have developed secondary porosity due to fracturing and jointing. The Late Zebbag Formation (Late albian–Late cenomanian) is made up by fissured carbonates. The Upper Zebbag Formation (Late Turonian) consists of fractured dolomitic limestone. The fractures and joints are conduits for the movement of groundwater and at the same time act as potential groundwater repositories. The fracture lineaments were identified and delineated with the help of intensive field observation, boring cuts correlations aided with seismic reflexion interpretations carried out in this area (Gasmi et al. 2006; Chenini 2009). A mean depth of the upper level is about 155 m, while the depth of the lower one is 285. The mean porosity of the fractured formation is about 15% (Illy 1967). Groundwater potential of these fractured hydrogeological units is important because of the important areal extent of these aquifers and a reduced exploitation.

3.1.3 Permeability

Permeability is one of the most important terms in studying hydrodynamic properties of porous and fractured media. Such a basic parameter must be well understood to establish with precision groundwater recharge structures sites for rational planning and efficient recharge. The permeability grade map of Maknassy basin is established while being based on the available local values from pumping tests and based on the common permeability value of sedimentary rock formation (Davis and DeWiest 1966). Figure 7 shows the permeability map of the study area. The most permeable zones are located in the outcrops of Mio–Plio–Quaternary porous deposits (3×10^{-2} m/s) and in the beds of watercourses (2×10^{-3} m/s). This map is superposed to the established map for suitable zone for groundwater recharge to test the efficiency of the operation and to recommend a good choice for the recharge structures sites.

3.1.4 Fractured Outcrops

Highly fractured rock columns hold the maximum amount of water and have the highest percolation rate. Consequently fractured zones are considered to be most

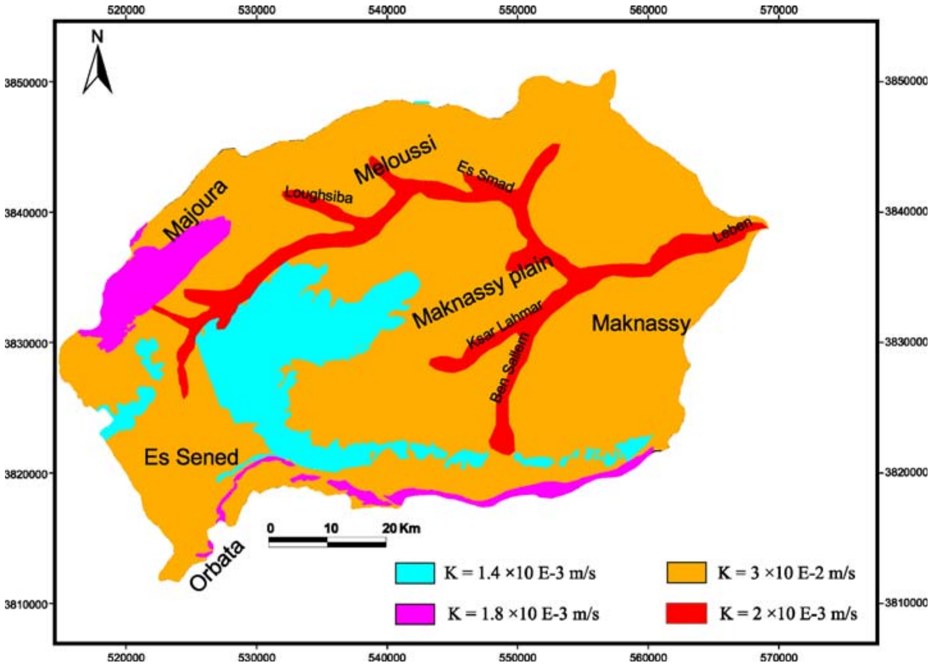

Fig. 7 Permeability map

suitable for artificial recharge. Therefore a contour map showing the fractured zone superposed to the structural map in the study area was constructed to improve the hydrogeological characterisation of outcropping formations (Fig. 8).

3.1.5 Lineaments

Associated to general geological structures in Maknassy basin, lineaments, which are linear or curvilinear features, can play a major role in identifying suitable sites for artificial recharge of groundwater because they reflect rock structures through which water can percolate (Fig. 8). Since areas around lineaments may play an important role in promoting recharge of water into the groundwater regime, a zone around each lineament was considered in our study.

3.1.6 Piezometry

In order to know his hydrogeologic aspect, we proceed by the interpretations of the three piezometric map related to the aquiferous levels and the coupling of the underground structure-flow to explain aquifers dynamics. According to the piezometric maps (Fig. 9), Maknassy basin aquiferous general flow makes from west to the east toward drainages axes constituted by Leben and Ben Sallem watercourse. Groundwater flow direction and recharge zone were demarcated according to the general aquifer hydrodynamic. The surrounding anticlines and lineaments (Fig. 8) are considered in interpretation the boundary conditions of the aquifers.

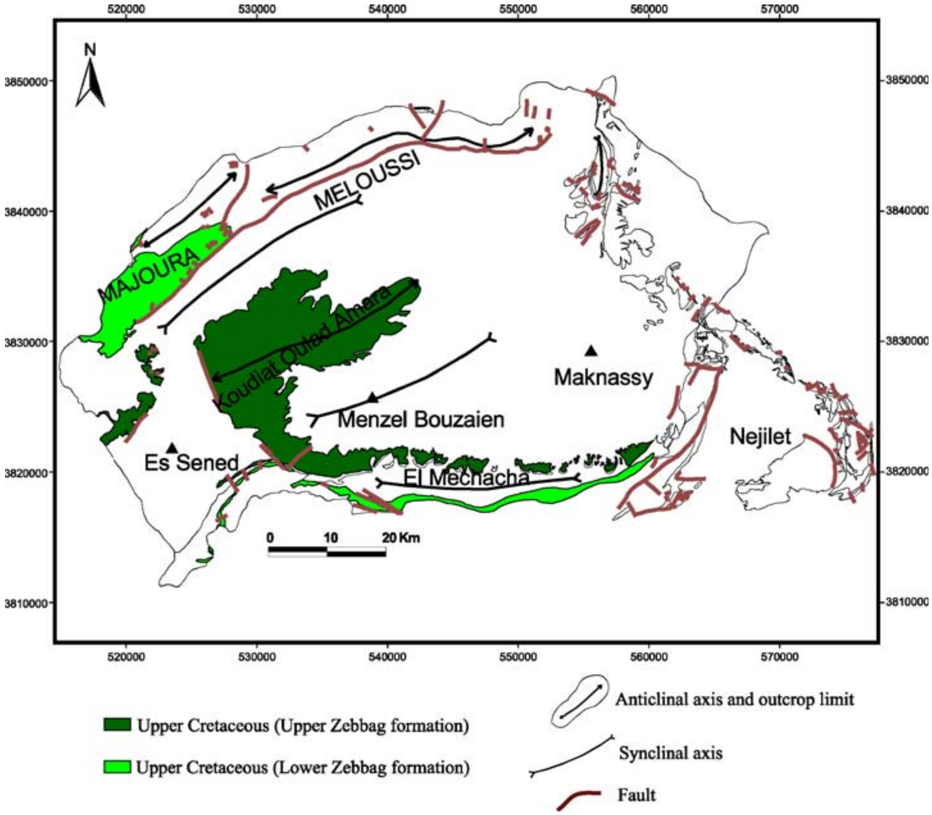

Fig. 8 Fractured and structural map of the study area

To demarcate areas suitable for artificial recharge of groundwater, a GIS based model was specifically developed for integrating and analyzing different thematic maps.

3.2 Categorization and Weight Assignment

Each polygon on each thematic layer was categorized according to its recharge characters as either (1) Excellent, (2) Very good, (3) Good, or (4) Poor. This categorization reflected thematic characteristics shown on the thematic map; it is based on the weight assigned.

The sub-basins limits layers described the section of thematic mapping were digitized. Different classes were weighted relative to their area importance in comparison to other classes in the same thematic layer. This categorization is based on the importance of the basin area and the surficial water resource available for artificial recharge of groundwater aquifers as shown in Table 2.

Drainage density indirectly indicates its permeability and porosity due to its relationship with surface run-off. Areas with high drainage density values indicate high surface run-off and higher permeability; hence such areas are to be considered favorable for arresting excessive run-off. Consequently infiltration toward aquifer

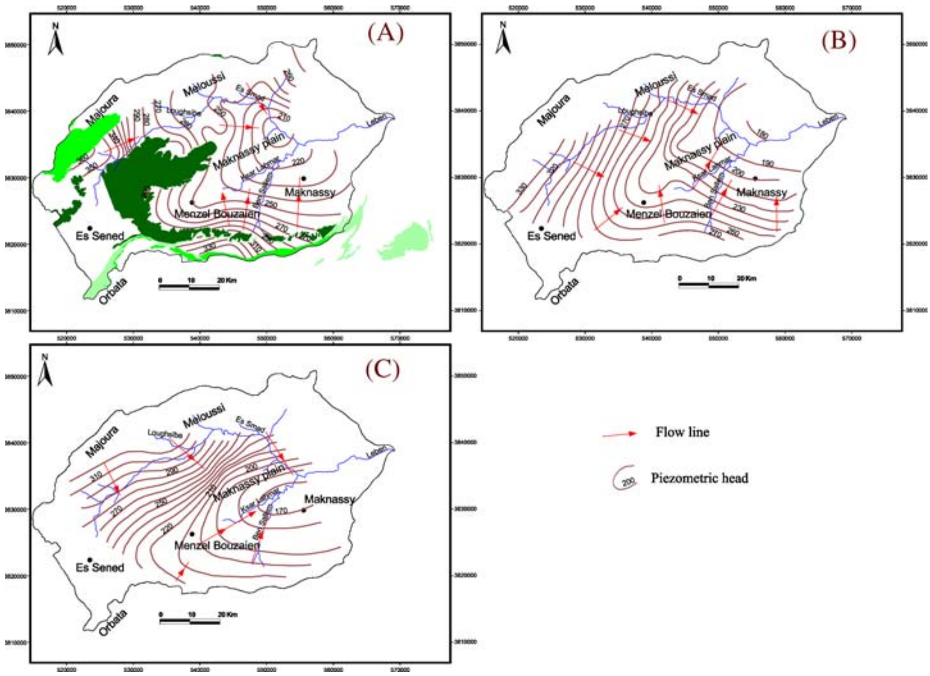

Fig. 9 The Maknassy basin aquifer piezometric maps for 2004. **a** Phreatic aquifer, **b** Upper Zebbag deep aquifer, **c** Lower Zebbag deep aquifer

outcrops in the watershed is significant. The basin no. 25 and no. 22 have the upper drainage density and are assigned 10 as weight regarding this parameter. The other sub-basins are weighted on the basis of the influence of these basins (Table 2).

After understanding their behaviour with respect to the available surficial water resource and drainage density, different sub-basin classes were weighted relative to the importance of potential hydrogeological level (porous media and fractured outcrops).

Table 3 summarizes the percentage of potential hydrogeological level in each sub-basin and relative weights assigned. On the other hand, in the aquiferous system, a maximum weight of 10 was assigned to sub-basins situated in aquiferous system recharge zone. Whereas, a weight of 0 was assigned to sub-basins located in the outlet part of the basin and there is no recharge (Table 3).

3.3 Integration of Thematic Layers

After categorization, all the thematic layers were integrated with one another by a GIS technique that uses the weighted aggregation method. In this method the total weights of the integrated polygons that were ultimately formed were derived as a sum or product of the weights that had been assigned to the different layers according to their suitability. The sequence followed to create the final integrated layers was:

In the first step, each two layers were integrated with one another. Theoretically this final layer should have a maximum value of 40 and a minimum value of 4, due

Table 2 Basin categorization using surface water resource and drainage density

Water resources weighting			Drainage density weighting	
Basin no.	Runoff (Mm^3/year)	Weight	Drainage density	Weight
1	2.8	4.72	1.93	9.74
2	3	5.06	1.71	8.63
3	1.42	2.4	1.95	9.84
4	0.92	1.5	1.91	9.64
5	1.36	2.3	1.72	8.68
6	1.44	2.44	1.81	9.14
7	2	3.37	1.32	6.66
8	4.13	6.98	1.51	7.62
9	1.08	1.8	1.9	9.59
10	2.76	4.6	1.78	8.98
11	1.44	2.4	1.5	7.58
12	2.69	4.55	1.96	9.89
13	1.08	1.82	1.69	8.53
14	0.64	1.08	1.75	8.83
15	1.14	1.93	1.93	9.74
16	1.93	3.27	1.83	9.24
17	2.16	3.64	1.97	9.94
18	1.14	1.92	1.65	8.33
19	1.08	1.82	1.73	8.73
20	5.92	10	1.42	7.17
21	3.72	6.35	1.93	9.74
22	1.88	3.17	1.98	10
23	3.24	5.45	1.97	9.94
24	3.94	6.66	1.56	7.80
25	2.32	3.91	1.98	10
26	1.28	2.16	1.65	8.33
27	1.91	3.22	1.85	9.34
28	4.16	7.02	1.82	9.19
29	2.52	4.25	1.75	8.83
30	3.6	6.08	1.5	7.57
31	1.48	2.5	1.7	8.58
32	1.24	2.09	1.82	9.19
33	2.64	4.4	1.68	8.48
34	4.48	7.56	1.7	8.58
35			1.28	6.46

to existing polygon combinations. The polygons of the final integrated layer were classed as either *excellent, good, fair and not suitable,* based on the weight ranges obtained from logical conditions that had been established. The way in which the upper and the lower limits of the weights were derived for demarcation of artificial recharge zones is given in Tables 4 and 5.

The areas which were categorized excellent for artificial recharge were delineated by grouping polygons that had weights between 31 and 26 in the final integrated layer. The theoretical upper limit is 40, if all the layers considered are categorized excellent. In the analysis presented in this paper a maximum weight of 30 was obtained due to the varying combination of polygons.

The good category artificial recharge zones involved polygons that had weights from 25.6 to 23. The upper weight limit was derived by adding layers categorized

Table 3 Weights according to sub-basins boundaries conditions and percentage of hydrogeological level outcrops

Basin no.	Phreatic aquifer		Deep aquifer upper level		Deep aquifer lower level	
	Weight (boundary conditions)	Weight (Percentage of outcrops)	Weight (boundary conditions)	Weight (Percentage of outcrops)	Weight (boundary conditions)	Weight (Percentage of outcrops)
1	0	0.7	10	9.3	0	0
2	0	1.8	10	8.2	0	0
3	0	1.3	10	8.7	0	0
4	0	2.4	10	7.6	0	0
5	0	3	10	7	0	0
6	10	5.7	10	4.3	0	0
7	0	3	0	0	0	0
8	0	6	0	1.5	0	0
9	0	7.4	0	0	0	0
10	0	7	0	1	0	0
11	0	4.5	0	0	0	0
12	10	6	0	1.5	10	2.5
13	10	6.6	0	1.4	10	1.7
14	10	5.4	10	1.7	10	2.1
15	10	5.6	10	3	0	1.3
16	10	6.7	0	1	0	1.8
17	10	5.3	0	0.5	10	2.7
18	10	7.3	0	1	0	1.2
19	10	5.2	0	1.2	10	3.3
20	10	6.1	0	0.3	0	0.5
21	10	5.7	0	0	0	0.6
22	0	1.8	0	0	0	0
23	0	5.8	0	0	0	0
24	0	7.1	10	2.9	0	0
25	0	0.4	10	9.6	0	0
26	10	6.3	0	1	0	0.7
27	10	7.5	0	0.6	0	0.8
28	10	10	0	0	0	0
29	10	5.6	0	0	0	0
30	10	6.3	0	1.2	10	2.5
31	0	5.4	0	0	10	4.6
32	0	1.3	0	0	10	8.7
33	0	2.2	0	0	0	0
34	0	3.5	0	0	0	0

Table 4 Total weight according to categories and thematic layers

Categories	Thematic layer				Total weights
	T1	T2	T3	T4	
Excellent	5.7	5.5	9.6	10	30.8
Very good	3.1	5	8	10	25.6
Good	2.5	4.5	5	10	22
Poor	0.6	3.6	0.5	0	4.7

Table 5 Final weight limit of each category

No.	Categories	Weight upper	Limits lower
1	Excellent	31	26
2	Good	25.6	23
3	Fair	22	5
4	Not suitable	4.7	

good in surficial water resource layer and boundary conditions layers and categorized very good in all other layers.

Fair artificial recharge zones were delineated by grouping polygons that had weights from 22 to 5. The upper value was derived by combining all layers categorized good.

The areas located in the eastern part of the basin, grouping polygons that had weights fewer than 4.7 (Table 5), were categorized not suitable. This limit was obtained by adding all least-values in all layers.

By utilizing the model discussed above, a map showing the artificial recharge zones of the study area was prepared (Fig. 10).

3.4 Discussion

The hydrogeologic model of Maknassy basin (Central Tunisia) (Fig. 3) used as an example in this research is previously explained and was validated in preceding

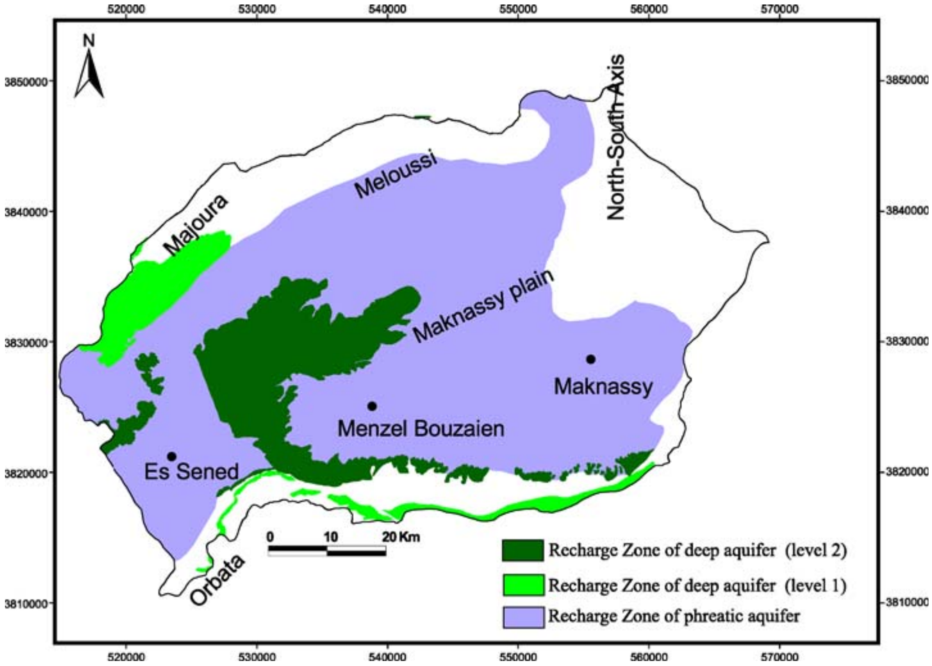

Fig. 10 Map of artificial recharge zones in the study area prepared using GIS techniques

studies (Chenini et al. 2008). Hydrogeological information system project, which is a GIS database regrouping all the considered layers, summarize the geometric features and boundary condition of the aquifer.

The methodology described above produced a multi-criteria scheme for the groundwater recharge area mapping within the study area located in arid region as reported in Fig. 4. Parameters considered in the selection of groundwater artificial recharge locations are diverse and complex. In this weighted aggregation method, no reasons were found to assign different weights to attributes at each step of layer combination and the importance of each criteria is not greater than the other. Further refinements of the considered criteria and the weight to be assigned in such a mapping procedure of groundwater recharge zone could easily be possible if such a method were adopted in alike arid area.

The study indicates that hydrodynamic conditions of the aquiferous system and availability of surface water resource are the major limitations for artificial groundwater recharge plans. The proximity of some fault which influences groundwater flow is considered as a limiting factor of artificial groundwater recharge. Besides this, outcrops of the deep aquifer levels are locally limited and the recharge area is restricted. The main cause of these limiting factors is essentially that Maknassy basin is located in the interference zone of two fold directions: NW–SE Gafsa fault direction and the north–south axis (Boutib and Zargouni 1998).

Integrating thematic layers using the weighted aggregation method in a GIS-based multi-criteria analysis is an easy applied approach that manipulates, simultaneously in a georeferenced maps, thematic layers reflecting factors that directly influence the groundwater recharge. In practice, it is unsuitable to give equal importance to each of the criteria being integrated. Thematic layers are weighted, depending on their relative participative aspect to the groundwater recharge.

4 Conclusion

Geographic information systems are useful tools for groundwater resources management by storing and manipulating the vast array of data that may be available in various formats. In order to demarcate artificial recharge zones, a methodology using the weighted aggregation method in a GIS-based multi-criteria analysis was used to map groundwater recharge zone in the Maknassy basin (Central Tunisia) for the purpose of improving groundwater resource.

The thematic layer linked to hydrological, lithological and hydrodynamic conditions of the study aquifer were prepared, classified, weighted and integrated in a georeferenced project using GIS utilities. The produced map shows the groundwater recharge area which is of great importance in planning artificial groundwater recharge using surface water as a integrative and participative aspect of water management.

Since the present approach was based on logical conditions and reasoning, the same process can be used elsewhere with appropriate modifications, especially in arid areas, where the occurrence of groundwater is more restricted with increasing of water conflicts. Finally, groundwater management requires that the study area must be further investigated in order to offer an accurate map because additional data improve the exactness of the groundwater recharge mapping.

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