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Identification of Suitable Sites for Groundwater Recharge Using the Boolean Model: Case Study: Sidi Bouzid Acquifers

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Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

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ABSTRACT

The scarcity of water can have harmful effects on human life. In addition, one noticeable issue humanity is faced with is managing water resources. This study aims at selecting the most suitable areas for groundwater artificial recharge using multi-criteria analysis. The fundamental element of this multi-criteria analysis is the choice of criteria that are the most sensitive part of the multi-criteria formulation of a decision problem. Such Criteria included: Slope, Soil Permeability, Soil Salinity, Depth of the Water table, Proximity to road networks, Proximity to the forest, proximity to wetlands, proximity to irrigation areas, proximity to urban areas, proximity to hydrographic networks, proximity to piezometer and borehole. Using Boolean Model, and in the GIS environment, the layers were produced and classified. The results suggested that the area's most suitable are equal to 12.1%. Also, use of the land had an impact on the removal of restrictions of artificial recharge areas. It could be claimed that 5.5% of the studied area were considered suitable for artificial recharge in Boolean logic using land-use filtering.

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Keywords: Boolean model; artificial recharge; combining layers; Sidi Bouzid aquifers.

1. INTRODUCTION

The Sidi Bouzid region corresponds to a large hydrogeological basin classified as one of the first water reservoirs in Tunisia. The high availability and the good quality of water resources have made the Sidi Bouzid region one of the first agricultural areas in the country. In fact, most economic activities are agricultural [1]. Among these agricultural activities are 75 of olive mills, 29 livestock feed processing centers, 13 storage refrigerators for agricultural products, 10 cereals depots, 9 forest nurseries, 15 milk collection center [1].

Agricultural development, in this region, is very important in particular that of legumes, particularly tomato which production is one of the most important in the country for both local consumption and export. The development of these activities comes at the expense of the availability of abundant and good quality water reserves. However, the rapid increase in water demand in this region, to meet these needs, has led to intensive use of groundwater (deep and phreatic acquifers).

On the other hand, water resources management in Sidi Bouzid region is proving increasingly difficult, since the supply-demand balances is expected to be negative shortly. For this reason, we need to think about an integrated management program for this resource, with a focus on controlling water demand.

The low rate of surface water mobilization (42.7%), despite the large number of projects carried out under the national strategy for water and soil conservation, Depletion of groundwater (continuous significant drawdown), excavation of surface wells and exploitation of deep water, Lack of groundwater recharge strategy, Exploitation of the groundwater by illegal boreholes, either in the safeguard and prohibition zones or in over-exploited zones, Significant use of water in traditional agriculture and lack of water valorization or orientation to other activities that can relieve water resource, Low integration of economic activities which could support agricultural activity, the whole thing could drive us to find solutions such as groundwater artificial recharge.

Groundwater recharge is a term used to explain the process of water moving downward from the surface or injecting it by an injection well into the saturated zone. Groundwater recharge occurs in nature by precipitation and infiltration originating from streams, lakes and other natural water bodies [2]. A typical natural recharge in humid climates is 30-50% of precipitation. This percentage goes down to 10-20% in Mediterranean climates and to 0-2% in dry climates [3].

Groundwater management is essential, in the sense that it regulates artificial recharge of aquifers by way of increasing the supply of groundwater. Artificial recharge is augmenting the amount of groundwater through human efforts to increase percolation of surface water into groundwater aquifers. Several artificial recharge methods such as recharge pitting, percolation ponding, flood spreading, induced recharging, and construction of well batteries have been proved to be of ultimate benefit globally [4,5].

Before undertaking a recharge scheme, it is paramount to assess the availability of adequate water sources for recharge. Treating wastewater (also called reclaimed water) can be a substitute for the aquifer recharge-related water sources [6]. As maintained by Bouwer [7], it is advantageous to use reclaimed wastewater for aquifer artificial recharge. A study carried out by Yuan et al. [8] considered managed aquifer recharge with reclaimed water. Several case studies about the safe use of wastewater from around the world were reported by Hettiarachchi and Ardakanian [9].

This approach aims at making the best reuse of wastewater for the sake of a well-thought-of groundwater augmentation for a wide variety of profitable uses.

Among principal profitable uses of groundwater are municipal and industrial water supply and agricultural irrigation. Mekni and Souissi [10] showed the effects of the utilization of treated wastewater for artificial recharge in combating seawater of Korba-El Mida aquifer, Cap Bon, Tunisia. Their results showed a decrease in groundwater salinity around the recharge area [10].

It is also possible to artificially recharge groundwater. To this end, reclaimed water is now refined through what can be called soil aquifer treatment or purification. Water gets polished as it moves through soils and aquifers [11]. Needless to say that there is a need to use a systematic scientific approach based on critical control points to ensure that no adverse effects on human health are caused by the use of reclaimed water for aquifer recharge. Some of the concerns are mainly about trace compounds, heavy metals and pathogens when domestic wastewater is involved [12].

For an effective recharge, which hinges on a number of parameters that must be analyzed together, suitable sites are to be selected for the best application of the appropriate artificial recharge techniques.

One needs to point out, however, that it is time-consuming and not a so easy undertaking to apply traditional data processing methods to select the most appropriate sites for artificial groundwater recharge. One reason for this is that data is both bulky and usually needs to be integrated. Such massive and complex data could be organized, processed and analyzed by geographic information systems.

One advantage of the use of geographic information system (GIS) is that it allows for easy integration of various layers of information, such as geology, topography and hydrology, in order to generate a better site selection prediction. In addition, remote sensing (RS) is considered cost-effective and also time-effective assessing and monitoring the conservation of groundwater resources, given the spectral, spatial and temporal availability of data covering a large and inaccessible area within a short time. Sener et al. [13] makes the point that an effective identification of the earth surface characteristics (like geology and lineaments) and examination of groundwater recharge can be done by using RS.

It is of paramount importance to find out the best sites for groundwater artificial recharge. This is at the very basis of guaranteeing accuracy and time-effectiveness. For this purpose, eleven factors of Slope, Soil Permeability, Soil Salinity, Depth of the Water table, Proximity to road networks, Proximity to forest, proximity to wetlands, proximity to irrigation areas, proximity to urban areas, proximity to hydrographic networks, proximity to piezometer and borehole were investigated.

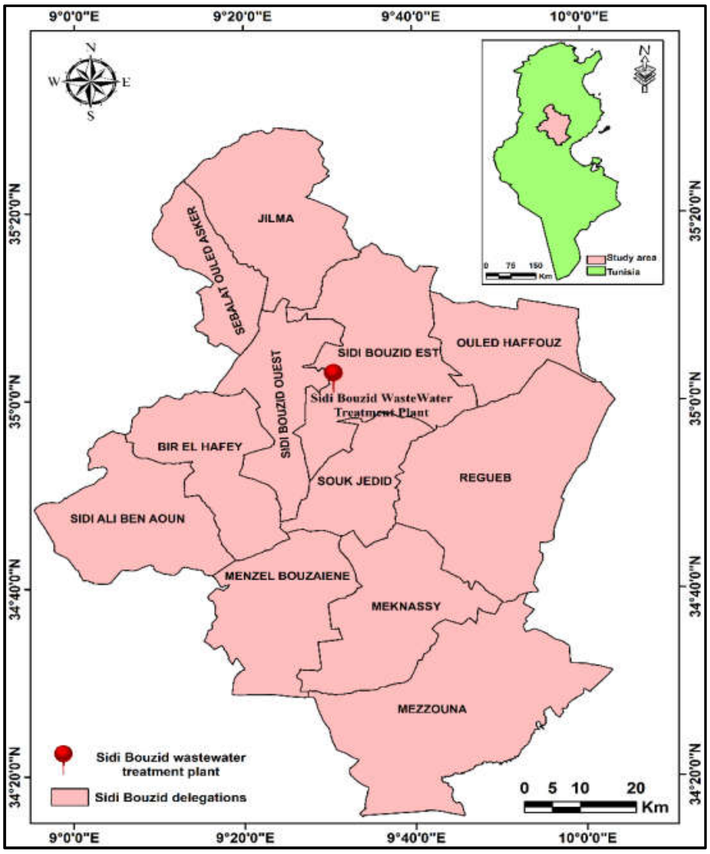

Fig. 1. Location of Study area

2. STUDY AREA

The area studied is in the Sidi Bouzid governorate, located in the center of Tunisia, between 08° 55’ 19’ E and 10° 13’ 36’ E longitude and 34° 16’ 53’ N and 35° 28’ 40’ N latitude (Fig. 1). Its total area is 9376 km2, the topography of the region lies between 50 and 1350 m above the sea level.

Its perimeter is 487 Km with an estimated population size in 2014 at approximately 419 912 thousand. The governorate of Sidi Bouzid is composed of twelve delegation (Fig. 1) and contains a wastewater treatment plant (Fig. 1).

The region’s annual rainfall ranges from 200 mm and 350 mm in dry and wet years, respectively. The long term average temperature and annual rainfall are 20ºC and 300 mm respectively.

The water resources of the hydrogeological basins in the Sidi Bouzid region are considered among the most considerable in central Tunisia. They are used for irrigation and for drinking even in neighbouring regions. These resources are divided into eight major hydrogeological basins (Hajeb Jilma bassin, Sidi Bouzid bassin, Oued El Hajal bassin, Sebkhat El Bhira bassin, Horchane – Braga bassin, Maknassy bassin, Regueb bassin and Sebkhat Noual bassin) (Fig. 2). Each of these basins contains several aquifers: phreatic aquifers and deep aquifers. This study concerns only the phreatic aquifers.

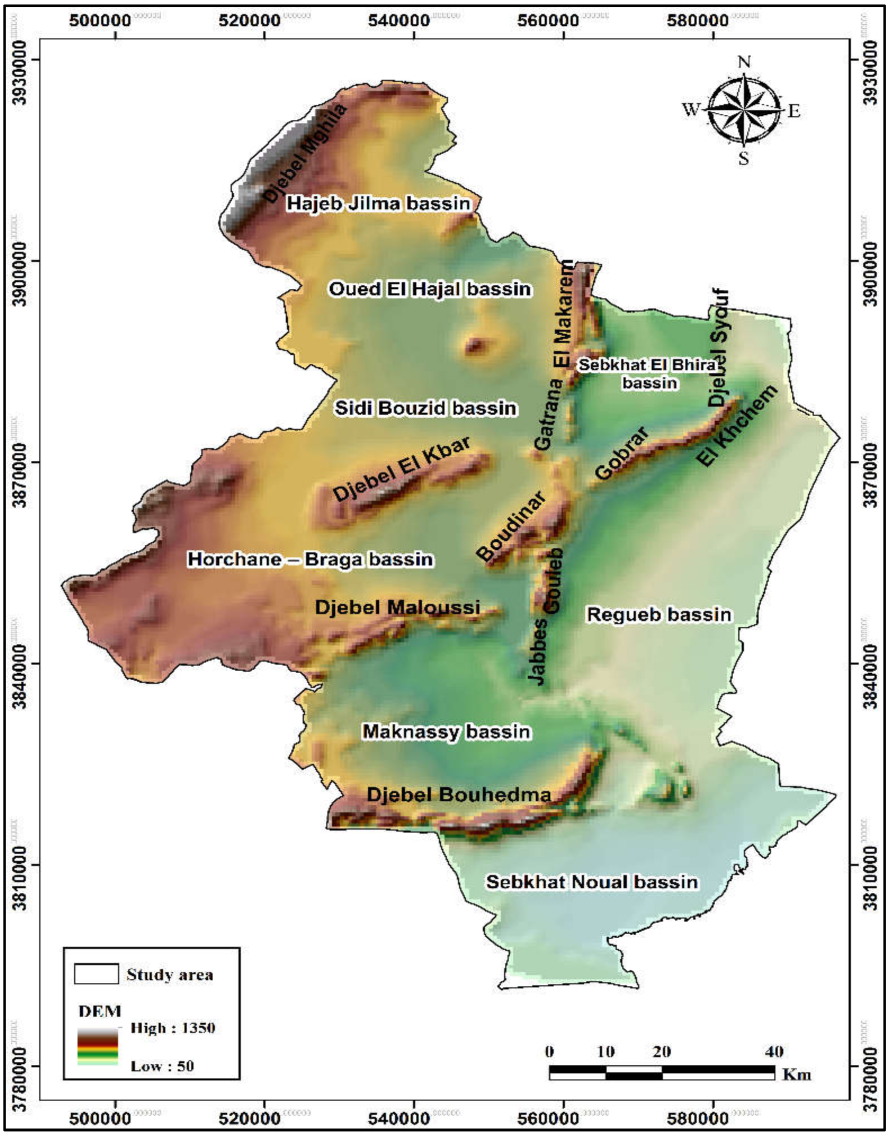

Fig. 2. Hydrogeological basins in Study area

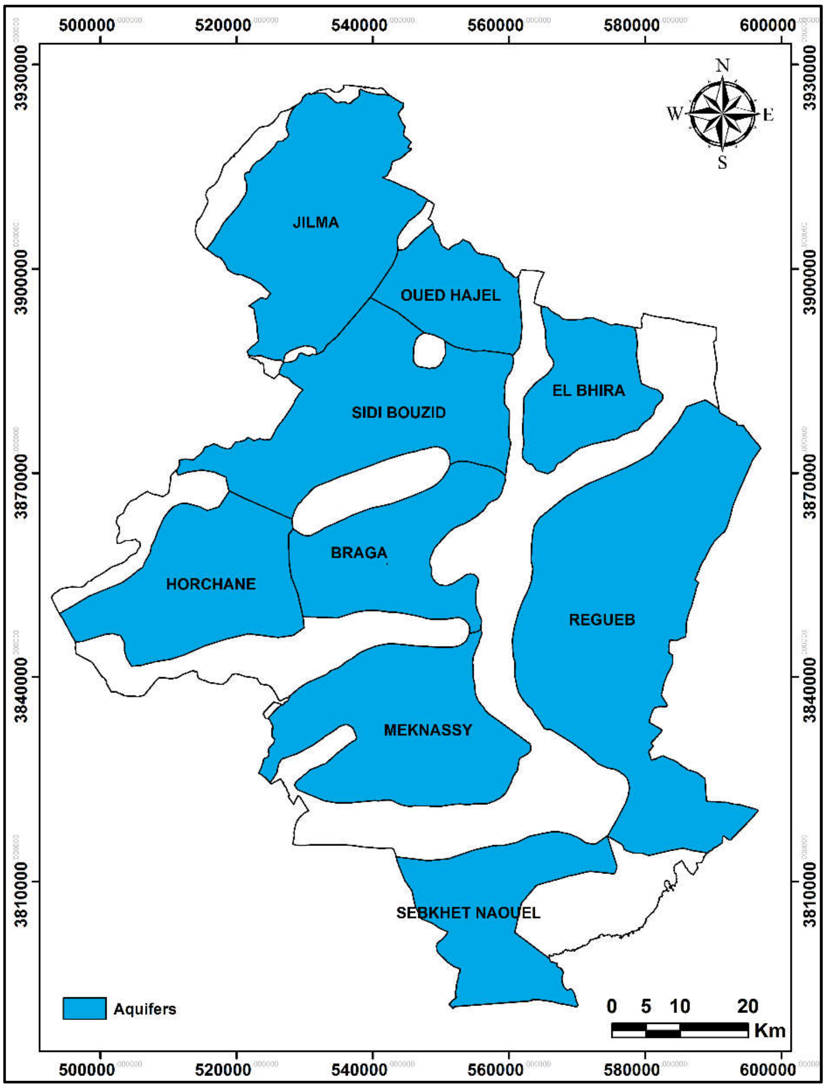

Fig. 3. Aquifers in study area

The area studied contains eight important phreatic acquifers: Sidi Bouzid, Hajeb Jilma, Braga, Maknassy, Oued El Hajal, Regueb, Sebkhat Noual and Sebkhat El Bhira (Fig. 3) [14] of Sidi Bouzid governorate, 2018). These acquifers are formed mainly by sandy deposits.

The aquifers known for their very high exploitation rates are those of Sidi Bouzid, Braga, Hajeb Jilma, Regueb and Maknassy. They are subject to an exploitation rate which is certainly becoming worrisome nowadays. The other aquifers are under low exploitation because of the high salinity of the water like Sebkhat Noual, Sebkhat El Bhira and Oued El Hajal.

This work seeks to identify potential sites for groundwater recharge of the Sidi Bouzid aquifers with reclaimed water of the Sidi Bouzid wastewater treatment plant that located in Sidi Bouzid East (Fig. 1). For an identification of the most suitable site and the creation of a suitability map, multi-criteria analysis needs to be integrated into a GIS. Multi-criteria analysis combines appropriate technical, economic, social and environmental criteria. GIS provides a spatial analysis, taking into consideration such criteria and provides a site suitability map.

3. MATERIALS AND METHODS

A number of factors need to be considered to determine the extent to which particular sites can be best suited for artificial recharge. Given that data is bulky needs to be integrate, it is difficult and time-consuming to apply any data processing methods which are considered traditional in order to select the best suited sites for artificial groundwater recharge. Therefore, GIS seems to be a much more reliable system as it helps developing the different thematic layers information and then integrating them- all with accuracy time-effectiveness. Therefore, the analysis in focus hinges on the application of such methods.

For a successful localization of the most suitable areas for artificial groundwater recharge, we considered the following factors: Slope, Soil Permeability, Soil Salinity, Depth of the Water table, Proximity to road networks, Proximity to forest, proximity to wetlands, proximity to irrigation areas, proximity to urban areas, proximity to hydrographic networks, proximity to piezometer and borehole. Such factors were considered main factors. Land use, however, was considered a filter.

For this purpose, existing maps and data sets were used to prepare different thematic maps. The thematic layers for the above parameters were prepared with the use of GIS software. These layers were overlaid using Boolean Logic.

Boolean Logic Model is basically governed by binary maps logical combinations through conditional operators- each with an input map (evidence) constituting a layer [15]. Zero and one are the two digits upon which layers weighting on Boolean model are based. The layers evidence is for the purpose of supporting a hypothesis, or a proposition. Each unit area is assigned only one value, either zero or one, and this specifies if it is satisfactory or not [16]. AND, OR, and NOT are the three most commonly used Boolean operators. Based on set theory, commons are extracted by AND and subsets are dealt with by OR. In Boolean logic, the areas containing both conditions are indicated by an AND operator between two information layers. As for places that contain either of the conditions, they are found by an OR operator. The conditions are negated by a NOT operator [17]. The AND Boolean operator is focused upon in this study.

In the following we define, for each parameter, the suitable range for artificial groundwater recharge, with reference to previous studies and expert opinion.

3.1 Slope

Factors like runoff, erosion, material transportation and permeability are controlled by this parameter. Topographic maps of the region were used to develop a slope map using the Digital Elevation Model.

The slope of the terrain is a key parameter according to which the flow of water is either slowed down (in case of less slow) or accelerated (in case of high slope) and this affects recharge [18].

The slope map was classified into 7 zones of slopes (Fig. 4). The infiltration site should be rigorously constructed with slope values less than 12% according to Pedro [6] and average slopes less than 15% according to Anane [19]. In this study, a slope of 15% was considered the maximum slope for the choice of artificial groundwater recharge sites.

It was found that areas falling in < 3% slope were the most favorable, among the 7 slope zones, for recharge. The remaining areas, however, were considered unfavorable zones and GIS database was generated.

3.2 Soil Permeability

Soil map used in this studied area was obtained from CRDA Sidi Bouzid. The studied area is characterized by three types of soil: sand, sandy loamy and loamy.

These soil types control the porosity and imperviousness of the terrain. Artificial recharge sites should be located in permeable areas for two main reasons: first to obtain high infiltration rates, and second to improve the process of removing trace organics, nutrients, heavy metals and pathogens [20,11,21]. Higher infiltration rate plays an important role in increasing of recharge volume per day. Recharge areas should not have layers of soil, such as clay, which may restrict water movement and form perched groundwater hills.

The favorable areas selected for artificial discharge were the sand and sandy loomy, due to their porosity. Other areas were considered unfavorable. These two polygon classes were delineated through the generation of the vector-based GIS database (Fig. 5).

3.3 Soil Salinity

Soil salinity should be as low as possible to avoid deterioration of groundwater quality. In our case, we will look at halomorphic soils and non-saline soils [20] (Fig. 6).

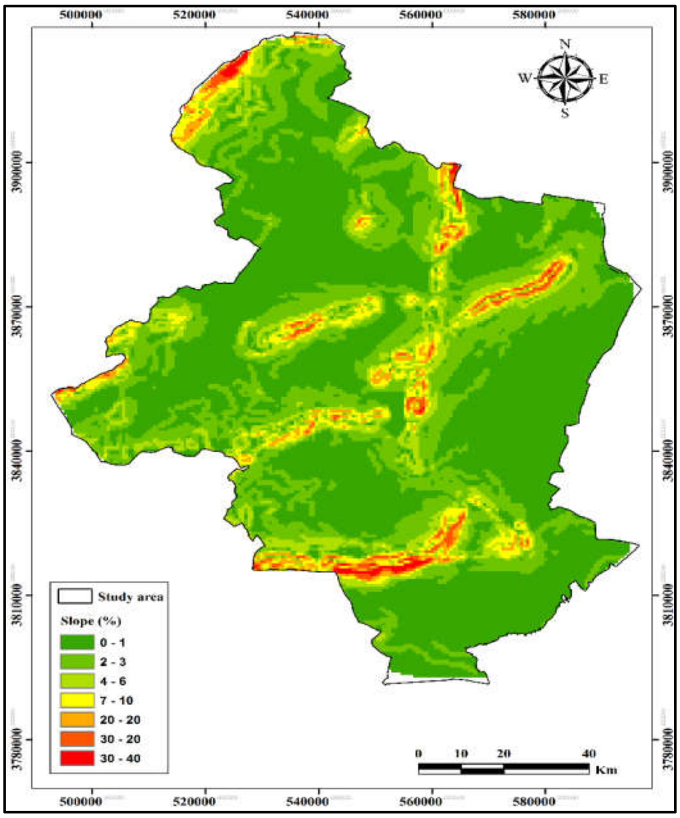

Fig. 4. Slope of the study area

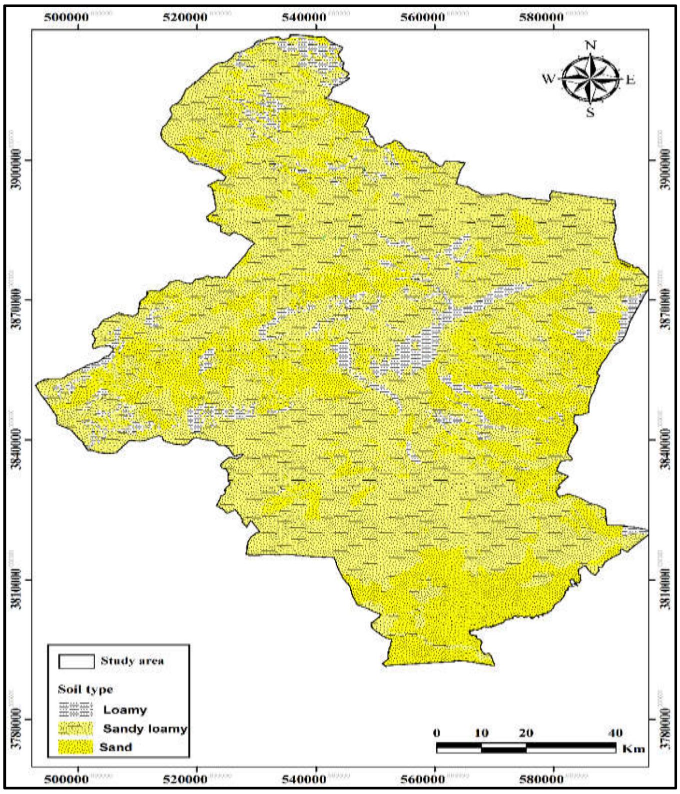

Fig. 5. Soil permeability in the study area

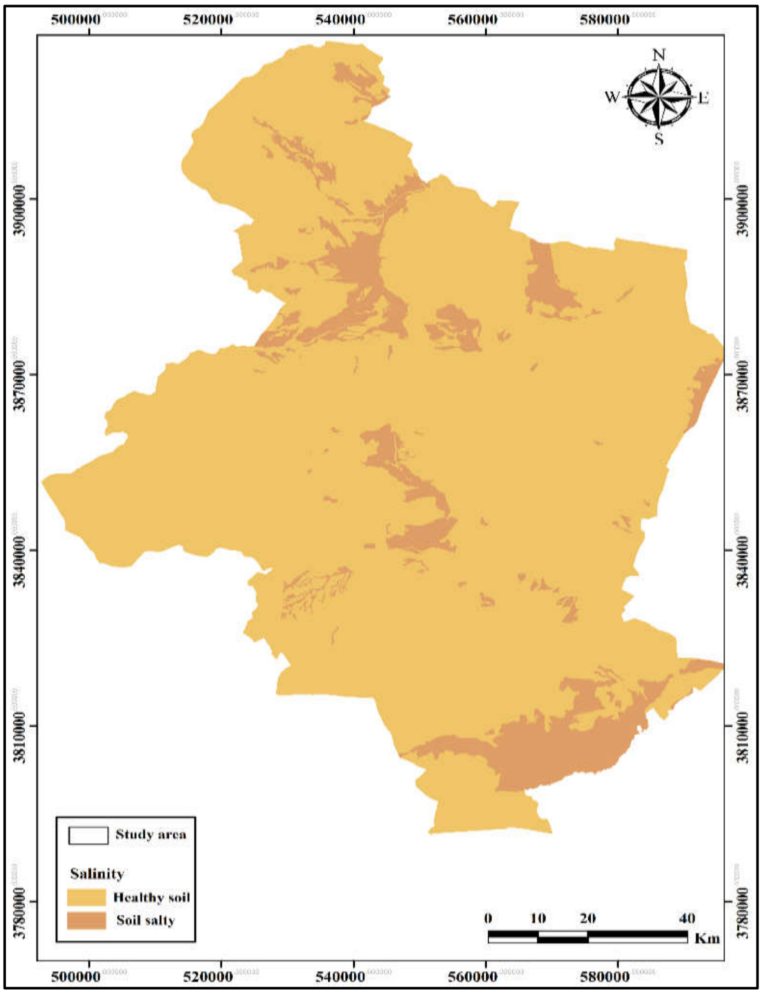

Fig. 6. Soil salinity in the study area

3.4 Depth of the Water Table

It is necessary for aquifers to be deep enough. This would prevent any possible rises of groundwater table caused by infiltration. 5m is the minimum static groundwater level accepted for reclaimed water infiltration. The reason is that a final purification requires having a sufficient vadose zone [22,23].

The CRDA, Sidi Bouzid collects, on a monthly basis, water level data from the already identified observation wells (Fig. 7) for the period of 2018 and maintains the same in their archives. These values were interpolated and the map shows that the groundwater level ranges from 3 to 66 meters (Fig. 8). The zones where groundwater level was deeper than 5 m [22,23,6,11] were considered suited for recharge. One reason is that comparatively deeper water level zones, only water can get stored to improve the infiltration of recovered water and to avoid groundwater contamination. Acoordingly, spatial GIS database was generated to show the favorable zones of deeper levels and the shallow and unfavorable water zones.

3.5 Proximity to Roads

Proximity of recharging sites to road helps when maintenance for recharging equipment is needed. As such, sites which are more than 50 m from roads were not included in this study Ribeiro et al.; Pedro et al. [24,11] used a distance of 50 m for roads, while Anane et al. [19] used a distance of 200 m. The road network in the region includes highways, main roads, and secondary roads and tracks (Fig. 9). Considering the enormous cost of transport, a distance of 50 m at roads was chosen as favorable areas for recharge.

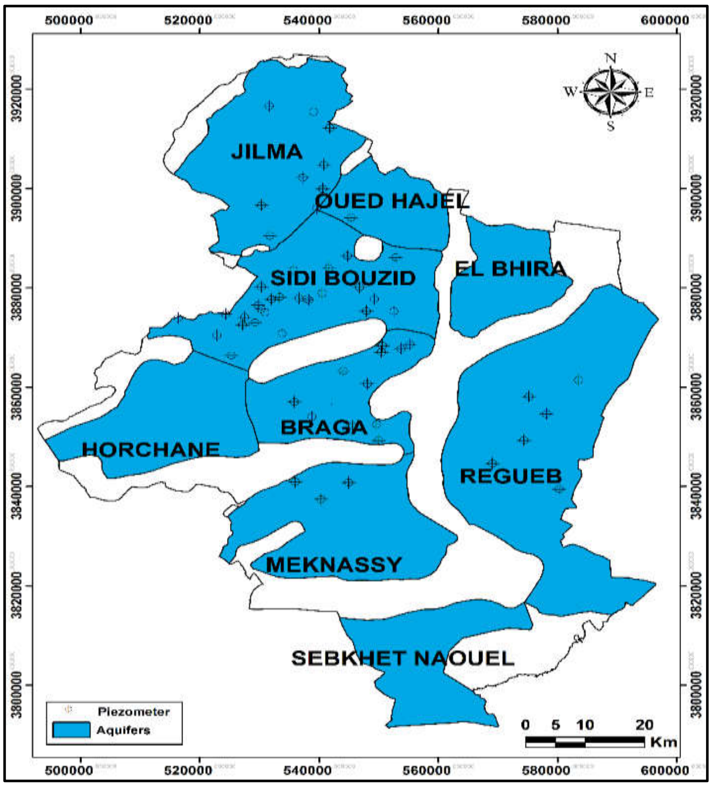

Fig. 7. Observation wells in the study area

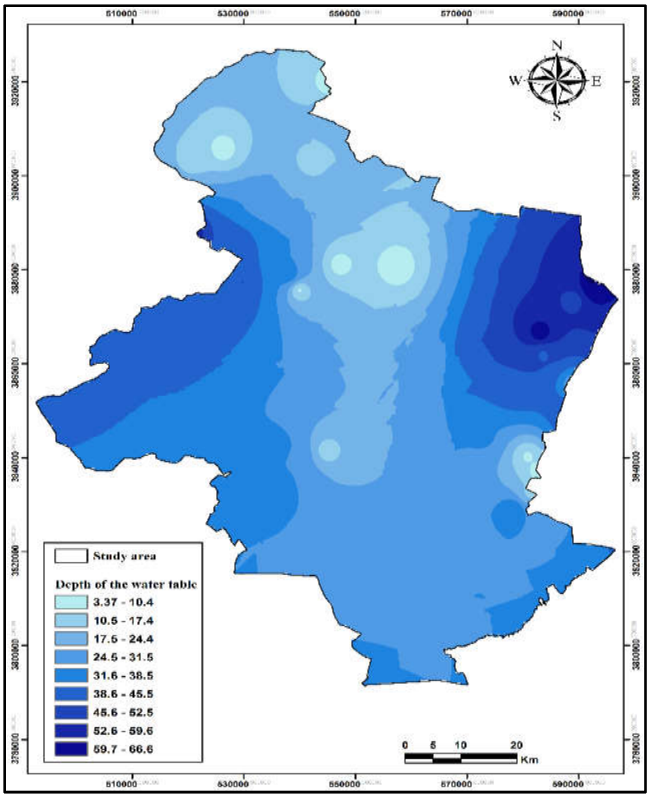

Fig. 8. Depth of the Water table in the study area

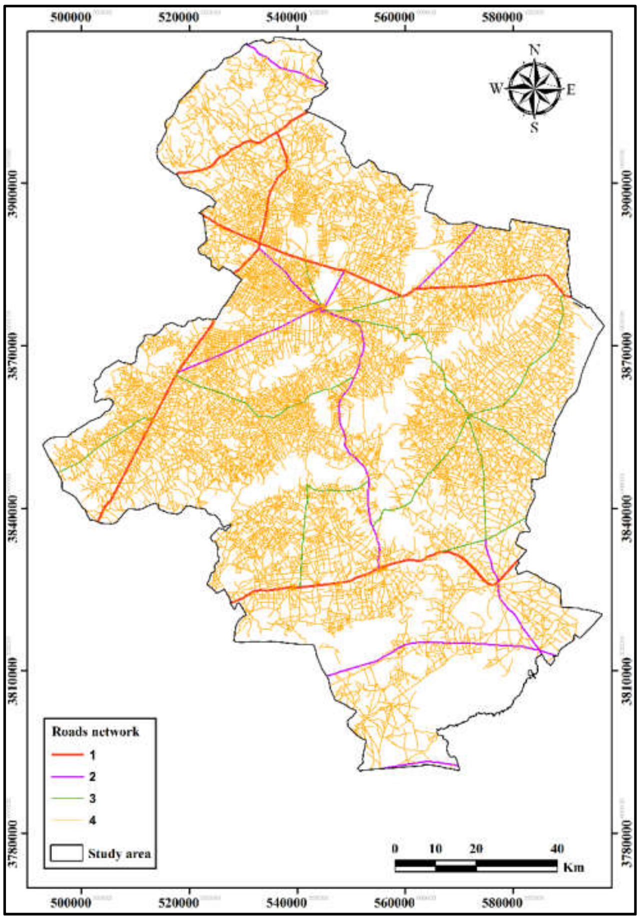

Fig. 9. The road network in the study area

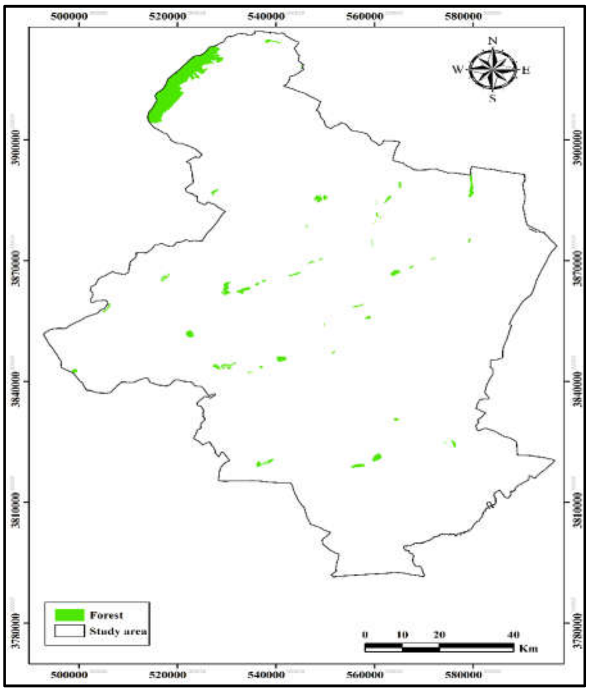

Fig. 10. The forest in the study area

3.6 Proximity to Forest

Artificial groundwater recharge sites should not be near the forest (Fig. 10). A buffer of 1000 m was selected as suitable for artificial recharge leaving remaining distance as unfavorable.

3.7 Proximity to Wetland

Artificial groundwater recharge sites must not be near the wetlands (lakes or sebkha) (Fig. 11). A buffer of 1000 m was chosen for the study area.

3.8 Proximity to Irrigation Canal

The artificial groundwater recharge sites must be away from irrigation canal (Fig. 12) with a buffer distance of 100 m to be protected from the contamination of wastewater treated by infiltration [25].

3.9 Proximity to Urban Zone

The urban areas (Fig. 13) must be far from the artificial groundwater recharge sites. Ahmadi et al. [26] proposed a buffer area of 400 m around residential areas and a buffer area of 600 m around airport. In the studied area, a buffer area of 500 m was defined. The objective was for the reclaimed water not to be in contact with population and livestock.

3.10 Proximity to Hydrographic Network

Artificial recharge constructions should be built in areas that are at the appropriate distance from the streams (Fig. 14). If this distance is long, it is not economical and if it is short, then injected water is drainage into river [27].

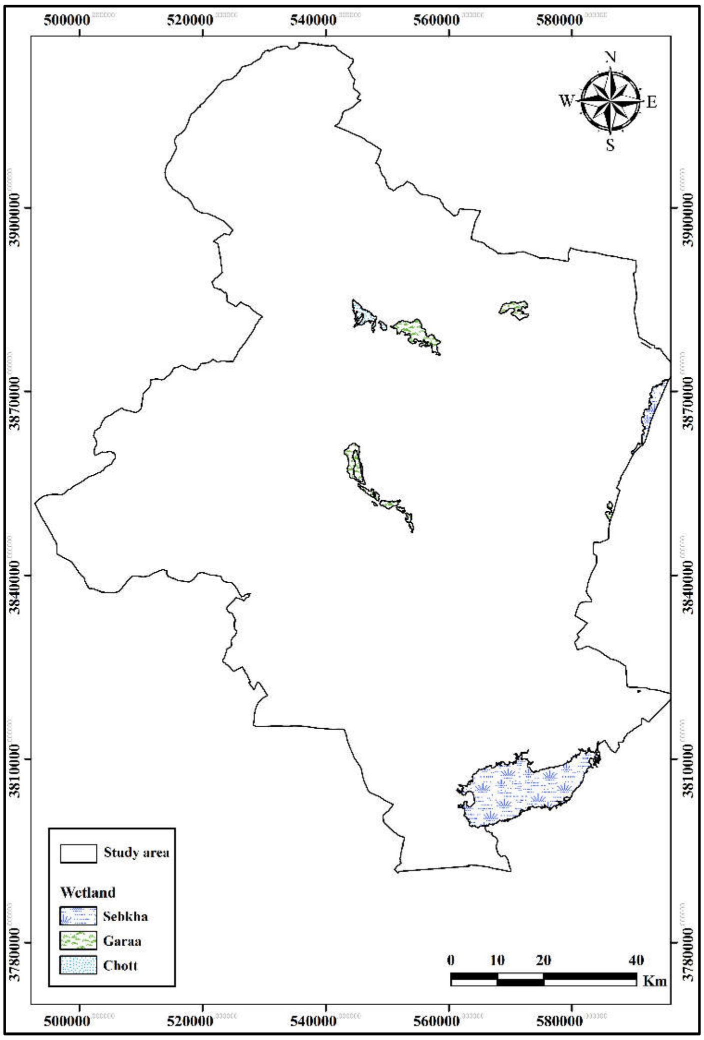

Fig. 11. The wetland in the study area

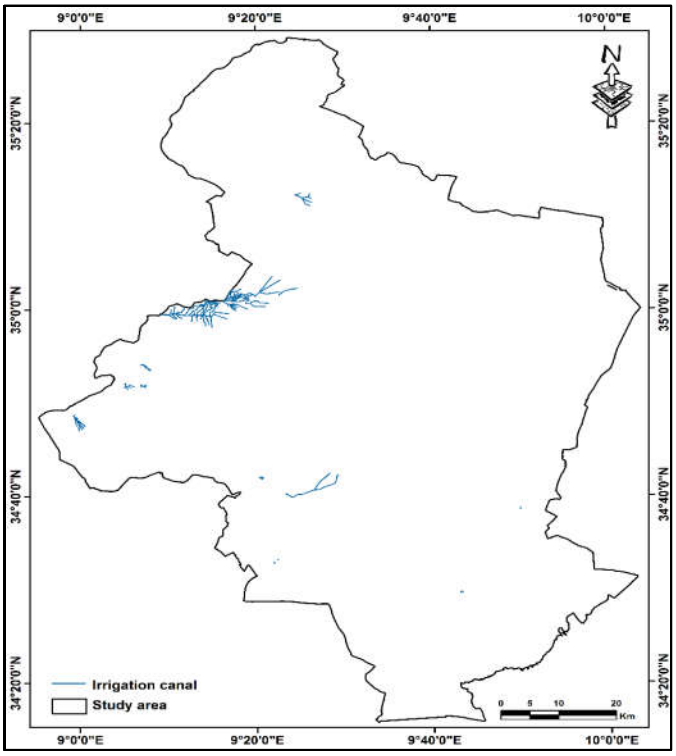

Fig. 12. The irrigation canal in the study area

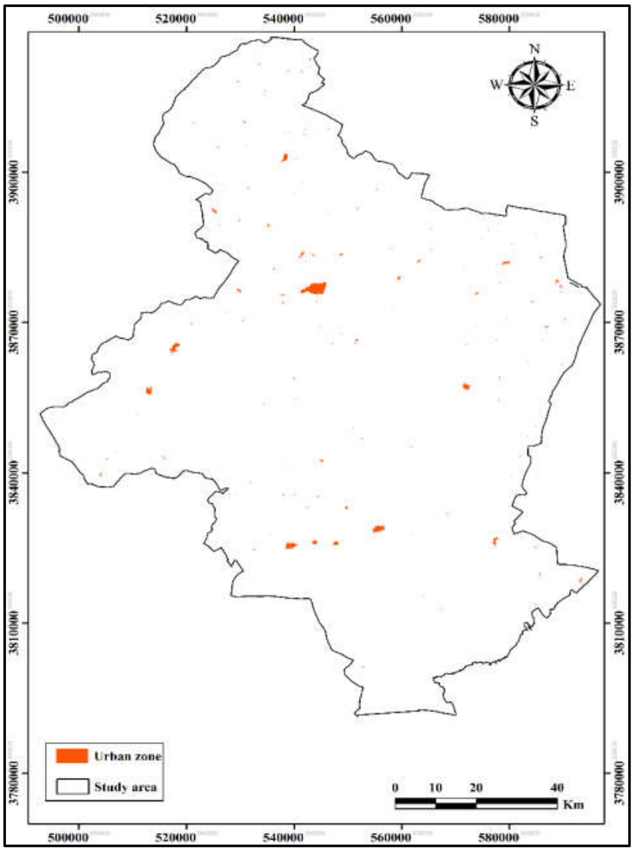

Fig. 13. The urban areas in the study area

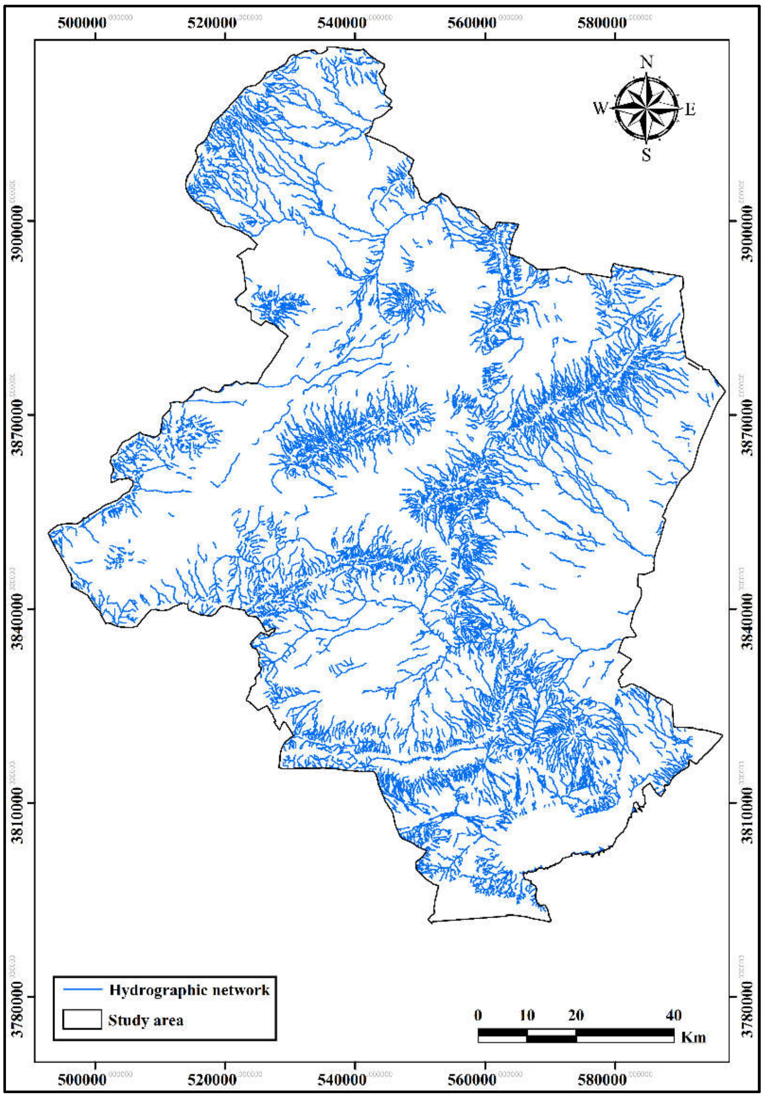

Fig. 14. The hydrographic network in the study area

Artificial groundwater recharge sites must not be located near rivers or in an area of risk of flooding. The choice of the minimum distance to hydrographic network varies from one country to another. The artificial recharge site must be located at 100 m away from the hydrographic network to avoid water contamination by infiltration [19].

3.11 Proximity to Piezometer and Borehole

As a result of an improper site selection, pollutants that are contained in the wastewater can cause the contamination of drinking water supplies [28]. Artificial groundwater recharge sites must not be installed near to water consumption or irrigation wells (Fig. 15). This helps avoid water contamination which could be the result of reclaimed water infiltration. Pedro [6] suggested a distance of 500 m. A buffer zone of 500 m around well to be satisfactory for the choice of recharging site for this study. It avoids any risk of water contamination [19]. Table 1 sums up the analysis of thematic layers on the basis of Boolean logic.

The interaction between the various criteria mentioned above so as to locate favorable sites for artificial groundwater recharge was accomplished by the Boolean approach, in four steps:

3.12 Spatial Resolution

The different information layers in the study area have different resolutions depending on the type of parameters, the density, the quality and the technical aspect of data [29]. Conscious of the influence of the resolution on the definition of the best sites for artificial groundwater recharge, an optimal value of 100 m is adopted, which represents the best compromise between decision factors while maintaining consistency in the available data [30].

3.13 Reclassification

It consists in selecting different areas which constitute a new information layer for the desired query condition. For example, we classified slope in two classes, assigning 1 at a slope of about 15% and 0 to others classes. The resulting image is called Boolean image [29].

3.14 Distance Operation

Most criteria considered in the location of the artificial groundwater recharge site include the distance notion in the spatial information analysis: proximity or distance (the creation of a buffer zone around spatial objects (roads, rivers, urban areas, water point.)). Each distance assessment produces an image representing the suitability of the sites to the criterion under consideration, after reclassification.

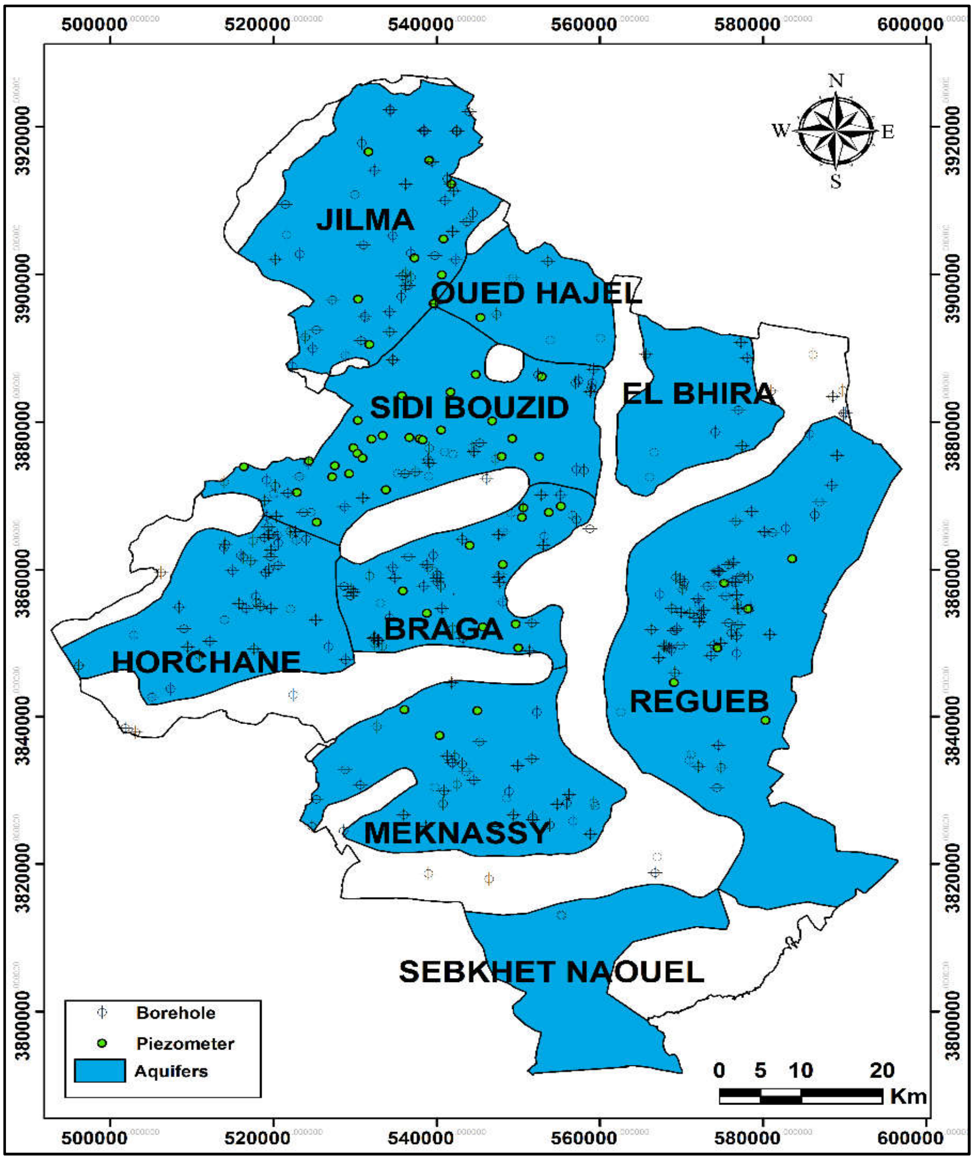

Fig. 15. Piezometer and borehole in the study area

Table 1. Acceptable ranges of thematic layers in Boolean logic

Parameters	Suitable range	Previous studies and expert opinion
Slope	15%	[6,19]
Soil Permeability	Sand and sandy loamy	[11,20,21]
Soil Salinity	Halomorphic soils and non-saline soils	[20]
Depth of the Water table	More than 5 m	[6,11,22,23]
Proximity to road networks	Less or equal than 50 m	[11,19, 24]
Proximity to forest	Buffer of 1000 m	[25]
proximity to wetlands	Buffer of 1000 m	[25]
proximity to irrigation areas	Distance of 100 m	[25]
proximity to urban areas	Distance of 500 m	[26]
proximity to hydrographic networks	Distance of 100 m	[19]
proximity to piezometer and borehole	Distance of 500 m	[19,26,28]

3.15 Overlay Analysis

Overall, the two methods through which overlay analysis can be implemented are raster overlay and feature overlay (overlaying points, lines, or polygons). The latter, i.e. overlay analysis is meant to help find locations subject to certain criteria, and is therefore preferred to raster overlay. In this study, overlay analysis consists in combining the Boolean layers satisfying the most criteria mentioned above. The logical operator "and" was used in this work; it reflects the intersection between the imposed conditions which must be absolutely all satisfied [31].

4. RESULTS AND DISCUSSION

Using the Boolean model to integrate thematic layers (Fig. 16a, b, c) indicate that 12 percent of the area is suited for artificial recharge (Fig. 17) and (Table 2). Complex and diverse parameters are taken into account to select groundwater artificial recharge locations. Integrated assessment of thematic maps using Boolean model developed based on GIS techniques was suitable as a method to identify the preferred sites for artificial recharge. Satellite data has proven to be of considerable utility for surface study, mainly when preparing the current land-use.

Table 2 indicates both suitable and unsuitable areas of artificial recharge in in Sidi Bouzid acquifers based on Boolean logic model. It could be claimed that suitable areas for artificial recharge in Boolean logic are 12.1% of total surface of Sidi Bouzid governorate (Table 2).

According to deferent types of land-use, both types of lands are made distinct on the land-use map. Rangelands are appropriate for artificial recharge were coded one, but non-rangelands were coded zero. The land-use as a binary map was integrated with resulted map (Fig. 17).

The land use, being a binary map, was now integrated with the resulted map (Fig. 17). It was found that the sustainability rate was reduced to a half by the land-use layer (Fig. 18) and (Table 3). After the resulted maps were filtered. We can conclude from this that: (i) 12.1% of the total area was suitable for artificial recharge in Boolean Model is composed of: (ii) 6.6% had land-use limitation; and (iii) the remaining 5.5% did not have any restriction (suitable for artificial recharge).

Table 2. Areas of suitable and unsuitable sites for artificial recharge based on Boolean logic

Value	Area (km2)	Area (%)
Suitable	833.06	12.1
Unsuitable	6492.76	87.9

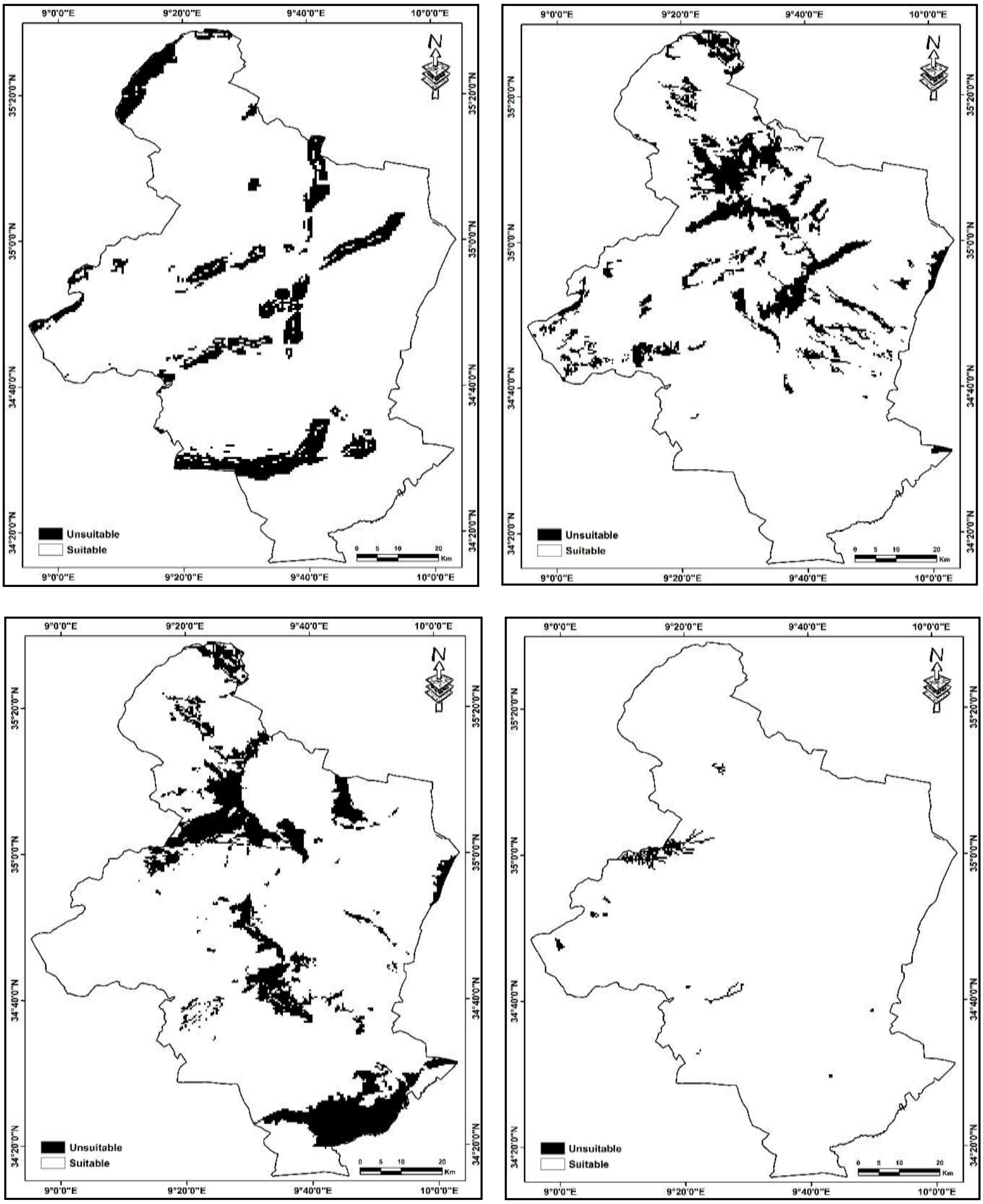

Fig. 16a. Boolean layers satisfying the most criteria for the artificial groundwater recharge site: a. Slope; b. Soil Permeability; c. Soil Salinity; d. proximity to irrigation areas (white: Suitable area; Black: Unsuitable area)

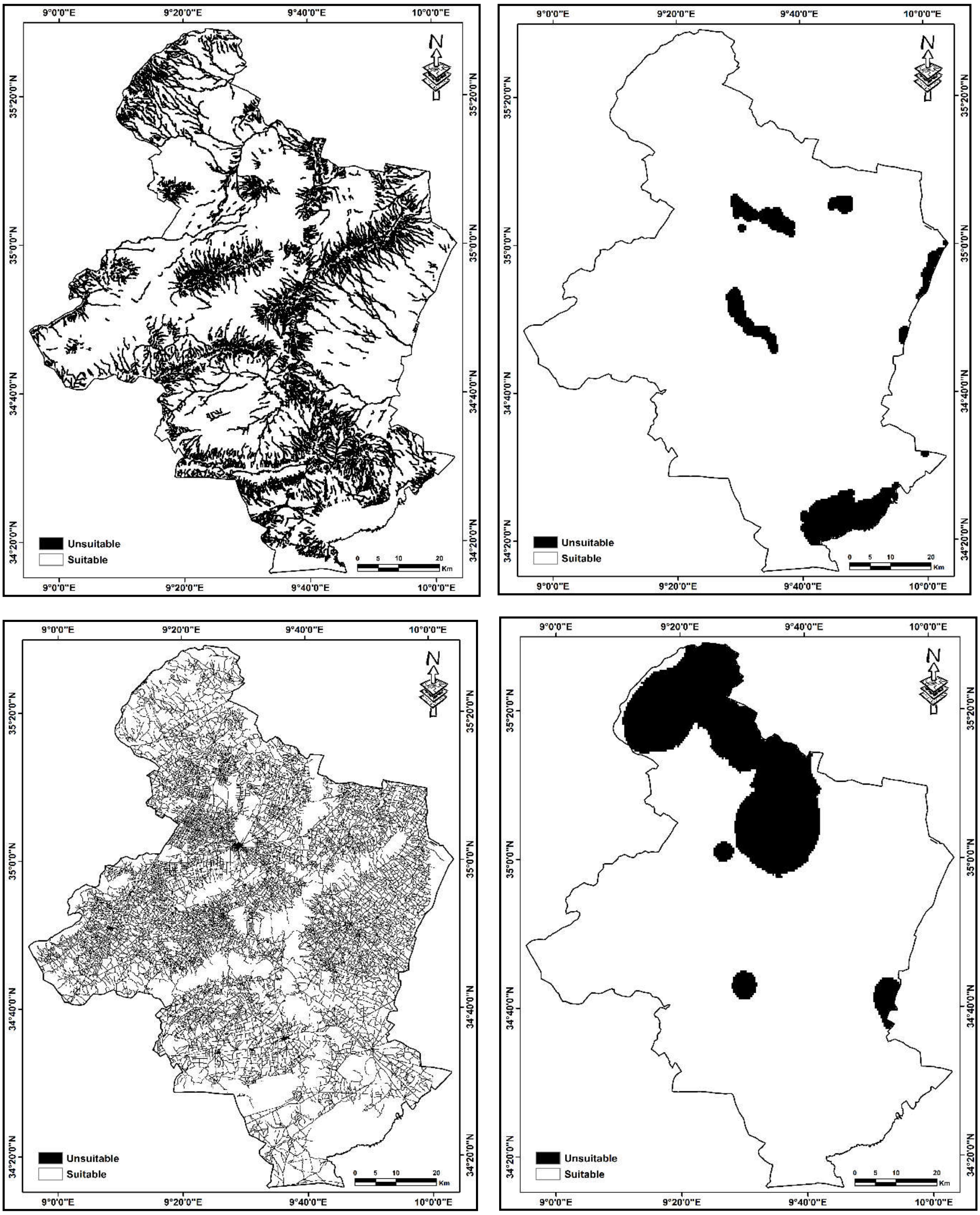

Fig. 16b. Boolean layers satisfying the most criteria for the artificial groundwater recharge site: e. Proximity to hydrographic networks; f. Proximity to wetlands; g. Proximity to road networks; h. Depth of the Water table (white: Suitable area; Black: Unsuitable area)

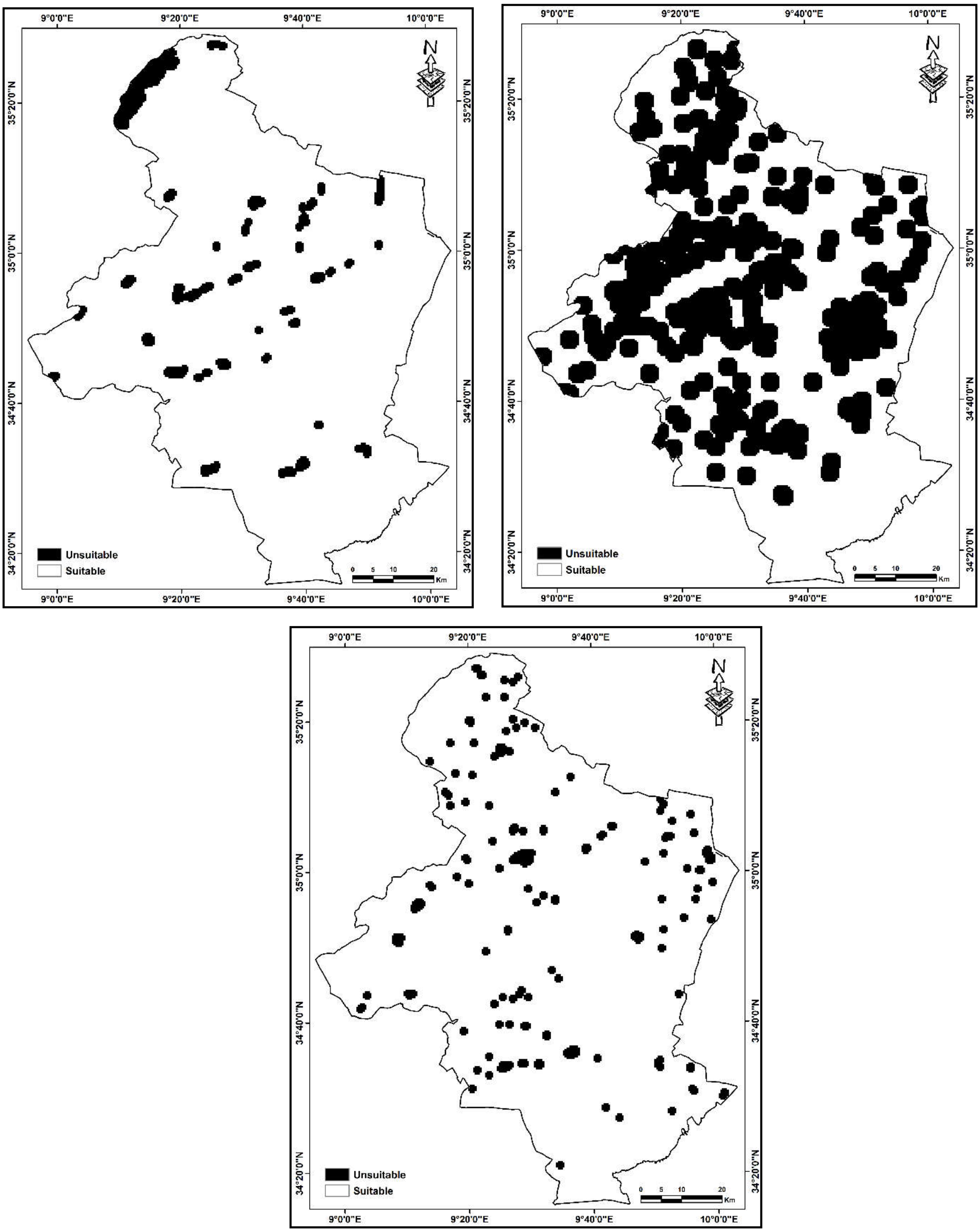

Fig. 16c. Boolean layers satisfying the most criteria for the artificial groundwater recharge site: i. Proximity to forest; j. Proximity to piezometer and borehole; k. Proximity to urban areas (white: Suitable area; Black: Unsuitable area)

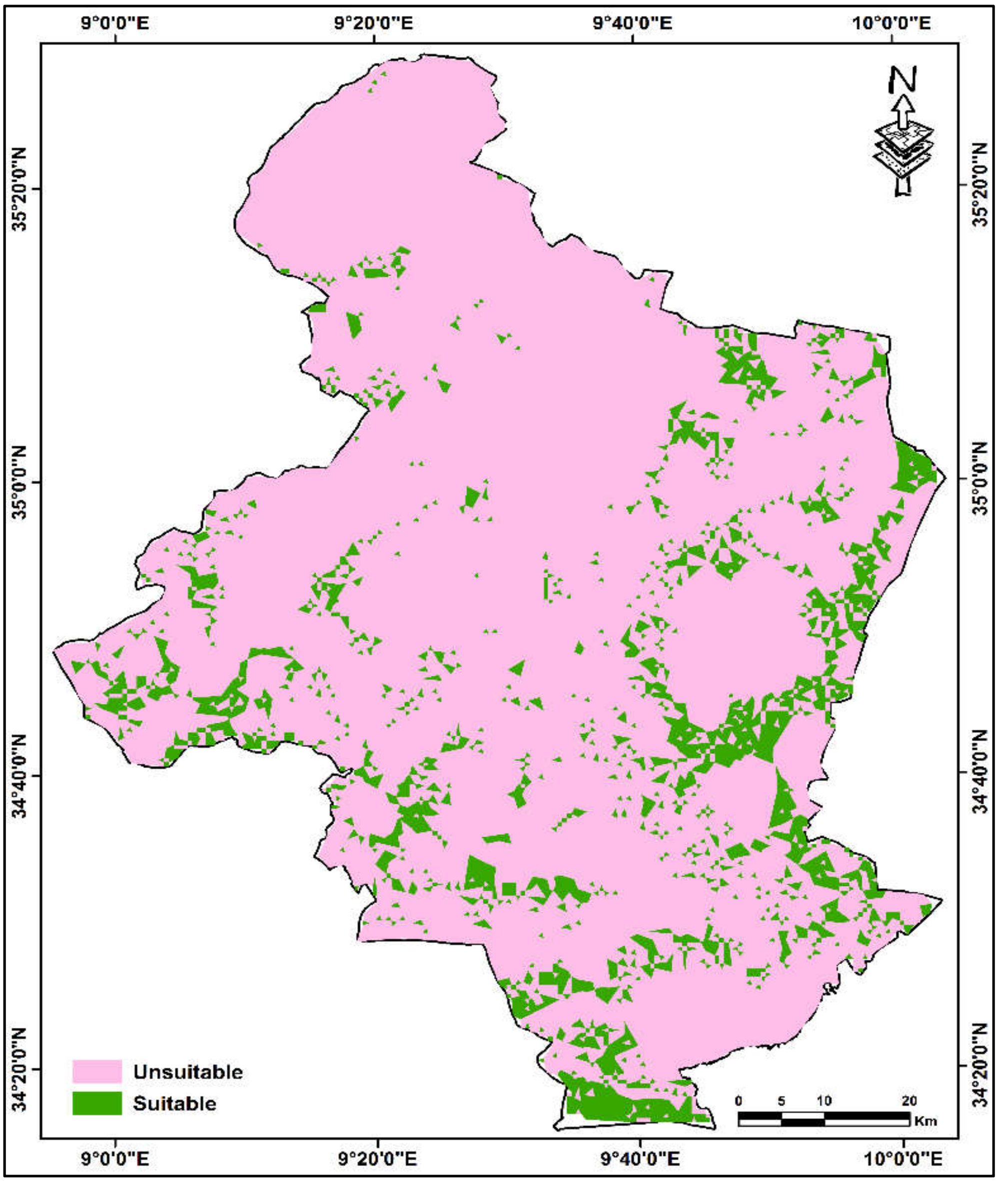

Fig. 17. Area suited for artificial Recharge in Sidi Bouzid acquifers on the basis of Boolean model

Table 3. Areas of suitable and unsuitable sites for artificial recharge based on Boolean logic using land use filtering

Value	Area (km2)	Area (%)
Suitable	334.19	5.5
Unsuitable	6983.86	94.5

The extent of suitability of different regions for artificial recharge has been measured using the Boolean logic. With reference to Tables 2 and 3, the use of land use map as a filter resulted in a decrease in areas suited for artificial recharge. With reference to Table 3, only 5.5 percent of study area is suitable for artificial recharge in Boolean model using land use filtering.

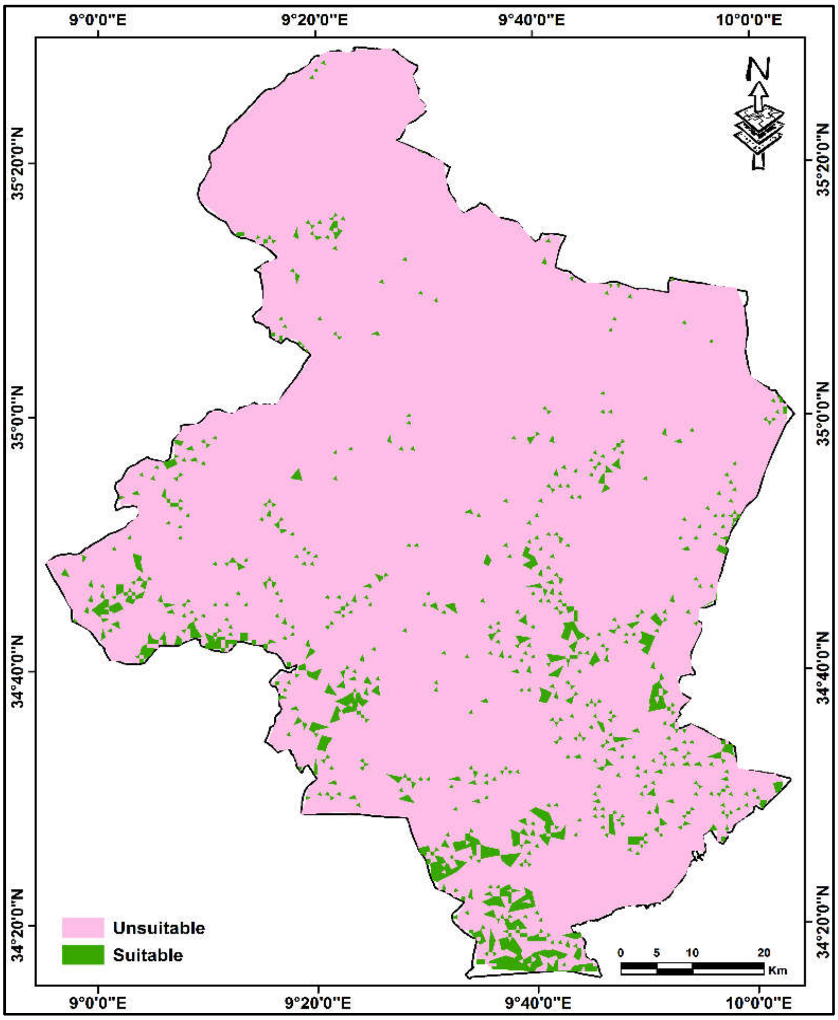

Fig. 18. Suitable and unsuitable sites for artificial recharge based on Boolean logic using land use filtering

5. CONCLUSION

Artificial recharge in Sidi Bouzid acquifers seems to be of paramount importance in helping increase the water table, bearing in mind the negative balance of ground water in the region. Determining the areas most suitable for artificial recharge is a key factor for a successful recharge of groundwater. This piece of research, therefore, has been carried out to determine the areas most suitable for artificial recharge of groundwater in Sidi Bouzid acquifers. Thus, Slope, Soil Permeability, Soil Salinity, Depth of the Water table, Proximity to road networks, Proximity to forest, proximity to wetlands, proximity to irrigation areas, proximity to urban areas, proximity to hydrographic networks, proximity to piezometer and borehole and land use factors were used as thematic layers. The Boolean model was used to overlay these thematic layers. Results showed that, based on Boolean model, only 12.1% of this region is suitable for artificial recharge.

Given that artificial recharge is best implemented in rangelands, ultimate maps have been produced by using land maps as a filter. It can be claimed that there is a decrease of 5.5% of suitable areas after using land use filter.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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