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Techniques to Identify Potential Artificial Groundwater Recharge Zones in Arid Regions: A GIS Based Approach

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Abstract: Groundwater forms the main source water supply in Saudi Arabia. Due to rapid development and agricultural activities in different parts of the Kingdom, the groundwater is depleting at an alarming rate. Therefore, studies must be carried out to enhance or sustain these underground water resources. Artificial Groundwater Recharge (AGR) is the most common and practical technique for augmenting the available water resources. The present study deals with GIS and logical approaches to identify the possible groundwater recharge sites. A GIS based model was developed to identify the suitable zones for implementing the AGR project. The site selection was based on 6 parameters which includes: (1) area slope (2) Aquifer type (3) Vadose zone thickness (4) Soil type (5) Groundwater quality and (6) Land use/land cover (LULC). The 6 thematic maps were integrated using both Boolean and Fuzzy logic to identify the best possible sites for AGR. Results from Boolean revealed 12.01% of the study area is suitable for AGR. However, integrating land use/land cover map, the recharge area reduced to 10.02%. Sand dunes and sheets, alluvial plain and alluvial fan are the main suitable geomorphological landforms for artificial recharge. Through Fuzzy technique 3.11% of the area was identified as very suitable, 25.22% suitable, 47.54% moderately suitable and 24.08% of the total area was unsuitable. Integrating the final map with LU/LC using Fuzzy logic, the suitable area reduced to 8.76%. The result of combination of Fuzzy logic and geomorphology map expresses that "sand dunes and sheet unit" are the most suitable zones. Alluvial fan, alluvial plain and wadis are moderately suitable to suitable for recharge. One of the objective of this study was also to compare the two methods (Boolean and Fuzzy) in terms of their effectiveness in identifying the best locations for AGR sites. Fuzzy logic and Boolean logic operate similarly in terms of calculation of 100% appropriate and risk-free areas. By means of fuzzy membership functions, available parameters can be classified into classes, ranging from very suitable to highly unsuitable. Whereas, in Boolean only classes of suitable and unsuitable are present. Based on our results we conclude that Fuzzy method is more suitable than Boolean.

Key words: Artificial Groundwater Recharge · Northern Saudi Arabia · Boolean Logic · Fuzzy Logic

INTRODUCTION

Saudi Arabia is the 13th largest country in the world and has an estimated population of 30 million and is one of the few countries in the world without major lakes or rivers. It has a rough natural desert environment, with an average annual rainfall of less than 100 mm, [1, 2]. Sustainability of groundwater resources can only be achieved by its safe and optimal exploitation. Overexploitation of groundwater resources has become a common phenomenon especially in developing countries mainly due to improper planning and management practices.

In some areas of the world, storing water in aquifers through artificial recharge is the best solution to protect and improve the water quality [3]. Artificial groundwater recharge (AGR) is an engineered scheme intended to introduce and store water underneath the ground surface [4]. It is actually a process to reinforce the underground formations by natural surface water, which can be through any construction, spreading water on surface or by artificially varying the natural surroundings.

Dincer *et al.* [5] did the first groundwater recharge study within the Kingdom of Saudi Arabia. By doing the stable isotopes study on groundwater samples, he concluded that recharge could only occur in the sand

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dunes if the rainfall amount is over 50 mm. After this initial study, numerous researchers did prominent work related to groundwater recharge studies for the various regions of the Kingdom [6, 7].

In 1986, a separate center "Center for Desert Studies" was established in Saudi Arabia to conduct research on the issues connected with the general aridity of its desert environment. The name was then changed to "The Prince Sultan Institute for Environmental, Water and Desert Research" (PSIEWDR). It is an independently administered research organization whose headquarter is in King Saud University, Riyadh.

As selection of suitable sites for artificial recharge is an unescapable essential requirement and is the foremost principle of creating this system of artificial recharge, therefore, it requires great care. Several geologic, hydrogeologic and physiographic parameters need simultaneous analysis and integration for locating the proper recharge sites. In this respect, GIS is a very handy tool where the thematic layers of various parameters can be prepared and integrated to select the best sites. [8]. The techniques of GIS and remote sensing have been used by several researchers for identifying the potential natural as well as artificial recharge zones, in addition to their use in groundwater resource management [9]. Numerous efforts have been made to outline probable groundwater sites using remote sensing (RS) data, by [10, 11, 12].

[13] in their study selected suitable zones for artificial recharge in Jazan Region, Saudi Arabia. They used five layers for locating the spatial extents of groundwater recharge (GWR) suitability areas. Zaidi et al. [14] used GIS and Boolean logic to identify the potential recharge sites in north-western Saudi Arabia.

The area of the present study lies in the northern and north-eastern part of Kingdom of Saudi Arabia, covering an area of approximately 126, 289 km^2. The principal objective and aim of this study is to contribute towards systematic groundwater studies by identifying the potential artificial groundwater recharge zones for Wasia-Biyadh aquifers in northern Saudi Arabia, using the Geographic Information Systems (GIS) and Remote Sensing techniques. The thematic maps such as drainage, geomorphology, slope, aquifer type, groundwater quality and land use/ land cover were prepared and then integrated using Boolean logic and Fuzzy logic to identify the best possible zones for artificial recharge.

Study Area Description

Location: Study area is situated between latitudes 27°26'0" N – 32°0'0" N and longitude 39°12'0" E – 46°14'0" E and lies in the northern part of Saudi Arabia, covering an approximate area of 126, 289 km^2 and includes parts of Al Jawf and Northern province (Figure 1). The north-eastern edge of the study area coincides with the border of Saudi Arabia with Iraq. Study region is covered by Wasia-Biyadh and Aruma Aquifer systems which are the major aquifer systems in the eastern and northern part of the Kingdom [15].

Climate and Topography: The typical climate of the study area (the northern part) can be categorized as arid. The annual rainfall is low and ranges from less than 75 mm/year in the upper northern parts (Arar, 59 mm/year) to 80-100 mm/year in the lower south and south-eastern parts (Rafha, 95 mm/year).

The groundwater recharge varies from >2.5 to >10 mm/year in different regions. Reasons for less recharge are low rainfall and high evapotranspiration (approximately 2000-2500 mm/year) except in areas where physical characteristics of the surface layers are favourable for infiltration of runoff water [16].

The maximum temperature in summer ranges from 33°C to 45°C during daytime. Temperature hardly drops below 0°C in winter, but the atmosphere becomes quite cold due to high wind-chill factor and practically total lack of humidity [14]. The elevation ranges from 1052 m amsl* to 282 m amsl (*above mean sea level). The average elevation of the study area is 667 m amsl. The highest elevation in the study area is situated along the western boundary (Figure 2) along with some neighboring mountains having elevations greater than 900 m. The topography along the western and north-western boundary is overall elevated as compared to the eastern and south-eastern side. Desert sands cover more than 35% of the study area, while the rest can be characterized as "Badlands" topography. The area gently dips eastward.

Geomorphology: Landform map was taken from [16] report. It was georeferenced and traced using ArcGIS 10.3. The different geomorphological landform units depicted are shown in Figure 3. These are also important input parameter for AGR sites selection. In the study area seven landforms were identified namely Active slope, Alluvial fan and footslope, Alluvial plain, Degraded plain, Pediplain, Sand dunes and sheets and Wadis.

Drainage: "Spatial analyst tools" were used to extract the stream network of the study area from available DEM data. 5th to 7th order channels are described as large or major ephemeral streams in Figure 4, while the remaining

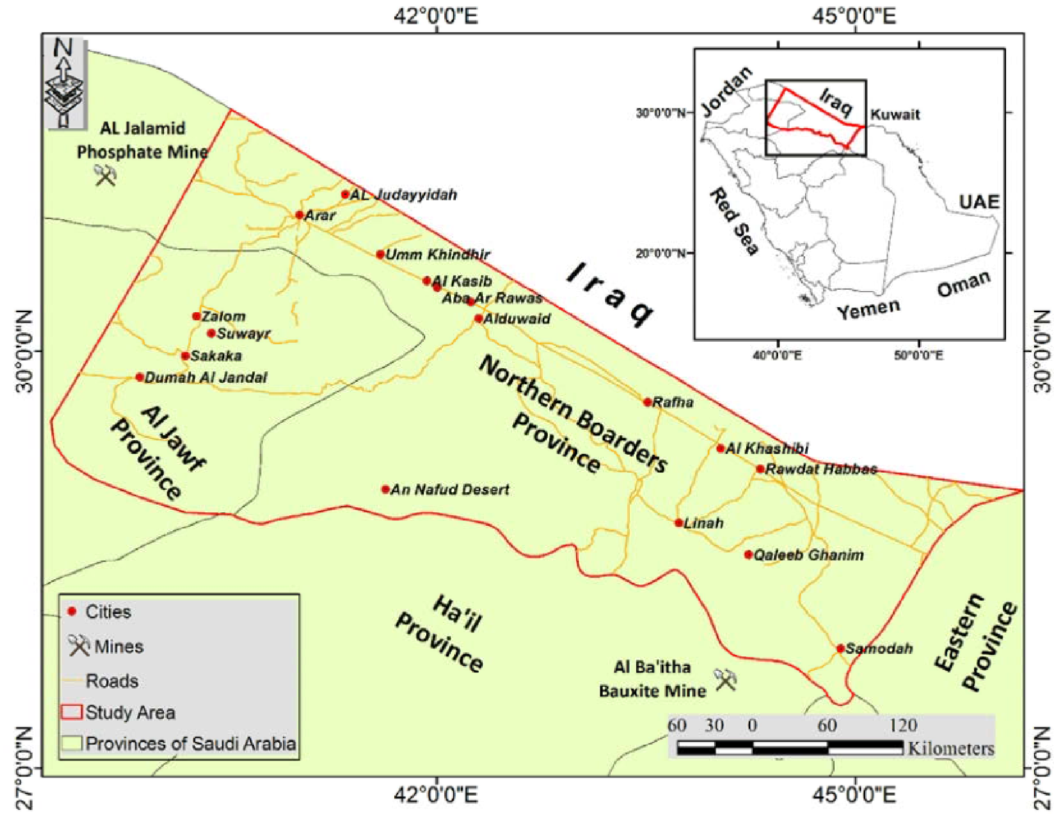

Fig. 1: Location map of the study area, highlighting the main cities and roads.

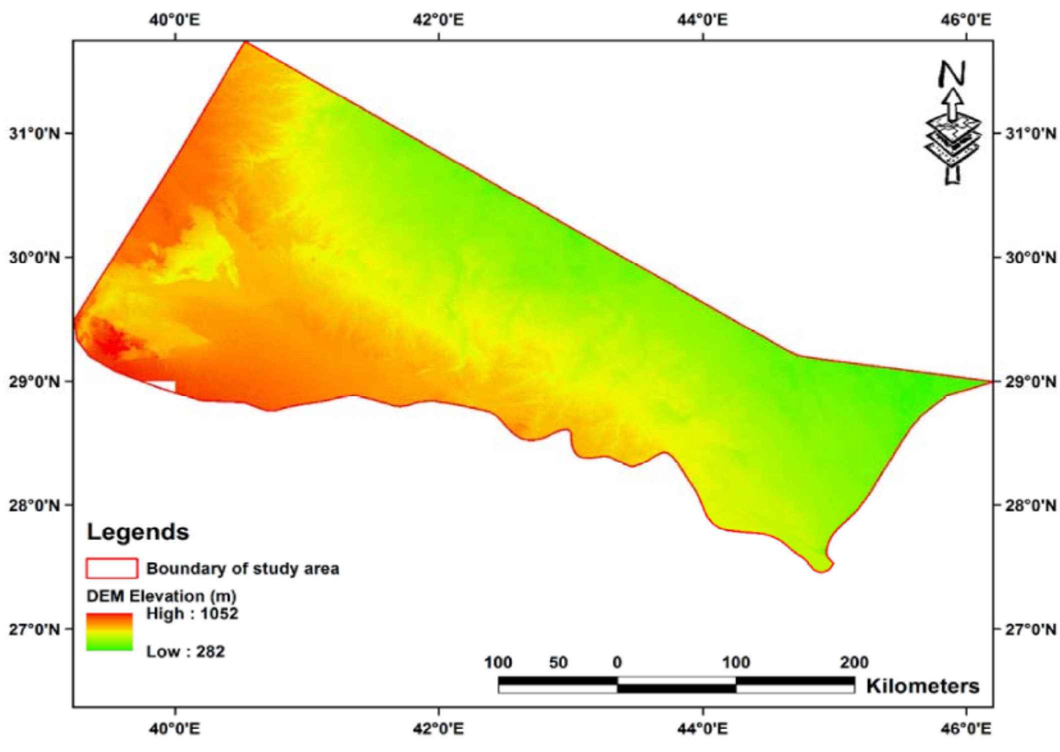

Fig. 2: DEM of the study area

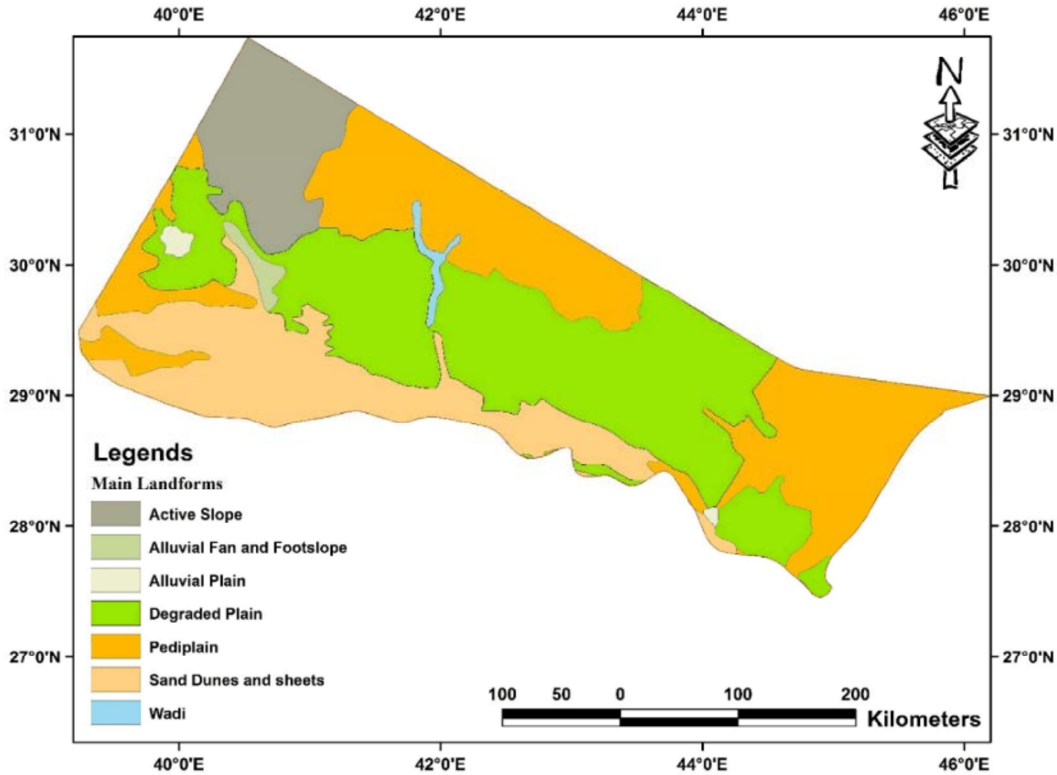

Fig. 3: Geomorphological landform map (modified from Water Atlas of Saudi Arabia)

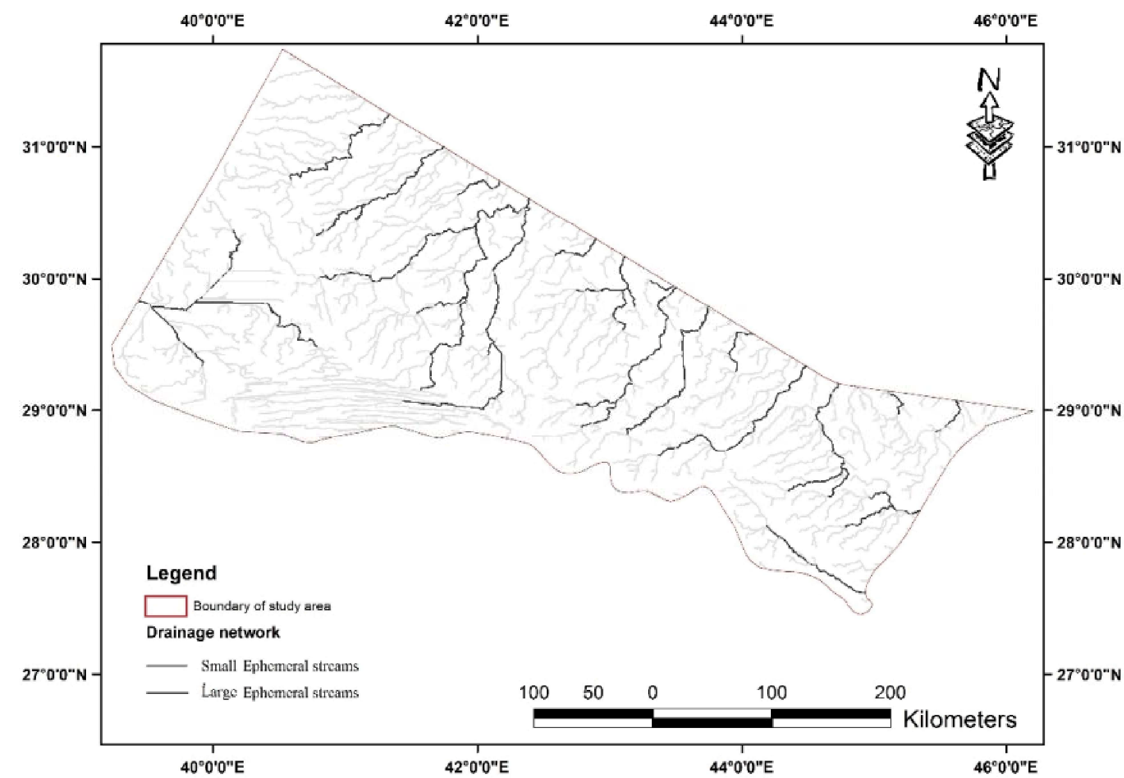

Fig. 4: Major streams and drainage pattern of the study area

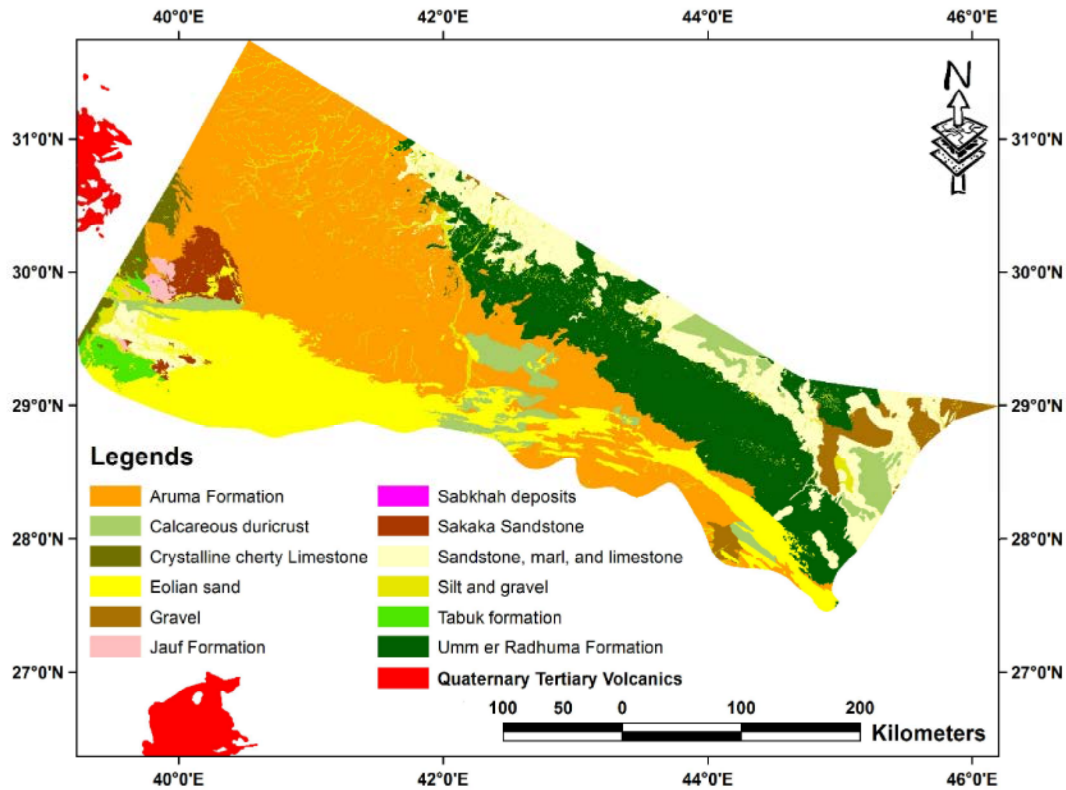

Fig. 5: Geological map of the study area, showing age wise distribution of exposed stratigraphic units

Table 1: Stratigraphic succession of the study area

Age			Formation	Lithology
			Eolian sand, Sabkhah deposits	Sand Silt, clay and muddy sand
			Silt and gravel Gravel	Gravel, sand, silt, gypsum Quartz pebbles with
Cenozoic	Quaternary		Calcareous duricrust	sandy matrix Sandy limestone
	Tertiary	(Miocene and Pliocene)	Sandstone, marl and limestone	Calcareous sandstone, silt- stoneand claystone
		(Eocene)	Crystalline cherty Limestone	Limestone, dolomitic
		(Paleocene and Eocene)	Umm erRadhuma	Limestone and dolomite
Mesozoic	Cretaceous	Upper Cretaceous	Aruma	Limestone and subordinate dolomite and shale
		Middle Cretaceous	Wasia /Sakaka	Sandstone; subordinate shale
		Middle Cretaceous		Sandstone; conglomeratic and micaceous
	Jurassic	Lower Jurassic	Dhruma	Aphanitic limestone and shale; subordinate calcarenite
Palaeozoic	Devonian	Upper Devonian	Jubah	Sandstone
		Middle Devonian	Jauf	Limestone, shale and sandstone
	Ordovician	(Devonian Silurian and Ordovician)	Tabuk	Sandstone and shale
	Ordovician	Lower Upper	Saq	Sandstone
	Cambrian			

2nd to 4th as small ephemeral streams. The recognized drainage patterns are mostly dendritic and parallel representing the lithological control due to low infiltration and also locally exhibits structural control to some extent.

Geology: Geologically the upper Ordovician Tabuk Formation, the Cretaceous to Paleogene Aruma formation, the Paleogene Umm Er Radhuma Formation and the Quaternary Eolian sand and the calcareous duricrust covers the entire study area. On the basis of the available lithologs from the drilled wells, the idea about the geologic succession is made, as the complete succession of rocks is not exposed in the area. Figure 5 represents the geological map of the study area where as the stratigraphic succession (based on lithology information) is given in Table 1.

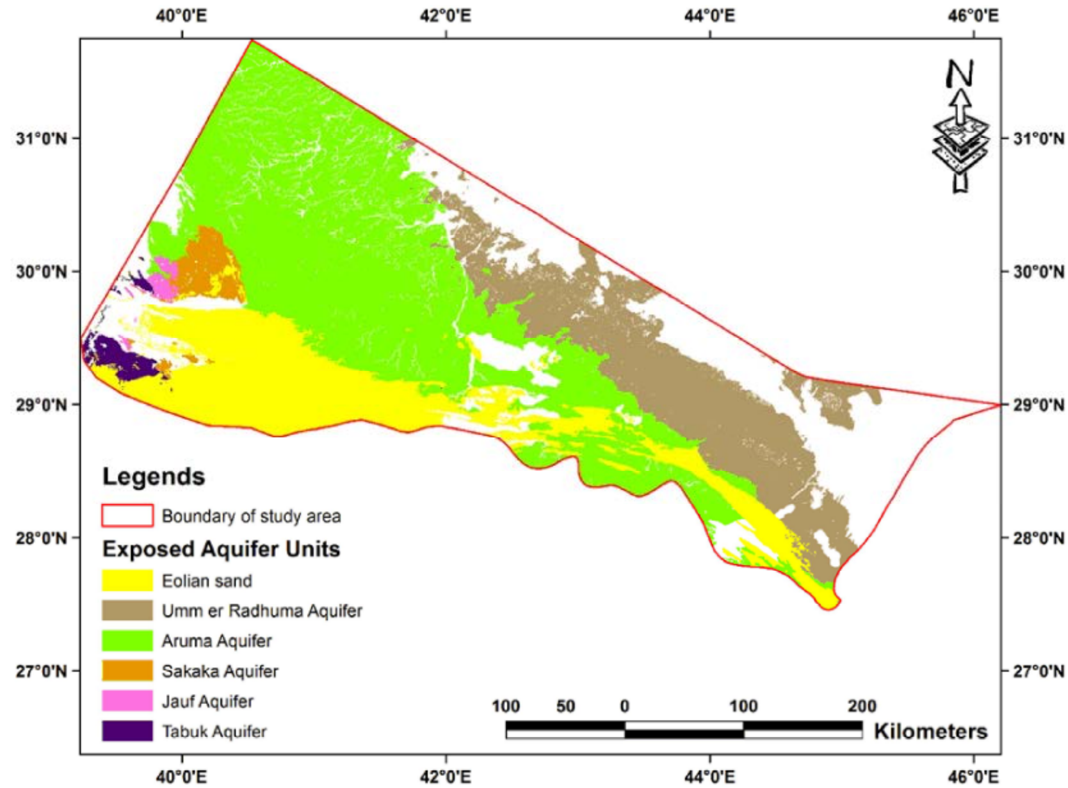

Fig. 6: Exposed aquifer units in the study area

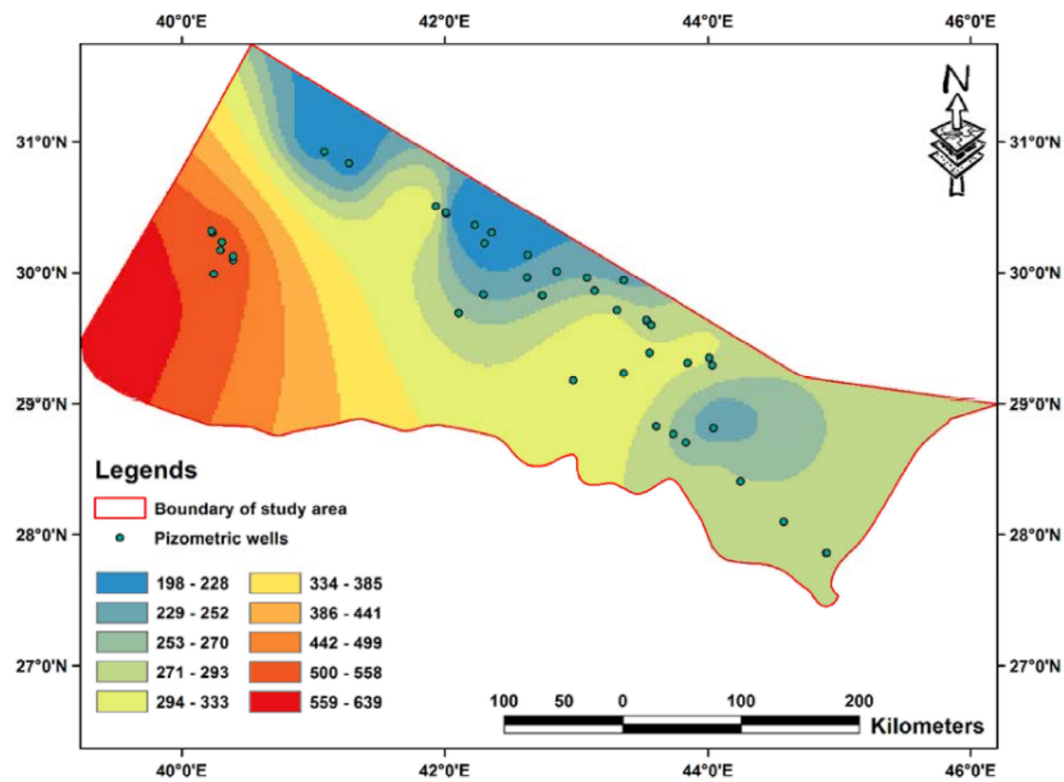

Fig. 7: Piezometric map for the study area (Values are in meters above mean sea level).

Hydrogeology: The exposed aquifer units in the study area include Umm erRadhuma, Aruma, Sakaka, Jauf and Tabuk aquifer (Figure 6). The piezometric map of the study area is shown in Figure 7. The piezometric level in the region varies from 198 to 639 m above mean sea level. The overall trend of water flow is from southwest to northeast.

Principal Aquifers of Study Area: Wasia-Biyadh Aquifer and the Tabuk aquifer are the main aquifers in the study area. Biyadh Formation is the most important aquifer in the eastern and north-eastern provinces in Saudi Arabia. Lithologically it is 425m thick unit of cross-bedded quartz sandstone with some interbeds of conglomerate and shale at places. Wasia Formation unconformably overlies Biyadh Sandstone. The two formations form one immense aquifer system in eastern and northern Saudi Arabia, [17]. In Sakaka region of northern Saudi Arabia, the Wasia Formation is about 200m thick. It is a good aquifer with encouraging hydraulic characteristics. It has a high effective porosity ranging from 10% to 29% and an average transmissivity of $3x10^{-4}$ to $2.8x10^{-3}$ m^2 /sec. The average storage coefficient ranges from $3x10^{-2}$ to $5x10^{-2}$ in the unconfined part and is about $7x10^{-3}$ in its confined part [18]. The united aquifer of Wasia-Biyadh is one of the largest regional potential aquifers having a very large amount of stored water.

The Tabuk aquifer consists of cross bedded sandstone, siltstone and shale. The three sandstone aquifer units of Tabuk are known as the Lower Middle and Upper Tabuk. Due to the lack of data the aquifer properties such as ground-water storage, recharge and other properties were difficult to determine.

Secondary Aquifers of the Study Area: Secondary aquifers also play significant role as local source of groundwater supply, but their water quality varies from poor to excellent. Similar to the principal aquifers of the Kingdom, they also differ from one another in their hydraulic character, extent, geology and state of development. The Jauf, Khuff and Jilh Aquifers, yields low to moderate supplies of poor to good potable water to wells in the northern and central parts of the Kingdom. Aruma aquifer is a secondary aquifer, except where it is connected hydraulically to the Wasia Aquifer, provides low yields of highly mineralized water. The Quaternary aquifers of the Kingdom occurs in the drainage ways and consist of the saturated part of the alluvial deposits which were formed by outwash deltas and fans. Most promising of these aquifers were to be found in the alluvium of the larger wadis and in the alluvium and related deposits of the western coastal plains. Wells in these aquifers are used to supplement water supplies for irrigation and municipalities.

MATERIALS AND METHODS

As discussed [10, 3] there are numerous factors that may affect artificial groundwater recharge (AGR) such as land use, morphology, geology, climatic, socio-economic activities and floods. To delineate the best suitable sites for AGR, the controlling factors considered in this research includes slope, groundwater quality (TDS), land use/land cover, soil texture, type of water bearing formation and vadose zone thickness of the area.

ArcGIS 10.3 was used for the generation, classification and combination of thematic layers of above stated parameters. There are diffierent methods that can be used for combination of all thematic layers. In present research, fuzzy logic and Boolean logic were used. The first has a range of values for diffierent suitable levels, whereas, the later consider only unsatisfactory or satisfactory conditions (zero or unit value).

Boolean Logic has been used by many workers for finding the suitable locations for artificial recharge [11, 12]. Boolean operations are possibly the best and simplest well-known type of GIS model, as once all the required thematic layers (datasets) have been generated, this analysis helps in finding all the suitable locations very easily. Boolean operations were used for the first time for reasoning using geological maps by [19].

The resulting binary maps after using conditional operators, are combined logically in Boolean modeling. To specify each unit area, just one or zero values are allocated to show whether it is satisfactory or unsatisfactory, respectively. Generally, Boolean Logic employ a binary condition for the inputs and assesses just for a binary condition for the output. There are several ways to express binary condition: "1" and "0", "True" and "False", "yes" and "no", "on" and "off" and so forth. Value of 0 represents the “False” condition, whereas any value except 0 denotes the “True” condition. The Boolean operators includes AND, OR, XOR and NOR [20]. In present research and Boolean operator was used for the integration of different thematic layers. The thematic layers analyzed using Boolean logic are listed in Table 2.

Table 2: Thematic layers with suitability classes used for Fuzzy and Boolean logics. Classes and respective weight was assigned based on available values and previous studies i.e [3, 10, 14, 39,]

Slope (Our Value = 0° to 59°)			
Ranges	Suitability Class	Fuzzy weight	Boolean weight
0 to 2	Very Suitable	10	0 to 5 =1
2 to 4	Suitable	7	> 5 =0
4 to 8	Moderately Suitable	5	
More than 8	Unsuitable	1	
TDS (Our Value = 239 to 3862 mg/L)			
Ranges	Suitability Class	Fuzzy weight	Boolean weight
0 to 900	Very Suitable	10	0 to 900 =1
900 to 1800	Suitable	7	> 900 = 0
1800 to 2500	Moderately Suitable	5	
More than 2500	Unsuitable	1	
Depth to water Table/Vadose Zone (Our Value = 55 to 350 m)			
Ranges	Suitability Class	Fuzzy weight	Boolean weight
100 to 150	Very Suitable	10	55 to 200= 1
150 to 250	Suitable	7	> 200 = 0
55 to 100	Moderately Suitable	5	
More than 250	Unsuitable	1	
Soil Texture			
Ranges	Suitability Class	Fuzzy weight	Boolean weight
Sandy	Very Suitable	10	1
Loamy	Suitable	7	1
Loamy/Rocky	Moderately Suitable	5	0
Rocky/Loamy	Moderately Suitable	5	0
Sandy/Clay	Unsuitable	1	0
Type of water bearing formation			
Ranges	Suitability Class	Fuzzy weight	Boolean weight
Aquifer	Very Suitable	10	1
Aquitard	Moderately Suitable	3	0
Aquiclude	Unsuitable	1	0

Fuzzy logic is one of the numerous useful models that can be used for combining information concerning artificial recharge and has already been used in various studies related to groundwater recharge [10, 21, 22]. A group of "degrees of membership" defines a "Fuzzy Set". A continuous scale of values from 1 to 0 (1=full membership, 0=Full non-membership) is usually used to display the membership of a fuzzy set. By means of fuzzy membership functions, maps can be classified into classes. At the end, individual class is designated by a membership degree on the basis of their effect in the range (0, 1). A range of processes can be involved for the combination of membership values. A range of rules for combination were discussed by [23]. There are five available fuzzy arithmetic operators [24] that can be utilized to merge the membership values together: namely fuzzy OR, fuzzy AND, fuzzy algebraic product, fuzzy gamma and fuzzy algebraic sum. The algebraic sum operator of Fuzzy logic is highly sensitive in identifying artificial recharge zones and was used in this study.

Four scales were considered for each layer including: very suitable, suitable, moderately suitable and unsuitable. Then, numerical ranges were specified on the scales based on experts' opinions and previous studies. The selected five fundamental parameters were categorized according to the aforementioned explanations; however, land use land cover is a qualitative factor which could be either appropriate or inappropriate for artificial recharge. In this study the logical (Boolean and Fuzzy logic) demarcation of the possible artificial recharge regions was limited to the unconfined aquifers.

RESULTS

Overall six factors were used for recognizing the possible artificial recharge zones. The descriptions of each of the parameters and the suitability or unsuitability of their values are discussed here.

Slope: Slope of an area is among the key factors to be considered for selection of an artificial recharge site as well as for the type of artificial recharge technique to be followed [25]. Terrain slope directly controls the erosion, surface runoff and transport of materials. It is an important factor for groundwater recharge because infiltration rate of water is a function of the slope i.e. rate of water

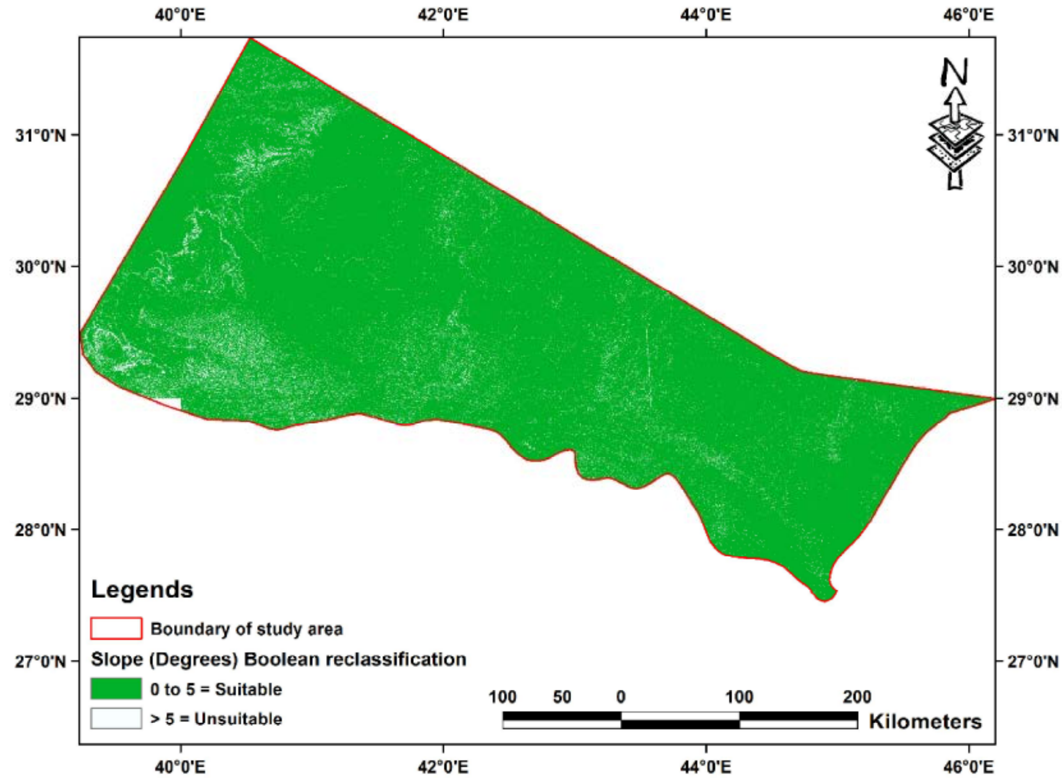

Fig. 8: Boolean classification ranges of slope for the study area (values are in degrees)

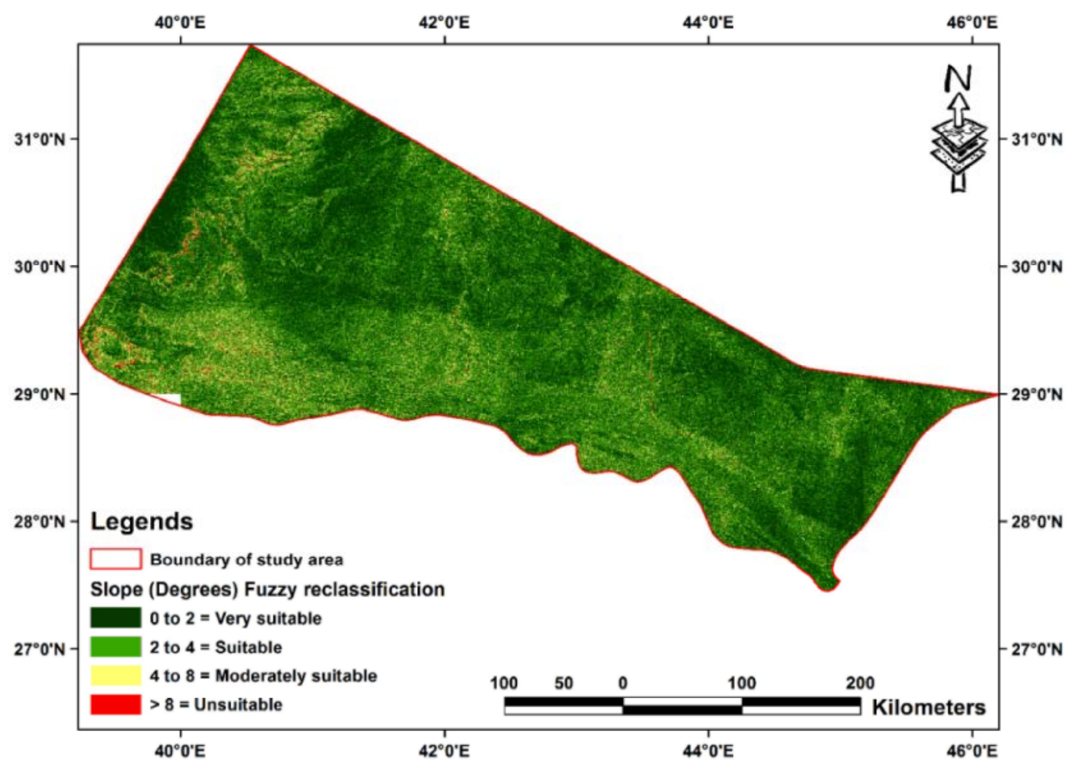

Fig. 9: Fuzzy classification ranges of slope for the study area (values are in degrees)

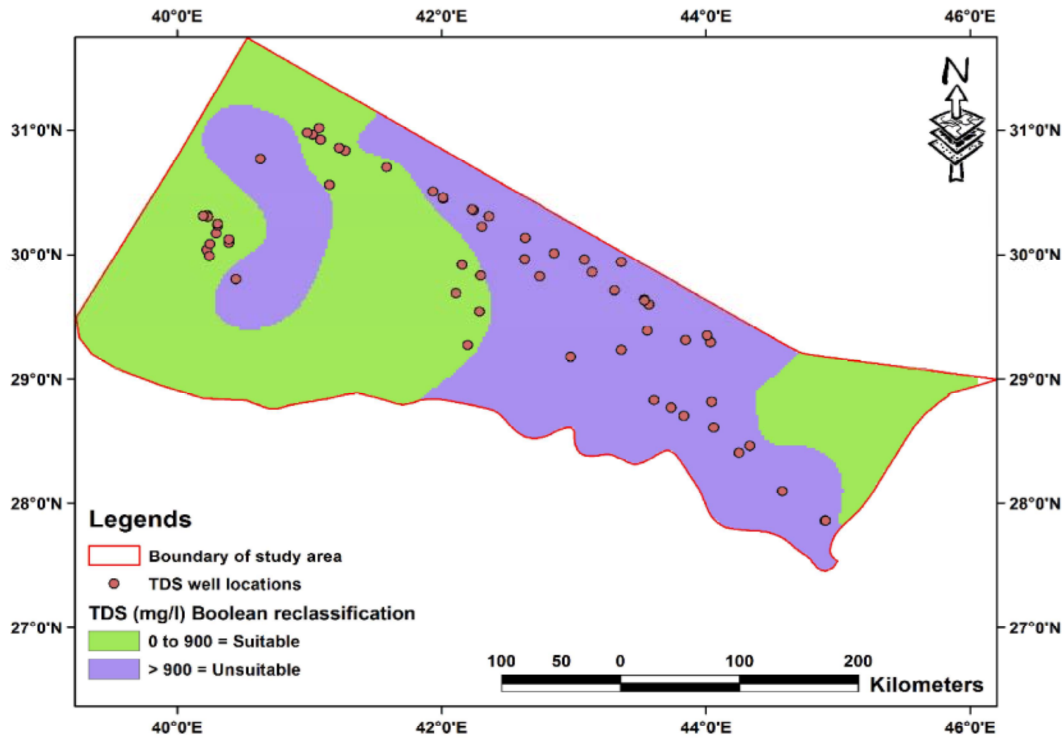

Fig. 10: Boolean reclassification map of groundwater Quality (TDS) with well locations

infiltration into subsurface is higher in a place where the terrain is flat or has a very gentle slope and vice versa. As it can be observed from Figure 8 that majority of the study area has very gentle to gentle slope and gentle slopes tend to slow surface runoff, so water gets more time to percolate and reach the groundwater table [26]. Sand dunes and flat land are also present in the study area. ArcGIS 10.3 was used to produce slope map from 30 m resolution Digital Elevation Model (DEM) attained from Earth Explorer (https://earthexplorer.usgs.gov/). Slopes of study area ranges from 0° to 59.6°. Over 60 % of the area have a slope of <5°. For calculation through Boolean logics, by keeping the distribution of slope values on histogram and previous studies in mind, the areas having a slope of less than 5° were taken as suitable for recharge and areas with slopes greater than 5° were considered unsuitable (Figure 8). Whereas, for Fuzzy classification of slope areas between 0 to 2 % were ranked as very suitable, 2° to 4° as suitable, 4° to 8° as Moderately suitable and above 8° were considered as unsuitable (Figure 9). Table 2 record the ranking grades of the slope parameters for both Fuzzy and Boolean classification.

Groundwater Quality (TDS): Studies have shown that the groundwater quality is also an essential factor and must be taken into consideration for AGR as the artificial recharge can assist in enhancement of the groundwater quality [27, 28].

Water with a very high TDS value will result in polluting the groundwater putting further restrictions on its usage. For this reason, to determine the characteristics of water, the total dissolved solids (TDS) was taken as a fundamental standard for the assessment of quality. The distribution maps of TDS were produced from data available from 61 wells. Before assigning any values or defining limits, two important controlling factors were kept in mind; the restricted recharge of water (either from treated waste water or rains) and a balance between aquifer replenishment and the groundwater quality. Therefore, just those areas were designated as "suitable for artificial recharge" which had TDS values less than 900 mg/l, whereas the sites with concentration above 900 mg/l were considered as "unsuitable" for Boolean calculations. Figure 10 shows the Boolean reclassification map for TDS.

For Fuzzy classification of TDS, values from 0 to 900 mg/l were considered as very suitable, 900 to 1800 mg/l as suitable, 1800 to 2500 m as moderately suitable and the values of above 2500 mg/l were taken as unsuitable (Figure11).

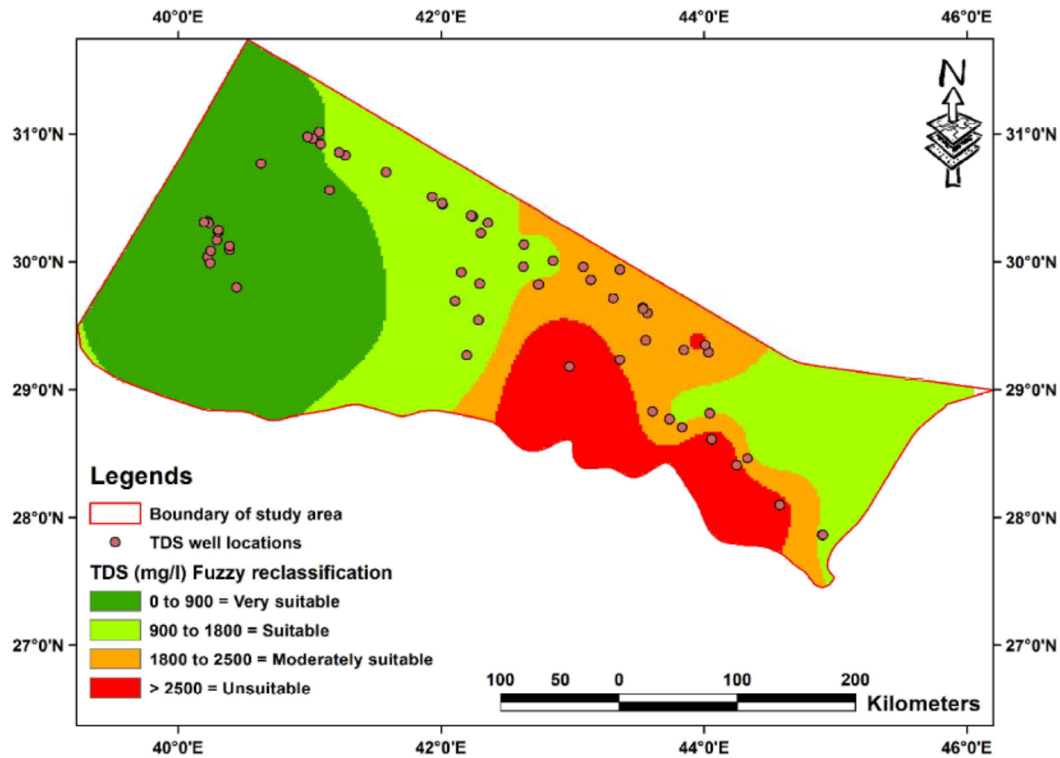

Fig. 11: Fuzzy reclassification map of groundwater Quality (TDS) with well locations

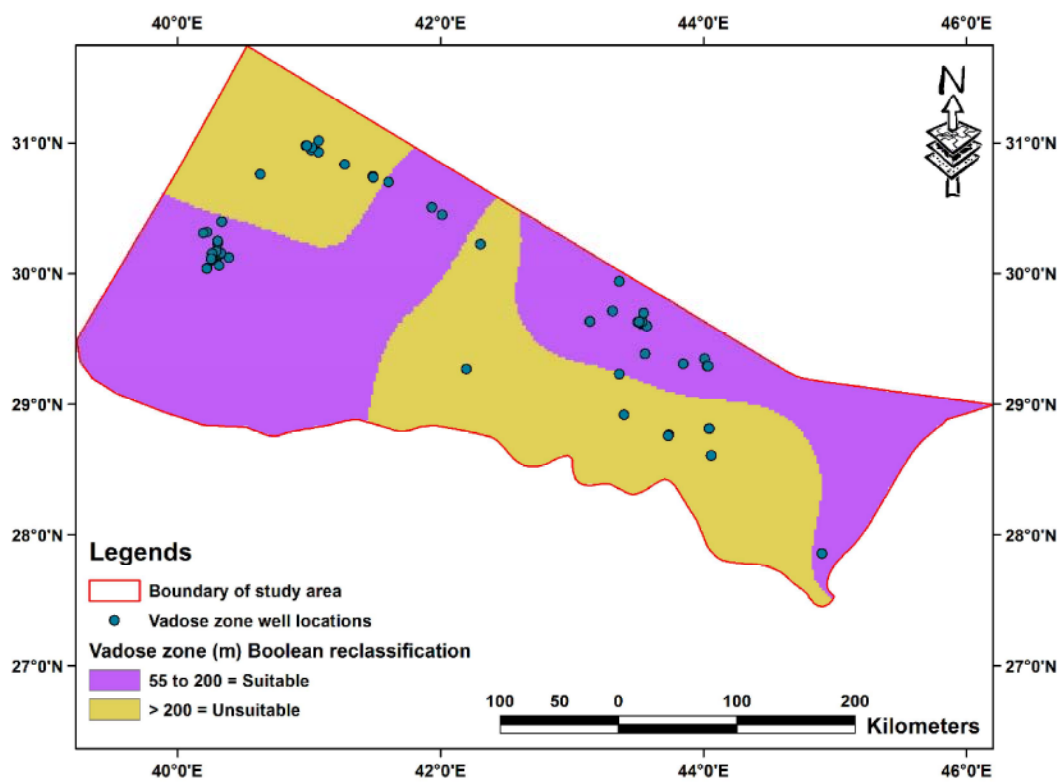

Fig. 12: Boolean reclassification map of vadose zone thickness for study area

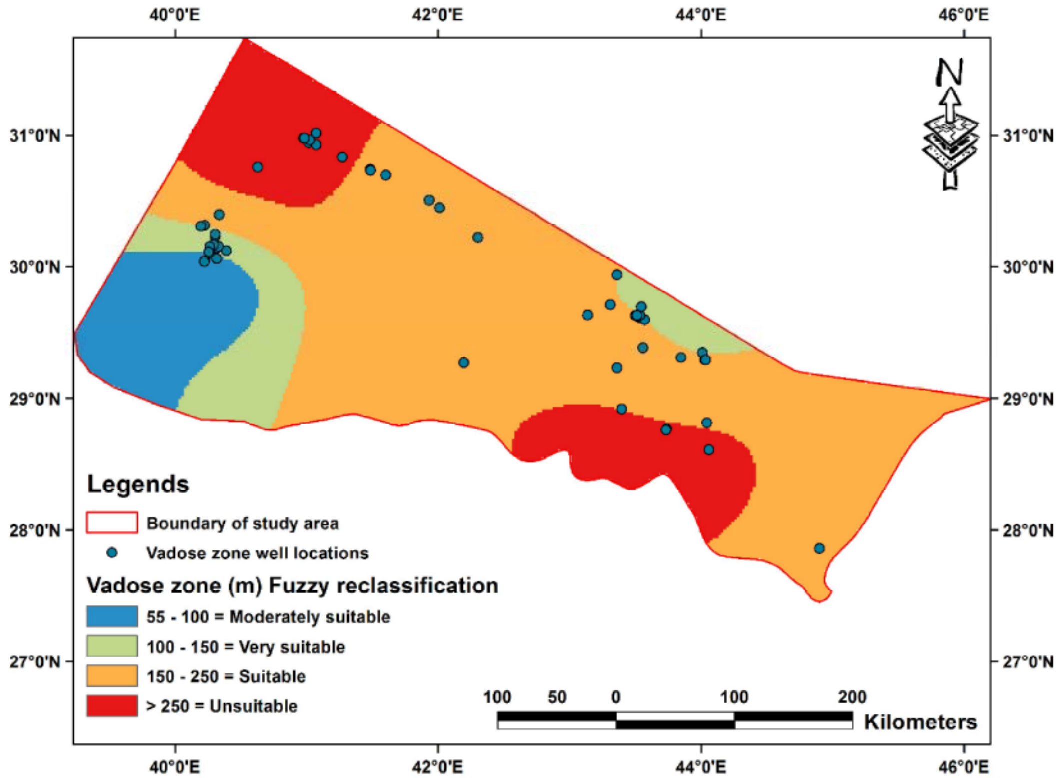

Fig. 13: Fuzzy reclassification map of vadose zone thickness for study area

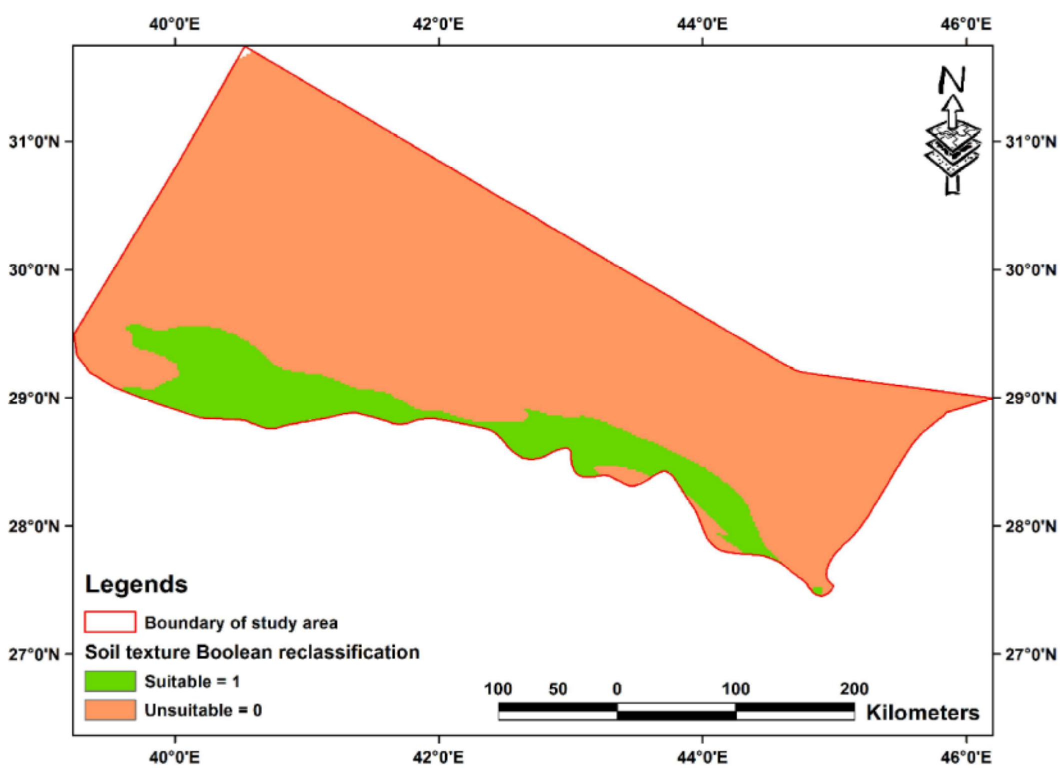

Fig. 14: Boolean reclassification map of soil texture of study area

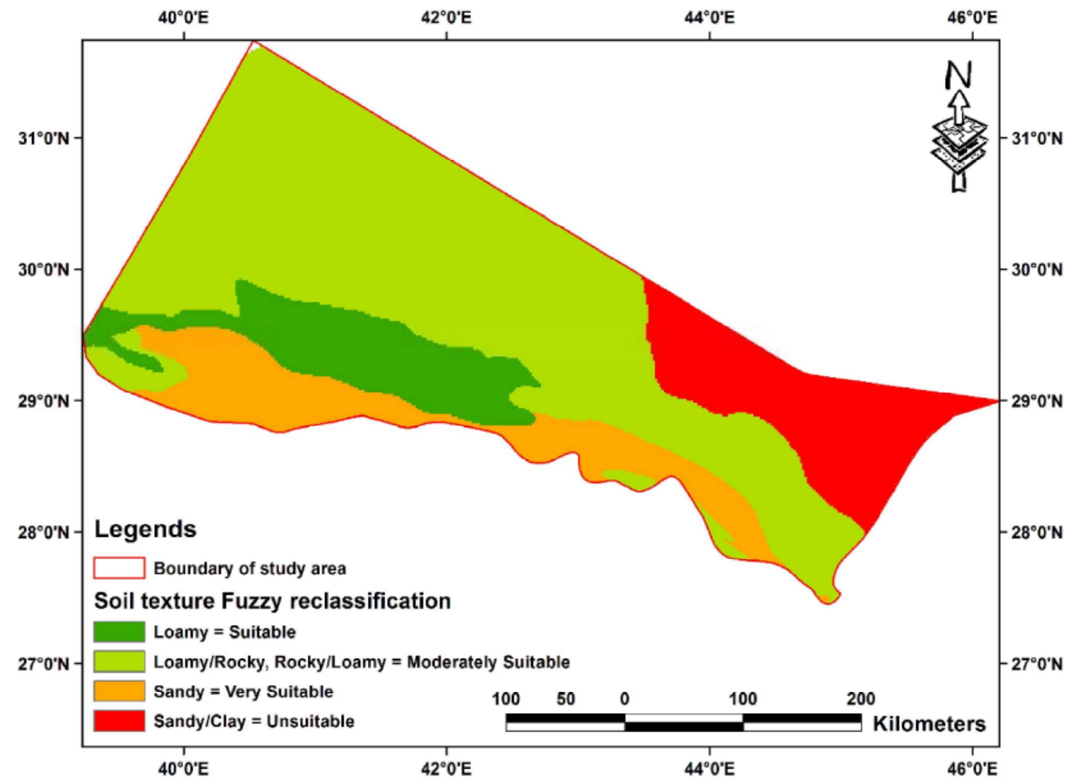

Fig. 15: Fuzzy reclassification map of soil texture of study area

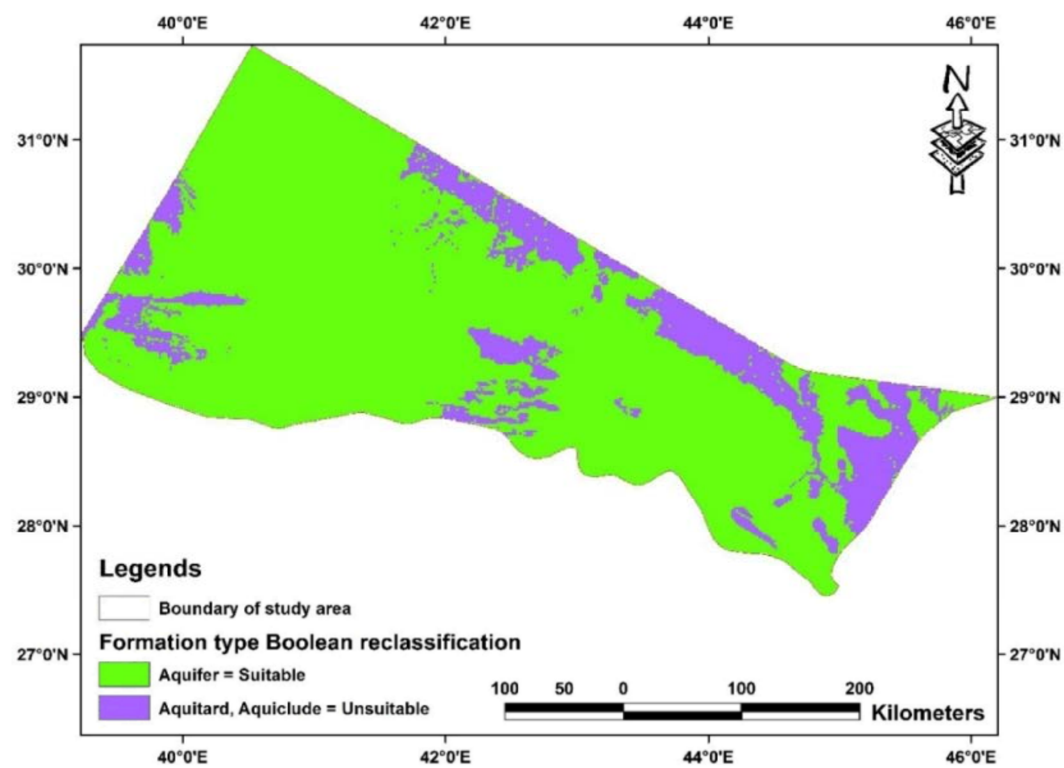

Fig. 16: Boolean reclassification map of outcrops of "type of water bearing formations" in the study area

Vadose Zone Thickness/Depth to Water Table: "Depth to groundwater can be described as the distance between the ground surface and water table", also known as vadose zone [29]. This is a zone through which infiltrated water percolates to reach the aquifer and its thickness influences the amount of percolation in the aquifer system [29]. The difference between the piezometric level and the ground elevation at a given point helps in determining the thickness of the vadose zone. Water level data from 61 wells were taken to prepare the vadose zone thickness map.

For Boolean classification, the effect of shallow water table and water logging conditions for some regions as well as the time required by the percolating water to reach the water table at greater depths, were kept in mind. A thickness between 55 and 200 m was taken as suitable, whereas, the areas with vadose zone thickness of less than 55 m and greater than 200 m were considered unsuitable (Figure 12). For Fuzzy classification of vadose zone thickness, 55 to 100 m thickness was considered as moderately suitable, 100 to 150 m as very suitable, 150 to 250 m as suitable and a thickness of above 250 m as unsuitable (Figure 13).

Soil Texture: Soil texture is an important input variable for delineations of potential recharge zones. The infiltration of water is primarily influenced by the soil texture. It has also been mentioned that the surface runoff potential of a region also depends on the texture of [30]. Characteristics of soils (texture and structure), along with slope and land cover, greatly affect the permeability. Slope and land cover being the same for most of the area, soil permeability is mostly influenced by the soil structure and soil texture. Recharge is more likely to occur in high permeability soils and is one of the most essential feature controlling groundwater recharge [31]. On the other hand, low permeabilities will result in surface ponding because of the low infiltration rate [32] and ultimately to the loss of water due to extremely arid conditions prevailing in the region.

Soil texture map was produced from the soil association map of Water Atlas of Saudi Arabia [17]. As shown in Table 2 soils in the study area can be classified into five types based on their texture. Sandy soils were categorized as suitable for recharge, while loamy/rocky, sandy/clay and rocky/loamy soils were categorized as unsuitable for Boolean classification (Figure 14). For Fuzzy classification, sandy soils were given the highest weightage as "very suitable" and sandy/clay with the lowest as "unsuitable". Whereas, loamy - loamy/rocky and rocky/loamy were considered as suitable and moderately suitable respectively (Figure 15).

Type of Water Bearing Formation: As discussed by [14, 33], another essential factor to be carefully taken into account in any artificial recharge probability studies is the type of water bearing formation in which the recharged water is going to be stored. Each geological formation has spatially varying properties, such as transmissivity, storage capacity and water quality, which affect the basin's response to artificial groundwater recharge [34]. The geological formations should have enough permeability and storativity to allow water to pass and to be stored at specific regions, otherwise it could result in an unproductive groundwater recharge.

In view of above mentioned factor, the surface outcrops of the formations in the area under study were categorized as aquiclude, aquitard and aquifer. This classification is established on the basis of lithological data from the geological maps of earlier studies and drilled wells. Classes and their respective weight can be seen in Table 2. For Boolean combination, the surface areas of aquifer were taken as suitable, in contrast to the aquitard and aquiclude that were taken as unsuitable for groundwater recharge (Figure 16).

Whereas, for Fuzzy classification, the aquifer was taken as very suitable, aquitard as Moderately suitable and aquiclude was taken as unsuitable for groundwater recharge (Figure 17).

Land Use/Land Cover: The only layer that is the result of human interference is land-use layer, while the rest all used layers are naturally shaped. Therefore, the effect of this characteristic was investigated separately. As discussed by [35], land use is the expression of human actions that are directly related to land (using land or impacting on it) whereas land cover represents the physical, chemical, or biological categorization of the terrestrial surface (i.e. soils, biodiversity, surfaces and groundwater etc.).

The flow behaviour of water on land surfaces and the recharge process is also influenced by this factor [36]. There are two opinions concerning groundwater recharge and the influence of land use/land cover (LU/LC) on it. In fact, agricultural practices could enhance recharge (dams, streams and rivers construction) and yet changes in LU/LC can have adverse effects on recharge rates particularly in semi-arid and arid regions, ultimately affecting groundwater quality [37].

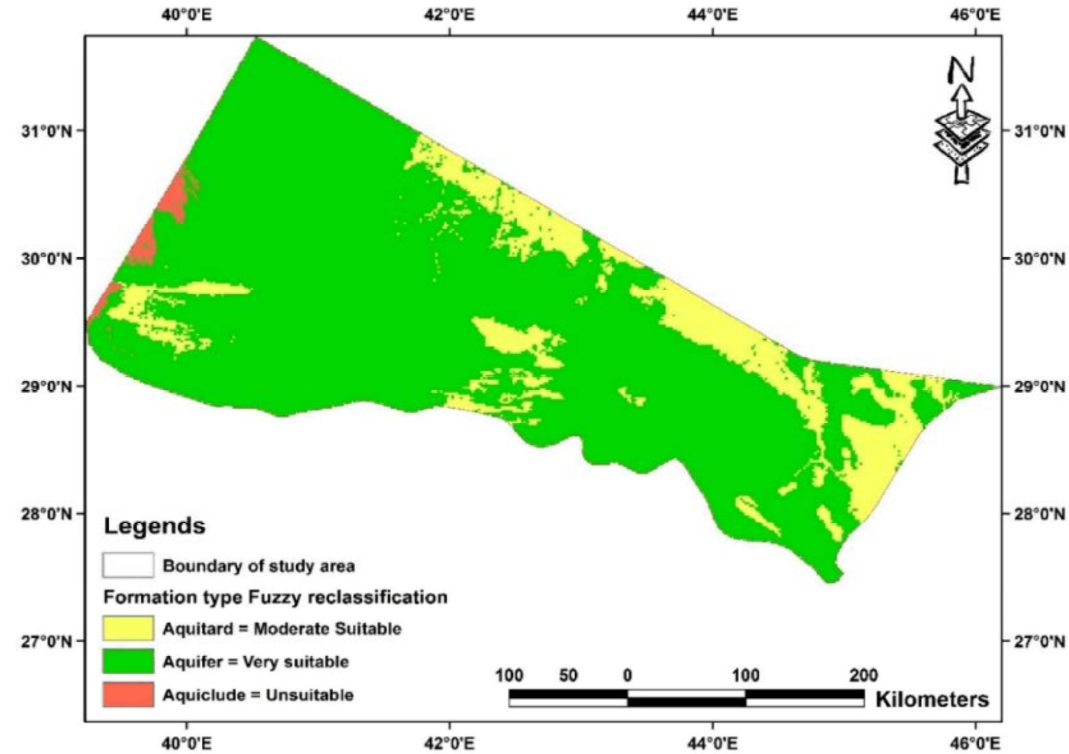

Fig. 17: Fuzzy reclassification map of outcrops of "type of water bearing formations" in the study area

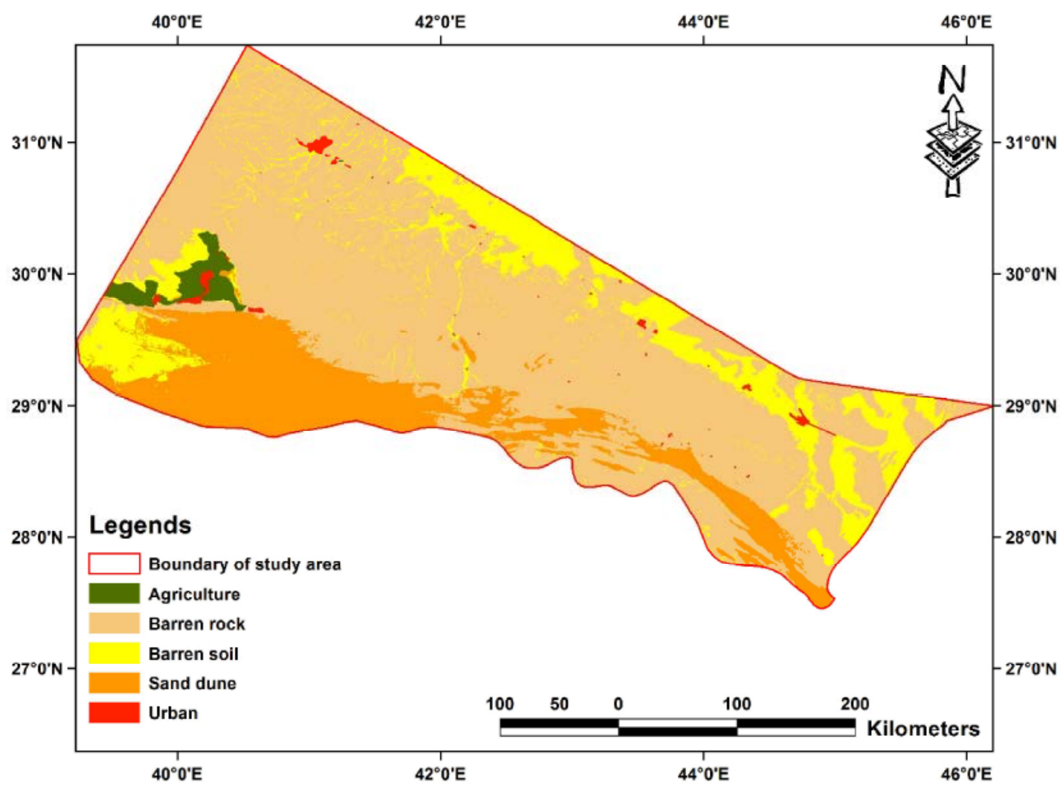

Fig. 18: Land use/Land Cover map displaying different classes in study region

As shown in Figure 18, for the region five types of land use and land cover classes has been detected and mapped by supervised minimum distance classification of Landsat TM 7 Enhanced Thematic Mapper Plus (ETM+) images (band combinations, Red= 6 and 4, Green= 6 and 3, Blue=6 and 2) as well as combining soil type map from water atlas of Saudi Arabia: agriculture, barren rock, barren soil, sand dunes and urban area.

In the present study, this map is used as filter map, as it plays a significant role for the selection of sites suitable for artificial recharge. It helps in the removal of areas with land-use restriction and in evaluating the feasibility of selected site and structure to be constructed [38].

Classification and Integration of Thematic Layers: To achieve the research objectives, an integrated approach was adopted. The first step was the generation of multiple thematic maps (Slope, Groundwater quality (TDS), Vadose zone thickness (m), Soil texture, Type of formation and land use/land cover) from existing data, remote sensing images, field investigations and earlier studies. Thematic layers of the above stated factors were than classified (suitable, unsuitable) and weighted according to the assigned values as displayed in Table 2. GIS environment was used to integrate these layers by means of Boolean logic (AND operator) and Fuzzy logic (algebraic product), to generate the final potential zone map of artificial groundwater recharge. The potential water sources recognized in study region includes ephemeral streams, sewage treatment plants and desalination plants.

DISCUSSION

Results of Boolean Logic: Thematic layers, as discussed in methodology were reclassified and "AND" Boolean operator was used to combine them. This resulted in an initial potential map for areas of AGR (Figure 19). Primarily, only five layers were combined i.e. slope, TDS, depth of water table, soil texture and type of water bearing formation. The results obtained after integrating these five layers are shown in Figure 19. The result shows that 12.01% of the total study area is considered appropriate for artificial recharge. The LU/LC later was not used in this calculation. However, when the LU/LC map is superimposed on the map shown in figure 19, it can be seen that some of the inhabited areas and the areas covered by agricultural activities also comes under the potential AGR zones (Figure 20). One of the objectives of the research was to select the potential recharge zones without disturbing the existing land use pattern.

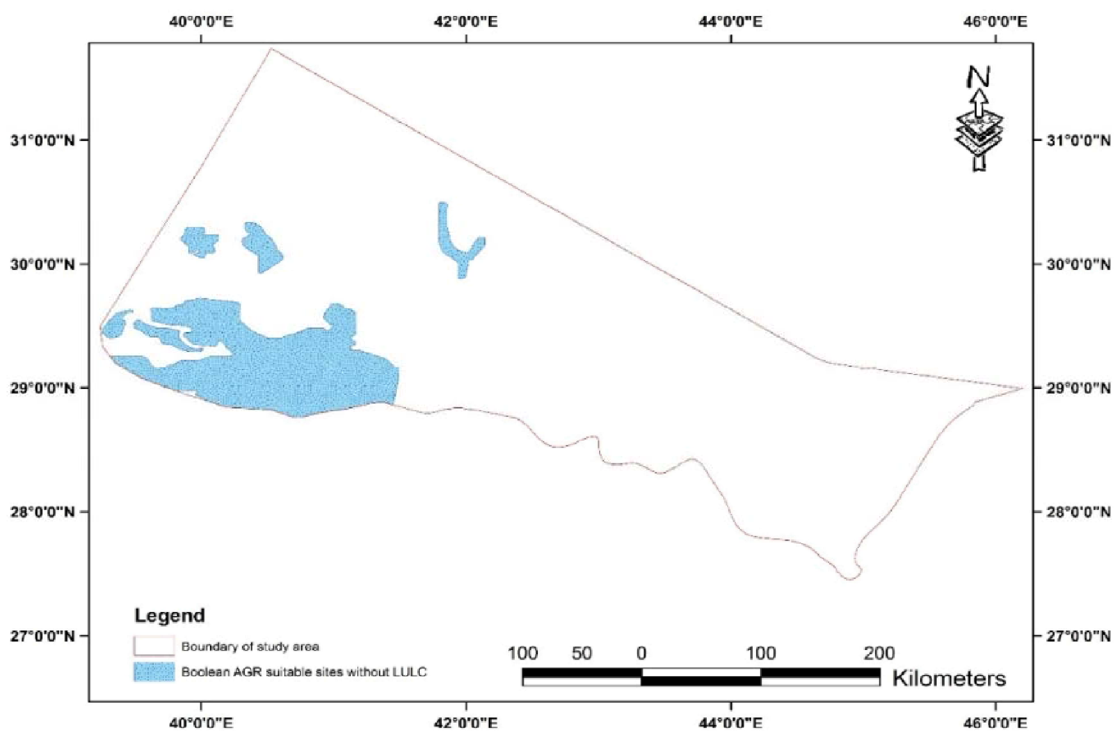

Fig. 19: Map of appropriate locations for AGR without layer of land use/land cover (using AND Boolean operator)

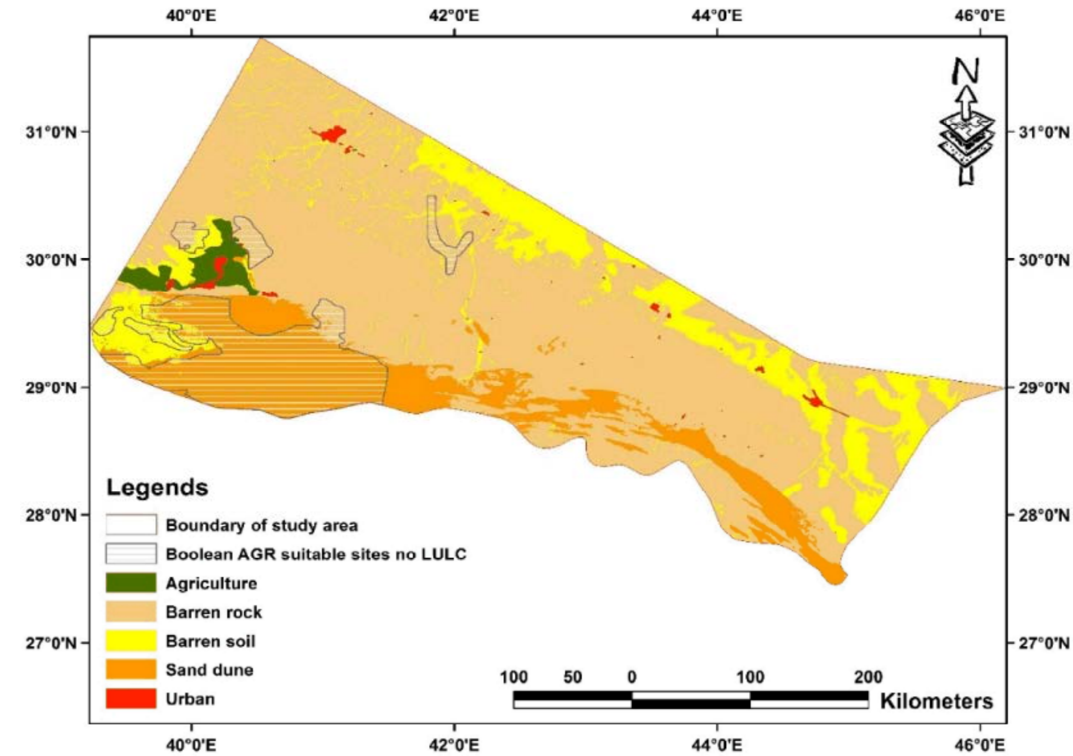

Fig. 20: LU/LC map superimposed on Boolean suitable sites

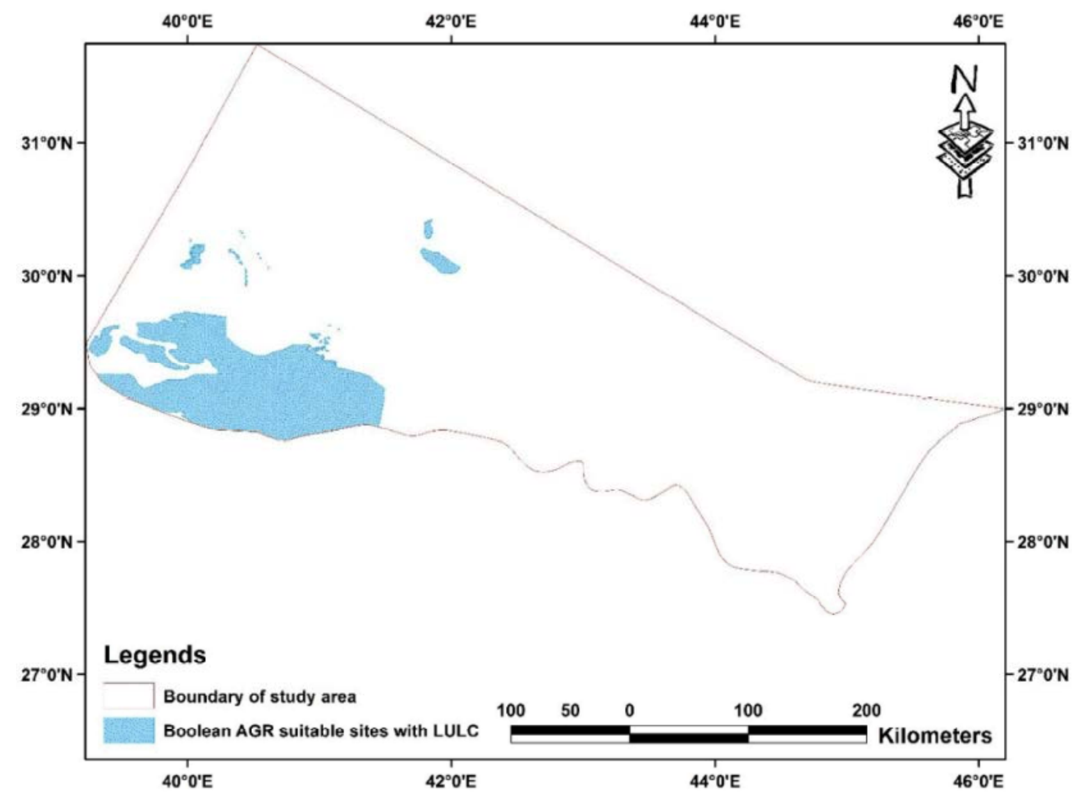

Fig. 21: Final Map of suitable sites for AGR including the land use/land cover based on Boolean logic

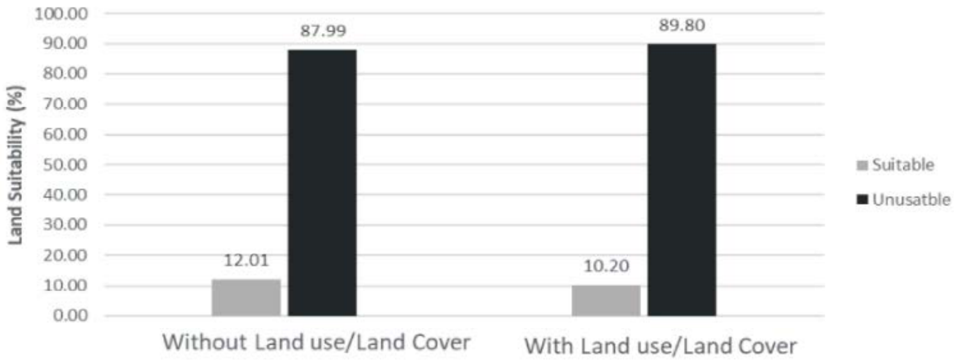

Fig. 22: Suitability bar chart showing the integrated results of Boolean logic for AGR site areas considering and without the land use/land cover using Boolean logic

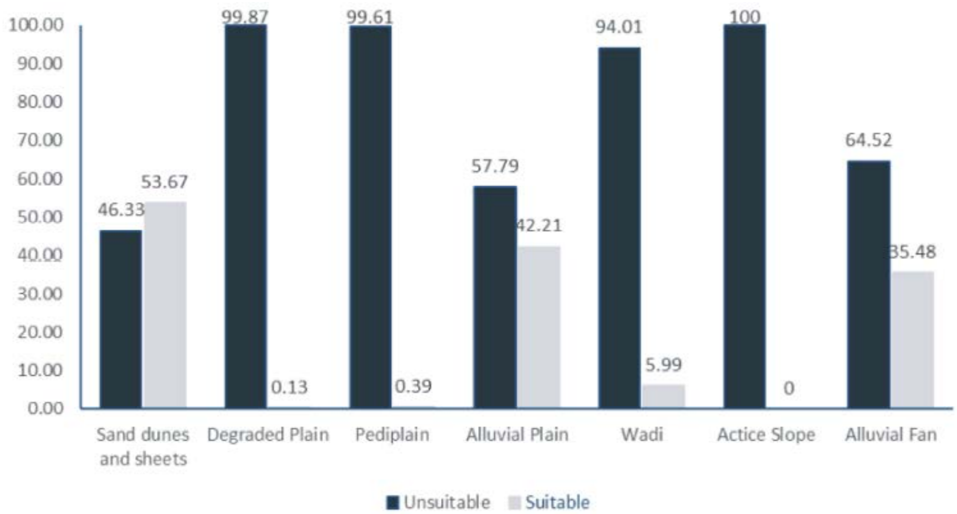

Fig. 23: Bar chart showing the area suitability for AGR sites with regard to geomorphological landforms units

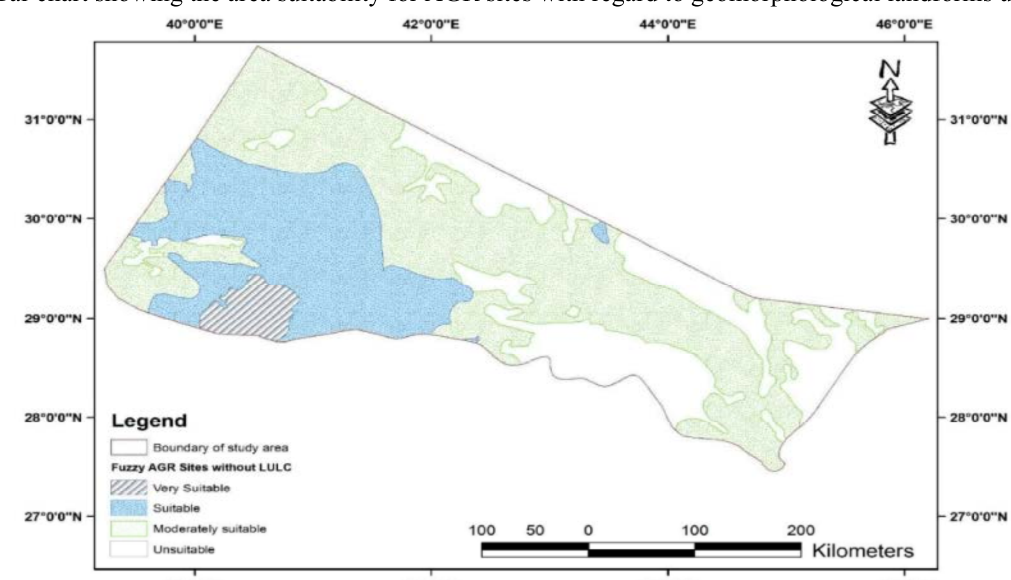

Fig. 24: Map of appropriate locations for AGR without layer of land use/land cover (using algebraic product operator of Fuzzy logic)

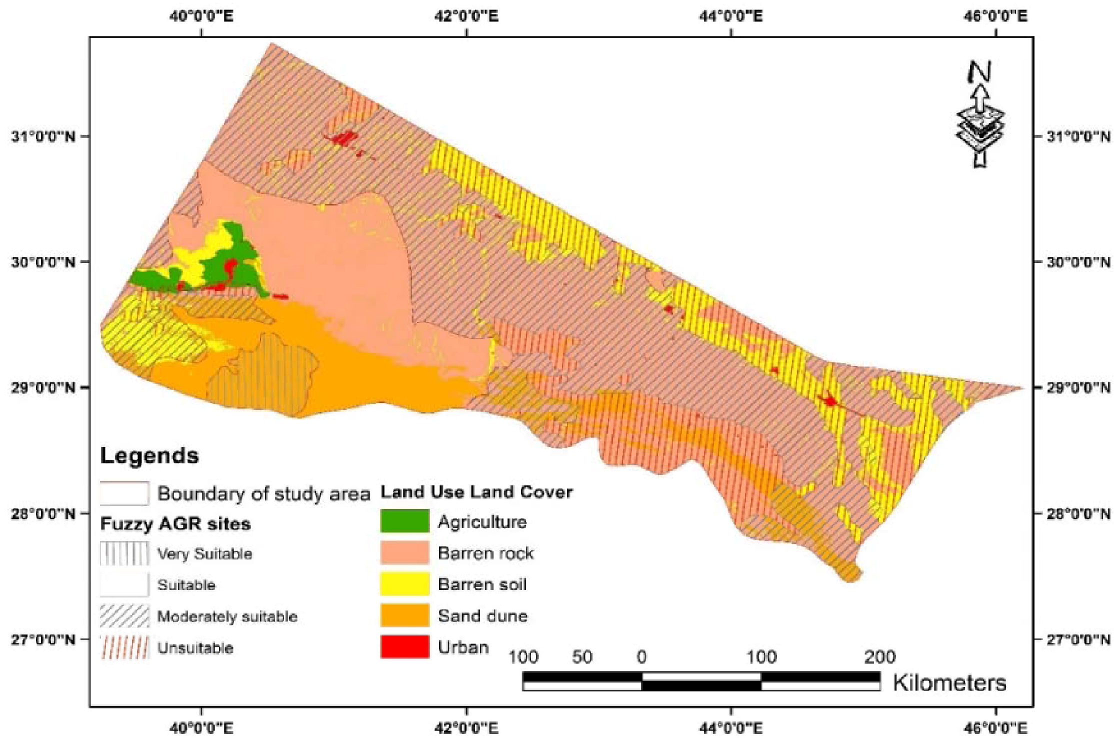

Fig. 25: LU/LC map superimposed on Fuzzy suitable sites

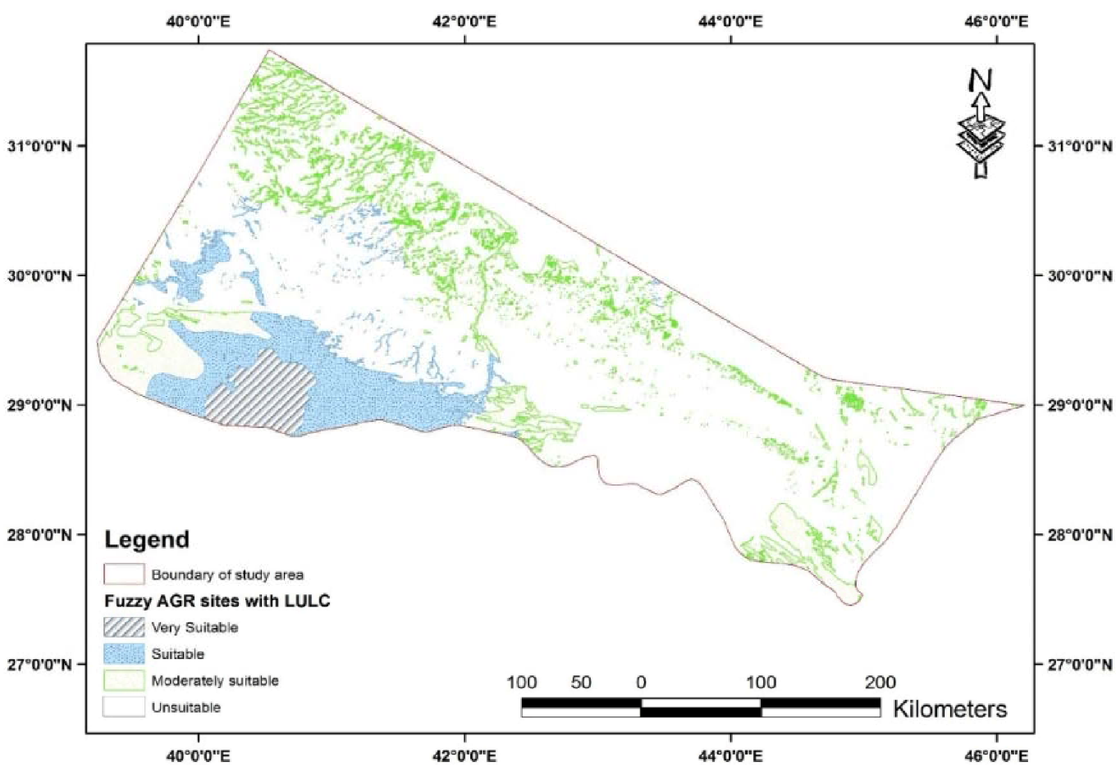

Fig. 26: Final Map of suitable sites for AGR including the land use/land cover based on Fuzzy logic

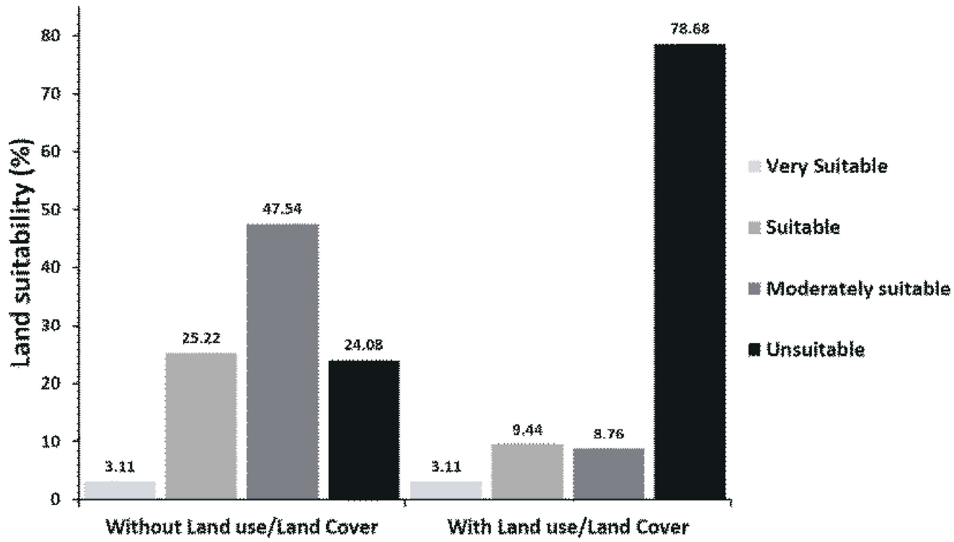

Fig. 27: Results of integrating basic maps using Fuzzy logic

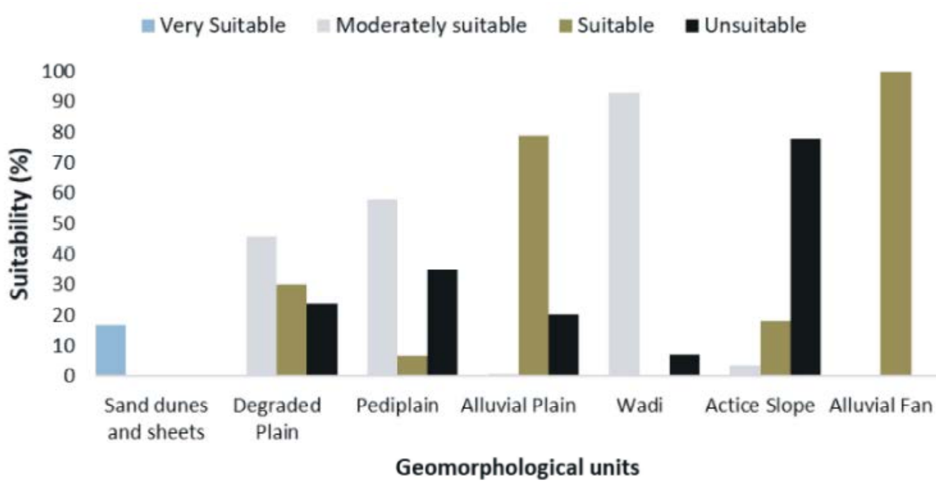

Fig. 28: Results of superimposing geomorphology and artificial recharge map of Fuzzy logic

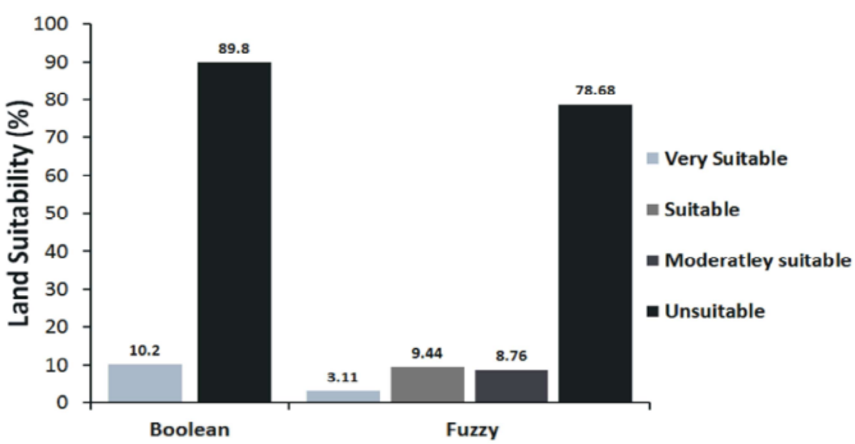

Fig. 29: Bar chart showing the comparison between the result of Boolean and Fuzzy techniques (with land use/land cover)

To achieve this objective, the potential AGR zones overlapping with the existing land use pattern as shown in Figure 20 were eliminated to produce a new map as shown in Figure 21. Figure 22 shows the total potential area for AGR with and without land use limitation. It can be seen that the potential AGR area is less (10.20 %) when the LU/LC map is also integrated.

In order to discuss the link between the possible suitable sites and geomorphological units, the landform map of the study area was integrated with initial identified potential AGR zones (without LU/LC). The graphical results (Figure 23) show that the sand dunes and sheets, alluvial plain and alluvial fan have the maximum percentage of AGR potential sites. Pediplain and degraded plain have minimal areas, where as areas covered by active slopes are not suitable at all.

Results of Fuzzy Logic: As it is generally inappropriate to give equal weightage to all of the parameters under consideration, therefore, all five layers of thematic maps were first weighted and reclassified as unsuitable, moderately suitable, suitable and very suitable depending upon their relative significance (Table 2). For AGR site selection, reclassified layers were combined by using Fuzzy "algebraic product" operator.

Initial output map as shown in figure 24, shows that 3.11% of the area was identified as very suitable, 25.22% suitable, 47.54% moderately suitable and 24.08% of the total area was unsuitable. Then, this resulted map was integrated with the filter map of land use/land cover (Figure 25) by superimposing the LU/LC map on initial fuzzy map and the results are shown in Figure 26.

The most effected classes by LC/LU are suitable and moderately suitable, as their areas reduced to 9.44% and 8.76% respectively. Unsuitable area was increased from 25.22% to 78.68% as compared in the bar chart of Figure 27.

The result of combination of the suitable areas for artificial groundwater recharge via application of Fuzzy logic and geomorphology map is shown in Figure 28. The figure expresses that sand dunes and sheet unit have the highest percentages for suitability mode. Alluvial fan, alluvial plain and wadis are moderately suitable to suitable.

CONCLUSION

In Boolean investigation, 10.20% of the land was found to be suitable (Figure 29), whereas in Fuzzy technique, 12.55% of the study area was suitable (very suitable and suitable) and 8.76% was moderately suitable.

Percentages of favorable areas in both algorithms were approximately equal. Fuzzy logic and Boolean logic operate similarly in terms of calculation of 100% appropriate and risk-free areas. The study involved the use of two methods for identifying the potential AGR sites namely the Boolean logic and Fuzzy logic, however based on the results obtained it is found that Fuzzy logic should be the more ideal method as it is based on a range of classifications for a given parameter rather than just classifying the parameter as suitable or unsuitable for recharge. However, there is a word of caution; as in any other study the quality of the results depends greatly on the quality of the input parameters and the judicious classification of the parameters by the researcher.

More site specific investigations are necessary if the AGR project is to be carried out in these areas such as detailed geological investigations, examination of existing well lithologsand information about the aquifer geometry. Geophysical investigations such as Electrical Resistivity surveys or Time domain electromagnetic surveys can assist in identifying the aquifer geometry and selecting the best possible sites and technique for recharge.

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