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Selection of Potential Sites for Artificial Groundwater Recharge Using GIS: a Case Study from North Western Saudi Arabia

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Abstract: The increasing aridity in the Arab region since the mid-Holocene climate change has resulted in human settlements relying heavily on the available groundwater resources. The exponential population growth and rapid urbanization in the Arabian Peninsula since the mid-twentieth century has put further pressure on the available deep seated groundwater resources. The need of the hour is to rely on better water management practices including artificial groundwater recharge (AGR) to augment the available groundwater reserves. Identifying potential groundwater recharge zones is a pre-requisite for any artificial recharge project. The present study deals with the identification of the potential AGR sites in north western Saudi Arabia. Thematic layers of parameters including slope, soil texture, vadose zone thickness, groundwater quality (TDS) and type of water bearing formation were integrated in a GIS environment using Boolean logic to select the best suitable sites. The results showed that 17.90 percent of the total investigated area is suitable for AGR. In order to avoid the use of agricultural and built up areas for AGR the identified zones were integrated with the land use/land cover map. This reduced the potential AGR area to 14.24 percent. Geomorphologically the wadi beds were found to be the most suitable for recharge. On the basis of the potential AGR zones proximity to the available recharge water supply (rain water, desalinated sea water and treated waste water) the potential zones were further classified into Category A (high priority) and Category B (low priority).

Key words: Arid Regions · Northwestern Saudi Arabia · Artificial Groundwater Recharge · Boolean Logic

INTRODUCTION

Over exploitation and mismanagement of the available freshwater resources coupled with the advancement in the field of drilling technologies and availability of cheap power have led to condition where aquifers are now being exploited at rates far in excess of natural recharge. This situation is particularly true in the arid and semi-arid areas of the world. Over-exploitation of the available water resources have already led to rapidly declining groundwater levels, saline water intrusions, land subsidence and droughts across many regions on the planet [1, 2, 3]. Global water scarcity studies carried out by different workers indicated that approximately two thirds of the world population will be affected by water scarcity in the next few decades [4, 5].

The normal groundwater recharge from precipitation is dependent on the climatic conditions (including the amount and intensity of precipitation), geology and land use pattern of the area. Natural recharge varies between 0 to 2 percent in the dry regions as opposed to 30 to 50 percent in temperate humid climates [6]. The low rainfall and high evaporation rates result in a practically negligible recharge from precipitation in arid area [7].

The ever increasing population which is linked with the industrial development, urbanization and food security, have directly contributed to the increasing water demands in the Arab region [8]. In the absence of plentiful surface water supplies, groundwater resources form the single most important source of fresh water supplies in these regions [9, 10, 11]. The ratio of the groundwater footprint to the area of the aquifer which is the means of assessing the groundwater stress in an area is one of the largest for Saudi Arabia [12]. According to the Saudi Arabia MoWE 2014 [13] reports, approximately 21.1 billion cubic meters of groundwater were extracted in the kingdom during the year 2012 of which approximately 81 percent of the water was used in agriculture. The situation gets more alarming considering the fact that most of these water resources are derived from the non-renewable

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groundwater reserves. At the present abstraction rates the reserves would be depleted in about 70 years.

Water resource management plans require effective management of aquifer recharge [14] so as to reduce the gap between water availability and water demand. This has re-established the context and relevance of centuries old practices of aquifer replenishment through artificial recharge and is gaining significance all over the world [15, 16, 17, 18]. Artificial recharge of groundwater is an effective technique of augmenting the available groundwater resources, thus avoiding the water (from rain, desalination or treated waste water) to be lost to the sea or by evaporation [19].

Artificial recharge techniques varies from direct surface/subsurface recharge to indirect recharge techniques, however before selecting a given technique it is necessary to identify the zones which will be most suitable for artificial recharge. GIS is one very useful technique where layered information from different thematic maps can be integrated quickly and can be used for identifying the potential zones [20, 21, 22, 23, 24, 25].

The objective of the present study was to integrate the thematic maps of the various factors such as slope (degree), soil texture, depth of vadose zone (m), type of water bearing formation, ambient groundwater quality (Total Dissolved Solids) and land use/land cover of the study area in a GIS environment using Boolean logic to determine the zones most suitable for AGR.

Study Area Description: The study area is located between latitudes 24° to 32°N and longitude 36° to 44°E and covers the Saq Aquifer (Fig. 1) which is one of the major groundwater sources located in the northwestern part of the Kingdom of Saudi Arabia, covering 375, 000 km^2 [26].

Geology and Hydrogeological Framework: The Arabian Peninsula can be divided into two main geologic units; a western part comprising of Pre Cambrian basement rocks known as the Arabian shield and an eastern part consisting of gradually thickening Phanerozic sedimentary sequence from west to east known as the Arabian Platform [27, 28]. The Saq Sandstone is found at the base of the sedimentary sequence and crops out in a strip unconformably overlying the basement and following the S-shape of the Arabian Shield (Fig. 1). Moving away from the contact with the basement towards the east, the overlying formations appear one after the other in chronological order [29]. The Cambro-Ordovician Saq formation comprising mainly of medium to coarse sandstones and ranging in thickness from 400 meters to 928 meters forms the major aquifer system in Northern Saudi Arabia [30].

The Saq aquifer receives a recharge of approximately 2.5mm/year in its outcrops along the Eastern margin of the Arabian shield. The rest of the aquifer is in a confined state overlain by progressively younger formations except for a small area to the North East of Buraidah in Qassim. At the scale of the entire Saq area, groundwater recharge most probably does not exceed 5 mm/year. The total volume of groundwater abstracted in the Saq area in 2005 (8, 727 Mm3/year) equals a water column of 24 mm covering the entire Saq area (~370, 000 km²). This is 5 to 10 times higher than the recharge occurring during the same period and is therefore not sustainable, [26]. There are seven aquifers or aquifer groups and from bottom to top they include:

- Saq Sandstone
- Kahfah sandstone
- Quwarah - Sarah sandstones
- Sharawra and Tawil sandstones
- Jubah sandstone
- Khuff limestone
- Secondary (Mesozoic) -Tertiary - Quaternary (STQ) sandstone and limestone.

Two layers act regionally as aquitards but they contain units that are locally exploited as aquifer:

- Jauf limestone and sandstone;
- Unayzah and Berwath sandstones.

Topography and Climate: The highest elevations are encountered in the mountains along the western boundary of the study area from the border with Jordan having elevations in excess of 1800 meters. The terrains along the western boundary of the Saq Basin are bordered by valleys with flat topography having elevations around 800 m. More than 85 percent of the study area is characterized by a flat topography gently dipping eastward from elevations near 900 m in the west to below 400 m along the eastern boundary.

The climate in the north and northwestern Saudi Arabia where the Saq Aquifer is the dominant groundwater resource is arid with low annual rainfall.

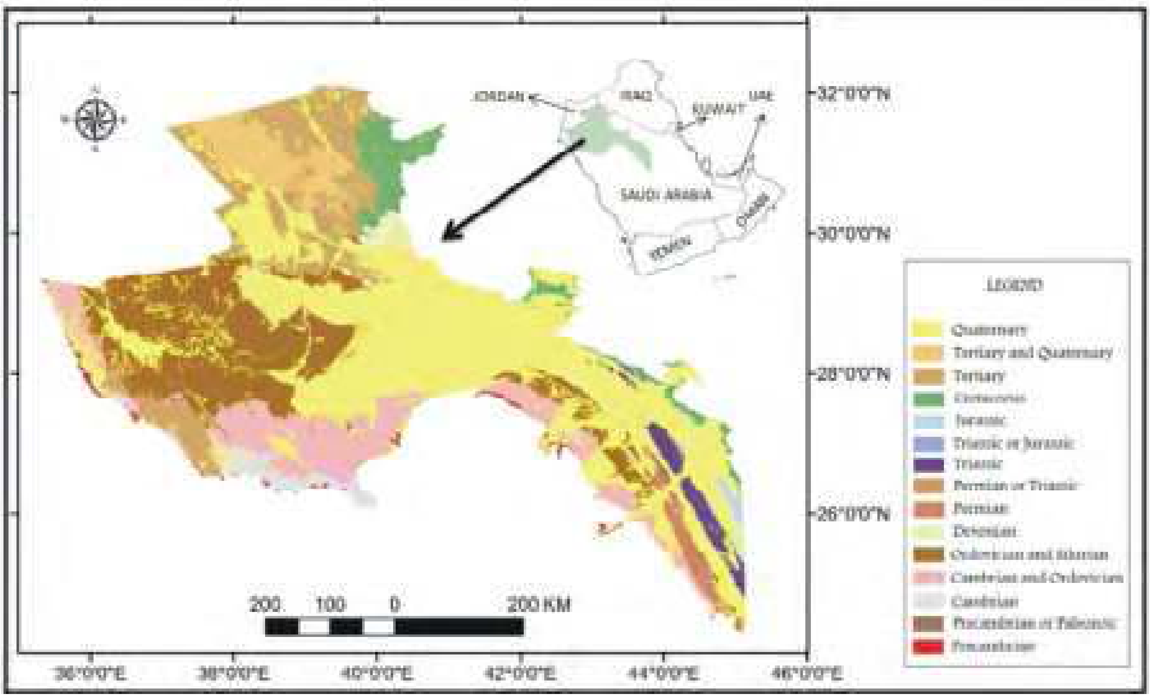

Fig. 1: Map showing the study area location and geology

Nevertheless some regional differences exist, with the lowest mean annual rainfall (less than 30 mm/year) being encountered in the western part of the area (Tabuk region) and the highest rainfall in the southeastern part (170 mm/year). With such a low rainfall and a potential evapotranspiration of nearly 2, 400 mm/year, groundwater recharge can only occur where concentration of runoff waters coincides with favorable infiltration characteristics of the surface layers. The temperature ranges from 43°C to 48° C during daytime and 32-36° C during night time in summer. In winter, it sometime falls to 0°C.

MATERIALS AND METHODS

There are numerous factors that may influence the AGR such as geology, climate, morphology, floods, land use and socio-economic behaviors [20]. In the present study six factors including slope, soil texture, vadose zone thickness, ambient groundwater quality (TDS), type of water bearing formation and land use of the study area were used to define the most appropriate sites for AGR. To achieve the desired results, multiple thematic maps were prepared from available data sets from previous studies, remote-sensing images and field investigations. Thematic layers for the above mentioned parameters were generated, classified and combined in a GIS environment by means of Boolean logic.

Boolean logical reasoning method is probably the most common and simplest type of GIS model used for thematic layers integration. George Boole, 1854 [31] introduced this method for the first time with a binary code classification system i.e. zero (unsatisfactory) and one (satisfactory). Boolean logic has its own operators which are AND, OR, NOT and XOR. Since the present research deals with integration of different thematic layers therefore AND Boolean operator was used. First time Boolean operation was used to prepare geological thematic maps by Robinov, 1989 [32]. According to Bonham-Carter, 1994 [33] Boolean modelling technique involves the logical combination of binary maps resulting from the application of conditional operators. Boolean helps to logically integrate various layers of evidence to support an assumption, or proposition. This technique also holds some drawbacks such as failure to consider some cases including priority of the factors, internal changes in each parameter, error in defining the conceptual model and the layers-error [34, 35].

RESULTS AND DISCUSSION

Six factors were considered for identifying the potential artificial recharge zones in the study area based on Boolean logic. The details of the factors and the suitable and unsuitable values for each of the factors have been discussed in the following sections.

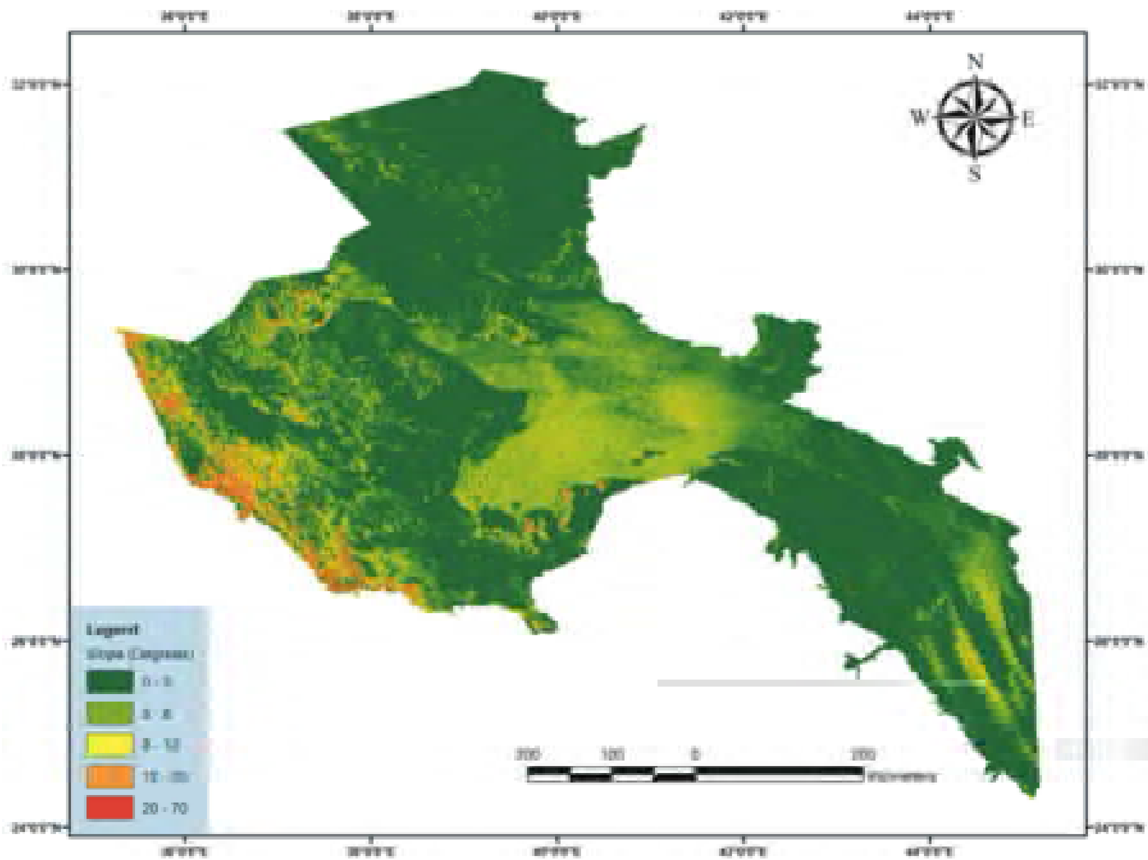

Fig. 2: Slope map of the study area

Slope: Slope is one of the major factors to discriminate the surface morphology (Flat lands & High lands) of the area. It directly governs surface water runoff, erosion, material transport and permeability. Water infiltration capacity is a function of the slope i.e maximum where the slope is minimum and vice versa [36]. Most of the study area consists of flat land and sand dunes. Digital Elevation Model (DEM) with 90m resolution acquired from SRTM was used to generate slope map using ArcGIS 10.2. On the slope map, slopes are classified into five broad classes. Fig. 2 shows the slope map of the study area. For the Boolean calculation areas having a slope of less than 2 degrees was considered suitable for artificial recharge and areas having slope in excess of 2 degrees was considered unsuitable.

Soil Texture: Another important factor controlling recharge implementation is the surface soil permeability. Areas of low relief (flat lands) coupled with low permeability will result in the ponding of water and eventually will be lost due to evaporation as a result of the extremely arid conditions prevailing in the region. Permeability greatly depends on soil characteristics, land cover and slope. Other things such as land cover and slope being the same soil permeability depends on the soil texture and soil structure. Soil permeability in the unsaturated zone is dependent on the soil texture and is one of the most crucial factors governing groundwater recharge [37]. Water Atlas of Saudi Arabia, 1984 [38] was the source for obtaining the soil texture map. The soil texture map was divided into five classes based on soil thickness, soil type, soil use, available water capacity and hydraulic conductivity (Fig. 3). Based on this map loamy/rocky and sandy/clay type of soil was classified as unsuitable for groundwater recharge whereas loamy, loamy/sandy and sandy soil were classified as suitable.

Vadose Zone Thickness/Depth to Water Table: The piezometric map was prepared from the water level measurements from 100 wells in the study area (Fig. 4a). The thickness of the vadose zone which is the zone between the surface elevation and the piezometric elevation was calculated and is shown in Fig. 4b. The cross-section along AA' and BB' shows the variation in

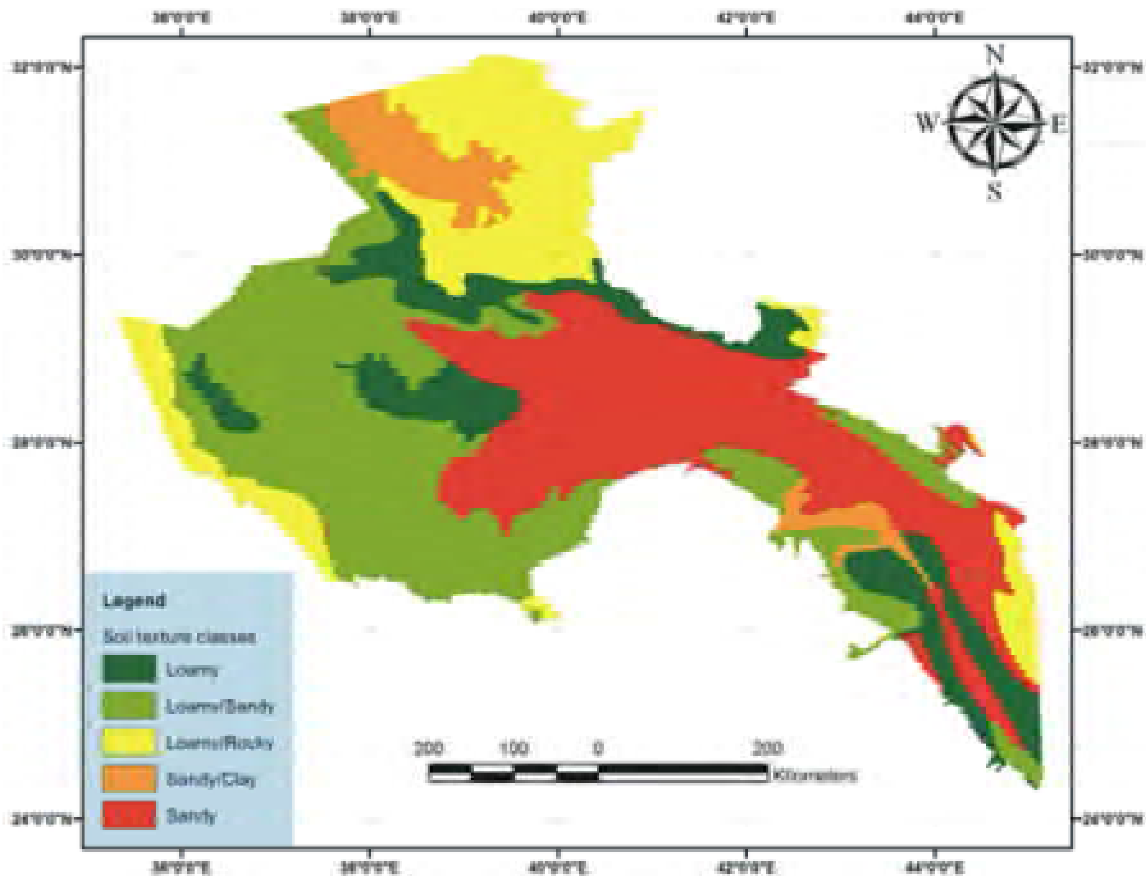

Fig. 3: Soil texture map

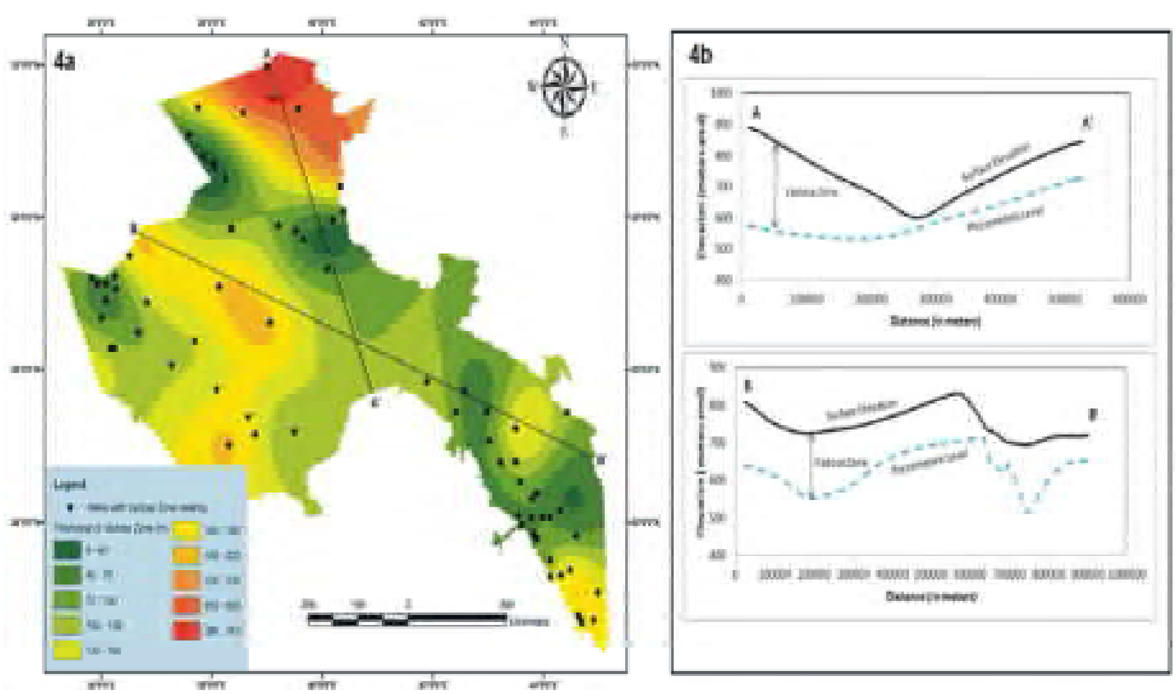

Fig. 4: 4a Vadose zone thickness map 4b Cross- section showing the thickness of vadose zone along AA' and BB'

the vadose zone thickness in the study area. Recharge rates decreases with the increasing depth to water table (greater thickness of vadose zone) and the recharge water takes a longer time to reach the water table [39]. A shallow vadose zone without intercalated impermeable layers is ideal for groundwater recharge as it reduces the travel time for the percolating recharge water to reach the water table [6]. However some studies have shown that a greater vadose zone thickness provides sufficient storage space and allows the water to move laterally rather than vertically after reaching the water table, [40, 41]. A shallow vadose zone if considered for AGR may also result in water logged conditions [20]. To avoid water logged conditions in areas of shallow water table and at the same time to reduce the travel time of percolating water to join the water table at greater depths a thickness of vadose zone between 20 meters to 140 meters was considered suitable. Areas having vadose zone thickness of less than 20 meters and in excess of 140 meters were considered unsuitable.

Groundwater Qualty (TDS): Rainfall is normally considered as the major source of recharge for groundwater. This water percolates all the way through surface soils to the subsurface rocks and finally makes it way to the aquifer. Due to the interaction of the percolating water with the earth material, the water quality is likely to change as the water is capable of dissolving many minerals present in the soils and rocks through which it passes. Therefore, the quality of the groundwater is an essential parameter to be considered for AGR and was investigated alongside other parameters. To quantify the nature of groundwater the total dissolved solids (TDS) was considered as basic criteria for quality assessment. TDS distribution maps were prepared from TDS measurements taken in 295 wells in the study area. Fig. 5 shows the location of all the sampled wells and the TDS distribution map for the study area.

Studies have shown that artificial recharge can help in improvement of the ambient groundwater quality [42, 43]. However in the present study, keeping in mind the limited availability of recharge water (either from rains, desalination or waste water) the focus was more on replenishing the groundwater resources rather than improving the ambient groundwater quality. To strike a balance between the ambient groundwater quality and aquifer replenishment only those areas showing TDS concentrations of less than 600 mg/l were designated as suitable for artificial recharge where-as those in excess of 600 mg/l were classified as unsuitable. For ease of integration of the TDS map with other parameters using Boolean logic the TDS data were transformed to log base 2.

Type of Water Bearing Formation: The characteristic of water bearing formation where the recharged water will be stored is an important factor to be considered in any artificial recharge feasibility studies [6]. If the geological formation does not have enough permeability and storativity, it may lead to ineffective groundwater recharge. Considering this factor the entire study area was classified as aquifer, aquitard and aquiclude, (Fig. 6) based on litholog information of the drilled wells from earlier studies. The areas covered by the aquifer were considered as suitable whereas the areas covered by aquiclude and aquitard were considered unsuitable for groundwater recharge.

Land Use/Land Cover: To address the human intervention related to AGR research, a separate parameter called Land Use/Land Cover (LU/LC) was investigated. Agricultural developments can lead to increased groundwater recharge [44]. Changes in LU/LC can alter the recharge rates which can have negative impacts on groundwater quality; especially in arid and semi-arid regions [46]. LU/LC map for the study area was prepared from the Landsat satellite imagery. Subsequently it was divided in to 5 major classes based on the NDVI values (Fig. 7). To avoid the potential artificial recharge zones from falling within agricultural and urban areas and to have a further negative impact on groundwater quality, these zones were classified as unsuitable. The areas occupied by rocky outcrops (barren rocks) were also designated as unsuitable. Sand dunes and barren soils were designated as suitable zones.

All the above parameters' thematic layers were integrated to generate the final potential zones of artificial groundwater recharge. Feasibility of these AGR sites was further analyzed based on the availability of nearby water source. The possible water sources for AGR in the current study were identified as natural streams, desalination plants and sewerage treatment plants.

Classification and Integration of Thematic Layers Using Boolean Logic: There are different methods for logical reasoning, classification and integration of thematic layers. In current research Boolean logic is adopted to reclassify the integrated maps in to suitable and unsuitable classes for AGR. Zero and unity value was assigned to unsuitable and suitable areas, respectively.

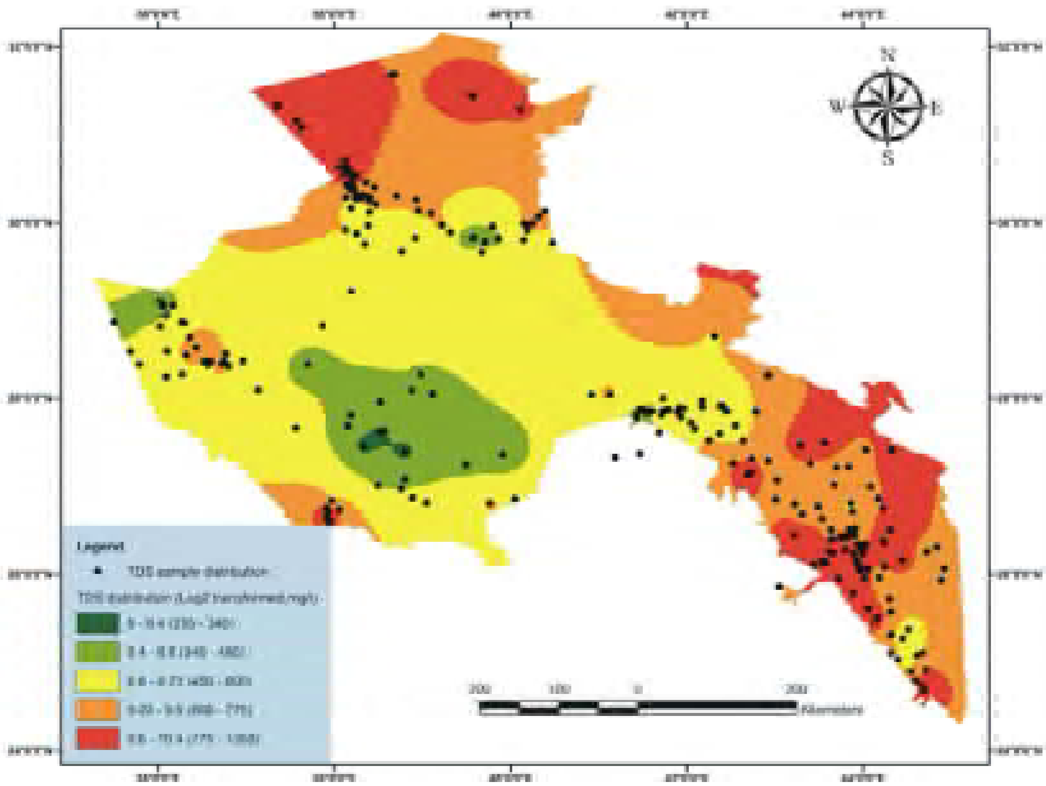

Fig. 5: Groundwater Quality (TDS distribution map) with well location map

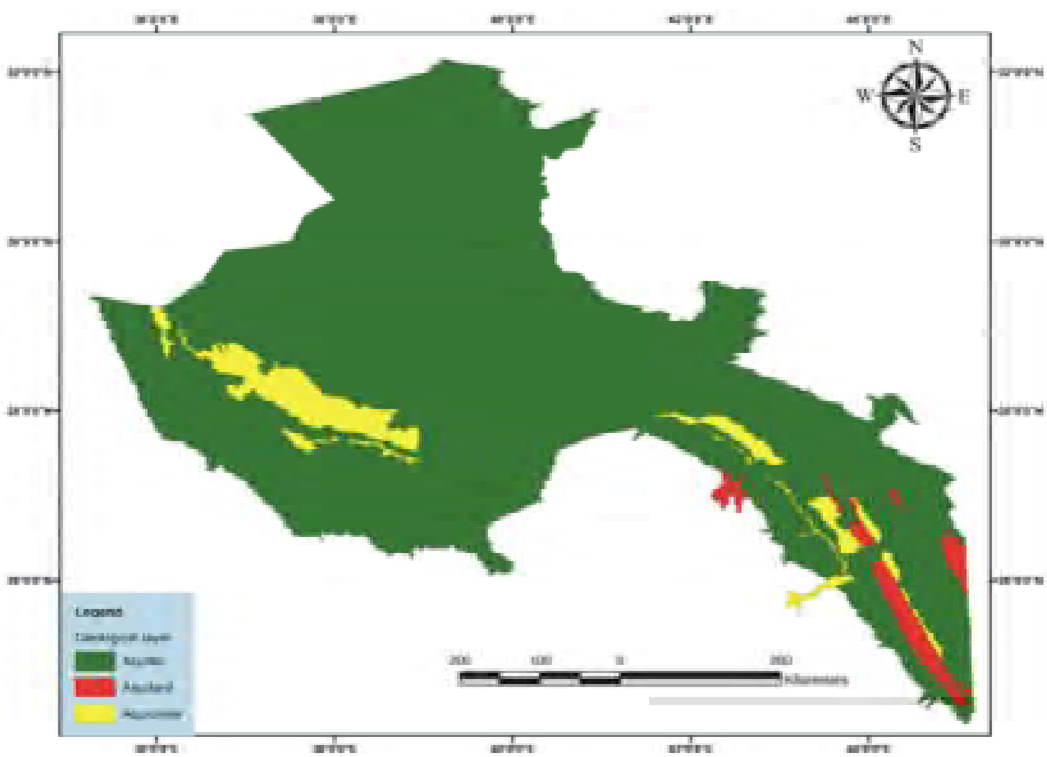

Fig. 6: Map showing the type of water bearing formation in the study area

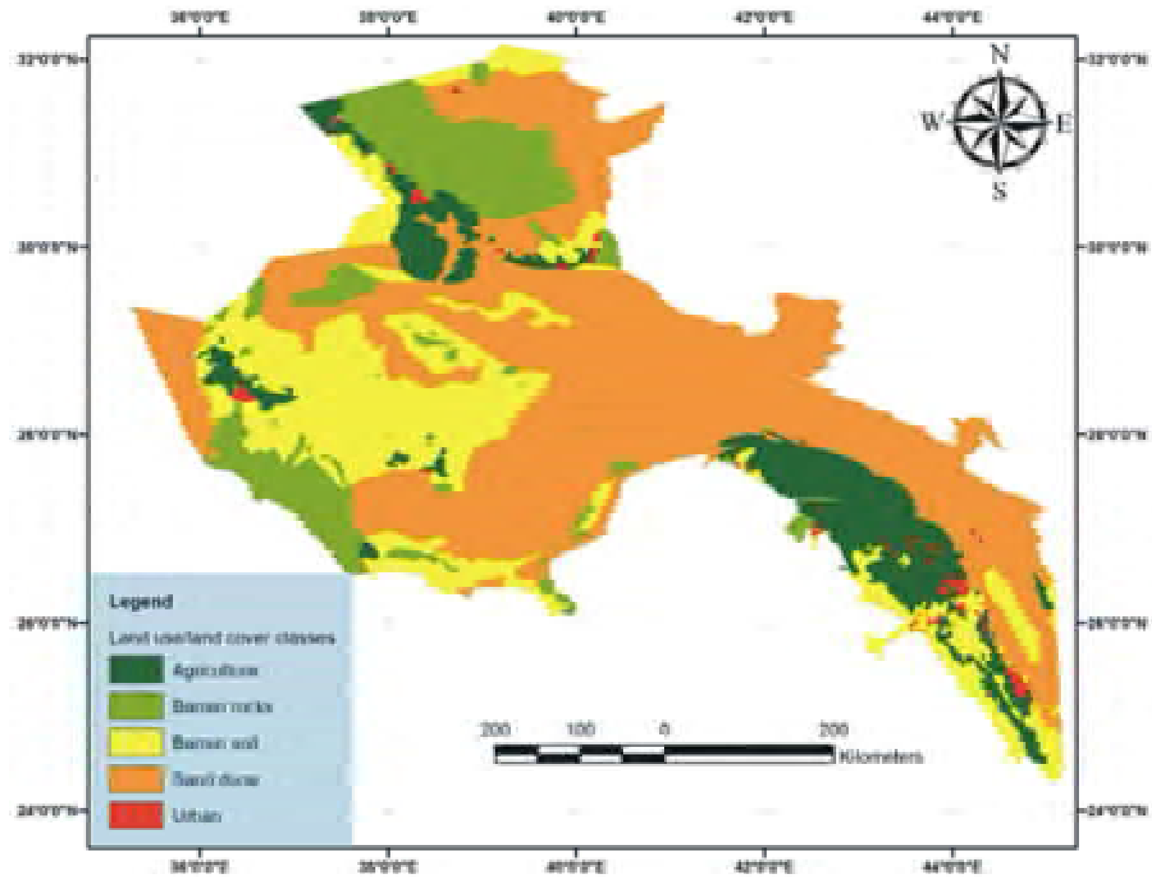

Fig. 7: Land use/ Land cover map

Table 1: Thematic layers with their classes used in Boolean logic

Thematic layers	Classes	Ranges	Boolean binary weight
Slope (degree)	Suitable	0-2	1
	Unsuitable	More than 2	0
Soil Texture	Suitable	Loamy Loamy / Sandy Sandy	1
	Unsuitable	Loamy / Rocky Sandy / Clay	0
Vadose Zone thickness (m)	Suitable	20 - 140	1
	Unsuitable	0 - 20 >140	0
Ambient groundwater quality, TDS(mg/l)	Suitable	Less than 600 (log_2 transformed value 9.23)	1
	Unsuitable	More than 600 (log2 transformed value 9.23)	0
Type of water bearing formation	Suitable	Aquifer	1
	Unsuitable	Aquiclude Aquitard	0
Land use/Land cover	Suitable	Sand dune Barren soil	1
	Unsuitable	Urban Barren rocks Agriculture	0

The thematic layers are classified and their binary logical map was developed using Boolean logic in GIS environment (Table 1). Slope (degree), soil texture, vadose zone thickness, ambient groundwater quality (TDS) and type of water bearing formation were used as the basic input for Boolean operations. The land use/land cover map was used as a filter map to avoid urban and agricultural area. After producing layers of individual parameters by application of Boolean binary logic (0 for unsuitable zones and 1 for suitable zones) and operator was used to combine all thematic layers to render the final potential AGR sites.

Boolean Result Discussion: Thematic layers given in the Table 1 were combined using the AND operator and finally a map of potential areas for AGR obtained.

Fig. 8: AGR suitable sites without land use/land cover layer obtained by using AND Boolean operator

Fig. 9: AGR suitable sites considering with land use/land cover

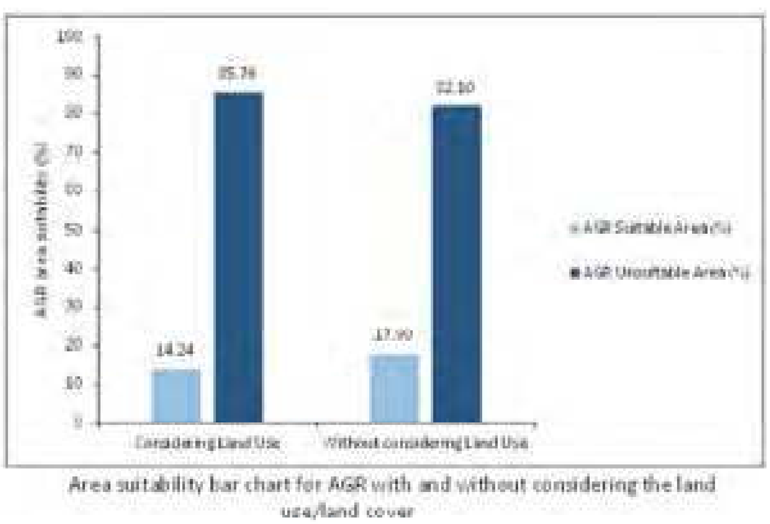

Fig. 10: Area suitability bar chart for AGR with and without considering the land use/land cover

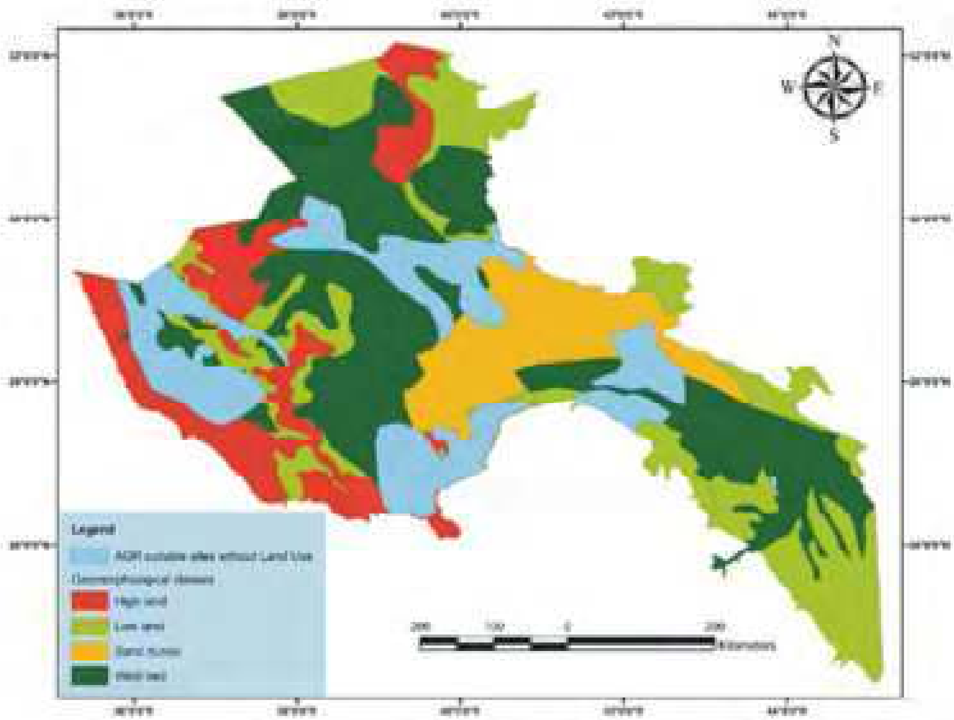

Fig. 11: Superimposed map of geomorphological units and AGR suitable sites (without considering land use

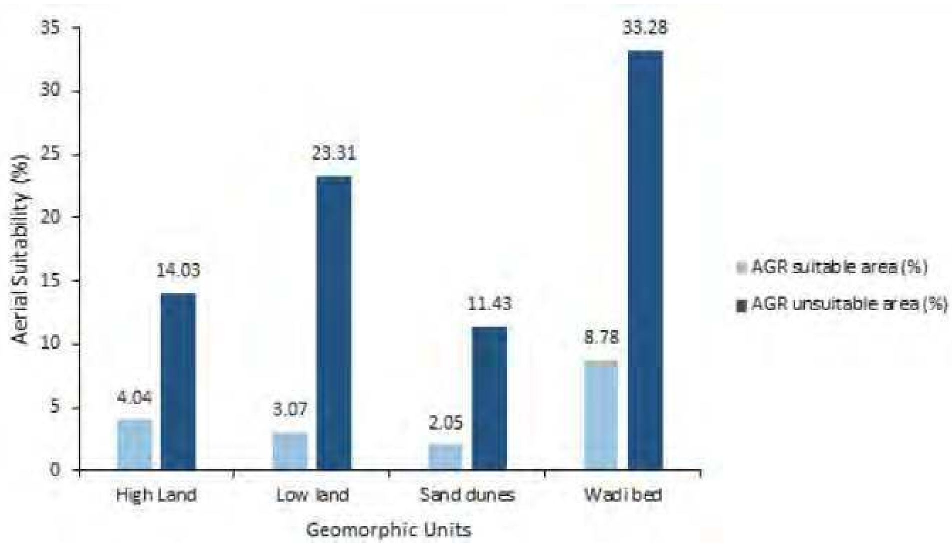

Fig. 12: Area suitability bar chart for AGR sites with respect to geomorphological units

Initially, 5 thematic layers were combined without the LU/LC layer (Fig. 8) which resulted in the suitability of 17.90 percent of the total area under study as potential zones for AGR, (Fig. 10). Next the LU/LC thematic layer was integrated with the other 5 layers and the identified potential zones for AGR is given in Fig. 9. Due to addition of land use/land cover filter the final AGR suitable area decreased to 14.24%. Therefore, it is concluded that of the total 17.90% area suitable for AGR, 3.66% is restricted by the LU/LC (Fig. 10). The map of the geomorphologic units in the study area (Fig. 11) was superimposed on the identified potential AGR zone (without considering LU/LC). The graphical representation (Fig. 12) shows that the wadi beds occupy the maximum share of AGR potential sites followed by the highlands, low lands and sand dunes.

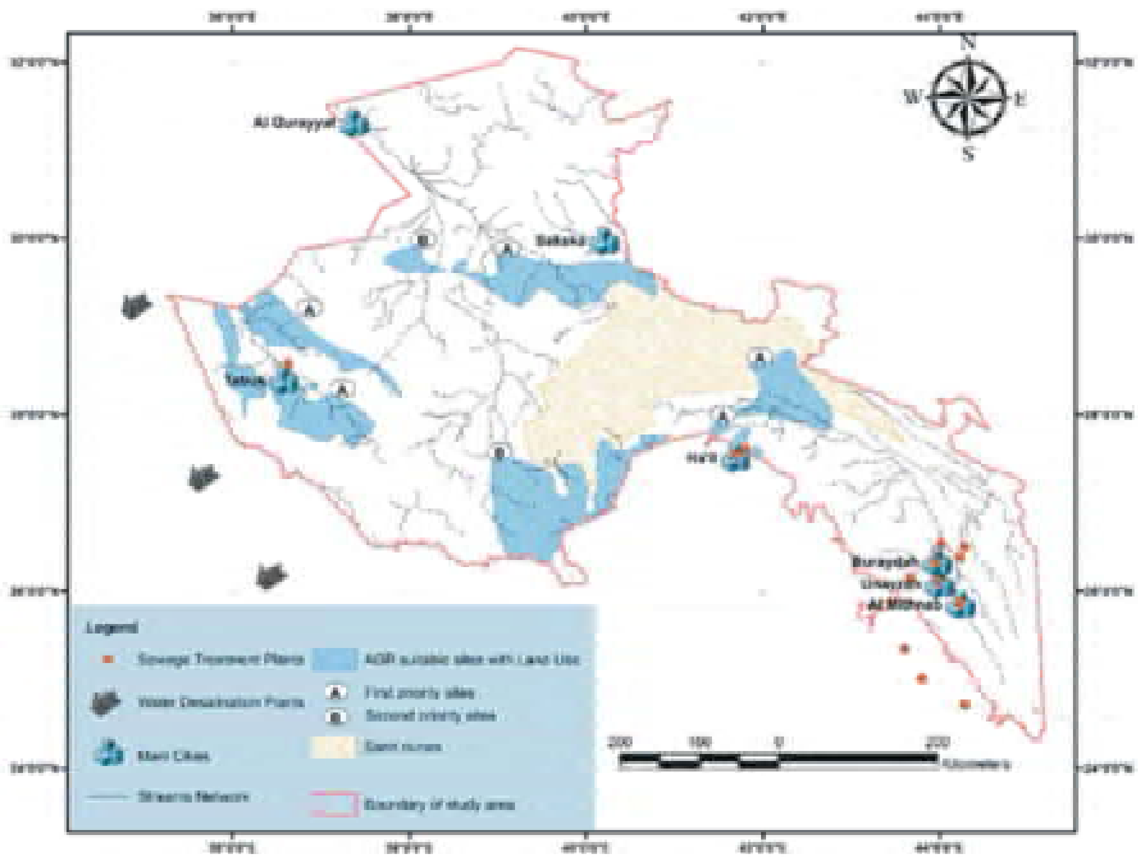

Fig. 13: AGR sites' selection based on the proximity analysis

Finally a proximity analysis was carried out based on the proximity of the identified potential AGR zone (considering LU/LC) to the drainage network, desalination plants and sewage treatment plants. Base on this map the AGR potential sites were further classified into categories “A” & “B”. Category “A” refers to first priority sites for artificial recharge based on their proximity to available water sources (Stream network, Desalination & Sewage Plants), while category “B” refers to second priority sites for artificial recharge (Fig. 13).

CONCLUSION

Artificial groundwater recharge is considered as one of the simplest ways of reducing the water demand and supply gap as it results in augmenting the available groundwater resources and is practiced in many regions across the world. In arid countries like Saudi Arabia where there is very limited availability of surface water and heavy dependence on groundwater AGR becomes even more important, however the success of any AGR project depends upon the precise selection of the AGR sites. In the present study detection of sites suitable for effective groundwater recharge was carried out for North western part of Saudi Arabia, a region which hydrogeologically comprises of the Saq aquifer. Thematic maps of the various parameters such as slope, soil texture, vadose zone thickness, ambient groundwater quality (TDS) and type of water bearing formation were integrated in GIS using Boolean logic to classify the area as suitable or unsuitable for AGR.

The innovation in the present study was to integrate the land use pattern with the other parameters so as to filter out the agricultural and urban areas in the final consideration of the suitable sites. The study reveals that 17.90 percent of the total study area was suitable for recharge without taking in consideration the land use/land cover pattern. However integration of the land use in the final result reduced the areas suitable for recharge to 14.24 percent. Taking into account the geomorphic units it was found that the wadi beds are most suitable for AGR whereas the sand dunes have the minimum potential for AGR. Since the rainfall in the region is very limited, artificial recharge of groundwater cannot be restricted only to rainwater recharge. Other sources such as treated waste water and excess desalinated sea water are also considered as the potential sources of recharging groundwater. This will not only help in replenishing the groundwater reserves but also prevent evaporation losses if they otherwise they are discharged in the open valleys. The final output map of the suitable recharge sites were further categorized into Priority A and Priority B areas depending on the proximity of the recharge sites to stream networks, sewage treatment plants and desalination plants. The type of recharge methodology to be adopted is beyond the scope of this work and requires site specific investigations on the identified potential AGR zones in this study.

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