Use of Space Technologies and GIS to Study Groundwater Potential Zones in the Western Coast of the Kingdom of Saudi Arabia

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Abstract

The problem of water shortage has been increasingly developed due to the climate change and growth in the population size. Also, the loss of water through the discharges into the sea is added to this problem. Therefore, water issues have become of great concern, notably in arid regions, and the Arabian Peninsula is a typical example. It has an average precipitation rate of less than 200mm, besides high evaporation rate that exceeds 60% of precipitated water.

The western coast of the Kingdom of Saudi Arabia is an area under water-stress; especially in the regions where the Holly cities are located. However, the available on water resources are still inadequate and incomprehensive, because the area has rugged topography and it is relatively vast to work on. This, in turn, exposes the essential role of space technology studying such areas. In this respect, satellite images, and more certainly those characterized with high spatial resolution, are able to identify different clues on the geomorphological and geological features, which can provide information on groundwater storage and flow conduits.

This study is a typical example to the use of space technology and Geographic Information System GIS, which are applied on Wadi Aurnah Watershed. Hence, satellite images of Landsat 7 ETM+ and ASTER were processed using ERDAS Imagine software, among which the major elements controlling groundwater accumulation and flow were determined. The majority of these elements are: rainfall, drainage systems, lineaments, lithology and land cover/ use. All these elements were manipulated in GIS system, and each of them was given a certain rate of effectiveness. Thus, a map describing groundwater potential zones was produced. It shows five major zones with different possibilities for groundwater storage, as well as it reveals the major groundwater conduits that transport water to the sea. Therefore, a range between 15-20% of the studies area is characterized by high groundwater potentiality. This is located mainly in areas where effective geologic structures exist, and more certainly along the major faults that divided the area into tectonic blocks.

Keyword*:* *geomorphology, groundwater, faults, Landsat7, Arabian Peninsula.*

1. Introduction

The Arabian Peninsula is known as a water-scarce region, where the precipitation rate does not exceed (in average) 100mm/year, besides an intensive evaporation rate, may reach 60%. Therefore, water resources are witnessing an obvious shortage that reflected on the socio-economic conditions. This is well increased with the dramatic population growth and the variability in climatic conditions.

The Arabian Peninsula occupies a number of large-scale streams, which are almost directed to the sea, but they are often dry all year long. These streams run water only during the torrential rain periods and for a limited time interval (i.e., a couple of days). Recently, most of the known springs have been dried, while the depth of groundwater level has been increased some several meters. Hence, water resources in the Arabian Peninsula are non-renewable in many aquifers, which is an alarming condition worth to be considered.

This hydrologic condition led the government to take action plans and several implementations to compensate water supply deficit. Examples of these implements are: the earth dams and channels, desalination of seawater as well as import of bottled water. However, the problem still exists and develops.

The geological setting of the Arabian Peninsula exposes a miscellany of rock formations capable to bear groundwater (Moor and Al-Rehaili, 1989; Sahl, 1987). This is well pronounced due to the existing fracture systems in hard rock massive. In addition, the porous sedimentary rocks (e.g. sandstone and gravel formations) contribute essentially in groundwater storage.

The exploration of groundwater has followed many methods. Some of them were succeeded, whilst others were not. Hence, a need for reliable method is an outmost issue of concern.

For groundwater exploration, all alternatives should be considered in selecting a suitable site for successful exploration. The survey usually consists of examining topographic and geologic maps, as well as available logs and reports of existing wells, and then a field reconnaissance on the area will done. This is followed by detailed study using methods such as test borings, fracture-trace analyses and geophysical survey (Fetter, 1994).

Recently, the development of remote sensing (RS) and Geographic Information System (GIS) techniques makes it easier and more accessible in getting supplementary information needed for ground water exploration, and almost on large-scale areas, like the current case study.

There are several applied studies used remotely sensed data (Meisler, 1963; Rauch & La Riccia, 1978; Taylor, 1980; Ahmeh et al., 1984; El-Baz, 1992; Savane et al., 1996; and Das, 2000). However, the implements of data extraction and interpretation do not follow the same procedures. This is why different results exist.

The use of remote sensing and GIS tools in groundwater assessment cannot be directly obtained, like the case of surface waters where terrain signatures can be directly observed. Nevertheless, it depends on surficial signatures that are indicative to favourable subsurface structures and lithologies.

This study aims to introduce a helpful procedure for groundwater exploration using remote sensing and GIS tools. Thus, groundwater potential zones are aimed to be determined in Wadi Aurnah (3110 km^2) catchment in the western side of the Arabian Peninsula, which represents a typical catchment area in the whole peninsula (Fig.1).

Wadi Aurnah is one of the major five catchments in the central part of the Tihamah-Hijaz (middle part of the Arabian Shield) region. It lies between the following geographic coordinates:

39° 12′ 00" E; 40° 18′ 00" E and
21° 01′ 30" N; 21° 35′ 30"N.

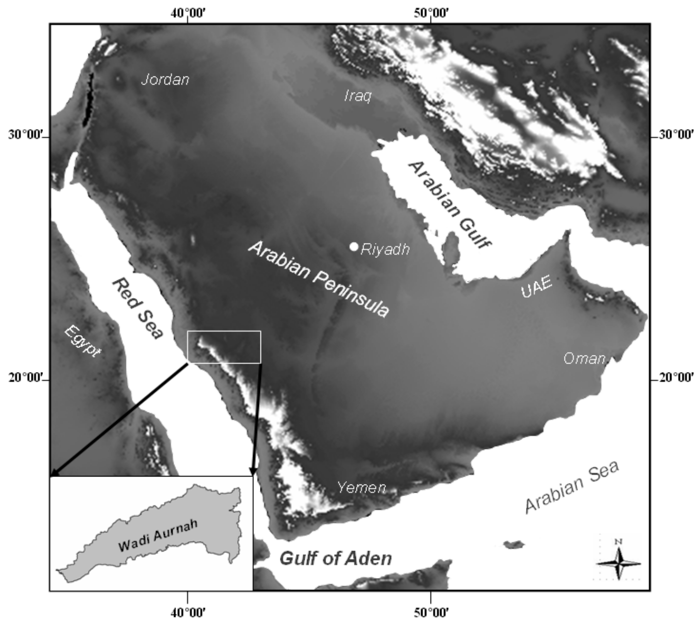

Figure 1. Location map of the study area.

2. Materials and Methods

Several applications have been created to explore groundwater by conventional methods. However, in the last two decades remote sensing techniques have been involved in groundwater assessment, and thus proved to be a useful tool.

These tools utilize different terrain signatures that can be observed from satellite data. The extracted signatures will be manipulated in GIS systems as factors influencing groundwater storage and flow.

Previously, the used factors were different from one study to another, and even the GIS manipulation followed different approaches. Therefore, the resulting information was contradicted. For example, one used only the lineaments in ground water assessment (Rauch, 1984), other utilized lineaments and drainage density (Ahmad et al., 1984). Whilst, geomorphic features, land cover, vegetation and geologic units were used in other studies (El Shazly et al, 1983).

In many case studies, the reliability of results was not convenient. This is attributed to the diversity of used factors and the manner of their integration with each other.

Table 1 shows selective studies obtained to determine groundwater potential zones in different regions of the world. It reveals different levels of satisfaction for the used factors, which must be different from one region to another.

Author	Year	Parameters	Results
Meisler	1963	Lineaments	Unsatisfactory
Rauch & LaRiccia	1978	Lineaments	Unsatisfactory
Taylor	1980	Lineaments & fracture traces	Unsatisfactory
El Shazly et al.	1983	Geomorphic features, land cover, vegetation and geologic units	Assumption*
Seelan	1983	Lithology, morphology, soil and land use	Unsatisfactory
Salman	1983	Drainage characteristics	Assumption
Ahmed et al.	1984	Lineaments and drainage intensity	Assumption
El-Baz	1992	Topography, lineaments and drainage	Satisfactory
Gustafsson	1994	Lineaments and vegetation	Satisfactory
Teeuw	1995	Lineaments	Satisfactory
Per Sander et al.	1996	Vegetation, drainage, lithology and lineaments	Satisfactory
Savane et al.	1996	Lithology and lineaments	Satisfactory
Edet et al.	1998	Lineaments and drainage	Satisfactory
Robinson et al.	1999	Drainage and lineaments	Assumption
Das	2000	Geology, geomorphology, soils, land cover/ land use and lineaments	Assumption
Bilal & Ammar	2002	Lineaments, drainage and lithology	Satisfactory
Shaban	2003	Lineaments, drainage and lithology	Satisfactory
Sener et al.	2005	Geology, lineaments, land use	Satisfactory
Kumar et al.	2007	Geomorphology, geology, fractures, slope	Satisfactory

Table 1. Selective studies used remote sensing for groundwater exploration.

There are several major factors controlling groundwater storage. First, is the rainfall, which must be available as a source to recharge groundwater.

In addition to rainfall, a terrain with permeable rock type and intensive rock fractures permits surface water to flow into deep rock stratum. Whilst, low recharge area prevents water to percolate and thus enhances surface water flow, then composing dense drainage network. Therefore, in such a case, the lithology and structure must be involved in determining groundwater potential zones. This is also applied to the density of drainage. Hence, they are considered as influencing factors.

In addition, the existence of dense human settlements does not allow water to percolate into rocks. Therefore, land cover/use can be involved as another two influencing factors.

In this study, five major factors were considered to compose a groundwater potential zones map. They influence water flow regime and accumulation in an arid region like the Arabian Peninsula. These are the: rainfall, lithology, rock fracture, drainage and land cover/use. Remotely sensed data contributes in identifying these factors at different levels. For example, rock fractures can be completely done from remote sensing, lithology can be obtained partially, whilst rainfall can be utilized from gauging records.

Each of these factors has its own element of influence as a controlling element on groundwater storage and flow. They are summarized in Table 2.

Influencing factor	Influencing element	Controlling element
Rainfall	Rainfall rate	Water as a source
Lithology	Rock type	Water permeability
Rock fracture	Fracture systems	
Drainage	Density	Water permeability and flow
Land cover/ use	Imperviousness	

Table 2. Selective studies used remote sensing for groundwater exploration.

Each of these factors was identified separately and considered as a layer. The integration of these layers will be done into the GIS system. Therefore, for each factor, a layer with five classes was achieved.

2.1. Rainfall

Rainfall is the major source of groundwater, thus areas with heavily rainfall amounts usually found to be plenty with groundwater and vice versa. Therefore, arid regions, often have low rainfall rates.

Wadi Aurnah is an example, where the rate of rainfall water is low (less than 200 mm). However, the geographic distribution of isohyets is different all over the region. It is clearly found that the elevated areas receive much more amounts than the low-land area. For example, on the elevated areas rainfall rate may reach 200mm, while it does not exceed 50mm in the coastal region

Thus, the obtained map by Awari (2005) was merged with recent climatic data done by the Organization of Forecast and Environmental Protection Research (2006), then classified into five major classes. Each class represents an interval of rainfall rate. It was classified as: >175, 150-175, 125-150, and 100-125 and <100 mm (Figure 2).

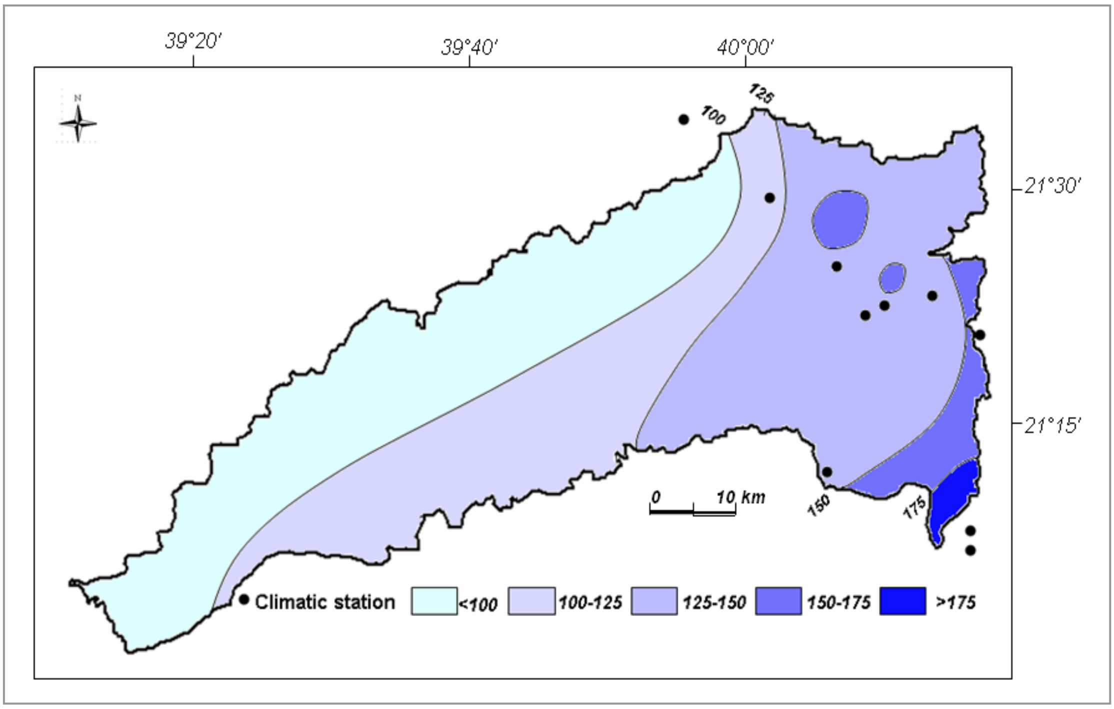

Figure 2. Rainfall map of Wadi Aurnah basin

2.2. Lithology

The distribution of different lithologic formations was adopted from the available geological maps of 1:50000-scale (Moor and Al-Rehaili, 1989; Sahl, 1987). They were used as base maps for further modifications by remote sensing. In this study, additional information on different lithologies was obtained from *ASTER* and *Landsat 7 ETM* satellite images.

ERDAS Imagine software was utilized since it owns a number of digital advantages. Thus, the combination of bands 7, 4 and 2, as well as the application of different advantages of filtering and contrasting distinguished the image units, which combined the textural and pattern attributes of the terrain surface. Thus, visual tracing of many lithological patches and their boundaries were plotted (Figure 3).

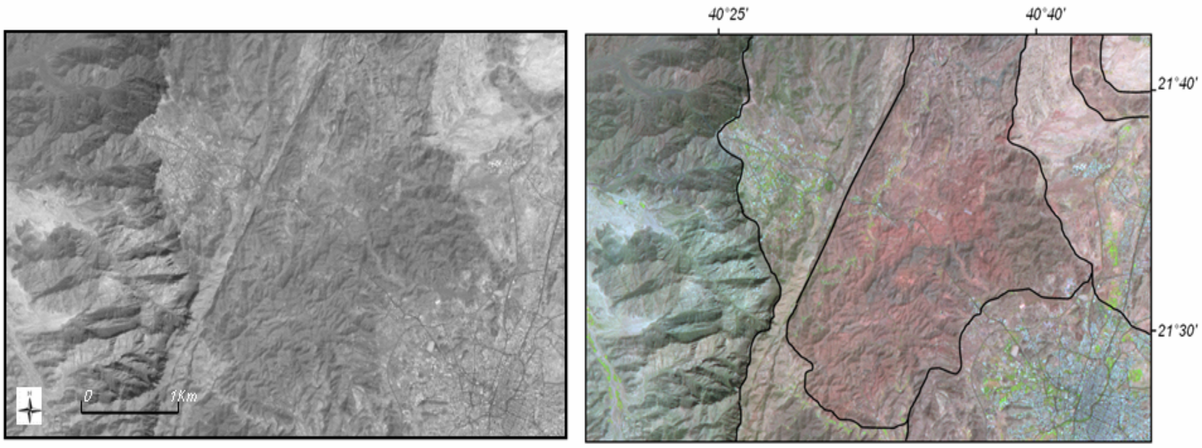

Figure 3. Example of using band combination on ERDAS Imagine to discriminate lithologic units in ASTER images

In classifying the lithologic formation into five classes, the rock formations of similar hydrologic characteristics were embedded in one layer. Hence, a number of hydrologic parameters were considered in this classification. The most important parameters are: clayey content and hardness, since clay prevents water flow and reduces its permeability, while the increase in rock hardness makes it brittle and facilitate its fracturing, then in creases rock permeability.

In this study, the major exposed rock formations in Wadi Aurnah were classified into five classes (Table 3). In the classification, similar hydrologically rock formations were embedded together. They classes were plotted in a map with five classes, which will be used later one as a GIS layer (Figure 4).

Major geologic group	Major rock type
Holocene	Quaternary alluvial and Aeolian deposits
Samran group	Limestone, , shale, breccia, basaltic rocks
Sugah & Fatima group	Sandstone, conglomerates, limestone and basalt
Zibarah group	Amphibole, , schist, and marble
Plutonic rocks	Gabbro

Table 3. Classification of major exposed rocks in Wadi Aurnah according to their potentiality to groundwater storage

2.3. Rock structures

Rock structures, with a special emphasis on fractures, have integral role in water movement, notably the vertical flow where it recharges groundwater. Therefore, it is an important factor to be included in identifying groundwater potential zones.

The identification of rock fractures from remote sensing depends mainly on extracting the linear features, which are ascribed as "*lineaments*". In geological remote sensing, the term "lineament" is a commonly used to describe any geomorphic linear features that attributed to geological structures (often breaks in rocks)/ or and lithologic contacts are related to geologic feature (O'Leary et al. 1976).

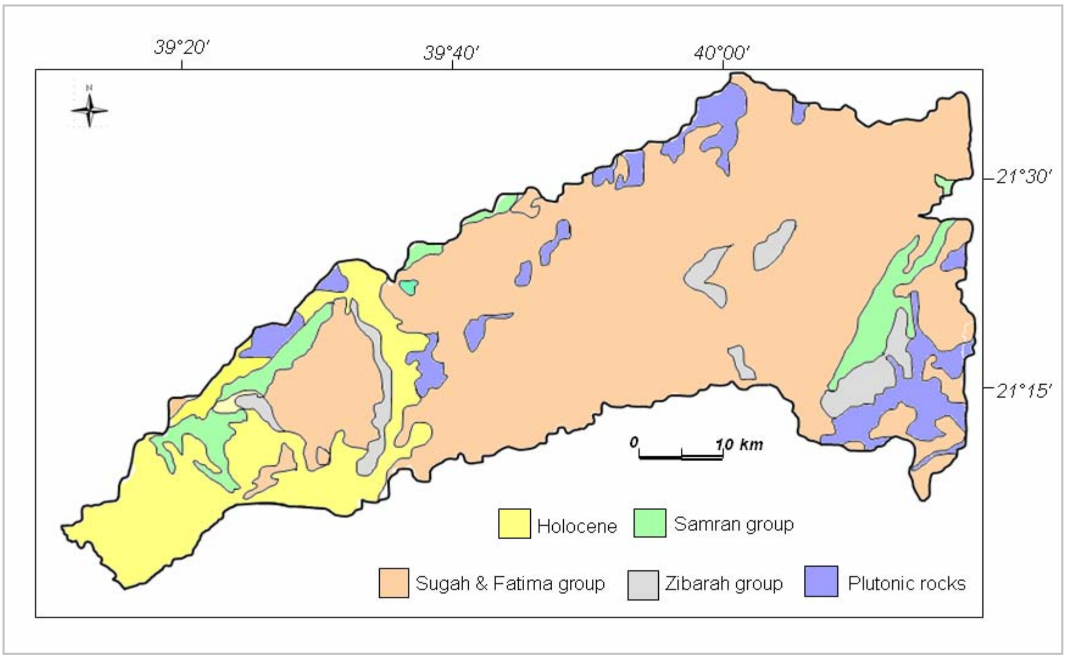

Figure 4. Major lithological classes in Wadi Aurnah basin.

In this study, the identification of lineaments was extracted from *Landsat 7 ETM* images (30 m resolution), by using ERDAS *Imagine* software. It has the advantage to detect "edge" features, e.g. lines of faults, which facilitate image interpretation. This application includes various steps, notably, directional filtering, contrasting and sharpness. In addition, single and multi-band enhancement was carried out.

Thus all linear features of different sizes and orientations regardless of their origin were plotted on a map. In this case, an error ratio is inevitably created in this case, because some of these features are not geologically related. To avoid this error, topographic maps, with special reference to linear objects such as roads, pipelines and terraces were overlapped on the produced lineament map to eliminate all non-geologic linear features as much as possible Therefore, a lineament map, with geologic-related linears, was produced (Figure 5).

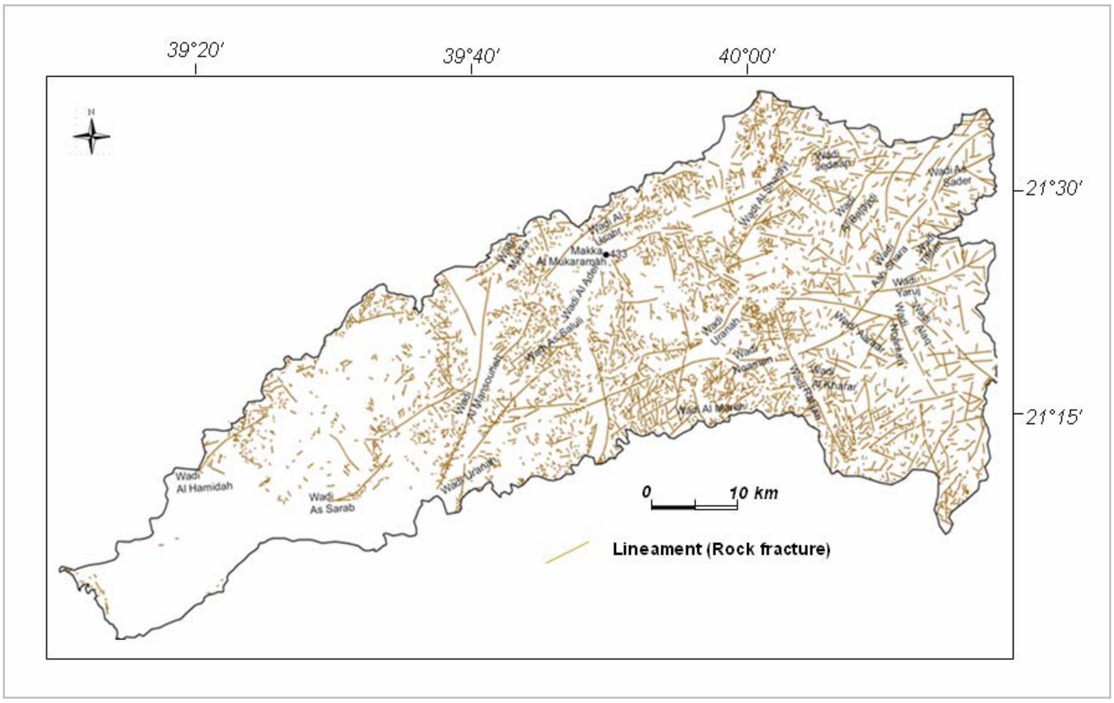

Figure 5. Lineament map as adopted from ASTER satellite images (Al Saud, 2008).

Normally, the dense the linear features (i.e., fracture systems) the high permeability rate. Therefore, the resulting lineament map was classified according to lineament density distribution. This was obtained by measuring the number of lineaments per unit area according to El-Baz and Himida (1995) and Shaban (2003).

In this respect, the geographic distribution of lineaments density was expressed in a contour-line map. The resulting map includes five classes, where each class owns an interval of lineament density. The class intervals represent the number of lineaments per a square frame area. In this study, the selected frame area was 5km x 5km (i.e., 25 km^2). Thus, it was ordered as: >400, 400-300, 300-200, and 200-100 and >100 lineaments/25km^2 (Figure 6).

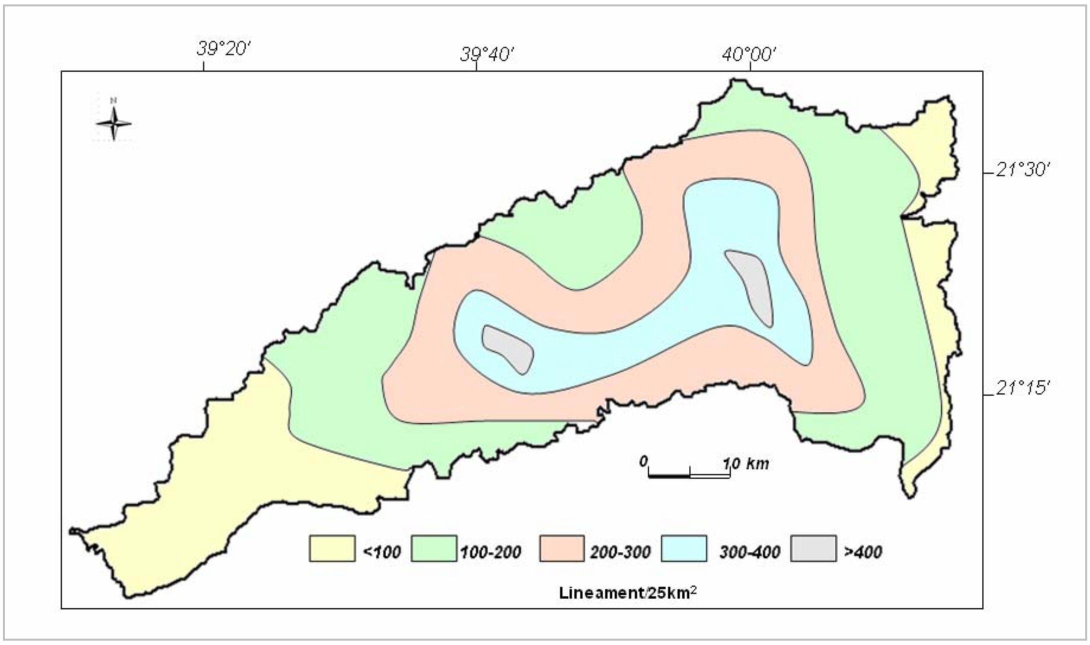

Figure 6. Lineament density map of Wadi Aurnah basin.

2.4. Drainage

The morphometric analysis of the drainage network is tightly related to the recharge property from surface water to groundwater. Many studies combine only the lineament map with drainage map to presume the target areas for groundwater (Tomes, 1975; El-Shazly *et al.*, 1983; Edet *et al.*, 1998).

Normally, the denser the drainage network, the less recharge rate and vice versa. The drainage number (frequency) can express the drainage density property, and it has the strongest relationship with water recharge into subsurface media.

In this study, the extraction of drainage networks was done directly from topographic maps (1:50000). The sampling approach of drainage network was subjected to some morphometric modifications by using ASTER images, notably in the connection between drained tributaries (Al Saud, 2008). Therefore, the resulting drainage map with five classes was prepared (the same as that in lineament density map) to be as a separate layer for the consequence GIS manipulation approach.

Likewise in the case of lineaments, each class represents an interval of the number of drainage segments (i.e., reaches) per a 25 km^2 frame area. They ordered as: <50, 50-100, 100-150, 150-200, <200 segments/25km^2 (Figure 7).

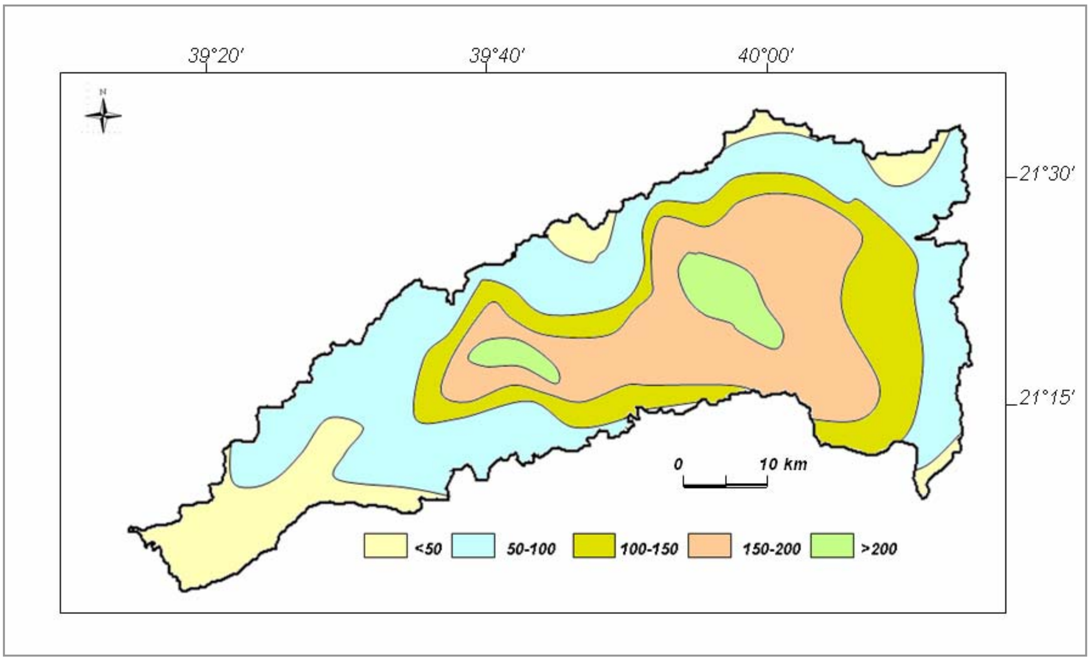

Figure 7. Drainage density map of Wadi Aurnah basin.

2.5. Land cove/ use

Different uses of terrain surfaces result a miscellany of surface water recharge processes. This factor involves a number of elements, but the major ones are: soil deposits, bare rocks, human settlements dense and spare vegetation cover (Su, 2000).
For example, soil deposits retards water infiltration through it and thus prevent water to reach groundwater reservoirs. This is also the case for human settlements and constructions, which work as a sealing surface that do not allow water to percolate.
For the case of bare rocks, they often give a chance to water to move through fissures and joints into deeper stratum, thus often considered as enhancing parameter.
Accordingly for vegetation cover, the higher the vegetation cover, the higher the evapotranspiration rate and this imply less chance for percolation to the subsurface layers (Darwich et al. 2003).
In this study, ASTER images (2006) were used, and a non-supervised classification was applied using the *ERDAS* software. Consequently, Wadi Aurnah was classified into five classes. They were ordered according to high advantage to water permeability. The classes are: bare rock, spare vegetation, dense vegetation, human settlements and soil deposits. Therefore a map was produced to show the distribution of these classes and to be considered as a separate GIS layer (Figure 8).

2.6. Data manipulation

The created classifications of the influencing factors on ground water storage (potential zoning), were ordered from high effect (i.e., high potentiality) to low, thus they were tabulated to reveal the trend of effect for each factor (Table 4). .

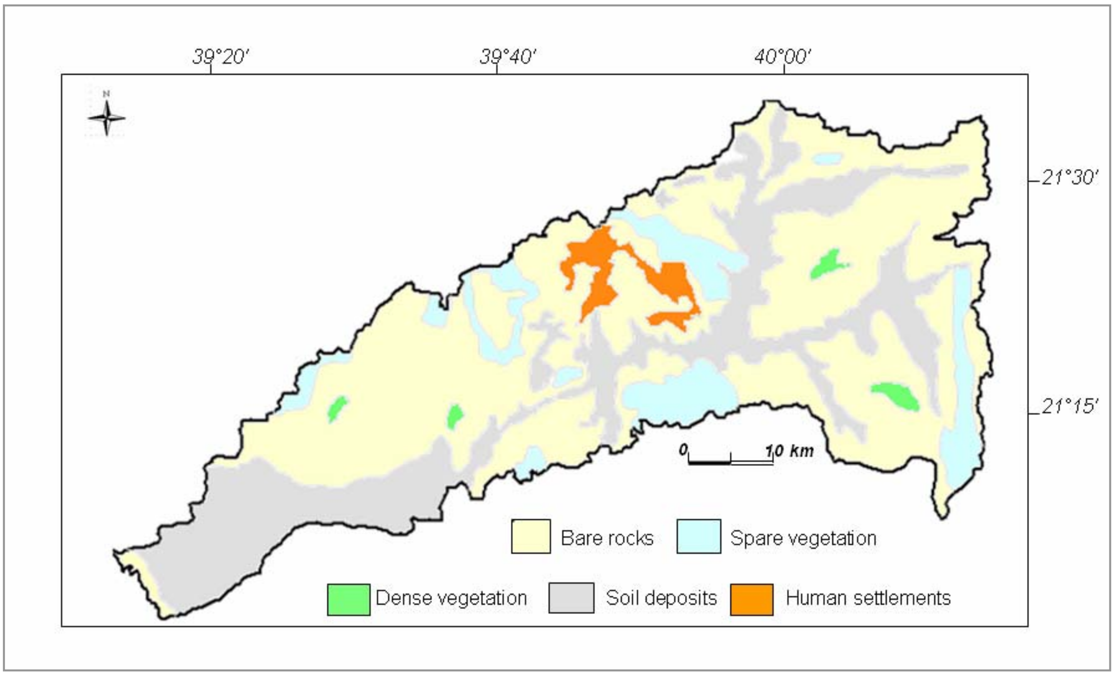

Figure 8. Major five classes of land cover/ use in Wadi Aurnah basin.

Accordingly, for each factors, a GIS layer was created and expressed as a map (as mentioned in the previous sections). The overlaying (integration) of these layers together in a GIS system will result a unique map with a number of polygons indicating special characteristics for groundwater potentiality. However, not all the involved factors have the same effect on groundwater potentiality. For example, the factor of rock fracture is much more effective than the drainage density, while rainfall factor is more effective than all other factors. For this reason, each factor was given a specific weight of effect on ground water storage.

In this study, the given weights were adopted, in addition to the field observation, from a miscellany of previous studies (Edet et al., 1998; Robinson, et al., 1999; Das, 2000 and Shaban, 2003).

Therefore, the integrated factors in this study were given the following weights (Figure 9):

- Rainfall (30%)

- Lineaments density (25%)

- Lithology (20%)

- Land cover/ use (15%)

- Drainage density (10%

Additionally, each factor was classified into five classes ranging from very high and described as I, to very low and described as V (Table 4). Thus, the average of ranging is 90, 70, 50, 30 and 10% for classes I to V; respectively.

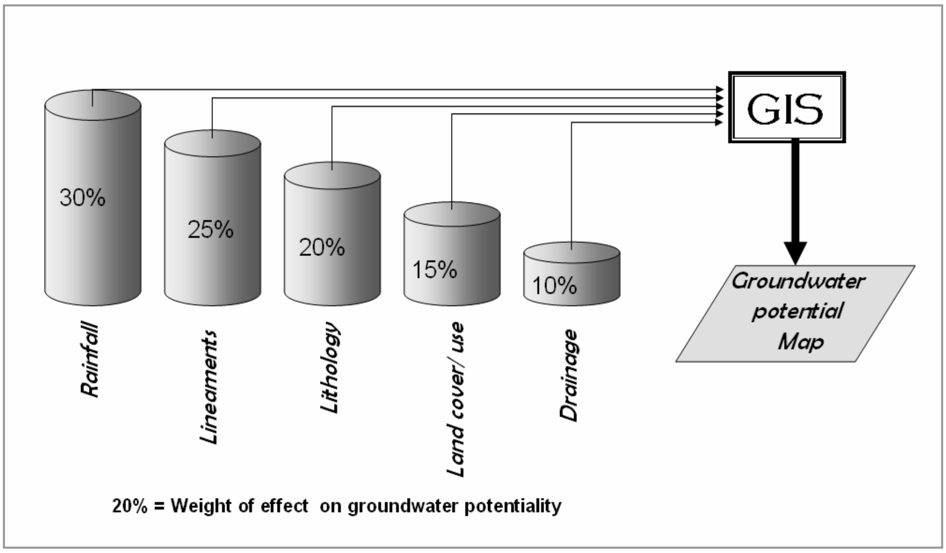

Figure 9. Schematic figure showing the application of different layers in GIS system.

In this classification, a degree of effectiveness was created to evaluate and compare different classes of the involved factors. Therefore, for each factor the weight was multiplied by the range of the class.
For example, the range of class IV in the rainfall factor equals 30%, if multiplied by the factor weight, which is 30; thus the degree of effectiveness will be:

$$30/100 \times 30 = 9$$

While the drainage factor, for example, the degree of effectiveness in class I will be:

$$90/100 \times 10 = 9$$

High	Groundwater potentiality →				Low
Class / ***Factor/weight***	**I**	**II**	**III**	**IV**	**V**
Rainfall *(mm)* **30%**	*> 150*	*150-135*	*135-120*	*120-105*	*< 105*
E*	*27*	*21*	*15*	*9*	*3*
Lineaments *(segment /25km^2)* **25%**	*> 400*	*400-300*	*300-200*	*200-100*	*< 100*
E	*22.5*	*17.5*	*12.5*	*7.5*	*2.5*
Litholgy 20%	*Gabbro*	*Amphibole and schist*	*Sandstone, breccia and limestone*	*Limestone, shale and basalt*	*Alluvial and Aeolian deposits*
E	*18*	*14*	*10*	*6*	*2*
Land cover/use 15%	*Bare rock*	*Spare vegetation*	*Dense vegetation*	*Soil deposits*	*Human settlements*
E	*13.5*	*10.5*	*7.5*	*4.5*	*1.5*
Drainage *(drain /25km^2)* **10%**	*< 50*	*100-50*	*150-100*	*200-150*	*< 200*
E	*9*	*7*	*5*	*3*	*1*

**E = Degree of effectiveness on groundwater potentiality.*

Table 4. The classification of the influencing factors on groundwater potentiality.

This means that the class IV in rainfall factor has the same effectiveness of class I in drainage factor. Hence, this approach helps evaluating the effectiveness of each factor, as well as to compare different factors with each other. Therefore, it is obvious from the obtained table that class I in the rainfall factor (i.e. $E = 27$) occupies the most effect influence on groundwater potentiality, besides the least influence is the class V (i.e. $E = 1$) in the drainage factor.

A model chart representing the integration of groundwater potentiality factors is formulated and followed in this study. This chart reflects the overlapping layers and their weight of influence (Figure 9).

The *ESRI's Arc View* software was utilized to manipulate the influencing factors (with their own weights) through superimposing of the different layers together in a GIS system. Therefore, the resulting polygons characterize special property with respect to groundwater potentiality.

3. Results and Discussion

The obvious diversity in the existing physical conditions in any area results different hydrogeological characteristics, weather in terms of surface water or groundwater behaviour. This is well pronounced in arid regions where rainfall is rare, while rugged topography and fractured rocks exist, which is the case in the western part Arabian Peninsula. For this purpose, the study aimed to tackle a major hydrogeological topic concerning groundwater storage in this area where water resources are rare.

Due to the large areal extent of the selected basin; however, remotely sensed data can fulfil the scope of the study. Hence, satellite images can capture a comprehensive view, selected distinguished terrain features with less cost and short time.

There is a miscellany of influencing factors, considering as parameters, in groundwater storage. However, they differ from one region to another.

In the area of concern, five major parameters were tackled. These are: rainfall, rock type, fracture systems, drainage and land cover/use.

Remote sensing techniques have an integral role in the recognition and analysis of these parameters, but at the different levels. In other words, remotely sensed data completely helps in detecting the lineaments (i.e. fracture systems) and land cover/ use, but it partially helps identify lithology, drainage and rainfall.

The integration of the influencing factors (parameters) to create groundwater potential map, works at different levels of effect. For example, the influence of rainfall is the most important, but it is not the case for drainage. Hence, in areas with no rainfall the other factors will be completely neglected.

The other step is the integration of these factors, which could be successfully done in the GIS system in order to merge different layers that represent the factors. Thus, the optimum map of groundwater potential zones was obtained (Figure 10).

The obtained map shows five major classes of groundwater potentiality. These are ascribed from very low to very high potentiality. This can be attributed as > 20%, 20-40, 40-60, 60-80 and > 80% of possibility for the very low until very high potentiality; respectively.

From the resulting map, it is obvious that a range between 15-20% of the study area occupies potential zones for groundwater storage (i.e. high and very high).

The obtained map shows that the promising zones for groundwater storage are almost located in areas where rainfall in higher and rock fractures is concentrated. This is mainly in the elevated region of Wadi Aurnah (Figure 10).

This study exhibits an empirical procedure of remote sensing and GIS analysis in groundwater exploration However, more factors can be integrated for better results. This approach can be applied elsewhere in different areas of water scarce.

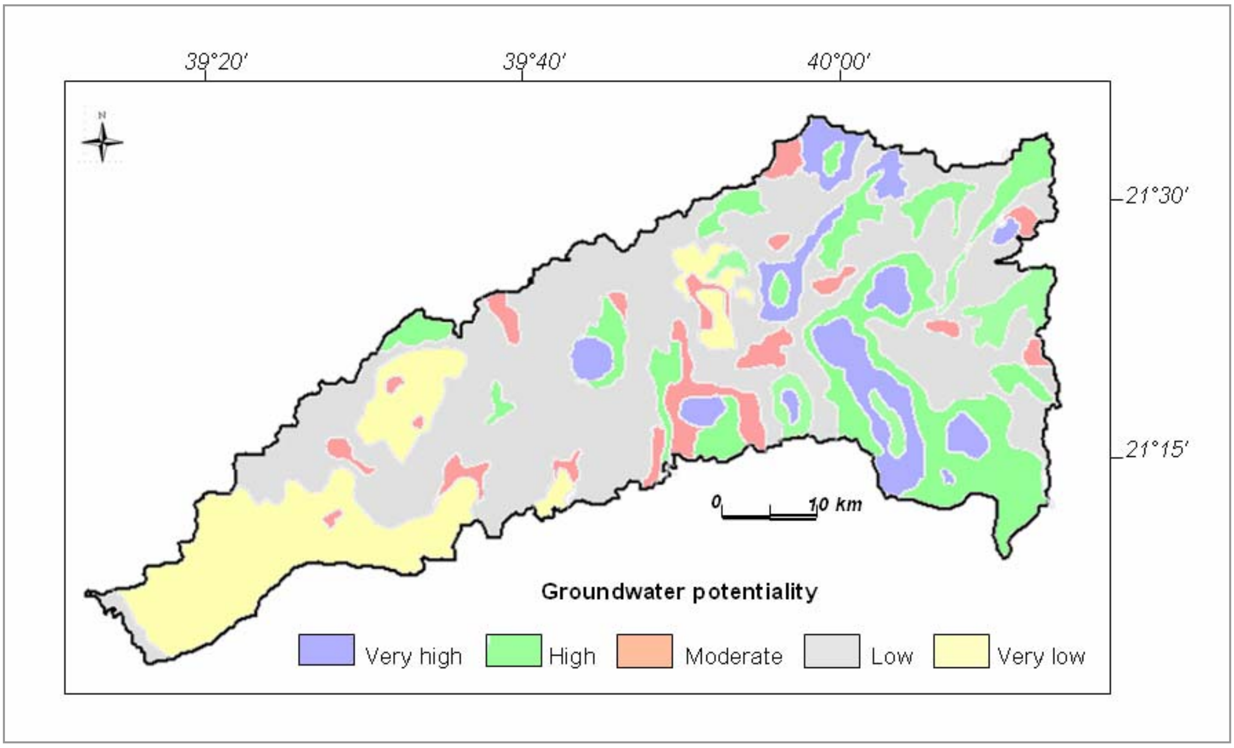

Figure 10. Groundwater potential zones of Wadi Aurnah basin.

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