جامعة الملك فهد للبترول والمعادن
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GIS Application in Groundwater Quality Estimation

CRP 514 – Term Paper

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ABSTRACT

Saudi Arabia has a rapid population growth with an increasing need for water resources. The two sources for water are: groundwater and desalination plants. Groundwater is being depleted rapidly due to heavy production. Hydrogeologists are responsible of monitoring the groundwater potential areas and quantity of recharge. Based on hydrogeologists groundwater utilization plants are formulated. GIS has been increasingly used by hydrogeologists to collect, store and analyze data aiding in groundwater potential areas estimation. Two case studies are analyzed in this paper to highlight different methods for groundwater estimation. Both case studies are based in Saudi Arabia and provide applicable examples of groundwater potential mapping.

INTRODUCTION

Water is a primary resource for the survival of mankind and all living organisms. The Kingdom is considered a semi-arid area with limited potable water sources. Due to this limitation, groundwater sources need vigilant and scientific management for a sustainable use [1]. With the predicted future water scarcity groundwater management becomes more important. Since 1992 investigations have shown a lower water table and water quality in Eastern Province of Saudi Arabia as a result of excessive withdrawal [2].

In 2011, groundwater provided around 39% of consumed water in Saudi Arabia with a total of 947 million cubic meters out of 2,423 [3]. A portion of groundwater is produced from fossil aquifers that will never be replenished. To maintain a sustainable agricultural development, groundwater quantity and location needs to identified accurately [4].

Due to varying characteristics of groundwater, specific chemical attributes are required depending on water use. Drinking water contains fewer concentrations of minerals than irrigation water. No smell should be noticed in drinking water and taste should be acceptable [5]. Hydrogeologists specialize in modeling and managing groundwater resources. They have traditionally overlaid multiple thematic maps to visualize regional potential water producing areas.

The quality of hydrogeological predictions depends greatly on the availability of quality sufficient data in the study area [6]. Nonetheless, the utilized thematic maps in each hydrogeological study are arbitrary and rely on researchers' subjective judgment [7].

In the last decade hydrogeologists have started using geographic information systems (GIS) to analyze aquifer's water quality [4]. This paper investigates multiple methods hydrogeologists have used GIS to assess groundwater potential. Two case studies will be examined in arid areas of Saudi Arabia. GIS can be used to produce input or output data for hydrogeological studies [6]. GIS strengths in managing spatial locations and related attributes as well as spatial statistical operations, like interpolation and extrapolation, are crucial in effective groundwater management.

SCOPE

This paper will study sample applications of GIS in groundwater assessment of available quantities and optimum drill locations. The assessment depends on geological structures that are optimal for retaining water. In addition, chemical attributes of water separate between suitable water for drinking and irrigation usage. Sustainable water withdrawal is also a key aspect of proper groundwater assessment. If water consumption exceeds recharge rate, groundwater will be depleted or quality will deteriorate.

STUDY LIMITATIONS

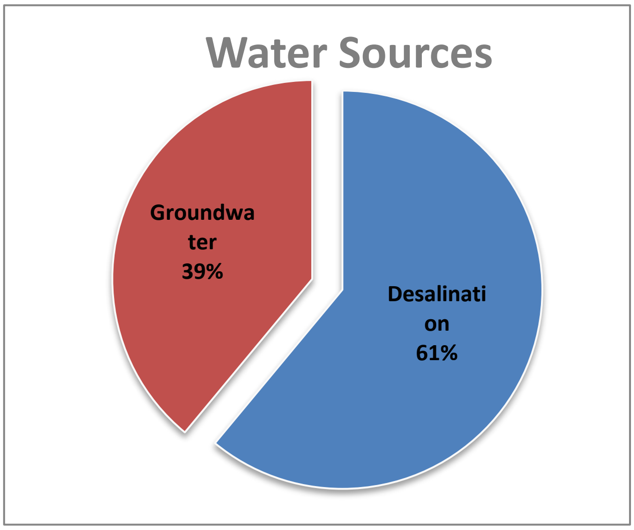
The study was carried in a limited time span for delivery as class project. Interviews with subject matter experts were not possible. Access to up-to-date and detailed data about Saudi Arabia's water sources and consumption data was limited. The writer is new to the field of groundwater management with its related topics in geology, chemistry, meteorology, remote sensing and hydrology.

METHODOLOGY

The main source of information in this paper is the literature review of publication found from King Fahd University of Petroleum and Minerals online library. Extensive investigation of literature was carried to investigate groundwater assessment in different geographic locations. Emphasis was given to GIS applications in Saudi Arabia which were carried in Wadi Rabigh, Khobar and Hada Al-Sham. Related governmental regulations and reports were referenced to capture the local setting.

LITERATURE REVIEW

The two water sources available at Saudi Arabia's disposal currently are groundwater and desalination plants. The produced amount from groundwater is 947 million cubic meters in 2011. A total of 7,114 government wells are used to extract this quantity of groundwater. Around 240 new government wells were drilled in year 2011 [3].



Excessive groundwater extraction [2] and low rainfall in Saudi Arabia [8] will lead to dwindling water supply and lower water quality. In 2010, agricultural irrigation amounts to 86% of water usage in Saudi Arabia [9]. Recent government plans encourage outsourcing the agricultural endeavors by investing in land-rich money-poor countries like Ethiopia and Sudan [10]. This new direction will lessen the burden on local water sources.

The remainder of the water demand will need to be met with scientific management of water supplies. Increasing the efforts of desalination will lead to increased salinity of water bodies. Groundwater can be a sustainable resource if utilized within acceptable conditions set by hydrogeologists. The role of hydrogeologists is to model groundwater systems and predict location and quantity of water storage. Quantity of stored water in aquifers fluctuates based on recharging by rainfall and withdrawal rates in addition to exterior factors [4].

Hydrogeologists have adopted GIS to analyze existing well information combined with thematic layers to assess aquifer's water quality [4]. Although the availability of reliable and sufficient data can be difficult, such data is mandatory to produce quality assessments [6]. Aided by the regulations set by World Health Organization and local governments for potable water [5], hydrogeologists can map zones of predicted acceptable water quality. Hence, GIS geo-database, spatial processes and mapping capabilities are required for effective groundwater management.

In the remainder of the paper, varying GIS techniques are investigated to showcase different ways of assessing groundwater potential. Several case studies have been found that utilize GIS in groundwater assessment around the world and a special attention was given to study areas in within Saudi Arabia. In 2005 a study was undertaken to determine groundwater availability in Hada Al-Sham in the western part of Saudi Arabia [1]. Similarly, in 2010 another study focused on Wadi Aurnah near Makkah city. This shows a growing attention to GIS for groundwater management in Saudi Arabia.

Case Studies

Two case studies will be discussed in details through the remainder of this paper. One case study [4] will cover Wadi Rabigh in western region of Saudi Arabia while the second case study [8] will focus on Wadi Aurnah also in the western region of Saudi Arabia. For each case study, the study area will be highlighted and a summary of its methodology and conclusions will be discussed. In the analysis section these case studies will be compared and contrasted based on their similarities and differences.

Case Study 1: A GIS approach for the assessment of groundwater quality in Wadi Rabigh aquifer, Saudi Arabia

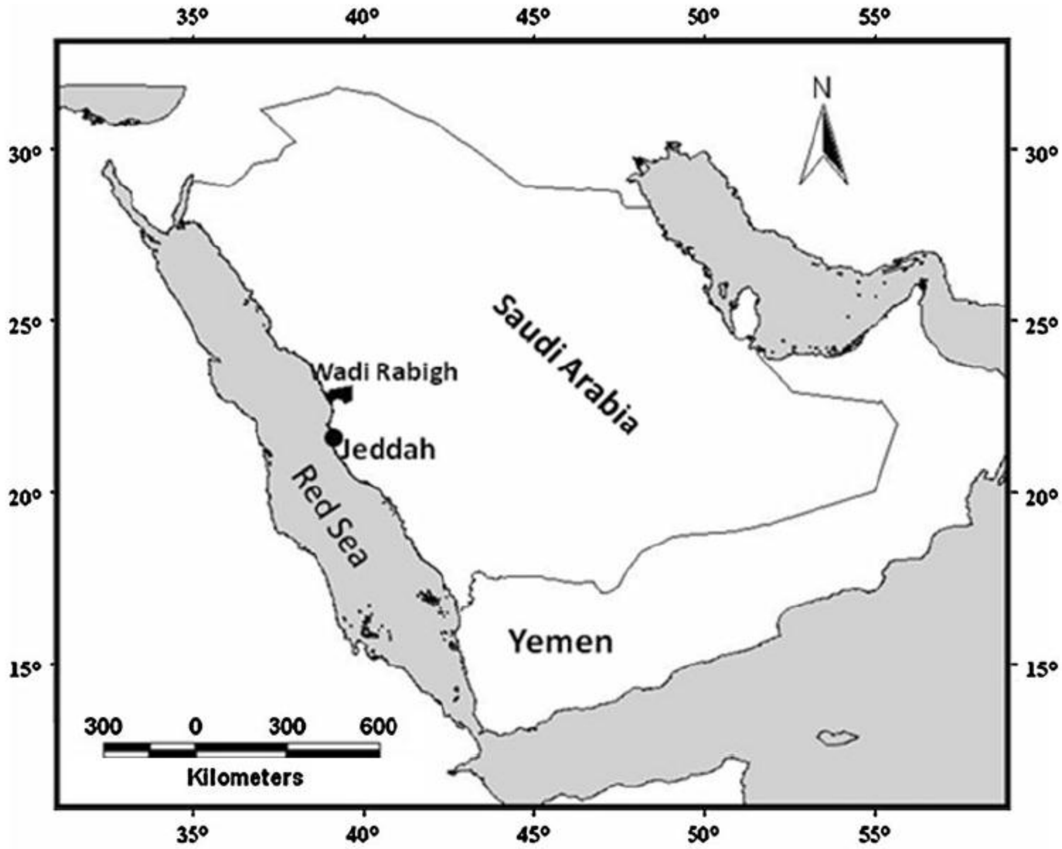


Figure 1: Study Area

The case study aims to analyze existing producing groundwater wells in the study area. Positions of wells along with related information are stored using a GIS solution. Shown in below figure, well locations are spread across the study area which is the catchment area. Water samples are collected from every well for chemical analysis.

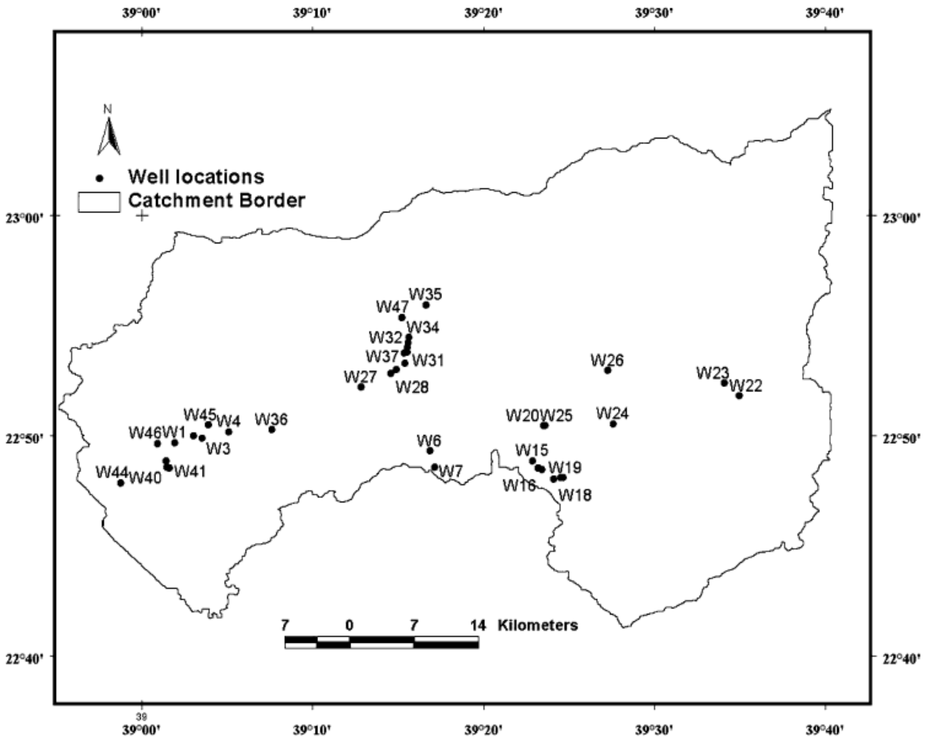


Figure 2: Well Distribution in Study Area

Well no.	Latitude	Longitude	Total depth (m)	Depth to water table (m)	pH	EC (µS/cm)
1	22° 48.69	39° 1.920	9.5	7.35	9,690	5,964
2	22° 49.107	39° 3.012	10.0	8.70	16,590	12,008
4	22° 49.347	39° 5.092	7.30	6.0	7,270	4,818
6	22° 48.22	39° 16.850	39.0	3.9	9,510	6,254
7	22° 47.242	39° 17.125	On surface	On surface	2,450	1,474
16	22° 47.216	39° 23.171	13.90	10.60	3,030	2,206
18	22° 46.584	39° 24.097	11.60	8.40	2,045	1,380
19	22° 46.666	39° 24.639	12.00	11.40	1,622	1,158

Table 1: Sample Well Basic Data

The results of the samples analysis show the concentration of certain minerals dissolved in each sample. This data is also appended to each well record. This will enable the GIS process to include these results in the calculations. Below are sample results. Additionally, in table 3 are a comparison of WHO drinking water range of acceptable concentrations against water samples results.

Well no.	Ca	Mg	Na	K	HCO_3	SO_4	Cl	TDS
1	622.44	133.03	1,250	16.5	162.69	1,228.21	2,198.64	5,964
2	1,270.54	303.27	1,950	72.39	259.49	1,610.18	5,018.47	12,008
4	554.31	24.32	975	19.64	299.82	448.64	2,059.81	4,818
6	152.3	233.47	1,660	19.49	195.23	1,117.08	2,533.55	6,254
7	89.78	50.83	250	14.56	210	272.48	523.12	1,474
16	211.62	112.84	300	6.416	202.2	520.26	612.56	2,206
18	131.66	69.53	130	7.73	156.9	298	388.85	1,380
19	113.43	53.5	125	4.135	237.06	194.28	289.8	1,158

Table 2: Results of Analysis

Parameter	Range in study area	WHO range	Samples within the WHO range
TDS (mg/l)	612–16,780	1,000	4
PH	7.16–8.32	6.5–8.5	30
EC (µs/cm)	1,123–24,500	1,400	1
Ca^{++} (mg/l)	35.27–2,106.22	500 as $CaCo_3$	16
Mg^{++} (mg/l)	10.46–352.64	–	–
Na^{+} (mg/l)	40–4,800	200	11
K^{+} (mg/l)	2.49–72.39	–	–
HCO_3^- (mg/l)	36.21–316.83	–	–
SO_4^- (mg/l)	60.09–3,026.91	400	12
Cl^-(mg/l)	181.51–7,819.74	250	4

Table 3: World Health Organization Acceptable Ranges

Four parameters are selected for the decision of suitability in this case study. They are: Ca, Na, Cl and SO_4. Total dissolved solids (TDS) results for samples are used eventually for consistency. For each parameter GIS process was used to extrapolate an area of acceptable range by WHO. For example, the values for Na in all wells are used to produce an area which is expected to contain 200 mg/l or less of Na content.

Following are resultant areas of acceptable concentrations for the 4 parameters:

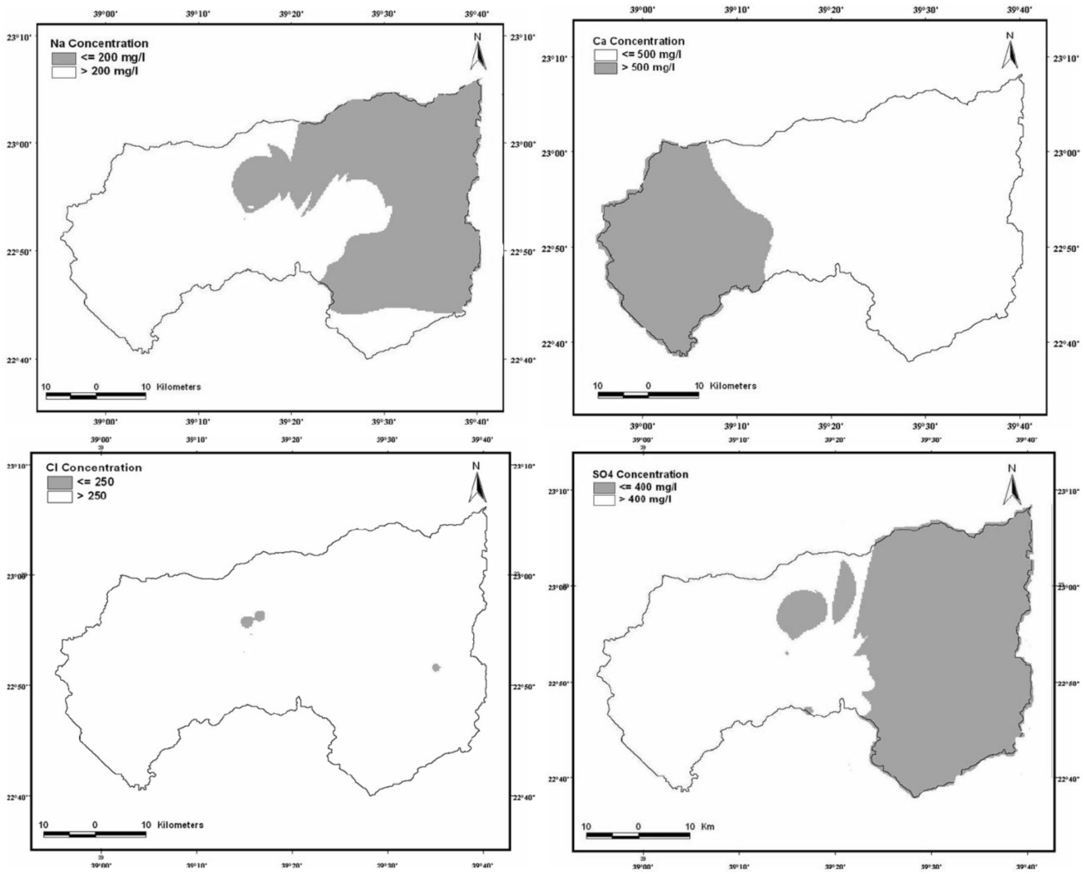


Figure 3: Concentration for Parameter

To determine an area where all the parameters are within acceptable ranges, all four layers were overlaid and the resulting intersection is shown below. This area resembles the expected area where drilled wells will produce water that is acceptable by WHO standards as drinking water. This area is very small compared with the total area of the catchment.

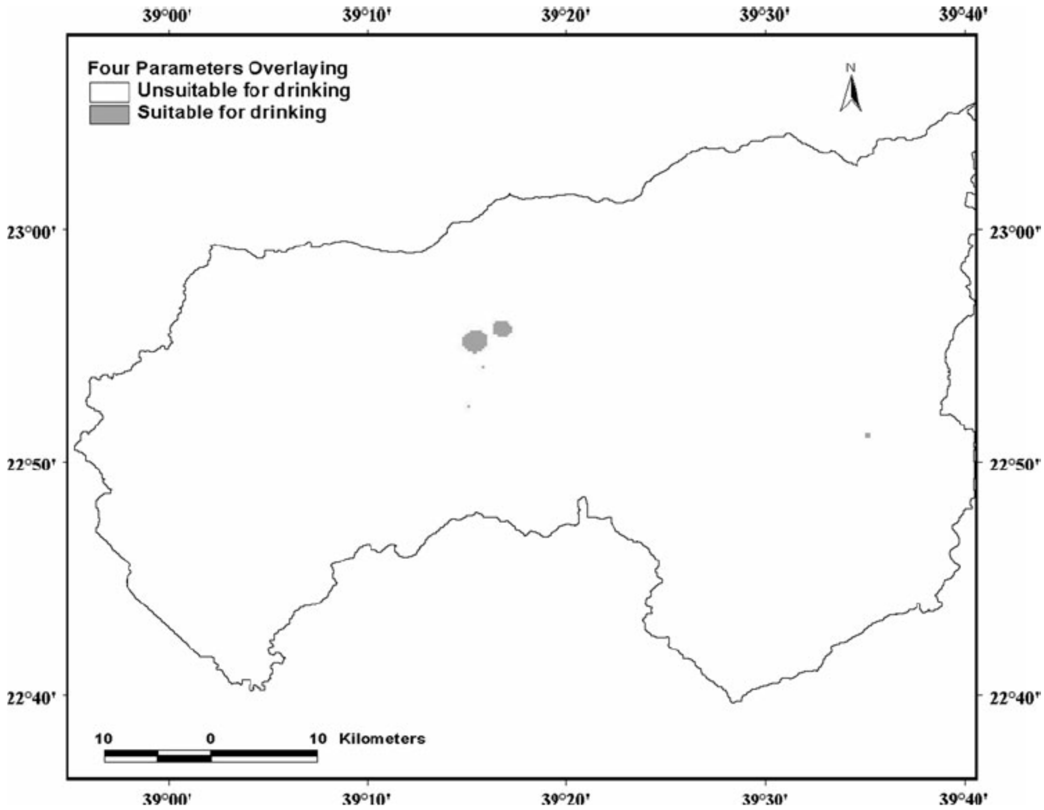


Figure 4: Four Parameter Overlaying

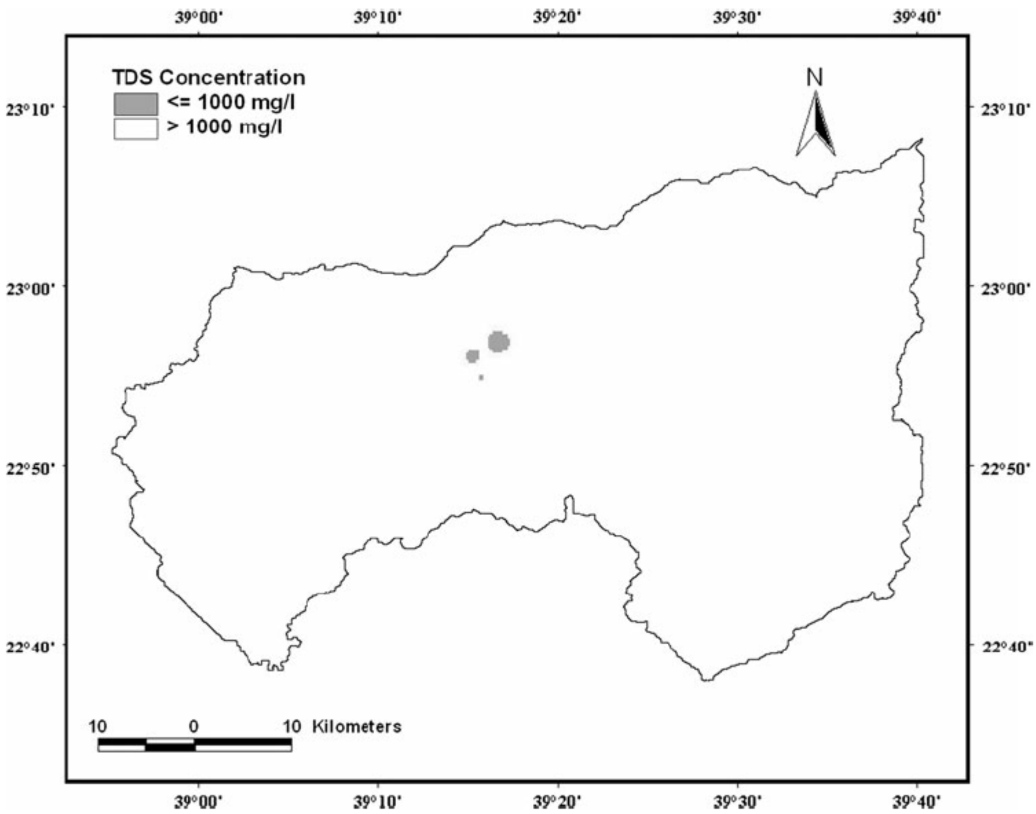


Figure 5: TDS Concentration

If the TDS concentration map is compared to the four parameter overlaid map they seem identical. This is due to the high correlation between TDS and the four parameters. The remainder of the aquifer areas can be drilled for irrigation purposes but not for drinking purposes. By the use of GIS, an optimal drill location was easily derived which can save drilling costs and yield improved water quality.

CASE STUDY 2: MAPPING POTENTIAL AREAS FOR GROUNDWATER STORAGE IN WADI AURNAH BASIN, WESTERN ARABIAN PENINSULA, USING REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM TECHNIQUES

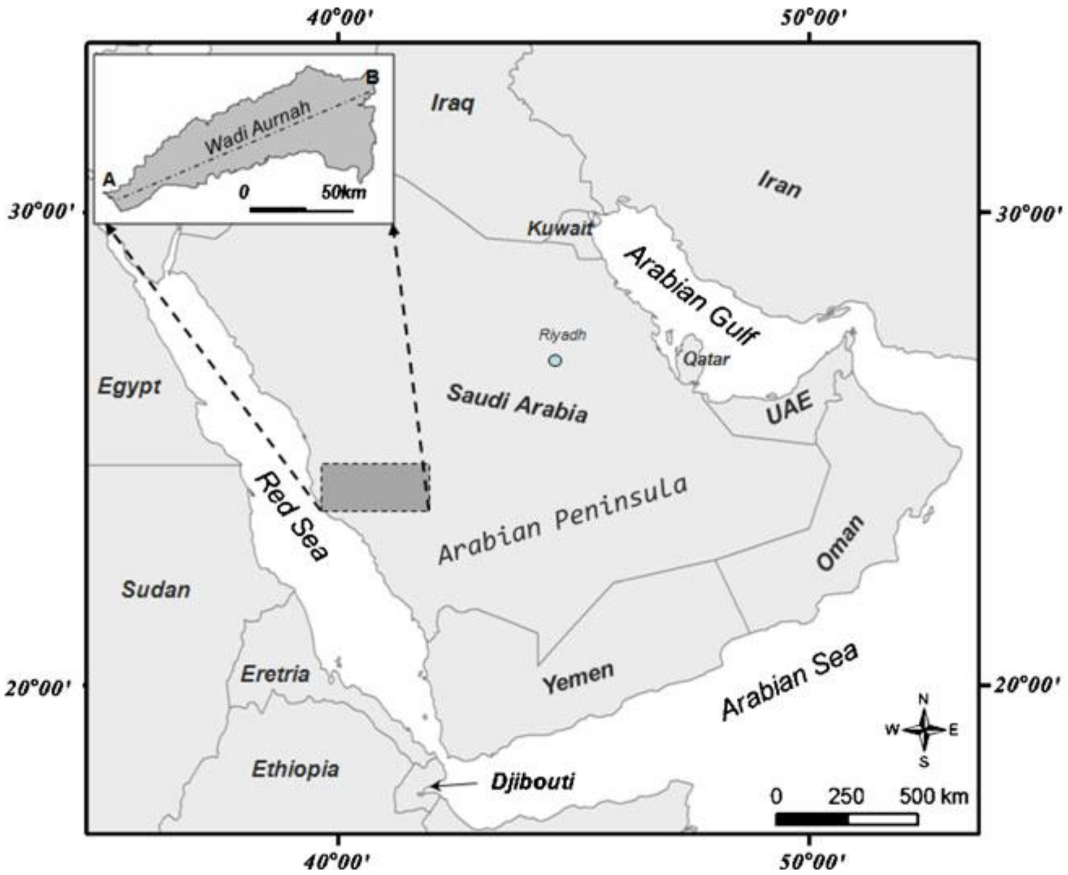


Figure 6: Study Area

In this case study, 6 thematic maps were created by the author using multiple remote sensing sources. Then, these layers were processed to calculate potential groundwater areas using GIS. Finally, the resultant map was verified using dug wells within the area.

Based on the case study's literature review, there is no consensus on thematic maps used for groundwater estimation. The author elected to use all maps that might contribute to groundwater charging even if minimally or negatively. The chosen six thematic maps are: rainfall, lithology, rock fractures, slope, drainage and land cover.

Following is a discussion of the used maps and some indication of their connection to groundwater accumulation.

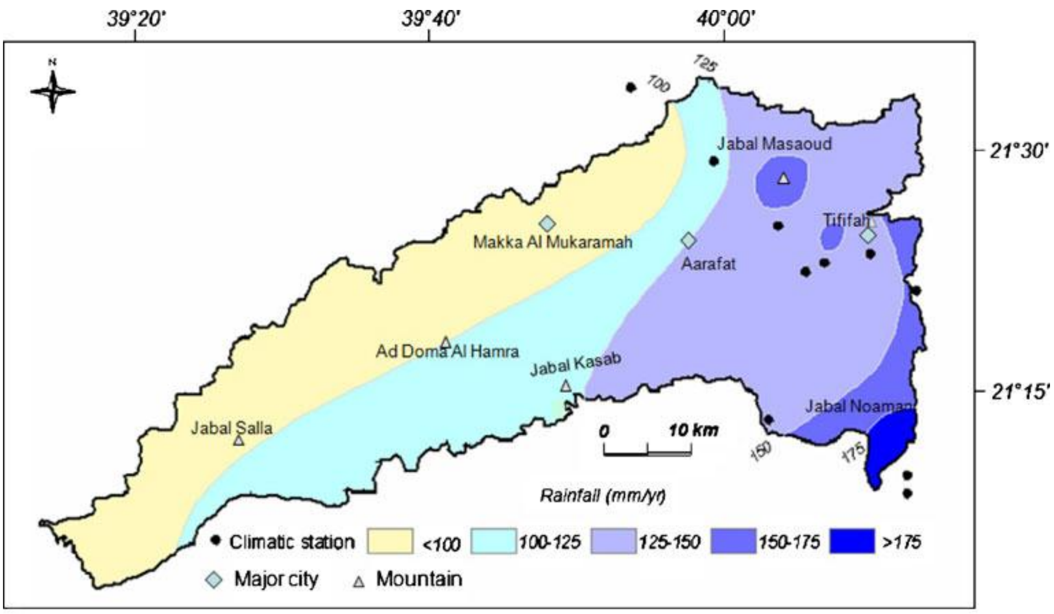


Figure 7: Rainfall

Expected levels of rainfall were digitized and classified into 5 categories as shown in figure 7. This data was collected from the Organization of Forecast and Environment Protection.

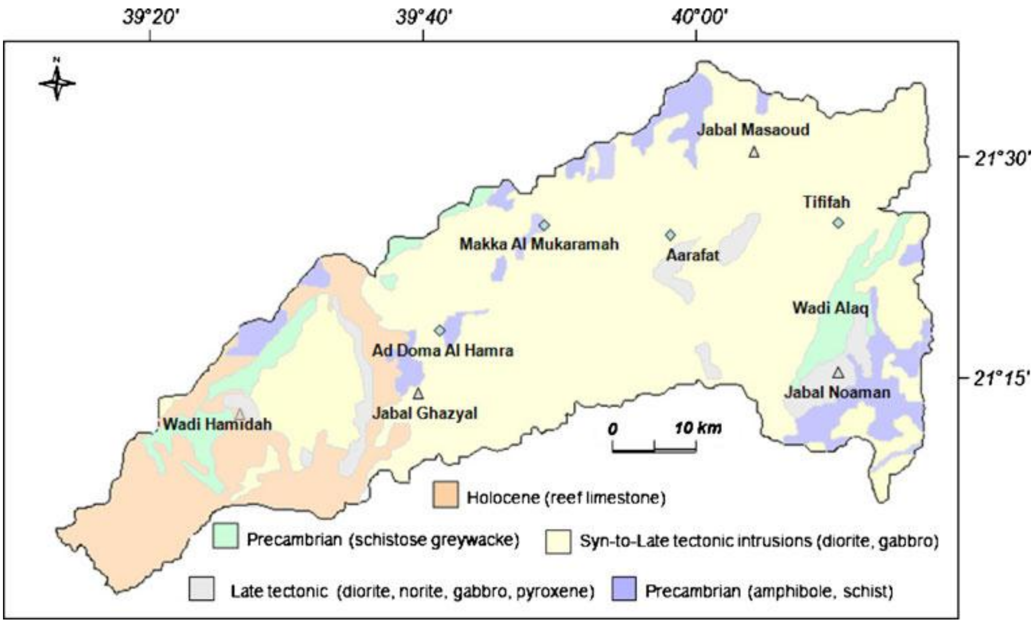


Figure 8: Lithology

Lithology thematic map was compiled using geological maps and refined using satellite imagery. The two satellite images used throughout most of this case study are: ASTER with pixel resolution of 15 meters and Landsat 7 ETM with pixel resolution of 30 meters. The images were used to correct boundaries. Five classes were also categorized for lithology based on hydrologic properties such as clay content and rock hardness.

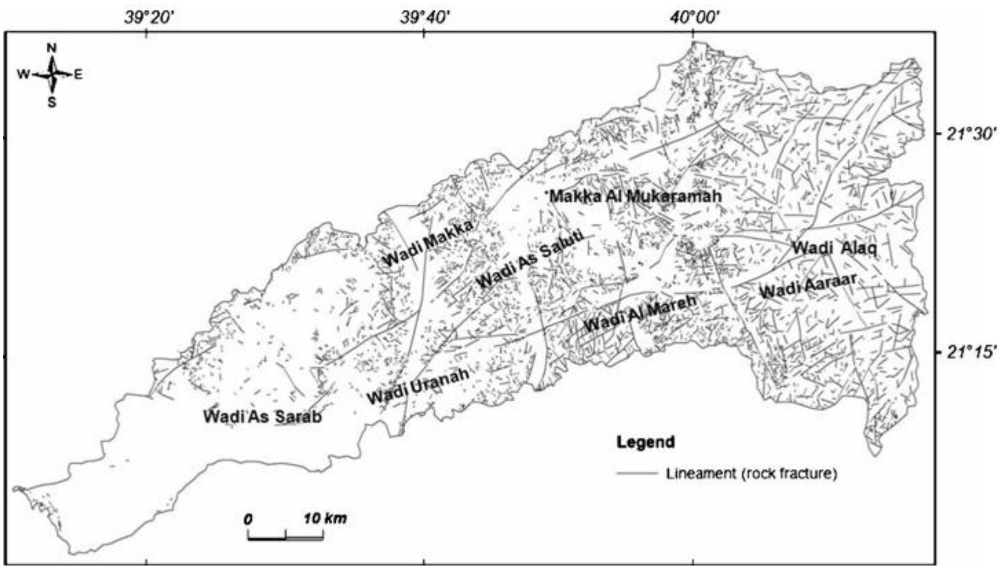


Figure 9: Rock Fractures

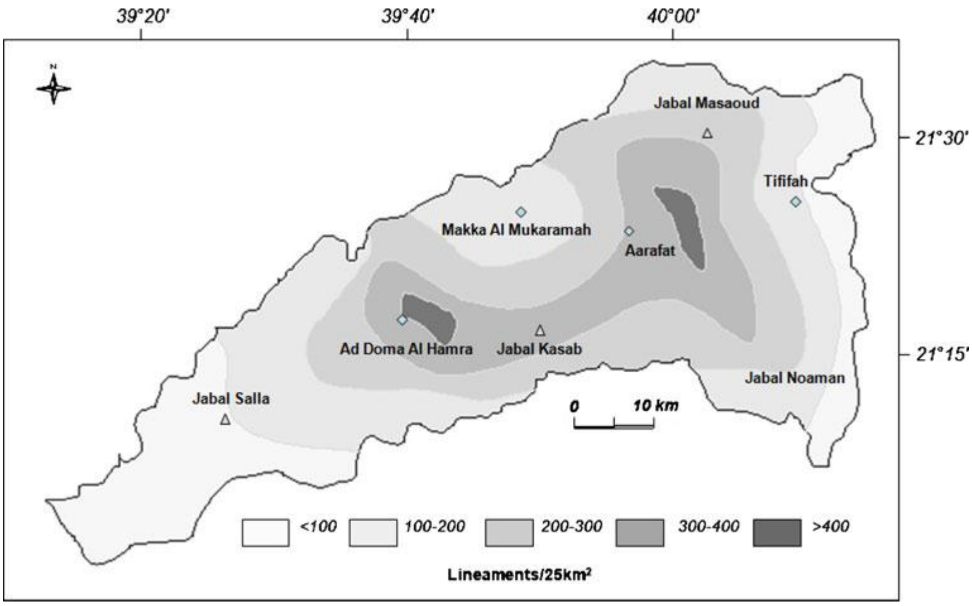


Figure 10: Rock Fractures Density

Rock fractures were first extracted from satellite images using multiple functions of ERDAS IMAGINE software package. The functions included edge detection and thermal bands to identify fractures easily. Then, a GIS process was used to identify 5 zones based on density of fractures. With more fractures the secondary permeability of rocks increases leading to more groundwater charging.

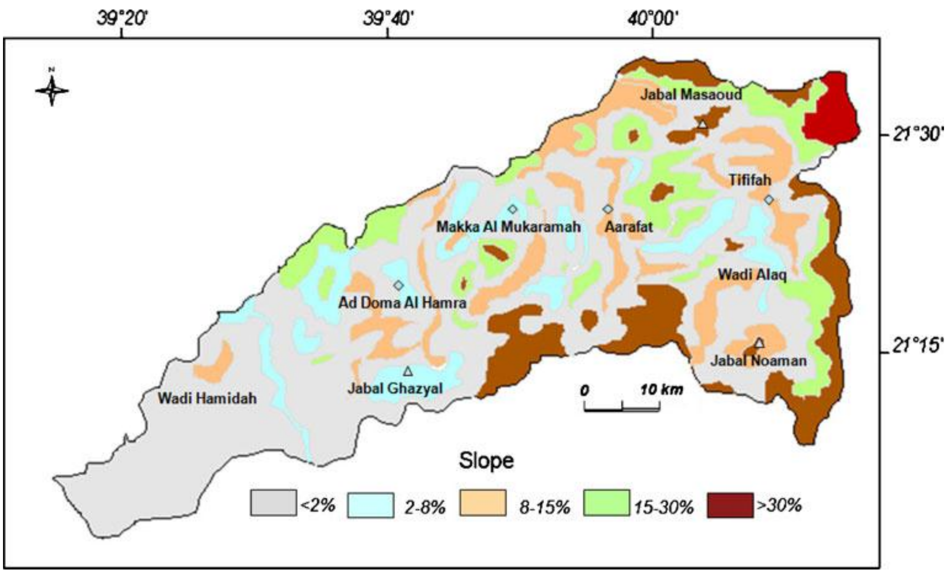


Figure 11: Slope

Slopes in the study area were also classified into 5 groups based on the SOTER model by the European Commission. With higher slopes the recharge rate will be lower due to fast passing of water over the area.

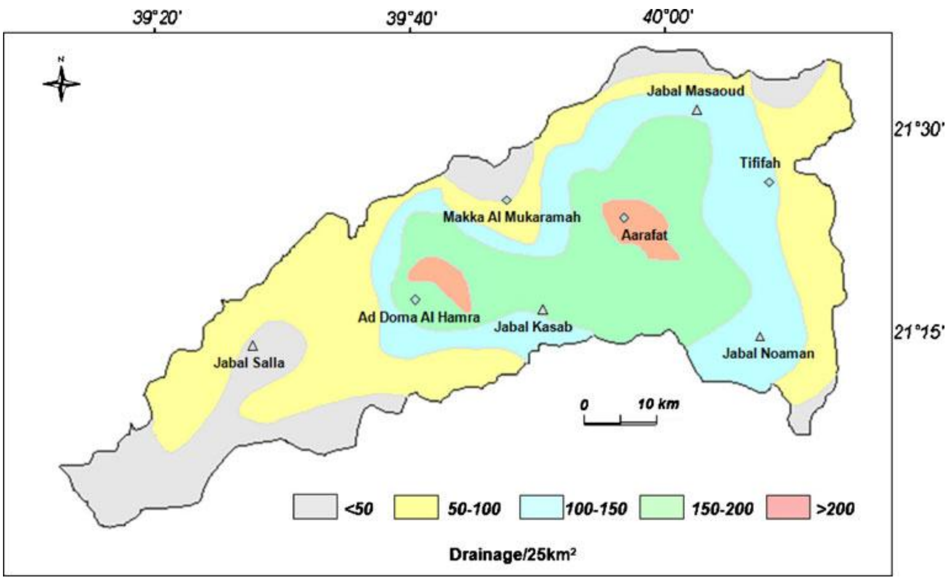


Figure 12: Drainage

Drainage information is classified based on the density within 25 km. With denser drainage groundwater recharge is lower.

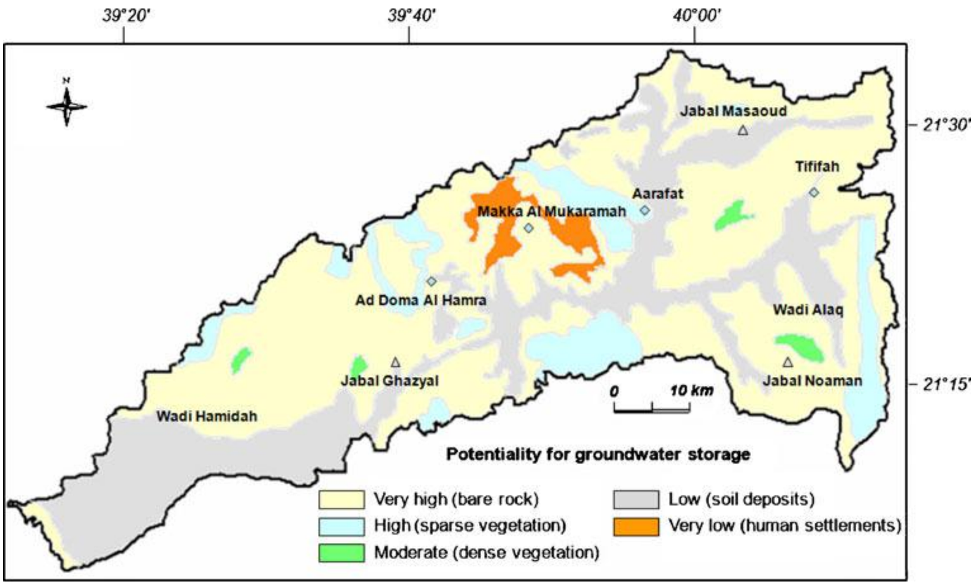


Figure 13: Land Cover

Land cover is also digitized from satellite and topographic maps. Mapping additional features that affect groundwater is essential for a more comprehensive analysis. Some of these features are settlements and vegetation which lower recahrge.

After creation of thematic maps is complete, proper weights are assigned to each map. In addition, each class is assigned a rate by which it can contribute to the creation of the potentional areas. A map feature with high weight but low rate might have a bigger impact on the calculation than a low weight feature with high rate.

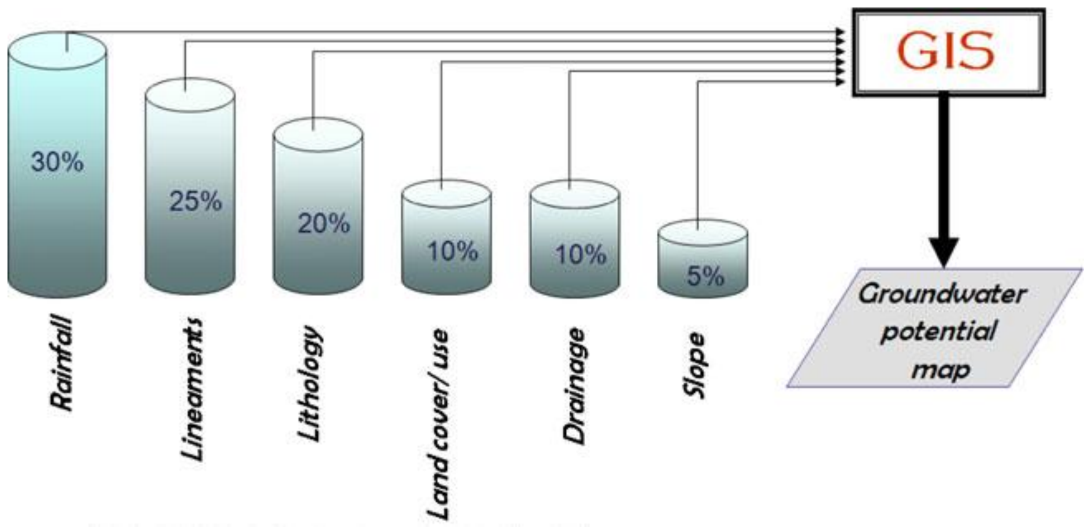


Figure 14: Thematic Maps Weights

As seen in above figure, the rainfall map has the highest weight in contributing to the calculation. Meanwhile, due to the conflicting effects slope has on groundwater, it is given a very low weight. Below figure showcases the final resulting map. Areas with the highest rainfall and rock fractures were shown to have the highest potential.

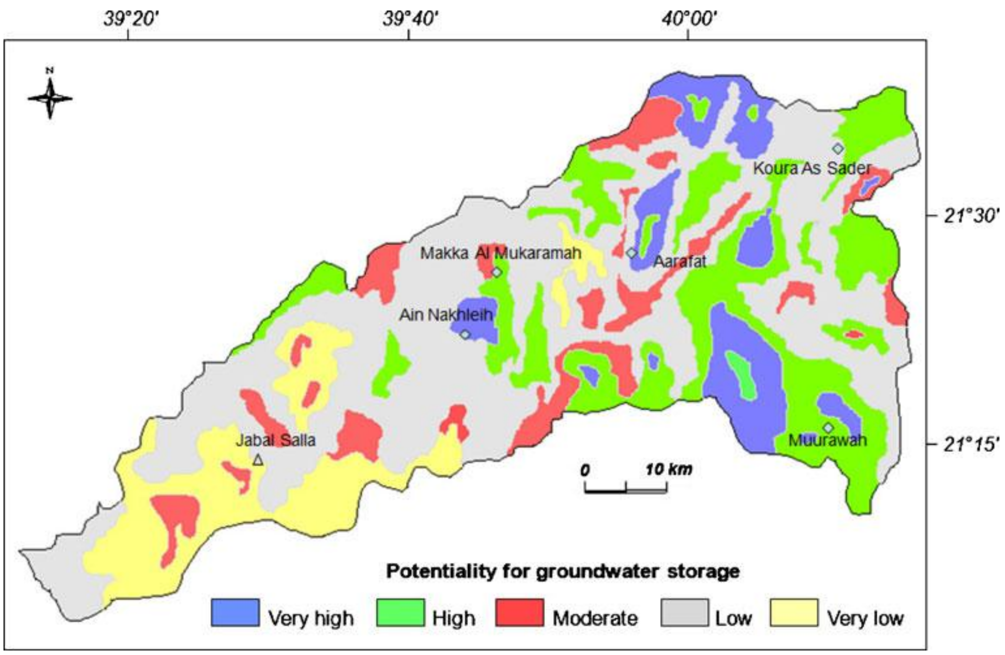


Figure 15: Final Potential Areas Map

For verification purposes, data about 56 dug wells in the area of study was collected. Wells were also classified into 5 groups to match the predicted potential areas. For very high and high areas the coincidence rate was 65% which shows a good estimate. The author anticipates an improved accuracy of the estimation by incorporating trusted data from operational wells.

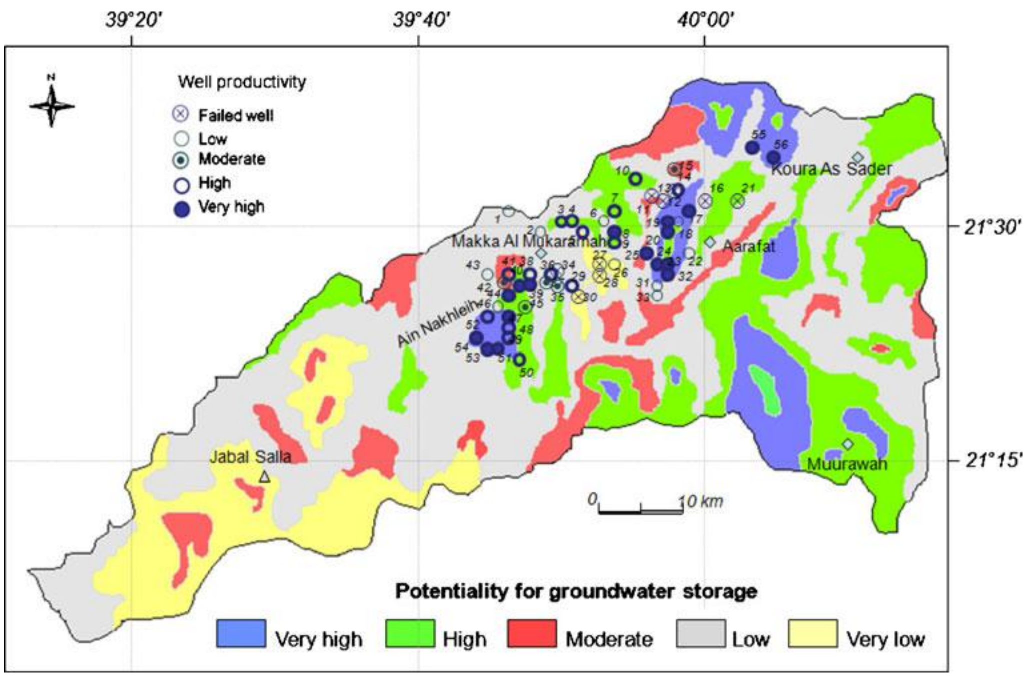


Figure 16: Verification Wells

ANALYSIS

Although both discussed case studies aim at mapping groundwater potential areas, they take opposing methods. Case study 1 uses produced water quality to extrapolate the quality parameters for the overall study area. Meanwhile, case study 2 uses a scientific method of analyzing remotely sensed images to predict groundwater potential. Then, well production data is used as a checking mechanism of the accurateness of the prediction methodology.

GIS has enabled both cases to digitize then geo-process and undertake geographic calculations of geologic data. Utilizing both methods can be useful in different situations. Relying on water quality from existing wells can be useful in smaller areas where the uncertainty is reduced.

Using remote sensing to infer geologic situations for perfect groundwater accumulation, as in case study 2, is mostly suited to larger areas. Satellite imagery and topographic maps can be obtained for a whole country and without any existing wells a rough estimation of optimum groundwater locations can be mapped.

CONCLUSION

In Saudi Arabia, an arid country, water is a valuable asset. With the rapid population growth and demand for water, water resources should be managed wisely. Groundwater is the most vulnerable source of water. With minimal rainfall, groundwater is being depleted. Hydrogeologists are responsible of monitoring and predicting groundwater aquifers.

Hydrogeologists are increasingly utilizing GIS to aid their efforts for groundwater estimation. Multiple methods were covered in this paper with varying degrees of data. With more reliable data, hydrogeologists can provide more accurate estimations.

To conclude, more attention should be given to Saudi Arabia's dwindling supply of groundwater. GIS is a must-have tool that will empower researchers and government agencies to perform groundwater management efficiently.

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