

**IDENTIFICATION OF AQUIFER STORAGE AND
RECOVERY POTENTIAL SITES IN CENTRAL – EAST
REGION OF SAUDI ARABIA**

BY

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MASTER OF SCIENCE

In

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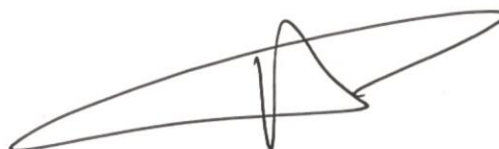
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Dedication

To Allah, parents, wife and daughter

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First and foremost, I want to dedicate my endeavor to Allah in gratitude for the wisdom he has bestowed upon me, as well as for the strength, peace of mind, and good health that have enabled me to complete my study at KFUPM.

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LIST OF ABBREVIATIONS

AGR	: Artificial Groundwater Recharge
AR	: Artificial Recharge
ASR	: Aquifer Storage & Recovery
ASTER	: Advanced Spaceborne Thermal Emission and Reflection Radiometer
BLM	: Boolean Logic Model
DEM	: Digital Elevation Model
EM	: Electromagnetic
ESRI	: Environmental Systems Research Institute
FAO	: Food and Agriculture Organization of the United Nations
GIS	: Geographic information system
GPZ	: Groundwater Potential Zones
IDW	: Inverse Distance Weighting
KML	: Keyhole Markup Language
LULC	: Land use/Land cover
MAR	: Managed Aquifer Recharge
MCDA	: Multi-Criteria Decision Analysis
MEWA	: Ministry of Environment Water & Agriculture

NASA	: National Aeronautics and Space Administration
RS	: Remote Sensing
UER	: Umm Er Radhuma
UNESCO	: United Nations Educational, Scientific and Cultural Organization
USGS	: United States Geological Survey
UTM	: Universal Transverse Mercator
WGS	: World Geodetic System
WOA	: Weighted Overlay Analysis

ABSTRACT

Full Name: [Ratno Pambudi]

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Groundwater is a significant source of water supply in arid and semi-arid countries, like Saudi Arabia. It accommodates approximately 75–85 percent of the country's entire water supply during the last decades. Due to domestic, industrial, and agricultural purposes, groundwater's abstraction was increased significantly. As a result, several areas of the country are experiencing groundwater depletion and water supply scarcity. Alternative solutions are required to explore new other water sources and to develop innovative management strategies to meet current and future water demand. Aquifer Storage & Recovery (ASR) is a significant approach for managing and restoring water resources that could provide water to the community. In establishing the ASR project, selecting suitable sites is an essential and critical factor of project success. The goal of this research is to identify potential sites for Aquifer Storage and Recovery (ASR) in central–east region of Saudi Arabia by integrating GIS, remote sensing, and Multi-Criteria Decision Analysis (MCDA) methodologies. The thematic data layers including Aquifer system, Geomorphology, Slope, Soil Textures, distance to lineament, Land cover, Aquifer depth, Aquifer thickness, Aquifer transmissivity, Groundwater salinity, and sources of injecting water (e.g. desalination plant and sewage treatment plant) were developed and utilized for the delineation of ASR potential sites. Each thematic layer was weighted according to its characteristics and relationship to groundwater recharge.

Finally, a weighted sum overlay analysis technique was used to integrate the thematic maps in order to identify suitable ASR locations. The map of artificial recharge zones was categorized into four different types, namely Good, Moderate, Low, and Very low. The good categories of ASR potential sites was selected as high priority depending on their proximity to the sources of injecting water (e.g. desalination plant and sewage treatment plant). The integration of GIS, Remote Sensing, and MCDA - Weighted Overlay Analysis (WOA) methods is assumed powerful tool for delineating ASR potential sites in the semi-arid region.

Keyword : Artificial Recharge, Water Resources Management, Multi-Criteria Decision Analysis (MCDA), Weighted Overlay Analysis (WOA), Remote sensing, Geographic information system (GIS).

الملخص الرسالة

الاسم الكامل: [رانتو فامبودي]

عنوان الرسالة: [تحديد المواقع المحتملة لتخزين واستعادة طبقة المياه الجوفية في المنطقة الوسطى والشرقية من المملكة العربية السعودية]

التخصص: [الجيولوجيا]

تاريخ الدراسة: [مايو ٢٠٢٢]

المياه الجوفية هي مصدر مهم لإمدادات المياه في البلدان الجافة وشبه الجافة مثل المملكة العربية السعودية، حيث تمثل ما يقرب من ٧٥-٨٥ ٪ من إجمالي إمدادات المياه في البلاد خلال العقود الماضية. بسبب الأنشطة المنزلية والزراعية والصناعية زاد استخراج المياه الجوفية بشكل كبير مما تسبب في نضوب المياه الجوفية وندرة إمدادات المياه في العديد من مناطق البلاد. ومن ثم هناك حاجة متزايدة لاستكشاف مصادر مياه بديلة جديدة وتطوير استراتيجيات إدارة مبتكرة لتلبية الطلب الحالي والمستقبلي على المياه. يعد تخزين واستعادة طبقة المياه الجوفية (ASR) نهجاً مهماً لإدارة موارد المياه. عند إنشاء مشروع ASR ، يعد اختيار المواقع المناسبة عاملاً أساسياً وحاسماً لنجاح المشروع. الغرض من هذا البحث هو تحديد المواقع المحتملة لتخزين واستعادة طبقة المياه الجوفية (ASR) في المنطقة الوسطى والشرقية من المملكة العربية السعودية من خلال دمج منهجيات نظم المعلومات الجغرافية والاستشعار عن بعد وتحليل القرار متعدد المعايير (MCDA) . تم إنشاء طبقات البيانات الموضوعية بما في ذلك نظام الخزان الجوفي، والتضاريس، والمنحدر، وقوام التربة، والمسافة إلى التضاريس الخطية، والغطاء الأرضي، وعمق الخزان الجوفي ، وسمك الخزان الجوفي ، ونفذية الخزان الجوفي ، وملوحة الخزان الجوفي ، ومصدر حقن المياه (مثل محطة تحلية المياه ومحطة معالجة مياه الصرف الصحي). وتم استخدام هذه البيانات لتحديد المواقع المحتملة لتخزين واستعادة طبقة المياه الجوفية من خلال ترجيح كل طبقة موضوعية وفئة مختلفة. تم وزن كل طبقة موضوعية وفقاً لخصائصها وعلاقتها بتغذية المياه الجوفية. أخيراً ، تم استخدام تقنية تحليل تراكب المجموع المرجح لدمج الخرائط الموضوعية من أجل تحديد المواقع المحتملة لتخزين واستعادة طبقة المياه الجوفية. تم تصنيف خريطة مناطق التغذية الصناعية إلى أربعة أنواع مختلفة ، وهي جيدة ، ومتوسطة ، ومنخفضة ، ومنخفضة جداً. تم اختيار الفئات المناسبة لمواقع تخزين واستعادة طبقة المياه الجوفية كأولوية عالية اعتماداً على

قربها من مصادر حقن المياه (مثل محطة تحلية المياه ومحطة معالجة مياه الصرف الصحي). يعد تكامل أساليب نظم المعلومات الجغرافية والاستشعار عن بعد و تحليل القرار متعدد المعايير أداة فعالة لتحديد مواقع تخزين واستعادة طبقة المياه الجوفية في المناطق شبه الجافة.

الكلمات الرئيسية: التغذية الاصطناعية ، إدارة الموارد المائية ، تحليل القرار متعدد المعايير (GIS) ، تحليل التراكم الموزون ، الاستشعار عن بعد ، نظام المعلومات الجغرافية (MCDA)

CHAPTER 1

INTRODUCTION

1.1. Background

Groundwater is one of the precious natural resources with a limited extent and volume, particularly in arid regions (Agarwal et al., 2013). In Saudi Arabia, Groundwater is considered a significant source of water. It provides approximately 75–85% of the country's total water supply during the last decades (Abderrahman, 2007; Gabr et al., 2017). Due to urbanization, human habitation, and agricultural and industrial activities, groundwater's abstraction increased significantly. Several areas of the country are experiencing groundwater depletion and water supply scarcity. Hence, there is a growing need to explore new alternative water sources and develop innovative management strategies to meet current and future water demand.

One of the most popular groundwater management methods in the arid-semi arid regions is Managed aquifer recharge (MAR) (Kadhem et al., 2020). Aquifer Storage & Recovery (ASR) is a practical MAR method that can provide excellent water storage and prevent saltwater intrusion, etc. (Gibson et al., 2018). This method is also called as Artificial Recharge (AR) (Committee on Ground Water Recharge, 1994; Al Qaran et al., 2013; Mahmoud et al., 2014). ASR involves injection of fresh water into aquifers through wells or ponds when surplus water is available (storage) and extracting water out from the same or adjacent wells when needed (recovery) (Lu et al., 2011). Sometimes it is also known as Planned Recharge, which is a method to store groundwater in a period of extra water to meet demand in scarcity periods. It is a

powerful approach for optimal water resources management. This could help to secure the water supply of the country for the indefinite future.

When planning the ASR project, selecting suitable sites is an essential and critical factor of project success. Several parameters affecting the implementation of ASR, are already tested in other research works such as geological description, land use, type of soils, groundwater level, geomorphology, topography, climate, aquifer characteristics, etc (Amineh et al, 2017). In this research, desalination and sewage treatment plant water were considered as the sources of injection water due to other sources waters such as rainfall in the study area did not meet the requirement. On the other hand, proximity analysis was conducted to find the closest ASR potential sites to the sources of the injection waters.

Lately, an integrated approach using GIS, Remote Sensing (RS), and Multi-Criteria Decision Analysis (MCDA) method has become a powerful method for managing groundwater resources. GIS, RS, and MCDA methods could be utilized effectively to identify the potential sites for ASR (Hammouri et al. 2013). Furthermore, geospatial technology is cost-effective and a rapid tool for delineating potential groundwater zones or Artificial Recharge (AR) (Amineh et al., 2017; Samson et al., 2015).

1.2. Problem Statement and Objectives

There has been a significant increase in groundwater demand due to the rise in industrial use, agricultural activates, and elevated population (Andualem et al., 2019). The extraction of a huge volume of groundwater has been carried out excessively in order to fulfill the water requirements of these numerous industries. Many regions worldwide are experiencing groundwater depletion. Moreover, in arid regions like Saudi Arabia, groundwater is scarce due to the minimal rainfall, low frequency of seasonal rainfall

events, and high evapotranspiration. But at same time, groundwater becomes the primary source of freshwater (Al-Qaran et al., 2013). Therefore, it seems to be experiencing more water scarcity intensively compared to other regions.

Under such severe conditions, numerous researchers are bolstering the search for new solutions by testing alternative ways to extend current water supplies and tap into new sources of supply, such as the Aquifer Recharge & Recovery (ASR) method. ASR is an important and relatively modern concept to meet current and future water use by storing water in a suitable aquifer or geologic structure and recovering it during high demand periods for various beneficial uses (Bajaba, 2012). ASR approach could significantly impact on meeting the rapid water demand increasing (Lopez et al., 2014). However, one of the essential factors in the ASR project is selecting the best potential sites (Amineh et al., 2017). This research tries to shed light on this issue.

The aim of the proposed research is stated in the following points:

1. To identify the potential locations for ASR in the central–east Region of Saudi Arabia.
2. To help decision-makers and water planners to explore alternative sustainable ways for enhancing and managing the groundwater resources.

1.3. Study area

The central-eastern Saudi Arabia (**Fig. 1**) is selected as a target area due to its closeness to main cities, agricultural areas, and possible water sources for ASR like desalination and wastewater treatment plants. At least, there are three provinces (Riyadh, Qasim, and the Eastern Province) and thirteen major cities in the central–east Region of Saudi Arabia. The cities are Riyadh, Al Majma'ah, Qbah, Al Zulfi, Unayzah, Al Ghat, Shaqra, Dammam, Al Hofuf, Al Khobar, Al Jubail, Kafji, Hafar Al-Batin, etc. It covers an area of about 350,000 km² that extends between latitude 26° 05' 59.99" N and longitude 51°

00' 0.00" E. Its elevation varies between 48 and 1272 meters above the mean sea level (**Fig. 2**). The climate of the proposed area is relatively arid with low average annual precipitation (± 74 mm/year). The water demands of the study area are mainly associated with industrial, domestic, municipal, and agricultural needs (Zaidi et al. 2015) (**Table 1**). The total consumption in three major provinces (Riyadh, Qasim, and Eastern Provinces) is about 1920 million m³ / year (**Table 3**). The primary sources of water consumption in the research region are groundwater and desalinated water (**Table 2**).

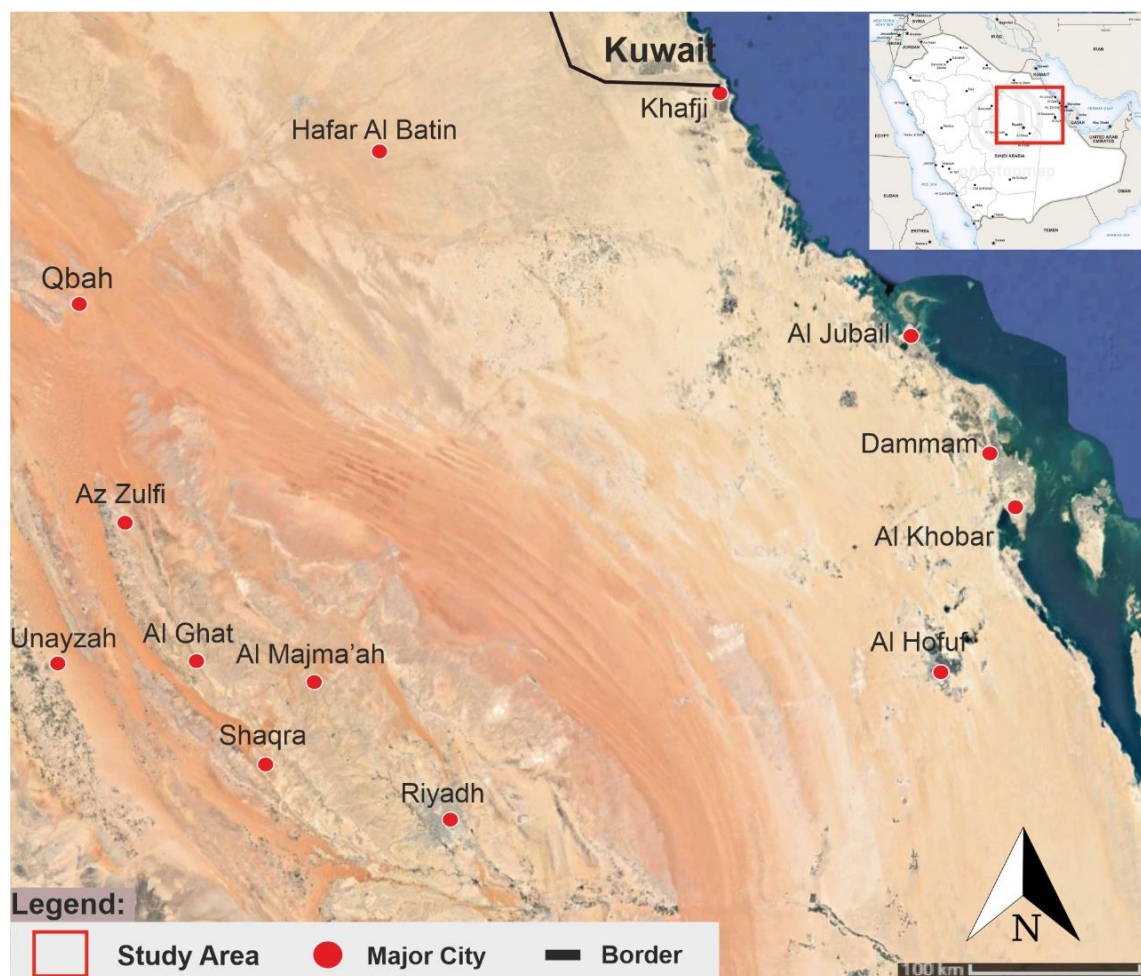


Figure 1. The satellite imagery from Google Earth of the study area.

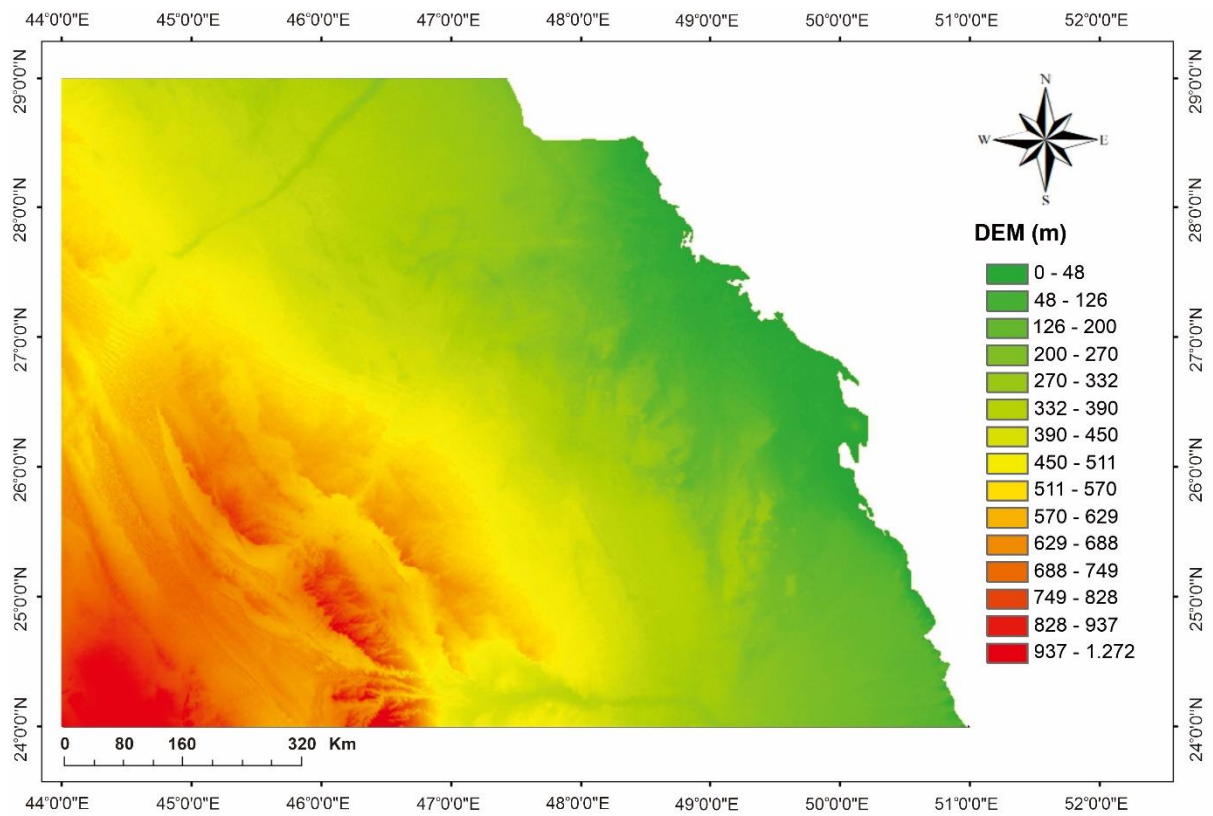


Figure 2. DEM of the research area.

Table 1: Water demand of Saudi Arabia from 2010 - 2018 (Unit in MCM/year) (MEWA, 2018).

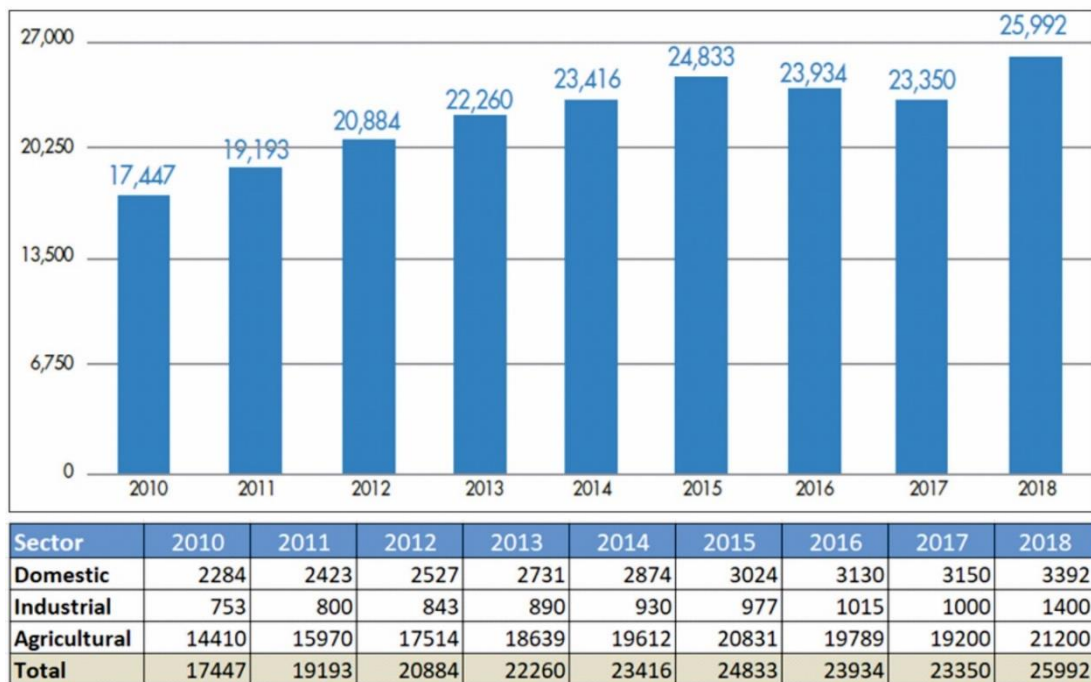


Table 2: Water demand of the proposed area according to the main sources 2016 - 2018 (Unit in MCM/year) (MEWA, 2018).

Province	2016			2017			2018		
	Groundwater	Desalinated water	Total	Groundwater	Desalinated water	Total	Groundwater	Desalinated water	Total
Riyadh	481	551	1032	444	626	1070	438	634	1072
Qasim	118	5	123	57	8	65	161	12	173
Eastern Province	292	367	659	246	436	682	269	406	675
Total	891	923	1814	747	1070	1817	868	1052	1920

Table 3: Total water consumption of study area by purpose (million m³ / year) (Unit in MCM/year) (MEWA, 2018).

Province	Commercial Consumption	Household Consumption	Total Consumptions (per year)
Riyadh	161	911	1072
Qassim	26	147	173
Eastern Province	101	574	675
Total	288	1632	1920

1.4. Thesis Structure

The structure of MS thesis comprises six chapters. The first chapter is an introduction (1). It discusses background, research objective and problem statement, study area, and thesis structure. The second chapter is literature review (2). It discuss about about the geological and hydrogeological background, and previous studies. Chapter (3) deals with the methodology of the research including data set and methodology. Chapter (4) deals with the results of the study including thematic layer preparation, weight assignment and ranking of the thematic layers, and aquifer storage and recovery potential sites. Chapter (5) discusses the parameters considered in determining ASR potential sites, ASR potential sites, and proximity analysis for ASR potential sites. Chapter (6) is the final chapter, which shows the conclusion of the study and the recommendations that will be benefit to future study.

CHAPTER 2

LITERATURE REVIEW

2.1. Geological and Hydrogeological Background

Geologically, the proposed area is situated in the Permian, Triassic, Jurassic, Tertiary (Paleogene, and Neogene sediments), and Quaternary. From bottom to top, the Permian rocks are divided into two formations: Unayzah Formation and Khuff Formation. These formations are mostly composed of shale, limestone, and sandstone. (**Fig. 3**). The Triassic–Jurassic rocks comprised of Minjur & Dhurma formations. The primary lithology of the formations is shale, sandstone, aphanitic limestone, and subordinate gypsum (Zaidi et al., 2015) (**Fig. 4**). Finally, the Paleogene – Neogene rocks consist of at least seven formations from bottom to the top, including Umm Er Radhuma (UER), Rus, Dammam, Hadruk, Dam, Hofuf Formation, as well as Quaternary (Sabkha Eolian Sand) (**Fig. 5**).

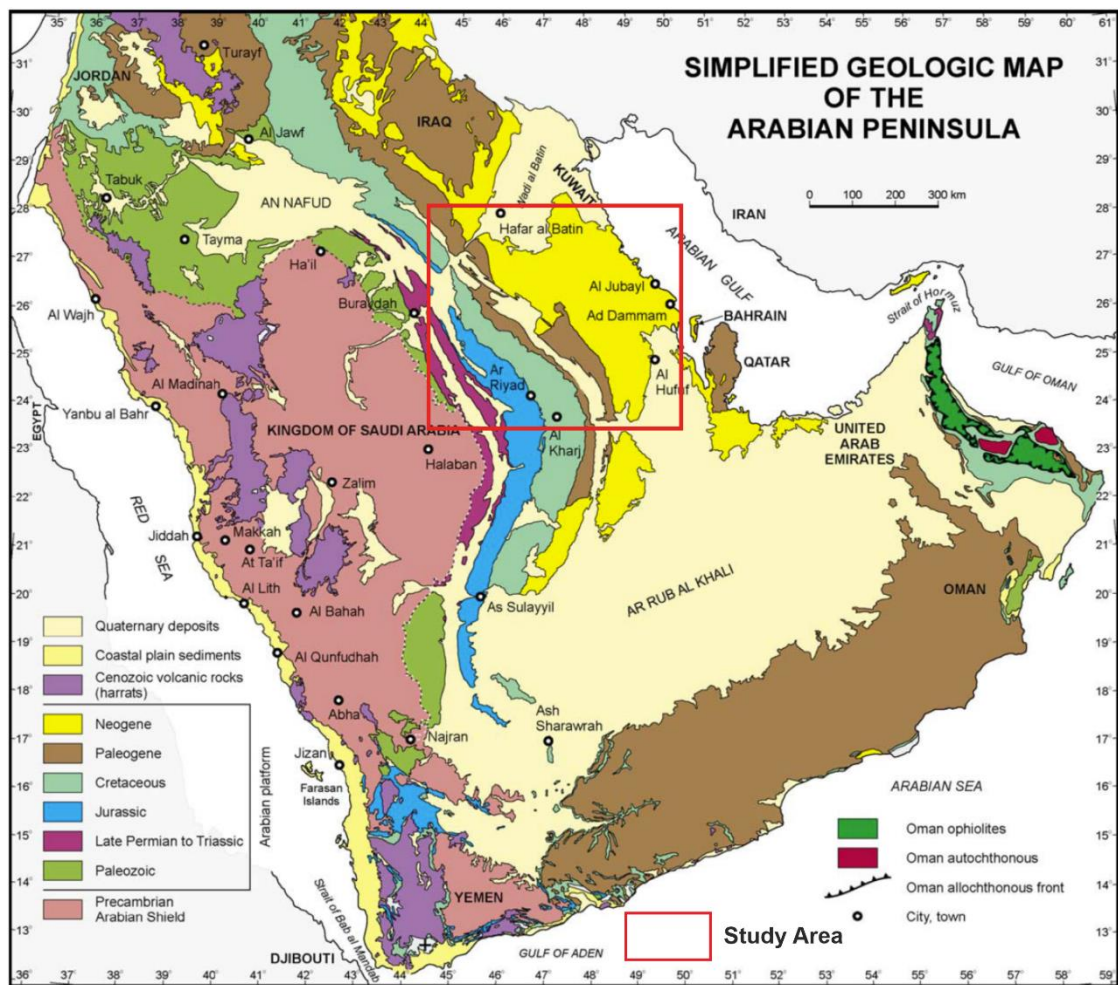


Figure 3. The geologic map of the study area (Modified from Le Nindre et al., 2003)

Geologic age		Group	Stratigraphic unit	Lithology	Comments	
CRETACEOUS	UPPER	ARUMA	Aruma		broad, gentle anticlines	
			Hiatus			
	MIDDLE	WASIA	Mishrif		Cretaceous and younger immature in Greater Ghawar area	
			Rumaila			
			Ahmadi			
			Wara			
			Mauddud			
			Nahr Umr			
	LOWER	THAMAMA	Shu'aiba			
			Hawar			
			Kharalib			
			Ratawi			
			Yamama			
Sulali						
JURASSIC	UPPER	RIYADH	Hith		regional seal rock	
			Arab			
	MIDDLE	TUWAIQ	Jubailah			A B C D ●<

Figure 4. The Paleozoic and Mesozoic stratigraphic units of Saudi Arabia (Pollastro, 2015).

The Geological structures in the study are dominated by Faults, Anticlines/Arcs, Synclines/Basins, and Grabens (Fox et al., 2002). The main morphology in the study area consist of wadis, sabkhas, karstic features, sand dunes, and the slope relatively towards the Arabian Gulf ((El Alfy et al., 2019). Structural trends along four main directions control the location of sedimentary provinces containing the aquifers and groundwater resources of Saudi Arabia. Among these, the NW–SE Erythraean trend that controls the subsidence, folding, and sediment distribution in the Arabian Gulf Basin. The Northern Interior Homocline also follows this structure alignment. The N-S Arabian Trend is seen in the En Nala Anticline (Ghawar) and Qatar Arc. The Ha'il – Rutbah Arch separates the Widyan Basin further to the east from Tabuk Basin, while the Qatar Arc separates the Arabian Platform from Rub' al Khali basin (Edgell. 1997). The Uplift with a trend toward the north cuts the Arabian Platform. These are the Khufaisah-Mubayhis Uplift, Jaham-Ma'aqala-Faridah-Wariah Uplift, Khurais-Burgan Uplift, En Nala Axis, and Qatif Uplift from the west to the east of the research area. The E-W structural trend can be seen in the Central Arabian Arch, which is cut by the Central Arabian Graben System. The NE-SW Aulitic Trend is seen in the axis of the Hadramaut–Dhofar bordering Saudi Arabia on the south and in the synclinal axis of the Rub' al Khali (**Fig. 6**) (Edgell. 1997). From west to east of the study area, at least, there are three intervening basins including Widyan basin, Dibdibah trough, and Central Basin. The Widyan Basin hosts the most significant aquifers in northern Saudi Arabia (Jaju et al., 2016). In Widyan basin joint Waisa-Biyadh Cretaceous aquifer are up to 650 m thick with abundant groundwater. The water-bearing strata in the Widyan basin consist primarily of thick, permeable Cretaceous sandstones. Dibdibah Trough is bordered by the summan Platform to west and Jauf anticline to east (Xiao et al., 2018). It was originally formed in Neoproterozoic and Early Cambrian. Dibdibah Trough is

sites of anomalously thick Triassic sediments, indicating that it underwent major subsidence (Faqira et al., 2009). Meanwhile, Central basin is located between Dibdibah Trough and En Nala Axis. It trends relatively the same with the En Nala Axis (**Fig. 7**).

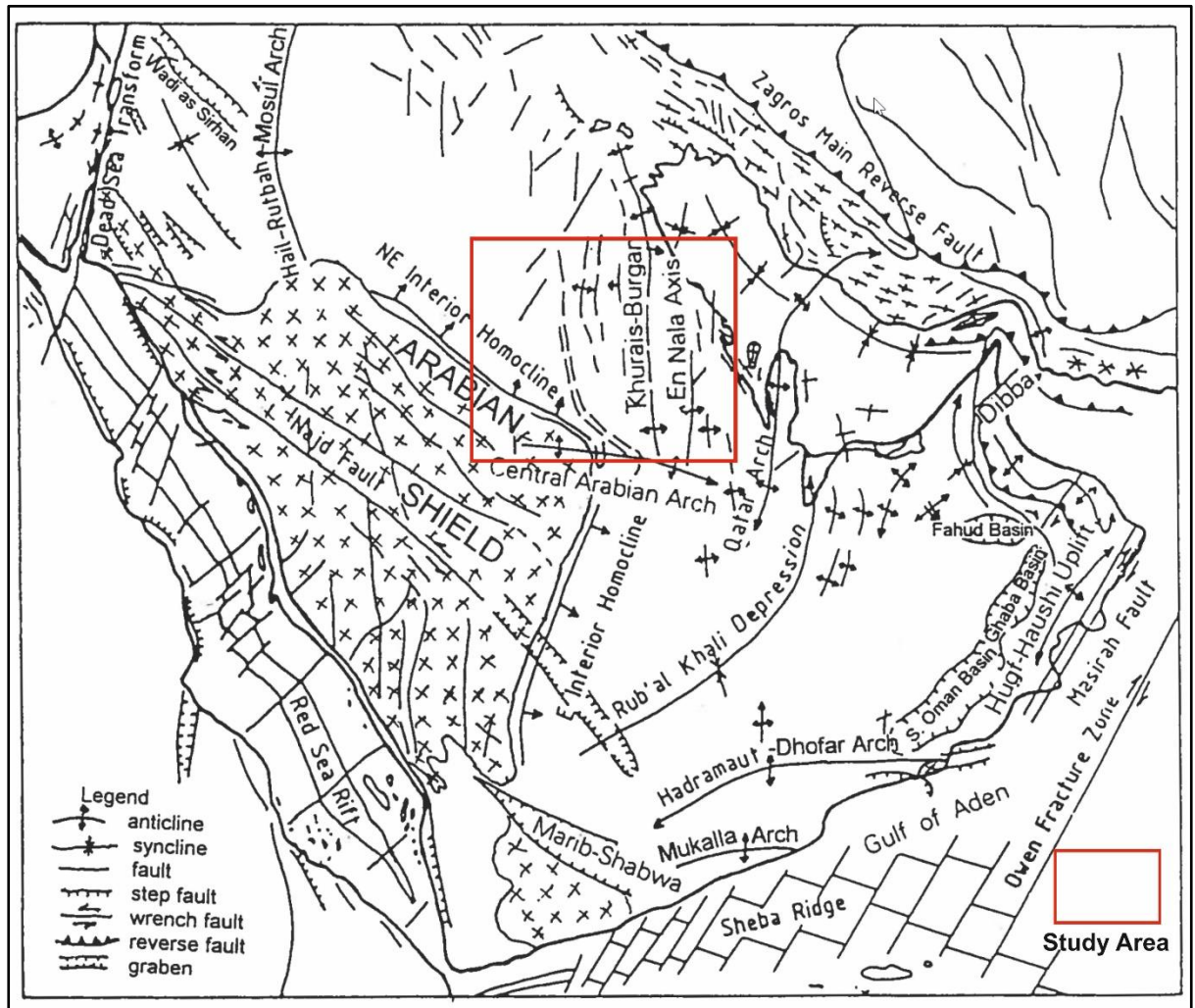


Figure 6. Tectonic and structural map of the Arabian Peninsula (Edgell, 1997)

Hydrogeologically, the principal aquifers system in the central – east region of Saudi Arabia are from bottom to top the Saq Aquifer, Minjur & Dhurma Aquifer, Wasia–Biyadh Aquifer, Aruma Aquifer, Umm Er Radhuma (UER) Aquifer, Dammam Aquifer, and Neogene Aquifer (Abderrahman et al., 2007; Kalbus et al., 2015) (**Fig. 8**). It comprises a sedimentary succession of Permian to Tertiary ages. The Saq Sandstone is the principle aquifer in northern Saudi Arabia (Edgell, 1997). It contains Cambro-Ordovician sandstone and has an average thickness of 400 to 500 m (Edgell, 1997). The Minjur & Dhurma aquifer is mainly made up of Upper Jurassic-age rock of limestone and sandstone and considered as a major groundwater supply for the City of Riyadh. Both Wasia-Biyadh and Aruma Aquifers consist of the Upper Cretaceous-age rock of sandstone and limestone (Zaidi et al., 2015). It contains a large amount of water, estimated at several billion m³ in the Riyadh Area. Aruma Aquifer considered as a secondary aquifer with relative minor importance for water supply in Saudi Arabia (Kalbus et al., 2011). The UER and Dammam are the major and essential aquifers in Eastern Saudi Arabia (Tajudeen, 2012). The UER formed of Paleocene-age rocks of limestone, and dolomitic limestone, whereas Dammam Aquifer is formed of Eocene-age rocks of limestone (Edgell, 1997). The summary of major aquifers in the research area is shown in the **Table 4**.

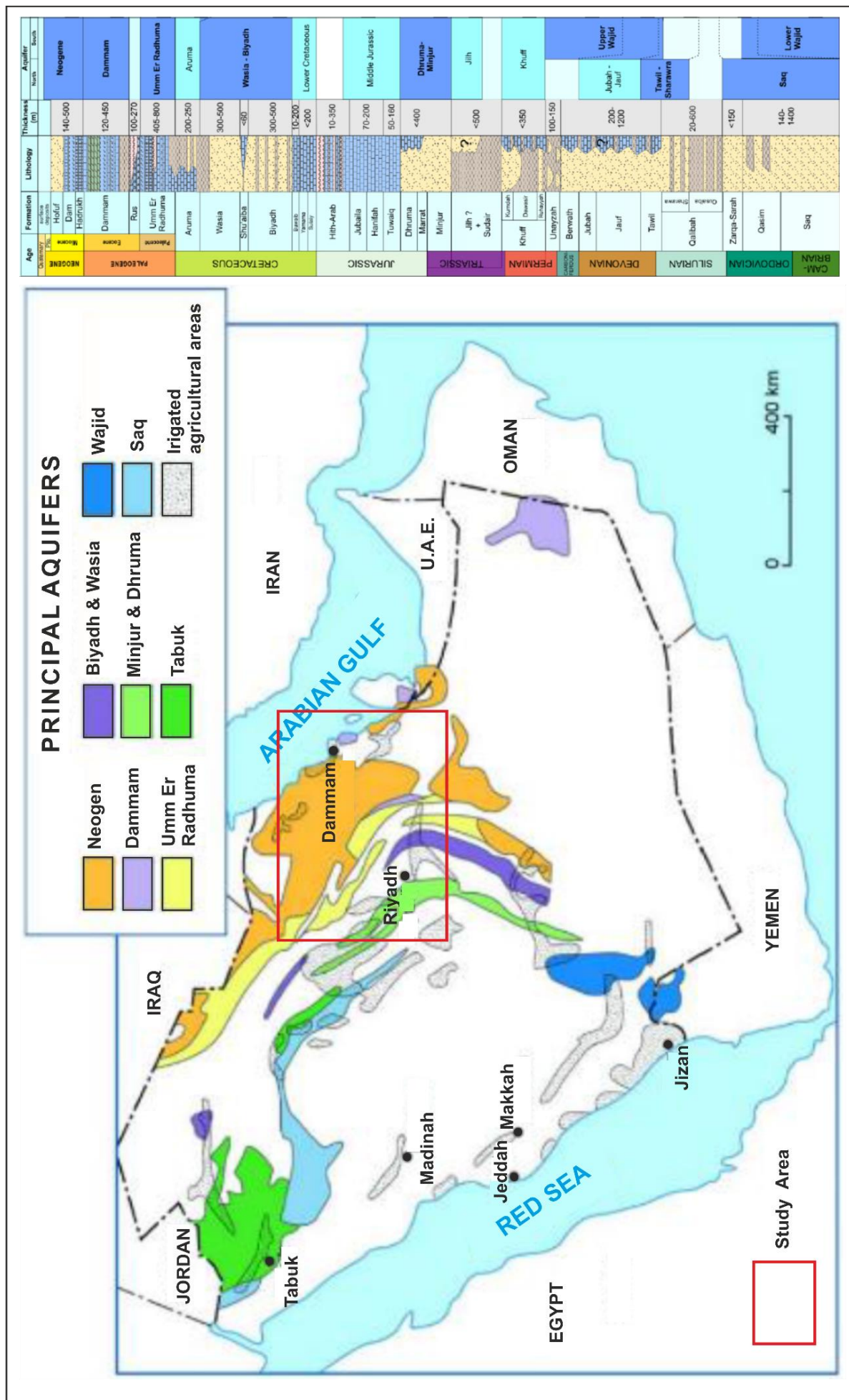


Figure 8. Principle Aquifers in Saudi Arabia (Molle et al., 2016).

Table 4: Summary of major aquifers in the study area (a: proven, b: probable, c: possible) (modified from Chowdhury et al., 2013).

Aquifer	Formation	Location	Depth	Yield	Water Quality	Reserves (BCM)		
						a	b	c
Dammam-Neogene	Five sections: Midra Shale, Saila, Shale, Alveolina Shale, aquicludes, Khobar limestone and Alat limestone.	The rock of Dammam aquifer extends over most of northeast Saudi Arabia and Rub al Khali	Depth: 80 m (Alat); 20 m (Khobar)		Dissolved solids: <1000 ppm	5	5	5
Umm er Radhuma Aquifer	Formed in shallow sea. Light colored, dense limestone, dolomitic limestone	Extends from Iraq border to Jordan border. 50–100 km wide, south for 1200 km to beyond Wadi Dawasir	The depth ranges from 240–700 m	4–32 L/s	Heavily mineralized	16	40	75
Wasia-Biyadh and Cretaceous sands Aquifers	Sandstone and shale	Biyadh: from Wadi Dawasir to nearly 650 km. Wasia: Nearly 1450 km from the Rub Al-Khali	Biyadh: 100 – 400 m thick. Wasia: 50–550 m thick. Maximum thickness: 1000 m	The average potentiometric ranges 210–300 m	Dissolved solids: 150,000 ppm	120	180	290
Minjur/Dhurma	Continental sandstone. Coarse quartzite sandstone with thin layers of limestone, shale, conglomerate, and gypsum	Ten to thirty km wide narrow band for 820 km from Haddar except for the break at the Wadi Brik and Wadi Rimah. It extends from Wadi Brik south as far east as the Rub Al-Khali	Depth: 1200–1500 m Thickness: Minjur: 310–400 m; Dhurma: 100–110 m	The average potentiometric ranges 210–300 m head lowered from 45 m below land surface in 1956 to 170 m in 1980	Salinity increases with depth. -TDS: 1200–15000 ppm; 1000–5800 ppm (near Haddar)	17.5	35	85
Saq	Medium to coarse grained sandstone. Locally contain finer material	Extends from eastern part to 1200 km northward near the Jordanian borders	About 2000 m; Thickness: 400–800 m	Tabuk: (9–228 L/s) Hail: (13–19 L/s) Qasim: (10–100 L/s)	Moderately mineralized. TDS less than 1000 ppm	65	100	200

2.2 Previous Studies

Over the last few decades, some researchers have adopted geospatial technology to identify Artificial Recharge zones (Agarwal et al., 2013). The majority of research have focused on the application of geographic information systems (GIS). (Saraf et al., 1998; Mahmoud, 2014). The use of an integrated remote sensing application and GIS methodology in ASR researches has just recently begun (Mahmoud et al., 2014). As MCDA is considered an effective tool for water management, several researchers from different regions merged it with GIS and Remote Sensing (RS) to delineate ASR potential sites such as in India (Chowdhury et al., 2010), Iran (Mehrabi et al., 2012; Amineh et al., 2016), Chad (Al-Djazouli et al., 2020), KSA (Mahmoud, 2014), UAE (Al Qaran et al., 2013), Ethiopia (Andualem et al., 2019), and Bahrain (Kadhem et al., 2020). Some researchers have also reported that the results obtained were satisfactory (Solomon et al., 2006; Andualem et al., 2019). The most widely used input layers include lithology, topography, drainage density, slope, precipitation, landcover, and lineament density (Zaidi et al., 2015; Amineh et al., 2016; Al Djazouli et al., 2020; Kadhem et al., 2020).

Chowdhury et al., 2010 is one of the earliest researchers that combined MCDA methods with remote sensing satellite within GIS environments to delineate suitable Aquifer Recharge areas in India. The various parameters including slope, geology, lineament, geomorphology, and drainage density have been considered thematic layers for outlining ASR's optimum sites. The MCDA technique is used to weight various thematic layers. Individual judgment is used to determine their relative relevance from the perspective of AR. Lastly, these thematic data layers are overlaid by the ArcGIS system to determine the favorable ASR sites. The integration of RS, GIS, and MCDA

methods have been effectively applied to determine the suitable sites for ASR. However, the inherent weakness of multi-criteria analysis is related to the data scarcity (in the quality and quantity term), especially in the developing country, which is often an obstruction problem for tackling the world water crisis.

Riad et al., (2011) compared the Weighted Overlay and Boolean Logic method to delineate suitable sites of ASR. Thematic maps for numerous factors were collected from published map and satellite imagery. Then, these data have been integrated and weighted in the ArcGIS system. The result showed that the overlay weighted model is recommended as a first evaluator for determining the potential sites since it is simpler and takes less time, while the Boolean logic is recommended as a second estimator because it is more accurate.

Al-Qaran et al., (2013) have conducted research in Al Ain Basin, UAE. The GIS-based multicriteria overlay analysis method has been employed to delineate the best locations for ASR. The three suitable zones of ASR have been obtained which have each different characteristic. Zone 1 is Jaw Plain which has lithology such as gravel and sand sediments (a relatively high permeability and storativity of water). Zone 2 is intensive in geological structure and lineament. Zone 3 is located between the alluvial plain and dunes which have a gentle land slope. It allows the water to stay for a longer time for recharging.

A research was carried out in Al Baha and Jazan Region, KSA (Mahmoud, 2014; Mahmoud et al., 2014). The research attempts to find suitable areas of artificial recharge by using a GIS-based MCDA. It combined MCDA technique, RS, and GIS. The thematic maps were derived from the soil type, slope, land cover, and rainfall. Meanwhile, other water sources will be considered as thematic layers in this research such as desalination saline water and sewage treatment plant (Zaidi et al., 2015). A

weight assignment of each thematic layers was applied to determine the favorable sites for groundwater recharge. The study's findings suggested four different categories of suitability: unsuitable, low, medium, acceptable, and exceptional. The study reveals that the most potential sites have slopes ranging from 4 % to 8 % which are cultivated intensively. The proposed method seems to be a significant benefit to hydrogeologists and is applicable in dry and semi-arid area.

Zaidi et al., (2015) have carried out research in Northwestern Saudi Arabia. The study area is characterized by a multilayered aquifer system in which most of the aquifers are exploited. Several thematic maps, such as lithology, geomorphology, rainfall, slope, and land cover were incorporated within the GIS System using Boolean Logic. This technique is developed by George Boole in 1854. Probably the Boolean logic is the most accepted and simplest GIS type model employed for input layers. It is divided into two classifications: satisfactory and unsatisfactory. There are various Boolean Logic operations, including OR, XOR, AND, and NOT. (Mahdavi et al, 2011). After integrating with land use maps to avoid the agricultural area and inhabited land, the results show that a suitable area for AGR is covering 14.24 % of the area. Morphologically, the Wadi beds are the most favorable zones for ASR installation. Based on the potential ASR sites closeness to possible water sources like desalination plants, sewage treatment facilities, and natural streams, the potential sites were categorized as High Priority (Zone A) and Low Priority (Zone B).

Senanayake et al., (2015) have conducted research to identify potential artificial recharge zones in the Ambalantota, Sri Lanka. In this study, the integrated of GIS and Weighted overlay approach were used to identify Artificial Recharge potential sites. Influential thematic layers such as Lithology, slope, lineament and drainage density, geomorphology, the characteristic of soil, rainfall, and land cover. The result showed

that around 49 % of the study area had a moderate to high groundwater recharge potential.

Amineh et al., (2016) demonstrated a MCDA technique in conjunction with the GIS system to delineate the suitable sites for Aquifer Storage & Recovery in Southeast Iran. The eight parameters including the geomorphology, lithology, landcover, drainage density, and sources water availability (e.g. rainfall, treated water, etc.), and extracted remote sensing image was considered as principle GIS layers. Then, these parameters were weighted based on their relative influence to Artificial Recharge. After assigning the weighted criteria, the GIS overlay produced maps of suitable groundwater recharge sites. It was suggested that 34 % of the total area is potential for ASR sites.

Andualem et al., (2019) have conducted research to identify the artificial recharge potential zones using GIS and RS in Ethiopia. The MCDA method was applied to explore groundwater potential prospect sites by incorporating various groundwater contributing thematic layers, such as soil texture, lineament, lithology, topography, slope, drainage pattern, geological structures, land cover, and sources water availability. Each thematic layer was assigned weights based on the attribute and correlation with the groundwater recharge. Lastly, the weighted thematic layers were combined using an overlay tool of GIS to determine the groundwater potential sites. It was suggested that the most favorable groundwater potential sites are located in the Fogera Flood Plain (the downstream part of the area). It covers approximately 833.49 km² area. This research is very helpful for water authorities by identifying the potential sites for development, and the method is applicable in other area of the country.

Abdou Karim et al, (2019) conducted research to find the best sites for artificial recharge. The study aim is to increase water resources management strategy in Abu Dhabi by selecting finding the suitable locations for ASR. In selection criteria for ASR

sites, this study considers several hydrogeological characteristics such as Aquifer Confinement, Aquifer Permeability and Transmissivity, Aquifer Thickness, Groundwater depth, and, Groundwater Salinity, and Infrastructural parameters.

Recently, Kadhem et al., (2020) conducted research to identify the optimal Rainfall Harvesting (RH) & Managed Aquifer Recharge (MAR) sites within a 780 km² area of Bahrain. They employed MCDA methodology using GIS to augment the groundwater supply as one of the government projects. The eight parameters controlling groundwater recharge were used to identify maximum MAR locations by implementing Weighted Overlay Analysis (WOA) methodology. The study indicated at least six general sites, which are potential for ASR (ranked excellent to very good). The study's limitations are the low accuracy of the satellite, which needs to improve map resolution and the infrastructure map. The study combined rainfall data with other sources of water to maximize ASR potentiality.

Based on the previous literature reviews, it is assumed that MCDA, using WOA approaches, has been applied effectively in many cases in groundwater exploration and environmental management (Al-Djazouli et al., 2020). The WOA methods are widely used and accepted in the MCDA model for delineating potential groundwater sites in many regions worldwide, particularly in arid-semi areas (Al-Djazouli et al., 2020). Also, the integration of GIS, RS, and MCDA-WOA was considered a powerful tool for delineating Artificial Recharge (AR) zones. These methods will help in solving the freshwater scarcity problem in the region and effectively minimize the time needed, labor, and cost (Al Djazouli et al., 2020).

CHAPTER 3

DATA AND METHODOLOGY

3.1. Data Set

In order to create the thematic maps for this study, data for ten criteria were collected from a variety of sources, as follows:

1. ASTER DEM was obtained in TIFF format from the Japan Space Agency and NASA website earthdata.nasa.gov with a 30m resolution (NASA, 2021). It was used to generate Slope, Geomorphology, and Lineaments maps.
2. Land use/cover (LULC) data were derived from Sentinel 2 Image 2020 (ESRI, 2020).
3. Aquifer map of study area was adopted from reports of Ministry of Environment, Water, and Agriculture (MEWA), KSA (MEWA, 2018).
4. Soil Texture data were collected from Water Atlas of Saudi Arabia (1984) (MEWA, 1984).
5. Hydrogeological parameters including Aquifer system, Aquifer depth, Aquifer thickness, Aquifer transmissivity, and Groundwater salinity were obtained from Ministry of Agriculture and Water, KSA and research publication (Edgell, 1997; (UN-ESCWA, 2013; Dirks et al., 2018; MEWA, 2018).
6. Sources considered of injecting water for ASR in the study area are desalinated saline water and treated wastewater plants (Chowdhury et al., 2013).

3.2. Methodology

To achieve the research objectives, the integration of RS, GIS, and MCDA-WOA methods will be implemented to map the artificial recharge potential sites. All collected

databases including a published map, remote sensing data, and sources of injecting water will be utilized to achieve the research's goals. Major steps to generate the potential ASR map are as follows (**Fig.11**):

1. Generating the thematic layers

Several parameters are used to generate the thematic data layers including: Aquifer system, Geomorphology, Slope, Soil Textures, Lineaments, Land cover, Aquifer depth, Aquifer thickness, Aquifer transmissivity, and Groundwater salinity, and source of injection water (e.g. desalination plant and sewage treatment plant). Primary desalination plants in the proposed area are Jubail, (1, 2 & RO), Khobar (2&3), and Khafji plant (Chowdhury et al., 2013) (**Fig.12**). In Addition, the sewage treatment plants in the study area are located in Al-Kharj, Qatif (Sanabis & Qatif), Al Hassa (Emran & Hufuf-Mubarraz), Riyadh (Al-Hayer old & Al-Hayer new plants), Dammam, and Khobar (Chowdhury et al., 2013) (**Fig. 13**).

Several researchers used these criteria based on their experiences and the availability of the data in the study area (Al Djazouli et al., 2019). These factors are proven useful to solve groundwater management problems in many regions worldwide (Chowdhury et al., 2010; Andualem et al., 2019). ArcGIS version 10.3. package is utilized to extract the above-mentioned parameters. All thematic layers were set to UTM coordinate system (WGS 1984 Zone 39 N) in the ArcGIS platform and transferred into a raster file in pixel size 30m x 30m resolution.

2. Weight assignment using MCDA-WOA method

The MCDA is a qualitative overlay approach that requires rating and weighting of several data layers related to a specific purpose within the GIS environment (Gibson et al., 2017). Within MCDA methods, there are various techniques such as Fuzzy Logic, Boolean Logic Model (BLM) and the most popular and common used are the Weighted

Overlay Analysis (WOA). A WOA approach is created utilizing the ArcGIS system to delineate potential areas for aquifer recharge based on the weighting of data layers and the ranking of various classes (Riad et al., 2011) (**Fig. 9**).

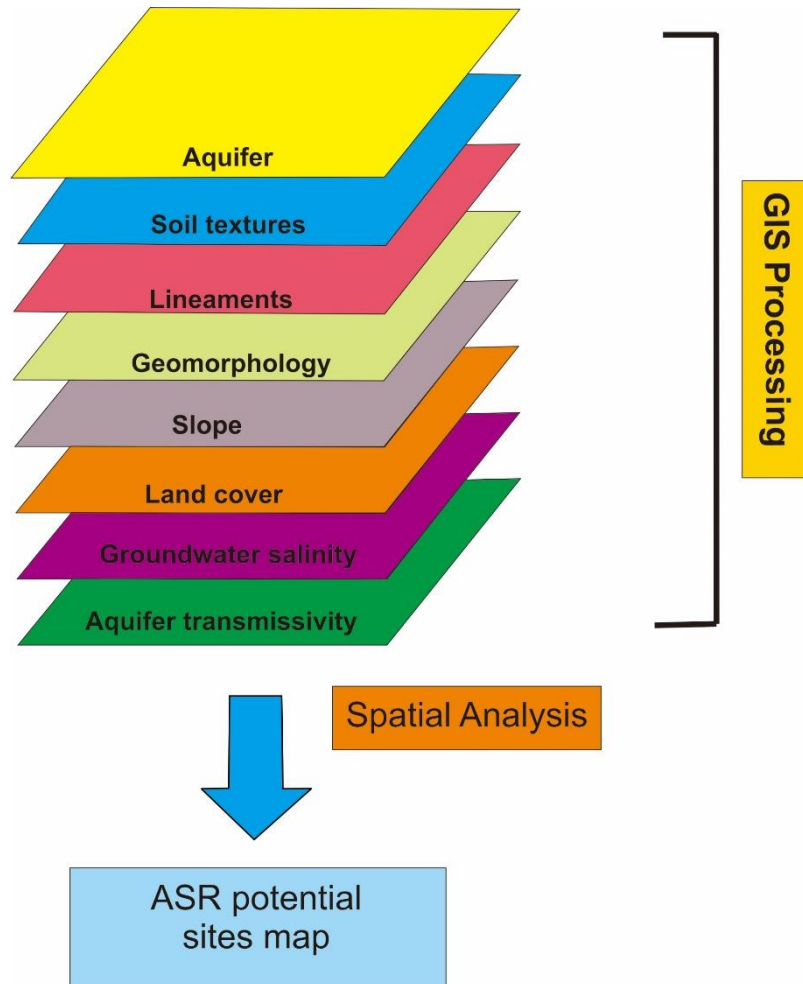


Figure 9. GIS analysis using Weighted Overlay tool to demarcate ASR potential zones.

During the weighted overlay analysis, the weight is assigned according to the influence of the different parameters and the ranks have been given for each feature of thematic map. The total weight for all thematic layers is equal to 100 %. The higher the percentage, the higher the influence. Each feature of a particular thematic layers is

ranked in the scale of 1-5 based on its significance where 1 is the lowest significance while 5 is the highest significance (**Fig.10**).



Figure 10. Ranking factor index.

After assigning weights, all thematic maps were overlaid using Weight Overlay Analysis (WOA) tools in ArcGIS 10.3 platform to delimit artificial recharge zones. It was determined by the following formula (Senanayake et al., 2015):

$$\mathbf{WOA} = (AQ_w \times AQ_r) + (GM_w \times GM_r) + (S_w \times S_r) + (ST_w \times ST_r) + (LE_w \times LE_r) + (LU_w \times LU_r) + (Ath_w \times Ath_r) + (AD_w \times AD_r) + (ATs_w \times ATs_r) + (GS_w \times GS_r) \dots \dots \dots (1)$$

Where: AQ=Aquifer System; GM=Geomorphology; S=Slope; ST=Soil Textures; LE=Lineament; LU=Landuse/cover; Ath=Aquifer Thickness; AD=Aquifer Depth; ATs=Aquifer Transmissivity; GS=Groundwater Salinity, **w**= the weight of each thematic layer/ parameter; **r**= the rank of each feature/class. The WOA equation is by multiplying the weight of each thematic layers with the rank of its features, and then sum up all of multiplications of each parameters. The example of the equation as follows:

Table 5: The example of Weighted Overlay Analysis (WOA)'s equation.

No	Thematic layer/factor	Weight of factor	Scoring for factor		Score for ASR site
1	Slope	8	0-2 % 2-4 % 4-8 % 8-15 % > 15 %	5 4 3 2 1	(8 * 5 = 40)
2	Land Cover	9	Crops land Scrub/Shrub Built Area Bare Ground	2 4 1 5	(9*5 = 45)
3	Aquifer Salinity (g/L)	13	< 1 g/L 1 - 3 g/L 3 - 5 g/L 5 - 10 g/L > 10 g/L	5 4 3 2 1	(13 * 5 = 65)
4	Other factors				

Overall score for ASR site = sum ((w1 x wi1) + (w2 x wi2) + (w3 x wi3)) = (40 + 45 + 65) = 150

3. Proximity Analysis for ASR sites

Feasibility of ASR sites will be analyzed based on the availability of nearby water sources. The final ASR sites map is dependent on their proximity to the water sources such as seawater desalination and sewage treatment plants (Zaidi et al., 2015)

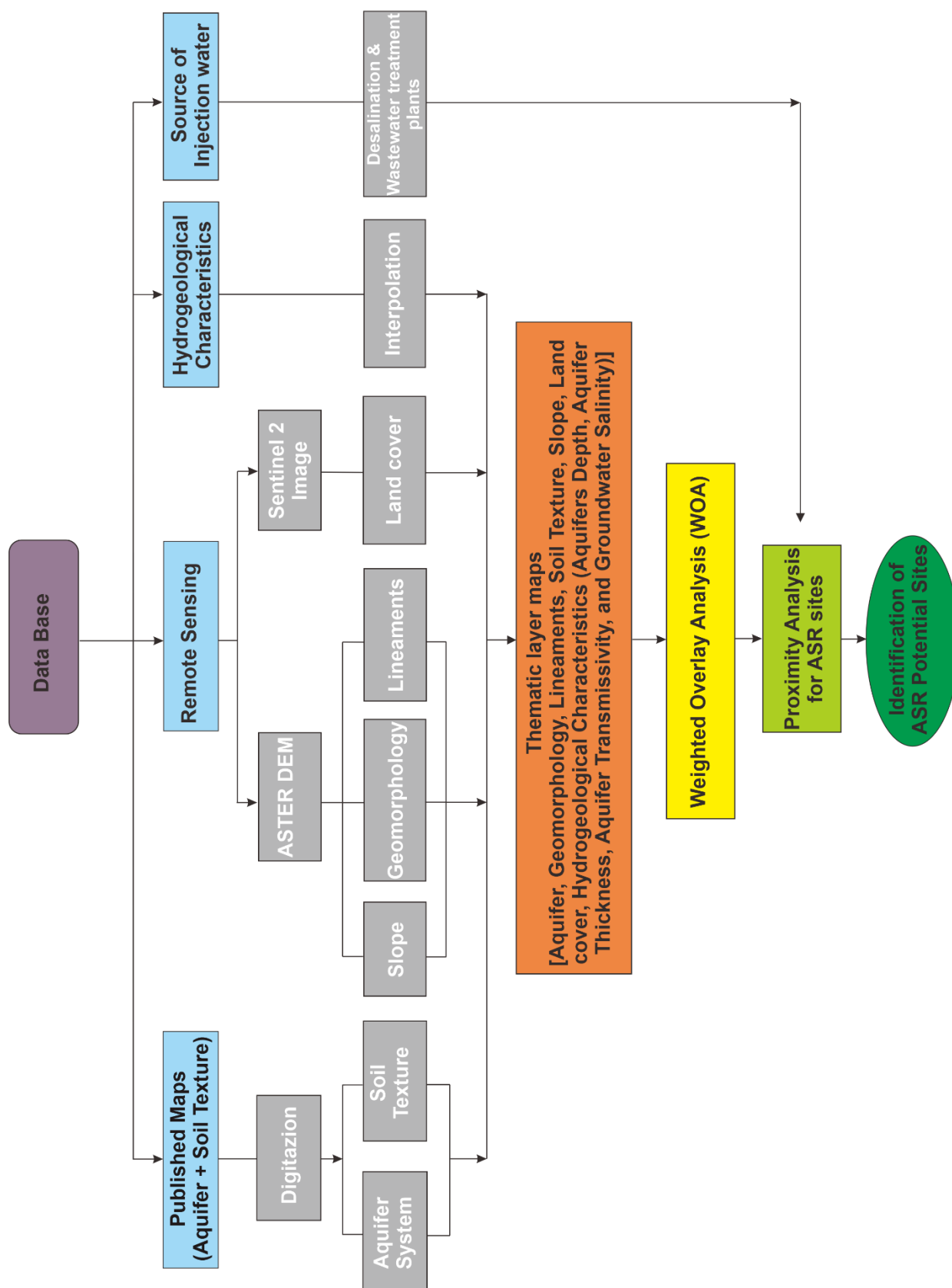


Figure 11. Systematic workflow of this study

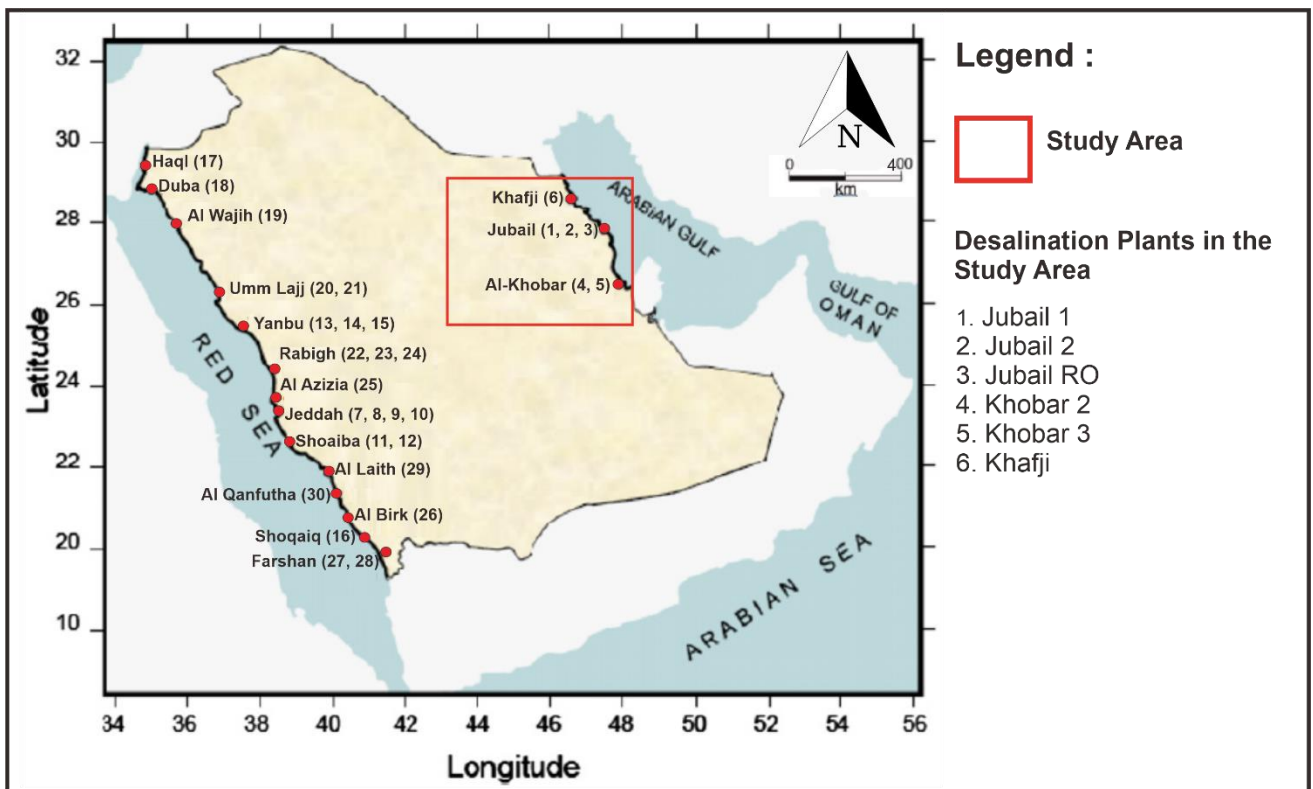


Figure 12. Location of desalination plants in the region (modified from Chowdhury et al., 2013).

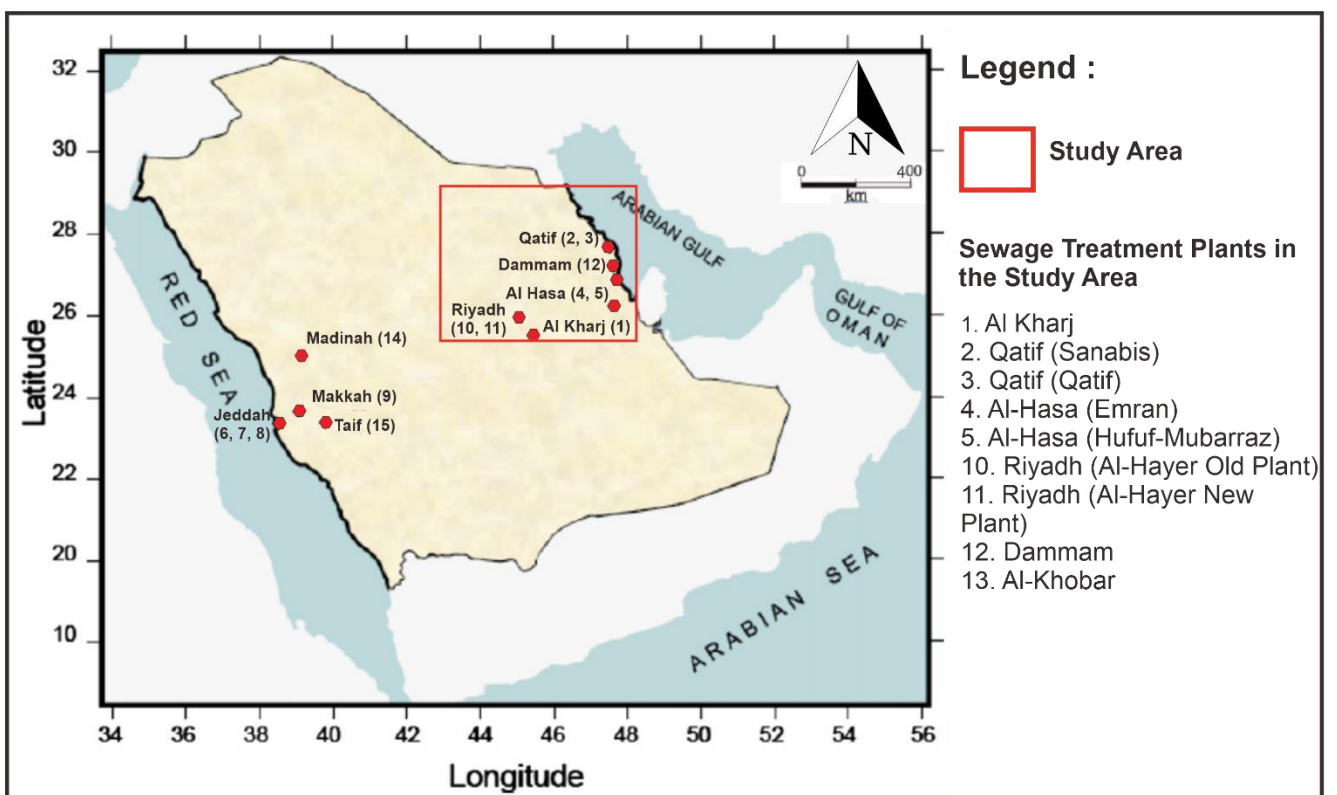


Figure 13. The major sewage treatment plant in the region (modified from Chowdhury et al., 2013).

CHAPTER 4

RESULTS

4.1. Thematic Layers Preparation

Ten characteristics were taken into consideration for delineating the favorable aquifer recharge sites in the research area based on (*Multi-criteria decision analysis*) MCDA method. After all thematic maps were set to WGS 1984 Zone, 39 N UTM coordinate system in the ArcGIS platform. Then, these vector layers were converted into a raster format in pixel of 30m x 30m resolution. The details of each thematic layer are discussed in the following sections :

4.1.1. Aquifer system

The aquifer map of the study area was adopted from Ministry of Agricultural and Water, KSA (1979). From bottom to top, the aquifer system includes Saq Aquifer, Minjur & Dhurma Aquifer, Wasia–Biyadh Aquifer, Aruma Aquifer, Umm Er Radhuma (UER) Aquifer, Dammam Aquifer, and Neogene Aquifer (Kalbus et al., 2015). It comprises a sedimentary succession of Permian to Quaternary ages. The Saq aquifer contains Cambro-Ordovician sandstone (Edgell, 1997). The Minjur & Dhurma aquifer is mainly made up of Upper Jurassic-age rock of limestone and sandstone. Both Wasia-Biyadh and Aruma Aquifers consist of the Upper Cretaceous-age rock of sandstone and limestone (Zaidi et al., 2015). The UER and Dammam are the major and essential aquifer in Eastern Saudi Arabia (Tajudeen, 2012). The UER is formed of Paleocene-age rocks of limestone, and dolomitic limestone. Dammam Aquifer is formed of Eocene-age rocks of limestone (Edgell, 1997). Quaternary aquifer contains silty sandstone, sandy limestone, and calcareous (Zaidi et al., 2015) (**Fig. 14**).

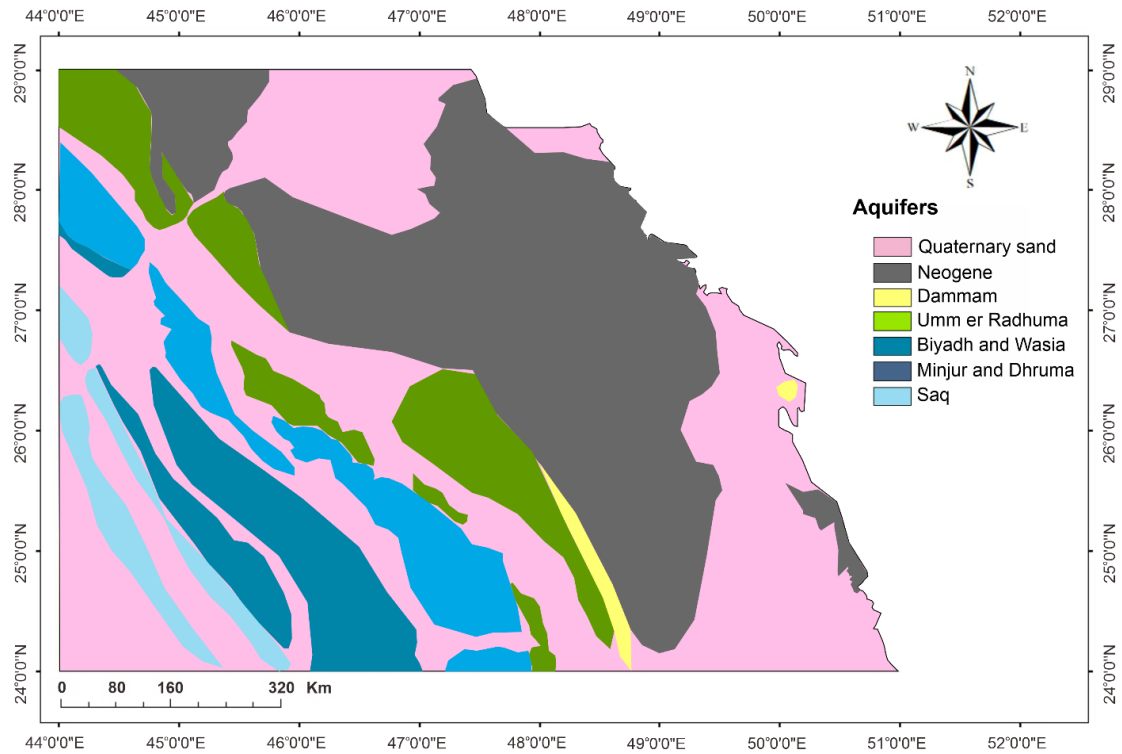


Figure 14. Aquifer map of the research region (Ministry of Agricultural and Water, KSA (1979).

4.1.2. Geomorphology

The geomorphological map of the central – east region of Saudi Arabia was delineated from ASTER DEM in a 30 m x 30 m resolution. It is developed using a semi-manual method through ArcGIS software. The study area is classified into three-geomorphological groups including Najd Plateau, Eastern Plateau, and Coastal plain (Al-Ahmadi et al., 2013) (**Figure 15; Table 6**).

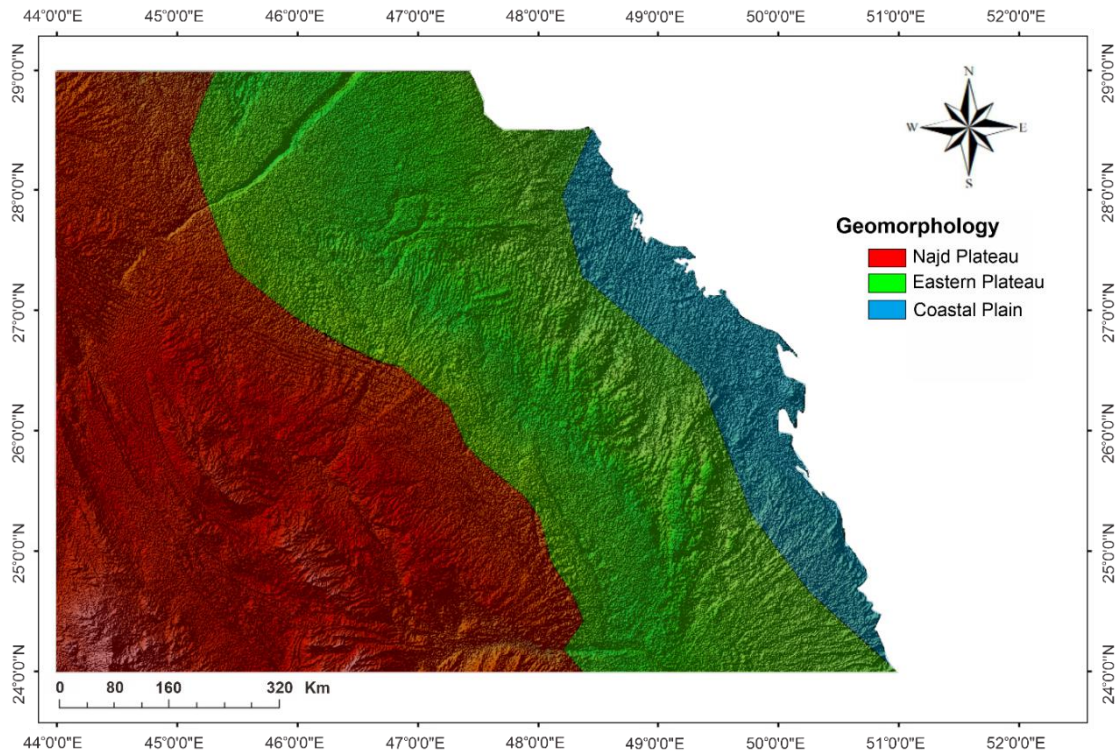


Figure 15. Geomorphology map (modified from Al-Ahmadi et al., 2013).

Table 6. Percentages of geomorphology in central – east region of Saudi Arabia

Geomorphology	Area (km ²)	Percentage (%)
Najd Plateau	157500	45
Eastern Plateau	148750	42.5
Coastal Plain	43750	12.5

4.1.3. Lineaments

ASTER DEM was used to create the research area's major lineament's map. These lineaments were digitized using a semi-automated method and processed in the GIS platform using the hillshade tool (Fig. 15). (**Fig. 16**). The four directions (N0°, N45°, N90°, N135°) were used to show the highest number of lineaments in the study area. Based on the lineament density map, the research region was reclassified into two categories: close to the lineaments area and other areas (far from the lineament area).

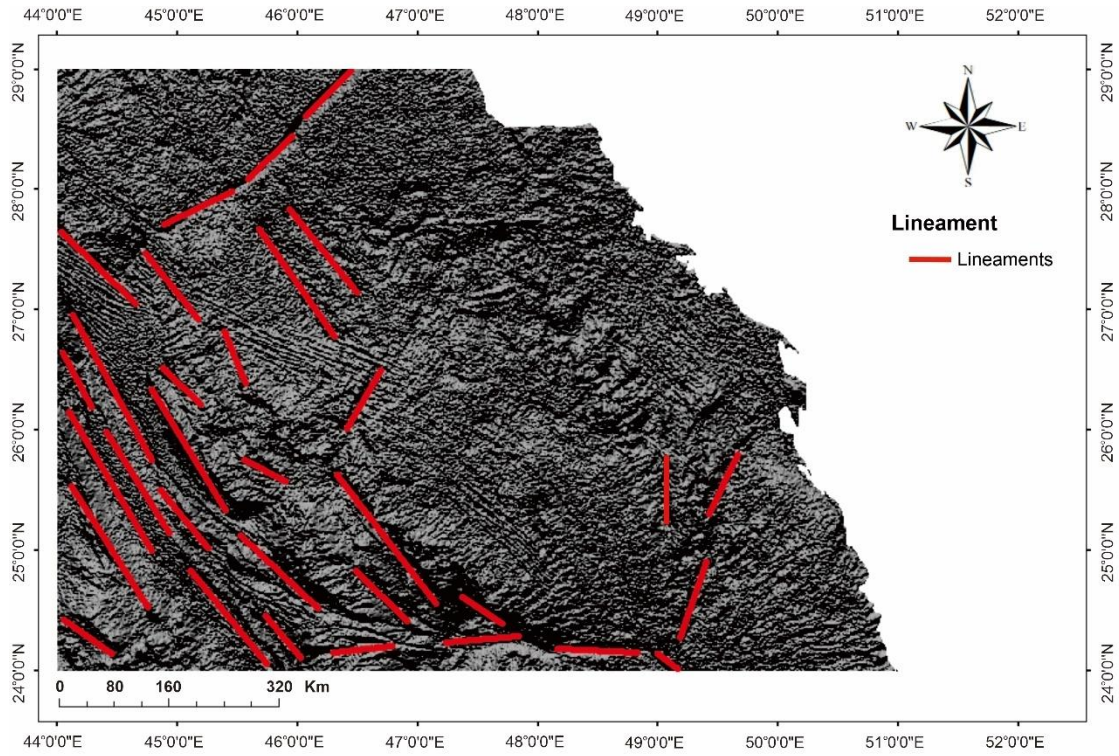


Figure 16. Lineaments map.

4.1.4. Soil Texture

The Soil texture map was extracted from the KSA water atlas (1984) as shown in (Fig. 17). Major Soil textures in the study area include: Loamy - clayey, Stratified loamy – skeletal, Loamy – skeletal, Loamy, Sandy – loamy, Stratified loamy, Sandy, Sandy – loamy, and Sandy – skeletal. Loamy – clayey is a soil mixture that comprises a greater proportion of clay than other types of rock or minerals. Loamy soil is characterized by the texture of fine earth, which comprises loamy very fine sand, very fine sand, and finer textures containing less than 35% clay (KGS, 2009). Sandy is a soil that contains majority sand-sized particles and normally has less than 8 % of clay (Morris, 2017). Sandy – loamy soils are dominated by sand particles. Sandy – skeletal is a common term with gravel or very gravelly loamy which contains more than 35% of the soil volume particles coarser than 2 mm (KGS, 2009; Morris, 2017). Loamy - skeletal soils include

particles that are larger than 2 mm in size and accounting for 35% of the total volume (KGS, 2009).

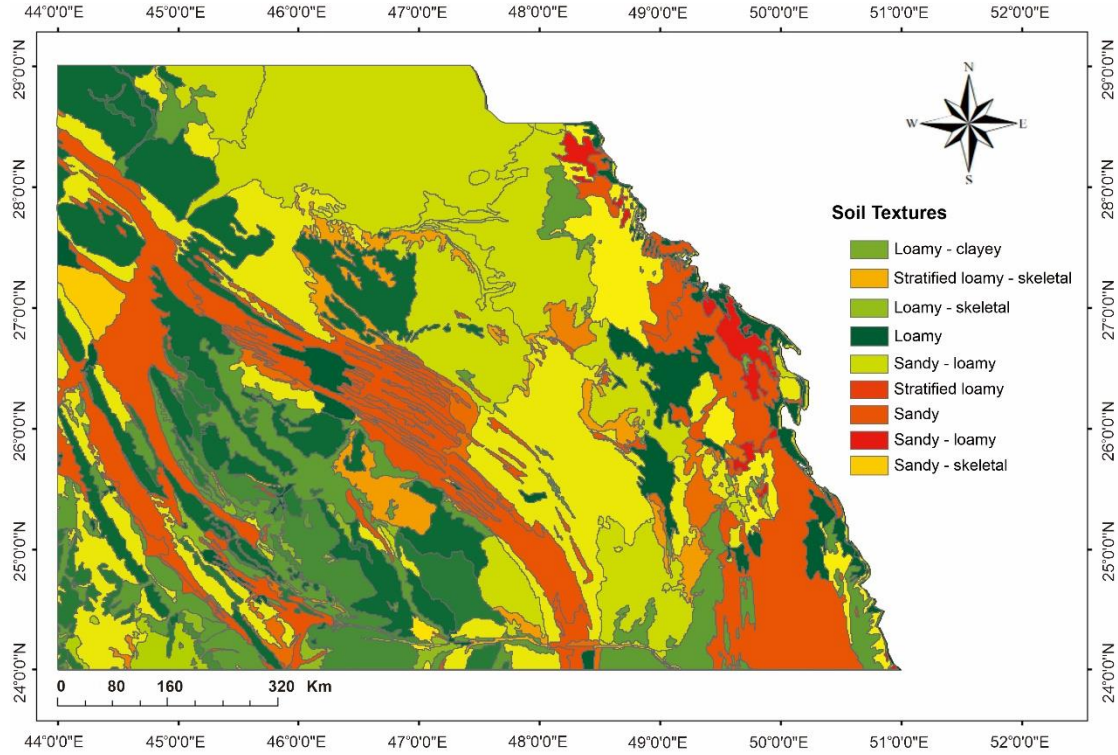


Figure 17. Soil texture map.

4.1.5. Slope

The Slope map of the central-east region of Saudi Arabia was generated from ASTER DEM with 30m spatial resolution using ArcGIS 10.3 software's spatial analysis tool (**Fig. 18**). The ASTER DEM was mosaicked and extracted to fit the research region and calculated according to (**Eq. 2**). The slope map of the research region ranges from 0 to 15 %. The slope values were divided into five groups including flat/nearly leveled (0 – 2%), gentle (2 – 4%), moderate (4 – 8%), moderate to steep (8 – 15%), and steep (> 15%).

$$\text{Slope} = \text{ATAN} \left(\sqrt{\left(\frac{dz}{dx} \right)^2 + \left(\frac{dz}{dy} \right)^2} \right) \times 57.29578 \dots\dots\dots(2)$$

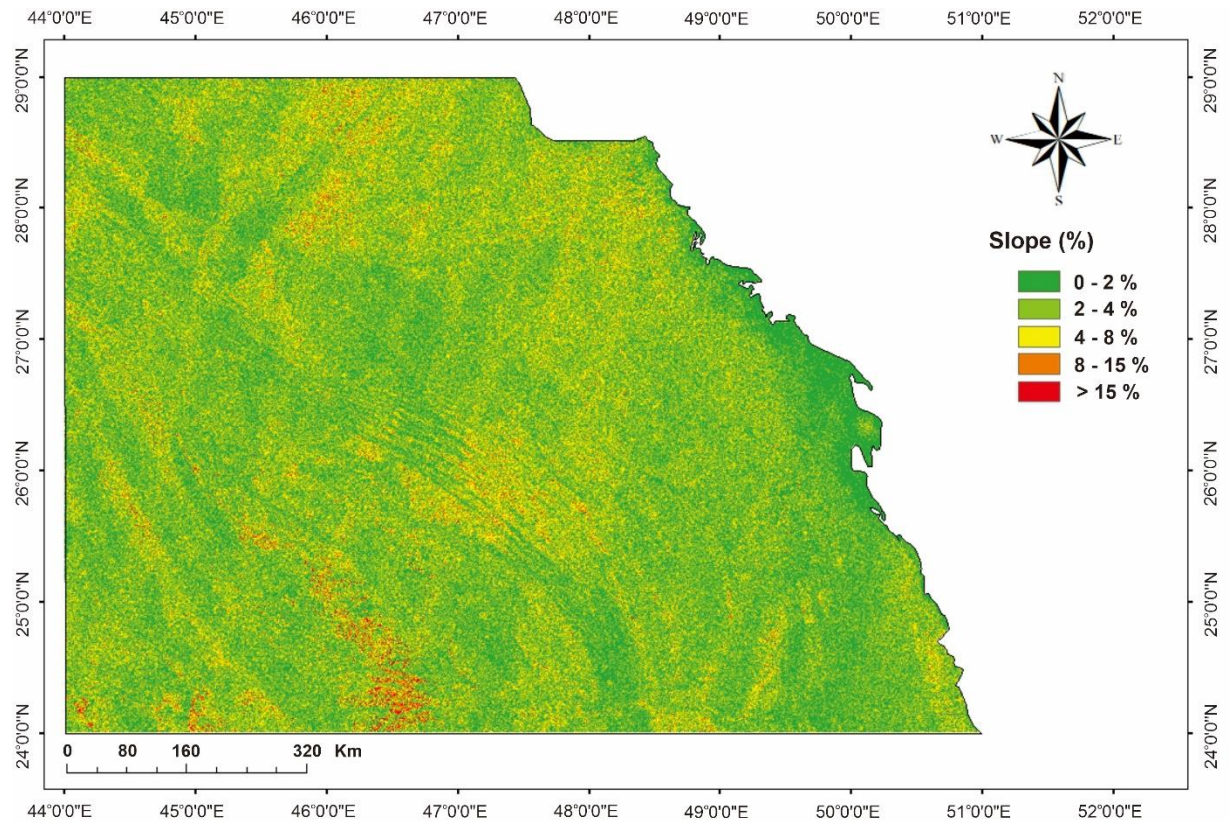


Figure 18. Slope map of the study area.

4.1.6. Land Use/Land Cover

The land cover map was derived from the ESRI global map of LULC. The land cover map has been categorized into four major groups: cropland, scrub/shrub, built area, and bare ground. Most of landform in the study area was dominated by bare ground followed by scrub/shrub. It covers 51 % and 45 % of the study area respectively (**Fig. 19**).

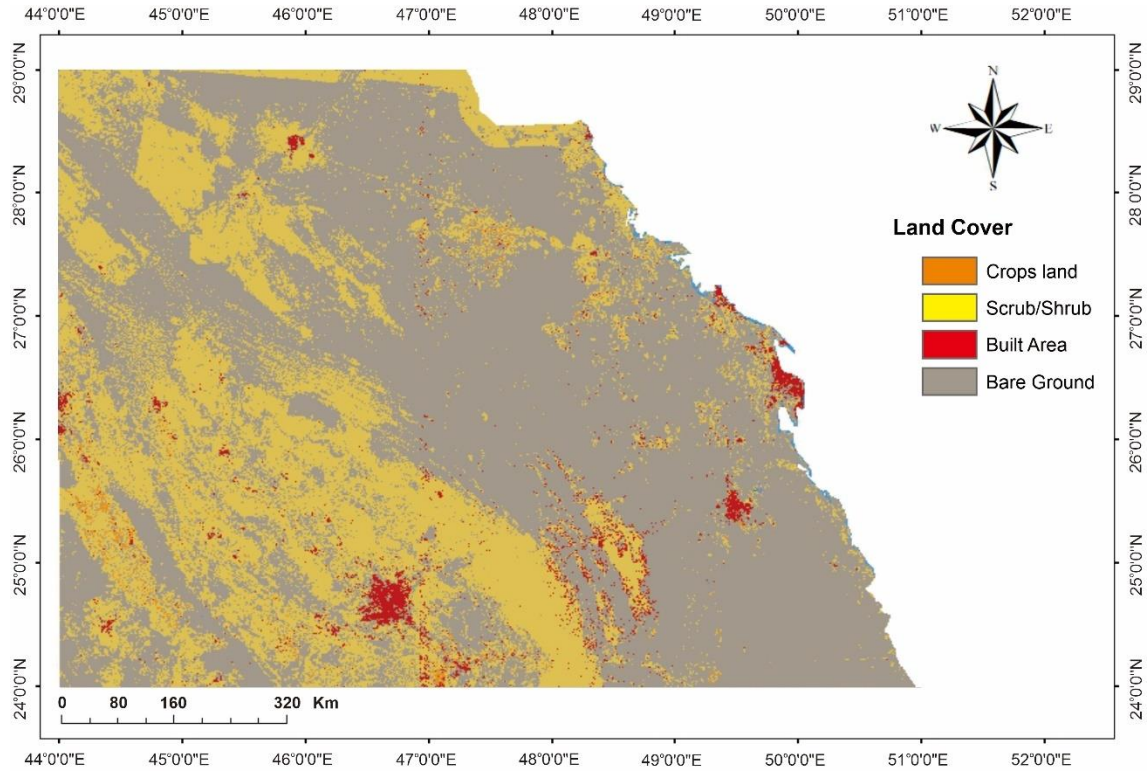


Figure 19. Landcover map.

4.1.7. Aquifer Depth (m)

The aquifer depth map was generated by employing interpolation technique using spatial analyst tool of ArcGIS 10.3 platform. Only three aquifers are considered in this research due to other aquifers did not meet the requirement for ASR implementation (very deep and saline). They include from the top to the bottom: Neogene aquifer, Dammam aquifer, and UER aquifer. For the details are as follows:

a. Depth of Neogene aquifer

The depth of Neogene aquifer ranges from $< 4 - 30$ m. The range of aquifer depth from $<4 - 8$ m exists in the middle part of study area. The northern part of study area ranges from $8 - 30$ m aquifer depth. Finally, the aquifer depth of $13 - 25$ m occupies in the major southern region of study area. **Figure 20** illustrates the depth of Neogene aquifer map.

b. Depth of Dammam Aquifer

Based on the depth of Dammam aquifer map (**Figure. 21**), it varies from <9 to 80 m. The Dammam aquifer depth from northwest to southeast region of study area is increasing continuously. The aquifer depth in the northwest area ranges from 18 to 45 m. Meanwhile, the aquifer depth in the southwest region ranges from 53 – 80 m. In the middle portion of study area, it has aquifer depth ranging approximately from 27 – 62 m.

c. Depth of UER aquifer

The depth of UER aquifer ranges from <100 to 700 m. The deepest part occupies the southeast area of the research region (ranging from 500 – 700 m). Meanwhile, the western region exists the shallowest part of the study area (ranging from 100 – 200 m). The north region of study area is having range from 300 – 400 m depth. The depth of UER aquifer map shows in **Figure 22**.

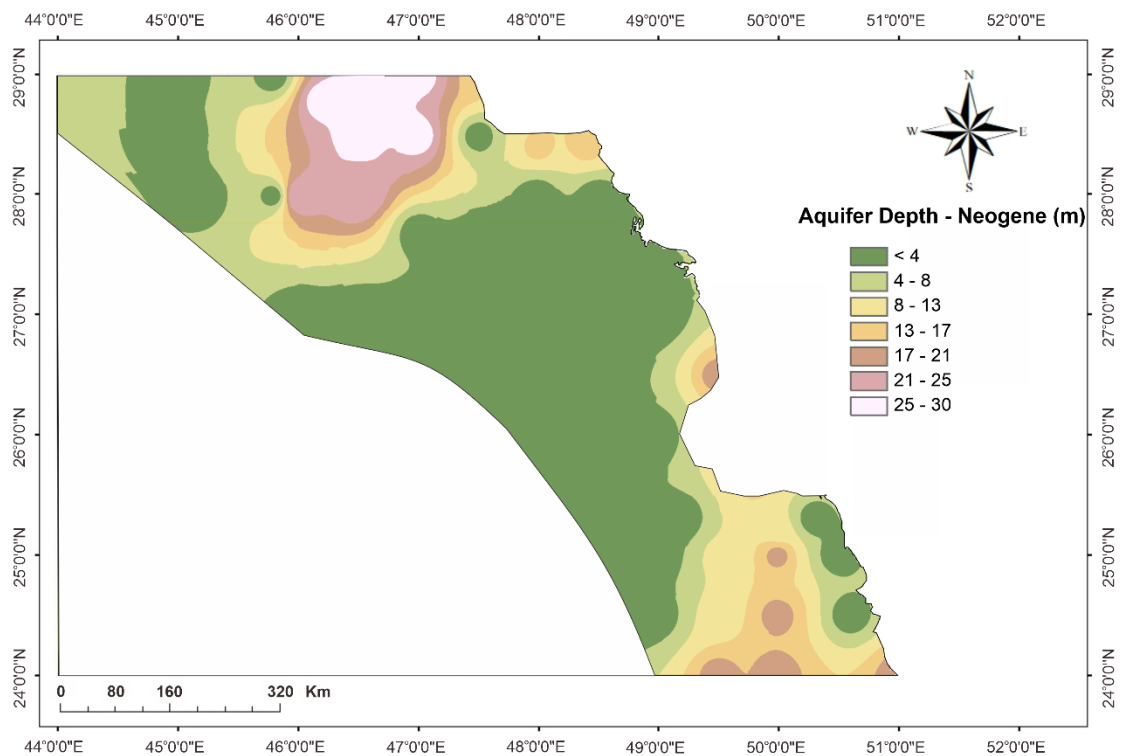


Figure 20. Aquifer Depth (Neogene) (Edgell, 1997; Dirks et al., 2018).

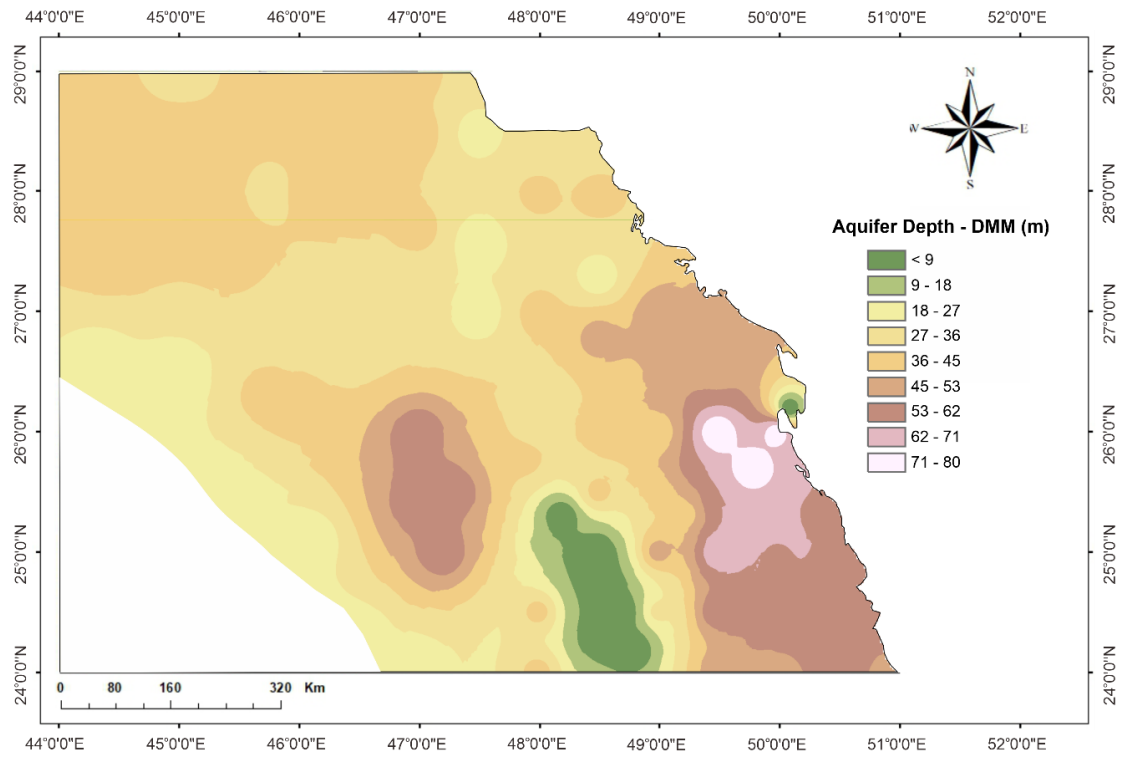


Figure 21. Aquifer Depth (Dammam) (Edgell, 1997; Dirks et al., 2018; Alslais et al, 2019)

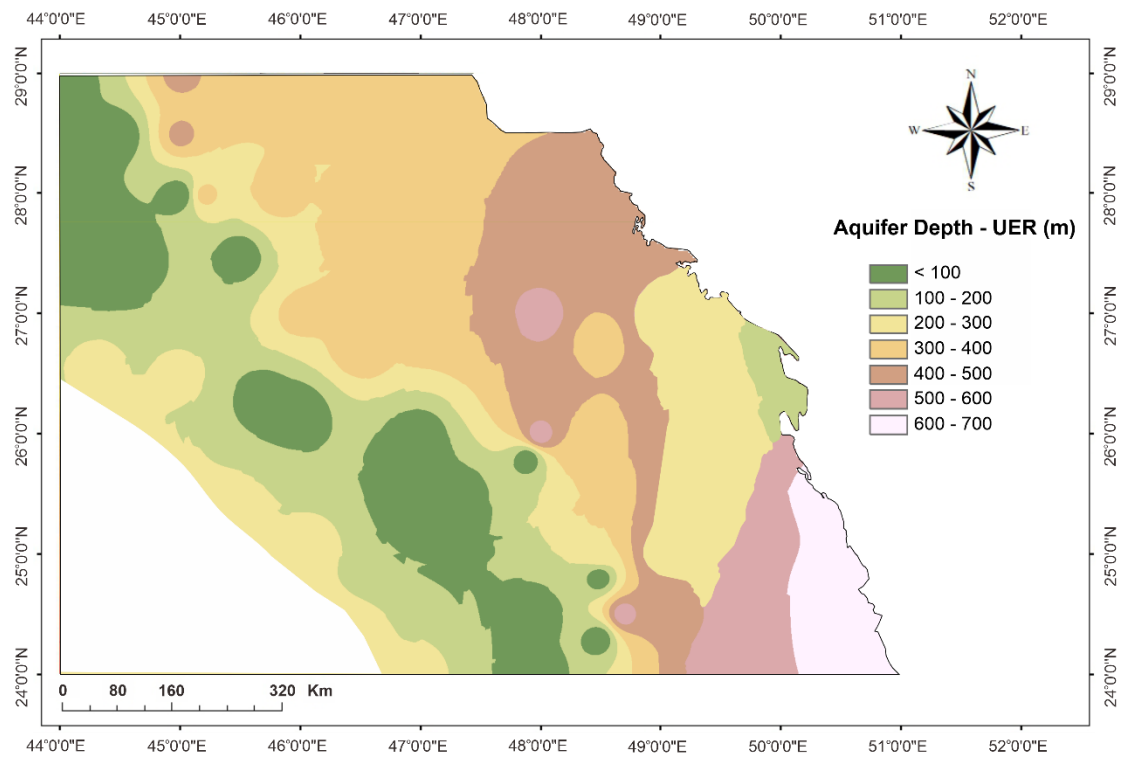


Figure 22. Aquifer Depth (UER) (Al Tokhais et al., 2008; Dirks et al., 2018)

4.1.8. Aquifer Thickness

The aquifer thickness map was derived by using Inverse Distance Weighting (IDW) interpolation of ArcGIS 10.3 system. It includes three-aquifer system such as Neogene aquifer, Dammam aquifer, and UER aquifer. The details of each aquifers has been discussed as follows:

a. Thickness of Neogene aquifer

Based on the Neogene aquifer thickness map, the smallest thickness exists in the western part of the study area (< 65 m). The biggest aquifer thickness varying from 295 to 345 m occupies the eastern region. The Neogene aquifer thickness is shown in the **Figure 23**.

b. Thickness of Dammam aquifer

The Dammam aquifer thickness varies from < 170 m to 450 m. The smallest thickness exist in the western and eastern part of the study area (ranging from < 170 m – 215 m thickness). Meanwhile, the biggest thickness varies from 310 m to 450 m which occupies in the central and southeast part of the study area. The thickness of Dammam aquifer is shown in the **Figure 24**.

c. Thickness of UER aquifer.

The thickness of UER aquifer ranges from < 40 m to 500 m. In the northeast portion of the study area, it has thickness varying from 360 m to 500 m which is the biggest thickness of the research region. In the western portion the study area, it exists the lowest thickness (ranging from < 40 m – 100 m). The UER aquifer thickness is illustrated in the **Figure 25**.

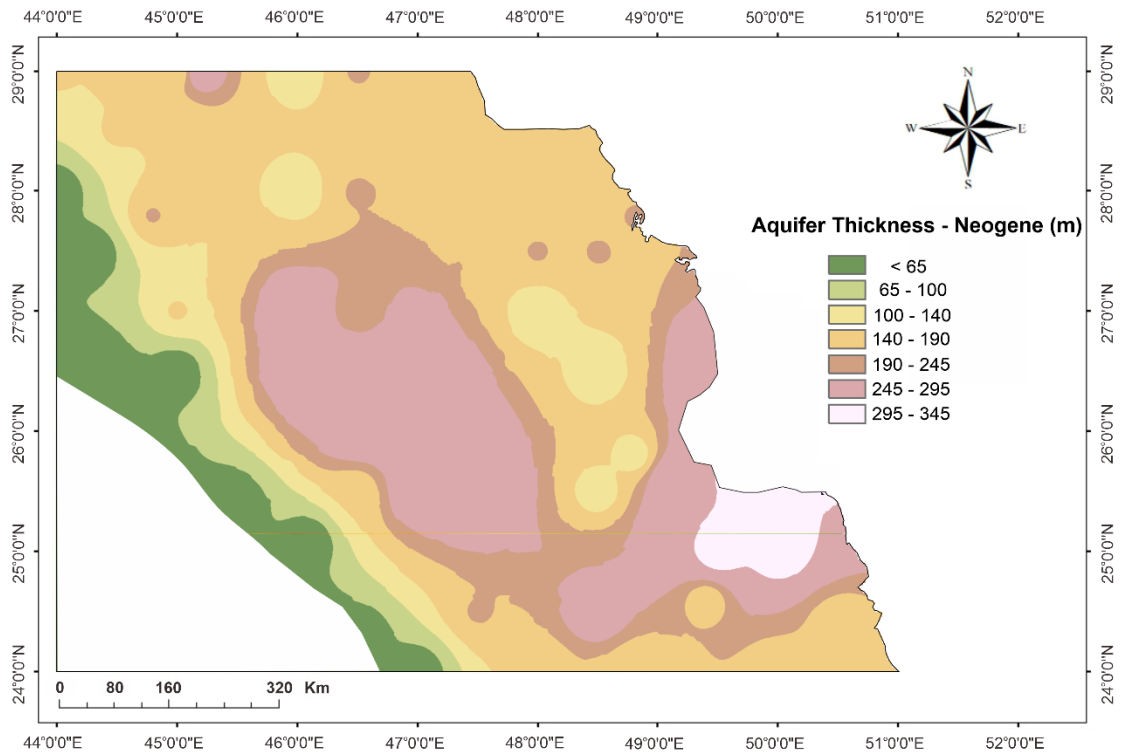


Figure 23. Aquifer Thickness (Neogene) (Edgell, 1997; Dirks et al., 2018).

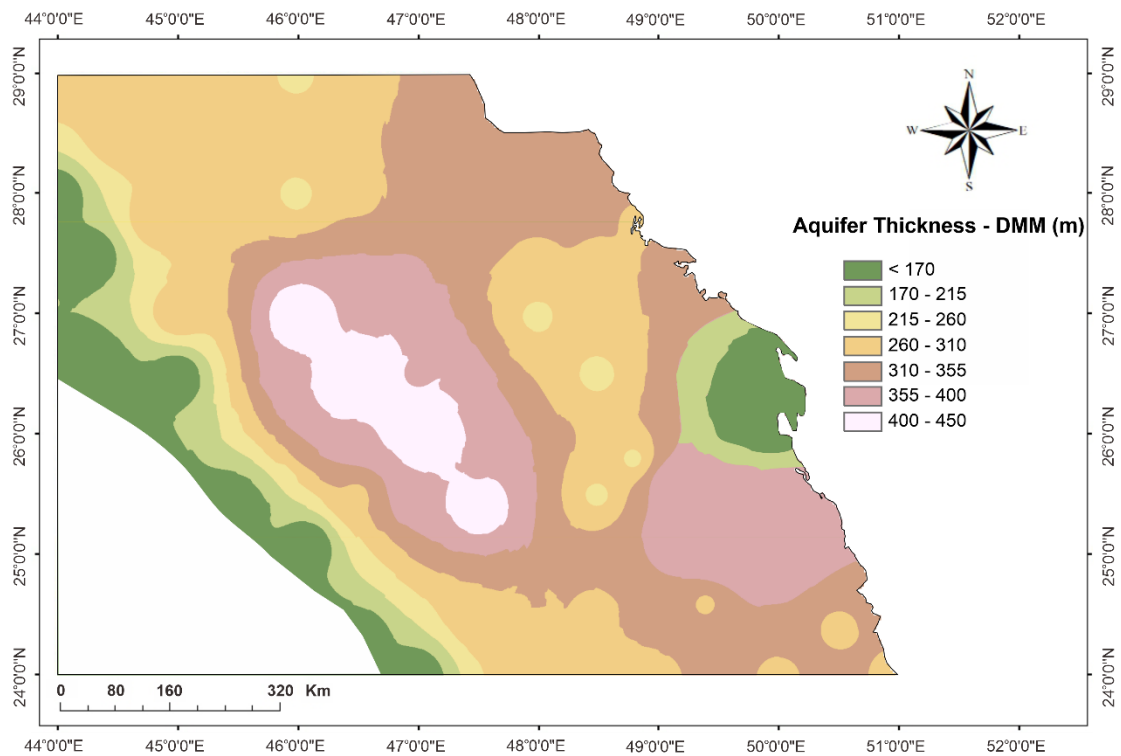


Figure 24. Aquifer Thickness (Dammam) (Edgell, 1997; Dirks et al., 2018; Alsais et al, 2019).

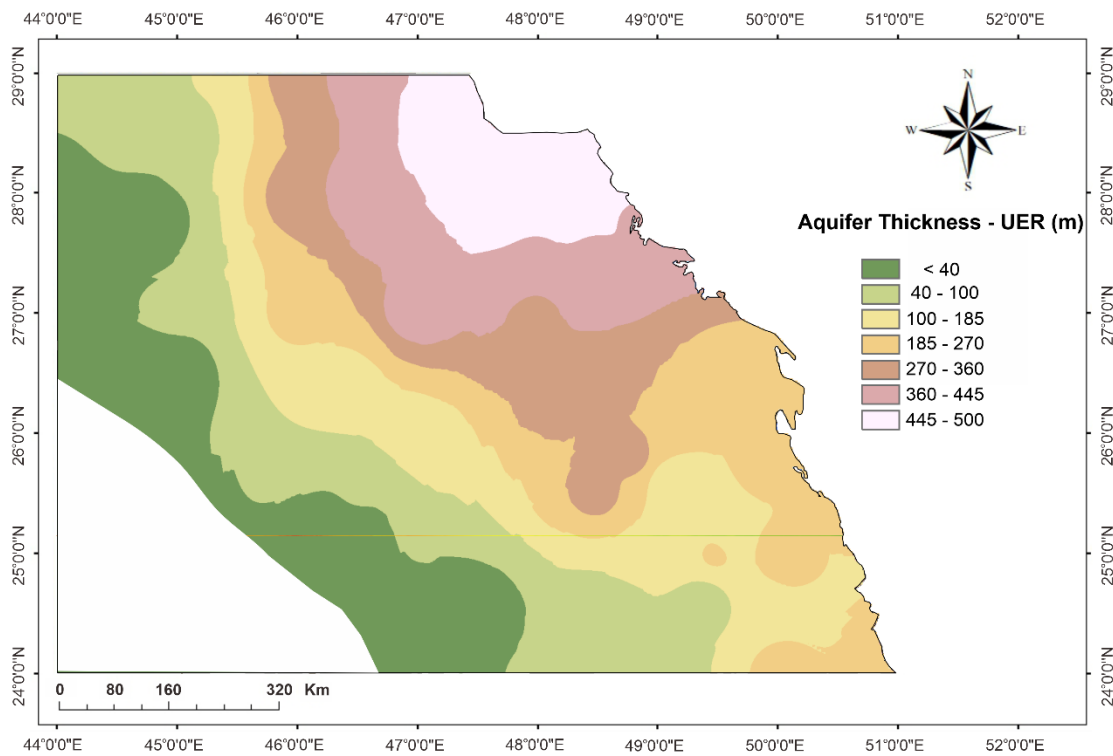


Figure 25. Aquifer Thickness (UER) (Al Tokhais et al., 2008; Dirks et al., 2018).

4.1.9. Aquifer Transmissivity

The aquifer transmissivity map was created by employing IDW interpolation using spatial analyst tool of ArcGIS 10.3 software.

a. Transmissivity of Neogene aquifer

The Neogene aquifer transmissivity ranges from < 1604 to $3455 \text{ m}^2/\text{day}$. The area with highest transmissivity occupies in the southeast portion of the research region, with the value ranging from $2530 \text{ m}^2/\text{day}$ to $3450 \text{ m}^2/\text{day}$. However, the lowest transmissivity exist in the northwest portion of the study area (ranging from $1603 \text{ m}^2/\text{day}$ to $1913 \text{ m}^2/\text{day}$). **Figure 26** shows the transmissivity of Neogene aquifer of the research region.

b. Transmissivity of Dammam aquifer

Based on the Dammam aquifer transmissivity map, the study area varies from $< 35 \text{ m}^2/\text{day}$ to $2497 \text{ m}^2/\text{day}$. The southeast region of study area has values varying from $1070 \text{ m}^2/\text{day}$ – $2497 \text{ m}^2/\text{day}$ while the western portion of the study area ranging from < 35

$\text{m}^2/\text{day} - 713 \text{ m}^2/\text{day}$. The map of Dammam aquifer transmissivity shows in the **figure 27**.

c. Transmissivity of UER aquifer

The research area's UER aquifer transmissivity map varies from $< 138 \text{ m}^2/\text{day} - 950 \text{ m}^2/\text{day}$. The range of aquifer transmissivity's values from $< 138 \text{ m}^2/\text{day} - 174 \text{ m}^2/\text{day}$ exists in the northern part of study area. The southeast part of study area have transmissivity values of $545 \text{ m}^2/\text{day} - 850 \text{ m}^2/\text{day}$. The map of UER aquifer transmissivity shows in the **figure 28**.

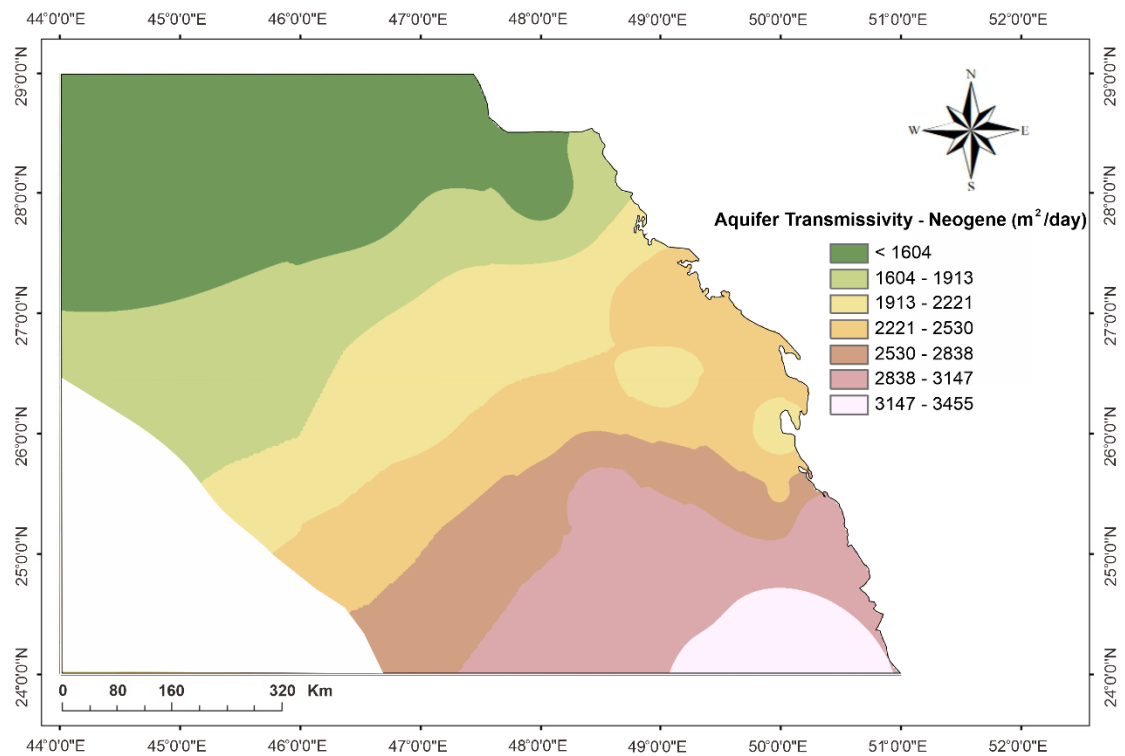


Figure 26. Aquifer Transmissivity (Neogene) (Edgell, 1997)

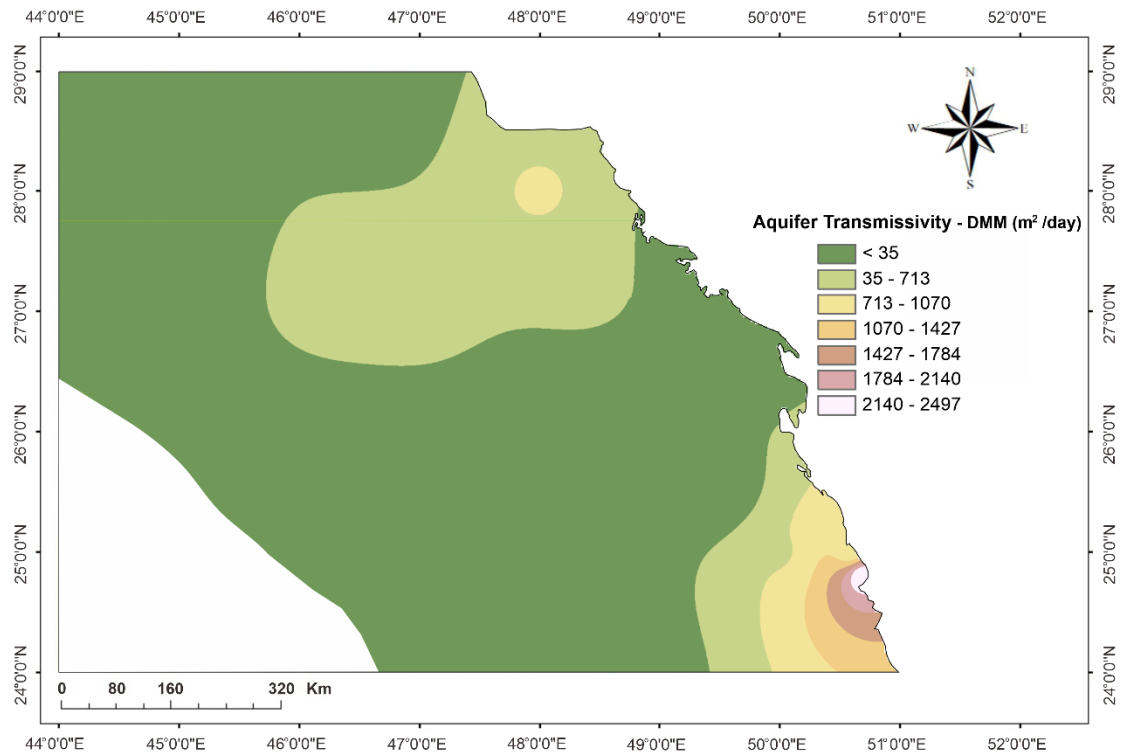


Figure 27. Aquifer Transmissivity (Dammam) (Edgell, 1997)

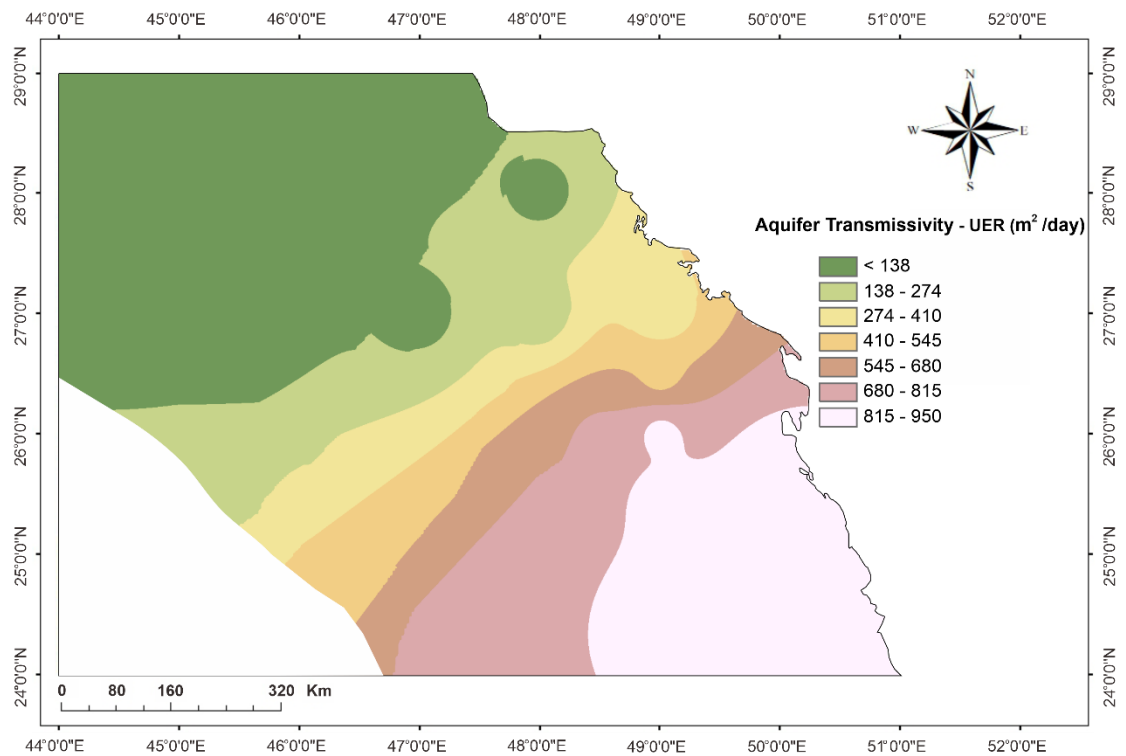


Figure 28. Aquifer Transmissivity (UER) (Edgell, 1997).

4.1.10. Groundwater Salinity

The Groundwater salinity map was generated by employing interpolation technique using spatial analyst tool of ArcGIS 10.3 platform. It was reclassified into six categories fresh or slightly brackish water, < 1 g/L, 1 – 3 g/L, 3 – 5 g/L, 5 – 10 g/L, > 10 g/L.

Figure 29. illustrates the groundwater salinity map.

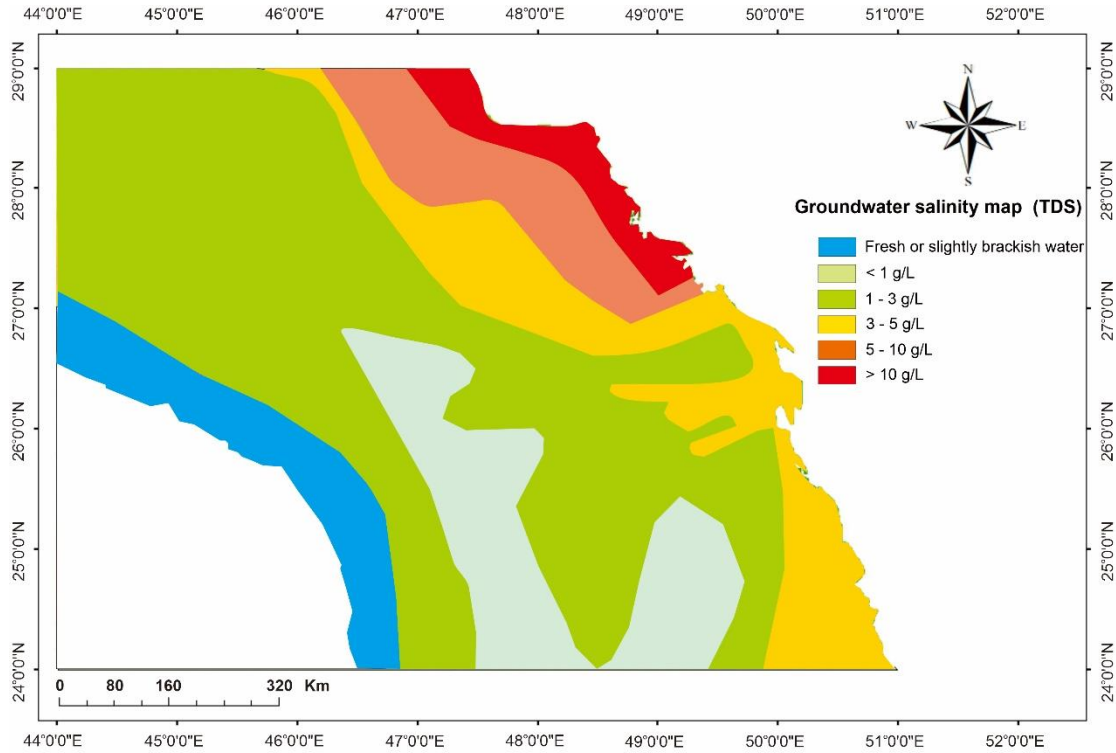


Figure 29. Groundwater Salinity map (UN-ESCWA, 2013).

4.2. Weight assignment and ranking of thematic layers.

The weight and feature/class of each parameter were determined using the Multi-Criteria Decision Analysis (MCDA) approach. All of these thematic maps (vector layers) have been converted to a raster format with a 30m x 30m. Then, ten layers were combined by giving weight to the thematic layers/parameters on a scale of 1-100 and ranking to features/classes on scale of 1 to 5. They were acquired depend on the expert knowledge and literature review (Andualem et al., 2019).

The assignment weight of ten parameters (Aquifer system, Geomorphology, Lineaments, Soil Texture, Slope, LULC, Aquifer thickness, Aquifer depth, Aquifer transmissivity, and Groundwater salinity) were given 11 %, 8 %, 7 %, 5 %, 8 %, 9 %, 13 %, 14 %, 12 %, and 13 % respectively, depending on literature and expertise decision (Abdou Karim et al, 2019; Olabode et al., 2019; Senthilkumar et al., 2019; Kadhem et al., 2020). Hydrogeological parameters (Aquifer thickness, Aquifer depth, Aquifer transmissivity, and Groundwater salinity) were given the highest percentage compared to other existing factors due to they are considered as the most influential factors in implementation of artificial recharge in the study area (Abdou Karim et al., 2019). Meanwhile the details of assignment rank of each features as follows:

1. Aquifer system

The Neogene aquifer and Dammam & Umm er Radhuma aquifer (Paleogene) (dominated by limestone, dolomitic limestone, sandy limestone, calcareous, etc) were given the given score of 5 (the highest significance for ASR), whereas Biyadh & Wasia, Minjur & Dhurma, and Saq, which consists of limestone and sandstone was given lowest rank (Zaidi et al., 2015; Kadhem et al., 2020).

2. Geomorphology

The Eastern plateau and coastal plain were given highest priority for groundwater recharge. Meanwhile, the Plateau area was assigned a low rank (Senthilkumar et al., 2019; Andualem et al., 2019; Kadhem et al., 2020).

3. Lineaments

The distance of lineament map were divided into two categories (close to the lineaments and other areas). The closest location to the lineaments was categorized as favorable for groundwater recharge zones and given the highest

score of 5, while the area with the furthers location to the lineaments was given with the lowest rank (Andualem et al., 2019; Kadhem et al., 2020).

4. Soil Texture

The soil texture categorized as a suitable for groundwater recharge including Sandy, Sandy & Sandy – Skeletal, Sandy - Loamy, and Sandy – Sandy & Loamy due to coarse texture, low clay content, and high infiltration rate. They were given the high rank; while those consisting finer grains and high clay content (e.g. Loamy, Loamy & clayey, Loamy – loamy, Loamy & Loamy skeletal, stratified loamy - loamy and loamy; Stratified loamy - skeletal) were given lower ranks (Mahmoud et al., 2014; Al-Shabeeb et al., 2015; Zaidi et al., 2015; Olabode et al., 2019; Kadhem et al., 2020).

5. Slope

The highest slope interval receiving a rank value of 1 and the lowest slope interval receiving a rank value of 5. The lowest slope percentage is more suitable for aquifer groundwater recharge zone, and the highest slope percentage is least favorable for recharge zones. (Al-Shabeeb, 2015; Arulbalaji, et al., 2019).

6. Land Cover

The Scrub, and Bare ground were given the highest score of 5 due to being suitable location for ASR. On the other hand, Build Area was given the lowest rank (score of 1) as it represents low infiltration (Kadhem et al., 2020; Al-Djazouli, et al. 2020).

7. Aquifer thickness

The thickest aquifer was assigned the highest rank while the thinnest aquifer were given lower rank (Abdou Khalil, 2019). The favorable thickness of three

aquifers (Neogene, Dammam, and UER) are $< 65 - 100$ m, < 170 m, and < 40 m respectively. Therefore, they were given the highest rank of 3, 2, and 3 respectively.

8. Aquifer depth

The near surface aquifer was assigned the highest rank. On the other hand, the deepest aquifer were given lower rank (Abdou Khalil, 2019). The Neogene, Dammam, and UER aquifers depth of < 4 m, < 9 m, and < 100 m respectively are the most suitable for ASR sites, with the rank of 5, 5, and 3 respectively.

9. Aquifer transmissivity

The highest value of transmissivity has been assigned the highest rank and the lowest transmissivity was given lowest rank (Ewusi et al., 2018). The Aquifer transmissivity value of $1604 - 3455$ m²/day, $1070 - 2497$ m²/day, and $274 - 950$ m²/day (Neogene, Dammam, and UER respectively) are the most favorable for artificial recharge sites. They were assigned rank of 5, 5, and 4 respectively.

10. Groundwater salinity

Based on the Groundwater salinity map, the lowest value of salinity was categorized the highest rank of 5 due to it categorized as the best location for ASR sites. The highest salinity has been given the lowest rank because it is unsuitable for artificial recharge (UN-ESCWA, 2013). The fresh or slightly brackish water, < 1 g/L, $1 - 3$ g/L, $3 - 5$ g/L, $5 - 10$ g/L, and > 10 g/L were assigned score of 5, 4, 3, 2, and 1 respectively.

The weightage of thematic layers and the ranking of each various class are shown in the **Table. 7**.

Table 7. Weight assignment criteria of thematic layers.

No	Thematic Layers / parameters	Weight / Influences (%)	Features / Classes	Assigned rank
1	Aquifer System	11	Neogene	4
			Dammam	5
			Umm er Radhuma	5
			Biyadh and Wasia	4
			Minjur and Dhruma	5
			Saq	1
2	Geomorphology	8	Najd Plateau	2
			Eastern Plateau	5
			Coastal Plain	3
3	Lineaments	7	Lineaments area	5
			Other areas	1
4	Soil Texture	5	Loamy - clayey	1
			Stratified loamy - skeletal	3
			Loamy - skeletal	2
			Loamy	2
			Sandy - loamy	4
			Stratified loamy	3
			Sandy	5
			Sandy - loamy	3
			Sandy - skeletal	5
5	Slope	8	0-2 %	5
			2-4 %	4
			4-8 %	3
			8-15 %	2
			> 15 %	1
6	Land Cover	9	Crops land	2
			Scrub/Shrub	5
			Built Area	1
			Bare Ground	5
7	Aquifer Thickness (m)	13	Neogene Aquifer (m)	
			< 65	3
			65 - 100	2
			100 - 140	1
			140 - 190	1
			190 - 245	1
			245 - 295	1
			295 - 345	1
			Dammam Aquifer (m)	
			< 170	2
			170 - 215	1
			215 - 260	1
			260 - 310	1
			310 - 355	1
			355 - 400	1
			400 - 450	1
			UER Aquifer (m)	
			< 40	3
			40 - 100	2
			100 - 185	1
			185 - 270	1
			270 - 360	1
			360 - 445	1
			445 - 500	1

No	Thematic Layers / parameters	Weight / Influences (%)	Features / Classes	Assigned rank
8	Aquifer depth (m)	14	Neogene Aquifer (m)	
			< 4	5
			4 - 8	4
			8 - 13	4
			13 - 17	4
			17 - 21	3
			21 - 25	3
			25 - 30	2
			Dammam Aquifer (m)	
			< 9	5
			9 - 18	4
			18 - 27	3
			27 - 36	2
			36 - 45	2
			45 - 53	2
			53 - 62	2
			62 - 71	2
			71 - 80	1
			UER Aquifer (m)	
			< 100	3
			100 - 200	2
			200 - 300	1
			300 - 400	1
			400 - 500	1
			600 - 700	1
9	Aquifer Transmissivity (m ² / day)	12	Neogene Aquifer (m²/day)	
			< 1604	4
			1604 - 1913	5
			1913 - 2221	5
			2221 - 2530	5
			2530 - 2838	5
			2838 - 3147	5
			3147 - 3455	5
			Dammam Aquifer (m²/day)	
			< 35	2
			35 - 713	3
			713 - 1070	4
			1070 - 1427	5
			1427 - 1784	5
			1784 - 2140	5
			2140 - 2497	5
			UER Aquifer (m²/day)	
			< 138	3
			138 - 274	3
			274 - 410	4
			410 - 545	4
			545 - 680	4
			680 - 815	4
			815 - 950	4
10	Groundwater Salinity (g/L)	13	Fresh or slightly brackish water	5
			< 1 g/L	5
			1 - 3 g/L	4
			3 - 5 g/L	3
			5 - 10 g/L	2
			> 10 g/L	1

4.3. Aquifer Storage & Recovery potential sites

The ASR potential sites were generated after assigning the weight of each ten thematic layers and ranking of various classes. Aquifer Storage & Recovery potential sites were developed by overlaying all these thematic layers using weight overlay analysis tools in ArcGIS version 10.3. Weighted Overlay Analysis (WOA) can be calculated using equation no.1 in Chapter 3:

$$\text{WOA} = (AQ_w \times AQ_r) + (GM_w \times GM_r) + (S_w \times S_r) + (ST_w \times ST_r) + (LE_w \times LE_r) + (LU_w \times LU_r) + (ATH_w \times ATH_r) + (AD_w \times AD_r) + (ATs_w \times ATs_r) + (GS_w \times GS_r) \dots\dots\dots(3)$$

Where:

AQ=Aquifer System; GM=Geomorphology; S=Slope; ST=Soil Textures; LE=Lineaments; LU=Landuse/cover; ATH=Aquifer Thickness; AD=Aquifer Depth; ATs=Aquifer Transmissivity; GS=Groundwater Salinity, **w**= the weight of each thematic layer/ parameter; **r**= the rank of each feature/class. Based on the weighted overlay analysis, the ASR potential sites were classified into four categories as Very low, Low, Moderate, and Good according to quantile classification in the ArcGIS platform (Senthilkumar et al., 2019; Duguma et al., 2021). The resulted map shown in the **Figure 30**.

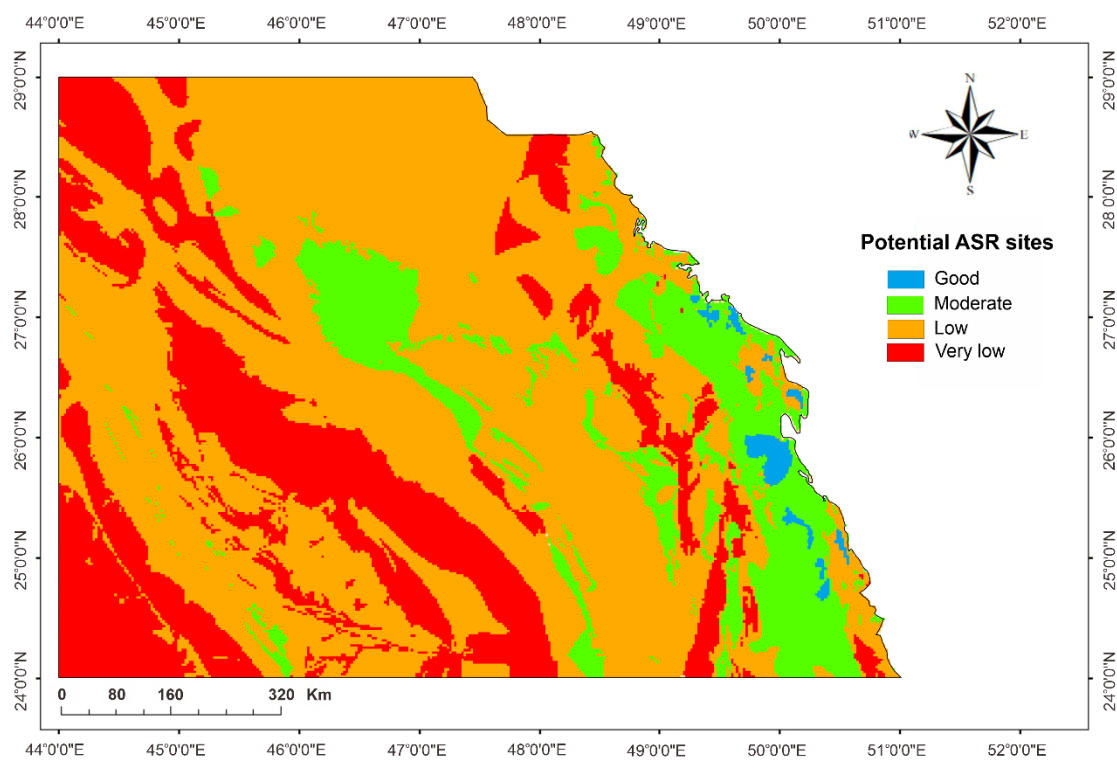


Figure 30. Artificial recharge potential sites.

Table 8. Classification and percentages of prospective artificial recharge locations in central – east region of Saudi Arabia

ASR Potential Sites	Area Percentages (%)
Good	2,2
Moderate	10,8
Low	54
Very low	33

CHAPTER 5

DISCUSSION

5.1. Parameters considered in determining ASR potential sites

In selection of aquifer recharge potential locations in central-east region of Saudi Arabia, artificial recharge indicators like Aquifer system, Geomorphology, Slope, Soil Textures, Lineaments, Land cover, Aquifer depth, Aquifer thickness, Aquifer transmissivity, and Groundwater salinity were considered for this study. These factors will be discussed as follows:

Aquifer system plays a significant role in determining the quantity and quality of groundwater in the region (Al-Djazouli et al., 2020). At least there are four different aquifer system in the study area that are suitable for artificial recharge sites including Tertiary rocks (primarily the Umm er Radhuma, Dammam. Hadrukh, and Dam formation), Cretaceous rocks (Wasia-Biyadh Formation), Jurassic rocks (Minjur–Dhruma Formation), Cambrian rocks (Saq formation) (Edgell, 1997). Tertiary aquifers are the most essential aquifers in the study area. They include the extensive Paleocene-Lower Eocene Umm er Radhuma aquifer system with its best aquifer in dolomites and calcarenites. Both Triassic – Jurassic Minjur-Dhruma Aquifer and Middle to Lower Cretaceous Wasia-Biyadh Aquifer are characterized by major sandstone aquifers with plentiful fair quality groundwater (Edgell, 1997). On the other hand, the 400 m – 500 m thick Saq Aquifer is characterized as high permeability, effective porosity from 12% to 30%, which favors more infiltration and groundwater storage (Edgell, 1997; Al-Djazouli et al., 2020).

Geomorphology is one of the essential factors for identifying aquifer recharge potential sites. It shows the topography and landform of the area and controls the groundwater movement in the surface and subsurface (Andualem et al., 2019). The major section of the study area is covered by a Najd plateau, followed by Eastern plateau. With elevations ranging from 800m to 1100m, the Najd Plateau in Saudi Arabia's central region includes the Tuwayq Mountains, which constitute a range extending 800 km (Al-Ahmadi et al., 2013). The Eastern plateau is ranging from 170 m to 400 m high (Al-Ahmadi et al., 2013). The Eastern plateau and Coastal plain were considered as suitable groundwater recharge covering about 28 % and 12,5 % of the study area respectively.

Lineaments provide excellent pathways for water to percolate vertically into the ground and to charge groundwaters (Arulbalaji et al., 2019). Most of the study areas were represented in a low – medium portion of lineaments. The high lineaments density was detected in the middle of the region, particularly in Najd plateau area. Higher lineaments are thought to be a good predictor of groundwater storage potential (Al-Djazouli et al., 2020).

Soil texture is one of the essential parameters controlling the recharge zones (Zaidi et al., 2014). It influences the rate of infiltration (Das et al., 2019; Kadhemi et al., 2020). The major of soil texture in the central – east region of Saudi Arabia are dominated by Sandy, Sandy – skeletal, Sandy - loamy, and Loamy which occupies 25 % of the study area. Sandy and sandy – loamy is the most appropriate soil texture for artificial recharge sites due to its coarse texture, low clay content, and poor water holding capacity which covers 5 % of the study area (Mahmoud, 2016).

Slope affects surface water movement, recharge, and runoff (Agarwal et al. 2013). It also dictates if the water is transported quickly to other places or it stays on the ground allowing the water to infiltrate into the ground. The major part of the study area is

dominated by a gentle slope ranging from 0-2% (**Table 9**), which covers 38 % of the study area. The research area's north and west regions are covered by a moderate slope ranging from 4% to 8%. The highest slope (>15 %) occupies 5 % of the study area. The area having a flat slope ranging from 0-2 % was considered the most favorable potential groundwater recharge candidate compared to the steep slope area (> 15 %).

Table 9. FAO slope classification

Slope Degree (%)	Slope Classification
0-3	Flat to Gentle
3-12	Moderate
12-20	Steep
20-35	Very Steep
>35	Extreme

Land cover is associated to soil moistures capacity, vegetation, evapotranspiration, and infiltration (Senthilkumar et al., 2019). Also, it is considered a good factor for quantifying runoff, infiltration, and recharge. Based on Land Use/ Land Cover classification, most of the study area is represented by Scrub/Shrub and Bare Ground. About 6 % of the study area is covered by Built Area, and a minor portion of the region is occupied by Cropland.

Aquifer depth is a critical hydrological component controlling aquifer recharge in the region (Al-Djazouli et al., 2020). According to the Neogene aquifer depth map, the shallowest aquifer covers in the middle of the study area with the depth < 4 m. It can be categorized as the most favorable site for ASR system. The deepest aquifer occurs in the northern part of the region with 25 – 30 m followed by southern part of the region with 21 – 25 m, which is less favorable site for groundwater recharge. Meanwhile, the major portions of study area covered by medium to deep Dammam aquifer system with 27 – 36 m and 36 – 45 m depth respectively. Lastly, the deepest of UER aquifer occupies

in the southern part of the region with 600 – 700 m depth while the middle part of research region dominated by shallow aquifer with 100 m depth.

Aquifer thickness is an essential factor for a successful ASR system. Based on the Neogene and Dammam thickness map, the thickest area occupies in the middle and eastern part of the study area with 295 – 345 m, 400 – 450 m thick respectively. On the other hand, the thickest area of UER aquifer covers northeast part of the research region about 445 – 500 m thick. The major part of western region dominated with thin aquifer thickness approximately 100 m thick.

Groundwater with low salinity exist in the central region of the study area with approximately TDS of < 1 g/L to 1 – 3 g/L, which is the most suitable for aquifer recharge. The area with highest salinity value exists in the northern coastal plain. It's TDS varies from 5 – 10 g/L to > 10 g/L. The salinity of groundwater should not reach 5000 ppm (5 g/L) for an effective ASR system (Abdou Khalil, 2019).

Aquifer transmissivity is the aquifer's capacity to transmit water (Cheremisinoff, 1997). Based on the aquifer transmissivity classification (modified after Ewusi et al., 2018), Neogene and Dammam aquifer are categorized as a very highly transmissivity aquifers (> 1000 m²/day) (**Table 10**). In Neogene aquifer, the transmissivity ranges from 1296 to 3455 m²/day from the northwest to southeast of the study area. In the southeast, the transmissivity of Dammam aquifer is dominated by very high transmissivity about 1070 – 2497 m²/day. Meanwhile, the transmissivity of UER aquifer varies from 3,5 to 950 m²/day with higher values concentrate in the southeast of the study area.

Table 10. Classification of transmissivity magnitude (modified after Ewusi et al., 2018)

Transmissivity (m ² / day)	Designation of T Magnitude	Groundwater Supply Potential
> 1000	Vey High	Withdrawals of great regional importance
100 - 1000	High	Withdrawals of lesser regional importance
10 - 100	Intermediate	Withdrawal for local water supply (small communities, plants etc)
1 -10	Low	Smaller withdrawals for local water supply (private consumption)
< 1	Very low	Withdrawal for local water supply with limited consumption

5.2. ASR Potential map

Based on the ASR potential map, it shows that the potential groundwater recharge sites were classified from Very low to Good categories. About 2,2 % and 10,8 % of the region are considered as Good and Moderate parts, respectively. The good part reflects a gentle slope (0-2%), good lineament density, sandy to sandy – loamy textures (a coarse texture with low clays content), high permeability (limestone, dolomitic limestone, calcarenit limestone), less aquifer depth (< 45 m), good aquifer thickness (100 – 300 m), medium groundwater salinity (3 – 5 g/L), and high – very high transmissivity. It occupies a minor part of the eastern part of the research area while the moderate category covers a major portion of the central part of the region. Geomorphologically the Eastern plateau and Coastal plain are the most favorable site for artificial recharge. The moderate category is unevenly distributed throughout the study area. It is explained by the medium slope (2– 8%), good permeability lithology, and low lineament density. The Low category covers about 54 % of the research region, which dominates the center of the region. This part is characterized by moderate to steep slope (ranging from 4 to 15 %), low lineament density, and good permeability lithology. Finally, the western part of the study area, which occupies around 33 % of the total area was considered a very low groundwater recharge potential due to a steep slope (>15%), low lineament density, a less-permeable lithology. In addition, the precipitation of this region is considered as low.

5.3. Proximity Analysis for ASR potential sites

The proximity of the injecting water facility influences the decision if ASR in a particular location is feasible or not. The proximity analysis in ArcGIS platform was carried out to get the final output map of the identified ASR potential sites. It was conducted on the basis of the closeness of identified suitable ASR locations to water injection sources. Since the rainfall is very limited in the study area, the desalination and sewage treatment plants were considered as water injection sources. The final output map of the potential groundwater recharge sites was categorized into first priority and second priority depending on their proximity to the desalination and sewage treatment plants. The good category of ASR potential sites was selected as a first priority while the moderate category was selected as a second priority. The ASR potential location's map that considers the sources of water injection is shown in **Figure 31**.

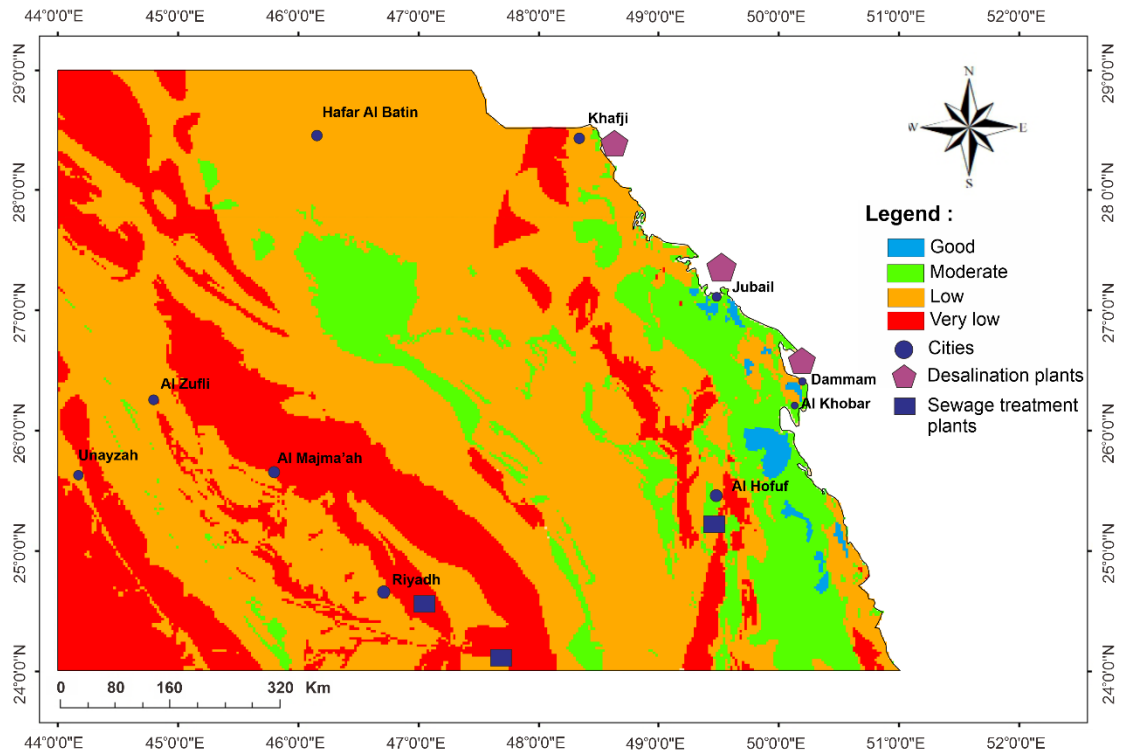


Figure 31. Artificial recharge potential sites map based on proximity analysis.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

The integration of GIS, Remote Sensing (RS), and MCDA - WOA methodologies was applied to identify ASR potential sites in Saudi Arabia's central-east region. The combination of these techniques is effective and useful for delineating Artificial Recharge potential sites. Ten parameters controlling groundwater recharge were integrated on ArcGIS platform utilizing Weight Overlay Analysis (WOA) tool. The result shows that the Artificial Recharge Potential sites in the study area are categorized into four different zones including Good (2,2%), Moderate (10,8%), Low (54%), and Very low (33%). The good artificial recharge sites cover about 2,2 % of the area with a gentle slope, good lineament density, sandy soils (a coarse texture with low clays content), high permeable with limestone, dolomitic limestone, calcarenit limestone, shallow – medium aquifer depth, thick aquifer (100 – 300 m), medium groundwater salinity, high – very high transmissivity, and near to the water injection sources. Depending on their proximity to the source of injecting water (e.g. desalination plant and sewage treatment plant), the most potential sites were located in the eastern part of the study area (mainly the coastal plain and eastern plateau). At least there are three potential sites (the “good” category) were selected as s high priority of ASR including Jubail, Dammam, and Al Hofuf area. Based on a geological point of view, the most recommended one is the Dammam area, particularly in the unpopulated areas of Dammam formation since the Dammam aquifer is one of the essential aquifers in the eastern provinces and also the presence of natural geologic structures (e.g. Dammam

dome). Furthermore, this study is beneficial as a guideline to water planners and decision-maker for managing groundwater resources.

6.2. Recommendations

It can be recommended that the selected area should be undergo further in-depth investigation like drilling study, detailed hydrogeological and geophysical surveys to verify the result obtained from this study.

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