GROUNDWATER SUSTAINABILITY POTENTIALS IN WADI ARABA THROUGH THE APPLICATION OF MANAGED AQUIFER RECHARGE, JORDAN

ALA' HAMED GABLAN ALELAIMAT

FACULTY OF SCIENCE
UNIVERSITI MALAYA
KUALA LUMPUR

2023

GROUNDWATER SUSTAINABILITY POTENTIALS IN WADI ARABA THROUGH THE APPLICATION OF MANAGED AQUIFER RECHARGE, JORDAN

ALA' HAMED GABLAN ALELAIMAT

THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF GEOLOGY
FACULTY OF SCIENCE
UNIVERSITI MALAYA
KUALA LUMPUR

2023

UNIVERSITY OF MALAYA
ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: Ala' Hamed Gablan Alelaimat

Matric No: 17201870/1

Name of Degree: Doctor of Philosophy

Title of Thesis ("**GROUNDWATER SUSTAINABILITY POTENTIALS IN WADI ARABA THROUGH THE APPLICATION OF MANAGED AQUIFER RECHARGE, JORDAN**"):

Field of Study: Earth Science

I do solemnly and sincerely declare that:

(1) I am the sole author/writer of this Work;
(2) This Work is original;
(3) Any use of any work in which copyright exists was done by way of fair dealing and for permitted purposes and any excerpt or extract from, or reference to or reproduction of any copyright work has been disclosed expressly and sufficiently and the title of the Work and its authorship have been acknowledged in this Work;
(4) I do not have any actual knowledge nor do I ought reasonably to know that the making of this work constitutes an infringement of any copyright work;
(5) I hereby assign all and every rights in the copyright to this Work to the University of Malaya ("UM"), who henceforth shall be owner of the copyright in this Work and that any reproduction or use in any form or by any means whatsoever is prohibited without the written consent of UM having been first had and obtained;
(6) I am fully aware that if in the course of making this Work I have infringed any copyright whether intentionally or otherwise, I may be subject to legal action or any other action as may be determined by UM.

Candidate's Signature Date: 9th July 2023

Subscribed and solemnly declared before,

Witness's Signature Date: 24th July 2023

Name:

Designation

GROUNDWATER SUSTAINABILITY POTENTIALS IN WADI ARABA THROUGH THE APPLICATION OF MANAGED AQUIFER RECHARGE, JORDAN

ABSTRACT

Globally one of the primary factors determining water security is water scarcity, which has a direct impact on the health and wellness of urban populations, environmental quality of cities, and socioeconomic. Over the next three decades, urban industrial and domestic water consumption is anticipated to increase 50–80% because of population expansion, urbanization, and socioeconomic development. Climate change will have an impact on the temporal and spatial distribution of water availability. Jordan considered one of the ten most waterscarce countries in the world, the country facing challenges in its water sector, Groundwater is the most crucial source of water in Jordan, it provides more than half of the total water demand, Some of Jordan's groundwater resources are presently exploited at maximum capacity, to meet this challenge, we should search for practical solutions that increase groundwater recharge, naturally or artificially. This study aims to select suitable sites for Managed Aquifer Recharge (MAR) through GIS and Groundwater Modeling and predict the climate change effect on water balance. Selected criteria were chosen based on Rainfall, Slope, Geological formations, Land Use, Soil texture, and Depth to the water table, these layers have been integrated into GIS software for generating (MAR) suitability map. The area falls into five categories of (MAR) potential zones i.e., very good, good, moderate, low, and very low. It is found that 16.7% with an area of 1473.7 km^2 and 30.15% with 2649.5 km^2 area are under very good and good category of (MAR) suitability respectively. An area of 1779.3 km^2 representing 20.24% is found under moderate category whereas 1944.24 km^2 and 890.94 km^2 equals 32.82% of Wadi Araba area falls under low and very low categories of (MAR) suitability respectively, most of the promising (MAR) locations are located within the alluvium aquifer. To enhance comprehension and assessment of the Wadi Araba Aquifer systems, a groundwater flow model was constructed using the existing geology and hydrogeology within the study area. This model facilitated the simulation of predictive scenarios to aid in long-term groundwater management for the alluvium aquifer. Groundwater flows in opposite directions over a split in the Wadi Araba Basin's middle area. According to the alluvial aquifer's groundwater level chart, groundwater flows northeast toward the Dead Sea in the northern portion of the valley. On the other hand, groundwater flows south-southwest, toward the Red Sea, in the southern part of the valley. According to the model's computation of the groundwater budget, precipitation-related infiltration is the main source of the system's inflow. In majority of the wells, the computed vs observed head comparisons showed a significant agreement between the estimated and observed water levels, thus verifying the accuracy and reliability of the model. Rainfall decreasing affected by climate change in the modelled area cause a drawdown on the alluvium aquifer which can mitigate, based on a predictive scenario by increasing the recharge from precipitation, which resulted an increase in the water table in 3 sites by 1.96%-3.12%.

POTENSI KELESTARIAN AIR TANAH DI WADI ARABA MELALUI APLIKASI IMBUHAN AQUIFER TERURUS, JORDAN

ABSTRAK

Di peringkat global, salah satu faktor utama yang menentukan keselamatan air ialah kekurangan air, yang mempunyai kesan langsung ke atas kesihatan dan kesejahteraan penduduk bandar, kualiti persekitaran bandar, dan sosioekonomi. dalam tempoh tiga dekad akan datang, penggunaan air industri dan domestik bandar dijangka meningkat 50–80% hasil daripada pengembangan penduduk, pembandaran dan pembangunan sosioekonomi. Perubahan iklim akan memberi kesan kepada pengagihan masa dan ruangan ketersediaan air. Jordan dianggap sebagai salah satu daripada sepuluh negara paling kekurangan air di dunia, negara yang menghadapi cabaran dalam sektor airnya, Air bawah tanah ialah sumber air paling penting di Jordan, ia menyediakan lebih separuh daripada jumlah permintaan air, Sebahagian daripada sumber air bawah tanah Jordan adalah yang kini dieksploitasi pada kapasiti maksimum, untuk menghadapi cabaran ini, kita harus mencari penyelesaian praktikal yang meningkatkan imbuhan semula air bawah tanah, secara semula jadi atau buatan. Kajian ini bertujuan untuk memilih tapak yang sesuai untuk Imbuhan Akuifer Terurus (MAR) melalui GIS dan Pemodalan Air Tanah dan meramalkan kesan perubahan iklim terhadap keseimbangan air. Kriteria terpilih telah dipilih berdasarkan Hujan, Cerun, Pembentukan Geologi, Guna Tanah, Tekstur Tanah, dan Kedalaman ke paras air, lapisan ini telah diintegrasikan ke dalam perisian GIS untuk menghasilkan peta kesesuaian MAR. Kawasan tersebut termasuk dalam lima kategori zon berpotensi (MAR) iaitu sangat baik, baik, sederhana, rendah dan sangat rendah. Didapati 16.7% dengan keluasan 1473.7 km^2 dan 30.15% dengan keluasan 2649.5 km^2 masing-masing berada di bawah kategori sangat baik dan baik bagi kesesuaian MAR. Kawasan seluas 1779.3 km^2 mewakili 20.24% didapati di bawah kategori sederhana manakala 1944.24 km^2 dan 890.94 km^2 bersamaan 32.82% daripada kawasan Wadi Araba masing-

masing berada di bawah kategori rendah dan sangat rendah kesesuaian MAR, kebanyakan lokasi (MAR) yang berpotensi terletak di dalam akuifer aluvium. Untuk meningkatkan pemahaman dan penilaian sistem Akuifer Wadi Araba, model aliran air bawah tanah telah dibina berdasarkan geologi sedia ada dan, hidrogeologi dalam kawasan kajian, simulasi senario ramalan untuk pengurusan air bawah tanah jangka panjang akuifer alluvium. Berdasarkan peta aras air bawah tanah untuk akuifer aluvium, terdapat pembahagian air bawah tanah di bahagian tengah Lembangan Wadi Araba, dan air bawah tanah mengalir dalam dua arah. Di bahagian utara lembah, aliran air bawah tanah adalah ke arah utara-timur laut, iaitu, ke arah Laut Mati. Di bahagian selatan lembah, aliran air bawah tanah adalah ke arah barat daya selatan, iaitu, ke arah Laut Merah. Berdasarkan persetujuan yang baik antara paras air yang dikira dan diperhatikan di kebanyakan telaga, anggaran air bawah tanah yang dikira daripada simulasi model menunjukkan bahawa aliran masuk utama ke dalam sistem berasal daripada penyusupan daripada kerpasan. Penurunan hujan yang dipengaruhi oleh perubahan iklim di kawasan yang dimodelkan menyebabkan kejatuhan aras air pada akuifer alluvium, berdasarkan senario ramalan yang boleh dimitigasi dengan meningkatkan imbuhan daripada kerpasan, yang mengakibatkan peningkatan dalam permukaan air tanah di 3 tapak sebanyak 1.96%-3.12%.

ACKNOWLEDGEMENT

Foremost, I express my gratitude to Allah the Almighty for His abundant blessings and guidance that facilitated the successful completion of this work.

I express my utmost gratitude and appreciation to my esteemed supervisors, Professor Ismail bin Yusoff, and his wife Professor Yatimah bint Elias, for their unwavering support and guidance throughout the years. They have been my biggest advocates from day one, providing continuous academic and moral support. I am also grateful to Dr. Ng Tham Fatt, who never hesitated to share his knowledge and offer advice, always welcoming any inquiries. Dr. Mohamed Khairul Nizar has been a valuable mentor, and Dr. Yahya Al-Majali has provided constant support, supplying the data and information on which this study was built.

I extend my thanks to the esteemed examination committee, whose valuable feedback has enhanced the quality and value of this work. A great appreciation goes to those whose support and prayers have been the driving force behind my success, my dear parents. I am immensely grateful to my beloved wife, Amnah, and my daughters, Zain and Leen, for their patience, sacrifice, and understanding throughout these years of study, travel, and separation from family. I also want to thank my brothers and sisters for their love and support during this journey.

I would be remiss not to express deep gratitude to my friends and colleagues who have consistently offered their assistance and support throughout this period. Lastly, I extend sincere thanks from me and my family for the wonderful moments we experienced in Malaysia, our second home, where we were warmly welcomed and treated with kindness.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

LIST OF SYMBOLS AND ABBREVIATIONS

amsl	:	Above mean sea level
ANS	:	Arabian Nubian Sheild
ASR	:	Aquifer Storage and Recovery
BCM	:	Billion Cubic Meter
bsl	:	Below sea level
C°	:	Celsius
DSTF	:	Dead Sea Transform Fault
GIS	:	Geographic Information System
m3	:	Cubic meter
MAR	:	Managed Aquifer Recharge
MCDA	:	Multi Criteria Decision Analysis
MCM	:	Million Cubic Meter
MODFLOW	:	The U.S. Geological Survey modular finite-difference flow model
MWI	:	Jordanian Ministry of Water and Irrigation
yr	:	Year

CHAPTER 1: INTRODUCTION

1.1 Background

Indeed, the increasing global water consumption and projected rise in demand present significant challenges in ensuring water availability for various sectors. Water scarcity is a growing concern, and addressing it requires innovative approaches and the exploration of non-conventional water resources. Research efforts are now focusing on finding sustainable solutions, such as Managed Aquifer Recharge (MAR), desalination, rainwater harvesting, and water recycling, to alleviate water shortages and reduce conflicts related to water availability across different regions and sectors. These efforts are crucial in promoting water security and ensuring a sustainable future for our planet (Ricart et al., 2021).

Among the regions facing severe drinking water scarcity, the Middle East and North Africa stand out. Climate change and excessive groundwater usage, already concerning in numerous arid and semi-arid areas, could exacerbate this issue (Whitman, 2019; Benfetta & Ouadja, 2020; Ouhamdouch et al., 2020). Climate change, manifesting of increased air temperature and reduced average rainfall, directly impacts aquifer recharge and, consequently, groundwater supplies.

Numerical models and evaluations are crucial in assessing the impacts of water abstraction and climate change when tackling the complexity of water-scarce places (Abdulaziz & Faid, 2015; Nassery & Salami, 2016; Al-Maktoumi et al., 2018; Alkhatib et al., 2019). When it comes to understanding and managing water supplies in such sensitive areas, these analytical techniques show to be of utmost importance.

In order to implement the integrated water management strategies that these nations are attempting to implement, Managed Aquifer Recharge has become essential throughout the Middle East (Arabi, 2012). Developing water resources from times of abundance to times of scarcity involves doing this, which can potentially mitigate climate change while minimizing problems with water supply. Even though such actions would not be able to stop climate change, they will be able to lessen its immediate negative consequences on water resources.

1.2 Problem Statement

Jordan faces a real problem in water sector because of the increasing demand for water, the scarcity of water resources, low rate of precipitation and the increase in the population, which leads us to find the most appropriate ways to manage water sources and search for new sources of water and the most optimistic use of rainfall. Therefore, (MAR) is considered one of the most appropriate procedures in solving the water problem in arid and semi-arid areas such as Jordan if the appropriate conditions are available to implement such a project. Many studies have been conducted to study the groundwater in Wadi Araba, we try in this research to cover one of the important aspects represented by the application of MAR in Wadi Araba.

1.3 Aims and Objective

Due to the water situation in Jordan and the exacerbation of the water problem, the demand is increasing to search for radical solutions to mitigate the scale of the disaster and the sustainability of groundwater sources. Therefore, the current study aims to implement Managed Aquifer Recharge (MAR), which is one of the solutions to deal with water scarcity and try to mitigate the effects of climate change and improve the water situation as much as possible, by determining suitable locations for MAR using the GIS and groundwater flow model techniques, and studying the effects of applying the MAR on groundwater levels at the present time and the expected effects in the future within well-study.

Based on the aims of the study, the main objective of the study is:

- Determination of suitable locations for MAR using the GIS and GW flow model techniques.
- Examine MAR's ability to help Jordan with its water shortage issues.
- Study the effectivity of MAR on groundwater levels as a long-term solution of climate change effect.

1.4 Scope of work

1- Employing Geographic Information System (GIS) software to create a Managed Aquifer Recharge (MAR) map using a multi-criteria combination technique. This map will assist in locating potential MAR implementation locations in the research area.

2- Studying the hydrogeological system of the basin, which involves analyzing the lithology and structural aspects. Additionally, calculating the water balance of the alluvium aquifer, including factors like recharge from rainfall and water released from storage due to declines in water levels.

3- Predicting how the hydraulic system will react to groundwater withdrawal. This analysis will assist in comprehending the effects of groundwater extraction on the aquifer system and possible impact on water supply.

4- Identifying groundwater resources that may be affected by Managed Aquifer Recharge (MAR) in future climate scenarios. By considering different climate projections, this assessment will provide insights into the resilience and sustainability of MAR initiatives under changing climatic conditions.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Due to competing demands from numerous stakeholders, fast population increase, urbanisation, herbicides and pesticides, and land degradation, planning and managing water resources in the twenty-first century is challenging (Ali & Kawy, 2012). Although water is crucial and plays a vital role in economic growth and food security, its accessibility in an adequate amount and quality is constrained by factors other than population growth and economic growth. According to numerous studies (Alvisi et al., 2003; Babel et al., 2007; Anseeuw et al., 2011; Ringler et al., 2011; Downing et al., 2013; Klöve et al., 2014; Panigrahy et al., 2015; Kumar, 2016), climate is regarded as a key determining factor in the hydrological cycle that alters the current state of the world.

Many people are worried that further global warming and related climate change may further reduce already depleted water supplies in water-stressed regions. The hydrological cycle is impacted by climate change through changes in precipitation, surface runoff, soil moisture, and groundwater recharge rates (Şen et al., 2012; Al-Hasan & Mattar, 2013; El-Naqa & Al Kuisi, 2013; Essefi et al., 2013). Additionally, due to increased evapotranspiration (Solomon, 2007), saltwater intrusion into aquifers and groundwater saline (i.e., increasing demand). Existing water management practises can be improved upon to increase the resilience of water supply systems and minimize their vulnerability to protracted drought (Bouwer, 2002; Preziosi et al., 2013; Sobowale et al., 2014).

2.2 Water Scarce in Jordan

Water scarcity is one of the main determinants of water security since it directly affects urban populations' health and well-being, the environmental quality of cities, and economical growth (McDonald et al., 2014; Garrick et al., 2019; Krueger et al., 2019a; Krueger et al., 2019b). Water scarcity currently affects a large portion of the world's urban populations (McDonald et al., 2014). Due to population growth, urbanization, and socioeconomic development, it is predicted that urban industrial and household water consumption would rise by 50–80% over the next three decades (Flörke et al., 2018; Garrick et al., 2019). Additionally, the temporal and spatial distribution of water availability will be impacted by climate change (Revi et al., 2014; Greve et al., 2018). Urban water scarcity will therefore probably get considerably worse in the future (Vorosmarty et al., 2000; Pachauri et al., 2014; Schewe et al., 2014).

Jordan, along with countries in the Middle East and North Africa, is one of those most severely hit by a shortage of adequate drinking water. Climate change may exacerbate the widespread groundwater usage that these arid and semi-arid regions currently experience (Berhail, 2019; Whitman, 2019; Ouhamdouch et al., 2020).

Semi-arid regions are characterised by high rates of evaporation and great spatial and temporal variability in precipitation, which leads to unpredictable surface water runoff. Because of this, groundwater is used to fill the gap left by the demand for agricultural and domestic use of available surface water supplies. The majority of the little natural groundwater recharge, which typically amounts to between 0.1 and 5% of long-term average precipitation, occurs indirectly in wadi beds (Scanlon et al., 2006). As a result, groundwater levels have dropped in a number of semi-arid areas. As a result, springs and shallow wells can dry out and salty water might get inside (Miller, 2005). Like the rest of Jordan, Wadi Araba's current water usage is already equal to or more than its renewable resources. The demand is primarily for irrigated agriculture, with potable water coming in second (MWI, 2020).

Jordan is a severely water-stressed country, ranking fourth among the world's water-stressed nations. Annual water resources were 3 600 m^3 per capita in 1946, and today there are less than 105 m^3/year per capita, far below the severe water scarcity threshold of 500 m^3 (Hadadin et al., 2010; JAEC & WorleyParsons, 2011; MWI, 2016; Memer, 2017). Jordan has successfully managed its limited water resources, especially in recent years due to regional wars and refugee waves that have been housed in the country since 1948. Water resource management has been negatively impacted by the waves of refugees that arrived in 1967 and later, as well as returnees from the Gulf States in 1991/92, during the first Gulf War, Lebanon in the 1970s and 1980s, Iraq in 2003 and later, and finally Syria from 2011 to 2017. This is especially true when it comes to allocating new water resources to meet the needs of the country (Taimeh, 2015; Khader et al., 2019; Salameh & Al-Alami, 2021).

About 28% of Jordan's total water supply comes from surface water. 288 MCM of water were provided in 2017 by surface water resources. The country's surface water system is largely composed of the Jordan, Yarmouk, and Zarqa rivers. But the water supplies that are accessible to each are now incredibly unpredictable. Jordan's water supply is directly impacted by upstream diversion and over pumping in Israel (Jordan River) and Syria (Yarmouk River, tributaries, and groundwater supplies from the same basin). The Jordan River's current flow is only 2% of its historic flow, which was 1.3 billion cubic meters per year (BCM/yr) in the 1930s (Gafny et al., 2010; Hussein, 2017; Zeitoun et al., 2019).

Jordan's primary source of water is groundwater. Groundwater resources are divided into twelve groundwater basins as shown in Figure 2.1, each one contains several groundwater aquifer systems.

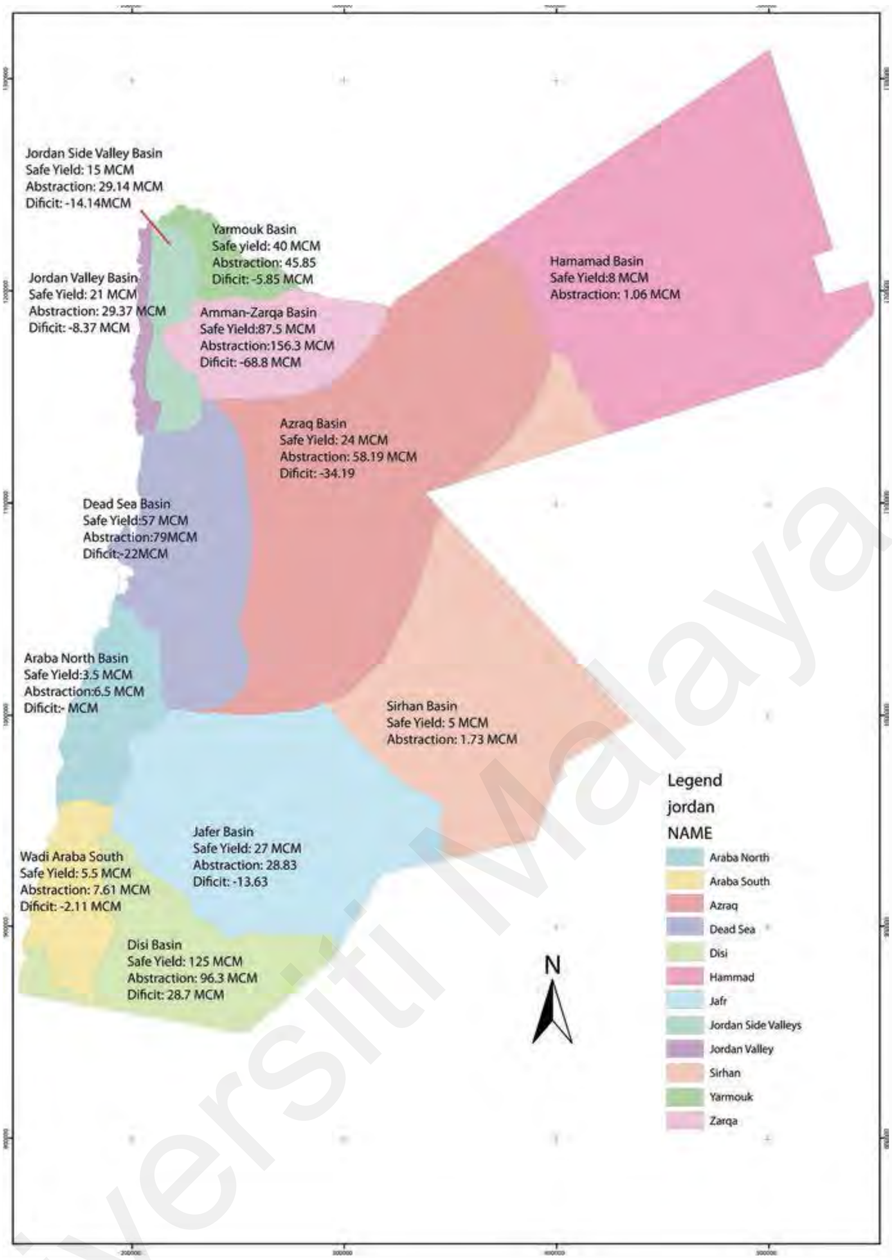


Figure 2.1: Groundwater basins in Jordan (MWI & BGR, 2019)

60% of Jordan's total supply comes from groundwater, which is distributed as 332.5 MCM for home and drinking purposes, 237.6 MCM for agriculture, and 31 MCM for industrial (MWI, 2016; Salameh et al., 2018; Salameh & Al-Alami, 2021), The appropriateness of groundwater for different uses depends on its quality. Groundwater will eventually become depleted and lose quality due to excessive pumping, continuous and excessive abstraction, and inadequate recharging rates (Magesh & Chandrasekar, 2011; Abbasnia et al., 2018).

2.3 Climate Change Effect on Groundwater Resources

Groundwater is utilized for development projects to meet local demand and is essential for maintaining ecosystems (Taylor et al., 2013). One-third of all freshwater withdrawals worldwide come from groundwater sources, which are utilized to satisfy 36% of household, 42% of agricultural, and 27% of industrial needs, respectively (Döll et al., 2012). Many variables, including climate change, have an impact on the quality and quantity of available water resources (Kumar, 2012). Water supplies, the natural ecology, and a few other aspects are all considered to be at risk from global climate change (Erwin, 2009). The factors influencing groundwater availability due to climate change and its fluctuation (Taylor et al,2013). According to scientific data (Houghton, 1996; Miller Jr, 1992; Woldeamlak et al., 2007), human activities and the industrial revolution have been responsible for a fast shift in climate for several centuries. Climate change is predicted to result in greater changes in the world's temperature and precipitation causes floods, which causes a rise in the sea's mean worldwide level and increases damage to places along the shore (Solomon, 2007; Woldeamlak et al., 2007). As a result, concern over climate change has grown in order to better forecast future climatic conditions and their impact on water resources, as well as to boost water availability and reduce potential harm.

Researchers and scientists throughout the world are examining how climate change may affect biological and hydrological aspects (Erwin, 2009). The impact of climate change on surface water bodies has been the subject of several research, including those by (Anandhi et al., 2008, 2009; Erwin, 2009; Rehana & Mujumdar, 2013). As groundwater is a key source of the world and is essential to sustaining an area's ecological value, some studies have looked at the possible effects of climate change on it (Batelaan et al., 2003; Solomon, 2007; Woldeamlak et al., 2007). According to certain research (Allen et al., 2004; De Wit et al., 2001; Woldeamlak et al., 2007), human influences such as agricultural operations and the installation of weirs for flow regulation affect groundwater recharge and discharge. For integrated water management, it is crucial to predict recharge and discharge under future climatic change conditions. Several hydrological models can be used to do this, but (Woldeamlak et al., 2007) used MODFLOW to calculate discharge and annual groundwater levels in the Grote-Nete catchment, Belgium. (Scibek & Allen, 2006) employed MODFLOW to investigate the spatiotemporal distribution of recharge to the Abbotsford-Sumas aquifers in northern Washington State and southwest British Columbia. Using MODFLOW, (Allen et al., 2004; Scibek & Allen, 2006) investigated how climate change might affect two minor aquifers in western Canada and the United States. In conclusion, using hydrological models to evaluate future changes in groundwater recharge provides useful information on the changes under various climate change scenarios. Since predicted changes in precipitation have a direct impact on groundwater recharge (Taylor et al., 2013).

2.4 Managed Aquifer Recharge (MAR)

The term "Managed Aquifer Recharge" (MAR) was coined by British hydrogeologist Ian Gale, who served as co-chair of the International Association of Hydrogeologists (IAH) Commission on Managing Aquifer Recharge from 2002 to 2011 (IAH-MAR, 2018), the purposeful replenishment of water in aquifers for reuse and/or environmental benefits is known as MAR, formerly known as artificial recharge (Herman Bouwer, 2002; Dillon, 2005; Sprenger et al., 2017; Page et al., 2018; Stefan & Ansems, 2018).

It is unrealistic to assume that groundwater replenishment will be adequate to reverse the impacts of excessive groundwater extraction in most places (Dillon et al., 2009). Managed aquifer recharge is a large and expanding body of practices that enable integrated management of surface and groundwater resources as well as active management of groundwater resources at the local and basin levels (Gale, 2005; Evans et al., 2012; Evans & Dillon, 2017), aquifers are water-bearing strata of the earth's crust that are often recharged by rainwater seeping through soil and rock or infiltration from lakes and rivers. There are a number of human endeavours that can enhance aquifer recharge, and they can be divided into three groups:

- Unintentional recharge occurs when land is cleared, deep-rooted vegetation is removed, deep seepage occurs under irrigation areas, and leaks from storm drains and sewers occur in urban areas (Jiménez et al., 2012).
- Unmanaged recharge includes storm water drainage wells and sumps, as well as septic tank drain fields, and is generally used for water disposal without recovery or reuse (Vanderzalm et al., 2011).
- Managed recharge—through purpose-built recharge structures such as injection wells and infiltration basins for subsequent recovery and use or storage to benefit the aquifer's environment (Greskowiak et al., 2006; Pavelic et al., 2007; Van Houtte et al., 2012; Kvitsand et al., 2017).

A technology known as Managed Aquifer Recharge (MAR), also known as "aquifer storage and recovery (ASR)", "artificial recharge," or "rainwater harvesting," is one way to adapt to climate change, particularly when those changes are anticipated to have a negative impact on the availability of water in arid and semi-arid regions (Salameh et al., 2019). Urban regions where impermeable cover has changed the natural recharge regime could benefit from improved natural groundwater recharge rates through MAR. For a number of reasons, MAR is frequently utilised to enhance sustainable urban water management, including:

- Improving urban economies, for instance, by producing horticulture.
- Improving the security of urban water supply.
- Stopping seawater from seeping into coastal aquifers.
- Giving access to storage without compromising priceless land surface space.
- Limiting the evaporation of water that has been stored.

- Preserving groundwater-dependent ecosystems and environmental flows, which boost local amenity, land value, and biodiversity.
- Improving coastal water quality by lowering urban discharges of nutrient-rich waste.
- Reducing flood damage and flooding.
- Facilitating land-value-boosting urban landscape improvements (Ayuso-Gabella et al., 2011; Luyun Jr et al., 2011; Page et al., 2012; Miotliński et al., 2014; Radcliffe et al., 2017; Tredoux et al., 2020).

Water must be transferred to an aquifer if enough runoff is captured. The transfer method depends on hydrogeological conditions and might be surface spreading for unconfined aquifers or well injection for confined ones. If there is an impermeable layer close to the surface, consider infiltration wells and trenches. Canals or pipelines can transfer surface water to the best infiltration location. Infiltration or spreading are most cost-effective and can handle the largest sediment loads for unconfined aquifers. A greater surface area with gentle slopes (<5%), soils with sufficient hydraulic conductivity, no salty horizons, and no impermeable layers between the surface and the groundwater table are required (Asano, 1985). Hydraulic loads affect depth and size. Deeper basins use both vertical and horizontal permeability, improving their quality. The basin floor can be covered with gravel and sand to increase hydraulic conductivity and prevent fines from penetrating deeper beneath (Bouwer, 2002). Wide basins are less active (Al-Kharabsheh, 1995). The wadi channel downstream of the dam can be used for infiltration if the wadi sediments are permeable enough. The wetted area can be increased through smaller stream channel modification like dikes, berms, ditches, T-levees etc to decrease water velocity and spread the water over the whole wadi channel (Asano, 1985; Bouwer, 2002). Infiltration ditches, drains, seepage trenches, galleries, and wells can overcome impermeable or crusted surfaces over unconfined aquifers. They are backfilled with coarse sand or fine gravel and coated with geotextiles to minimize sediment penetration and evaporation. If the aquifer is confined, recharge wells or injection wells must be used to penetrate the permeable aquifer formation. In the Aquifer Storage and Recovery (ASR) or Aquifer Storage, Transport, and Recovery (ASTR) schemes, a single well is used for recharge and recovery. The latter is utilized when it is necessary to ensure a specific residence duration for attenuation processes or when groundwater flow velocities are high. Water quality must be very good since there is no attenuation in the unsaturated zone and clogging is a significant problem. The recharge water shouldn't have more than 10 mg/L of TSS, TOC, or total nitrogen in it (T-N) (NRMMC-EPHC-NHMRC, 2009). If the recharged aquifer is utilized to deliver drinkable water, it could be necessary to ensure its purity (Tredoux et al., 2009). Although disinfecting recharge water could be necessary to prevent the growth of biofilms, doing so might also result in the production of dangerous disinfection byproducts (Pyne, 1995; McQuarrie and Carlson, 2003).

GIS and remote sensing techniques have become more prevalent in recent years for use in extensive investigations. The usefulness of this method depends on the size that is chosen, as well as, of course, on the level of information and input data that is available. It will provide a basic notion of what information is lacking, where to do additional monitoring, and which zones are preferred or ignored for additional research (Steinel et al., 2016). The strategy involves creating various themed maps based on the data at hand or the best guesses. Each parameter or requirement is categorised according to its numerical or linguistic quantifiers, and the appropriateness of each class is determined. The various thematic maps are then layered. This can only be done statistically once weights have been assigned to each theme map or subjectively with a limited number of thematic maps (Alraggad & Mohammad, 2010). Due to the enormous amount of geographic data that must be obtained, collated, and analysed for MAR project site evaluation, applying typical data processing techniques for site selection can be extremely challenging and time-consuming (Anbazhagan et al., 2005). In groundwater management studies, land use appropriateness mapping, and other geographical research, GIS and remote sensing technologies have been utilized singly or in combination to process, integrate, and analyse spatial data (Krishnamurthy et al., 1996). GIS and remote sensing are widely used in studies to select MAR locations (Saraf and Choudhury, 1998; Brown et al., 2008; Ghayoumian et al., 2007; Werz et al., 2009).

There are two main overlay techniques. Boolean logic, which only allows ratings that are suitable or unsuitable (0 and 1 values), is widely used to generate constraint maps. The location will be ruled unsuitable if just one of the characteristics falls below the minimal requirement; however, if the minimal level is fulfilled for all thematic maps, the area will be rated suitable. Using this technique, locations that are completely unsuitable will be eliminated. The weighted overlay is used to construct maps of suitability (Malczewski & Rinner, 2005; O'Sullivan & Unwin, 2010), allows classification within each theme map to be combined with different weights across all themed maps based on their worth. In other words, sites that are undesirable for one attribute can nevertheless earn a high class if all other criteria are assessed to be sufficient. Only a small number of research have focused on identifying places where MAR is not feasible (Brown et al., 2008, Ghayoumian et al., 2007). To distinguish between areas that are and are not viable, Boolean logic is frequently used. Studies generally focus on categorizing maps based on their relative relevance. Each thematic map is categorized based on how important the associated depicted parameters are. Linguistic classifiers, such as very good, good, suitable, etc. (Jothiprakash et al., 2003; Ghayoumian et al., 2005) and class 1 to class 4 value type classifiers are used in these research (Ghayoumian et al., 2007). In many research, stepwise functions are employed to standardize thematic maps for aggregate (Ghayoumian et al., 2007).

To examine the responsiveness or to analyse various facets of the MAR scheme, various ratings and weights can be assigned. Rates and weights can be changed to rank sites according to expert opinion or risks accepted (Rahman, 2011). Many MAR suitability assessments include a mixture of catchment suitability for runoff generation, aquifer suitability and site appropriateness for retention and transfer to the subterranean. However, it would be ideal to explicitly distinguish these concerns as the same parameter (such as sandy soils or a gentle slope) can be inappropriate for runoff generation but extremely suitable for infiltration.

MAR projects using flood water must identify a suitable catchment and site for water retention and a suitable site for recharging. The evaluation of water harvesting structures used for residential, agricultural, and livestock watering is comparable to evaluating the possibility for retention structures for later recharging with regard to surface water runoff generation, but it differs greatly in many other characteristics (Steinel et al., 2016), for basic water harvesting structures impermeable soil and distance to faults is important to prevent harvested water from infiltration, while vicinity to communities and infrastructure is recommended to decrease the costs of water transport (Al-Adamat et al., 2010). Because these factors control the groundwater recharge process, site suitability analysis for MAR is frequently based on intrinsic factors such as hydrogeology, topography, soil type, land use, and climate (Sallwey et al., 2019). Even though many studies have used GIS-based multi-criteria decision analysis GIS-MCDA for MAR site selection, there is no consensus on the criteria, weights, and methods to be used. In fact, the methods used for classification and weighting vary greatly. This can be attributed to data availability, local characteristics, as well as expert opinion and problem formulation (Government of India, 2007; Chowdhury et al., 2010; Russo et al., 2015).

Alraggad & Mohammad, 2010 create MAR potential map under GIS environment in the Azraq Basin/Jordan by using four thematic layers:

1) Hydrogeological classification.

2) Slope classification.

3) Urban areas.

4) Proximity to water sources.

Their research attempted to restore over-exploited groundwater and increase the amount of stored groundwater. Raise the standard of the groundwater, reduce soil erosion and storm runoff, limit the incursion of salt water into the area, guard against potential subsidence brought on by excessive pumping, and reduce the loss of fresh surface water due to evaporation.

They discovered that due to the existence of superficial deposits, low slope, aquifer conditions, and proximity to water resources, more than 20% of the research area had a very high potential for MAR. More than 61% of the region was made up of high potential zones. It is located in the centre of the Azraq basin, where the water depth is quite shallow, increasing the MAR processes. Areas with limited MAR potential make about 4.03% of the basin's total area, as shown in Figure 2.2 (Alraggad & Mohammad, 2010).

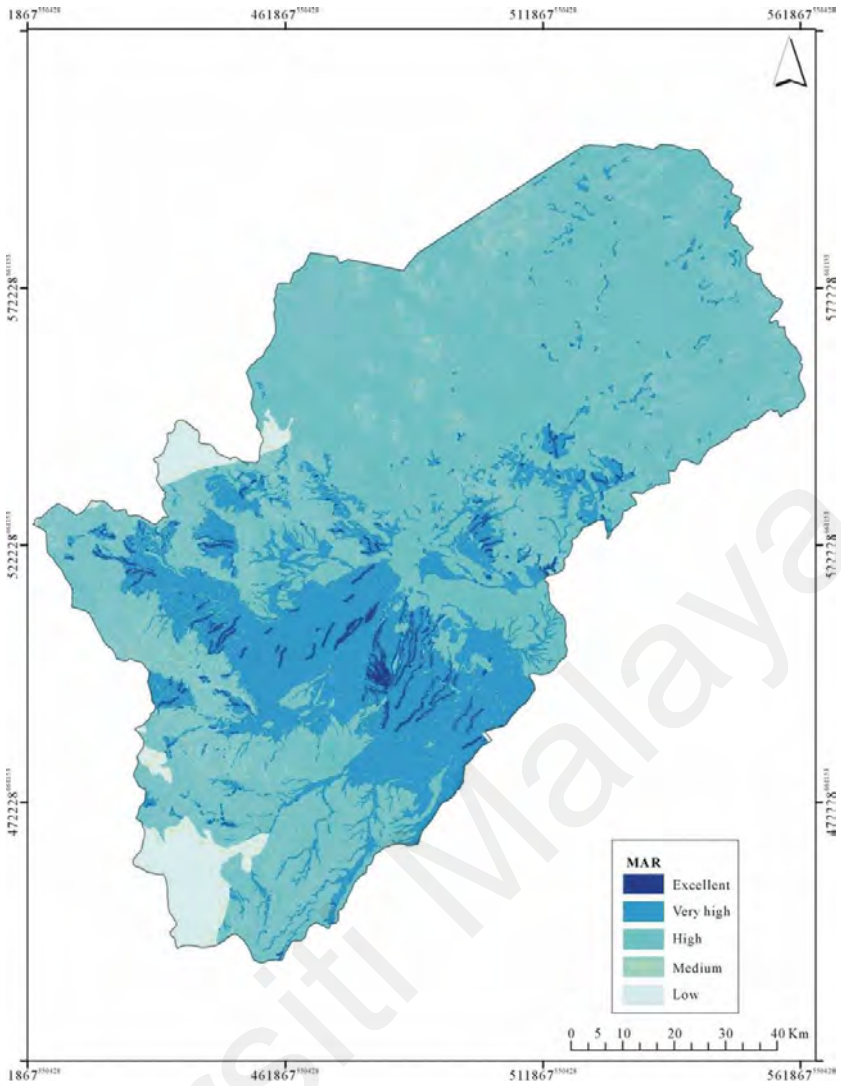


Figure 2.2: Azraq basin-Jordan, MAR potential map (Alraggad & Mohammad, 2010)

Salameh et al.'s 2019 research was motivated by the failure of numerous Managed Aquifer Recharge projects that had already been executed, and they examined the necessary conditions for the effective implementation of MAR. The methodology includes assessing whether the managed aquifer projects that were put into action in Jordan succeeded or failed in recharging the aquifers, as well as identifying the causes of the success or failure. They observed that Managed Aquifer Recharge, in the instance of Jordan, can alleviate the consequences of diminishing groundwater levels and can mitigate the effects of climate change by utilising leftover water. Before starting any artificial recharge initiatives, more research must be done, including establishing the aquifer parameters and tracking how the water quality changes after recharge, in addition to comprehending the results of the recharged water. As a method to save water and lessen the impact of climate change on the stocks of groundwater resources, MAR is steadily gaining importance in Jordan, a semi-arid region. Lower wadis that discharge into the Gulf of Aqaba have a high potential for MAR. (Salameh et al., 2019).

2.5 Groundwater Modelling

To explain the dynamics of an aquifer system, characterise subsurface water flow, and simulate the results of different actions, numerical groundwater models are frequently utilised. scenario planning (Zhou, 2009). In order to accomplish these objectives, numerical groundwater models are utilised a means of addressing problems like excessive groundwater withdrawal from irrigation (Ramireddygari et al., 2000; Mao et al., 2005; Zhang et al., 2012), analysis of the availability of groundwater (Uddameri & Kuchanur, 2007; Valley, 2009). Subsidence brought on by groundwater (Shearer, 1998; Larson et al., 2001) or density-dependent flow brought on by salt infiltration in coastal locations. (Kourgialas et al., 2016; Calvache & Pulido-Bosch, 1997; Sherif et al., 2012). Models can help in decision-making as well. When making decisions about water management practices, it is important to take water re-allocation into account.

Engineering and environmental sectors, among others, have found success using GIS as a tool for managing geographical data and making decisions (Goodchild et al., 1993; Juster & Stafford, 1991). GIS offers a way to portray the actual world by integrating layers of individual geographical data (Corwin & Wagenet, 1996). The majority of GIS can access overlay and index operations with ease; however, they cannot represent the flow and transport mechanisms of groundwater. Yet, combining a GIS with models of groundwater that are based on processes can offer an efficient tool for handling, storing, modifying, visualizing, and displaying hydrogeological data. The four kinds of data utilized in groundwater modelling are the aquifer system stress factor, aquifer system geometry, hydrogeological parameters, and primary measurable variables (Gogu et al., 2001). The time needed for data preparation, processing, and presentation throughout the modelling process can be greatly decreased by using a well-designed GIS database. In hydrogeology, groundwater models are primarily used to simulate multicomponent chemical reactions, advection, and steady or transient state groundwater flow. The use of GIS in groundwater evaluation and management research projects has increased significantly in recent years. In the IDRISI GIS environment, (Lasserre et al., 1999) created a straightforward GIS linked model for groundwater nitrate transport. Another user-friendly program that can produce 3D visualization visuals and input GIS data is Visual MODFLOW. To model the dynamics of groundwater, (Xu et al., 2009) employed MODFLOW 2000 (Harbaugh et al., 2000) in conjunction with GIS. Every one of them varies across time and space, therefore using a Geographic Information System (GIS) in conjunction with a model is beneficial.

It may be possible to conceptualize and characterize hydrogeological and hydrologic systems using GIS technology in conjunction with a process-based groundwater model (Gogu et al., 2001; Hinaman, 1993; Kohn, 1996), as well as properly adapt the groundwater flow model to the research region (Brodie, 1998). The majority of groundwater modeling programs, such FEFLOW, MODFLOW, and the Groundwater Modeling System (GMS), have an interface that connects raster and vector data in appropriate GIS formats like tif, bmp, and img.

Groundwater flow models have been applied as interpretive tools for analysing flow patterns and groundwater system dynamics, assimilation tools for analysing how stresses affect the groundwater system, assessment tools for assessing recharge, discharge, and aquifer storage processes, and predictive tools for predicting future conditions or impacts of human activity, In addition, they can serve as screening tools for analysing groundwater development scenarios, management tools for reviewing potential policies, and visualization tools for conveying important signals to the general public and decision-makers.

In their research, Patil et al. (2020) concentrated on measuring and evaluating groundwater resources by modelling technique for the Hiranyakeshi watershed using Visual MODFLOW Flex software. They also examined the impact of potential climate change scenarios on groundwater levels in the Hiranyakeshi watershed. Model calibration was accomplished using Parameter Estimation (PEST), and model performance has been assessed using coefficients R^2, RMSE, and NRMSE. It should be noted that the calculated R^2, RMSE, and NRMSE coefficients are 0.98, 1.68, and 3.41 %. The findings of the model simulation indicate a 1.8 m increase in head during the course of the simulation's five-year operating span. The model was once more run using Hadley Regional Model 3 (HadRM3) data for the Hiranyakeshi watershed for the years 2021–2050 in order to evaluate the effects of climate change on groundwater recharge. According to the long-term output research, the average annual temperature is expected to increase by 2.59 °C, precipitation by 81.50%, and groundwater recharge by 24.91%. (Patil et al., 2020).

In order to evaluate the impacts of the pumping and recharging on the aquifer there, Aslam et al. 2022 conducted their study in a specific location of the Chaj doab, Punjab, Pakistan. For the purpose of simulating three major groundwater scenarios, they used a distributive surface water model called WetSpass and a groundwater flow model called MODFLOW. The groundwater flow model, MODFLOW, was manually calibrated with data from 12 years (2003-2014) and 5 years of validation (2015-2019), and the results are highly beneficial for assessing the aquifer's capacity for recharge and discharge. They discovered that:

1- If the current conditions from the years 2003 to 2019 persisted until 2035, the results of Scenario-I show that there would be an 18.1 m decline in the groundwater table at that time (to estimate the impact of the pumping).

2- The model predicts drops in the water table of 2.0, 5.5, 9.8, and 14.3 m in the year 2029 as a result of increases in the pumping capacity of 25, 50, 75, and 100%, respectively. Scenario-II (to evaluate the aquifer's response to a 25-100% increase in pumping capacity over the next ten years).

3- According to the results of Scenario-III, the water table would drop by 0.7 m with a reduction in recharge from rainfall and by 2.4 m with a reduction in recharge from open water bodies (to assess the effect on the aquifer of a reduction in the average groundwater recharge from the river by 50% by following the same pumping trend). (Aslam et al., 2022).

Boufekane et al. developed a groundwater model. The groundwater model was calibrated twice in 2019 for the Jijel plain region of Algeria to examine the effects of drought and pump discharge on groundwater supplies and seawater intrusion:

1. Steady-state calibration under conditions typical for 2012.

2. Transient conditions calibration from 2012 to 2042 (30 years).

Studies have been done on the evolution of groundwater levels in relation to pumping discharge and drought. As the population develops and the requirement for groundwater pumping increases after 2012, it may be expected that the actual level of seawater intrusion and anthropogenic pollution in the future will be worse than that forecast by the model. The reduction (near cities) has been attributed to overexploitation, which causes advancing seawater in the northern region and anthropogenic pollution in the central region. To maintain freshwater aquifers and protect them from contamination, better groundwater development and management techniques such as modern irrigation systems and artificial recharge will be needed. (Boufekane et al., 2019).

In order to simulate the behaviour of the flow system under various stresses and reflect the aquifer's actual hydrogeological conditions, El-Naqa & Rimawi (2012) built a 3D model of the Amman-Wadi Es Sir (B2/A7) aquifer system in the Jafr Basin, Southern Jordan. They also estimated the missing hydraulic parameters, such as transmissivity and storativity, for both steady-state and transient conditions, in order to predict Findings from the study were based on a geodatabase in ArcGIS format:

1- When the model is calibrated for a steady state environment, the observed and simulated beginning water level contours closely match.
2- Transient state calibration also shows strong agreement using drawdown data spanning 36 years, from 1989 to 2025.
3- According to the calibrated flow model (steady and transient states), the research area's horizontal hydraulic conductivity varies between 0.6 m/d and 26.6 m/d. Specific yield values that have been calibrated range from 0.01 to 0.15.
4- Total abstractions from the B2/A7 Aquifer were 18.4 MCM/y. Based on the current withdrawal rate (18.4 MCM/y), the maximum drawdown in the Eshidya Phosphate Mines' wellfield will be roughly 9.95 m, 8.37 m, and 8.6 m in the years 2000, 2005, and 2025, respectively.
5- Within 50 years of abstraction, the groundwater system would not reach balance.
6- The B2/A7 Aquifer System's may be accepted predicted future yield of 20 MCM/a abstraction from the wellfields in the Jafr Basins. (El-Naqa & Rimawi, 2012)

In the Al-Buraimi area, close to the Oman-UAE border, Izady et al. (2017) developed a numerical model to simulate groundwater flow and evaluate sustainable groundwater extraction. They used information from hundreds of drilled borehole logs to develop a three-dimensional stratigraphic model of the study area, and their work significantly advances knowledge of the region's groundwater supplies. According to the study's findings, the sustained long-term regional groundwater extraction has been 18.09 MCM/year for 17 years, compared to estimations of 14.51, 16.31, and 36.00 MCM/year for dry, normal, and rainy periods based on SPI climate conditions. The average long-term lateral groundwater flux from the cracked eastern ophiolite mountains to the alluvial zone is 5.67 MCM/y, with a range of 4.23 to 11.69 MCM/year. Decision-makers might better understand the groundwater budget components in this large transboundary hard rock-alluvium aquifer by using the results of their groundwater model, which is located close to the UAE-OMANIA border. Making better decisions for anticipated changes in diverse climate circumstances would assist decision-makers improve their existing strategies (Izady et al., 2017).

In 2020, Radulovic et al. constructed a regional groundwater flow model employing numerical modeling techniques, specifically using the MODFLOW NWT version. The model comprised four layers to accurately depict the aquifer systems within the study area. The primary objectives of this modeling endeavour were twofold: first, to ascertain a sustainable yield for the groundwater resources, and second, to identify suitable locations for new wellfields in the Wadi Araba Basin in Jordan. Through this modeling approach, the researchers aimed to enhance the understanding and management of the region's groundwater resources.

1- Alluvium aquifer

2- A7/B2 aquifer

3- A1-A6 aquitard

4- Kb/Ram aquifer

The findings of Radulovic et al. revealed that the safe yield in the Wadi Araba basin amounts to approximately 20 million cubic meters per year (MCM/year). Based on their study, the researchers recommended the establishment of five new wellfields in Wadi Araba, with four proposed for the central part of the basin and one for the northern region.

Through their modeling simulations, the researchers explored various scenarios for the future water table in the area. In the most pessimistic scenario, they projected a potential water table decline of 60 meters by the year 2050. Conversely, in the most optimistic scenario, they anticipated a potential water table rise of 24 meters for the same year (Radulovic et al., 2020). These projections offer valuable insights into the possible impacts of water usage and climate conditions on the groundwater levels in the Wadi Araba Basin.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

One of the most effective approaches to solve the shortage of groundwater resources is to artificially or naturally replenish the water levels (Reid & Dreiss, 1990). To choose the ideal locations for groundwater recharge, new methodologies must be applied. One of these methods is Geographic Information Systems (GIS), which is crucial for data management and analysis of ideal places. GIS saves the time and expense associated with site selection while also offering a digital data bank for future site monitoring. Groundwater recharge zones can be mapped using RS and GIS techniques. Rainfall, slope, geology, soil, and other thematic maps can be generated (Yeh et al., 2016).

The current study aims to create a Managed Aquifer Recharge (MAR) potential map of the Wadi Araba basins. Various thematic maps of Wadi Araba, such as rainfall, slope, and soil geology, have been created. A groundwater recharge zone map for the region was created by combining these maps using GIS software.

To enhance our comprehension and evaluation of the alluvium aquifer system in Wadi Araba concerning Managed Aquifer Recharge (MAR) and the impact of climate change. This will be achieved through a series of steps, including the development of necessary data sets for the groundwater model, creation of a conceptual groundwater flow model based on the existing geological and hydrogeological conditions in the study area, construction of a digital groundwater flow model, simulation of predictive scenarios for long-term groundwater management of the alluvium aquifer, and fulfilment of the study requirements outlined below:

1. Project area is bounded by the sandstone aquifer to the east, international border in the west, Dead Sea to the north and Red Sea to the south.

2. All potential data and resources to fulfil the model have been considered throughout the study steps.

3. Identification the role of faults and fractures in the groundwater flow path.

4. Develop a three-dimensional groundwater flow model for Wadi Araba using MODFLOW.

5. Determine the safe yield for Wadi Araba Basins.

6. Investigate different scenarios of groundwater management of Wadi Araba reflect the climate change effect including variation of abstraction and recharge rates.

7. The study considered the possibility and effect of Apply Managed Aquifer Recharge within Wadi Araba

3.2 Literature Review

Gather all data on land use, geological, hydrogeological, and hydrological conditions that are present in technical reports, papers, journals, or other sources, as well as any data on these topics that are available.

3.3 Field Work

Geological, hydrogeological, hydrological, and other related data were obtained over the course of this research in order to confirm the data already gathered and to complete the missing data compilation. To compile missing or site-specific data.

Field investigations are needed to get site-specific information on soil, geology, hydrology, climate, topography, land use and access as well as catchment information on up- and downstream users and hazards to water quality.

3.4 Data Collection and Preparation

In the process of identifying suitable sites for groundwater recharge projects, extensive efforts were made to gather and compile all relevant information on geological, hydrogeological, hydrological, land use, and other environmental data. This data was sourced from various technical reports, research papers, journals, pumping test reports, and other reliable references.

Altitudes, locations, pumping rates, static and dynamic water levels, and evaluations of pumping test results are among the data gathered. To ensure accuracy and completeness, missing data was synthesized based on the existing information. The collected data was then organized and tabulated, utilizing attributes, to create shape files through Geographic Information System (GIS) software. These shape files cover various aspects, including geological formations, hydrogeological features, hydrological parameters, and environmental characteristics within the research area.

Structured contour maps, groundwater flow systems, drainage boundaries, aquifer boundaries, and aquifer properties (such transmissivity, permeability, and storage coefficient) were all converted to shape files through digitization and conversion. Additionally, topographic maps, springs maps, abstraction and monitoring wells, and meteorological data including rainfall and evaporation were included.

In order to better understand the aquifer system, calculations for formation thickness, saturation thickness, and depth to water levels were made. All relevant books and papers that were examined and verified throughout data collection and evaluation were included in a thorough reference list. To ensure data reliability, a verification process was conducted, eliminating any notable outliers from the collected data sets. Visualization techniques, such as x/y plots, contouring, and map overlays, were employed to identify trends and patterns in the data. By combining and analyzing this diverse set of data, suitable sites for groundwater recharge projects were identified, and the assessment of potential MAR implementation was informed by a robust foundation of geological, hydrogeological, and hydrological information.

To organise and transfer the data sets as needed into the groundwater modelling environment, project data is stored in a project GIS and database. This makes it simple to transfer and compile input files for the study's model phases. To assign acceptable values to the appropriate cells, all data gathered by studying the documentation has been processed and presented in sufficient formats suitable for direct insertion into the model. As a result, the following multiple digital files for each spatially variable parameter were produced:

- A map with the boundary of the model
- Elevation maps of layers contacts
- A recharge map from precipitation data
- Tables with coordinates of the springs
- Tables with coordinates of abstraction wells and tables with transient abstraction data
- Tables with coordinates of the observation points and tables with transient observation data
- Maps of zones for the hydraulic parameters
- A map of the main wadis
- Generalized geological maps.

3.5 Managed Aquifer Recharge (MAR)

The three main questions to be answered for MAR suitable sites map locations:

1) Is there enough source water available for recharge.

2) Can the aquifer accept this water in terms of storage space.

3) Can the water get to the groundwater rapidly enough.

Using MAR in conjunction with demand reductions and other management techniques can be useful for minimizing these adverse consequences at the local level. The main benefits of MAR in these conditions are the abundance of free storage space (due to over abstraction) and the avoidance of challenges with surface storage, like as evaporation losses, massive space needs, algae blooms, and potential pollution (Asano, 1985; Pyne, 1995). Additionally, during recharging and storage, many pollutants naturally attenuate. (Dillon, 2005). MAR can be conducted with a range of diverse source waters into several aquifer types using a variety of techniques, which will be selected based on the site-specific conditions. Several publications provide a general overview of MAR techniques and issues related to various sources of water (stormwater, treated wastewater, desalinated drinking water, river runoff, etc.), hydrogeological set ups (unconfined or confined; porous or fractured/karst) and operational conditions. This thesis will focus primarily on stormwater recharge via infiltration. Infiltration or spreading techniques are usually applied for unconfined aquifers because they are the most cost-effective and can manage the greatest sediment loads. A larger surface area with mild slopes (5%), soils with adequate hydraulic conductivity, the absence of salty horizons, and impermeable barriers between the surface and the groundwater table are required (Asano, 1985). Size and depth change according on hydraulic loads. Deeper basins are better because they use both horizontal and vertical permeability. The basin bottom can be filled with gravel and sand to boost hydraulic conductivity and prevent particulates from penetrating deeper beneath (Herman Bouwer, 2002). Long, narrow basins are more active than broad basins (Al-Kharabsheh, 1995). The opposing method for avoiding possible clogging, which requires slopes of 1% to 3%, is very shallow inundation across wide regions (Asano, 1985). Spreader canals and level-silled channels can create a uniform, thin-sheet flow. Due to the buildup of particles, flooded regions might be transformed into agricultural soil despite the considerable rise in evaporation (van Steenbergen et al., 2011).

The main parameter have been used to select MAR suitable sites in Wadi Araba; rainfall, slope, soil texture, hydrogeology, land use, and depth to water level. The primary factors include the presence of an appropriate aquifer with surface storage space, the accessibility to surface water resources, the potential for harvesting water to infiltrate the aquifer, and more general factors like geography, depth to water level, and land use.

All maps utilize the same coordinate system, which is Palestine Belt 1923[9] (PB), a Transverse Mercator projection based on the Clarke 1880 (Benoit) spheroid.

3.5.1 Collected Data Assessment and Classification

To facilitate further research, all vector shape files from different layers were transformed into raster format using a conversion programme, it is required to integrate the maps that have been created after giving these maps weights and ranks in accordance with their influence on artificial groundwater recharge in order to create a MAR zone map. (Allafta et al., 2020; Awawdeh et al., 2014; El-Naqa et al., 2010; Elewa & Qaddah, 2011).

3.5.2 Thematic Map Overlay

Numerous studies of MAR suitability or site selection for water collecting systems based on GIS and remote sensing have been published.

Different thematic maps were made and overlaid according on the scale and data availability. While other studies focused primarily on aquifer characteristics, several studies also considered the distance between supply and demand or the availability of source water. For each parameter, most studies utilise 2 to 4 classes. It is also possible to establish a rating for a parameter using linear or other functions (Rahman, 2011). Some research did not use weights; they simply performed a qualitative overlay. The importance of the major and supporting criteria could also be considered when weighing, as shown in Table 3.1.

Table 3.1: Selected references using GIS/remote sensing for assessment.

	reference / parameter	(Alraggad & Mohammad, 2010) Jordan	(Rapp, 2008) (Jordan)	(Al-Adamat et al., 2010) (Jordan)	(Ghayoumian et al., 2007)(Iran)	(Jasrotia et al., 2007)(India)	(Kallali et al., 2007) (Tunisia)	(Mukhopadhyay & Fadlelmawla, 2009)	(Rahman, 2011) (Portugal)	(Steinel et al., 2016) (Jrdan)	this study (Jordan)
no of classes for each parameter	slope	2	2	4	4	6	2		L	3	3
	land use/cover	3	2		2	8			2	3	3
	geomorphology					8					
	superficial deposits	2	2							3	3
	soil texture			4		6	2			6	
	infiltration rate				4	9			L		
	aquifer type/lithology	2	3			8	2			3	3
	aquifer thickness								L	3	
	aquifer permeability					9					
	aquifer storativity					8					
	aquifer transmissivity					8		2			
	aquifer specific capacity					8					
	depth to water table				4	5	2	3	L	3	4
	flow gradient							2		3	
	residence time								4		
	gw salinity				4		2	2	L	3	
	gw contamination								L	3	
	rainfall			4						3	5
	distance from supply	2	2	4			2			3	
	distance from faults	2		2						2	
	distance to urban areas			4			2			2	
	distance to roads			4				2		3	
	distance to wells			2						3	
	distance to int. borders			2						2	

The yearly average rainfall, hydrological parameters, local geology, slopes, and soil type all influence groundwater recharge. An increase in rainfall raises the level of the groundwater (Igboekwe & Ruth, 2011). Even though various studies have employed GIS-based multi-criteria decision analysis GIS-MCDA for the selection of MAR sites, there is no consensus on the criteria, weights, or procedures to be used. Many different classification and weighting methods exist. This can be related to the availability of data, regional features, expert judgement, and the wording of the problem (Chowdhury et al., 2010; Government of India, 2007; Russo et al., 2015), Only water that is gathered that would otherwise evaporate or run off unused without being sufficiently recharged to an aquifer is useful for MAR. Climate change should be considered in the feasibility evaluation since it may have a substantial impact on the availability of source water. (Steinel et al., 2016).

3.6 Groundwater Modeling

In challenging natural field scenarios, the process of abstraction and simplification allows us to create models that can be applied interpretively to gain insights into the factors governing specific site-specific situations. These models act as organizing and compiling frameworks for field data collection and the development of system dynamics theories. By substantially modeling the relationships between inputs and outputs, they provide a simplified approximation of the actual groundwater system. A set of presumptions defining our comprehension of the natural system and its behaviour are used to create this simplification. (Al Mahamid, 2005).

The key advantages of modeling include enhancing our understanding of how various simultaneous processes and impacts interact, identifying current issues and potential solutions to minimize them, and offering different approaches for addressing challenges. Once it has been determined that a numerical model, such as Modflow, is required and the goals of the modeling exercise have been clearly stated, the process of model creation and implementation normally starts. The modeling process includes a number of steps, such as conceptual model development, code selection, model design, calibration, verification, sensitivity analysis, and prediction. These steps collectively contribute to a comprehensive and rigorous modeling process, facilitating a better understanding of complex hydrogeological systems and guiding informed decision-making in water resource management.

3.6.1 Conceptual Modeling

An illustration of the groundwater flow system, often in the form of a cross section or block diagram, is known as a conceptual groundwater model. It organizes the field data and makes the field problem simpler in order to choose the grid's dimensions and configuration. It is made up of several hypotheses that lessen the complexity of the actual system while still meeting the model's goals.

3.6.2 Modeling Software

The Groundwater Mathematical (Numerical) Model consists of 'n' differential equations representing groundwater flow and 'n' unknowns. To solve this system of equations, software such as Visual MODFLOW Flex is employed, which facilitates the numerical solution of these equations. In the specific study, a finite difference model was adopted, where the original differential equations are approximated by finite differences, and numerical techniques are used to solve them.

The well-known finite difference model MODFLOW, created by the United States Geological Survey (USGS), was used for the groundwater mathematical model of the Wadi Araba Basin. Since the equation for groundwater flow relates to the center of each block or cell in the modeling area, MODFLOW is a member of the group of block-centered models. (M. G. McDonald & Harbaugh, 1988). The research area's groundwater flow dynamics are accurately represented and calculated due to this decision. Six significant versions of the main MODFLOW version have been made: MODFLOW-84, MODFLOW-88, MODFLOW-96, MODFLOW-2000, MODFLOW-2005, and MODFLOW 6. The MODFLOW-84, MODFLOW-88, and MODFLOW-96 groundwater flow models were initially created with the goal of replicating particular features of groundwater systems utilizing modular programming units known as "Packages." These packages, like the Well Package and River Package, made it possible to simulate different groundwater flow system components. With the introduction of MODFLOW-2000, the modular structure of MODFLOW was enhanced by the addition of "Processes." Processes are collections of underlying packages that express large equations or sets of linked equations. The primary method for resolving the groundwater-flow equation is now known as the groundwater flow (GWF) procedure. Although more processes have been created for MODFLOW, the GWF Process is still crucial since it serves as the basis for other MODFLOW simulation capabilities.

MODFLOW-2005 introduced changes primarily related to internal data management compared to MODFLOW-2000. It refined the approach used for managing internal data within the code. The MODFLOW system is able to handle new models and their interactions because of a new framework introduced in MODFLOW 6, on the other hand. The capability of MODFLOW 6 to solve many tightly connected numerical models in a single system of equations is one of its important features. The types of these models can be the same or different. A considerable improvement, MODFLOW 6 is an entirely new version of the MODFLOW software. Throughout the various releases, MODFLOW has evolved, incorporating new functionalities, and expanding its capabilities to address the complexities of groundwater modeling.

3.6.3 Model Design

Block-centered and mesh-centered finite difference grids are the two main categories. Flux boundaries in mesh-centered grids coincide with nodes, as opposed to flux boundaries in block-centered grids, which are found at the borders of the blocks. The Modflow Processing Visual The block-centered finite difference methodology serves as the foundation of Flex. According to this method, the aquifer system is represented as a discretized domain made up of a collection of nodes and associated cells, also known as finite difference blocks. All numerical model calculations are built on the nodal grid. The thickness of each model cell and the hydrostratigraphic units are defined using the geometry and features of the model, such as layers, rows, and columns (M. P. Anderson et al., 1992).

By employing this block-centered finite difference technique, the Processing Visual Modflow Flex provides a robust framework for simulating groundwater flow and analyzing aquifer systems, facilitating accurate and efficient numerical model calculations.

3.6.4 Boundary Conditions

An important step in the creation of a model is the choice of the boundary conditions. They must be defined accurately because they significantly affect the model's results in every way. They describe the conditions, i.e., how the considered domain interacts with its surroundings, such as known water fluxes or known values of state variables, like piezometric head. The steady state is influenced by the boundary conditions to achieve the initial condition and the temporary solution, for instance, when the impacts of the cone of depression during the transient stress strike the boundary condition. To accurately simulate the Managed Aquifer Recharge (MAR) model, a drainage gallery within the (Recharge Package) was selected based on GIS analysis. The gallery was strategically positioned in an area with higher hydraulic conductivity to facilitate the efficient infiltration of rainwater. This approach ensures that water can easily penetrate the subsurface layers, optimizing the effectiveness of the MAR system. To accurately simulate the Managed Aquifer Recharge (MAR) model, a drainage gallery within the Recharge package was selected based on GIS analysis. The gallery was strategically positioned in an area with higher hydraulic conductivity and a rainfall rate exceeding 75mm. This ensures efficient infiltration of rainwater into the subsurface layers, optimizing the effectiveness of the MAR system. By considering both the hydraulic properties of the site and the rainfall characteristics, the chosen location facilitates the successful replenishment of the aquifer through enhanced water infiltration.

3.6.5 Assigning Parameter Values

Generally, the model can be assigned to two types of data: Physical framework that determines the system's geometry, including topographic contour lines, formation-specific structure contour lines, and the geographic range of each hydrostratigraphic unit. As opposed to this, hydrogeological factors such water levels, hydraulic conductivity, transmissivity, specific yield, etc.

3.6.6 Steady State Model

By comparing the observed piezometric heads of the alluvium aquifer with the calculated hydraulic heads, the output heads of the steady state simulation were used as the initial head condition for the transient flow model to calibrate the model at steady state.

3.6.7 Transient State Model

Both the calculated initial water levels and the calibrated hydraulic parameters from the steady state calibration were used for the long-term simulation of the transient flow. This method guarantees that the initial circumstances of the model appropriately reflect the state of the groundwater system presently.

The transient simulations were conducted to obtain the current drawdown levels, providing insights into the existing conditions of the aquifer system. Additionally, these simulations were employed to make predictions about the hydraulic system's response over time to changes in storage and drawdown levels.

By running these transient simulations, the model can forecast how the groundwater levels will evolve and how the hydraulic system will react to variations in storage and drawdown levels in the future. This allows for the assessment of potential impacts and the development of informed management strategies for sustainable groundwater resource utilization.

3.6.8 Model Prediction

In the context of sustainability and future water resource management, additional model runs were performed to simulate the period of abstraction from 2020 to 2050. Two scenarios were considered, based on the IPCC report, which projected a potential decline in yearly precipitation. The two scenarios represented a 10% and 30% reduction in rainfall compared to current levels.

By applying these scenarios, the model was able to forecast the potential impacts of these changes on the aquifer system and groundwater levels over the next 30 years. This information is crucial for developing sustainable water usage strategies and ensuring the effective management of water resources in the region.

These scenarios not only aid in understanding the potential challenges posed by changing climatic conditions but also provide valuable insights and alternative approaches for future projects. By exploring different scenarios, decision-makers can evaluate the effectiveness of various management strategies, allowing for informed planning and decision-making to safeguard the availability and sustainability of water resources in the Wadi Araba Basin.

3.6.9 Sensitivity Analysis

A thorough sensitivity analysis was undertaken to examine the impact of important parameters on the study's results in order to fully analyze the robustness and trustworthiness of the research findings. The sensitivity study specifically sought to investigate the effects of recharge, a crucial factor in groundwater systems, on the dynamics of the water table.

Through systematic manipulation of Recharge values within predefined ranges, the sensitivity analysis probed the response of the groundwater model to variations in Recharge inputs. By observing the resulting changes in the water table, valuable insights were gained into the sensitivity and responsiveness of the aquifer system to alterations in Recharge rates. This meticulous examination shed light on the significance of recharge as a driving factor in shaping the behaviour of the groundwater system.

The outcomes of the sensitivity analysis unequivocally indicated a pronounced association between recharge and the water table dynamics. Noteworthy fluctuations in the water table were directly attributable to variations in recharge values, thus affirming the substantial influence of recharge on the overall stability and level of the groundwater system. These findings underscore the crucial role of recharge in groundwater management and underscore the necessity of accurately estimating and predicting recharge rates for effective resource planning.

By elucidating the connection between recharge and the water table in the groundwater system, the implications of this analysis are manifold. Firstly, it emphasizes the paramount importance of comprehending the sensitivity of the groundwater model to pivotal parameters. Particularly, the sensitivity of the aquifer system to changes in recharge underscores the need for meticulous estimation and monitoring of recharge rates to ensure sustainable and judicious groundwater resource management.

Moreover, the insights derived from this comprehensive sensitivity analysis hold considerable significance for decision-making processes associated with groundwater management. By recognizing the profound influence of recharge on the water table, stakeholders can formulate informed strategies and implement measures to mitigate the potential ramifications of climate change or other factors affecting recharge dynamics.

This enhanced understanding facilitates the development and implementation of sustainable groundwater management practices that safeguard the long-term availability and quality of this vital resource.

In summary, the focused sensitivity analysis about recharge contributes a nuanced comprehension of the intricate interplay between this fundamental parameter and the water table dynamics in the groundwater system. By interlinking these findings with the broader sensitivity analysis discussed previously, the salience of considering recharge as a critical factor in groundwater modeling and management is further underscored. The profound insights gained from this rigorous analysis augment the overall robustness and reliability of the research outcomes, advancing our understanding of the complex hydrological dynamics governing groundwater systems.

CHAPTER 4: STUDY AREA

4.1 Location

Located in the Middle East, the Hashemite Kingdom of Jordan shares borders with Syria to the north, Saudi Arabia to the east and southeast, the West Bank and Israel to the west, and Iraq to the northeast. It is located west of Asia. It is organized into twelve governorates administratively and is ruled by a constitutional monarchy with a representative government. Jordan has a surface area of 88,778 km^2 and is known for its sparse natural resources, large elevation differences, and varied geography, particularly between the plateaus and the Dead Sea region. Four main physiographic zones are created as a result of these variations: the rift valley, the plains, the highlands, and the desert, which makes up three-quarters of the country's geographical area (Ababsa et al., 2014). Jordan's climate varies from semi-arid in the northwest to dry desert in the east and south (Hadadin, 2015), with summertime highs of up to 45 °C and wintertime lows of only a few degrees above zero (Howari & Ghrefat, 2011; Myszograj & Qteishat, 2011).

Wadi Araba is located in the southern part of the Jordan Valley extent from the Gulf of Aqaba in the south, and to the south of Dead Sea, it includes the northern and southern Wadi Araba basins. Geographically, is located between 29º 5´ to 31º 00 N latitude and 35º 25´ to 35º ´35 E longitudes (Garfunkel et al., 1981). Surface drainage of Wadi Araba's northern section flows northward, toward the Dead Sea, as opposed to its southern section, where it flows southward, toward the Red Sea. As a result, two sub-basins are identified: both the Northern and Southern Wadi Araba Basins (El-Naqa & Al Adas, 2019), as shown in Figure 4.1.

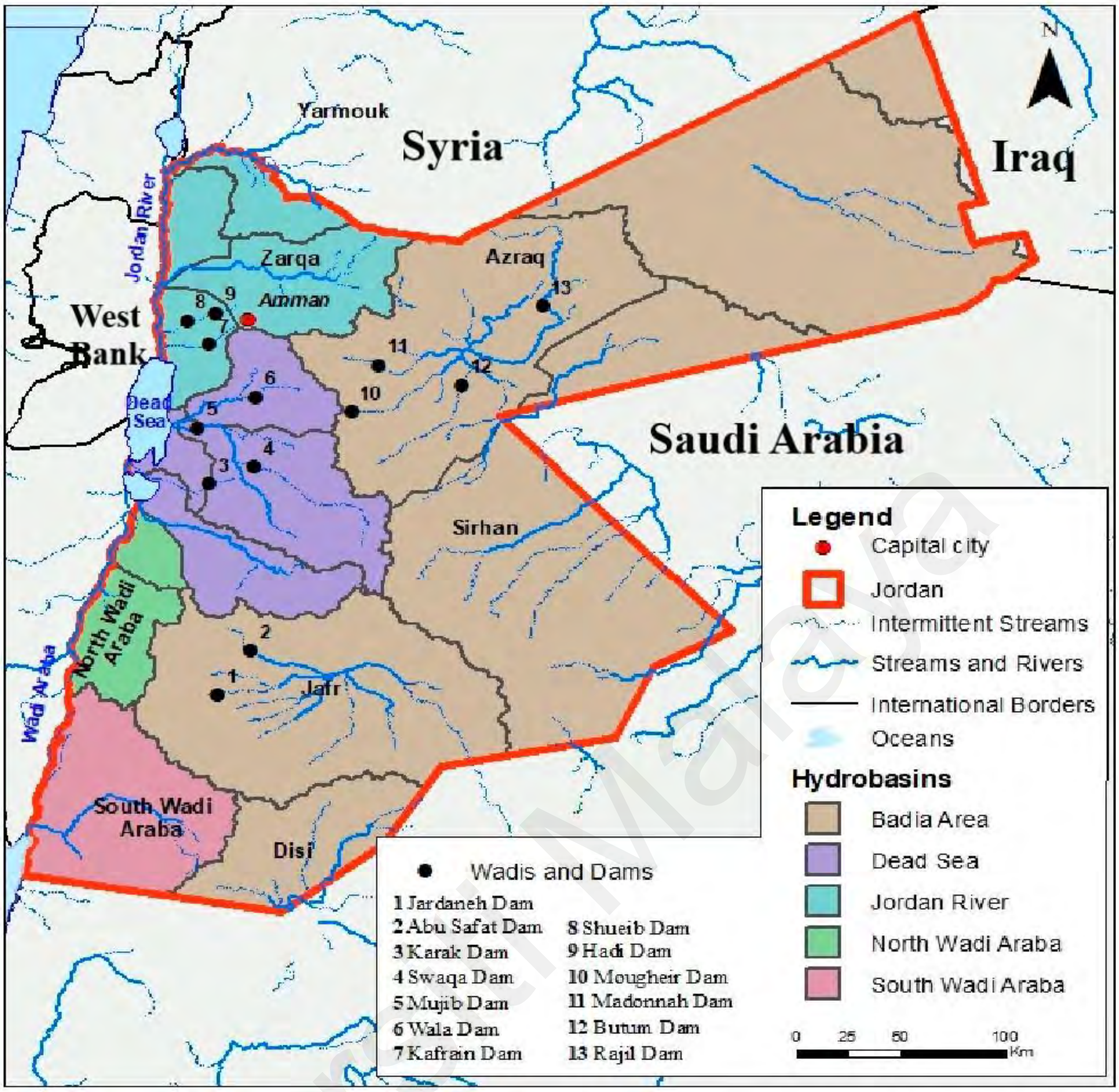


Figure 4.1: Study area location map

4.2 Topography

The geography in Jordan is very diverse, especially in the western region where mountains meet the Jordan Valley. The Jordan Valley, the Mountains Heights Plateau, and the Eastern Deserter Badi are the three geographical divisions of Jordan. (Water Yearbook Hydrological Year 2016–2017.) The Wadi Araba floor climbs gradually from the Gulf of Aqaba to an elevation of about 200 m (amsl) at Jabal Al Risha, which is located in the centre of the west margin of the Basin. After there, the ground drops gently, 300(bsl) metres northward to the Dead Sea Lake's surface. While the altitude quickly increases to roughly 1700 m (asl) in the western edges, forming a steep slope and craggy slopes, as shown in Figure 4.2.

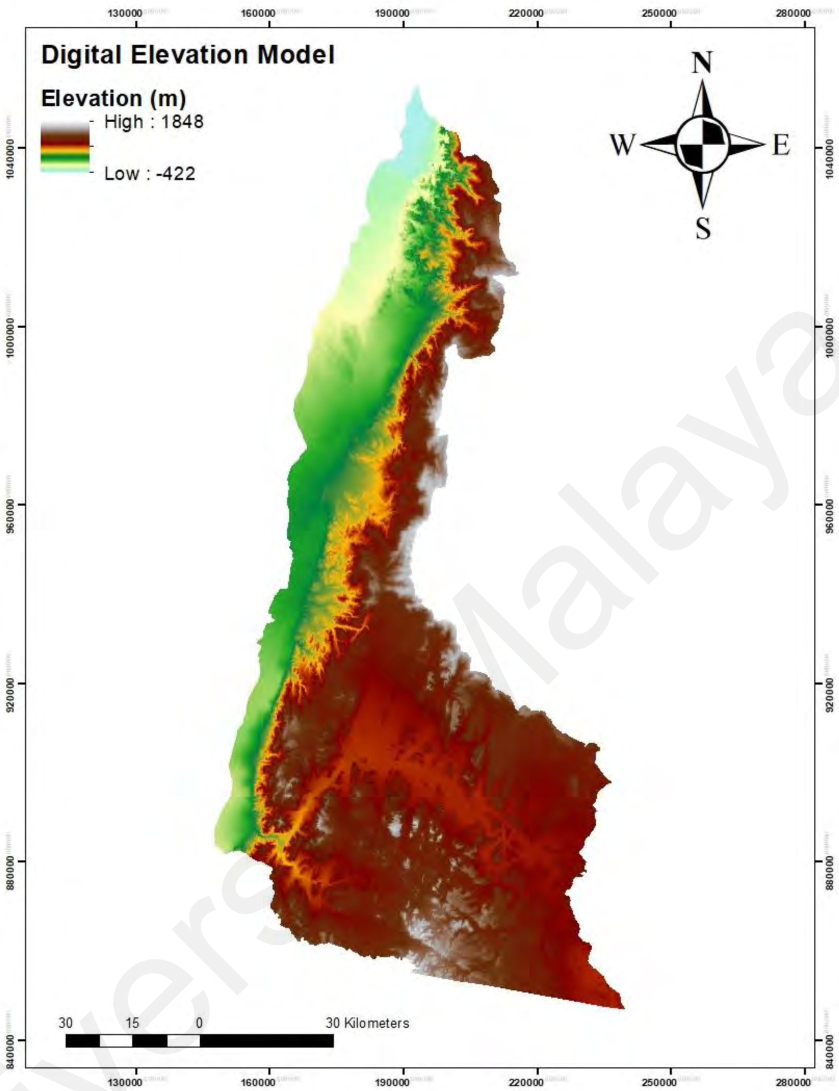


Figure 4.2: Wadi Araba surface basin digital elevation model

The floor of the Wadi Araba rises gradually from the Gulf of Aqaba to an altitude of about 200 m (amsl) at Jabal Al Risha central of the west margin of the Basin. At roughly 300 meters above sea level (bsl), the floor then gently slopes northward to the Dead Sea Lake's surface. Wadi Araba has a slope that runs from 0% to 82.5%, with a steeper slope in the northeast and a lower slope in the western and northeast area. This contrasts with the western boundaries, where the height increases quickly to around 1700m (asl) and forms steep slopes and rough flanks, as shown in Figure 4.3.

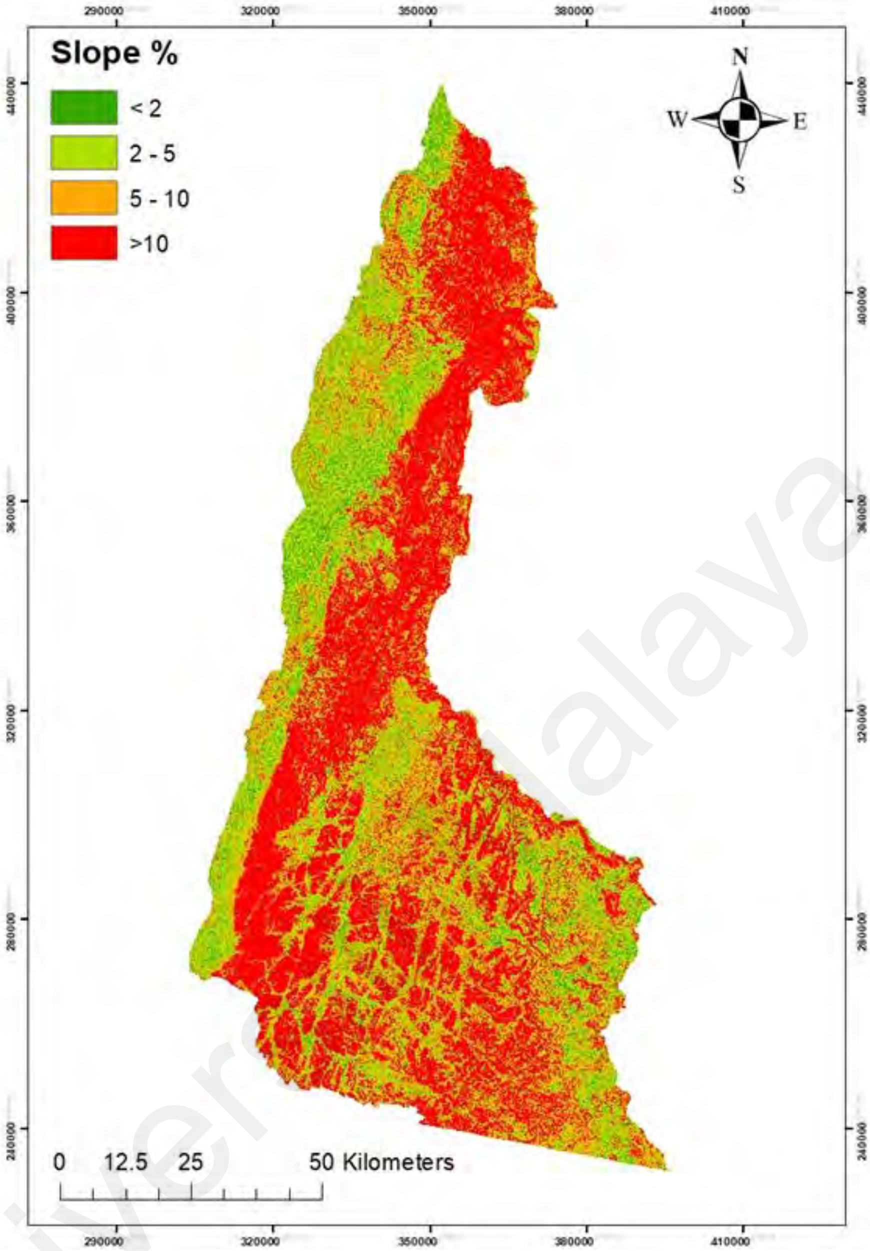


Figure 4.3: Wadi Araba slope map

The generation and velocity of runoff are influenced by the slope. The catchment prefers slopes that are moderate. If the slopes are too steep, there is a risk of erosion and an increase in sediment load. If the slope is too low, water will pool in shallow depressions rather than generate runoff.

4.3 Climate

Jordan is situated in a region of the world with a semi-arid climate, with the exception of the highlands, which have a Mediterranean climate. The Jordan Rift Valley experiences summertime temperatures that can reach 45 °C, with an average of 35 °C. 24 °C is the average yearly temperature. In the winter, the temperature in this area rises a few degrees above zero. Frost is uncommon, but it does occasionally occur. The highlands have a moderate climate, with hot, dry summers that reach 35 °C at noon with a relative humidity of 15–30%, and cold, rainy winters that dip to a few degrees below zero at night. Temperatures frequently fall below 20 °C at night during the summer, which causes dew to form. The eastern and southern parts experience scorching summers and chilly winters, with summertime highs exceeding 40 °C and wintertime lows just a few degrees below zero, particularly at night. Normal relative humidity levels range from 50 to 60 % in the winter and from 15 to 30 % in the summer. For the bulk of the year, the relatively low humidity makes the sweltering summer days more tolerable and the very cold winter days harsher. (Salamah & Helen, 1993; Salameh, 1996; DOM, 2017).

Snowfall occurs only once or twice a year in Jordan, especially in the highlands, and precipitation there is mostly in the form of rain. The rainy season lasts from October to April, with January and February seeing the heaviest rainfall. The intensity of the precipitation decreases with decreasing rainfall in a given location. The highest annual average precipitation totals, respectively 600, 550, 350, and 300 mm, are found in the highlands of Ajlun, Balqa, Karak, and Shoubak. To the east and even more so to the west of the highlands, precipitation decreases sharply. For instance, from 300 mm/year in Shoubak to 50 mm/year around 30 km to the east in the Jafr area, the easterly reduction is less than the westward decrease. (DOM, 2017).

Precipitation in Jordan is generally stated as follows:

- Jordan's areas experience 7200 MCM of precipitation annually on average, with rainy years reaching 12,000 MCM and dry years only 6000 MCM.
- About 1.3 % of Jordan's land area receives more than 500 mm of precipitation annually, 1.8 % between 300 and 500 mm, 3.8 % between 200 and 300 mm, 12.5

% between 100 and 200 mm, and the remaining areas receive less than 100 mm/year. (MWI, 2017) as shown in Figure 4.4.

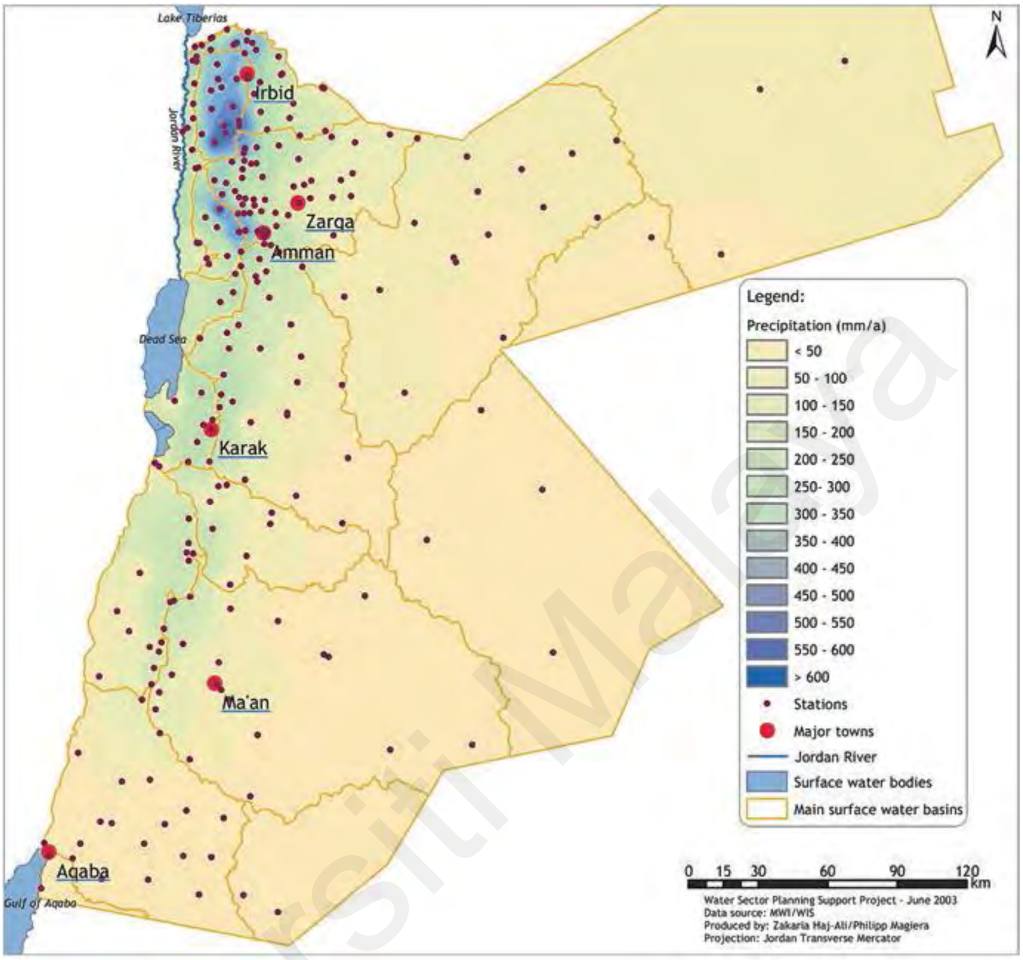


Figure 4.4: Rainfall stations in Jordan with average amount of precipitation (MWI, 2017)

Within the Wadi Araba basin, there are a total of 26 rainfall stations. However, only 13 of these stations have nearly complete records spanning 40 years from 1980 to 2020. In accordance with the topography, the distribution of precipitation exhibits a pattern where the highest rainfall, exceeding 250 mm, occurs in the eastern mountains. As we move towards the southwestern desert region, the precipitation gradually diminishes, reaching approximately 50 mm. This variation in rainfall is closely linked to the geographical features of the area. Most of southern part of Wadi Araba has less than 100mm/y rainfall, in the northern part especially on the highlands can reach over 250mm/y. In general, the amount of precipitation in northern basin of Wadi Araba are greater than in southern basin as shown in Figure 4.5.

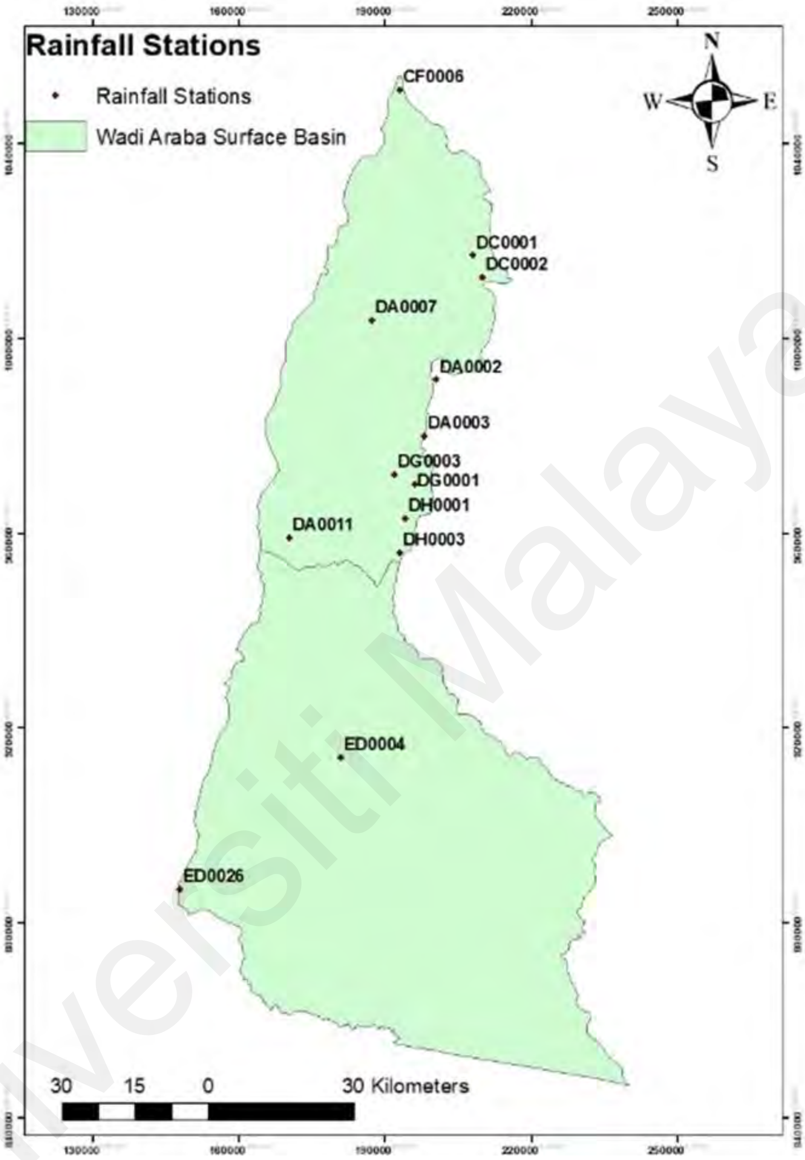


Figure 4.5: Study area rainfall stations

Annual variations are large shown in Figure 4.6. For example, some stations in Wadi Araba basin record 0- less than 50mm/y for some years and more than 500 mm in others, which their location and altitude play essential role on rainfall amount.

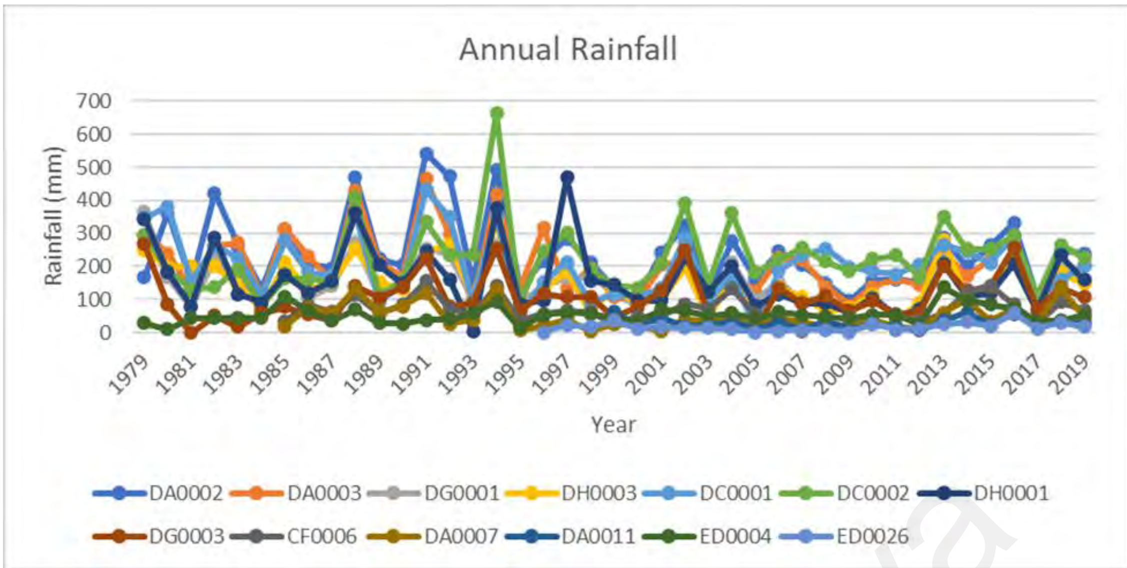
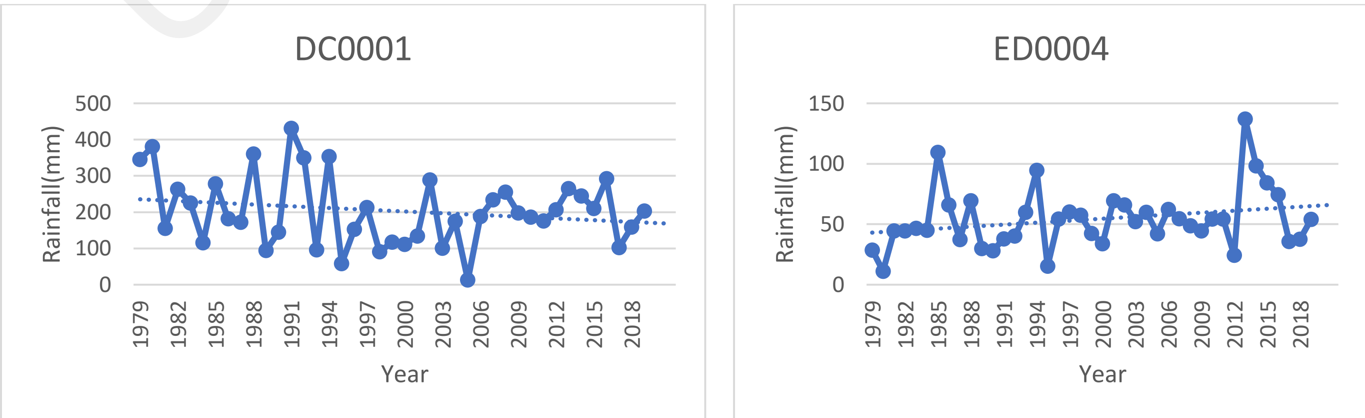


Figure 4.6: Rainfall distribution in Wadi Araba 1979 to 2019 arranged after (MWI-WIS, 2019)

For the Middle East, regional and global climate models predict a significant decrease in rainfall (Kunstmann et al., 2007; Zereini & Hötzl, 2008), while downscaled regional climate models also predict a decline in rainfall due to a decline in rainfall events through cyclones (Black et al., 2011). Because groundwater recharge will be reduced by up to 30% in most locations due to climate change, Jordan may see substantial effects(Margane et al., 2009; Alwreikat & Lananan, 2022). Rainfall has been observed to be decreasing for the Wadi Araba basin (MWI, 2017).

For many sites, long-term trends (1979–2019 data) show a decline in yearly rainfall. Nevertheless, some stations exhibit an increase in rainfall, as shown in Figure 4.7.



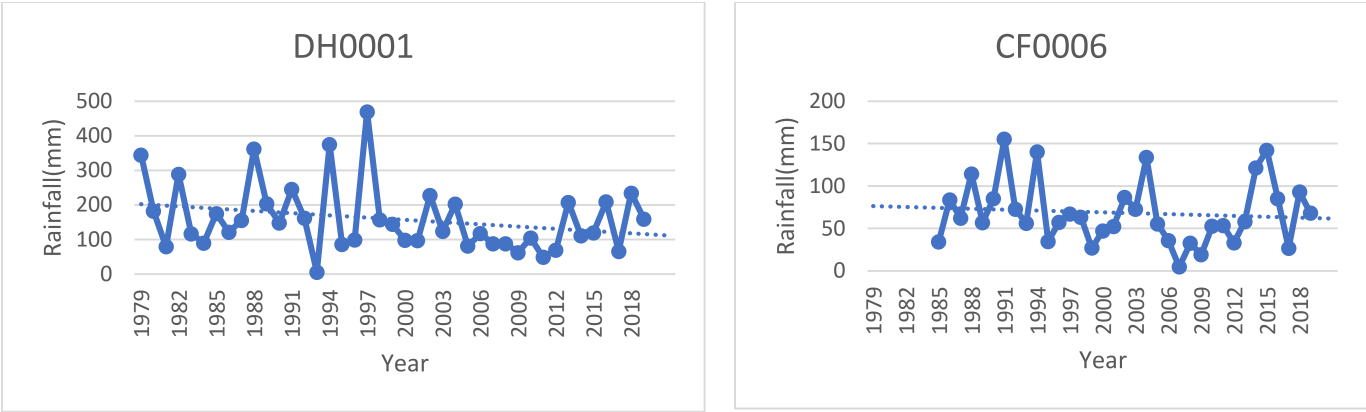


Figure 4.7: Annual variations in precipitation for selected stations (MWI-WIS, 2019)

The distribution of rainfall over a year reveals a rise in precipitation from October to January or February, followed by a drop until May and a period of no precipitation from June to September, with the majority of precipitation falling between December and March. High rainfall regions—particularly the highland ridge to the east of the study area—experience recharge. Groundwater recharge is highly dependent on precipitation. The most important factors for groundwater recharge are the frequency and quantity of storms with rainfall. Direct recharge is negligible in regions with precipitation of 200 mm (Lloyd, 1986). The MAR catchment should generate enough runoff, which is determined primarily by catchment size and rainfall volume. Catchments in areas with rainfall of less than 50 mm can be ignored (Al-Kharabsheh, 1995). The study area's rainfall map was created using data from 13 rainfall stations along Wadi Araba from 1979 to 2019 a map displaying the distribution of rainfall in a particular area was created by estimating the values of average annual rainfall at different locations using the kriging method of spatial interpolation, as shown in Figure.4.8

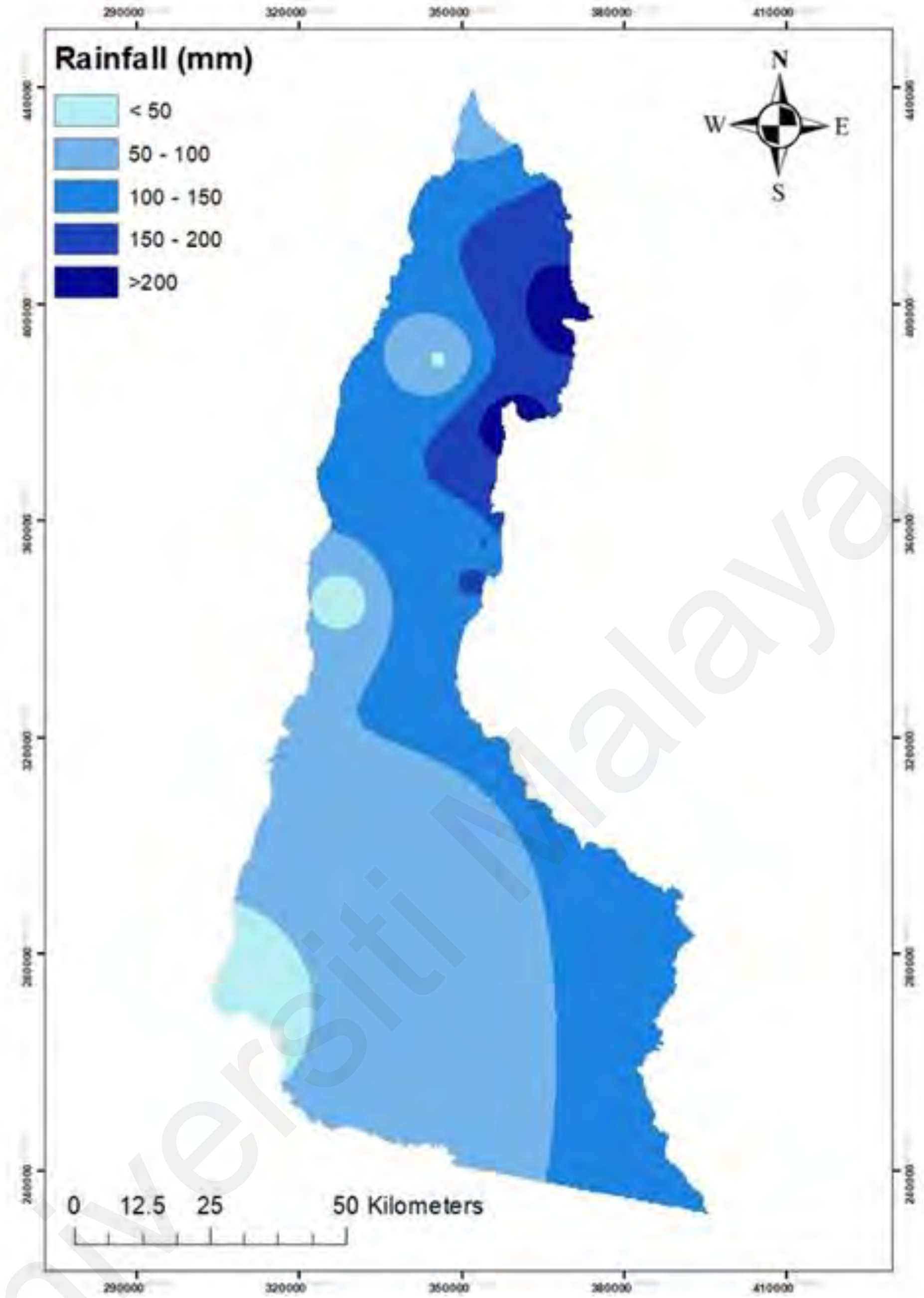


Figure 4.8: Wadi Araba rainfall map

Rainfall is one of the key factors that influence groundwater recharge. In the western parts, when the elevation descends to -400m below MSL, the long-term average annual precipitation ranges from 50mm to 250mm.

As precipitation infiltration is critical for replenishing the aquifers within the Wadi Araba Basin, it is essential to create a clear relationship between rainfall and infiltration in order to run the groundwater model successfully. The amount of infiltrating water in the southern section of the basin, where precipitation is less than 75 mm, is low and has little impact on aquifer recharging. (Margane et al., 2002).

It has been determined that the recharge via rainwater infiltration makes up about 4% of the total rainfall in the basin's areas with greater precipitation rates, especially above 75 mm (Margane et al., 2002). Consequently, a significant amount of infiltration contributes to aquifer recharge in the north-eastern region of the Wadi Araba basin, where precipitation is highest. However, as we move towards the west and south, the amount of precipitation gradually decreases, affecting the recharge potential in those areas. Understanding this relationship is crucial for accurate groundwater modeling and management in the Wadi Araba Basin. The Wadi Araba basin has 13 rainfall stations. The mean annual rainfall and recharge rates for each year and each set of outlined contours have been calculated after the time series have been analysed. These numbers have been incorporated into mathematical models as transient recharge data; Thiessen polygons used for rainfall calculations of Wadi Araba groundwater basin as shown in Figure 4.9.

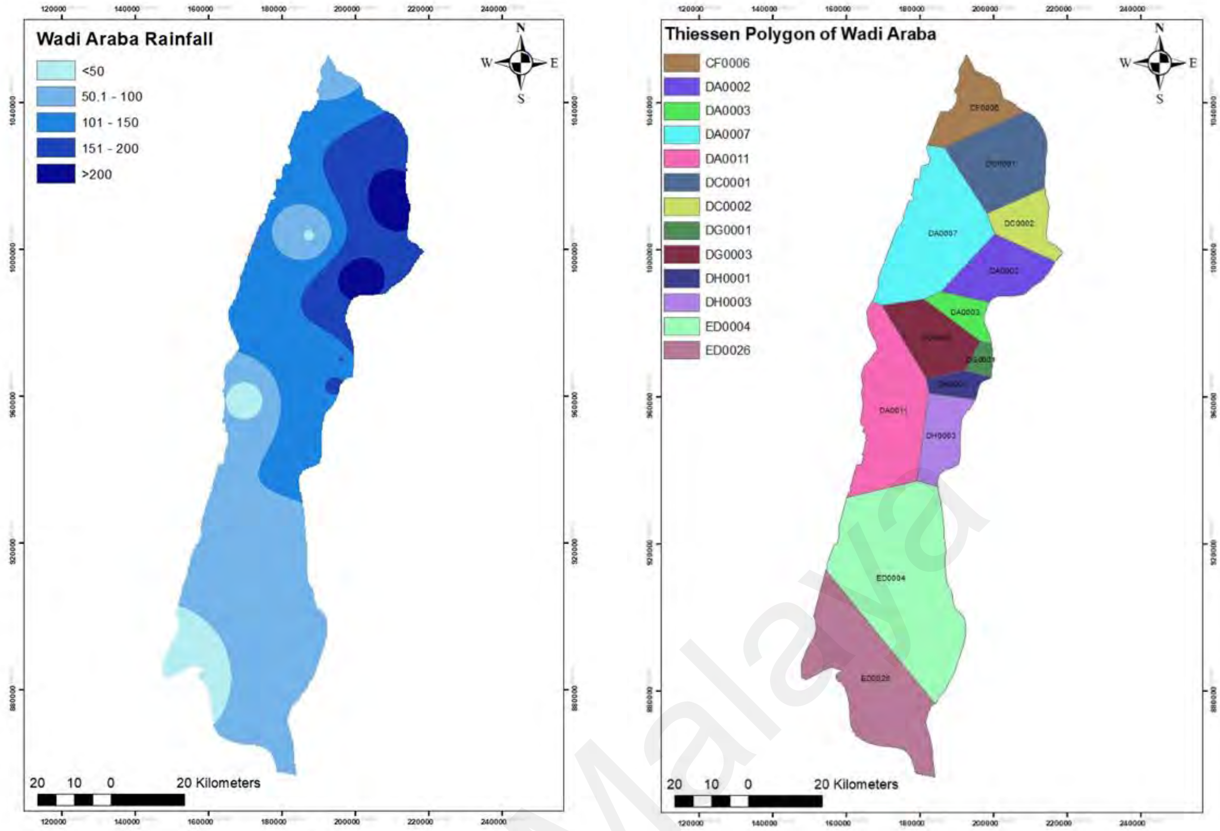


Figure 4.9: Rainfall distribution & Thiessen Polygon of Wadi Araba (MWI-WIS, 2019)

In addition to total annual precipitation, Jordan's semi-arid climate also impacts potential evaporation, which varies from roughly 1600 mm/year in the northern highlands to more than 4000 mm/year in the south-eastern desert portions of the country. Potential evaporation diminishes along the Jordan Rift Valley from a high of 4000 mm/year in the Aqaba region to about 2500 mm/year in the Dead Sea and about 2000 mm/year in the north. Over these regions, the potential evaporation rates might be up to 80 times higher than the annual precipitation average. Due to Jordan's high capacity for evaporation, precipitation is worthless there, especially in the eastern and southern parts of the country where it evaporates almost immediately, depriving the soils of moisture and preventing the growth of plants and other vegetation. The salt concentrations in flood and recharge water tend to increase due to high evaporation rates, limited precipitation, and relatively high salt levels in precipitation water. (DOM, 2017) as shown in Figure 4.10.

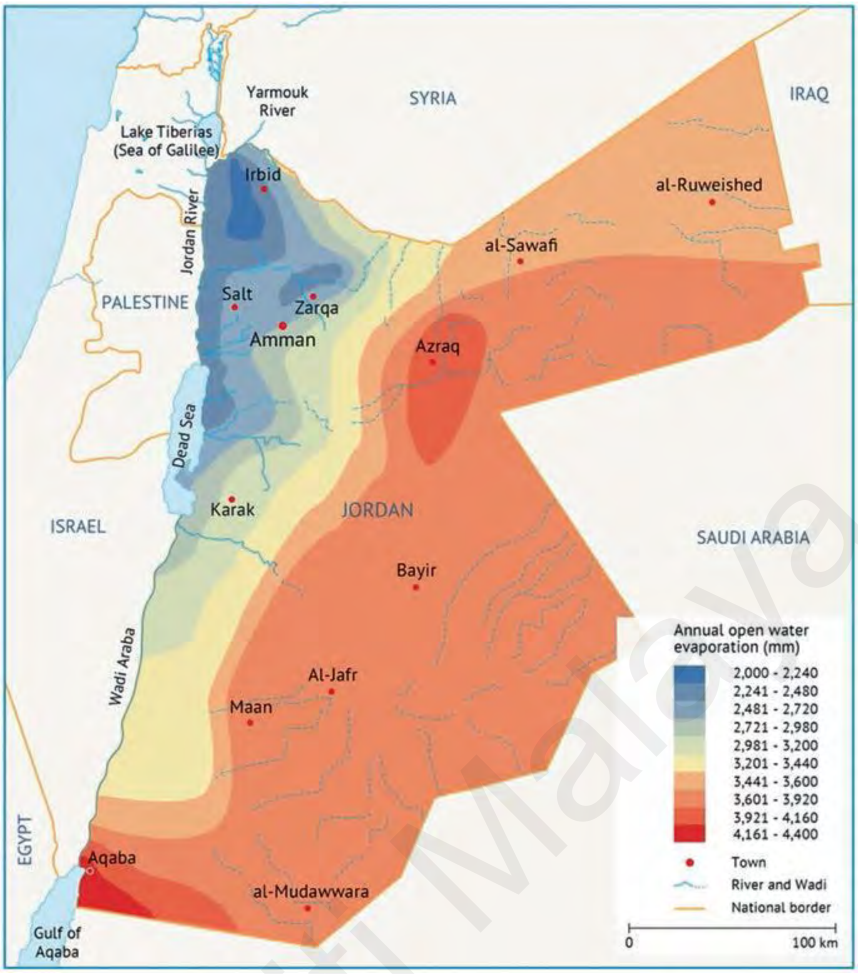


Figure 4.10: Potential annual evaporation in Jordan (DOM, 2017)

4.4 Geology

Wadi Araba runs along the Dead Sea Transform Fault (DSTF) between the Gulf of Aqaba basin in the south and the Dead Sea Basin in the north. According to (Burdon & Quennell, 1959; Bender, 1975), the DSTF began as a rift valley about 25 million years ago. Geological formations were continuous on both sides of the rift valley before the Miocene. The eastern block escarpment's foothills were exposed to an older basement complex and volcanic rocks during the DSTF's formation because the eastern rim was upthrown relative to the western rim. (Bender, 1975). The southernmost sections of the basin had the oldest rocks. In the northern and central regions, rocks from the Mesozoic and Cainozoic eras are exposed in varied thicknesses. The sequence outcropping of these formations and the topography of the region have both been influenced by the structural context of the area. as shown in Figure 4.11.

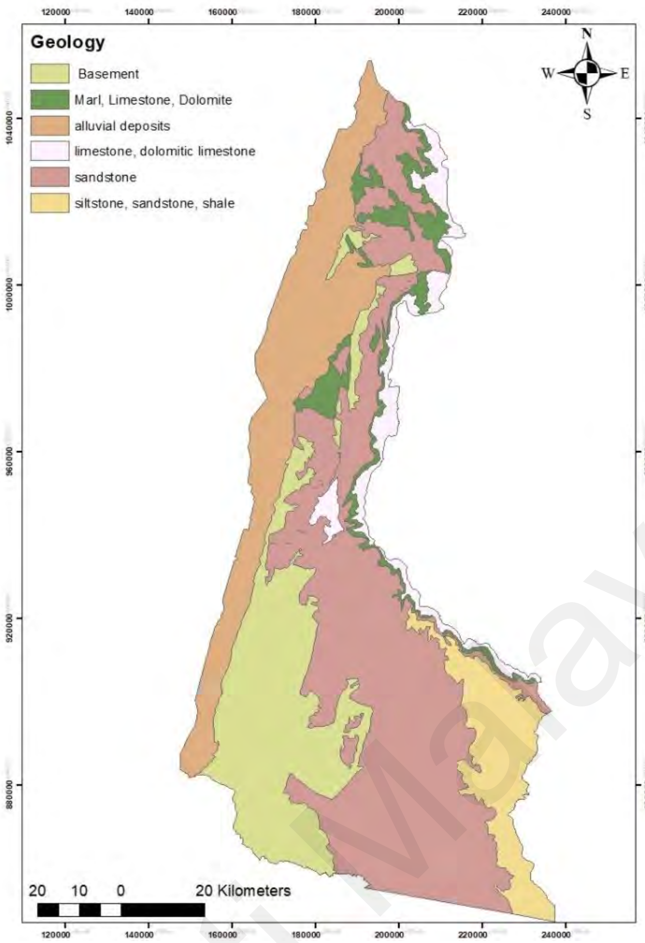


Figure 4.11: Geological Map of Wadi Araba, modified after (NRA, 2002)

I. PRECAMBRIAN BASEMENT COMPLEX

The basement rocks of south and southwest Jordan, which make up the northernmost part of the Arabian Nubian Shield (ANS), have been split into two complexes and are separated from one another by a regional unconformity. Lower Palaeozoic Sandstones are overlain to the north and east of the basement rocks, which are composed primarily of Late Proterozoic meta-volcano sedimentary sequences, plutonic calcalkaline granitoids, andesitic volcanics, andesitic volcanics, and many dykes (McCourt & Ibrahim, 1990; Bandel & Salameh, 2013).

The southern parts of the study area are dominated by Precambrian metamorphic and post-metamorphic plutonic rocks (Aqaba complex). The oldest are migmatites and high-grade metamorphic rock. The former is grey to silver medium to fine grained politic schist and the latter is grey to silver medium to fine grained biotite orthogenesis. The majority of these rocks are granite-biotite, gneiss, biotite-hornblende gneiss, and biotite schist (Bender, 1975; Al khatib, 1987; Rashdan, 1988; Ibrahim, 1991) A thin slip of microgranites and rhyolites from the Araba Complex is extensively exposed in the Quweira area to the north west along the eastern margin of Wadi Araba. Numerous dykes cross-cut the metamorphic and igneous rocks that indicate several phases of activity to the north of the Aqaba Complex (Rabba & Ibrahim, 1988).

II. PALEOZOIC ROCKS; KHREIM AND RAM

The Palaeozoic sedimentary rocks in southern Jordan lie unconformably above late Proterozoic basement rocks. These sediments are well exposed in the southern desert and extend in a southeast direction. The Cambrian, Ordovician, and Silurian sediments form the cycles of fluvial siliciclastic, marine siliciclastic, and marine sediments that make up the sequence of Palaeozoic rocks. These sedimentary cycles offer important insights into the region's geological past and pre-Paleozoic conditions. (Powell, 1989).

Cambrian sedimentary rocks are exposed in a built from the southern end of the country to the Dead Sea on the east side of Wadi Araba. The Khreim Group Aquitard Dubeideb Formation dominates the west southern part of the study area, filling the valleys of a distinct surface cut in the Precambrian basement complex. Conglomerates are absent east of Wadi Araba, where bedded arkosic sandstones from the Ram Group Aquifer (about 200m thickness) rest on peneplated Precambrian rocks. This formation is composed of fine grained sandstone, siltstone, and shale (Bender, 1975; Ibrahim, 1991).

Marine beds crops out above the bedded Arkosic Sandstone along the east side of Wadi Araba between the Dead Sea and Gharandal, according to (Barjous, 1987; Ibrahim, 1991). These marine beds near Gharandal are white, fine-grained sandstone with a thickness of about 110 m. To the south and east, massive brownish weathered sandstone (Disi formation) of about 350 m thickness replaces the lower part. The white fine-grained sandstone lies to the north of these rocks.

On the east side of Wadi Araba, Ordovician Sandstone (Ram) crops out conformably above Cambrian clastic rocks. The Ordovician sequence is more complete in the south because it dips gently east-northeast beneath Cretaceous rocks, which rest on Paleozoic rocks with a slight angular unconformity (Bender, 1975; Barakat, 1986; Abdelhamid, 1988; Rabba & Ibrahim, 1988).

III. MESOZOIC ROCKS

Triassic and Jurassic Rocks do not outcrop in the study area.

- Lower Cretaceous series; Kurnub Sandstone Group (*Kurnub Aquifer*):

140 m of varicoloured silty and marly coarse-to fine grained sandstones with several layers of marine origin (silty, glauconitic marls, locally with some gypsum-presence of Bivalves). The thickness of these marine strata is up to 40m. Varicoloured medium to coarse-grained sandstones alternate with shales, marls, dolomitic marly limestones, and limy sandstones over 100m. The lithological transition from sandstones to dolomitic marls and limestones marks the upper limit of the Lower Cretaceous (Bender, 1975; Beicip, 1981; Tarawneh, 1988; Powell, 1989; Moumani, 1996).

It should be noted that the Lower Cretaceous poorly consolidated sands have good to excellent reservoir characteristics. With a slight angular unconformity, this formation overlies the Um Ishrin sandstone member. It has a thickness of 250 to 280 m. Grey, white, medium to coarse-grained sandstone with planar cross bedding distinguishes the lower part. The upper layer is a variegated medium to coarse-grained sandstone (Powell, 1989; Moumani, 1996).

- Upper Cretaceous and Lower Tertiary Series

Because the Upper Cretaceous is widely outcropping in the area, it can only be considered prospective in limited areas (Dead Sea graben). It does, however, play an important role in the burial of the underlying objectives as a thick overburden. Several authors have described and studied these marine formations (Bender, 1975; Beicip, 1981; Tarawneh, 1988; Powell, 1989; Moumani, 1996;).This series of lithological units From the oldest to the youngest:

Nodular Limestone Member; *Shueib (A5/6)/Hummar (A4)/Fuheis (A3)/Nau'r (A1/2)* Formations; (*A1-A6 Aquitard*)

This formation comprises the northern parts of the Basin of about 175-300m of alternating marls, marly limestones, nodular limestones partly dolomitic limestones. The fauna indicates the age Cenomanian for the whole member formations (Bender, 1975; Beicip, 1981; Tarawneh, 1988; Powell, 1989; Moumani, 1996).

The Echinoidal Limestone Member; *Wadi es Sir Limestone* (*A7 Aquifer*)

This formation can be found on the Basin's eastern and northern margins. It is comprising of thick and thin bedded limestones, dolomitic limestones, and marly limestones with a thickness of up to 300m. The upper part is consisting of massive, thickly bedded limestones with chert concretions. According to the fossil content, the lower third of the Echinoid Limestone is Cenomanian in age, while the upper third ranges from Turonian to Santonian in age formations (Bender, 1975; Beicip, 1981; Tarawneh, 1988; Powell, 1989; Moumani, 1996).

Wadi Umm Ghudran Limestone Member (*B1 Aquitard*)

It is a massive limestone member (60m thick) consists of massive limestones with marl layers of Santonian age (Bender, 1975; Beicip, 1981; Tarawneh, 1988; Powell, 1989; Moumani, 1996).

The Amman Silicified Limestone Member (*B2 Aquifer*)

It is comprising the areas of the Basin. Existing studies showed that it is composed mainly of massive chert beds overlaid by oyster lumachellic limestones, silicified limestones, and silicified phosphorites. This rock unit is assigned to Companian age (Tarawneh, 1988; Powell, 1989; Moumani, 1996).

Al Hisa Phosphorite Member (*B2 Aquifer*)

This formation comprises thick limestones beds, phosphorites bearing oyster lumachelles and phosphate layers. It is considered as Campanian to Maestrichtian in age (Beicip, 1981; Tarawneh, 1988; Powell, 1989; Moumani, 1996)

*The Muwaqar Chalk Mar*l Member (*B3 Aquitard*)

This member is mostly found in the central eastern part of the area that is overlain by the Um Rijam Limestone Member (B4). It is composed of yellowish, grey-green chalk marl with beds of limestone concretions up to several metres thick; some chert layers and thin gypsum bands are intercalated in the chalk marls. This member is Maestrichtian Danian – Lower Paleocene in age. Within short distances, there are large variations in thickness. A thickness of 300m has been observed in the Yarmuk area, and this phenomenon has also been observed in the Azraq depression, which has very rapid variations in thickness. These variations appear to be linked to the presence of Synsedimentary faults. Stratigraphic breaks discovered in the West Bank indicate the presence of tectonic activity during the Campanian and Maestrichtian periods (Beicip, 1981; Tarawneh, 1988; Moumani, 1996).

IV. CENOZOIC ROCKS

- Tertiary Rocks

Thin chert beds and thick horizons of white chalk alternate within the Eocene sedimentary unit to create a sedimentary package that is more than 200 meters thick (Powell, 1989). An obvious erosional unconformity that marks the unit's contact with the underlying Oligocene conglomerates.

The reddish conglomerates, calcarenites, and small amounts of calcilutites that characterize the late Oligocene-Miocene deposits. Four primary cycles, each of which is overlaid on several smaller cycles, are used to organize these sedimentary facies. These sediments have a total thickness of about 250 meters.

These distinct sedimentary layers provide important geological information about the Eocene and late Oligocene-Miocene periods, shedding light on the environmental conditions and geological processes that shaped the region's history. (Abed, 2000).

- *Dana Conglomerates*

This formation is restricted in outcrop in the Shaubak, Karak, and Gharandal areas. These beds form a synformal monocline flextures where the basal sediments resting unconformably on the Umm Rijam with the formation steeply dipping. It consists mainly of a sequence of conglomerates, calcarenites and marls (Barjous, 1987; Ibrahim, 1991).

- Quaternary Sediments

In Jordan, wide areas are covered by Quaternary sediments, which overlie older rocks. These Quaternary sediments consist of poorly sorted fluvial and lacustrine deposits from the Pleistocene epoch. The Rift Valley in Jordan is characterized by the presence of very thick sediment layers.

The Quaternary sediments in Jordan encompass a variety of depositional environments, including lacustrine (lake deposits), alluvial fans, alluvium (river deposits), wadi sediments (deposits from intermittent streams), aeolian sand (windblown sand), sand dunes, mudflats, and soil.

In particular, the Wadi Araba floor and the eastern margins of the study area are extensively covered by these Quaternary sediments. This formation is composed of lisan marls, gravels, gypsum, and sand, with the thickness varying up to 40 meters near the lake.

These diverse sedimentary deposits provide valuable insights into the geological history, climatic conditions, and landscape evolution of the region during the Quaternary period. (Moumani, 1996; Powell, 1989; Tarawneh, 1988).

- Alluviums and Wadi Sediments; Holocene-Recent

It comprises most of the floor of Wadi Araba and consist mainly of wadi sediments, lacustrine, sandy, and fluviatile sediments.

4.5 Structural Setting

The Dead Sea Transform Fault (DSTF), which connects the Dead Sea Basin in the north with the Gulf of Aqaba Basin in the south, goes across the study area, Wadi Araba. The Wadi al Araba-Jordan Rift, which includes this region, is characterized by a complicated structural history that is still not fully understood.

It is crucial to give a comprehensive overview of the structural setting of the Dead Sea Transform Rift, of which the study area is a part, in order to comprehend the complexity of the structural setting of the study area and its impact on groundwater flow. Jordan is geologically unique and is divided from the African Plate by the Dead Sea Transform (DST), which is found in the Arabian Plate's northwest. Jordan's western boundary is formed by the DST, which also significantly influences the country's tectonic environment.

In a thorough structural analysis carried out by (Beicip, 1981), Jordan has two primary geologic units, the Dead Sea Transform Fault (DST) region and the Jordan Platform, each of which has a unique set of structural characteristics. The Jordan Platform is further separated into two parts: the eastern part, which consists of a Plateau Unit, and the western part along the DST, which contains an extended hinge zone along the west borders. The geological subdivisions put out by (Bender, 1975) are consistent with this classification, based on the structural evolution, pattern, and type of deformation, which classified Jordan into four main physiographic structural provinces. The Wadi Araba - Jordan Rift (Dead Sea Transform) is one of these provinces, along with the Nubo-Arabic Shield in southern Jordan, Block Faults in central and southeast Jordan, Up Warping, Tilting, and Block Faulting in northern Jordan, and Anticlinorium, Up Warping, and Block Faulting West of the Jordan River.

The Wadi Araba area has a distinct geological setting as part of a plate boundary in the Arabian Plate's Tertiary to Holocene development. As a result, it has a complex structural setting with NNE-trending wrench faults intersecting NW-trending cross faults that are genetically related to the Red Sea spread centre. Because of the structural interaction of these two trends, a series of horsts and Basin areas form sub-basins within the Jordan Valley Dead Sea Rift. One of the echelon folds along the trend of the NW wrench faults, high standing horsts, is the local structural pattern (NRA, 1989). The Wadi Araba fault, which runs along a valley blanketed in Quaternary sediments, is the fault's southern segment (Le Béon et al., 2012).

The primary fractures linked with the rift trend north-south and are caused by a regime of transgressional stresses that were first oriented east south east-west north west (Burdon & Quennell, 1959; Mikbel & Zacher, 1986) . Over geologic time, this led to a deformation process in the area. (Mikbel & Zacher, 1986). Another studies, such as (Segev et al., 1999), based on geophysical measurements in Timna Valley (22 km north of the Gulf of

Aqaba), confirm a sinistral strike-slip of 105 km, as reported by (Burdon & Quennell, 1959; Garfunkel et al., 1981; Hatcher Jr et al., 1981; Rybakov et al., 1997). As a result of the Rift tectonics, the regional structure of the study area is dominated by vertical to sub-vertical faults with principal direction approximately N-S, E-W, and NESW. Also, it is characterized by folding elements trending NE-SW and faulting comprising the following major fault systems (Rabba & Ibrahim, 1988; Rashdan, 1988), Figure 4.12 illustrates the complicity of study area.

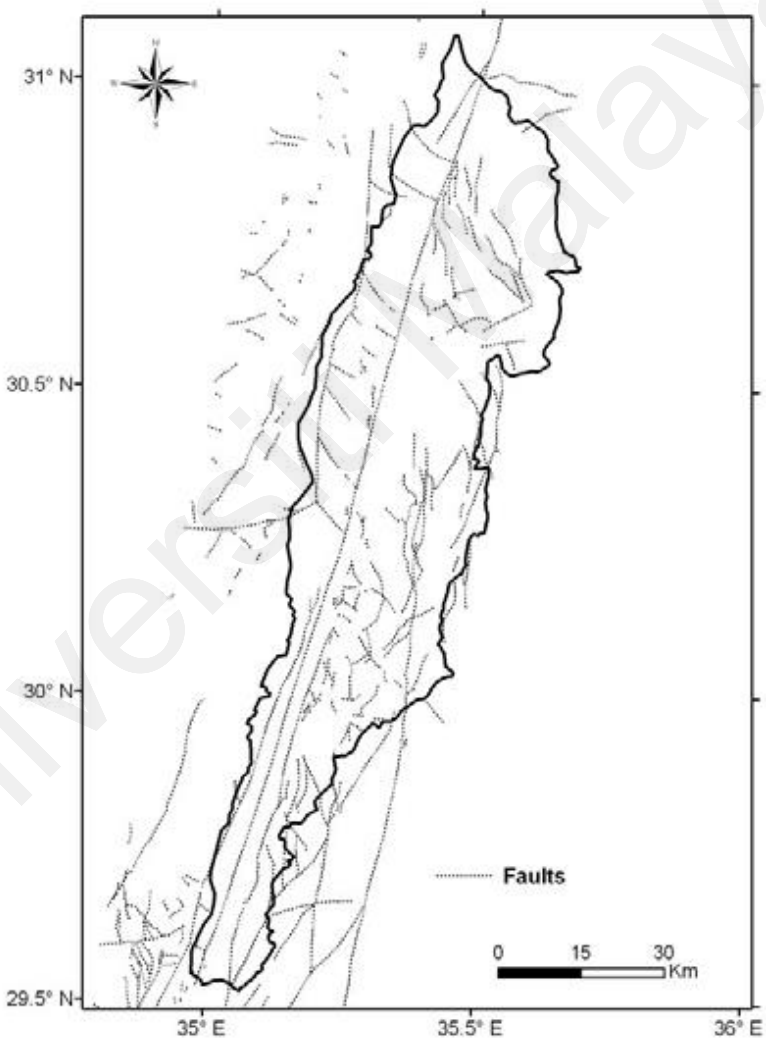


Figure 4.12: Major structural faults in Wadi Araba basin (NRA, 2002).

4.6 Hydrogeology

The Wadi Araba Basin is separated into a northern sub-Basin and a southern sub-Basin; the drainage divide between the two coincides with the groundwater division. It is located about 75 km north-northeast of Aqaba, to the north of Qa' es Sai'diyeen on the western side of Jabal Ar-Risha. The northern sub-Basin flows into the Dead Sea, while the southern one flows into the Gulf of Aqaba (MWI, 2017).The geology of any area is critical to the distribution and occurrence of groundwater. The type of rock exposed at the surface has a significant impact on ground water recharge (Yeh et al., 2016). Table 4.1 shows the lithological description of Wadi Araba. The lithological composition of the aquifer is very heterogeneous, with conglomerates, gravels, sands, silts, and clays in some places mixed, interbedded and/or intercalated.

Table 4-1: Lithostratigraphy and hydrogeological classification of rock units outcropping in Wadi Araba basin, after (MWI, 2017)

period	Age	Group	Formation	Lithology	Aquifer Type
Quaternary	Recent		Fan Talus,Terrace,	Sand ,Clay Gravel	Alluvial Aquifer
	Pleistocene	Jordan Vally	Lisan	Marl,Sand Gypsum,Clay,Gravel	
Tertiary	Pliocene		Undifferentiated	Conglomerate,Marl	
	Miocene				
	Oligocene				
	Eocene	Belqa	Wadi Shallala(B5)	Sandstone	B5 Aquifer
	Paleocene		Umm Rijam(B4)	Chert, limestone	B4 Aquifer
Upper Cretaceous	Mastrichtion		Muaqqar B(3)	Chalk, marl	B3 Aquitard
	Companion		Al Hasa(B2a)	Phosphate Silicified Ls	B2/A7 Aquifer
	Santonion		W.Ghudran(B1)	Chalk,Chlky marl	
	Turonian	Ajlun	Wadi Es SIR(A7)	Limestone	
	Cenomanian		Shueib(A5-6)	Marly Limestone	A1/6 Aquitard
			Hummar(A4)	Dolomitic Ls	
			Fuheis(A3)	Marl	
			Na'ur(A1-2)	Marly Limestone	
Lower Cretaceous	Albian	Kurnub	Kurnub Sandstone	White Sandstone, dol	KB Aquifer
	Aptian			Varicolored Sandstone	
	Neocomian			Lst,Shale,Marl,dol	
Permo-Triassic		Zarqa	Dardur	Sandstone,Marl,Shale	Zarqa (not present in Wadi Araba
			Ma'in	Sandstone,Silts,Clay	
			Umm Irna	Sandstone,Silts,Shale	
Silurian		Khryim	Khushasha	Sandstone,Shale	Kh Aquitard (not present in Wadi Araba)
			Mudawwara	Sandstone,Shale,Mud	
Ordovician			Dubaydib	Sandstone,Shale	
			Hiswa Sandstone	Mudstone,Sandstone	
		Ram	Umm Sahm	Sandstone	Ram Aquifer
			Disi	Sandstone	
Cambrian			Umm Ishrin	Sandstone,Siltstone	
			Burj dolomite	Sandstone,Shale,dol	
			Salib	sandstone,siltstone	
Pre-Cambrian		Safi	Sarmuj Conglomerate	Conglomerate	potential low yeild aquifer is weatherd

The aquifer's lithological character is quite diverse, with conglomerates, gravel, sand, silt, and clays occasionally combined, interbedded, and/or intercalated. In the Wadi Araba region shown in Figure 4.13, the following aquifer systems can be summarized up as follows. from (MWI, 2016).

1. Alluvium Aquifer

2. B2/A7 Aquifer

3. A1-A6

4. Deep Sandstone Aquifer Complex (Kurnub + Ram)

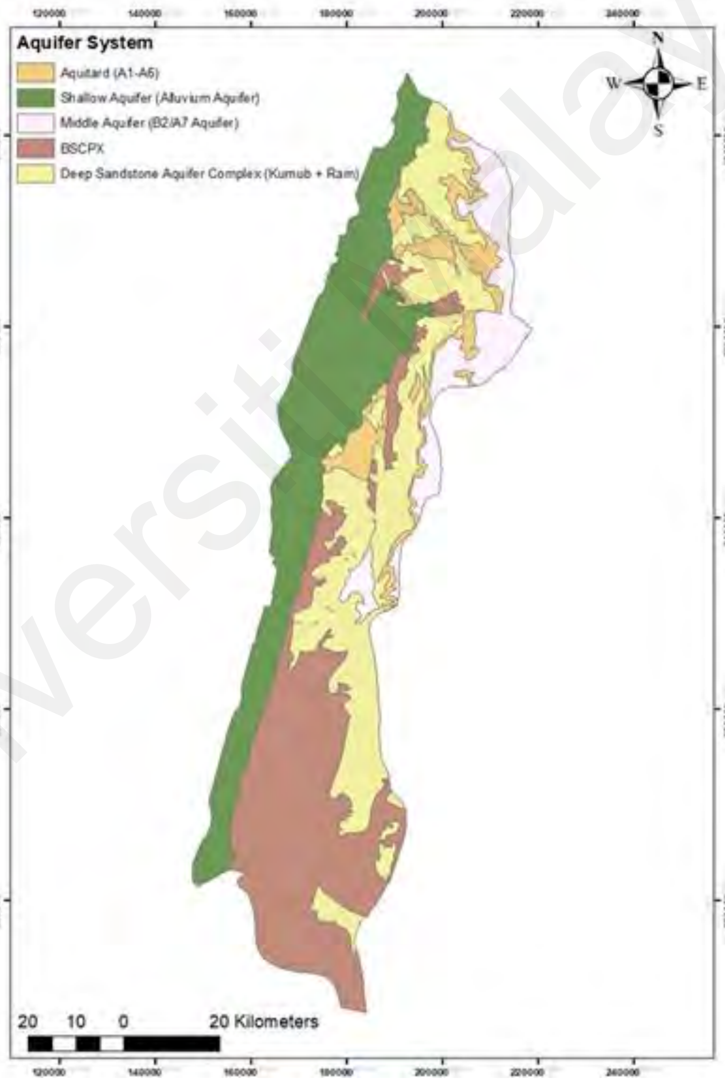


Figure 4.13: Hydrogeological units of Wadi Araba (MWI, 2017)

- Shallow Aquifer (Alluvium Aquifer)

Wadi Araba Valley is covered by the alluvium aquifer, also known as the Shallow Aquifer. The average depth to groundwater level in this aquifer is about 70 metres, and its principal constituents are interbedded sand, gravel, and clay deposits. There are three methods for recharging this Aquifer: baseflow, wadi flood infiltration, and rainwater infiltration (MWI & BGR, 2019). Within the modelled area, the alluvium aquifer has a thickness of up to 400 m (Radulovic et al., 2020), there are three methods for replenishing this aquifer: baseflow, wadi flood infiltration, and rainwater infiltration, The alluvium aquifer is discharged mainly by abstraction wells. From the groundwater divide the flow of the alluvium aquifer naturally outflows to the Red Sea and Dead Sea. In some parts of Wadi Araba the percolation of the groundwater to the deep sandstone aquifer is possible. (MWI, 2017).

- Middle Aquifer (B2/A7 Aquifer)

Amman Wadi Esir Hydrogeological Unit (B2/A7) is a representative of the Middle Aquifer. Most of this hydrogeological unit is constituted of porous limestone. The Wadi Araba basin's northeastern border is marked by the distribution of the B2/A7 aquifer. These terrains have elevations ranging from about 1200 to over 1600 m asl. The eastern slope of this aquifer is present. Precipitation that infiltrates recharges the aquifer. The wadi's springs and baseflow serve as the route for the discharge (MWI & BGR, 2019).

- Aquitard (A1-A6)

Aquitard known as the Lower Ajlun (A1-A6) is located beneath the B2/A7 Aquifer in the northeastern portion of the Wadi Araba basin. This aquitard prevents groundwater from flowing downward, which causes it to collect in the B2/A7 Aquifer at higher elevations. The distribution and storage of groundwater in this area are further influenced by the Lower Ajlun aquitard's comparable strike and dip to the B2/A7 Aquifer (MWI, 2017).

This geological configuration significantly impacts the hydrogeological behaviour in the area, affecting the recharge, flow, and storage of groundwater within the B2/A7 Aquifer. Understanding the relationship between the aquifer and the underlying aquitard is essential for proper groundwater management and sustainable utilization of water resources in the Wadi Araba basin.

- Deep Sandstone Aquifer Complex (Kurnub + Ram)

The Deep Aquifer and the Alluvium Aquifer are two key aquifers that characterized the Wadi Araba Basin. The Deep Aquifer consists of of two sandstone-based hydrogeological units called the Kurnub and Ram aquifers. These aquifers are divided in the eastern portion of the basin by the Khreim aquitard, which serves as a confining layer and limits groundwater flow between the two aquifers.

However, as we move towards the Wadi Araba basin, the Khreim aquitard thins out and eventually disappears (pinches out). This geological feature allows the Kurnub and Ram aquifers to directly overlie each other, enabling the potential for interconnection and communication between the two aquifers. This hydrogeological configuration significantly influences the movement and distribution of groundwater within the basin and plays a crucial role in understanding the overall groundwater dynamics and management in the region.

4.7 Depth to Water Table

Shallow water tables have limited storage capacity, while areas with very deep groundwater tables are less preferred for managed aquifer recharge (MAR) due to potential difficulties in infiltrated water reaching the groundwater layer through impermeable layers. The cost of pumping is also a concern when the lift required is high. The thickness of the aquifer unit plays a significant role in determining its suitability for MAR. Thin aquifer units have limited storage capacity and are not ideal for recharge purposes. Conversely, if groundwater is not being utilized and the water table is close to the surface, recharge efforts may lead to raising the water table to the extent that the area becomes marshland.

To identify suitable locations for groundwater recharge, the thickness of the unsaturated zone (the distance between the ground surface and the water table) is a crucial factor. Researchers gathered water table depth measurements from various observation wells in the Wadi Araba basin and used the inverse distance weighting (IDW) approach to create an interpolated map of the unsaturated zone thickness. Figure 4.14 depicts the diverse unsaturated zone thicknesses within the study area. This information is essential for making informed decisions regarding managed aquifer recharge in the region. (Mahdavi et al., 2010).

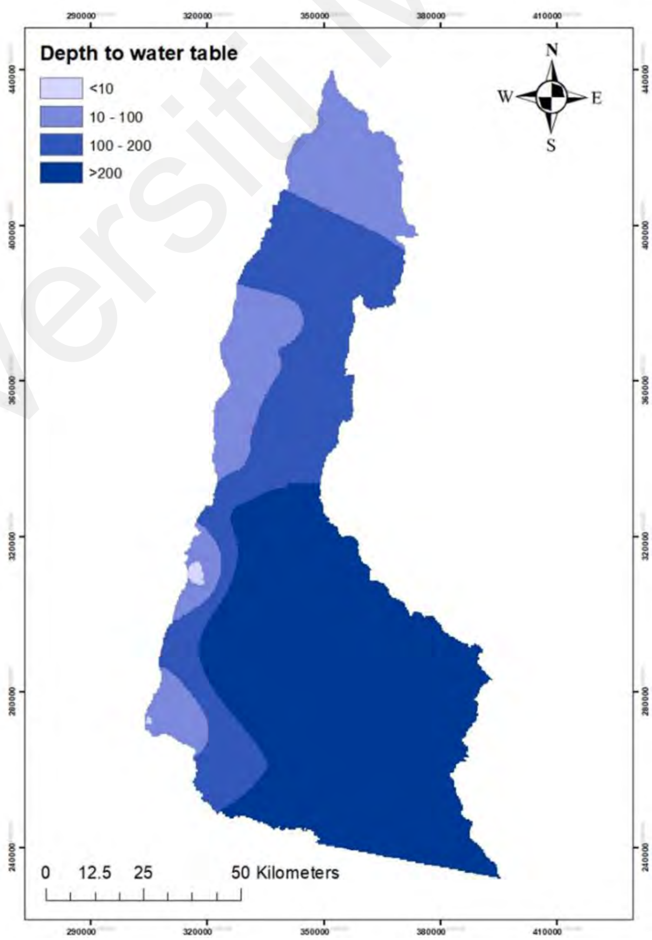


Figure 4.14: Depth to water table

4.8 Soil

The infiltration capacity of a soil depends on the effective porosity which is governed by grain size distribution and packing density. Infiltration rates are dominated by the top surface layer and decrease significantly even with only a thin clogging layer. According to the amount of weathering and the amount of rainfall in the research area, clay content decreases from east to west, and loamy soil extends on the western side of Wadi Araba, (HTS & SSLRC, 1994). Figure 4.15 shows soil texture distribution in Wadi Araba.

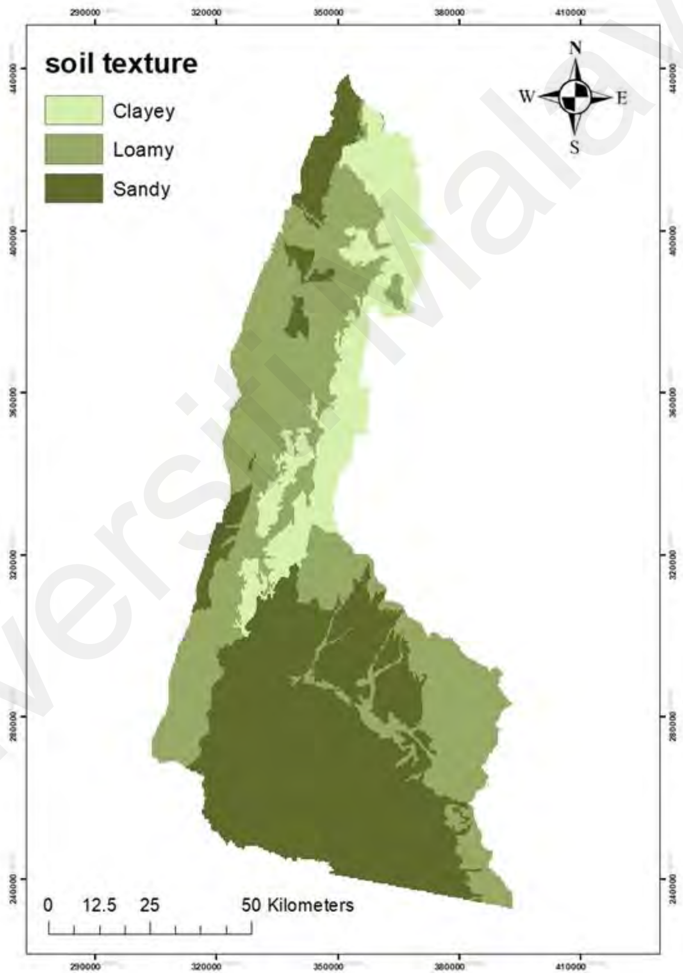


Figure 4.15: Wadi Araba soil texture map, modified after (HTS & SSLRC, 1994)

The complexity of infiltration depends on the distribution of pore sizes, the connectedness of pores, the moisture content of the soil, and it may be hampered by trapped air (Grismer et al., 1994; Ma et al., 2011; Philip, 1957, 2006). The saturated and unsaturated hydraulic conductivity must be distinguished. While the latter rely on permeability and gravity forces, the former also depend on capillary forces, fillable porosity, and moisture content. With a rise or reduction in saturation, capillary forces change the flow and cause hysteresis effects (Seiler & Gat, 2007). During the saturation phase infiltration rates are higher due to the initial saturation than reducing to a constant saturated hydraulic conductivity. The wetting front moves depending on small scale heterogeneities (Warburton, 2012; Sorman & Abdulrazzak, 2017) which is not reflected by grain size distribution analysis, but requires infiltration tests. Hence, infiltration can be very heterogeneous in spatial and temporal respect even under seemingly homogeneous conditions (Sharma et al., 1980; Racz et al., 2012; Warburton, 2012). Generally coarse soil textures allow higher infiltration rates, as shown in Table 4.2.

Table 4.2 saturated hydraulic conductivity values for different soil textures, after (Clapp & Hornberger, 1978).

texture	m/d	texture	m/d	texture	m/d
sand	15.21	loam	0.60	sandy clay	0.19
loamy sand	13.51	sandy clay loam	0.55	silty clay	0.09
sandy loam	2.99	silty clay loam	0.15	clay	0.11
silty loam	0.62	clay loam	0.21		

Infiltration rates typically range from a few m/d on gravel/sand to tens of cm/d on loamy soils to a few mm/d if the basins become clogged. Infiltration rates greater than 1 m/d are suitable; rates less than 0.5 m/d are unsuitable (Haimerl, 2004; Ghayoumian et al., 2007; Zeelie, 2020). Recharge occurs either directly through precipitation infiltration or indirectly through runoff infiltration in wadis. Aside from the intensity and depth of the rainfall, the permeability of the soil and underlying formation, slope, vegetation, and antecedent soil moisture conditions all play a role. In general, coarse soil textures allow for greater infiltration (Clapp & Hornberger, 1978).

4.9 Landuse

Apart from rainfall characteristics, the most important parameters for runoff generation are land use including vegetation, slope, soil characteristics and antecedent moisture conditions (Chow et al., 1988; Anderson et al., 1990; Fetter, 2018). Runoff quality is also highly variable depending mainly on land use and soil characteristics, but is commonly low in salinity (Eriksson et al., 2007). The infiltration of groundwater is affected by land use and land cover. The adequacy of the current land use for groundwater possibilities is evaluated. It covers the distribution of agricultural land, bare rock, and populated areas. Numerous hydrogeological processes, such as evapotranspiration, runoff, and groundwater recharge, are influenced by land use. Figure 4.16 land use map demonstrates that more than 99% of Wadi Araba is comprised of bare rock, which is further classified into three categories: built-up area, agricultural land, and bare rock. The quality of surface water is significantly influenced by land use. The catchment area should be kept as far away from quarries and metropolitan areas as is practical. It will be simpler to add sediments, fertilizer, and pesticides in agricultural areas, making them less desirable. Forest areas would have significant evapotranspiration, which would limit the amount of runoff that could be created. Large volumes of organic material are anticipated to be produced in forest ecosystems.

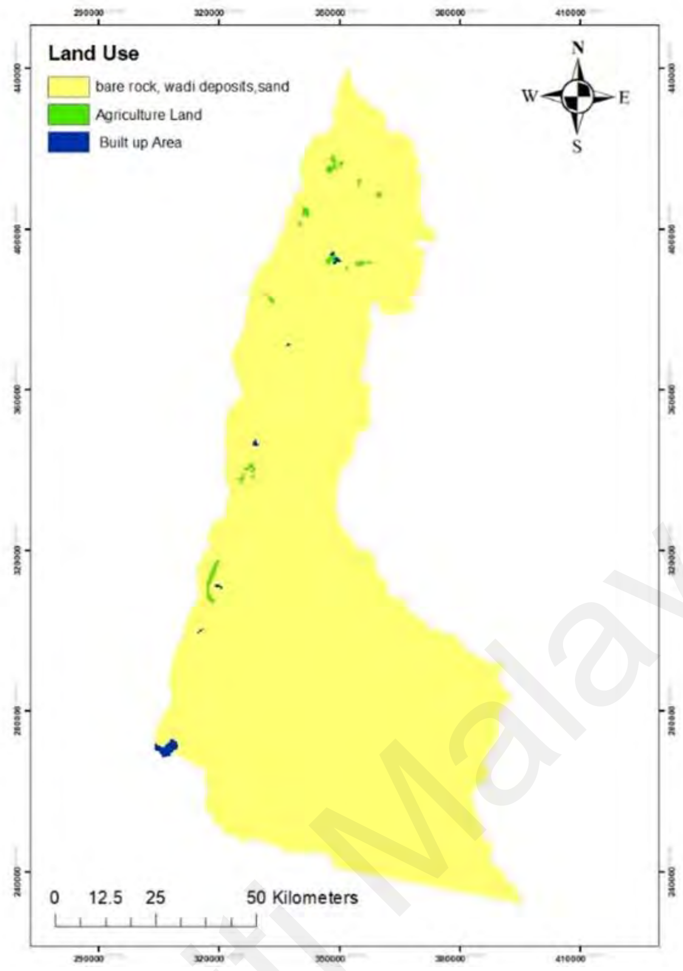


Figure 4.16: Wadi Araba landuse map

4.10 Surface Features

In recent years, water flows from the wadis have been diverted to agricultural uses because the eastern Jordanian escarpment is mainly dry during the hot summer months. The wadis that drain Wadi Araba generally have a decreasing annual streamflow pattern (MWI, 2017). Figure 4.17 shows the wadis that flow into Wadi Araba.

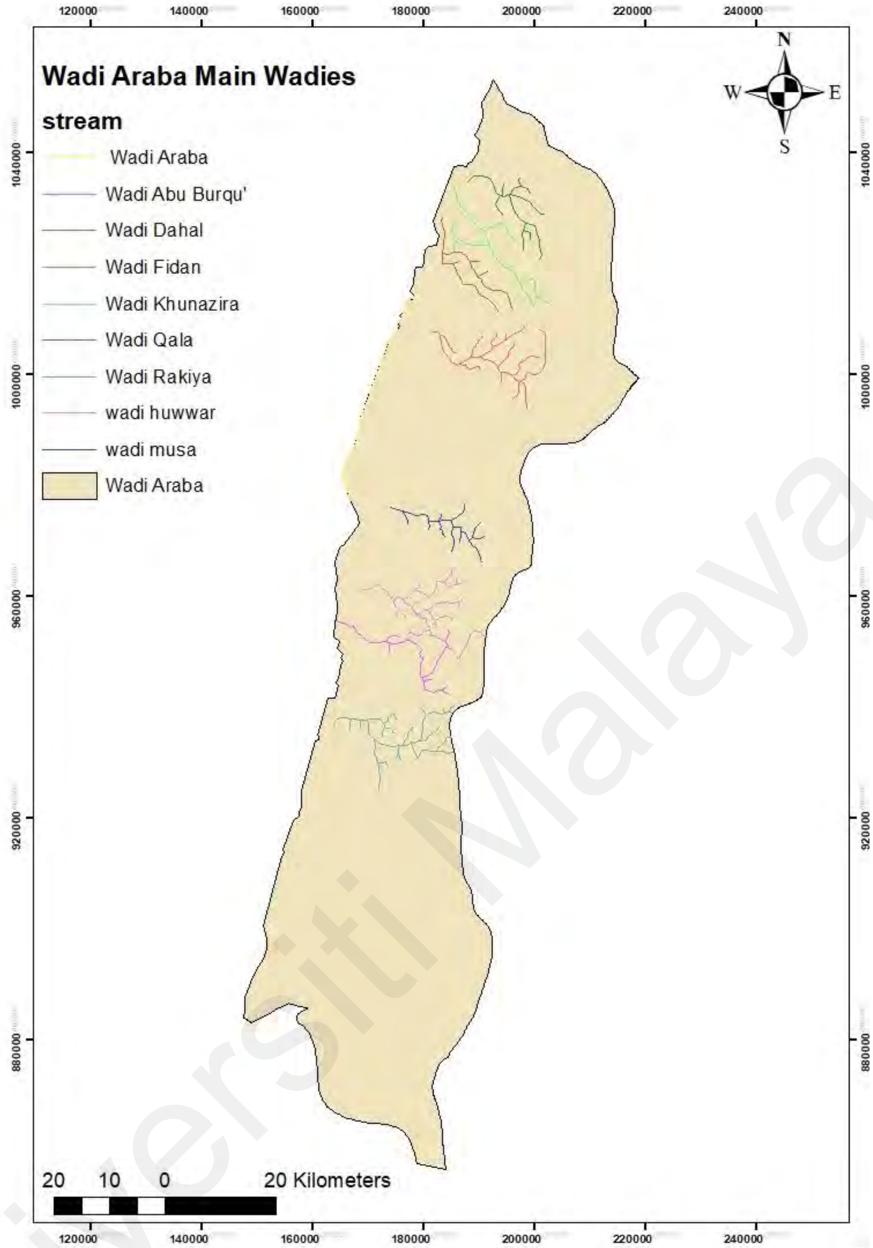


Figure 4.17: Wadi Araba main wadies (Wadi Araba stream in yellow colour on the upper eastern edge of the study area)

The catchment area is drained into Wadi Araba by many wadis. Wadi Khuneizir, Wadi Fidan, and Wadi Buweirida are among the most significant of them, with average discharges of roughly 11.4, 5.5, and 3 MCM/year, respectively. The base flow of wadis makes up most of the discharge. The region is drained by numerous tiny inter-catchments in addition to the main wadi catchments. Wadi Araba receives 26 MCM of annual flow from all northern wadis combined (Salameh et al., 2018).

In recent years, the flows from springs and wadis have mostly been used for irrigation of agricultural land, with little to no flow reaching the outflows at the Red Sea for South Wadi Araba and the Dead Sea for North Wadi Araba. Wadi Araba springs distribution as shown in Figure 4.18.

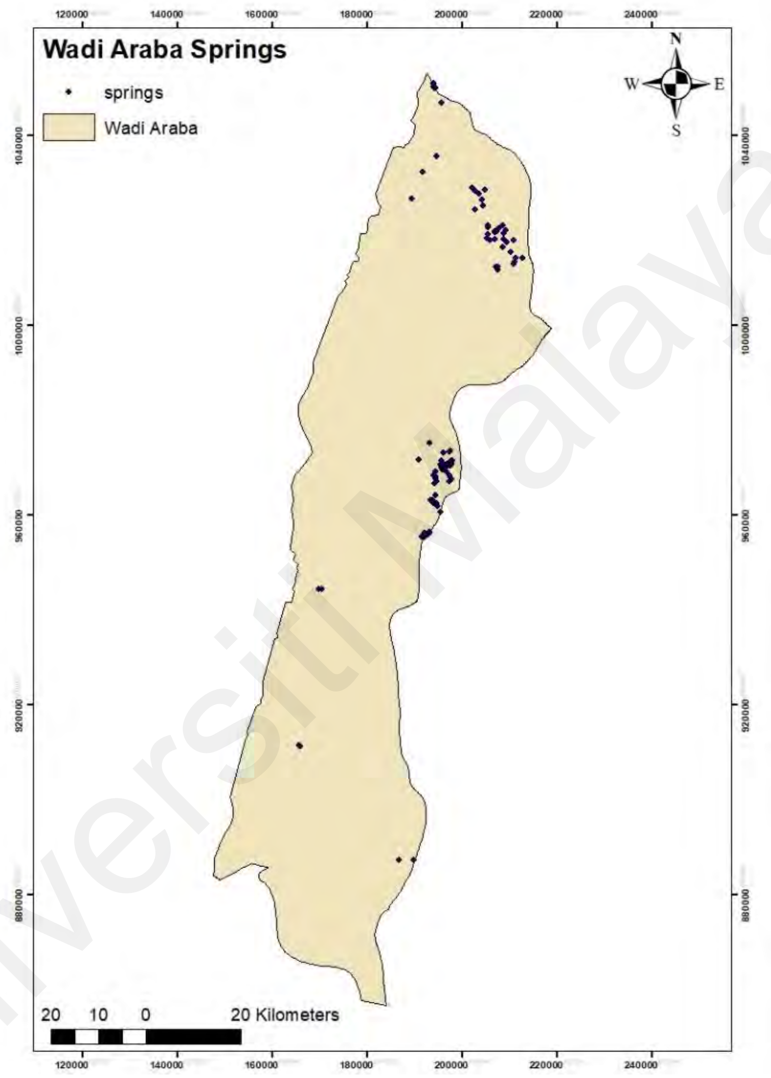


Figure 4.18: Springs locations in Wadi Araba (MWI-WIS, 2019)

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Managed Aquifer Recharge (MAR)

Recharging the water tables naturally or artificially is one of the most efficient ways to address the deficit in groundwater resources (Reid & Dreiss, 1990). New techniques must be used to select the best sites for groundwater recharge. GIS is one of these techniques, and it is essential for data maintenance and analysing optimal locations, it reduces the time and cost of site selection while also providing a digital data bank for future monitoring of the selected sites. RS and GIS techniques can be used to map groundwater recharge zones. Rainfall, slope, geology, soil, and other thematic maps can be generated (Yeh et al., 2016).

The current study aims to create a Managed Aquifer Recharge (MAR) potential map of the Wadi Araba basins. Various thematic maps of Wadi Araba, such as rainfall, slope, and soil geology, have been created. These maps were combined using GIS software to create a groundwater recharge zone map for the area.

5.1.1 MAR Criteria Reclassify

According to previous studies, all maps must be reclassified, assigned weightages and ranks depending upon their influence on artificial groundwater recharge, to prepare MAR zone map. To account for the impact of perception on groundwater, these precipitation levels were rated, more precipitation will increase the amount of water that is available for surface runoff and groundwater recharge. The classification for the mean annual precipitation scores, areas with high scoring values are found in the basin's western regions, the area with > 200mm given the highest score 5 (very good), and the lowest score 1 (very low) given to the areas with precipitation < 50mm.

The generation and velocity of runoff are influenced by the slope. For the watershed, moderate slopes are preferred; if the slopes are excessively steep, there is a risk of erosion and an increase in sediment load. If the slope is too low, water will accumulate in shallow depressions rather than generate runoff. This means that a large portion of Wadi Araba is suitable for runoff generation. The area is divided into four classes: 0-2, 2-5, 5-10, and >10, the slope reclassifies as low 0-2, good 2-5, and very good 5-10.

Study area has been classified into three classes based on hydrogeological properties; Alluvium aquifer assigned as very good, A2/B7 and Sandstone aquifers good, and the aquitard B3 with basement rocks as very low.

Soil's infiltration capacity is determined by its effective porosity, which is determined by grain size distribution and packing density. The top surface layer dominates infiltration rates, which decrease significantly even with a thin clogging layer (Al-Khatib, 1999). Soil texture within Wadi Araba has been classified as per texture and infiltration rate into three classes: sandy soil as very good, moderate for loamy texture, and clayey soil as low.

The best locations are desolate, uninhabited places or pastures. Because runoff generation will be significant, a catchment coated in surface crusts, is particularly ideal. Due to the slope, fine particles, and frequently increased salinity of the soil, mudflats are undesirable. Wadi Araba landuse map has been classified as per land cover to very good for bare rock, good for agriculture cover and the built-up area as low.

Site that is ideal for groundwater recharge is one where the unsaturated zone is at least 10 metres thick. When it came to the map's suitability for groundwater recharge, there were four classes, as: very good (10-100 m), good (100-200 m), moderate (>10 m) and very low (>200 m), as shown in Figures 5.1-5.6.

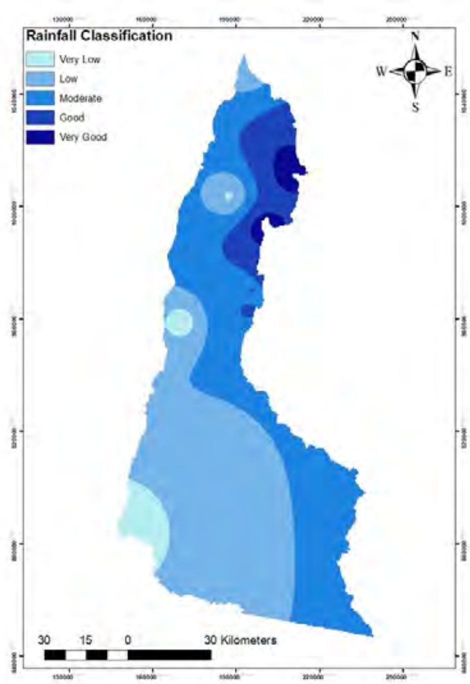


Figure 5.1: Annual rainfall classification

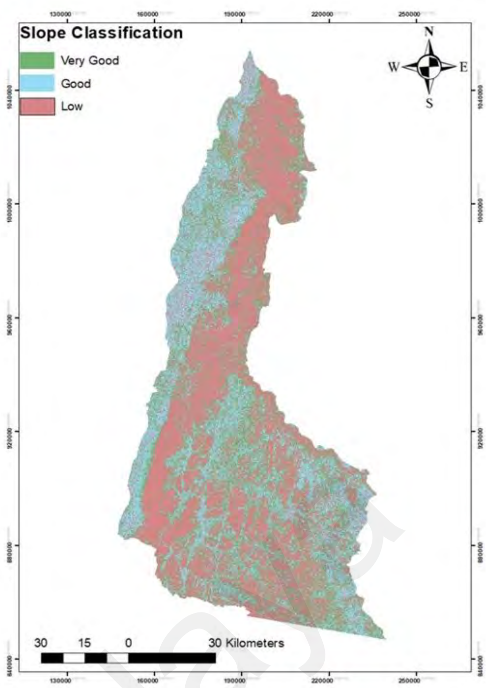


Figure 5.2: Wadi Araba slope classification

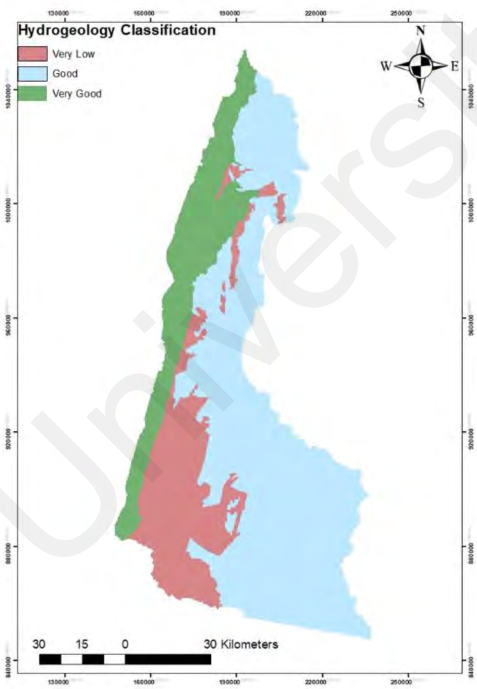


Figure 5.3: Hydrogeological classification of Wadi Araba

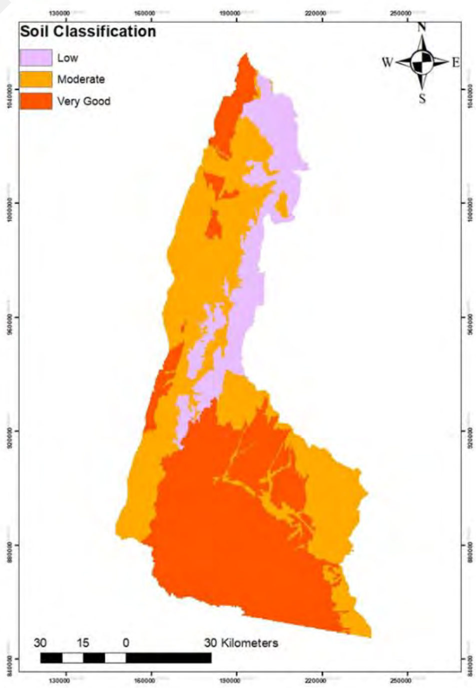


Figure 5.4: Wadi Araba soil texture classification

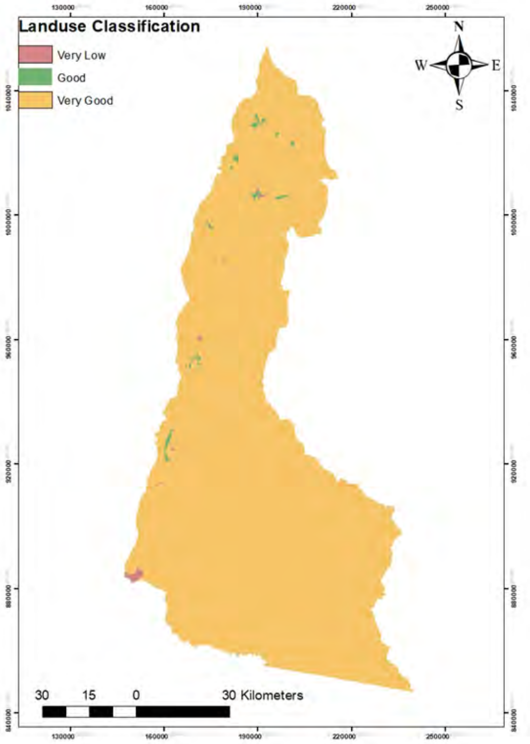


Figure 5.5: Wadi Araba landuse classification

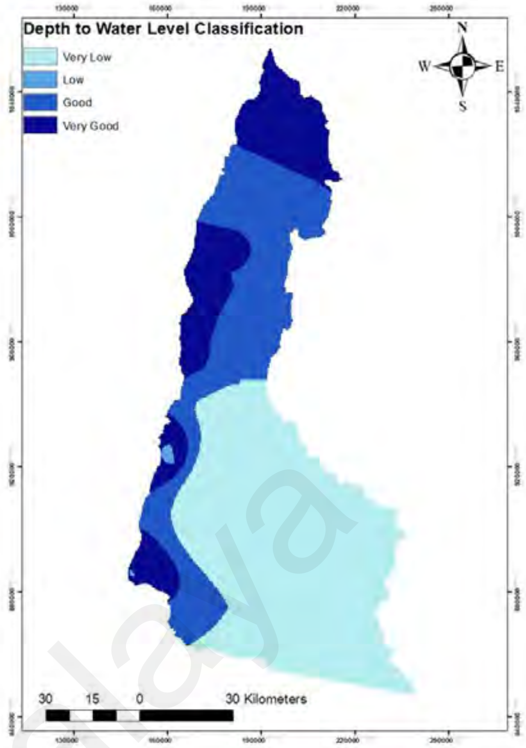


Figure 5.6: Depth to water table classification

5.1.2 Thematic Map Overlay

After the available data are presented, they had to be evaluated in the light of MAR criteria and turned into thematic maps, With the overlay of these thematic maps, the different criteria can be weighted, which will again be assessed for the catchment and for the site selection. Suitability maps are produced using the weighted linear combination, which enables the combining of categorization within each criterion with various weights across all criteria. It indicates that if all other criteria are adequate, regions that are unsatisfactory for one criterion might still receive a good grade.

Combine the maps that have been generated after giving them weights and rankings to generate a MAR zone map (El-Naqa et al., 2010; Elewa & Qaddah, 2011; Awawdeh et al., 2014 Allafta et al., 2020). After overlaying all thematic layers using a weighted overlay, the groundwater MAR zones were estimated using a spatial analysis tool (Raster

Calculator) in GIS software. Each unique parameter received a weighting and a ranking, as shown in Table 5.1.

Table 5.1: Criteria weight and rank for MAR potential zone

Criteria	Weight %	Classification	Rank	Class
Rainfall	35	>250	5	very high
		250-150	4	high
		150-100	3	moderate
		100-50	2	low
		<50	1	very low
Slope	25	5-10	5	very high
		2-5	4	high
		0-2	2	low
		>10	2	low
Hydrogeology	15	Alluvium	5	very high
		Sandstone	4	high
		limestone, dolomitic limestone	4	moderate
		chalky marl, marl, limestone	1	very low
		Granite	1	very low
Land use	5	bare rock, sand, wadi deposits	5	very high
		field and trees	4	high
		built-up land	1	very low
Soil	10	gravelly and sandy	5	very high
		loam	3	moderate
		silt clay	2	low
Depth to GW	10	0-10	1	very low
		10-100	5	very high
		100-200	4	high
		>200	1	very low

Numerous publications (Asano, 1985; Pyne, 1995; ASCE, 2001; Gale et al., 2002; Herman Bouwer, 2002; Gale, 2005; Bouwer et al., 2008; NRC, 2008) provide a general overview of MAR techniques and issues related to various water sources (stormwater, treated wastewater, desalinated drinking water, river runoff, etc.), hydrogeological setups (unconfined or confined; porous This study will mostly discuss stormwater recharge by infiltration. Rainfall the main source of water in the study area and slope were given more weight, while land use was given less. Individual ranks are assigned to classes within those parameters after different parameters have been weighted. The highest ranking of 5 is given to features that have the greatest potential for groundwater recharge. The feature with the lowest potential for groundwater recharge receives the lowest rank. The thematic maps presented under section 5.1 were now combined into one catchment suitability map using weighted linear combination. The weights and ratings used are compiled in Table 5.1, The suitability map can be created as a union of shape files (the slope raster was reclassified and converted to shape file) calculating the final score with the field calculator or all shape files can be converted to raster and processes with the raster calculator, in this study the second procedure has been used to get the final map, Figure 5.7 showing Wadi Araba MAR suitability map.

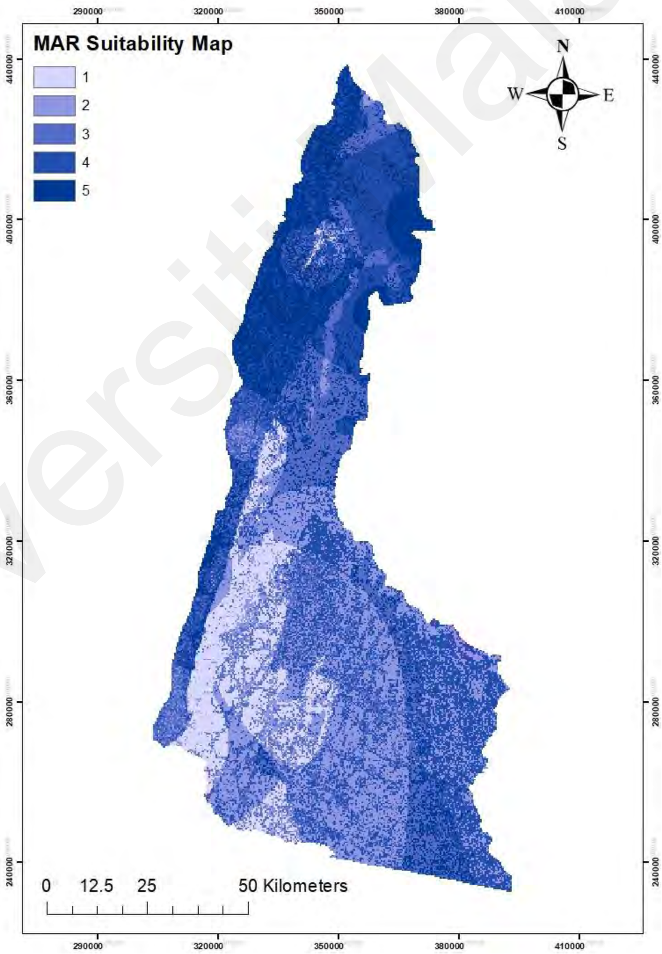


Figure 5.7: Wadi Araba MAR suitability map

As shown on the final map Figure 5.7, that Wadi Araba is covered under five MAR potential zones categories, ranging from very good, good, moderate, low to very low. Wadi Araba MAR potential map shows that 16.7% with area of 1473.7 km^2 and 30.15%

as 2649.5 km^2 area is under very good and good category of MAR suitability respectively. An area of 1779.3 km^2 represent 20.24% is found under moderate category whereas 1944.24 km^2 and 890.94 km^2 equals 32.82% of Wadi Araba area falls under low and very low category of (MAR) suitability respectively, summarized as shown in Table 5.2.

Table 5-2: Wadi Araba MAR category

Rank	Class	Area (km^2)	Area %
5	Very good	1473.713	16.77
4	good	2649.49	30.15
3	moderate	1779.293	20.25
2	low	1994.249	22.69
1	very low	890.943	10.14

The northern and north-eastern portions of the Wadi Araba watershed are categorized as good to very good for managed aquifer recharge (MAR). These areas exhibit favourable conditions for MAR due to higher precipitation intensity compared to the southern parts of the study area. Additionally, the absence of basement aquitard formations in the north allows for better infiltration and recharge potential, as there are present aquifers to store the water.

The soil texture also plays a crucial role in determining the suitability of MAR locations. The northern regions are more suitable due to more favourable soil characteristics. Moreover, the slope of the land significantly influences surface runoff, and the northern areas with more appropriate slope ratios facilitate the transfer of water from the eastern heights to the Wadi floor, offering promising locations for MAR.

On the other hand, Wadi Araba's eastern and southern areas, where precipitation is less than 50 mm/year and basement rocks are exposed, falls under the low and very low suitability category for MAR. These areas are less suitable for recharge due to the arid conditions and the presence of impermeable basement rocks that hinder the infiltration and recharge process. The rest of the study area is classified as moderate, offering potential but not as ideal conditions for managed aquifer recharge. The findings highlight the importance of considering various factors, such as rainfall, soil texture, and geological formations, in determining suitable locations for MAR to effectively replenish groundwater resources.

5.1.3 Field Validation

Field visits were carried out in 2021 to compare the Managed Aquifer Recharge (MAR) site selection results from the Geographic Information System (GIS) with the actual situation on the ground and to validate the data gathered for elevation, soil texture, accessibility, land cover, etc.. These visits involved physically going to 20 different sites along the study area in the Wadi Araba region. Figure 5.8 presents photos captured during these field visits, providing visual documentation of the actual conditions and characteristics of the sites.

Field visiting is an essential step in the research process to ensure the accuracy and reliability of the data collected through GIS and other remote sensing techniques. By comparing the GIS results with the real observations on the ground, researchers can verify the suitability of the selected MAR sites and make necessary adjustments or confirm the validity of their findings. The combination of remote sensing data and field validation enhances the robustness of the study's outcomes and supports better decision-making in managing groundwater resources in the Wadi Araba Basin.

Figure 5.8: Wadi Araba field work photos

To test the validity of the GIS, MAR site selection results and their conformity on the ground, a comparison of the results which have been obtained with the actual state in the field has carried out, and by choosing 20 sites, the results came as shown in the Table 5.3, The coordinate system has been used in this table is Palestine Belt 1923[9] (PB), a Transverse Mercator projection based on the Clarke 1880 (Benoit).

Table 5.3: Results validation by field work

Location	East	North	Field Suitability	GIS Suitability	Result
1	208211	1014073	X	√	X
2	184574	1014221	√	√	√
3	197027	990786	√	√	√
4	178349	992854	√	√	√
5	160439	929558	X	√	X
6	152104	891360	√	X	X
7	166168	915732	X	X	√
8	174262	952354	X	X	√
9	178162	1004666	√	√	√
10	197247	1042783	X	X	√
11	165383	881588	X	X	√
12	183336	1026017	√	√	√
13	192262	1026160	√	√	√
14	169701	941780	X	X	√
15	157599	909560	√	√	√
16	172403	986983	√	√	√
17	206109	1030583	X	X	√
18	197714	997100	X	X	√
19	172081	974112	√	√	√
20	186254	1007683	X	X	√
Percent of Accuracy					**85%**

Most of the promising areas for the application of MAR are located within the alluvium aquifer, given that the conditions to be fulfilled in the requirements of the MAR, and the availability of abstraction and monitoring wells data for the past 40 years are sufficient to generate a successful model which simulates reality and predict the future situation, the alluvium aquifer was only modeled in this present study.

5.2 Groundwater Modeling

This section is dedicated to advancing the understanding and evaluation of the Wadi Araba Aquifer systems in relation to Managed Aquifer Recharge (MAR) and the influence of climate change. To achieve these objectives, a series of crucial steps will be taken. These include the development of comprehensive datasets necessary for the groundwater model, the formulation of a conceptual groundwater flow model based on the existing geology and hydrogeology within the alluvium aquifer, to enable efficient long-term management of the alluvium aquifer in the Wadi Araba region, a digital groundwater flow model will be built and forecast scenarios will be simulated. This section seeks to considerably advance knowledge and comprehension of the Wadi Araba Aquifer systems in the context of MAR and climate change implications through various endeavours.

5.2.1 Conceptual Modeling

The geological and hydrogeological models of the alluvium aquifer in Wadi Araba were significantly improved by utilizing the previously gathered information. This led to the development of a comprehensive conceptual digital model, which aids in understanding and visualizing the hydrogeological system in the region. Boundary conditions for the model were established based on a sound conceptual understanding of the hydrogeological processes in Wadi Araba.

Data visualization techniques were employed to assist in comprehending and communicating the concepts and results obtained from the models. In areas requiring complex modeling, three-dimensional data analysis, such as interpolation of stratigraphy and water level data, was utilized for visualization purposes. This approach provided a more detailed and intuitive representation of the aquifer system. To determine the impact of fault structures on groundwater flow, existing borehole logs, cross sections, and 3D visualizations were employed. These tools allowed researchers to assess the degree of offset and direction of the fault structures, helping determine whether these structures acted as partial or complete barriers to groundwater flow.

The integration of geological, hydrogeological, and visualization techniques enables a better understanding of the alluvium aquifer's behaviour and the influence of geological structures on groundwater movement in Wadi Araba. This comprehensive approach provides valuable insights for effective groundwater management and decision-making in the region.

The geological model, which is typically generated from existing borehole information to assist in establishing the hydrostrtigraphic units Table 4.1, is a spatial representation of the distribution rock unit in the subsurface, as shown in Figure 5.9 (MWI, 2017).

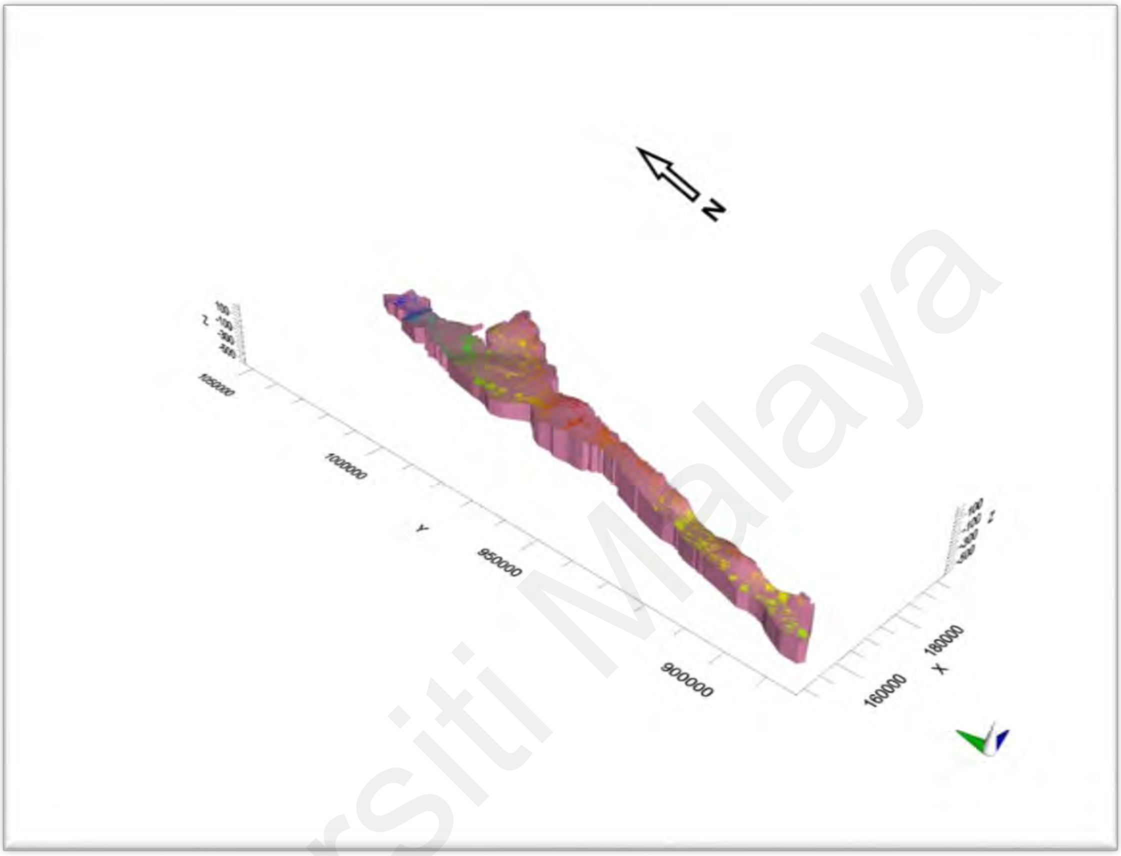


Figure 5.9: Conceptual model of alluvium aquifer

The main components of Wadi Araba's geology are as follows:

1. It crosses the region between the Dead Sea in the north and the Gulf of Aqaba in the south.

2. Western border of Wadi Araba border runs parallel with the Dead Sea rift (DSR) trending northeast that is a 105 km long transform fault formed in the Meocene epoch (about 25 million years ago) whereby the western edge was down thrown relative to the eastern edge, the older rocks consisting of volcanics and basement complex were exposed along the eastern part of the Jordanian escarpment. Active movement of about 5mm/yr.

3. There is a vertical displacement of more than 1000 m between the floor of the DST and the eastern rift highlands.

4. Mean annual precipitation varies between < 50mm in the South Basin comparative to > 200mm in the north-eastern highlands, and the land is poorly vegetated.

5. The topography of the region is characterized by granitic basement rock complexes that rise steeply above the valley floor following the DST escarpment. Cretaceous sediments are exposed along the basin's northern and eastern boundaries, while the deep sandstone complex and its underlying alluvial deposits are exposed in the basin's center. The valley bottom is covered with Holocene to Pleistocene alluvial fans, sand dune areas, and mudflats.

The primary fault blocks should stand in for various hydraulic parameter zones. Although the faults in the Wadi Araba Basin are permeable, fault blocks could nevertheless be formed from rocks with various hydraulic properties, for example, in some parts along Wadi Araba the contact between permeable sandstone and impermeable granite is represented by transform fault. Additionally, the permeability of the Salawan fault's northern block's sandstone aquifer is different from that of the southern block. Due to its extremely low permeability, the Kharawi dyke may function to direct the flow of groundwater. Despite being outside the Wadi Araba Basin, this dike has the potential to affect how groundwater is transferred from the Disi basin to the Wadi Araba basin (MWI, 2017). Topographical and geological data have been prepared to construct the model's geometry. The elevations for the base of the alluvium aquifer are shown in Figure 5.10, which was created using geometry data from (MWI-WIS, 2019). (Excel file).

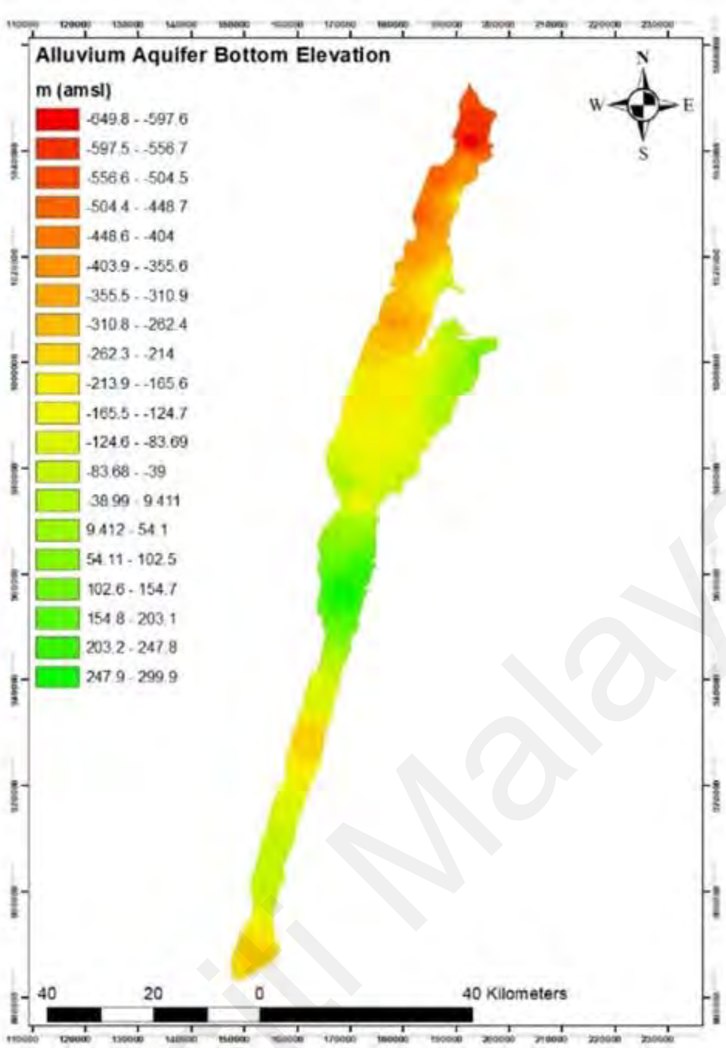


Figure 5.10: Alluvium aquifer bottom elevation

The hydrogeological units are characterized based on their hydrogeological attributes, utilizing lithological information from boreholes along with supplementary data like water level measurements and hydraulic parameter findings from pumping tests. Among these units, the Shallow Aquifer (Alluvium Aquifer) stands out as the primary layer identified in the conceptual model, as depicted in Figure 5.9. By integrating multiple sources of data, the conceptual model provides a comprehensive understanding of the hydrogeological system in the region, especially highlighting the characteristics and behaviour of the Shallow Aquifer. This information is crucial for effective groundwater management and informed decision-making concerning the Alluvium Aquifer in Wadi Araba.

5.2.2 Modeling Software

Visual MODFLOW is a popular commercial Graphical User Interface (GUI) for the USGS MODFLOW software, which is a modular finite-difference flow model. Hydrogeologists often prefer Visual MODFLOW due to its user-friendly features and ease of use. The software is primarily utilized for groundwater flow and contaminant transport simulations under various scenarios.

The US Geological Survey (USGS) developed and released MODFLOW, which makes use of finite-difference solutions for predicting groundwater flow and pollutant migration. The source code considers to be "free public domain software."

Visual MODFLOW serves as a commercial GUI for MODFLOW, introduced by the "Waterloo Hydrogeologic" company in August 1994. The primary difference between MODFLOW and Visual MODFLOW lies in the input data format. While MODFLOW requires text files as input data, Visual MODFLOW utilizes Excel files, Surfer grids, GIS data, and AutoCAD data, making modeling more user-friendly and reducing processing time. The software's ability to interpret MODFLOW's raw text and binary output files allows it to produce colour and contour maps and charts, further enhancing its capabilities and visual representation of simulation results.

5.2.3 Model Design

The alluvium aquifer in the Wadi Araba basin has been extensively studied through flow modeling, covering an area of 2518.417 km^2. The modeling approach divides the area into a uniform grid with cells measuring 100 x 100 meters. The model grid is composed of 840 rows and 300 columns, resulting in a total of 252,000 cells that cover the entire basin.

The model represents a 1-layer case, reflecting the aquifer's characteristics in a single vertical dimension. The data from contour elevation maps of aquifer tops and bottoms, along with the 3D hydrogeological model, were presented in section 5.2.1. To facilitate modeling and analysis, these data have been formatted into XYZ Excel files. The visual MODFLOW Flex pre-processor can automatically compile these files, generating various layer distributions as illustrated in Figure 5.11. This comprehensive approach provides a detailed and accurate representation of the alluvium aquifer, enabling scientists and researchers to study groundwater flow patterns and make informed decisions regarding water management in the Wadi Araba basin.

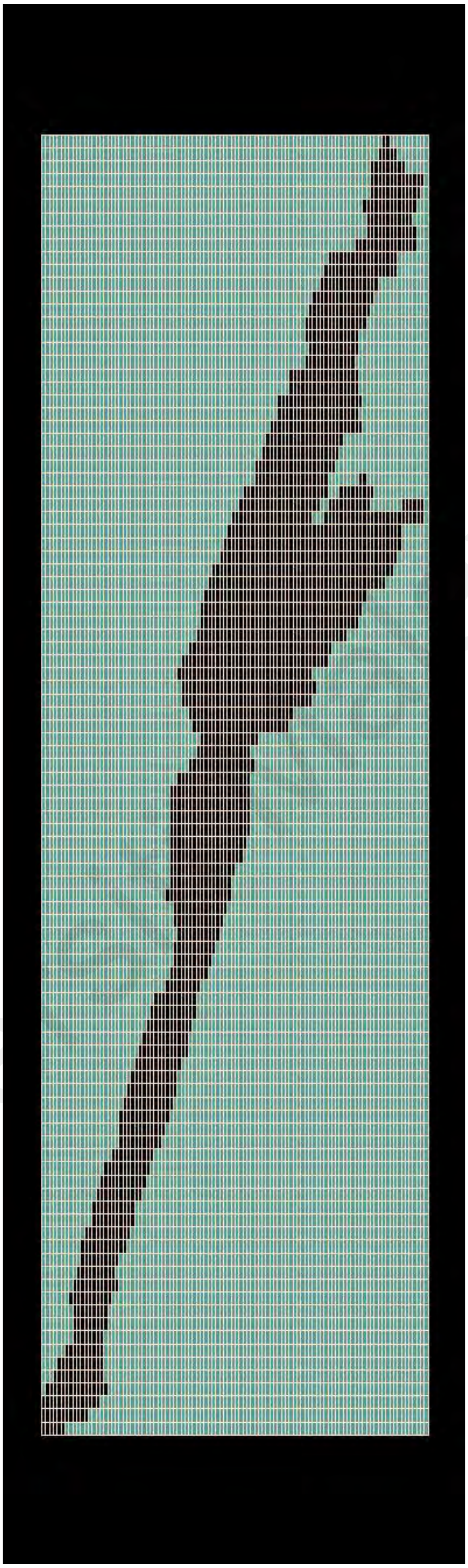


Figure 5.11: Model grid sitting.

5.2.4 Boundary Conditions

The model boundary conditions are designed to replicate the conceptual hydrogeological model's conditions as accurately as possible. However, due to the complexity of natural situations, creating an exact copy of the current physical state is not feasible.

Cells in the basement complex or outside the flow path are marked as inactive cells with a no-flow boundary condition after the model region has been discretized. A continuous head border with a defined elevation of 0 meters above sea level (asl) is used to depict the Red Sea. The Dead Sea is also represented in the steady-state model as a constant head boundary with an elevation of -400 meters asl.

To simulate the inner boundary conditions, both the head-dependent flow boundary and the specified flow boundary are applied. Groundwater recharge from infiltration and evaporation is achieved using the Recharge package, which is based on precipitation data. The most active cells within the recharge zones of the alluvium aquifer receive this recharge.

The defined flow boundaries indicate groundwater recharge and abstraction wells. The zones for recharging and evaporation are defined by the precipitation thissen polygon map, and the transient model incorporates the temporal distribution of the recharge rate for each zone independently.

The Well package (WELL1) simulates pumping from wells. For each time period, the proper cells are filled with the measured abstraction rates.

In summary, the model incorporates various boundary conditions and packages to simulate groundwater flow, recharge, and abstraction in the alluvium aquifer of the Wadi Araba basin. Figure 5.12 illustrates the model boundary conditions for reference.

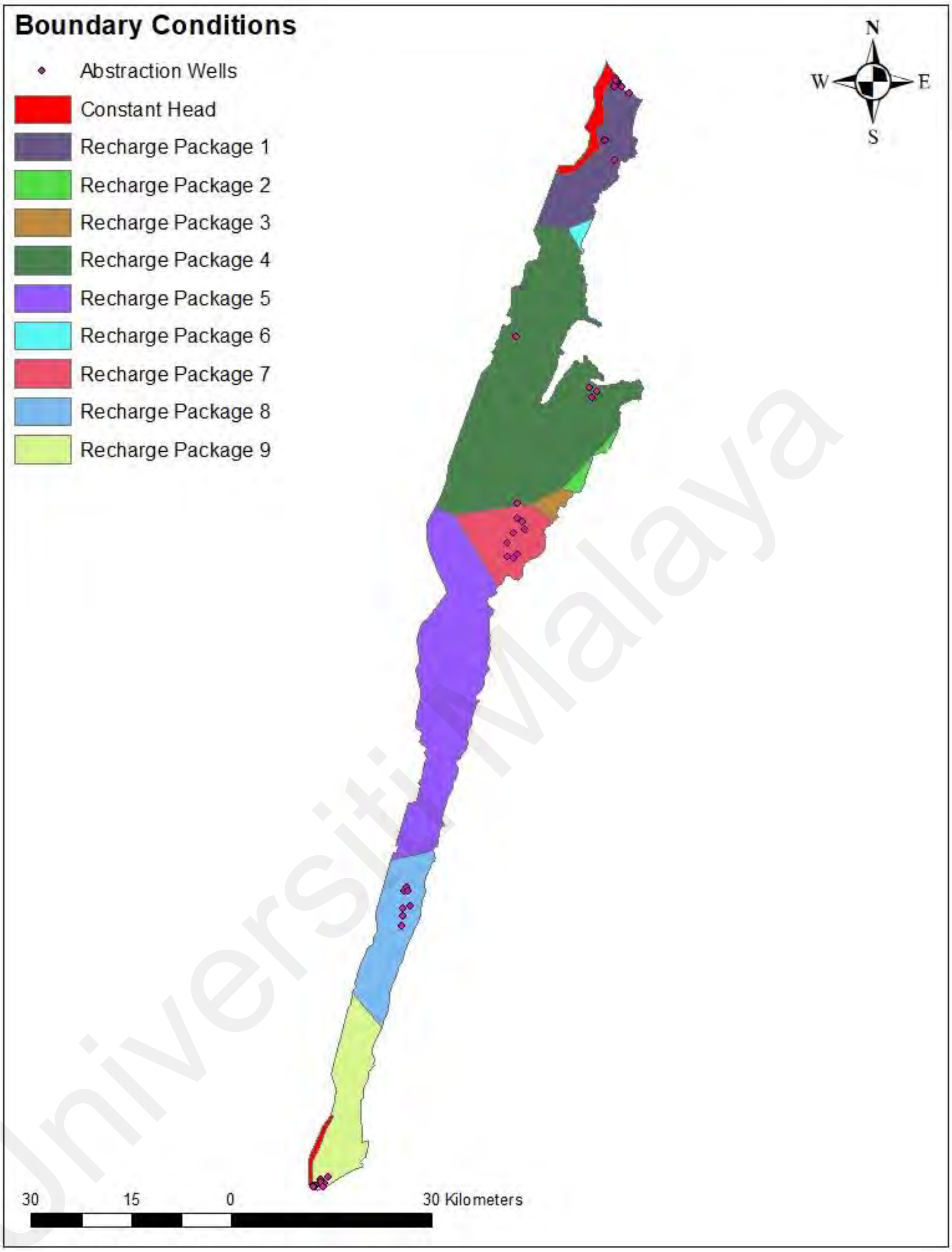


Figure 5.12: Model boundary conditions

To accurately simulate the Managed Aquifer Recharge (MAR) model, a drainage gallery within the Recharge package was selected based on GIS analysis. The gallery was strategically positioned in an area with higher hydraulic conductivity to facilitate the efficient infiltration of rainwater. This approach ensures that water can easily penetrate the subsurface layers, optimizing the effectiveness of the MAR system.

5.2.5 Assign Parameters

According to the references (MWI-WIS, 2019; Radulovic et al., 2020), the Wadi Araba basin has been divided into 12 zones, with 6 of these zones located within the alluvium aquifer. This zoning was based on analyses of hydraulic parameters and structural data, and each tectonic block represents a distinct zone. Figure 4.15 illustrates the spatial distribution of these zones. Table 5.4 provides the assessment of hydraulic conductivity and porosity for each delineated zone. These parameters are essential for understanding the groundwater flow characteristics and aquifer properties within each zone. Furthermore, the transmissivity values for the various aquifers were obtained through pumping tests conducted on wells. Transmissivity is a crucial parameter that represents the ability of an aquifer to transmit water under hydraulic gradient conditions. By considering these hydraulic parameters and structural data, the hydrogeological model gains a better representation of the groundwater flow behaviour and the variations in aquifer properties across the different zones in the Wadi Araba basin. This information is crucial for effective groundwater management and resource utilization in the region.

Table 5.4: Hydraulic parameters of Alluvium aquifer (MWI-WIS, 2019)

Zone	Aquifer/Aquitard	Hydraulic conductivity (m/s)	Porosity (-)	Ss	Sy
Zone 1	Alluvium/aquifer	2.8 x 10-5	0.2	4.00×10^{-4}	6.78×10^{-2}
Zone 2	Alluvium/aquifer	3 x 10-5	0.2	1.82×10^{-7}	3.06×10^{-5}
Zone 3	Alluvium/aquifer	4 x 10-6	0.2	4.00×10^{-4}	6.80×10^{-2}
Zone 4	Alluvium/aquifer	1 x 10-4	0.2	1.55×10^{-5}	2.60×10^{-3}
Zone 5	Alluvium/aquifer	6 x 10-5	0.2	8.90×10^{-4}	1.49×10^{-1}
Zone 6	Alluvium/aquifer	9 x 10-5	0.2	9.00×10^{-4}	1.51×10^{-1}

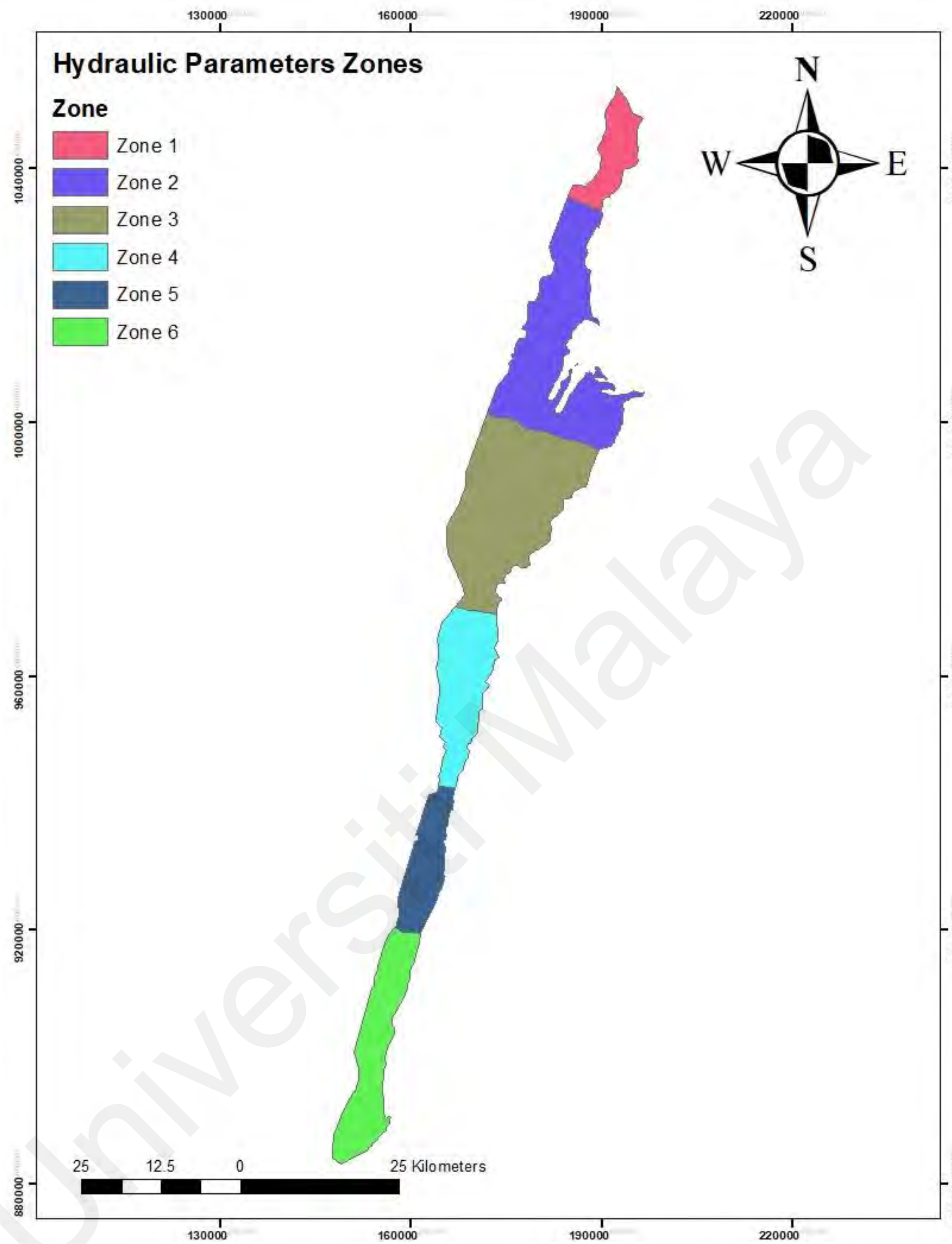


Figure 5.13: Alluvium aquifer Hydraulic parameters zones

For the calibration of the transient model, historical water level data from 23 piezometers in the alluvium aquifer have been collected from MWI WIS. These piezometers provide continuous groundwater level readings from the years 1980 to 2020, offering valuable information on the aquifer's water level fluctuations over the past four decades. Figure

5.14 visually presents the groundwater level readings from these piezometers, providing insights into the temporal variations and trends in the alluvium aquifer's water levels.

By incorporating this historical water level data into the transient model, researchers can calibrate and validate the model's performance. This calibration process involves adjusting model parameters to closely match the observed water level data, ensuring that the model accurately represents the groundwater flow dynamics in the alluvium aquifer. The calibrated model can then be utilized for various scenarios and predictions, aiding in effective groundwater management and decision-making in the Wadi Araba basin.

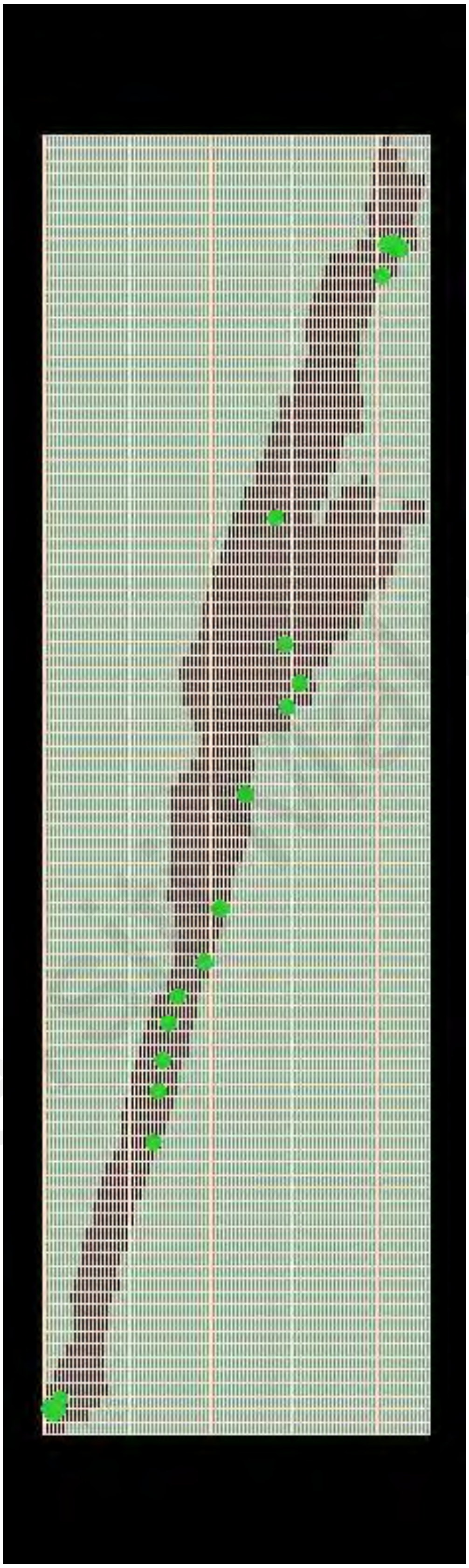


Figure 5.14: Observation wells setting.

5.2.6 Steady State Model

The conceptual hydrogeological model created in section 5.2.1 serves as the foundation for the steady-state flow condition. The transient flow model uses the output heads from the steady-state simulation as its initial head condition.

The boundary conditions from the conceptual hydrogeological model are simulated as realistically as possible using the geometry derived from the steady-state model. This ensures that the transient flow model accurately represents the hydrogeological system's behaviour over time. Details about the boundary conditions and their implementation can be found in section 5.2.3 and Table 5.5 of the study. These boundary conditions play a crucial role in capturing the dynamic changes in groundwater flow and head levels over time in response to various stresses and influences. The transient flow model can contribute to a more thorough understanding of the hydrogeological processes in the Wadi Araba basin by using the steady-state model as a base and accurately simulating the boundary conditions. This can give useful insights into the temporal variations of groundwater flow.

Table 5.5: Wadi Araba model boundary

Model Configuration	Comments
Model area	Consists of alluvium aquifer within Wadi Araba with a total area of 2518.417 km^2.
Grid spacing	Grid spacing of the rows and columns is 100m by 100m.
Constant Head (CH)	Along the Dead Sea and Red Sea coasts
No-Flow boundary (Inactive cells)	Along the groundwater divide of alluvium aquifer and along the contact between the aquifer and impermeable Basement Complex
Evaporation	range between 90-97% of rainfall
Well package (WEL1)	On the locations of abstraction wells
Recharge package (RCH1)	For the simulation of rainwater infiltration recharging aquifers (applicable to regions with precipitation above 75 mm)
Observation Wells	On the locations of monitoring wells

As mentioned previously, precipitation plays a crucial role in recharging the aquifers in the Wadi Araba basin. The region experiences higher precipitation in the north-eastern heights, gradually decreasing towards the southern half of the basin. Consequently, the areas with higher precipitation rates offer better potential for groundwater recharge. The amount of infiltration is limited and has little impact on aquifer recharging in the southern portion of the basin, where precipitation is less than 75 mm. Around 7% of rainfall is expected to contribute to aquifer recharge in places with precipitation rates higher than 75 mm (MWI, 2017). According to this estimate, in areas with adequate precipitation, some of the rainfall infiltrates into the ground and replenishes the groundwater supply.
The steady-state heads of the alluvium aquifer in the Wadi Araba basin have been obtained and contoured using current data, providing valuable insights into the distribution of groundwater levels across the region. By understanding the relationship between precipitation patterns and groundwater recharge, researchers can gain a more comprehensive understanding of the hydrogeological processes and water availability in the Wadi Araba basin. This information is essential for sustainable groundwater management and resource utilization in the region.

5.2.7 Transient State Model

The dynamic model's time division is based on 40 yearly intervals, spanning from 1980 to 2020. In section 5.2.5, the particular storage and yield values for the indicated zones are listed. These data serve as crucial inputs for simulating the groundwater behavior over time. From 2003 to 2020, groundwater extraction in the Wadi Araba basin has been observed. However, data on groundwater extraction prior to 2003 are limited. Information from Energoprojekt (1989, 1990) indicates that well rehabilitation and drilling programs enabled an annual withdrawal of 8.8 MCM between 1990 and 2003. It is estimated that groundwater withdrawal was nearly 50% lower before 1990. Along the border, wells have consistently been used for extraction as part of the 1994 Peace Treaty between Israel and Jordan, with the current estimated annual production of 8 MCM.

Figure 5.15 illustrates the annual extraction rates for each aquifer used in the dynamic model, providing insights into the trends and variations in groundwater extraction over time. Table 5.6 provides detailed data on these extraction rates for reference.

By incorporating this information into the dynamic model, researchers can assess the impact of groundwater extraction on the aquifer system and gain a comprehensive understanding of the sustainability of groundwater resources in the Wadi Araba basin. This knowledge is crucial for effective water resource management and to ensure the long-term availability of groundwater for various uses in the region.

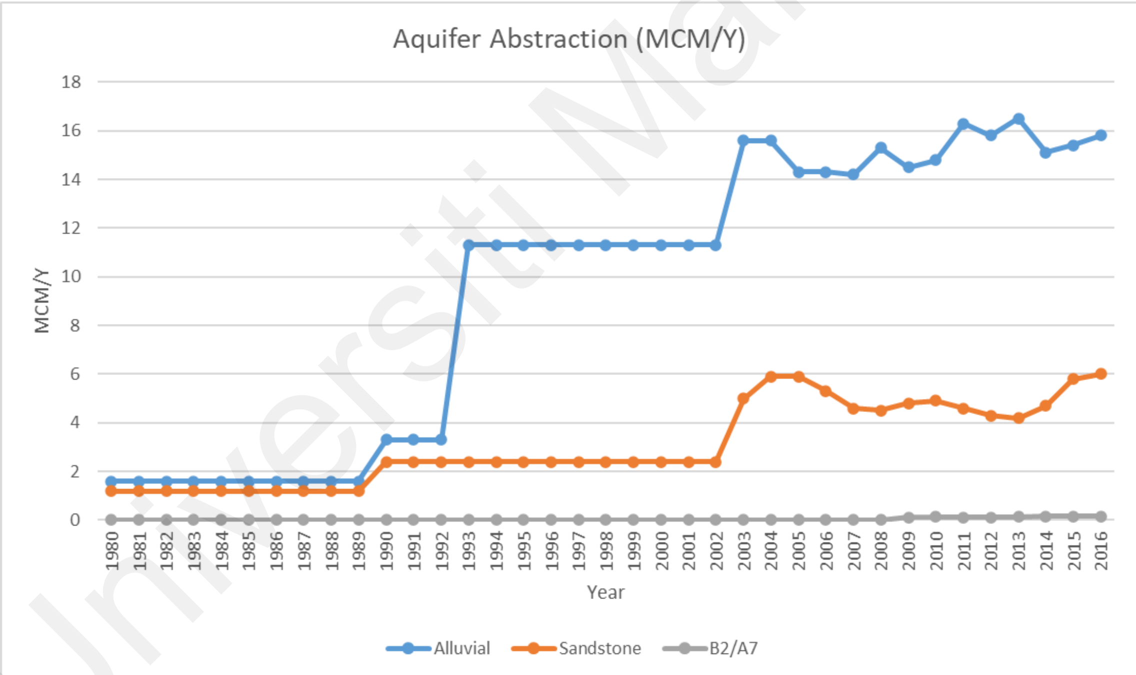


Figure 5.15: Wadi Araba aquifers abstraction MCM/y

Table 5.6: Wadi Araba aquifers yearly abstraction 1980-2020

	Alluvial	Sandstone	B2/A7
1980	1.6	1.2	-
1981	1.6	1.2	-
1982	1.6	1.2	-
1983	1.6	1.2	-
1984	1.6	1.2	-
1985	1.6	1.2	-
1986	1.6	1.2	-
1987	1.6	1.2	-
1988	1.6	1.2	-
1989	1.6	1.2	-
1990	3.3	2.4	-
1991	3.3	2.4	-
1992	3.3	2.4	-
1993	11.3	2.4	-
1994	11.3	2.4	-
1995	11.3	2.4	-
1996	11.3	2.4	-
1997	11.3	2.4	-
1998	11.3	2.4	-
1999	11.3	2.4	-
2000	11.3	2.4	-
2001	11.3	2.4	-
2002	11.3	2.4	-
2003	15.6	5	-
2004	15.6	5.9	-
2005	14.3	5.9	-
2006	14.3	5.3	-
2007	14.2	4.6	-
2008	15.3	4.5	-
2009	14.5	4.8	0.12
2010	14.8	4.9	0.13
2011	16.3	4.6	0.12
2012	15.8	4.3	0.12
2013	16.5	4.2	0.13
2014	15.1	4.7	0.15
2015	15.4	5.8	0.15
2016	15.8	6	0.15
2017	15.3	6.2	0.15
2018	15.4	9.4	0.15
2019	11.6	7	0.15
2020	14.1	7.6	0.15

The observed abstraction rates for all production wells have been inserted into the appropriate cells across the necessary time periods in the transient model, which has allocated specific cells for wells. This data on groundwater extraction rates was obtained from the Jordanian Ministry of Water and Irrigation (MWI), which serves as the authorized government authority responsible for overseeing the water sector in Jordan. Detailed information can be found in Appendix A of the MWI-Water Information System (WIS) report from 2019.

The transient model also considers the drop in the Dead Sea level, which is simulated as a variable head constant. Data on the declining Dead Sea levels is sourced from various references, including (EcoWatch, 2016; Hammour, 2014; ISRAMAR, 2022), and is presented in Table 5.7.

By incorporating these essential data points into the transient model, researchers can assess the dynamic changes in groundwater flow and levels, considering the impacts of both groundwater extraction and the changing Dead Sea levels. This enables a more comprehensive understanding of the hydrogeological system and supports sustainable water resource management practices in the Wadi Araba basin.

Table 5.7: Dead Sea surface level

Year	Water Level (m asl)	Source
1980	-400	Hammour 2014
1992	-407	
1997	-411	
2004	-417	
2010	-423	
2016	-430.5	https://www.ecowatch.com/
2017	-431.2	https://isramar.ocean.org.il/isramar2009/DeadSea/LongTerm.aspx
2018	432.2	
2019	432.9	
2020	433.6	

Calibration of the transient state model have been done, by using measurements data of groundwater level within alluvium aquifer recorded for 12 monitoring wells located within the promising locations that meet required MAR criteria, within the good and very good category, based on MAR suitability map, to achieve the most appropriate and realistic simulation that show the climate change effect on the groundwater in the alluvium aquifer, and the sensitivity of the water table to these changes. The years 1980 to 2020 are represented by 40 yearly stress periods in the model's time discretization. In order to simulate groundwater flow and changes over the course of an entire year, each stress period is further divided into ten time steps. The model time for the predicting scenarios has been increased by 30 years, ending in the year 2050. This extension allows researchers to analyze and predict the behaviour of the hydrogeological system in the Wadi Araba basin over a more extended timeframe, considering potential changes and challenges related to water availability and groundwater management in the future. Figure 5.16 provides a visual representation of the model's time discretization setting, illustrating the stress periods and time steps used for modeling groundwater flow and head variations. By encompassing this comprehensive time range, the model can support decision-making processes and sustainable water resource planning, considering both historical trends and future projections.

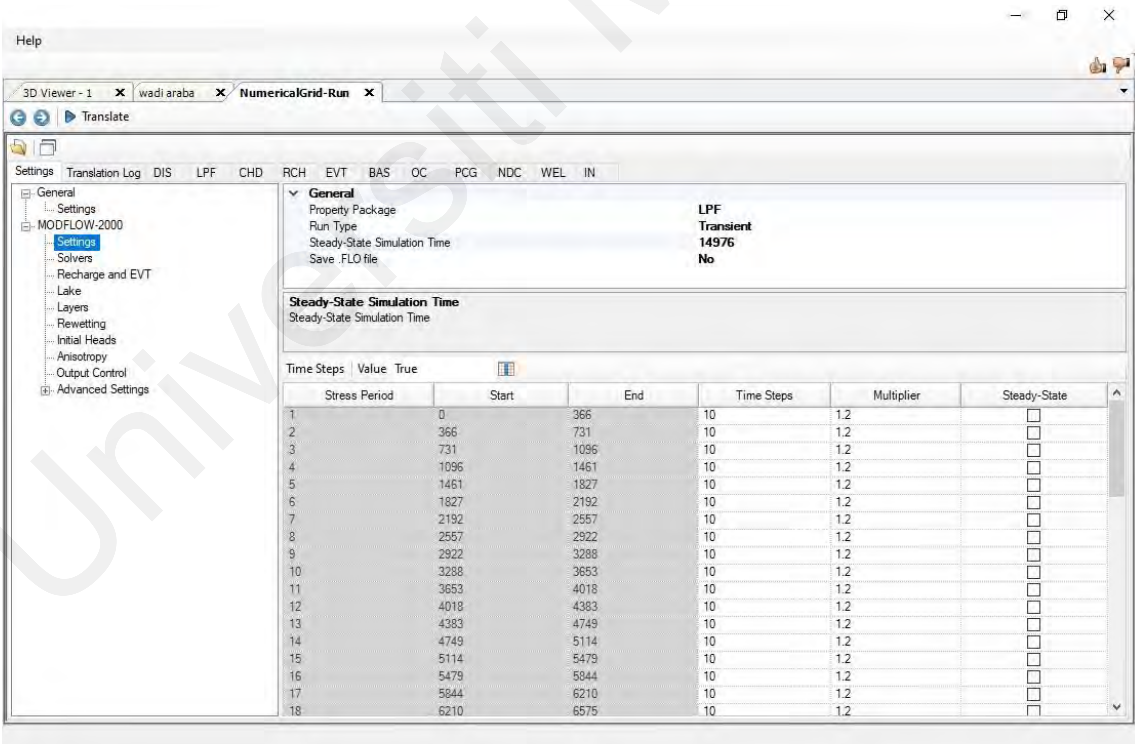


Figure 5.16: Model time discretization setting

5.2.8 Model Run Results

The manual method of trial-and-error parameter adjustment was used to calibrate the model until results were within acceptable tolerance of the observations. Changing the conductivity values yields the calibration curve. The scatter plot of computed versus observed head for observation wells, the calculated and observed water levels in most of the wells are in good agreement. The model's run-time error was reduced by calibration, Figure 5.17 illustrates calculated vs observed head.

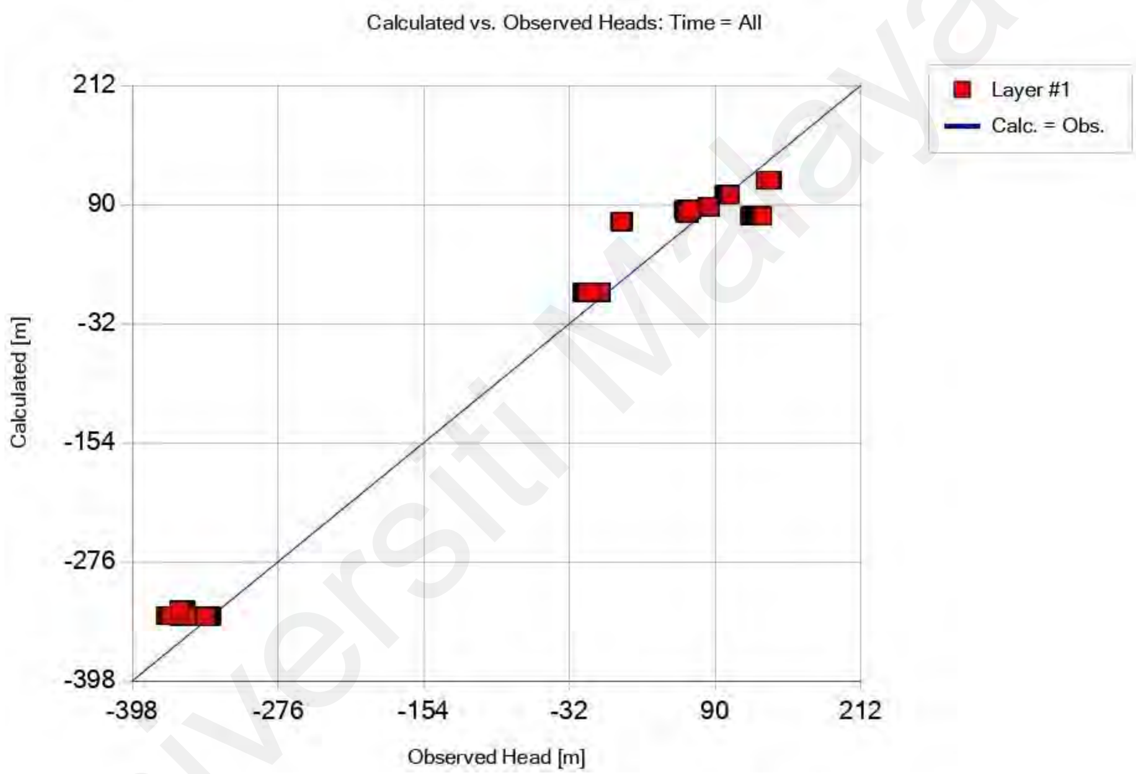


Figure 5.17: Calculated vs observed head.

The north-central portion of the Wadi Araba Valley's groundwater distribution shows a clear divide where groundwater flows in two different ways. The groundwater in the northern portion of the valley flows in the direction of the Dead Sea, toward the north-northeast. On the other hand, the groundwater in the southern half of the valley moves in the direction of the Red Sea, flowing in the south-southwest. These flow patterns are accurately represented by the head contour maps displayed in Figures 5.18 and 5.19.

These head contour maps provide a comprehensive view of the regional groundwater levels in the Wadi Araba Basin, which is consistent with the conceptual hydrogeological model described earlier. Additionally, these maps offer valuable insights into the flow directions within the Alluvial Aquifer, providing a realistic representation of the hydrogeological dynamics in the area.

By understanding the groundwater flow patterns and distribution, researchers can make informed decisions and develop effective strategies for groundwater management and utilization in the Wadi Araba Basin. These hydrogeological insights are vital for ensuring sustainable water resource planning and conservation in the region.

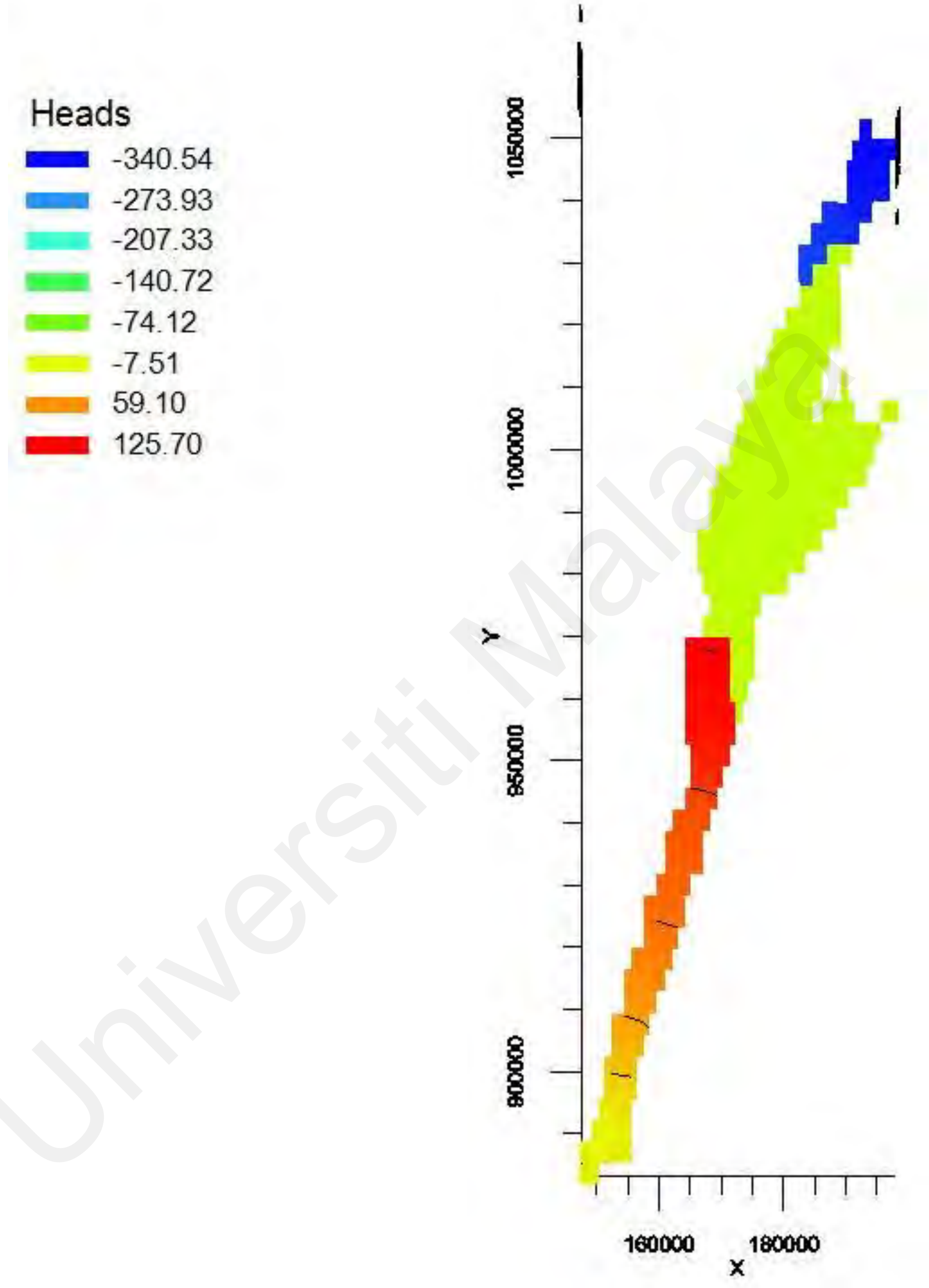


Figure 5.18: Groundwater heads of Alluvial aquifer

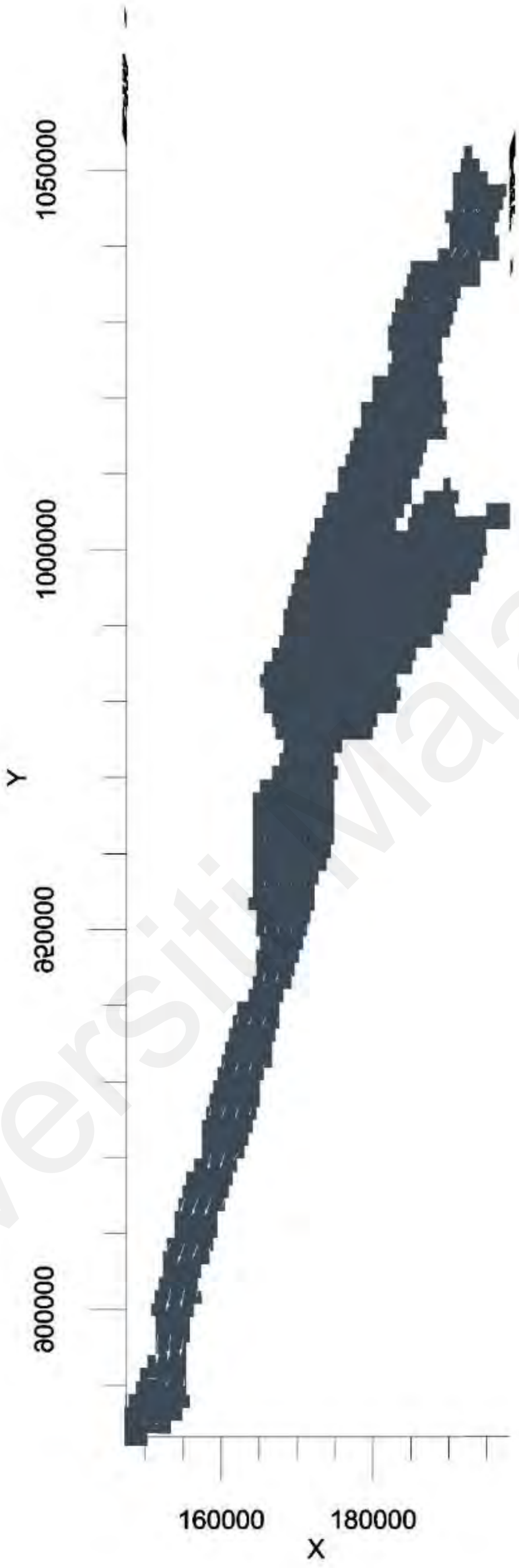


Figure 5.19: Groundwater flow direction map

The calculated groundwater budget from the model simulation highlights that the primary source of inflow into the aquifer system is precipitation infiltration. This finding reinforces the significance of rainfall as a crucial factor in creating Managed Aquifer Recharge (MAR) suitability maps. Understanding the relationship between precipitation and aquifer recharge is essential for effective groundwater management and planning.

Given the importance of rainfall in groundwater recharge, it becomes essential to investigate the potential effects of climate change on precipitation patterns. Future scenarios that reflect anticipated changes in climate can help predict the amount of rainfall that will be available for aquifer recharge in the future.

By conducting such investigations, researchers can gain insights into how climate change may impact groundwater recharge rates and the overall availability of groundwater resources. This information is crucial for developing adaptation strategies and sustainable water management practices to cope with potential changes in rainfall patterns and ensure the long-term viability of aquifer systems in the Wadi Araba Basin.

5.2.9 Model Prediction

In order to evaluate how groundwater recharge would alter in the future under various climate change scenarios, hydrological models are used. Reduced precipitation, maximum temperature, rise, drought/dry days, and evaporation are the primary climate-related risks to the water sector. The water sector will be affected by the increased evaporation and decreased rainfall in a number of ways, including less recharge and consequently less replenishment of surface water and groundwater supplies, which would cause substantial soil deterioration that may eventually end in desertification. As the population grows, the economy develops, and more refugees arrive, the effects of climate change on water demands are becoming more pronounced. Jordan's water industry is incredibly vulnerable to climate change, particularly to temperature rise, precipitation decline, and increased evapotranspiration. Eight climate models' combined output for three time periods (2020–2050, 2040–2070, and 2070–2100) indicates a large increase in temperature and consequently in evaporation. (Change, 2018). Additionally, the results point to decreased precipitation and, consequently, drought. The availability and distribution of water resources in Jordan as well as the study area will be put under additional stress as a result of this large change in the potential evaporation. Based on extensive historical data from the Ministry of Water and Irrigation (MWI) and the Jordanian Meteorology Department (JMD), climatic variables are significantly changing at the national and station levels, indicating that climate change is becoming more obvious. The dynamic projections predict a drier climate with a medium degree of confidence. Using the RCP 4.5 scenario and the RCP 8.5 scenario, respectively, the cumulated precipitation in 2070-2100 might drop by 15% [-6% to -25%] and by - 21% [-9% to -35%]. In the southern region of the nation, the decline would be more pronounced, as shown in Figure 5.20

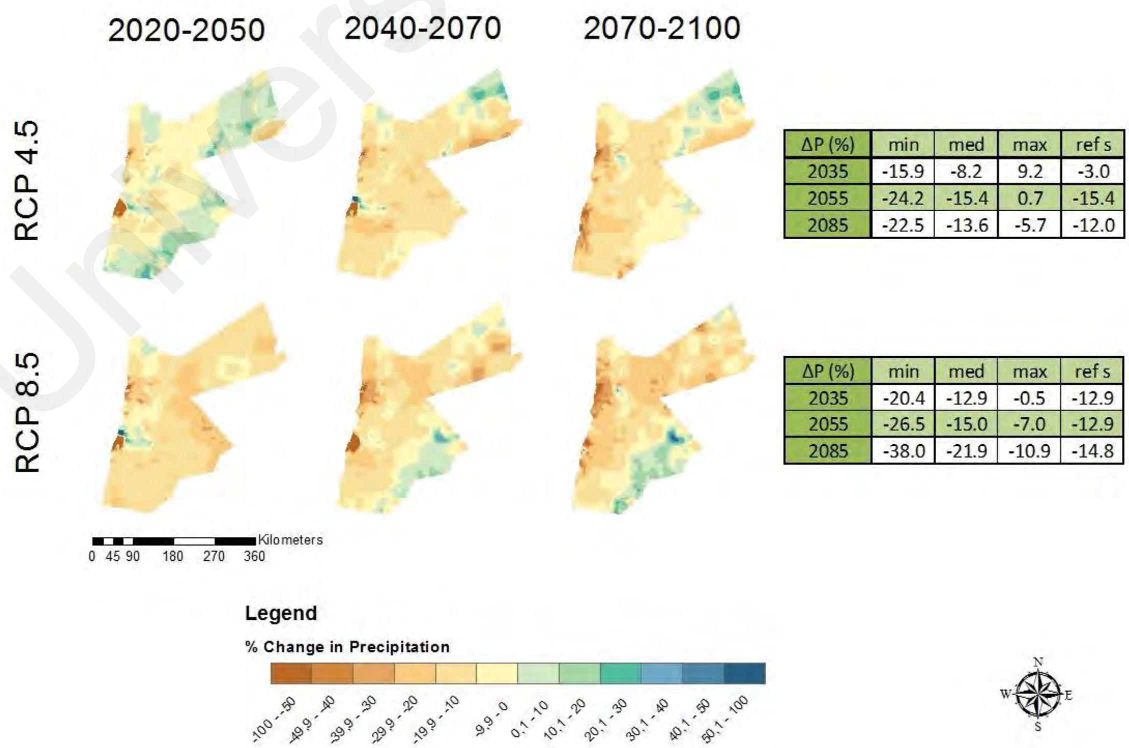


Figure 5.20: Changes in annual precipitation over Jordan for 2020 - 2100 times-period for RCP 4.5 and 8.5 (MOPIC, 2021).

Based on the existing abstraction, additional model scenarios covering the years 2020–2050 were conducted. According to the MAR site selection map, the 30-year period was separated into the 2030, 2040, and 2050 time periods, with rainfall reductions of 10% and 30% for each scenario. Table 5.8 shows model predictions for monitoring wells inside the proposed MAR locations.

Table 5.8: Groundwater level changes (2020-2050) of the monitoring wells according to the predictive scenarios

MAR sites	Observation Well	Present Condition Water Level (amsl) (calibrated model)	Scenario 1 (Rainfall -10%) WL(amsl)						Scenario 2 (Rainfall -30%) WL(amsl)					
			2030	%	2040	%	2050	%	2030	%	2040	%	2050	%
Site 10	DA1011	-336.02	-341.33	-1.58	-345.47	-2.81	-350.25	-4.23	-344.41	-2.5	-349.8	-4.11	-352.63	-4.94
	DA1012	-358.21	-362.03	-1.06	-365.64	-2.07	-367.38	-2.56	-367.44	-2.58	-372.2	-3.89	-380.31	-6.17
	DA1013	-352.84	-363.04	-2.89	-366.27	-3.81	-369.09	-4.61	-368.7	-4.49	-371.9	-5.39	-379.21	-7.47
	DA1019	-365.09	-371.02	-1.62	-375.41	-2.83	-382.22	-4.69	-376.68	-3.17	-381.6	-4.52	-390.71	-7.02
Site 12	DA1032	-358.68	-361.58	-0.8	-366.16	-2.09	-369.4	-2.99	-368.67	-2.79	-373.4	-4.11	-380.55	-6.1
Site 9	DA3028	-80.31	-83.18	-3.57	-86.5	-7.71	-89.11	-11	-85.03	-5.88	-88.74	-10.5	-92.68	-15.4
Site 16	DF1003	72.44	74.96	-3.47	77.42	-6.87	80.86	-11.6	77.53	-7.03	80.41	-11	85.35	-17.8
Site 19	DA3005	183.7	185.22	-0.82	187.19	-1.9	190.15	-3.51	188.46	-2.59	192.3	-4.68	195.67	-6.52
Site 8	EA1011	136.22	139.68	-2.54	143.85	-5.6	146.46	-7.52	142.55	-4.65	146.08	-7.24	149.34	-9.63
Site 14	EA1026	85.38	88.96	-4.19	92.65	-8.51	95.08	-11.4	89.47	-4.79	94.36	-10.5	99.89	-17
Site 5	EA3004	66.72	67.92	-1.79	68.84	-3.18	70.24	-5.28	68.35	-2.44	70.16	-5.16	73.2	-9.71
	EA1015	129.9	130.69	-0.6	132.15	-1.73	133.69	-2.92	132.21	-1.78	133.96	-3.13	135.16	-4.05

As shown on the table the maximum drawdown -15.4%, -17.8%, and -17% occurs in site 9, 16, and 14, respectively, in the middle part of the aquifer, impacted by rainfall decreasing which play a role on the aquifer recharge due to the climate change effect, these location as per MAR suitability map and field investigation considered as one of the most reliable locations to apply MAR technique.

In general, the alluvial aquifer drawdown stabilises over the duration of the model predictions in all scenarios this most likely caused by the constant head boundary along the Red and Dead Sea. Predictive simulation presents the effect of climate change in the study area due the drawdown shows on the observation wells.

One more scenario has been conducted to examine MAR efficiency to mitigate the drawdown in the water table, by increasing the recharge caused by precipitation, assuming that we are able to increase the recharge from precipitation by 10% from the current situation for the next 30 years. Results based on these scenario shows that the water table increase in site 16, 14, and 9 by 2.3%, 3.12%, and 1.96% respectively, while approximately stay at the same rate on the other sites, this leads us to the result that, sites 16, 14, and 9, as shown in Figure 5.21, considered to be one of most affected by climate change effect, and at the same time it was one of the sites most responsive to apply the MAR.

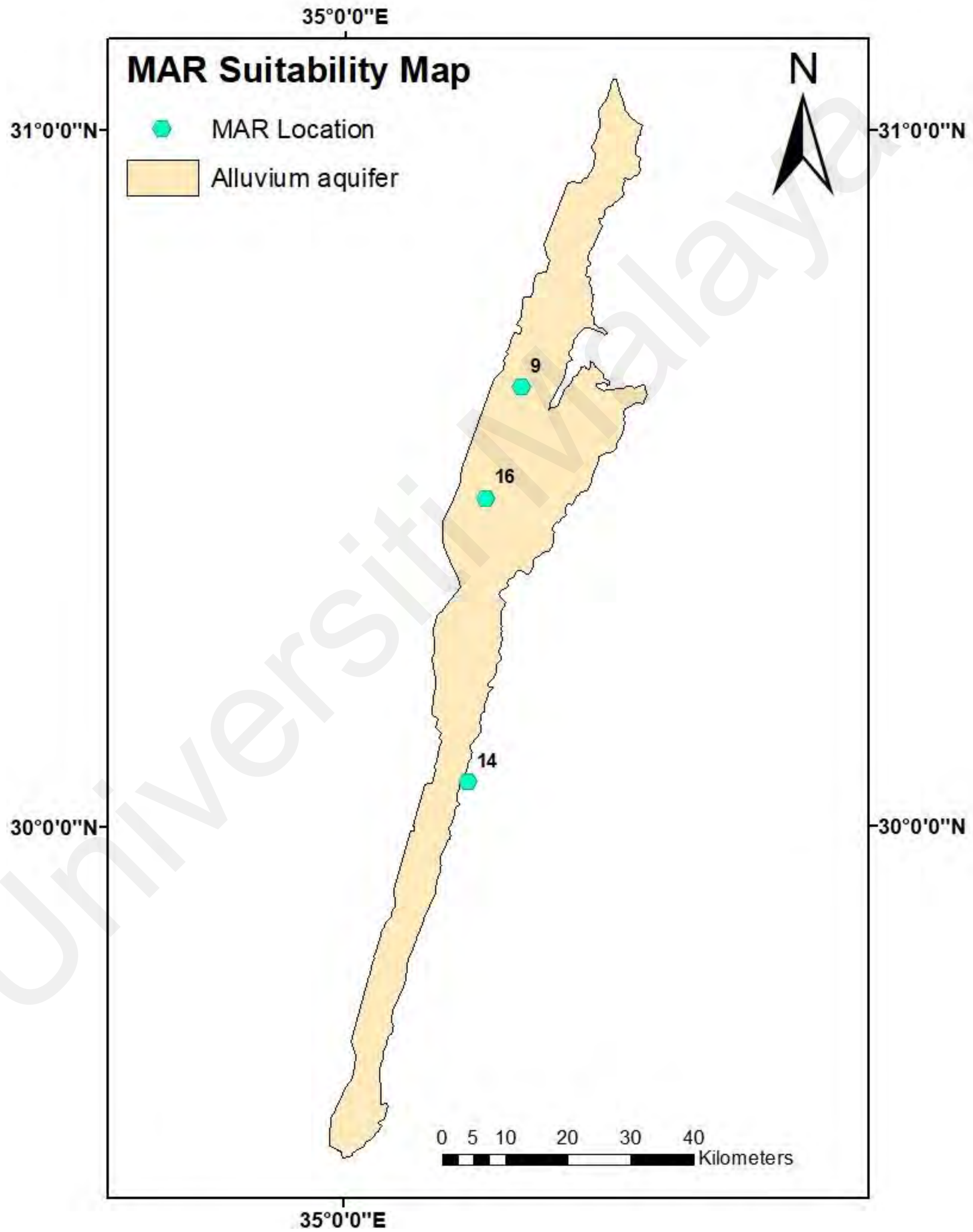


Figure 5.21: MAR suitable locations based on groundwater modeling.

5.3 Discussion

5.3.1 Introduction

High evaporation rates and precipitation variability in semi-arid environments make surface water discharge unpredictable. Hence, groundwater is used to meet agricultural and household needs. Several semi-arid countries have exploited groundwater resources, causing groundwater levels to drop due to low natural groundwater recharge. Spring and shallow wells dryness and salty water ingression might result. Population growth and living standards will raise demand. Climate change and source pollution will reduce supplies. Drilling deeper wells, higher pumping lift, creating new resources like water desalination, and long-distance water transport raise water supply costs and degrade groundwater-dependent ecosystems. Indeed, the management of water resources is a crucial and pressing concern, especially for countries situated in arid and semi-arid regions. Managed Aquifer Recharge (MAR) presents an effective and sustainable approach to enhance water availability by augmenting the natural recharge of groundwater resources.

This study employed groundwater modeling and a geographic information system (GIS) to evaluate the suitability of MAR sites in the Wadi Araba region. GIS offers helpful spatial data analysis capabilities that make it possible to find potential locations that are most suitable for MAR implementation.

Furthermore, the study investigated the potential impacts of climate change on the water balance of the region. By understanding the potential effects of climate change on precipitation patterns, researchers can evaluate how these changes may influence groundwater recharge rates and overall water availability.

The integration of GIS and groundwater modeling techniques allows for a comprehensive analysis of MAR suitability and the impact of climate change on water resources in the

Wadi Araba basin. The insights gained from this study can serve as a foundation for developing informed water resource management strategies and policies to address future water challenges in the region. By adopting sustainable practices like MAR, countries can work towards ensuring the long-term availability and equitable distribution of water resources for their communities and ecosystems.

5.3.2 Managed Aquifer Recharge

Managed Aquifer Recharge (MAR) is a technology that helps address the challenges of climate change in arid and semi-arid regions (Salameh et al., 2019). By enhancing natural groundwater recharge, MAR supports sustainable urban water management (Ayuso-Gabella et al., 2011; Luyun Jr et al., 2011; Page et al., 2012; Miotliński et al., 2014; Radcliffe et al., 2017; Tredoux et al., 2020). It offers a reliable water source and helps mitigate water scarcity, making it an important adaptation strategy for climate-related water challenges. MAR, together with demand reductions and other management strategies, can reduce these local consequences. In these regions, MAR reduces surface storage issues such as evaporation losses, space needs, algae blooms, and pollution by creating a huge free storage space from over-abstraction.

Various human activities can contribute to the enhancement of aquifer recharge, which can be categorized into different types. Unintentional recharge occurs as a result of land clearance, removal of deep-rooted vegetation, deep seepage in irrigation areas, and leakage from urban storm drains and sewers (Jiménez et al., 2012). On the other hand, unmanaged recharge involves storm water drainage wells, sumps, and septic tank drain fields, typically used for water disposal without recovery or reuse (Vanderzalm et al., 2011). In contrast, managed recharge involves the deliberate implementation of recharge structures such as injection wells and infiltration basins, with the aim of subsequent recovery, utilization, or storage to benefit the aquifer and its environment (Greskowiak et al., 2006; Pavelic et al., 2007; Van Houtte et al., 2012; Kvitsand et al., 2017). These different approaches to aquifer recharge demonstrate the range of techniques and strategies available for effectively managing and utilizing water resources. Infiltration basins are appropriate for unconfined aquifers and are capable of handling recharged water of low quality. For confined aquifers, injection wells are necessary, but they also need high-quality recharge water. If the surface layers are impermeable, infiltration trenches or wells can be utilized, but they also need high-quality recharge water because backflushing is not an option. Infiltration basins are the favoured technique in (semi-arid) locations with a harsh climate, a sparse population, low financial resources, and abundant land availability.

Studies conducted several themed maps were made and overlaid according to the scale and data availability. While other research focused primarily on aquifer features, several studies also considered the distance between supply and demand or the availability of source water. For each parameter, studies most commonly utilize 2 to 4 classifications. To establish a rating for a parameter, linear or other functions may also be used. Most research utilizes some criteria with Boolean overlay to remove unsuitable locations, however, some studies just did a qualitative overlay without giving weights. In recent years, the application of GIS and remote sensing techniques has gained significant prominence in conducting extensive investigations. The effectiveness of this approach relies on the chosen scale as well as the availability of information and input data. Utilizing GIS and remote sensing can provide valuable insights into the existing data gaps, identify areas for additional monitoring, and determine the preferred or neglected zones for further research (Steinel et al., 2016). The methodology involves generating thematic maps based on the available data or informed assumptions, where each parameter or requirement is categorized and assessed based on numerical or linguistic quantifiers. These thematic maps are then overlaid, allowing for statistical analysis by assigning weights to each map or subjectively using a limited number of thematic maps

(Alraggad & Mohammad, 2010). The conventional data processing techniques for site selection in Managed Aquifer Recharge (MAR) projects can be challenging and time-consuming due to the vast amount of geographical data that needs to be collected, integrated, and analysed (Anbazhagan et al., 2005). In several groundwater management studies, land use appropriateness mapping, and other geographical research endeavors, GIS and remote sensing technologies have been widely used, both separately and in combination, to efficiently process, integrate, and analyze spatial data (Krishnamurthy et al., 1996). GIS and remote sensing have been extensively used in the selection of MAR sites. (Saraf and Choudhury, 1998; Brown et al., 2008; Ghayoumian et al., 2007; Werz et al., 2009). Groundwater recharge is influenced by the annual average precipitation, hydrological variables, local geology, slopes, and soil type. The level of the groundwater rises as precipitation increases. There is no consensus about the standards, ratios, or methods to be applied in the selection of MAR sites. There are many other categorization and weighting methods. This may be influenced by the availability of data, local characteristics, professional opinion, and the formulation of the problem, the only water that may be used for MAR is water that would otherwise evaporate or run off unused without fully replenishing an aquifer. Wadi Araba area is characterized by a unique geological and hydrogeological setting, which necessitates careful consideration of various criteria to identify suitable sites for MAR. Rainfall is the primary source of water in the region, making it an essential factor in the selection process. The study area is also marked by a distinct topography, with highland areas in the east and flat terrain in the west, which can have a significant impact on the suitability of a site for MAR.

The soil's texture, which influences the permeability of the soil and its capacity to let water infiltration to the aquifer, should also be taken into account. Aquifer availability is greatly influenced by the hydrogeological formations found in the studied area. Moreover, the unsaturated thickness between the surface and water table, known as the depth to water table, is a vital consideration for identifying suitable MAR sites. The greater the unsaturated thickness, the more available area there is to store water.

Lastly, land use is an important factor to consider as it can affect the infiltration and runoff of water. Land use changes, such as urbanization and deforestation, can have a significant impact on the hydrological cycle and the availability of water for recharge. By considering these various criteria, the study was able to generate a comprehensive MAR suitability map for the Wadi Araba area, which can inform future groundwater management and help mitigate the impacts of climate change on water resources. These layers were integrated into GIS software to generate a MAR suitability map for the study area. The results showed that the Wadi Araba area falls into five categories of MAR potential zones, ranging from very good to very low. Approximately 16.7% of the area 1473.7 km^2 was classified as having very good potential for MAR, while 30.15% of the area 2649.5 km^2 was classified as having a good potential. An area of 1779.3 km^2, representing 20.24% of the study area, was classified as having moderate potential, while 32.82% of the area 1944.24 km^2 and 890.94 km^2 were classified as having low and very low potential, respectively MAR site selection map generated in this study highlights that the majority of the promising sites for MAR are located within the alluvium aquifer in the western part of the study area. This is mainly because the alluvial deposits in this region are characterized by their high permeability and porosity, which are essential properties for efficient water infiltration and storage in the subsurface. In addition, the absence of steep slopes in this area enhances the suitability of these sites for MAR, as it reduces the risk of runoff and erosion that can hinder infiltration and reduce the effectiveness of recharge. Furthermore, the suitability of these sites is also influenced by soil texture, which is an important factor in determining the infiltration rate and water holding capacity of the subsurface. The alluvial deposits in the western part of Wadi Araba are characterized by their coarse and well-sorted texture, which facilitates the infiltration of water and provides an acceptable ratio of permeability to allow water to infiltrate to the aquifer. Absolutely, the depth of the water table is a crucial criterion in the selection of suitable sites for Managed Aquifer Recharge (MAR). It directly influences the available storage capacity for storing recharged water. In the alluvium aquifer of Wadi Araba, the depth to the water table is relatively shallow. This characteristic is highly advantageous for MAR initiatives as it enhances the availability of water for recharge. A shallow water table means that groundwater is closer to the surface, making it more accessible for recharging.

Additionally, the shallow water table makes it easier to build and use MAR facilities. It simplifies and lowers the expense of pumping water from greater depths, improving the process' sustainability and effectiveness.

Considering the appropriate depth of the water table is essential in MAR site selection, as it allows for optimal utilization of available aquifer storage capacity. With a shallow water table in the alluvium aquifer of Wadi Araba, MAR can be a viable and effective solution to improve water availability and contribute to sustainable water resource management in the region.

In summary, the selected criteria for MAR site selection in this study, including rainfall, slope, geological formations, land use, soil texture, and depth to the water table, have all contributed to the identification of promising sites for MAR in Wadi Araba, with most of these sites located within the alluvium aquifer in the western part of the study area. These sites have been found to fit well with the selected criteria due to their high permeability and porosity, absence of steep slopes, suitable soil texture, and appropriate depth to the water table, which enhance their suitability for MAR. The study conducted a field investigation to validate the results obtained from the GIS-based MAR site selection process. The investigation involved selecting 20 sites that were identified by the GIS as suitable for MAR and comparing the results with the actual field conditions. The study found that 85% of the selected sites were suitable for MAR, which indicates the reliability and accuracy of the GIS-based site selection process. Furthermore, it is worth noting that most of the promising sites selected by the GIS were located within the alluvium aquifer, which is consistent with the selected criteria for site suitability. The availability of water, suitable soil, appropriate depth of water table, and absence of slopes in the alluvium aquifer make it an ideal location for MAR implementation. Therefore, the GIS-based site selection process proved to be an effective tool for identifying suitable locations for MAR, and the field investigation confirmed the validity of the results obtained.

5.3.3 Groundwater Modeling

Groundwater flow models have been used as interpretive tools to examine flow patterns and groundwater system dynamics, assimilation tools to examine how stresses affect the groundwater system, assessment tools to evaluate recharge, discharge, and aquifer storage processes, and predictive tools to foresee future conditions or the effects of human activity (Ramireddygari et al., 2000; Mao et al., 2005; Zhang et al., 2012). In addition, they can serve as screening tools for analyzing groundwater development scenarios, management tools for reviewing potential policies, and visualization tools for conveying important signals to the general public and decision-makers (Uddameri & Kuchanur, 2007; Valley, 2009). To comprehend the dynamics of aquifer systems, quantify subsurface water flow, and simulate the results of different actions or situations, numerical groundwater models are frequently utilized. These models are often used by researchers and hydrogeologists to address a variety of groundwater-related issues.

Some common applications of numerical groundwater models include; Analyzing excessive groundwater withdrawal from irrigation and assessing groundwater availability, studying groundwater-related subsidence, such as land sinking due to excessive groundwater extraction, valuating density-dependent flow phenomena, such as saltwater intrusion in coastal areas, and, supporting decision-making processes related to water management and allocation, helping make informed choices for sustainable water use.

Numerical groundwater models play a pivotal role in advancing our understanding of groundwater systems and assist in developing effective water management strategies. By considering different factors, scenarios, and potential impacts, these models provide valuable insights for addressing water resource challenges and fostering sustainable groundwater management practices. The cited references (Shearer, 1998; Larson et al., 2001; Calvache & Pulido-Bosch, 1997; Sherif et al., 2012; Kourgialas et al., 2016; Zhang et al., 2012; Ramireddygari et al., 2000; Mao et al., 2005; Uddameri & Kuchanur, 2007; Valley, 2009; Zhou, 2009) highlight the diverse applications and significance of numerical groundwater models in the field of hydrogeology.

A groundwater flow model was constructed based on the existing geology and hydrogeology within the research area to better understand and manage the Wadi Araba aquifer system. For the purpose of managing the alluvium aquifer over the long term, the model was utilized to generate predicted scenarios. A northern sub-Basin and a southern sub-Basin exist inside the Wadi Araba Basin. About 75 km to the north-northeast of Aqaba, the drainage divide between the two is located to the north of Qa' es Sai'diyeen on the western side of Jabal Ar-Risha and overlaps with the groundwater divide. Groundwater level and flow direction maps indicate that groundwater from the north-central region of the Wadi Araba Valley, where there is a groundwater division and outflow is in two directions, originates from the southern sub-Basin, which drains into the Gulf of Aqaba, and the northern sub-Basin, which drains into the Dead Sea. Groundwater in the northern part of the valley flows in a north-northeaste direction, toward the Dead Sea. On the other hand, groundwater flows south-southwest, toward the Red Sea, in the southern portion of the valley.

While creating MAR suitability map, rainfall has been given the highest weight, that's agreed with the calculated groundwater budget from the model simulation which shows that the primary inflow into the system comes from infiltration from precipitation, this result gives a strong motivation to study the effect of climate change on the groundwater recharge in the study area.

Hydrogeological research is challenged by the predicted effects of climate change on groundwater recharge because there are still many unanswered questions, especially in arid and semi-arid regions, about how groundwater resources will react to changes in the hydrological cycle through precipitation, evaporation, runoff, and soil moisture in both the present and the past. The evaluation of potential changes in groundwater recharge using hydrological models provides vital insight into the effects of various climate change scenarios. While the recharging of groundwater is highly dependent on forecasted changes in precipitation, there is a strong link between the two. This study aims to present a climate change and its implications on precipitation and Managed Aquifer Recharge over the Alluvium aquifer of Wadi Araba using groundwater MODFLOW under RCP 4.5 and 8.5 climate change scenarios from 2020 to 2050, as well as a scenario by increasing recharge on the study area to examine MAR's (infiltration basin) ability to adapt to climate change effects and enhance aquifer recharge using groundwater MODFLOW modeling method under transient state condition.

Findings based on these scenarios indicate a variation in the water table at three locations owing to changes in precipitation, a withdrawal in the water table in all climate change scenarios from 2020 to 2050, and a rise in the water table by enhancing the recharge when MAR is used. In conjunction with demand reductions and other management strategies, MAR can be a helpful strategy for mitigating these negative effects at the local level. In addition to the fact that MAR is not a substitute for demand control, further groundwater resources management would be beneficial in addressing groundwater over-abstraction.

Groundwater is a vital resource for meeting local demand and maintaining ecosystems, with one-third of all freshwater withdrawals worldwide coming from groundwater sources. However, climate change has a significant impact on the quantity and quality of available water resources, putting water supplies, natural ecology, and other aspects at risk (Erwin, 2009). The simulations conducted in this study showed that the maximum drawdown occurred in the middle part of the aquifer, with a decrease of 15.4%, 17.8%, and 17% in sites 9, 16, and 14, respectively, due to the impact of decreasing rainfall on aquifer recharge. These locations, identified as one of the most reliable to apply MAR technique, have also been identified as the most affected by climate change.

Moreover, the study found that alluvial aquifer drawdown stabilizes over the duration of the model predictions in all scenarios due to the constant head boundary along the Red and Dead Sea. Predictive simulations also revealed that the effect of climate change in the study area is evident, as drawdown was observed in the observation wells. To examine the effectiveness of MAR to mitigate the drawdown in the water table, the study conducted an additional scenario, assuming a 10% increase in recharge from precipitation for the next 30 years. Results showed an increase in the water table at sites 16, 14, and 9 by 2.3%, 3.12%, and 1.96%, respectively, while remaining approximately the same rate on other sites. This finding indicates that sites 16, 14, and 9, which are considered the most affected by climate change, are also the most responsive to applying MAR techniques. These findings are consistent with previous studies that have used hydrological models, such as MODFLOW, to evaluate future changes in groundwater recharge under various climate change scenarios (Allen et al., 2004; De Wit et al., 2001; Scibek & Allen, 2006; Woldeamlak et al., 2007). By predicting changes in precipitation, these models provide valuable information for integrated water management and for reducing potential harm caused by the impact of climate change on groundwater availability (Taylor et al., 2013).

In conclusion, the impact of climate change on groundwater resources is a growing concern, and it is essential to better forecast future climatic conditions and their impact on water resources. The Wadi Araba aquifer's vulnerability to climate change highlights the need for effective management strategies to ensure sustainable use of this vital resource. MAR techniques offer a promising solution to mitigate the effects of climate change on groundwater levels, particularly in areas such as sites 16, 14, and 9, which are most vulnerable to its impact.

CHAPTER 6: SUMMARY, CONCLUSION, AND RECOMMENDATIONS

The most dependable source of water supply in Jordan, as in many other arid and semi-arid regions, is groundwater. Due to the country's declining natural water resources and its primarily dry and semi-arid environment, there is currently a sizable imbalance between water supply and demand, which puts further stress on water resources. Jordan has 12 groundwater basins, making groundwater the most important source of water, it meets more than half of the country's water needs, most renewable groundwater reservoirs are used at rates that are higher than their sustainable yield. The current study aims to implement Managed Aquifer Recharge (MAR), which is one of the solutions to deal with water scarcity and try to mitigate the effects of climate change and improve the water situation as much as possible, by determining suitable locations for MAR using the GIS and Groundwater flow model techniques. Additionally, the study examines the impacts of implementing Managed Aquifer Recharge (MAR) on present-day groundwater levels and anticipates its effects in the future, considering well-defined scenarios.

6.1 Summary

As a result of research carried on through this study, this thesis can be summarized within the main goals of the research:

1- Determination of suitable locations for MAR using the GIS
2- Study the effectivity of MAR on groundwater levels as a long-term solution of climate change effect through developing Groundwater model of the study area.

To create a Managed Aquifer Recharge potential map of the Wadi Araba basins. Various thematic maps of Wadi Araba, such as rainfall, slope, and soil geology, have been created. These layers have been integrated via GIS software to create a map of Wadi Araba's MAR suitability using weighted and ranked scores. According to the possibility of (MAR) suitable places, the area is divided into five categories of (MAR) prospective zones, namely very good, good, moderate, low, and very low.

Based on this study, it is found that approximately 47% of Wadi Araba basin falls into very good and good category of MAR suitability, while 32.8% under the low and very low MAR suitability category.

In aim to enhance the understanding and appraisal of the Wadi Araba Aquifer systems, in terms of MAR and climate change effect, a groundwater model has been generated, include all data have been gathered through research phases, and calibrated for period 1980-2020, three predictive scenarios were conducted in this study to improve forecasting of climate change effect on groundwater recharge from precipitation and abstract till 2050.

Groundwater flows in opposing directions due to a groundwater divide in the Wadi Araba Basin's central area. According to the alluvial aquifer's groundwater level map, groundwater moves northeasterly, toward the Dead Sea, in the valley's northern half. In contrast, groundwater flows south-southwest, toward the Red Sea, in the southern part of the valley. The Wadi Araba Basin's hydrogeological system is complicated, as seen by this distinctive groundwater flow pattern.

The calculated groundwater budget from the model simulation shows that the primary inflow into the system comes from infiltration from precipitation, according to computed versus observed head, which showed that there is a clear agreement between the calculated and observed water levels in most of the wells. The highest drawdown of the alluvial aquifer occurs at site 9, with a magnitude of -15.4%, followed by site 16 (-17.8%) and site 14 (-17%), located in the middle part of the aquifer. These areas are particularly impacted by the decreasing rainfall, which hinders aquifer recharge due to the effects of climate change. Based on the MAR suitability map and field investigation, these locations are considered reliable for implementing MAR techniques. An additional scenario was conducted to evaluate the efficiency of MAR in mitigating water table drawdown by increasing precipitation recharge by 10% over the next 30 years. The results of this scenario indicate a water table rise of 2.3% at site 16, 3.12% at site 14, and 1.96% at site 9, while the water table levels at other sites remain relatively stable. This underscores that sites 16, 14, and 9 are the most suitable locations for implementing MAR techniques, considering their potential to counteract drawdown effects and their identification in the MAR suitability map and field investigation.

6.2 Conclusion

The output of this study can be concise as per next:

- Groundwater overexploitation on parts of the alluvium aquifer within Wadi Araba can be mitigate through a sustainable solution represented by Managed Aquifer Recharge (MAR).
- MAR is not a substitute for demand management in resolving groundwater over abstraction, additional groundwater resources management should be affective.
- Infiltration by precipitation is the main source of water to recharge alluvium aquifer, whether artificially or naturally.
- Rainfall, slope, hydrological formation, Soil texture, land use, and unsaturated thickness are the main criteria that play essential role in MAR site selection in Wadi Araba, as per this study.
- Wadi Araba (MAR) potential map shows that 16.7% with area of 1473.7 km^2 and 30.15% as 2649.5 km^2 area is under very good and good category of (MAR) suitability respectively. An area of 1779.3 km^2 represent 20.24% is found under moderate category whereas 1944.24 km^2 and 890.94 km^2 equals 32.82% of Wadi Araba area falls under low and very low category of (MAR) suitability.
- Groundwater levels in the modeled area clearly affected by climatic change as a result of decreasing in rainfall, the simulations conducted in this study showed

that the maximum drawdown occurred in the middle part of the aquifer, with a decrease of 15.4%, 17.8%, and 17% in sites 9, 16, and 14, respectively, due to the impact of decreasing rainfall on aquifer recharge.

- Three main locations in the middle of alluvium aquifer considered as the most suitable locations to apply MAR in term of GIS and groundwater modeling.
- Indeed, based on the groundwater modeling, the Wadi Araba Basin's central part exhibits a groundwater divide. In this region, groundwater flow directions diverge, resulting in different flow paths. In the northern part of the basin, groundwater flows towards the Dead Sea, while in the southern part, it moves towards the Red Sea in the south. This groundwater divide indicates the separation of flow directions in the central area, contributing to the understanding of the hydrogeological dynamics within the Wadi Araba Basin.

6.3 Recommendations

The findings of this study recommend taking the following factors into account for current and future research:

1- The outputs of this study should be considered in water resources management or climate change effects reduction plans in Wadi Araba.

2- Due to the lack of information from the other layers, Sandstone, B2/A7, and A1/6, it is advised to drill new observation wells on all Wadi Araba aquifers. This would increase knowledge of the water level and provide more information about the hydraulic parameters.

3- Another flow model recommended cover the whole Wadi Araba aquifers system to understand the hydraulic system and the interaction between the different aquifers.

4- A transport and contaminate model will be required to provide long term monitoring and management of Wadi Araba.

5- It is strongly advisable to enhance the utilization and presentation of the available data by the Ministry of Water and Irrigation (MWI). Expanding beyond yearly budgets, providing more detailed interpretations of the data can offer valuable insights and aid in better decision-making processes. Access to comprehensive and well-interpreted data can contribute significantly to improving water resource management, sustainable planning, and addressing water-related challenges effectively.

REFERENCES

Abdelhamid, G. (1988). *Jabal Umm Ishrin Sheet, 3049 II, 1:50,000 geological map series*.

Abed, A. M. (2000). *Geology of Jordan*. Jordanian Geologists Association.

Al-Adamat, R., Diabat, A., & Shatnawi, G. (2010). Combining GIS with multicriteria decision making for siting water harvesting ponds in Northern Jordan. *Journal of Arid Environments*, *74*(11), 1471–1477.

Al-Kharabsheh, A. (1995). *Possibilities of artificial groundwater recharge in the Azraq Basin: potential surface water utilization of five representative catchment areas (Jordan)*. Friedrich-Schiller-Universität Jena.

Al-Khatib, M. A. M. . (1999). *Development of a groundwater model for the two upper aquifers (shallow and middle) of the Azraq basin*. Jordan University of Science and Technology.

Al khatib, F. (1987). *Geological Map of Al Yamniyya - 2948-1 & Jabal Al Mubarak - 3048-IV, SCALE 1:50,000.*

Allafta, H., Opp, C., & Patra, S. (2020). Identification of groundwater potential zones using remote sensing and GIS techniques: A case study of the Shatt Al-Arab Basin. *Remote Sensing*, *13*(1), 112.

Allen, D. M., Mackie, D. C., & Wei, M. (2004). Groundwater and climate change: a sensitivity analysis for the Grand Forks aquifer, southern British Columbia, Canada. *Hydrogeology Journal*, *12*, 270–290.

Alraggad, M., & Mohammad, A. H. (2010). Managed Aquifer Recharge (MAR) through Surface Infiltration in the Azraq Basin/Jordan. *Journal of Water Resource and Protection*, *02*. https://doi.org/10.4236/jwarp.2010.212125

Alwreikat, L., & Lananan, F. (2022). *The Impact of Climate Change and Variability on Groundwater Resources in Jordan: Literature Review*. *4*, 272–282.

Anandhi, A., Srinivas, V. V, Kumar, D. N., & Nanjundiah, R. S. (2009). Role of predictors in downscaling surface temperature to river basin in India for IPCC SRES scenarios using support vector machine. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *29*(4), 583–603.

Anandhi, A., Srinivas, V. V, Nanjundiah, R. S., & Nagesh Kumar, D. (2008). Downscaling precipitation to river basin in India for IPCC SRES scenarios using support vector machine. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *28*(3), 401–420.

Anderson, M. G., Burt, T. P., & others. (1990). Subsurface runoff. *Process Studies in Hillslope Hydrology.*, 365–400.

Asano, T. (1985). Recharge of Groundwater. *Artificial Recharge of Groundwater*, 1.

ASCE, A. S. of C. E. (2001). *Standard Guidelines for Artificial Recharge of Ground Water* (EWRI/ASCE). American Society of Civil Engineers. https://doi.org/10.1061/9780784405482

Aslam, M. A., Vijay, P. S., & Muhammad, A. S. (2022). Hydrological Modeling of Aquifer’s Recharge and Discharge Potential by Coupling WetSpass and MODFLOW for the Chaj Doab, Pakistan. *Sustainability*, *14*(8), 4421. https://doi.org/10.3390/su14084421

Awawdeh, M., Obeidat, M., Al-Mohammad, M., Al-Qudah, K., & Jaradat, R. (2014). Integrated GIS and remote sensing for mapping groundwater potentiality in the Tulul al Ashaqif, Northeast Jordan. *Arabian Journal of Geosciences*, *7*(6), 2377–2392.

Bandel, K., & Salameh, E. (2013). *Geologic Development of Jordan -Evolution of its Rocks and Life*.

Barakat, H. (1986). *GEOLOGIC MAP OF AYN Al HASHIH 3048-1 , SCALE 1 : 50 , 000*.

Barjous, M. (1987). *Structural Study of the area between Petra and Ash Shawbak*.

Batelaan, O., De Smedt, F., & Triest, L. (2003). Regional groundwater discharge: phreatophyte mapping, groundwater modelling and impact analysis of land-use change. *Journal of Hydrology*, *275*(1–2), 86–108.

Beicip. (1981). *GEOCHEMICAL, STRUCTURAL AND HYDRODYNAMIC FOR EXPLORATION OF THE HYDROCARBONS POTENTIAL OF JORDAN*.

Bender, F. (1975). *Geology of Jordan Supplementary Edition in English with Minor Revision*. Gebrueder Borntraeger.

Black, E., Brayshaw, D., Slingo, J., & Hoskins, B. (2011). Future climate of the Middle East. In S. Mithen & E. Black (Eds.), *Water, Life and Civilisation: Climate, Environment and Society in the Jordan Valley* (pp. 51–62). Cambridge University Press. https://centaur.reading.ac.uk/18242/

Boufekane, A., Saibi, H., Benlaoukli, B., & Saighi, O. (2019). Scenario modeling of the groundwater in a coastal aquifer (Jijel plain area, Algeria). *Arabian Journal of Geosciences*, *12*(24), 1–14.

Bouwer, H, Pyne, R., Brown, J., St Germain, D., Morris, T. M., Brown, C. J., Dillon, P., & Rycus, M. J. (2008). Design, operation and maintenance for sustainable underground storage facilities. *Report, American Water Works Association Research Foundation, Denver, CO*.

Bouwer, Herman. (2002). Artificial recharge of groundwater: hydrogeology and engineering. *Hydrogeology Journal*, *10*(1), 121–142. https://doi.org/10.1007/s10040-001-0182-4

Brodie, R. S. (1998). Integrating GIS and RDBMS technologies during construction of a regional groundwater model. *Environmental Modelling & Software*, *14*(2–3), 119–128.

Burdon, D. J., & Quennell, A. M. (1959). *Handbook of the geology of Jordan : to* *accompany and explain the three sheets of the 1:250,000 Geological map of Jordan east of the Rift*. Government of the Hashemite Kingdom of Jordan.

Calvache, M. L., & Pulido-Bosch, A. (1997). Effects of geology and human activity on the dynamics of salt-water intrusion in three coastal aquifers in southern Spain. *Environmental Geology*, *30*(3), 215–223.

Change, I. P. on C. (2018). *Global warming of 1.5° C: An IPCC special report on the impacts of global warming of 1.5° C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate chang*. Intergovernmental Panel on Climate Change.

Chow, V. Te, Maidment, D. R., & Larry, W. (1988). Mays. Applied Hydrology. *International Edition, MacGraw-Hill, Inc*, *149*.

Chowdhury, A., Jha, M., & Chowdary, V. (2010). Delineation of groundwater recharge zones and identification of artificial recharge sites in West Medinipur district, West Bengal, using RS, GIS and MCDM techniques. *Environmental Earth Sciences*, *59*, 1209–1222. https://doi.org/10.1007/s12665-009-0110-9

Clapp, R. B., & Hornberger, G. M. (1978). Empirical equations for some soil hydraulic properties. *Water Resources Research*, *14*(4), 601–604.

Corwin, D. L., & Wagenet, R. J. (1996). Applications of GIS to the modeling of nonpoint source pollutants in the vadose zone: A conference overview. *Journal of Environmental Quality*, *25*(3), 403–411.

De Wit, M., Warmerdam, P. M. M., Torfs, P., Uijlenhoet, R., Roulin, E., Cheymol, A., Van Deursen, W., Van Walsum, P. E. V, Ververs, M., & Kwadijk, J. (2001). *Effect of climate change on the hydrology of the river Meuse*. Wageningen University.

Dillon, P. (2005). Future management of aquifer recharge. *Hydrogeology Journal*, *13*(1), 313–316. https://doi.org/10.1007/s10040-004-0413-6

Döll, P., Hoffmann-Dobrev, H., Portmann, F. T., Siebert, S., Eicker, A., Rodell, M., Strassberg, G., & Scanlon, B. R. (2012). Impact of water withdrawals from groundwater and surface water on continental water storage variations. *Journal of Geodynamics*, *59*, 143–156.

DOM, (Department of Meteorology). (2017). *Publications and files of the Department of Meteorology/Amman*.

EcoWatch. (2016). *The Dead Sea is Shrinking at Alarming Rate, a Record Low-Point for Earth*. https://www.ecowatch.com/the-dead-sea-is-shrinking-at-alarming-rate-a-record-low-point-for-eart-1891181208.html

El-Naqa, A., & Al Adas, A. A. (2019). *Development of Irrigation Water Quality Index for Wadi Araba Basin, Southern Jordan*.

El-Naqa, A., Hammouri, N., Ibrahim, K., & Al-Taj, M. (2010). Integrated Approach for Groundwater Exploration in Wadi Araba Using Remote Sensing and GIS. *Jordan Journal of Civil Engineering*, *3*.

El-Naqa, A., & Rimawi, O. (2012). Groundwater Modelling of Eshidya Phosphate Mining Area in Jafr Basin, Southern Jordan. *Journal of Advanced Science and Engineering Research*, *2*(4), 265–278.

Elewa, H. H., & Qaddah, A. A. (2011). Groundwater potentiality mapping in the Sinai Peninsula, Egypt, using remote sensing and GIS-watershed-based modeling. *Hydrogeology Journal*, *19*(3), 613–628.

Eriksson, E., Baun, A., Scholes, L., Ledin, A., Ahlman, S., Revitt, M., Noutsopoulos, C., & Mikkelsen, P. S. (2007). Selected stormwater priority pollutants—a European perspective. *Science of the Total Environment*, *383*(1–3), 41–51.

Erwin, K. L. (2009). Wetlands and global climate change: the role of wetland restoration in a changing world. *Wetlands Ecology and Management*, *17*(1), 71–84.

Fetter, C. W. (2018). *Applied hydrogeology*. Waveland Press.

Flörke, M., Schneider, C., & McDonald, R. I. (2018). Water competition between cities and agriculture driven by climate change and urban growth. *Nature Sustainability*, *1*(1), 51–58.

Gafny, S., Talozi, S., Sheikh, B., & Ya'ari, E. (2010). *Towards a Living Jordan River: An Environmental Flows Report on the Rehabilitation of the Lower Jordan River*. https://doi.org/10.13140/RG.2.1.2364.3360

Gale. (2005). *Strategies for managed aquifer recharge in semi-arid areas*. UNESCO-IHP Publ. https://recharge.iah.org/files/2017/01/%0AGale-Strategies-for-MAR-in-semiarid-areas.pdf

Gale, I. N., Williams, A. T., Gaus, I., & Jones, H. K. (2002). *ASR-UK: elucidating the hydrogeological issues associated with aquifer storage and recovery in the UK*.

Garfunkel, Z., Zak, I., & Freund, R. (1981). Active faulting in the dead sea rift. *Tectonophysics*, *80*(1), 1–26. https://doi.org/https://doi.org/10.1016/0040-1951(81)90139-6

Garrick, D., De Stefano, L., Yu, W., Jorgensen, I., O'Donnell, E., Turley, L., Aguilar-Barajas, I., Dai, X., de Souza Leão, R., Punjabi, B., & others. (2019). Rural water for thirsty cities: A systematic review of water reallocation from rural to urban regions. *Environmental Research Letters*, *14*(4), 43003.

Ghayoumian, J., Saravi, M. M., Feiznia, S., Nouri, B., & Malekian, A. (2007). Application of GIS techniques to determine areas most suitable for artificial groundwater recharge in a coastal aquifer in southern Iran. *Journal of Asian Earth Sciences*, *30*(2), 364–374.

Gogu, R., Carabin, G., Hallet, V., Peters, V., & Dassargues, A. (2001). GIS-based hydrogeological databases and groundwater modelling. *Hydrogeology Journal*, *9*, 555–569.

Goodchild, M. F., Steyaert, L. T., & Parks, B. O. (1993). GIS and environmental modeling. *Fort Collins: GIS World Books*.

Government of India. (2007). *Manual on Artificial Recharge of Ground Water*. Ministry Resources, of WaterCentral Ground Water Board, Faridabad, India. http://cgwb.gov.in/documents/Manual on Artificial Recharge of Ground Water.pdf

Greskowiak, J., Prommer, H., Massmann, G., & Nützmann, G. (2006). Modeling Seasonal Redox Dynamics and the Corresponding Fate of the Pharmaceutical Residue Phenazone During Artificial Recharge of Groundwater. *Environmental Science \& Technology*, *40*(21), 6615–6621. https://doi.org/10.1021/es052506t

Greve, P., Kahil, T., Mochizuki, J., Schinko, T., Satoh, Y., Burek, P., Fischer, G., Tramberend, S., Burtscher, R., Langan, S., & others. (2018). Global assessment of water challenges under uncertainty in water scarcity projections. *Nature Sustainability*, *1*(9), 486–494.

Grismer, M. E., Orang, M. N., Clausnitzer, V., & Kinney, K. (1994). Effects of air compression and counterflow on infiltration into soils. *Journal of Irrigation and Drainage Engineering*, *120*(4), 775–795.

Hadadin, N., Qaqish, M., Akawwi, E., & Bdour, A. (2010). Water shortage in Jordan—Sustainable solutions. *Desalination*, *250*(1), 197–202.

Haimerl, G. (2004). *Groundwater recharge in Wadi channels downstream of dams*. TU München.

Hammour, S. A. (2014). River Basin Management. *International Integrated Basin Management Workshop*.

Harbaugh, A. W., Banta, E. R., Hill, M. C., & McDonald, M. G. (2000). *Modflow-2000, the u. S. Geological survey modular ground-water model-user guide to modularization concepts and the ground-water flow process*.

Hatcher Jr, R. D., Zietz, I., Regan, R. D., & Abu-Ajamieh, M. (1981). Sinistral strike-slip motion on the Dead Sea rift: confirmation from new magnetic data. *Geology*, *9*(10), 458–462.

Hinaman, K. C. (1993). USE OF A GEOGRAPHIC INFORMATION SYSTEM TO ASSEMBLE INPUT-DATA SETS FOR A FINITE-DIFFERENCE MODEL OF GROUND-WATER FLOW 1. *JAWRA Journal of the American Water Resources Association*, *29*(3), 401–405.

Houghton, E. (1996). *Climate change 1995: The science of climate change: contribution of working group I to the second assessment report of the Intergovernmental Panel on Climate Change* (Vol. 2). Cambridge University Press.

HTS, H. T. S. L., & SSLRC, S. S. and L. R. C. (1994). *The Soils of Jordan. Level 1 Reconnaissance Soil Survey. National Soil Map and Land Use Project*.

Hussein, H. (2017). Whose 'reality'? Discourses and hydropolitics along the Yarmouk River. *Contemporary Levant*, *2*(2), 103–115. https://doi.org/10.1080/20581831.2017.1379493

Ibrahim, K. (1991). *The geology of Wadi Rahma area map sheet 3049 IV.*

Igboekwe, M., & Ruth, A. (2011). Groundwater Recharge Through Infiltration Process: A Case Study of Umudike, Southeastern Nigeria. *Journal of Water Resource and Protection*, *03*. https://doi.org/10.4236/jwarp.2011.35037

ISRAMAR. (2022). *Long-Term Changes in the Dead Sea*. https://isramar.ocean.org.il/isramar2009/DeadSea/LongTerm.aspx

Izady, A., Abdalla, O., Joodavi, A., & Chen, M. (2017). Groundwater Modeling and Sustainability of a Transboundary Hardrock–Alluvium Aquifer in North Oman Mountains. *Water*, *9*, 161. https://doi.org/10.3390/w9030161

JAEC, & WorleyParsons. (2011). White paper on nuclear energy in Jordan. Final Repport. *Laka-Library*.

Jasrotia, A. S., Kumar, R., & Saraf, A. K. (2007). Delineation of groundwater recharge sites using integrated remote sensing and GIS in Jammu district, India. *International Journal of Remote Sensing*, *28*(22), 5019–5036.

Jiménez, B., Chavez, A., R., G., & Maya, C. (2012). *Unplanned Aquifer Recharge in El Mezquital/Tula Valley, Mexico*.

Juster, F. T., & Stafford, F. P. (1991). The allocation of time: Empirical findings, behavioral models, and problems of measurement. *Journal of Economic Literature*, *29*(2), 471–522.

Kallali, H., Anane, M., Jellali, S., & Tarhouni, J. (2007). GIS-based multi-criteria analysis for potential wastewater aquifer recharge sites. *Desalination*, *215*(1–3), 111–119.

Khader, B. F. Y., Yigezu, Y. A., Duwayri, M. A., Niane, A. A., & Shideed, K. (2019). Where in the value chain are we losing the most food? The case of wheat in Jordan. *Food Security*, *11*(5), 1009–1027.

Kohn, K. E. (1996). Conceptualization and characterization of ground-water systems using Geographic Information Systems. *Engineering Geology*, *42*(2–3), 111–118.

Kourgialas, N. N., Dokou, Z., Karatzas, G. P., Panagopoulos, G., Soupios, P., Vafidis, A., Manoutsoglou, E., & Schafmeister, M. (2016). Saltwater intrusion in an irrigated agricultural area: combining density-dependent modeling and geophysical methods. *Environmental Earth Sciences*, *75*(1), 1–13.

Krueger, E. H., Borchardt, D., Jawitz, J. W., Klammler, H., Yang, S., Zischg, J., & Rao, P. S. C. (2019). Resilience dynamics of urban water supply security and potential of tipping points. *Earth's Future*, *7*(10), 1167–1191.

Krueger, E., Rao, P. S. C., & Borchardt, D. (2019). Quantifying urban water supply security under global change. *Global Environmental Change*, *56*, 66–74.

Kumar, C. P. (2012). Climate change and its impact on groundwater resources. *International Journal of Engineering and Science*, *1*(5), 43–60.

Kunstmann, H., Suppan, P., Heckl, A., & Rimmer, A. (2007). Regional climate change in the middle east and impact on hydrology in the upper jordan catchment. *IAHS-AISH Publication*, 141–149.

Kvitsand, H., Myrmel, M., Østerhus, S., & Fiksdal, L. (2017). Evaluation of bank filtration as a pretreatment method for the provision of hygienically safe drinking water in Norway: results from monitoring at two full-scale sites. *Hydrogeology Journal*, *Kvitsand,* 1–13. https://doi.org/10.1007/s10040-017-1576-2

Larson, K. J., Ba\csağaoğlu, H., & Marino, M. A. (2001). Prediction of optimal safe ground water yield and land subsidence in the Los Banos-Kettleman City area, California, using a calibrated numerical simulation model. *Journal of Hydrology*, *242*(1–2), 79–102.

Lasserre, F., Razack, M., & Banton, O. (1999). A GIS-linked model for the assessment of nitrate contamination in groundwater. *Journal of Hydrology*, *224*(3–4), 81–90.

Le Béon, M., Klinger, Y., Mériaux, A.-S., Al-Qaryouti, M., Finkel, R. C., Mayyas, O., & Tapponnier, P. (2012). Quaternary morphotectonic mapping of the Wadi Araba and implications for the tectonic activity of the southern Dead Sea fault. *Tectonics*, *31*(5).

Lloyd, J. W. (1986). A review of aridity and groundwater. *Hydrological Processes*, *1*(1), 63–78.

Ma, Y., Feng, S., Zhan, H., Liu, X., Su, D., Kang, S., & Song, X. (2011). Water infiltration in layered soils with air entrapment: modified Green-Ampt model and experimental validation. *Journal of Hydrologic Engineering*, *16*(8), 628–638.

Malczewski, J., & Rinner, C. (2005). Exploring multicriteria decision strategies in GIS with linguistic quantifiers: A case study of residential quality evaluation. *Journal of Geographical Systems*, *7*(2), 249–268.

Mao, X., Jia, J., Liu, C., & Hou, Z. (2005). A simulation and prediction of agricultural irrigation on groundwater in well irrigation area of the piedmont of Mt. Taihang, North China. *Hydrological Processes: An International Journal*, *19*(10), 2071–2084.

Margane, A., Borgstedt, A., & Subah, A. (2009). *Water Resources Protection Efforts in Jordan and their Contribution to a Sustainable Water Resources Management* (pp. 325–345). https://doi.org/10.1007/978-3-540-85047-2_21

McCourt, W., & Ibrahim, K. (1990). *The geology, geochemistry and tectonic setting of the granitic and associated rocks in the Aqaba and Araba complexes of Southwest Jordan.*

McDonald, R. I., Weber, K., Padowski, J., Flörke, M., Schneider, C., Green, P. A., Gleeson, T., Eckman, S., Lehner, B., Balk, D., & others. (2014). Water on an urban planet: Urbanization and the reach of urban water infrastructure. *Global Environmental Change*, *27*, 96–105.

MEMER. (2017). *Annual Report 2016*.

Mikbel, S., & Zacher, W. (1986). Fold structures in northern Jordan. *Neues Jahrbuch Für Geologie Und Paläontologie - Monatshefte*, *1986*(4), 248–256. https://doi.org/10.1127/njgpm/1986/1986/248

Miller Jr, G. T. (1992). *Living in the environment: an introduction to environmental science.* (Issue Ed. 7). Wadsworth Publishing Company, Inc.

MOPIC. (2021). *The National Climate Change Adaptation Plan of Jordan*. Ministry of Planning and International Cooperation. https://mop.gov.jo/EN/List/Climate_Change_Adaptation_Program1

Moumani, K. (1996). *Quaternary sediments of the Jurf Ed Darawish area, Central Jordan University of Wales, Cardiff, 1996.* https://doi.org/10.13140/RG.2.1.4210.0965

Mukhopadhyay, A., & Fadlelmawla, A. (2009). Selection of suitable sites for artificial recharge in Kuwait using GIS technology. *Proc. Symp. ISMAR (Achieving Groundwater Supply Sustainability and Reliability through Managed Aquifer Recharge) Held at Abu Dhabi (UAE) During*, 9–13.

MWI-WIS, M. of water and irrigation. (2019). *WIS-MWI, Water Information System. Open Files*.

MWI. (2020). *Vulnerable Water Resources in Jordan, Hot Spots*.

MWI & BGR. (2019). *Groundwater Resources Assessment of Jordan*. Ministry of Water and Irrigation; Bundesanstalt für Geowissenschaften und Rohstoffe.

MWI, M. of water and irrigation. (2016). *National Water Strategy of Jordan, 2016 – 2025*.

MWI, M. of water and irrigation. (2017). *HKO (2017) Groundwater modeling and simulation of Wadi Araba aquifers, under the project for developing the Wadi Araba integrated development master plan*.

NRA. (1989). *The geology of the Karak area. Explanatory notes and geological map, 1:50,000*.

NRA. (2002). *National Geological Mapping Project, 1987-2002*.

NRC, N. R. C. (2008). *Prospects of managed underground storage of recoverable water*.

O'Sullivan, D., & Unwin, D. J. (2010). Geographic information analysis and spatial data. *Geographic Information Analysis*, 1–32.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., Church, J. A., Clarke, L., Dahe, Q., Dasgupta, P., & others. (2014). *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Ipcc.

Patil, N. S., Chetan, N. L., Nataraja, M., & Suthar, S. (2020). Climate change scenarios and its effect on groundwater level in the Hiranyakeshi watershed. *Groundwater* *for Sustainable Development*, *10*, 100323.

Pavelic, P., Dillon, P. J., Barry, K. E., Vanderzalm, J. L., Correll, R. L., & Rinck-Pfeiffer, S. M. (2007). Water quality effects on clogging rates during reclaimed water ASR in a carbonate aquifer. *Journal of Hydrology*, *334*(1), 1–16. https://doi.org/https://doi.org/10.1016/j.jhydrol.2006.08.009

Philip, J. R. (1957). The theory of infiltration: 1. The infiltration equation and its solution. *Soil Science*, *83*(5), 345–358.

Philip, J. R. (2006). The theory of infiltration. 1. The infiltration equation and its solution. *Soil Science*, *171*(6).

Powell, J. (1989). Stratigraphy and sedimentation of the Phanerozoic rocks. *Central and South Jordan*, 1–72.

Pyne, R. D. G. (1995). *Groundwater Recharge and Wells: A Guide to Aquifer*.

Rabba, I., & Ibrahim, K. (1988). *Petrography of the plutonic rocks of the Aqaba Complex, Jordan*.

Racz, A. J., Fisher, A. T., Schmidt, C. M., Lockwood, B. S., & Huertos, M. L. (2012). Spatial and temporal infiltration dynamics during managed aquifer recharge. *Groundwater*, *50*(4), 562–570.

Radulovic, M. M., Wong, H., & Al Tarawneh, M. (2020). Groundwater flow modelling for an assessment of abstraction and climate change impacts on groundwater resources—an example from the Wadi Araba Basin (Jordan). *Arabian Journal of Geosciences*, *13*(21), 1–14.

Rahman, M. A. (2011). *Decision support for managed aquifer recharge (MAR) project planning to mitigate water scarcity based on non-conventional water resources*.

Ramireddygari, S. R., Sophocleous, M. A., Koelliker, J. K., Perkins, S. P., & Govindaraju, R. S. (2000). Development and application of a comprehensive simulation model to evaluate impacts of watershed structures and irrigation water use on streamflow and groundwater: the case of Wet Walnut Creek Watershed, Kansas, USA. *Journal of Hydrology*, *236*(3–4), 223–246.

Rapp, M. (2008). Evaluation of potential sites for managed aquifer recharge via surface infiltration in NW-Jordan. *Unpublished Diploma Thesis, Department of Applied Geology (AGK), University of Karlsruhe (TH), Karlsruhe, Germany*.

Rashdan, M. (1988). *The Regional Geology of the Aqaba-Wadi Araba Area, Map Sheet 3049 III, 2949 II, Bulletin 7*.

Rehana, S., & Mujumdar, P. P. (2013). Regional impacts of climate change on irrigation water demands. *Hydrological Processes*, *27*(20), 2918–2933.

Reid, M. E., & Dreiss, S. J. (1990). Modeling the effects of unsaturated, stratified sediments on groundwater recharge from intermittent streams. *Journal of Hydrology*, *114*(1–2), 149–174.

Revi, A., Satterthwaite, D. E., Aragón-Durand, F., Corfee-Morlot, J., Kiunsi, R. B. R., Pelling, M., Roberts, D. C., & Solecki, W. (2014). Urban areas Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed CB Field et al. *Field, CB, Barros, VR, Dokken, DJ et Al*, 535–612.

Russo, T. A., Fisher, A. T., & Lockwood, B. S. (2015). Assessment of managed aquifer recharge site suitability using a GIS and modeling. *Groundwater*, *53*(3), 389–400.

Rybakov, M., Goldshmidt, V., & Rotstein, Y. (1997). New regional gravity and magnetic maps of the Levant. *Geophysical Research Letters*, *24*(1), 33–36.

Salamah, E., & Helen, B. (1993). *Water Resources of Jordan: Present Status and Future Potentials*. Friedrich Ebert Stiftung. https://books.google.com.my/books?id=HA7PAAAAIAAJ

Salameh, E. (1996). Water Quality Degradation in Jordan. *Friedrich Ebert Stiftung and*

Royal Society for the Conservation of Nature, Amman, Jordan, 178.

Salameh, E., Abdallat, G., & van der Valk, M. (2019). Planning considerations of managed aquifer recharge (MAR) projects in Jordan. *Water*, *11*(2), 182.

Salameh, E., & Al-Alami, H. (2021). Jordan's Water Sector—Alarming Issues and Future. *Journal of Geoscience and Environment Protection*, *9*(12), 100–117.

Salameh, E., Shteiwi, M., & Raggad, M. Al. (2018). Water Resources of Jordan: Political, Social and Economic Implications of Scarce Water Resources. *Water Resources of Jordan*.

Sallwey, J., Bonilla Valverde, J. P., Vásquez López, F., Junghanns, R., & Stefan, C. (2019). Suitability maps for managed aquifer recharge: a review of multi-criteria decision analysis studies. *Environmental Reviews*, *27*(2), 138–150. https://doi.org/10.1139/er-2018-0069

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., Dankers, R., Eisner, S., Fekete, B. M., Colón-González, F. J., & others. (2014). Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences*, *111*(9), 3245–3250.

Scibek, J., & Allen, D. M. (2006). Comparing modelled responses of two high-permeability, unconfined aquifers to predicted climate change. *Global and Planetary Change*, *50*(1–2), 50–62.

Segev, A., Goldshmidt, V., & Rybakov, M. (1999). Late Precambrian-Cambrian tectonic setting of the crystalline basement in the northern Arabian-Nubian Shield as derived from gravity and magnetic data Basin-and-range characteristics. *Isr. J. Earth Sci*, *48*(3–4), 159–178.

Seiler, K.-P., & Gat, J. R. (2007). *Groundwater recharge from run-off, infiltration and percolation* (Vol. 55). Springer Science \& Business Media.

Sharma, M. L., Gander, G. A., & Hunt, C. G. (1980). Spatial variability of infiltration in a watershed. *Journal of Hydrology*, *45*(1–2), 101–122.

Shearer, T. R. (1998). A numerical model to calculate land subsidence, applied at Hangu in China. *Engineering Geology*, *49*(2), 85–93.

Sherif, M., Kacimov, A., Javadi, A., & Ebraheem, A. A. (2012). Modeling groundwater flow and seawater intrusion in the coastal aquifer of Wadi Ham, UAE. *Water Resources Management*, *26*(3), 751–774.

Solomon, S. (2007). IPCC (2007): Climate change the physical science basis. *Agu Fall Meeting Abstracts*, *2007*, U43D--01.

Sorman, A. U., & Abdulrazzak, M. J. (2017). Estimation of wadi recharge from channel losses in Tabalah Basin, Saudi Arabia. In *Recharge of phreatic aquifers in (semi-) arid areas* (pp. 187–200). Routledge.

Steinel, A., Schelkes, K., Subah, A., & Himmelsbach, T. (2016). Spatial multi-criteria analysis for selecting potential sites for aquifer recharge via harvesting and infiltration of surface runoff in north Jordan. *Hydrogeology Journal*, *24*, 1753–1774.

Taimeh, A. Y. (2015). Food Security in Jordan. *The University of Jordan Press*.

Tarawneh, B. (1988). *THE GEOLOGY OF AT TAFILA, MAP SHEET NO. 3151-IV*.

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J. S., & Edmunds, M. (2013). Ground water and climate change. *Nature Climate Change*, *3*(4), 322–329.

Uddameri, V., & Kuchanur, M. (2007). Simulation-optimization approach to assess groundwater availability in Refugio County, TX. *Environmental Geology*, *51*(6), 921–929.

Valley, S. (2009). Groundwater availability of the Central Valley aquifer, California. *US Geological Survey Professional Paper*.

Van Houtte, E., Cauwenberghs, J., Weemaes, M., Thoeye, C., Kazner, C., Wintgens, T.,

& Dillon, P. (2012). Indirect potable reuse via managed aquifer recharge in the Torreele/St-Andre project. *Water Reclamation Technologies for Safe Managed Aquifer Recharge. IWA, London*, 33.

van Steenbergen, F., Tuinhof, A., Knoop, L., & Kauffman, J. H. (2011). *Transforming landscapes, transforming lives: the business of sustainable water buffer management*. 3R Water.

Vanderzalm, J., Page, D., & Dillon, P. (2011). Application of a risk management framework to a drinking water supply augmented by stormwater recharge. *Water Science and Technology : A Journal of the International Association on Water Pollution Research*, *63*, 719–726. https://doi.org/10.2166/wst.2011.294

Vorosmarty, C. J., Green, P., Salisbury, J., & Lammers, R. B. (2000). Global water resources: vulnerability from climate change and population growth. *Science*, *289*(5477), 284–288.

Warburton, J. (2012). A reconnaissance survey of surface water infiltration characteristics. *Arid Land Resources \& Their Mana*, 157.

Woldeamlak, S. T., Batelaan, O., & De Smedt, F. (2007). Effects of climate change on the groundwater system in the Grote-Nete catchment, Belgium. *Hydrogeology Journal*, *15*(5), 891–901.

Xu, X., Huang, G., & Qu, Z. (2009). Integrating MODFLOW and GIS technologies for assessing impacts of irrigation management and groundwater use in the Hetao Irrigation District, Yellow River basin. *Science in China Series E: Technological Sciences*, *52*(11), 3257.

Yeh, H.-F., Cheng, Y.-S., Lin, H.-I., & Lee, C.-H. (2016). Mapping groundwater recharge potential zone using a GIS approach in Hualian River, Taiwan. *Sustainable Environment Research*, *26*(1), 33–43.

Zeelie, S. (2020). OMDEL dam and recharge ponds to enhance recharge in the Namib

Desert. In *Management of aquifer recharge for sustainability* (pp. 387–392). CRC Press.

Zeitoun, M., Abdallah, C., Dajani, M., Khresat, S., Elaydi, H., & Alfarra, A. (2019). The Yarmouk Tributary to the Jordan River I: Agreements Impeding Equitable Transboundary Water Arrangements. *Water Alternatives*, *12*, 1064–1094.

Zereini, F., & Hötzl, H. (2008). *Climatic Changes and Water Resources in the Middle East and North Africa*.

Zhang, Y., Ma, J., Chang, X., van Wonderen, J., Yan, L., & Han, J. (2012). Water resources assessment in the Minqin Basin: an arid inland river basin under intensive irrigation in northwest China. *Environmental Earth Sciences*, *65*(6), 1831–1839.

Zhou, Y. (2009). A critical review of groundwater budget myth, safe yield and sustainability. *Journal of Hydrology*, *370*(1–4), 207–213.