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Doctoral School of Environmental Sciences

Ph.D. Dissertation

COMPREHENSIVE RISK ASSESSMENT FOR SUSTAINABLE GROUNDWATER MANAGEMENT IN ARID AREAS

CASE STUDY: AGRICULTURAL EASTERN JORDAN DESERT

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by

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Approval of Head of Doctoral School Approval of Supervisor

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Dedication

قال تعالى: " قُلْ إِنَّ صَلَاتِي وَنُسُكِي وَمَحْيَايَ وَمَمَاتِي لِلَّهِ رَبِّ الْعَالَمِينَ" صدق الله العظيم

''Surely my Prayer, all my acts of worship, and my living and my dying are for Allah alone, the Lord of the whole universe" (Quran: Chapter 6 سورة الأنعام - Al-Anaam: Verse 162).

This Thesis is dedicated to my Treasure in this short life

My everything

My

♡ *Parents* ♡

(To my great father Soul, the teacher of mathematics "Moh'd Najeeb" who is my greatest teacher (RIP))

And my *brothers* and *Sisters* and my cute *nephews*

For their real unconditional endless love and encouragement

<u>Excerpts from the Quran and the Bible ask human beings not to harm the environment:</u>

قال تعالى: "ظَهَرَ الْفَسَادُ فِي الْبَرِّ وَالْبَحْرِ بِمَا كَسَبَتْ أَيْدِي النَّاسِ لِيُذِيقَهُمْ بَعْضَ الَّذِي عَمِلُوا لَعَلَّهُمْ يَرْجِعُونَ"

"Corruption has appeared throughout the land and sea by [reason of] what the hands of people have earned so He may let them taste part of [the consequence of] what they have done that perhaps they will return [to righteousness]". (Quran: Chapter 30 سورة الروم - Ar-Rum: Verse 41).

"و لا تنجسوا الأرض التي انتم مقيمون فيها التي أنا ساكن في وسطها اني أنا الرب" (سفر العدد 34:35)

"Do not defile the land where you live and where I dwell, says the Lord" (<u>Bible</u>, Book of Numbers, 35:34)

Osama MN Gazal,
Hungary
2021

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List of nomenclature and abbreviations:

A: Aquifer media
A1/A6: Aquitard layer
A1-2: Naur formation (aquifer)
A4: Hummar formation (aquifer)
A5-6: Shueib formation (aquitard)
APHA: American Public Health Association
APNC: The agricultural potential nitrate contamination
ARD: Associates in Rural Development
AZB: Amman–Zarqa Basin
B1: Wadi Umm Ghudran formation (aquifer)
B2/A7: Amman Wadi As Sir formation (aquifer)
B2: Amman-Al Hisa formation (aquifer)
B3: Muwaqqar formation (aquitard)
B4: Umm Rijam formation (aquifer)
B5: Wadi Shallala formation (aquifer)
BGR: Bundesanstalt fur Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Ressources), Hannover, Germany (www.bgr.bund.de)
C: Hydraulic conductivity parameter
CLWAJ: Central Laboratories of Water Authority of Jordan
CSS: Center for Sustainable Systems
D: Depth to water table
DD: Drawdown
DEM: Digital elevation model
DOS: Department of Statistics
DVIM: DRASTIC vulnerability indexes map
EC: Electrical conductivity
FMB: Fertilizers mixing bonds
GIS: Geographic Information System
GIZ: German Agency for Technical Cooperation (Deutsche Gesellschaft Fur Internaionale Zusammenarbeit (GMBH).
GRA: Groundwater Risk Assessment
GW: Groundwater
GWR: Groundwater recharge

I: The effect of the vadose zone
IdRC: Interdisciplinary Research Consultants
IGRAC: International Groundwater Resources Assessment Centre
IUCN: International Union for the Conservation of Nature
JDWQS: Jordanian Drinking Water Quality Standards
JVA: Jordan Valley Authority
K: Kurnub
m/d: Meter per day.
m/s: Meter per second.
m^3/d: Cubic meter per day.
masl: Meter above sea level
MEMR: Ministry of Energy and Mineral
mm/year: Millimeter per year
MM^3: Million Cubic Meters
MOA: Ministry of Agriculture
MOA: Ministry of Agriculture
MOPIC: Ministry of Planning and International Cooperation
MRSA: Map removal sensitivity analyses
MWI: Ministry of Water and Irrigation
MWI: Ministry of Water and Irrigation
NCR: Nitrate contamination risk
NDVI: Normalized Difference Vegetation Index.
NO_3: Nitrate
NRA: Natural Resources Authority
OK: Ordinary Kriging
PGE: Palestinian Grid East
PGN: Palestinian Grid North
PGWM: Participatory Groundwater Management
PM: Participatory management
PNC: Potential nitrate contamination
Ppm: Part per millions
PuPNC: The Peri-urban Potential Nitrate Contamination
R': Net recharge but by modified ratings
R: Net recharge parameter
r: Rating
RS: Remote Sensing
S: Soil media parameter
SADP: Statistical analyses of DRASTIC rated parameters
SAK: Sakhra soil type
SAR: Sodium adsorption ratio
SCS: Soil Conservation Service
SEN: sensitivity analysis
SPSA: Single-parameter sensitivity analysis
SRTM: Shuttle Radar Topography Mission
SWL: static water level
T: Topography (slope%) parameter

TDS: Total dissolved solids
TH: Total hardness as CaCO3
UPNC: The urban potential nitrate contamination
USAID: United States Agency for International Development
V: The unperturbed DVIM (the initial one calculated by the DRASTIC govern equation)
V′: The perturbed vulnerability indices (calculated by modified DRASTIC equation)
w: Weight
WAJ: Water Authority of Jordan
WAJ: Water Authority of Jordan
WHO: World Health Organization
WIS: Water Information System

1. INTRODUCTION

1.1 General Introduction

Protecting groundwater from contamination is essential for safe, sustainable drinking water management (Sasakova et al. 2018), and it is not a new activity, but since ancient times many cultures have considered the importance of protecting the quality of the groundwater and ensuring that it is not contaminated. Foster and Loucks (2006) stated the old Arabic Proverb "*Into the well from which you drink do not throw stones"*. Groundwater represents about 30 % of the planet freshwater, while only 0.3 % in form of surface water bodies (lakes and rivers) and more than 68 % of the planet freshwater are in form of glacial (Yano et al. 2015). Groundwater accounts for 98 % of all available freshwater on earth (Velis et al. 2017). Total reservoirs of fresh groundwater are around 100 times bigger than reservoirs of fresh surface water (Fitts 2013), see the modified sketch after Gleick (1996) (Figure 1-1).

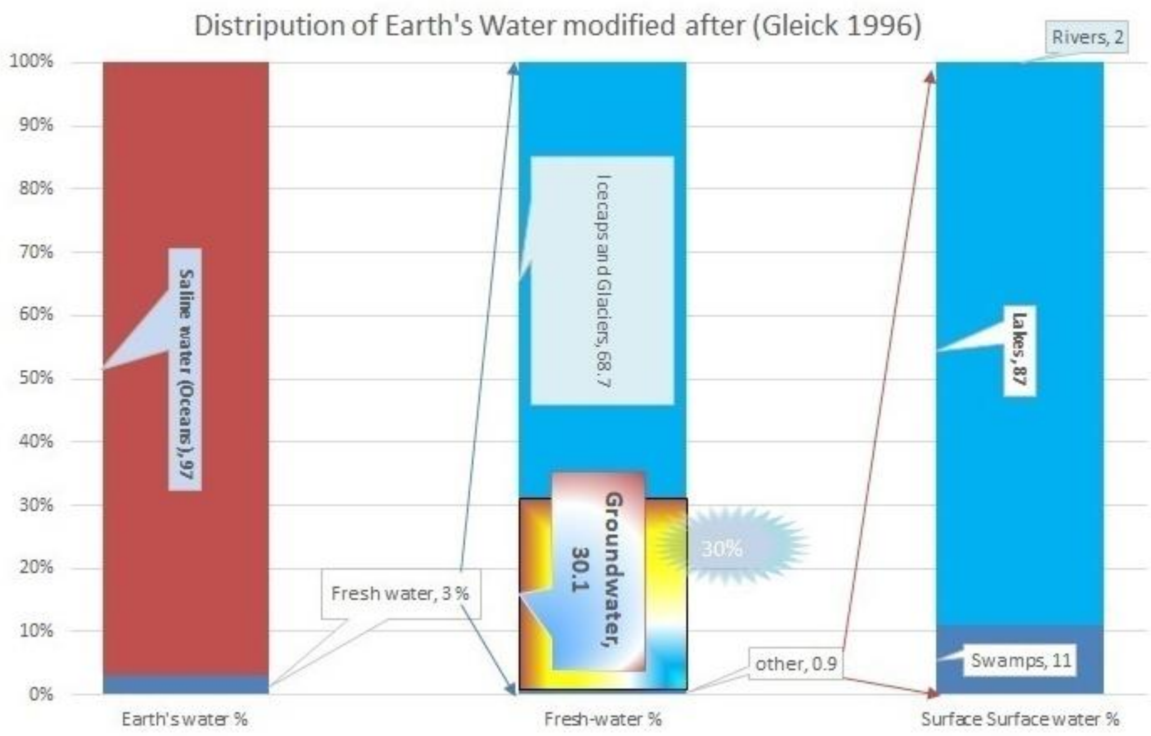


Figure 1-1 Distribution of Earth's water modified after Gleick (1996)

Currently, in Jordan groundwater resources cover 44 % of the irrigation requirements and more than 58 % of the country's water requirements (Figure 1-2). The percentage of the water used in agriculture to the total water uses in 2019 was 51 % while it was above 70 % at the beginning of the nineties. This is due to the agricultural policies, increasing the profitability and efficiency of the irrigation methods to cope with the water scarcity in Jordan (WIS 2020). Besides, groundwater is, in fact, the world's largest extracted natural material (Vogelbacher et al. 2019). This increase is significant in arid and semi-arid areas where groundwater can be the only available drinking water resource (MWI, 2004; Margane & Hobler 1994). The low-efficiency uses of water resources in the dry and semi-dry areas agitate the problems of losing these resources, while several factors contribute to the deterioration of groundwater aquifers, exacerbated by drought and climate change impacts affecting arid and semi-arid areas that threaten groundwater resources (El-Beltagy & Madkour 2012; Balon & Dehnad 2006).

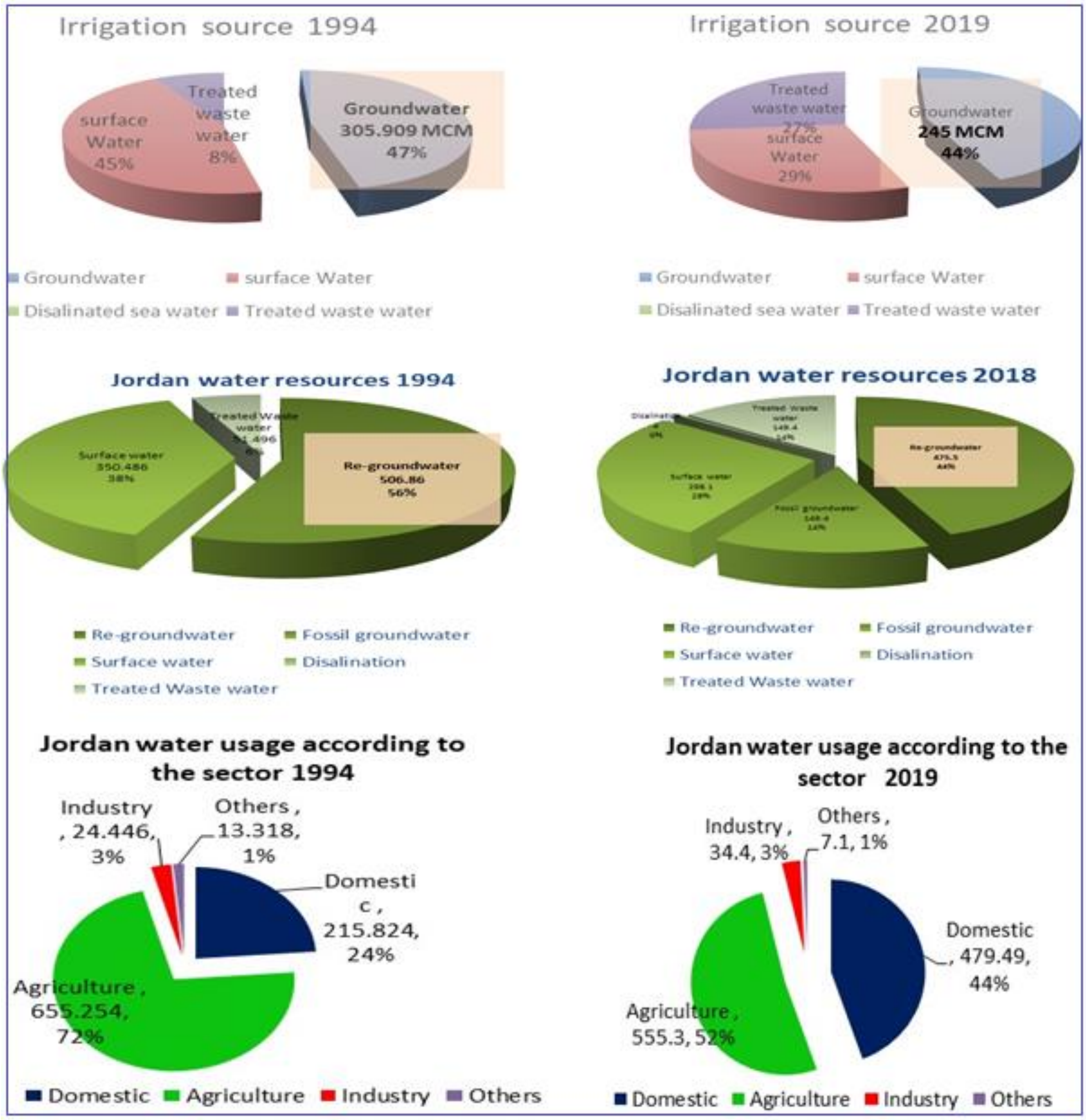


Figure 1-2 Jordan water resources, usages, and irrigation water resources in (MCM/year), for the years 1994 and 2019, own processing and the water raw data retrieved from WIS (2020)

Groundwater resources contain 99% of all freshwater accessible on the earth and are widely distributed across all continents (Puri 2009). They can be classified as renewable (phreatic aquifer) or un-renewable (confined aquifer), according to the natural flow and storage of (GW) aquifer (Ge & Gorelick 2015), where the renewal periods range from less than 10 years up to 100,000 years. However, both classes can be considered as non-renewable according to the limited possibility of natural replenishment due to low annual rainfall and over abstraction in many arid and semi-arid areas (Margat et al. 2006).

The abstraction of groundwater dates back to the period of early human existence (Ajami 2020). However, the use of groundwater has increased since the second half of the last century of the 2nd millennium, the 20th century, due to major developments in well-drilling and pumping technology (Foster et al. 2013).

Ground water differ from surface water as they are naturally protected from contamination caused by human agricultural and industrial activities on the land, whereas this natural protection varies from region to region, depending on the type and the load of contaminant and on the ability of the above-water layers to prevent the downflow of pollutants (Morris & Foster 2001).

Agricultural contaminants have the most severe and widespread effects on groundwater and the most studied contamination parameter is the nitrate which mainly increases where there are intensive agricultural activities. Agricultural activities can result in high concentrations of nitrate in the groundwater (USGS 2017). Groundwater quality degradation and low annual rainfall may create other environmental problems too, while some of the pollution impacts in the groundwater basin might be irreversible such as loss of biodiversity and deterioration of human health (IdRC & IUCN 2006).

1.2 Groundwater sustainability:

Groundwater is an important resource for the ecosystem and one that needs to be properly managed, making the world more focused on sustainable groundwater resource management studies that continue to increase and improved (Kresic & Stevanovic 2009). Preserving continuous and adequate supplies of drinkable water from groundwater sources is a critical issue for sustained agriculture, industry and domestic use throughout arid and semi-arid areas, specifically in developing extremely water-scarce countries that suffer from huge refugee fluxes from the surrounding countries like Jordan the case study of this research.

Contaminants can reach groundwater via transport through the soil profile and, depending's entirely on their nature, can have very serious consequences, making it a key requirement for sustainable development to protect groundwater resources from contamination that will increase the sustainability of high-quality drinking water (Sasakova et al. 2018).

The definition of the sustainable development according to Brundtland (1987) is a "*development that meets the needs of the present without compromising the ability of future* *generations to meet their own needs"*. The concept of groundwater sustainability was defined by Alley et al. (1999) as "*development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences"*.

Two main factors are controlling the sustainability of the groundwater recourse, the climate change effects that will cause the expansion of the arid and semi-arid regions and decrease water availabilities (Balon & Dehnad 2006). The second factor is demographic growth and the rapid economic activities development, combined with the agricultural intensification of food production, which is threatening to expand the arid areas and innervating the natural resources (Fernández-Cirelli et al. 2009). Water security in arid and semi-arid regions require sustainable and integrated management tools, and a clear understanding of the interactions between the groundwater aquifers and the human surface activities (Dawoud & Sallam 2012).

Sustainable groundwater management is dictated not only by the availability of groundwater resources but also by water quality degradation (Foster et al. 2013), and the process of studying groundwater quality has progressed considerably over the last decade with several significant advances in groundwater investigation technology including enhanced integration of groundwater statistical models and contaminant transport with external systems.

1.3 Rationale of present study

Human population growth often coincides with changes in land use, including the creation of urban areas, requiring an increase in the amount of drinking water available. Groundwater is naturally abundant in the Karst and Basalt regions, where intensive agricultural areas are also situated, as in the case study area of this research. Due to several reasons, these areas face a higher risk of groundwater contamination. Taking these aspects in consideration, a detailed groundwater risk assessment was planned in the Amman Zarqa Basin (AZB) located in northern part of Jordan. The comprehensive groundwater risk assessment (GRA) was carried out into two steps, the first was the investigation of the contamination load and the natural groundwater potential protectiveness. The last step was the use of the overlying modelling approaches to visualize the results of the GRA into maps. The resulted maps were evaluated by matching it with the groundwater nitrate concentration zones.

Establishing a scientific methodology that is widely and comprehensively applicable at the lowest cost is one of the most important priorities in enabling the water sector to manage groundwater resources sustainably in any water resource-poor country, with a view to ensuring water protection for future generations, by protecting these sources from contamination, to enhance water security and sustainability.

This comprehensive groundwater risk assessment research considered the possibility of implementing, in any region similar to the case study area, an integrated study to investigate the vulnerability of groundwater to contamination and to identify the contaminants in the area by the use of modern applications centred on statistical analyses, remote control, geographic information systems (GIS) and use the available data that includes water quality, hydrogeology and climate data.

1.4 Study objectives

1. The main objectives of this study were to assess the contamination load and groundwater natural potential protectiveness which is called a comprehensive groundwater risk assessment. And selecting the appropriate groundwater risk assessment approaches is at the core of the current research. To begin with, the following objectives were primarily to appropriately conduct a comprehensive groundwater risk assessment research.
    a. Review the available methods of groundwater contamination risk assessment to develop appropriate methods for karstic and basaltic aquifers in dry areas.
    b. Development of a multipurpose hydrogeological database for effective storage and processing of information in the GIS environment.
    c. Improving and updating the quality of input datasets through the reduction of errors and thus provided data for future groundwater management research. The data updated in this research includes the hazards, land use, soil texture, groundwater quality and the hydrological information.
    d. Characterization of the geological and hydro-geological setting necessary for applying all the required groundwater contamination risk assessment analysis.
    e. Assess the groundwater quality in the Study area by analysing the long-term groundwater quality measurements of approximately 498 wells (WIS 2020) from 1970 to 2018.
    f. Evaluate Jordan's and the study area's climatological parameters and generate the groundwater recharge map, by analysing daily climatological data from 346 weather stations.
    g. Investigate the state of groundwater levels and draw the water depth and groundwater flow using historical measurements from around 80 observation wells in the study area.

2. Assess the contamination load.
3. Investigate the natural protectiveness of groundwater.
4. Creating overlying modelling approaches to visualize the results of the groundwater risk assessment into maps, to be used in land use management and creating protection zones in further studies.
    a. Therefore, the first main objective of the overlying modelling part of this study was to evaluate the aquifer vulnerability in arid areas.
    b. The second main objective was to evaluate the potential risk of nitrate contamination.
    c. The third main objective in the overlaying modelling part was to integrate the intrinsic vulnerability and the potential risk of nitrate contamination.
    d. The last main objective was to validate the vulnerability and contamination risk maps by comparing the results to the observed water quality variables in the region. Aside from comparing the results to a previous vulnerability map.
    e. An additional objective was to demonstrate the combined use of DRASTIC and geographical information system (GIS) as an effective method for groundwater pollution risk assessment and water resource management.
    f. The second additional objective was to evaluate the relative importance of the DRASTIC model parameters for assessing aquifer vulnerability in arid agricultural areas through sensitivity analysis. And providing a comprehensive analysis on the potential application of the DRASTIC model in arid areas.

2. LITERATURE REVIEW

2.1 Review of Jordan's water crisis

The study area was chosen in Jordan, a country which is an example of a developing nation living in a severe water crisis and striving to develop strategies to reduce the severity of the problems that is facing because of this multifaceted water crisis that impacts water supply and quality throughout the country. The Jordanian population reached on 12/14/2020 according to DOS (2020) 10,813,747 inhabitants (Jordanian and non-Jordanian) with a population density of around 121.7 for each square kilometer, with total land area equal 88849 km^2. The growing water crisis puts Jordan's population among the most water-deprived in the world, with a current water supply of only 145 m^3/person/year that is projected to fall to only 91 m^3/person/year by 2025 (MWI 2016). According to Water Reallocation Policy report MWI (2016b) and recent official water figures and numbers from the Ministry of Water and Irrigation (WIS 2020) the domestic water share in liters per person per day is 125.5 (Per capita of supplied water (l/day)) (Figure 2-1). While water billed in villages and cities in Jordan indicates that about 76 % of customers consume less than 80 l/day and 85 % consume less than 100 l/day.

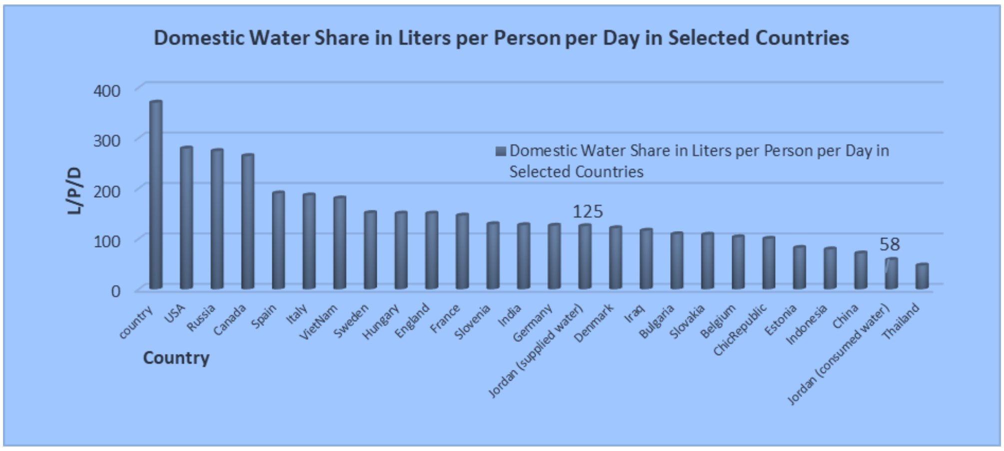


Figure 2-1 Domestic water share in Liters per person per day in selected countries (MWI 2016b)

The recent estimated per capita water supply (l/day) reached 100 l/day for the 2020, which is ten percent less than the global poverty line. While the water demand increased by 20 percent due to the Syrian refugee, and the increase rate reached 40 percent in the northern governorates, the water sector consumes about 15 % of the total electricity consumed in Jordan and each Syrian refugee costs the water sector around 440 JD/year (MOPIC 2014; MWI 2016). Numerous literature reviews have declared Jordan as one of the poorest water resource countries. FAO (2003) has indicated that the Hashemite Kingdom of Jordan is one of the 10 driest countries in the world with limited and insufficient water resources. Several studies ranked Jordan 4th among the world's poorest countries in available renewable freshwater resources per capita (MWI 2016; Daniel et al. 2013; WBG 2020). While other recent studies ranked Jordan 2nd among the world's poorest countries in water resources (MOE 2014; USAID 2018). The available renewable water per capita decreases from around 3,600 m^3/year in 1946 (Courcier et al. 2005) to around 77 m^3/year (MWI 2016; WBG 2020). In addition to the limited water resources in Jordan, a variety of accompanying factors have significantly aggravated the water deficit problems in recent decades according to numerous studies (USAID 2018; Arsenault 2017; MWI 2016).

2.1.1 Jordan as a poor water resource country relative to other countries

The degree of water stress (freshwater withdrawal as an extent of accessible freshwater resources) as indicated by WBG (2020) arrived at 150 % in Jordan and it was (110 %, 22.6 %, and 8 %) in Israel, the USA and Hungary respectively. While the yearly freshwater withdrawal, for horticulture (% of the absolute freshwater withdrawal), was 52.08 % in Jordan on the year 2015, and it was 57.7 %, 36 %, 6.4 % in Israel, the USA, and Hungary for the years (2004, 2010 and 2012). And for local uses it arrived at 44 %,36 %, 12 %, and 14.2 % for Jordan, Israel, the USA, and Hungary separately. Estimated water use in the United States in 2015 according to the U.S. Geological Survey Circular 1441 (Dieter et al. 2018) was 36.7 % for irrigation and groundwater covered 25.6 % of the USA water demands (CSS 2019; Dieter et al. 2018; EPA 2013). The agricultural sector in Israel is the largest water user about 58 % of the country water resources, consuming around 1,205 million cubic meters (MCM) of water in 2013 (WAI 2015).

Desalination output was estimated at 307 MCM per year in 2011, enough to satisfy Israel's drinking water needs by about 40 % (Rejwan 2011) the desalination output in Israel in 2011, the water resources come from the desalination project in Israel equal 29 % of the overall Jordan water resources for the year 2019. To further compare Jordan as a poor water resource country with other arid countries, it was considered that the degree of water stress for Kuwait was 2603.5 % and for the UAE was 2346.5 %, however, as these countries have big seawater desalination projects and per capita water over the 1000-liter global neediness line every day. The UAE accounts for 14 % of the world’s desalinated water according to UAE (2018) where more than 41.4 % of the UAE water resources come from the desalination projects, UAE residents use up to 550 liters of water per day while the international average is 170-300 liters per day, making it 82 % higher than the world average. Kuwait No. 1 in global water consumption at 500 liters per person per day. However, according to official reports from the Kuwait Institute for Scientific Research, Kuwait has reported the highest global per capita water consumption of 500 liters per person per day, where 65 % of Kuwait's water resources come from the desalination projects according to the Water-Energy-Food Nexus project in Kuwait (MFA 2019). In Jordan desalination water accounts for 0.372 % of the total water resources for the year 2019 (Figure 2-2).

The following (Figure 2-2) was designed to compare the renewable internal freshwater resources per capita (RIFR) (in cubic meters) (RIFR) between Jordan and Israel, the Arab countries, and the world average (RIFR). The trend line of Jordan (RIFR) shows a sharp decrease more than Israel (RIFR) even both are facing the same climatic change scenarios but the difference due to the high number of refugees in case of Jordan. This demonstrates the need for ambitious strategies to protect and use groundwater in a sustainable manner. And therefore, the water sector in Jordan shows a rapid official interest in developing maps of groundwater vulnerability to determine groundwater protection zones in the country

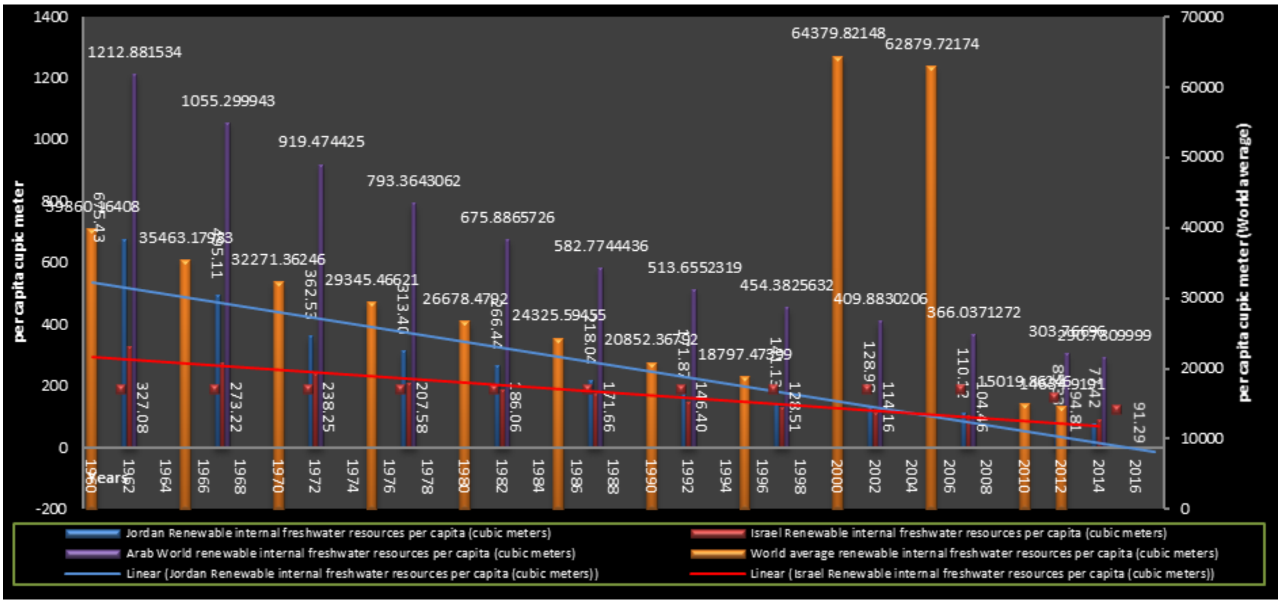


Figure 2-2 Renewable internal freshwater resources per capita (cubic meters) data source the WBG (2020) the high peak of average world renewable internal freshwater due to including the Greenland data (10652016.4638132 and 10662187.2513482 for the years 2002 and 2007).

2.1.2 Driving forces of water resources in Jordan

The water scarcity and limited water resources come together in Jordan with other Driving forces and pressures which can be categorized according to DPSIR Framework by Gazal (2020) into the following main pressures:

1. Climate change and the increasing frequency of drought events

Jordan's annual areal precipitation has a decreasing trend, with an average -0.674 mm/year estimated by the linear regression analysis of the annual precipitation from 1937 to 2019 at a 95 % significant level, a trend line equation is y = -0.295x + 104.31, a multiple R is

0.256637 and the P-value is very small equal 0.007746 indicating to reject the null hypotheses, so that the regression is statistically significant but not strong (Gazal 2020) (Figure 2-3).

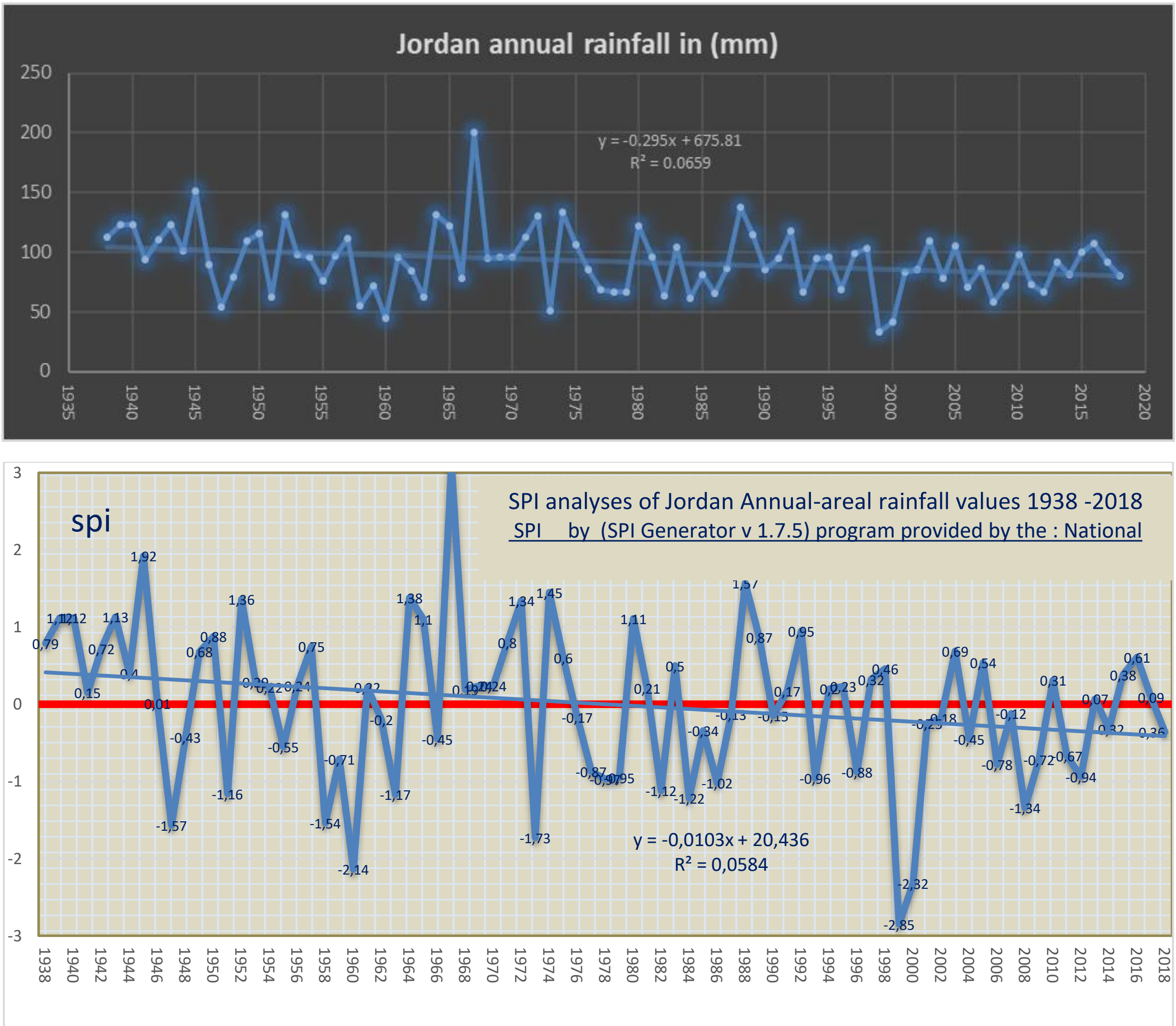


Figure 2-3 A: Jordan annual precipitation from 1937 up-to 2019 the rainfall data from the WIS (2020), B: Drought analyses of Jordan annual-areal rainfall values 1938 -2018, own processing relied on the rainfall stations data (Gazal 2020).

The long annual areal precipitation approximately in the last 82 years from 1937 to 2019 is P average = 92,2 mm) as calculated by the weighted average method, and measurements of the representative area of each station were performed using the Thiessen polygon method. The same study using the standard precipitation index SPI showed that the rate of drought they occur is projected to increase every 25 years, with an average normal drought of 2-3 years and severe drought every 8–11 years.

These droughts are rising and further adverse effects of climate change in Jordan are expected to further reduce water availability by 15–20 % according to several studies (Daniel et al. 2013; Rahman et al. 2015). A problematic forecasted water situation for Jordan is predicted by taking into account both RCP4.5 and 8.5 scenarios (UNDP 2016; UNDP 2017). Whereby the RCP 4.5 the study predicted a median value of decrease is 14 mm (-7 %) for 2021-2050, and 22mm (-11 %) for 2071-2100, while by the RCP 8.5 the projection study predicted a median value of decrease of 11 mm (-5 %) for 2021-2050, of 52 mm (-25 %) for 2071-2100. One of the main conclusions of this previous studies (UNDP 2016; UNDP 2017) is even in the absence of a strong precipitation trend, the combination of increased temperature and evapotranspiration makes it clear that the water management situation will worsen, with increasing water demand and stress.

In this study a daily climatological data from 346 weather station were analyzed to summarize the climatological parameters of Jordan in Table 2-1. About 74 stations of these stations collect temperature, wind speed, and evaporation data as well. Jordan is divided into three climatic zones depending on the annual precipitation special variation, according to the Jordanian ministry of water and irrigation (MWI), these three very different climatic zones are the Jordan valley, the mountains heights plateau, and the eastern desert or Badia region (MWI & BGR 2018). The Jordan valley climate is arid to semi-arid, with a dry hot summer and a warm winter. The average annual rainfall is very small with mostly below 200 mm/yr. The Jordan mountains heights plateau's northern and central parts are characterized by a Mediterranean climate with hot, dry summers, cool, wet winters, and two short transitional seasons. This climate zone has the highest precipitation levels in Jordan. While the annual average precipitation in the eastern desert and Badia zone is less than 100 mm/year.

According to precipitation zones adopted by MWI (2016), updated, and modified by Gazal (2020), there are five precipitation zones (desert, arid, marginal, semi-arid, semi-humid) each zone represents (71.5 %, 22.27 %, 2.25 %, 3.27 %, 0.68 % respectively) of the total area of the country, each zone receives an average annual precipitation about (less than 100 mm, 100-200 mm, 200-300 mm, 300-500 mm, 500-650 mm respectively). Only the semi-humid zone, which is about 620 km^2 and represent 0.68 % of the country area can receive 500-650 mm/year.

The average areal rainfall in Jordan was estimated by interpolating the long average annual precipitation of 296 weather stations using the ordinary kriging method, and using the raster statistical overview of the resulted average precipitation map, the average areal precipitation measured for Jordan is 82.98 mm. While the standard deviation is equal to 78.29, it reflects the widely varied precipitation variability across the country (Figure 2-4). Rainfall in Jordan has an uneven distribution over the rainy season, with a long average rainy day equal to 26 rainy days per year with an average temperature of 19.1 C° (Table 2-1).

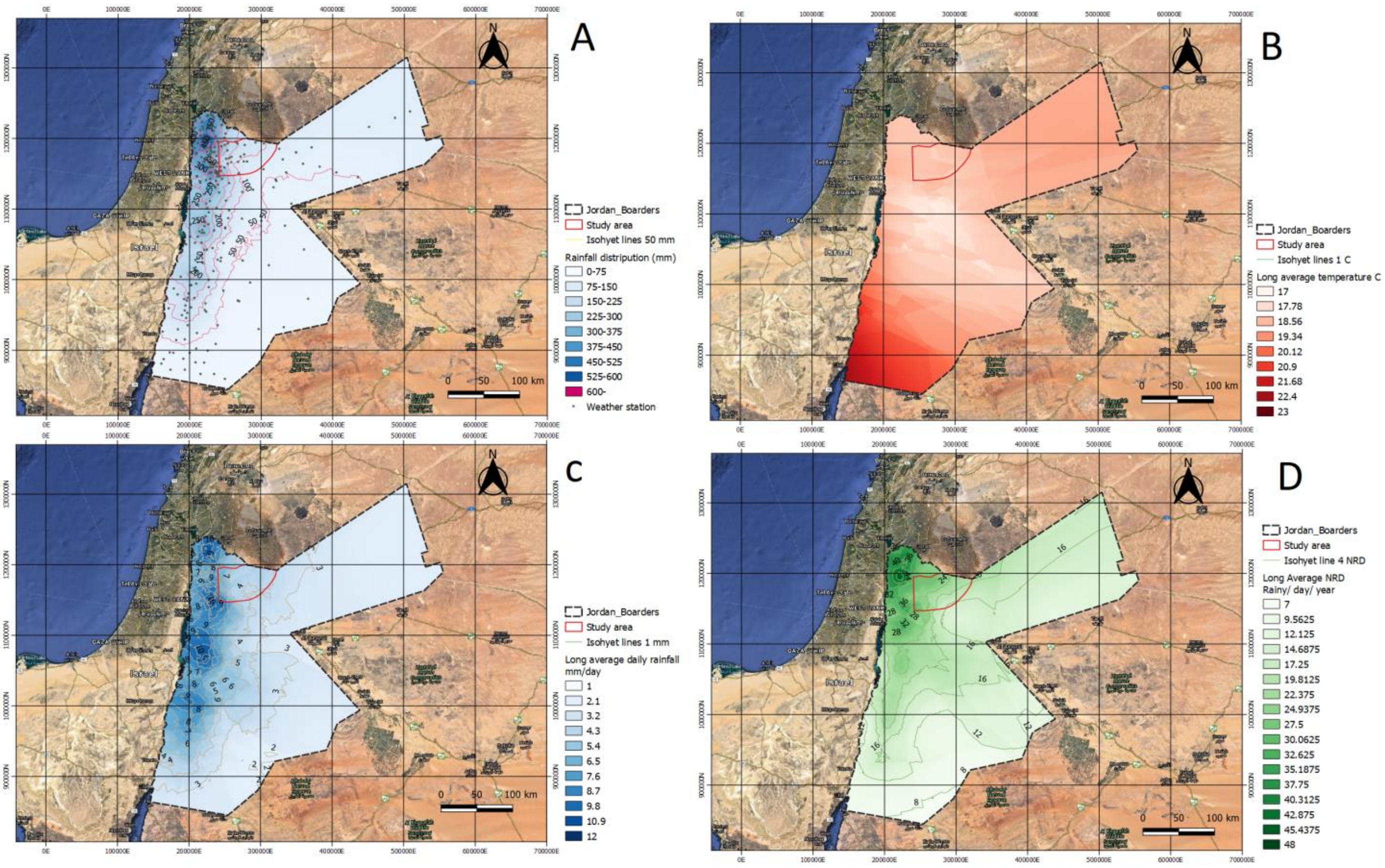


Figure 2-4 A: Jordan average precipitation B: Jordan average temperature C: Jordan daily average rainfall, and D: Jordan average NRD (Own processing).

Table 2-1 Summary of Jordan climatic parameters own processing from 346 weather stations (using the daily data 1937-2019 from the WIS (2020)

Temperature (C°)	For all the measurements from (1937-2019): Average of all daily temperature = 19.15658486 c° Maximum record= 50 c° Minimum record = -13 c° Standard deviation= 10.34												
	month	January	February	March	April	May	June	July	August	September	October	November	December
	Max of value	37	40	41	45	47.5	48	50	47	48	48	40	42
	Min of value	-13	-12	-12	-8	-1	0	0.32	0	0	-2	-13	-11
	Average of value	9.59	10.88	13.98	18.37	22.54	25.42	27.11	27.1	25.36	21.7	15.89	11.17
	Average of the maximum	25.9	28.05	33.01	38.49	42.26	42.9	43.5	42.97	42.065	39.1	33.5	27.52
	Average of the minimum	-6.96	-5.82	-3.42	-0.35	3.53	7.14	8.9	8.98	6.82	3.56	-1.65	-5.12
	Average of the average temperatures	9.61	10.95	14.01	18.45	22.6	25.58	26.9	27.11	25.4	21.7	15.95	11.24
Wind (km/hr)	Long average of wind velocity =7.969081535. maximum wind velocity =78. Minimum =0												
	Average	7.78	8.28	8.93	8.9	8.13	8.32	8.75	7.9	7.27	6.84	7.01	7.452
	Maximum	77	77	72	76	70.4	68	73	78	72	70	76.5	77
Sunshine hours	average sunshine = 8.976286322 hr			Maximum= 14.2 hr				Minimum= 0.15hr					
	Maximum	14	14	13.8	14	14	14.2	14.2	14	13.3	13	12.5	14
	Minimum	0.15	0.2	0.2	0.2	0.15	0.2	1	1.1	0.2	0.2	0.2	0.15
	Average	6.29	6.92	7.72	8.85	10.25	11.58	11.69	11.31	10.15	8.796	7.51	6.21
Precipitation	Long annual average of NRD = 26.06573259 Days. The maximum annual NRD= 88.79012346 days and the minimum annual NRD = 1.50617284 day												
	Average of monthly NRD	6.48	5.79	4.9	2.73	1.63					2.19	3.562	5.49
	Average of the minimum NRD	1.39	1.22	1.13	0.91	1.04					0.9	0.93	1.195
	Average of the Maximum NRD	11.89	11.49	9.54	6.194	2.87					4.05	8.42	10.51
	Annual average precipitation (1937-2019) = 92.2mm				Long average daily precipitation (mm/day) (1937-2019) = 9.4174mm/day, the maximum average of daily precipitation occurs in 2010 = 14.056 mm/day, the minimum average daily precipitation occurs in 1937 = 5.8 018 23 mm/day								
	Average monthly mm	61.332	50.567	44.044	17.818	13.64					10.28	27.45	50.29
	Average of the minimum monthly mm	3.859	3.044	2.031	0.505	0.898					0.37	0.55	2.713
	Average of max monthly mm	165.177	140.76	117.48	94.912	43.99					35.33	95.02	154.27

2. Unpredictable high population growth

This is mainly due to the refugee waves (DOS 2020) that increase the pressure on water resources and water authorities to meet the increasing demand of water for all sectors: despite a local growth rate of 2.2 %, there is a massive increase in population, mainly due to the sudden influx of refugees from other countries, mainly Syria and Iraq recently. A process that brings serious pressure on Jordanian scarce and depleted water resources. From the early 1900s to today, Jordan has witnessed waves of refugees (Druze, Chechens, Armenians, Circassians, Palestinians, Iraqis, Yemenis, Libyans, and Syrians) (DOS, 2016) (Table 2-2). The number of Syrian refugees registered in the UNHCR (2020) in Jordan reached 656,733. But the number of Syrian refugees within Jordan's borders was estimated to be about 1.4 million by government surveys (MOPIC, 2014). According to Gazal (2020) 83 % of them live outside the camps in the Jordanian cities and about 124,444 people living in three major camps (Azraq, the Emirati Jordanian camp (Murijeb-Alfhoud), and Zaatari) according to UNHCR (2020). The last two camps located in the study area (Figure 2-5). The estimated number of refugees from all neighboring countries in Jordan in 2015 was 2,890,138 (DOS, 2016), and other estimates indicate that the actual number of Syrian refugees alone is 2,7 million (Jordan Zad 2015).

Table 2-2 Estimated Jordan population during (2015-2050) (DOS 2016).

High- Basic Scenario (continuation of the current situation)				*By the Medium Scenario*			*By the Low Scenario*		
	total	Nationality		total	Nationality		total	Nationality	
Year		Non-Jordanians	Jordanians		Non-Jordanians	Jordanians		Non-Jordanians	Jordanians
2015	9401993	2890138	6511855	9401992	2890137	6511855	9401992	2890137	6511855
2020	10466345	3178857	7287488	10294911	3054097	7240814	10044153	2817574	7226579
2025	11641209	3508885	8132324	11188353	3239395	7948958	10644336	2753048	7891288
2030	12919279	3880622	9038657	11995549	3385627	8609922	11145040	2670790	8474250
2035	14275995	4292926	9983069	12394488	3157883	9236605	11614924	2600609	9014315
2040	15727857	4763274	10964583	12778164	2934233	9843931	12077487	2533184	9544303
2045	17306979	5300094	12006885	13136053	2714931	10421122	12515598	2468661	10046937
2050	19042373	5913070	13129303	13447942	2500244	10947698	12901390	2407186	10494204

The percentages of refugees in Jordan (DOS 2016) by nationality are, 87.9 % Syrian 9 % Iraqi 2 % Yamani's 0.8 % Sudanese 0.1 % Somali 0.2 % different nationalities. According to UNRWA about 2.3 Palestinian refugees registered at UNRWA programs, 400 thousand of them live in refugee camps in the main Jordanian cities. Then the vast majority of Palestinian refugees entered Jordan during the last century have the Jordanian nationality, except for some 158,000 'ex-Gazan' refugees (Palestinians who fled from Gaza to Jordan in the aftermath of the June 1967 hostilities) (UNRWA 2018). According to the UNHCR list of the top twenty Countries to have granted protection to refugees in the 21st century (UNHCR 2014) by comparing the number of refugees to the national population of a host country confirmed that Lebanon topped this list with 206 refugees per 1,000 inhabitants. Jordan (88) and Nauru (39) ranked second and third, respectively. But Jordan can be considered as the first country in the world in such list by returning to the previous paragraph which showed the vast number of Palestinian refugees got the Jordanian nationality since the last century while the UNHCR (2014) list compared the number of registered refuges to the national population while in Jordan big part of the national population come from Palestine during the last century and have the Jordanian nationality. The President of the Arab Thought Forum (ATF) Prince Hassan bin Talal, claimed that Jordan's population, without the refugees waves in modern Jordan's history, was projected to reach two and half million (Talal 2011). The population number has increased and shifting lifestyle consumption and the need for more agricultural activities besides the availability of cheap labor in the agricultural sector causes an agricultural expanding. According to Talal (2015) Jordan, as the third country to host refugees in the world today relative to the number of indigenous people in this small geographical area, is facing a major challenge to meet the rising water demands.

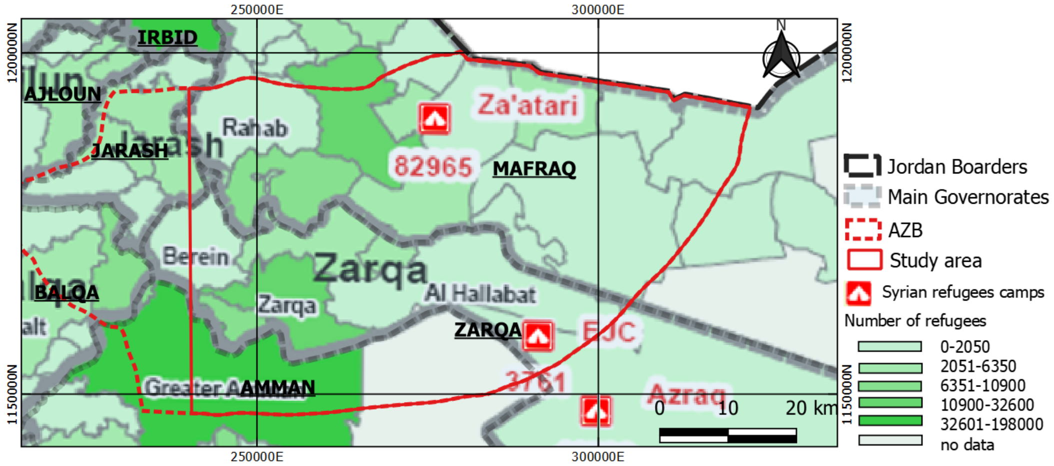


Figure 2-5 Distribution of Syrian refugees registered–UNHCR modified after MOPIC (2014) and UNHCR (2020).

3. The agricultural activities

The agricultural sector has changed significantly for the worse. While Jordan depended on covering its basic cereals needs from producing its grains and others, it became an importer, the agricultural situation in Jordan before the fifties, and how agricultural production exceeded the internal needs explained in the Ministry of Agriculture reports Archives and the agricultural situation during the period 1929-1950 by Mashaqbeh (2019). It retreated heavily and Jordan became dependent on imports to meet its grain needs, while vegetables agricultural investments and fruits plus olives trees in the desert regions flourished, relying on groundwater and prospered significantly in the 1980s and reached the maximum flourishing in the 1990s as it’s called the "super green revolution" by Elmusa (1994) and groundwater has been a cornerstone of this revolution (Courcier et al. 2005; Venot & Molle 2008). Due to population increase, agricultural expansion and changing the lifestyle, this increase has caused an irreversible depletion of the renewable groundwater aquifers, especially in most populated groundwater basin Amman Zarqa basin (AZB) as the actual abstraction is far away beyond the safe yield of the renewable aquifers in all the groundwater basins (BGR and MWI 2019). According to the latest water budget report the total safe yield amount not more than 418 MCM while the abstraction reached 641 MCM the over-abstraction causes a deficit of about 222 MCM (Table 2-3). The gap between supply and demand has been widening mainly due to rapid population growth, rising living standards, and agricultural expansion.

Table 2-3 Groundwater abstraction 2019 and the safe yield values according to latest updated estimations (BGR & MWI 2019), and number of wells in each basin according to WIS (2020).

*	Groundwater Basin		Safe Yield (MCM)	Abstraction (MCM)	Deficit (MCM)	% of abstraction	Number of wells
1	Amman-Zarqa (AZB)		**87.5**	**177.81**	**-90.31**	**203.211**	**1009**
2	Azraq		24	62.54	-38.54	260.583	624
3	Dead Sea		57	83.12	-26.12	145.825	480
4	Disi Non-Renewable**		125	144.02	-19.02	115.216	112
5	Hammad		8	1.34	6.66	16.750	9
6	Jafer	Renewable	9	39.69	-30.69	441.000	227
		Non-Renewable**	18	1.92	16.08	10.667	
7	Jordan Valley		21	26.97	-5.97	128.429	393
8	Jordan Side Valley		15	42.37	-27.37	282.467	142
9	Sirhan		5	0	5	0.000	0
10	Araba North		3.5	6.28	-2.78	179.429	37
11	Araba South		5.5	12.41	-6.91	225.636	61
12	Yarmouk		40	42.9	-2.9	107.250	228
	total		418.5	641.37	-222.87	153.2544803	3322

*Jordan consists of 15 surface water basins and 12 groundwater basins. **The safe yield abstraction from non-renewable groundwater for 50 years is about 143 MCM annually according to the Ministry of Water and Irrigation studies (MWI 2016).

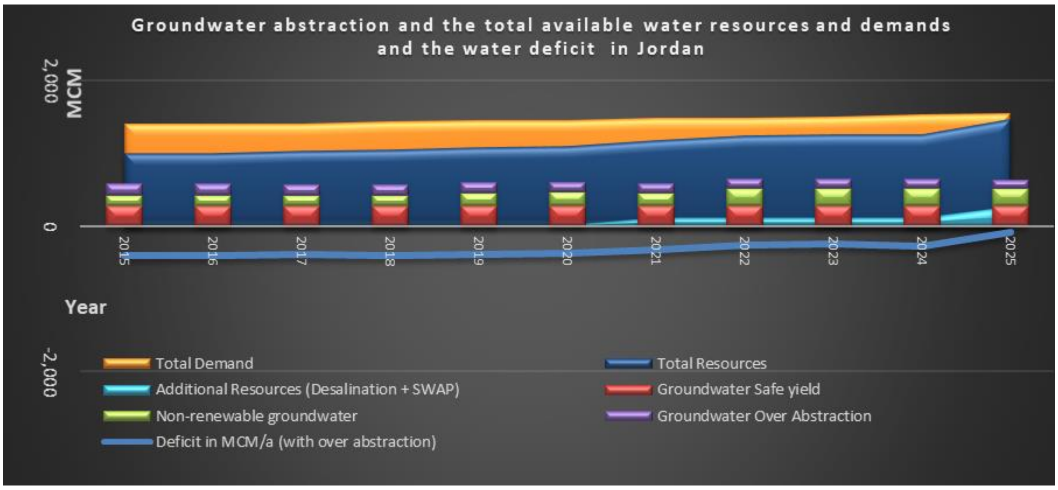


Figure 2-6 Groundwater abstraction, total available water resources, total demands, and the water deficit in Jordan. Modified after the national water strategy 2016 – 2025 (MWI 2016).

The deficit between water supply and demand in MCM/year (with over-abstraction) was estimated at -409 on 2015, increased to -384 in 2019, and it is projected to reach -88 MCM by 2025 (MWI 2016). This by supposing the successes of developing unconventional water supplies and rising water harvesting projects, plus the most important water desalination project in Jordan (Red Dead Canal project), which makes the 2025 forecast very positive (Figure 2-6).

2.2 Review of Jordan's sustainable groundwater management and vulnerability maps:

Groundwater resources cover 44 % of the Irrigation requirements and more than 58 % of the country water requirements. Agricultural activities in the Jordan's eastern desert regions flourished, relying on groundwater and prospered significantly in the 1980s and reached the maximum flourishing in the 1990s as it's called the "*super green revolution*" by Elmusa (1994) and groundwater has been a cornerstone of this revolution (Courcier et al. 2005; Venot & Molle 2008). The percentage of water used in agriculture for total water usage in 2019 was 51 % when it was above 70 % at the beginning of the 1990s, according to agricultural policies, increasing the profitability and efficiency of irrigation methods to cope with water scarcity in Jordan (WIS 2020) (Figure 2-7).

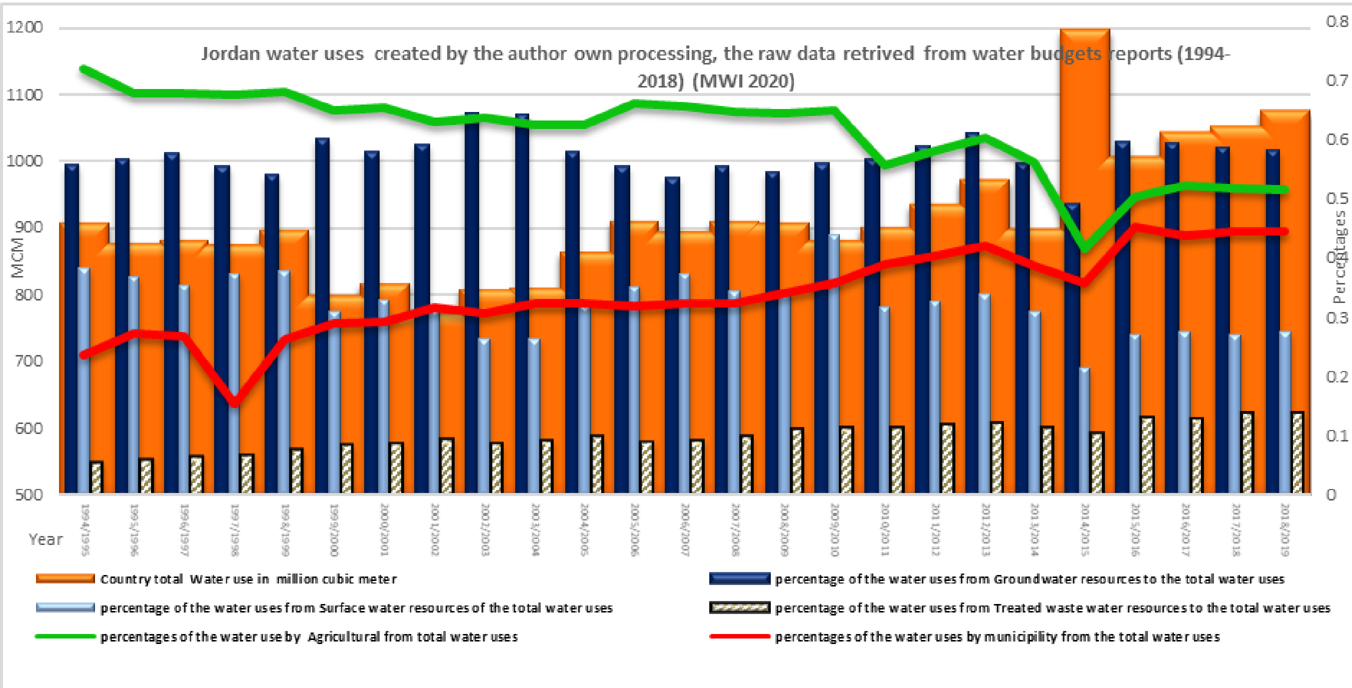


Figure 2-7 Jordan water resources, and percentages of water use per sector 1994-2018, Raw data retrieved from the water information system WIS (2020), (Own processing).

The challenging water situation in Jordan has demonstrated the urgent need to implement sustainable management strategies as set out in the national water strategy (MWI 2016) and specifically for groundwater resources in the groundwater sustainability policy report (MWI 2018). However, reaching the sustainable use of the groundwater resources in an arid country like Jordan is a challenge, while the country deficit in the water requirements is covered by unsustainable abstractions.

Accordingly the depletion in the renewable groundwater aquifer reaches 2 m/year for the studied period from 1995 to 2017 (MWI & BGR 2018) while some groundwater table observation wells in areas within AZB show a suddenly drawdown rate increase since 2013, up to 12 m/year. Groundwater sustainable management not only related to the availability of the groundwater and its quantity but also the quality deterioration (Foster et al. 2013). Therefore according to the groundwater sustainability policy (MWI 2018) the need is urgent to protect the limited groundwater resources from being contaminated. This could be done through the preparation of groundwater protection schemes to avoid groundwater resources contamination by delineation of groundwater protection zones according to the drinking water resources protection guideline which was in first official report in Jordan to guide the delineation of water resources protection zones released in 2006. This was recently updated by releasing the water resources protection guidelines reports (MWI 2018) which comes as supplementary to the underground water control by-law No. 85 of the year 2002 and its amendments in the years (2003, 2004, 2007, 2013, 2014) (PMJ 2014) and according to the water control law statements 4 and 44 of the law number 85 and its amendments.

Towards this goal, the collaboration between the Ministry of Water and Irrigation (MWI) and the federal Bundesanstalt fuer Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources) (BGR), commissioned by the Federal Ministry for Economic Cooperation and Development (Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung, (BMZ) have developed several vulnerability maps for different groundwater basins and well-field areas in the country using a variety of methods and considering many hydrogeological and environmental aspects as one of the primary tools in this process for delineation the groundwater protection zones. The GLA-Model is the first vulnerability model used in Jordan, developed by the Geological Surveys of the individual states of the Federal Republic of Germany which is called GLA-Model developed by Hölting et al. (1995). The map was produced for the Irbid area, from the Yarmouk River in the north to the area north of Ajlun and Jerash at a scale of 1:100000, (Margane et al. 1997), and it was republished by Margane et al. (1999) and other researchers with modifications. While the same study, stated that the need is urgent to create the groundwater vulnerability map parallel with the expanding of the intensively cultivated areas that led to a noticeable increase of the nitrate content of more than 100 mg/l as it was recorded in several areas like Dhuleil, and Mafraq, which is included in the study area of this research.

2.3 Groundwater Contamination Risk Assessment

Groundwater risk assessment (GRA) defined by Morris & Foster (2001) "*as the probability that groundwater in the aquifer will become contaminated to an unacceptable level by activities on the immediately-overlying land-surface, the risk will be the result of the interaction between the subsurface contaminant load and the aquifer pollution vulnerability at the location concerned*". The identification of vulnerable groundwater levels is crucial to the sustainable management and conservation of limited groundwater resources. Arid and semi-arid areas are specifically reliant on groundwater sources. However, due to several factors linked to the disproportionate use of groundwater and the agricultural activities, contamination has increasingly become a serious problem, specifically in areas where fertilizers are extensively used to enhance the productivity of a soil characterized by low fertility. The common causes of groundwater quality deterioration can be classified by genesis are explained by Foster et al. (2002). This classification assumed a four classes of groundwater quality problems the aquifer pollution, the wellhead contamination, the saline water intrusion, and the naturally occurring contamination.

The present work designed to address the first problem the "aquifer contamination" in a comprehensive groundwater contamination risk assessment (GRA) of a renewable groundwater aquifer in a dry agricultural area. The aquifer contamination has the following underlying causes according to Foster et al. (2002) "inadequate protection of vulnerable aquifers against manmade discharges and leachates from urban/industrial activities and intensification of agricultural cultivation" and the following contaminants of concern "pathogens, nitrate or ammonium, chloride, sulfate, boron, arsenic, heavy metals, dissolved organic carbon, aromatic and halogenated hydrocarbons, certain pesticides". The time needed to the surface contaminants to reach the groundwater aquifer depends on several factors related to the load of the contamination and the characteristic of the aquifer. While the contamination load mainly depends on the land use activities (Figure 2-8), this explains the significance of contracting aquifer pollution vulnerability and the difference between the contamination load according to the land uses.

Groundwater resources are safer and less vulnerable to pollution than the surface water resources (such as rivers and lakes) since groundwater aquifers are naturally protected by soil and unsaturated layers over the water table. But that does not mean that groundwater contamination is less serious than contamination of surface water. Groundwater is not fully out of harm's way just because it is out of sight, and that just because a contaminated aquifer might not be as offensive to our senses as a polluted river, that does not mean that groundwater contamination is less serious than surface water contamination (Freeze and Cherry 1979; Foster 2001).

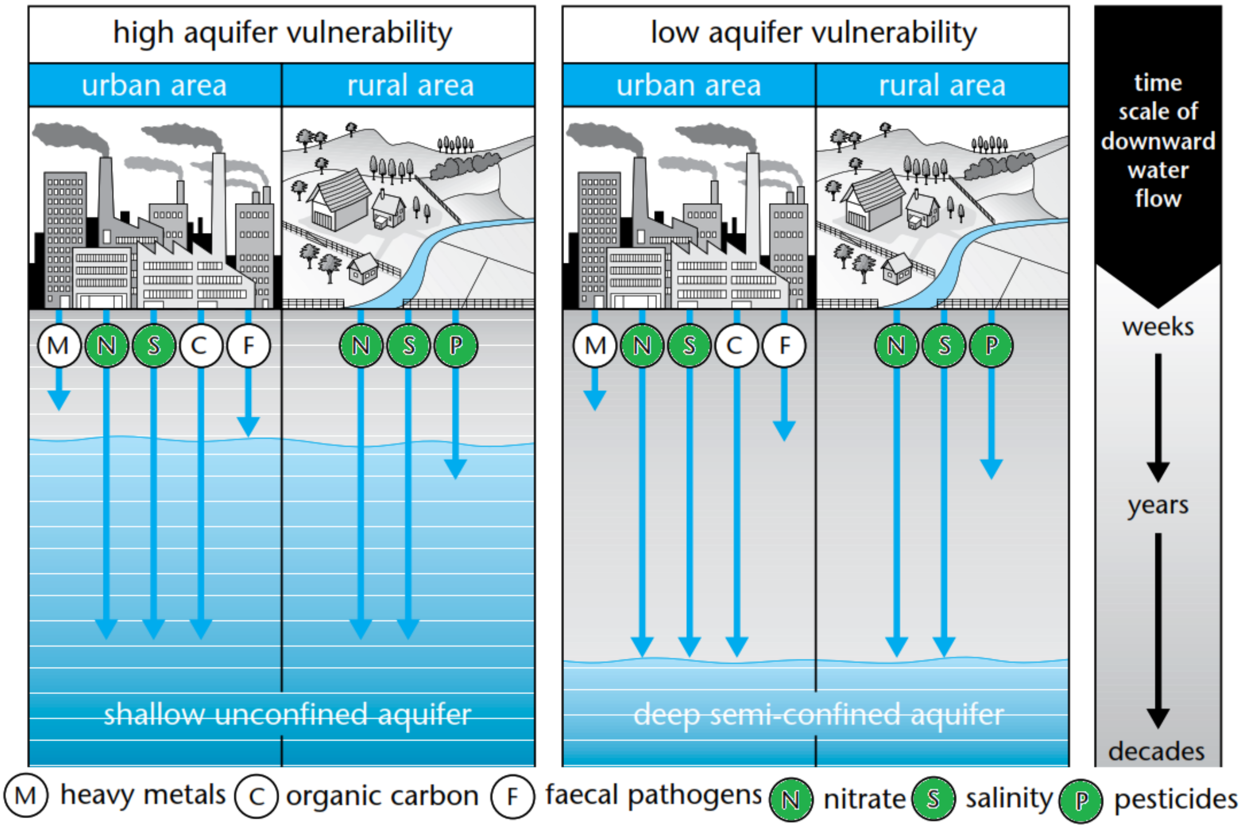


Figure 2-8 Significance of contrasting aquifer pollution vulnerability (Foster et al. 2002)

Groundwater contamination is more difficult to detect and track and that the source is more difficult to locate than surface water. Maybe most important, if the aquifer is contaminated, the job of cleaning it up, even if it is feasible, is immense. Perhaps more than in the case of surface water contamination, the maxim of groundwater contamination is that prevention is better than treatment (Price 2013). However, the potential for this natural protection depends on a variety of factors, and natural protection varies from place to place, depending on the hydrogeological nature of the aquifer and the contamination load on the surface.

Groundwater aquifer contamination occurs where the contaminant load produced by man-made discharges and leachates (from urban, manufacturing, agricultural and mining activities) is poorly regulated and exceeds the natural attenuation ability of the overlying soils and the unsaturated strata. Figure 2-9, and Table 2-4 summarize the common groundwater contaminations and association pollution sources. The biochemical degradation and chemical reaction are the product of the auto-elimination of pollutants during sub-surface transport in the vadose (unsaturated) zone, but contaminant retardation processes due to sorption phenomena are also of significance as they increase the time available for processes resulting in contaminant elimination. Not all subsoil profiles and underlying unsaturation layer, however, are equally successful in attenuating pollutants, and aquifers would be especially vulnerable to contamination where, for instance, strongly fissured consolidated rocks are present.

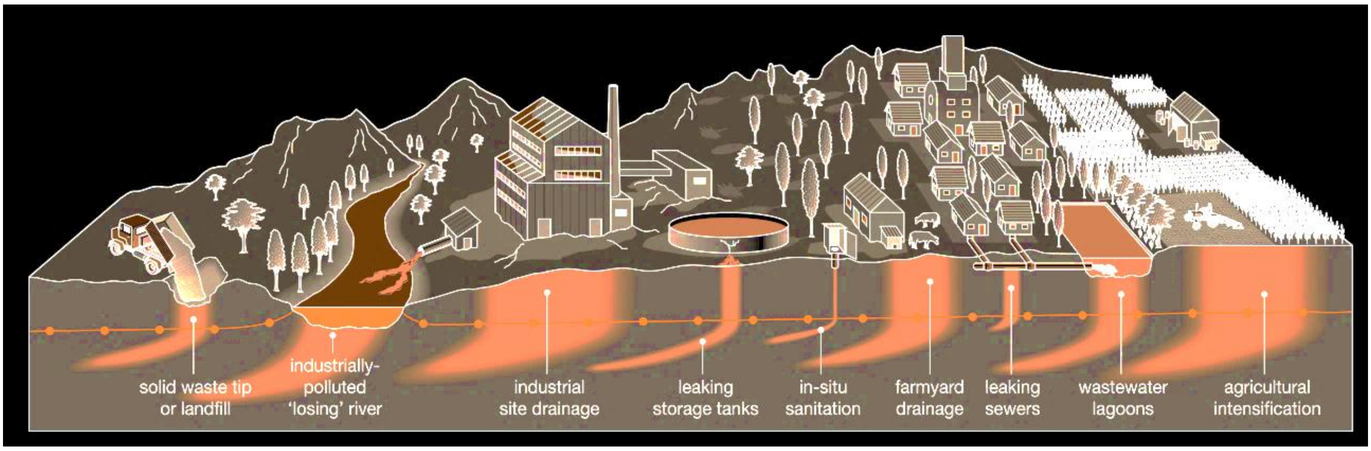


Figure 2-9 Common processes of groundwater pollution (Foster et al. 2002).

Table 2-4 Common groundwater contaminants and associated pollution sources (Foster et al. 2002).

Pollution source	Type of contaminant
Agricultural activity	Nitrates; ammonium; pesticides; fecal organisms
In-situ Sanitation	nitrates; halogenated hydrocarbons; microorganisms
Gas Stations and Garages	Aromatic hydrocarbon; benzene; phenols; halogenated hydrocarbons
Solid Waste Disposal	Ammonium; salinity; halogenated hydrocarbons; heavy metals
Metal Industries	Trichloroethylene; tetrachloroethylene; halogenated hydrocarbons; phenols; heavy metals; cyanide
Painting and Enamel Works	Alkylbenzene; halogenated hydrocarbons; metals; aromatic hydrocarbons; tetrachloroethylene
Timber Industry	Pentachlorophenol; aromatic hydrocarbons; halogenated hydrocarbons
Dry Cleaning	Trichloroethylene; tetrachloroethylene
Pesticide Manufacture	Halogeneted hydrocarbons; phenols; arsenic
Sewage Sludge Disposal	Nitrates; halogenated hydrocarbons; lead; zinc chromium;
Leather Tanneries	Chromium; halogeneted hydrocarbons; phenols
Oil and Gas Exploration/Extraction	Salinity (sodium chloride); aromatic hydrocarbons
Metalliferous and Coal Mining	Acidity; various heavy metals; iron; sulfates

The degree of attenuation in any given setting will also vary widely with pollutant forms and pollutant processes. Natural soil profiles actively attenuate many, but not all, water pollutants (Glower 1983; Foster et al. 2002) briefly clarified the key mechanism of attenuation of pollution in the groundwater system as follows:

1. Many, but not all, are subject to naturally occurring attenuation processes when waterborne contaminants move below the ground surface through the soil layer. This can be a potentially efficient device if the contaminant enters through a natural soil profile because soils are

typically aerated by soil fauna and very biologically active. This favors bacterially mediated degradation, which in an aerobic environment is more successful for many compounds.

2. Soils can also have elevated content of clay and/or humus, creating opportunities for sorption and ion exchange.
3. However, in an urban environment, by systems that bypass the soil zone, such as septic tanks, and latrines, many pollutants directly penetrate the subsurface. As these systems are built to dispose of waterborne wastes rapidly, they will almost invariably enforce a higher hydraulic loading, or surcharge, than contaminants entering through the soil layer. The increased speeds of percolation, resulting in a subsequent decrease in residence times and the possibility of contaminant degradation.
4. Contaminant attenuation processes in the unsaturated zone continue to a lesser degree with depth. Figure 2-10 qualitatively shows their relative value in the soil, above, at and below the groundwater table.

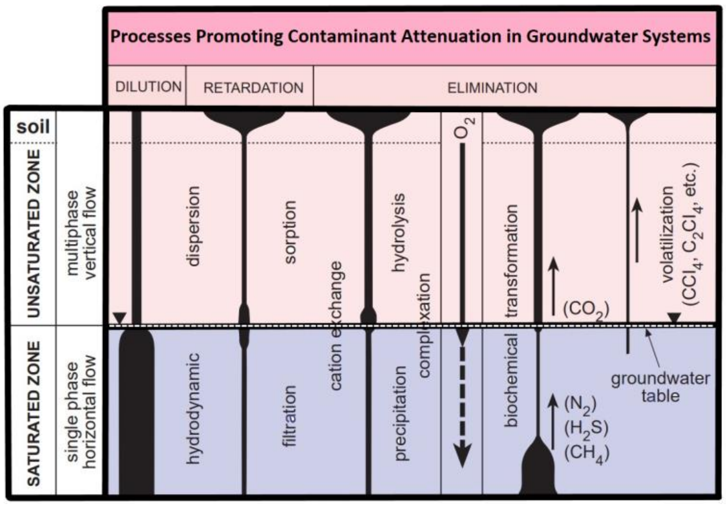


Figure 2-10 The main process promoting contamination attenuation in groundwater systems (Glower 1983)

The groundwater contamination risk could then be described as the possibility that groundwater in the aquifer would become polluted by activities on the immediately overlying land-surface to an unacceptable degree. The danger would arise from the relationship between the load of the subsurface contaminant and the vulnerability of aquifer contamination at the location concerned. Then the groundwater contamination risk can be evaluated by studying tow component the contamination load and the natural groundwater potential protectiveness. The most logical approach in the groundwater contamination risk assessment is studying the result of the interaction between the subsurface contaminant load and the aquifer pollution vulnerability at the location concerned (Foster et al. 2002; Foster & Hirata 1988; Civita 1990). (Figure 2-11) explain the general scientific concepts in this regard. Implementing such a simple scheme we may have high groundwater vulnerability, but there is no chance of contamination in the absence of a substantial contaminant load, and vice versa. Both are perfectly consistent.

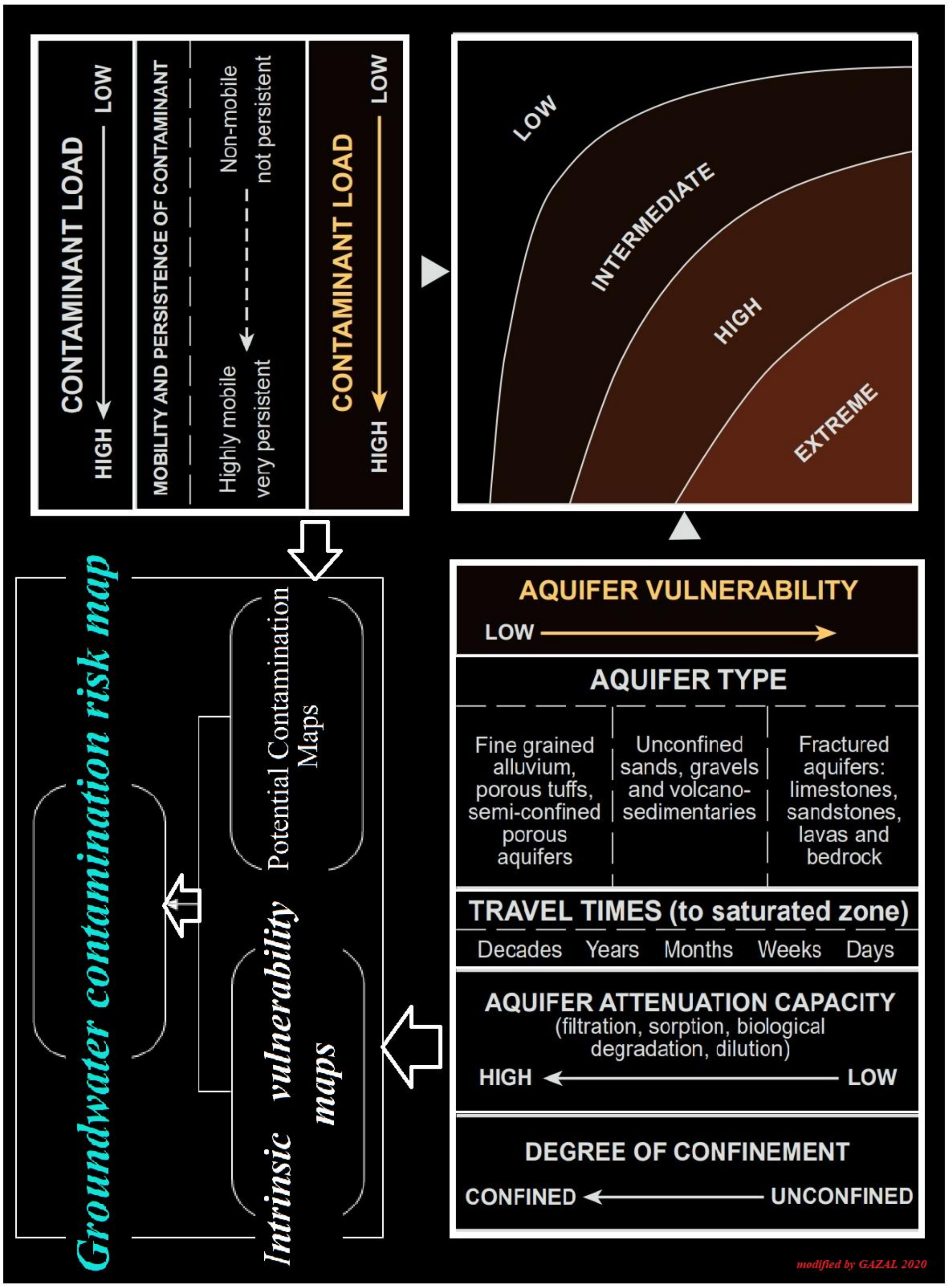


Figure 2-11 The conceptual basis scheme for groundwater contamination risk modified after (Foster et al. 2002; Foster & Hirata 1988; Civita, 1990).

In addition, the contaminant load may be managed or changed, but the vulnerability of the aquifer is basically an inherent, natural aspect (other than where the geological profile is removed or disrupted by quarrying, mining or civil engineering excavation). Therefore, the groundwater contamination risk map created in this study with a simple modified overlying approaches (a combination between modified DRASTIC model and land use) is worthwhile to be used and to apply the same technique to construct a groundwater contamination risk map for the whole country (Jordan) and any related dry areas in the world. However, it is more important to rely on the vulnerability map itself to manage the land use process because the contamination status may change over time, but the natural groundwater potential protectiveness is fixed over time unless the geological profile is removed or disturbed by human activities. To conclude and according to NRC (1993) the assessment of the groundwater vulnerability can be done in two ways:

1. The Groundwater Risk Assessment of specific vulnerability, which is a combination of the intrinsic vulnerability and of the potential or the actual sources of contamination.
2. The Assessment of the General Groundwater Aquifer intrinsic vulnerability: (In the modeling part of this study DRASTIC model was used to assess the intrinsic vulnerability through several modified approaches). The intrinsic (inherent) vulnerability depends only on the characteristics of the groundwater aquifer, which are as follows (Napolitano 1995):
    a. Hydrogeology of the unsaturated layers (vadose zone): It defines the vertical and horizontal permeability and, consequently, it controls the speed of pollutant diffusion and the capability of the rocks to attenuate the action of the pollutant.
    b. Water table depth: It defines the thickness of the vadose zone (from the topographic surface) and is proportional to the capability of attenuation from pollutants.
    c. Hydro-lithologic characteristics of the aquifer: It controls the diffusion of the pollutants when they reach the saturated zone.

Groundwater risk map generally, is a combination of existing hazardous substances and the aquifer vulnerability. But due to the difficulties of recognizing all possible sources of contaminants and the presence of a real contamination problem, the susceptibility is more directed towards a particular contaminant which is in the case study of this dessertation the nitrate contaminant.

2.4 Some terms definitions related to the groundwater vulnerability

1. The “Aquifer vulnerability” defined by Albinet & Margat (1970) as “*The possibility of percolation and diffusion of contaminants from the ground surface into natural water table reservoirs, under natural conditions*”.
2. Vulnerability was described by Villumsen et al. (1983) as “*The risk of chemical substance used or disposed of on or near the ground surface to influence groundwater quality*”.
3. Vulnerability was described by Vrba & Zaporožec (1994) as “*An intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural*

impacts". Besides they defined the groundwater vulnerability relates to subsurface contamination from nonpoint pollution on as the measure of the "*degree of insulation" of groundwater from the land surface contaminants*".

4. Groundwater vulnerability described by Bachmat & Collin (1987) as "*The sensitivity of groundwater quality to anthropogenic activities which may prove detrimental to the present and/ or intended usage or value of the resource*".
5. Aquifer pollution vulnerability described by Foster (1987) as "*The intrinsic characteristic which determines the sensitivity of various parts of an aquifer to being adversely affected by an imposed contaminant load*". And described the "Groundwater Pollution Risk" as "*The interaction between (a) the natural vulnerability of the aquifer, and (b) the pollution loading that is, or will be applied on the subsurface environment because of human activity*".
6. Vulnerability of a Hydrogeological system explained by Sotornikova & Vrba (1987) as "*The ability of this system to cope with external, natural and anthropogenic impacts that affect its state and character in time and space*".
7. The United States General Accounting Office (USGAO) (1991) described "Hydrogeological Vulnerability" as "*A function of geologic factors, as soil texture and depth to groundwater*". While the "Total Vulnerability" as "*A function of these hydrogeologic factors as well as the pesticide use factors that influence the site's susceptibility*", and "Total Risk" as "*This last approach is even broader, for it incorporates the size of the population at risk from potential pesticide contamination- that is, the number of people who obtain their drinking water from groundwater in the area*".
8. The aquifer Vulnerability was described by Pettyjohn et al. (1991) as "*The geology of the physical system determines vulnerability.*", and the "Aquifer Sensitivity" as "*Aquifer sensitivity is related to the potential for contamination, i.e., aquifer that has a high degree of vulnerability and are in areas of high population density, are the most sensitive*".
9. The United States Environmental Protection Agency (USEPA) (1993) described "Aquifer Sensitivity" as "*The relative ease with which a contaminant (in this case a pesticide) applied on or near the land surface can migrate to the aquifer of interest. Aquifer sensitivity is a function of the intrinsic characteristics of the geologic materials of interest, any overlying saturated materials, and the overlying unsaturated zone. Sensitivity is not dependent on agronomic practices or pesticide characteristics*", and the "Ground Water Vulnerability" as "*The relative ease with which a contaminant (in this case a pesticide) applied on or near the land surface can migrate to the aquifer of interest under a given set of agronomic management practices, pesticide characteristics and hydrogeologic sensitivity conditions*".

10. The National Research Council (NRC) (1993); (NRC) (1994) described the "Groundwater Vulnerability to Contamination" as "*The tendency or likelihood for contamination to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer*".

2.5 Review of the groundwater vulnerability mapping approaches.

Scientists and resource managers have tried to establish a methodology for estimating areas that are more likely to become polluted by activities on or near the surface of the earth than others (NRC 1993). Creating a vulnerability map for the groundwater aquifers is a relatively modern procedure in groundwater sustainability studies (Vrba and Zaporozec 1994). Groundwater Vulnerability is one of the terms that led to a breakthrough in water resource sustainable management, enabling decision-makers and researchers in the field of groundwater pollution to identify the causes of pollution and the severity of pollution from one place to another and help to put the guidelines to create groundwater protection zones. Years before the notion of groundwater vulnerability and protection emerged in the 1960s, along with the rapid expansion and application of zoning and indexing-rating models, most studies employed coherent physicochemical parameters for geological and hydrogeological characteristics. For example, the travel time needed for the pollution front to enter groundwater from the source of contamination, the retardation factor, the hydraulic resistance of the cover, and water-bearing deposits, the contamination front to reach groundwater from the source, the retardation factor (ratio of velocities of seepage water, and contaminant particles) (Faybishenko et al. 2013).

The first mention of the concept of groundwater vulnerability as an alternative of "natural protection against contamination" in the 1960s was made by French hydrogeologist Jean Margat, currently, Vice-President of the Association du Plan Bleu and regularly consulted as an expert by international organizations such as FAO, UNESCO, World Bank, and UNDP, and won the IASH, UNESCO and WMO International Hydrology Prize in 2008. Margat (1968) for the first time defined the concept of groundwater vulnerability as "*the ease with which the contaminant introduced into the ground surface may enter and diffuse into groundwater*" and this simply, the lower the natural protection, the higher the vulnerability (Nguyet & Goldscheider 2006). And after the first definition by Margat since the 1960s, this basic concept of groundwater vulnerability has taken on a range of definitions in the technical literature, and several terminologies have since been given.

The National Research Council (NRC) (1993) identified two general types of vulnerability assessments. The first type is needed to address the specific vulnerability of the site to a specific contaminant or contaminant class due to human activity. The second type is intended to address intrinsic vulnerability of groundwater without consideration of the attributes and behavior of specific contaminants. While according to the NRC (1993) the approaches to investigate the groundwater vulnerability can be categorized into three main traditional approaches (Table 2-5):

1. Overlay and index methods: Involves obtaining and combining maps of the parameters that affect the transport of contaminants from the surface to groundwater, then assigning an index value to those parameters; the results are a spatially oriented vulnerability index. The combination of several parameters by assigning a numerical index or score to each parameter attribute with values indicating the degree to which that parameter indicates the possibility of protection of groundwater from contamination, or otherwise, in the study area. The simplest overlay approach (schemes) defines areas where parameters that imply vulnerability have the same effects, such as shallow groundwater and sandy soil, which would represent similar vulnerability measurements. While, based on many parameters' inputs, more sophisticated approaches assign numerical scores.

Table 2-5 Selected methods used to Evaluate Groundwater Vulnerability (NRC 1993)

Method	**Reference**	**Map Scale***	**Reference Location**	**Intrinsic and/or Specific**
1- Overlay and Index methods				
Kansas	(Kissel et al 1982)	Small	Soil	Intrinsic
DRASTIC	(Aller et al. 1987)	Variable	Groundwater	Intrinsic
California Hotspost	(Cohen et al 1986)	Large	Water Table	Intrinsic and Specific
Washington Map Overlay	(Sacha et al 1987)	Small	Groundwater	Intrinsic and Specific
SEEPAGE	(Moore 1988)	Variable	Groundwater	Intrinsic
Lowa Groundwater	(Hoyer & Hallberg 1991)	Small	Groundwater	Intrinsic
EPA/UIC	(Pettyjohn et al 1991)	Small	Groundwater	Intrinsic
2- Process-Based Simulation models				
PESTANS	(Enfield et al. 1982)	Large	Soil	Specific
BAM	(Jury et al 1983)	Large	Soil	Specific
MOUSE	(Steenhuis et al 1987)	Large	Groundwater	Specific
PRZM	(Carsel et al. 1984)	Large	Soil	Specific
RF/AF	(Rao et al 1985)	variable	Soil	Specific
GLEAMS	(Leonardo et al 1987)	Large	Soil	Specific
CMLS	(Nofziger & Hornsby 1986)	Large	Soil	Specific
RITZ/VIP	(McLean et al. 1988)	Large	Soil	Specific
LEACHM	(Wagenet & Huston 1989)	Large	Large	Specific
RUSTIC	(Dean et al. 1989)	Large	Groundwater	Specific and Intrinsic
3- Statistical methods				
Discriminant	(Teso et al. 1988)	Small	Groundwater	Specific
Regression	(Chen & Druliner 1988)	Small	Groundwater	Specific

* "Large Scale" means that the method is typically applied at a level of detail of at least a 1:24,000 scale map to a small spatial area. "Small Scale" means that the method is typically applied at a level of detail less than that of a 1:50,000 scale map to larger spatial area (NRC 1993).

2. Process–based simulation models: Involves numerical modeling and is useful at the local level but not the regional level, therefore the map scale in such approach is small and as example of those models PRZM, GLEAMS and LEACHM which can predict the fate and transport of contaminants from known sources with notable accuracy in a localized area by applying fundamental physical principals to predict the flow of water in porous media and the behavior of chemical constituents carried by that water. Models in these groups range from indices based on simple transport models to analytical solutions for one-dimensional transport of contaminants through the vadose zone to saturated zones on to several phases (two or three-dimensional models).
3. Statistical methods: Involves correlating actual water quality data to spatial variables and requires a large amount of site-specific data. These models are often used as a validation test for other models.

Although a comprehensive review of the applied groundwater vulnerability assessment methods since the first mention of this term by Margat (1968) may indicate the following list of the most significant groundwater vulnerability and protectability assessment approaches:

1. Hydrogeological zoning methods (HZM): This approach was scientifically first explained by Margat (1968) and used for the assessment of groundwater vulnerability, also it was used by (Vrana 1968; Vrana 1984; Albinet & Margat 1970; Josopait & Schwerdtfeger 1979; Ball et al. 2004; and others). Also Margane et al. (1997) called this approach as the hydrogeological complex and setting methods (HCS) and defined it as a method of assessing vulnerability to groundwater by defining groups of two or more vulnerabilities. Classes are based on parameters considered to be indicative of the groundwater vulnerability under such hydrogeological conditions. This form of mapping is used mostly for maps of medium to large scale areas.
2. Mapping vulnerability of the shallow aquifers by estimation the groundwater age: The main concept behind making vulnerability maps using age data is that the older the groundwater, the less chance it has of being anthropologically polluted (Kazemi et al. 2005).
3. Parametric (scoring and index system) methods:
   a. Matrix systems, assess groundwater vulnerability based on a selection of two or more parameters considered to be representative for a certain area (UNESCO-IHP 2004; Vrba & Zaporožec 1994; Margane et al. 1997).
   b. Rating Systems and Point Count System Models:
      I. Rating systems: Using various hydrogeological parameters with defined ranges of ratings according to their variation. The overall rating is determined by overlaying the

ratings for these various parameters and then splitting the overall rating into different vulnerability rates. GOD and GLA approaches can be assigned to this method. GOD developed by Foster (1987); and Foster & Hirata (1988) for geological conditions of Great Britain, the German GLA-Model developed by Hölting et al. (1995) and used in Jordan groundwater studies by Margane et al. (1997). Also SUPRA model proposed by Zaporozec (1985); Zaporozec (2002), and the German PI model of regional assessment of intrinsic groundwater vulnerability was created by Goldscheider (2005), and the German COP-model by Vías et al. (2006) which was developed through the EU project COST-620 (Zwahlen 2004) and the latest groundwater vulnerability map for Jordan created by applying COP model (BGR & MWI 2018), and the Pesticide root zone model for groundwater (PRZM-GW) to estimate concentrations of pesticides in groundwater for drinking water exposure assessments since 2012 which was created as part of the North American Free Trade Agreement (NAFTA) to develop a unified groundwater modeling protocol (HC and USEPA 2012) developed by the US Environmental protection agency (USEPA), office of pesticide programs (OPP) (HC & USEPA 2012).

II. Point count system models (PCSM): Also called parameter weighting and rating methods which are used to measure the most important hydrogeological characteristics and use the same approach as rating methods but attribute different weights in the form of a multiplier to reflect the importance of each parameter for the overall assessment of groundwater vulnerability so all the (PCSM) models belong to the rating system. Among the scoring and index approaches the DRASTIC model is one of the earliest methods for determining aquifer vulnerability and the first point count system models (PCSM) or parameter weighting and rating methods. The most widespread PCSM method of evaluation of the groundwater vulnerability developed by Aller et al. (1987) ordinary DRASTIC index can vary within the range of 23–230 (intrinsic vulnerability) or 26–260 for agricultural DRASTIC which used in this study (vulnerability to pesticides). DRASTIC later was subjected to several modifications of its parameters weights by applying statistical methods, also, to be modified by adding other parameters as Denny et al. (2007) proposed to include the structural geology by adding the geological lineaments maps and other index-rating assessment methods where developed like the Italian model SINTACS developed by Civita & Maio De (2004). Unlike DRASTIC, the scores table for SINTACS indicator includes more detailed lithological variations and disruptions, EPIK model was created especially for use at karst areas in Switzerland by Doerfliger et al. (1999), and Chines model DRAV developed by Zhou et al. (2010).

4. Confined groundwater protectability: can be measured using Goldberg's qualitative groundwater protection assessment (Goldberg 1983; Goldberg 1987) of the thickness of the overly-permeable (low-permeable) confining layers, including the groundwater hydraulic head ratio in confined and upper unconfined aquifers.
5. Modeling methods:
   a. Deterministic: The deterministic (processed-based) approaches involves numerical modeling and is useful at the local level but not the regional level, for example of the deterministic approaches the A3D model was constructed in the work of Loague et al. (1998) based on the MODFLOW-MT3D to study the groundwater susceptibility to DBCP (1,2-dibromo-3-Chlo-ropropane) contamination in Fresno County, California.
   b. Statistical: Involves correlating actual water quality data to spatial variables and requires a large amount of site-specific data. It was developed by Jury & Roth (1992) These approaches are based on stochastic algorithms and are represented by the use of special probability density functions for the solution of groundwater migration problems such as the Monte Carlo method (Faybishenko et al. 2013). Evans (1995) used this approach for statistical evaluation of the susceptibility of groundwater to nitrate pollution.

2.6 DRASTIC groundwater vulnerability model:

Among the Scoring and index approaches the DRASTIC model is one of the earliest methods for determining aquifer vulnerability and the first point count system models (PCSM) or parameter weighting and rating methods. And the most widespread PCSM method. There are two DRASTIC approaches, ordinary DRASTIC index which can vary within the range of 23–230 or 26–260 for agricultural DRASTIC. In the case study agricultural DRASTIC-model was selected as a suitable method of choice for large-scale agricultural areas study and in areas where the availability of data is low, but the general hydrogeological specifications are known according to Margane (2003); and Foster & Hirata (1988). Aller et al. (1987) created the DRASTIC model for the United States Environmental Protection Agency (EPA), to develop a framework that would allow any hydrological setting to systematically determine the potential for groundwater contamination. The DRASTIC system has two components: the classification of mapped units, called hydrogeological settings; and the implementation of a scheme for the relative ranking of hydrogeological parameters, called DRASTIC, which enables the determination of the relative potential of any hydrogeological setting to contaminate groundwater. Though the two parts of the DRASTIC system are interrelated, they are addressed in a logical progression separately. A hydrogeological setting is a composite definition of all the major geological and hydrological factors affecting and controlling the flow of groundwater into, and out an area. It is characterized as a mappable unit with common hydrogeological characteristics and, as a result, a common vulnerability to pollution caused by pollutants introduced. The second part of the system was determined to be the seven DRASTIC parameters according to the most important mappable factors which control the groundwater pollution potential. These variables have been arranged to form an acronym, DRASTIC for quick and easy reference, where the position of each parameter in this arranged does not reflect its importance to other parameters. The model yields a numerical index deriving from the ranges, ratings, and weights assigned to the model parameters. Each DRASTIC parameter is subdivided into ranges or relevant forms of media types, which are ranked between 1 and 10 based on their relative effect on the potential for contamination (Aller et al. 1987). Depending on its relative significance the seven parameters are assigned weights ranging from 1 to 5, The most important factors are 5 weights; the least significant is 1.

The DRASTIC index is then determined by applying a linear combination of all variables, according to the following governing equations:

1. DRASTIC Index (Pollution Potential) = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw ... (1). Where r = rating and w = weight D= Depth to water, R= Net recharge, A= Aquifer media, S= Soil media, T=Topography, I= Impact of the vadose zone media, C= Aquifer hydraulic conductivity.
2. Agricultural (Pesticide) DRASTIC = 5Dw + 4Rw + 3Aw + 5Sw + 3Tw + 4Iw + 2Cw …. (2).
3. Ordinary or Generic DRASTIC = 5Dw + 4Rw + 3Aw + 2Sw + 1Tw + 5Iw + 3Cw……... (3).

The only way agricultural (Pesticide) DRASTIC varies from generic DRASTIC is by allocating relative weights for the seven DRASTIC variables. All other aspects of both indexes are similar; the ranges, scores, and implementation instructions are similar. The sum of the Pesticide DRASTIC parameters weight is 26 and is also called Agricultural DRASTIC, while the sum of the Generic DRASTIC parameters weight is 23.

According to Aller et al. (1987), agricultural (Pesticide) DRASTIC is recommended to be used where agricultural activity is of concern in the study area.

Parameter ratings are derived from data on each parameter, then to be classified into ranges while each range assigned a rate according to DRASTIC ratings and ranges found in form of tables or scaling graphs of ranges and ratings (Figure 3-13) suggested by Aller et al. (1987).

The significance weights are contained in the governing DRASTIC equations (equation 2, and 3), which lists weights for factors of higher applicability (Aller et al. 1987). The higher the DRASTIC rating, the higher the risk for relative contamination. The DRASTIC index can be further divided into four categories: low, moderate, high, and very high.

2.6.1 DRASTIC potential uses

DRASTIC provides a measure of the relative vulnerability of groundwater to pollution and may, therefore, be one of the many criteria used in the decision-making process but should not be the sole criterion. An example of proper use of DRASTIC would be the use of the system as a screening tool or a hydrogeological zoning map to determine whether the area is generally vulnerable to the release of contaminants on the surface. DRASTIC can be used for preventive purposes by giving priority to areas where groundwater protection is of paramount importance, particularly in arid areas.

Besides, DRASTIC can be used to classify places where special attention or protection efforts are needed. DRASTIC may be used to identify land-use practices concerning the production of contamination liability policies and the economic impact assessment of disposal costs in highly vulnerable areas. DRASTIC cannot be used in all potential applications replacing site-specific investigations or avoiding the consideration by a professional hydrogeologist of particular factors that may be relevant to the study area. While DRASTIC can be a very useful tool, the greater the likelihood of problems with resulting accuracy, the further the application strays from the assumptions inherent in the methodology (Aller et al. 1987).

DRASTIC can be an incredibly valuable method if the assumptions of the Methodology are completed. The four main assumptions listed by Aller et al. (1987) are:

1. The contaminant is introduced at the ground surface.
2. The contaminant is flushed into the groundwater by precipitation.
3. The contaminant has the mobility of water.
4. The area evaluated using DRASTIC is 100 acres or larger. In considering areas of 100 acres or greater, DRASTIC attempts to determine Potential groundwater pollution from a regional perspective, rather than a site-specific focus.

2.6.2 The drawback of the DRASTIC approach:

The model's results do not equate to reality by 100 %. However, to simplify and provide approximate good results and explanations from the model, all the potential constraints and factors affecting were considering. It is worth to mention the model definition by Box & Draper

(1987) "*all models are approximations, essentially, all models are wrong, but some are useful. However, the approximate nature of the model must always be borne in mind*". Beside that Thaddeus (2009) quoted "*All models are right, most are useless*" which is a more positive quote. While Breiman (2001) stated "*as data becomes more complex, the data models become more cumbersome and are losing the advantage of presenting a simple and clear picture of nature's mechanism*".

Even the fact that one of the DRASTIC advantages is the large number of data layer inputs which is indeed reducing the effect of individual parameter errors or uncertainties on the result (Ouedraogo et al. 2016). Several studies discussed the reducing of the drastic parameters to achieve greater accuracy at a lower cost (Barber et al. 1993; Merchant 1994; McLay et al. 2001). And still, as in any model, there is a flaw that is the inability to interpret reality as it is, when in fact, when the model input increases, the model becomes more complex and not easy to execute and the errors increase.

Secunda et al. (1998) discussed that DRASTIC model missing important parameters like the geological lineament density and land-use layers. However, the most interesting research in the critique of the DRASTIC model with a scientifically applicable adjustment to solve the problem was carried out by Napolitano & Fabbri (1996) the problem they discussed was the unavoidable subjectivity of the set of the seven DRASTIC parameters, the ratings, and the weights used to measure the DVIM. The key downside to the DRASTIC model is the subjectivity of the determination of the rating scale and the weighting coefficients which simply was solved by the simple statistical approach to find the effective weights by Napolitano & Fabbri (1996). Doubts have also been raised regarding the selection of specified variable and the exclusion of others. In brief, this approach was mainly questioned on the following points:

1. Too many parameters are taken into account in the final DRASTIC index that important parameters of groundwater vulnerability can be influenced by other parameters that do not affect vulnerability in a specific setting (Vrba & Zaporožec 1994; Merchant 1994).
2. The choice of DRASTIC parameters is based on qualitative intuition and not on quantitative data analysis (Garrett et al. 1989).
3. Several doubts were affirmed by Rosen (1994):
    a. Several important scientifically specified parameters, such as sorption capacity, groundwater travel time and water dilution, are not explicitly considered in the model.

b. In contrast to aquifers in fractured media, the DRASTIC model appears to overestimate the vulnerability of porous media aquifers.
c. It is difficult to carry out a model accuracy test since it requires that a pollutant with the characteristics expected by the DRASTIC model (introduced into the ground surface, flooded into the groundwater by precipitation and water mobility) be deposited with a uniform concentration in the test area and over a substantial period of time of several years to allow the hydrogeological setting to react.

Despite these concerns, several of the advantages of the DRASTIC approach have been recognized like:

1. The DRASTIC approach has a low implementation cost and can be implemented in broad regions due to the relatively few and easy-to-collect data needed (Aller et al. 1987).
2. The collection of several parameters and their interrelationship decreases the likelihood of missing certain significant parameters, limits the effect of an accidental error in the measurement of the parameter and thus increases the statistical precision of the model (Rosen 1994).
3. DRASTIC approach produces reasonably reliable results for large regions with a complex geological structure, despite the lack of measurements of precise parameters required by the more advanced methods (McLay et al. 2001).

2.6.3 DRASTIC approach developments:

Through the reviewing of several recent studies that used the DRASTIC model to assess the susceptibility of groundwater contamination, the simpler statistical approach produced by Napolitano & Fabbri (1996) is the most referenced and most relevant, and many researchers still rely on it to reduce the subjectivity in ratings the DRASTIC parameters and improve dependability (Gogu & Dassargues 2000; Ramos-Leal & Rodríguez-Castillo 2003).

This statistical approach was first proposed by Lodwick et al. (1990) to implement a Map Removal Sensitivity Analysis (MRSA) to classify the significant and less important of the seven DRASTIC parameters so that DRASTIC users can determine if any parameters can be omitted without effectively altering the results. Following this a single parameter sensitivity analysis (SPSA) was implemented on the same track by Napolitano & Fabbri (1996), following the same previous method but omitting one map in each sensitivity analysis, but applying the developed (SPSA) approach to the actual (or effective) weight calculation of the DRASTIC parameters used to construct a modified DVIM in this study.

In a nutshell, the next list also discusses the most important basic joints that have attempted to modify the DRASTIC model using different scientific methods over the last decades since the DRASTIC model appeared in the world of groundwater contamination risk studies.

1. Adding the land use parameter: Several earlier studies attempt of integrating a land use maps as the eighth parameter in the DRASTIC model. For example, to create a vulnerability map to the Sharon region in Israel, Secunda et al. (1998) applied DRASTIC method by adding land use parameters. Land use ratings (Lr) is arranged based on extensive land use as effluent irrigation of crops as possible sources of groundwater contamination (Table 2-6). Land use parameter (Lw) was assigned weight of “5”, due to its potential impact on pollutant percolation to the groundwater table. Assigned ratings and weightings for the extensive agricultural land use parameter were added to the final DRASTIC Index (DI) to produce a composite DRASTIC–Extensive-Land-Use-Index (CDI) for each cell i. The modified DRASTIC index was created by the formula CDIi = DIi + Lr.Lwi. Parallel to this study and for the same region (Secunda et al. 1998; Melloul & Collin 1998) developed an index of aquifer water quality and used this index to test the validation of the DRASTIC map.

Table 2-6 Ratings of land use categories as modified by Secunda et al. (1998).

Site-specific land usage	Ratings	Extensive land usage	Ratings	Extensive land usage	Ratings
Toxic – waste disposal	9	Cotton	10	Orchards of other fruit	6
Oil spillage	8	Built-up areas	8	Pasture or other land unsuitable for agricultural use	5
Industries	7	Irrigated fields crop	8	Uncultivated land	5
Solid-waste disposal (regional)	6	Greenhouses/tomatoes	8	Vineyards, Olives	5
Domestic-waste disposal (local)	5	Reservoirs	7	Non-irrigated fields	4
Effluent irrigated fields	4	Citrus orchards	7	Forests, Natural areas, or reserves	1
Effluent reservoirs	3	Orchards of other fruit	6	Dune sand – open areas	1

2. Adding the land use parameter according to nitrate pollution index: Like the approaches to create of the nitrate contamination index for groundwater risk assessment (GRA) introduced by Ramolino (1988), which have been explained by Canter (2019); Ramolino & Canter (1990); Canter (1987). This approach distinguishes the Nitrate Pollution Index for Groundwater based on the ranges and scores for nitrogen fertilizer (Table 2-7). The land use layer (Nitrate Pollution Index (NPI)) can be created by the following formula: NPI= Ffi + Rri + Ssi + Ddi … Where, F, R, S

and D= importance weights for Nitrogen fertilizer (F), net recharge (R), Soil texture (S) and depth to groundwater (D). fi, ri, si and di= factor ratings for the four considered factors.

Table 2-7 Ranges and Ratings for nitrogen fertilization by Ramolino (1988).

Range	Ratings Fi
Over-fertilized	10
Fertilized to meet crop need	6
No fertilizer applied	1

3. Simple Land use categories ratings: Hussain (2004) modified the previous modification of integrating the land use in a simple approach to solve the limited available information about the land use and soil quality in the study area based on the groundwater quality observations, while the qualitative ratings were proposed for only three general types of land use (Table 2-8).

Table 2-8 Land use categories ratings modified in simple approach (Hussain 2004)

Land use	Ratings
Urban	10
Rural and agriculture	8
Forest	1

4. Adding geological lineament maps: Lee et al. (1998) created vulnerability map for the Young wang County in Korea using a modified DRASTIC model by adding the “geological lineament maps” to consider the preferential migration of contamination through fractures.
5. Adding land use instead of recharge DRASTIC parameter: The National Water Quality Assessment Program (NAWQA) to create a vulnerability map to the Eastern Snake River Plain, Idaho three of the seven DRASTIC parameters, the depth to water (D), net recharge (R) (land use) and soil media (S) were used. The land use parameter was used as a surrogate for net recharge because the studied areas having irrigated agriculture provided the largest amount of recharge (Table 2-9). And the final vulnerability map was correlated with nitrate concentration (NAWQA 1999).

Table 2-9 Land use categories instead of recharge DRASTIC parameter (NAWQA 1999)

Land Use	Rating	Land Use	Ratings
Urban	3	Dryland agriculture	1
Irrigated agriculture	2	Forest	1
Rangeland	1		

6. Validate the DRASTC results using the water quality: Navulur & Engel (1994); and Navulur & Engel (2003) Validated the accuracy of DRASTIC approach by comparing the vulnerability maps with existing groundwater quality data sampled across the Indiana state in the U.S.A.
7. Changing DRASTIC original rating: In the Turbio river valley, in Guanajuato Atate, vulnerability map Ramos & Castillo (2003) modified the range of depth to water parameter by using a scale 5 times the original rating.

8. Correlation with nitrate contamination: Wei (1989) created vulnerability map to the Fraser Valley aquifer in southwestern British Columbia (BC) and correlated between DRASTIC and AVI method with nitrate occurrence.
9. For the present study: Modified a simple overlaying approach to create a land use layer attempts of integrating it with the modified reliable DRASTIC framework to be the parameter number eight. The DRASTIC is an overlying method to detect the intrinsic vulnerability so the DRASTIC itself modified in this research to assess this vulnerability then the intrinsic vulnerability map was combined with the land use for the groundwater risk assessment of specific vulnerability. The particular contaminant in this approach is the nitrate so the land use layer was created to reflect the potintial nitrate contamination (PNC) in the study area.

Based on the literature review the method developed here is simple, reliable, and can be widely implemented. Beside this the DRASTIC model was modified by the statistical approach introduced by Napolitano & Fabbri (1996) through tow practical ways the first by applying the analyses directly using the raster calculator and the second by extracted two points files and the statistical approach was implemented in excel sheets to calculate the real DRASTIC-parameters weight. Besides that, in this study two scenarios were used in implementation both the ordinary and the agricultural DRASTIC approaches, the first scenario without changing the DRASTIC-parameters rating while in the second scenario a modified suggested range of recharge (R') by using a scale100 times the original rating because the recharge in the study area varied from 0 to 42mm/year (Table 4-10). Which is a very low amount as the area is in the dry climatic zone, with low precipitation Therefore the area was entirely rated by 1 using the original recharge parameter rating. While suggested rating was to simulate the potential increase in recharge by irrigation return flow (IRF) in intensive agricultural areas. However, the agricultural activities are not only increasing the GWR through (IRF) but the processes of ploughing that disintegrate the soil layer which increases permeability and enhancing the recharge. Finally, long-term groundwater nitrate, sulfate and total dissolved solid concentration analyses were used to produce six spatial continuous data (SCD) maps and match the resulting vulnerability and risk map for nitrate contamination. And a comparison with the COP Intrinsic Vulnerability Indexes has been made and the analysis shows that the DRASTIC preferability is particularly versatile by simple modification by measuring the effective weight of the parameters so that the DRASTIC can be appropriate for dry and wet areas, but the COP model is only applicable in wet areas.

3. MATERIALS AND METHODS

3.1 Introduction and study area general description:

This chapter, provides basic descriptions of the study area (location, atmosphere, geological, etc.) A description of the methods used in the study, a description of the design and construction of the database system, a description of the preparation of thematic maps and underlying processes (using GIS) proposed for evaluation in the research work, a description of the groundwater quality assessment approach. The comprehensive assessment of groundwater risk in this research is defined in the following scheme (Figure 3-1).

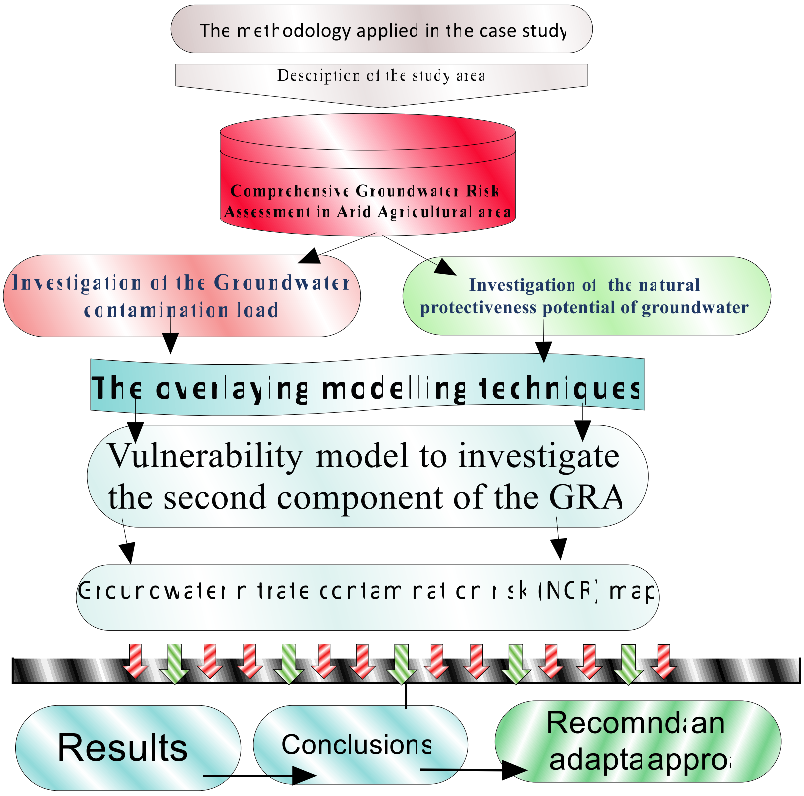


Figure 3-1 The general methodological scheme of the study.

3.1.1 Selection of the study area

Several factors were considered in the selection of the study area. The data availability, the importance of the study area, the extend and outcropping of the phreatic aquifers throughout the area and to be a good representative example of an arid agricultural area. For this purpose, a review of the hydrogeological situation of all the groundwater basins in Jordan was carried out to find the most important basin to be the study area. Jordan is divided into 15 surface water basins according to the topography (BGR MWI 2019) and into 12 groundwater aquifers according to the groundwater movement as outlined by Schmidt et al. (2004) and updated recently by MWI & BGR (2018). The most important and usable basin is Amman Zarqa Basin (AZB) (Figure 3-2).

Amman Zarqa groundwater Basin (AZB), situated in the north-eastern part of Jordan, has a total area of 4104.7 km^2, while the area of the Amman Zarqa surface basin is 3588 km^2. The increasing population growth and economical activities within the study area (AZB) increase the abstraction from the main shallow groundwater aquifer to satisfy the rapidly increasing water demands which causing and continues increase of the depth to the renewable groundwater table.

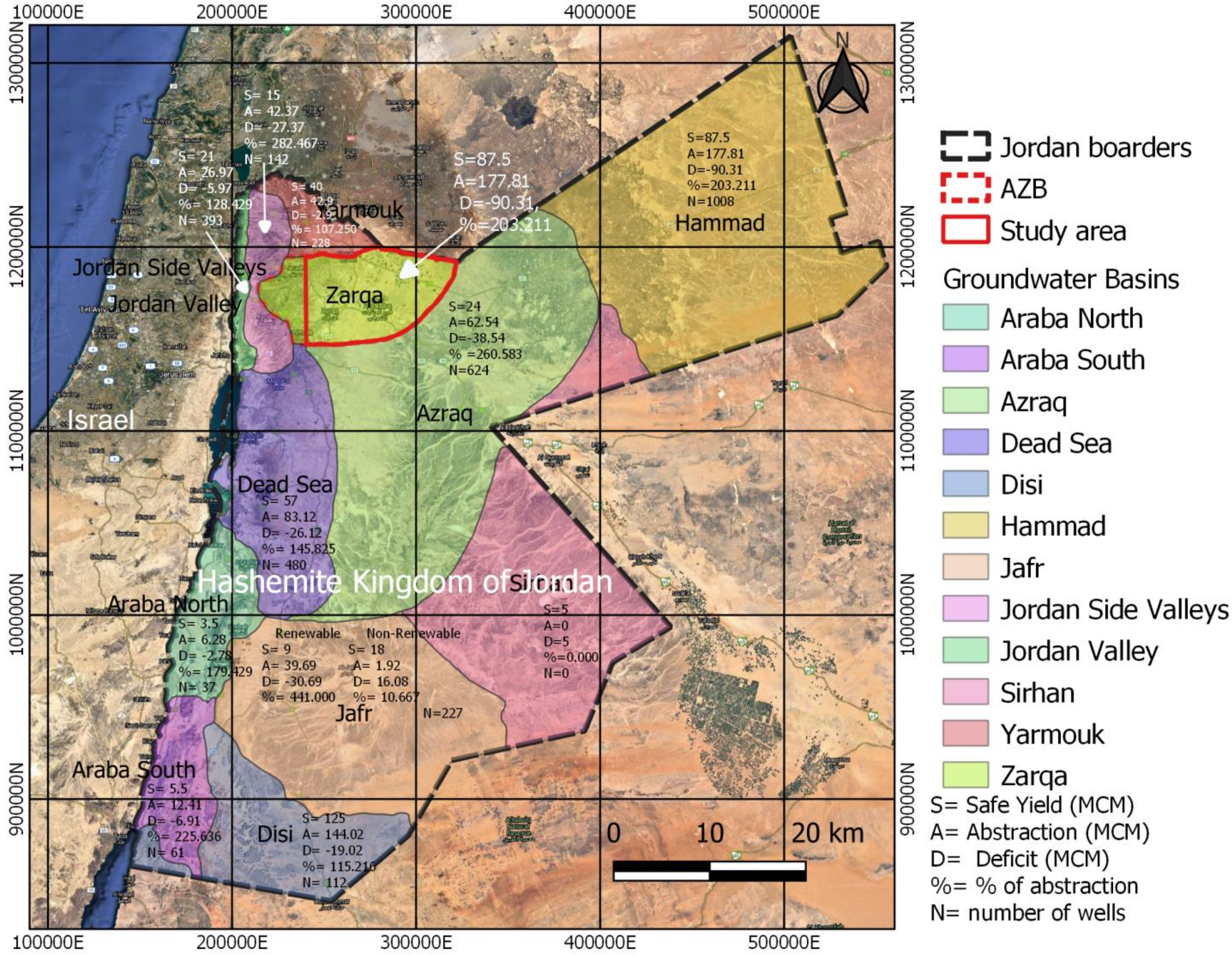


Figure 3-2 Groundwater basin in Jordan, and the annual abstraction. (Own processing) retrieving the raw data from WIS (2020).

Abstraction in the Amman Zarqa Basin (Figure 3-3) increased gradually from 8.46 MCM in 1965 to 123.4 MCM in 1998 (MWI/USAID/ARD 2001) and it reaches 203.211 % of the safe yield in Amman Zarqa Basin by a 177.81 MCM in 2019, (WIS 2020), to be at the top of the groundwater basin ranking table of groundwater abstraction, with having the greatest portion of Jordan's production wells, see the table of abstraction from the groundwater basin (Table 2-3). AZB is the most important part and groundwater basin in Jordan as it is a concentrated human activity area, where 85 % of the industries (Al-Mashaqbeh et al. 2014; Daniel et al. 2013) and more than half of the country's population is located in this basin which is only around 4 % of the total country area (DOS 2020).

The potential for water quality and quantity degradation of the phreatic Aquifer in the study area is high, due to several factors, especially to the increase of agricultural water demands in the AZB. As agriculture is the largest water consumer in the basin according to the National Water Master Plan (NWMP) (MWI 2004; MWI 2016a), with a continuous population growth and improving life standards, that results in rapidly increasing per capita water demands.

3.1.2 The boundary of the study area and general description

The boundary of Amman Zarqa Basin (AZB) was considered to sketch the boundary of the study area, which was carried out in the eastern part of this most important and populated groundwater basin in Jordan, which is characterized by a rapid agricultural expansion which is raising the threat of groundwater contamination (MWI/USAID/ARD 2001; MWI & JWA 2010; Daniel et al. 2013; MWI 2013; Al Kuisi et al. 2009).

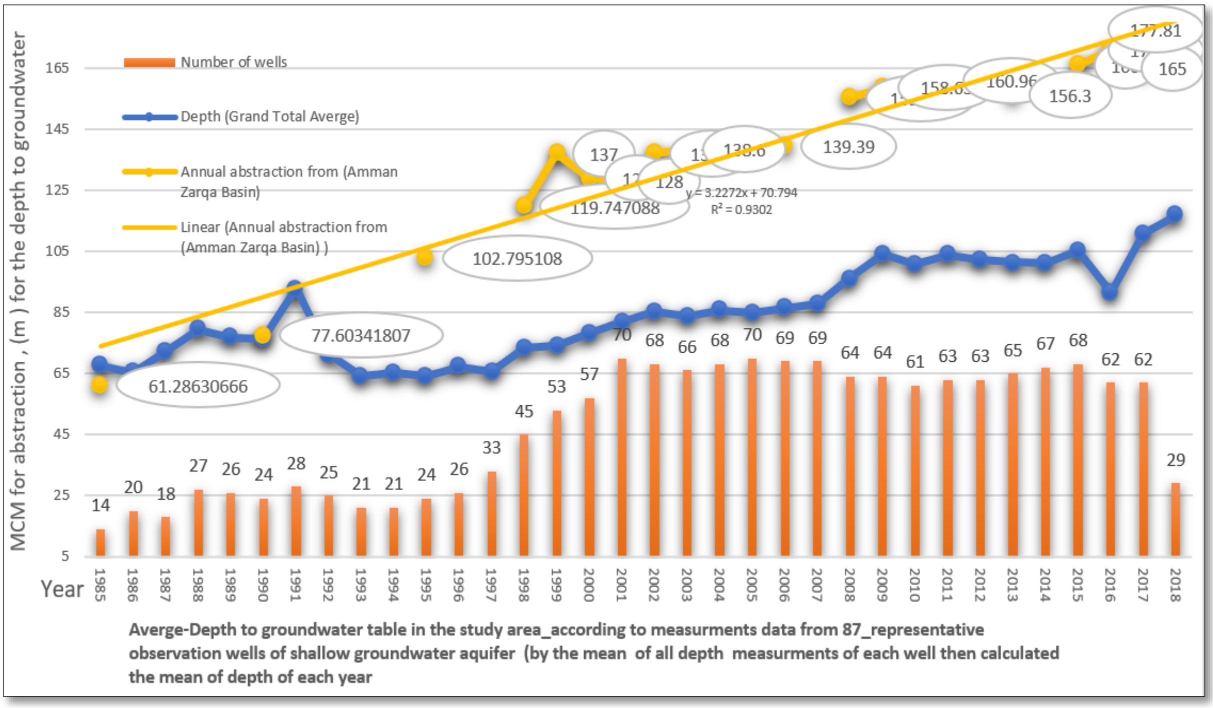


Figure 3-3 Depth to groundwater table in the Study Area, and the annual groundwater abstractions, (own processing). (The raw data retrieved from the WIS (2020)).

The study area geographical coordinates extend from PGE 240,000 – 322,000 and PGN 1145,000–1200,000, (the coordinate reference system used in this study is the Palestinian-belt where the PG is the Palestine grid, PGE: East; PGN: North). The study area covers a surface area of 3329.9 km^2 (3.7 % of Jordan land area and more than 81 % of the (AZB) area). According to the administrative divisions' maps recovered from the Royal Jordanian Geographic Centre

(RJGC 2020) in a shapefile format. The study area is governed by four governorates, Mafraq, Zarqa, Amman, and Jerash, accounting for 57 %, 28 %, 15 % and 0.4 % of the study area, respectively. And divided into districts and sub-districts where the study area is administratively subordinate to 11 districts (Figure 3-4).

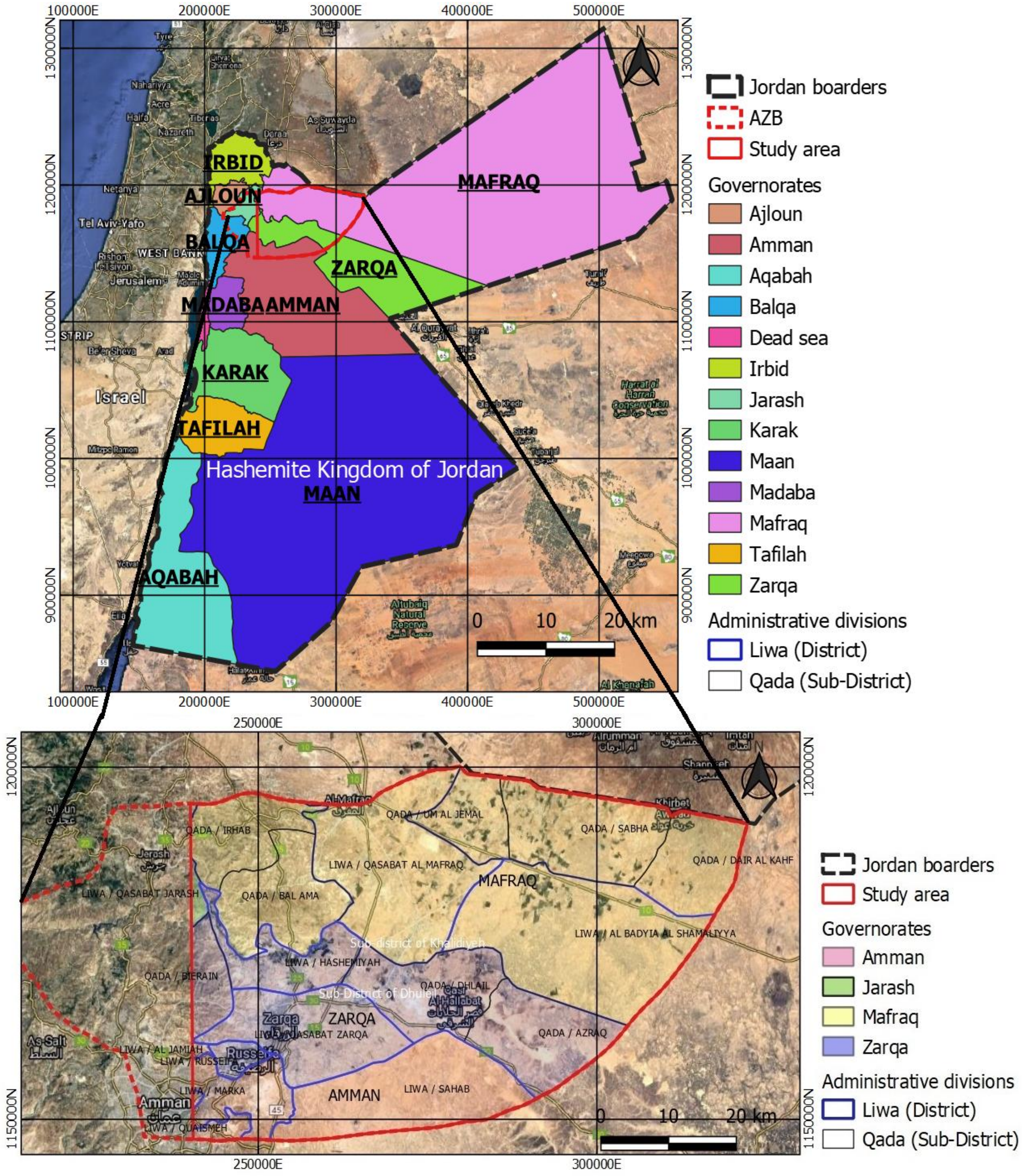


Figure 3-4 Study area location and the administrative divisions according to RJGC (2020).

The study area is the eastern part of the AZB after the western hilly areas which located within the semi-humid zone, have been excluded as they are relatively densely populated and rain-fed agriculture is the most dominant, and receive precipitation ranges between 200-550 mm/year see the average precipitation map of Jordan (Figure 2-4), and the agricultural activities dominated by rain-fed and there are no highly irrigated areas, therefore, the return flow from agriculture is probably neglectable. Instead, the eastern part of the basin is completely desert and almost unpopulated but has dense irrigated agricultural activities as explained in the next paragraphs. According to the geographical classification the study area belongs to the Badia region or the dry region in Jordan with less than 200 mm/year rain rates. It is located east of the historical Ottoman railroad\ Hijaziya, and the location of that railroad line in Jordan was as a bordering line between two different climatic zones.

3.2 Groundwater risk assessment in the case study area:

The groundwater risk assessment (GRA) approach in this study consists of three steps, the contamination load investigations, then the comprehensive hydrogeological review. The last step is to visualize the groundwater vulnerability, and the nitrate contamination risk in maps utilizing the overlying modelling techniques.

3.2.1 Investigation the contamination load in the study area

The primary source of nitrate in groundwater, however, is the non-point source (Large-scale-sources(LSS)), especially cropland above shallow aquifers (Exner et al. 2014; Spalding & Exner 1993). Groundwater contamination may be from various sources, but the most dominant sources in the world are agricultural fertilizers and pesticides, and nitrate (NO_3^{-1}) from excessive fertilizer usage in intensive agricultural areas is a widespread contaminant (Sasakova et al. 2018; Chowdhury 2016; Angelopoulos et al. 2009; Gardner & Vogel 2005; Spalding & Exner 1993). There are two leading synergic causes responsible for nitrate contamination in groundwater the large surplus of this element, especially in highly productive agricultural and changing the landscape, making nitrogen species, especially nitrate, much more mobile (Angelopoulos et al. 2009).

The major human activities on the surface of the study area are farming activities however, the following assessment of the study area contamination sources has been carried out.

3.2.1.1 Water quality analyses

Water quality monitoring is a crucial aspect for the protection of water resources, the Jordan Water Authority regularly collects water samples from the production wells and analyses conducted at the Ministry of Water and Irrigation (MWI), the Laboratories and Water Quality sector of the Water Authority of Jordan (WAJ). All the analyses follow the Standard Methods of examination of water and wastewater of the American public health association (Rice et al. 2012). For this research analyses of about 498 wells were retrieved from WIS (2020).

However, according to MWI, the water quality analyses raw data were provided in two files, the first containing data on water quality analyses for the period since 1970 to 2005 which was found to be very good and have a continues records while the second file for the period from 2006 to 2018 characterized by more analyses results in inputs for each sample but many mistakes were found and required to eliminate the human mistakes occurred during entering of the values in the storing system so for the period from 2006-2018 only data of 241 wells were considered. In this study, the following analyses were done to investigate the water quality in the study area

1. A summary table was drawn up and discussed for the analysis of the main water parameters.
2. Correlation analyses of the main water parameters.
3. Piper diagram of the major cations and anions, to sketch the main cation and anion concentration of the studied wells using the Plots Piper diagram model.
4. Three parameters were selected nitrate, sulfate, and the total dissolved solids to prepare spatial continuous concentration maps, to evaluate the water quality in the study area and compare it with the created vulnerability maps.

The recommended limit for nitrate in drinking water in the USA is 45 mg/l. Throughout Europe, the limit recommended by the World Health Organization (WHO) (2017) is 50 mg/l, as excessive concentrations of $N0_3^{-1}$ are likely to harm infants and livestock when taken regularly. In Jordan according to the Jordanians standards for drinking water quality (JISM) (2008), water quality is drinkable if the values of total dissolved solids (TDS), Nitrate, and Sulfate, less than (1000 mg/l, 50 mg/l, 500 mg/l) respectively. Even the_maximum permissible limit of nitrate according to the WHO guidelines in 2017, was 50 mg/l (WHO 2017). In Jordan, it can reach 70 mg/l in the absence of a public water source of better quality.

The total dissolved solids (TDS) value can be estimated from electrical conductivity (EC) measurements in most cases whereas both EC and TDS represent the total salt content in water. TDS in mg/L = 0.54 EC in µS/cm (0.54 is the conversion factor used in Jordan by the MWI). According to Goode et al. (2013); and Salameh (1996) an EC of 1,500 µS/cm is the upper limit of freshwater suitability for all human uses. The total dissolved solids (TDS) content can be calculated using the following equation (APHA 2006): TDS (mg/L)= $Ca^{2+} + Mg^{2+} + Na^{+1} + K^{+1} + 0.5 \times HCO_3^{-1} + Cl^{-1} + SO_4^{2-} + NO_3^{-1}$. According to Caroll (1962) classification of groundwater based on TDS values, into four water types (fresh, brackish, saline, brine), if the TDS range from (0-1000, 1000-10000,10000-100000, more than 100000) respectively.

3.2.1.2 Water quality spatial analysis

The spatial and temporal behavior of hydrochemical parameters in groundwater can be investigated using geostatistical techniques (Hu et al. 2005). The use of GIS is necessary for any water quality management work, mainly due to the vast amount of spatially related data that must be stored and processed to represent the water quality parameters for the study area (Nobre et al. 2007). The long-term data on water quality was used to explore the spatial distribution of TDS, NO_3^{-1}, and SO_4^{-2} within the study area.

In this research, TDS, NO_3^{1-}, and SO_4^{-2} concentrations were measured at unknown locations using ordinary kriging (OK) techniques to generate spatial continuous distribution (SCD) maps for TDS, nitrate, and sulfate concentrations in the study area. OK, technique can be used for data that seems to have a trend such as the concentration of parameters in water, and OK technique gives the best linearity unbiased estimation of the regional variable to the unsampled variable location, known as the Best Linear Unbiased Estimator (BLUE) (Dash et al. 2010).

3.2.2 Investigate the natural protectiveness potential of groundwater in the study area.

In this part, the aim is to provide an overview of all available hydrogeological and climatic parameters that contribute to the GRA to study the natural potential protectiveness of the groundwater aquifer.

3.2.2.1 Climate of the study area

Approximately 61 metrological stations exist in the study area, only 21 representative stations have good precipitation data records, and 9 metrological stations have good climate data records. Among these stations is the first metrological station in Jordan, located at Amman Airport, which is situated in AZB during the year 1922/23. After the establishment of the Jordanian metrological department (JMD) in 1951, the number of metrological stations increased in Jordan. According to the JMD (2019), the general pattern in precipitation indicates a strong decrease from north to south, from west to east, far from the Mediterranean, and from a higher to the lower elevation. The research area is bordered in the west by the high lands and in the Syrian portion by the foothills of (Jabal al-Arab) in the northeast. Thus, the area of research is in a rain-shadow zone. The study area is therefore situated in the west between Mediterranean climatic conditions or Semi-humid as classified by the MWI (2016) and the arid environment in the south-east and east (MWI/USAID/ARD 2001; Daniel et al. 2013; MWI & JWA 2010) see the precipitation map of Jordan (Figure 2-3). According to the classification of (MWI) in 2016, which rely on the amount of precipitation (MWI 2016; Gazal 2020) the study area classified as an arid to semi-arid areas and the marginal area towards the western part which is classified as a semi-humid or Mediterranean climate, which is excluded from the studied area due to the focusing on the increasingly agricultural activities in arid areas which mainly relay on the limited and deteriorated groundwater resources while the western part of the AZB as discussed before dominated by rain-fed agriculture.

In this work, statistical analyses were carried out to describe the climatic parameters in the study area and find the trend of precipitation and calculating the areal average rainfall by the long annual average precipitation of the 21 stations through the weighted average of each station and by interpolation methods, also the precipitation map was used to examine the net recharge maps of the study area which was created by Gazal (2020) according to the methodology adopted by Hobbler et al. (2001). However, the approach suggested by Feng et al. (2004) was implemented to remove human errors in the retrieved raw climate data. The weighted average of each station was calculated using the Thiessen polygon method (Thiessen 1911). Thiessen polygons are otherwise referred to as voronoi polygons or voronoi diagrams (Boots 1999), as seen in the Qgis3.8.2 toolbar feature. But for the removal of human errors in the retrieved climate raw data from the water information system (WIS) (2020), the approach adopted by Gazal (2020) was implemented to deal with the current erroneous. Moreover, the study area was classified into climatic zones according to the most popular climatic classification (Köppen-Geiger) (Kottek et al. 2006). Besides the available FAO irrigation programming software's (CROPWAT-8.0), was used for the (ETo) calculation, the effective precipitations and create the study area Thermo-pluviometric Bagnauls-Gaussen diagram. CROPWAT was used to calculate the (ETo) of the study area by entering the following:

1. Site location: altitude above sea level, latitude, and longitude which is very important for the program to estimate the radiation in MJ/m^2/day, for example in this study it was used an altitude equal 700 m, latitude equal 31.58° N, and longitude: 35.59° E, for the station Amman Airport (Al0019) the program not require exact latitude and longitude so using the coordinates of any station within the study area is enough, (the program only require degree and minutes do not need seconds).
2. Air temperature (C°): monthly mean maximum and minimum temperature.
3. Monthly average relative humidity.
4. Monthly average sun hours (hours/day).
5. Wind speed (km/day).

3.2.2.2 Structural geology and the Hydrogeology of the study area:

The study of the hydrogeological mapping and the description of the geological formations of the study area is the basis for the creation of a vulnerability map with a view to the creation of the depth to water table (D), the groundwater recharge (R), the aquifer media (A), the soil (S), the topography (T), the impact of vadose zone (I) and aquifer hydraulic conductivity (C), the DRASTIC parameters maps which created by assigning a rates for these maps according to the ranges and ratings scales of Aller et al. (1987).

To understand the nature of the geology of the study area, here is a brief review of the geology of Jordan. Jordan is located on the northern border of the African-Arab Pre-Cambrian granite shield. Over the geological times, the shield has pulsated up and down, allowing seas ingressions (and sedimentation when down) or huge erosion phases (when up) (Schuermann 1966; and Burdon 1959), along with the most profound tectonic event on the earth crust: the Aqaba - the Dead sea - Jordan Valley – Rift. Over a long period, detailed geological studies have been conducted since the 19th century through one of the first geological missions by the United States expedition to explore the Dead Sea, followed by Lartet's (1869)**;** Blanckenhorn (1903); and Blanckenhorn (1914), who published the geological map of Jordan. But the United States expedition started earlier than the dates of publishing its results as stated in p.5 of Quennell reports it exactly started in 1852 (Quennell 1951).

Quennell (1951) was the first prominent geologist to classify the Jordanian Cretaceous formations into two groups, Ajlun and Belqa, after fieldwork between 1946 and 1948, by which he prepared the first geological map of Jordan at a scale of 1:250,000 in collaboration with the British Geological Survey (BGS) and the Jordanian department of land and surveys, where he published the geology and mineral resources report (Quennell 1951) and the geological map (Quennell 1956), whereas Wetzel and Morton depending on the previous geological maps and reports and fieldwork published a detailed study of the geology of Jordan (Wetzel & Morton 1959). Burdon (1959) published the handbook of the geology of Jordan, to explain the three geological maps sheets of Quennell (1956).

The second new version of the Jordanian geological map at a scale of 1:250,000 was published under the supervision of Prof. Bender by the cooperative geologic research and assistance provided by the German Geological Survey for the period 1961-1968 (Bender 1975; Bender 1968). Between 1965-1968, following the establishment of the Jordanian natural resources authority (NRA) in 1965, the accumulation of geological information from government surveys began**.**

Officially the geological mapping project at the scale of (1:50000) started on 1981 and was under the British Geological Survey (BGS) cooperation and after 1995 the project is managed by Jordanian experts up to now. However, officially the 1:50,000 scale geological maps of this project have been under the jurisdiction of the Ministry of Energy and Mineral Resources of Jordan (MEMR) following the closure of the Natural Resources Jurisdiction (NRA) in 2014. In this work the last update of the geological index 2017 was used (MEMR 2017).

The geologic sketch-map of the study area was compiled and edited for accuracy from an original 14 geological maps of a scale 1:50000 (see appendix 10.4), (Figure 3-5) the null data pixels occurred by the process of digitizing the hard copy maps and compiling all together were filled by the spline interpolation using the QGIS fill the null function. In addition, due to the different times of mapping and authors, some unites such as basalt units are sometimes differently mapped that required a modification to avoid mistakes by augments all the basaltic geological units in one unites in the maps shape files. The description and thickness of the lithological units were mainly taken from the accompanying text to the relevant 14 geological maps representing the study area, deep boreholes database retrieved from the (WIS) (2020) which also listed in the annex at the rehabilitation groundwater wells of AZB reports (MWI & JWA 2010). The BGR hydrogeological cross sections exist in the annex of the reports like (Margane & Hobler 1994; BGR & MWI 2019) in addition to the review of the old and recent geological studies.

There are two major groundwater aquifers in the study area, according to hydrogeological surveys which have spanned the last decades, see the lithostratigraphy and hydrogeological classification of rock units table (Table 3-1). The first are the renewable aquifers, which consider the most exploited aquifers not only in the AZB but in all the groundwater basins in Jordan as the average depth to the water table of less than 200 m. And the second is the deep sandstone groundwater aquifers (Disi and Zarqa aquifers), which began their actual exploitation in 2013 through the project to transport water from the Disi sandstone aquifer to Amman. The study focuses on the risk assessment of phreatic aquifers in the study area so that the geological setting of the study focuses on these aquifers. Based on the geological setting of these phreatic aquifers, it is considered to be sustaining from rainfall recharge, even though the amount of water extracted from the renewable aquifer is very difficult to replace and exceeds the sustainable allowable amount (safe yield) as estimated by the MWI & BGR (2018) (Table 2-3). This is due to the nature of the climate in Jordan, the lack of rain, the period of drought and over-pumping beyond the safe yield of renewable aquifers, which could lead to the risk of groundwater aquifer depletion as it appeared in the A7B2 karstic aquifer in the study area abstraction from AZB

(Figure 3-3). This phreatic aquifer, therefore, is like a confined aquifer and not a renewable aquifer in such a dry area that receives a small amount of precipitation and increasingly has groundwater abstraction over the safe yield due to intensive agricultural expansion.

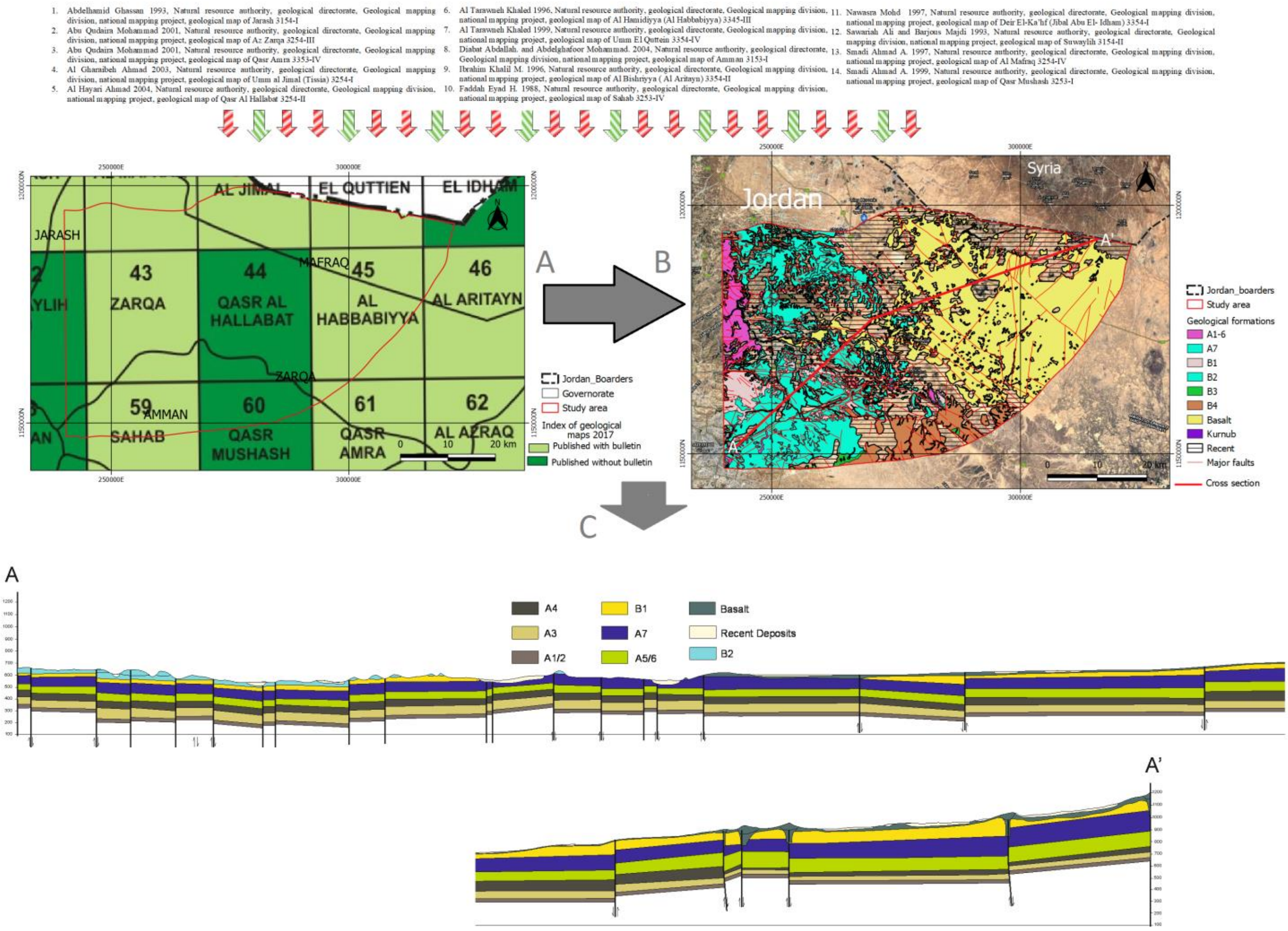


Figure 3-5 A: Index of the 14 geological maps, B: The outcropping of the geological formations in the study area compiled from 14 geological maps and, C: Geological cross-section referring to the geological descriptions of the wells penetrating the aquifer and the 14 structural geological maps.

The phreatic aquifer network is exposed to easy contamination from sources of surface contamination, where the quality of these aquifers in the study area has deteriorated as a result of the expansion of agricultural activities and exploitations (Gazal 2015; Margane et al. 1999; Daniel et al. 2013). The phreatic aquifer system in the study area consists of two dominant systems, the upper and middle system while the lower system only outcropping in the western part of AZB. In a brief, the description of the study area aquifer system is as follows:

1. The upper aquifer system: the late Tertiary basalt and the underlying Amman-Wadi Es Sir (A7/B2) Formation, which is the main aquifers in the study area. The basalt aquifer is in

direct contact with the A7/B2 aquifer and both, therefore, form a combined upper aquifer system in AZB (BGR MWI 2019; Gazal 2015; Borgstedt et al. 2007) (Figure 3-5).

a. A7/B2: Wadi As Sir Limestone Formation (A7), together with the Amman Silicified Limestone (B2) is considered to be the main renewable aquifer in Jordan (BGR & MWI 2019; Margane & Hobler 1994). It consists of well-bedded thin to massive limestone, dolomitic limestone, and dolomite with chert. This aquifer is the most important renewable aquifer not only in AZB but also in Jordan, a well-matured karst aquifer distinguished by its vast extend and favorable auriferous properties (Gazal 2019; Borgstedt et al. 2007; Margane et al. 2002). Approximately 41 % of the Jordanian well pump from this karstic aquifer and about 80 % of the AZB groundwater abstraction (Table 3-2). Generally, karst formations are characterized by high heterogeneity and anisotropy. In mature karstic-aquifers rapid infiltration and high flow rate are usual. Therefore, the water levels can fluctuate considerably, and discharge typically responds quickly to events of groundwater recharge. Contaminants can easily infiltrate into karst aquifers through sinkholes and other features of the karst and rapidly spread through the duct network over wide distances (Steinel & Margane 2011).

b. Basalt: Basalt formations are the second dominant outcropping formation cover about 41.4121 % of the study area according to the simplified hydrogeological maps (Figure 3-6). 1.68 % of the groundwater abstraction in AZB from this aquifer and about 5.3 % of the Jordanian wells pumping from this aquifer (Table 3-2). The Basaltic aquifers are characterized by hydraulic anisotropy, and heterogeneity discontinuous. In basalt aquifer systems, there may be broad differences in hydraulic conductivity. Relatively high permeabilities and preferential pathways are connected to the boundary layers, to individual basaltic flows, and the cooling and tectonic stress joints and fractures. Porosity can be high in vesicular lava flows, but in solid lava flows, the effective porosity is usually less than 1%. Young basalts are typically more permeable than older flows, where alterations in weathering and cementing fluid movement are lowered the permeability (UN-ESCWA 1996). This formation is a volcanic rock that originated from magma and spreads over different parts of Jordan generated by a paleo-volcanic activity during the Neogene-Quaternary age accompanied by opening continental rifts since the beginning of the Oligocene and frequently in the Miocene, Pliocene and Pleistocene (Schuermann 1966; Hobbler et al. 2001; Borgstedt et al. 2007), mainly in the north-east of Jordan, belonging to the Harrat As Sham basaltic supergroup, which covers more than 11,400 km^2 of Jordan according to Smadi et al. (2018) and according to the most recent modified hydrogeological map it covers 11678.9 km^2, about 13.19 % of Jordan total area (Figure 3-6).

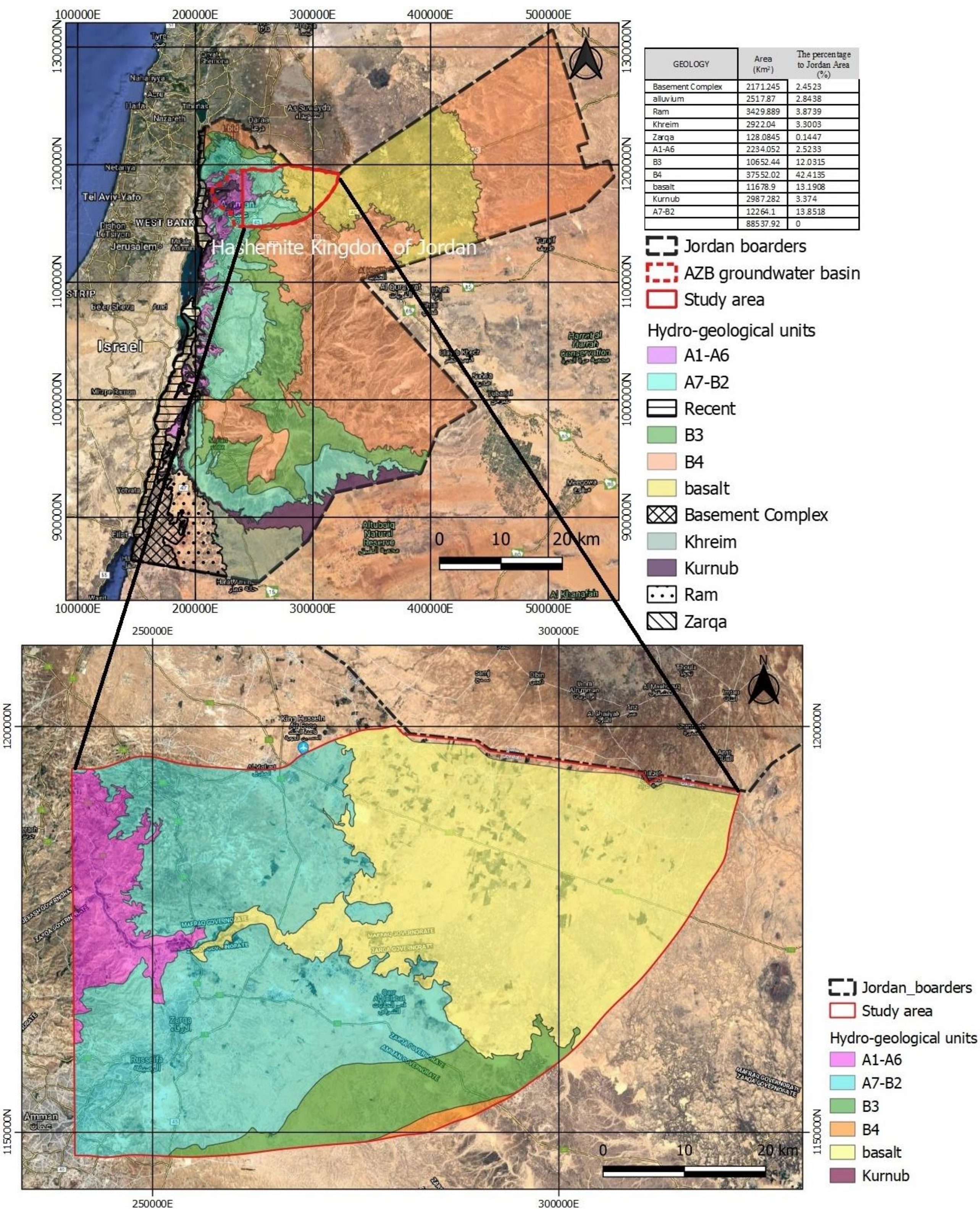


Figure 3-6 Simplified hydrogeological units modified after BGR & MWI (2019).

Harrat As Sham basaltic supergroup is one of 16 large Cenozoic harrats in the Arabian Plate, Which cover more than 180,000 km^2, representing one of the world's largest alkali basalt volcanic provinces (Camp & Roobol 1989; Stelten et al 2019; Stelten et al 2019). Harrat is the possessive form of the singular Arabic noun "Harra" which mean stony area, volcanic country and related to the adjective "Harr" meaning "Hot" (Wehr 2013) (Figure 3-7).

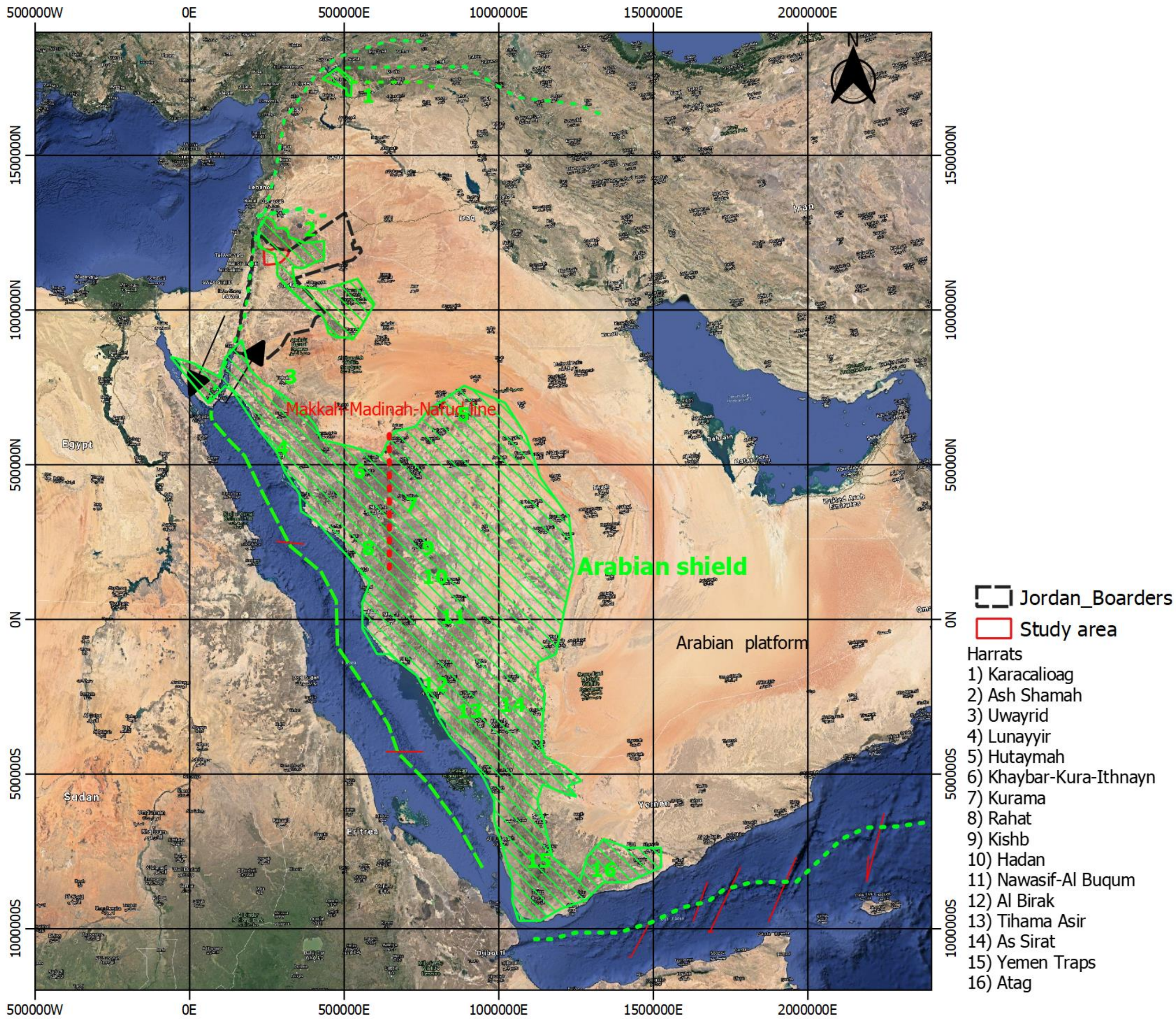


Figure 3-7 Basaltic plateau within the Arabian Plate which hosts 16 large Cenozoic harrats modified after Stelten et al. (2019); Camp & Roobol (1989).

It is considered that the first basaltic flow occurred during Miocene–Pleistocene and volcanic activity progressed until the Holocene (UN-ESCWA 1996). The basalts Neogene and Quaternary show no significant differences in structural and textural characteristics (UN-ESCWA 1996). The varieties exhibit different weathering properties, depending on their geographical setting and climatic conditions. The Neogene basalt is typically more weathered than the Quaternary basalt and mainly weathered in large boulders. Basalt flows classified in the study area into 5 groups according to Boom & Sawan (1966).

However, according to UN-ESCWA and BGR (2013); Wagner (2011); Allison et al. (2000); UN-ESCWA (1996) the different basaltic formations were compiled into one formation in the preparation of the geological map of this study from 14 original hard copies maps, which were digitized and modified to create the geological map.

Table 3-1 The general stratigraphic rocks succession since Pre-Cambrian in Jordan modified after BGR & MWI (2019).

EON	ERA	System (Period)	Epoch	Group	Formation	*Symbo	Lithology	Thickness (m)	Aquifer unit***
Phanerozoic	CENOZOIC	Quaternary	Holocene	Jordan valley (JV)	Alluvium JV3	RC	Clastic, Marl, clay, evaporites	<50	Alluvium (aquifer)
			Pleistocene		Lisan JV1-2	Basalt		>300	Basalt (aquifer)
		Tertiary, Neogene	Pliocene		Samra		Basalts flows cover large area (and/ or) Conglomerate with siliceous cement, sand, gravel	100–350	
			Miocene		Neogene				
			Oligocene						
		Paleogene	Eocene	Belqa (B)	Wadi Shallala	B5	Chalky and marly limestone …	0–555	B4/5 (aquifer)
					Umm Rijam	B4	Limestone, chalk, chert…	0–311	
			Paleocene		Muwaqqar	B3	Chalky marl, marl, limestone,	80–320	B3 (Aquitard)
	MESOZOIC	Upper Cretaceous	Maastrichtia		Amman-Al Hisa	B2	Limestone, chert, chalk, phosphorite…	20–140	A7/B2 (aquifer)
			Campania						
			Santonian		W. Umm Ghudran**	B1	Dolomitic marly limestone, marl,	20–90[a]	
			Coniacian		Wadi As Sir	A7	Limestone, dolomitic limestone, chert, marl…	60–340	
			Turonian	AJLUN (A)					
					Shueib	A5/6	Marl, limestone	40–120	A1/6 (Aquitard)
					Hummar	A4	Limestone, dolomite	30–100	
			Cenomania		Fuheis	A3	Marl, limestone	30–90	
					Naur	A1/2	Limestone, dolomite, marl	90–220	
		Lower Cretaceous	Albian	KURNUB (K)	Subeihi	K2	Sandstone, shale	120–350	Kurnub (aquifer)
			Aptian						
			Barremian						
			Berriasian		Aarda	K1	Sandstone, shale		
		Jurassic		ZARQA (Z)	Azab	Z	Siltstone, sandstone, limestone	0 –>600	Zerqa (aquifer)
		Triassic			Ramtha		Siltstone, sandstone, shale	0–	
	PALEOZOIC	Permian			Hudayb		Siltstone, sandstone, shale	0–>300	
		Silurian		Khreim (KH)	Alna	KH	Siltstone, sandstone, shale	0–	Khreim (aquitard)
					Batra		Mudstone, siltstone	0–	
					Trebeel		Sandstone	0–130	
					Umm Tarifa		Sandstone, siltstone, shale	0–	
		Ordovician			Sahl as Suwwan		Mudstone, siltstone, sandstone	0–200	
				Ram (D)	Amud	D	Sandstone	0–	Ram sandstone (disi) (aquifer)
					Ajram		Sandstone	0 - 500	
		Cambrian			Burj		Siltstone, dolomite, limestone	0- 120	
					Salib		Arkosic sandstone, conglomerate	0 –750	
					Unassigned clastic unit		Sandstone, argillaceous, siltstone, claystone	0–1,000	Basement complex
Proterozoic		Precambrian			Saramuj		Conglomerate, sandstone	up to 420	
					Crystalline basement				
	Proterozoic								
Archean									
Hadeon									

* Blue color for aquifers and the space for each formation reflect the wieght of the existent. **Hamza graben equivalent to Rajil Fm., Hamza Fm. and Hazim Fm., total thickness up to 2,000 m, *** Aquifer unit: classification of aquifers and aquitard and assigned the aquifer as the strong or weak aquifer is according to BGR MWI (2019); Struckmeier & Margat (1995).

2. The middle aquifer system, about 9.24 % and 2.4 % of groundwater abstraction in AZB from A4, and A1/2 and about 4.5 % of Jordanian wells pumping from this aquifer system (Table 3-2). In Brief, this aquifer system belongs to the Ajloun group A1 to A6, which contains a low productive water holding formations the Hummar (A4) and the Naur (A1/2) Formations, which are the dominant outcropping formation within the study area. Six geological formations belong to cretaceous three of which are aquifers and three aquitards.
3. The lower phreatic aquifer system (Kurnub Group) about 6.5 % of AZB groundwater abstraction from this sandstone aquifer which outcropping on the western part of the AZB at the part which was excluded from the case study area and in the study area all the production wells mainly penetrate the upper aquifer and do not reach the sandstone aquifer according to wells geological description obtained from the (WIS) (2020). The lower aquifer complex consists of the Ram group aquifer (also called Disi aquifer), partially connected with the Kurnub aquifer. Kurnub aquifer hydro-geologically is partly connected with the deep confined sandstone aquifer complex formed by the Ram aquifer group (also known as Disi fossil aquifer), which is found in the study area at a depth of more than 1500 m with a high level of mineralization and is therefore not of interest for groundwater exploitation while the extend of this deep aquifer in the south of Jordan characterized by very good water quality and found at a shallower depth (Margane et al. 2002).

Table 3-2 Number of wells in each groundwater aquifer by own processing of spatial well data files retrieved from the (WIS) (2020).

Number of wells in each groundwater aquifer					Amount of abstraction in the study area 2019 from each aquifer MCM
Aquifer	Domestic	Agriculture	Industry	Total	
A7/B2	454	805	125	1384	142.5
B4/B5	126	1203	39	1368	-
Basalt	46	129	3	178	2.99
A1/A6	91	50	9	150	16.4 from A4 and 4.4 from A1/2
Ram/Disi	60	65	1	126	-
Kurnub	44	50	7	101	11.5
Alluvium	0	6	3	9	-
Zarqa	3	2	1	6	-
Sum	824	2310	188	3322	177.81 MCM from AZB only

3.2.2.3 Superficial deposit (Holocene to recent sediments).

The recent sedimentary deposits in the study area are the Alluvial Fans and alluvial mudflats, they cover 35 % of the study area (Figure 3-5). These sediments overly the aquifers outcropping formations the basalt and A7/B2 aquifers, see the simplified hydrogeological map where these deposits were removed (Figure 3-6) according to the description of the original 14 geological maps the thickness of these deposits in average less than 15 m and characterized by highly permeable layers. The soil cover of the study area by reviewing previous studies like Al-Qinna et al. (2008) indicated that (AZB) soil fertility and thickness are very weak and that the texture does not have a good capacity to retain water, indicating that the water flow through the soil is high and this reduces the protectivity of the soil cover in the study area.

For creating a study area soil map (Figure 3-8) to understand the thickness, the texture of the soil layer and to be used in creating the DRASTIC soil (S) parameter, a thorough review of the soil maps and data in Jordan was done. It was found that the soil mapping and classification started in Jordan in the 1950s at a scale of 1:1,000,000, using the US soil classification system. The comprehensive soil map classification and profile descriptions through the national soil map and land use project (NSMLUP), started in 1986 with funding being identified in 1988 through the commission of the European communities (MOA 1994). The output of this project was three levels of soil maps, Level-1 soil survey, a broad reconnaissance of the soils of the whole kingdom with mapping at 1: 250,000 scale, the second level involved semi-detailed soil survey and production of soil, land use, and land suitability maps at 1: 50,000 scale and level-3 present soil, land cover and land suitability maps at 1: 10,000 scale based on a detailed soil survey. In this study level-1, soil map was used as the other levels partially covered the study area. This level 1 of the soil project map produced by studying 41,578 soil profiles, 10 % of which are in the study area of each soil profile includes the location, texture analysis and chemical analysis with a description of the soil properties and taxonomy according to USDA, land cover, slope, physiographic profile sketch and description of land agricultural capability. Four original soil map sheets (sheets numbers 1,2,4 and 5) from level-1 soil maps created by MOA (1994), were compiled and about 4,274 soil profiles have been investigated and a soil map at scale (1:25.000) and soil thickness map, have been consulted for an accurate representation of soil thickness and soil texture precise description of the soil units in the study area (Figure 3-8).

The created study area soil map consists of 25 soil units. According to USDA soil taxonomic classification that is used in Jordan the soil of the study area was developed under a torric (aridic) moisture regime and the soils belong to the soil taxonomy order: Aridisols (which cover 60 % of the total area of Jordan) and two great groups of this order exist in the study area the Calciorthids and Camborthids. The percentages of soil classification according to moisture and temperature by the USDA soil classification is 2.249 % Aridic, 26.79 % Xeric, and 70.95 % Xeric/Aridic. While according to the temperature 97.75 % thermic and 2.249 % Thermic/Hyperthermic. There are five soil texture according to USDA (2014) classification (Figure 3-9), which used to assign a ratings to the soil units in the study area according to Aller et al. (1987) ratings and ranges scale to create the soil DRASTIC parameter (S).

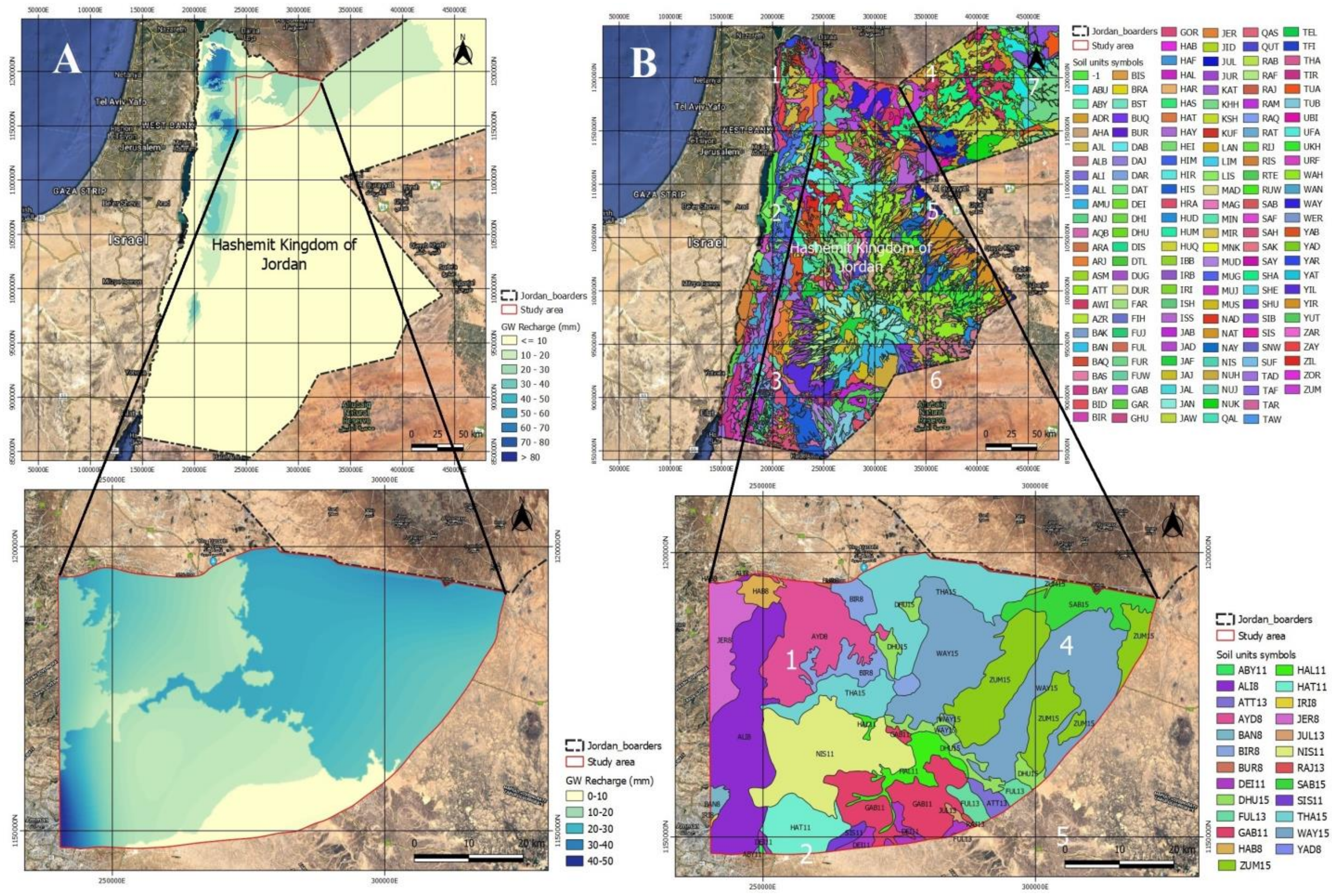


Figure 3-8 A: Study area groundwater recharge from Gazal (2020), B: Study area soil units modified after MOA (1994).

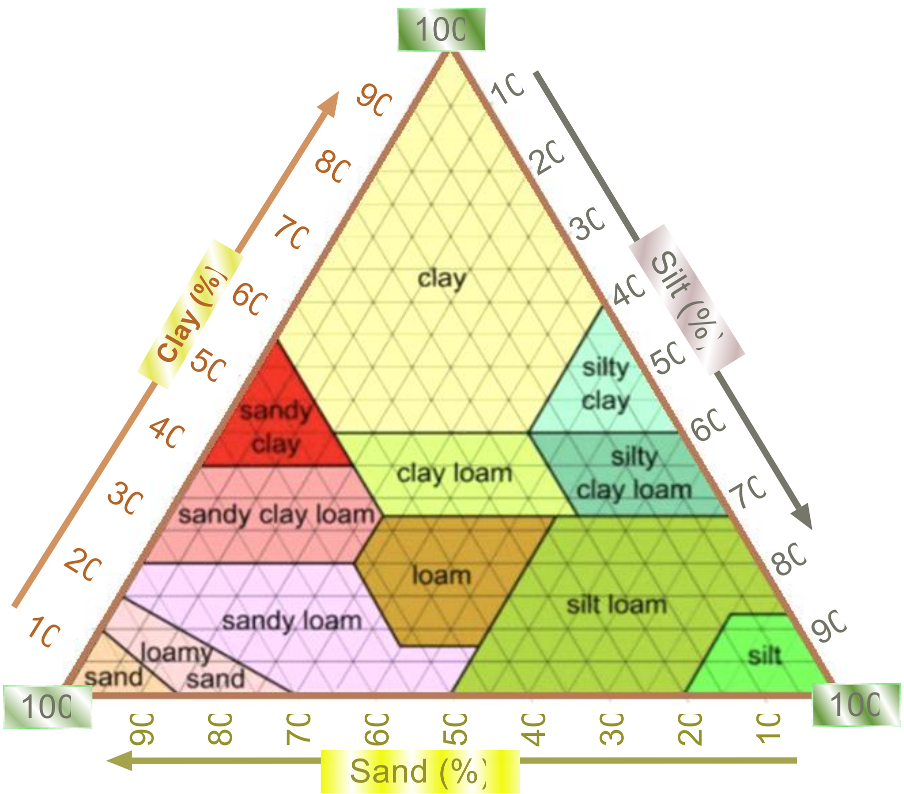


Figure 3-9 Soil texture re-sketched from the USDA (2014).

In the study area the dominant soil texture is the silty clay loam which covers 53 % of the study area. The percentages of silt, clay, and sand content in each soil units were calculated by the average content of theses component in the representative soil profiles retrieved in a hard copy from the MOA (1994).

3.2.2.4 Groundwater recharge

Groundwater Recharge (GWR) described by Lerner et al. (1990), as the downstream movement of percolated water to the groundwater table supporting the sustainability of the renewable groundwater aquifers. In this study, the GWR of the study area calculates the natural recharge occurs from the precipitation. However, there are an intensive irrigated agricultural areas which may contribute to increasing the recharge through the irrigation return flow (IRF) which is defined by Dewandel et al. (2007) as the "*the excess of irrigation water that is not evapotranspiration or evacuated by direct surface drainage, and which returns to an aquifer*". IRF is considered to be the main source of non-point contamination that contributes to surface and groundwater contamination (Jafari et al. 2012).

The GWR map (Figure 3-8) of the study area clipped from Jordan's average GWR map prepared by Gazal (2020) which estimated the long-term average GWR of Jordan's 12 groundwater basins while raw data (groundwater basin boundary and the rainfall data) from the WIS (2020) and the recent simplified hydrogeological map compiled from the simplified geological maps produced by BGR & MWI (2018).

These GWR maps was prepared according to the recharge explanations of Hobbler et al. (2001), the percolation rate was determined based on rainfall-recharge equations. These equations were applied depending on outcropping formations in Jordan, in the study area, for example, the adopted average recharge percentage of rainfall for the outcropping geological formations, Basalt, B4, B3, A7/B2, A1/6, Kurnub, were (15 %, 7.5 %, 0,15 %, 7.5 % ,7.5 % respectively) (Table 3-3). Although these recharge equations and the calculation of rainfall recharge percentages are based on Hobbler et al. (2001).

Hobbler et al. (2001) covered in detail the GWR estimations methodologies and projects in Jordan and concluded that the recharge in the outcropping areas of the karstic aquifer A7B2 in Jordan, which outcropping accounts for 43 % of the study area and the most important renewable aquifer in Jordan, can reach 30 % in the extremely wet year and can vary from 5 % to 25 % of precipitation depending on rainfall distribution, karstification maturity degree, vegetation, soil properties and thickness, topography and climate variability.

Table 3-3 Groundwater recharge to the geological units in the study area by own processing from the created groundwater recharge map by Gazal (2020).

Geological units	Area (km^2)	Area (%)	Percentage of rainfall	statistical summary					Total GWR (MCM/year)
				Average (mm/year)	Min	Max	SD	CV	
Basalt	1367.194	41.4121	15	19.93037	1.832989	26.24999	2.821967	0.14159132	27.24868
B4	20.7873	0.62964	7	0.646183	0.311291	0.763375	0.207149	0.32057377	0.013432
B3	263.7302	7.98835	0	0	0	0	0		0
A7-B2	1420.75	43.0343	15	11.99958	4.439375	42.625	6.3625783	0.56814749	17.0535464
A1-A6	228.6716	6.92643	7.5	11.38936	4.5	26.46383	3.234173	0.28421402	2.604423
Kurnub	0.302303	9.16E-03	7.5	15.13374	14.85183	15.625	0.226668	0.01497766	0.004575
Sum:46.9246592 MCM/Year									
Study area recharge map statistical summary				14.00505	0	42.625	7.485969	0.53451944	46.92549 MCM/Year

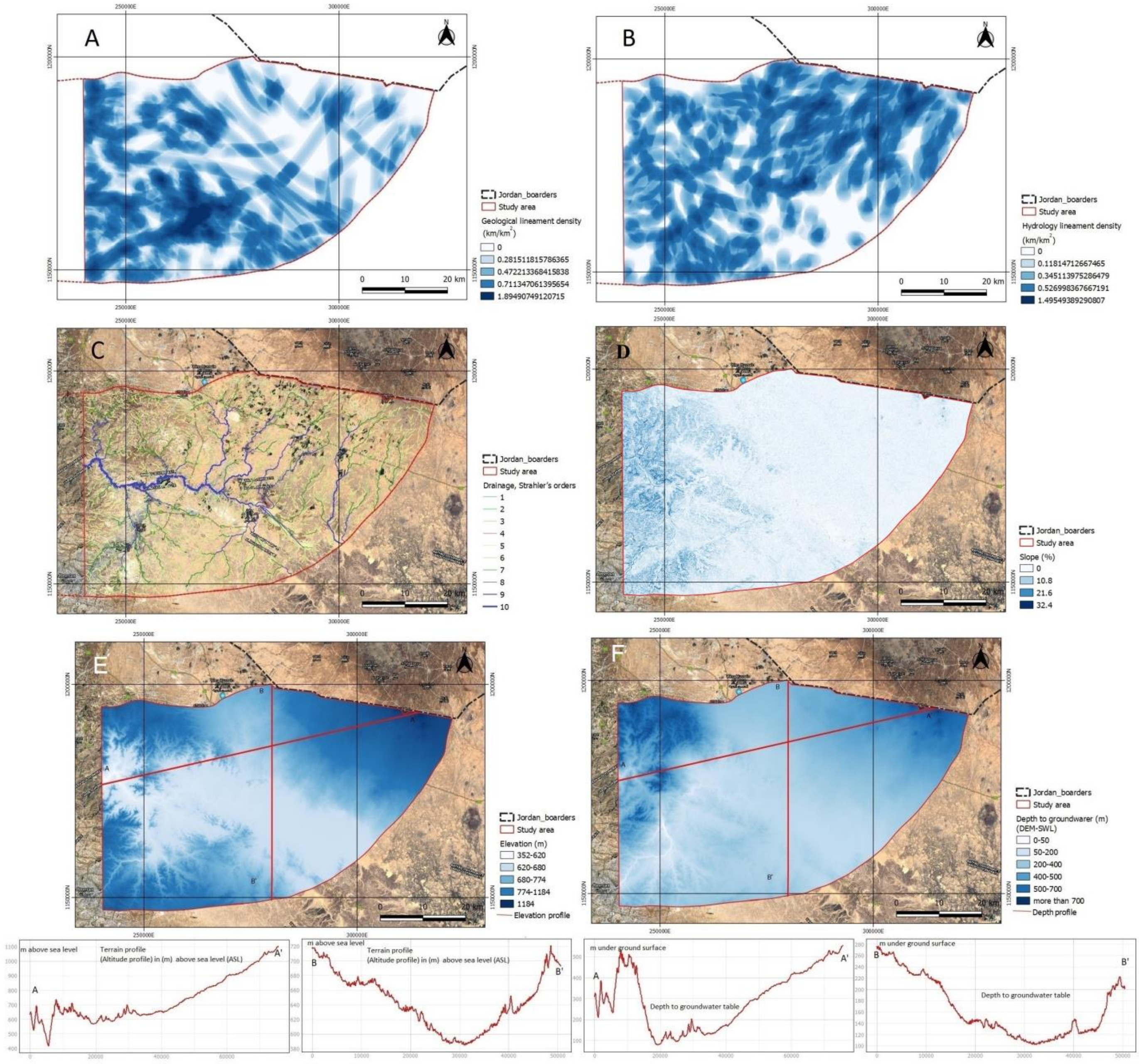
S.D. stands for standard deviation and CV for the coefficient of variation.

3.2.2.5 Related physical features of the landscape obtained from remote sensing (RS) technique for groundwater condition assessment

3.2.2.5.1 Geological lineaments and structural setting

Groundwater primarily flows through a network of voids, vents, joints, and fractures, therefore, the density of the geological lineament reduces the natural potential protection of the groundwater and increases the flow rate of recharge to the aquifer plus is considered to be a fast path of contamination to the groundwater (Li et al. 2015; Sarikhani et al. 2014). In general, the analysis of fractures or structures by remote sensing refers to lineaments (Abdullahi et al. 2013). Fissures, cracks, and joints are very critical factors in predicting groundwater vulnerability. Lineaments are structurally controlled surface manifestations of features such as joints, fractures, folds, faults, straight streams, and alignment of vegetations (Gazal 2020).

Detailed information was used in this study for mapping the fault density. Specific image processing and enhancement techniques were applied to various remote sensing data including Landsat ETM-7 (Enhanced Theme Mapper) satellite images and SRTM (The Shuttle Radar Topography Mission) (NASA 2019) to obtain sufficient details using specific methods of extraction. The thematic lineaments map created (Figure 3-10) was compared and matched to the geological structure maps of digitized hard copies created from existing 14 geological maps with scale 1:50000, and the BGR structural geological map (BGR MWI 2019). Unlike conventional approaches, the topographic fabric algorithm, which uses DEM to construct a map of geological lineaments, has proved to be a powerful tool for performing linear features in time and economic efficiency over large levels. Orientations of the geological lineaments are compared using the rose diagrams, which shows a concentration of lineaments orientations of the major faults, jointing systems exist with the general trends of SE-NW and NE-SW directions. Only in some locations a weakly developed joint system striking E-W is found.



Statistical summary of the maps obtained from the raster statistics summary.

Thematic Layer	Mean	Minimum	Maximum	Standard deviation	Coefficient of variation
Dem	706.8671948	352	1184	118.1246263	0.16711007
Depth to water (Dem-SWL)	239.3441033	2.56976318	678	135.9042537	0.56781952

Pixel Size: 26, -26, CRS: EPSG:28192-Palestine 1923 / Palestine Belt- Projected

Figure 3-10 A: Geological lineament density B: Hydrology lineaments density C: Study area surface drainage according to Strahler's orders D: Slope % created from the DEM , E: Digital elevation model of the study area, elevation profiles, F: Depth to groundwater table calculated by subtracting the SWL map from the DEM map with depth to water profiles, and a statistic summary of the DEM and Depth to groundwater table thematic maps.

3.2.2.5.2 Surface water drainage density

Surface drainage is one of the most important landscape features which have a strong interpretation for groundwater situation. Although the drainage density is related to the low-high-to-moderate potential of groundwater, while the drainage pattern, gives an idea about the joints and faults in the bedrock, which in turn indicates the presence or absence of groundwater (Jha &

Chowdary 2007). The density of the surface drainage network has a relation to surface runoff and soil permeability and is considered one of the important hydrological measures of groundwater occurrence this means a high density indicate a low groundwater potential in the area which also can be related to weak development of major surface water flow lines like major revers. The areas with low drainage density and with major surface water flows have more potential of occurrence of groundwater at a shallower depth.

According to Drainage density classification in term of groundwater potential by Jha et al. (2016) the area with 0–0.50 km/km^2 drainage density can be considered as a “very good” for groundwater occurrence, drainage density of the range 0.50–0.75 km/km^2 can be considered as good, 0.75–1 km/km^2 is moderate,” and above 1 km/km^2 can be considered poor from the viewpoint of groundwater storage. The DEM (digital elevation model) of the case study area was derived from the high-resolution Shuttle Radar Topography Mission (SRTM) (NASA 2019) (Figure 3-10), which was used to create the drainage density of the study area. And was used to create the slope thematic layers which used in this research to create the topography DRASTIC parameter (T) by classify the slope map according to the ratings and ranges of Aller et al. (1987).

The ASTER Global Digital Elevation Model (GDEM) version 3 ASTGTM provides a global digital elevation model (DEM) of the Earth's land areas with a spatial resolution of 1 arc (about 30 meters horizontal equator position). The downloaded DEM processed by GIS with original high resolution of about 27 m as pixel size, the extent of the downloaded thematic layer (35.67,31.91: 36.83,32.39) with a width 4140 km and height 1764 km, with a coordinating system CRS EPSG:4326-WGS 84–Geographic, which has been converted to EPSG:28192-Palestine1923/Palestine-Belt, which is the system of coordination implemented in all thematic layers in this work. Runoff is generated after precipitation events only as there is no permanent surface flow water in the study area (No perennial flows). Surface runoff occurs only in winter, in flood form. The runoff coefficient increases with increasing rainfall amounts and intensity and this flow which is subject to flash flooding in the study area depend on several factors, such as precipitation level, duration and intensity, evaporation, wadi filling, and rock bed permeability, size and drainage basins character. The created surface area drainage map is according to Strahler’s orders, wherein the created map (Figure 3-10) the order of the stream is one if a stream has no contributing tributaries (Strahler 1957).

3.2.2.5.3 Hydraulic conductivity of the aquifer system in the study area

Hydraulic conductivity (HC) values of the hydrogeological formations can be estimated by the Empirical approach (correlation methods) which can figure up by the pore and grain, size and distribution and the texture, while in the experimental approach HC is determined by applying Darcy's law (Darcy 1856). The Experimental approach can be performed on a small scale using samples in Laboratory (Ikechukwu 2017), but the large-scale field test is commonly by the pumping tests analyses to estimate the hydraulic conductivities of the geological formations (Kruseman et al. 2000). Calculations of HC by laboratory hydraulic experiments of geological formation samples not available for the geological formations of the case study area. While numerous pump tests have been carried out by the Water Authority in the study area, basically all production wells have at least one pumping test sheet.

For this work, all the available groundwater wells hard and digital pumping test sheets in the study area have been investigated and studied. Table 3-4 shows the estimated HC of the geological formations in the study area rely on the pumping test data and these numbers adopted by several studies like Margane et al. (1997) and numerous of hydrogeological studies used this HC values estimated from pumping test data. Gazal (2020) noticed the big difference between the HC estimated values of several geological formations compared with HC values for the same formation in several literature reviews.

Table 3-4 A: Hydraulic conductivity values of the main hydrogeological units in Jordan estimated by the statistical evaluation of pumping test data, source (Hobbler et al. 2001; Margane et al. 2002) and adopted by several scientific and official studies like MWI (2013); and MWI (2010) B: Ranges and Ratings for (HC) according to the DRASTIC model of the U.S. Environmental Protection Agency (Aller et al 1987) .

A: Hydraulic conductivity values of the main hydrogeological units in Jordan estimated by the statistical evaluation of pumping test data (Hobbler et al. 2001).

Hydrogeological Unit	**Aquifer**	**Horizontal Hydraulic Conductivity (Kh) m/s**	**Vertical Hydraulic Conductivity (Kv) m/s**	**Specific Storage Coefficient (m/s)**	**Specific Yield (m/s)**
Basalt	I	2.000E-04	2.00E-05	1.00E-05	0.01
B4/B5	I	3.50E-06 ~~ 1.00E-04	3.50E-06 ~~ 1.00E-05	1.00E-05	0.05
B3	Aquitard	4.20E-10 ~~ 4.20E-07	2.00E-11~~ 2.0E-09	1.00E-05	0.01
A7/B2	I	1.30E-04 ~~ 7.00E-3	2.00E-06~~ 1.00E-04	1.00E-05	0.05
A1/A6	Aquifers and Aquitards	5.00E-08	5.00E-11	1.00E-05	0.01
Kurnub	II	3.00E-08	2.50E-08 ~~ 1.30E-06	1.00E-05	0.025
Zarqa	Aquitard	1.40E-07	1.40E-10	1.00E-05	0.01
Upper Ram Group	III	5.00E-07	2.50E-07	1.00E-05	0.05
Lower Ram Group	III	5.00E-07	2.50E-07	1.00E-05	0.01

B: Ranges and Ratings for (HC) according to the DRASTIC model of the U.S. Environmental Protection Agency (Aller et al. 1987).

	gallons/day/square feet GPD/Ft^2	m/d*		m/s*		Weight	
rate	Ranges according to Aller et al. (1987)	from	to	from	to		In case of using the (HC) values estimated from the well pumping test all the C layer will be assigned a rating equal 1
1	1-100	0.040816	4.081633	2.834467E-05	2.834467E-03	Generic DRASTIC 3	
2	100-300	4.081633	12.2449	2.834467E-03	8.503401E-03		
4	300-700	12.2449	28.57143	8.503401E-03	1.984127E-02		
6	700-1000	28.57143	40.81633	1.984127E-02	2.834467E-02	Agricultural (Pesticide) DRASTIC 2	
8	1000-2000	40.81633	81.63265	2.834467E-02	5.668934E-02		
10	2000+	81.63265	above	5.668934E-02	above		

*Converted the original ranges of Aller et al. (1987) from GPD/Ft^2 to other units by http://www.groundwatersoftware.com/calculator_3_unit_conversion.htm

Theis equation (1935) was used for confined aquifer and (Neuman equation) (1974) for unconfined aquifers, but by studying the wells pumping test sheets data it was found that different units were used in these sheets, the range of the values for each formation from well testing to another shows big differences this might be to the karstification characteristic of some of these aquifers (Gazal 2020). Moreover, it was not good idea to calculate the HC as average for each formation from these pumping test data without taking into consideration that the values of HC represent more than one formation in these wells (Gazal 2020).

A list of some pumping tests values was listed in the MWI/USAID/ARD (2001); and MWI & JWA (2010) official reports and used to create a groundwater model while the second report itself-mentioned the strange wide range of hydraulic conductivity values from 0.02 m/day to 358 m/day from the wells used in that reports. Still up to now many researchers in Jordan return to the HC values estimated from the pumping tests by the BGR listed in the Margane et al. (1997), While the BGR itself, which practically studied all the pumping test data for all Jordanian wells in a comprehensive manner and summarized them in tables that are easy to retrieve and use with great effort in cooperation with the Ministry of Water and Irrigation, warned against relying on these figures in scientific hydrogeological studies.

Professor of Hydrogeology Manfred Hobbler (2001), explained in detail why these hydraulic conductivity (HC) estimates are not valid for scientific purposes. Hobbler et al. (2001) thorough explanation to not use such values in the field of scientific studies, and the fact that they are impractical or constitute incorrect numbers which do not give real values to the hydraulic conductivity (HC) of the Jordanian aquifers. He discussed several explanations like, in almost the pumping tests, stable conditions (too short pumping test duration) had not been reached, recovery data could not be interpreted, wells have been screened in several aquifers and the whole sequence has been tested; the transmissivity values are not valid for a certain aquifer. Aquifer penetration is always incomplete, yield was not monitored regularly during the test, and it was confirmed that Jordanian water authority (WAJ) is primarily interested in well performance tests to assess the yield and efficiency of the water well and not the hydraulic parameters of the aquifer. Then, many other explanations and by checking theses pumping tests have shown the extent of scientific error based on using these HC estimated values from the pumping tests in the case of Jordan (Gazal 2020). The HC ranges of Aller et al. (1987) have been converted to (m/s), as listed in the Table 3-4 and compared with the estimated HC values from the pumping tests in Jordan which do not represent the HC of the Jordanian aquifers. Consequently, the range of the HC and permeability values created by Freeze & Cherry (1979) and adopted by Aller et al. (1987) were used in this study.

3.2.3 The overlaying modelling techniques:

To simulate the previous investigations of both GRA components (the intrinsic vulnerability and the contamination load) an overly modelling techniques were used as explained by Figure 3-11. Three overlay modelling steps were performed to create the groundwater intrinsic vulnerability map, potential nitrate contamination (PNC) map and the groundwater nitrate contamination risk (NCR) map.

3.2.3.1 Investigate the second component of the GRA by modified intrinsic vulnerability model:

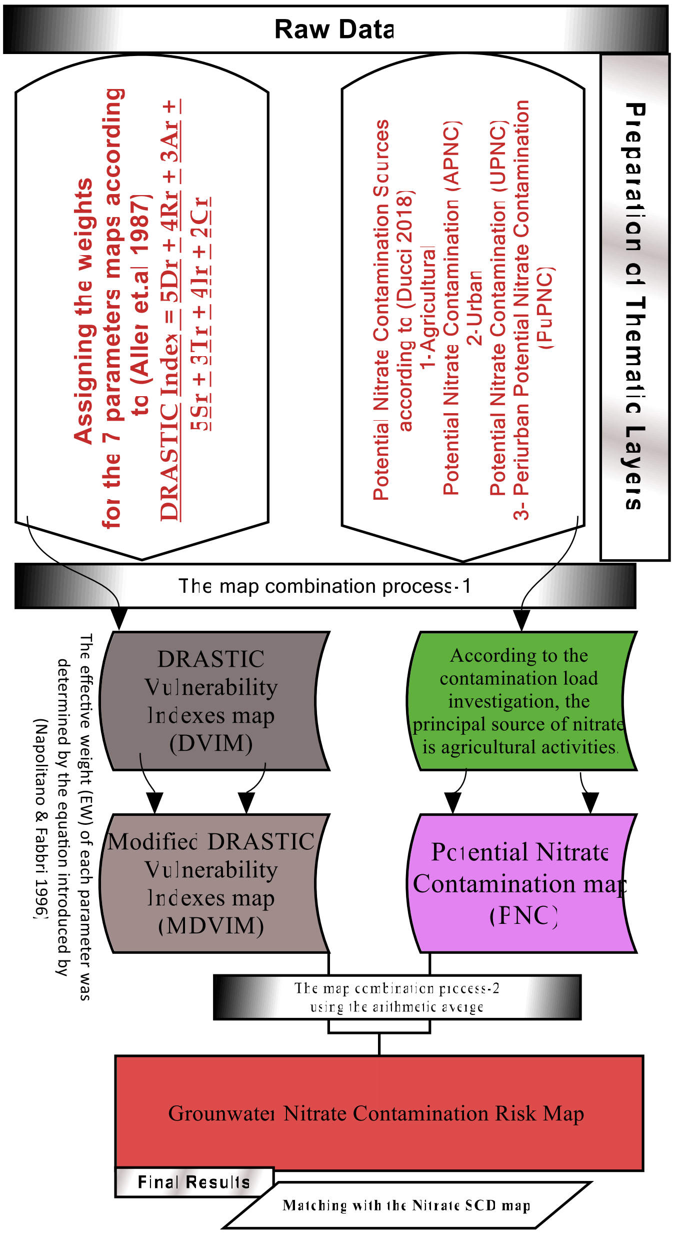


Figure 3-11 Flow chart simplifies the overlaying modelling techniques used in the case study.

Figure 3-12 summarized the tow DRASTIC approaches applied in this research. The Agricultural and Ordinary (generic) DRASTIC approaches were used in this study to develop the groundwater intrinsic vulnerability map in addition to the former intrinsic vulnerability map created by COP-model as set out in Vías et al. (2006). Aller et al. (1987) created the DRASTIC model for the United States environmental protection agency (EPA).

The DRASTIC seven parameters thematic maps, depth to water table (D), net recharge (R), aquifer media (A), soil media (S), topography (slope%) (T), the effect of the vadose zone (I), and hydraulic conductivity (C) were prepared relay on the hydrogeological, soil, groundwater recharge, depth to water table and the created slop maps. Where the (A), (I) and (C) parameters prepared by referring to the geological maps utilizing the geological attribute of the prepared hydrogeological map of the study area which was used to encode the geological units according to the DRASTIC model rating system for aquifer media (A), impact to vadose zone (I), and hydraulic conductivity (C). While the soil units attribute in the prepared soil map was used to encode the soil units according to DRASTIC model rating system for soil (S). The prepared depth to water table, recharge, and slope % thematic layers were classified into DRASTIC (D), (R), and (T) rates, according to the ranging of depth to groundwater table, recharge, and slope % (Figure 3-13).

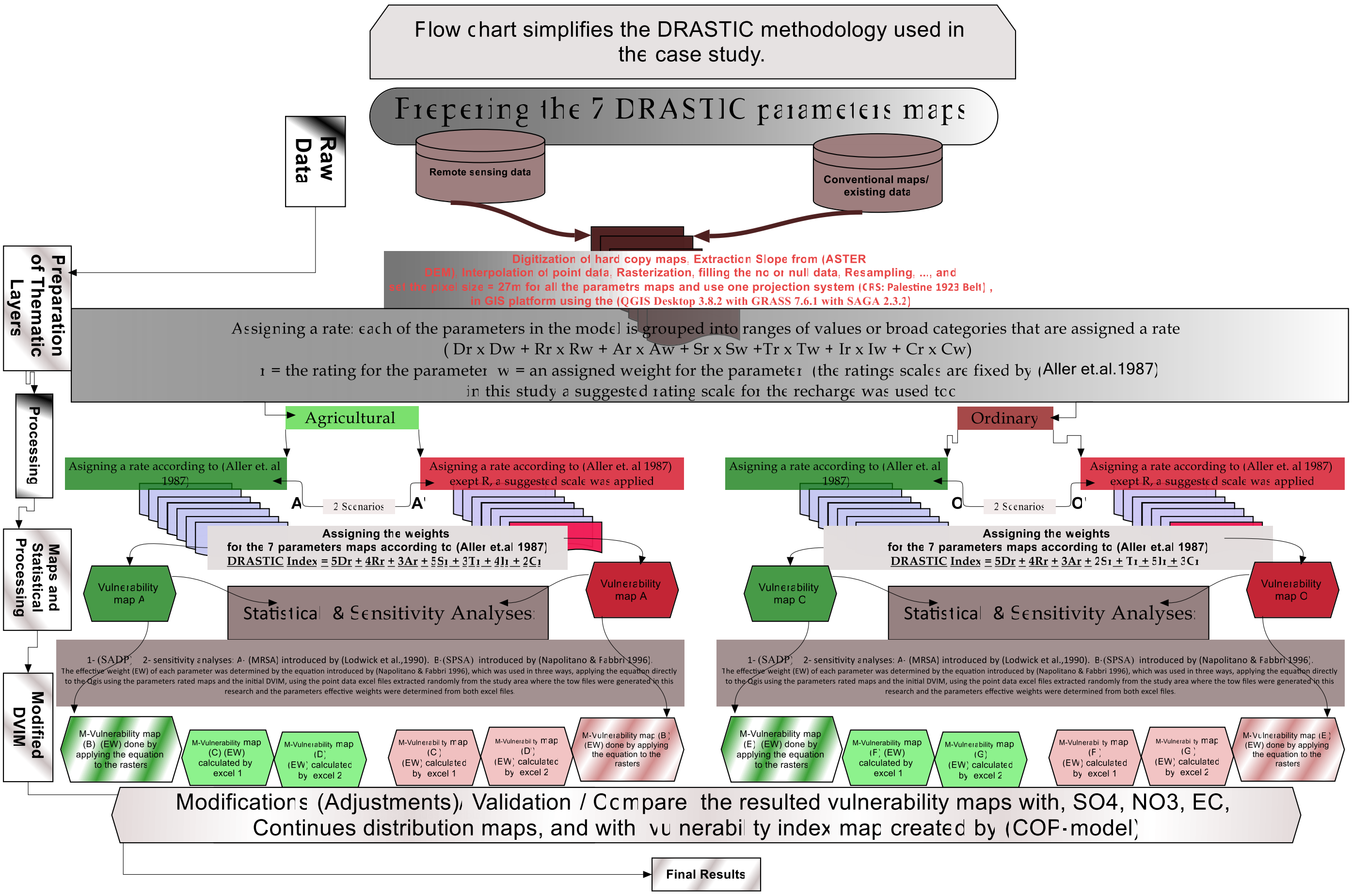


Figure 3-12 The schematic flow chart describes the DRASTIC-model approaches used for this study to create appropriate intrinsic vulnerability map.

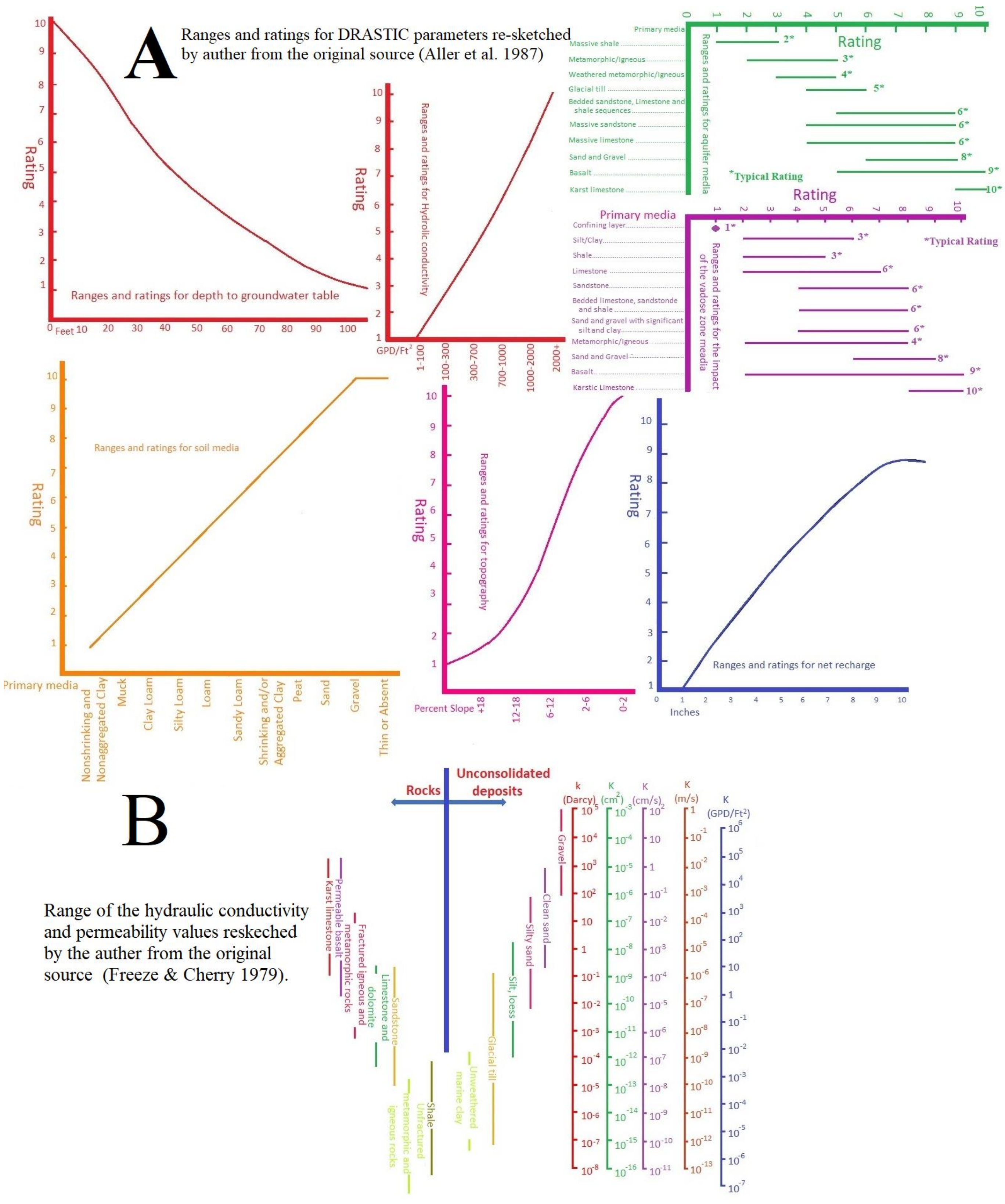


Figure 3-13 Ranges and ratings for DRASTIC parameters according to Aller et al. (1987). B: Range of hydraulic conductivity and permeability values (Freeze & Cherry 1979).

The model yields a numerical index deriving from the ranges, ratings, and weights assigned to the seven parameters of the model. According to Aller et al. (1987), the DRASTIC index vulnerability map (DIVM) is determined by applying a linear combination of all variables, according to the governing equations (see section 2.6). Agricultural (Pesticide) DRASTIC is recommended to be used where agricultural activity is of concern in the study area (Aller et al. 1987), thus the last decision was to use the result obtained by performing this approach. The preparation of the DVIM and the statistical and sensitivity analyses to modify it processed in the Geographical Information System (GIS) and was performed in the free available software used in this study the QGIS Desktop 3.8.2 with GRASS 7.6.1 with SAGA 2.3.2.

In this study, the two DRASTIC approaches were performed based on equations 2 and 3 described in the literature review chapter section 2.6. There were two scenarios in each of the two approaches as mentioned in Figure 3-12. The last decision, however, was to follow the Agricultural Approach. The next steps clarify the development of vulnerabilities maps through the implementation of the Agricultural Approach, although the same steps have been implemented in the ordinary DRASTIC approach.

3.2.3.1.1 Development of the DRASTIC seven thematic Layers:

Several data types and sources were used to create thematic layers of the seven DRASTIC parameters. All the DRASTIC parameters were subdivided into ranges according to Aller et al. (1987) and have been assigned and a relative weight according to equation 2. Each DRASTIC parameter was processed in the Geographical Information Systems (GIS) and was performed in the QGIS Desktop 3.8.2 with GRASS 7.6.1 with SAGA 2.3.2 software and prepared as thematic layers. The DRASTIC approach in this study was performed by two scenarios, A and A´, the first one with the original ranges and ratings the second one only the ratings of recharge were suggested to be changed as discussed in the preparation of (R) parameter below. The resulted from the DRASTIC vulnerability index map (DVIM) from the two scenarios (A and A´) were followed by complete statistical and sensitivity analyses and were modified by the calculated effective weight of the DRASTIC parameters as described below.

Depth of groundwater (D), according to the DRASTIC model, (D) the distance from the ground surface to the groundwater table in an unconfined aquifer is considered to be one of the important factors in assessing the area’s most vulnerable to contamination where, with a higher groundwater depth, there is a lower risk of contamination.

Deeper groundwater table implies longer travel times, as well as the longer the passage period for the water that flows to the groundwater table from the surface, the greater the likelihood that the water will get rid of part of the pollutants that it may carry from the surface, therefore areas with a large depth of water are less prone to contamination. The depth to groundwater map was prepared after creating the static water level (SWL) map (Figure 3-14) by ordinary kriging (OK) interpolation of the observation wells SWL average measurements.

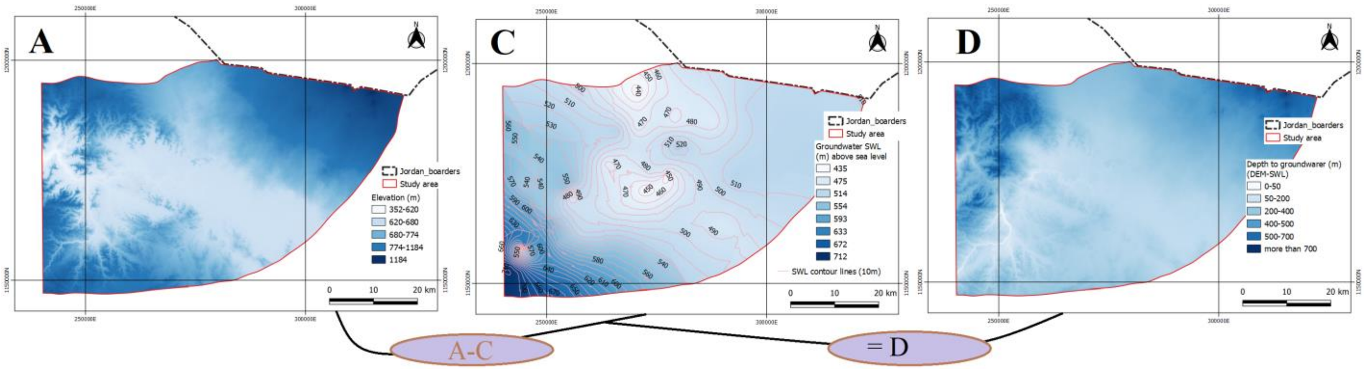


Figure 3-14 Creating the groundwater depth map.

Then Subtracting the SWL map from the DEM thematic layer to obtained depth to the groundwater table map. Then the depth to the groundwater table map was classified into the DRASTIC (D) rates, according to the ranging of depth to groundwater table the minimum rate assigned by DRASTIC is one reflecting a low groundwater risk while the maximum rate is ten reflecting a high groundwater risk of contamination. According to groundwater depth more than 99 % of the study area belongs to the lowest risk DRASTIC (D) range (D >39). Therefore, almost all the study area was rated by one, so the dominant scoring index of D is 5.

Net recharge (R), groundwater recharge (GWR) is the estimated annual amount of water that infiltrates from the ground surface into the aquifer. The natural GWR is considered one of the most important factors in groundwater risk assessment as a significant medium for transporting the contaminants, whereby pollutants are transferred to the groundwater, and the higher the recharge percentage, the greater the groundwater risk. The GWR map of the study area created from Jordan's average GWR map, which prepared by Gazal (2020) according to the Jordan recharge approaches by Hobbler et al. (2001), the percolation rate was determined based on rainfall-recharge percentages equations which were previously adopted and used by MWI (2019). These equations were applied depending on outcropping formations in Jordan, in the study area, for example, the adopted average recharge percentage of rainfall for the outcropping geological formations according to Hobbler et al. (2001), Basalt, B4, B3, A7/B2, A1/6, Kurnub, are (15 %, 7.5 %, 0.15 %, 7.5 %, 7.5 % respectively).

According to the created study area thematic GWR layer (Figure 3-8), the mean GWR is 14 mm/year, the maximum 42.6 mm/year, the minimum is zero in the south part as the outcropping formation there is the B3 which is aquitard. According to the average precipitation rate of the study area which is 134 mm/year, the calculated GWR to precipitation in the study area is 10.4 % which is a good percentage. But the precipitation rate is very small in the study area, so according to the DRASTIC ranges and ratings, when the GWR ranges between zero to 0.05 m/year the assigned rate is one (as low-risk potential from the GWR point of view). Accordingly, the area was entirely rated one, therefore the second scenario was suggested by changing the recharge ranges and ratings (R'), by multiplying the ranges by 100. These suggested ranges and ratings of (R') are intended to simulate the potential increase in recharge by irrigation return flow (IRF) in intensive agricultural areas. However, the agricultural activities are not only increasing the GWR through (IRF) but the processes of ploughing that disintegrate the soil layer which increases permeability and enhancing the recharge.

Aquifer media (A) refers to the (consolidated or unconsolidated materials) characteristics of the saturated zone that control the process of attenuation of the pollutant. The ranges and ratings of the DRASTIC assigned according to the water travel time in the aquifer, the longer the travel time will result in more attenuation of the pollutant and the rate is in reverse relation to this travel time. Each Aquifer media in the ranges and rating scale of DRASTIC is listed in the order of increasing pollution potential, the aquifer media with the highest pollution potential is assigned the highest scores of the rate as it suggested for karstic and basalt aquifer 10, while in this study the suggested typical DRASTIC rates for basalt and karstic were used 9,10 respectively. Consequently, the other aquifers media in the study area were assigned rates, according to the geological description of each unit then return to the scale of ranges and ratings to assign a representative scoring rate. For example, the scoring rates of sandstone media can be between 6-9 according to the Figure 3-13, while the choice is governed by the specific characteristics and properties of this media, the sandstone aquifer (K) in the study area was assigned a scoring rate of 8 which is the typical suggested rating score for sand and gravel aquifer media by Aller et al. (1987). Both Aquifer (A) and hydraulic conductivity (C) thematic layer were prepared by referring to the geological formation in the study area, and the geological attribute of the prepared hydrogeological map (Figure 3-6) was used to encode the geological units according to the DRASTIC-model rating system for aquifer media and hydraulic conductivity.

Soil (S), soil media refers to the vadose zone's uppermost part, marked by substantial biological activity (Aller et al. 1987). The prepared study area soil map (Figure 3-8) was used to create the thematic layer of a DRASTIC rated soil map, which include an attribute of the texture class of each soil units according to the soil textural classification triangular chart of USDA (2014), therefore each soil unit was rated according to DRASTIC soil ranges and ratings. There are 5 soil classes in the study area the dominant class is the Silty clay loam which was assigned a scoring rate of 3 according to DRASTIC ranges and ratings (Figure 3-13) so by multiplying with the soil weight then the dominant scoring index of the DRASTIC S (wSr) is 15.

Topography (T) parameter refers to the inclination degree of the ground surface (terrain slope), land surface slope variability as an input in the DRASTIC model expresses the flow rate at the surface in the approach of determining the most susceptible areas to pollution. The slope parameter determines how much the water stays on the surface. Whereas water stagnates in low slope areas, increases infiltration, and there is a greater potential for contaminant migration. While the sloping areas with a higher inclination are considered less susceptible to pollution because of the periods of water to settling on the surface not enough to high rate of water infiltration to the water table, including the contaminants it contains potential presence due to agricultural activities, for example. A slope degree map was created using data from the digital elevation model (DEM) derived from the high-resolution Shuttle Radar Topography Mission (SRTM) (NASA 2019) (Figure 3-10). according to the slop degree thematic layer, only 0.016 % of the study area has a slope degree above 18 degrees and the degree of slope exhibited by the study area varies from 0 to 32.43 degrees and the standard deviation of the slope degree map is 4.249 and the coefficient of variation is 0.965 (before classified it into DRASTIC scoring ratings according to ranges of slope degree). Therefore, the study area is considered a gentle slope area with an average slope degree of 4.4. Then topography (T) parameters are prepared by classified the slope degree map into five classes according to ranges and ratings of Aller et al. (1987). Areas with low slopes (<2 %) were typically assigned a high rating score (Tr=10) indicating their high effect on the aquifer vulnerability, thus the scoring index of the highest rating calculated by multiplying the rating score (Tr) with the (wT) then the scoring index is 30 the highest T DRASTIC index.

Impact of vadose zone (I) refers to the hydrogeological characteristics of the vadose zone materials, which the discontinuously saturated or unsaturated layers above the water table of the renewable aquifers. These characteristics determine the process of attenuation of the pollutant within the distance from the soil layer down to the water table of the saturated aquifers. Aller et al. (1987) classified the vadose medium into an order of increasing groundwater pollution potential (Figure 3-13). The (I) parameter map was prepared from the 14 structural geological maps retrieved from MEMR (2017), compiled, processed and the geological attribute was used to encode the vadose zone formations with rating scores according to Aller et al. (1987). In the study area, the highest DRASTIC (I) risk rating score was assigned to the Wadi As sir limestone (A7 formation), as this formation characterize by a highly fractured and karstification, thus the highest contamination risk index of (I) the (wIr) is 40 as the weight of the I is four.

Hydraulic conductivity (C), according to Aller et al. (1987), HC refers to the ability of aquifer materials to transmit water, which in turn regulates the rate at which groundwater flows under a given hydraulic gradient. The rate at which groundwater flows also influences the rate at which a contaminant is moving away from the point at which it reaches the aquifer. HC was inferred from the range of values of HC and permeability of Freeze & Cherry (1979) (Figure 3-13), with taking into consideration the geological characteristics of the aquifers which discussed before, which assure that the dominant aquifer media in the study area are the karstic highly-fractured limestone of B2/A7 formations and the basaltic formations both are highly permeable so by referring to the ranges of HC both A7/B2 and Basalt are considered according to DRASTIC ranges and ratings to be assigned a scoring rate of 10 for A7/B2 and basalt, as they belong to the highest risk DRASTIC (C) range (>2000 m/s), so the dominant scoring index for C (wCr) in the study area is 20 as the Cw is two. In the original Aller et al. (1987) ranges and ratings of parameter C, the HC ranges were plotted using GPD/Ft^2 unit (Table 3-4), but the unit of the estimated HC values from the pumping well test in Jordan is (m/s). So, the HC ranges of Aller et al. (1987) have been converted to (m/s), as listed in the Table 3-4. According to Gazal (2020); Hobbler et al. (2001) the HC estimations from the pumping well test in Jordan are not valid for scientific purposes. As a result, the range of hydraulic conductivity and permeability values created by Freeze & Cherry (1979) has been used in this study.

3.2.3.1.2 DRASTIC Statistical and Sensitivity analyses:

Using a large number of data layer inputs is one of the advantages of the DRASTIC model, such as increasing the number of data layers, reducing the effect of individual parameter errors, or uncertainties on the result (Ouedraogo et al. 2016). Nonetheless, many studies, such as Barber et al. (1993); Merchant (1994); McLay et al. (2001) discussed approaches to reduce the number of DRASTIC input parameters to achieve greater accuracy at a lower cost. Rosen (1994) statistically studied the interrelations between the seven DRASTIC parameters in several sites in Sweden and found they are quite and representative to assess the vulnerability. However, others studied like Secunda et al. (1998) assumed constancy of the missing other parameters as well as several recent studies include more parameters in the DRASTIC approaches such as the lineament density and land-use layers. Moreover, Napolitano & Fabbri (1996) criticized the unavoidable subjectivity of the collection of the seven DRASTIC parameters, the ratings, and the weights used to measure the DVIM. Generally, the approaches to groundwater vulnerability assessment need validation to minimize subjectivity in ratings and range the parameters of input and improve dependability (Gogu & Dassargues 2000; Ramos-Leal & Rodríguez-Castillo 2003). Therefore, modifications attempts were carried out in this study to accurately determining groundwater susceptibility in the study area. Statistical and sensitivity analysis was carried out to understand the influence of the ratings and weights assigned to each of the DRASTIC parameters and calculated the effective weight of each DRASTIC parameters.

1. Statistical analyses of DRASTIC rated parameters (SADP), a compare investigated study accomplished utilizing the statistical summary of each DRASTIC rated parameter thematic layer to study the variability, in addition to a correlation analyses to examine the independence of the DRASTIC rated parameters, where the independence of the DRASTIC parameters reduces the possibility of error, while generally, the DRASTIC parameters are naturally closely related parameters according to Rosen (1994). While the low variability of the DRASTIC rated parameter indicates a smaller contribution to the variation of the vulnerability index across the study area (Babiker et al. 2005).
2. Sensitivity analyses: Analysis of sensitivity offers useful information about the effect of rating values and weights applied to each parameter and helps to determine the importance of subjective parameters. Two sensitivity analyses were carried out in this study; the map removal sensitivity analyses (MRSA) introduced by Lodwick et al. (1990) and the single parameter sensitivity analysis (SPSA) introduced by Napolitano & Fabbri (1996) in addition to applied the developed (SPSA) approach (Napolitano & Fabbri 1996) in the real or the effective weight calculation of the DRASTIC parameters which were used to create a modified DVIM.
   a. Map removal sensitivity analyses (MRSA), introduced by Lodwick et al. (1990), the MRSA identifies the sensitivity of the vulnerability map towards removing one or more maps from the creating the DVIM analysis, which is calculated by the following equation:

   $S=\left(\frac{\left|\frac{V}{N}-\frac{V'}{n}\right|}{V}\right)*100$ … (4) Where the sensitivity associated with removing one or more maps (S): is the sensitivity measure expressed in terms of variation index*, (V) is the unperturbed DVIM. The unperturbed (initial) vulnerability maps were calculated by the DRASTIC govern equation 2 in the first approach (Agricultural DRASTIC) and DRASTIC govern equation 3 in the second approach (Ordinary DRASTIC), V′ is perturbed vulnerability indices, N, and n, are the number of data layers used to calculate the V and v. while the variation index = (V- V′)/V.

In this study four initial vulnerability maps DVIM were created by the two DRASTIC approaches. The first tow initial vulnerability maps were created according to the two scenarios of implementing the Agricultural DRASTIC, so the test will be performed twice one with the DVIM created by the first scenario (map A) and the second by the DVIM created by the second scenario (map A') (Figure 3-12). While the same step was performed in the case of the Ordinary DRASTIC where the tow initial maps DVIM were (map O) in the first scenario and (map O') in the second scenario.

b. Single-parameter sensitivity analysis (SPSA), performed to modify the weight of the DRASTIC parameters (Napolitano & Fabbri 1996), indicated that SPSA provides valuable weighting impact information allocated to each parameter and enables analysts to determine the value of subjectivity. In the discussion through the results of this study, these analyses were used to determine the effect of each DRASTIC parameters on the resulted DRASTIC vulnerability indexes map (DVIM) to evaluate whether it was necessary to use all the seven DRASTIC parameters, the higher influence of a parameter compared by another parameter, indicate a higher real weight of this parameters. The calculated variation index of the perturbed DVIM is the measure of the real influence of the removed parameter on the final DVIM.

In this analyses that initiated for the first time by Napolitano & Fabbri (1996) the equation of Lodwick et al. (1990) number 4 is used but as the number of the removed parameters is fixed by only one so the equation can be retyped the same as, $S=\left(\frac{\left|\frac{V}{7}-\frac{V'}{6}\right|}{V}\right)*100$ …(5) which by the raster calculator can be for example as S=(absolute((V/7)-((V-(X*Xw))/6))/V where X is the removed rated parameters, Xw the parameter theoretical weight.

Each DRASTIC parameter contributes to the DVIM with an effective weight (W) which can be calculated in % for each parameter $\text{E}ffictive\ (real)\ W = \left(\frac{PrPw}{V}\right) * 100$…(6) pioneered by Napolitano & Fabbri (1996), where V: DVIM calculated by the original parameter weights, Pr, Pw are the ratings and the weights respectively of the parameter P.

3.2.3.1.3 DRASTIC validation:

To examine the vulnerability maps created by DRASTIC model a long-term groundwater nitrate, sulfate, and total dissolved solid concentration analyses were retrieved from the (WIS) (2020). Theses parameters were selected considering agricultural activities as the main contamination sources in the study area, while the common chemical fertilizers used by farmers are the ammonium sulfate fertilizers (Gazal 2020; Gazal 2015). The real maximum and the average concentration measurements of Nitrate sulfate and EC (TDS in mg/L = 0.54 EC in μS/cm, 0.54 is the conversion factor used by the MWI (JISM 2008)) were interpolated by Ordinary Kriging (OK) method to create six spatial continuous data (SCD) maps.

To conclude, the recent Jordan's intrinsic vulnerability map by COP-model (BGR & MWI 2018) was used in this study to compare with the created DVIM. COP-model as set out in Vías et al. (2006) uses three parameters, the C: Concentration of Flow (slope and surface features) the O: Overlying Layers (soil and geological formations), and P: Precipitation (quantity and intensity), which give the precipitation factor third of the weight in determining the groundwater vulnerability.

3.2.3.2 Groundwater nitrate contamination risk (NCR) map

The last step in the overlying modeling application in this study is creating the groundwater nitrate contamination risk (NCR) map as discriped in Figure 3-11. Groundwater risk map generally, is a combination of existing hazardous substances and the aquifer vulnerability. But due to the difficulties of recognizing all possible sources of contaminants and the presence of a real contamination problem, the susceptibility is more directed towards a particular contaminant. While, due to the results of the contamination loads investigation, Nitrate was selected as a particular contaminant in the study area.

The first component of the NCR is the potintial nitrate contamination (PNC) was created by overlapping three land use weighted thematic layers responding to the nitrate contamination factors. According to Ducci (2018) each layer was classified into five classes described below:

1. The agricultural potential nitrate contamination (APNC): Mainly related to the fertilizers load which is high in the areas with high agricultural intensity. While the agricultural intensity map (AIM) created by compiling a set of AIMs recovered from MOA (2020) in hard copy format, reflecting the AIM of the year 2019 was considered to create the APNC layer. Five APNC classes were assigned to the study area, whereas the areas with high agricultural intensity were assigned a high APNC class, while the areas with very low agricultural intensity were assigned a very low APNC class.
2. The urban potential nitrate contamination (UPNC): It associated with the likelihood of leakage of the sewage network and expressed by the population density which is low to very low in the study area. This layer was prepared utilizing the administrative divisions' maps recovered from the (RJGC) (2020) and population data from DOS (2020). The population density in Jordan reached 121 inhabitant/km^2 which is a assigned a moderate UPNC according to the population density classification used in this study. The population density in the studied area (the eastern part of AZB) is low to very low and moderate to high in the excluded part of AZB.

3. The Peri-urban Potential Nitrate Contamination (PuPNC): Linked to the percentages of the sewer system coverage (SSC), where the areas with low SSC were assigned a high PuPNC class considering the existing of the illegal sewage connections coexist with on-site sewage disposal like septic tanks, while the areas with high SSC were assigned a low PuPNC class. This layer was prepared by combining the administrative divisions' maps recovered from the RJGC (2020) and the SSC percentage for each administration unit retrieved from the WIS (2020).

The index overlay combination, considering all the above three classified land use maps of equal weight the resulting values are the arithmetic average of the input values, starting from 1 (very low) to 5 (very high) PNC classes. The final step to create the NCR map was by overlapping the PNC map and the modified DVIM map according to the equation:

$$NCR = \frac{PNC + DVIM}{2} \ldots (7)$$

The NCR map was matched with the nitrate SCD map to evaluate the above adopted methodology.

4. RESULTS AND DISCUSSION

In this chapter are given, the results of:

1. Investigation of the groundwater contamination load.
2. Investigation of the natural protectiveness potential of groundwater.
3. The overlaying modelling techniques:
   A. Vulnerability model to investigate the second component of the GRA.
   B. Groundwater nitrate contamination risk (NCR) map.

The results show the consistency and reliability of the procedural approaches developed and adopted in this study and verify the possibilities for implementing such approaches worldwide in arid areas to study groundwater contamination risk and to use clear visualization approaches to present the situation of groundwater vulnerability to land use decision-making.

4.2 Investigations of the first component of GRA (the contamination load) results

In the selected study area through the field visits, the hazard files, water quality analyses, classification of the production wells into purposes of uses (Figure 4-1) shows the highest portion of contamination is related to the agricultural uses so it turns out that the most important potential source of pollution drives from agricultural activities, which depend on the groundwater extracted from the renewable aquifer.

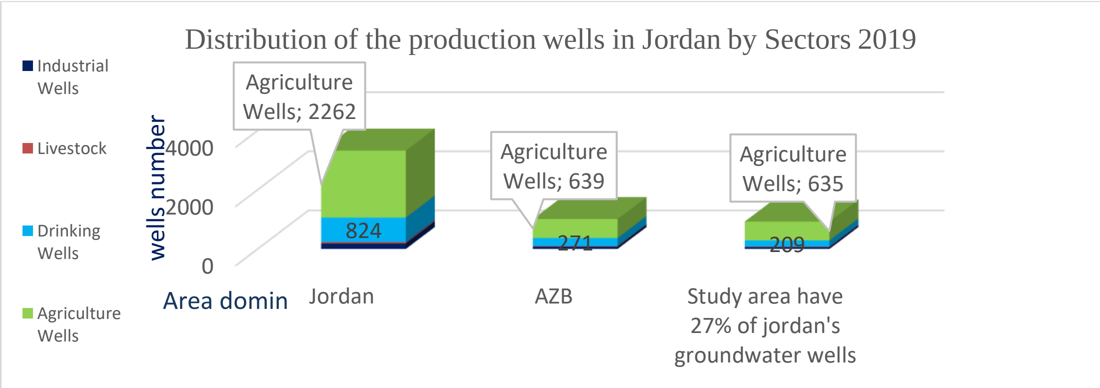


Figure 4-1 Distribution of the production wells in Jordan by Sectors 2019, (Own processing).

The agricultural activity intensity map (Figure 4-2) was prepared depending on the agricultural intensity maps collected from the MOA (2020) which provide agricultural intensity and classification in each administration from which the map of agricultural intensity of the study area was prepared after digitized and compiled the hard copy maps of agricultural intensity of the different administrations of the study area, the map shows several spatial agricultural intensity zones, about 8.4 % of the study area has a high level of intensive agricultural activity with 75 % of the area equipped by intensive farming, 5.92 % has intensive agricultural activity with 50-75 % of the area equipped by intensive farming, 27.84 % has a moderate agricultural activity with 25-50 % of its area equipped by intensive farming, and 3.87 % has a low level of activity with 10-25 % of its area equipped by intensive farming, and 23.63 % has a very low agricultural activating with less than 10% of its area equipped by intensive agriculture.

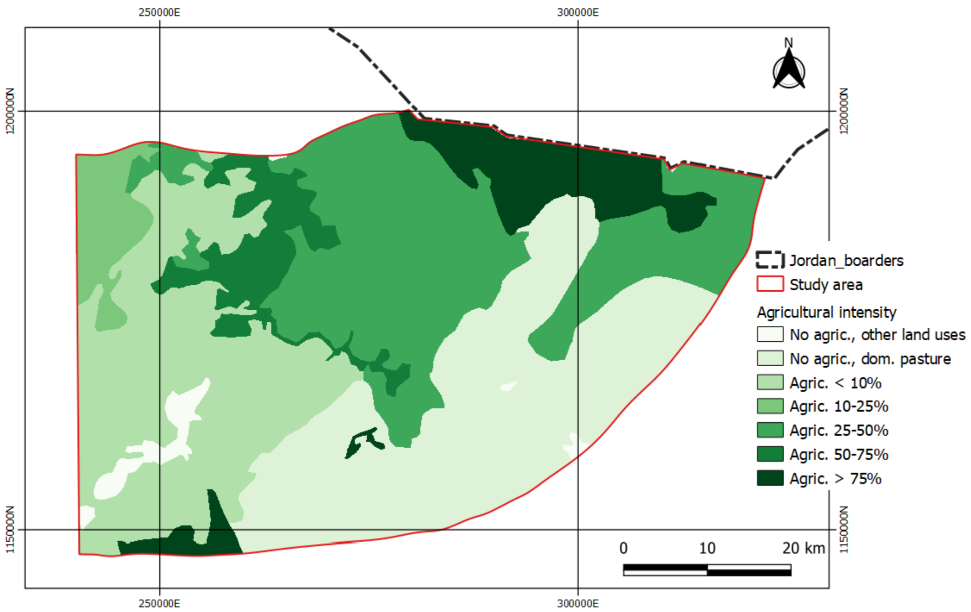


Figure 4-2 Study area agricultural intensity map modified after MOA (2020)

Finally, 30 % of the study area does not have any agricultural activity. Nearly more than 50 % of the farms in the study area are characterized by the presence of fertilizers mixing bonds (FMB) which was discussed by (Gazal 2020; Gazal 2015) as point sources of nitrate and sulfate contamination. The urban expansion in Jordan municipalities is damaging agricultural lands and risks the countries' food security. Only for the period of 12 years (2003–2015), 50 % of the agricultural lands of Amman (in the western part of AZB) were converted into urban lands. Similarly, 20 % of Irbid agricultural lands that existed in 2003 were contaminated (Al-Kofahi et al. 2018). The western part of AZB is more populated and the irrigated agricultural activities concentrate on the eastern part of the basin (DOS & MOA 2018; Gazal 2015) while in the western part the rain-fed agricultural is more dominant (DOS & MOA 2018).

4.2.3 Major surface contamination load in the study area:

According to the field works and (author personal communications) and previous studies of areas located in the study area of this research the common chemical fertilizers used by farmers in the study area are the ammonium sulfate fertilizers from numerous brands and sources (Gazal 2020; Gazal 2015; Meerbach 2004). Nitrogen and other elements are added as fertilizers to enhance the productivity of the soil which is characterized in the study area by poor productivity soil cover according to the soil profiles descriptions and soil samples analyses retrieved from MOA (1994). The average rate of organic matter (OM) in this soil cover is low (0.7 %) and it is concentrated in the upper layer. Al-Qinna et al. (2008) found out that (AZB) soil fertility and thickness are very poor, and the texture does not have a strong water holding capacity. Gazal (2020) studied the historical nitrate concentration analyses in areas locates in the study area of this research and found an increasing trend of theses concentration in the majority of the studied production wells and suggested, without adopting plant fertilizer requirements calculations and environmental awareness programs, farmers are expected to use fertilizers according to their own experience, while the excess amount can be reached in groundwater. In the study area of this research some irrigation wells were found to have a very high nitrate concentration, as they are located near to a high irrigated area, and close to big fertilizers mixing bonds (FMB). Gazal (2015) studied the groundwater contamination in (sub-district of Dhuleil and sub-district of Khalidiyyeh) which is located within the study area of this research (Figure 3-4). The analyses of groundwater samples collected in 2015 showed a parallel relation of the sulfate and nitrate concentrations, as an indicator of the source of the contamination it’s the Ammonium sulfate fertilizers (Figure 4-3).

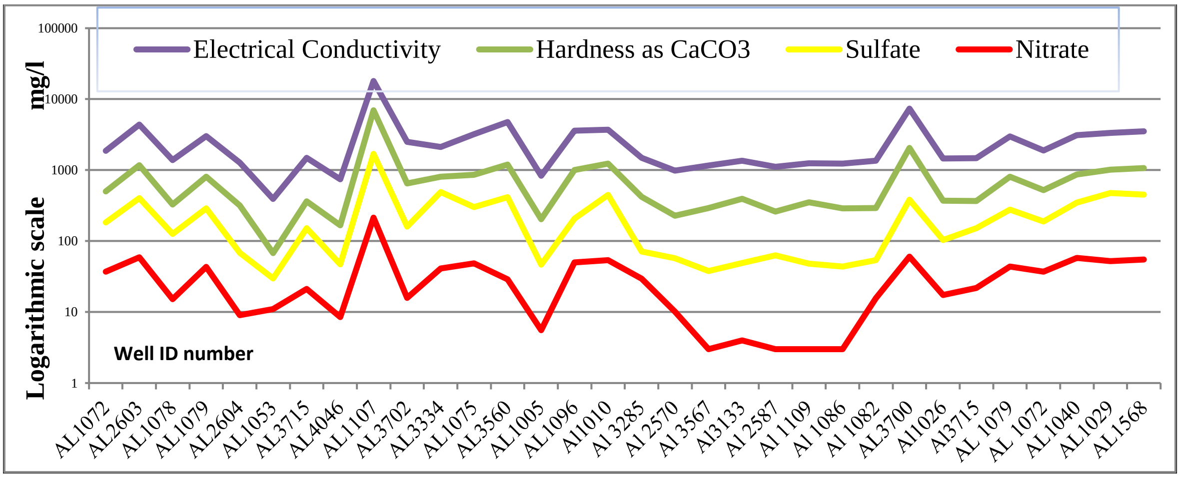


Figure 4-3 Trends of Nitrate, Hardness, Sulfate, and EC, concentrations from the chemical analyses by Gazal (2015) of groundwater samples collected of 32 wells from sub-district of Dhuleil and sub-district of Khalidiyyeh within the study area for this research.

According to Gazal (2015) when nitrite concentration in the sample is less than 20 mg/l the average of sulfate concentrations among the detected samples is around 50 mg/l only in some cases the sulfate can be high even with low nitrate concentration due to geological reasons, otherwise the sulfate concentration is high whenever the nitrate concentration is high. Furthermore, in the same study, the sampling and the analysis procedure were repeated several times, but the values were very high with an average nitrate concentration above 214 mg/l in one of the 32 studied wells which are close to the intensive agricultural area and FMB. In general the trend of the nitrate show increase in the AZB (Daniel et al. 2013), even at the end of the 90s of the last century. Dr. Armin found a high concentration of nitrate in many irrigated areas in Jordan, like Dhuleil, and the area east of Mafraq (Margane et al. 1997; Margane et al. 1999).

4.2.4 Farming activities in the study area:

The expansion of intensive agricultural activities supported by the low-priced workers and the stability of the country which attract the investments. Loads of factors leading the farmers to use a vast quantity of fertilizers, (Zhou et al. 2010) is influencing the farmers' decisions on fertilizer use and the implications for water quality. The irrigated agricultural activities concentrate in the eastern part of the AZB, (Al-Kofahi et al. 2018; Gazal 2015) while the western part which is excluded from this study, is characterized by the dominant rain-fed agricultural as it receives more precipitation rate than the eastern part due to orographic effects, besides the agricultural holdings in the western area are smaller and are not ideal for large-scale agricultural activities (DOS & MOA 2018).

Figure 4-4 Fertilizer mixing ponds and dry farm. Photos by Gazal (2015).

The agricultural activity intensity map which was prepared depending on the agricultural intensity data retrieved from the MOA (2020), indicated that there is an intensive irrigated agricultural activity in the northeastern part of the study area (Table 4-1). While the study area original natural vegetation is scattered with short plants and it is within the range proposed for rain-fed cereals crops, not intensive crops according to land suitability maps prepared by MOE & UNDP (2015). However, this approach to rain-fed crops is possible near the mountain range, but further to the east, as precipitation becomes scarcer, a few localized plots of GW-based irrigated agriculture can be found.

Table 4-1 The agriculture intensity in the study area, the original map source from MOA (2020).

Agricultural activities	% of the study area
Agric. > 75 %*	8.354084
Agric. 50-75 %	5.923244
Agric. 25-50 %	27.84274
Agric. 10-25 %	3.878595
Agric. < 10 %	23.63339
No agric., dom. pasture	28.59867
No agric., other land uses	1.769272

*The intensive agricultural activities cover 75 % of the agricultural areas in these areas.

History of irrigated activities in the study area back to the last century, during the 1960s and 1970s, some government projects aimed at the settlement of the Bedouin population was initiated in the study area and later gave way to modern market-oriented agriculture set up by small-to-medium-sized entrepreneurial farmers supplying the growing cities and exporting their surplus (Elmusa 1994; Venot & Molle 2008). But these activities accelerated the depletion of the GW table, which occurred parallel to a drop in water quality due to a rise in salinity and over-use of fertilizers to increase soil productivity, which is naturally characterized by low fertility. In addition to these salinity issues, aquifer overdraft incurs rising pumping costs for all users and, in some cases, leads to the abandonment of farms due to increasing soil salinity. Several farms in the study area were abandoned due to the salinity problems (Figure 4-4). However, agricultural revenues increased tenfold for vegetables and more than doubled for fruit trees during the Super Green Revolution of the 1990s (Courcier et al. 2005), which was the key factor in increasing irrigated agriculture in this area despite the high cost of GW abstraction and low soil fertility.

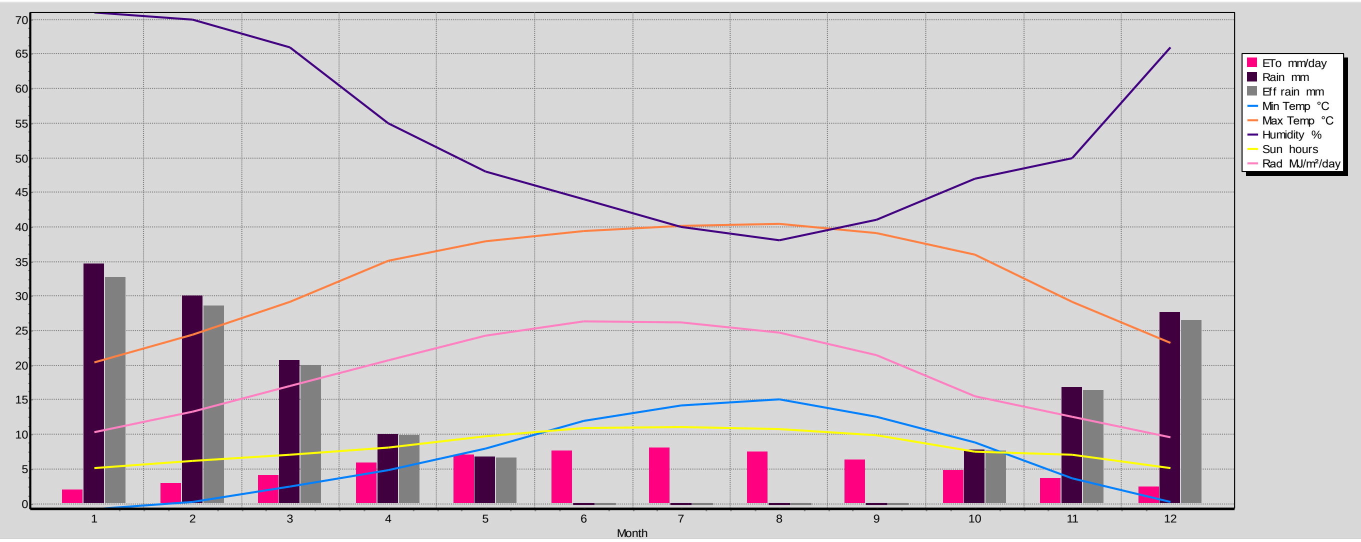


Figure 4-5 Modified Thermo-pluviometric Bagnauls-Gaussen diagram, own processing utilizing the study area representative metrological stations climatic parameters daily data and sketched using the FAO CROPWAT software.

Nevertheless, the CROPWAT software was used to estimate the reference evapotranspiration (ET_0) according to the FAO Penman-Monteith equation (Table 4-2), and the same software was used to create the Thermo-pluviometric Bagnauls-Gaussen diagram (Figure 4-5) which is an indicator of the dry period corresponding to the irrigation season, the ET_0 and the diagram input data was based on the average long-term historical data from the representative climatic stations. The diagram shows that the dry period is from May to September, which may correspond to the period of the year in which irrigation is required to sustain agricultural production or in which the farmer may start sowing and in which rain-fed farming is possible or not. However, referring to this diagram, the amount of precipitation during the rainy season cannot provide enough water to support good crop production.

Table 4-2 Calculation of the study area average ET0, own processing using the FAO CROPWAT software.

Month	Min Temp °C	Max Temp °C	Humidity %	Wind km/day	Sun Hours/day	Rad MJ/m²/day	ETo mm/day	days/ month	ETo mm/month
January	-0.8	20.4	71	168	5.2	10.3	2.05	31	63.55
February	0.2	24.4	70	188	6.2	13.3	2.85	28	79.8
March	2.4	29.1	66	197	7	16.9	4.04	30	121.2
April	4.9	35.1	55	208	8.1	20.7	5.85	30	175.5
May	7.9	37.9	48	212	9.7	24.3	7.07	31	219.17
June	11.9	39.4	44	201	10.9	26.3	7.61	30	228.3
July	14.2	40.1	40	229	11	26.2	8.16	31	252.96
August	15	40.4	38	196	10.7	24.8	7.53	30	225.9
September	12.6	39.1	41	176	9.9	21.5	6.38	31	197.78
October	8.9	36	47	163	7.5	15.6	4.8	30	144
November	3.7	29.2	50	176	7.1	12.6	3.64	31	112.84
December	0.2	23.2	66	175	5.1	9.6	2.4	31	74.4
Average	6.8	32.9	53	191	8.2	18.5	5.2		157.95

4.2.5 Number of functioning production wells in the study area:

In Jordan, the shallow renewable aquifer was first developed by farmers using hand-dug wells (Gazal 2019), and the first governmental wells were dug during the 1930s in the Azraq oasis to meet local agricultural demand and water needs in Amman. Then groundwater exploration started progressively since the 1960s to provide freshwater resources for the municipal and irrigation water supply since then, total groundwater abstraction has increased to meet the growing needs of agriculture, industries and cities (Venot & Molle 2008). Irrigated agriculture in Jordan enjoyed a boom in production and economic profitability during the 80s and early 90s of the past century that was also described by Elmusa (1994) as the “Super Green Revolution”. According to a comprehensive evaluation of the groundwater resources of the Hashemite Kingdom of Jordan by the GTZ & NRA (1977), there were only 400 wells and few deep oil exploration wells had been drilled until the 1970s, the number of production wells increased after that as it reaches 2779, 2839,2917,3021, 3030, 3098, 3121, 3043, 3034, 3031, 3138, 3146 wells for the years 2005, up to 2016 respectively, and it reaches 2322 wells in 2019 according to the Ministry of water and irrigation water budgets from 2005-2019 (MWI 2020). The high portion of the groundwater wells existing in the study area reflect the significance of studying this area, while according to the own processing of the hydrological and meteorological information systems data using the Qgis analysis functions, there are 271 observation wells located in Jordan, 92 of these observation wells within the AZB, 91 of which located in the eastern part of the AZB that have been selected to be the study area of this research, all for the measuring the static water level of the shallow renewable aquifer and in this study, the measurements of static water level of the phreatic aquifer from 87 representative observation wells were studied (Figure 3-3).

The total number of productive groundwater wells in Jordan in 2019 reached 3321 wells, 1009 of which are in the AZB and 900 of these wells in the study area, and thus more than 28 % of Jordan's wells are in the study area. Most of these wells for agricultural purposes with a percentage reach 69 % of the total number of the production wells in the study area and 23 % for drinking water purposes It demonstrates the agricultural nature of human activities in the study area rather than industrial activities (Figure 4-1). To conclude in the study area, agricultural activities are the key sources of contamination by both non-point sources or by point sources such as FMB and other sources of contamination as hazard locations exist in the study area, for example, fertilizer factories and poultry farms.

4.2.6 Analyses of groundwater quality data

By analyses the two water quality files it was found that in the first file for the period from 1970 to 2005 there were about 6459 nitrate measurements and about 2607 of which were above 50 mg/l, and about 7427 TDS measurements 1901 of which were above 1000 mg/l (1850 μS/cm), and 6364 sulfate measurements, 213 of which were above 500 mg/l. While the second data file from 2006-2018 there were 976 nitrate measurement 268 of which were above 50 mg/l, and about 35 TDS measurements 6 of which were above 1000 mg/l, and there were 873 sulfate measurements 76 of which were above 500 mg/l. A descriptive statistic for the main chemical compositions for all the wells long-term measurements summarized in the Table 4-3. In the studied wells the long-term Sulfate concentration less than 500 mg/l is possibly derived naturally from gypsum dissolution while the high concentration may be derived from the use of the fertilizer. Potassium ions may have come from irrigation return flow (IRF) as the concentration varied from 0.1 to 257 mg/l with an average concentration equal 8.5 while the commercial chemical fertilizers used in AZB have a high concentration of potassium. The nitrate concentration varied from 0.2 to 376 mg/l with an average of 46 mg/l and the phosphate ranges from 0.01 to 0.27 mg/l, the high nitrate and phosphate concentration in the groundwater of the study area is mainly related to the use of fertilizers in agricultural areas.

Table 4-3 Statistical summary of the water quality parameters long-term data measurements, own processing data source WIS (2020).

Statistical summary of the wells long-term measurements (selected parameters)													
	Bicarbonate	**Calcium**	**Carbonate**	**Chloride**	**EC**	**Phosphate**	**Hardness**	**Magnesium**	**Nitrate**	**pH**	**Potassium**	**Sodium**	**Sulfate**
No. of measurements	**7507**	**7519**	**7645**	**7586**	**8952**	**751**	**7489**	**7485**	**7989**	**6809**	**7449**	**7537**	**7597**
average	**210.6**	**89.7**	**0.502**	**284.93**	**1461.**	**0.032**	**531.75**	**49.041**	**45.2**	**7.69**	**8.520**	**132.80**	**116.8**
max	**601**	**921**	**22.95**	**2112.25**	**7840**	**0.27**	**1823**	**408.88**	**378**	**8.9**	**257.67**	**824.033**	**1535.52**
min	**1.65**	**0.59**	**0.9**	**0.69**	**290**	**0.1**	**54**	**0.8**	**0.2**	**6.28**	**0.1**	**1.560**	**0.37**
SD*	**90.78**	**69.21**	**1.580**	**297.46**	**1116**	**0.05**	**372.73**	**47.311**	**32.02**	**0.31**	**12.713**	**113.82**	**155.46**
skewness	**0.0124**	**2.8894**	**8.1423**	**2.3806**	**2.368**	**1.568**	**1.5844**	**3.3277**	**2.295**	**0.05**	**16.2096**	**2.2916**	**4.0042**
Kurtosis	**-1.198**	**15.007**	**95.84**	**7.38**	**7.23**	**10.3**	**2.335**	**15.930**	**9.468**	**0.56**	**313.534**	**7.573**	**23.843**
CV*	**0.431**	**0.772**	**3.147**	**1.044**	**0.764**	**1.563**	**0.701**	**0.965**	**0.708**	**0.04**	**1.492**	**0.857**	**1.331**

4.2.6.1 Temporal changes in water quality:

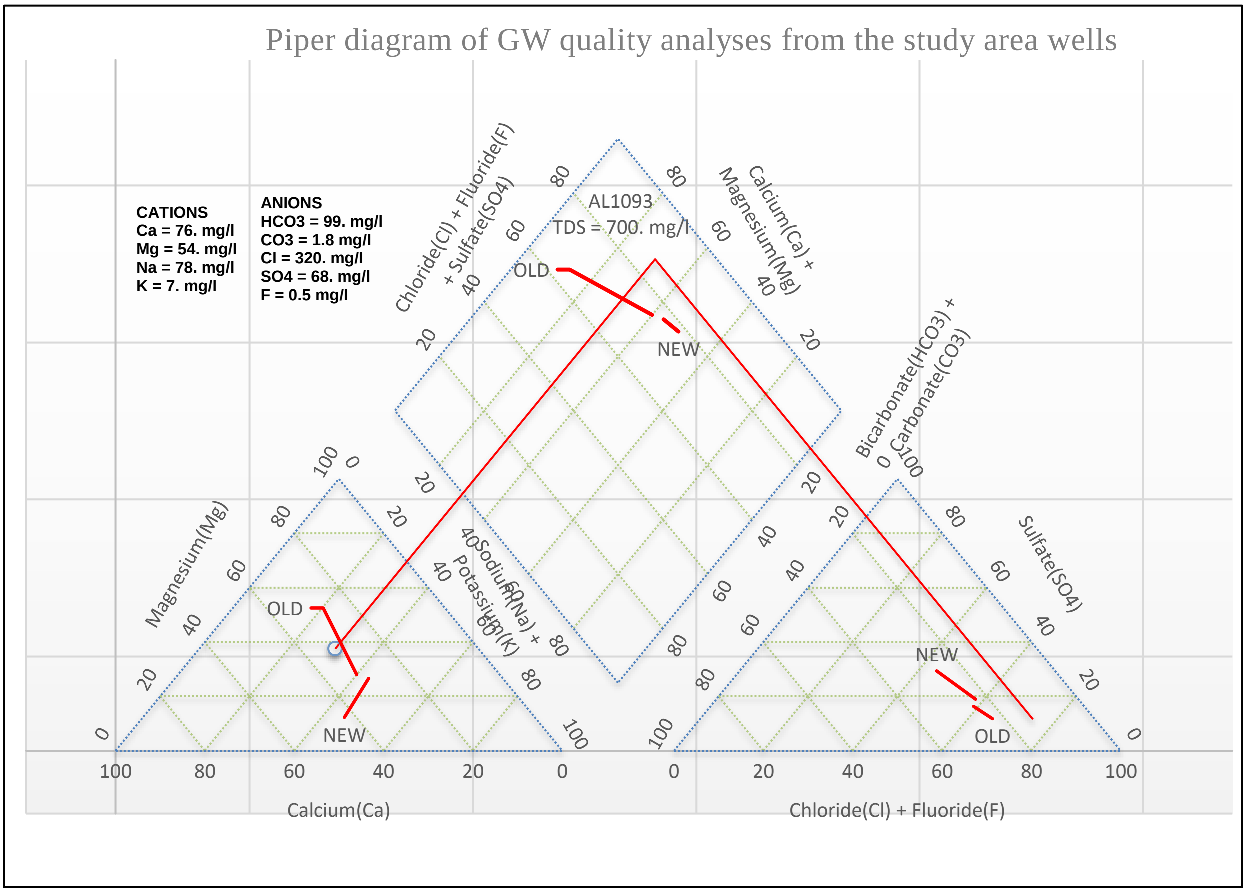
Several groundwater quality temporal analyses and studies showed an increasing pattern of the concentration of nitrate and salinity (Daniel et al 2013; Gazal 2015; Gazal 2020) many of these studies showed an increasing trend of the concentrations especially nitrate and salinity in many studied wells in AZB. Kuisi et al. (2009) investigated all the measurements from 1970 to 2005 for each well in AZB to detect the accumulation of salt and nitrate over time, and to define if well water quality is deteriorating or enhancing the study concluded that AZB suffers from the serious accumulation of salt and nitrate loads. The rate of nitrate accumulation is 21.96 mg/l/year and for TDS is 29.28 µS/cm/year. Gazal (2020) investigated all the nitrate concentration measurements from 1970 to 2010 in several wells represents nitrate concentration zones which all showed an increasing trend in nitrate. The increasing trend was discussed by Gazal (2015) by studying the TDS and nitrate and sulfate concentrations trends in selected wells represent concentration zones in the middle of AZB. But according to the last groundwater quality study by the MWI with cooperation with the BGR for the periods 2002-2017 (MWI & BGR 2018) a positive trend for TDS in all aquifer was observed. But the study showed, unlike all previous studies, that there is a very small negative trend in nitrate levels for all basins and the nitrate median levels for all aquifers have a slight decrease.

4.2.6.2 Piper diagram:

The Piper-trilinear model was used for the first time in water quality scientific studies (Piper 1944; Piper 1953) to define the hydro-chemical facies of groundwater (Langguth & Voigt 2004; Sarikhani et al. 2014). In this study, the results of the chemical analyses of about 498 wells were plotted in a piper diagram (Figure 4-6) to classify the water. Each well appears as a point in this diagram, where the points are grouped closely together showing quite constant water quality in the studied wells. To check the old and new quality files retrieved from the WIS (2020) also the average of all the concentration measurements of the cation and anion also were plotted and they appear in the Figure 4-6 as tow circles and labelled as old and new. Generally, according to the Piper-trilinear model, the dominant hydro-chemical facies in the studied wells are the Ca–Mg–Cl and Na–Cl, according to the order of their dominance, with an average sodium/potassium around 40 %, 35 % carbonate, 70 % chloride, 40 % sulfate, 60 % calcium/magnesium, while calcium reach more than 80% but the wells plotted ranges from less than 20% up to more than 80% because part of the wells pumping from the basalt aquifer and some wells from the highly karstic A7/B2 aquifer and some wells from both aquifers as both aquifers hydrogeological connected in the eastern part of the study area see the cross-section (Figure 3-5). The range of carbonate concentration among the wells is high again due to the different types of aquifers, the basaltic wells show very low concentration, but the karstic A7B2 wells show higher concentration. The low solubility of minerals through the limestone in the A7/B2 aquifer indicates the major ions (+/-) concentration have to be with a natural origin. However, it was observed from the plots that calcium does not exceed sodium and potassium, and that chloride-sulfate exceeds other ions, suggesting an anthropogenic source (Sarikhani et al. 2014) which is mainly in this study area due to the agricultural activities. Moreover, as the plot shows, the high sulfate concentration indicates an anthropogenic source for the wells classified in the piper diagram above the average sulfated plotted line of the study area wells 40 % (more than 65 % of the wells plotted above the 40 % sulfate average concentration line). The combination of Na–HCO3 and Ca–Mg–HCO3 is mainly the result of precipitation water infiltration, IRF, and anthropogenic activity.

4.2.6.3 Correlation coefficient matrix of major water parameters

The matrix for the correlation coefficient at a 95 % significant level for 498 wells is shown in the Table 4-4. The correlation between the water parameters measured, such as nitrate and TDS and sulfate, indicates a strong correlation which can be due to the use of commercial chemical fertilizers used in AZB, which consist mainly of ammonium sulfate compositions. TDS was found to correlate strongly with major cations, magnesium, calcium, sodium (r=0.895, r=0.86, r=0.896, respectively) and moderately acceptable correlation with potassium (r=0.4). TDS correlate strongly with the anions, chloride, sulfate, nitrate, and phosphate (r=0.9496, r=0.863 r=0.6, r=0.6 respectively). Sodium concentrations showed a very good correlation with chloride (r=0.89679) indicating that these ions have been derived from the same sources. calcium and magnesium concentrations showed a very good correlation (r=0.85) indicating the presence of the same source of Ca and Mg, from the dissolution of calcite and dolomite the main minerals in the karstic aquifer's geological formations A7/B2.



	CATIONS (mg/l)				ANIONS (mg/l)				
	Bottom	Left	DIAMOND	DIAMOND	DIAMOND	DIAMOND	Bottom	Right	Bottom
Group	**Ca**	**Mg**	**Na**	**K**	**HCO3**	**CO3**	**Cl**	**SO4**	**F**
OLD	99.32796	52.69844	137.2468	8.521363	222.5656	0.396061	308.0237	115.884	0.51
NEW	99.2321	53.31584	160.0075	7.34302	218.0385	1.795752	323.8889	143.9064	0.544821

Figure 4-6 Piper diagram of long-term water quality data for all wells studied in the study area, and the average of all measurements of the old water quality data file 1970-2005 and the new water quality data for 2006-2018 represented in the diagram by two different circle colors, (Author own processing).

Table 4-4 The correlation coefficient matrix of the long-term parameter measurements of study area wells (n=489), own processing data source WIS (2020).

	Bicarbonate	Calcium	Carbonate	Chloride	EC	Phosphate	Magnesium	Nitrate	pH	Potassium	Sodium	Sulfate
Bicarbonate	**1**											
Calcium	**0.2133**	**1**										
Carbonate	**-0.21149**	**-0.11948**	**1**									
Chloride	**-0.20492**	**0.850725**	**0.02842**	**1**								
EC	**-0.08627**	**0.861579**	**-0.018**	**0.95**	**1**							
phosphate	**-0.261**	**0.421**	**-0.09**	**0.351**	**0.564**	**1**						
Magnesium	**-0.18281**	**0.855543**	**-0.05541**	**0.95**	**0.895825**	**0.562**	**1**					
Nitrate	**0.063285**	**0.714841**	**-0.1246**	**0.622**	**0.606527**	**0.291**	**0.649288**	**1**				
pH	**-0.67965**	**-0.44602**	**0.408714**	**-0.097**	**-0.25899**	**-0.571**	**-0.11907**	**-0.33533**	**1**			
Potassium	**-0.1114**	**0.392032**	**0.013521**	**0.4523**	**0.41348**	**0.151**	**0.470065**	**0.269718**	**-0.0181**	**1**		
Sodium	**-0.07701**	**0.736467**	**0.08752**	**0.898**	**0.896798**	**0.112**	**0.769556**	**0.480924**	**-0.0961**	**0.317555**	**1**	
Sulfate	**-0.07272**	**0.806927**	**-0.04174**	**0.851**	**0.863351**	**0.532**	**0.840274**	**0.520982**	**-0.1429**	**0.316309**	**0.8795**	**1**

4.2.6.4 Spatial continuous data (SCD) of groundwater parameters

The development of water parameters spatial distribution maps by the available interpolation methods using the GIS to figure up the contamination sources has a valuable role principle in arid and semiarid regions (Kazemi et al. 2017). In this study as conferred in the methodology chapter three parameters were selected nitrate, sulfate, and TDS. The statistical summary of the resulted maps created by OK interpolation techniques is listed in Table 4-5.

Table 4-5 Raster's Statistical summary of the No_3^{-1}, SO_4^{-2}, and EC concentration maps. And the study area Recharge and SWL maps

Map parameters		Mean	Minimum	Maximum	S.D*	CV%*
Average	NO_3^{-1} in mg/l	31.145	9.171	100.24	17.9	57.44
	SO_4^{-2} in mg/l	101.27	17.8144	422.94	62.42	61.64
	EC in µS/cm	1376.8	333.221	4227.8	820.5	59.6
Maximum	NO_3^{-1} in mg/l	45.05	11.7625	155.97	26.6	59.1
	SO_4^{-2} in mg/l	158.344	30.8223	675.5	103.7	65.5
	EC in µS/cm	1771.4	342.73	5742.64	1053.9	59.5

CV*: Coefficient of variation. S.D*: Stands for standard deviation.

The maps (Figure 4-7) show a very strong correlation of the concentration zones of the three studied parameters maps, and a relatively very close probability of distribution which calculated by the coefficient of variation (relative standard deviation) for each parameter long average concentration spatial distribution map 57 %, 61 %, and 59 % for the nitrate, sulfate and EC respectively. And 59.1 %,65.5 %, and 59.5 % for the nitrate, sulfate, and EC respectively, by interpolating the maximum concentration records (Table 4-5).

The raster's correlation test of the three examined parameter maps, showed strong spatial relative dependents following a related parallel anisotropic distribution pattern with a same positive good correlation between these parameters approved in the correlation matrix table which implemented directly by the measured concentrations values not the interpolated continues data by OK interpolations. Table 4-4 using the data analyses function in the online version of Microsoft-Excel-365, shows a strong positive correlation, between sulfate and nitrate (r=52 %), sulfate and EC (r=86 %), and between and nitrate (r=EC 60 %), while by the raster's correlations the values were even higher, between nitrate and sulfate (r=78 %) , nitrate and EC (r=85 %) between sulfate and EC (r=91 %). This strong correlation indicated a possibility of the same resources causing the increase of these parameters' concentrations in the study area.

The suggested common source of the nitrate and sulfate can be related to the type of the fertilizers used in AZB, while the EC is also related to agricultural activities by the effect of the irrigation return flow (IRF) and by the SCD maps of the three selected parameters, the correlation becomes more obvious and concluded the high spatial correlation for nitrate, sulfate, and TDS may involve the effects of the large-scale source (non-point pollution sources) such as agricultural activities (Figure 4-2) or may contribute to large-scale pollution controlling factors such the weak groundwater natural protective potential in the study area which reflected mainly by the characteristics of the geological formations, groundwater recharge rates, soil cover, and topography, which is investigated in the second components of GRA of this study and by utilizing groundwater overly modelling techniques in the next sections.

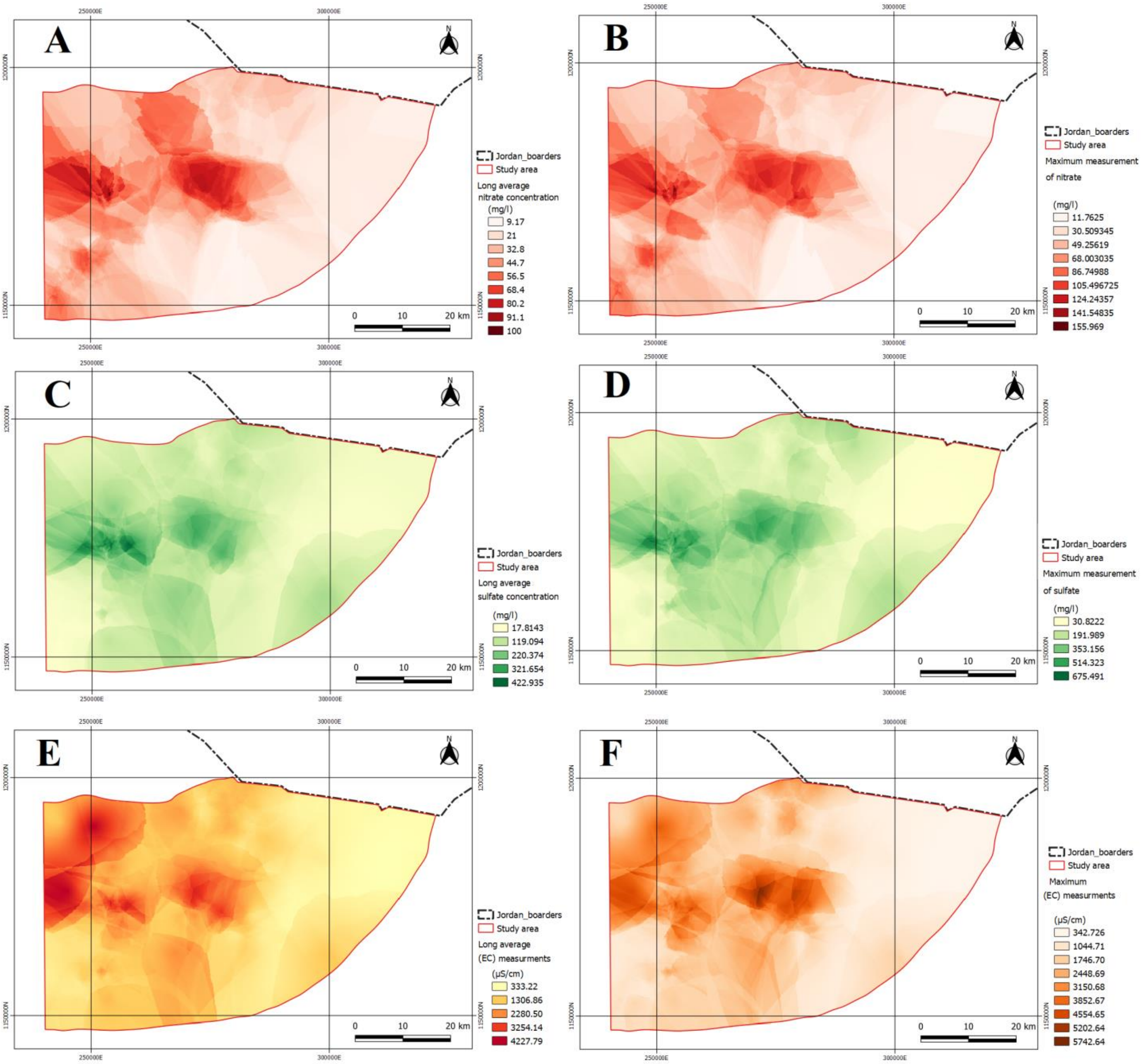


Figure 4-7A: Average Nitrate SCD. B: Maximum Nitrate SCD. C: Average Sulfate SCD D: Maximum Sulfate SCD E: Average EC SCD. F: Maximum EC SCD.

4.3 Investigation the second component of GRA (natural potential protectiveness of the groundwater aquifer in the study area) results:

4.3.1 The study area hydrogeological units' investigations results

Based on the hydrogeology, geological studies, fault density, thickness, and texture of the soil layer, the area is considered almost naturally unprotected from the intensive agricultural activity on the surface. The main outcroppings geological formations characterized by high permeability as they are even the karstic A7/B2 formation or the fractured basaltic formations which cover 43 % and 41 % of the study area respectively. While the most southern part in the study area the outcropping formation there is aquitard (B3 formation) but its percentage to the study area not high its about 7.9 % of the study area. The soil cover thickness and texture were computed and listed in Figure 4-8 and Table 4-6, which illustrate the thickness of the soil cover and texture calculated by returning to all the soil profiles within the study area. Besides of studying the geological formations and the soil properties, the climatic data were analyzed to show the fragility of this area in the view of low precipitation, which conclude the natural replenishment of the deterioration groundwater aquifer can be very difficult as according to numerous researches indicated the groundwater deteriorations in quality and quantity in arid areas more severe and difficult to solve than wet areas.

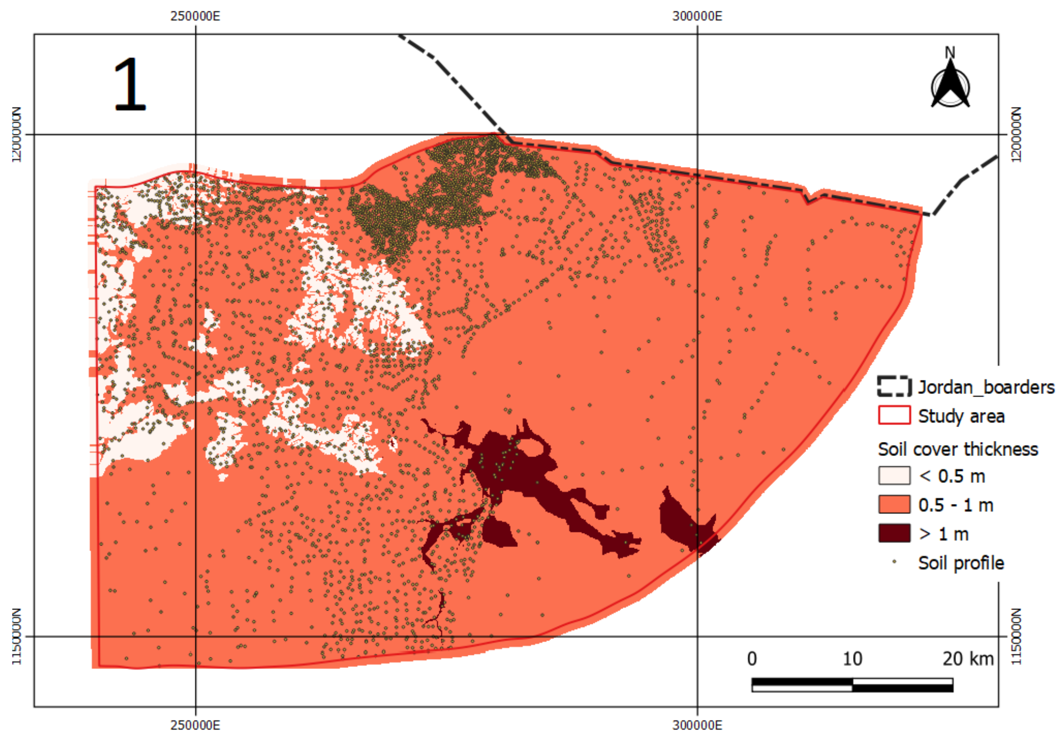


Figure 4-8 The study area soil cover thickness by OK interpolation of the soil profiles thickness.

Moreover, in this part also the geological and drainage lineament density were studied and the GWR was calculated which indicated a good rate of precipitation is percolating through the vadose zone (infiltrating) to reach the groundwater but the amount very low as the precipitation rate is low in the study area. In addition the investigations of the hydraulic conductivity (HC) values of the studied area hydrogeological formations show a high HC of the these formations, where the values of the HC estimated according to HC estimations tables of Freeze & Cherry (1979) which adopted by Aller et al. (1987) to be used in preparation of the hydraulic conductivity thematic parameter of the DRASTIC model.

Table 4-6 Physical properties of all the soil units found in the study area the raw data (the soil maps and the soil profiles description) retrieved from MOA (1994) and by own processing by the GIS this table was created with precise numbers to well understanding the soil characteristic of the study area

Representative profile	capability	Soil unit*	According to USDA (2014) soil taxonomic								the total area of each unit in the study area Km2	Area (%) to the study area	the total area of each unit in Jordan Km2	(%) coverage of each unit to the total area of Jordan
			Clay (%)	Silt (%)	Sand (%)	Rock outcrop (%)	Texture	MOISTURE	Soil Temperature Regime	Soil association				
PG007**	Good	1- (Abyad) ABY 11	31	60	7.2	15	silty clay loam	Xeric/Aridic	Thermic	(70 %) Xerochreptic Camborthid and Calciorthid, (5 %) Calcixerollic Xerochre	1.59	0.0478	795.07	0.891
PM079	low	2- (Abu alih) ALI 8	42.4	43.8	11.2	15	silty clay	Xeric	Thermic	(25 %) Calcixerollic xerochrept, (15 %) Typic xerochrept	352.54	10.5952	586.11	0.657
PA314	Fair	3- 2- (Ramtha) THA 15	38.21	46.25	15.4	10	silty clay loam	Xeric/Aridic	Thermic	(40 %) Xerochreptic Calciorthid (20 %) Xerochreptic Paleorthid, (10 %) Xerochreptic Camborthid, (10 %) Lithic (Xerochreptic) Camborthid, (5 %) Lithic Xeric Torriorthent, (5 %) Rock	358.96	10.7880	493.18	0.552
PH009	Fair	4- 25- (Huwaynit) WAY 15	37	41.4	21.57	10	clay loam (fine silty)	Xeric/Aridic	Thermic	(30%) Xerochreptic Calciorthid and Lithic (Xerochreptic), (15 %) Xerochreptic Camborthid, (15 %) Xerochreptic Paleorthid, (15 %) Lithic Torriothent and Lithic Xeric Torriothent, (10 %)	641.09	19.2673	673.02	0.754
PA128	Poor	25- (Zumlat) ZUM 15	26.7	50	23.3	15	Silt Loam	Xeric/Aridic	Thermic	(15 %) Xerochreptic Calciorthid (15 %) Lithic Torriorthent and Lithic Xeric Torriorthent (12 %) Xerochreptic Paleorthid and (10 %) Xerochreptic Camborthid, (10 %) Lithic (xerochreptic) Cambor, (15 %) Rock	348.73	10.4806	830.43	0.930
Average			32.3071	48.52752	17.78434	12.2	Silty clay loam			Sum	3327.37	100.00	10348.62	11.59

* Jordan soil cover is classified into 160 soil units, 25 of these units exist in the study area **several profiles in the study area located within AYD soil unit, which cover 795 km^2 of Jordan and includes 226 observation sites, ALI8 soil units includes 212 observation sits (soil profiles), ext. the total of observation sites in Jordan 41578 was used to create the soil map level-1, 10% of which located in the study area. Capability, according to soil profiles descriptions here related to the agricultural productivity properties of the soil. Soil maps of sheets 1, 2, 4, and 5 were used to create this table with soil profiles sheets of each soil unit, (Own processing).

4.3.2 Study area climatic data analyses:

The case study area classified into 4 climatic zones (Figure 4-9) rely on the most popular world climatic classification, this climate classification was first described and invented by Wladimir Köppen and published for the first time in 1900 and updated in its latest version by Rudolf Geiger in 1961 the soft copy map used in this study from the updated world map of Köppen-Geiger climate classification which was based on temperature and precipitation observations for the period 1951-2000 by Kottek et al. (2006).

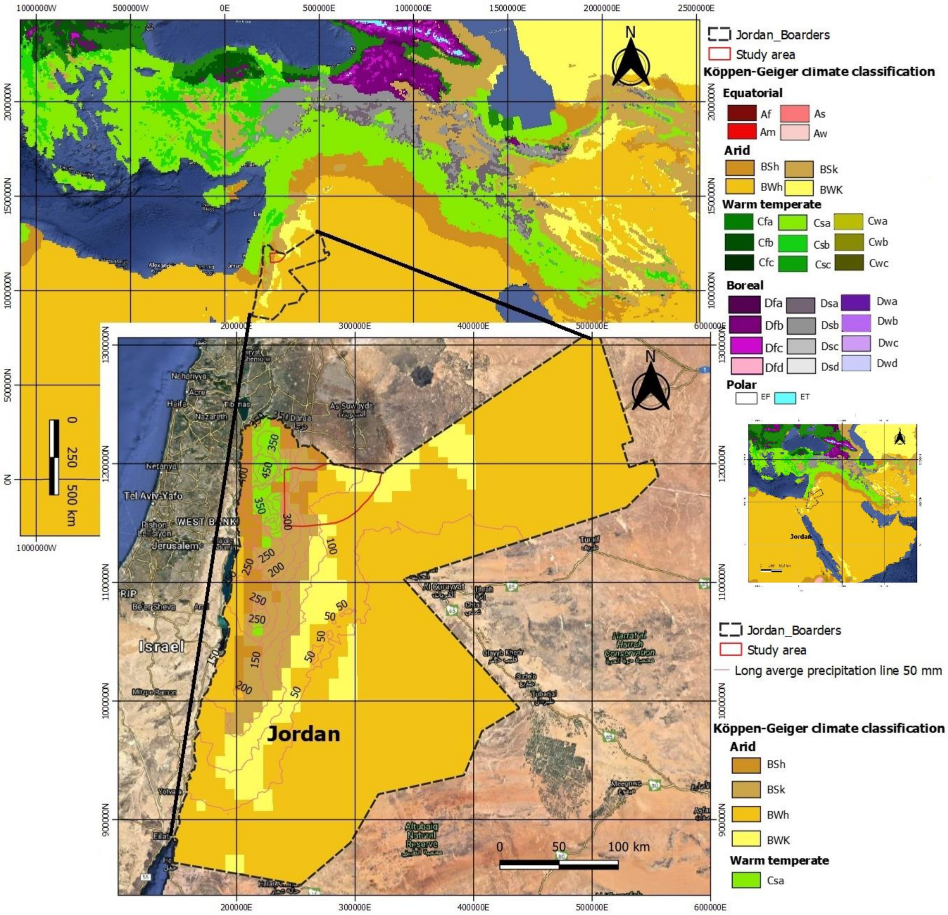


Figure 4-9 The climatic zones in the study area, using the available Köppen-Geiger climate classification map (own processing).

The main climate class in the study area is arid (Table 4-7), as well as the very small area in the western part of the case study area is warm-temperate, which receives more precipitation amount and, according to the Ministry of Water and Irrigation, is semi-humid, so that the western part of AZB was excluded in this case study, which focuses on the arid agricultural area, while the western part of AZB is warm temperate climate according to Köppen-Geiger classification and semi-humid according to MWI (2016); and Gazal (2020). And it belong to the Mountains Heights Plateau with Mediterranean climate class according to recent Ministry of Water and Irrigation classification (MWI & BGR 2018). According to the Updated world map of the Köppen-Geiger climate classification by Kottek et al. (2006) the climate in the working area is warm desert and warm semi-arid climate.

Table 4-7 The percentage of climatic zones in the study area and Jordan, Own processing using the available Köppen-Geiger climate classification map modified after Gazal (2020)

Main climate	studied area					Jordan	
	Precipitation	Temperature	climate class	Area km^2	% Of the study area	Area km^2	% Of the Jordan area
warm temperature	Summer dry	Hot summer	Csa	28.68525	0.75188	2667.728	2.547247329
Arid	Desert	Hot arid	BWh	1587.251	41.60401	77421.5	73.92495207
Arid	Steppe	Hot arid	BSh	497.211	13.03258	4235.856	4.044554003
Arid	Steppe	Cold arid	BSk	812.7488	21.30326	8462.149	8.079978088
Arid	Desert	Cold arid	BWk	889.2428	23.30827	11942.63	11.40326851

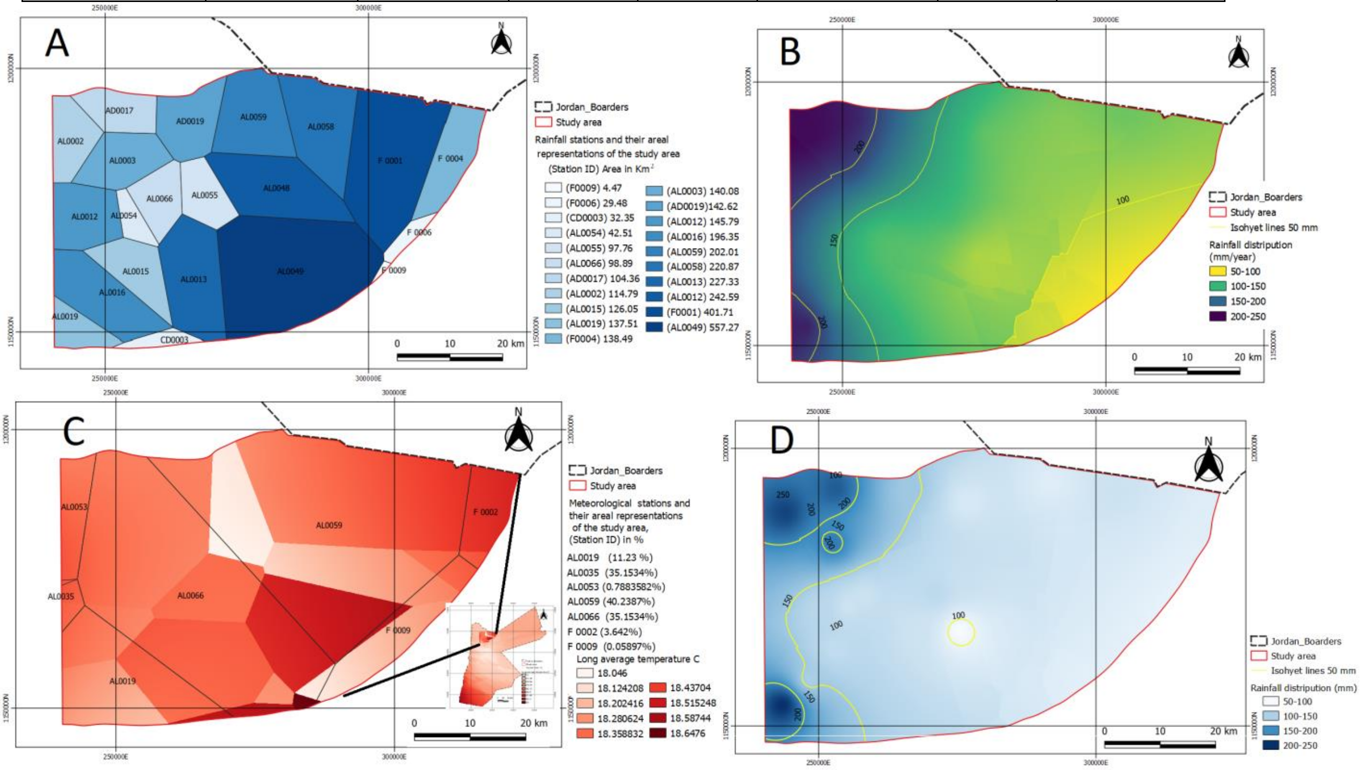


Figure 4-10 A: Rainfall stations and the Theisen polygon of the 21 representative stations, B: Study area average precipitation by OK interpolation C: long average temperature and Theisen polygon of the 7 representative stations, D: Study area average precipitation.

Table 4-8 Statistical summary of the study area precipitation maps (own processing).

Range (mm/y)	Interpolation by IDW		Interpolation by Kriging	
	area in km^2	Area extent (in %)	area in km^2	Area extent (in %)
50-100	14.44641	0.434	406.8972	12.2223
100-150	2597.411	78.0312	2094.616	62.9175
150-200	497.1194	14.9344	563.2083	16.9175
200-250	219.7079	6.6004	264.4263	7.9428

methods	Interpolation (IDW)	Interpolation (kriging)	Weighted average
Dry year (mm/year)	101.3265	100.77038389514	100.8366
Average (mm/year)	135.9029	132.79391219594	135.1409

Statistical summary obtained from study area precipitation thematic map and the precipitation trend map						
Map	Interpolation by	Mean	Min	Max	S. D	CV
Average areal precipitation (mm/year)	OK, technique	132.7939122	82.9471	231.356	35.5651	0.26782
Average areal precipitation (mm/year)	IDW, technique	135.902866	90.7489	248.335	30.4293	0.22391
Areal precipitation trend (mm/year)	OK, technique	-0.509117398	-1.4663	2.64493	0.5673	-1.1142

S.D. stands for standard deviation and CV for the coefficient of variation.

The areal long average annual rainfall in the vicinity of the case study area was calculated by three methods first by the weighted average methods and by interpolation techniques using ordinary kriging (OK) and inverse distance weighting (IWD). The average areal rainfall distribution by the weighted average was determined by Theisen polygon and given an aerial weight to each station, the result was 135.1 mm/year, and 135.9 mm/year by the IDW interpolation of the long average annual rainfall of the 21 stations, while by OK it was 132.79 mm/year (Figure 4-10) and (Table 4-8).

Table 4-9 Summary of study area climatic parameters own processing, from 9 metrological stations for climatic parameters and 21 stations for precipitation.

Monthly average Temperature (C°)														Station weight
Stations ID	Station name	January	February	March	April	May	June	July	August	September	October	November	December	
AL0019	Amman Airport	8.36531165	9.50612392	12.6784846	17.1573599	21.3157233	24.4733273	26.3527138	26.3462654	24.4305699	20.9961337	14.9194877	10.1091422	0.112294970297199
AL0035	K.H. Nursery (Balqa)	8.64895987	9.65214797	12.2220852	16.2351301	20.7694086	23.3406065	25.5157215	25.2013262	23.4706796	20.2765437	14.9137036	10.1967468	0.00788358197792907
AL0066	Khirebit Es Samra	9.06812354	10.259669	13.5072092	18.0887595	21.9876894	25.1057118	26.4170845	27.0685886	25.3504367	21.5302338	15.6987404	10.6616393	0.351534485113784
AL0053	King Talal Dam	12.0917896	13.0686413	16.1390964	20.3327533	25.1940139	27.7749697	29.4928782	29.9962406	28.1173315	24.4352751	18.2112811	13.9883228	0.0305067520545769
AL0059	Um El-Jumal	8.83977312	10.2889522	13.701489	18.1884342	22.3113953	25.102962	26.8400344	27.1384804	26.0054464	21.1174733	15.4608968	10.6559162	0.402387207831557
AL0057	Wadi Es-Sir	6.74604798	6.71828023	13.1201599	15.6094193	20.5850545	25.8267857	24.8473693	25.3306062	23.6449221	21.1958865	15.246236	9.58369565	-
F 0009	Azraq Evap	8.50749774	10.9594675	14.1324698	27.4056324	23.0303742	29.4127434	27.9201472	27.3831709	25.7036122	21.3147333	14.6573727	9.67171171	0.0589733093909403
CD0026	Ez-Zeithna Evap	7.33757962	8.09090909	9.92592593	14.3371429	18.1725067	21.0666667	21.9160714	21.5942029	20.8129252	17.9217877	12.6856369	8.13109756	-
F 0002	H5 Evap	8.28614583	10.3709071	14.3725636	18.6636043	24.816105	27.3356984	29.2593254	28.8198985	26.6450108	21.988809	14.7400848	9.8537561	0.0364196933340145
Study area monthly average Temperature by weighted average		8.92471239	10.3130567	13.6308719	18.648502	22.2951968	25.4363221	26.8589263	27.1725255	25.6482735	21.3868997	15.4896627	10.6073129	Average 18.8676885
the average of the maximum Temperature (C°)		20.4115	24.35476	29.12809	35.09173	37.92821	39.35182	40.10904	40.44951	39.06208	35.97304	29.23118	23.24417	32.86126
the average of the minimum Temperature (C°)		-0.76804	0.153359	2.381693	4.927276	7.936498	11.85084	14.15455	15.03362	12.60293	8.869908	3.675525	0.24115	6.754942
Average wind speed km/hr.		7.007768	7.839132	8.204975	8.663231	8.811264	8.354397	9.534781	8.184368	7.320813	6.772584	7.332585	7.296056	7.943496
Monthly Ev-pan mm/month		81.76704	92.32224	148.6363	215.0759	295.8617	331.1705	350.6606	316.2108	262.8355	204.4754	135.6354	90.80303	210.4545
Daily Ev-pan mm/d		3.411825	4.17081	5.490415	8.116622	10.8642	12.6263	12.69037	12.36384	9.996043	7.449231	5.480394	3.292111	7.996013
Study area monthly average precipitation (mm)		January	February	March	April	May	Study area precipitation analyses from 21 daily-rainfall station data, (by the weighted average method)				October	November	December	
		34.5655837	30.0525485	20.6405094	9.97377446	6.75298652					7.73572295	16.8404018	27.6541222	
Average of monthly NRD (d/month)		6.27894998	5.45115131	4.17565403	2.31558001	1.75076801					2.13992215	3.38778326	4.99067099	
Monthly average of the maximum NRD (d/month)		14.23774	15.39904	11.38127	7.29531	3.88812					6.132514	11.28519	13.59451	
Monthly average of the minimum NRD (d/month)		1.124238	1.069153	1	1	1					1	1	1.029054	
The 21 representative rainfall stations of the study area:														
Station weight		0.03065594	0.04189833	0.03372396	0.04115565	0.04283409	0.06679388	0.03700765	0.057703	0.04042675	0.07126586	0.163772	0.01249224	0.02872632
Station identifying symbols		AD0017	AD0019	AL0002	AL0003	AL0012	AL0013	AL0015	AL0016	AL0019	AL0048	AL0049	AL0054	AL0055
Average annual P (mm/year)		224.06383	151.204255	238.038298	206.161702	136.351064	122.548936	130.604255	145.455319	248.33617	126.159574	90.7489362	122.082979	134.714525
Average annual NRD (d/year)		28.4189189	35.4285714	27.2318841	26.1403509	27.9565217	21.8448276	24.3414634	24.8472222	44.097561	24.9423077	17.1372549	25.627451	28.2641509
Station Weight		0.0648862	0.05935167	0.02905386	0.11803719	0.00866619	0.0013155	0.04072426	0.00950946	the areal average precipitation by average weight of the 21 stations equal 135.1409 mm/year		The long average annual NRD in the study area calculated by average weight of 21 stations equal 24.944 day/year		
Station identifying symbols		AL0058	AL0059	AL0066	F 0001	F 0006	F 0009	F 0004	CD0003					
Average annual P (mm/year)		109.157447	114.712766	123.346549	123.163169	71.6948981	55.7106383	109.285319	145.180851					
Average annual NRD (d/year)		23.0192308	29.7884615	27.7647059	23.9166667	16.375	17.08	20.537037	22.3421053					

*NRD: Number of rainy days, P: Precipitation Tm: Temperature, Ev-pan: Evaporation measured by pan class A, the weighted average of each station used to calculate the precipitation temperature and evaporation and wind velocity and the number of rainy days of the study area from the metrological stations' data.

The areal average precipitation occurs in an average number of rainy days range from (16-35) rainy days with an average of 24 rainy days per year, calculated by the weighted average methods from the 21 stations. This number of average rainy days in the study area shows a strong variation in the occurrence of rainfall, and a wide variation in the range of long rainy days for each station is also seen. In arid regions this flocculation and spatial variable of distribution and frequency of precipitation are normal. Besides, linear regression analysis with a 95 % confidence level, was performed for the annual precipitation of the 21 stations, therefore, by the weighted average, the precipitation trend was calculated to be decreasing -0.62 mm/year. Although by the OK interpolation technique the precipitation trend of the 21 stations was used to create precipitation trend map which indicates an average decreasing trend of precipitation equal -0.509 mm/year, the north-western stations show a positive precipitation trend and eastern station show a higher decreasing trend the range of trend in the study area is (+2.6 to -1.4) mm/year. Table 4-9 overview of the study area climate parameters.

4.3.3 Groundwater recharge

According to a statistical summary of the study area thematic GWR layer created (Figure 3-8) the mean GWR in the study area is 14 mm/ year, the maximum 42.6 mm/year, the minimum is zero in the south part as the outcropping formation there is the B3 which is aquitard (Table 3-1), and the standard deviation is 7.4859 and the coefficient of variation 0.534519445. while the long average recharge in AZB clipped from the same GWR map of Jordan created by Gazal (2020) is 16.53 mm/year and the maximum value is 69.7 mm/year with a standard deviation 10.8 and coefficient of variation 0.653502 (Table 4-10). The difference between the GWR of the study area and GWR of AZB is due to the higher precipitation on the western part of the basin which excluded from the study area see the Jordan precipitation map (Figure 2-4). By calculating the recharge in each aquifer according to its outcropping and the amount of precipitation these outcrops received, the highest amount of recharge was estimated to basalt then A7B2, 27, 17 MCM respectively even the recharge percentage of rainfall for both is 15 % estimated by Hobbler et al. (2001). Subsequently, the study area has an average GWR rate of 14 mm/year, and an average rainfall rate of 134 mm/year, therefore, 10.4 % of the study area precipitation amount is recharging the groundwater renewable aquifer in the study area, which is close to the recharge percentage of rainfall in the entire (AZB) region, calculated by the water budget reports and discussed by (Gazal 2020; MWI/USAID/ARD 2001). The study area recharge represents 12 % of the total groundwater recharge in Jordan (Figure 4-11).

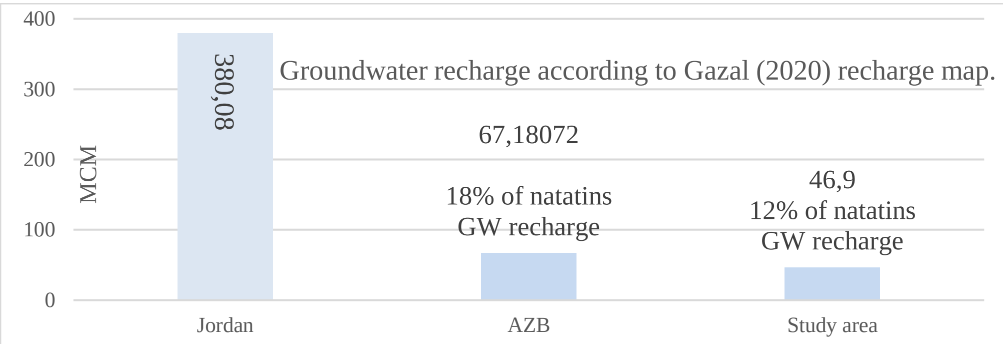


Figure 4-11 Study area average groundwater recharge estimated by GW recharge map created by Gazal (2020).

The average infiltration rate in AZB is between 7 % and 10 % of the total amount of rainfall according to Gazal (2020); MWI/USAID/ARD (2001). Since the average areal rainfall of the study area, shows mean precipitation of 132.79 mm/year by OK technique, 135.9 mm/year by IDW technique and 135.1 mm/year by weighted average method, all using the long annual average precipitation of the 21 representative precipitation stations in the study area. It means that the study area will be recharged at a rate of (9.5-13.6 mm/year or 9.3-13.3 mm / year or 9.5-13.5 mm/year) as the average recharge in AZB is between 7-10 % of precipitation. Nonetheless, the GWR map shows a recharging rate of 14 mm/year, which is also very small recharging amount according to Aller et al. (1987) any zone with a groundwater recharging rate less than 0.05 m/year (50mm/year) has to be categorized as low-risk potential from the GWR point of view (Figure 3-13).

Table 4-10 Statistical summary of the several created maps in the hydrogeological investigations obtained from the raster statistics summary.

Thematic Layer	Mean	Minimum	Maximum	S.D	CV
fault density (km/km^2)	0.521363899	0	3.027009	0.40149	0.77008
wadi density (km/km^2)	0.42471795	0	1.554567	0.27815	0.6549
W+F density (km/km^2)	0.944145446	0	3.325547	0.46504	0.49255
Dem (m asl)	706.8671948	352	1184	118.1246263	0.16711007
Depth to water (Dem-SWL)	239.3441033	2.56976318	678	135.9042537	0.56781952
Slop (%)	4.402743651	0	32.434738	4.249284126	0.96514457
Study area recharge map (mm/year)	14.0051	0	42.625	7.48597	0.53452
Study area SWL map (m)	519.0932	435.1402	711.8843	45.753	0.08814

Pixel size:26, -26, CRS: EPSG:28192-Palestine 1923 / Palestine Belt- Projected, S.D: Standard deviation CV: Coefficient of variation.

4.3.4 Geological lineaments results:

Existing of a high geological lineament density increased the permeability of the geological layers (Florinsky 2016), while the calculated geological lineament density in the study area is considered to be high density based on Muthumaniraja et al. (2019) classification. The study area has more than 1554 geological lineaments according to the created structural shapefiles which consist of major faults, tick shows downthrow side, fault inferred beneath superficial deposits, synclinal axis, and strike-slip fault. The mean density obtained from the statistical analysis of the created thematic layer of geological lineaments (Figure 3-10) is 0.5214 km/km^2 with a standard deviation of 0.4015 and the coefficient of variation is 0.77 (Table 4-10).

4.3.5 Drainage density:

Based on the drainage density of the micro watersheds in the study area (Figure 3-10), it was very parallel to the geological lineament density which is normal since the drainage pattern somehow follows the joining systems along with parts of the flow regime and is further controlled by the topography, thus giving an idea of the joints and faults in the bedrock, which in turn indicates the presence or absence of groundwater, while according to Jha & Chowdary

(2007), the high drainage density indicates an unfavorable location for the presence of groundwater, moderate drainage density indicates moderate groundwater capacity and low / no drainage density indicates high potential groundwater.

The average drainage density in the study area is 0.425 km/km^2 with a standard deviation of 0.278, and the coefficient of variation is 0.655, according to Jha et al. (2016) the groundwater potential in the study area is very good but it locates at high depth because of the nature of the low amount of precipitation in this arid area and the over-abstraction which cause increasing of the depth to water table (Figure 3-3). The occurrence of the renewable groundwater table at high depth with an average of 239m below ground surface according to the depth to groundwater map created by subtracting the static water level (SWL) map which created by OK interpolation of the average SWL measurements of the observation wells (Figure 3-14) from the digital elevation model DEM map.

4.4 The overlaying modelling techniques results

The results of the three overlying modelling steps are described and discussed as follows:

1. Investigate the second component of the GRA (the intrinsic vulnerability model results): Figure 3-12 illustrated this longest step in this section and mostly aims to present the capability of different techniques in groundwater intrinsic vulnerability mapping for groundwater management against contamination in arid agricultural area. The two DRASTIC approaches were implemented in this study and the results of the agricultural DRASTIC approaches were presented and discussed while the same steps were also applied to implement the ordinary DRASTIC approach and the results of this approach also presented in the tables and figures. While a former COP model results were utilized aiming to do a comparison with the DRASTIC approaches (ordinary and agricultural DRASTIC).
2. Create a land use thematic layer to simulate the possible Nitrate contamination load.
3. And the suggested simple approach in this part aiming to create the nitrate contamination risk map by combining the land use thematic layer created in the second step with the most representative intrinsic vulnerability map created in the first step. While according to intrinsic vulnerability scheme in this study the number of the instinct vulnerability maps is 16 plus the COP intrinsic map.

4.4.3 Vulnerability model to investigate the second component of the GRA (intrinsic vulnerability) results and discussion:

Three main models were used here, Agricultural DRASTIC, Ordinary DRASTIC, and former COP vulnerability index model. The tow DRASTIC approaches were performed twice, the first scenario without changing the recharge parameter rating and in the second scenario the recharge parameter rating was modified by multiplying it by 100 to simulate the effect of the intensive irrigation activities.

Table 4-11 Range and rating of the Agricultural DRASTIC parameters for the case study area.

Depth to water table (D)				
ranges (m)	Aarea	Area (%)	Rating (Dr)	Index
> 39	3375.652	0.99623	1	5
30-39	7.074852	0.002088	2	10
20-30	3.993012	0.001178	3	15
12-20	0.877721	0.000259	5	25
6-12	0.453041	0.000134	7	35
2-6	0.187616	5.54E-05	9	45
0-2	0.18907	5.58E-05	10	50
Weight (Dw) = 5				

Topography/ slope				
Range of slope %	area	Area (%)	Rating (Tr)	Index
0-2	1528.515	0.365938	10	30
2-6	1657.062	0.396713	9	27
6-12	658.3575	0.157616	5	15
12-18	265.9471	0.06367	3	9
>18	67.10034	0.016064	1	3
Weight (Tw) = 3				

Aquifer	Area (Km^2)	Area (%)	Aquifer media (A)		Hydraulic conductivity (C)	
			Rating (Ar)	Index	Rating (Cr)	Index
A1-A6	228.6716	6.92643	6	18	8	16
B3	263.7302	7.98835	2	6	1	2
B4	20.78728	0.62964	6	18	8	16
Basalt	1367.194	41.4121	9	27	10	20
Kurnub	0.302303	9.16E-03	8	24	10	20
A7-B2	1420.75	43.0343	10	30	10	20
Weight (Aw) = 3					Weight (Cw) =2	

Recharge (R) according to Aller et al. (1987)				
Range (m/year)	Area	Area (%)	Rating (Rr)	Index
0.0 -0.05	3329.9	100	1	4
Recharge (R´) suggested ratings				
Range (mm/year)	Area	Area (%)	Rating (Rr)	Index
> or 25	88.59091	0.026605	9	36
18-25	1067.725	0.320646	8	32
10-18	968.2032	0.290759	6	24
5-10	913.9751	0.274474	3	12
0-5	291.4244	0.087517	1	4
Weight (Rw) =4				

soil texture	Soil media (S)			
	Area (Km^2)	Area (%)	Rating (Sr)	Index
Clay	133.51	4.01	2	10
Silty clay	704.67	21.18	2.5	12.5
Silty clay loam	1759.86	52.89	3	15
Silty loam	482.85	14.51	4	20
loam	246.48	7.41	5	25
Weight (Sw) = 5				

Soil Thickness in the study area	area (Km2)	Area (%)
0.5 - 1 m	2962.55	89.3095
> 1 m	118.2202	3.5639
< 0.5 m	236.4022	7.1266

According to original modified complex geological map not the simple hydrogeological map			Impact to vadose zone (I)			
geological formation	Age (Epoch)	Aquifer I.C*	Area (Km2)	Area (%)	Rating (Ir)	Index
Na'ur limestone	Cenomanian-Turonian	A1-6	95.75312	2.878	6	24
Wadi As sir limestone	Coniacian	A7	370.642	11.1401	10	40
Wadi Umm Ghudran	Santonian	B1	148.376	4.4596	6	24
Amman silicified limestone	Campanian to Maastrichtian	B2	367.7481	11.0531	10	40
Muwaqqar Chalk Marl	Paleocene-Eocene	B3	10.47362	0.3148	1	4
Umm Rijam (chert - limestone)	Eocene	B4	141.8831	4.2645	6	24
Fahda Vesicular Basalt*	Oligocene to Holocene	Basalt	1024.991	30.8072	9	36
Kurnob Sandstone	Lower Cretaceou (Alpian, Aptian, Neocomian)	K	0.769653	0.0231	8	32
Alluvium and Wadi Sediments	Oligocene to Holocene	Recent	1166.475	35.0597	3	12
			Weight (Iw) = 4			

*: Index is the scoring index by applying the DRASTIC linear equation number 2 (the agricultural DRASTIC approach), **: Basalt in the study area from several basaltic formations, I.C: Aquifer Identifier codes, the same Range and rating parameters used in the second DRASTIC approach (Ordinary) but applying DRASTIC linear equation number 3, so to calculate the Index the parameters weight must be referred to the equation number 3.

4.4.3.1 Result of DRASTIC parameters and the DRASTIC indexes vulnerability map (DIVM):

Ranges and ratings of the DRASTIC parameters in the study area were listed in Table 4-11. Figure 4-12 Displayed the seven rated DRASTIC parameter maps used to calculate the DIVM. The initial agricultural DIVM of both scenarios (A and A´) were obtained using the seven hydrogeological DRASTIC data layers (the seven DRASTIC parameters), according to the agricultural DRASTIC governing equation-2 and processed by GIS software environment. In the second DRASTIC approach the initial DIVM of both scenarios (O and O′) were obtained by applying the ordinary DRASTIC model governing equation 3.

To understand the created DIVM values, a representation method must be chosen that can reveal the vulnerability of the study area in an acceptable visualization manner and at the same time allow for comparability between different areas (Aller et al 1987). Therefore, these values were reclassified into four classes using the Jenks natural breaks classification. All the created DIVMs of the study created in this research were classified into four groups according to DRASTIC Indexes scorings (DIS) as low, moderate, high, and very high ((DIS<100), (DIS 100-140), (DIS 140-200) and (DIS>200) respectively).

In the Agricultural DRASTIC approach, the range of DIS for both initial vulnerability maps in the first scenario (A) ranges from 39 to 171, and ranges from 139-192 in the second scenario (A′) While in the Ordinary DRASTIC approach, the range of the DIS for both initial vulnerability maps in the first scenario (O) ranges from 30 to 170, and ranges from 30 to 183 in the second scenario (O′). Table 4-12 presents all the created intrinsic vulnerability maps DIS values and the covering percentage of each vulnerability classes in the study area.

4.4.3.2 DRASTIC statistical and sensitivity analyses result and discussions:

Three statistical analyses were performed in this section, statistical analyses of the DRASTIC rated parameters (SADP), map removal sensitivity analyses (MRSA), and single parameter sensitivity analyses (SDAP), the results and discussion for these analyses as follows:

4.4.3.2.1 Statistical analyses of DRASTIC rated parameters (SADP):

The statistical summary of the seven rated parameter maps used to create the DVIM is provided in Table 4-13. The uppermost risk of contamination of groundwater in the study area originates from the hydraulic conductivity parameter (C) (mean value is 9.1). Then the high risk in the study area caused by the Aquifer media parameter map (A) (mean value is 8.64) and the topography parameter map (T) (mean value is 8.22). The impact of vadose zone parameter map (I) (mean value is 6.74) the soil media parameter map (S) (mean value is 3.14) imply moderate risks of contamination, while depth to groundwater parameter map (D) and the net recharge parameter map (R) impose a very low risk of contamination of groundwater (mean value is 1). While the recharge parameter map (R′) used to compute the DVIM in the second approach by modified the recharge scale, (not the original recharge rating scale provided by Aller et al. (1987)), have a moderate influence, not a very low as in the first approach (mean value is 5.5).

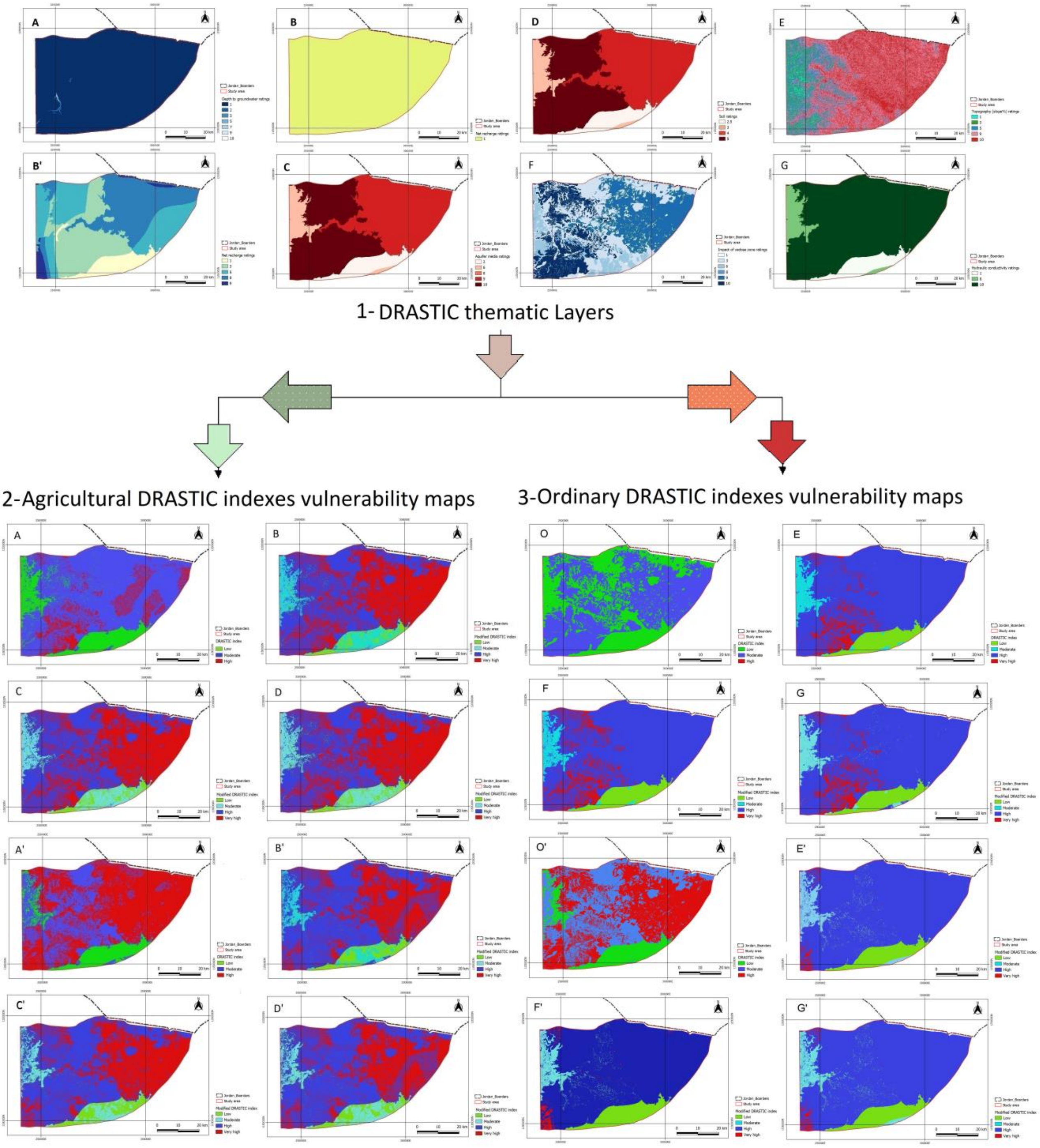


Figure 4-12 1) DRASTIC thematic Layers: (A) Depth to water, (B) Net recharge, (C) Aquifer media, (D) Soil, (E) Topography (slope%), (F) Impact of vadose zone, (G) Hydraulic conductivity. (B') Net recharge with a suggested rating.2) Agricultural DRASTIC indexes vulnerability maps: (A) DRASTIC Vulnerability map A (first scenario), (B) Modified DRASTIC vulnerability map, (C)Modified DRASTIC using extracted 6000 random points, (D) Modified DRASTIC using the extracted 9000points, (the Second scenario with suggested R ratings): (A') DRASTIC Vulnerability map, (B') Modified DRASTIC,(C')Modified DRASTIC using the extracted 60000 points, (D') Modified DRASTIC using the extracted 900000 points.3) Ordinary DRASTIC indexes vulnerability maps: (O) DRASTIC Vulnerability map (first scenario), (E) Modified DRASTIC vulnerability map, (F)Modified DRASTIC using extracted 6000 random points, (G) Modified DRASTIC using the extracted 9000points, (the Second scenario with suggested R ratings): (O') DRASTIC Vulnerability map, (E') Modified DRASTIC, (F') Modified DRASTIC using the extracted 60000 points, (G') Modified DRASTIC using the extracted 900000 points.

Table 4-12 The statistical summary of all the created DVIMs and the percentages of areas covered by the assigned vulnerability classes.

Model	DRASTIC qualitative category		Very high	High	Moderate	Low	A statistical summary of the vulnerability maps obtained from the raster statistics summary of each map.					
	Map	Range of DRASTIC Indexes	>200	140-200	100-140	1-100	Classify or before	Mean	Min	Max	S.D*	CV*
AGRICULTURAL	A	(%)	0	12.6401	71.7061	15.6537	Before R*	120.55386	39	171	19.332661	0.16037
		Area *	0	416.7262	2364.04	516.08	After R	1.9698641	1	3	0.5310653	0.26959
	B	(%)	40.4712	45.4974	10.1875	3.8439	Before R	178.94326	38.54239	224.4368	32.155637	0.1797
		Area	1336.077	1502.004	336.32	126.9	After R	3.2296841	1	4	0.7696764	0.23831
	C	(%)	40.7954	45.8052	9.889	3.5104	After R	3.238886	1	4	0.7682529	0.2372
		Area	1344.656	1509.781	325.951	115.705	Before R	181.4108	38.17675	228.8616	33.192957	0.18297
	D	(%)	40.5432	45.4866	10.2839	3.6864	After R	3.228896	1	4	0.7767558	0.24056
		Area	1336.342	1499.28	338.966	121.506	Before R	179.006	38.52064	226.4578	32.276059	0.18031
	A'	(%)	0	55.6655	33.9722	10.4671	After R	2.4546267	1	3	0.6729662	0.27416
		Area	0	1833.39	1118.9	344.743	Before R	138.48848	39	192	24.751174	0.17872
	B'	(%)	32.4107	54.8449	7.3785	5.3659	After R	3.1480977	1	4	0.7698346	0.24454
		Area	1068.592	1808.255	243.272	176.916	Before R	177.81262	37.0173	223.9578	33.394612	0.18781
	C'	(%)	36.2841	50.6752	7.6414	5.3993	After R	3.178471	1	4	0.7895548	0.24841
		Area	1195.958	1670.302	251.869	177.965	Before R	178.9076	36.39834	226.8094	34.75371	0.19426
	D'	(%)	32.3902	54.558	8.6035	4.4483	After R	3.148926	1	4	0.7521341	0.23885
		Area	1067.611	1798.284	283.58	146.619	Before R	177.6217	37.02233	223.9517	33.602388	0.18918
ORDINARY	O	(%)	0	0.000196	0.590544	0.40926	After R*	1.5909367	1	3	0.49206	0.30929
		Area		0.647201	1946.935	1349.267	Before R	110.52887	30	170	22.51896	0.203738
	E	(%)	0.074298	0.779633	0.066754	0.079316	After R	2.84980883	1	4	0.654943	0.22982
		Area	244.9481	2570.331	220.0782	261.4917	Before R	164.716141	31.18456	207.0496	36.06777	0.218969
	F	(%)	0.102751	0.755768	0.060282	0.081199	After R	2.88144646	1	4	0.682568	0.236884
		Area	338.6573	2490.94	198.6854	267.625	Before R	167.317097	30.99712	209.2608	36.992	0.221089
	G	(%)	0.074393	0.780616	0.068999	0.075992	After R	2.8532436	1	4	0.650311	0.22792
		Area	245.2759	2573.717	227.4931	250.5488	Before R	164.990342	31.16264	211.0975	35.88672	0.217508
	O'	(%)	0	0.473492	0.405473	0.121035	After R	2.35628906	1	3	0.684013	0.290292
		Area		1561.118	1336.859	399.057	Before R	128.5163	30	183	27.98408	0.217747
	E'	(%)	0.011902	0.833308	0.075648	0.079142	After R	2.77778692	1	4	0.595435	0.214356
		Area	39.25601	2748.416	249.5011	261.0271	Before R	163.016696	30.10293	208.5107	36.1955	0.222035
	F'	(%)	0.015971	0.830388	0.068079	0.085562	After R	2.77665483	1	4	0.61339273	0.220911
		Area	52.67209	2738.578	224.5225	282.1781	Before R	163.941765	29.746956	210.53909	37.4744613	0.228584
	G'	(%)	0.011686	0.833606	0.075216	0.079492	After R	2.77748546	1	4	0.59611959	0.214626
		Area	38.5289	2748.428	247.9883	262.0893	Before R	162.890783	30.112646	208.48181	36.248837	0.222535

After R*: after reclassifying the vulnerability map according to the DRASTIC qualitative category (1: Low 2: Moderate 3: High 4: Very high), CV*: coefficient of variation, S.D*: stands for standard deviation, Max: maximum Min: Minimum, Area* in (km^2).

(R´) and (I) are highly variable among the DRASTIC rated parameters with the coefficient of variation (CV=0.44), while T, C, A, and S are moderately variable (CV are 0.283 and 0.268, 0.257, 0.227 respectively). D and R are the least variable parameter (CV are 0.1 and 0 respectively) those tow parameters maps are created according to Aller et al. (1987) ranges and ratings as the other parameters but D and R in the study area mainly got a scoring rate of one because the depth to water in the study area is mostly plotted in the lowest risk range of the depth ranges while the recharge despite the good percentage to recharge to the precipitation (10 %) but the amount of recharge very low which indicated to be plotted in the lowest risk range of the recharge DRASTIC ranges and ratings scale (Figure 3-13).

Table 4-13 Statistical summary of the DRASTIC parameter maps obtained from the raster statistics summary of each parameter.

	Mean	Minimum	Maximum	SD	CV
D	1.008456844	1	10	0.157833866	0.156510283
R	1	1	1	0	0
R´	5.460099765	1	9	2.426668486	0.444436657
A	8.640746545	2	10	2.220990709	0.2570369
S	3.144699878	2	5	0.714368179	0.227165773
T	8.218790147	1	10	2.328928045	0.283366287
I	6.744893275	1	10	3.000613286	0.44487187
C	9.129945878	1	10	2.452714538	0.268645025

S.D. stands for standard deviation and CV for the coefficient of variation, (R´): used a modified rating scale, not the original rating.

Table 4-14 Statistical summary of DRASTIC rated parameters, calculated in excel sheet, from a randomly generated point within the study area.

	Statistical summary of DRASTIC rated parameters created by the statistical analyses of the 610863 random points								*Statistical summary of DRASTIC rated parameters created by the statistical analyses of the 990261random points*							
	D	R	R´	A	S	T	I	C	D	R	R´	A	S	T	I	C
Average	1.00396	1	6.26115	9.04671	2.97714	8.16858	6.86044	9.77756	1.00746	1	5.43499	8.64209	3.1454	8.21258	6.76713	9.08331
S.D	0.1407	0	2.02055	1.1745	0.53432	2.39218	2.96536	0.629	0.16045	0	2.4248	2.21501	0.7172	2.33362	2.90784	2.5373
max	10	1	9	10	5	10	10	10	10	1	9	10	5	10	10	10
min	1	1	0	6	2	0	1	8	1	1	1	2	2	1	1	1
CV	0.140143	0	0.322712	0.12982	0.179473	0.292851	0.432241	0.064312	0.159258	0	0.44614	0.256304	0.228	0.284152	0.4297	0.279332
Skw	49.12425	####	-0.73736	-1.7382	0.702349	-1.38862	-0.36408	-2.4731	34.36345	#DIV/0!	-0.3641	-2.18608	1.2094	-1.41274	-0.31161	-2.76007
median	1	1	6	9	3	9	9	10	1	1	6	9	3	9	8.9169	10
quartile minimum	1	1	0	6	2	0	1	8	1	1	1	2	2	1	1	1
quartile first 25%	1	1	6	9	2.5	9	3	10	1	1	3	9	2.5	9	3	10
quartile median 50%	1	1	6	9	3	9	9	10	1	1	6	9	3	9	8.9169	10
quartile third	1	1	8	10	3	10	9	10	1	1	8	10	3	10	9	10
q-maximum	10	1	9	10	5	10	10	10	10	1	9	10	5	10	10	10

Max. maximum, min. minimum, Skw. Skewness, S.D. stands for standard deviation and CV for the coefficient of variation, R´ used a suggested rating scale, not the original rating.

Table 4-14 provided the statistical summary of the seven used rated parameters calculated by extracted a random points files within the study area where each point have the values of those parameters maps after extracted those values by the generated random points layers function in the GIS, the attribute tables of those points files were exported and statistical analyses were done for both points layers (the first layer have 610863 random points, and the second layers have 990261 random points), according to the tow points layers statistic summary it’s obvious that when the points number increased the statistic become very close to the summary of the statistical summary obtained from the raster of each parameter map. The summary of the correlation analysis result is provided in Table 4-15. The analyses were done by creating random points using Qgis algorithmic function of creating a random points layer, all the points within the study area extent, the number of the points created were (610863 points) in the first trial, then on the second trial other points layer of about (990261 points) were created to compare and for precision results, multiple values from the DRASTIC parameters maps were extracted to each point in those points layers. Original numbers of the generated points were more than those numbers, but null data points were removed.

Table 4-15 The correlation analysis summary (correlation matrix) between seven DRASTIC rated parameters by two scenarios with and without changing the recharge ratings.

	Correlation matrix created from 610863random points cover the study area								*Correlation matrix created from 990261 random points cover the study area*							
		D	*R*	*A*	*S*	*T*	*I*	*C*		*D*	*R*	*A*	*S*	*T*	*I*	*C*
first scenario	*D*	*1*							*D*	*1*						
	R	*#DIV/0!*	*1*						*R*	*#DIV/0!*	*1*					
	A	*-0.053941*	*#DIV/0!*	*1*					*A*	*0.01588*	*#DIV/0*	*1*				
	S	*-0.007344*	*#DIV/0!*	*0.222764*	*1*				*S*	*-0.0205*	*#DIV/0*	*-0.2844*	*1*			
	T	*-0.010901*	*#DIV/0!*	*0.318913*	*0.472225*	*1*			*T*	*-0.0144*	*#DIV/0*	*-0.0071*	*0.37108*	*1*		
	I	*0.024261*	*#DIV/0!*	*-0.013621*	*0.069906*	*-0.03100*	*1*		*I*	*-0.0332*	*#DIV/0*	*0.24957*	*-0.0335*	*-0.1204*	*1*	
	C	*-0.061738*	*#DIV/0!*	*0.917668*	*0.447387*	*0.501621*	*0.00964*	*1*	*C*	*0.01152*	*#DIV/0*	*0.94365*	*-0.3246*	*-0.0167*	*0.25013*	*1*
second scenario (R´)		*D*	*R´*	*A*	*S*	*T*	*I*	*C*		*D*	*R´*	*A*	*S*	*T*	*I*	*C*
	D	*1*							*D*	*1*						
	R´	***-0.050823***	***1***						***R´***	***-0.0383***	***1***					
	A	***-0.05394***	***-0.086552***	***1***					***A***	***0.01588***	***0.4092***	***1***				
	S	***-0.007344***	***0.334626***	***0.222765***	***1***				***S***	***-0.020***	***-0.200***	***-0.2844***	***1***			
	T	***-0.010901***	***0.243769***	***0.318913***	***0.472225***	***1***			***T***	***-0.0144***	***0.0585***	***-0.0071***	***0.37108***	***1***		
	I	***0.024260***	***0.031163***	***-0.013621***	***0.069906***	***-0.03100***	***1***		***I***	***-0.0332***	***0.2061***	***0.24957***	***-0.0335***	***-0.1204***	***1***	
	C	***-0.061737***	***0.207553***	***0.917668***	***0.447386***	***0.501621***	***0.00963***	***1***	***C***	***0.01152***	***0.5605***	***0.94365***	***-0.3245***	***-0.0167***	***0.25013***	***1***

The attribute tables of the layers of the random points were used to perform the correlation analyses. first, the correlation used the DRASTIC rated parameters when R rated by the original recharge rating scale, then the correlations analyses were done using the same rated parameters but by using a modified rating scale (R´) instead of R. The correlation analysis between the DRASTIC parameters indicated a strong relationship exists between (A) aquifer media and Hydraulic conductivity (C) ($r > 0.9$) this result can be explained by the same origin of those parameters where they were created from the simplified hydrogeological map. On the first correlation analyses from both points layers where R is used the correlation between R and all the other parameters do not exist because the value of R is constant and equal 1 but on the second analyses the correlation between R´ and the other DRASTIC parameters exist but like the correlations between other DRASTIC parameters the relationship exists is weak. Due to fairly low correlations between the DRASTIC-rated parameters at (95 % confidence-level), these DRASTIC-rated parameters in the study region were generally considered to be independent.

4.4.3.2.2 Map removal sensitivity analysis (MRSA):

The results of these analyses calculated by removing one or more DRASTIC layers at a time from the initial created agricultural vulnerability map DVIM for both scenarios are shown in Table 4-16 the statistical measures of MRSA of the DVIM for the removal of multiple parameters at once are summarized. In carrying out this MRSA, two or more DRASTIC parameter layers were removed, the DVIM was computed, and the corresponding statistical measures of the variation index from the initial DVIM were calculated. For both scenarios of DRASTIC implementation in this study it can be noticed from the table of MRSA that with increasing the number of the removed parameters, the variation index does increase, which illustrated the significance of using all seven parameters, otherwise the computed DVIM would be sensitively influenced. Table 4-17 presents the results of the MRSA applied to the ordinary DRASTIC approach and the same results repeated by the increasing trend of the variation index by increasing the number of the removed parameters thus indicates the significance of using all the seven DRASTIC parameters, otherwise, the computed ordinary DVIM would be sensitively influenced.

Table 4-16 Statistics of the one or more than map removal sensitivity analysis (Agricultural DRASTIC approach).

Statistics of the map removal sensitivity analysis/ Agricultural DRASTIC first scenario DVIM*						Statistics of the map removal sensitivity analysis/ Agricultural DRASTIC second scenario with suggested (R´)					
Variation index (%)						Variation index (%)					
Parameters used	Mean	Minimum	Maximum	S.D	CV	Parameters used	Mean	Minimum	Maximum	S.D	CV
D, R, S, T, I and C	1.361	0.009	3.399	0.472	34.671	D, R´, S, T, I and C	0.897	0.000	2.867	0.479	53.373
D, R, S, T, and I	2.152	0.000	5.862	0.969	45.006	D, R´, S, T, and I	1.229	0.000	4.816	1.100	89.457
R, S, T, and I	2.234	0.000	7.813	1.637	73.276	R´, S, T, and I	2.074	0.000	7.984	1.642	79.184
R, S and T	2.657	0.000	9.778	2.001	75.31	R´, S and T	2.110	0.000	11.560	1.880	89.067
R and S	6.088	0.016	9.247	1.641	26.95	R and S	5.721	0.000	12.577	2.891	50.532
R	10.864	4.530	11.814	0.673	6.197	R´	5.321	0.000	16.051	2.721	51.136
A	8.165	0.054	20.396	2.831	34.671	I	7.709	0.000	31.691	3.945	51.177
T	7.539	0.001	30.830	4.608	61.123	T	5.600	0.000	30.524	4.599	82.135
D	9.985	0.099	17.515	0.920	9.217	A	5.381	0.000	17.203	2.872	53.373
S	3.074	0.000	24.507	2.958	96.235	D	10.499	0.014	23.101	0.975	9.285
I	9.437	0.000	36.562	5.441	57.655	S	4.281	0.000	26.467	2.730	63.781
C	5.714	0.000	12.500	3.213	118.377	C	4.280	0.000	12.646	3.048	133.708

*The initial overall vulnerability index used in the calculation here for the first scenario is for sure the DVIM (A), but in the second scenario is (A´).

Table 4-17 Statistics of the one or more than map removal sensitivity analysis (Ordinary DRASTIC approach).

Statistics of the map removal sensitivity analysis/ Ordinary DRASTIC first scenario DVIM*						Statistics of the map removal sensitivity analysis/ Ordinary DRASTIC second scenario with suggested (R´)					
Variation index (%)						Variation index (%)					
Parameters used	Mean	Minimum	Maximum	S.D	CV	Parameters used	Mean	Minimum	Maximum	S.D	CV
D, R, S, T, I and C	1.606	0.003	3.626	0.644	40.086	D, R´, S, T, I and C	1.123	0.000	9.525	0.723	64.391
D, R, S, T, and I	4.218	0.006	7.813	1.422	33.706	D, R´, S, T, and I	2.901	0.007	9.726	1.272	43.840
R, S, T, and I	3.139	0.000	8.203	1.834	58.446	R´, S, T, and I	1.740	0.000	13.190	1.634	93.918
R, S and T	8.381	0.002	11.866	2.083	24.850	R´, S and T	4.765	0.000	11.882	2.068	43.396
R and S	8.381	0.002	11.866	2.083	24.850	R and S	3.682	0.000	10.563	2.359	64.081
R	10.448	1.242	11.742	1.147	10.978	R´	5.776	0.000	21.453	3.035	52.545
A	9.634	0.018	21.754	3.862	40.086	A	10.056	0.000	19.110	1.575	15.662
T	6.738	0.000	13.486	2.426	36.008	T	9.127	0.007	11.861	2.118	23.207
D	9.467	0.000	20.997	1.477	15.607	D	10.056	0.000	19.110	1.575	15.662
S	8.419	0.007	11.278	2.007	23.832	S	7.691	0.000	13.639	2.359	30.669
I	15.397	0.013	51.312	9.917	64.409	I	12.364	0.000	50.323	8.526	68.954
C	11.580	0.119	20.909	3.403	29.390	C	8.139	0.034	18.098	2.907	35.713

*The initial overall vulnerability index used in the calculation here for the first scenario is for sure the DVIM (O), but in the second scenario is (O´).

4.4.3.2.3 Single-parameter sensitivity analysis (SPSA):

According to these analyses (Table 4-18) it can be understood that agricultural DVIM seems to be most sensitive to the hydraulic conductivity parameter (C) in the first scenario, as it shows a clear high variation of the vulnerability index, with mean variation index 2.362 %. While in the second scenario the removal of the depth parameter (D) showed the highest variation, in general, the agricultural DVIM showed a noted sensitivity of removing any of its seven components in the study area in both scenarios. Table 4-19 presents the SPSA results performed for the ordinary DRASTIC which indicated that the ordinary DVIM most sensitive to the impact to the vadose zone (I) in the first scenario, as it showed the highest variation of the vulnerability index, with mean variation index 2.149 %. While in the second scenario the removal of the Topography parameter (S) showed the highest variation, and from the results the ordinary DVIM showed a noted sensitivity of removing any of its seven parameters in both scenarios.

Table 4-18 Statistics of the one map removal sensitivity analysis (Agricultural DRASTIC)

Statistics of MRSA/ for the first scenario Agricultural DVIM*						Statistics of MRSA/ for the second scenario (with suggested R´)					
Removed parameter	Variation index (%)					Removed parameter	Variation index (%)				
	Mean	Minimum	Maximum	S.D	cv		Mean	Minimum	Maximum	S.D	cv
5D	1.6642	0.0165	2.91922	0.1534	9.2174	5D	1.7499	0.00239	3.8502	0.1625	9.285
4R	1.8107	0.7549361	1.96901	0.1122	6.1968	4R´	0.8869	0	2.6752	0.4535	51.136
3A	1.3608	0.00894	3.39939	0.4718	34.6714	3A	0.8969	2.82E-15	2.8672	0.4787	53.373
5S	0.5123	0	4.08453	0.4931	96.2352	5S	0.7135	0	4.4112	0.4551	63.781
3T	1.2566	0.0000885	5.13831	0.768	61.123	3T	0.9333	1.15E-09	5.0874	0.7665	82.135
4I	0.4524	0	2.08333	0.5355	118.3765	4I	1.2848	0	5.2819	0.6575	51.177
2C	2.362	2.3191201	2.38082	0.0128	0.5425	2C	0.38	0	2.1077	0.508	133.708

*The initial overall vulnerability index used in the calculation here for the first scenario is for sure the DVIM (A), but in the second scenario is (A´)

Table 4-19 Statistics of the one map removal sensitivity analysis (Ordinary DRASTIC)

Statistics of MRSA/ for the first scenario Ordinary DVIM*						Statistics of MRSA/ for the second scenario (with suggested R´)					
Removed parameter	Variation index (%)					Removed parameter	Variation index (%)				
	Mean	Minimum	Maximum	S.D	cv		Mean	Minimum	Maximum	S.D	cv
5D	1.578	0.000	3.499	0.246	15.607	5D	1.713	0.000	11.128	0.506	29.564
4R	0.774	0.000	6.053	0.647	83.629	4R´	1.002	0.000	10.448	0.613	61.190
3A	1.606	0.003	3.626	0.644	40.086	3A	1.123	0.000	9.525	0.723	64.391
5S	1.403	0.001	1.880	0.334	23.832	5S	1.568	0.000	9.525	0.551	35.104
3T	1.123	0.000	2.248	0.404	36.008	3T	13.136	10.012	14.180	0.552	4.202
4I	2.149	1.588	2.318	0.106	4.915	4I	2.098	0.000	8.262	1.439	68.581
2C	1.930	0.020	3.485	0.567	29.390	2C	1.376	0.002	11.003	0.594	43.180

*The initial overall vulnerability index used in the calculation here for the first scenario is for sure the DVIM (O), but in the second scenario is (O´).

Conclusively, upon both sensitivity analyses results (MRSA) and (SPSA), a significant variation in the DVIM assessment is expected if a lower number of DRASTIC seven parameters have been used. This conclusion is the aim of implementing the sensitivity analyses as according to studies which discussed the possibilities to reduce the parameters of this model to reduce the cost (McLay et al. 2001) as discussed before these sensitivity analyses according to several studies is essential to examine the necessity to not reduce the number of this model parameters. Through showing the variations in vulnerability assessment in case of removing a parameter from the DRASTIC calculations. But Napolitano & Fabbri (1996) discussed the criticism against the DRASTIC parallel to the success of this model, and they introduced a methodology to estimate the real weight of each DRASTIC parameters, which easy approach to modify the

DVIM instead of trying to exclude one or more of the DRASTIC parameters by comparing the variation occurs while removing the parameters from the DVIM.

4.4.3.3 DRASTIC modifications:

Table 4-20 and Table 4-21 summarized the statistical analysis to compare the effective (real) weight that each parameter had in the study area for both scenarios according to Napolitano & Fabbri (1996). In both tables, the effective weight was calculated by applying the equation 6, but in the first table, the calculations were implemented as the ordinary approach introduced by Napolitano & Fabbri (1996) to calculate the effective weight directly by applying the equation on the parameters and the initial DVIM raster's, while in Table 4-21 the same equation was applied to all the extracted points.

Table 4-20 Calculations of the DRASTIC parameters effective weight by rasters calculations (Agricultural DRASTIC)

The calculation for the first scenario *										The calculation for the second scenario (with suggested R´)									
parameters	Theoretical		Effective weight (weight (%))						parameters	Theoretical		Effective weight (weight (%))							
	weight	weight (%)	mean	Min	Max	S.D	CV	Weight		weight	weight (%)	mean	Min	Max	S.D	CV	Weight		
D	5	19.231	4.316	3.247	32.154	1.053	24.407	1.122	D	5	19.231	3.799	2.874	38.462	1.085	28.56	0.988		
R	4	15.385	3.425	2.339	10.256	0.688	20.081	0.891	R´	4	15.385	15.215	2.614	33.333	5.941	39.05	3.956		
A	3	11.538	21.394	5.357	35.714	5.009	23.414	5.562	A	3	11.538	18.584	5	32.432	4.39	23.62	4.832		
S	5	19.231	13.423	7.194	40.984	4.218	31.424	3.49	S	5	19.231	11.895	5.848	40.984	4.508	37.9	3.093		
T	3	11.538	20.696	2.362	45.455	6.463	31.228	5.381	T	3	11.538	18.266	2.048	45.455	6.371	34.88	4.749		
I	4	15.385	21.78	4.706	53.333	8.142	37.382	5.663	I	4	15.385	19.219	3.54	45.977	7.313	38.05	4.997		
C	2	7.692	14.966	1.786	23.81	4.193	28.018	3.891	C	2	7.692	13.022	1.667	22.695	3.484	26.75	3.386		
	26	100	100					26		26	100	100					26		

*The initial overall vulnerability index used in the calculation here for the first scenario is the DVIM (A), but in the second scenario is (A´)

Table 4-21 Calculated the effective weight of the DRASTIC parameters using the extracted Excel sheets from the DRASTIC rated parameter maps (Agricultural DRASTIC).

parameters	Scenario 1				Scenario 2 with the suggested R´			
	Using the 610863 random points		*Using the 990261random points*		*Using the 610863 random points*		*Using the 990261random points*	
	Mean %	Weight	Mean %	Weight	Mean %	Weight	Mean %	Weight
D	4.179724	1.086728	4.308022	1.120086	3.568591	0.927834	3.798113	0.987509
R	3.332674	0.866495	3.422962	0.88997	17.341178	4.508706	15.221225	3.957518
A	22.379538	5.81868	21.329534	5.545679	19.140868	4.976626	18.595448	4.834816
S	12.22706	3.179036	13.41339	3.487482	10.426372	2.710857	11.899057	3.093755
T	19.834183	5.156887	20.691592	5.379814	16.935583	4.403252	18.288559	4.755025
I	21.856717	5.682746	21.922628	5.699883	18.767293	4.879496	19.263064	5.008397
C	16.190104	4.209427	14.911873	3.877087	13.820114	3.59323	12.934534	3.362979
	sum	26	sum	26	sum	26	sum	26

In both tables the weight value of each parameter which used to modify the Agricultural DVIM calculated from the mean % by multiplying it with the total Agricultural DRASTIC seven parameters weight (26) which is fixed by Aller et al. (1987) to the agricultural DRASTIC model used in this research. In general, as the tables of the effective weights show the effective weights of the depth to water parameter (D) is less than the original assigned weight this due to the low variability of this parameter and low a risk contribution to contamination as almost all the study area belongs to the lowest risk DRASTIC (D) range. Hence it can be concluded here that the real weight for the aquifer media, impact to vadose zone, and hydraulic conductivity increased as these elements reflect the geological formation in the study area which are dominated by karstic and fractured basaltic formations thus have a high influence on the agricultural DVIM assessment. The same steps were applied to modify the ordinary DRASTIC, and the calculated effective parameters weight in Table 4-22, and Table 4-23. The effective weight for the (I), (A), and (C) parameters is higher than the theoretical weight.

Table 4-22 Calculations of the DRASTIC parameters effective weight by raster's calculations (Ordinary DRASTIC)

The calculation for the first scenario *									The calculation for the second scenario (with suggested R´)								
parameters	Theoretical		Effective weight (weight (%))						parameters	Theoretical		Effective weight (weight (%))					
	weight	weight (%)	mean	minimum	maximum	S.D	CV	Weight		weight	weight (%)	mean	minimum	maximum	S.D	CV	Weight
D	5	21.74	4.84	3.60	34.97	1.59	4.54	1.11282	D	5	21.74	4.239	3.012	40.984	1.671	39.426	0.975
R	4	17.39	3.84	2.35	13.33	1.16	8.69	0.88351	R´	4	17.39	16.371	2.632	35.294	6.137	37.486	3.765
A	3	13.04	23.35	6.82	36.00	5.16	14.33	5.3702	A	3	13.04	20.085	6.122	32.609	4.446	22.138	4.620
S	2	8.70	6.12	3.01	26.32	2.86	10.89	1.40721	S	2	8.70	5.399	2.424	26.316	2.984	55.269	1.242
T	1	4.35	7.87	0.74	25.64	3.32	12.96	1.81	T	1	4.35	6.899	0.637	25.641	3.312	48.005	1.587
I	5	21.74	29.62	9.26	66.67	10.22	15.33	6.81243	I	5	21.74	26.011	5.155	63.291	9.601	36.912	5.983
C	3	13.04	24.36	3.41	33.80	6.73	19.90	5.60393	C	3	13.04	20.996	3.061	33.803	5.492	26.155	4.829
	23	100	100					23		23	100	100					23

*The initial overall vulnerability index used in the calculation here for the first scenario is the DVIM (O), but in the second scenario is (O´).

Table 4-23 Calculated the effective weight of the DRASTIC parameters using the extracted Excel sheets from the DRASTIC rated parameter maps (Ordinary DRASTIC).

parameters	Scenario 1				Scenario 2 with the suggested R´			
	*Using the 610863 random points **		*Using the 990261random points ***		*Using the 610863 random points*		*Using the 990261random points*	
	Mean %	Weight	Mean %	Weight	Mean %	Weight	Mean %	Weight
D	4.50	1.04	4.830	1.111	3.799	0.87	4.24	0.98
R	3.59	0.83	3.839	0.883	18.494	4.25	16.38	3.77
A	24.17	5.56	23.260	5.350	20.418	4.70	20.11	4.62
S	5.30	1.22	6.115	1.406	4.458	1.03	5.41	1.24
T	7.23	1.66	7.871	1.810	6.086	1.40	6.92	1.59
I	28.98	6.67	29.832	6.861	24.644	5.67	26.11	6.01
C	26.22	6.03	24.253	5.578	22.101	5.08	20.83	4.79
	sum	23	sum	23	sum	23	sum	23

*The extracted random points Excel sheet-1 ** the extracted random points Excel sheet-2

As a result, the effective weight results indicate that the three geological parameters, which have an effective weight higher than the theoretical weight, generally regulate the vulnerability in the region. Figure 4-12 presents the updated DVIM of the study area following the statistical modifications made using the effective weights of the seven parameters measured for the agricultural and ordinary DRASTIC approaches and for the two applied scenarios in three ways discussed above. The updated DVIM indicates that the case study region is under low, moderate, high, and very high groundwater vulnerability to contamination. The second scenario by the suggested R´ doesn’t offer better visualization of the reality and it was enough to adjust and modify the DVIM by the effective weights. The updated DVIM in both scenarios using the effective weights calculated by the extracted points values shows similar results close to the updated DVIM results by the values of the effective weights calculated directly by applying the effective weights calculation approaches of Napolitano & Fabbri (1996) on the raster’s, especially the second estimations as the number of the points increased (map D and D´ in the agricultural DRASTIC approach) and (map G and map G´ in the Ordinary DRASTIC approach) see (Table 4-12), and (Figure 4-12). Figure 4-14 show the percentages of each assigned vulnerability classes in the study area by each prepared DVIM and the statistical summary of each map.

The modification by the effective (real) weight for both agricultural DVIM generated by the tow adopted scenarios (with original R and with modified R´), shows a new vulnerability indexes class the very high vulnerability in the modified agricultural DVIM (B, and B´) which wasn’t present in the initial agricultural DVIM (A and A´). Also, the same results obtained after the modification by the effective weight for both ordinary DVIM generated by both scenarios, a new vulnerability indexes class the very high vulnerability presents in the modified agricultural DVIM (E and E´) which this very high vulnerability class wasn’t present in the initial ordinary DVIM (O and O´). The same high vulnerability class also presents in the other modified DVI maps by the effective weights computed by the extracted point values but applying the same approach used in raster calculated in the tow extracted points excel sheets (excel sheet1 with 610863points and excel sheet2 with 990261points). While the percentages of the vulnerability classes assigned after the modification by the real weight created by the excel sheet calculation show almost the same percentages like the vulnerability maps (B, B´, E, and E´) which were modified by the effective weights calculated by the raster calculator, especially the DVI maps (D, D´, G, and G´) than the modified DIV maps (C, C´, F, and F´) because the number of the points extracted in the second excel sheet more than the number of the extracted points in the first excel sheet (990261 points, and 610863 points respectively).

The explanation for the existence of a new vulnerability class (a very high vulnerability class) in all modified DVIMs can be explained by reference to the effective weight tables. Which indicates an increase in (I, C, and A) weight as these DRASTIC-parameters have a greater effect on the vulnerability index assessment process in the study area while the weight of the less influencing parameters (D and R) decreased (Table 4-20) and (Table 4-21) for the agricultural DRASTIC effective weight calculation and referring to the tables (Table 4-22) and (Table 4-23).

This approach of finding the real DRASTIC-parameters weight make this model more flexible and able to represent the real natural protectiveness of the groundwater aquifer in different areas. For example, in this research, the actual measured weight of parameters D and R is 1.1 and 0.8, while the original theoretical weight for these parameters is 5 and 4 respectively. Although applying the same model and approach to the measurement of real DRASTIC-parameters weight in areas with a higher rate of recharge as the findings of Napolitano & Fabbri (1996) throughout the study area in Italy gave a higher weight for R than the original theoretical weight given by Aller et al. (1987).

4.4.3.4 DRASTIC Validation:

The agricultural modified DRASTIC map (B) was selected to represent the study area intrinsic groundwater vulnerability as the ordinary DRASTIC less estimated the vulnerability of the study area and the Agricultural DRASTIC designed by Aller et al. (1987) to assess the vulnerability when the agricultural activities are the main source of the possible contamination.

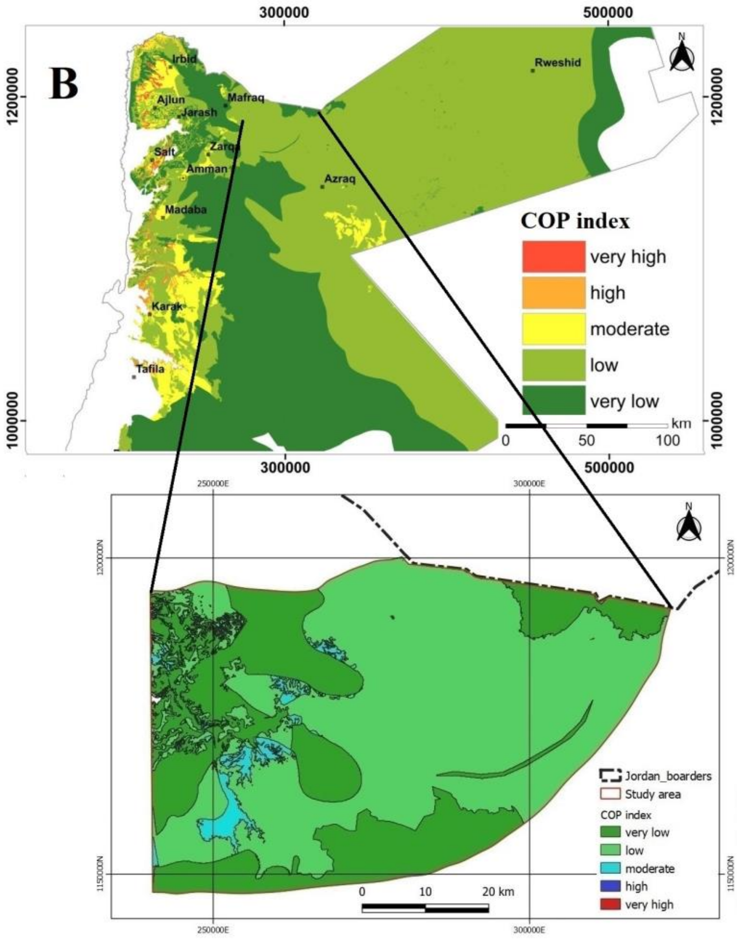


Figure 4-13 COP vulnerability map retrieved from BGR & MWI (2018).

Even though the agricultural modified DRASTIC map (B´) by the second scenario (the modified R´ ratings) doesn't give better visualization as mentioned before so the modification by calculating the effective weight was enough in this study. Therefore, the agricultural modified DRASTIC map (B) was validated by studying the matching and correlation between the groundwater vulnerability map (B) and the water quality SCD maps (Figure 4-7). Besides the comparison with the COP intrinsic vulnerability indexes map (Figure 4-13) created by BGR & MWI (2018). There is a relatively very close probability of distribution according to the coefficient of variation (relative standard deviation) for each parameter spatial distribution map 57 %, 61 %, 59 %,59 %,65 %, and 59 % for the average and maximum nitrate, sulfate, and EC, SCD maps respectively (Table 4-5). Besides, the raster's correlation of the three water quality parameters SCD maps also shows strong spatial relative dependents with raster's correlations values, between nitrate and EC (r=85 %), between sulfate and EC (r=90 %), nitrate and sulfate (r=78 %). This strong correlation indicated a possibility same resource causing the increase of these parameters' concentrations, which is related to the effects of the large-scale source (non-point pollution sources), which is the agricultural activities or may contribute to large-scale pollution controlling factors such the weak groundwater natural potential protectiveness in the study area. The high EC values are also related to agricultural activities by the effect of the (IRF). It is evident that the modified agricultural DVIM corresponds to the continuous distribution maps of the average and maximum concentrations of nitrate, sulfate, and EC elements.

Besides the agricultural activity intensity map which was prepared depending on the agricultural intensity data retrieved from the MOA (2020), also comes in parallel to the susceptibility approaches by DRASTIC as the high intensive agricultural activities occur at the north-eastern part of the study area which according to modified agricultural DVIM (B) is a highly vulnerable area, but the high concentration of nitrate, sulfate, and EC is clear in the middle of the study area which is within the high vulnerability zone according to (B) map, the explanation comes through the groundwater movement which moves from high elevation to the lowest and according to the static groundwater level map (Figure 3-14) the groundwater moves from the north-eastern part which has high intensive agricultural activities to the middle part.

According to COP-model, the study area is assigned as the very low to moderate vulnerable areas (Figure 4-14). Which is against the study area geological nature which characterized by highly karstification aquifers and fractured high permeable basalt in addition to the failure of this model to coop with the several studies discussed the groundwater quality deterioration and the increasing trend of the groundwater contamination and the recommendations to regulator the agricultural activities in this highly vulnerable area.

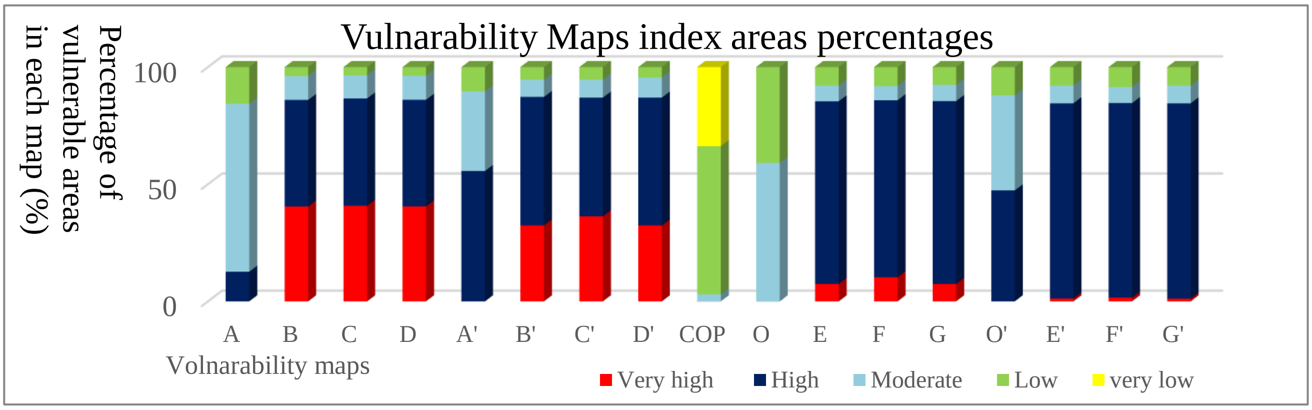


Figure 4-14 Percentage of vulnerable areas in each approach : 1- Agricultural DRASTIC indexes vulnerability maps: (A) DRASTIC Vulnerability map A (first scenario), (B) Modified DRASTIC vulnerability map, (C)Modified DRASTIC using extracted 6000 random points, (D) Modified DRASTIC using the extracted 9000points, (the Second scenario with suggested R ratings): (A') DRASTIC Vulnerability map, (B') Modified DRASTIC, (C') Modified DRASTIC using the extracted 60000 points, (D') Modified DRASTIC using the extracted 900000 points. 2- And the middle column represents the areas percentages assigned vulnerability classes by the COP-Model, 3- Ordinary DRASTIC indexes vulnerability maps: (O) DRASTIC Vulnerability map (first scenario), (E) Modified DRASTIC vulnerability map, (F)Modified DRASTIC using extracted 6000 random points, (G) Modified DRASTIC using the extracted 9000points, (the Second scenario with suggested R ratings): (O') DRASTIC Vulnerability map, (E') Modified DRASTIC, (F') Modified DRASTIC using the extracted 60000 points, (G') Modified DRASTIC using the extracted 900000 points.

This underestimation of the groundwater susceptibility in arid low precipitation areas is due to the COP-model govern equation according to Vías et al. (2006) which was developed for the regions in Germany which characterized by humid climate and high annual precipitation. COP-model by giving high weight to the precipitation in calculating the vulnerability indexes can give a representative vulnerability map for the wet areas but in dry areas, it may have weakness by underestimating the possible highly vulnerable areas and by creating the COP vulnerability map it wasn't subjected to any statistical modification analyses or validations. The influence of precipitation in vulnerability assessment by DRASTIC-model, is presented by the groundwater recharge and it is theoretical weight percentage relative to the rest of the seven elements of this model is 15.3 % and after finding the actual weight of R the effective weight percent of R became 3.4 % (Table 4-20). Therefore, the DRASTIC model is more appropriate for dry areas to simulate the susceptibility of pollution. While the simple approaches of findings the effective weight of DRASTIC parameters makes it a more flexible model to be used in dry and wet areas. Besides in arid areas even the precipitation is low the groundwater recharge can be increased in some agricultural areas due to excessive IRF (Srivastava 2013). Therefore, the COP-model isn’t suitable to evaluate the natural potential protectiveness of groundwater in arid areas, especially agricultural arid areas.

4.4.4 Groundwater nitrate contamination risk (NCR) map.

This part was created to simplify the use of an enormous amount of spatial data, using overlying modelling techniques, to produce the visualization results of groundwater nitrate contamination risk (NCR) in the study area. The results of the three overlying models used in this research are shown in Figure 4-15. These simulations represent as far as possible:

1. The natural groundwater protectiveness by intrinsic vulnerability model, via the agricultural modified (DVIM) DRASTIC vulnerability indexes map (B), which was selected after creating several modified DVIMs by the tow DRASTIC approaches the Ordinary and the Agricultural, and by adopted tow implementation scenarios for each DRASTIC approaches and modified all the resulted DVIMs by the statistical approach introduced by Napolitano & Fabbri (1996) (see the whole results of this part in section 4.4.3 above). DVIM (B) indicate that 40% of the study area fall under the very high vulnerability condition (value of the DRASTIC Indexes scorings (DIS) > 200) and about 45 % of the study area fall under the high vulnerability condition (value of the DIS is between 140-200), which reflect the fragility of the groundwater natural protectiveness in the study area (Figure 4-14). While the findings of the previous GRA (section 4.3) investigations suggest that agricultural practices are the key cause of contamination, and the natural potential protectiveness of the groundwater by studying the geological and hydrogeological parameters revealed a fragility of this protectiveness.
2. The nitrate potential contamination by a land use thematic map created via simple overlying model to simulate the possible nitrate contamination loads. The overly of the three-land use nitrate contamination potential maps indicated parallel to the contamination load investigation that the main source of the nitrate contamination in the study area is related to agricultural activities, where the study area classified into very high, high, moderate, low, and very high APNC classes in 8.35 %, 5.92 %, 27.84 %, 27.51 % and 30.36 % of the studied area, respectively (Table 4-24). While a very low, low, moderate, and high UPNC classes were classified in 95.9 %, 3.5 %, 0.9 %, and 0.01 % of the studied area, respectively. Then very low and low PuPNC classes were classified in 95 % and 5 % of the studied area, respectively. The PNC map resulted by overlapping the previouse three classified land use thematic layers responding to the nitrate contamination factors indicated that the study area classified into five PNC clasess from very low to very high (Figure 4-15).

3. The nitrate contaminaton risk (NCR) map created by overlapping the PNC map and the modified agricultural DVIM (B) of equal weight (using the arithmetic average of the input values) indicated the study area assigned a very high, high, moderate, low, very low NCR classes in 2.96 %, 25.42 %, 51.72 %, 16.73 %, 3.15 % of the studied area, respectively.

Table 4-24 The three-land use thematic layers responding to the nitrate contamination factors. Classified into five classes According to Ducci (2018) land use approach.

A: Land use classification in the agricultural potential nitrate contamination.			
km^2	agricultural activities intensity	Area (%)	Agricultural potential nitrate contamination (APNC)
277.9706	Agric. > 75 %*	8.354084	very high
197.0878	Agric. 50-75 %	5.923244	high
926.4287	Agric. 25-50 %	27.84274	moderate
129.0549	Agric. 10-25 %	3.878595	low
786.3686	Agric. < 10 %	23.63339	low
951.5815	No agric., dom. pasture	28.59867	very low
58.87007	No agric., other land uses	1.769272	very low

B: Population density classes and reclassification in the urban potential nitrate contamination.			C: Sewer system coverage and reclassification in the peri-urban potential nitrate contamination.		
Population density per km^2	Urban potential nitrate contamination (UPNC)	Area (%)	Sewer system coverage %	Peri-urban potential nitrate contamination (PuPNC)	Area (%)
<5	Very low	95.55	>90	Very low	95
25-5	Low	3	70-90	Low	5
25-250	Moderate	1	50-70	Moderate	
250-1000	High	0.1	25-50	High	
>1000	Very high	0	<25	Very high	

*75 % of the area equipped by intensive farming.

Both the modified agricultural DVIM (B) and the NCR maps corresponds to the continues distribution maps of the average concentrations of nitrate, sulfate, and TDS elements, where it was discussed the matching distribution relation of both nitrate, sulfate, and EC concentration maps as the source of these elements is the agricultural contaminations via the fertilizers used in the study area which include these elements. Completely, the matching between the resulted NCR map and the nitrate SCD map (Figure 4-15) to evaluate the overlying modelling techniques results indicated a strong corresponding matching between the NCR and the nitrate SCD zones. But the highly intensive agricultural activities occur at the north-eastern part (Figure 4-2) of the study area which according to DVIM is a very highly vulnerable area and categorized as very high NCR area. The high concentration of nitrate is clearer in the middle of the study area which is within the high vulnerability zone according to modified DVIM and categorized as high NCR area, not very high. The explanation comes through the groundwater movement which moves from high elevation to the lowest according to Darcy law and by referring to the static groundwater level map (E) (Figure 3-14) the groundwater moves from the north-eastern part which has the highly intensive agricultural activities to the middle part of the study area. As mentioned in the introduction page number 18 the intrinsic vulnerability map more applicable to be used for land use planning because the contamination risk map does not reflect the intrinsic groundwater vulnerability but also the contamination status which subjected to be changed according to the human activities on the surface. Only the intrinsic vulnerability can also have the same weakness in case of a massive human activities causing removal or disruption of the vadose zone.

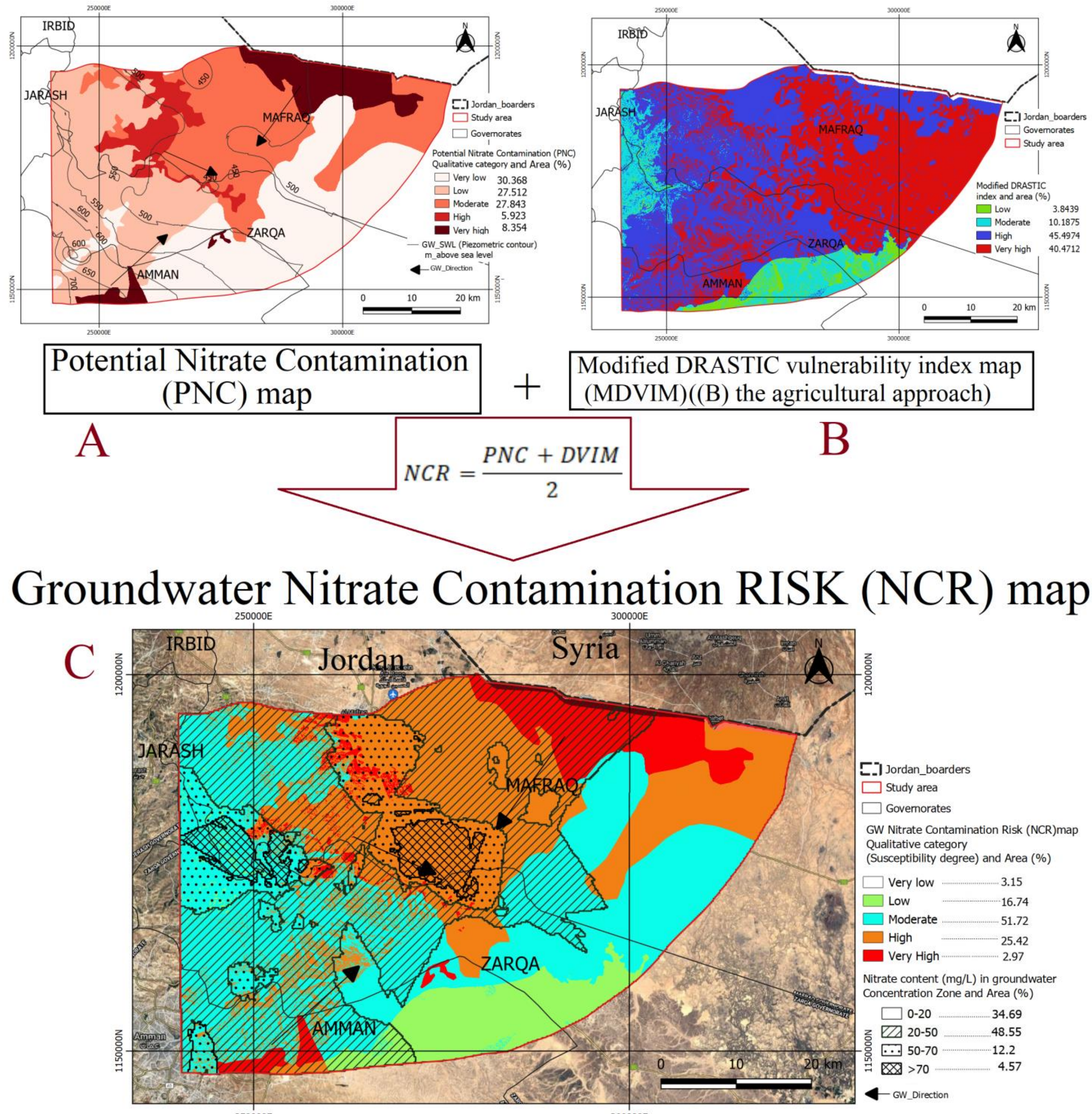


Figure 4-15 A: Potential Nitrate contamination (PNC) map, B: Modified Agricultural DRASTIC vulnerability index map (MDVIM) (B). the agricultural approach, and C: Groundwater Nitrate contamination RISK (NCR) map.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions.

The comprehensive GRA implemented in this research revealed that the main contamination risk load is agricultural, while almost the entire area is characterized by weak natural groundwater potential protectiveness. However, it was difficult to visualize and clarify the findings of the study especially the second component of the GRA without using the overlaying modelling techniques. Thus, the study revealed the following main conclusions:

1. The SCD of the nitrate, sulfate, and EC concentration distributions in the groundwater aquifer demonstrates a very strong correlation, and a relatively very close probability of distribution for each parameter long average concentration spatial distribution maps and following a related parallel anisotropic distribution pattern. This ensures that these three parameters come from the same source.
2. The positive good correlation between these three parameters approved in the correlation matrix table which implemented directly by the measured concentrations values. This strong correlation indicated a possibility of the same resources causing the increase of these parameters' concentrations in the study area.
3. The primary factors influencing groundwater chemistry are derived from the natural dissolution of the aquifer rocks, especially the carbonates. While the chemical fertilizers and the irrigation return flows (IRF) are the main anthropogenic sources of disturbing the natural groundwater composition.
4. The dominant groundwater hydro-chemical facies in the study area are the Ca–Mg–Cl and Na–Cl, according to the order of their dominance, with an average sodium/potassium around 40 %, 35 % carbonate, 70 % chloride, 40 % sulfate, 60 % calcium/magnesium, while calcium reach more than 80 % but the wells plotted ranges from less than 20 % up to more than 80 % because part of the wells pumping from the basalt aquifer and some wells from the highly karstic A7/B2 aquifer and some wells from both aquifers as both aquifers hydrogeological connected in the eastern part of the study area.
5. The range of carbonate concentration among the wells is high due to the different types of aquifers, the basaltic wells show very low concentration, but the karstic A7B2 wells show higher concentration. The low solubility of minerals through the limestone in the A7/B2 aquifer indicates the major ions (+/-) concentration must be with a natural origin. However, it was observed from the plots that calcium does not exceed sodium and potassium, and that chloride-sulfate exceeds other ions, suggesting an anthropogenic source which is mainly in the study area the agricultural activities.

6. The high sulfate concentration indicates an anthropogenic source for the wells classified in the piper diagram above the average sulfated plotted line of the study area wells 40% (more than 65 % of the wells plotted above the 40 % sulfate average concentration line).
7. The natural groundwater potential protectiveness can be recognized as weak in the study area according to the hydrogeological overview, the outcropping of the high permeable geological formations, and the thin weak protectiveness texture of the soil cover and high density of geological lineaments. Combined with a good percentage of groundwater recharge from the precipitation which is indicator that the irrigation in the study area will cause an increase in the recharge and increase the passages of the agricultural contamination.
8. The overlying modelling techniques used in this study to simulate the intrinsic vulnerability and the specific vulnerability, concludes the following:

   a. The DRASTIC-model, even though it gives relatively satisfactory results in the evaluation of groundwater intrinsic vulnerability to pollution, cannot be used for the truthful assessment of the groundwater pollution risk in the arid highly permeable areas without modifications. Besides, the hydrogeological conditions provided in the original DRASTIC-model by Aller et al. (1987) do not make special provisions for hazardously sensitive, karstic, and fractured basaltic rocks domains. However, the flexibility of the application DRASTIC model and its ability to be applied in areas belong to different environmental characteristics was clear by the ease, efficiency, and simplicity of finding the parameters real weight in the modification approach.

   b. Using the statistical sensitivity analysis approach to avoid subjectivity associated with the selection of ratings and weights of the seven model parameters conclude that the seven DRASTIC components were essential and significant in the calculations of DVIM. Furthermore, optimizing the weights of the DRASTIC parameters using the aforementioned optimization procedure by Napolitano & Fabbri (1996) which can be easily achieved using simple statistical approaches was more effective and reliable than changing the ratings of the DRASTIC parameters as suggested in the second scenario.

   c. The statistical analyses show that aquifer media (A) and hydraulic conductivity (C) are the most significant parameters which dictate the high vulnerability in the study area.

   d. The correlation between the modified DIVM (both DRASTIC approaches the ordinary and Agricultural) and the concentration of the contaminants indicates a better representation than the COP-model. Besides DRASTIC model shows great correspondence between the sensitivity of the area to pollution and the distribution of geological outcropping. One of the key findings is the importance of using a suitable vulnerability model that is appropriate for the hydrogeological, climatic, and contamination risk load in the study area. While, referring to the comparison results between COP-model and DRASTIC-model its recommended not to use, COP-model for dry areas and to use DRASTIC model.

e. The application of DRASTIC model needs to be adjusted by finding the actual weight of the parameters to improve the consistency of the implementation of the model.
f. Using the contamination-prone maps models showed the ease of simulating the area's susceptibility to pollution in a visualization map. And the overlying modeling techniques used in this study are very simple to use and require for the appropriate management of agricultural areas.
g. The modified agricultural DIVM demonstrated that (40 %, 45 %, 10 %, 3 %) of the case study area is under very high, high, moderate, and low groundwater vulnerability to contamination respectively. This calls for an urgent plan to control the spread of agricultural activities, especially in the mid-and north-eastern areas, while the southern part of which about 3% of the study area is somehow naturally protected as the outcropping layer is aquitard.
h. The groundwater NCR indicated the study area, assigned a very high, high, moderate, low, very low NCR classes in 2.96 %, 25.42 %, 51.72 %, 16.73 %, 3.15 % of the studied area, respectively.
i. The groundwater NCR map represents a particular current groundwater contamination risk, whereas the current land use might have been changed so that the created groundwater NCR may not be reliable and may require to be modified to represent changes in land use or changes in the selected contamination parameters. Therefore, the modified DVIM is more reliable to be used for future strategic land use planning.

Ultimately, the main benefits of the approaches proposed in this study are the potential of being implemented on a broad scale, simple availability, and versatility of starting data, even from various sources. Besides, the reliability of the overlying modeling techniques used to create the NCR map (in terms of accordance with the nitrate concentration zones) and the intellectual methodology of the NCR map generated, seems to be useful and have a significant potential for being employed worldwide.

5.2 Recommendations

1. Groundwater vulnerability and contamination risk mapping are exemplary decision-making devices to be considered in land use planning and global water resource management

programs. It is therefore necessary to follow plans to create a contamination susceptibility map using an appropriate model that is suited to geological, hydrogeological and weather conditions of the study area. Through the study, it was found that the modified DRASTIC-model is the most suitable for the arid areas, while (COP-model), due to its heavy dependence on the rate of precipitation to estimate the intrinsic groundwater vulnerability indexes cannot be used for dry areas.

2. Updating, validating, studying, and analysing geological, hydrogeological and water quality data through scientific and accurate methods, avoiding data errors.
3. Follow-up the practices of farmers using excessive quantities of fertilizers, studying the effects of (FMP), persuading farmers to mix fertilizers in special tanks and considering the calculation of the actual plant requirements for water and fertilizers to avoid excessive use.
4. Conduct government-sponsored pilot projects to show the farmers the benefits of the science-based technologies, whether by changing patterns of crops or investing in solar and wind energy.
5. Gazal (2020) presented three alternatives for the incisive agricultural activity in dry areas:
    a. Rainfed agriculture and the selection of water-stress-tolerant crops
    b. Partly depends on rainfed by developing an irrigation technique rely on the regulated deficit irrigation (RDI) where the deficit irrigation (DI) is aimed at maximizing economic crop production when water is scarce.
    c. Hydroponic, which is the most recommended option according to Sharma et al. (2018) in terms of water use efficiency and protecting groundwater aquifers from contamination.

6. KEY SCIENCTIFIC FINDINGS AND IMPORTANT OUTPUT OF THIS RESEARCH

The efforts to incorporate the methodological approaches proposed here would result in a cost-effective solution to maintaining the source of community drinking water and achieving the desired protection of groundwater for future generations. The research can also be used as a method to raise public awareness of groundwater problems in developed countries. The research is intended to establish a holistic pattern for the use of several scientific methods in a systematic and monotonous manner to investigate groundwater risk in support of sustainable ground water management. The study has shown that the overlay models used to create contamination vulnerability maps are better suited for dry areas through Jordan as an example. The developed integrated overlaying approach is mostly aimed at assessing groundwater vulnerability and evaluating the estimation problem of nitrate contamination in arid agricultural areas. This included the use of the updated version of the DRASTIC vulnerability mapping methodology, the fuzzy hierarchy methodology for contamination source mapping, and the computational simulation of the nitrate contamination risk map. The modification implemented in this study with the application of the widespread intrinsic vulnerability model (DRASTIC) is based on a series of innovations that have taken place on this model since the beginning of its use in groundwater vulnerability studies. In my doctoral research I have applied a Modified simple overlaying approach to create a land use layer attempts of integrating it with the modified reliable DRASTIC framework to be the parameter number eight in the overlaying approach of this study. The updated composite DRASTIC-land use model was then able to determine specific groundwater vulnerabilities by including the introduced land use parameter. But in this study due to the difficulties of recognizing all possible sources of contaminants, the susceptibility is more directed towards a particular contaminant which is in this dissertation the nitrate. Therefore, the land use layer has been created to represent possible nitrate contamination (PNC) in the study area. Lastly, the thesis presents the following key findings on the level of groundwater studies in Jordan:

1- Improved the quality of input datasets through the reduction of errors.
2- Showed that spatially explicit methods can improve the analysis of pollution sources and risks in the study area and Jordan. As well as the SCD representation and the statistical methods for assessment and representation and analyzing groundwater quality data can determine the extent of pollution in a cost-effective manner.
3- Provided a comprehensive analysis on the potential application of the DRASTIC model in arid areas.

7. SUMMARY

John F. Kennedy who said, "*anyone who can solve the problems of water will be worthy of two Nobel prizes - one for peace and one for science*".

The study demonstrates that intensive land use in arid areas imposes tremendous pressure on groundwater. The comprehensive investigations of the contamination loads, the potential protectiveness of the aquifers and the anthropogenic activities indicate that the contamination load is primarily attributable to agricultural activities and accompanied with a high susceptibility to contamination. This study, shows that remote sensing and GIS techniques are powerful tools in groundwater studies, providing possibilities for the use of vast spatial data, especially in the overlaying modelling techniques. And concluded that a significant proportion of the case study area is hazardous to contaminants, demonstrated by the vulnerability and nitrate contamination RISK Maps.

Groundwater vulnerability models are the most useful tools to simulate the various control factors that govern the surface contamination leaching process towards the aquifers. A study illustrating the significance of vulnerability models in dry areas, in the case of Jordan, and its contribution to groundwater sustainability. Two DRASTIC approaches (ordinary and agricultural DRASTIC) were performed with two scenarios. Sensitivity tests were applied to modify and examine the original theoretical weights and avoid the subjectivity in ratings and ranges of the parameters. Real parameters weights were calculated for the two scenarios in each DRASTIC approach by different methodologies rely on the (GIS) and using the extracted random points with the values of the seven rated DRASTIC parameters-maps. Long average and maximum concentrations of nitrate, sulfate, and salinity were used to assess the DRASTIC results since agriculture is the main source of pollution in the area. The comparison between the COP-model and the DRASTIC-model indicates the appropriate use of DRASTIC in arid areas.

The procedure, successfully applied in this study with a reasonably good match between the RISK map and the nitrate distribution in groundwater, appears to be accurate and has with the contamination load investigations a large potential to be applied worldwide.

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With my thanks, Osama MN Gazal,

Former Head of Environment and Climate Change Department at the MWI Jordan

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10. LIST OF APPENDICES

10.2 Appendices 1. Guideline values for chemicals from agricultural activities that are of health significance in drinking-water (WHO 2017b).

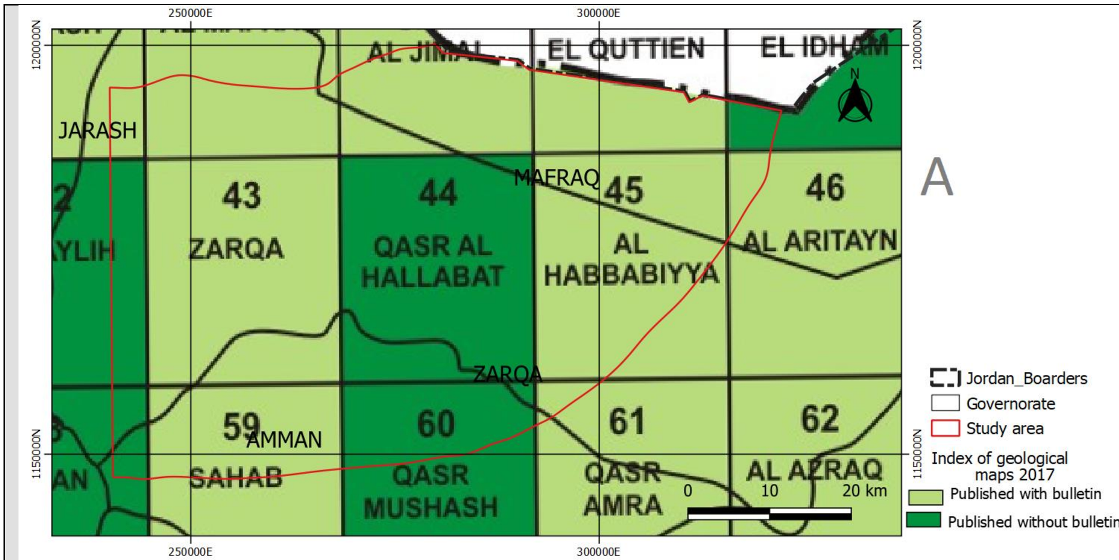
Chemical	Guideline value µg/l	Guideline value mg/l	Remarks
Non-pesticides			
Nitrate (as NO_3^-)	50 000	50	Based on short-term effects, but protective for long-term effects
Nitrite (as NO_2^-)	3 000	3	Based on short-term effects, but protective for long-term effects
Pesticides used in agriculture			
Alachlor	20[a]	0.02[a]	
Aldicarb	10	0.01	Applies to aldicarb sulfoxide and aldicarb sulfone
Aldrin and dieldrin	0.03	0.000 03	For combined aldrin plus dieldrin
Atrazine and its chloro-s-triazine metabolites	100	0.1	
Carbofuran	7	0.007	
Chlordane	0.2	0.000 2	
Chlorotoluron	30	0.03	
Chlorpyrifos	30	0.03	
Cyanazine	0.6	0.000 6	
2,4-D[b]	30	0.03	Applies to free acid
2,4-DB[c]	90	0.09	
1,2-Dibromo-3-chloropropane	1[a]	0.001[a]	
1,2-Dibromoethane	0.4[a] (P)	0.000 4[a] (P)	
1,2-Dichloropropane	40 (P)	0.04 (P)	
1,3-Dichloropropene	20[a]	0.02[a]	
Dichlorprop	100	0.1	
Dimethoate	6	0.006	
Endrin	0.6	0.000 6	
Fenoprop	9	0.009	
Hydroxyatrazine	200	0.2	Atrazine metabolite
Isoproturon	9	0.009	
Lindane	2	0.002	

10.3 Appendices 2. Jordanian standard of Non-Organic Chemical Substances that has an Effect on Public Health ((JISM) 2008).

Chemical Substance	Symbol	Permissible Level mg/liter
Arsenic	As	0.01
Lead	Pb	0.01
Cyanide	CN	0.07
Cadmium	Cd	0.03
Chrome	Cr	0.05
Barium	Ba	1.5
Selenium	Se	1.5
Boron	B	2.0
Mercury	Hg	0.002
Silver	Ag	0.1
Nickel	Ni	0.07
Antimony	Sb	0.005
Fluoride	Fl	2.0
Nitrite	NO2	2.0
Nitrate	NO3	50.0 *

* Maximum contamination level of 70 mg/liter is permissible in the absence of a public water source of better quality

10.4 List of the original (14) Geological maps of a scale 1:50000 used to create the study area geological map.



1. Natural resource authority, geological directorate, Geological mapping division, national mapping project, geological map of Umm al Jimal 3254-I Ahmad Al Gharaibeh 2003
2. Natural resource authority, geological directorate, Geological mapping division, national mapping project, geological map of Az Zarqa 3254-III by Mohammad Abu Qudaira 2001
3. Natural resource authority, geological directorate, Geological mapping division, national mapping project, geological map of Al Mafraq 3254-IV by Ahmad A. Smadi 1997
4. Natural resource authority, geological directorate, Geological mapping division, national mapping project, geological map of Sahab 3253-IV by Eyad H. Faddah 1988
5. Natural resource authority, geological directorate, Geological mapping division, national mapping project, geological map of Qasr Al Hallabat 3254-II by Ahmad Al Hayari 2004
6. Natural resource authority, geological directorate, Geological mapping division, national mapping project, geological map of Qasr Mushash 3253-I by Ahmad A. Smadi 1999
7. Natural resource authority, geological directorate, Geological mapping division, national mapping project, geological map of Umm El Quttein 3354-IV by Khaled Al Tarawneh 1999
8. Natural resource authority, geological directorate, Geological mapping division, national mapping project, geological map of Al Hamidiyya (Al Habbabiyya) 3345-III by Khaled Al Tarawneh 1996
9. Natural resource authority, geological directorate, Geological mapping division, national mapping project, geological map of Qasr Amra 3353-IV by Mohammad Abu Qudaira 2001
10. Natural resource authority, geological directorate, Geological mapping division, national mapping project, geological map of Deir El-Ka’hf (Jibal Abu El- Idham) 3354-I by Mohd Nawasra 1997
11. Natural resource authority, geological directorate, Geological mapping division, national mapping project, geological map of Al Bishriyya (Al Aritayn) 3354-II by Khalil M. Ibrahim 1996
12. Natural resource authority, geological directorate, Geological mapping division, national mapping project, geological map of Jarash 3154-I by Ghassan Abdelhamid 1993
13. Natural resource authority, geological directorate, Geological mapping division, national mapping project, geological map of Suwaylih 3154-II by Ali Sawariah and Majdi Barjous 1993
14. Natural resource authority, geological directorate, Geological mapping division, national mapping project, geological map of Amman 3153-I by Dr. Abdallah Diabat and Mohammad Abdelghafoor 2004

10.5 Appendix 3. examples of the soil profiles and soil units' descriptions in the study Area. Retrieved from the Ministry of Agricultural (1994):