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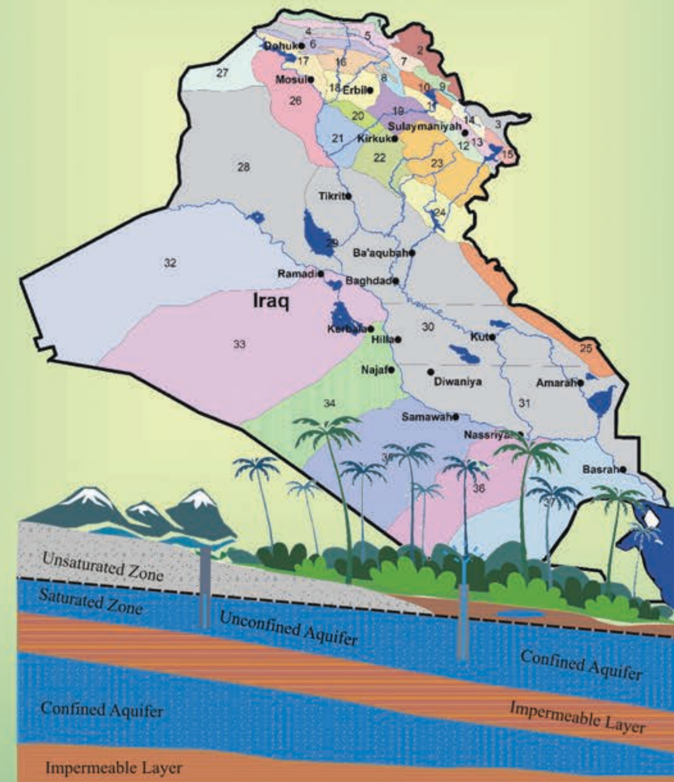
Ahmed Srdah Al-Zubedi

Al-Karkh University of Science
Remote Sensing and Geophysics College



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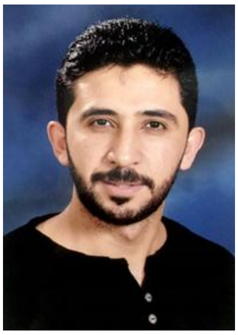

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In this book, Iraq has been divided into five hydrogeological regions and thirty-seven Hydrogeological areas based on the physiographic, tectonic, geological, and hydrogeological characteristics. The goal of this classification is incorporating the previous classifications more accurately in determining the characteristics of hydrogeological regions and their areas.

This book attempts to cover the hydrogeological conditions of Iraq to present the updated hydrogeological and hydrochemical data. Groundwater is one of Iraq's most important water resources, especially in the areas distant from surface water resources. It plays a significant role in people's livelihood by supplying water for drinking, irrigation, industrial and other purposes, particularly in Western, Southern Desert, and al Jazeera areas. In addition to large areas in the Kurdistan region, the Tigris and Euphrates rivers and their tributaries flow mainly in a narrow zone along the river valleys in the Kurdistan region and the Mesopotamian plain in central and southern Iraq. Therefore, this book is designed to study, analyze and discuss all available hydrogeological data to determine the hydrogeological conditions of the groundwater aquifers and their hydrogeological characteristics, such as aquifers extension, depths of the water-bearing layers, the direction of groundwater flow, recharge, and discharge zones, and water quality.

This book consists of five chapters. The first chapter provides an introductory but comprehensive description of the topographic, geological, hydrological, climatological, and hydrogeological conditions to facilitate knowledge of the groundwater setting of Iraq.

The second one is devoted to discussing and analyzing the previous hydrogeological classifications of Iraq to present a new classification and more accurate in determining the characteristics of hydrogeological areas in Iraq. The Hydrogeological Regions in North and East Iraq are covered in chapter three; it includes the hydrogeological and hydrochemical characteristics of aquifer systems in hydrogeological areas within these Regions. Chapter four is devoted to determining the hydrogeological conditions in Al-Jazira and Mesopotamia Hydrogeological Region. Finally, chapter five is designed to determine the hydrogeological conditions of the main aquifers in the Desert Hydrogeological Region. The book layout is designed to serve as a teaching manual for university students and staff members of groundwater exploration companies.

Author

Dedication

The Messenger of Allah Mohammed (peace be upon him and his family) said -:

When the human being dies, his deeds end except for three: ongoing charity, beneficial knowledge, or a righteous child who prays for him".

my lord, I beg you to make this work as a beneficial science and its reward is for me, Ahmed A. Oudah, Kaiwan K. Fatah, my parents, my brothers, my wife, my sons, my teachers, my friends and for all Muslims and believers....... and I hope it will be in the balance of my goods on the show day and accept these from us....... you are hearing and replying.

Ahmed

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Finally, I would like to direct my great appreciation to my family for their continuous support and encouragement, and I like to extend my great thanks to all who supported me during the conducting of this work.

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Chapter One
An Overview of Iraq Water Resources

Chapter One: - An Overview of Iraq Water Resources

1-1 Introduction

Groundwater is one of the most important water resources in Iraq, especially in the areas distant from surface water resources. It plays major role in the livelihood of people by supplying water for drinking, irrigation, industrial and other purposes, particularly in Western, Southern Desert, and al Jazeera areas, In addition to large areas in the Kurdistan region, where the Tigris and Euphrates rivers and their tributaries are flow mainly in a narrow zone along the river valleys in Kurdistan region and the Mesopotamian plain in central and Southern Iraq.

Tigris and Euphrates enter Iraqi territory from North and West, from Turkey and Syria, respectively. The flood period of these two rivers is during wet seasons, mainly in winter and spring. The main recharge source to these rivers is the rainfall and melting of the accumulated snow at highlands of mountainous areas. The main tributaries of the Tigris River in Iraq are represented by: Al-Khabour, Greater Zab, Lesser Zab, Al-Udhaim and Diyala Rivers. These tributaries are flowing within the Eastern (left) side of the Tigris River. They flow from outside of the Iraqi territory, except Al-Udhaim River, which originated totally inside Iraq. Whereas, the Euphrates River has no tributary inside Iraq, except the presence of intermittent Wadis at the right bank, flowing from the Western desert and are flooded during rainfall seasons, and especially after storm rainfall. The Tigris and Euphrates rivers merge together to form Shatt Al-Arab, which discharges into the Arabian Gulf.

In Iraq, groundwater occurs nearly at depths ranging from land surface to more than (700m) below the earth's surface within different aquifer systems. Some of this water comes out to the surface of the earth through springs. Most of these aquifer systems were formed within carbonate rocks, and few of them were formed in clastic rocks. These aquifers have been penetrated by more than (150) thousand groundwater wells. The discharge of these wells represents (14%) of the national water resources in Iraq, according to reports of the General Commission for Ground Water.

The annual rate of national water resources in Iraq is nearly (60.00 billion m^3/year), including surface water and renewable groundwater, while consumption quantity reaches to (70 billion m^3/year). So, during the last few decades, a critical scarcity of water has occurred in Iraq, due to climate changes and shortage of surface water supply as a result of retaining water to the Tigris and Euphrates rivers within the neighboring countries. Therefore, the present work attempts to evaluate the groundwater resources in Iraq on a regional scale to detect their quantities and qualities and to determine their suitability and sustainability for different purposes.

This chapter provides an introductory but comprehensive description of the topographic, geological, hydrological, climatological, and hydrogeological conditions to facilitate knowledge of the groundwater setting of Iraq to discuss in the following chapters.

1-2 Location and Topography

Iraq is located Southwestern Asia between six countries: Turkey in the North, Iran in the East, Syria in the Northwest and West, Jordan in the west, Saudi Arabia in the West and Southwest and Kuwait in the South. During antiquity, lands that now constitute Iraq were known as Mesopotamia “Land between the Rivers”.

Iraq occupies a total area of (437,072 Km^2). Land forms (432,162 Km^2), while water forms (4,910 Km^2) of the total area, and it has (58 km) of coastline along the Northern end of the Arabian Gulf, as shown in figure (1-1).

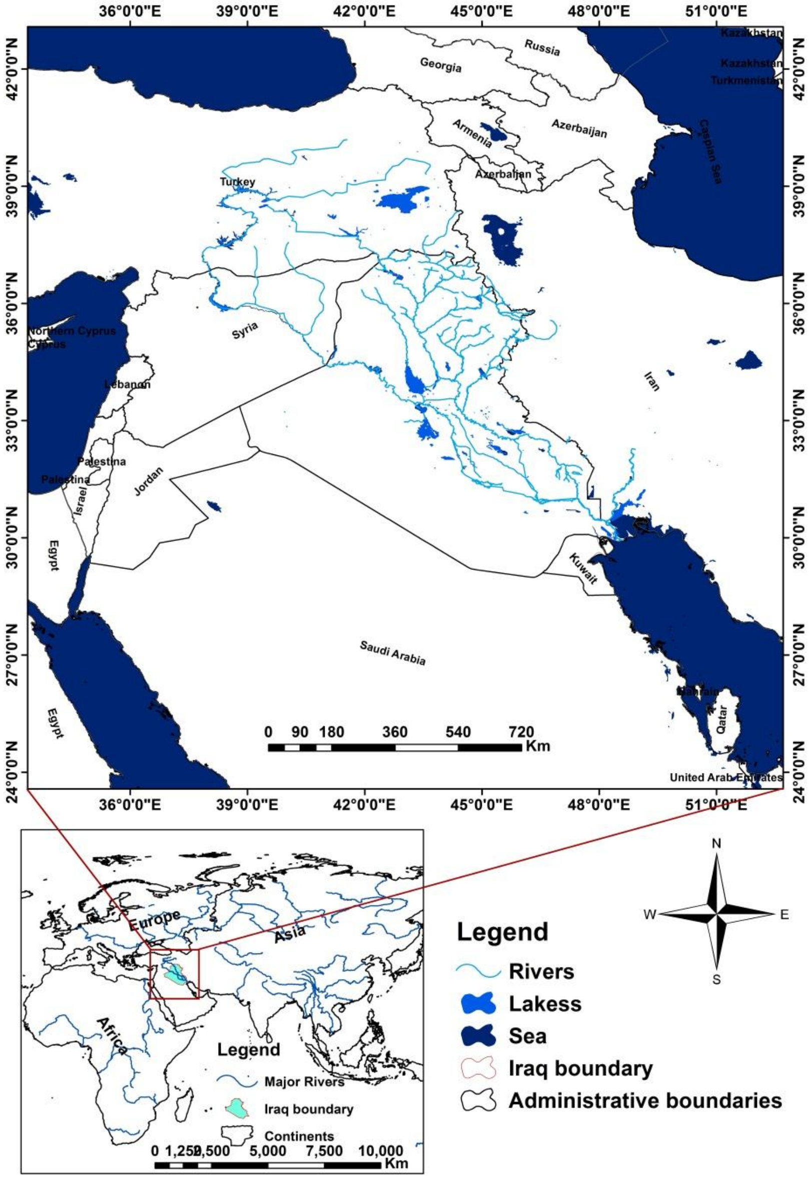

Figure (1-1):- The location map of Iraq.

Topographically, Iraq is shaped like a basin, consisting of the Mesopotamian plain of the Tigris and the Euphrates rivers. This plain is surrounded by mountains in the North, Northeast and East, which can reach altitudes to more than (3000m) above sea level, and by desert areas in the south and west, which account for over (40%) of the land area, (Fao, 2008). It is an upland region with altitudes of (100 to 900m), above sea level declines gently toward the Euphrates River. Ground elevations started from sea level in Faw district South Basra, and rose to (3661 m) above sea level in Cheekha Dar Mountain on the Iraq - Iran border in the Zagros mountain range of Kurdistan, as shown in figure (1-2).

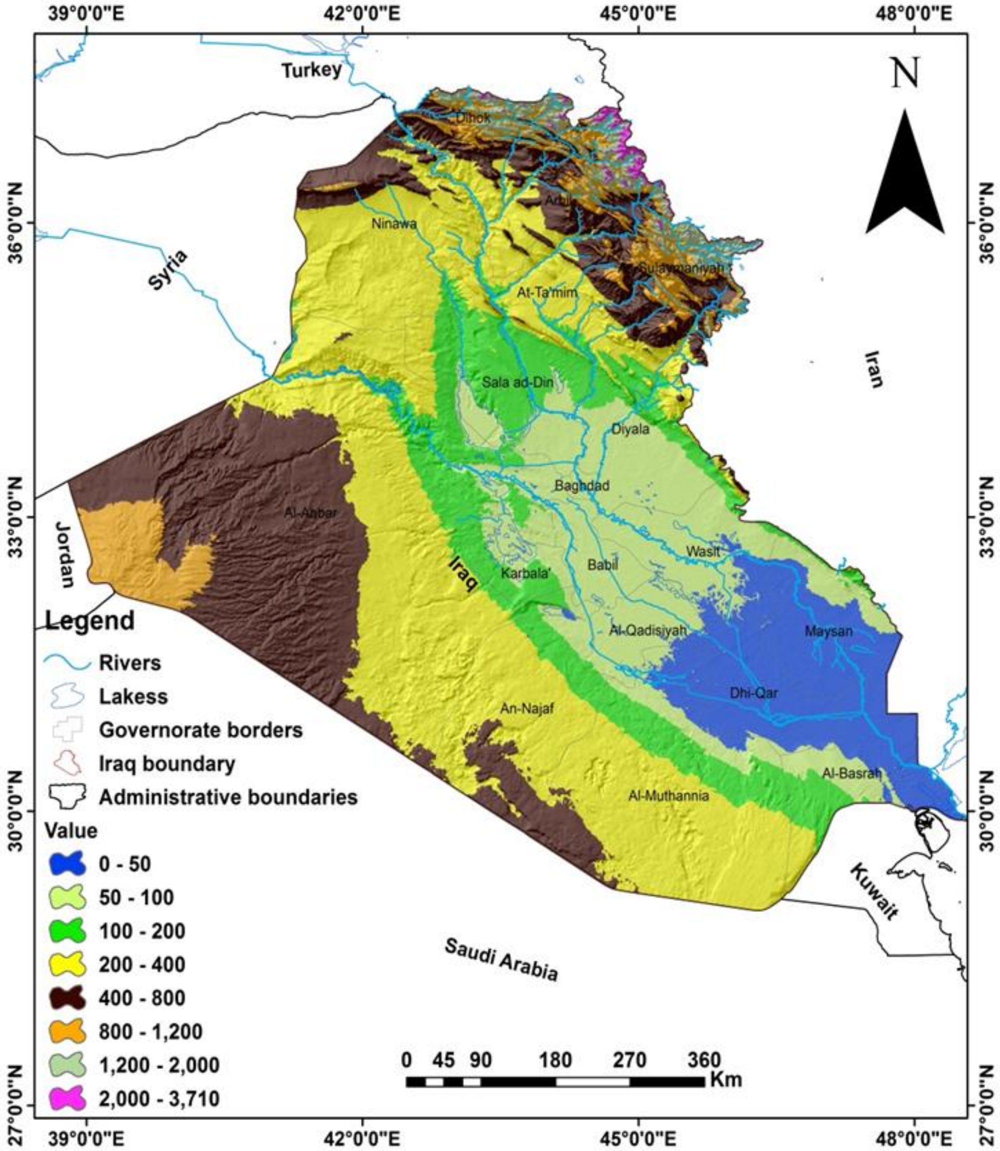

Figure (1-2):- Topographic map of Iraq.

Iraq has been divided into seven physiographic Zones according to Al-Khalaf J. M., (1959). Each zone has its specific topographic, geological, hydrological and climatological conditions, (Al-Jiburi and Al-Basrawi, 2015), as shown in figure (1-3). The general topographic information of these zones is as follow:

A- Suture and Thrust Zone

This zone represents the mountains of North and North Eastern Iraq and occupies a small area about (1.32%) of the total area of Iraq, (Al-Madhlom, et. al., 2020). In addition, this zone contains the highest mountain peak in Iraq, Cheekha Dar Mountain on the Iraq - Iran border in the Zagros mountain range of Kurdistan that reaches maximally (3661m) above sea level.

B- The High Folded Zone

The High Folded Zone is characterized by rugged topography, deep canyons and narrow valleys with defined mountainous structures. This zone covers (4.82%) of Iraq territories is bounded from the North and Northeast by the Suture and Thrust Zone and from the South and Southwest by the Low Folded Zone, (Al-Madhlom, et. al., 2020). They are two main topographical parts in this region, the elevated mountain parts and the flat and adulatory parts. These two topographical parts are parallel the main strikes NW-SE and SE-NW, (Sissakian et. al., 2014b).

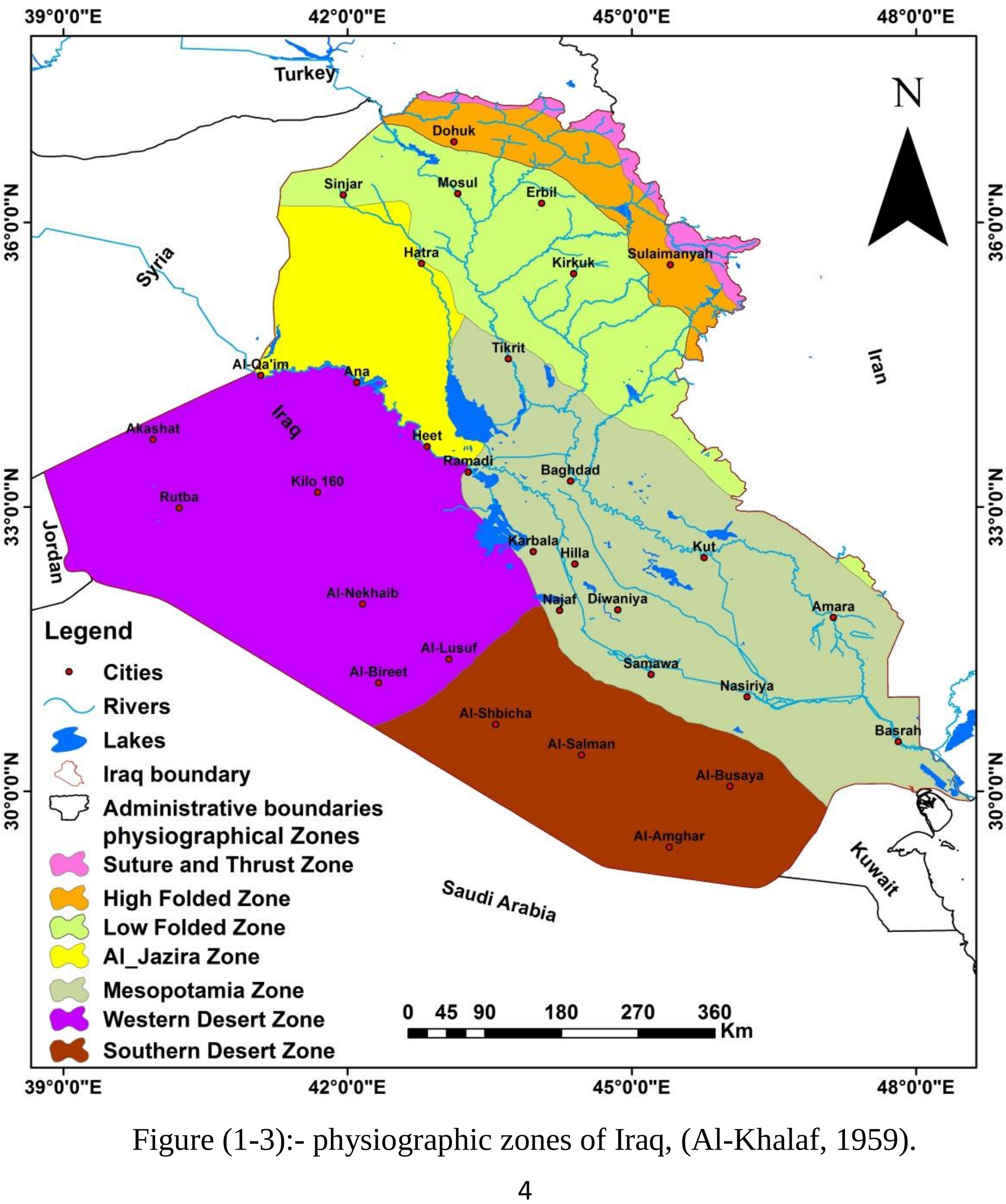

Figure (1-3):- physiographic zones of Iraq, (Al-Khalaf, 1959).

C- The Low Folded Zone

This zone covers about (13.20%) of the total area of Iraq, and it has an area of (56930 km^2) (Yacoub et al., 2012). It extends in the central Northern and Northeastern parts of Iraq and is bounded from the North and Northeast by the High folded Zone, and the South and Southwest by Mesopotamia and Al-Jazira zones.

The topographic surface of this zone generally rises in elevation from its Southwestern boundary about (125 – 300m) above sea level towards the North and Northeastern boundaries (900 – 1000m) above sea level. The Sinjar Mountain represents the most prominent hill in this zone, whose highest peak reaches an elevation of (1462m) (Yacoub *et al.*, 2012).

D- Al-Jazera Zone

Al-Jazira Zone is located in the central Northwestern part of Iraq between Euphrates and Tigris Rivers. It covers about (29270 km^2), which represents about (8.1%) of the Iraq area. This region is sloping towards the South. The lowest elevation is (50m) above sea level, and the highest elevation is (400m) above sea level (Ma'ala, 2009a).

E- Mesopotamia Zone

This zone is located between the Tigris, and Euphrates Rivers extends from Tikrit city in the North to Faw city on the Arabian Gulf coastline in the South. This zone covers more than (116,000 km^2), representing about (27.48%) of the area of Iraq. It is characterized by its very gentle slope from the North towards the South. The highest elevation of this zone is about (140m) above sea level in the Fatha area, and the lowest elevation is less than 1m above sea level in the extreme Southeastern margin near the Arabian Gulf (Yacoub, 2011).

F- The Western Desert

This zone represents about (27.22%) of the Iraq area and covers about (104000 km^2). The Northwest Iraqi-Syrian border borders it and the Euphrates River from the North and Northeast, Iraqi-Jordanian and Iraqi-Saudi Arabian borders in the West and Wadi Al-Khir in the South (Sissakian and Mohammed, 2007). This zone rises gradually from east to west with a gentle slope of (5m/km) toward the east and the northeast. The prominent topographic features are some positive features (mesas and buttes), cliffs, canyons, major valleys and depressions. The positive features are represented by Jabel Anah, in the North and Jabel Aneiza, in the West (Hamza, 2007).

H- The Southern Desert

This zone covers about (76000 km^2), which represents about (16.81%) of the total Iraq area. It extends from the Euphrates River, in the North and Northeast, and Wadi Al-Khir in the Northwest to the Iraqi – Saudi Arabian borders in the South, Southwest and the Iraqi – Kuwaiti borders, in the Southeast, (Ma'ala, 2009c). It forms relatively flat terrain, sloping gently towards the East and

Northeast. The elevated parts extend along the Iraqi – Saudi Arabian borders (300 – 400m) above sea level, while the apparent lowest part (20 – 50m) above sea level along the Euphrates River, (Jassim and Al-Jiburi, 2009).

There is another topographic classification carried out by Al-Ansari (2020), as shown in figure (1-4).This classification is based on the nature of the land terrain, and divide the topography of Iraq into four regions as follow:-

1- Mountain Region
2- Plateau and Hills Region
3- The Mesopotamian plain
4- Jazera and Western Plateau

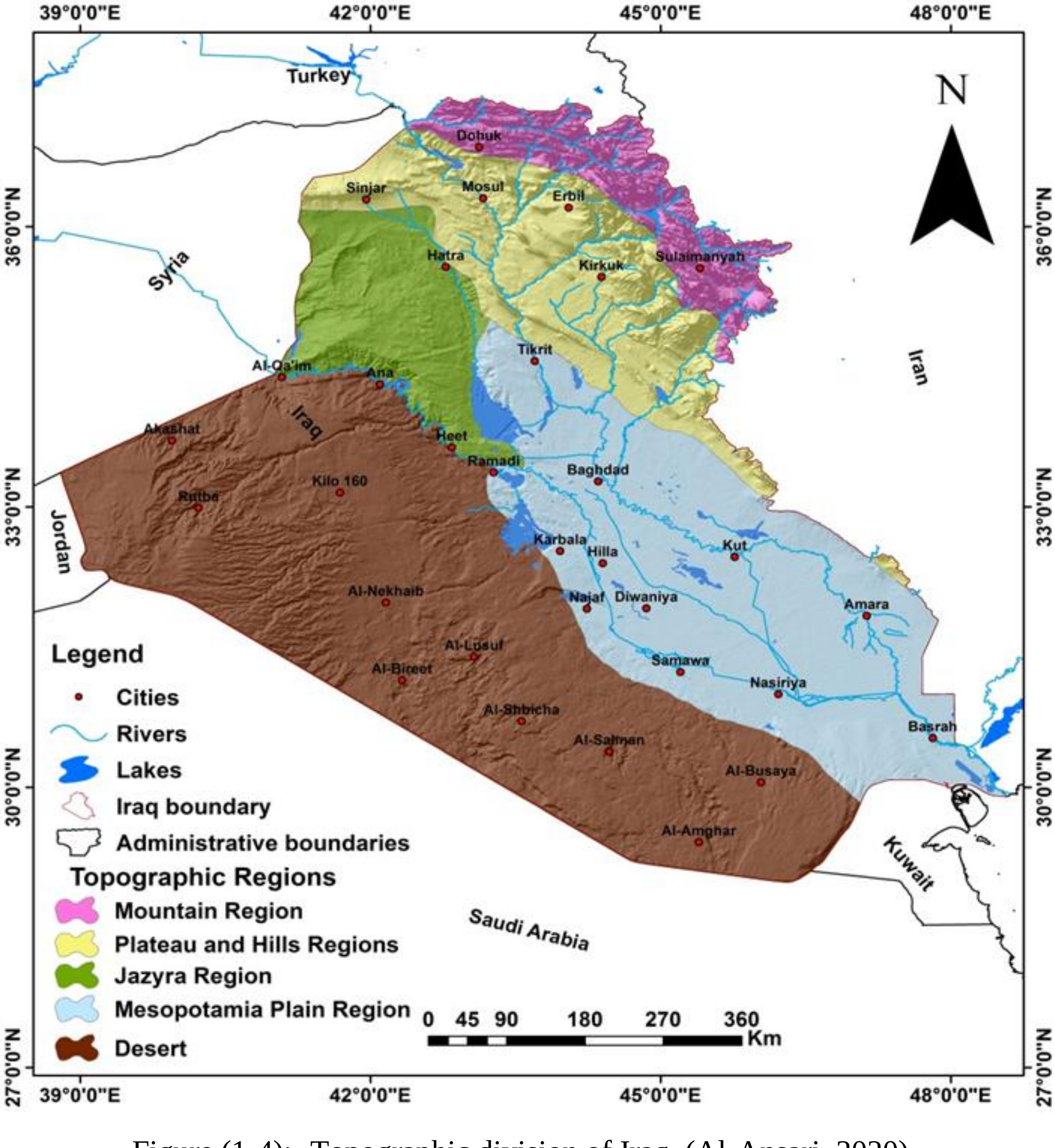

Figure (1-4):- Topographic division of Iraq, (Al-Ansari, 2020).

1-3 Surface Geology of Iraq

Surface Geology of Iraq has been reviewed and redefined according to Jassim and Buday in Jassim and Goff, (2006). The exposed geological Formations and sediments on the surface of Iraq are extended, age wise, from Quaternary period to Paleozoic period, as shown in figure (1-5).

The surface geological map shows that the Paleozoic succession appears in small areas north and west of Iraq. The Khabour Formation is the oldest exposed rock unit in Iraq in Cambro – Ordovician age (Baban and Lawa, 2016). In contrast, Ga’ara Formation (Permian) is exposed in Western Iraq, and it is considered the main aquifer in this area. The Triassic and Jurassic successions are also exposed in western Iraq's central part, represented by Mulosa, Zor Houran, Ubaid, Hussainite, and Amej Formations.

The outcrops of the Cretaceous sediments are exposed mainly in three parts. The first part is located in north and northeastern Iraq.

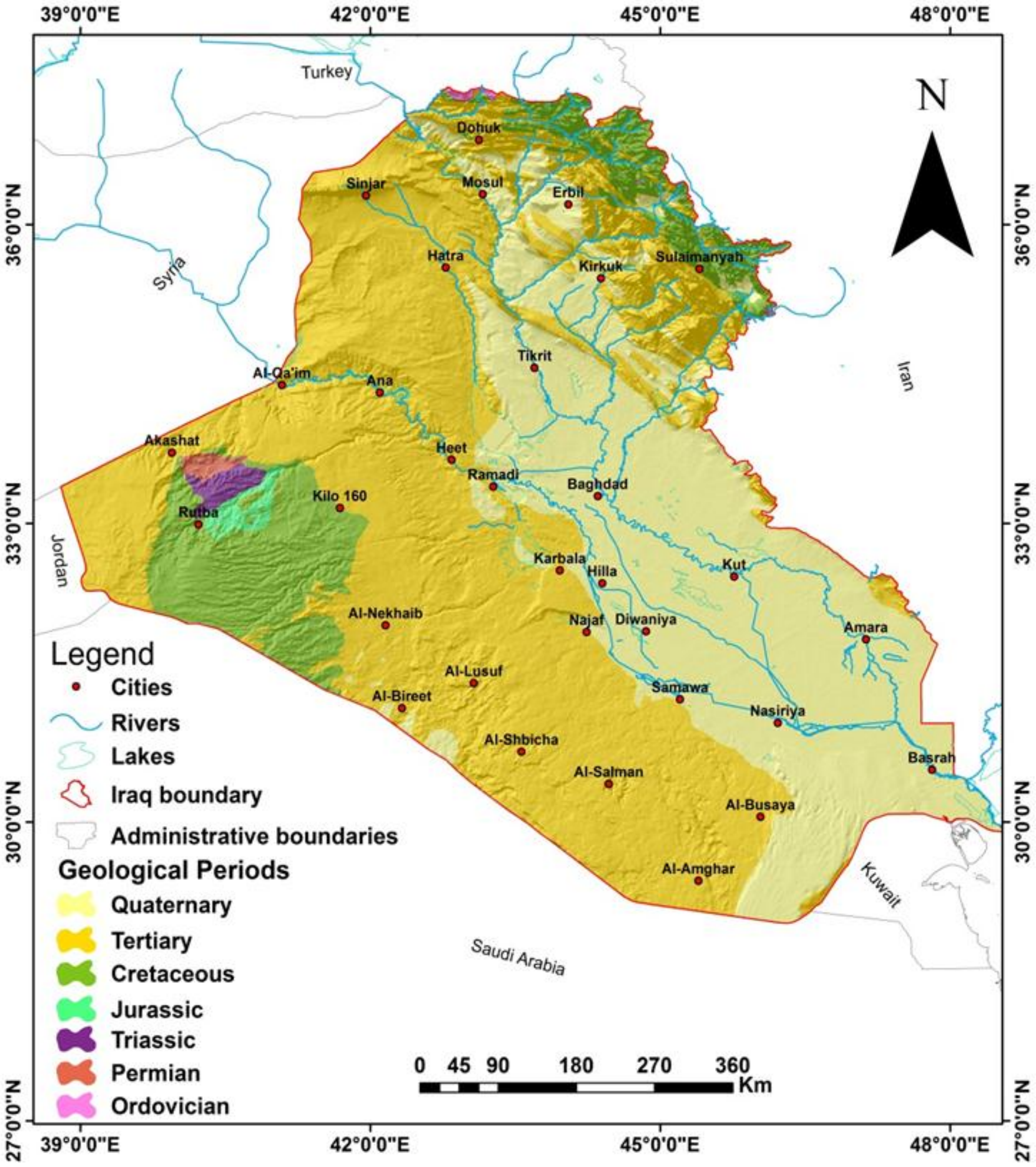

Figure (1-5):- Surface Geology map of Iraq.

The second part represents a very small area and is located in Northeastern Iraq near Sinjar Mountain. The third part is located in the Western part of Iraq and is extended until the Iraqi-Saudi border.

Tertiary successions cover all parts of the Iraq surface. They appear in the Northeastern and Northwestern parts and all the Western and Southwestern regions of Iraq, as they appear in very small areas in Eastern Iraq. Quaternary sediments of the Tigris and Euphrates Rivers with their tributaries and distributaries cover the area located in central and Eastern Iraq and some parts in North and West, as shown in figure (1-5).

1-4 Tectonic Setting of Iraq

Tectonically, most of the Iraq zone is located within the Northeastern part of the Arabian plate except for a very small area in the extreme Northeast part of the country named Shalair Terrane that extends within the Eurasian (Iranian) plate,(Fouad,2015). There are two tectonic divisions of Iraq currently being adopted in research into tectonic setting of Iraq. The first done by Jassim and Buday, 2006 in Jassim and Goff, (2006), and the second carried out by Fouad, (2015).

Jassim and Buday, 2006 in Jassim and Goff, (2006) proposed tectonic divisions based on concepts of plate tectonic theory. In this tectonic division, Iraq is divided into three tectonic different areas: the Stable Shelf, Unstable Shelf and Zagros Suture. These areas are further divided into subdivision zones, as follows:-

A- The Stable Shelf
- 1- Rutba – Jezira Zone
- 2- The Salman Zone
- 3- Mesopotamian Zone
  - a- Zuber Subzone
  - b- Tigris Subzone
  - c- Euphrates Subzone

B- Unstable Shelf
- 1- Foothill zone
  - a- Makhule – Hemrine Subzone
  - b- Butmah – Chemchemal Subzone
- 2- High folded Zone
- 3- Balambo – Tanjero Zone
- 4- Northern Thrust (Ora) zone

C- Zagros Suture
- 1- Qulqala – Khwakurk Zone
- 2- Penjwen – Walsh Zone
- 3- Shalair Zone

Fouad, (2015) proposed different tectonic divisions based on concepts of plate tectonic theory also. In this tectonic division, Iraq is divided into two main tectonic units: the outer and inner Arabian platforms. The outer platform is unstable and includes the Zagros Fold-Thrust belt and the Mesopotamia Foredeep. While the inner platform is stable and covers the West and South desert of Iraq, which is a part of the Arabian platform, (Abdulnaby, 2018), as shown in figure (1-6). In both classifications the boundary between the two major tectonic parts is considered to be Anah – Abu Jir – Euphrates fault system. Based on tectonic – sedimentary basins, Mohammed *et al* ., (2021) divide Iraq into Zagros Fold – Thrust Belt and the Mesopotamia Foreland Basin (wege top – fordeep - fore bluge – back bluge zones) as a part of Arabian – African foreland basins due to Arabian – Eurasia collision sine Late Cretaceous to present.

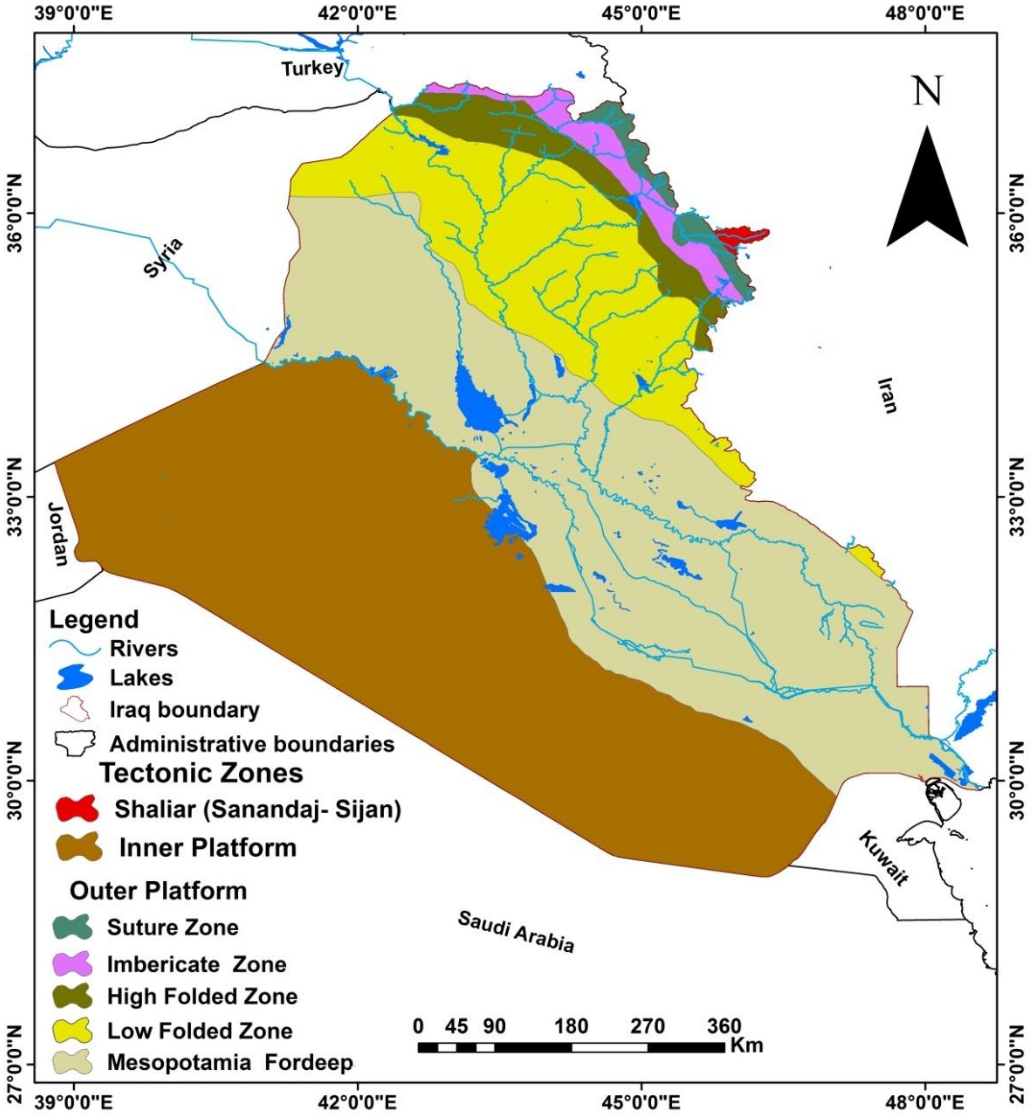

Figure (1-6):- Tectonic divisions of Iraq (after Fouad, 2015).

1-5 Water Resources and Climate in Iraq

Surface water represents the main water resource of Iraq. Euphrates River, and Tigris River and its tributaries are the backbone of the water resources in Iraq (86 %) while the remainder of water resources (14%) comes from groundwater resources, either shallow or deep groundwater aquifers, (Yousuf, et al., 2018). Both Rivers are joining together in the South part of Iraq to create Shatt Al-Arab that drains towards the Arabian Gulf, as shown in figure (1-7). The average annual flow of the Euphrates and Tigris River of the period from (1986 – 2020) is about (40 km^3), while the average annual flow of their tributaries is about (20.7 km^3) for the same period (Al-Ansari, 2021). Most of this water comes from Turkey (71%), Iran (16.9%), Syria (4.1%) and (8%) internal sources. The total annual rate of surface water in Iraq is in the range of about (35 – 55 km^3) depending on the annual rate of rainfall. All the water flowing in the Euphrates River comes from the outside of Iraqi borders, while more than (65%) of the Tigris water comes from outside sources. There is no tributary inside Iraq for Euphrates River, except the water of some intermittent Wadis that flows after storm rainfall to this River (Al-Jiburi and Al-Basrawi, 2015). Al-Khabour, Greater Zab, Lesser Zab, Al-Udhaim and Diyala rivers are represented the main tributaries of the Tigris River in Iraq. These tributaries flow from outside of the Iraqi territory, except Al-Udhaim River, which originates from inside Iraqi territory.

The second source of water resources in Iraq is groundwater. It is represented by more than (26) aquifers, including shallow and deep aquifers, confined and unconfined aquifers.

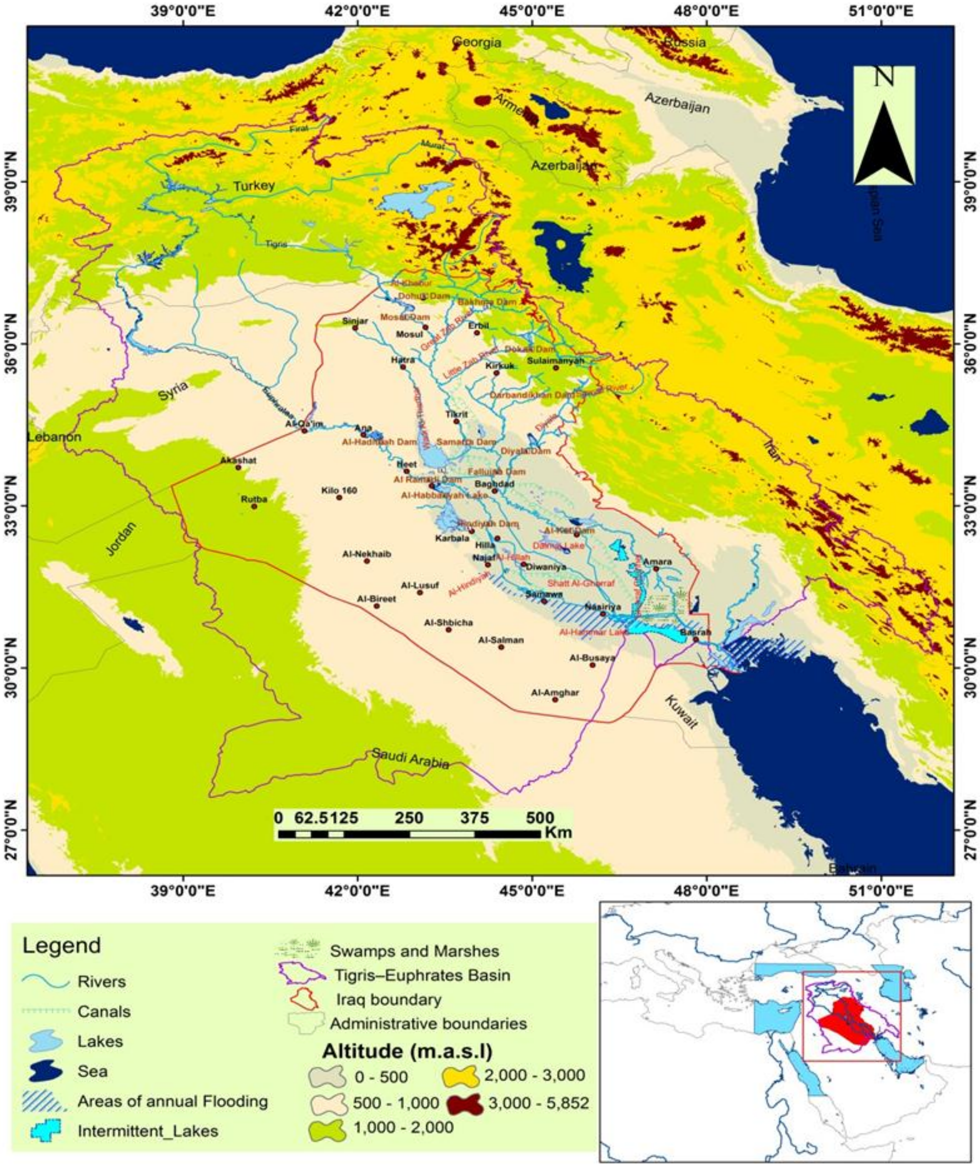

Figure (1-7):- Shows Tigris and Euphrates Rivers and their tributaries.

The geographic distribution of these aquifers includes most of the Iraqi regions, from North to South and from East to West.

Groundwater is invested in these aquifers in two methods, the first is natural, and the second is man-made. The natural source for investing groundwater in Iraq are springs that are widely spread in Northern Iraq and West of the Euphrates River along the Abu Jir – fault. The man-made groundwater investment includes the hand-dug wells, Kahariez channels, and drilled wells where the first mechanical well was drilled in (1935). Despite the presence of the Tigris and Euphrates rivers and their tributaries, groundwater is the main source of water in many Iraqi regions faraway from surface water resources, such as the Northern region and the Iraqi desert. However, during the three last decades the groundwater exploitation has increased significantly to compensate for the shortage in surface water due to climate changes and decrease the main rivers flows with increase the hydraulic structures in the neighboring countries, especially Turkey. Therefore, the number of drilled wells increased in Iraq to reach (130) thousands in (2020) according to the statistics of the General Commission of Groundwater (G.C.W.G).

According to Yousuf, et al., (2018), the researches carried out in North Iraq shown that the drawdown of groundwater levels in Duhok city was approximately (3.79 m) in confined aquifers and (7.09 m) in unconfined aquifers in (2010). As for the Aqra-Bardarash basin, the groundwater levels declined by (4.78 m) in the Eastern part, and (4.13 m) in the Western part of the Khazir River. The groundwater level in the Erbil plain had decreased by approximately (30 m) in some areas. In some regions of the Sulaimaniyah governorate, the groundwater level decreased by up to (50 m). With regard to central and Southern Iraq, groundwater levels decreased to more than (2m) in southern Iraq, especially in the Southern desert, as well as to more than (4 m) in parts of the Western Desert and to more than (2 m) in the eastern part of central Iraq during the last ten years.

Climaticity, which depends largely on the geographic location, is the main factor controlling the hydrological cycle (Wilson, 1983). The amount of rainfall, its geographical spread, and changes in temperature degrees are among the most important factors affecting the abundance of water resources in any region of the world. So, the hydrology and hydrogeology conditions of any area depend mainly on the climate and on topography and geology.

A critical scarcity of water has occurred in Iraq due to climate change and water projects in Turkey and Syria as well as the mismanagement of water resources. With regards to climate change, Iraq has witnessed successive droughts due to the scarcity of rain and high temperatures. The amount of rainfall in Iraq is significantly change depending on the geographic location and topographic elevations, where it varies from (1000 mm/year) in the far Northeastern part to less than (100 mm/year) in the Southwestern parts, as shown in figure (1-8).

The mean annual rainfall, temperature, and Evaporation for the period (1979 – 2014) are drawn as maps based on the data recorded in different meteorological stations (Iraqi Organization for Meteorological Information, (2015). They are shown that the mean annual rainfall in Iraq ranges between (69 – 970 mm/yr), the means annual temperature ranges between (14.7° – 26.6º C) and the mean annual evaporation ranges between (2062 – 4114 mm) as shown in figure (1-8).

According to Khayyun and Mahdi (2020) the climate change conditions for the period of (2020–2050) will cause the decline in rainfall by (6.247%), and a decline in groundwater levels by an average of (1.8–4.8 m) will occur for the upper zone of Iraqi aquifers over the next (31 years).

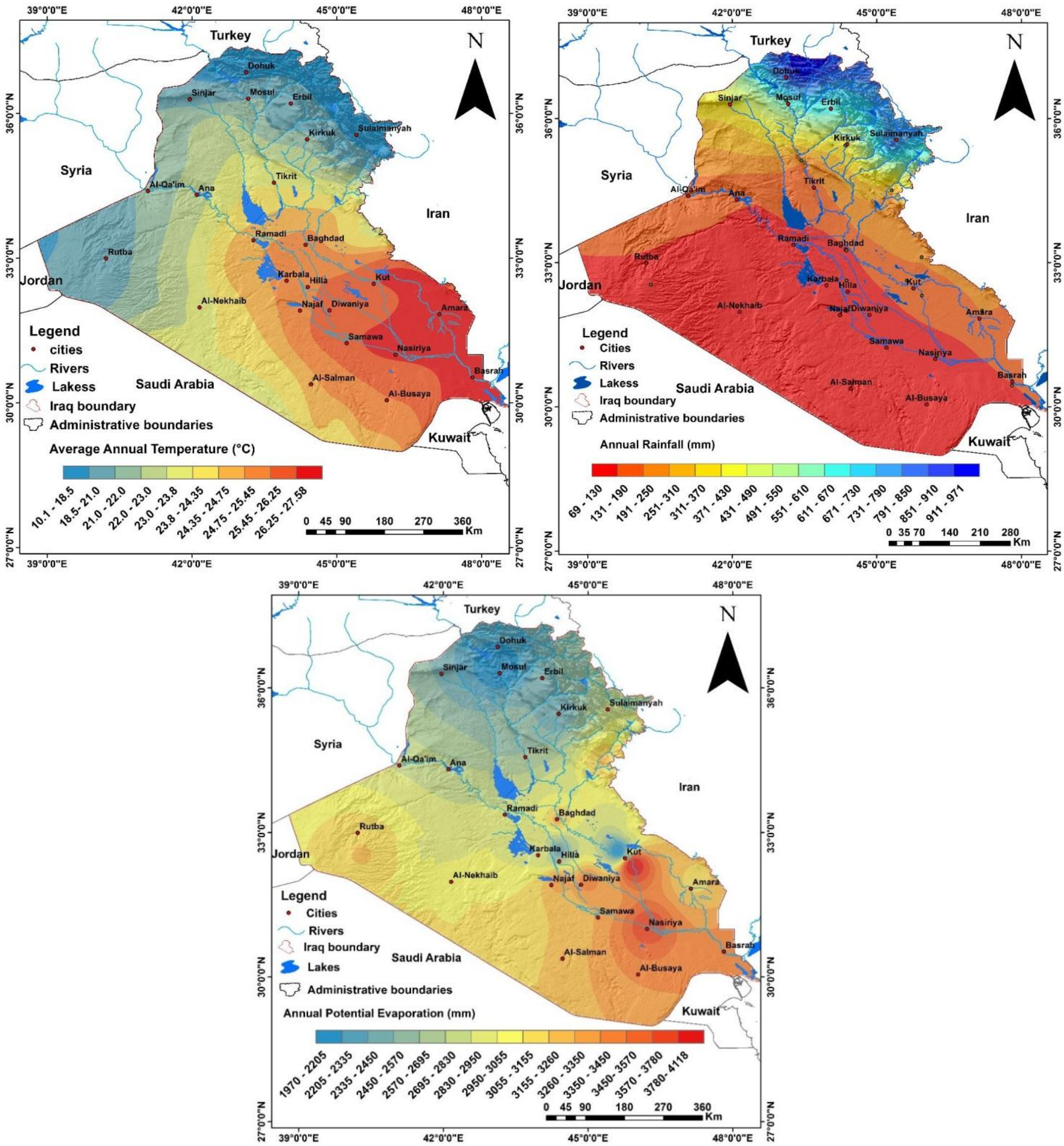

Figure (1-8):- Mean annual values of rainfall, temperature, and Evaporation maps of Iraq.

1-6 Groundwater in Iraq

In general, groundwater is the water present beneath Earth's surface in rock and soil pore spaces and in the fractures of rock formations. A unit of rock or an unconsolidated deposit is called an aquifer when it can yield a usable quantity of water. The depth at which soil pore spaces or fractures and voids in rock become completely saturated with water is called the water table, as shown in figure (1-9).

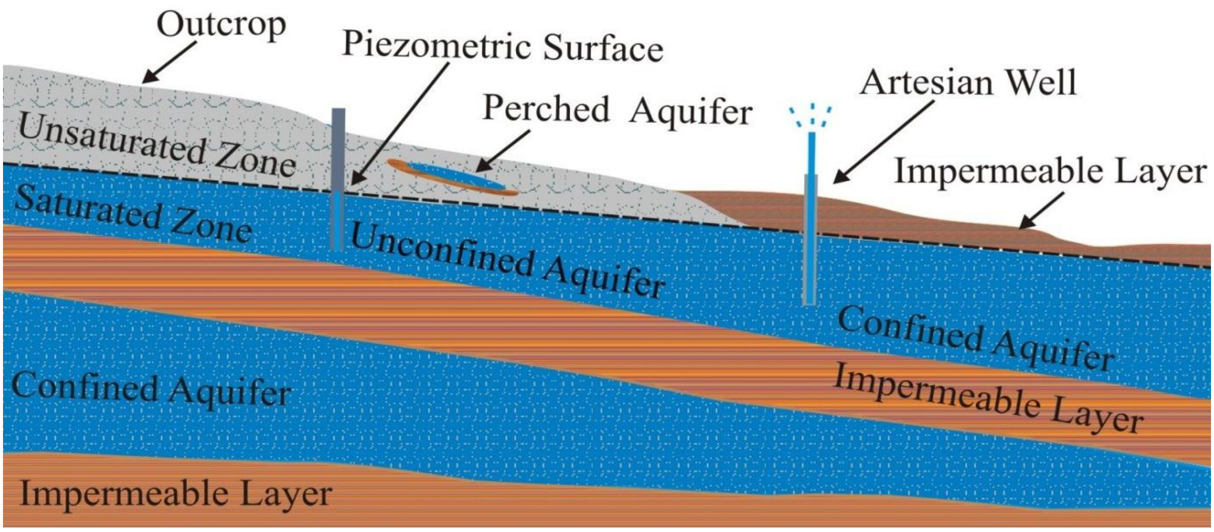

Figure (1-9):- Schematic showing water table, saturated zone, unsaturated zone and aquifer types.

The water table is located between two zones, the first one is an unsaturated zone and the second is the saturated zone. The unsaturated zone is the area between the surface and the water table. In this zone, the spaces and fractures within the soil, sediment and rock are filled with both air and water. It is divided into three sections, the soil zone or root zone, the intermediate zone and the capillary zone. In the saturated zone all spaces and fractures are completely filled with water; if it readily transmits water to wells or springs, it is called an aquifer.

The groundwater in Iraq occurs in two main types of aquifers, confined and unconfined. A confined aquifer is a permeable unit of rock or Sediment that is overlain by a confining layer that restricts movement of water into another aquifer. Groundwater in confined aquifers can be under high pressure because of the confining layer on top and bottom of the aquifer and the recharge zone is higher in the catchment. Therefore, when a borehole penetrates the confined aquifer the water level (Piezometric or potentiometric surface) will rise to a level higher than the top of the aquifer under the effect of the high hydrostatic pressure, and the well is described as an artesian well, as shown in figure (1-9).

The main confined aquifers in Iraq within carbonate rocks are Dammam and Umm Er Radhuma aquifers that are located in some parts of Western and Southern desert, while in the clastic rocks are Mukdadiya and Bai Hassan aquifers in the Northern and Eastern parts of Iraq.

An unconfined aquifer is a permeable unit rock or Sediment that is not overlain above by impermeable layer, so the surface of the saturated zone is at atmospheric pressure. In this type of aquifer the water table at the top saturated zone is free to rise or fall within the sediment or formation, depending on how much water is stored there. In a borehole penetrating an unconfined aquifer the water level will be at the same depth as the water table in the aquifer .So, it is also called water table aquifer, as shown in figure (1-9). At all events, most aquifers in Iraq are unconfined.

There is a special case of an unconfined aquifer referred to as a perched aquifer that occurs above the water table and is generally a relatively small body of water that lies above an impermeable layer within an unsaturated zone, as shown in figure (1-9). This type is common in most parts of Iraq, especially in Mesopotamian Plain.

Depending on their physical characteristics of geological materials, aquifers can be classified into unconsolidated, consolidated sedimentary and karstic -fractured rock aquifers. Unconsolidated aquifers composed of silts, sands and gravels. They are found in river valleys, deltas and lakes, (Khare, et. al., 2017), like aquifer in recent sediments in Mesopotamia zone. Consolidated aquifers are generally available in sandstone, such as Bai Hassan aquifer. As for karstic - fractured aquifers can be found in carbonate rocks, where groundwater is found and moving in the fractures, joints or cracks, for example Pila Spi, Sarmord, Tayarat, Umm Erdhumah and Dammam aquifers.

Based on the above classifications of aquifers, the hydrogeological studies that were carried out in Iraq have distinguished the following aquifers in Iraq, as shown in table (1-1).

Table (1-1):- Main Hydrogeological Information of Aquifers Occurs in Iraq.

No.	Aquifer	Type of Aquifer	Water Bearing Strata	Location	Age
1	Alluvium	Mostly Unconfined Semi-Confined or Confined	Gravel, Sand and Silt	Most parts of Iraq	Quaternary
2	Dibdbba	Mostly Unconfined	Pebbly Sandstone and Sandstone	Southeastern Part of the Southern Desert and Karbala – Najaf Plateau	Pliocene – Pleistocene
3	Bai Hassan (Upper Bakhtiari)	Partly Confined	Sandstone	Low Folded Zone and Mesopotamia Zone	Pliocene – Pleistocene
4	Mukdadia (Lower Bakhtiari)	Partly Confined	Pebbly Sandstone, Sandstone and Siltstone	Low Folded Zone and Mesopotamia Zone	Late Miocene - Pliocene

5	Injana (Upper Fars)	Mostly Unconfined	Sandstone and Siltstone	Low Folded Zone, Al-Jazira Zone and Northeastern Part of the Western Desert	Late Miocene
6	Fatha (Lower Fars)	Mostly Unconfined	Karstic Fracture Carbonate Rocks	Low Folded Zone, Al-Jazira Zone and Northeastern Part of the Western Desert	Middle Miocene
7	Char Equivalent of Euphrates	Partly Confined	Sandstone, Pebbly Sandstone and Limestone	Southeastern Part of the Southern Desert	Early Miocene
8	Euphrates	Mostly Unconfined	Karstic Fracture Carbonate Rocks	Al-Jazira Zone and Middle Part of the Western Desert	Early Miocene
9	Dammam	Mostly Unconfined	Karstic Fracture Carbonate Rocks	Western and Southern Desert	Early – Late Eocene
10	Pila Spi	Partly Confined	Karstic Fracture Carbonate Rocks	High Folded Zone, Low Folded Zone	Middle Late Eocene
11	Sinjar	Partly Confined	Karstic Fracture Carbonate Rocks	High Folded Zone, Low Folded Zone	Middle Paleocene-Early Eocene
12	Khurmala Equivalent of Sinjar	Partly Confined	Karstic Fracture Carbonate Rocks	High Folded Zone and Low Folded Zone	Middle Paleocene-Early Eocene
13	Umm Er Radhuma	Mostly Confined	Karstic Fracture Carbonate Rocks	Western and Southern Desert	Middle – Late Paleocene
14	Akashat Equivalent of Umm Er Radhuma	Mostly Confined	Karstic Fracture Carbonate Rocks	Western Part of the Western Desert	Middle – Late Paleocene
15	Qamchuqa	Confined	Karstic Fracture Carbonate Rocks	High Folded Zone	Early – Late Cretaceous
16	Sarmord	Partly Confined	Karstic Fracture Carbonate Rocks	High Folded Zone	Early – Late Cretaceous
17	Dokan	Partly Confined	Karstic Fracture Carbonate Rocks	High Folded Zone	Late Campanian – Early Maastraichtian
18	Aqra–Bekhme	Partly Confined	Karstic Fracture Carbonate Rocks	High Folded Zone and Low Folded Zone	Late Campanian – Late Maastrichtian
19	Tayarat	Confined	Karstic Fracture Carbonate Rocks	Western and Southern Desert	Late Maastriachtian
20	Kometan	Confined	Karstic Fracture Carbonate Rocks	High Folded Zone	Turonian – Early Campanian
21	Hartha	Confined	Karstic Fracture Carbonate Rocks	Western Part of the Western Desert	Late Campanian – Early Maastraichtian
22	Rutbah	Unconfined	Sands and Sandstone	Western Part of the Western Desert	Late Cretaceous, Cenomanian
23	Muhaiwir	Unconfined	Karstic Fracture Carbonate Rocks	Western Part of the Western Desert	Middle Jurassic

			and Sandstone		
24	Mulussa	Mostly Confined	Karstic Fracture Carbonate Rocks	Western Part of the Western Desert	Late Triassic
25	Ga`ara	Mostly Confined	sandstones	Western Part of the Western Desert	Early – Late Permian
26	Suffi	Confined	Sandstone and Carbonate Rocks	Northwestern Parts of the Western Desert	Middle Permian

There are many water-bearing Formations in the Iraq that are not considered as main productive aquifers because of their low productivity with limited extension, such as Chia Zairia , Naokelekan, Ubaid, Anah, Sheikh Alas, Amij, Hussainiyat and Zahrah Formations.

1-7 Hydrogeological Studies in Iraq

The database for the present work was obtained from many studies that carried out to determine the hydrogeological conditions of the groundwater aquifers and their hydrogeological characteristics in Iraq. Where the all data were collected analyzed, and discussed to determine the hydrological conditions of the groundwater aquifers and their hydrological characteristics within whole hydrogeological zones and basins.

The first inclusive hydrogeological study in Iraq carried out by the Parsons Company and published with 13 volumes between 1955 and 1957. Between 1973 and 1975, some researchers presented important studies of groundwater in Iraq, such as Elerdashvili (1973), Marinov *et al*., (1974) and Riykov *et al*., (1975).

In the period between 1970 and 1989, the most important regional hydrogeological studies were carried out for the 8 blocks of the desert and Al-Jazira zones by different companies as follows, GEOSURV, (1983) for blocks 1-3, southern desert Salman area; Idrotecnico, (1977) for block 4, southwest part of western Desert-Nukhaib area; Consortium Yugoslavia (1978 and1981), for block 7, western desert-Ramdi-Anah-Al- Qa'im, KI 160 settlement and block 5, Rutbah area; Al-Furat Co.,(1989) for block 8, South and North Sinjar and Al- Jezira areas. In addition to, a study on the Akashat area that represents Block 6, which was carried out Anarbaev et al., (1976). Russian team, (1980) carried out a groundwater study of the Mesopotamian Plain.

During the period from 1990 to 2015, (GEOSURV) conducted many regional hydrogeological studies during geological mapping projects. In Northern Iraq the regional hydrogeological project was carried by the FAO (Stevanovic and Markovic, 2004), and Krasny, *et al*., (2006), publishing a chapter on groundwater in Iraq in the book Geology of Iraq, which was edited by Jassim and Goff, (2006). Studio, *et al*., (2015) conducted project on water resources and land development in Iraq is called Strategy for Water and Land Resources in Iraq (SWLRI).

The UNESCO project "Advanced Hydrogeological Survey for sustainable groundwater development in Iraq" called ASHRI Phase 1and ASHRI Phase 2 carried out between (2010- 2018). General Commission of Groundwater of Iraq was implemented of the inclusive hydrogeological survey for water points in Iraq, (2013).

In recent years, most of these studies data were discussed through postgraduate students' theses and published as papers.

Chapter Two
Hydrogeological Classifications

2-1 Introduction

Hydrogeological classifications are among the most essential methods used to evaluate the hydrogeological conditions and spatial distribution of groundwater, recharge, discharge areas, and groundwater flow systems. These classifications are based on the tectonic, geological, climatic, morphological, and hydrographical factors, which directly affect the surface drainage and groundwater flow paths. The tectonic setting determines the hydrogeological basins' geometry that affects the groundwater flow and accumulation within aquifers. The geological setting determines the porosity, permeability, and groundwater's hydrogeological facies. Climatic conditions determine the natural rates of recharge, discharge, and water losses, finally controlling the groundwater chemistry. Ultimately, morphological and hydrographical conditions determine the Catchment areas and the relationship between surface water and groundwater. However, most of these classifications divide the hydrogeological areas into basins, Physiographic zones, and hydrogeological regions.

2-2 Hydrogeological Classifications of Iraq

There are two different classifications of hydrogeological bodies in Iraq based on the scientific concepts that were used. The first classification carried out by Krasny, *et. al*., 2006 in Jassim and Goff, (2006). The second was done by Al-Jiburi and Al-Basrawi, (2015). In addition, some researchers classified some Hydrogeological areas of Iraq on small scale. Where Hassan and Al Kubaisi, (2002) subdivided Iraqi desert into six hydrogeological basins, while Stevanovic and Markovic, (2004) are subdivided north Iraq (Kurdistan region) into Sixteen basins. Below is a brief description of the most important hydrogeological classifications:-

2-2-1 Krasny Hydrogeological Classification

Krasny, *et. al*.,(2006) divided hydrogeological bodies in Iraq into fourteen main aquifer groups based on geological age, structural, and lithological conditions of aquifers and aquitards, and their hydrological characteristics, as shown in figure (2-1). These groups are briefly described as follows:-

1- Aquifer group 1(Palaeogene Carbonate):- Cretaceous-Tertiary limestone of the Rutbah, Digma, Tayarat Akashat and Ratgha Formations.

Remarks:-

a- The Rutbah Formation consists mainly of sandstone with thin horizons of fossiliferous dolomitic limestone and marl.

b- The Ratgha Formation is not considered as an aquifer in this area, where it is located above the regional groundwater level.

2- Aquifer group 2 (Permian Sandstone):- this group is represented by the Ga`ara and Bir Al-Rah (Suffi) aquifers.

3- Aquifer group 3 (Mesozoic Fracture Carbonate and Sandstone):- this group is represented by the Triassic - Cretaceous, Mulussa and Muhaiwir aquifers.

4- Aquifer group 4 (Miocene Carbonate):- the Euphrates aquifer is the main aquifer along the western bank of the Euphrates River.

5- Aquifer group 5 (Karstified Paleogenic Carbonate):- this group is characterized by Karstified and fractured limestone of Umm Erdhumah, Jil and Dammam aquifers in the Southern Desert.

6- Aquifer group 6 (Quaternary Nukhaib Gravel).

7- Aquifer group 7(Miocene-Pliocene Dibdibba Sandston):- this group is represented by the Dibdibba sandstone aquifer.

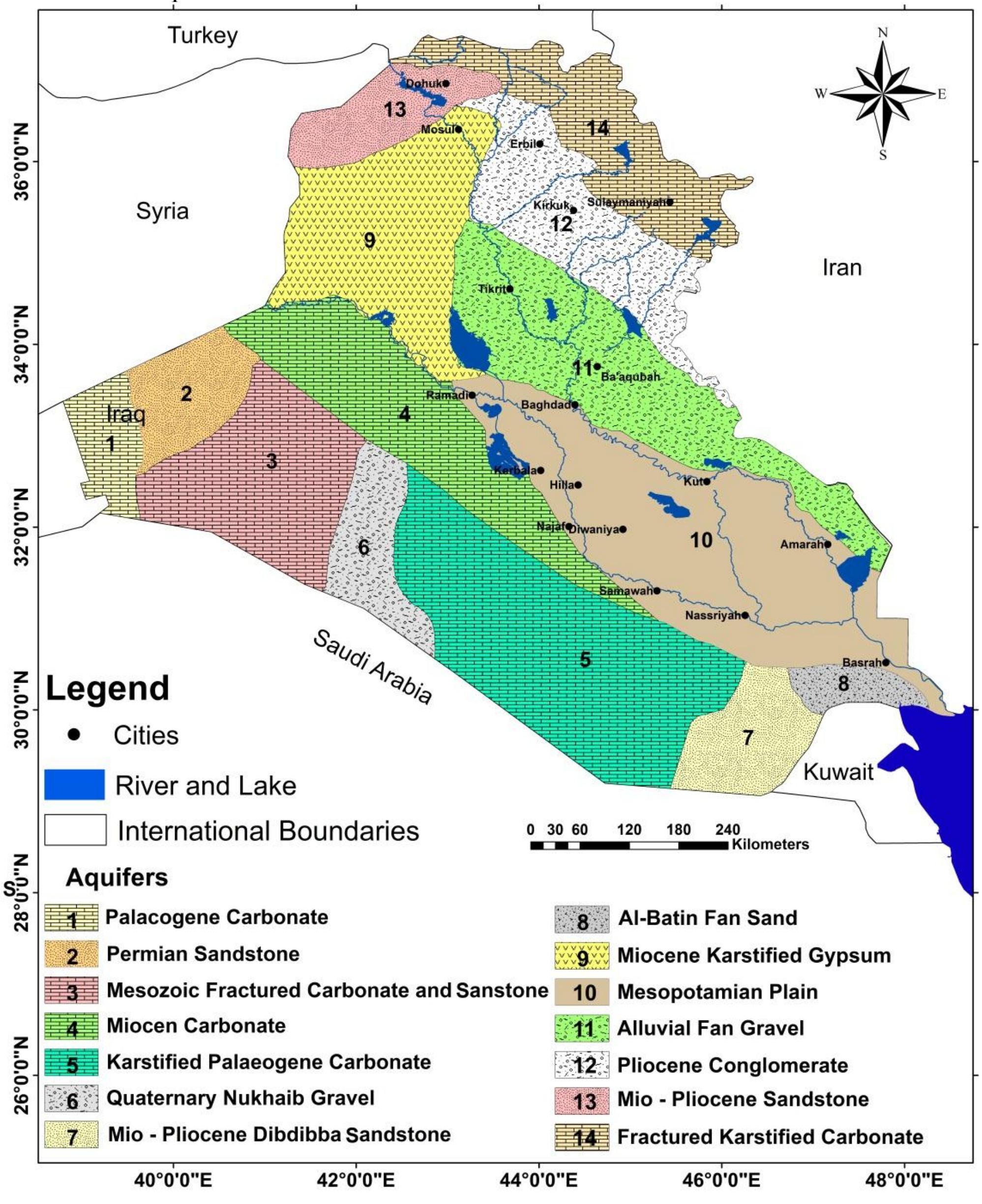

Figure (2-1):- Aquifer groups in Iraq, after Alsam *et al.*, 1990 in Krasny, *et. al.*, 2006 in Jassim and Goff, (2006).

8- Aquifer group 8 (Al-Batin Fan Sand): The gravels and coarse sand, alternating with marl, represent the main aquifer in the Al-Batin area.

Remarks:-

The Dibdibba Sandston aquifer is the main aquifer in the Al-Batin area due to the alluvial fan deposits having a few thicknesses in this area.

9- Aquifer group 9 (Miocene Karstified Gypsum):- this group is represented by Fatha (Lower Fars) aquifer in the Al- Jezira zone northwest of Iraq. However, according to Al-Jiburi and Al-Basrawi (2015), the clastic sediments of Injana Formation represent the main aquifer in the Northern part of the Al- Jezira zone.

10- Aquifer group 10 (Mesopotamian Plain):- this group is represented by Quaternary sediments aquifers in Mesopotamian Plain.

11- Aquifer group 11 (Alluvial Fan Gravel):- the alluvial fans that extend along the Iraqi Iranian border are represented the main aquifer within Mandali - Badra - Al-Teeib areas.

12- Aquifer group 12 (Pliocene Conglomerate):- this group is represented by the Foothill aquifer system.

13-Aquifer group 13(Miocene - Pliocene Sandstone):- the conglomerates' aquifers in the Quaternary and Miocene -Pliocene aquifers are represented the main aquifers in this group.

14- Aquifer group 14 (Fracture Carbonate Karstified):- the Mesozoic and Triassic aquifers characterized by the intensity of fractures and fissures are represented the main aquifers the High Folded and the Suture Zones Northern Iraq.

2-2-2 Al-Jiburi and Al-Basrawi Hydrogeological Classification

The second classification is simple and Presented by Al-Jiburi and Al-Basrawi, (2015). In this classification, Iraq was divided from the hydrogeological point of view into seven zones based on the physiographical, structural, geological and hydrogeological characteristics, as shown in figure (2-2). Every zone is characterized by hydrogeological and hydrochemical properties of aquifer systems. These zones can be briefly described as follows:-

1- Mesopotamian Zone

Quaternary Aquifer System within Quaternary sediments of the Mesopotamia plain is considered the main aquifers in this zone.

2- High Folded Zone

According to Stevanovic and Markovic (2004) in Al-Jiburi and Al-Basrawi, (2015), there are two main groups of carbonate aquifers in this zone. The Bekhme Karst Aquifer systems that include carbonates of Qamchuqa, Dokan and Kometan Formations are represented the first group. The Pila Spi Fractured Karst Aquifer systems that include carbonates of Sinjar, Khurmala and Avanah

Formations are described as the second group.These two groups are distributed in the following basins:-

A- Zakho Basin

B- NW Barzany Basin

1- Amadia – Barzan Sub-Basin
2- Atrush – Dinarta Sub-Basin

C- Central Harir Basin

1- Diana – Merga Soor Sub-Basin
2- Harir – Shaqlawa Sub-Basin

D- Central Dokan Basin

1- Sangasar Sub-Basin
2- Rania – Choarqurna Sub-Basin
3- Bangard – Surdash Sub-Basin

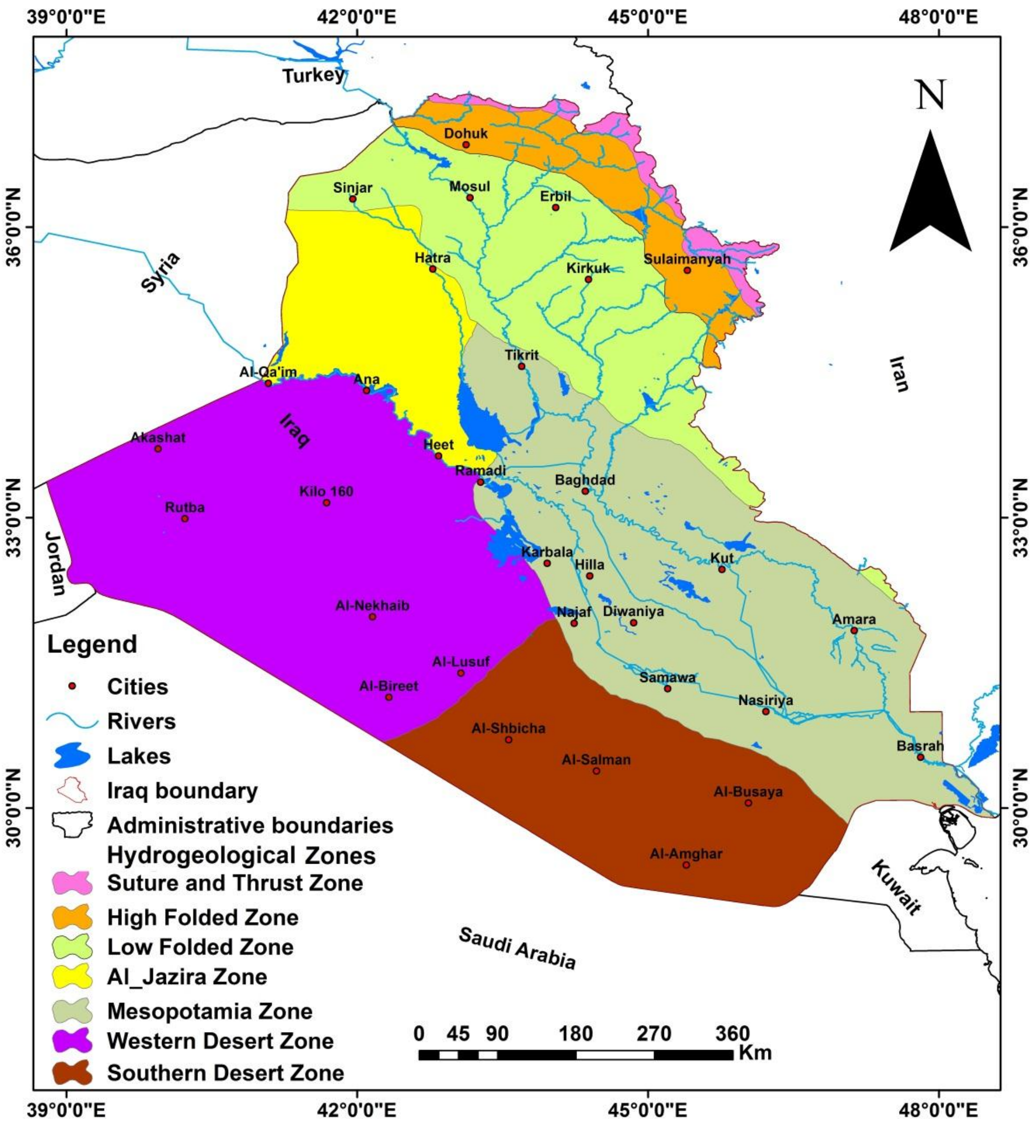

Figure (2-3):- Hydrogeological Zones of Iraq based on (Al-Jiburi and Al-Basrawi, 2015).

E- Sharazoor Basin

1- Bazian – Qaradagh Sub-Basin

2- Sarchinar – Arbat Sub-Basin

3- Suture and Thrust Zone

The shallow aquifers in this zone are near-surface fractured hard rocks. Three hydrogeological basins are determined within this zone, and as follows:-

A- Kani Mase Basin

B- Sidakan Basin

C- Penjween Basin

4- Low Folded Zone

Fatha, Injana, Mukdadiyah, and Bai Hassan Formations, as well as Quaternary sediments, represent the main aquifers in this zone. The Low Folded Zone is divided into thirteen Sub provinces, as follow:-

A- Sinjar – Rabee'a Sub Province

B- West Tigris River Sub Province

C- Khazir – Gomel Sub Province

D- Dohuk – Alqosh Sub Province

E- Erbil Sub Province

F- Altun Kupri Sub Province

H- Dibiga Sub Province

K- Makhmour Sub Province

L- Kirkuk – Hawija – Tuz Khurmatu Sub Province

M- Cham Chamal – Qadir Karam – Qara Too Sub Province

N- Kalar – Khanaqeen Sub Province

R- Qara Tappa – Al-Sa'adiyah Sub Province

T- Mandili – Zurbatiya – Teeb Sub Province

5- Al-Jazira Zone

The Quaternary sediments, Fatha and Injana Formations are main aquifers in this zone.

6- Western Desert Zone

The main aquifers in the Iraqi Western Desert Zone from the oldest to youngest formation are Suffi, Ga'ara, Mulussa, Ubaid, Muhaiwir, Rutba, Ms'sad, Hartha, Tayarat, Umm Er-Radhuma, Akashat, Dammam, Euphrates, and Injana aquifers.

7- Southern Desert Zone

The Hartha, Tayarat, Umm Er Radhuma, Dammam, Ghar/ Euphrates and Dibdibba are the main water bearing formations in the Southern Desert Zone.

In this classification, the topography plays a significant role in determining the direction of groundwater movement and its recharged and discharged areas. However, the problem in this classification is using of different terms in subdividing these zones, such as the terms basin, province and sub province. Another criticism of this classification, the sediments of the Mesopotamian zone are extended to the Iraqi-Iranian border, which is not the case, where the alluvial fan sediment and tertiary sediment extend along the Iraqi-Iranian border, especially in the northeast of the Amara city.

2-2-3 Hassan and Al Kubaisi Hydrogeological Classification of Iraqi Desert

The Iraqi desert was divided into six hydrogeological basins by Hassan and Al Kubaisi, (2002) in accordance of the tectonic, structural, geological and groundwater flow system, and as follows:-

1- Al- Rutba Basin: - This basin covers an area of about (56000 km^2) that represents (27.3%) of total Iraqi desert, as shown in figure (2-3). The main aquifers in this basin are Suffi, Ga'ara, Mulussa, Muhaiwir, Rutba, Tayarat, Akashat, Umm Er Radhuma, Dammam and Euphrates aquifers. Most of these aquifers are fractured, consisting mainly of carbonate rocks of slightly brackish water.

2- Al-Razzaza Basin: - It represents about 29.3% from total Iraqi desert and covers about (60000 km^2). The main aquifers in this basin are the Ga'ara, Mulussa, Muhaiwir, Rutba, Hartha, Tayarat, Umm Er-Radhuma, and Dammam.

3-Al- Maanya Basin: - This basin covers about (16000 km2) which represents back (7.8%) of the total Iraqi desert. The main aquifers in this basin are Umm Er-Radhuma and Dammam aquifers.

4-Shabcha – Al- Salman Basin: - It represents about (9.9%) from total Iraqi desert and covers about of (20000 km^2). The main aquifers in this basin are Tayarat, Umm Er-Radhuma and Dammam aquifers.

5- Takhade – Al-Busssaya Basin: - This basin covers about (31000 km^2) that represents about (15.1%) of total Iraqi desert. The Tayarat, Umm Er Radhuma, Dammam, Ghar/ Euphrates and Dibdibba are the main water bearing Formations in this basin.

6- Safwan – Al-Rukhema Basin: - It represents about (10.7%) of total Iraqi desert and covers about (22000 km^2). The Dibdibba aquifer is the main aquifer in this basin.

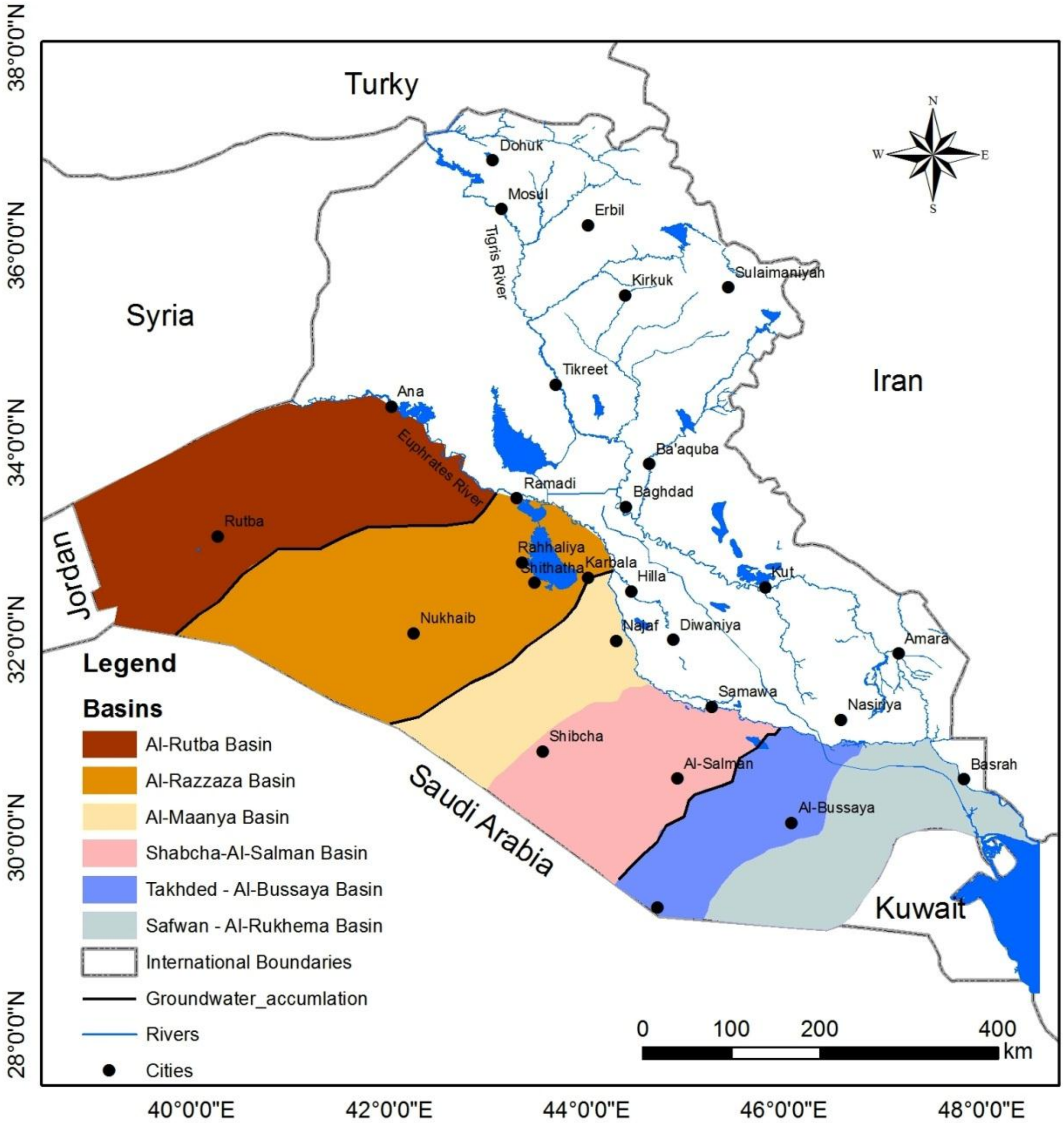

Figure (2-3):- Hydrogeological basins divisions of the western and the southern desert, (Hassan and Al Kubaisi, 2002).

2-2- 4 Stevanovic and Markovic Hydrogeological Classification

Stevanovic and Markovic, (2004) subdivided northeast Iraq into (16) Hydrogeological basin depending on multi factors. Those basins are identified in term of water quality and quantities from surface runoff and Aquifer types. These basins are:-

1- Zakho Basin
2- Sumail Basin
3- Amadia-Barzan-Bekhme Basin
4- Dinarta- Mabruke Basin
5- Diana- Mergasoor- Sidakan Basin
6- Akre- Bardarash Basin
7- Shaqlawa- Harir Basin
9- Surdash- Koya Basin
10- Chamchamal Basin
11- Chuwarta- Penjween Basin
12- Sangaw – Bazian Basin
13- Sulaimaniyah – Sharazoor Basin
14- Arbat – Khumala Basin
15- Qaradagh- Kalar Basin

8- Between Merga Basin 16- Akre Basin

These basins include three main aquifer systems, as well as fourth that represents an aquifer having mixed characteristics, according to Stevanovic and Markovic, (2004). These aquifer systems are distributed in the following:-

1- **Bekhma Aquifer System**: - this system is characterized by the Karst feature and is widespread in high folded zone. It consists of Qamchuga, Dokan, Kometan, Bekhme, Aqra, Sarmord and other Cretaceous / Paleocene age Formations developed mainly in carbonate facies (limestones and dolomites and their varieties).

2- Pila Spi Aquifer System: - this system consists of Fissured-karstic aquifer that includes carbonates of Sinjar, Khurmala and Avanah Formations. This aquifer system is widespread high folded zone and some part of low folded zone.

3- Intergranular Bakhtiari (Bi Hassan and Mukdadiya) Aquifer System: - This system is often found in the low folded zone and some part of high folded zone. It consists of an overlying Pleistocene terrace and recent alluvium deposits.

4- Complex Aquifers System: - it consists of a merging of the two or three aquifers mentioned above, mostly fissured-karstic or karstic type often over-laid by younger or recent sediments. The Injana (Upper Fars), Fatha (Lower Fars), Kolosh or Tanjero Formations, which have limited and varying quantities of groundwater also consider as Complex aquifers.

2-3 New Hydrogeological Classification of Iraq

The hydrogeology of the Basin and Range Physiographic Province are terms previously used in the hydrogeological classification, in recent years, for the sake of increasing spatial scale. A conceptual model for the spatial hierarchy of hydrogeology was developed for the Basin and Range Physiographic Province and consists of hydrogeological components. This hierarchy is formed from hydrogeological areas, hydrogeological flow systems, and hydrogeological regions, (Anning and Konieczki, 2005), as shown in figure (2-4). The hydrogeological components are soils and streams, basin fill, and consolidated rocks. Hydrogeological areas consist of hydrogeological components; hydrogeological flow systems consist of single or multiple hydrogeological areas and hydrogeological regions are composed of hydrogeological flow systems. It represents a new framework for hydrogeological classification, (Anning and Konieczki, 2005). So, in the present work, Iraq has been divided into five hydrogeological regions and thirty-seven Hydrogeological areas based on the physiographic, tectonic, geological, and hydrogeological properties of the subsurface conditions, as shown in figure (2-5). The most important in this classification is incorporate the previously classifications in one classification more accurate in determining the characteristics of hydrogeological regions and their areas, because the concept of basin or drainage basin for surface water is defined as any area of land where precipitation collects and drains off into a common outlet. In the groundwater system, the water may flow towards the outlet of another basin because groundwater flow directions do not always match within the same basin. This means more than the outlet of groundwater drainage and not one as for the surface water basins. In addition, this classification involved small changes in the original groundwater basin boundaries to align better with surface drainage patterns. However, Northern and Eastern Iraq have been divided into three Hydrogeological Regions, The Suture and Thrust, High and Low Folded Hydrogeological Regions. These regions are characterized by the large number and small extension of Hydrogeological Areas compared with other Regions because they are more affected by deformation of the Alpine tectonic movements. The tectonic movements in these Regions have caused many faults and folds, which represent hydrogeological boundaries between the Hydrogeological Areas. The Mesopotamian and Al-Jazira zones have been merged in one region called Al-Jazira and Mesopotamia Hydrogeological Region. The Western and Southern Desert zones have been integrated into the Desert Hydrogeological Region. In this classification, the Al-Jazira and Mesopotamia and Desert Hydrogeological Regions are characterized by few hydrogeological areas with large areas due to the presence of few faults and folds, which represent hydrogeological boundaries between the hydrogeological areas. Anyway, these regions and locations can be summarized as follows:-

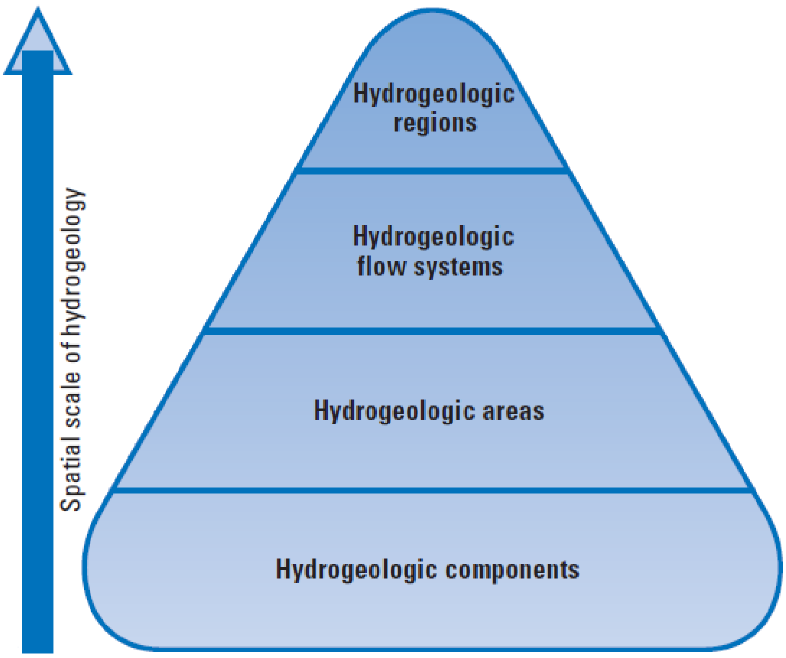

Figure (2-4):- Spatial hierarchy and relation between the hydrogeological components, (Anning and Konieczki, 2005).

Suture and Thrust Hydrogeological Region

1- Kani Masi Hydrogeological Area

2- Sidakan Hydrogeological Area

3- Penjween Hydrogeological Area

High Folded Hydrogeological Region

4- Zakho Hydrogeological Area	
5- Amadia – Barzan Hydrogeological Area 6- Atrush – Dinarta Hydrogeological Area	NW Barzany Hydrogeological Flow System
7- Diana – Mergasoor Hydrogeological Area 8- Harir – Shaqlawa Hydrogeological Area	Central Harir Hydrogeological Flow System
9- Sarsang Hydrogeological Area 10- Dokan Hydrogeological Area 11- Bangard – Surdash Hydrogeological Area	Central Dokan Hydrogeological Flow System
12- Bazian – Qaradagh Hydrogeological Area 13- Sarchinar – Arbat Hydrogeological Area 14- Choarta – Baraznja Hydrogeological Area 15- Khurmal – Halabja Hydrogeological Area	Sharazoor Hydrogeological Flow System

Low Folded Hydrogeological Region

16- Khazar – Gomal Hydrogeological Area

17- Dohuk – Alqosh Hydrogeological Area

18- Erbil Hydrogeological Area

19- Altun Kupri Hydrogeological Area

20- Dibiga Hydrogeological Area

21- Makhmur Hydrogeological Area

22- Tawuq Hydrogeological Area

23- Cham Chamal – Kalar Hydrogeological Area

24- Qara Tapa – Khanaqin – Al-Saadia Hydrogeological Area

25- Mandali – Zurbatia – Teeb Hydrogeological Area

26- Sinjar – Rabi’a Hydrogeological Area

27- West Tigris River Hydrogeological Area

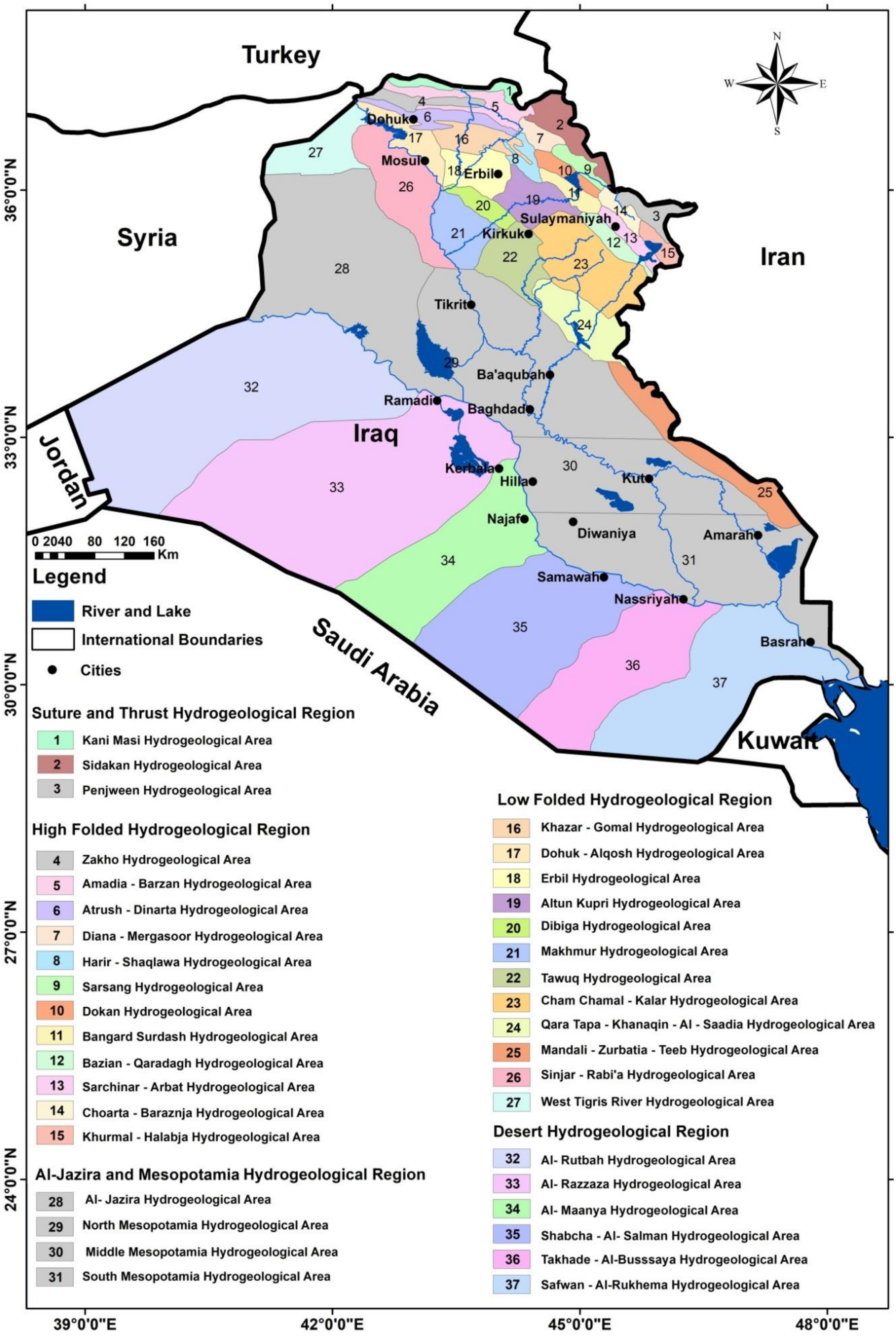

Figure (2-5):- Hydrogeological Classification of Iraq.

Al-Jazira and Mesopotamia Plain Hydrogeological Region

28- Al-Jazira Hydrogeological Area

29- North Mesopotamia Hydrogeological Area

30- Middle Mesopotamia Hydrogeological Area — Mesopotamia Hydrogeological Flow System

31- South Mesopotamia Hydrogeological Area

Desert Hydrogeological Region

32- Al- Rutbah Hydrogeological Area

33- Al-Razzaza Hydrogeological Area

34- Al- Maanya Hydrogeological Area

35- Shabcha – Al- Salman Hydrogeological Area

36- Takhade – Al-Busssaya Hydrogeological Area

37- Safwan – Al-Rukhema Hydrogeological Area

Note :- by Prof. Dr. Eng. Miroslav Markovic

In the discussed chapter-2, Stevanovic and Markovic (2004) are mentioned several times as references. The data probably refers to the book "Hidogeology of Northern Iraq (FAO, 2004)." This book was created as a result of the research work of the team of three FAO experts (Zoran Stevanovic, Adrian Iurkiewicz and Miroslav Markovic), in cooperation with a group of professors from local universities in Kurdistan. The book was published by the UN FAO in Rome. The name of the author Dr. Adrian Iurkiewicz, was left out by the unforgivable rough technical error of the local editor. So, only Zoran and I are listed as authors. The error is all the greater because the authors of the volume 2 of above mentioned book (general hydrogeology and aquifer systems) are Stevanovic and Iurkiewicz. I am pleading you to correct the injustice inflicted on my friend Dr. Adrian Iurkiewicz.

Belgrade, 21. 11.2021. Prof. Dr. Eng. Miroslav Markovic,

Retired

Chapter Three

Hydrogeological Regions in North and East Iraq

3-1 Hydrogeological Regions in North and East Iraq

Northern and Eastern Iraq has a relatively complex geological and structural setting that directly affects the geomorphology and hydrogeological setting. These complex settings have led to many hydrogeological areas on a small scale with isolated to semi-isolated aquifer systems. These areas can be considered the most promising sites in Iraq to invest groundwater for large-scale because it is characterized by the availability of groundwater and fertility of the land. The main aquifers in the areas are present in the Cretaceous and Paleogene Formations and the Quaternary deposits. These areas have been studied by Parsons (1955), Krasny (1983a), and Stevanovic and Markovic (2004). First, Krasny (l983a) divided the large Low Folded Zone (Foothill Zone) into ten aquifer sub-systems. Then this division was modified by Krasny *et. al.*, 2006 in Jassim and Goff (2006) based on studies conducted by Stevanovic and Markovic (2004) to include the Suture and Thrust, High and Low Folded Zones. In this work, the North and East Iraq have been divided into three hydrogeological regions according to the physiographical, structural, geological and hydrogeological properties of these regions, and then these regions subdivided into twenty-seven hydrogeological areas, as shown in figure (3-1).

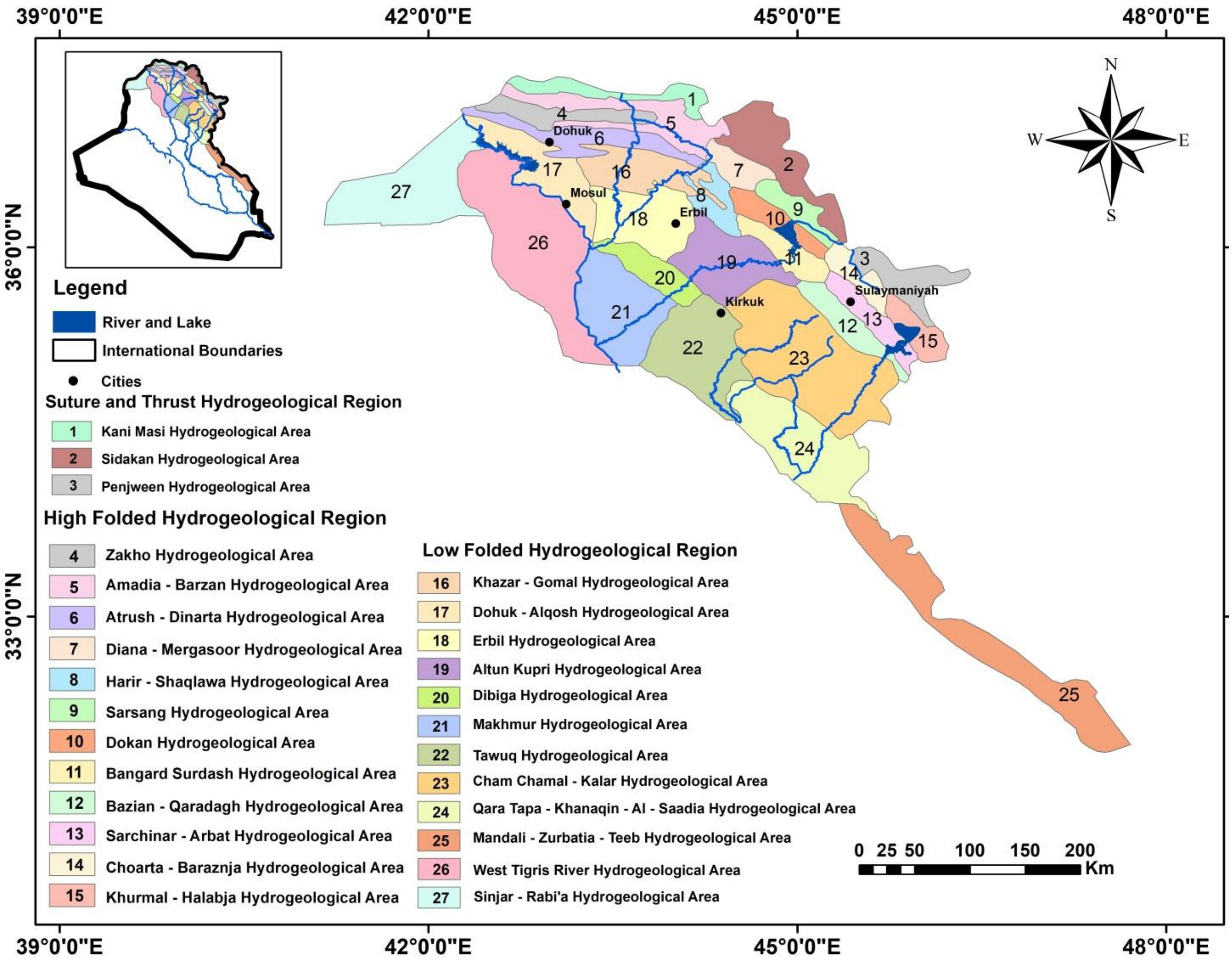

Figure (3-1):- Hydrogeological regions and areas map of North and East Iraq.

Each region has its hydrogeological and hydrochemical characteristics of aquifer systems. Stevanovic and Markovic (2004) classified the aquifer systems in the High Folded Zone and some parts of Low Folded Zone into three main aquifer systems based on similarities in age, lithology, and other hydrogeological characteristics, and named according to commonly known Formations in this group as mentioned in chapter two. In this work, these systems were redistributed to cover all hydrogeological regions in North and East Iraq, as follows:-

A- Bekhme Karst Aquifer System

The Karst water-bearing formations characterize this system. It includes Kometan, Aqra-Bekhme, Dokan, Sarmord, Qamchuga, and other Cretaceous / Paleocene aquifer developed mainly in carbonate facies (limestones and dolomites and their varieties).

Stevanovic and Markovic (2004) state that this aquifer system is non-homogenous, anisotropic, and contains ample groundwater storage but varies in space and time. The aquifers in this system are characterized mainly by large thickness and wide spread area. They are well-developed karstic features, highly fissured with many channels and caves registered on the surface or during drilling many wells (cavities sometimes exceed 10 m in length). A turbulent water-flow regime is one of the main characteristics of these aquifers. In general, the base of karstification (depth to the fissured and porous level of the rock) is more profound than (100 m), which is very important for static water reserves accumulated in the deeper parts of the aquifers. The high discharge capacity often characterizes deep wells drilled in the karstified rocks.

In most cases, their depth ranges between (150-250 m). During pumping tests, the well yields sometimes reached (40-50 l/s), with minimal drawdown (e.g., Harir- Shaqlawa hydrogeological area). As a result, the average adequate infiltration capacity of the Bekhma Karst aquifer system may attain (50%) of total rainfall. In many cases, transmissivity values (approximated based on recovery tests) were very high (6-9 x 10^{-2} m^2/s).

The main aquifers in this system are Kometan and Aqra-Bekhme aquifers. They are characterized by high groundwater productivity through springs or drilled wells, unlike the Dokan, Sarmord, and Qamchuga aquifers, characterized by low productivity with limited extension. The main aquifers in this system are briefly described as follows:-

Kometan Aquifer

Dunnington (1953) was defined the type section of the Kometan Formation (Turonian – Early Campanian) at Kometan village Northeast of Ranya town in the High Folded Zone. It is exposed widely in this Zone, especially East of the Greater Zab River and in different locations between Sulaimaniyah and Halabja towns (Sissakian and Al-Jibuori, 2014a). The outcrops of Kometan Formation that represent recharge areas for the aquifer only appear in the areas bounded between the South of Dokan lake and the Iraqi-Iranian border. The subsurface extensions of this Formation are located within the High Folded Zone and even behind the Southern limits of the suture and Thrust and Low Folded Zone (Sissakian and Al-Jibuori, 2014a). It is composed mainly of Karst carbonate rocks and considered an aquifer only in the area between Dokan Lake and the Iraqi-Iranian border and shaped like a narrow zone, as shown in figure (3-2). It is considered the most critical petroleum reservoir in the Kurdistan region and other parts of Northern Iraq (Aqrawi et al., 2010).

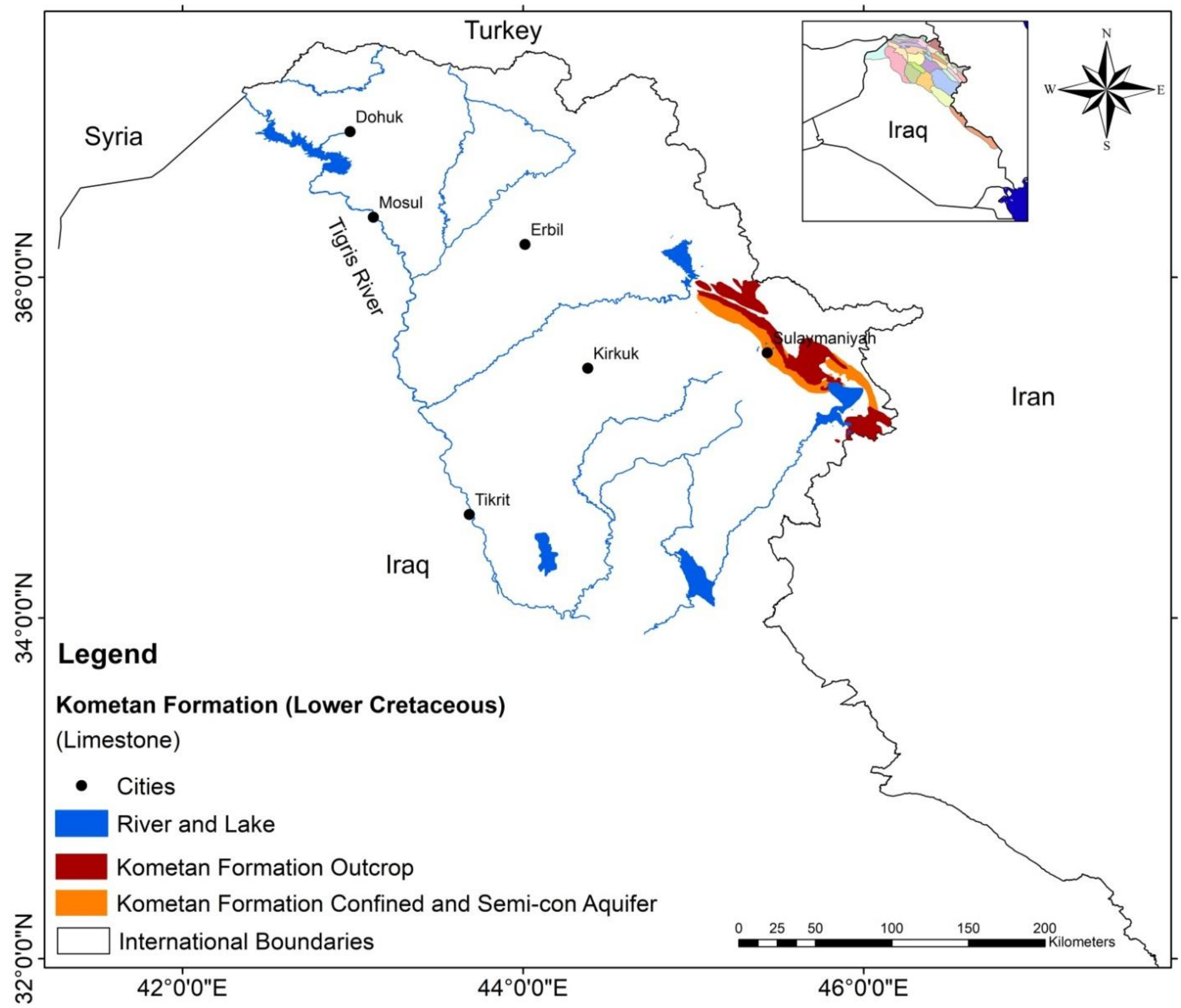

Figure (3-2):- Shows extensions map of Komaten Formation and its aquifer (after Al Jawad and Ridha, 2008).

The Kometan Formation is one of the most essential spring water sources in different areas, such as Sarchinar, Sarwchawa, and Betwata springs (Mustafa et al., 2015). Searching spring is one of the most important drinking water sources in Sulaymaniyah city, where groundwater is issuing from karstic and fissured conduits of the Kometan Formation (Amin, 2009).

Kometan Formation is well-karstified and contains a large amount of groundwater, varying in space and time. Highly fissured aquifer confined to semi-confined conditions and overlain by Shiranish Formation. The Kometan aquifer is the most important fresh-water-bearing layer in Sulaimaniyah, Sharazoor and Dokan areas located at depths between (100 – 150 m), (Stevanovic and Markovic, 2004).

Aqra–Bekhme Aquifer

Jassim *et. al.* (1984) merged two Formations, Aqra and Bekhme, together in one Formation. The Aqra – Bekhme Formation (Late Campanian – Late Maastrichtian) has extensive exposures in the middle part of the High Folded Zone. The subsurface extensions are obscure, but it has been identified as a confined aquifer in the area bounded between North Aqra and Sulaimaniyah town, as shown in figure (3-3).

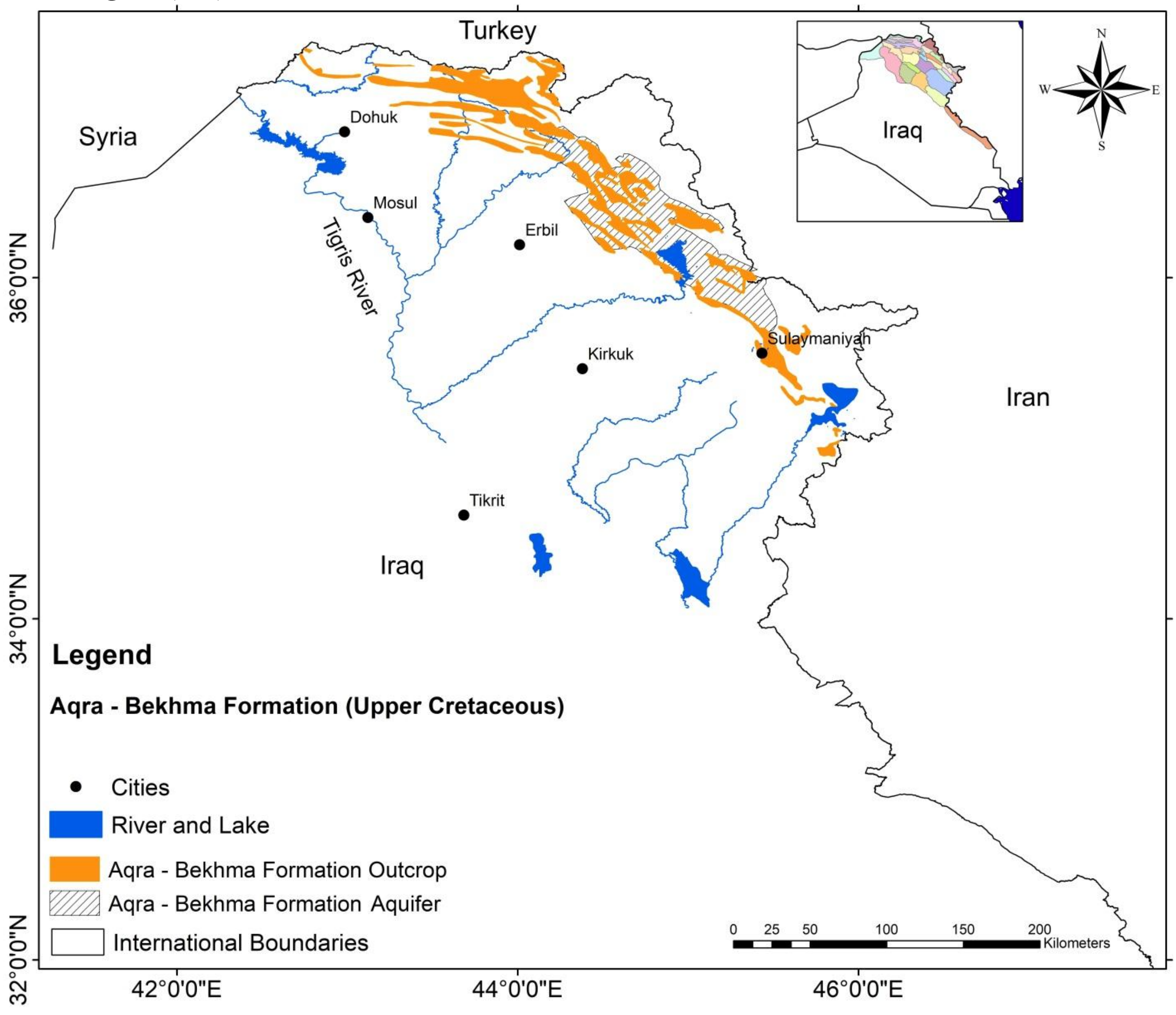

Figure (3-3):- Shows extensions map of Aqra–Bekhme Formation and its aquifer (after Al Jawad and Ridha, 2008).

The Aqra Formation represents a massive limestone, while the Bekhme Formation consists of dolomitic detrital limestone, closely associated with the former (Al-Qayim 1989). Stevanovic and

Markovic (2004) indicate that the Aqra–Bekhme aquifer is a medium to high productive Karstic aquifer – well-developed karstic features and fissure systems are privileged groundwater flow paths. Discharge through high yielded springs or drilled deep wells.

B- Pila Spi Karstic-Fissured Aquifer System

According to Stevanovic and Markovic (2004), the Pila Spi aquifer System consists of Eocene carbonate aquifers of similar age Formations include Sinjar and Khurmala. Fissured-karstic water-bearing Formations characterize this system. It is widespread in the High Folded Zone and some parts of the Low Folded Zone. The Pila Spi aquifer system also is heterogeneous and anisotropic aquifers with more than (200 m) thick, which contains medium to ample groundwater storage. The degree of karstification of the Pila Spi aquifer system is lesser than in the Bekhma aquifer system. The karstification base is located at a depth of more than (80 m), while the depth of the drilled wells ranges between (120 – 150 m), with yields of up to (40 l/s). The transmissivity of the wells that drilled in this aquifer ranges between (3.5 – 42000 m^2/day) according to Stevanovic and Markovic (2004) and Krasny *et. al.*, 2006 in Jassim and Goff (2006). The effective infiltration capacity of the Pila Spi aquifer system has been estimated as average at (30 to 40 %) of total rainfall (Stevanovic and Markovic, 2004).

The main aquifers in the High Folded hydrogeological Region are Pila Spi, Sinjar, and Khurmala aquifers. Some water-bearing clastic units within the Kolosh and Tanjero Formations are considered local fractured aquifers; they are characterized by the low productive aquifers in most hydrogeological areas, especially Kolosh Formation. The Sinjar formation is usually disconnected from the Pila Spi aquifer by Gercus Formation in the High Folded Region except in the south of Sulalmaniya town where the Gercus layers are missing, Krasny et al., 2006 in Jassim and Goff, (2006).

Sinjar Aquifer

The Sinjar water-bearing Formation (Late Paleocene – Early Eocene) is considered the main aquifer within the Pila Spi aquifer system in the High Folded hydrogeological Region. Keller (1941) was first described from the Jabal Sinjar area (near Mantissa village), as mentioned in Jassim and Buday, 2006 in Jassim and Goff (2006). However, it is exposed in a different locations in the High Folded Zone, as shown in figure (3-4). The Sinjar Formation mainly consists of fractured, massive, and fine crystalline limestone (Al-Shwaily *et. al*., 2012). In the type section, the thickness of the Sinjar Formation is equal to (179m). In the Southwest of the High Folded Zone at Derbendikhan area, the Sinjar Formation has thicknesses (120m). It increases in some parts of the Low Folded Zone to reach (213m) as appeared in the lithological sections of a well Alan-I (Jassim and Buday, 2006 in Jassim and Goff, 2006).

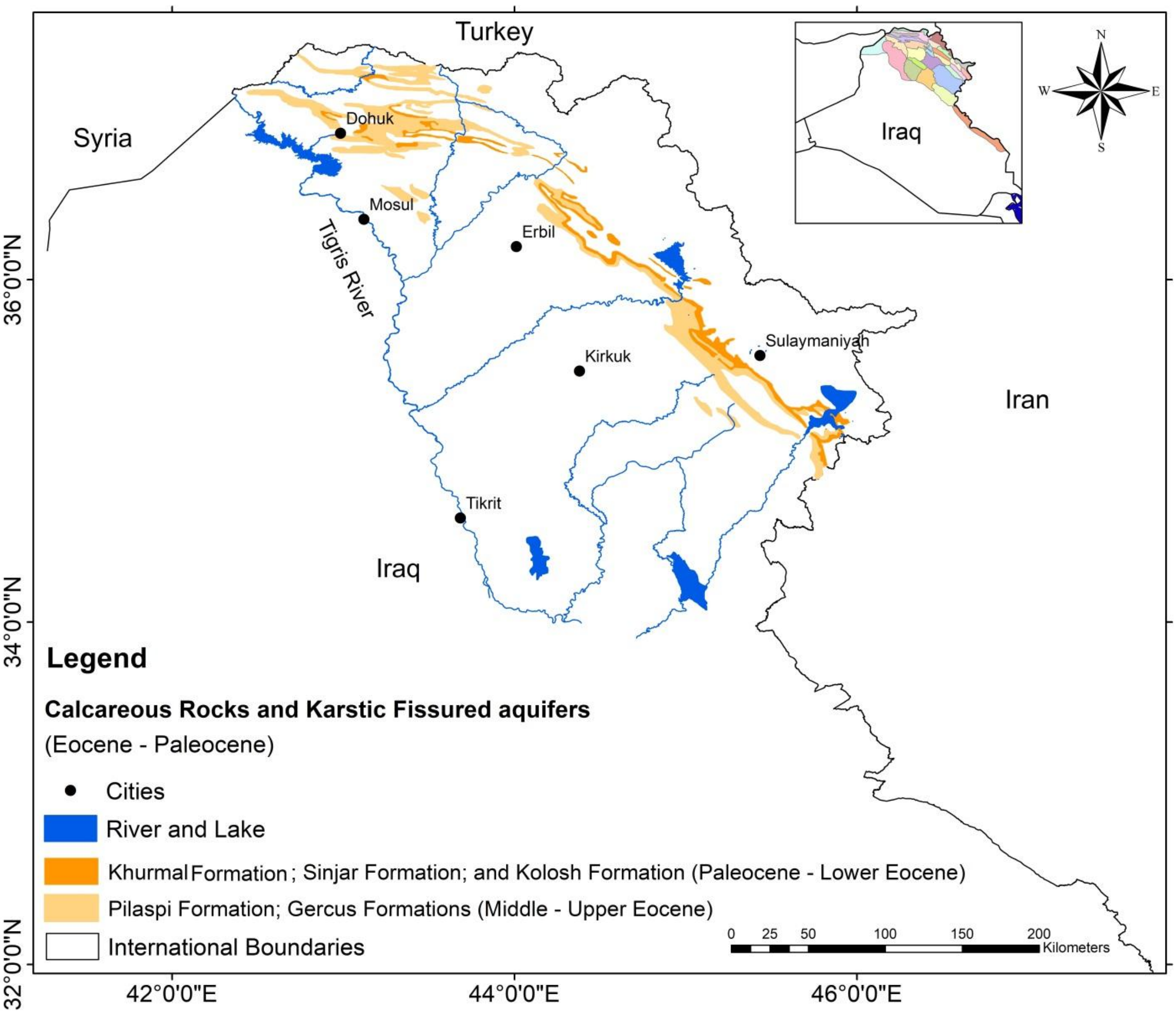

Figure (3 - 4):- Shows extensions map of Pila Spi Karstic-Fissured aquifers system (after Al Jawad and Ridha, 2008).

Khurmala Aquifer

The Khurmala Formation (Late Paleocene – Early Eocene) was first defined by Bellen (1953) in oil well Kirkuk-114. This Formation is exposed in a different locations within the High Folded Zone, as shown in figure (3-4). It is consists of recrystallized limestone and beds of anhydrite and gypsum (Jassim and Buday, 2006 in Jassim and Goff, 2006). In addition, some part of the High Folded Zone is composed of dolomitic, fine conglomeratic, and pebbles are mainly of carbonate and chert (Sissakian and Al-Jibuori, 2014a).

Pila Spi Aquifer

The Pila Spi Formation (Middle-Late Eocene) is first defined by Lees (1930) from the Pila Spi area of the High Folded Zone. It was redefined by Wetzel (1947) and amended by Bellen (1957) according to Jassim and Buday, 2006 in Jassim and Goff (2006). This Formation is exposed in the High Folded Zone and some Northern parts of the Low Folded Zone, as shown in figure (3-4).

The Pila Spi Formation consists of two parts. The upper part comprises bituminous limestone with chalky marl bands and chert nodules towards the top. The lower portion includes hard, porous, and bituminous limestones with algal or shell sections (Sissakian and Al-Jibuori, 2014). The Formation thickness ranges between (100-200 m) (Jassim and Buday, 2006; Jassim and Goff, 2006). It is considered an aquifer in some Northwest parts of this Zone.

C- Intergranular Bai Hassan and Mukdadiya(Bakhtiari) Aquifer System

According to Stevanovic and Markovic (2004). This system consists of Bai Hassan (Upper Bakhtiari) and Mukdadiya (Lower Bakhtiari) aquifers and the recent alluvium deposits. Both Bai Hassan and Mukdadiya aquifers are very rich aquifers and extend in large parts of the Low Folded Region and cover a surface of several thousand square parts of the High Folded Region kilometers with confined or semi-confined aquifers. Based on the lithological sections of deep wells, the total thickness at the center of the Erbil hydrogeological area is estimated at more than (850 m). They are surrounding Erbil city, where the thickness of layers is more significant than (250-300 m). The total depth of water wells in the Erbil hydrogeological area reaches between (400- 500 m) within the Mukdadiya Formation. The water from Both Bai Hassan and Mukdadiya aquifers and recent deposits are generally good quality.

Mukdadiya Aquifer

Mukdadiya Formation (Late Miocene – Pliocene) was previously known as the Lower Bakhtiari Formation, and Jassim *et. al.*, (1984) renamed to the Mukdadiya Formation. The type locality of the Mukdadiya Formation is located along the Northeastern limb of Himreen South anticline in Mukdadiya. It is exposed in different North and East Iraq locations from Zakho to the Southwest of Sulaimaniyah, as shown in figure (3-5). The Mukdadiya Formation consists of pebbly sandstones, claystone, and siltstone (Jassim and Buday, 2006 in Jassim and Goff, 2006). The thickness of the Mukdadiya Formation is (2000m) in the type section. In High Folded Zone, it has a thickness (600 m) near Halabja, (150 m) in Shaqlawa, and (50m) in the Dohuk, (Sissakian and Al-Jibuori, 2014).

Bai Hassan Aquifer

The Bai Hassan Formation (Pliocene – Pleistocene) was previously known as the Upper Bakhtiari Formation and also renamed by Jassim et al., (1984) to the Bai Hassan Formation. The type locality of this Formation is located Northwest of Kirkuk city in Bai Hassan anticline (Sissakian and Al-Jibuori, 2014). The Bai Hassan Formation is exposed in a different locations in the High and Low Folded Zone, from Zakho in the North of Iraq to North Amara city in the Southeastern part of Iraq, as shown in figure (3-6). It is mainly composed of conglomerate, claystone, and sandstone (Jassim *et al.*, 1984). In the type section, the thickness of this Formation is (638 m) and ranges between (100 – 200m) near Halabja, while reaches (125 m) in Shaqlawa (Sissakian and Al-Jibuori, 2014a).

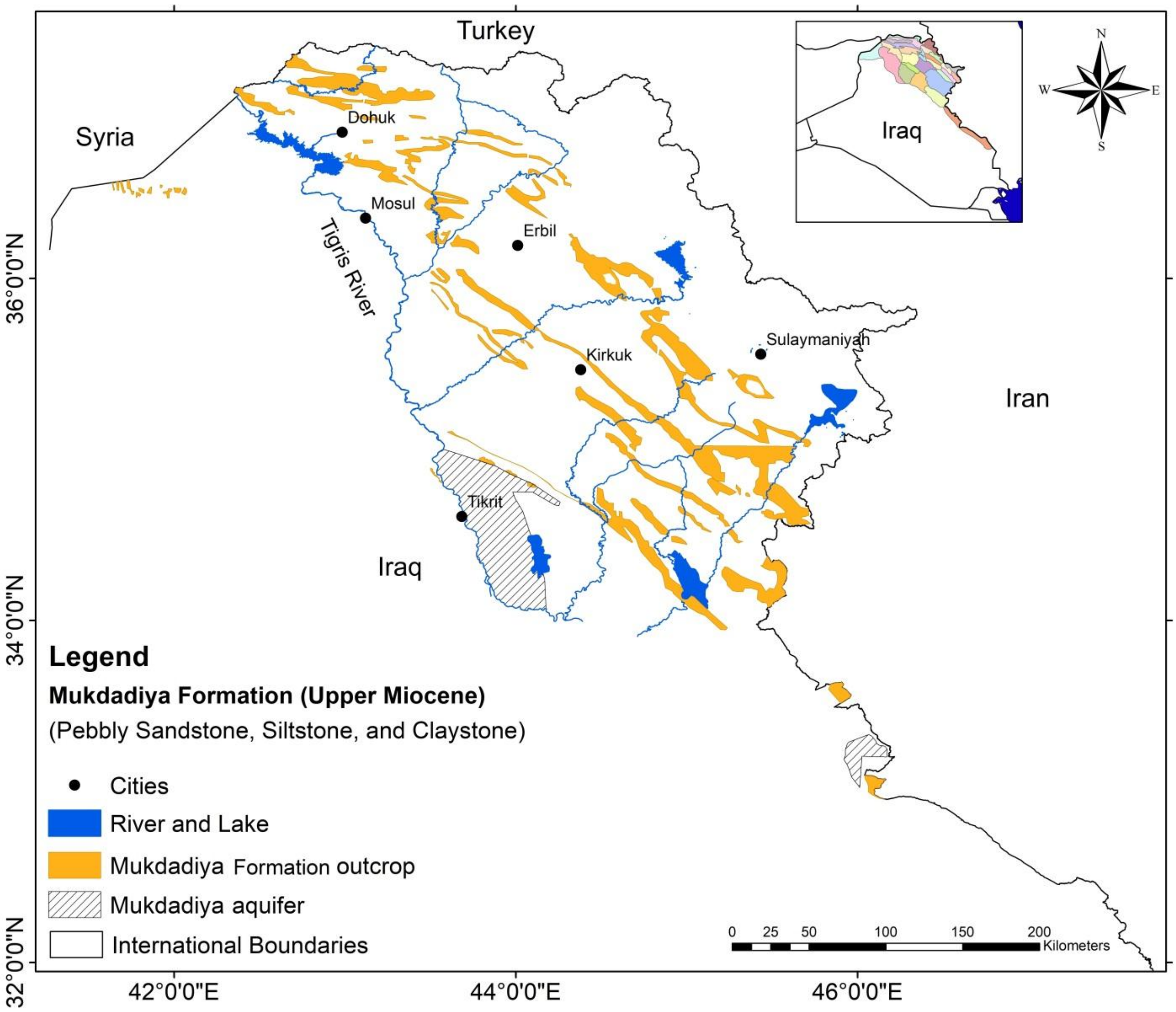

Figure (3 - 5):- Shows extensions map of Mukdadiya Formation and its aquifer (after Al Jawad and Ridha, 2008).

Recent Alluvium Aquifer

The recent alluvium deposits are represented the main aquifer in most hydrogeological areas within the High and Low Folded Zones. It consists of different boulders, gravel, sand, and silt (Stevanovic and Markovic, 2004). The coarse sediments of the alluvial fans are generating shallow aquifers in the broad plains, especially in the middle and South parts of the High Folded Region. The surface water that percolates through the riverbeds and rainwater is considered the main recharge resource of a shallow alluvial aquifer. Currently, these aquifers are becoming dry to semi-dry during the summer months in different locations due to the scarcity of rain and high temperatures. However, most of the wells drilled in alluvial fans and plain sediments have depths between (100-200m).

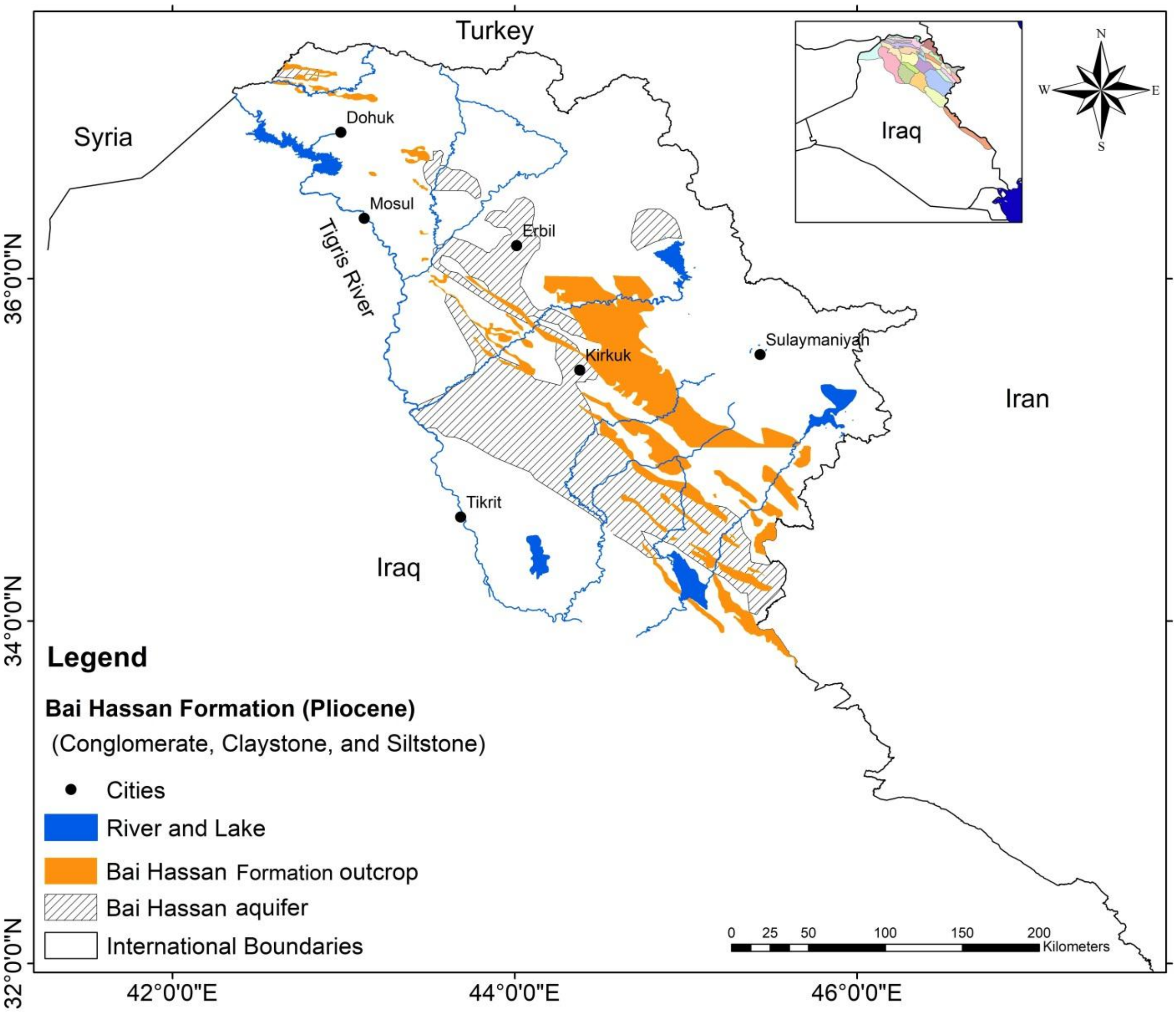

Figure (3 - 6):- Shows extensions map of Bai Hassan Formation and its aquifer (after Al Jawad and Ridha, 2008).

Complex Aquifer Systems

According to Stevanovic and Markovic (2004), the Fatha (Lower Fars) and Injana (Upper Fars) water-bearing Formations are classified as complex intergranular aquifers because they are characterized by low to medium productivity in siltstone and sandstone intervals. In a few cases, the aquitard or aquiclude functions may dominate. In general, groundwater that flows from Fatha Formation depends on local factors, mainly the presence of gypsum or anhydrite layers; where they are present, total mineralization increases parallel with the content of Na, Cl, NO_3, SO_4, and Fe ions. So, the Fatha Formation is not considered a good aquifer because it consists of anhydrite and gypsum with little groundwater with a high percentage of sulfates. As for Injana aquifer is a good aquifer, especially in the Khazar – Gomal, Dohuk – Alqosh, and Sinjar- Rabia hydrogeological areas, which are located in a Low Folded Region.

Injana Aquifer

The Injana Formation (Late Miocene) was previously known as the Upper Fars Formation and was also renamed by Jassim et al., (1984) to the Injana Formation. The type locality of this Formation is located along the Northeastern limb of Himreen anticline at the Injana area (Sissakian and Al-Jibuori, 2014a). The Injana Formation is exposed in a different location in the High and Low Folded Region, from Rabia to the Zurbatia hydrogeological areas, as shown in figure (3-7). According to Jassim and Buday 2006 Jassim and Goff (2006), it mainly consists of sandstone, claystone, and siltstone. This Formation has a very variable thickness due to subsequent erosion over significant folds. It has a maximum thickness of (2000 m) in the central depositional area in the Low Folded Zone. While it has a thickness reaches (900m) near Kirkuk city. This thickness is reduced to (300 m) near Halabja, (200 m) in Dohuk, and (150m) in Shaqlawa (Sissakian and Al-Jibuori, 2014).

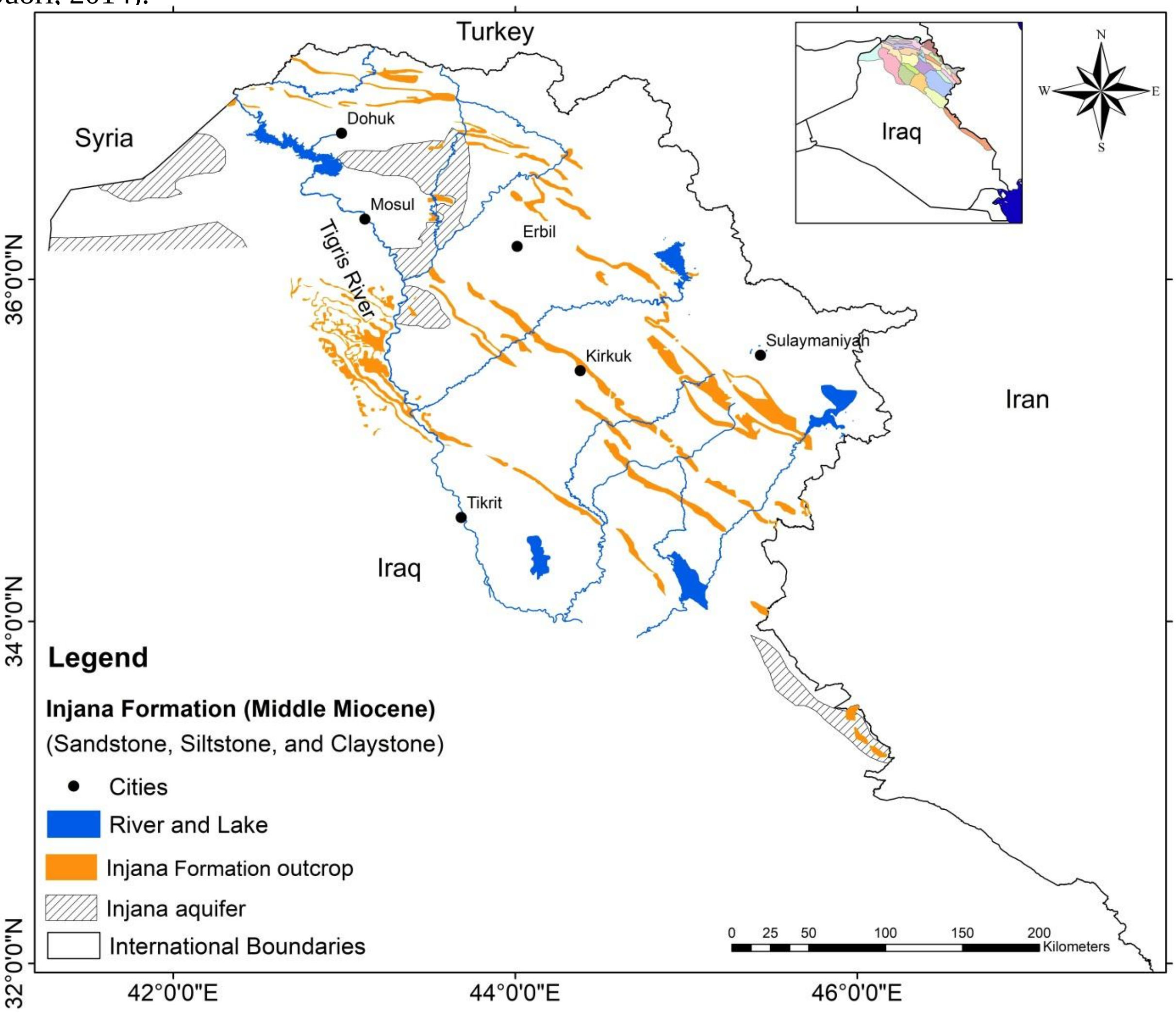

Figure (3 - 7):- Shows extensions map of Injana Formation and its aquifer (after Al Jawad and Ridha, 2008).

Based on what was mentioned above, the groundwater in North and East Iraq is present mainly in carbonate and clastic rocks. The carbonate rocks are characterized by karstic fissures and fractures representing secondary porosity. Secondary porosity in carbonate rocks plays an essential role in determining groundwater's quantity and flow direction. On the other hand, the clastic rocks are characterized by primary porosity that depends on grain size, and it is very high in coarse sandstone and gravel and reveals high well discharges. The complex structural geology and variations in rock type within aquifer systems are the main factors determining groundwater flow direction. The regional flow direction of the groundwater in the North and East Iraq is generally to the Southwest and South towards the Tigris River, with other different approaches towards the Greater Zab, Lesser Zab, Khabour, Sirwan, and Al-Udhaim rivers, due to the complexity of the structure and topography of this area, as shown in figure (3-8).

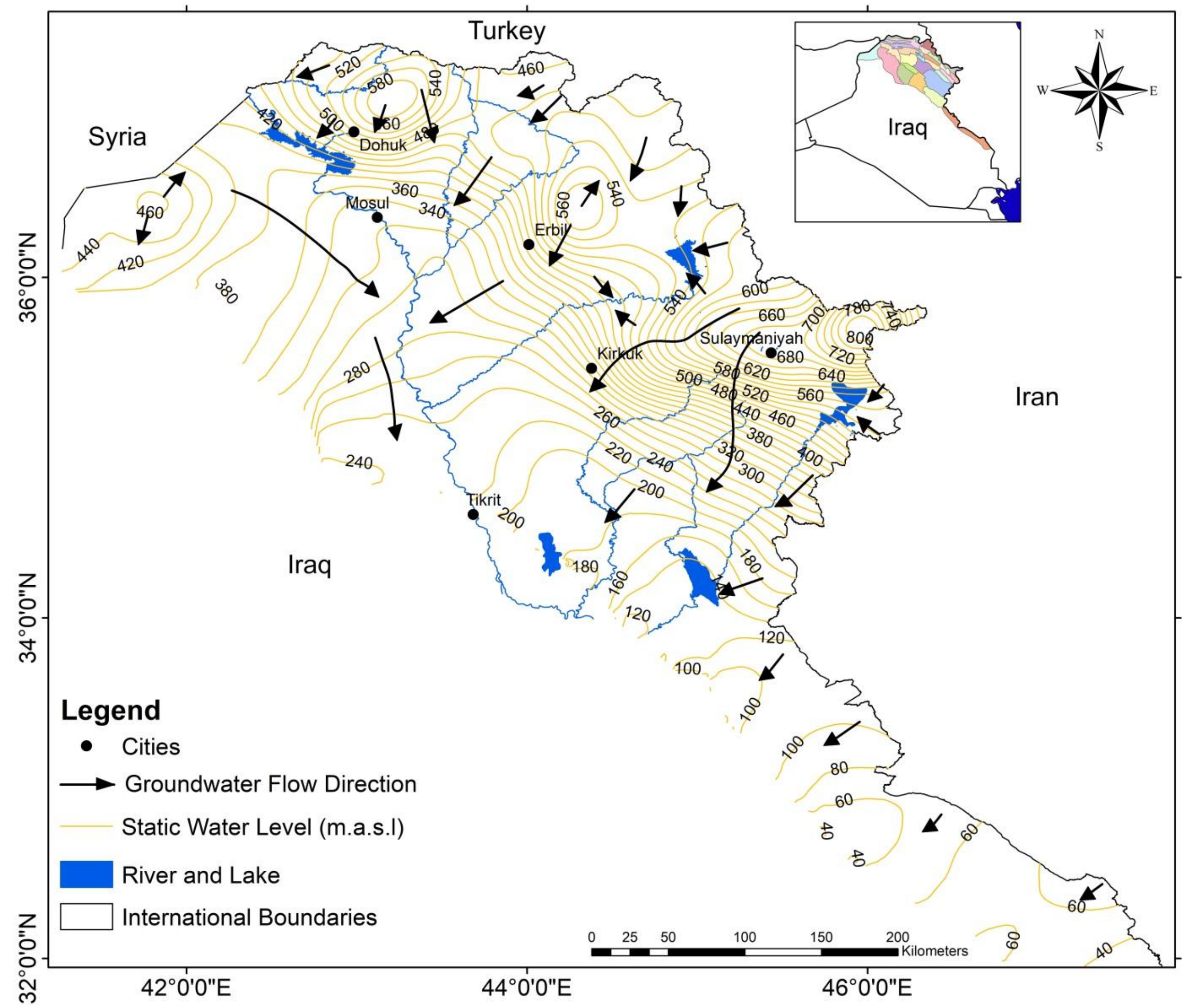

Figure (3 - 8):- Shows flow direction map of the groundwater in North and East Iraq.

The groundwater salinity in North and East Iraq is characterized by variable values ranging between (124 - 7170 mg/l), as shown in figure (3-9). This variation reflects the variations in rock type within aquifer systems as well as natural conditions controlling groundwater recharge and discharge. Generally, the salinity of the groundwater increases from East to West. In the Low Folded Hydrogeological Region, the saltiness of the groundwater increases from North to South with values ranging between (500 to more than 7000 mg/l), as shown in figure (3-9). The groundwater in Suture and Thrust and High Folded Hydrogeological Regions is characterized by freshwater being Ca (Mg)-HCO3 with the prevailing bicarbonate type. As for the Low Folded Hydrogeological Region, the chemical composition of the groundwater changes from a prevalent bicarbonate type to sulfate type due to the presence of gypsum, anhydrite, and halite within the Fatha Formation in the North part of this region (Krasny *et al.*, 2006 in Jassim and Goff, 2006). While in the southern part, the increase in salinity is due to the increase in the evaporation rate of surface water, and then it leaches into the water-bearing layers. The chemical analyses showed that the most water samples of upper aquifers were under saturated by (Gypsum, Anhydrite, Chalcedony and Halite) minerals, (Al-Kaabi, 2009). In general, the hydrogeological conditions of these aquifer systems can be described in detail within hydrogeological regions as follows:-

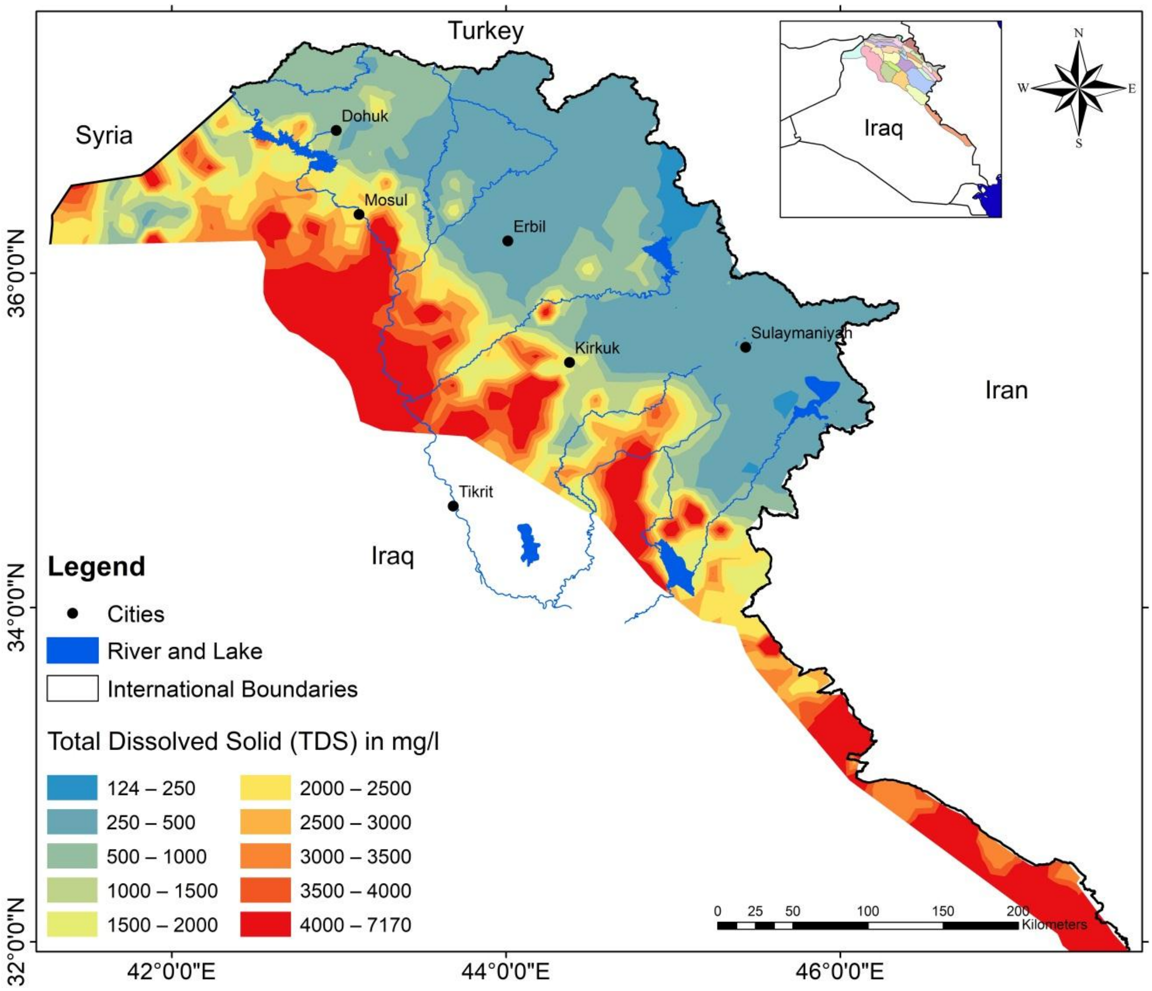

Figure (3 - 9):- Shows the groundwater salinity (mg/l) map of North and East Iraq.

3-2 Suture and Thrust Hydrogeological Region

This region represents the mountains of North and Northeastern Iraq and occupies a small area of about (1.32%) of the total area of Iraq, (Al-Madhlom *et al.*, 2020). It is extended as a narrow belt along the Iraqi-Turkish-Iranian border. This region consists of igneous rocks, including ophiolites, metamorphic and highly folded and faulted Paleozoic and Lower Mesozoic sedimentary rocks (Aqrawi *et al.*, 2010). The hydrological data of this region is minor and only based on the information provided by Stevanovic and Markovic (2004). This region is characterized by a small extent and distance from main population centers. According to Stevanovic and Markovic (2004), the largest known Zulam spring in the region has a minimum yield of (0.38 m^3/s) and a typical yield of over (2.0 m^3/s). Krasny et al., 2006 in Jassim and Goff (2006) described the specific hydrogeological characteristics of this region as follows:-

The close-to-surface aquifer represents the shallow zone of the relatively high permeability of rugged rocks that reaches depths of several tens of meters. It consists of a weathered upper site of basement rocks with non-indurated Quaternary deposits and a lower fractured zone. The transmissivity of the close-to-surface aquifer is usually (1-10 m^2/day), but it may exceed many tens of (m2/day) in intensively fractured zones. The shallow or "close-to surface aquifer" is located below so-called massive layers where only a few permeable fractures exist. This region is divided into three hydrogeological areas, as follows:-

3-2-1 Kani Masi Hydrogeological Area

The Kani Masi hydrogeological area is located along the Iraqi-Turkish border in the extreme Northern part of Iraq. Its coverage area is about (1621.8 Km^2) with elevation ranges from (521 m) to (2780 m) above sea level, as shown in figure (3-10). The watersheds flow to the Al-Khabour, and Great Zab River, the average annual rainfall, temperature, and potential Evaporation of this area is about (850 mm/yr), (16.8 °C) and (2191.5mm) respectively for the period (1979 – 2014).

The results of pumping tests that were conducted by Stevanovic and Markovic (2004) of two wells drilled in this area showed that the transmissivity of the unconfined aquifers ranges between (53 – 80 m^2/day), Hydraulic conductivity ranges between (0.8 – 1.0 m/day), while the discharge varies between (660 – 778 m^3/day) and the static water level ranges between (11 – 19 m) below the ground surface. Furthermore, the hydrochemical analysis of the water samples from these aquifers indicates that the total dissolved solids (TDS) were less than (1000 mg/l) with bicarbonate water type in general.

Depending on the results of the hydrochemical analysis, the groundwater of this area is suitable for different uses.

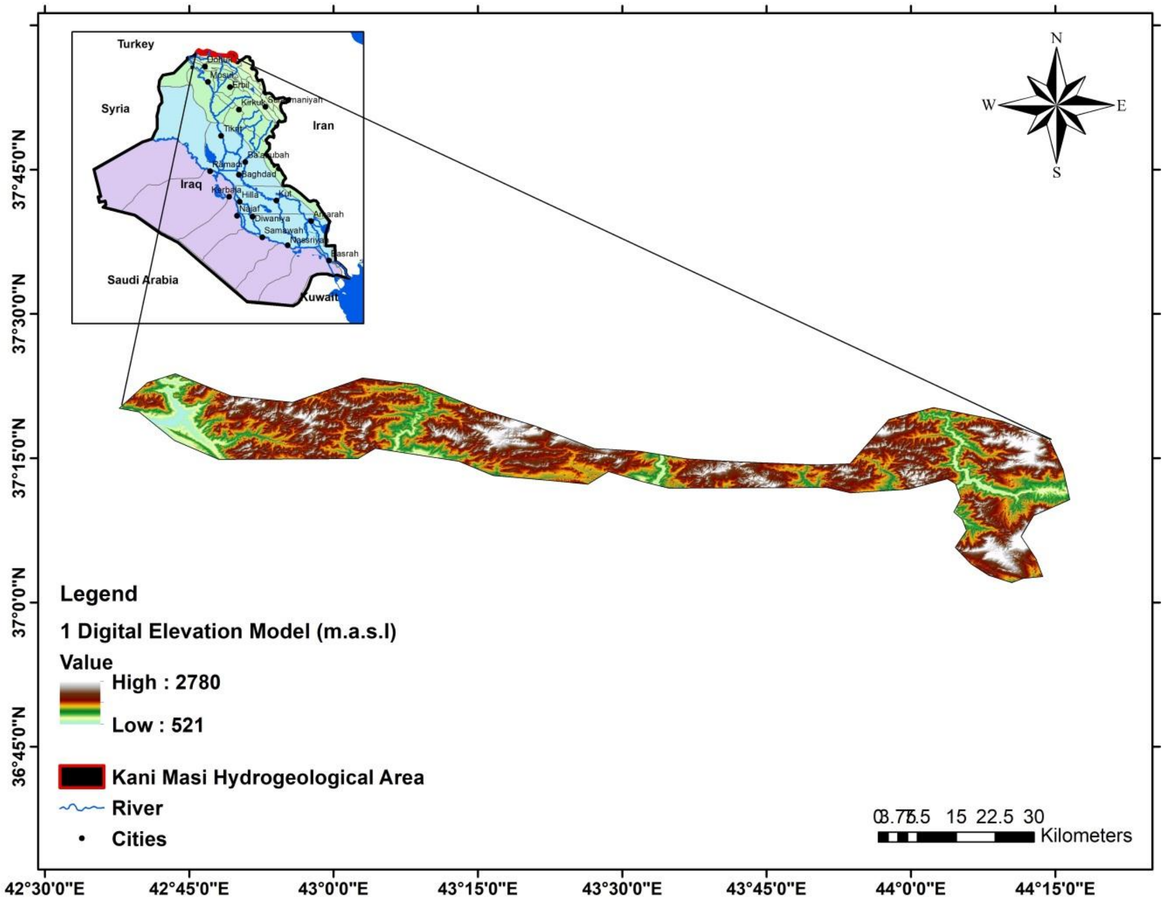

Figure (3 - 10):- Shows the watersheds map of the Kani Masi hydrogeological area.

3-2-2 Sidakan Hydrogeological Area

This area represents the central part of the Suture and Thrust hydrogeological region, and it is located along the Northern part of the Iraqi – Iranian border. It occupies an area is about (3509.8 Km^2) with elevation ranges from (603 m) to (3609 m) above sea level, as shown in figure (3-11). The average annual rainfall, temperature, and potential Evaporation of this area is about (850 mm/yr), (16.8 °C) and (2128 mm) respectively, for the period (1979 – 2014).

Based on the results of Stevanovic and Markovic (2004) study, the pumping tests of wells showed that the transmissivity ranges between (85 – 134 m^2/day), Hydraulic conductivity ranges between (0.3 – 1.8 m/day); well discharge ranges between (524 – 968 m^3/day) and static water level ranges between (6 – 32 m) below ground surface. The results of the hydrochemical analysis indicate that the groundwater is mainly fresh water with (TDS) values were less than (1000 mg/l) with bicarbonate water type. In general, the groundwater quality of this area is suitable for different uses according to specifications standards.

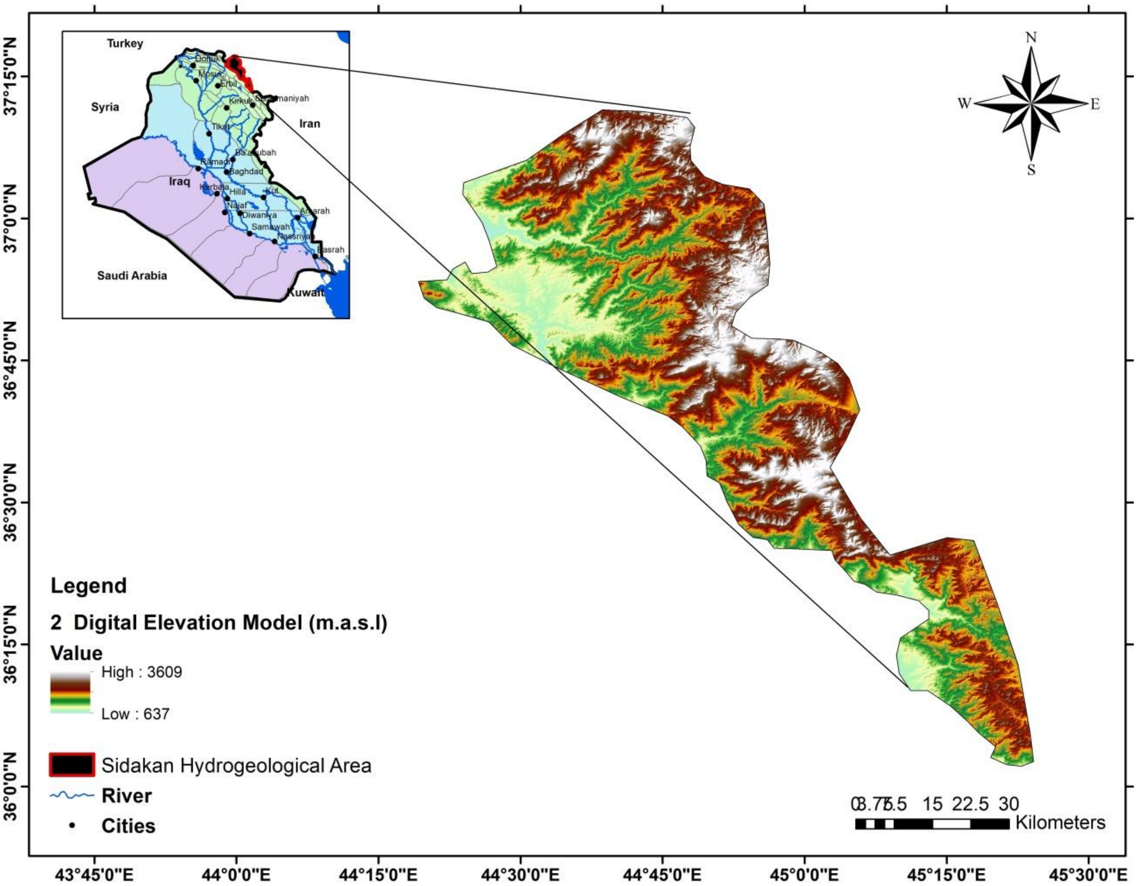

Figure (3 - 11):- Shows the watersheds map of the Sidakan hydrogeological area.

3-2-3 Penjween Hydrogeological Area

The Penjween hydrogeological area is located along the Iraqi – Iranian border in the Southeastern part of this region, with an estimated area, is about (2057.4 Km²). Its elevation ranges from (714m) to (2682 m) above sea level, as shown in Figure (3-12). The average annual rainfall, temperature, and potential Evaporation of this area is about (760 mm/yr), (16.8 °C) and (2191.5 mm) respectively, for the period (1979 – 2014).

The presence of confined aquifers characterizes this area. The results of the pumping test that carried out in (22) wells showed that the transmissivity ranges between (14 – 783 m^2/day), Hydraulic conductivity ranges between (0.2 – 29 m/day); well discharge ranges between (518 – 5789 m^3/day) and static water level ranges between (2 – 12 m) below ground surface, (Stevanovic and Markovic, 2004). The results of the hydrochemical analysis indicate the groundwater is mainly fresh water with (TDS) values were less than (1000 mg/l) with bicarbonate water type. Therefore, depending on the results of the hydrochemical analysis, the groundwater of this area is suitable for different uses.

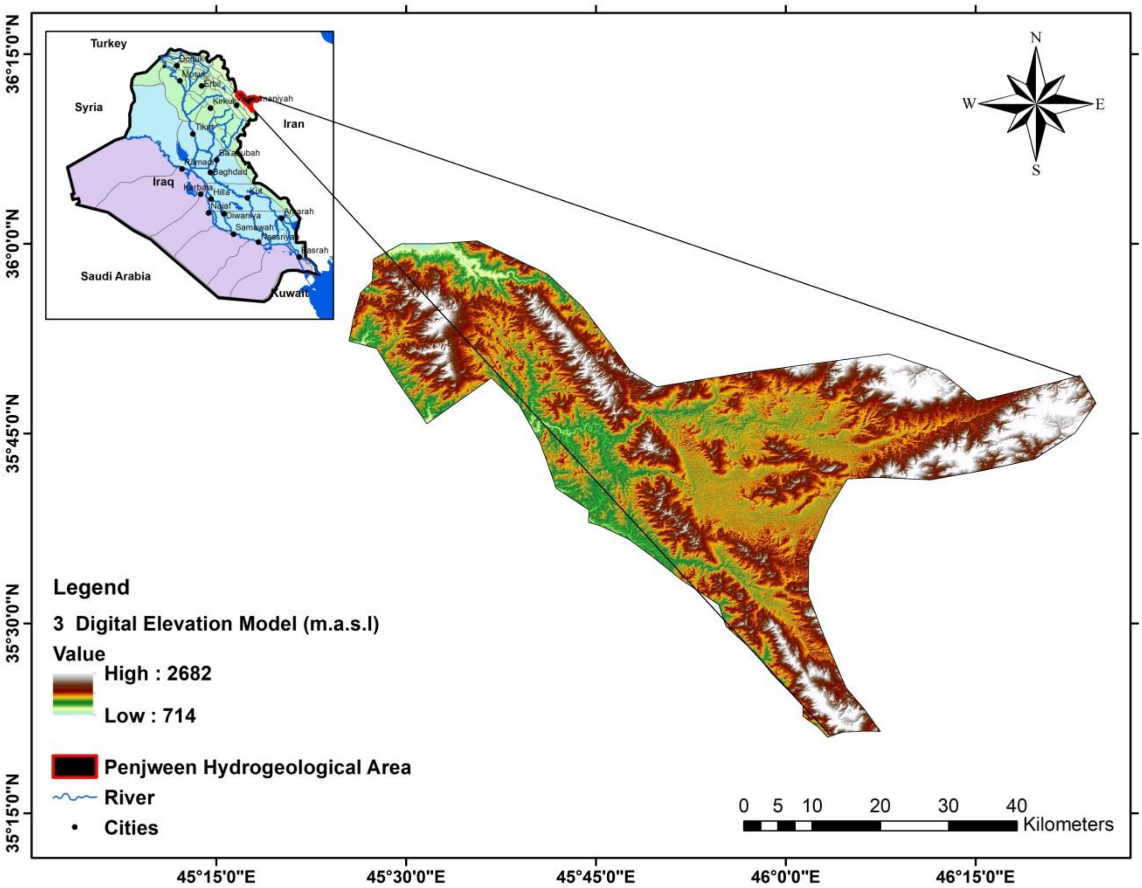

Figure (3 - 12):- Shows the watersheds map of the Penjween hydrogeological area.

3-3 High Folded Hydrogeological Region

The High Folded Hydrogeological Region locates in the Northern and Northeastern parts of Iraq between the Suture and Thrust and Low Folded Hydrogeological Regions. Topographically, Sissakian and Al-Jibuori (2014b) indicate two main topographical features in this region. The first is the elevated parts (mountainous) that consist of the rocky surface expound by streams and valleys. The second is the flat and undulatory parts that form limited areas from small plains and are covered by classics of different Formations and Quaternary sediments. Tectonically, the High Folded Hydrogeological Region belongs unstable Shelf of the Arabian Platform (Al-Kadhimi et al., 1996; Jassim and Buday in Jassim and Goff, 2006), whereas Fouad (2012) considered it represents a part from the Outer Platform. However, this region is characterized by a large number of folds with higher amplitudes and short wavelengths with different shapes and sizes. Moreover, deep and narrow synclinal valleys separate these folds (Fouad, 2012).

The main source of groundwater recharge in this region is direct precipitation and snowmelt at the highest elevated areas and from the Suture and Thrust Region in the Northeast. At the same time, the Low Folded Region represented the discharge areas of the High Folded Region, beside wells and springs (Stevanovic and Markovic, 2004). Therefore, springs represent the most important sources of groundwater discharge in this region. Stevanovic and Markovic (2004) classified two types of springs. The first one is located within the Karstic Bekhme aquifer systems, including Sarchinar and Bekhal springs. They are often are closely related to faults locations, fractures systems, and bordering massive carbonate rocks at their contact with non-carbonate rocks. The second is located within the Fractured – karstic Pila Spi aquifer systems, including the springs of Dera Boon and Bani Khelan. In general, these two types of springs are distinguished by yield freshwater (less than 600 mg/l) of predominately bicarbonate type (Krasny *et al*., 2006 in Jassim and Goff, (2006) and Al-Jiburi and Al-Basrawi, 2014). Some spring water in contact with gypsum layers of Fat'ha Formation has yielded water of salinity greater than (1000 mg/l) with Sulphatic water type due to contamination with sulfate. As for those springs related to the clastic sediments like Injana, Mukdadiya, and Bai Hassan formations, they are characterized by yield freshwater (less than 1000 mg/l) and predominantly calcium–bicarbonate water (Al-Jiburi and Al-Basrawi, 2014). In general, the groundwater quality of this area is suitable for different uses according to specifications standards.

The High Folded Region was divided into twelve major hydrogeological areas and as follows:-

3-3-1 Zakho Hydrogeological Area

The Zakho hydrogeological area is located in the North part of the High Folded Region as a closed East-West trending intermountain area filled by more than (2000 m) of clastic sediments of Injana, Mukdadiya, and Bai Hassan Formations and Quaternary deposits, according to Stevanovic and Markovic, (2004). Although this area is located within the High Folded Region, it has similar hydrogeological characteristics to the hydrogeological areas within the Low Folded Region (Krasny et al., 2006 in Jassim and Goff, 2006). However, groundwater flows towards the main river Khabour and its tributaries. The eastern extension of the Zakho area passes into the narrow Amadia – Barzan hydrogeological area, which is in the catchment area of the upper reaches of the Greater Zab River (Al-Jiburi and Al-Basrawi, 2014). The catchment area of Zakho hydrogeological area of about (1695.8 km^2) and only (23%) of the average annual rainfall (850 mm) infiltrates into the ground to reach the aquifer systems. The average temperature and potential Evaporation of this area are about (16.8 °C) and (2191.5mm) respectively, for the period (1979 – 2014). Its elevation ranges from (331 m) to (2268m) above sea level, as shown in Figure (3-13). The presence of Formations characterizes the geology of the area is range from the Cretaceous to Quaternary Period with various lithology including clastic and carbonate rocks (Aqra - Bekhme, Shiranish, Kolosh, Khurmala, Gercus, Avanah, Pila Spi, Fatha, Injana , Bai Hassan and Mukdadiya Formations and Quaternary sediments).

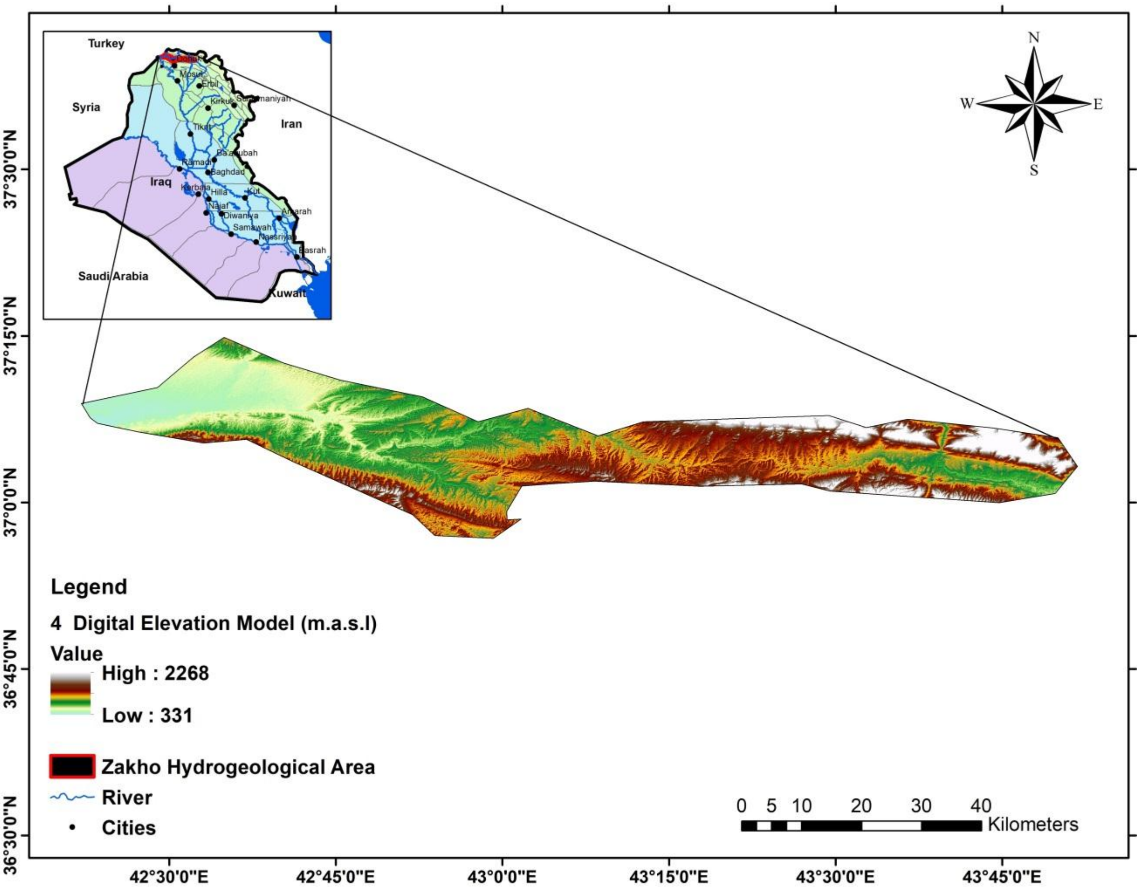

Figure (3 - 13):- Shows the watersheds map of the Zakho hydrogeological area.

The major spring in the Zakho hydrogeological area is (Dera boon), which is located near the Iraqi-Turkish border at the contact between the Pila Spi Formation and the less permeable overlying Fatha (Lower Fars) Formation, and that has a discharge of (0.83-1.13 m^3/s), (Stevanovic and Markovic,2004).

Based on the results of Stevanovic and Markovic (2004) studies, the pumping tests of wells showed that the transmissivity ranges between (5 – 227 m^2/day), Hydraulic conductivity ranges between (0.1 – 2.2 m/day); well discharge ranges between (46 – 1760 m^3/day) and static water level ranges between (1 – 42 m) below ground surface. The results of the hydrochemical analysis indicate the groundwater is mainly fresh water with (TDS) values were less than (500 mg/l) with bicarbonate water type. According to specifications standards, the groundwater in this area is suitable for different uses.

3-3-2 Amadia – Barzan Hydrogeological Area

The Amadia – Barzan hydrogeological area is located in the Northern part of the High Folded Region. It represents a part from the boundaries of the High Folded Region with the Suture and Thrust Hydrogeological Region. It covers an area of about (3244 Km^2) with elevation ranges from (380 m) to (2343m) above sea level, as shown in figure (3-14). The watersheds flow to the Great

Zab River, the average annual rainfall, temperature, and potential Evaporation of this area is about (850 mm/yr), (16.8 °C) and (2191.5mm) respectively for the period (1979 – 2014).

The main conditions of aquifers in this area are confined and unconfined aquifers within intergranular Bakhtiari (Bai Hassan and Mukdadiya) aquifer system, with recent alluvium aquifers in small areas and different locations, Stevanovic and Markovic, (2004). According to Al-Jiburi and Al-Basrawi, (2014), the results of pumping tests performed in many wells in this hydrogeological area showed that the transmissivity of the aquifers ranges between (3 – 134 m^2/day), Hydraulic conductivity ranges between (0.1 – 5 m/day), discharge of wells varies between (19 – 1555 m^3/day), and the static water level ranges between (8 – 24 m) below ground surface. The groundwater is mostly freshwater with salinity ranges between (300 – 900 mg/l) with bicarbonate and sulphatic water type.

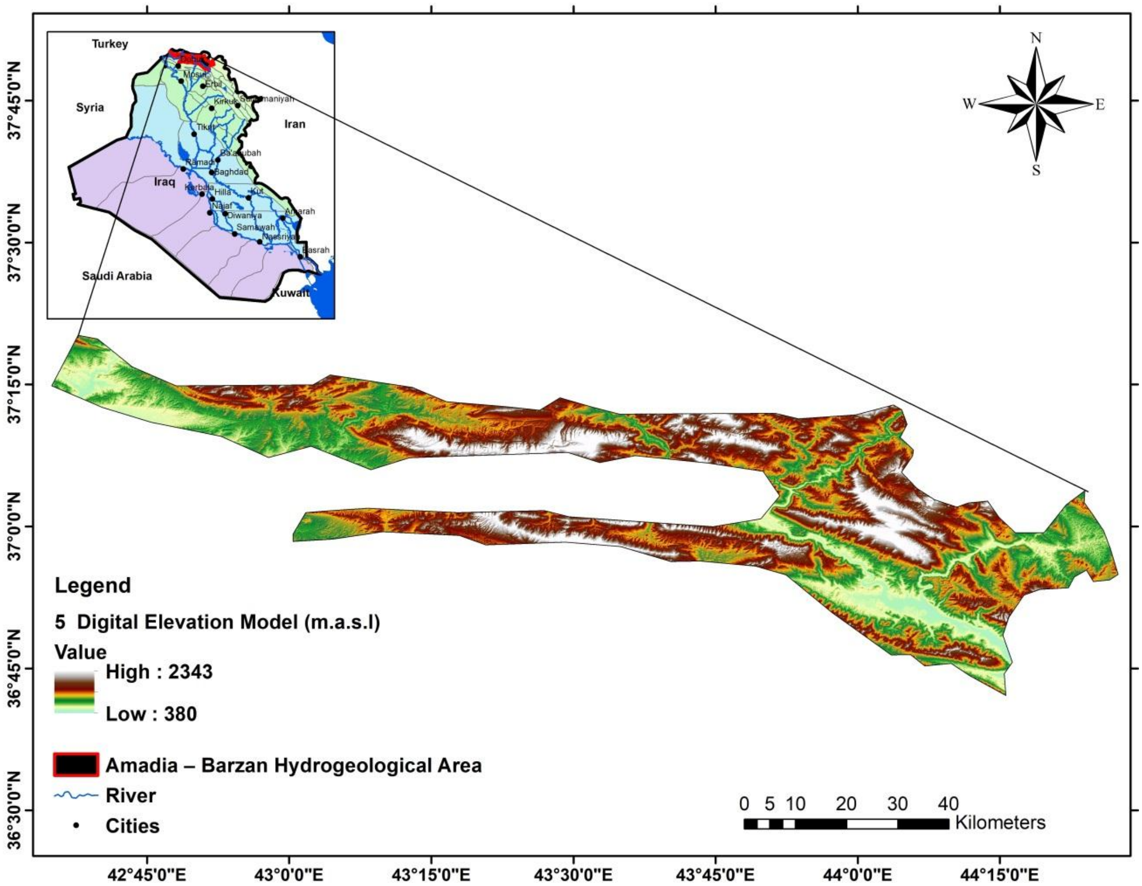

Figure (3 - 14):- Shows the watersheds map of the Amadia – Barzan hydrogeological area.

3-3-3 Atrush – Dinarta Hydrogeological Area

The Atrush – Dinarta hydrogeological area represents a part from the Southern boundaries of the High Folded Region with the Low Folded Region. It extends as a narrow belt from the Iraqi-Turkish border in the Northwest to the Greater Zab River in the Southeast, passing through the Dohuk town. It covers an area of about (2518.1 Km²) with elevation ranges from (307m) to (2076

m) above sea level, as shown in figure (3-15). The watersheds flow to the Great Zab River, the average annual rainfall, temperature, and potential Evaporation of this area is about (850 mm/yr), (16.8 °C) and (2191.5mm) respectively for the period (1979 – 2014).

Based on the lithological section of water wells, this area consists of Injana, Mukdadiya and Bai Hassan Formations clastic sediments, representing water-bearing formations with the confined and unconfined aquifer type (Stevanovic and Markovic, 2004).

The results of the pumping test of wells in this hydrogeological area indicated that the transmissivity of the aquifers ranges between (3 – 2082 m^2/day), Hydraulic conductivity ranges between (0.1 – 17.3 m/day), discharge of wells varies between (53 – 2970 m^3/day) and the static water level ranges between (1.5 – 60 m) below ground surface. Therefore, the groundwater is freshwater with salinity ranges between (300 – 500 mg/l) with bicarbonate water type mostly (Al-Jiburi and Al-Basrawi, 2014).

The Amadia – Barzan, and Atrush – Dinarta hydrogeological areas are considered hydrogeological flow system called NW Barzani. Hydrogeological flow system were delineated based on the hydrogeological area boundaries and interbasin flows between these two hydrogeological areas.

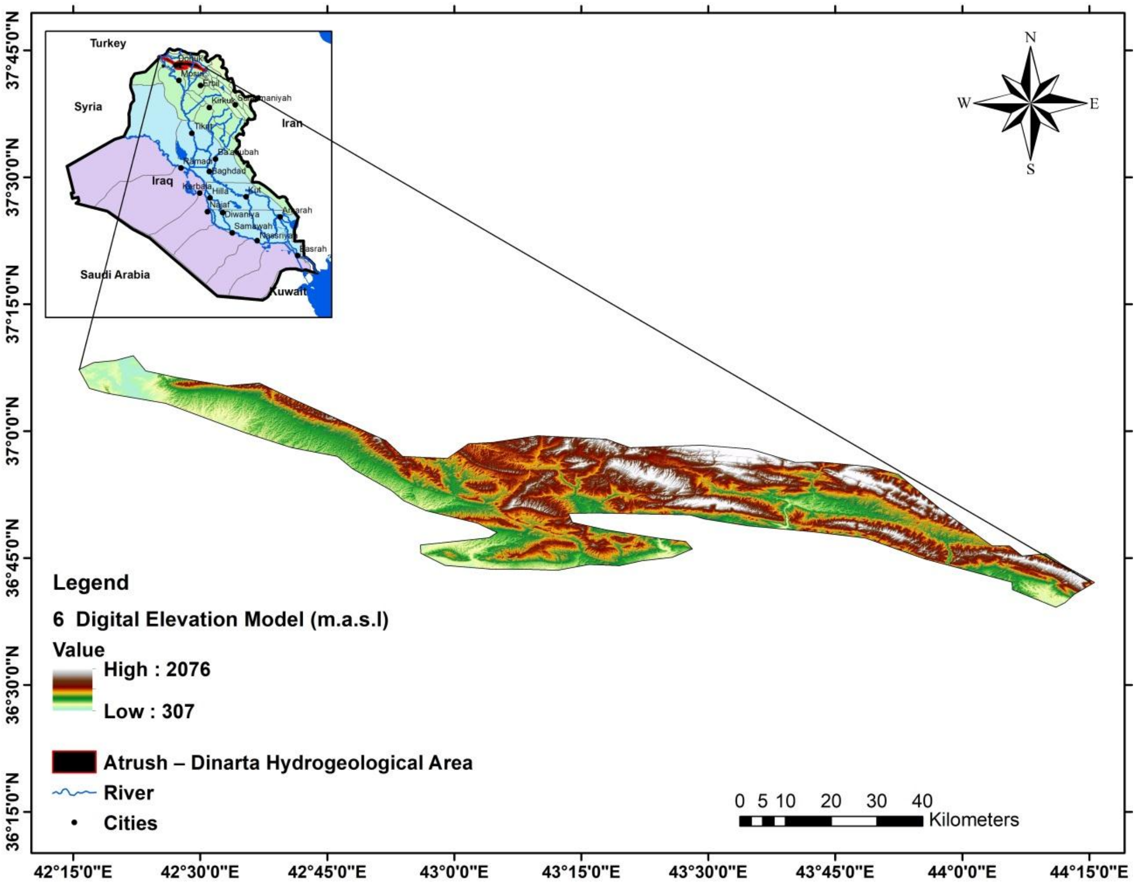

Figure (3 - 15):- Shows the watersheds map of the Atrush – Dinarta hydrogeological area.

3-3-4 Diana – Merga Soor Hydrogeological Area

The Diana – Merga Soor hydrogeological area, represents a small part from the Northern boundaries of the High Folded Region with the Suture and Thrust Region. It has a total area of about (1170 Km²) with elevation ranges from (307 m) to (2076 m) above sea level, as shown in figure (3-16). The watersheds flow to the Great Zab River, the average annual rainfall, temperature, and potential Evaporation of this area is about (850 mm/yr), (16.8°C) and (2191.5mm) respectively for the period (1979 – 2014). It is characterized by two conditions of aquifers, confined and unconfined aquifers. The main aquifers are represented by karstic and karstic–fissured aquifer systems (Stevanovic and Markovic, 2004).

According to Al-Jiburi and Al-Basrawi, (2014), the results of pumping tests performed in many wells in this hydrogeological area showed that the transmissivity of the aquifers ranges between (6 – 662 m^2/day), Hydraulic conductivity ranges between (0.1 – 14.6 m/day), discharge of wells varies between (20 – 2070 m^3/day), and the static water level ranges between (1.2 – 60m) below ground surface. Therefore, the groundwater is mainly fresh water with less than (1000 mg/l) and bicarbonate water type mostly.

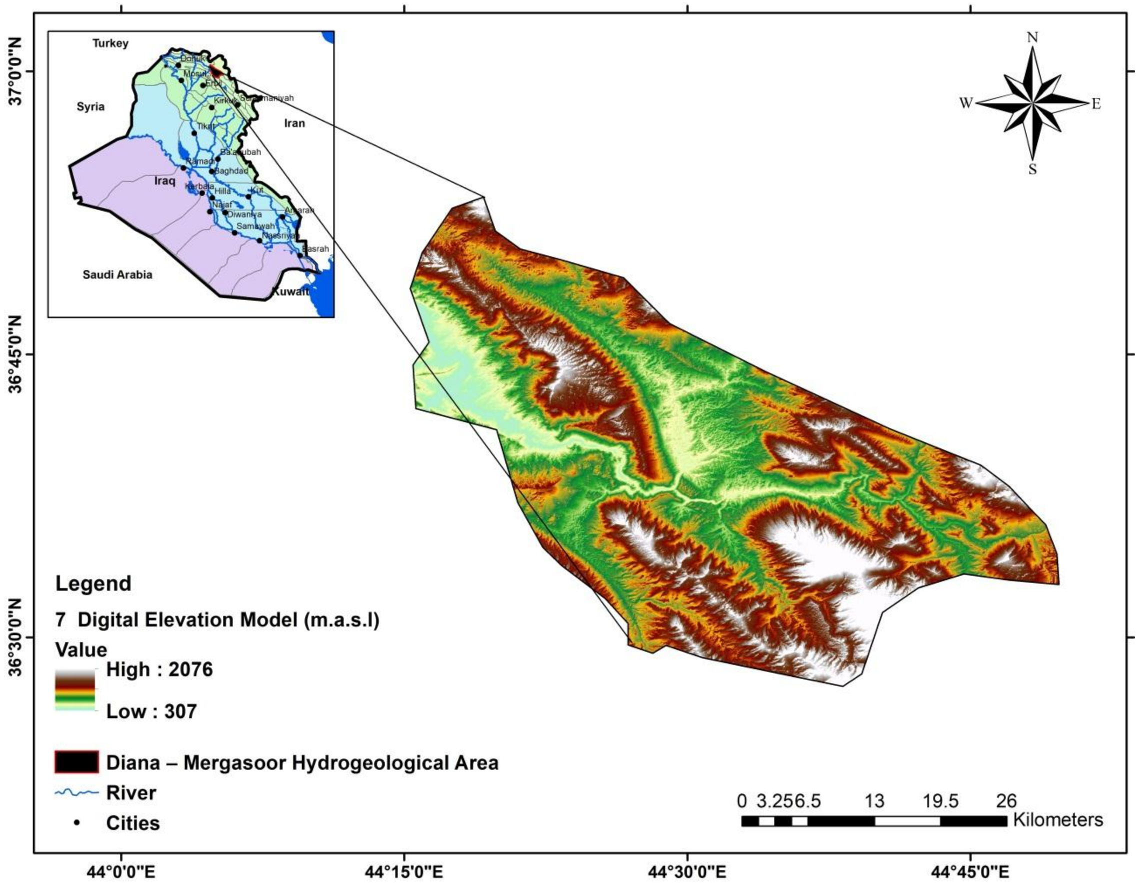

Figure (3 - 16):- Shows the watersheds map of the Diana – Merga Soor hydrogeological area.

3-3-5 Harir – Shaqlawa Hydrogeological Area

The Harir – Shaqlawa hydrogeological area lies approximately (50 km) to the Northeast of the Erbil City, between Harir anticline in the Northeast and Safin anticline in the Southwest, and occupies an area is about (1223.7 Km²) with elevation ranges from (314 m) to (1688m) above sea level, (Fatah *et. al.,* 2020). It represents watersheds flow to the Greater Zab River, as shown in figure (3-17). The average annual rainfall, temperature, and potential Evaporation of this area is about (835 mm/yr), (16.6°C) and (2191.5mm) respectively, for the period (1979 – 2014).

The lithological sections of water wells drilled in this area showed that the principal aquifers are recent alluvium deposits, Injana, Mukdadiya aquifers (Stevanovic and Markovic, 2004).

The results of the pumping test of wells in this hydrogeological area indicated that the transmissivity of the aquifers ranges between (3 – 611 m^2/day), Hydraulic conductivity ranges between (0.1 – 19.1 m/day), discharge of wells varies between (37 – 2310 m^3/day) and the static water level ranges between (4 – 60 m) below ground surface. The groundwater is mainly freshwater with salinity ranges between (300 – 500 mg/l) with bicarbonate water type mostly (Al-Jiburi and Al-Basrawi, 2014).

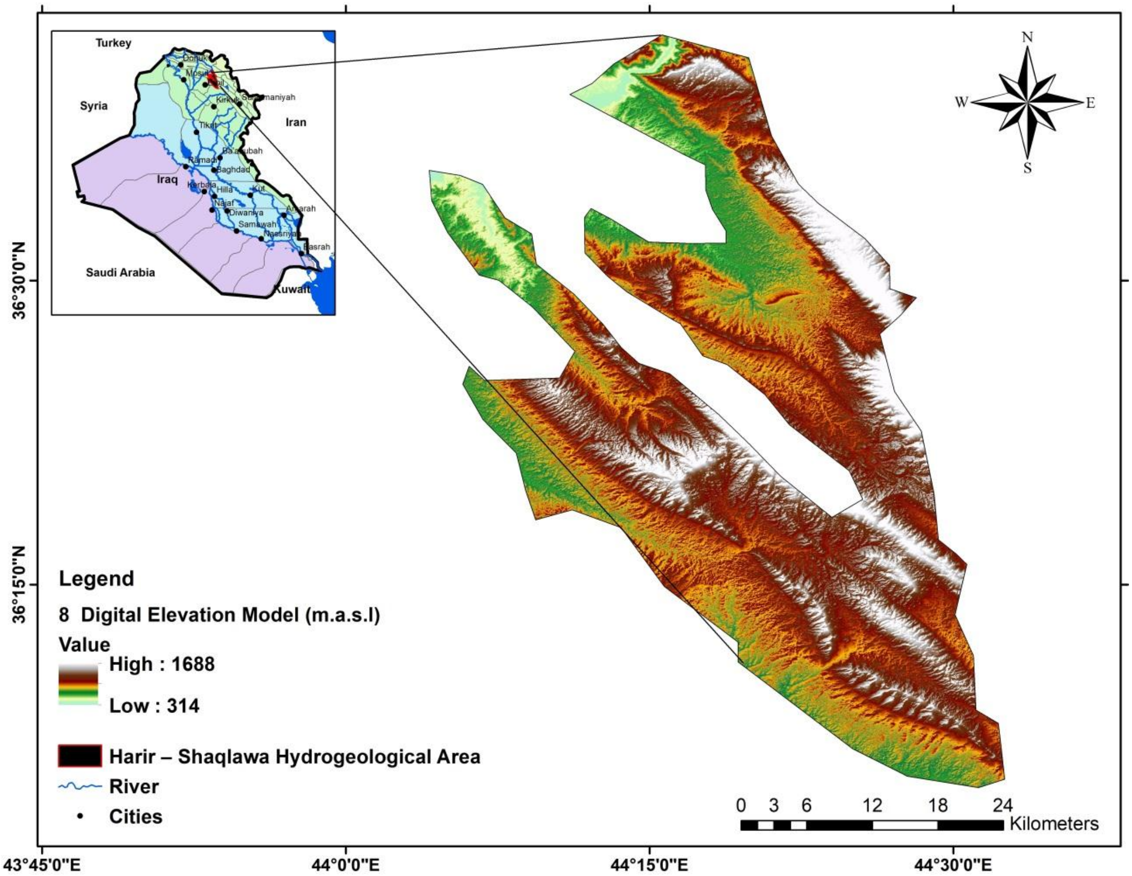

Figure (3 - 17):- Shows the watersheds map of the Harir – Shaqlawa hydrogeological area.

The Diana – Merga Soor and Harir – Shaqlawa hydrogeological areas are considered hydrogeological flow system called Central Harir Hydrogeological flow system were delineated based on the hydrogeological area boundaries and interbasin flows between these two hydrogeological areas.

3-3-6 Sarsang Hydrogeological Area

The Sarsang hydrogeological area is located in the central part of the High Folded Region. It represents a catchment area of the Dokan Lake and Lesser Zab River, which is covered an area of about (1223.6 Km²) with elevation ranges from (429 m) to (2656m) above sea level, as shown in figure (3-18). The average annual rainfall, temperature, and potential Evaporation of this area is about (850 mm/yr), (16.3°C) and (2191.5mm) respectively, for the period (1979 – 2014).

The main aquifers are represented by karstic and karstic–fissured aquifer systems with two types of aquifers, confined and unconfined aquifers (Stevanovic and Markovic 2004).

According to Al-Jiburi and Al-Basrawi, (2014), the results of pumping tests performed in many wells in this hydrogeological area showed that the transmissivity of the aquifers ranges between (3 – 540 m^2/day), Hydraulic conductivity ranges between (0.1 – 14.6 m/day), discharge of wells varies between (99 – 1749 m^3/day), and the static water level ranges between (6 – 80 m) below ground surface. In general, this area is characterized by fresh water with salinity less than (1000 mg/l) and with bicarbonate water type mostly.

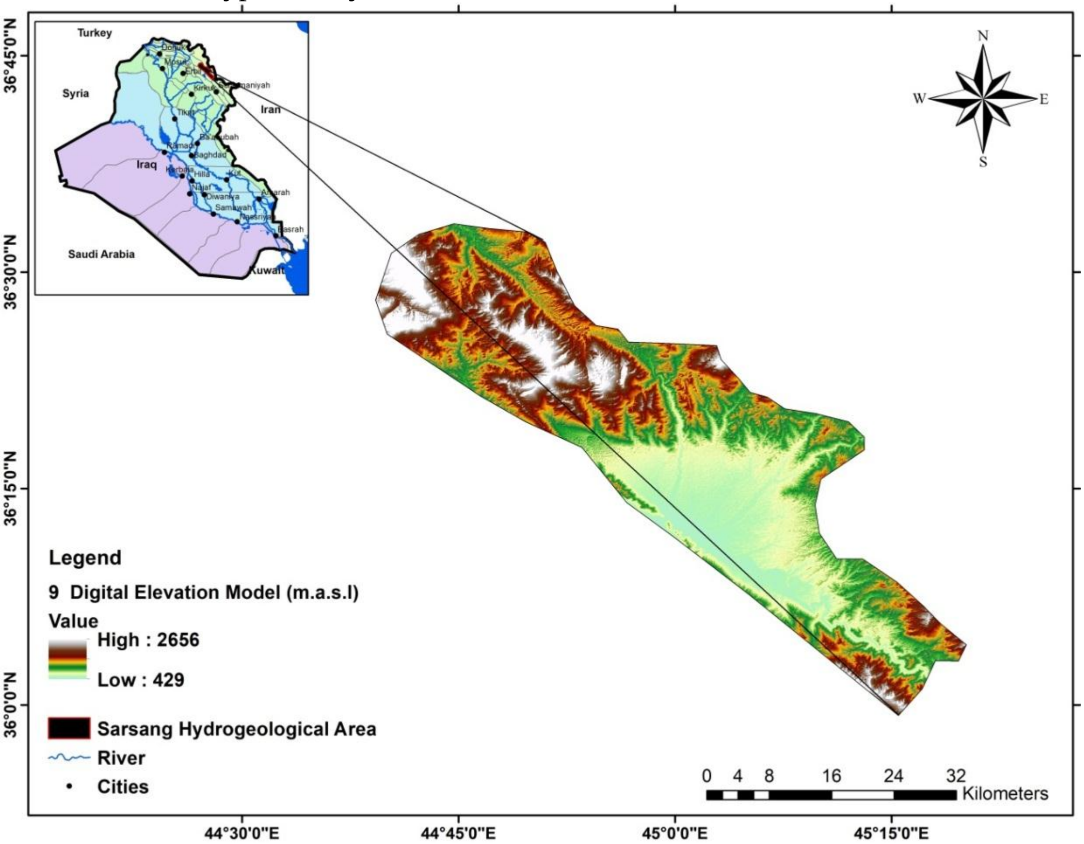

Figure (3 - 18):- Shows the watersheds map of the Sarsang hydrogeological area.

3-3-7 Dokan Hydrogeological Area

Dokan Hydrogeological Area extends from Northeast to Southeast of Dokan Lake. It represents a catchment area of the Dokan Lake, which is covered an area of about (1440.8 Km^2) with elevation ranges from (469 m) to (2520 m) above sea level, as shown in figure (3-19). The average annual rainfall, temperature, and potential Evaporation of this area is about (640 mm/yr), (16.3°C) and (2318 mm) respectively, for the period (1979 – 2014).

The lithological sections of water wells drilled in the Southeast of Dokan Lake showed that the main aquifers are recent alluvium deposits, karstic and karstic–fissured aquifer systems with two types of aquifers, confined and unconfined aquifers. While the lithological sections of water wells drilled in the Northwest of Dokan Lake (Rania plain) inducted that the main aquifers are recent alluvium deposits and Bai Hassan aquifer, (Stevanovic and Markovic 2004).

The results of the pumping test of wells indicated that the transmissivity of the aquifers ranges between (15 – 864 m^2/day), Hydraulic conductivity ranges between (0.2 – 12.8 m/day), discharge of wells varies between (53 – 2970 m^3/day) and the static water level ranges between (3 – 61 m) below ground surface. This area is characterized by fresh water with a salinity ranges between (300 – 500 mg/l) with bicarbonate water type mostly, (Al-Jiburi and Al-Basrawi, 2014).

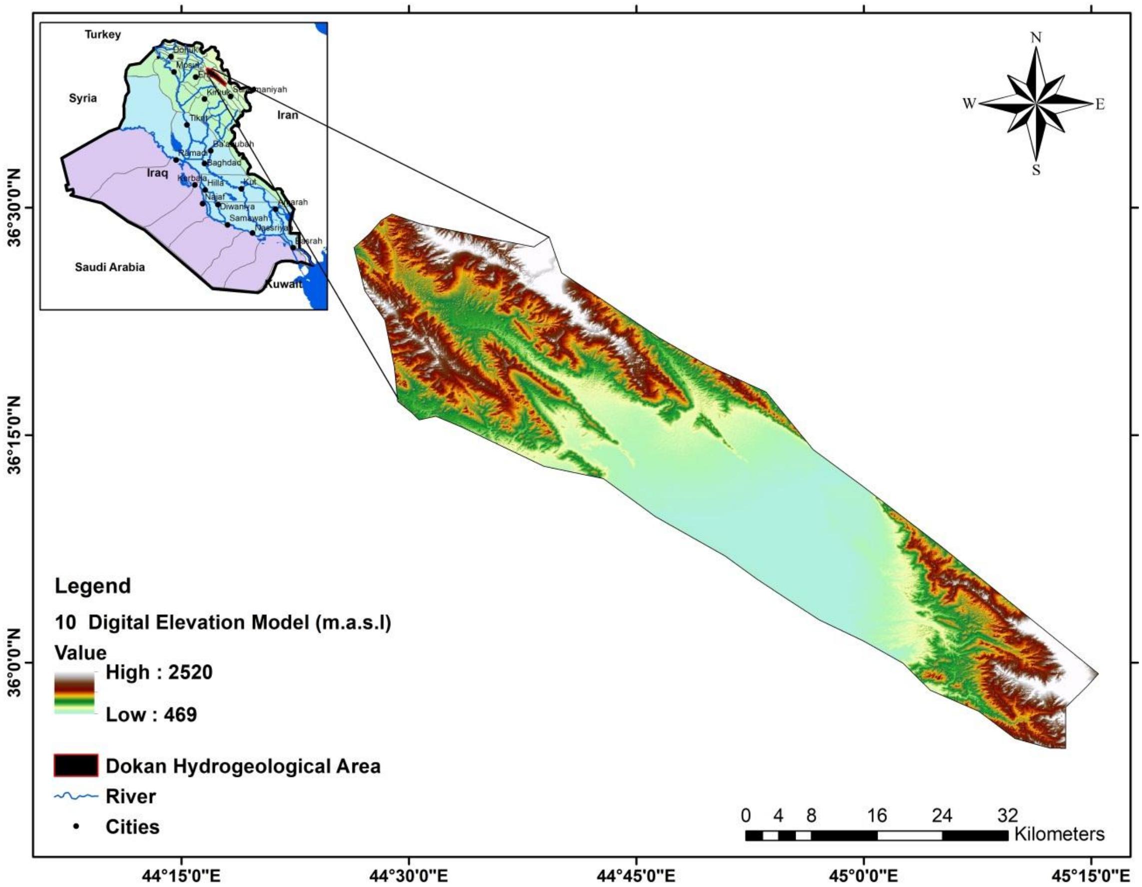

Figure (3 - 19):- Shows the watersheds map of the Dokan hydrogeological area.

3-3-8 Bangard – Surdash Hydrogeological Area

The Bangard – Surdash hydrogeological area represents a part from the Southwestern boundaries of the High Folded Region with the Low Folded Region. It is a part of the catchment area of the Lesser Zab River, which is covered an area of the watershed is about (1497.5 Km^2) with elevation ranges from (349 m) to (2575 m) above sea level, as shown in figure (3-20). The average annual rainfall, temperature, and potential Evaporation of this area is about (850 mm/yr), (16.3°C) and (2191.5mm) respectively, for the period (1979 – 2014).

The main aquifers in this area are confined and unconfined aquifers within karstic and karstic–fissured aquifer systems with recent alluvium aquifers in small areas and different locations, (Stevanovic and Markovic, 2004).

According to Al-Jiburi and Al-Basrawi, (2014), the results of pumping tests performed in many wells in this hydrogeological area showed that the transmissivity of the aquifers ranges between (14 – 597 m^2/day), Hydraulic conductivity ranges between (0.2 – 4.4 m/day), discharge of wells varies between (330 – 1961m^3/day), and the static water level ranges between (0.7 – 35 m) below ground surface. This area is characterized by fresh water with less than (500 mg/l) and bicarbonate water type mostly.

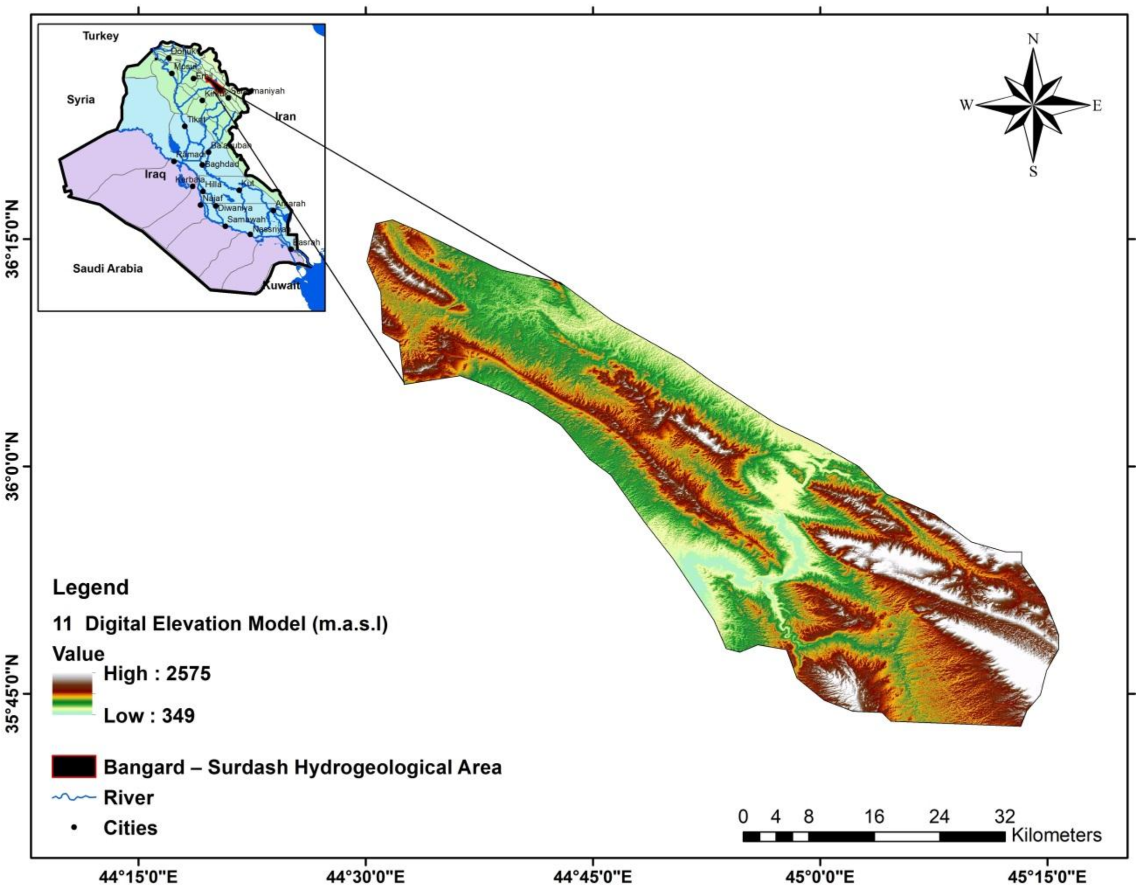

Figure (3 - 20):- Shows the watersheds map of the Bangard – Surdash hydrogeological area.

The Sarsang, Dokan, and Bangard – Surdash hydrogeological areas are considered hydrogeological flow systems called Central Dokan Hydrogeological flow system were delineated based on the hydrogeological area boundaries and interbasin flows between these two hydrogeological areas.

3-3-9 Bazian – Qaradagh Hydrogeological Area

The Bazian – Qaradagh hydrogeological area represents the Southwestern boundaries of the High Folded Region with the Low Folded Region. This area extends from the Bazian town in the Northwest of the Sulaymaniyah city to the Iraqi-Iranian border in the Southeast. It has a total area of about (1750.6 Km²) with elevation ranges from (366 m) to (1599 m) above sea level. This area represents a part of the catchment area of the Al-Udhaim River, as shown in figure (3-21). The average annual rainfall, temperature, and potential Evaporation of this area is about (695 mm/yr), (18.5°C) and (2756.5mm) respectively, for the period (1979 – 2014).

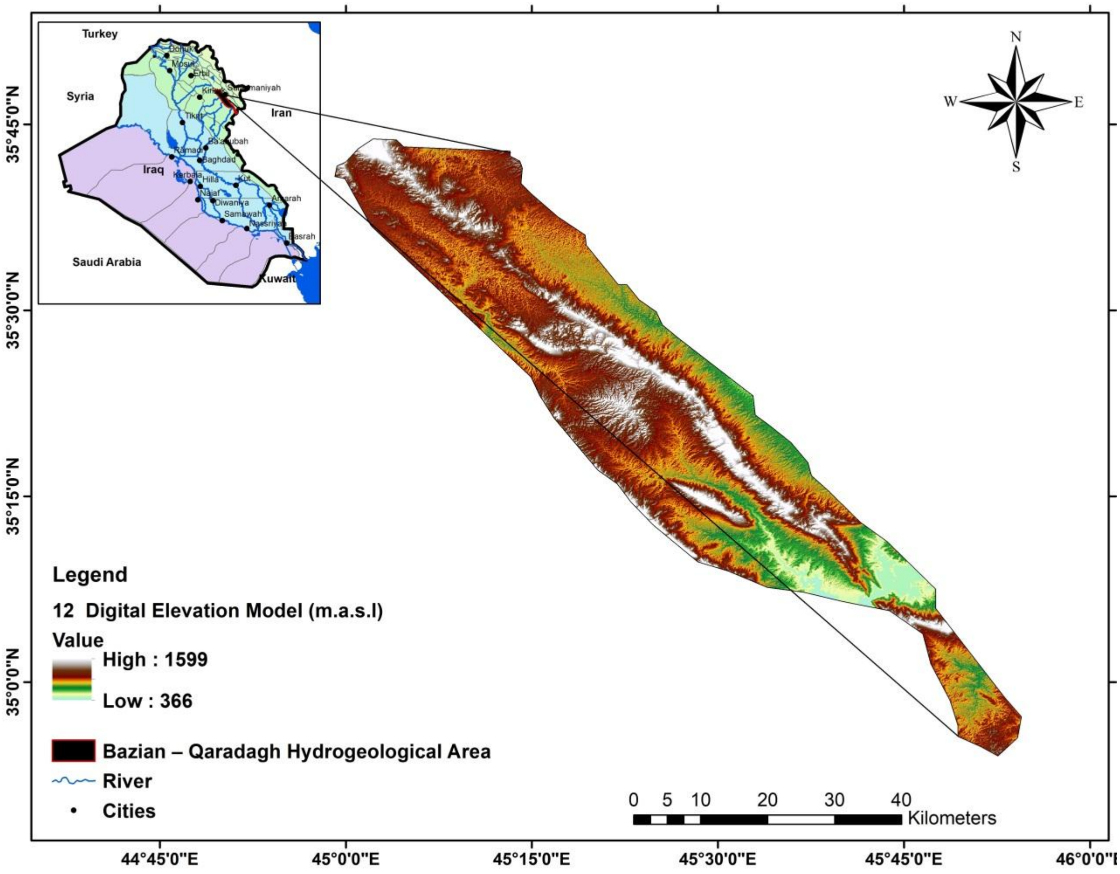

Figure (3 - 21):- Shows the watersheds map of the Bazian – Qaradagh hydrogeological area.

The main aquifers in this area are confined and unconfined aquifers within karstic and karstic-fissured aquifer systems, intergranular Bakhtiari (Bai Hassan and Mukdadiya) aquifer system with recent alluvium aquifers in different locations (Stevanovic and Markovic, 2004).

The results of the pumping test of wells indicated that the transmissivity of the aquifers ranges between (4 – 749 m^2/day), Hydraulic conductivity ranges between (0.2 – 20.6 m/day), discharge of wells varies between (107 – 1620 m^3/day) and the static water level ranges between (3 – 61 m) below ground surface. This area is characterized by fresh water with a salinity ranges between (300 – 500 mg/l) with bicarbonate water type mostly (Al-Jiburi and Al-Basrawi, 2014).

3-3-10 Sarchinar – Arbat Hydrogeological Area

The Sarchinar – Arbat hydrogeological area extends from Sarchinar town in the Northwest of the Sulaymaniyah city to the Iraqi-Iranian border in the Southeast. It is a part of the catchment area of the Diyala River, which is covered an area is about (1608 Km²) with elevation ranges from (441 m) to (2173 m) above sea level shown in figure (3-22). The average annual rainfall, temperature, and potential Evaporation of this area is about (760 mm/yr), (18 °C) and (2756.5 mm) respectively, for the period (1979 – 2014).

The main aquifers in this area are confined and unconfined aquifers within karstic and karstic–fissured aquifer systems with recent alluvium aquifers in small areas and different locations, Stevanovic and Markovic, (2004).

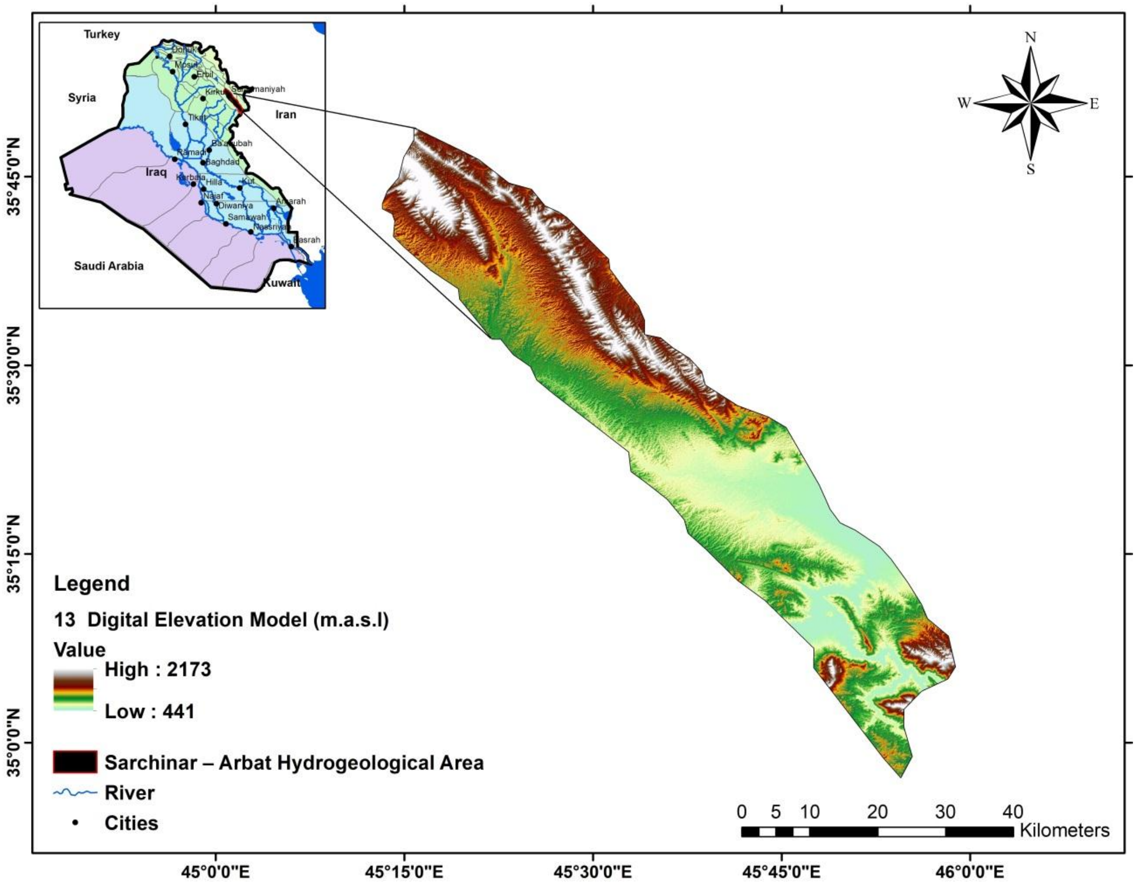

Figure (3 - 22):- Shows the watersheds map of the Sarchinar – Arbat hydrogeological area.

According to Al-Jiburi and Al-Basrawi, (2014), the results of pumping tests performed in many wells in this hydrogeological area showed that the transmissivity of the aquifers ranges between (5 – 409 m^2/day), Hydraulic conductivity ranges between (0.2 – 4.9 m/day), discharge of wells varies between (52 – 1642 m^3/day), and the static water level ranges between (3 – 59 m) below ground surface. At the same time, this area is characterized by fresh water with salinity less than (500 mg/l) with bicarbonate water type mostly.

3-3-11 Choarta – Baraznja Hydrogeological Area

This area extends from Choarta town in the Northeast of the Sulaymaniyah city to the Baraznja town. It is a part of the catchment area of the Lesser Zab River, which is covered an area of the watershed is about (1134.6 Km^2) with elevation ranges from (566 m) to (2482 m) above sea level, as shown in figure (3-23). The average annual rainfall, temperature, and potential Evaporation of this area is about (850 mm/yr), (16.3°C) and (2191.5mm) respectively, for the period (1979 – 2014).

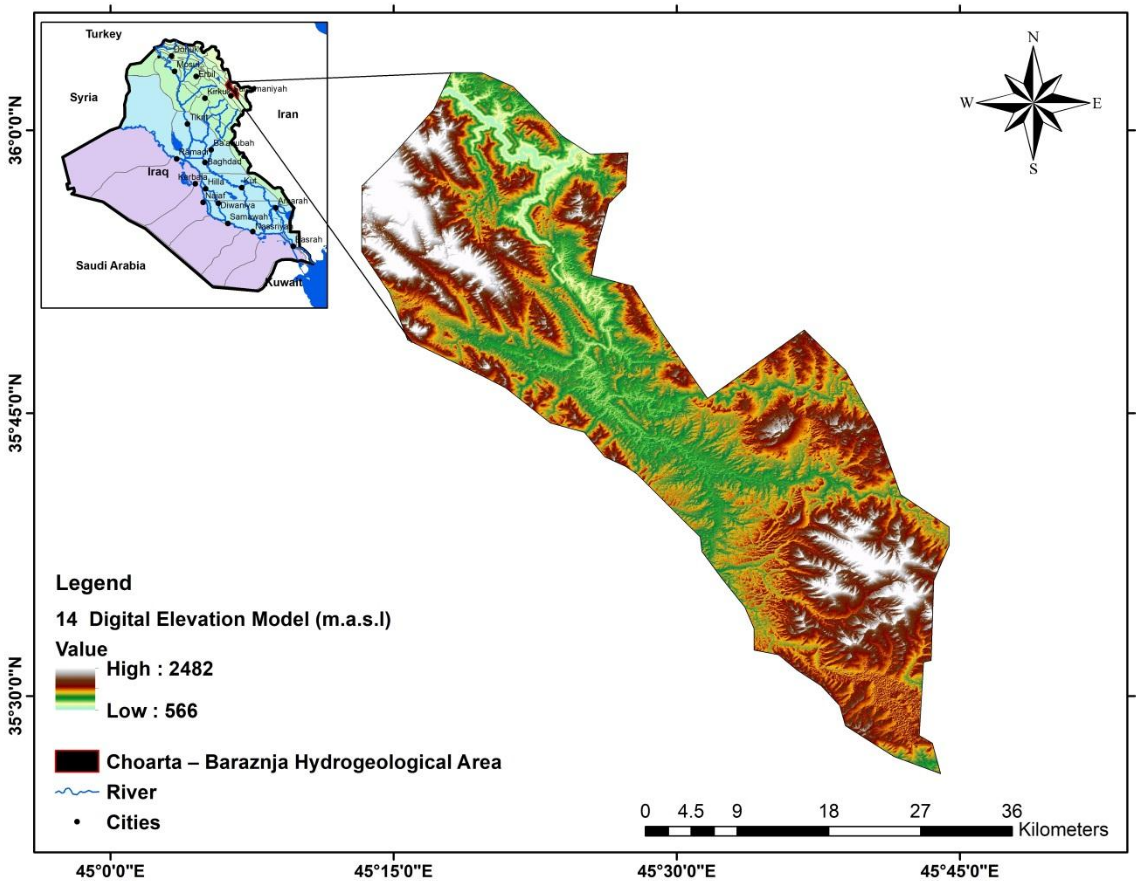

Figure (3 – 23):- Shows the watersheds map of the Choarta – Baraznja hydrogeological area.

The lithological sections of water wells, which drilled in this area, showed that the main aquifers are recent alluvium deposits, karstic and karstic–fissured aquifer systems with two types of aquifers, confined and unconfined aquifers (Stevanovic and Markovic 2004). The results of the pumping test of wells indicated that the transmissivity of the aquifers ranges between (8 – 239 m^2/day), Hydraulic conductivity ranges between (0.2 – 2.3 m/day), discharge of wells varies between (98 – 1382 m^3/day) and the static water level ranges between (5 – 59 m) below ground surface. This area is characterized by fresh water with a salinity ranges between (300 – 500 mg/l) with bicarbonate water type mostly (Al-Jiburi and Al-Basrawi, 2014).

3-3-12 Khurmal – Halabja Hydrogeological Area

The Khurmal – Halabja hydrogeological area represents a small part from the Southern boundaries of the High Folded Region with the Suture and Thrust Region. It has a total area of about (1359.4 Km²) with elevation ranges from (441m) to (2834 m) above sea level, as shown in figure (3-24). The watersheds flow to the Darbandikhan Dam from the Tanjero River in the North, the Sirwan River, and the Zalim Stream in the East. The average annual rainfall, temperature, and potential Evaporation of this area is about (640 mm/yr), (16.8°C) and (2191.5mm) respectively, for the period (1979 – 2014).

It is characterized by two types of aquifers, confined and unconfined aquifers. The main aquifers are represented by karstic and karstic–fissured aquifer systems (Stevanovic and Markovic 2004). This area contains Darbandikhan Lake and many large springs such as Chawg and Biara springs (Ali, 2007).

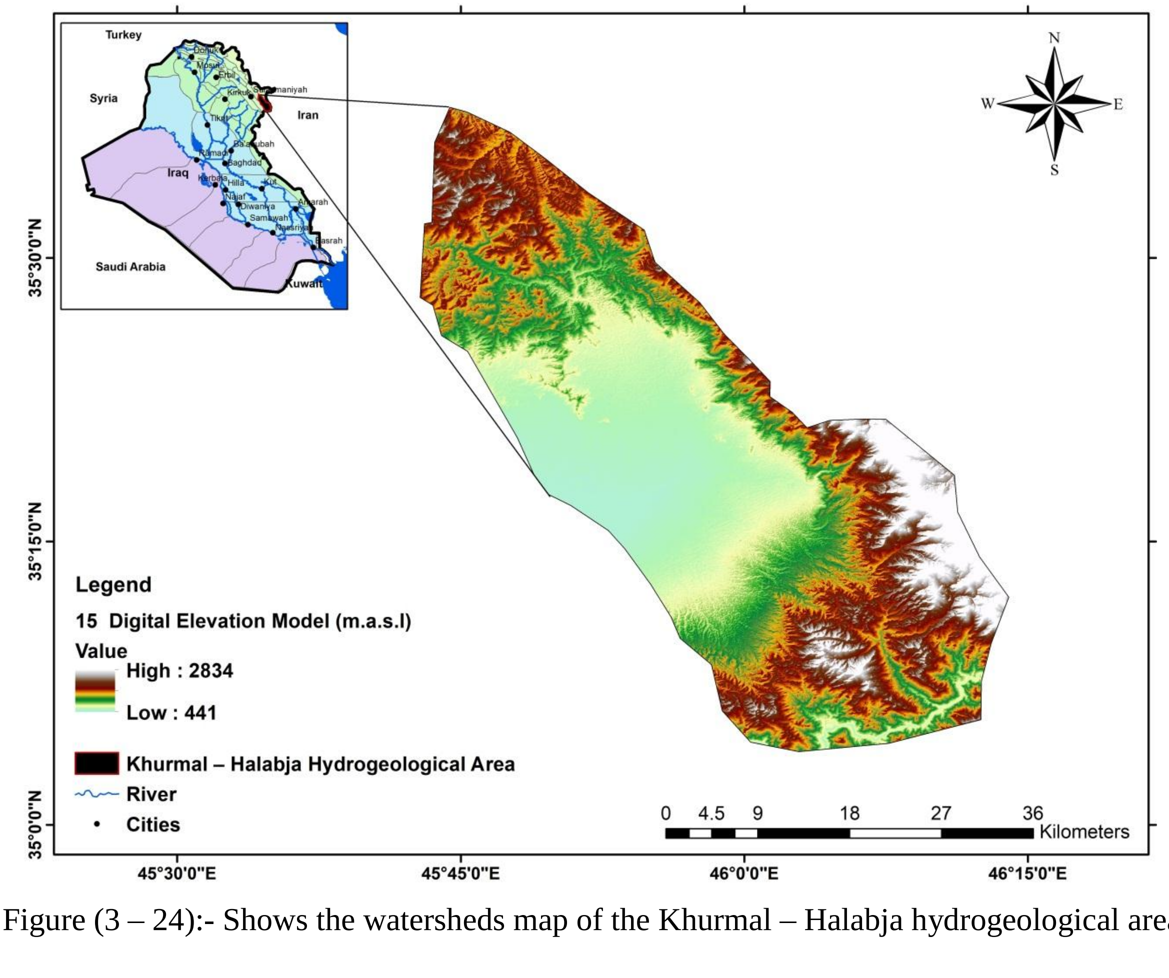

Figure (3 – 24):- Shows the watersheds map of the Khurmal – Halabja hydrogeological area.

In this area, many wells that penetrated these aquifers were tested. The pumping test results indicated that the transmissivity of the aquifers ranges from (1.7 – 553 m^2/day), well discharge from (22 – 864 m^3/day), and static water level ranges between (5 –50 m) below ground surface. The hydrochemical analysis results indicate total dissolved solids (TDS) range from (200 – 885 mg/l), with Bicarbonatic water type. According to Ali (2007), three kinds of drainage characterize aquifers in this area: the springs, subsurface drainage, and artificial drainage by pumping the wells.

The Bazian – Qaradagh, Sarchinar – Arbat, Choarta – Baraznja, and Khurmal – Halabja hydrogeological areas are considered hydrogeological flow systems called Sharazoor Hydrogeological Flow System. Some researchers believe this flow system is a hydrogeological basin called Sharazoor - Piramagroon.

3-4 Low Folded Hydrogeological Region

The Low Folded Hydrogeological Region extends from the Iraqi-Syrian borders in the Northwestern to the Iraqi-Iranian borders in the Southeastern. It is bounded from the North and Northeast by the High Folded Hydrogeological Region and from the South and Southwest by Al-Jazira and Mesopotamia Hydrogeological Region, as shown in figure (1-3). This region covers about (13.20%) of the total area of Iraq, with an area of (56930 km2) (Yacoub et al., 2012). Generally, the ground surface rises in elevation from its Southwestern boundary about (125 – 300m) above sea level towards the North and Northeastern boundaries (900 – 1000m) above sea level. Therefore, it is characterized by two main topographical features, the mountainous parts and the flat and undulate plains (Yacoub *et al.*, 2012).

Tectonically, this region locates in an unstable shelf or outer platform of the Arabian Platform (Al-Kadhimi et al., 1996; Jassim and Buday, 2006 in Jassim and Goff,(2006); Fouad, 2012). It is distinguished by a series of narrow anticlines with different amplitude separated by broad synclines, which trending NW-SE, except Sinjar Mountain has the trend of E-W.

The Tigris River and its tributaries represent the main resources of surface waters in this region. The Tigris River passes in the western part of this region from north to south. While the tributaries Greater Zab, Lesser Zab, Diyala, and Adhaim flow from Northeast to Southwest.

The synclinal valleys that include water-bearing Formations and Quaternary sediments are considered the major hydrogeological areas in this region. The Injana, Bai Hassan, and Mukdadiya Formations and Quaternary sediments represent the main water-bearing Formations and sediments in this region. The Fatha water-bearing Formation is not considered an aquifer in this region because it consists of anhydrite and gypsum with little groundwater content that has a high percentage of sulfates. Still, the farmers use this water for irrigation and livestock purposes, especially in the western part of this region.

The High Folded Hydrogeological Region represents the main source of recharge water for this region and direct rainfall. In contrast, the Tigris River and its tributaries, wells, and springs represent the regional discharge areas of this region. The water wells' data indicate that the groundwater's depth increases at the high lands and decreases at the central parts of the hydrogeological areas and near the discharge zones. Most of these wells have depths of (50 – 500 m) below ground surface (Al-Jiburi and Al-Basrawi, 2012).

The groundwater movement in this region is divided into three main directions with some different local directions based on the topographical and structural features. In the western part of this region (West of Tigris River), the groundwater movement from North and Northwest towards South and Southeast, shown in figure (3-8). In the North Sinjar Mountain, the groundwater flow towards the Iraqi – Syrian border. While to the East of the Tigris River, the groundwater movement is from the North and Northeast towards the South and Southwest.

The salinity of the groundwater increases from North to South with values ranging between (500 to more than 7000 mg/l). Generally, it rises in the direction of the groundwater flow, as shown in figure (3-9). The groundwater quality in this region is bicarbonate at the recharge areas and change to the sulphatic at the discharge areas.

The Low Folded Region was divided into twelve major hydrogeological areas, according to hydrogeological, structural, geological, and topographic features, and as follows:-

3-4-1 Khazir – Gomel Hydrogeological Area

The Khazir – Gomel hydrogeological area is bounded from the North and South by high mountain ridges of Aqra, Makloub, and Barda Rash Mountains. This area comprises parts of the Harir – Shaqlawa hydrogeological area in the East. While its western boundary to be with Dohuk – Alqosh hydrogeological area, as shown in figure (3-1) (Stevanovic and Markovic, 2004 and Krasny et al., 2006 in Jassim and Goff, 2006). It has a total area of about (2940.5 Km^2) with elevation ranges from (222 m) to (1947 m) above sea level, as shown in figure (3-25). The watersheds flow to the Great Zab River and its tributary, Khazir and Gomel Rivers, representing the central groundwater discharge zone along the Greater Zab River. At the same time, the High Folded Hydrogeological Region and direct rainfall represent the main source of recharge water of this area. The average annual rainfall, temperature, and potential Evaporation of this area is about (850 mm/yr), (18 °C) and (2318 mm) respectively, for the period (1979 – 2014).

The main aquifers in this area are confined and unconfined aquifers within Mukdadiya and Bai Hassan Formations and the recent alluvium aquifers in small areas and in different locations (Stevanovic and Markovic, 2004). The water wells' data indicate that the groundwater's depth ranges from (30 – 40 m) below the ground level. There are many self-flowing wells in this area, especially those that penetrate the deep aquifers.

The wells' pumping test results indicated that the transmissivity of the aquifers ranges between (100 – 7000 m^2/day). This area is characterized by fresh water with a salinity ranges from (300 – 700 mg/l) with bicarbonate water type mostly (Al-Jiburi and Al-Basrawi, 2012).

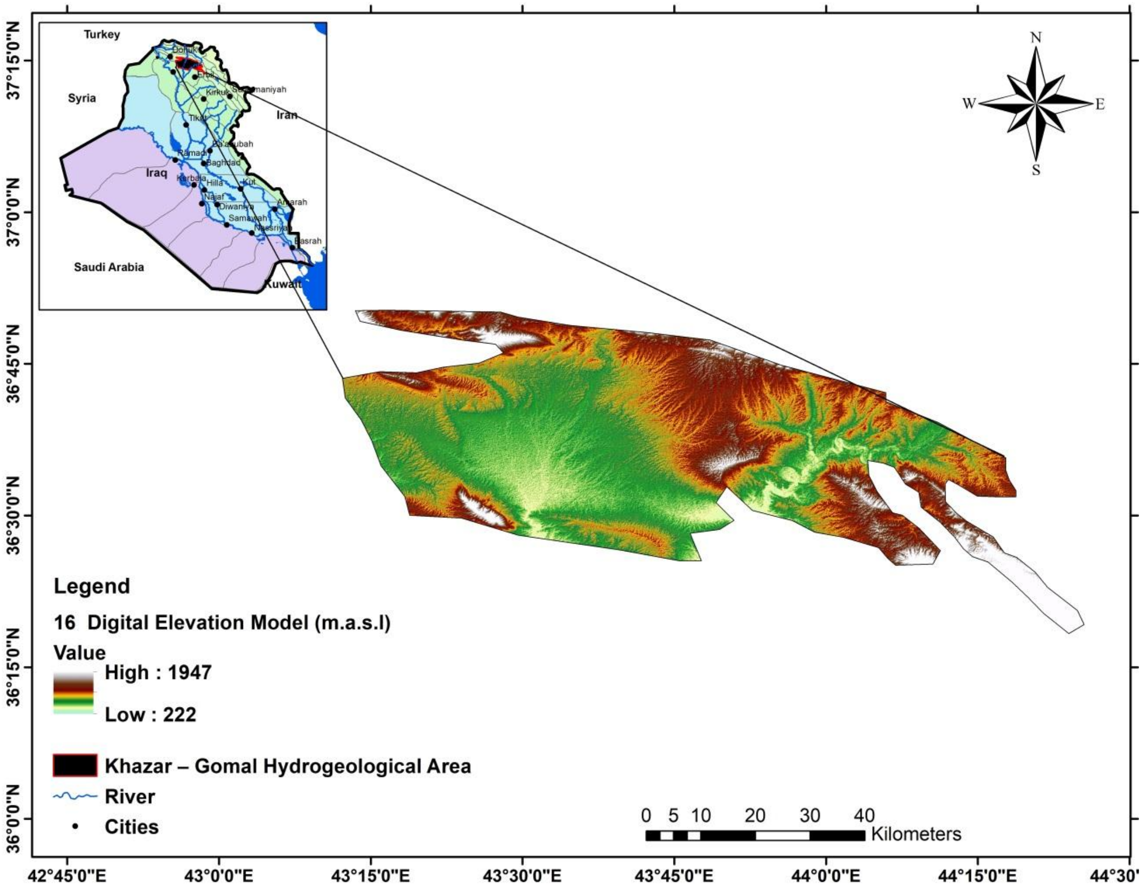

Figure (3 – 25):- Shows the watersheds map of the Khazir – Gomel hydrogeological area.

3-4-2 Dohuk – Alqosh Hydrogeological Area

Dohuk – Alqosh hydrogeological area locates in the west of the Tigris River. It extends from the Iraqi-Syrian borders in the Northwestern to the junction of the Tigris River with the Great Zab River in the Southeast, as shown in figure (3-1). This area is bounded from the North and Northeast by Atrush – Dinarta hydrogeological area. It is bordered by the Khazir – Gomel and Erbil hydrogeological areas in the East and Southeast. It has a total area of about (3378 Km^2) with elevation ranges from (152 m) to (1006 m) above sea level, as shown in figure (3-26). The watershed of this area flows to the Tigris River. Therefore, it represents the main zone of groundwater discharge along the Tigris River. The groundwater movement in this area is towards the Southwest, mainly along the Tigris River, with some different local directions based on the topographical and structural features, especially at the eastern parts of this area. The average annual rainfall, temperature, and potential Evaporation of this area is about (760 mm/yr), (18 °C) and (2191 mm) respectively, for the period (1979 – 2014).

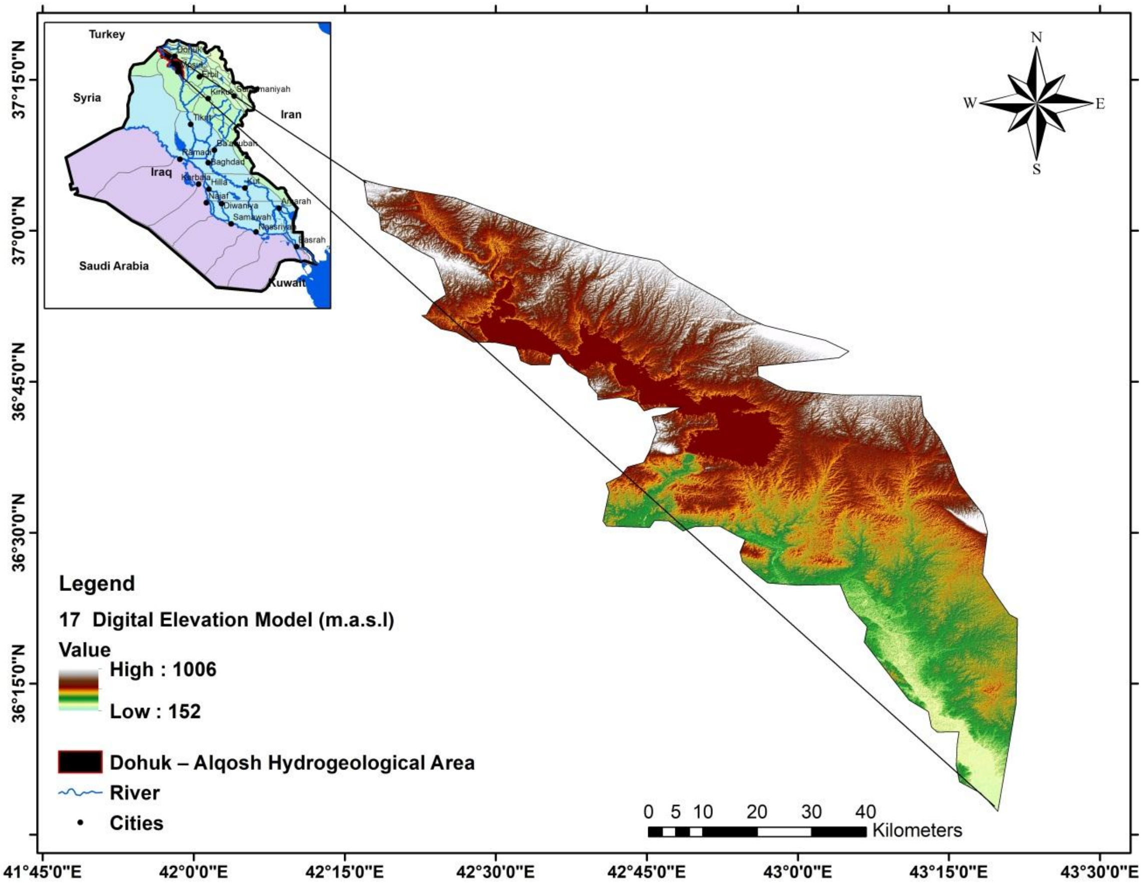

Figure (3 – 26):- Shows the watersheds map of the Dohuk – Alqosh hydrogeological area.

Injana Formation covers this area except for the Eastern parts at the anticlinal ridges, where the Fat'ha and Pila Spi formations are exposed. Quaternary deposits are mainly found near the Tigris River and some of the different locations in this area.

The lithological sections of water wells, which were drilled in this area, showed that the main aquifers are Injana and Pila Spi aquifers with two types of aquifers, confined and unconfined. The results of the pumping test of Injana aquifer indicated that the transmissivity ranges between (6.5 – 622 m^2/day), Hydraulic conductivity ranges between (0.1 – 16.8 m/day), discharge of wells varies between (25 – 2890 m^3/day) and the static water level ranges between (5 –90 m) below ground surface. The salinity of the groundwater in this aquifer ranges between (450 – 4750 mg/l) with sulphatic and bicarbonate water types. While the results of the pumping test of Pila Spi aquifer indicated that the transmissivity ranges between (4 – 375 m^2/day), Hydraulic conductivity ranges between (0.1 – 5.1 m/day), discharge of wells varies between (60 – 2722 m^3/day), and the static water level ranges between (6 – 108 m) below ground surface. The groundwater salinity in this aquifer ranges between (187 – 1224 mg/l) and with sulphatic and bicarbonate water types (Al-Jiburi and Al-Basrawi, 2012).

3-4-3 Erbil Hydrogeological Area

The Erbil hydrogeological area is one of the most critical promising hydrogeological areas for the groundwater resources in the Low Folded Region for its water quality and quantity. Thick sediments characterize it at the middle of the plain reaching more than (850 m) in thickness. Extensive plains represent this area to the South of the Barda Rash and Pirmam Mountains. The northwestern extension of Kirkuk Structure represents its southwestern boundary. While in the west and east boundaries are represented by the boundaries of adjacent hydrogeological areas (Krasny et al., 2006 in Jassim and Goff, 2006). It covers an area of approximately (3752.5 Km²) with elevation ranges from (157 m) to (773 m) above sea level. This area represents the watershed of the lower reaches of the Khazir and Greater Zab rivers, as shown in figure (3-27). The average annual rainfall, temperature, and potential Evaporation of this area is about (575mm/yr), (19 °C) and (2234 mm) respectively, for the period (1979 – 2014). The general groundwater flow is towards the Greater Zab River and partly towards the Khazir River, representing the main zone of groundwater discharge for the Western part of this area. In the Southern part of this area, the groundwater flows to the Southwest towards the Lesser Zab River.

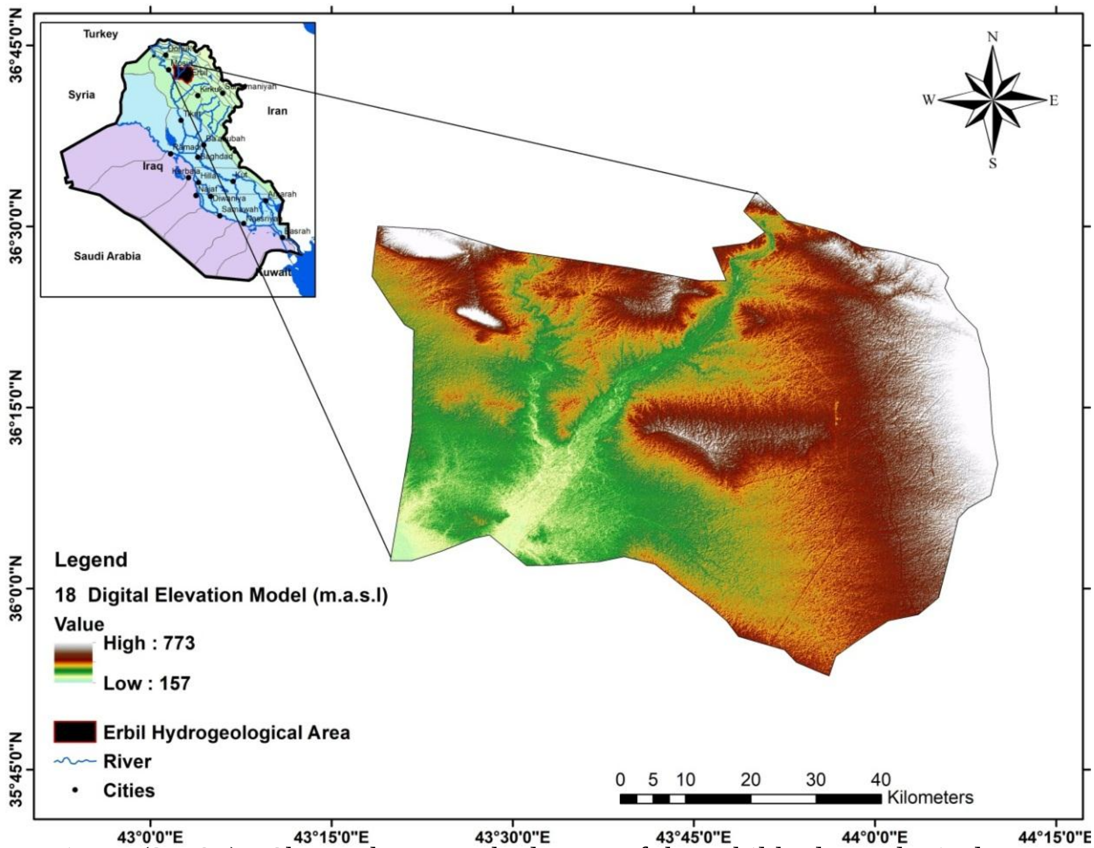

Figure (3 – 27):- Shows the watersheds map of the Erbil hydrogeological area.

The geological and topographic characteristics played an essential role in determining the discharge and recharge zones of this area (Krasny et al., 2006 in Jassim and Goff, (2006). The main aquifers in this area are confined and unconfined aquifers within intergranular Bakhtiari (Bai Hassan and Mukdadiya) aquifer system, with recent alluvium aquifers in small areas and different locations, (Stevanovic and Markovic, 2004).

According to Al-Jiburi and Al-Basrawi, (2012), the results of the pumping test of Mukdadiya and Bai Hassan aquifers indicated that the transmissivity ranges between (3– 1296m^2/day), Hydraulic conductivity ranges between (0.1 – 30.4 m/day), discharge of wells varies between (5 – 4790 m^3/day), and the static water level ranges between (25 – 40 m) below ground surface. At the same time, the salinity of the groundwater in this aquifer ranges between (100– 1000 mg/l) with sulphatic and bicarbonate water types, and with chloridic water types, on the local scale. On the other hand, the results of the pumping test of Quaternary sediments aquifers indicated that the transmissivity ranges between (10 –1225 m^2/day), Hydraulic conductivity ranges between (0.4 – 35.2 m/day), discharge of wells varies between (122– 2211m^3/day), and the static water level ranges between (10 – 30 m) below ground surface. The groundwater salinity in this aquifer ranges between (500 – 700 mg/l) with sulphatic and bicarbonate water types.

3-4-4 Altun Kupri Hydrogeological Area

The High Folded Hydrogeological Region bounds this area from the Northeast and by Kirkuk Structure from the Southwest. While the Northwestern and Southeastern boundaries are represented by the boundaries of adjacent hydrogeological areas (Krasny et al., 2006 in Jassim and Goff, (2006). It has a total area of about (3885.7 Km^2) with elevation ranges from (203m) to (1318 m) above sea level. This area represents the catchment area of the upper parts of the Lesser Zab River. Therefore, this River represents the regional discharge zone of this hydrogeological area, as shown in figure (3-28). The average annual rainfall, temperature, and potential Evaporation of this area is about (575 mm/yr), (18 °C) and (2381.5 mm) respectively, for the period (1979 – 2014).

The main aquifers in this area are confined and unconfined aquifers within intergranular Bakhtiari (Bai Hassan and Mukdadiya) aquifer system, with recent alluvium aquifers in small areas and different locations.

The results of the pumping test of wells drilled in Mukdadiya and Bai Hassan aquifers indicated that the transmissivity ranges between (4 – 1738 m^2/day), Hydraulic conductivity ranges between (0.1 – 47.9 m/day), discharge of wells varies between (22 – 3888 m^3/day) and the static water level ranges between (7 – 90 m) below ground surface. In addition, the salinity of the groundwater in these aquifers ranges between (152– 1260 mg/l) with bicarbonate and sulphatic water types (Al-Jiburi and Al-Basrawi, 2012).

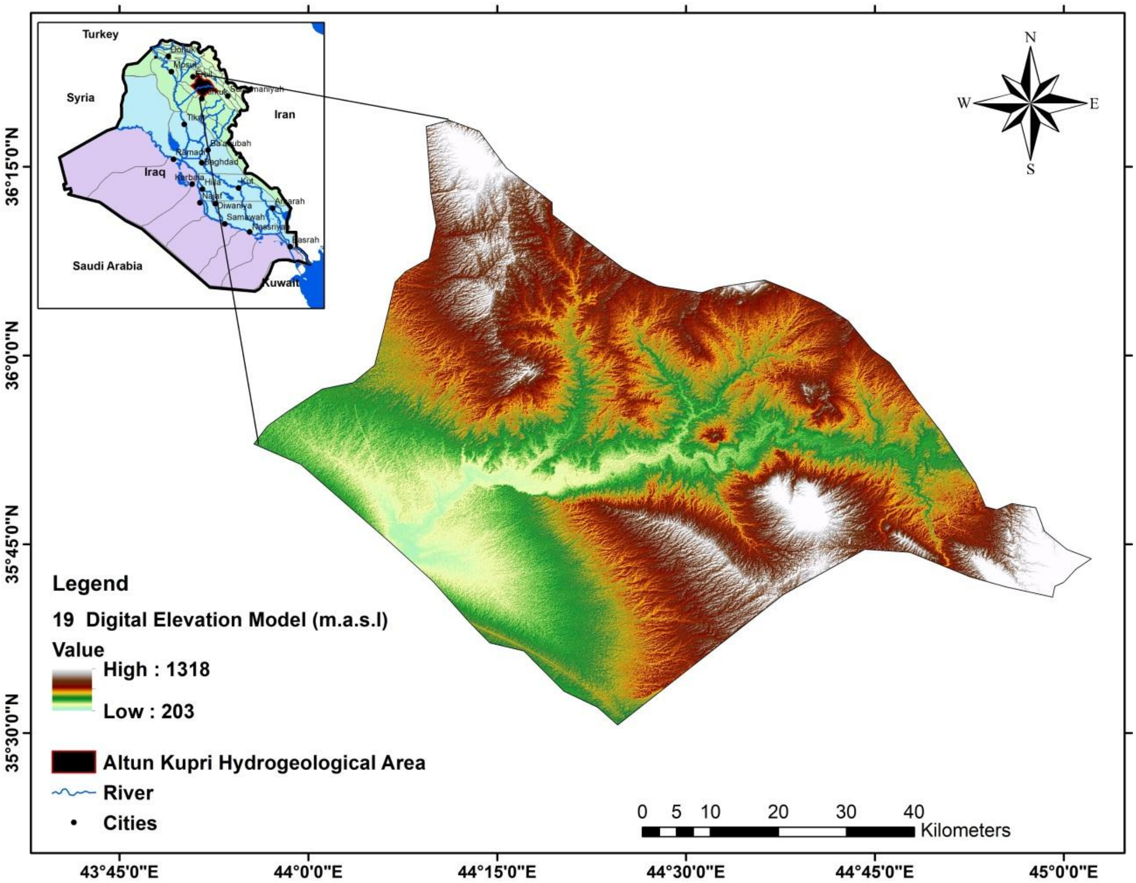

Figure (3 – 28):- Shows the watersheds map of the Altun Kupri hydrogeological area.

3-4-5 Dibiga Hydrogeological Area

The Dibiga hydrogeological area is located between Quwair anticlines in the Northeast and the Qara Chouq and Batiwa mountains in the Southeast (Krasny et al., 2006 in Jassim and Goff, (2006). It covers an area of approximately (1791.3 Km²) with elevation ranges from (157 m) to (782 m) above sea level. This area represents the watershed of the middle reach of the Lesser Zab River, as shown in figure (3-29). The Lesser Zab River represents the Southeastern hydraulic boundary, while the Greater Zab River represents the Northwestern hydrogeological boundary. This area is characterized by synclines, which are trending NW – SE filled by clastic sediments of Mukdadiya and Bai Hassan Formations. The anticlines that bound this area represent water divides and sources of groundwater recharge (Krasny et al., 2006 in Jassim and Goff, (2006). The average annual rainfall, temperature, and potential Evaporation of this area is about (440 mm/yr), (19 °C) and (2381.5 mm) respectively, for the period (1979 – 2014).

The groundwater flow in this area is divided into two directions. The first is the movement toward the Greater Zab River in the Northwest direction. The second is the movement toward the Lesser Zab River in the Southeast direction.

The main aquifers in this area are confined and unconfined aquifers within Mukdadiya and Bai Hassan Formations and the recent alluvium aquifers in small areas and different locations. The results of the pumping test of Mukdadiya and Bai Hassan aquifers indicated that the transmissivity ranges between (5 – 1650 m^2/day), Hydraulic conductivity ranges between (0.1 – 28.5 m/day), discharge of wells varies between (30 – 3150 m^3/day) and the static water level ranges between (20 – 80 m) below ground surface. The salinity of the groundwater ranges from fresh water less than (1000 mg/l) to moderate brackish water more than (3000 mg/l) with mainly sulphatic and bicarbonate water types (Al-Jiburi and Al-Basrawi, 2012).

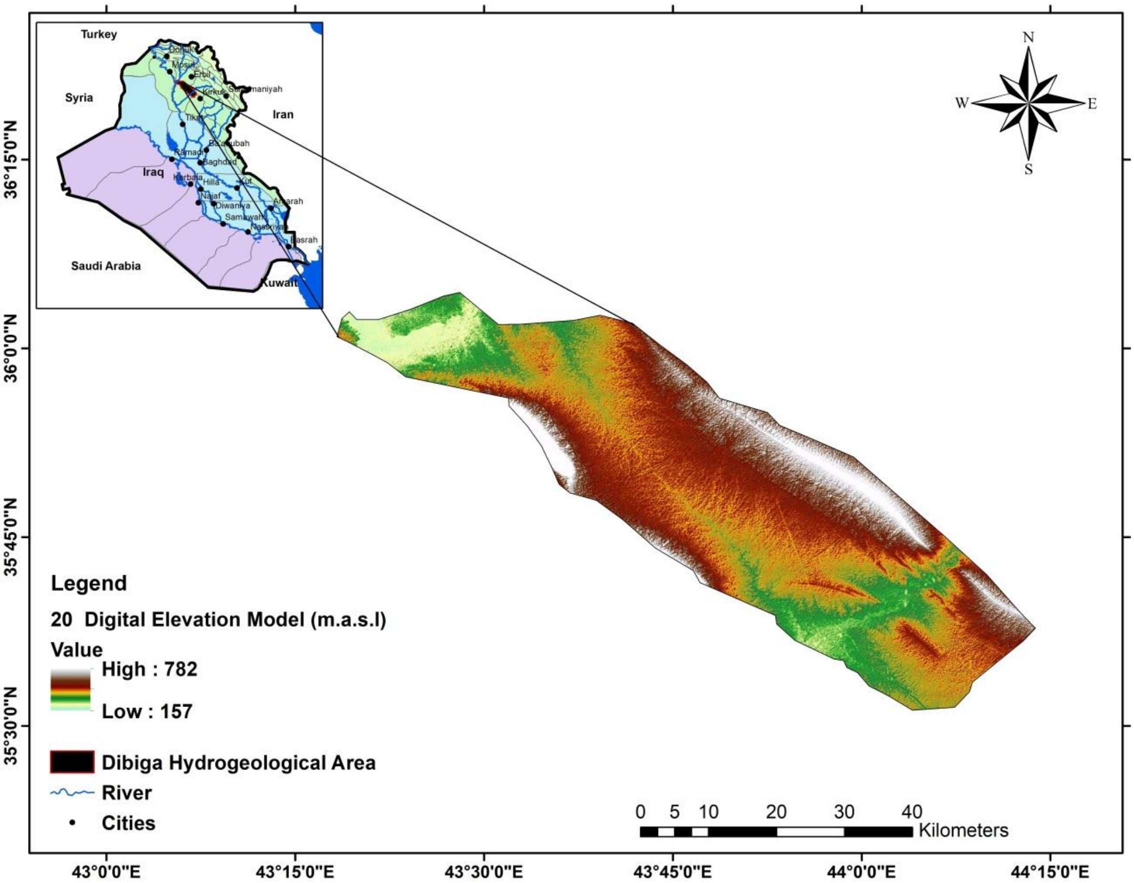

Figure (3 – 29):- Shows the watersheds map of the Dibiga hydrogeological area.

3-4-6 Makhmur Hydrogeological Area

This area locates west of the Tigris River; it is bounded by the Hemrine Mountain in the Southern part and by Qara Chouq Mountain in the Northeast (Krasny et al., 2006 Jassim and Goff, (2006). It has a total area of about (5192.5 Km²) with elevation ranges from (45 m) to (852 m) above sea level. This area represents the catchment area of the parts of the Tigris and Greater Zab Rivers. Therefore, these Rivers represent this hydrogeological area's regional discharge zone, as shown in figure (3-30). Thus, the general groundwater flows from Northeast to Southwest towards the Tigris and Lesser Zab Rivers. The average annual rainfall, temperature, and potential Evaporation of this area is about (380 mm/yr), (23.4 °C) and (2439.5 mm) respectively, for the period (1979 – 2014).

The main aquifers in this area are confined and unconfined aquifers within intergranular Bakhtiari (Bai Hassan and Mukdadiya) aquifer systems, with recent alluvium aquifers in small areas and different locations. The results of the pumping test of Mukdadiya, Bai Hassan, and the Quaternary aquifers indicated that the transmissivity ranges between (6 –1350 m^2/day), Hydraulic conductivity ranges between (0.1 – 25.6 m/day), discharge of wells varies between (20 – 3200 m^3/day) and the static water level ranges between (4 – 60 m) below ground surface. The salinity of the groundwater in these aquifers ranges from fresh water less than (1000 mg/l) to moderate brackish water more than (7000 mg/l) with mainly sulphatic water type (Al-Jiburi and Al-Basrawi, 2012).

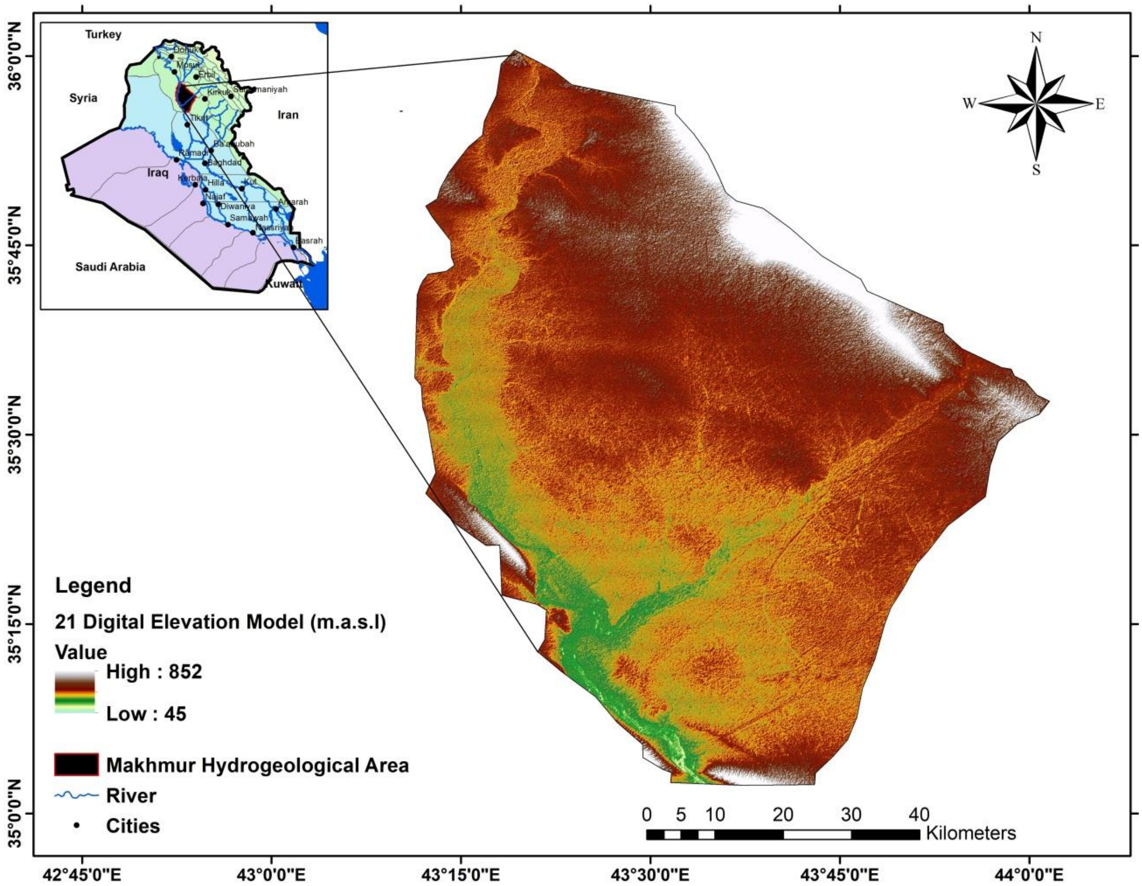

Figure (3 – 30):- Shows the watersheds map of the Makhmur hydrogeological area.

3-4-7 Tawuq Hydrogeological Area

The Tawuq hydrogeological area locates between a series of low anticlinal ridges with NW – SE trend, representing the Northeastern and Eastern complex boundaries of this area. From North to South, Kirkuk, Tawuq, and Pulkhana (Kifri) anticlines. The extensive plain located Southeast and South of the town of Kirkuk has a prevailing southwesterly regional groundwater flow (Krasny et al., 2006 in Jassim and Goff, (2006). It covers an area of approximately (4775.4 Km²) with elevation ranges from (100 m) to (460 m) above sea level. This area represents the watershed of the middle reach of the Adhaim River to the Northeast of Hemrine Mountain, which means the central groundwater discharge of this area, as shown in figure (3-31). Direct rainfall is the primary source of groundwater recharge and influent seepage from the streams originating beyond the Northeast boundary of this area (Krasny et al., 2006 in Jassim and Goff, (2006).

The main aquifers in this area are confined and unconfined aquifers within intergranular Bakhtiari (Bai Hassan and Mukdadiya) aquifer system, with recent alluvium aquifers in large areas and different locations.

The results of the pumping test of Mukdadiya, Bai Hassan, and the Quaternary aquifers indicated that the transmissivity ranges between (3 – 2775 m^2/day), Hydraulic conductivity ranges between (0.1 – 57.8 m/day), discharge of wells varies between (20 – 5460 m^3/day) and the static water level ranges between (1 – 90 m) below ground surface. The salinity of the groundwater in these aquifers ranges from fresh water less than (1000 mg/l) to moderate brackish water more than (8000 mg/l) with mainly sulphatic water type. In general, the salinity increases from the recharge areas to the discharge area due to the various lithological, structural, and topographic influences along the flow direction (Al-Jiburi and Al-Basrawi, 2012).

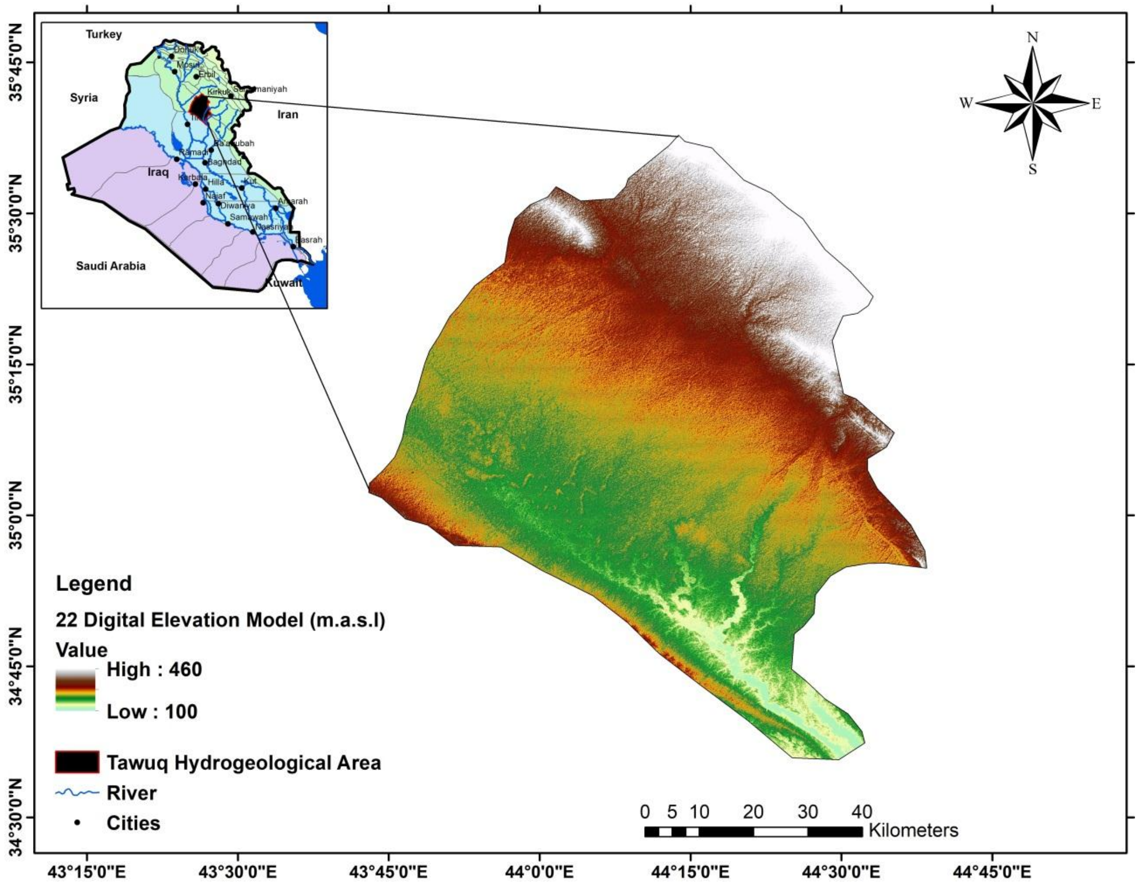

Figure (3 – 31):- Shows the watersheds map of the Tawuq hydrogeological area.

3-4-8 Cham Chamal – Klar Hydrogeological Area

This hydrogeological area represents the Northeastern boundaries of the Low Folded Hydrogeological Region with the High Folded Hydrogeological Region. It's extended from Kirkuk Structures in the North and Northwest to the Iraqi-Iranian border in the Southeast. This area has a total area of about (9863.1 Km²) with elevation ranges from (158 m) to (1855 m) above sea level. This area represents the catchment area of the upper reaches of the Udhaim and Diyala Rivers. Therefore, these Rivers are represented the regional discharge zone of this hydrogeological area, as shown in figure (3-32).

Stevanovic and Markovic (2004) defined large parts of this area with Chamchamal and Sangaw – Bazian Basins. However, the average annual rainfall, temperature, and potential Evaporation of this area is about (380 mm/yr), (20.9 °C) and (2805.5 mm) respectively, for the period (1979 – 2014). The general groundwater flows from Northeast to Southwest (Krasny et al., 2006; Jassim and Goff, (2006).

The main aquifers in this area are confined and unconfined aquifers within intergranular Bakhtiari (Bai Hassan and Mukdadiya) aquifer system, with recent alluvium aquifers in small areas and different locations.

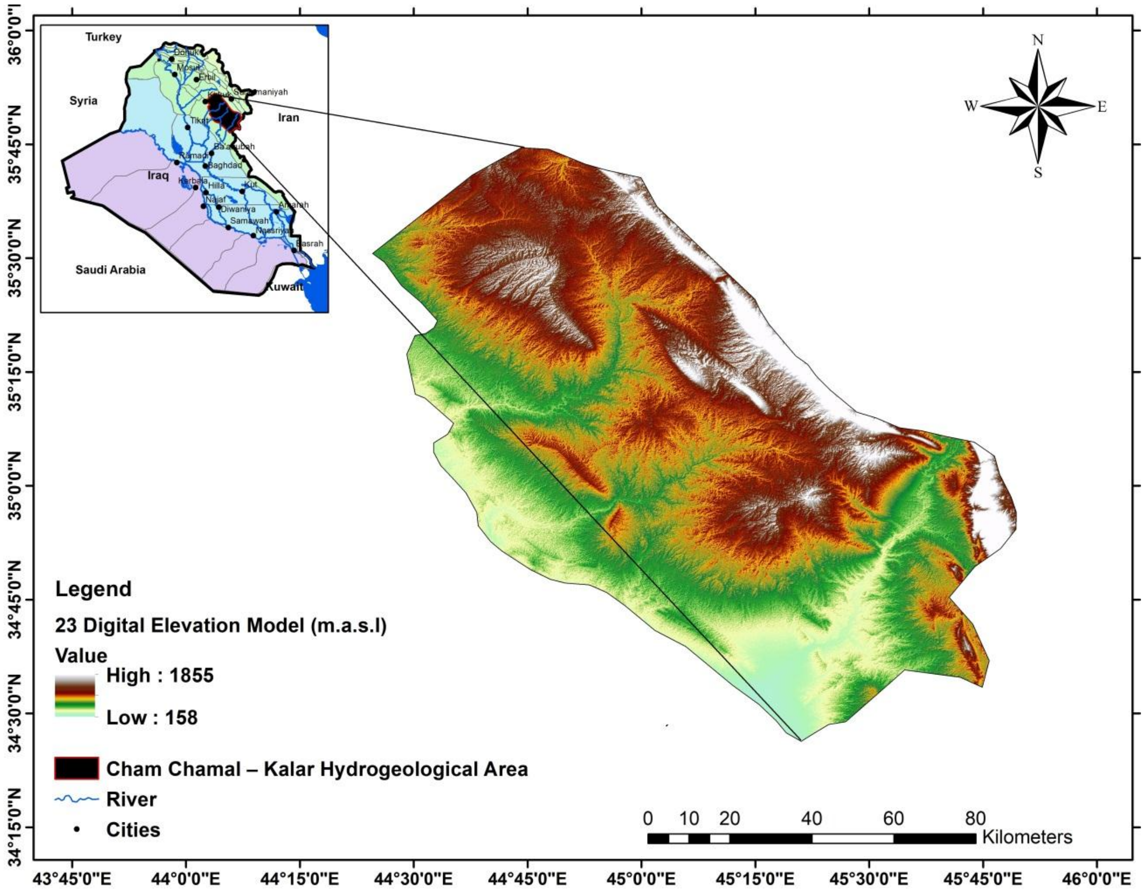

Figure (3 – 32):- Shows the watersheds map of the Cham Chamal – Klar hydrogeological area.

The results of pumping test in wells penetrating Mukdadiya and Bai Hassan aquifers indicated that the transmissivity ranges between (3 – 1950 m^2/day), Hydraulic conductivity varies between (0.1 – 42.6m/day), discharge of wells ranges between (20 – 3360 m^3/day) and the static water level ranges between (5 – 90 m) below ground surface. The salinity of the groundwater in these aquifers ranges between (150– 1600 mg/l) with bicarbonate and sulphatic water types (Al-Jiburi and Al-Basrawi, 2012).

3-4-9 Qara Tapa – Khanaqin – Al-Saadia Hydrogeological Area

This area represents the Southeastern boundaries of the Low Folded Hydrogeological Region with the Al-Jazira and Mesopotamia Hydrogeological Region. It's extended from the Udhaim River in the Northwest to the Iraqi-Iranian border in the Southeast. This area represents the catchment area of the upper reaches of the Udhaim, Diyala Rivers, and Hemrine reservoir. Therefore, these Rivers and Lake have represented the regional discharge zone of this hydrogeological area, as shown in figure (3-33). This area has a total area of about (5195.9 Km²) with elevation ranges from (31 m) to (635 m) above sea level.

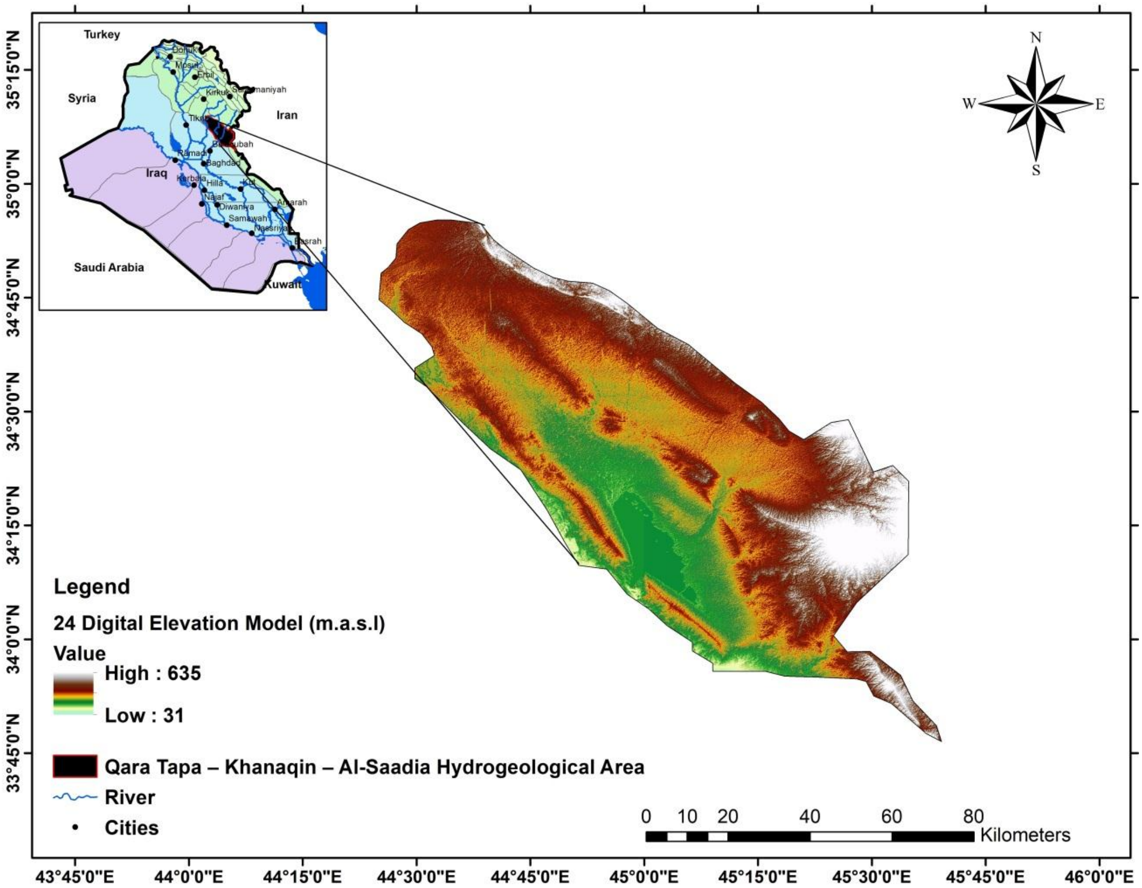

Figure (3 – 33):- Shows the watersheds map of the Qara Tapa – Khanaqin – Al-Saadia hydrogeological area.

The average annual rainfall, temperature, and potential Evaporation of this area is about (235 mm/yr), (24.2 °C) and (2815.5 mm) respectively, for the period (1979 – 2014). The general groundwater flows from Northeast to Southwest.

The lithological sections of water wells, which drilled in this area, showed that the main aquifers within intergranular Bakhtiari (Bai Hassan and Mukdadiya) aquifer system, with recent alluvium aquifers in small areas and different locations with two types of aquifers, confined and unconfined aquifers. The results of the pumping test in wells penetrating Bai Hassan and Mukdadiya aquifers indicated that the transmissivity ranges between (15 – 1170m^2/day), Hydraulic conductivity ranges between (0.1 – 24 m/day), discharge of wells varies between (22 – 5400 m^3/day) and the static water level ranges between (3 – 45 m) below ground surface. The salinity of the groundwater in these aquifers ranges between (1000 – 4750 mg/l) with sulphatic, bicarbonate, and chloridic water types. While the results of the pumping test of alluvium aquifers indicated that the transmissivity ranges between (20 – 540 m^2/day), Hydraulic conductivity ranges between (0.4 – 35.5 m/day), discharge of wells varies between (90 – 1650 m^3/day), and the static water level ranges between (2 – 25 m) below ground surface. The groundwater salinity in this aquifer ranges between (1000 – 5000 mg/l) with sulphatic and bicarbonate water types (Al-Jiburi and Al-Basrawi, 2012).

3-4-10 Mandili – Zurbatiya – Teeb Hydrogeological Area

This area represents the southeastern extension Low Folded Hydrogeological Region. It is a narrow belt along the Iraqi – Iranian border. This area has a total area of about (7285.9 Km^2) with elevation ranges from (50 m) to (975 m) above sea level, as shown in figure (3-34). The average annual rainfall, temperature, and potential Evaporation of this area is about (185 mm/yr), (25.6 °C) and (3233.5 mm) respectively, for the period (1979 – 2014). The general groundwater flows from East to West toward the Al-Jazira and Mesopotamia Hydrogeological Region.

The lithological sections of water wells, which drilled in this area, showed that the main aquifers within intergranular Bakhtiari (Bai Hassan and Mukdadiya) aquifer system, with recent alluvium aquifers in small areas and different locations with two types of aquifers, confined and unconfined aquifers. The results of the pumping test of Bai Hassan and Mukdadiya aquifers in the Mandili town and its vicinities indicated that the transmissivity ranges between (3 – 445 m^2/day), Hydraulic conductivity ranges between (0.1 – 12.2 m/day), discharge of wells varies between (12 – 1620 m^3/day) and the static water level ranges between (1.5 – 64 m) below ground surface. The salinity of the groundwater in these aquifers ranges between (1000 –5000 mg/l) with sulphatic and chloridic water types (Al-Jiburi and Al-Basrawi, 2012).

The results of the pumping test in wells penetrating Bai Hassan and Mukdadiya aquifers in the Zurbatiya – Badra vicinity indicated that the transmissivity ranges between (7 – 533 m^2/day), permeability ranges between (0.1 – 14.1 m/day), discharge of wells varies between (132 – 2224 m^3/day) and the static water level ranges between (3 – 45 m) below ground surface. Therefore, the groundwater salinity in these aquifers ranges between (1000 –7170 mg/l) with sulphatic and chloridic water types. As for the results of the pumping test in wells penetrating Bai Hassan and Mukdadiya aquifers in the Teeb and Fakka areas and their vicinities showed that the transmissivity ranges between (12 – 290 m^2/day), Hydraulic conductivity ranges between (0.5 – 15.5 m/day), discharge of wells varies between (115 – 1782 m^3/day) and the static water level ranges between (1 – 64 m) below ground surface. At the same time, the salinity of the groundwater in these aquifers ranges between (1000 –7170 mg/l) with sulphatic and chloridic water types (Al-Jiburi and Al-Basrawi, 2012).

The results of the pumping test of alluvium aquifers indicated that the transmissivity ranges between (21 – 670 m^2/day), Hydraulic conductivity ranges between (0.4 – 37.3 m/day), discharge of wells varies between (90 – 1650 m^3/day), and the static water level ranges between (2 – 35 m) below ground surface. The groundwater salinity in this aquifer ranges between (1000 – 7170 mg/l) with sulphatic and bicarbonate water types.

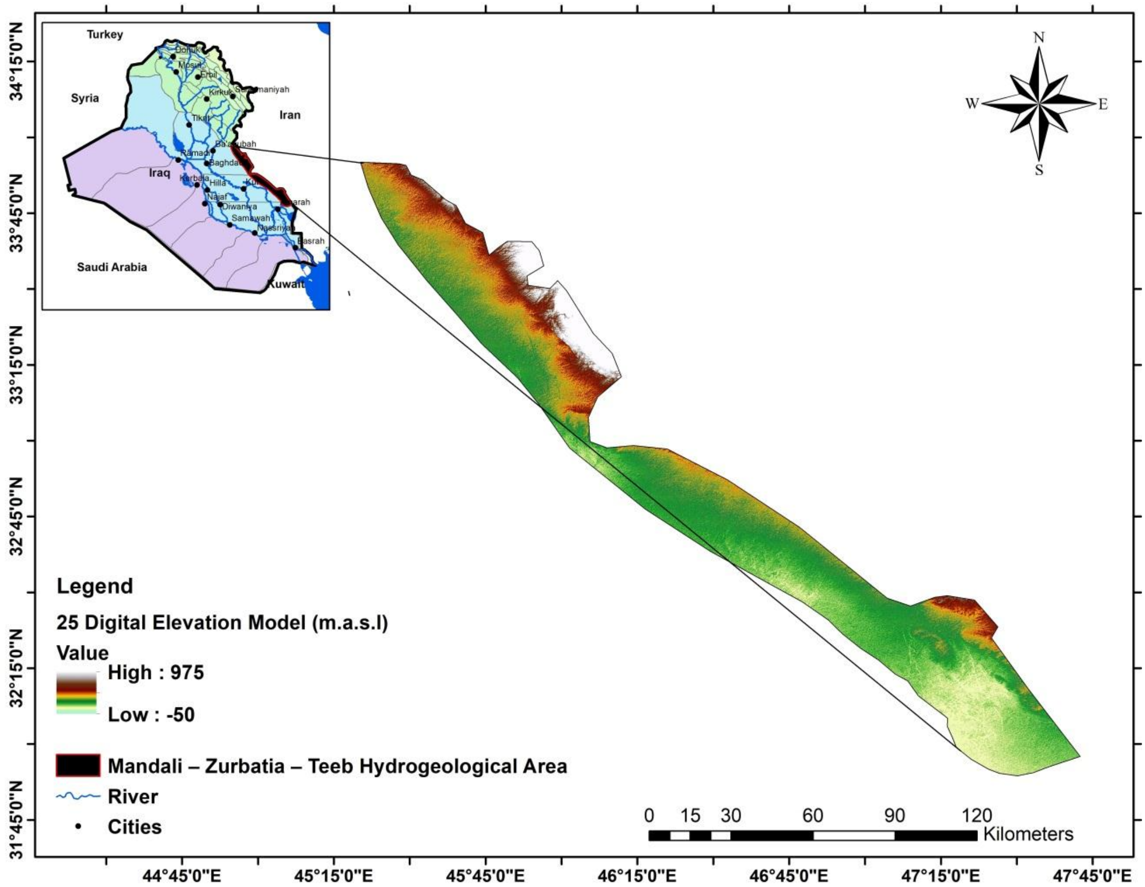

Figure (3 – 34):- Shows the watersheds map of the Mandili – Zurbatiya – Teeb hydrogeological area.

3-4-11 West Tigris Hydrogeological Area

The West Tigris hydrogeological area locates West Tigris River and represents the Northern and Western boundaries of the Low Folded Hydrogeological Region with the Al-Jazira and Mesopotamia Hydrogeological Region. It's extended from Mosul reservoir in the North to the Fat'ha area in the Southeast as undulated lands. This area has a total area of about (5782.4 Km²) with elevation ranges from (90 m) to (630 m) above sea level, as shown in figure (3-35). It is covered mainly by Fat'ha and Injana Formations, while Quaternary sediments cavers some parts of these Formations in different localities. Therefore, direct rainfall is the main source of groundwater recharge in the area. The general water flow direction is towards the Tigris River. This area is not essential from a hydrogeological point of view because the main aquifer is the Fat'ha (Lower Fars).

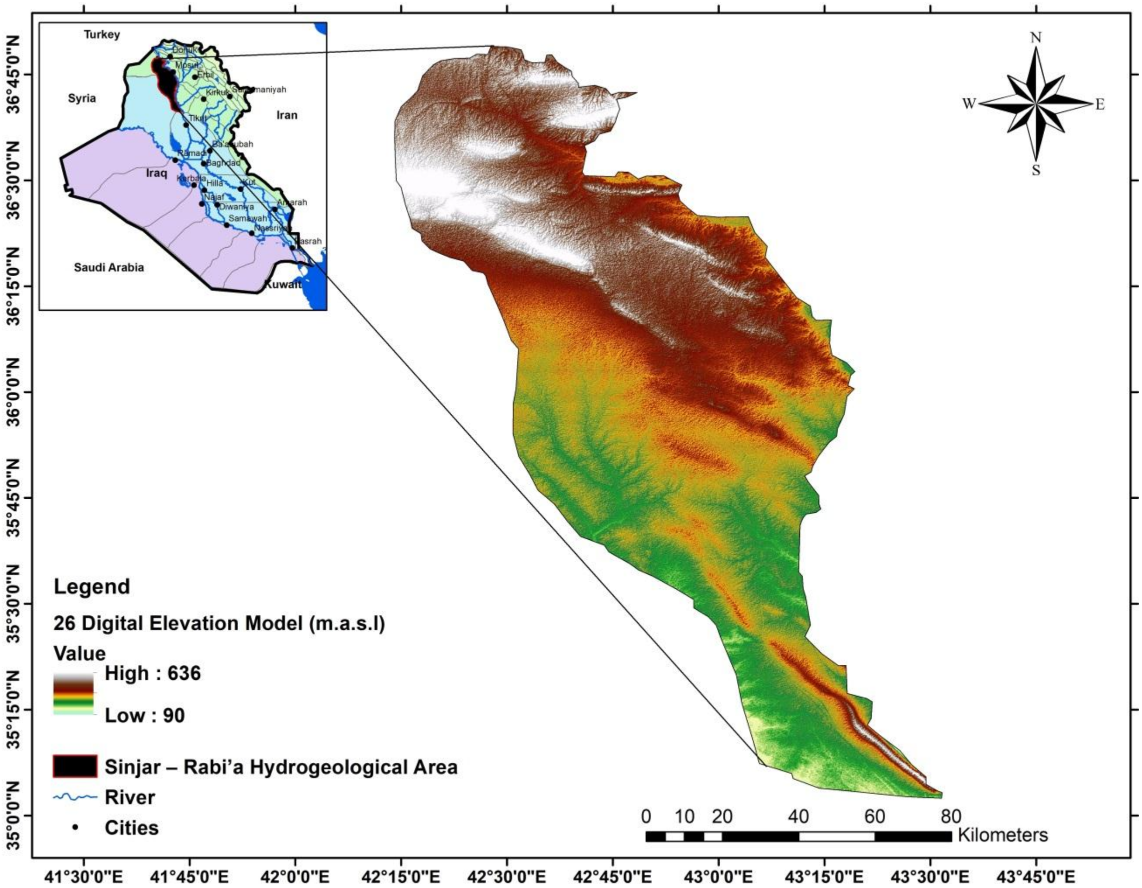

Figure (3 – 35):- Shows the watersheds map of the West Tigris hydrogeological area.

The results of the pumping test of Fat'ha aquifer indicated that the transmissivity ranges between (8 – 360 m^2/day), Hydraulic conductivity ranges between (0.1 – 8 m/day), discharge of wells varies between (7 – 13320 m^3/day) and the static water level ranges between (3 – 65.5 m) below ground surface. The salinity of the groundwater in these aquifers ranges between (2100 – 10000 mg/l) with mainly sulphatic and chloridic water types on the local scale. While the results of the pumping test of Injana aquifer indicated that the transmissivity ranges between (3 – 626 m^2/day), Hydraulic conductivity ranges between (0.1 – 18.5 m/day), discharge of wells varies between (27 – 2970 m^3/day), and the static water level ranges from self-flowing (-1.2 – 100 m) below ground surface. As a result, the groundwater salinity in this aquifer ranges between (450 – 7000 mg/l). Groundwater quality is mainly sulphatic and bicarbonate with chloridic type on the local scale (Al-Jiburi and Al-Basrawi, 2012).

3-4-12 Sinjar – Rabi'a Hydrogeological Area

This area is extended from the South of the Sinjar Mountain to the Iraqi-Syrian border. It covers a size of approximately (9198.1 Km^2) with elevation ranges from (266 m) to (1464 m) above sea level, as shown in figure (3-36). Sinjar Mountain forms a water divide between South Sinjar Plain and north Sinjar – Rabi'a Plain (Al-Jiburi and Al-Basrawi, 2012). Where the Sinjar Mountain is controlling the groundwater flow pattern. In the north of Sinjar – Rabi'a Plain, the groundwater flows towards the North and Northwest, while from this East of this mountain, the groundwater movement towards the Tigris River. In the South of this mountain, the groundwater flows towards the south, southwest, and southeast, mainly into the Jazira area, as shown in figure (3-8).

The data of water wells, which drilled in this area, showed that the main aquifers within Fat'ha and Injana Formations, with Quaternary sediments aquifers in different locations with two types of confined and unconfined aquifers. The results of the pumping test Fat'ha aquifer indicated that the transmissivity ranges between (4 – 337 m^2/day), Hydraulic conductivity ranges between (0.1 – 6.8 m/day), discharge of wells varies between (104 – 1804 m^3/day), and the static water level ranges between (8 – 37m) below ground surface. The salinity of the groundwater in these aquifers ranges between (2500 – 7170 mg/l) and with sulphatic and chloridic water types (Al-Jiburi and Al-Basrawi, 2012). While the results of the pumping test of the Injana aquifer indicated that the transmissivity ranges between (2 – 1274 m^2/day), Hydraulic conductivity ranges between (0.1 – 11.4 m/day), discharge of wells varies between (1 – 3960 m^3/day) and the static water level ranges from self-flowing (-0.6 – 67 m) below ground surface. The salinity of groundwater in this aquifer ranges between (110 – 16970mg/l). Groundwater quality is mainly sulphatic and bicarbonate with chloridic type on the local scale (Al-Jiburi and Al-Basrawi, 2012).

The results of the pumping test of with Quaternary sediments aquifers indicated that the transmissivity ranges between (15 – 91 m^2/day), Hydraulic conductivity ranges between (1.4 – 6.7 m/day), discharge of wells varies between (104 – 415 m^3/day) and the static water level ranges between (4 – 15 m) below ground surface. As a result, the groundwater salinity in this aquifer ranges between (526 – 5463mg/l) with sulphatic water types.

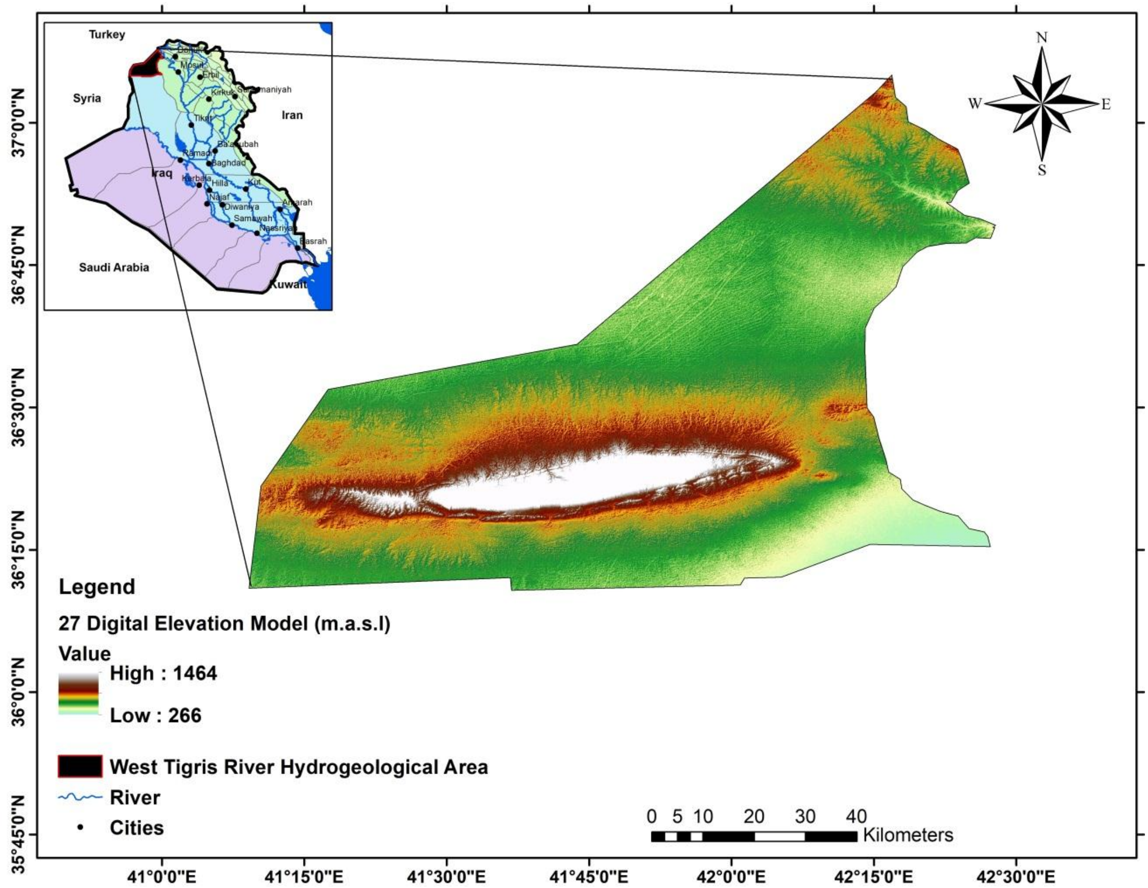

Figure (3 – 36):- Shows the watersheds map of the Sinjar – Rabi'a hydrogeological area.

Chapter Four

Al-Jazira and Mesopotamia Hydrogeological Region

4 - 1 Al-Jazira and Mesopotamia Hydrogeological Region

Al-Jazira and Mesopotamia Hydrogeological Region extend between Low Folded and Desert Hydrogeological Regions, which occupies about (145270 Km2). Sinjar Mountains bound it in the North and by Lowe Folded Region from Northeast to Southeast, Iraqi – Syrian border and Desert Hydrogeological Regions in the West, Southwest, and South, and the Iraqi-Iranian border in the extreme Southeast, as shown in figure (2-5) in chapter two. However, this region can be divided into four hydrogeological areas based on hydrogeological, structural, geological, and topographic features, as shown in figure (4-1).

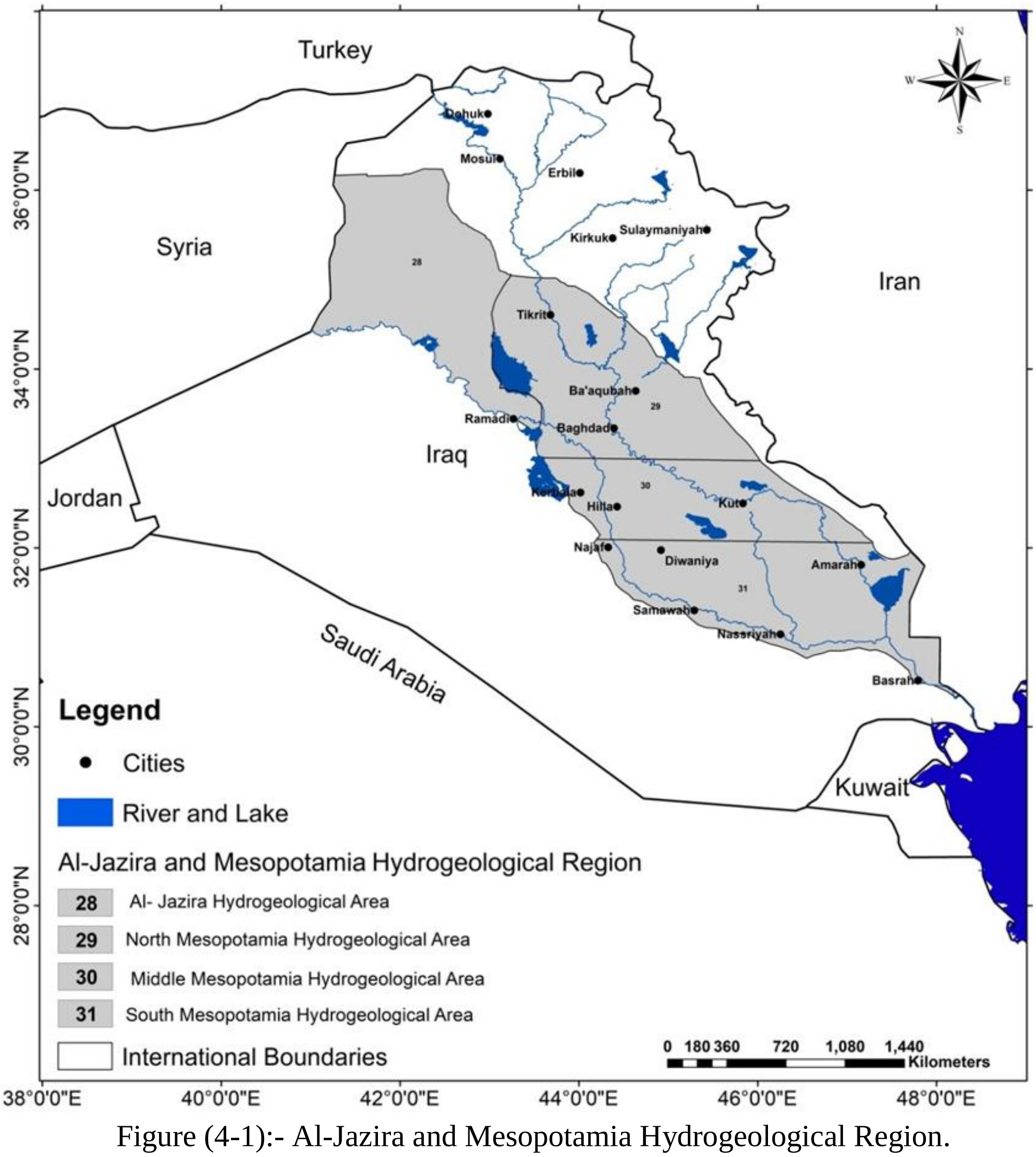

Figure (4-1):- Al-Jazira and Mesopotamia Hydrogeological Region.

According to Sissakian's (2000) geological map, this region is covered by sedimentary successions of carbonate, evaporates, and clastic facies, with ages ranging between Early Miocene and Pliocene - Pleistocene in the Al-Jazira hydrogeological area and some parts of Mesopotamia

Plain. At the same time, the Quaternary sediments cover most other aspects of the Mesopotamia Plain. The Formations that cover the North part of this region are Euphrates, Fat'ha, Injana, Mukdadiya, and Bai Hassan. The Euphrates Formation (Early Miocene) outcrops within a limited area along the Euphrates River in the South and Southwest Al-Jazira hydrogeological area, as shown in figure (4-2). The Fat'ha (Middle Miocene) is exposed in the middle and southern parts of the Al-Jazira hydrogeological area. The Injana Formation (Late Miocene) is exposed in the North and Northwest, in the East and South parts of the Al-Jazira hydrogeological area, and the Northwest part of the North Mesopotamia hydrogeological area. The Mukdadiya and Bia Hassan Formations (Pliocene –Pleistocene) are exposed in the Northeast part of the North Mesopotamia hydrogeological area. While the Quaternary sediments are covered the rest of the parts of the Mesopotamia Plain, as shown in figure (4-2).

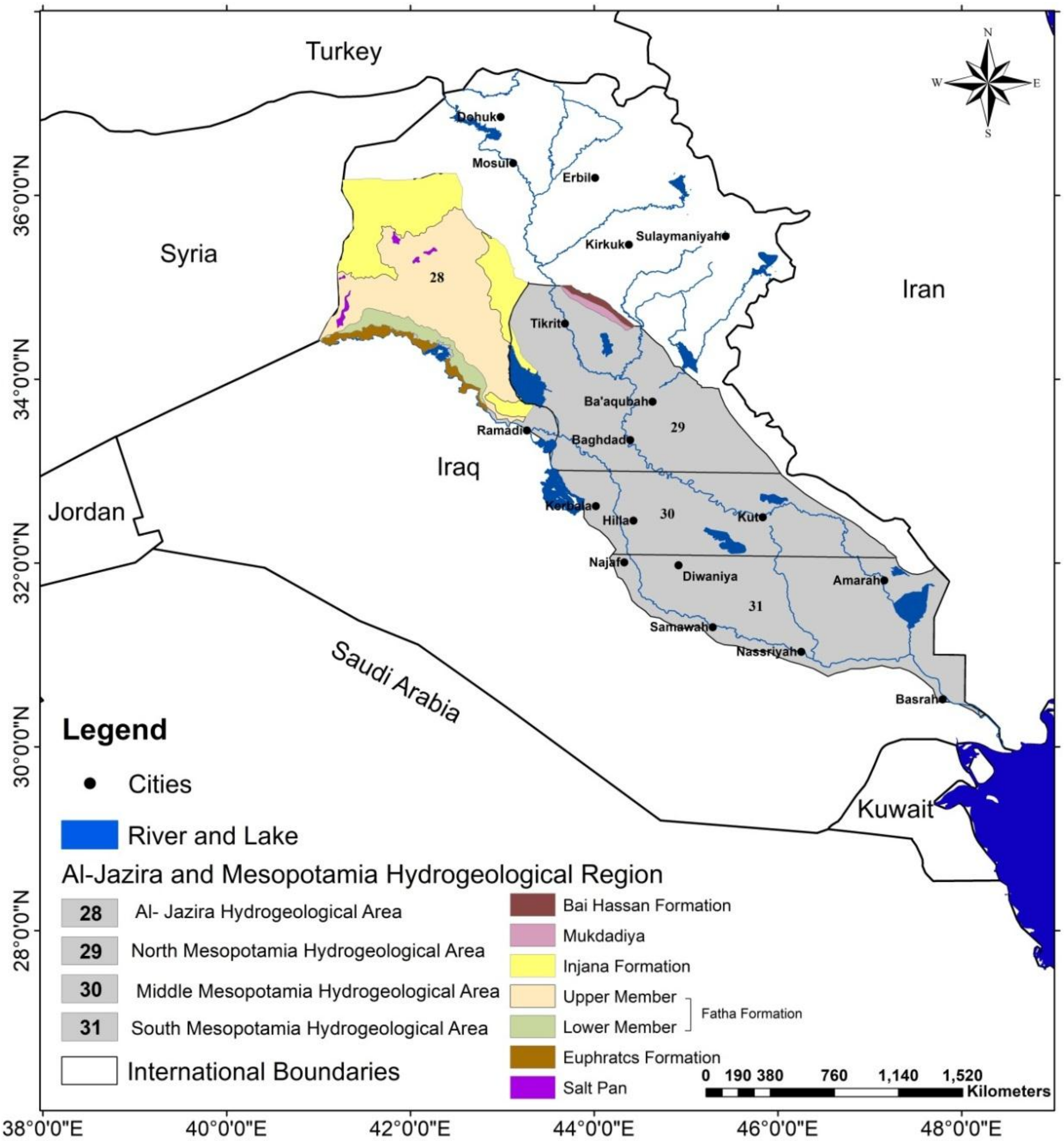

Figure (4-2):- Geologic map of Al-Jazira and Mesopotamia Hydrogeological Region, modified from (Sissakian, 2000).

This region is characterized by flat terrain with rugged to undulated topography and scattered isolated hills with shallow wadis in the Al-Jazira area and by flat plain that slopes gently between Baghdad and Basra in the Mesopotamia Plain. From the tectonic point of view, this region represents the part of the Unstable Shelf (Al-Kadhimi et al., 1996). Jassim and Buday,2006 in Jassim and Goff (2006) considered the lower part of this region (the Mesopotamia Plain) as a part of the Stable Shelf of the Arabian Platform. Fouad (2012) believed it represents a part of the Outer Platform. Also, Fouad (2012) considered this region Mesopotamia foredeep and subdivided into Al-Jazira and Basra subzone in the North and South respectively, as shown in the figure (1-6). The foredeep contains many surfaces and subsurface structures with neotectonic activities presented depending on different mobility and activity in this region (Fouad, 2012).

The general groundwater flow in this region is generally from North to the South toward Al-Tharthar Lake in the North part of this region, and towards the center of the Mesopotamia Plain in the middle and South parts of this region, with local groundwater flows in different directions depending on geological, topographic and structural features, as shown in figure (4-3). The Mesopotamia plain represents a regional discharge zone for the whole Mesopotamian aquifers system of Iraq, and the Tigris and Euphrates Rivers have formed the drainage system of this plain. These Rivers are merging North Basra city to form Shatt Al-Arab that flows to the Arabian Gulf.

The salinity of the groundwater in this region increases, generally from the recharge areas, in the North part towards the discharge areas in the South part. The quality of the groundwater is mainly sulphatic and chloride, with the presence of bicarbonate water types in some areas. This region is considered the least important hydrogeological region in Iraq due to the bad quality of its water, which is characterized by very high salinity in most hydrogeological areas within this region. However, the hydrogeological conditions of these areas can be described in detail as follows:-

4-2 Al-Jazira Hydrogeological Area

This area is located in the Northwestern part of Iraq and extends from the North Mesopotamia plain to Sinjar Mountain. It's bounded on the Northeast and East of the Low Folded hydrogeological region and the Northern part of Mesopotamia in Southeast and South. From the West, it is bordered by the Iraqi – Syrian boundary and by the Desert Hydrogeological Regions in the Southwest and South, as shown in figure (4-1). It covers an area of about (36680.3 Km^2) with elevation ranges from (450 m) to (50 m) above sea level. The watersheds generally flow to the Al-Tharthar Lake, as shown in figure (4-4). The topographical nature reflects the presence of two plains, Ba'aj and the Hadhr Plains.

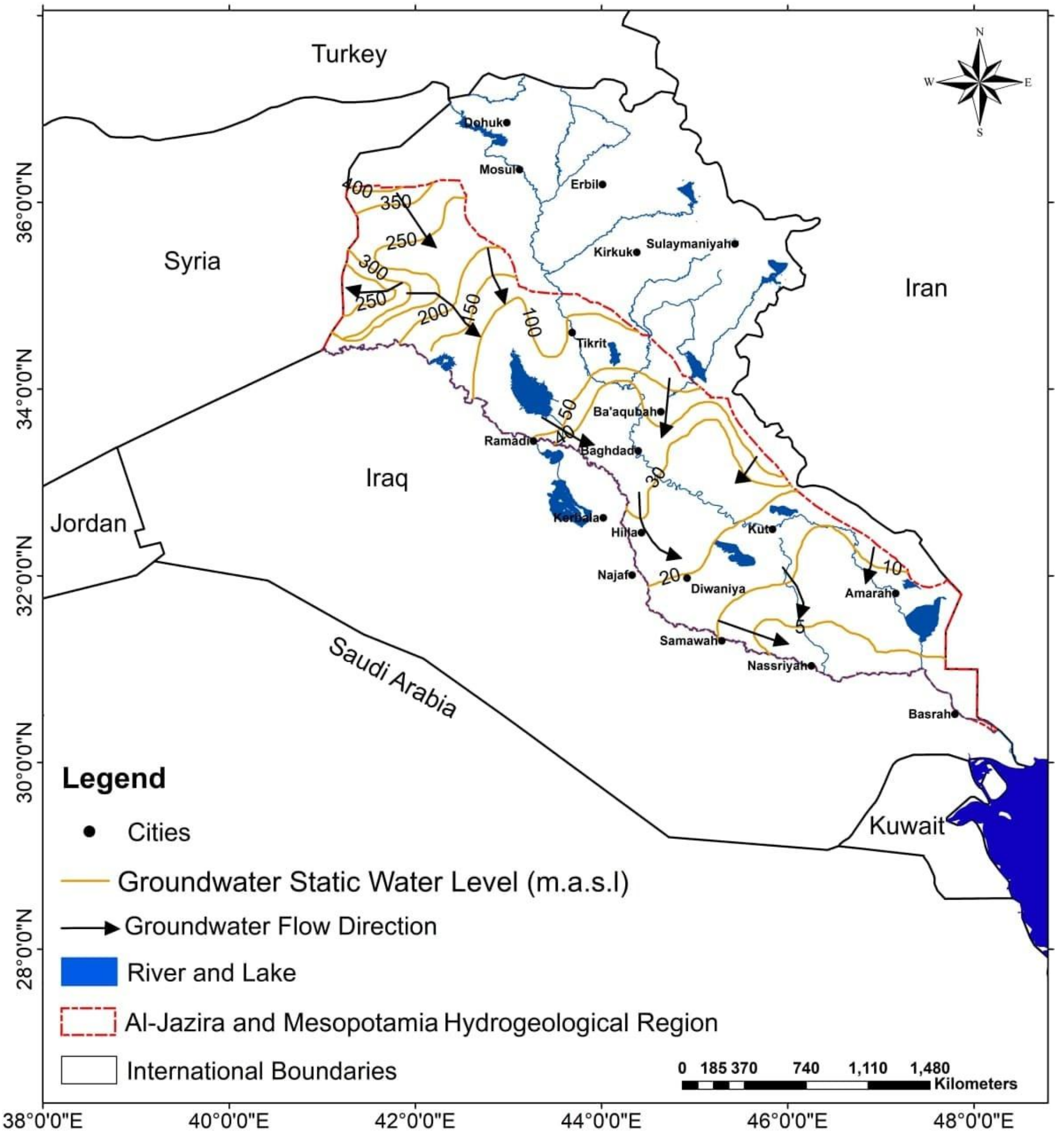

Figure (4 - 3):- Shows flow direction map of the groundwater in Al-Jazira and Mesopotamia Hydrogeological Region.

These Plains are penetrated by the Al-Tharthar Valley in the East part of this area, and some Valleys have slopes gently towards the South and Southeast to the Al-Tharthar Lake and Euphrates River. In addition, some Valleys are slope towards the Iraqi – Syrian border and towards the center of this area. These Valleys form salt marshes (Ma'ala, 2009). However, this area is characterized by a semi-arid climate. The average annual rainfall, temperature, and potential Evaporation of this area is about (265 mm/yr), (21.8 °C) and (2709.5 mm) respectively, for the period (1979 – 2014). Direct rainfall represents the primary recharge source of the groundwater in Al- Jazira area. While considered Tharthar Lake and salt marshes the main groundwater discharge zones in this area (Al-Jiburi and Al-Basrawi, 2009b).

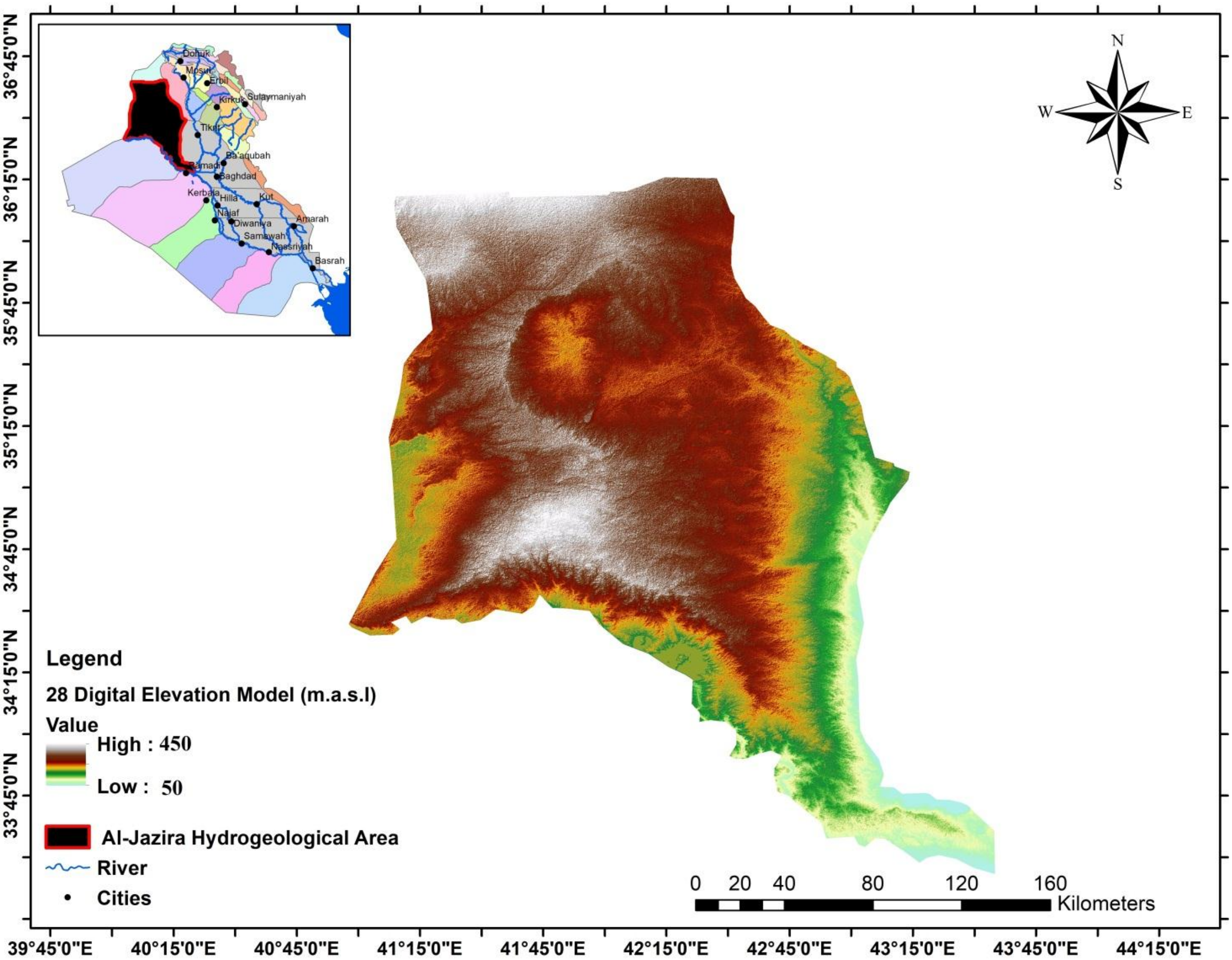

Figure (4 - 4):- Shows the watersheds map of the Al-Jazira hydrogeological area.

The groundwater movement is controlled mainly by the structure and geological settings of water-bearing Formations in the Al-Jazira area. Anticlinal structures and some hidden sub-surface structures are barrier boundaries (Araim, 1984). These structures and the karst phenomena within Fat'ha Formation play a significant role in controlling the groundwater movement in this area. So, the direction of the groundwater movement within this area is variable from one place to another. Three main directions of groundwater movement and some secondary trends were distinguished in this area according to Al-Jiburi and Al-Basrawi (2009b). The groundwater movement is towards the South in the Northern parts and takes different directions in the central regions. The groundwater movement towards the salt marshes or sabkhas represents topographic depressions in the main features. The general trend of groundwater movement towards Tharthar Valley and Tharthar Lake and toward the Euphrates River in the Southeastern parts. As for the Western and Southwestern parts, the groundwater movement takes different directions towards South – Southeast, and West – Northwest towards Bawara, Albu Gharis, and Taweel Salt Marshes in the Iraqi – Syrian borders.

Many springs in the Al- Jazira area occur along the wadis within Fat'ha Formation; some of them occur within the Quaternary sediments. A limited yield characterizes these springs. Therefore they are called water table springs (Al-Jiburi and Al-Basrawi, 2009b). The discharge of these springs ranges from less than (l/sec to 10 l/sec) (Krasny et al., 2006 in Jassim and Goff, 2006). These springs are characterized by highly mineralized groundwater, with a salinity of more than (20000 mg/l) especially near salt marshes. Still, it has salinity within the range of (2500 – 6600 mg/l) in other areas (Al-Jiburi and Al-Basrawi, 2009b).

Confined and unconfined aquifers represent the main water-bearing Formations in this area within Fat'ha, Injana Formations, and Quaternary sediments.

A- Fat'ha Aquifer

The Fat'ha Formation consists of many cycles from claystone, marl, limestone, and gypsum in regular order (Ma’ala and Al-Kubaysi, 2009). It is characterized by cavities, fractures, sinkholes, and solution channels in the gypsum layers. The groundwater is found in these structures connected by karstification. Unfortunately, the groundwater in this Formation is of bad quality because it is rich in gypsum layers that cause chemical contaminants to the groundwater, mainly in the form of calcium sulfate (Al-Jiburi and Al-Basrawi 2009b). Despite that, the people use this water for irrigation and livestock due to the shortage of surface water resources.

The runoff in the intermittent wadis caused by rainfall forms many salt marshes (sabkhas) in the exposure area of this Formation, which is an additional source for the salinity of the groundwater. Therefore, we do not recommend the use of water from this aquifer.

According to Al-Jiburi and Al-Basrawi, (2009b), the results of the pumping test of Fat'ha aquifer indicated that the transmissivity ranges between (2 – 246 m^2/day), Hydraulic conductivity ranges between (0.1 – 6.3 m/day), discharge of wells varies between (276 – 1555 m^3/day), and the static water level ranges between (3 – 49 m) below ground surface. The salinity of the groundwater in this aquifer ranges between (5320 – 19900 mg/l) with sulphatic water types.

B - Injana Aquifer

The Injana Formation was described in the previous chapter. It is exposed widely in the Northern part of the Al-Jazira area, as shown in figure (4-2). This Formation consists of a cyclic alternation of sandstones, siltstones, and claystones. The sandstone layers represent the main water-bearing layers within this Formation. Therefore, it is considered the most important aquifer. However, many deep wells in different locations penetrated this Formation totally or partially. The lithological sections of these wells showed that a variable thickness characterizes it from one place to another, generally decreasing gradually from the mountainous area towards the central parts of the Al-Jazira hydrogeological area.

The results of the pumping test that carried out in water wells within this aquifer showed that the transmissivity coefficient ranges between (2 – 1274 m^2/day), Hydraulic conductivity ranges between (0.1 – 20 m/day), discharge of wells varies between (11 – 3960 m^3/day) and static water level goes from artesian to (67 m) below the ground surface. The total dissolved solids vary between (450 – 25353 mg/l) with the Sulphatic water type, bicarbonate, and chloride water types in some locations. At the same time, the total dissolved solids range between (1189 – 7812 mg/l) of groundwater in hand-dug wells (Al-Jiburi and Al-Basrawi, 2009b).

C- Quaternary Sediments Aquifer

Quaternary sediments cover the older formations near the mountainous areas in the northern parts of the Al-Jazira hydrogeological area and cover some parts of the Fatha Formation in this area's central and Southern regions. It consists mainly of loam, pebbles, and sand in the Northern parts and from rock fragments, silty, and gypseous soils in the central and southern regions. These sediments are characterized by a small thickness of one to a few meters and reach more than (30 m) near the mountainous areas. Therefore, it considers perched water-table aquifers (Al-Jiburi and Al-Basrawi, 2009b). The groundwater from this aquifer is exploited mainly through hand-dug wells. According to Al-Jiburi and Al-Basrawi, (2009b), the results of the pumping test of this aquifer indicated that the transmissivity ranges between (5 – 257 m^2/day), Hydraulic conductivity ranges between (0.2 – 24.7 m/day), discharge of wells varies between (26 – 660 m^3/day), and the static water level ranges between (3 – 28 m) below ground surface. The salinity of the groundwater in this aquifer ranges from (526 – 2627 mg/l) with sulphatic water types. At the same time, it ranges between (2235 – 8400 mg/l) in the hand-dug wells that are drilled in the Southern parts of the area.

4-3 North Mesopotamia Hydrogeological Area

This area is located in the Northern part of Mesopotamia plain and extends from the Fat'ha area to the South of Baghdad city at the latitude (33^0 00’ 00”). It's bounded on the East by the Low Folded hydrogeological region and Desert Hydrogeological Region in the West, as shown in figure (4-1). This area is covered by different Quaternary sediments, Bai Hassan, Mukdadiya, and Injana Formations in small locations of the Northeast and Northwest parts, respectively, according to the geological map of Sissakian (2000). Dunes cover large North parts of this area. Some of them are still active (Sissakian, 2000). The lithological sections of water wells show that the Quaternary sediments are characterized by a variable thickness from one location to another, which ranges between (5 m) to more than (600 m) in the South Baghdad area. Generally, the thickness increases towards the Southern part of this area.

Tectonically, Al-Kadhimi et al. (1996) indicate subsurface anticlines still rising, such as Balad, Samarra, Tikrit, and Baiji anticlines. These anticlines with other surfaces feature indications for neotectonic movements (Kumanan, 2001 and Cohen *et al*., 2002 in Fouad and Sissakian, 2011). However, this area covers an area of approximately (35752.9 Km^2) with elevation ranges from (140 m) in the Fatha vicinity to (22 m) above sea level in Southeast Baghdad. The average annual rainfall, temperature, and potential Evaporation of this area is about (180 mm/yr), (24.6 °C) and (2814 mm) respectively, for the period (1979 – 2014). It represents the northern part of the Mesopotamia Plain watershed, as shown in figure (4 -5).

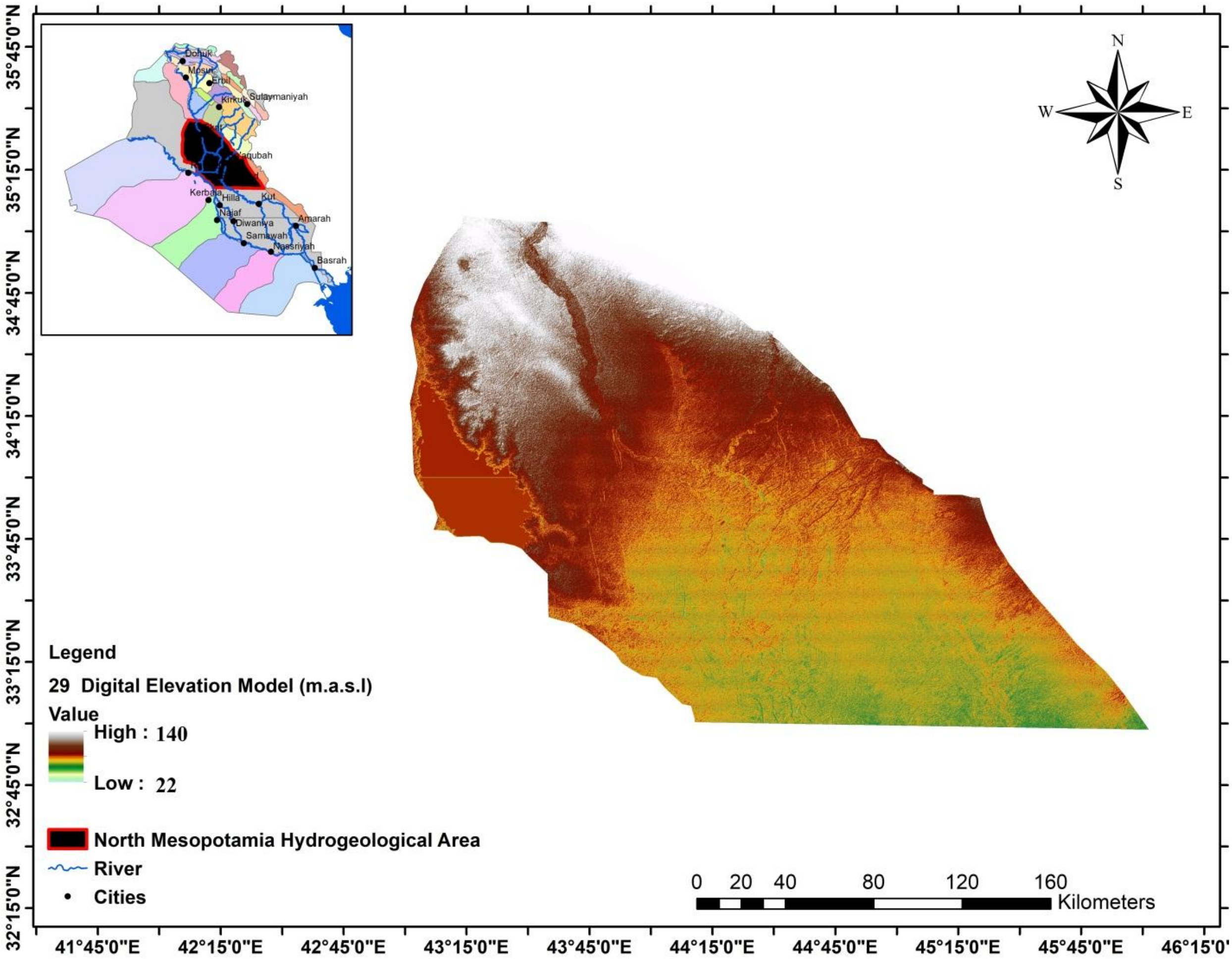

Figure (4 - 5):- Shows the watersheds map of the North Mesopotamia hydrogeological area.

The general direction of the groundwater flows in this area towards the center of the Mesopotamia Plain with some different local directions based on the topographical and structural features. Between Tikrit and Baiji towns, the flow is from the highlands in Himreen Mountain towards the Tigris River. There are two locally flow directions between Tharthar Lake and Tigris River, Westerly into Tharthar Lake and Easterly into Tigris River. In general, the Tharthar Lake, Shari Salt Lake, the left and right bank of the Tigris River, and Diyala and Adhaim Rivers are the main groundwater discharge zones of this area. The groundwater recharge is mainly from direct rainfall infiltration from intermittent streams and irrigation channels (Al-Jiburi and Al-Basrawi, 2011).

The main aquifers in the North part of this area are Injana, Mukdadiya, Bai Hassan Formations, and Quaternary sediments. The Quaternary sediments aquifer is the main aquifer in most parts of this area, especially in the South part. The Injana aquifer is located in the western part of the right bank of the Tigris River. Mukdadiya aquifer exists on the left bank of the Tigris River. At the same time, the Bai Hassan aquifer exists along highlands in Northeastern parts of this area (Ahmad and Al-Jiburi, 2005).

The results of the pumping test of the Injana aquifer indicated that the transmissivity ranges between (4 – 503 m^2/day), Hydraulic conductivity ranges between (0.1 – 47 m/day), discharge of wells varies between (58 – 1037 m^3/day) and the static water level ranges between (1.6 – 69 m) below ground surface. The salinity of the groundwater in these aquifers ranges between (300 – 6819 mg/l) and with the mainly sulphatic and chloridic water type on the local scale (Ahmad and Al-Jiburi, 2005). While the results of the pumping test of Mukdadiya aquifer in the Samara vicinity indicated that the transmissivity ranges between (3 – 774 m^2/day), Hydraulic conductivity ranges between (0.1 – 55.4 m/day), discharge of wells varies between (49 – 1452 m^3/day), and the static water level ranges between (2 – 95 m) below ground surface. The groundwater salinity in this aquifer ranges between (300 – 12000 mg/l). The groundwater quality is mainly sulphatic with chloridic type on the local scale (Al-Jiburi and Al-Basrawi, 2011).

There are some wells drilled in the Bai Hassan aquifer. The pumping test results of these wells show that the transmissivity ranges between (4 – 829 m^2/day), Hydraulic conductivity ranges between (0.1 – 43 m/day), discharge of wells varies between (20 – 5862 m^3/day), and the static water level ranges between (2 – 48 m) below ground surface. The groundwater salinity in this aquifer ranges between (334 – 11075 mg/l). Groundwater quality is mainly sulphatic with chloridic type on the local scale (Ahmad and Al-Jiburi, 2005).

According to Ahmad and Al-Jiburi, (2005), the results of the pumping test of the Quaternary sediments aquifer indicated that the transmissivity ranges between (21 – 555 m^2/day), Hydraulic conductivity ranges between (1.5 – 29.7 m/day), discharge of wells varies between (16 – 657 m^3/day), and the static water level ranges between (1.5 – 21 m) below ground surface. The salinity of the groundwater in this aquifer ranges between (526 – 2627 mg/l) with sulphatic water type and chloridic type on the local scale.

In the area between Samara town and the South Baghdad city, the Quaternary sediments aquifer represents the main aquifer. The results of the pumping test of this aquifer indicated that the transmissivity ranges between (6 – 1089 m^2/day), Hydraulic conductivity ranges between (0.5 – 126 m/day), discharge of wells varies between (7 – 1118 m^3/day), and the static water level ranges between (1.0 – 15.2 m) below ground surface. The salinity of the groundwater in this aquifer ranges between (3000 – 42312 mg/l) with sulphatic water type and chloridic type on the local scale (Ahmad and Al-Jiburi, 2005). Generally, the salinity of the groundwater is low near the banks of rivers and irrigation channels.

In the Southeast part of this area, the Quaternary sediments aquifer is the main aquifer in these areas. They consist of fluvial, sheet run-off and alluvial fan sediments, (Al-Jiburi and Al-Basrawi, 2011). Pumping test results of some drilled wells in the alluvial fan sediments aquifer indicated that the transmissivity ranges between (4 – 1382 m^2/day), Hydraulic conductivity ranges between (0.1 – 374.8 m/day), discharge of wells varies between (100 – 6480 m^3/day) and the static water level ranges between (0.6 – 48 m) below ground surface. The salinity of the groundwater in this aquifer ranges between (3000 – 96000 mg/l) with sulphatic water type (Ahmad and Al-Jiburi, 2005).

4- 4 Middle Mesopotamia Hydrogeological Area

This area represents the central part of the Mesopotamia plain and extends from the South of Baghdad to latitude (32º 00’ 00”), as shown in figure (4-1). This area covers an area of approximately (22515.4 Km^2) with elevation ranges from (10 m) to (48 m) above sea level. The average annual rainfall, temperature, and potential Evaporation of this area is about (132 mm/yr), (26.1 °C) and (3614 mm) respectively, for the period (1979 – 2014). It represents the watershed of the central part of the Mesopotamia Plain, as shown in figure (4 - 6). This area is covered by different Quaternary sediments, represented by the main water-bearing layers.

In the Western part of this area within the vicinity of Karbala city, the results of the pumping test of the aquifer indicated that the transmissivity ranges between (10 – 165 m^2/day), permeability ranges between (1 – 27 m/day), discharge of wells varies between (35 – 596 m^3/day), and the static water level ranges between (0 – 7 m) below ground surface. The salinity of the groundwater in this aquifer ranges between (3000 – 42200 mg/l) with sulphatic water type and chloridic type in the areas located along the Euphrates River (Al-Jiburi, 2002). Generally, the salinity of the groundwater is low near the banks of rivers and irrigation channels, and shallow wells.

Within the vicinities of Kut city and Ali Al-Gharbi town in the central and eastern parts of this area, the results of the pumping test of the aquifer indicated that the transmissivity ranges between (13 – 742 m^2/day), Hydraulic conductivity ranges between (0.8 – 72 m/day), discharge of wells varies between (132 – 864 m^3/day), and the static water level ranges between (2 – 14 m) below ground surface. The salinity of the groundwater in this aquifer varies between (3000 – 149000 mg/l) with sulphatic water type and chloridic type in the areas located along Tigris River (Al-Jiburi and Al-Basrawi, 2011).

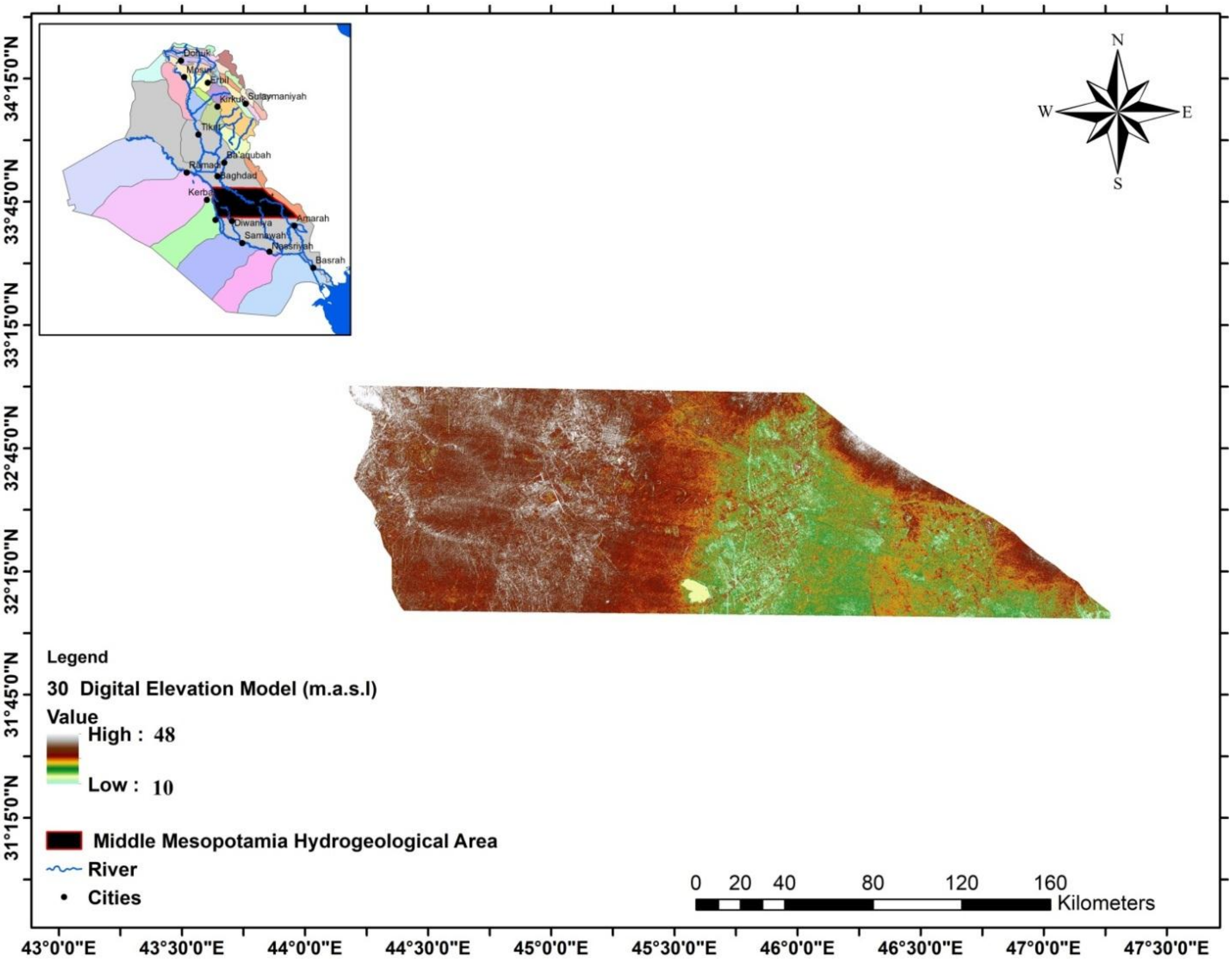

Figure (4 - 6):- Shows the watersheds map of the Middle Mesopotamia hydrogeological area.

4-5 Southern Mesopotamia Hydrogeological Area

This area is located in the South part of the Mesopotamia plain. It is extended from the South of latitude (32º 00’ 00”) to the Arabian Gulf, as shown in figure (1- 4). This area is covered by vast marshy regions, particularly Nasiriyah and Amara vicinities. It covers a size of approximately (33971.7 Km²) with elevation ranges from (1 m) to (25 m) above sea level. The average annual rainfall, temperature, and potential Evaporation of this area is about (110 mm/yr), (26.4 °C) and (3610 mm) respectively, for the period (1979 – 2014). It represents the watershed of the middle part of the Mesopotamia Plain, as shown in figure (4 -7). The general direction of the groundwater flows in this area towards Al-Ghar'raf, Tigris, Euphrates, Shatt Al-Arab Rivers, marshes and swamps, representing the main groundwater discharge zones of this area. The presence of sabkhas and mudflats characterizes the Western part of this area. It is also characterized by the presence of self-flowing wells due to it representing the contact area of the plain with the Southern part of the Iraqi Desert. This part is characterized by the presence of intensive fracture systems, (Araim, 1990).

The results of the pumping test of wells drilled in this aquifer in this area indicated that the transmissivity ranges between (36 – 439 m^2/day), Hydraulic conductivity ranges between (1.1 – 36.6 m/day), discharge of wells varies between (65 – 528 m^3/day) and the static water level ranges between (2 – 8 m) below ground surface. The salinity of the groundwater in this aquifer ranges between (3000 – to more than 82000 mg/l) with chloridic and sulphatic water types (Al-Jiburi and Al-Basrawi, 2011).

The North Mesopotamia, Middle Mesopotamia, and South Mesopotamia Hydrogeological Areas are considered as hydrogeological flow system called Mesopotamia. The hydrogeological flow system was delineated based on the boundaries of the hydrogeological area and interbasin flows between these two hydrogeological areas.

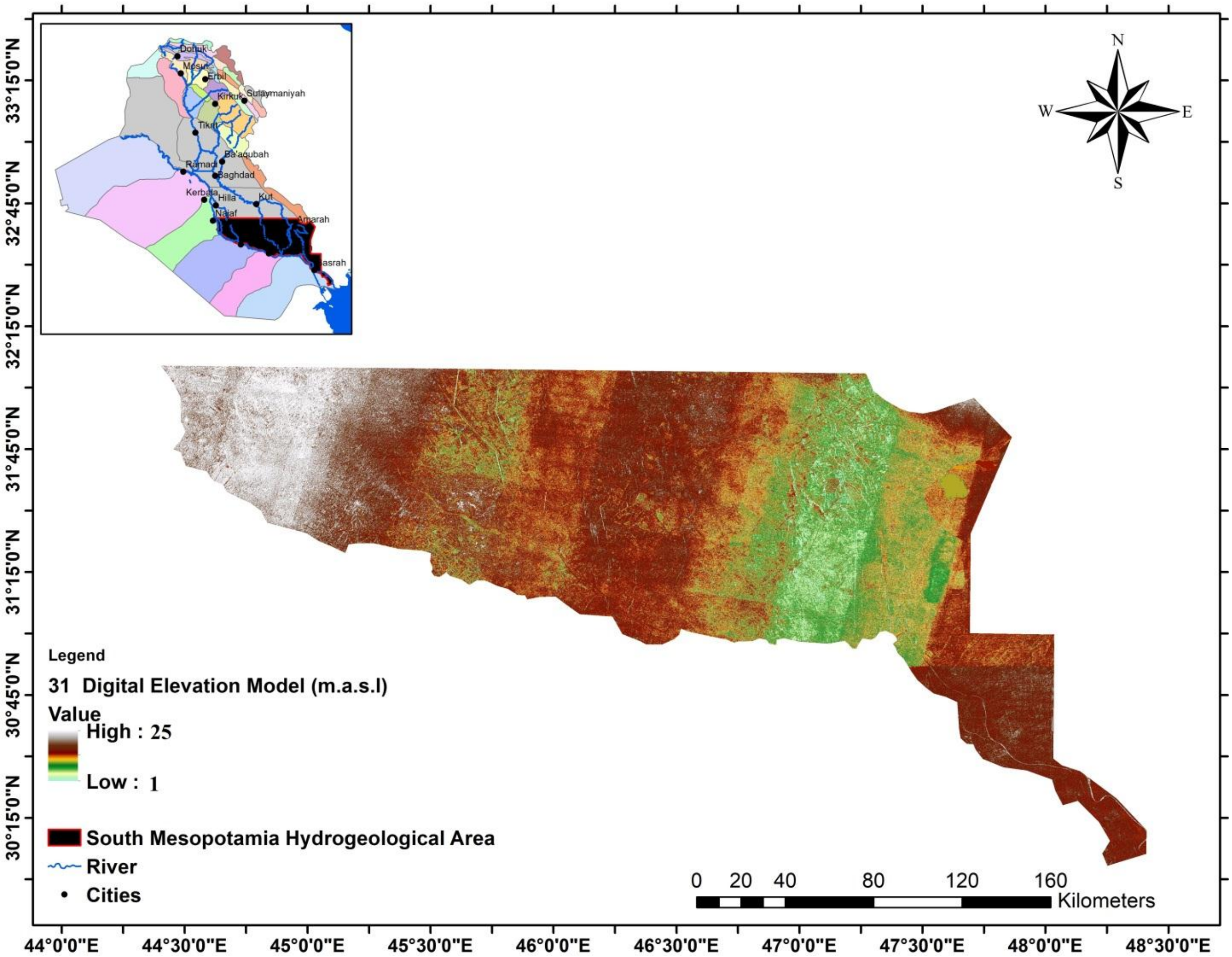

Figure (4 - 7):- Shows the watersheds map of the Southern Mesopotamia hydrogeological area.

Chapter Five
Desert Hydrogeological Region

5-1 Desert Hydrogeological Region

The Iraqi Desert represents the Western and Southwestern parts of Iraq. It covers about (180000 km^2) approximately, representing about (44.03%) of the total Iraq area. This region extends from the Iraqi-Syrian border in the North and Northwest to the Iraqi – Saudi Arabian borders in the South, Southwest, and the Iraqi – Kuwaiti borders. In addition, it is bordered by the Iraqi-Jordanian and Iraqi-Saudi Arabian borders in the West and Southwest and by the Al-Jazira and Mesopotamia Hydrogeological Region from Northeast to the Southeast as shown in figure (5-1).

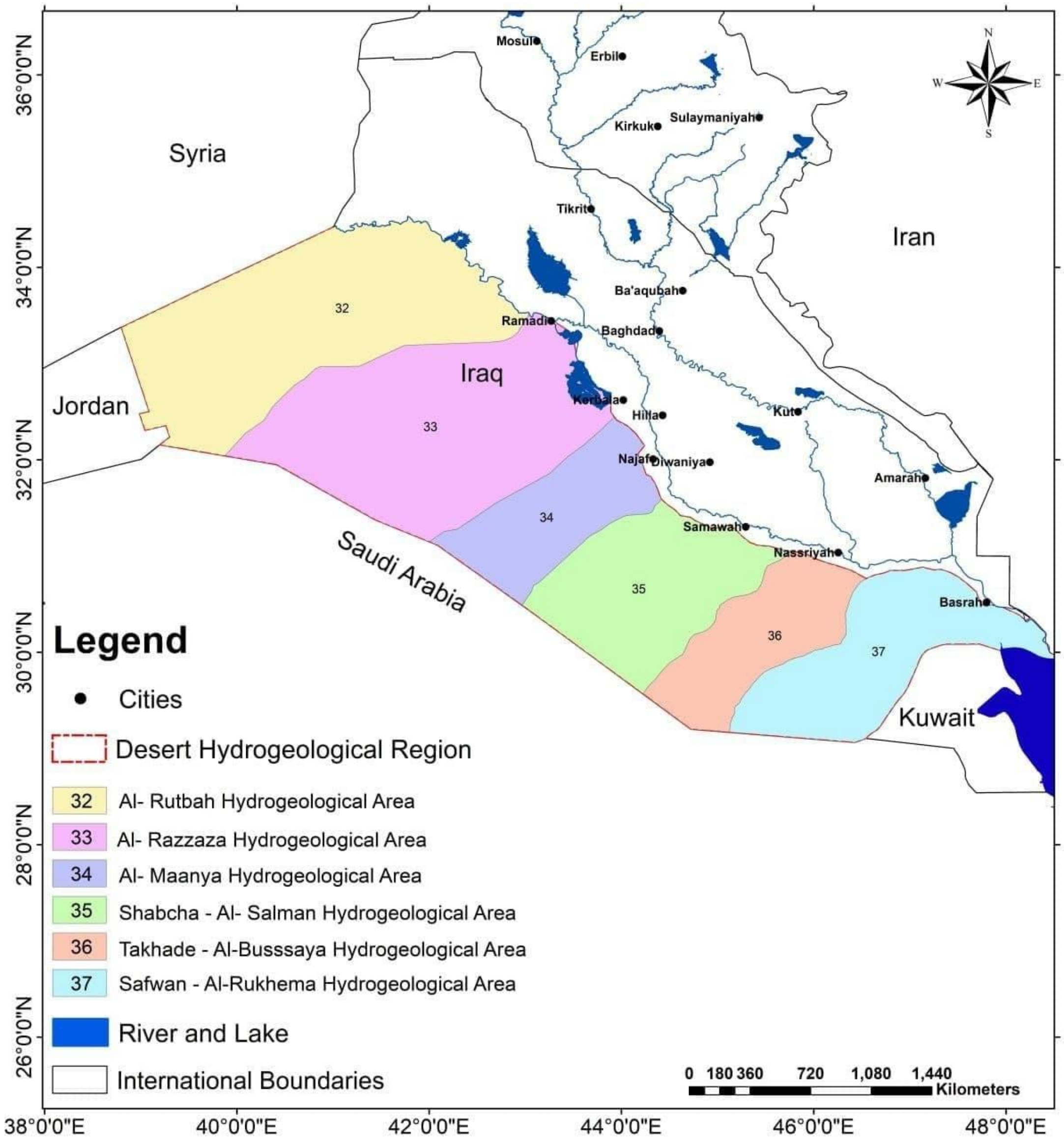

Figure (5-1):- Desert Hydrogeological Region.

Physiographically, the Iraqi Desert was divided into Western and Southern Deserts, according to Al-Khalaf (1959). The Western Desert is about (27.22%) of the Iraq area and covers about (104000 km^2). It is bordered by the Northwest Iraqi-Syrian border and the Euphrates River from the North and Northeast, Iraqi-Jordanian and Iraqi-Saudi Arabian borders in the West and Wadi Al-Khir in the South (Sissakian and Mohammed, 2007). The Southern Desert covers about (76000 km^2), which represents about (16.81%) of the total Iraq area. It extends from the Euphrates River in the North and Northeast, and Wadi Al-Khir in the Northwest to the Iraqi – Saudi Arabian borders in the South, Southwest, and the Iraqi – Kuwaiti borders, in the Southeast (Ma'ala, 2009c).

Topographically, the Iraqi Desert is characterized by the gradual decrease in elevation from West to East, with some exceptions. It represents the extension of the Northern part of the regional plateau of the Arabian Peninsula (Ma'ala, 2009c). According to Ma'ala (2009c) and Hamza (1997), this region has many positive and depressed topographic features. Jabel Anah represents the positive features in the North, Jabel Aneiza in the West, Karbala – Najaf Plateau in the East, Jabal Sanam in the South, and some mesas buttes. The major depressions are Ga`ara, Nukhaib, Shinana, Al-Birreet, Al-Juthoom, Haditha, Al-Habbaniya, Razaza Lakes in the Western Desert, and the Bahr Al-Najaf, Hor Al-Milih, Sawa Lake, Samawa Saline, and Slaibat depressions in the Southern Desert. The Iraqi Desert is characterized by the thin soil cover and sedimentary facies of carbonates, classics, and evaporates sequence (Hamza, 1997).

Tectonically, the Iraqi Desert is located in the Stable Shelf of the Arabian Platform, characterized by block tectonics and significant faults, such as the Euphrates and Abu Jir Faults (Jassim and Buday in Jassim and Goff, 2006). Fouad (2004 and 2007) indicated that the Euphrates Fault Zone extends the Abu Jir Fault Zone. In addition, there are many subsurface structures and faults that are playing a significant role in the determination of hydrogeological conditions in this region, such as Rutbah Uplift and Safawi, and many faults that can be shown in the Tectonic Map of Iraq of Jassim and Buday in Jassim and Goff, (2006).

From the hydrogeological point of view, this region is divided into six hydrogeological areas based on hydrogeological, structural, geological, and topographic features, as shown in figure (5-1). The general groundwater direction in this region is towards the Northeast, East, and Southeast to the discharge zones along the right bank of the Euphrates River, Al- Razaza Lake, and Mesopotamia plain, with some different local directions based on the topographical and structural features, as shown in figure (5-2). The main groundwater recharge of the Iraqi Desert is direct rainfall and infiltration from intermittent wadis. Most of these wadis are extended outside the Iraqi territory from Saudi Arabia. The salinity of groundwater of upper aquifers in this region varies from one place to another depending on the type of water-bearing Formations and its depths. Still, it is generally increased from the recharge areas to the discharge areas along the Euphrates River and Mesopotamia plain, with local salinity values.

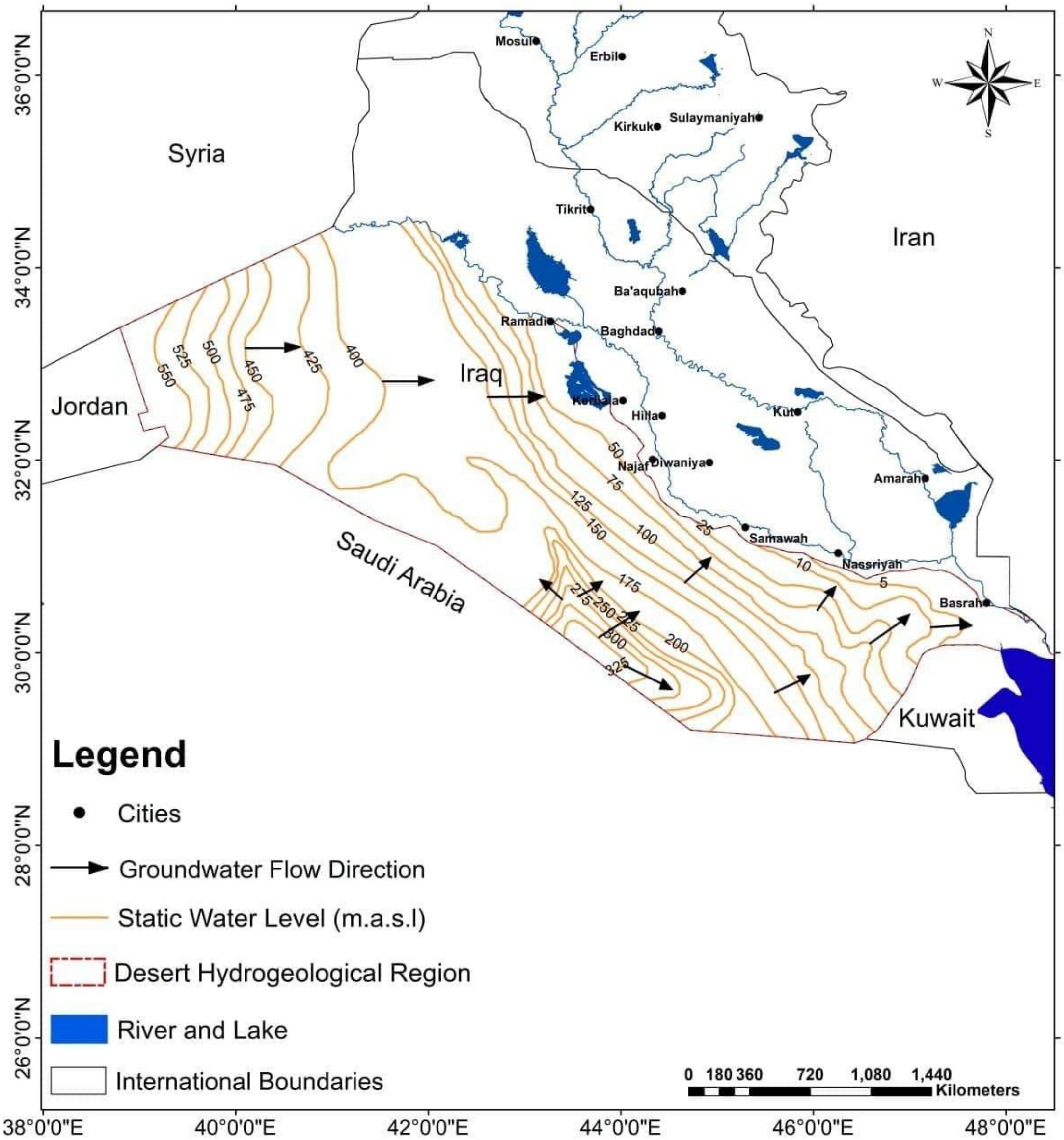

Figure (5-2):- Shows flow direction map of the groundwater in the Desert Hydrogeological Region.

5-2 Hydrogeological Areas

The Desert Hydrogeological Region was divided into six major hydrogeological areas and as follows:-

5-2-1 Al- Rutbah Hydrogeological Area

Al- Rutbah Hydrogeological Area covers an area of about (56000 km^2) that represents (27.3%) of the total Iraqi desert, as shown in figure (5-1). It is bordered by the Iraqi-Syrian border from the Northwest and West. By the right bank of the Euphrates River from the North and East, Iraqi-Jordanian and Iraqi-Saudi Arabian borders in the West and by Amij – Samara- Halabja Fault in the South. This area rises gradually from East to West with elevation ranges from (64m) to (902 m) above sea level, as shown in figure (5-3). The watersheds flow to the Euphrates River, the average annual rainfall, temperature, and potential Evaporation of this area is about (164 mm/yr), (17.8 °C) and (2977.5mm) respectively for the period (1979 – 2014).

The general direction of the groundwater within this area is toward the East and Southeast to the discharge zone along the right bank of the Euphrates River. Some studies, such as Jassas et al. (2019), have indicated the presence of a water divide caused by the Rutbah Uplift. In the western part of Rutbah town, the direction of the groundwater flow is towards the west, extending beyond the Iraqi borders.All hydrogeological studies have not mentioned this water divide within this part of the Western Desert (Al-Jiburi and Al-Basrawi, 2007) due to the water-bearing formations that have been deposited in this area before the occurrence of the Rutbah Uplift. Maybe and locally, some different flow directions occur throughout this area, especially within Tayarat and Jeed aquifers, but in general, the direction of the groundwater towards the east along the right bank of the Euphrates River. Most aquifers in this area are recharged from rainfall and runoff of the intermittent wadis through permeable layers, fractures, fissures, joints, and cavities into shallow aquifers (Al-Jiburi and Al-Basrawi, 2007).

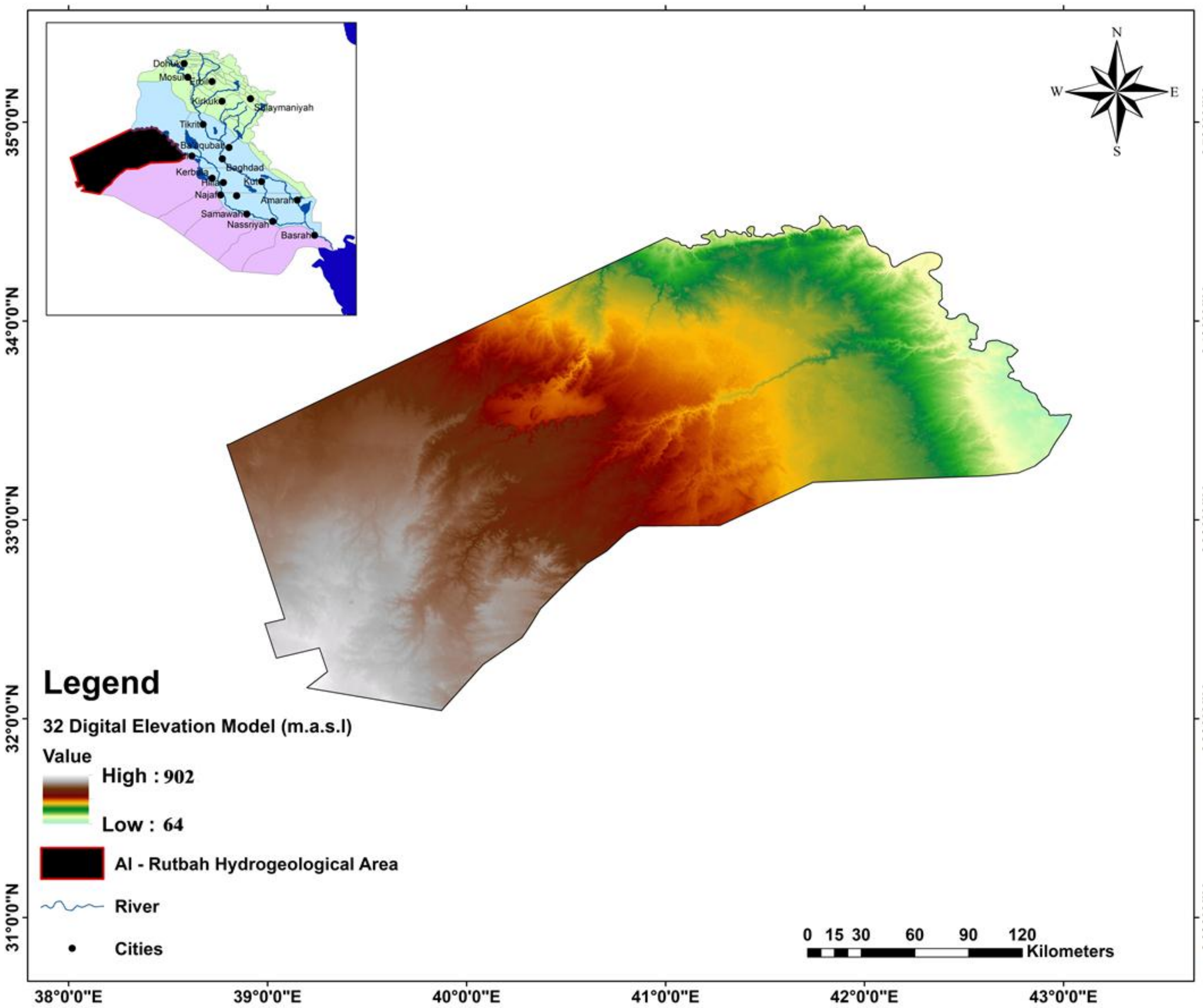

Figure (5-3):- Shows the watersheds map of the Al- Rutbah hydrogeological area.

The main aquifers in this Hydrogeological Area are Suffi, Ga'ara, Mulussa, Muhaiwir, Rutba, Tayarat, Akashat, Umm Er Radhuma, Dammam, and Euphrates aquifers. Most of these aquifers are fractured, consisting mainly of carbonate rocks of slightly brackish water.

5-2-2 Al-Razzaza Hydrogeological Area

Al-Razzaza Hydrogeological Area represents about (29.3%) from total Iraqi Desert, and it covers about (60000 km^2) with elevation ranges from (29 m) to (801 m) above sea level that gradual increase from East to West with some exceptions, as shown in figure (5-4). This area is bordered by Amij – Samara- Halabja Fault from the North, by the right bank of the Euphrates River from the East, and by Iraqi-Saudi Arabian borders in the West, by Diyala Fault in the South. Therefore, this area represents the catchment area of the Euphrates River.

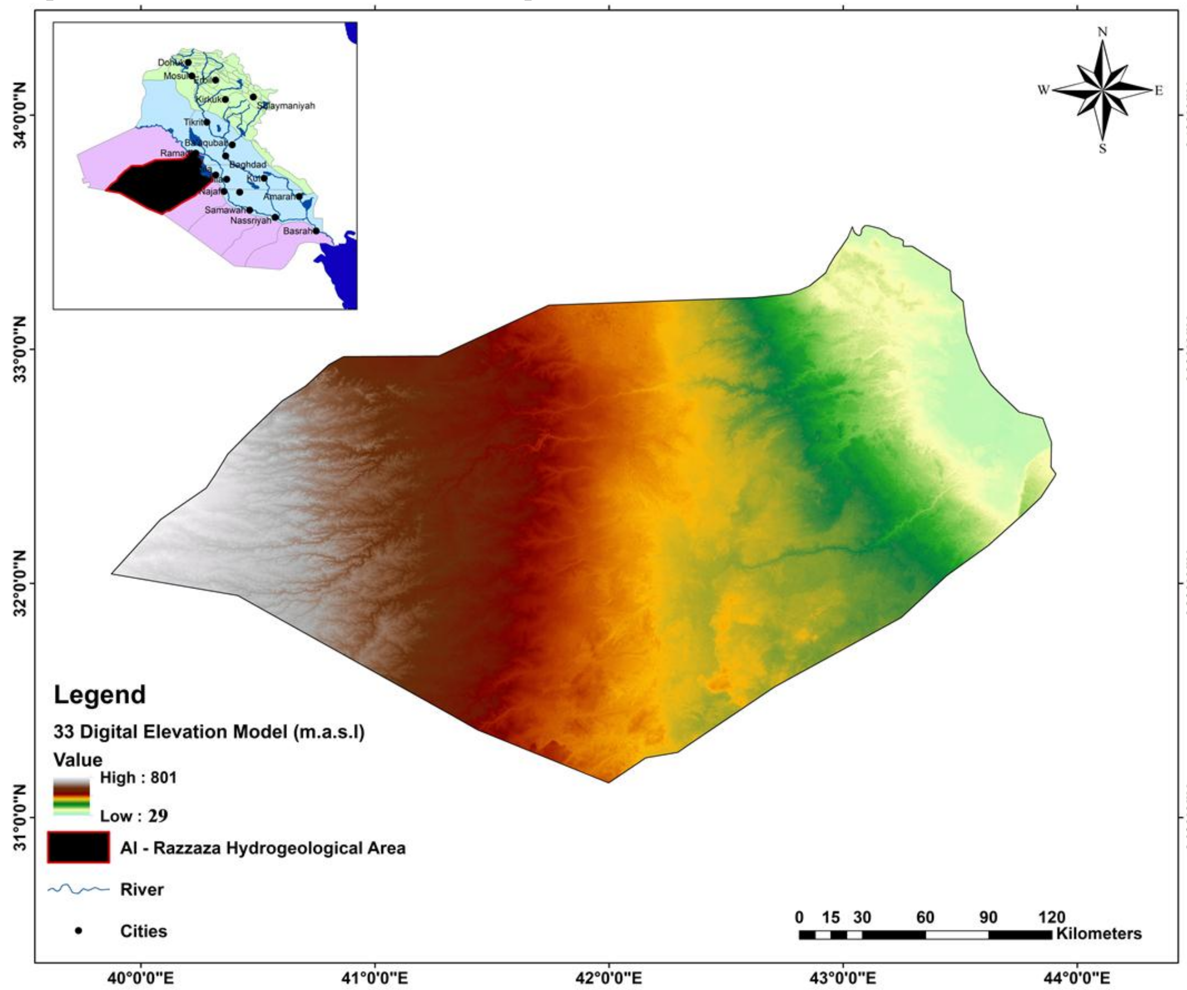

Figure (5-4):- The watersheds map of the Al- Al-Razzaza hydrogeological area.

The general trend of the groundwater is towards the East along the right bank of the Euphrates River. Locally, different flow directions may occur throughout this area, depending on the geological setting of water-bearing Formations and the nature of structures and topography. In general, the groundwater discharge zone of this area is located along the right bank of the Euphrates

River. This water is discharged underground into the Euphrates River, Habbaniya, and Razzaza lakes or springs (Al-Jiburi and Al-Basrawi, 2007).

Direct rainfall is the main source of groundwater recharge, and the vertical movement of groundwater represents the leakage of water from the deep Aquifers to the upper aquifers. However, the average annual rainfall, temperature, and potential Evaporation of this area is about (99.5 mm/yr), (21.1 °C) and (2755 mm) respectively, for the period (1979 – 2014).

The main aquifers are the Ga'ara, Mulussa, Muhaiwir, Rutba, Hartha, Tayarat, Umm Er-Radhuma, and Dammam.

5-2-3 Al- Maanya Hydrogeological Area

Al- Maanya Hydrogeological Area is bounded from the West and East by Iraqi-Saudi Arabian borders and right bank of the Euphrates River, respectively. This area is determined by the Al-Razzaza Hydrogeological Area in the North. At the same time, the Southern boundaries are represented by Rhaimawi – Hilla fault. This area covers about (16000 km^2), representing about (7.8%) of the total Iraqi Desert. It rises gradually from East to West with elevation ranges from (49 m) to (434 m) above sea level, as shown in figure (5-5).

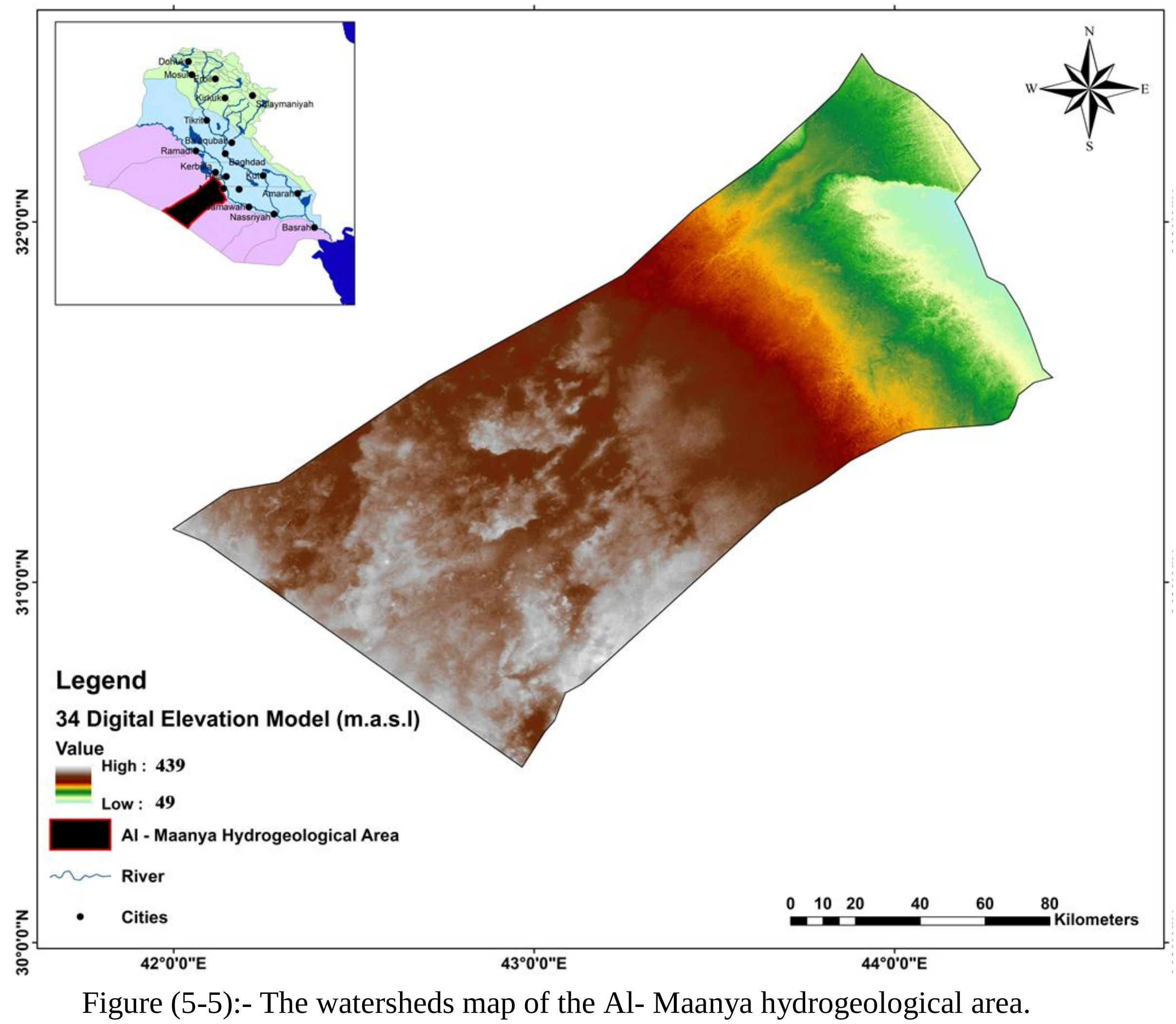

Figure (5-5):- The watersheds map of the Al- Maanya hydrogeological area.

The watersheds flow to the Euphrates River, representing the discharge zone of this area and the springs, which are located along the regional Abu-Jir faults zone. The recharge zone is situated to the West part of the area, represented by the rainfall and transboundary runoff infiltrated water. The general trend of the groundwater is towards the East along the right bank of the Euphrates River. Locally, different flow directions occur in this area, especially near the Iraqi-Saudi border, depending on the geological setting of water-bearing Formations and the nature of structure and topography, as shown in figure (5-2). However, the average annual rainfall, temperature, and potential Evaporation of this area is about (99.5 mm/yr), (23.7 °C) and (2812 mm) for the period (1979 – 2014). The main aquifers in this area are Hartha, Tayarat, Umm Er-Radhuma, and Dammam aquifers.

5-2-4 Shabcha – Al- Salman Hydrogeological Area

This area is located between Al- Maanya Hydrogeological Area in the North and the Takhade – Al-Busssaya Hydrogeological Area in the South, and bounded from the West and East by Iraqi-Saudi Arabian borders and right bank of the Euphrates River, respectively. The Takhadeed - Suq Al-Shoyokh-Amara fault represents the sharp boundary between this area and Takhadeed – Bussaya Hydrogeological Area. It means about (9.9%) of the total Iraqi Desert. It covers about (20000 km^2) with elevation ranges from (19 m) to (453 m) above sea level that gradually increases from East to West with some exceptions, as shown in figure (5-6).

The watersheds flow to the Euphrates River, representing the discharge zone of this area and the springs and Sawa Lake, which is located along the regional Abu-Jir faults zone. The general trend of the groundwater towards the East along the right bank of the Euphrates River. Locally, different flow directions occur in this area, especially near the Iraqi-Saudi border near the Safawi area, depending on the geological setting of water-bearing Formations and the nature of structure and topography, as shown in figure (5-2).

Direct rainfall is the main source of groundwater recharge, and the vertical movement of groundwater represents the leakage of water from the deep Aquifers to the upper aquifers. However, the average annual rainfall, temperature, and potential Evaporation of this area is about (99.5 mm/yr), (24.1 °C) and (3312 mm) respectively, for the period (1979 – 2014).

The main aquifers in this area are Tayarat, Umm Er-Radhuma, and Dammam aquifers.

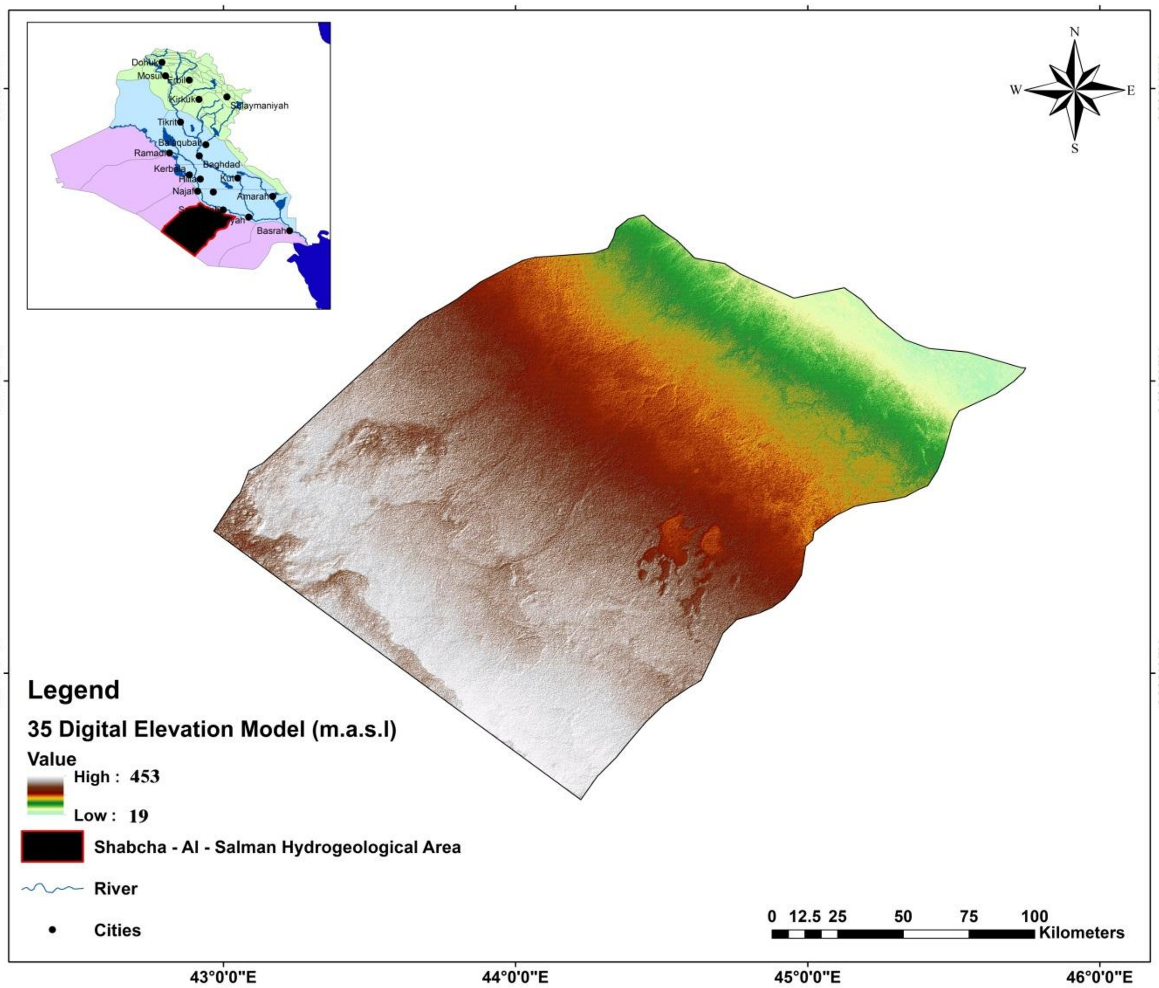

Figure (5-6):- The watersheds map of the Shabcha – Al- Salman hydrogeological area.

5-2-5 Takhade – Al-Busssaya Hydrogeological Area

This area covers about (31000 km^2), representing about (15.1%) of the total Iraqi Desert. It is located between Shabcha – Al- Salman Hydrogeological Area in the North and the Safwan – Al-Rukhema Hydrogeological Area in the South, and bounded from the West and East Iraqi-Saudi Arabian borders and the Euphrates River, respectively. The Al-Busssaya - Qurna fault represents the sharp boundary between this area and Safwan – Al-Rukhema Hydrogeological Area. It rises gradually from East to West with elevation ranges from (22 m) to (385 m) above sea level, as shown in figure (5-7).

The watersheds flow to the Euphrates River, representing the discharge zone of this area and the springs, which are located along the regional Abu-Jir faults zone. The recharge zone is situated to the West part of the area, represented by the rainfall and transboundary runoff infiltrated water. The general trend of the groundwater is towards the Northeast along the right bank of the Euphrates River with different directions of flow occur in this area, especially near the Iraqi-Saudi border in the Ansab area, depending on the geological setting of water-bearing Formations and the nature of structure and topography, as shown in figure (5-2). However, the average annual rainfall, temperature, and potential Evaporation of this area is about (99.5 mm/yr), (23.7 °C) and (3412 mm) respectively, for the period (1979 – 2014).

The Tayarat, Umm Er Radhuma, Dammam, Ghar/ Euphrates, and Dibdibba are the main water-bearing Formations in this area.

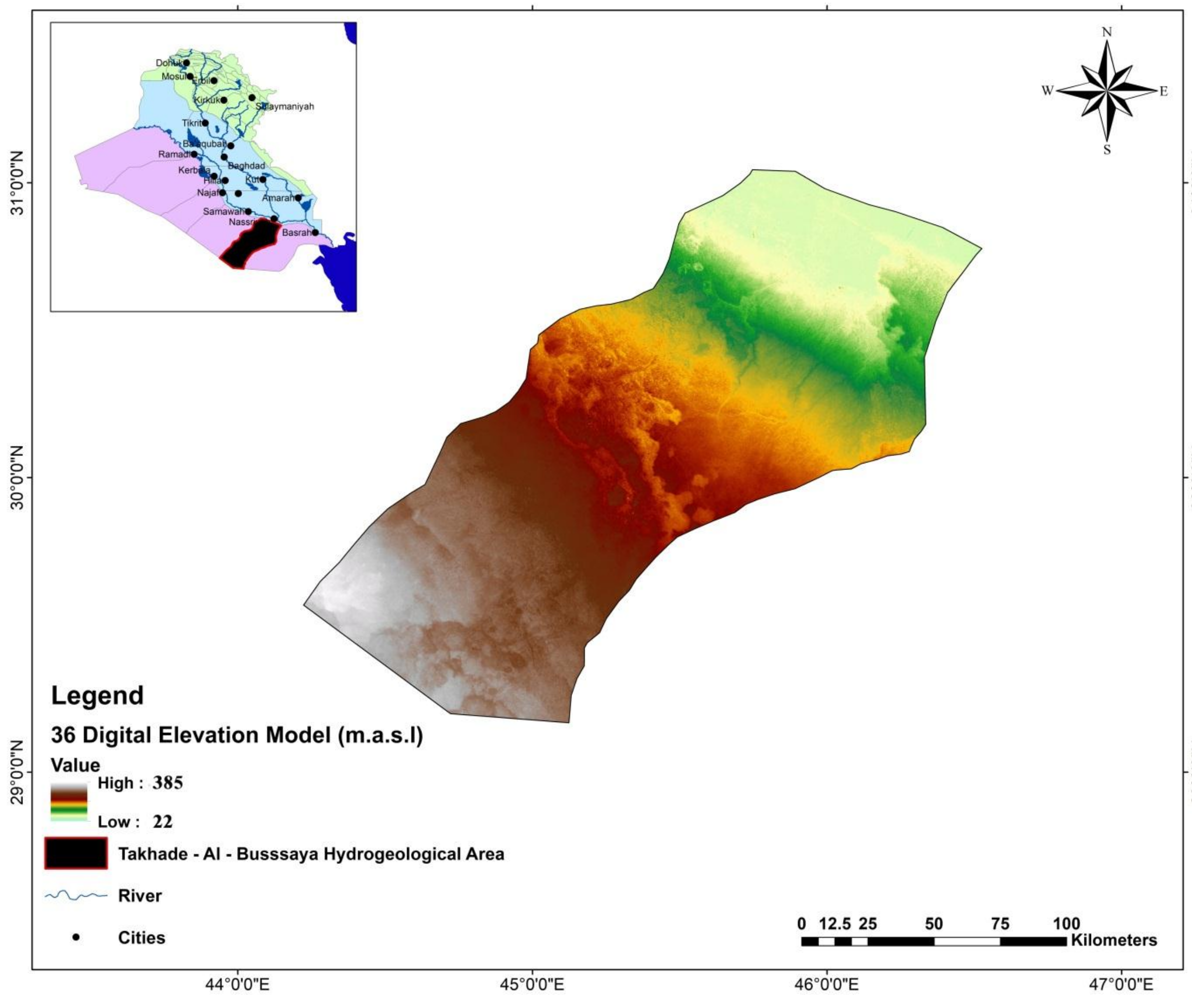

Figure (5-7):- The watersheds map of the Takhade – Al-Busssaya hydrogeological area.

5-2-6 Safwan – Al-Rukhema Hydrogeological Area

This area is located in the Southwestern part of the Iraqi Desert between the Iraqi-Saudi-Kuwaiti borders and Takhade – Al-Busssaya Hydrogeological Area. It represents about (10.7%) of the total Iraqi Desert. It covers about (22000 km^2) with elevation ranges from (3 m) to (324 m) above sea level that gradually increases from Northeast to Southwest with some exceptions, as shown in figure (5-8). This hydrogeological area extends outside Iraq to Kuwait and Saudi Arabia.

The watersheds flow to the Euphrates and Shatt Al-Arab Rivers represent the discharge zone of this area. The recharge zone is located in the South and Southwest parts of the area, represented by the rainfall and transboundary runoff infiltrated water. Therefore, the general trend of the groundwater is towards the East and Southeast, as shown in figure (5-2). However, the average annual rainfall, temperature, and potential Evaporation of this area is about (99.5 mm/yr), (26.3 °C) and (4000 mm) respectively, for the period (1979 – 2014). The Dibdibba aquifer is the main aquifer in this area.

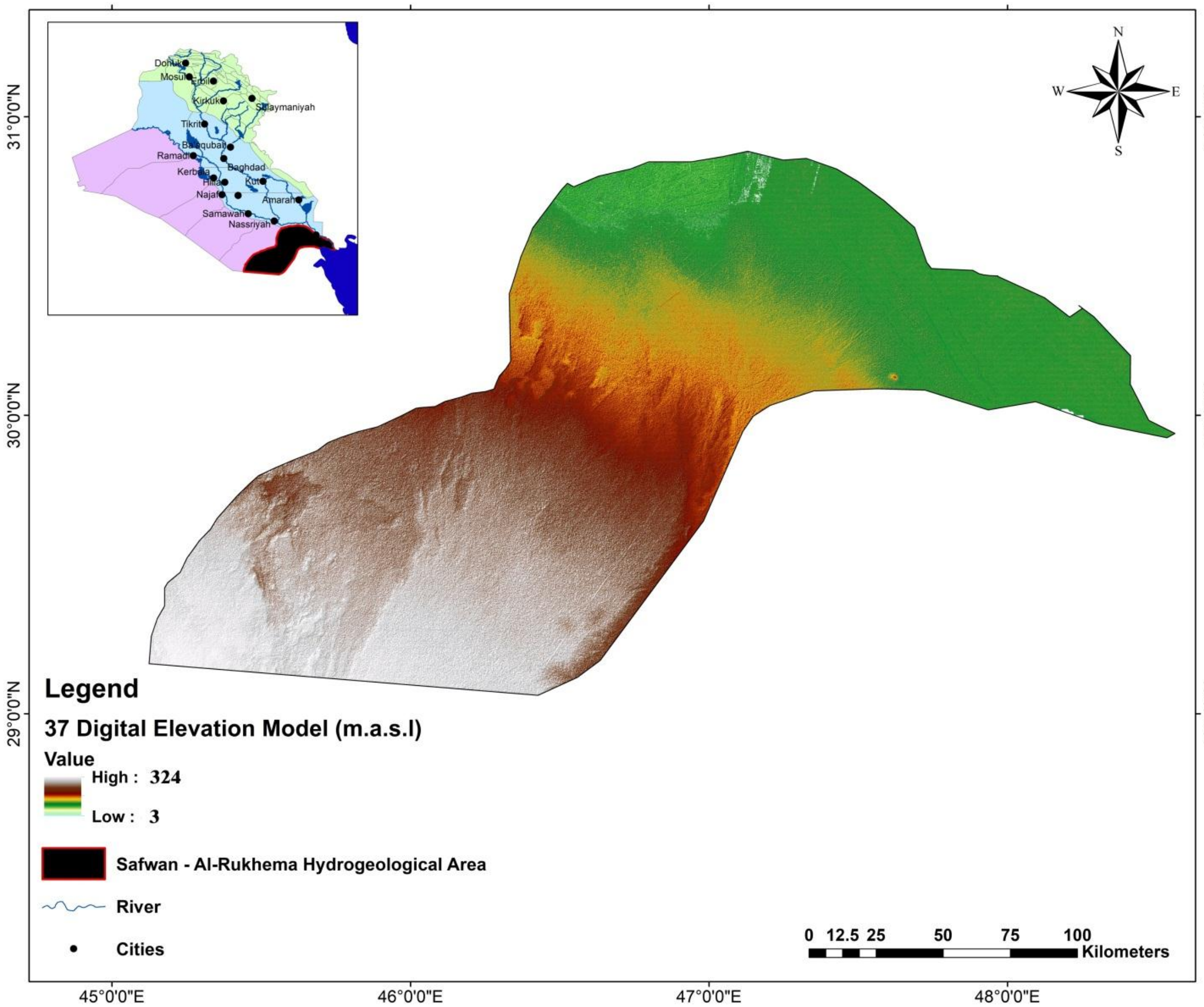

Figure (5-8):- The watersheds map of the Safwan – Al-Rukhema hydrogeological area.

5-3 Main Aquifers in the Desert Hydrogeological Region

There are fourteen main water-bearing Formations in the Iraqi Desert. It has aged from Permian within the Paleozoic era to Pliocene – Pleistocene age in the Cenozoic period, as shown in table (5-1). These Formations are considered the most extensive and essential water-bearing Formations in this region due to their high water content. These formations are composed of carbonate and clastic rocks, including confined, semi-confined aquifer types. The hydrogeological and hydrochemical characteristics of these aquifers will be briefly described:-

Table (5-1):- Main hydrogeological information of Aquifers occurs in the Iraqi Desert.

No.	Aquifer	Type of Aquifer	Water Bearing Strata	Age
1	Suffi	Confined	Sandstone and Carbonate Rocks	Middle Permian
2	Ga`ara	Mostly Confined	sandstones	Early – Late Permian
3	Mulussa	Mostly Confined	Carbonate Rocks	Late Triassic
4	Muhaiwir	Unconfined	Carbonate Rocks and Sandstone	Middle Jurassic
5	Rutbah	Unconfined	Sands and Sandstone	Late Cretaceous, Cenomanian
6	Hartha	Confined	Carbonate Rocks	Late Campanian – Early Maastrichtian
7	Tayarat	Confined	Carbonate Rocks	Late Maastrichtian
8	Akashat Equivalent of Umm Er Radhuma	Mostly Confined	Karstic Fracture Carbonate Rocks	Middle – Late Paleocene
9	Umm Er Radhuma	Mostly Confined	Karstic Fracture Carbonate Rocks	Middle – Late Paleocene
10	Dammam	Mostly Unconfined	Karstic Fracture Carbonate Rocks	Early – Late Eocene
11	Euphrates	Mostly Unconfined	Karstic Fracture Carbonate Rocks	Early Miocene
12	Char Equivalent of Euphrates	Partly Confined	Sandstone, Pebbly Sandstone and Limestone	Early Miocene
13	Injana-Dibdbba	Mostly Unconfined	Sandstone and Siltstone	Late Miocene
14	Dibdbba	Mostly Unconfined	Pebbly Sandstone and Sandstone	Pliocene – Pleistocene

5-3-1 Suffi Aquifer

The Suffi Formation is the only water-bearing Formation within the Paleozoic era. It is renamed by Jassim and Buday in Jassim and Goff (2006) as Bir Al-Rah Formation. Sissakian and Mohammed (2007) indicate that this Formation is considered an informal unit. However, this Formation has Permian age and is mainly composed of an alternation of claystone, shale, sandstone (various grain sizes), and dolomitic limestone. In contrast, black shale with sandstone is present in the lower part (Sissakian and Mohammed,2007). It is similar to Ga`ara Formation that is located above it, but it includes more carbonate and evaporates sediments (Consortium, 1981).

This water-bearing Formation is represented an important untapped groundwater source because it is located at large depths. It has a subsurface extension over nearly an area of (38000 km^2) at the Western parts of the Desert Hydrogeological Region, as shown in figure (5-9).

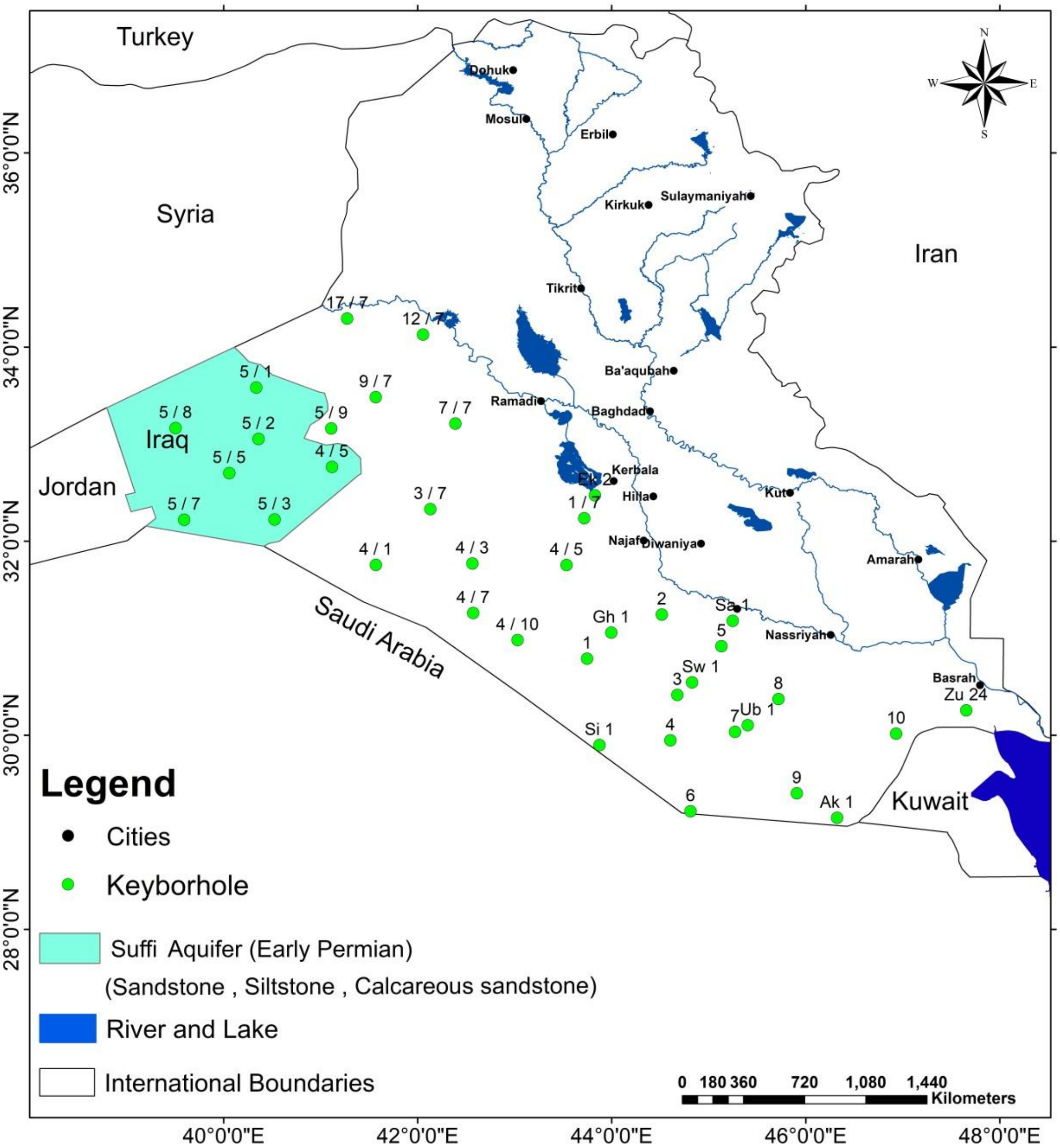

Figure (5-9):- The extensions of the Suffi Aquifer in the Iraqi Desert.

The available data of the Suffi aquifer was obtained from deepwater wells drilled in block (5) by Consortium (1981) within Al- Rutbah and Al-Razzaza Hydrogeological Areas. These wells have partially penetrated this aquifer, as shown in table (5-2). Lithological description of the well (KH 5/1) illustrated the presence of two aquifers within this Formation. The first aquifer appeared at a depth interval of (720 to 1350 m). This aquifer was tested together with the lowest ones of the

Ga`ara Formation, and the results had been shown the transmissivity was (100 m^2/day). While the second aquifer appeared at a depth interval of (855 – 1350 m), and the pumping test results show the transmissivity was (37 m^2/day). While the discharge was (535m^3/day), and the static water level was (57.8 m) below ground surface. Pumping results for other wells (KH 5/3 and KH 5/5) show the transmissivity was (36 m^2/day), discharge was (704 m^3/day). The static water level was (316.6 m) below the ground surface of the well (KH 5/3). In contrast, the transmissivity was (350 m^2/day), discharge was (1000 m^3/day), and the static water level was (300.3 m) below the ground surface of the well (KH 5/5), (Consortium, 1981).

The results of hydrochemical analysis for water sample from the deep well (KH 5/5) show the salinity of the water was (2332 mg/l) with Na-Chloridic water type. These results are more likely Ga`ara aquifer. This indicates no hydrogeological boundary between the Ga`ara aquifer and the uppermost part of Suffi aquifer. Therefore, both aquifers are in a relatively close hydrodynamic interconnection. The chemical analysis of a water sample from the deep well (KH 5/1) shows the salinity of groundwater is (8316 mg/l), representing the impact of black shale in the lower part of this Formation. At the same time, Al-Jiburi and Al – Bassrawi (2007) indicate that this water may represent oil-water or may be mixed with deep oil-water. However, recharge to the Suffi aquifer may be located outside the Iraqi borders (Consortium, 1981).

Table (5-2):- Penetration thicknesses in Suffi Formation.

Well No.	Penetration Depth (m)	Penetrated Thickness (m)
KH 5/1	720 – 1600	880
KH 5/2	870 – 950	80
KH 5/3	1055 – 1200	145
KH 5/4	475 – 600	125
KH 5/5	385 – 850	465
KH 5/7	700 – 750	50
KH 5/8	750 – 802.2	52.5

5-3-2 Ga`ara Aquifer

The Ga`ara Formation (Early – Late Permian) is extended in the Northwestern part of the Iraqi desert. It occupies an area of (45000$km^2$) approximately and exposes only in the Ga`ara depression within an area of (1500km^2) (Al Jawad and Ridha, 2008), as shown in figure (5-10). This Formation is composed of red and varicolored sandstones, siltstone, shales, and claystone. The sandstone beds are porous and alternated with low permeable claystone beds. They are dominantly medium to fine-grained, whereas coarse-grained sandstones scarcely occur (Tamer Agha, 1989). Alternating between sandstone, and claystone beds led to more than one aquifer within this Formation with confined, semi-unconfined, and unconfined types. The Ga`ara Formation is the main aquifer at the Desert Hydrogeological Region and represents the deepest aquifer in some localities, according to Consortium (1981).

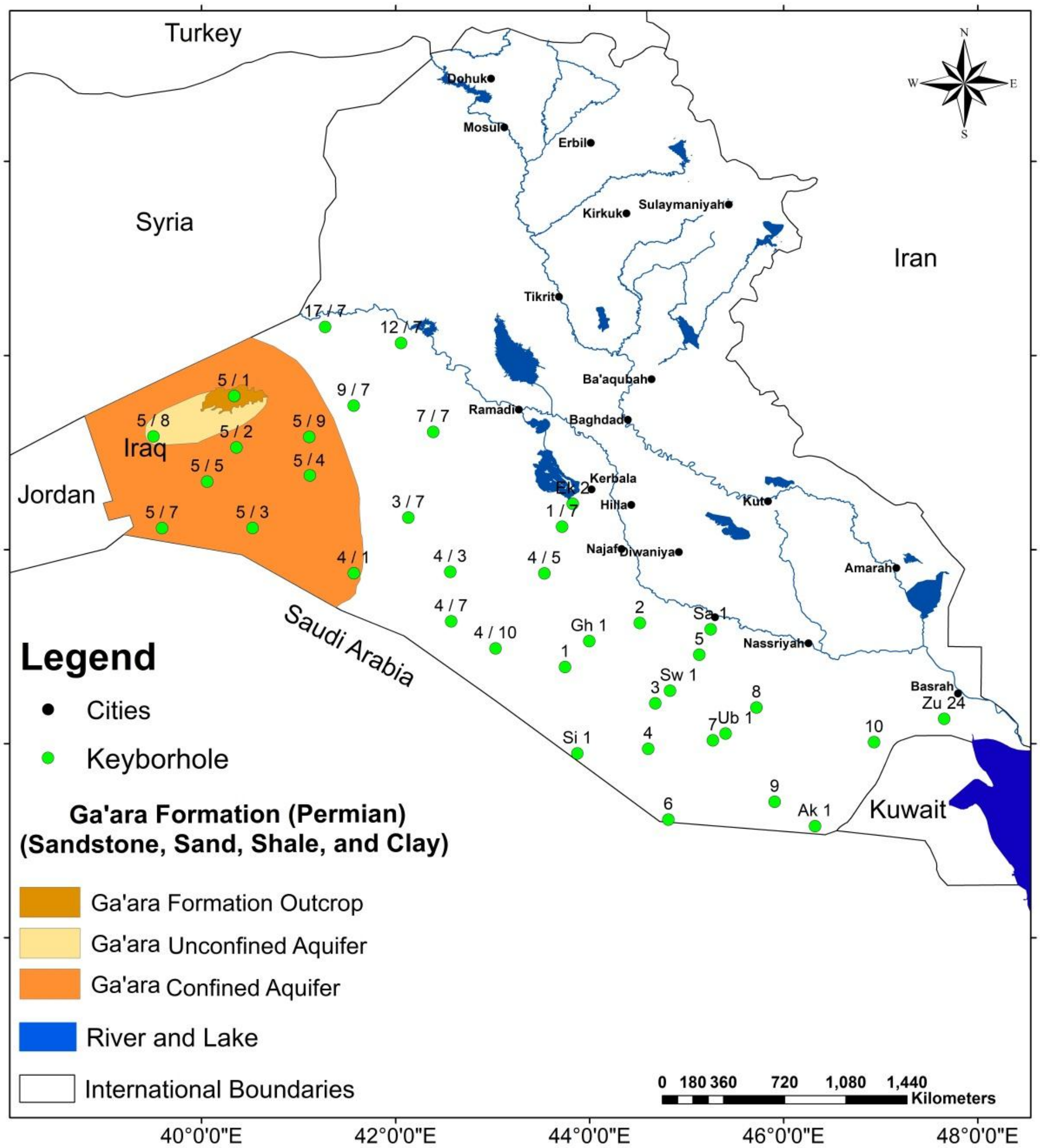

Figure (5-10):- Show extensions of Ga`ara Aquifer (after Al Jawad and Ridha, 2008).

The water-bearing layers in this Formation have been fully and partially penetrated by many water wells in the Al- Rutbah and Al-Razzaza Hydrogeological Areas, as shown in table (5-3). The available data of these wells indicated two aquifers, upper and lower aquifers. The upper aquifer in this Formation is unconfined or semi-unconfined aquifer. The hydraulic characteristics of this aquifer show that the transmissivity coefficient is between (0.5 – 620 m^2/day), Hydraulic conductivity ranges between (0.1 – 13.9 m/day), discharge of wells ranges between (48 – 540 m^3/day), and static water level varies between (29.8 – 461m) below ground surface. In regards to the lower aquifer, these data indicate that it is mostly a confined aquifer and have the transmissivity coefficient ranges between (10 – 250 m^2/day), Hydraulic conductivity varies between (0.1 – 19 m/day), discharge of wells ranges between (226 – 2872 m^3/day) and static water level ranges between (83.5 – 379.5 m), below ground surface. Furthermore, the hydrochemical analysis data are shown that the total dissolved solids (salinity) of the upper aquifer ranges between (318 – 2279 mg/l), while in the lower aquifer is mostly higher and ranges between (1120 – 2208 mg/l). In general, various types of water occur in these aquifers Chloridic, Sulphatic, and Bicarbonatic water (Consortium, 1981). In comparison, the upper aquifer is best than the lower aquifer because it has excellent and high water content. Moreover, the recharge of the upper aquifer is directly from rainfall and intermittent wadis runoff or through the overlying rocks (Al-Jiburi and Al – Bassrawi, 2007).

Table (5-3):- Penetration thicknesses in Ga`ara Formation, (Consortium, 1981; Al-Jiburi and Al – Bassrawi, 2007).

Well No.	Penetration Depth (m)	Penetrated Thickness (m)	Type of penetration
KH 5/1	0 – 720	720	Fully
KH 5/2	154 – 870	716	Fully
KH 5/3	385 – 1055	670	Fully
KH 5/5	92 – 385	293	Fully
KH 5/7	242 – 700	458	Fully
KH 5/8	750 – 802.2	423	Fully
RW-3	167 – 400	233	Partial
RW-5	120 – 425	300	Partial
RW-9	162 – 167	5	Partial
BH 2	80 – 505	425	Partial
BH 6	229.5 – 280.1	50.6	Partial
BH 15	333 – 362	29	Partial
KH 4/1	773 – 807	34	Partial

5-3-3 Mulussa Aquifer

The Mulussa Formation (Late Triassic) consists of dolomite, dolomitic limestone, limestone, sometimes sandy, with intercalations of marl and clay. It is exposed only in the Ga`ara depression in the Western part of the Iraqi Desert. It eroded between the Ga`ara depression and the Euphrates river (Jassim and Buday in Jassim and Goff, 2006). This Formation is considered an aquifer in the area located Southwest of the Ga`ara depression within Al- Rutbah and Al-Razzaza Hydrogeological Areas and occupies nearly an area of (19300 km$^2$) (Al Jawad and Ridha, 2008), as shown in figure (5-11). Some researchers consider it a perched aquifer over the underlying Ga`ara aquifer within the Rutbah area, and it gets deeper. The confined aquifer gradually substitutes the perched water in the North and Southwards of this area (Al-Jiburi and Al-Basrawi, 2007).

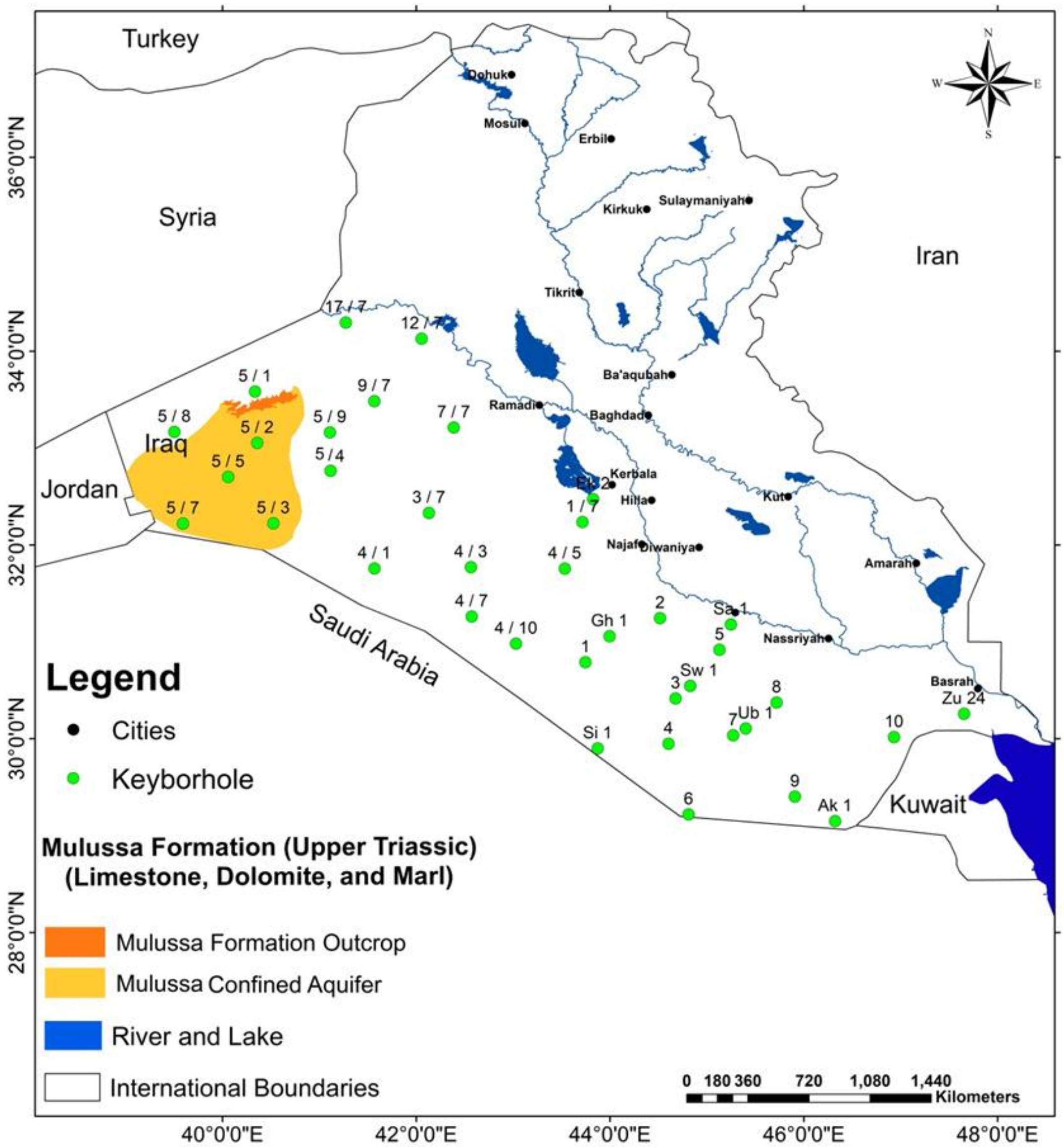

Figure (5-11):- Extensions of Mulussa Aquifer (after Al Jawad and Ridha, 2008).

Many wells penetrate this aquifer totally or partially. These wells appeared that the aquifer is characterized by a variable thickness from one area to another. In the water well (KH 5/6), which is currently located outside Iraqi borders (in Jordan), the aquifer appeared at a depth of (440 – 525m), with a thickness is about (85 m). In the water well (KH 5/9), the aquifer has appeared at a depth between (438 – 580 m) with a total thickness is (142 m). In the water well (KH 5/2), the thickness of this aquifer is about (131m). At the same time, its extension ends at the edge of the Ga'ara depression.

Executed pumping tests in many wells indicates that the transmissivity of the aquifer ranges from (0.8 – 397 m^2/day), Hydraulic conductivity varies between (0.03 – 4.4 m/day), well discharge from (22 – 864 m^3/day), and static water level ranges between (2 – 350 m) below ground surface. These results indicate the wide range of variations in the hydrogeological parameters. These variations may be due to the nature and characteristics of the aquifer rocks composed of dolomite and dolomitic limestone with low cavities. Therefore this aquifer has been classified as high - medium transmissivity and low to medium Hydraulic conductivity (Al-Jiburi and Al – Bassrawi, 2007). The hydrochemical analysis results indicate total dissolved solids (TDS) range between (265 – 2943 mg/l) with Bicarbonatic, Chloridic, and Sulphatic water types, respectively. In general, it is fresh and less than (1000 mg/l). So, it represents the best available water quality in Rutbah town and surrounding areas (Al-Jiburi and Al-Basrawi, 2002b; Al-Dabbaj and Al-Khashab, 2002a) in (Al-Jiburi and Al-Basrawi, 2015).

The recharge area of this aquifer is Rutbah Uplift along Hauran valley and its tributaries. In addition, the exposed area of this Formation in the Southern part of Ga'ara depression is considered another source of recharge (Hussien and Fayyadh, 2011).

5-3-4 Muhaiwir Aquifer

The Muhaiwir Formation (Middle Jurassic) is a relatively heterogeneous unit composed mainly of two parts. The upper part consists of limestone alternated with sandstone and marly limestone. The lower part consists mainly of limestone, with thin bands of sandstone (Jassim and Buday in Jassim and Goff, 2006). This Formation is exposed in Wadi Hauran, located at (10 Km) East of Qasir Muhaiwir (Sissakian and Mohammed, 2007). The subsurface extension is obscure, especially in the Western parts of Rutbah town, as shown in figure (5-12). It only appears in deep wells (KH 5/9, 5/4, 7/7, 7/9, and 7/12) located within Al- Rutbah and Al-Razzaza Hydrogeological Areas, as shown in table (5-4). However, the water-bearing layers in this Formation are characterized by good and significant water content due to the presence of cavities and voids (Al-Jiburi and Al-Basrawi, 20015).

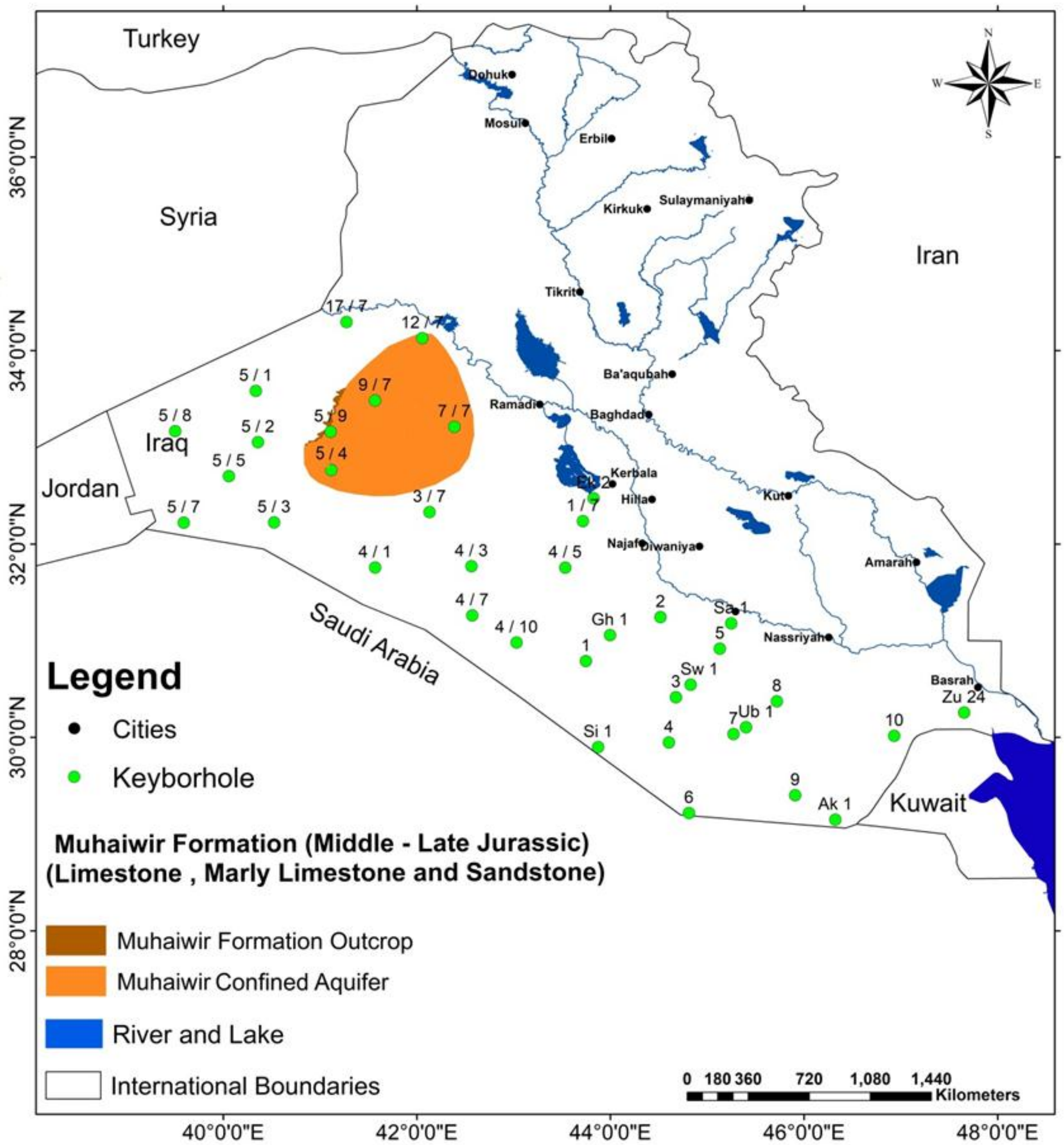

Figure (5-12):- Show extensions of Muhaiwir Aquifer (after Al Jawad and Ridha, 2008).

The hydrogeological parameters of this aquifer showed that the transmissivity ranges between (9 – 1243 m^2/day), Hydraulic conductivity varies between (0.1 – 9.3m/day); well discharge ranges between (46 – 1296 m^3/day) and static water level ranges between (99.6 – 306.4 m) below ground surface. The hydrochemical analysis results indicate total dissolved solids (TDS) range between (355 – 5868 mg/l) with Bicarbonatic, Chloridic, and Sulphatic water types. According to Consortium (1978 and 1981), two types of aquifers were distinguished in the deep well (KH 9/7) and individually tested. The results are shown that the water salinity of the upper aquifer at a depth between (225 – 320 m) was (580 mg/l) with Bicarbonatic water type, while in the lower aquifer located at a depth between (367 – 500m) was (14398 mg/l) with Chloridic water type. This indicates that Bicarbonate water type reflects the near and direct source of recharge to groundwater.

In contrast, the water of the lower aquifer probably means leakage of deep oil water to the aquifer (Al-Jiburi and Al-Basrawi, 2015).

Table (5-4):- Penetration thicknesses in Muhaiwir Formation, (Consortium, 1978 and 1981).

Well No.	Penetration Depth (m)	Penetrated Thickness (m)	Type of penetration
KH 5/4	714 – 870	139	Fully
KH 5/9	870 – 950	190	Fully
KH 7/7	714 – 870	156	Partial
KH 7/9	199 – 580	381	Fully
KH 7/12	552 – 902	350	Partial

5-3-5 Rutbah Aquifer

Most researchers confirmed that the Rutbah Formation (Late Cretaceous, Cenomanian) is exposed in wadi Hauran at about (20 Km) South of Rutbah town, then extends in subsurface South and Eastwards to be as an aquifer in the Al- Rutbah, Al-Razzaza, and Al- Maanya Hydrogeological Areas, as shown in figure (5-13). It consists of fine to coarse-grained sandstone, occasionally conglomeratic and quartzitic. Then, it passes upwards to yellow marly siltstone, locally dolomitic, and silty sandy limestone with oysters (Jassim and Buday in Jassim and Goff, 2006; Sissakian and Mohammed, 2007). This aquifer was penetrated totally or partially by many deep wells in different locations of the Iraqi Western Desert, as shown in the table (5-5). The lithological sections of these wells showed that it is characterized by a variable thickness from one location to another. The most significant thickness of this aquifer was (301.6 m) in well (B4/7), which is located North of the deep well (KH 7/7), while its lowest thickness was (20 m) in the deep well (5/4) (maybe dry).

In well (B4/7), the transmissivity was (2533 m2/day), Hydraulic conductivity was (16.6 m/day), well discharge was (1924 m3/day), and static water level was (155.2 m) below ground surface. At the same time, the hydrochemical analysis of the water sample from this aquifer indicates that the total dissolved solids (TDS) were (2590 mg/l) with Chloridic water type (Al-Jiburi and Al-Basrawi, 2015).

The hydrogeological parameters of this aquifer in well (B13/7) that located Northeast of the deep well (KH 7/9) within Al- Rutbah Hydrogeological Area showed that the transmissivity was (500 m^2/day), Hydraulic conductivity was (9 m/day); well discharge was (219 m^3/day) and static water level was (223.7 m) below ground surface. In comparison, the hydrochemical analysis of the water sample from this aquifer indicates that the total dissolved solids (TDS) were (1250 mg/l) with Sulphatic water type (Al-Jiburi and Al-Basrawi, 2015).

In the deep well (KH 4/1) that is located westward Nukhab town within Al-Razzaza Hydrogeological Area, the hydrogeological parameters of this aquifer indicate that the transmissivity was very high, well discharge was (639 m^3/day). As a result, the static water level was (235.5 m) below the ground surface. In contrast, the hydrochemical analysis of the water sample from this aquifer showed that the total dissolved solids (TDS) were (1000mg/l) with Chloridic water type (Idrotechneco, 1977).

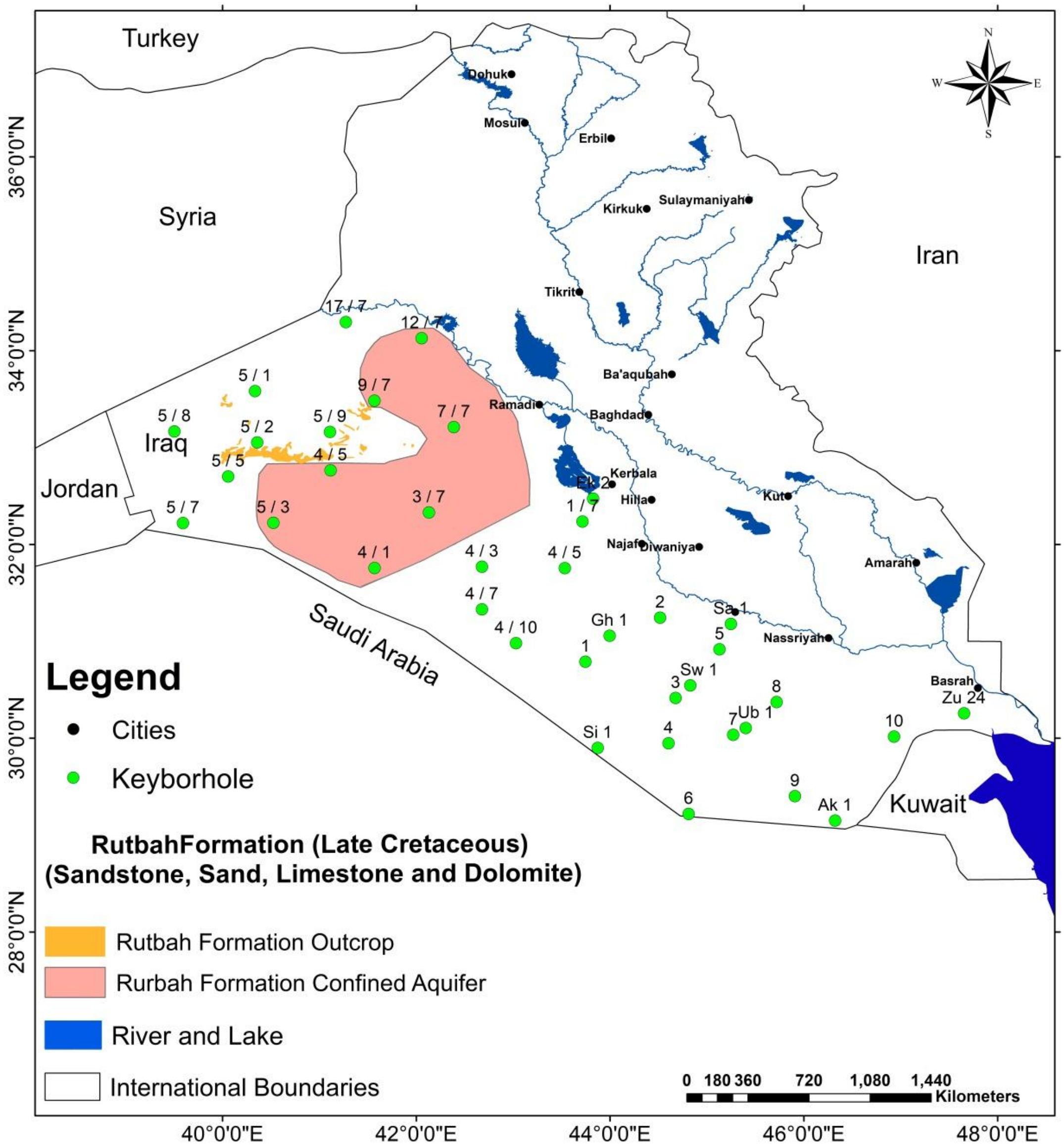

Figure (5-13):- Extensions of Rutbah Aquifer.

In general, The hydrogeological parameters of this aquifer showed that the transmissivity ranges between (2 – 7000 m^2/day), Hydraulic conductivity varies between (0.2 – 19.8m/day); well discharge ranges between (52 – 2920 m^3/day) and static water level ranges between (150.5 – 256 m) below ground surface. In addition, the hydrochemical analysis results indicate total dissolved solids (TDS) range between (1000 – 3000 mg/l), with Bicarbonatic, Chloridic, and Sulphatic water types (Consortium, 1978 and 1981). These data reflect that the Rutbah aquifer has excellent and significant water content and represents the main aquifer within Al- Rutbah, Al-Razzaza, and Al-Maanya Hydrogeological Areas (Al-Jiburi and Al-Basrawi, 2007).

Table (5-5):- Penetration thicknesses in Rutbah Formation (Consortium, 1978 and 1981; Idrotechneco, 1977; Al-Jiburi and Al – Bassrawi, 2007).

Well No.	Penetration Depth (m)	Penetrated Thickness (m)	Type of penetration
KH 5/3	76 – 280	65	Fully
KH 5/4	76 – 96	20	Fully
KH 7/3	476.25 – 695	218.75	Fully
KH 7/7	0 – 199	199	Fully
KH 7/9	357.5 – 552.5	195	Fully
KH 7/12	127 – 263	136	Fully
B 4/7	0 – 301.6	301.6	Partial
B 13/7	0 – 246	246	Partial
B 7/3	29 – 250	211	Fully
B 7/12	437.5 – 534.5	97	Fully
KH 1/4	546 – 679	133	Fully

5-3-6 Hartha Aquifer

Hartha Formation (Late Campanian – Early Maastrichtian) is exposed in the South of the Rutbah town with an area of (1550 Km^2) approximately. Then it extends in the subsurface in most parts of Iraq except the suture and thrust, High and Low Folded zones (Kurdistan Region), (Sissakian and Mohammed, 2007). It is considered as an aquifer only in the Al-Razzaza and Al- Maanya Hydrogeological Areas with an area of (32718 Km^2) (Al Jawad and Ridha, 2008), as shown in figure (5-14). This Formation is composed mainly of carbonate and clastic rocks. Al-Mubarak and Amin (1983) divided this Formation into two Western Desert members: upper carbonate and lower clastic members. The upper carbonate member alternates dolostone, marl, marly dolostone, and sandstone alternates with the marl. At the same time, the lower clastic member consists of the conglomerate to conglomeratic sandstone and sandy dolostone.

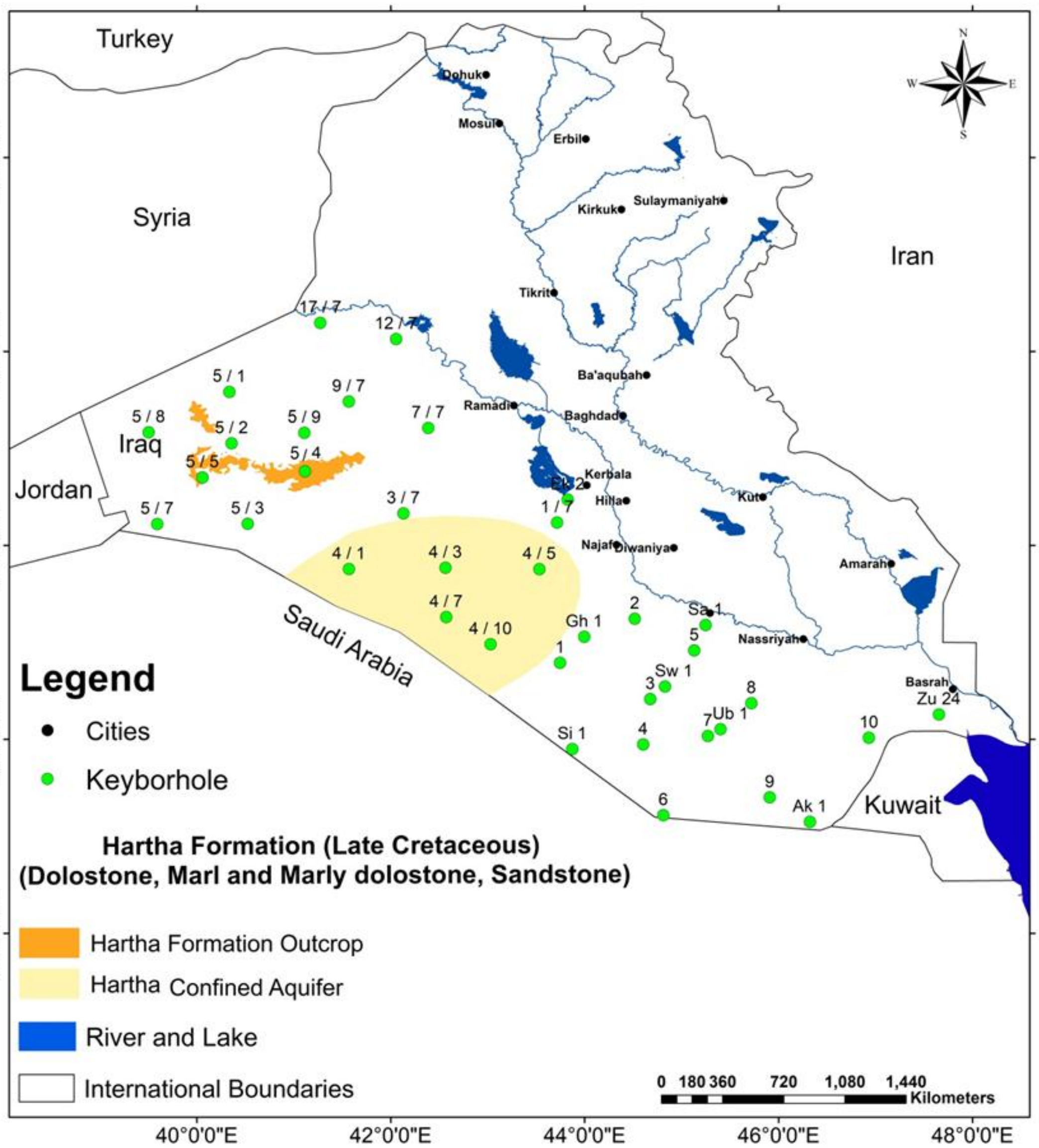

Figure (5-14):- Shows extension of Hartha Aquifer (after Al Jawad and Ridha, 2008).

This aquifer has relative thicknesses in different locations within the middle of the Iraqi desert, as shown in the table (5-6). Where it has a thickness equal to (426) m in a deep well (KH 4/3), (407 m) in a deep well (KH 4/10), and (394 m) in a deep well (KH 4/7) within Al- Maanya Hydrogeological Area, then the thickness decreases slightly towards the North and Northwest to reach (371m) in a deep well (KH 4/5) and (311m) in a deep well (KH 4/1) within Al-Razzaza and Al- Maanya Hydrogeological Areas, (Idrotechneco, 1977). The results of pumping tests that were carried out in these wells can be briefly described as follows:-

In the deep well (KH 4/1) that is located Westward Nukhab town within the Al-Razzaza Hydrogeological Area, the hydrogeological parameters of this aquifer indicate that the transmissivity was very high, well discharge was (785.3 m^3/day), and the static water level was (260.7 m) below ground surface. In contrast, the hydrochemical analysis of the water sample from this aquifer showed that the total dissolved solids (TDS) were (1500mg/l) with Chloridic water type (Idrotechneco, 1977).

The hydrogeologic parameters of this aquifer in a deep well (KH 4/3) that located Southeast of the deep well (KH 4/1) within the Al-Razzaza Hydrogeological Area showed that the transmissivity was (2 m^2/day), well discharge was (198.7 m^3/day), and static water level was (117.95 m) below ground surface. In comparison, the hydrochemical analysis of the water sample from this aquifer indicates that the total dissolved solids (TDS) were (4006 mg/l) with Sulphatic water type (Idrotechneco, 1977).

In deep well (KH 4/5) that located Southeast of the deep well (KH 4/1) within Al- Maanya Hydrogeological Area, the hydrogeologic parameters of this aquifer indicate that the transmissivity was (163.9 m2/day), well discharge was (803.5 m^3/day), and static water level was (39.5 m) below ground surface. At the same time, the hydrochemical analysis of the water sample from this aquifer showed that the total dissolved solids (TDS) were (4800 mg/l) with Sulphatic water type (Idrotechneco, 1977).

Table (5-6):- Penetration thicknesses in Hartha Formation (Idrotechneco, 1977).

Well No.	Penetration Depth (m)	Penetrated Thickness (m)	Type of penetration
KH 4/1	168 – 479	311	Fully
KH 4/3	260 – 686	426	Fully
KH 4/5	569 – 941	371	Fully
KH 4/7	262 – 656	394	Fully
KH 4/10	391 – 798	407	Fully

The hydrogeological parameters of this aquifer in a deep well (KH 4/7) that located South of the deep well (KH 4/1) within Al- Maanya Hydrogeological Area showed that the transmissivity was (181.4 m^2/day), well discharge was (164.7 m^3/day), and static water level was (205.1 m) below ground surface. In comparison, the hydrochemical analysis of the water sample from this aquifer indicates that the total dissolved solids (TDS) were (1800 mg/l) with Sulphatic water type (Idrotechneco, 1977).

In the deep well (KH 4/10) located Southeast of the deep well (KH 4/7) within Al- Maanya Hydrogeological Area, the hydrogeological parameters of this aquifer indicate that the transmissivity was (588 m^2/day), well discharge was (2032 m^3/day). The static water level was (117.7 m) below the ground surface. At the same time, the hydrochemical analysis of the water sample from this aquifer showed that the total dissolved solids (TDS) were (1868.8 mg/l) with Sulphatic water type.

The results generally showed variations in the transmissivity values due to variations in rocks and the area's geologic structure. For example, secondary porosity in rocks occurs due to fracture fissures in bed rocks and is more active in regions affected by main structural parameters (Al-Jiburi and Al-Basrawi, 2015). These results also show that the total dissolved solids (TDS) generally increase towards the South. Therefore, the best area to invest in this aquifer is near the well (KH 4/1) because it is located near recharge areas.

This Formation in the deepwater well (KH 7/1) located northeast well (KH 4/5) containing hydrocarbons and continues as an oil reservoir towards the South.

5-3-7 Tayarat Aquifer

Bellen *et al.* (1959) defined Tayarat Formation (Maastrichtian) in Jabal Tayarat, located about (36 Km) South of Rutbah town. It is widely exposed in the middle part of the Iraqi Western Desert and is composed of limestone, clayey limestone, marly dolomitic limestone, and dolostone. Sometimes consists of conglomerate and sandy siltstone are overlain by marl with chert nodules in the lower part (Buday and Hak, 1980). Tayarat Formation is considered one of the main and most important confined aquifers within large parts of the Desert Hydrogeological Region, as shown in figure (5-15). Al-Jiburi and Al-Basrawi (2015) consider Tayarat Formation as the most important aquifer within all Hydrogeological Areas of this Region, especially in Akashat and Rutbah areas within Al- Rutbah Hydrogeological area. At the same time, the hydrogeological studies of deep wells did not show any evidence that this Formation is an aquifer in these areas. It appeared as an aquifer only in the Eastern and Southwestern parts of the Western Desert and the West part of the Southern Desert, as shown in figure (5-15).

This aquifer was penetrated totally or partially by many deep wells in different locations within Desert Hydrogeological Region. The lithological sections of these wells showed that it is characterized by obscure subsurface extension, especially in the deep wells (KH 12/7, 7/7, and 3/7) because it is combined with other Formations. According to Consortium (1978), Idrotechneco (1977), and GEOSURV (1983), the hydrogeologic parameters of this aquifer in different locations can be briefly described as follows:-

The lithological sections of the deep well (KH 12/7) that located West of the Haditha town within the Al- Rutbah Hydrogeological Area show the thickness of the Tayarat Formation is (73 m) and appeared at depth (165m). The upper part of water-bearing strata for this Formation was tested at depth intervals (0 – 390 m) and the lower ones of the Umm Er Radhuma Formation. The hydrogeological parameters of this part indicate that the transmissivity was (4039 m^2/day), well discharge was (1296 m^3/day), and the static water level was (99 m) below the ground surface. In comparison, the hydrochemical analysis of the water sample from this part showed that the total dissolved solids (TDS) were (2528 mg/l) with Chloridic water type.

The hydrogeological parameters of this aquifer in a deep well (KH 7/7) that located West of the kilo 160 area within Al- Rutbah Hydrogeological Area showed that the transmissivity was (3607 m^2/day), well discharge was (2208 m^3/day). The static water level was (108.9 m) below the ground surface. In contrast, the hydrochemical analysis of the water sample from this aquifer indicates that the total dissolved solids (TDS) were (1914 mg/l) with Chloridic water type.

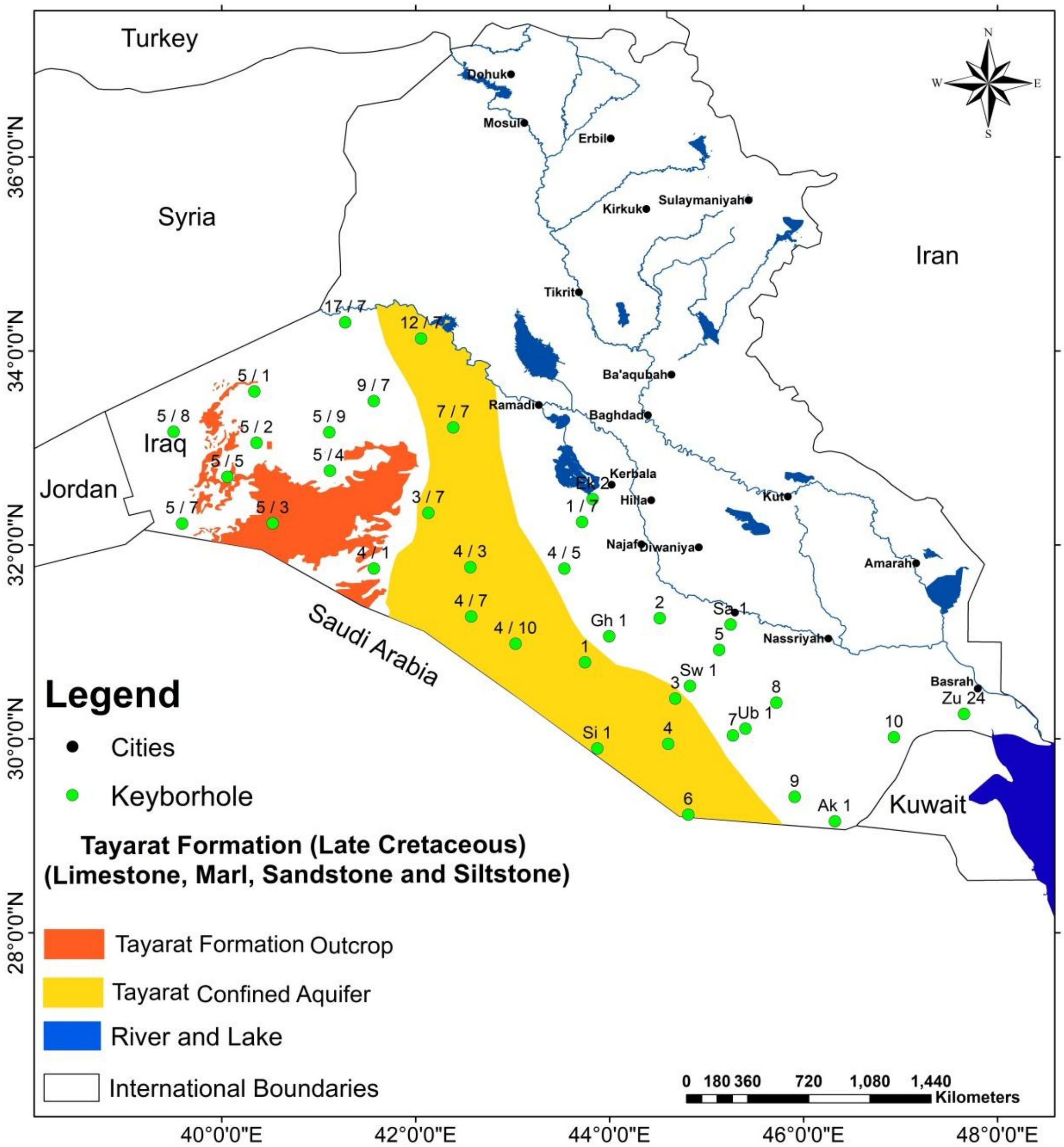

Figure (5-15):- Shows extension of Tayarat Aquifer (after Al Jawad and Ridha, 2008).

The hydrogeological parameters of this aquifer in a deep well (KH 3/7) that is located North of the Nukhaib area within the Al-Razzaza Hydrogeological Area showed that the transmissivity was (4070 m2/day), well discharge was (2200 m3/day). Therefore, the static water level was (150.6 m) below the ground surface. At the same time, the hydrochemical analysis of the water sample from this aquifer indicates that the total dissolved solids (TDS) were (2312 mg/l) with Chloridic water type.

The lithological sections of the deep well (KH 4/3) that are located South of the Nukhaib area within the Al-Razzaza Hydrogeological Area show the thickness of the Tayarat Formation is (146.5 m) and appeared at depth (15 m). The lower part water-bearing strata of this Formation were tested at depth intervals (127 – 311 m) and the upper ones of the Hartha Formation. The hydrogeological parameters of this part indicate that the transmissivity was (555 m^2/day), well discharge was (2469 m^3/day), and the static water level was (117 m) below the ground surface. In contrast, the hydrochemical analysis of the water sample from this part showed that the total dissolved solids (TDS) were (3407 mg/l) with Sulphatic water type.

The deep well (KH 4/5) that is located Southeast of the Nukhaib area within Al- Maanya Hydrogeological Area shows the thickness of the Tayarat Formation is (110 m) and appeared at depth (324 m). The lower part water-bearing strata were tested at depth intervals (424.5 – 426 m). The hydrogeological parameters of this part indicate that the transmissivity was (0.1 m^2/day), well discharge was (75 m^3/day), and the static water level was (137.2 m) below the ground surface. In comparison, the hydrochemical analysis of the water sample from this part showed that the total dissolved solids (TDS) were (4115 mg/l) with Sulphatic water type.

The lithological sections of a deep well (KH 4/7) that are located Southwest of the Nukhaib area within Al- Maanya Hydrogeological Area shows the thickness of the Tayarat Formation is (129.6 m) and appeared at depth (132.4 m). The upper part of the water-bearing strata was tested at depth intervals (88 – 203 m) and the lower part of the Umm Er Radhuma Formation. The hydrogeological parameters of this part indicate that the transmissivity was (293.7 m^2/day), well discharge was (959.04 m^3/day), and the static water level was (84.9 m) below ground surface. At the same time, the hydrochemical analysis of the water sample from this part showed that the total dissolved solids (TDS) were (3030 mg/l) with Sulphatic water type.

The deep well (KH 4/10) that located South of the Nukhaib area within Al- Maanya Hydrogeological Area shows the thickness of the Tayarat Formation is (150.9 m) and appears at depth (240.2 m). The upper part of the water-bearing strata was tested at depth intervals (101 – 370 m) and the lower part of the Dammam Formation. The hydrogeological parameters of this part indicate that the transmissivity was (3801.6 m^2/day), well discharge was (803.52 m^3/day), and the static water level was (103.2 m) below ground surface. In contrast, the hydrochemical analysis of the water sample from this part showed that the total dissolved solids (TDS) were (3522 mg/l) with Sulphatic water type. Also, in this well, the lower part of water-bearing layers of this Formation was tested at depth intervals (341.5 – 464 m) together with the upper ones of the Hartha Formation. The hydrogeological parameters of this part indicate that the transmissivity was (1209.6 m^2/day), well discharge was (1900.8 m^3/day), and the static water level was (103.2 m) below ground surface. In comparison, the hydrochemical analysis of the water sample from this part showed that the total dissolved solids (TDS) were (2960 mg/l) with Sulphatic water type.

It is noted from the above information that there are no accurate data about the Tayarat aquifer in the area between (KH 12/7 and KH 4/10) where the pumping tests conducted of this aquifer were together with other aquifers at the same time.

The lithological sections of a deep well (KH 3) located in the Shibcha area within Shabcha – Al-Salman Hydrogeological Area show the Tayarat Formation appeared at depth (397 m). The results of pumping tests of this aquifer indicate that the transmissivity was (0.5 m^2/day), well discharge was (86 m^3/day), and static water level was (-5.6 m) below ground surface. In comparison, the hydrochemical analysis of the water sample from this part showed that the total dissolved solids (TDS) were (2000 mg/l) with Sulphatic water type.

The deep well (KH 4) located within Takhade – Al-Busssaya Hydrogeological Area shows the total thickness were penetrated in this Formation is (225 m) at depth intervals (220 - 445 m). Furthermore, the results of pumping tests of this aquifer indicate that the transmissivity was (1883 m^2/day), well discharge was (700 m^3/day), and the static water level was (53.5 m) below ground surface. At the same time, the hydrochemical analysis of the water sample from this aquifer showed that the total dissolved solids (TDS) were (4040 mg/l) with Sulphatic water type.

The lithological sections of the deep well (KH 6) that are located in the Ansab area within Takhade – Al-Busssaya Hydrogeological Area shows the thickness of the Tayarat Formation is (253.1 m) and appeared at depth (270 m). The results of pumping tests of this aquifer indicate that the transmissivity was (77 m^2/day), well discharge was (691 m^3/day), and static water level was (69 m) below the ground surface. At the same time, the hydrochemical analysis of the water sample from this part showed that the total dissolved solids (TDS) were (1981 mg/l) with Sulphatic water type. The Tayarat Formation contains hydrocarbons and continues as an oil reservoir in the areas south Al-Razzaza Lake and Karbala – Najaf Plateau towards the South, except in the Salman vicinity according to the lithological sections of deep water well (KH 7/1) and oil wells (Mj-1, Mj-2, Kf-3, Wk-1and Zu- 24).

Some hydrogeological studies such as that conducted by Al-Jiburi and Al-Basrawi (2014) and Hussien (2018) show that Digma (Jeed) Formation (Maastrichtian) has been formed aquifer with Tayarat Formation only in the area located Northern and Northwestern parts of Al- Rutbah Hydrogeological Area along the Iraqi – Syrian borders. This aquifer is called the Tayarat-Jeed aquifer, as shown in figure (5-16). Both Formations in this area are composed mainly of limestone, dolomitic and chalky limestone and are characterized by water fractures (Al-Jiburi and Al-Basrawi 2014). The Tayarat-Jeed aquifer was penetrated totally or partially by many wells in different Al-Rutbah Hydrogeological Area locations. The lithological sections of these wells showed that a variable thickness characterizes it from one place to another, as shown in the table (5-7). The most significant thickness of this aquifer was (162.6 m) in well (BH 1), which is located in the Northwest Akashat area near Iraqi – Syrian borders. In comparison, its lowest thickness was (38 m) in the well (BH 11) located near the Akashat area (GEOSURV, 1976 in Al-Jiburi and Al-Basrawi, 2014). The hydrogeological parameters of this aquifer show that the transmissivity coefficient ranges between (2.2 – 120 m2/day), discharge of wells varies between (33 – 272 m^3/day) and static water level ranges between (42.3 – 232.7 m) below the ground surface. The total dissolved solids range between (485 – 2000 mg/l) with water quality of bicarbonate and sulphatic water (Al-Jiburi and Al-Basrawi, 2007).

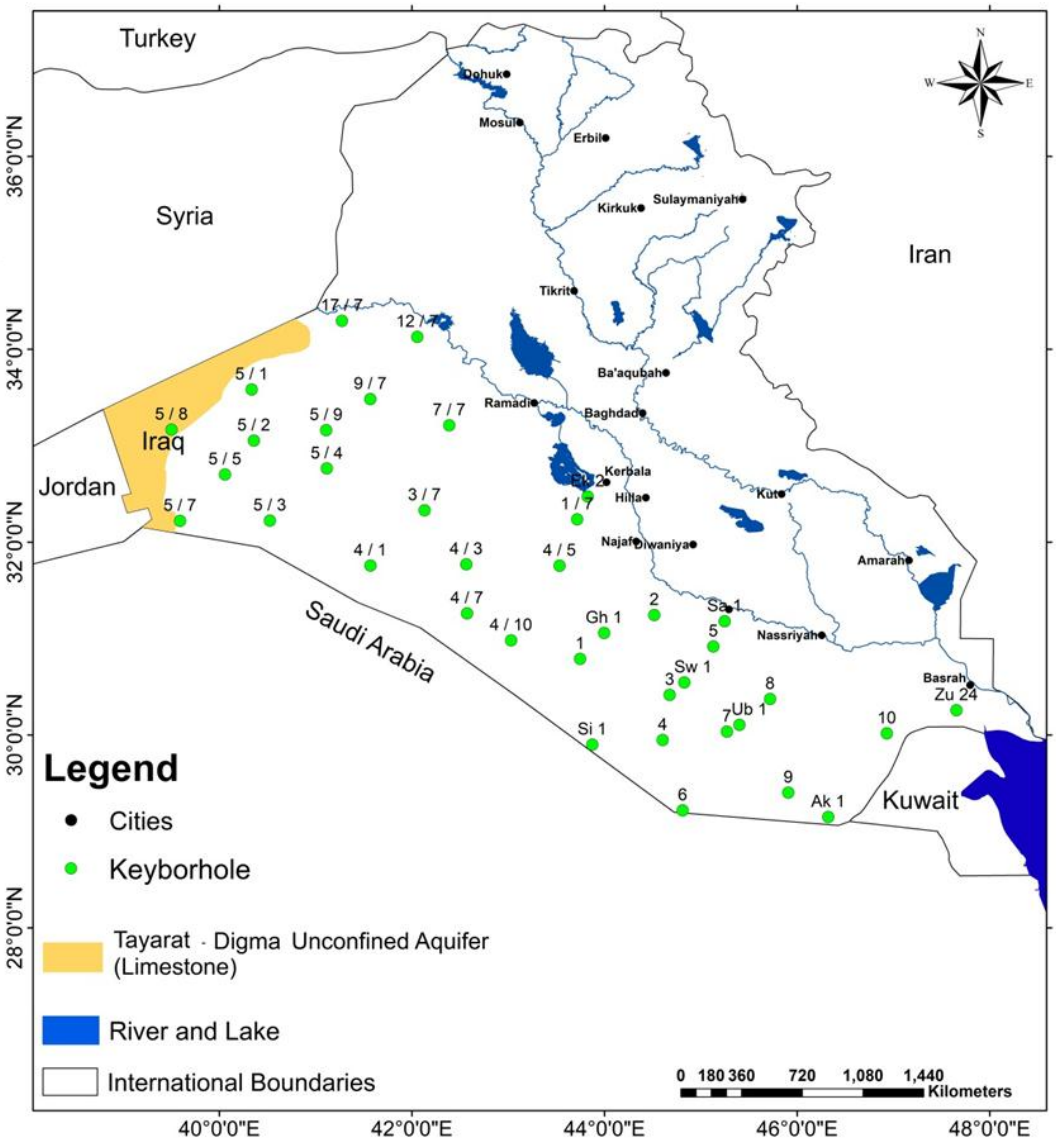

Figure (5-16):- Shows extension of Tayarat -Jeed Aquifer (modified from Hussien, 2018).

Table (5-7):- Penetration thicknesses in Tayarat-Jeed aquifer (Al-Jiburi and Al-Basrawi, 2014).

Well No.	Penetration Depth (m)	Penetrated Thickness (m)	Type of penetration
KH 5/8	176.6 – 265.5	88.9	Partial
BH 1	113 – 275.6	162.6	Fully
BH 2	0 – 80	80	Fully
BH 3	16.5 – 57.5	41	Fully
BH 5	162.5 – 325	162	Fully
BH 6	96.5 – 229.5	160	Fully
BH 7	74 – 155.6	81.6	Partial
BH 10	91 – 197	106	Partial
BH 11	112 – 150	38	Partial
BH 12	42 – 131.3	89.3	Partial
BH 13	546 – 679	133	Partial
BH 15	182 – 333	151	Fully
BH 16	330 – 491	161	Fully

5-3-8 Akashat Aquifer

The Akashat Formation (Middle-Late Paleocene) was previously considered Umm Er Radhuma Formation and was recently added to the stratigraphic column of Iraq by Jassim et al. (1984). However, according to Sissakian and Mohammed (2007), since 1990, the name of Akashat Formation was used instead of Umm Er Radhuma Formation by GEOSURV in the area located in the northwestern part of the Iraqi Western Desert. This Formation is composed mainly of alternation of phosphatic limestone, phosphorite, and phosphatic conglomerate or breccia (Al-Bassam et al., 1990).

The lithological sections of wells that penetrated totally or partially this Formation show a minimal extension of it, and it represents the aquifer in a small area located in the northwestern part of the Al- Rutbah Hydrogeological Area along the Iraqi – Syrian borders, as shown in the figure (5-17).

The available data about this aquifer were obtained only from Al-Jiburi and Al-Basrawi (2014). These data showed that it is characterized by a variable thickness from one location to another, as shown in the table (5-8). The most significant thickness of this aquifer was (95.5 m) in well (BH 5) that is located Southwest of the muger Al-Deeb area, while its lowest thickness was (4.5 m) in the well (BH 3) that located Southwest Akashat mine. The pumping test results showed that a low discharge characterizes this aquifer. In general, these results reflect that the transmissivity coefficient ranges between (2 – 620 m^2/day), well discharge ranges between (53 – 475 m^3/day) and static water level ranges between (26.6 – 69.7 m) below ground surface. At the same time, the hydrochemical analysis of the water samples from this aquifer showed that the total dissolved solids (TDS) range between (179 – 1072 mg/l), and main bicarbonate with the presence of chloridic water type (Al-Jiburi and Al-Basrawi, 2014). Despite the low discharge of this aquifer, it has freshwater due to direct recharge from rainfall and surface runoff in valleys.

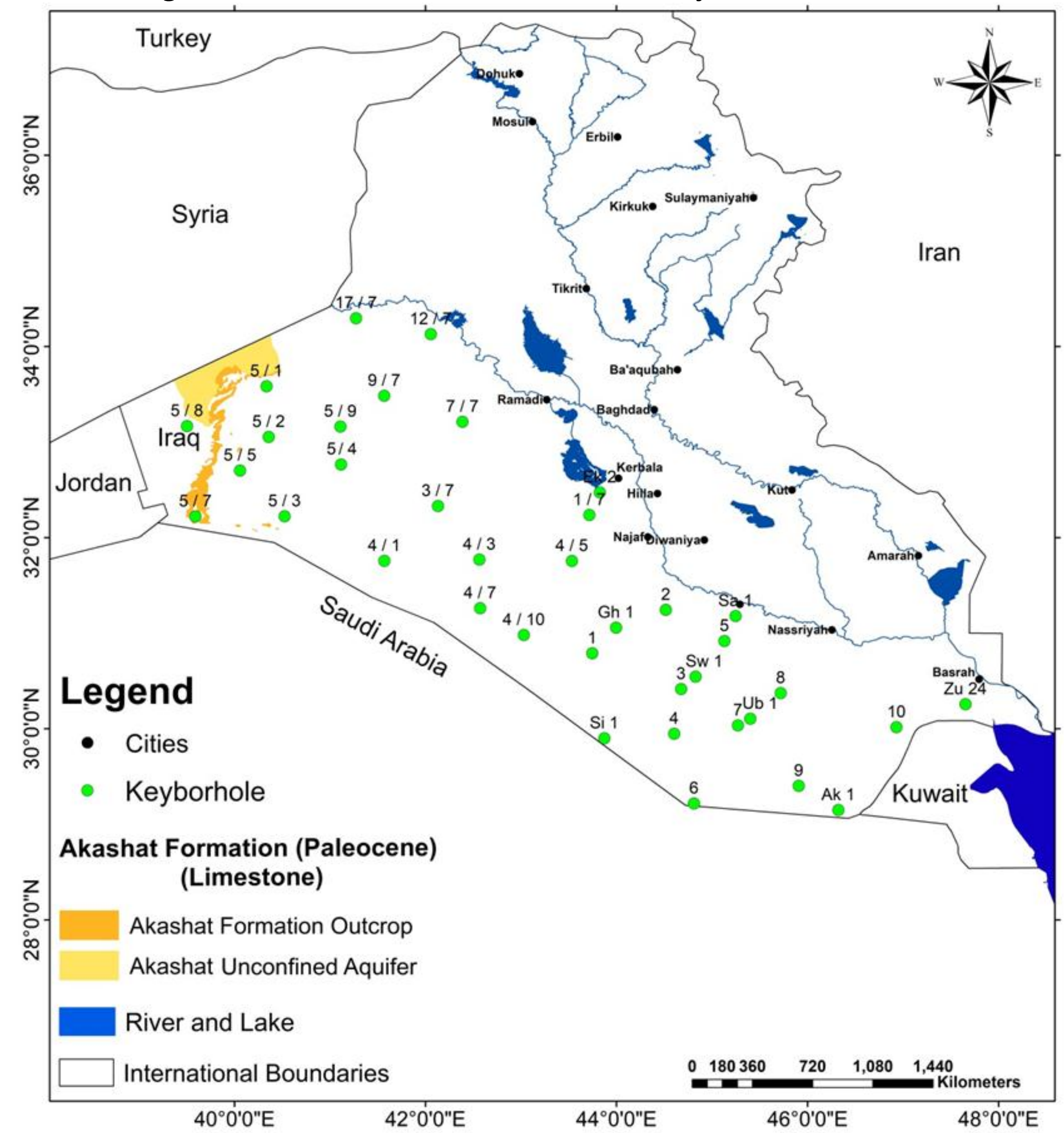

Figure (5-17):- Shows extension of Akashat Aquifer.

Table (5-8):- Penetration thicknesses in Akashat Formation (Al-Jiburi and Al-Basrawi, 2014).

Well No.	Penetration Depth (m)	Penetrated Thickness (m)	Type of penetration
BH 1	48 – 113	65	Fully
BH 3	12 – 16.5	4.5	Fully
BH 5	67 – 162.5	95	Fully
BH 6	7.5 – 69.5	62	Fully
BH 7	40 – 74	34	Fully
BH 9	30.5 – 80	49.5	Partial
BH 10	41 – 91	50	Fully
BH 11	41 – 112	71	Fully
BH 12	23 – 66.5	43.5	Fully
BH 13	5 – 42	27	Fully
BH 14	28 – 83.5	55.5	Partial
BH 15	114 – 182	67	Fully
BH 16	246 – 330	84	Fully

5-3-9 Umm Er Radhuma Aquifer

Umm Er Radhuma Formation (Middle-Late Paleocene) was first described in the Umm Er Radhuma oil well in Saudi Arabia. In Iraq, it was first described in south Iraq within Zubair oil well three by Owen and Nasr (1958). Then a surface type section was determined by Jassim et al. (1984) in the Nukhaib area in the Western Desert according to Sissakian and Mohammed (2007). This Formation is exposed as a belt parallel the Iraqi – Saudi Arabia borders in Western and Southwestern parts of the Iraqi Desert (Al Barit to Ansab vicinities) (Al-Mubarak and Amin, 1983). It is composed mainly of dolomitic limestone and dolomite with thin beds of anhydrite (Sissakian and Mohammed, 2007). This Formation is considered one of the main essential aquifers within all Hydrogeological Areas in the Desert Hydrogeological Region because it is characterized by fractures, fissures, and cavities with high and good water content. It represents confined and unconfined aquifers in most parts of the Desert (Al-Jiburi and Al-Basrawi 2007), as shown in figure (5-18).

The confined aquifer is located in the Eastern and the Northeastern parts of the Western Desert and most parts of the Southern desert and covers an area of (60,068 km2). In contrast, the unconfined aquifer located in the West of the Northeastern Western Desert and the West and

Southwestern parts of the Southern Desert Hydrogeological Region near the Iraqi-Saudi Arabia borders and covers an area of (91,766) km2) (Al-Fatlawi, 2011).

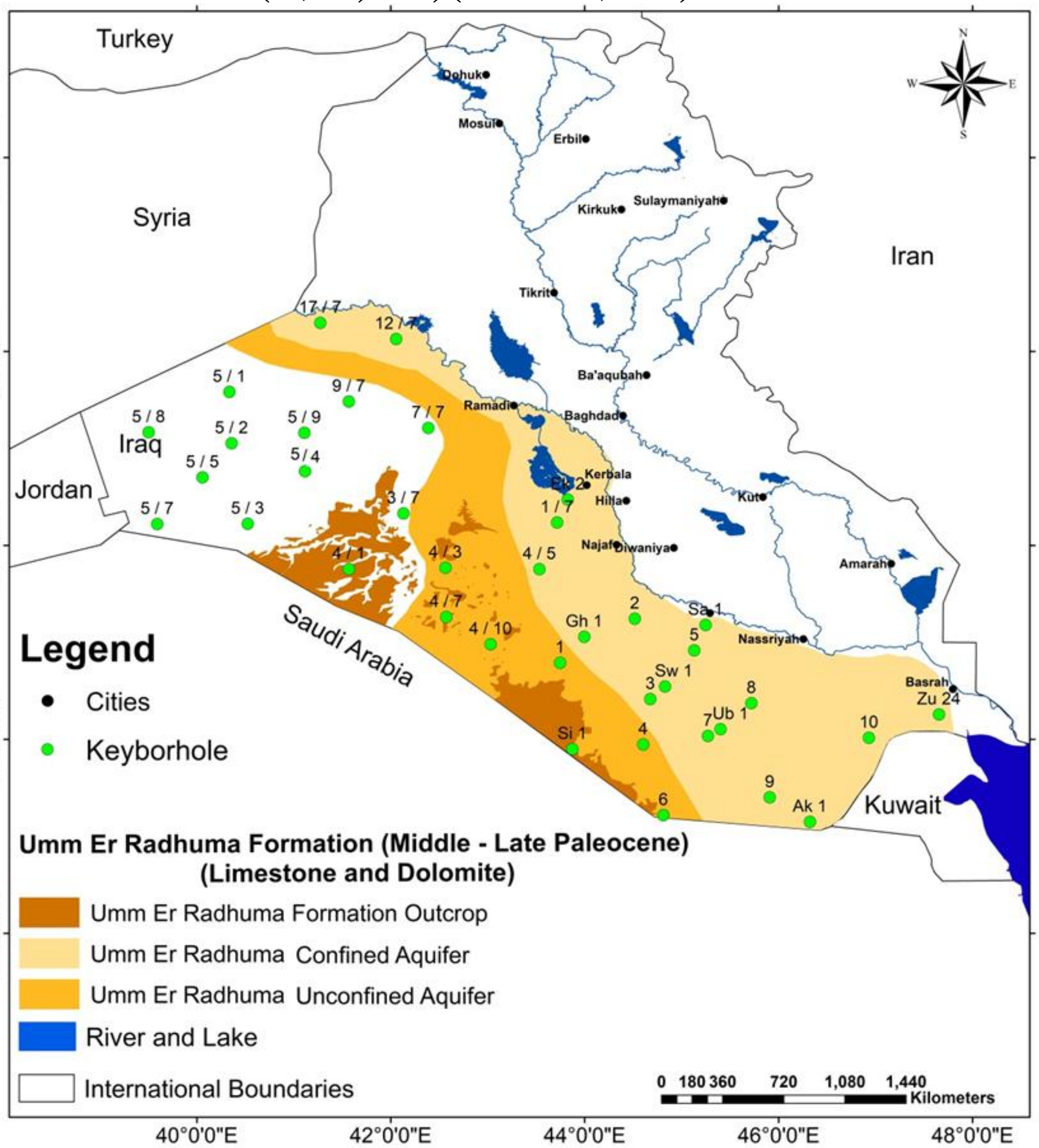

Figure (5-17):- Extension of Umm Er Radhuma Aquifer (after Al Jawad and Ridha, 2008).

Umm Er Radhuma aquifer represents a complex hydrogeological system with other aquifers within other geological Formations, such as Tayarat and Dammam Formations. However, the recharge area of this aquifer extends widely inside and outside the Iraqi borders within Saudi Arabia that a good source of recharge (Al-Jiburi and Al-Basrawi, 2009).

This Formation was penetrated totally or partially by many deep wells in different locations of the Desert Hydrogeological Region. The lithological sections of these wells showed that a variable thickness characterizes it from one place to another. The most significant thickness of this Formation was (500m) in the Southern Desert around Salman area and the South-East of the Southern Desert Within Shabcha – Al- Salman and Takhade – Al-Busssaya Hydrogeological Areas, then this thickness decreases towards the Western Desert to less than (50 m) in the area located

North of Al Razzaza Lake and South of Al Qadisiyah reservoir within Al-Razzaza Hydrogeological Area, (Al-Fatlawi, 2011).

The thickness map mapped by Al-Fatlawi, (2011) shows that the Euphrates River marks the end of the normal boundary of the Formation to the East, where it becomes deeper under the river bed towards the Mesopotamian plain. It also shows the disappearing areas around Rutbah uplift and toward the Iraqi- Jordanian –Saudi Arabia borders.

The areas around the Rutbah uplift in the Northeast, East, and Southeast represent the boundary of the unconfined aquifer and the outcrops areas of the Formation inside Iraq and Iraqi – Saudi Arabia borders in Western and Southwestern parts of the Desert Hydrogeological Region. Umm Er Radhuma unconfined aquifer transform into a confined aquifer when extension toward Eastwards the Euphrates river in the Northern Desert in Husaybah, Ana, Heet, Bahr Al-Najaf reaching to South Al-Ansab area in the Southern parts of the Desert Hydrogeological Region. The extension area of the unconfined aquifer and the exposed surface of this Formation represent all the aquifer's recharge areas. According to Al Jawad et al. (2001) (Al-Fatlawi, 2011), the unconfined aquifer has saturated thickness ranges between (50 m) in the West of the Southern Desert near the international borders within Takhade – Al-Busssaya and Safwan – Al-Rukhema Hydrogeological Areas to (213 m) in the East where the unconfined aquifer becomes confined.

Two recharge methods characterize the umm Er Radhuma aquifer. The first one is represented by Rainfall, which considers an essential source of groundwater recharge. The rain water cause floods in valleys and depressions. Then, the parts from it infiltrate downward through the Formation outcrops. The second is occurrences by the subsurface water flow that coming through the aquifer from Saudi Arabia then entering the Desert Hydrogeological Region from the South, the South-West, and the West through faults and subsurface channels. The discharge areas of the Umm Er Radhuma aquifer are the springs located along Abu Jir fault zone or underground flow into Mesopotamian Plain sediments. Locally, deviations from the main groundwater direction may occur due to the area's geological, structural, and topographic nature, affecting groundwater movement (Al-Fatlawi, 2011).

The regional trend of groundwater movement in the Umm Er Radhuma aquifer can be divided into two types. The first type is located in the Al- Rutbah and Al-Razzaza Hydrogeological Areas. The groundwater movement flows towards the East and the Northeast in these areas. But, locally, the groundwater flow takes different directions throughout the site based on geological, topographic, and structural features (Al Jiburi and Al Basrawi, 2007). The second type of groundwater movement within the Umm Er Radhuma aquifer occurs in the Al- Maanya, Shabcha – Al- Salman, Takhade – Al-Busssaya, and Safwan – Al-Rukhema Hydrogeological Areas. In these areas, the groundwater flows from the Southwest to the Northeast and Southeast, towards the discharge areas along Euphrates River, Hor Al-Hammar and Shatt Al- Arab (Al-Jiburi and Al-Basrawi, 2009).

Al-Fatlawi, (2011) indicated the presence of a vertical movement of groundwater within the Umm Er Radhuma aquifer upward to the Dammam aquifer. The vertical movement of groundwater has represented the leakage of water from Umm ER- Radhuma aquifer to the Dammam aquifer that lies above it. The vertical leakage between the two aquifers is attributed to the hydrostatic pressure difference that arises between them, where the pressure of the Umm ER- Radhuma aquifer is higher than that of the Dammam aquifer and leads to the upward water leakage as a result of natural and artificial discharging from the upper aquifer. The artificial discharging due to pumping plays a significant role in determining the direction and velocity of groundwater flow (Al-Jawad et al.,2001; AL-Azawi, 2009). Al-Zubedi and Thabit (2014) confirmed the hydraulic connection between Umm ER- Radhuma and Dammam aquifers depending on 2D Resistivity Imaging Technique in the area located within Abu-Jir fault zone South of Al- Razazza Lake, South- West of Karbala city where it appeared that the hydraulic connection between these aquifers led to the similarity between the resistivity values of Dammam and Umm Er Radhuma layers.

According to Consortium (1978), Idrotechneco (1977), and GEOSURV (1983), the hydrogeological parameters of this aquifer in different locations can be briefly described as follows:-

1- The results of pumping tests that carried out in water wells in the Al- Rutbah and Al-Razzaza Hydrogeological Areas showed that the transmissivity coefficient ranges between (2 – 1550 m^2/day), Hydraulic conductivity ranges between (0.1 – 21.1 m/day), discharge of wells varies between (2 – 3960 m^3/day) and static water level goes from artesian to (170.3m) below the ground surface. The total dissolved solids range between (278 – 6640 mg/l) with water quality of Chloridic, bicarbonate, and sulphatic water (Al-Jiburi and Al-Basrawi, 2007).

2- The results of pumping tests that carried out in water wells in the Al- Maanya, Shabcha – Al-Salman, Takhade – Al-Busssaya and Safwan – Al-Rukhema Hydrogeological Areas showed that the transmissivity coefficient ranges between (3 – 2100 m^2/day), Hydraulic conductivity ranges between (0.1 – 21.1 m/day), discharge of wells varies between (33 – 3266 m^3/day) and static water level ranges between (6.6 -142.7 m) below the ground surface. The total dissolved solids vary between (167 – 4500 mg/l) with predominant sulphatic water quality and chloridic and some bicarbonates water types (Al-Jiburi and Al-Basrawi, 2009).

Al-Fatlawi (2011) indicated that the variations in the transmissivity values reflect a highly heterogeneous aquifer due to the variations in the density of fractures and the porosity of rocks within the Umm Er Radhuma aquifer. Therefore, it is also recommended that the best quality of water in the Umm Er Radhuma aquifer is located in the Al- Rutbah and Al-Razzaza Hydrogeological Areas, where it is recharged from wadi Horan and others wadis. Groundwater TDS value ranges between (1000 – 2000 mg/l), increasing in the flow direction toward the East and the Southeast until attaining a value around (5000 mg/l). Therefore, the aquifer has to be well managed and protected from contamination.

5-3-10 Dammam Aquifer

Dammam Formation (Early – Late Eocene) was first described in Saudi Arabia on the Dammam Dome. In Iraq, Owen and Nasr (1958) were described the type section of this Formation in oil well Zubair 3 (Jassim and Buday, 2006 in Jassim and Goff, 2006). It is widely exposed in the Southern Desert and some parts of the Western Desert, as shown in figure (5-19). In the northwestern parts of the Western Desert near the Iraqi-Syrian and the Iraqi-Jordanian borders, the Ratga Formation is exposed, equivalent to the Dammam Formation. The Ratga Formation does not contain water because it is located above the regional groundwater level in the exposed area (Al-Jiburi and Al-Basrawi, 2007). However, the Dammam Formation mainly composes limestone and dolomitic limestone with marl and chert. In the Southern Desert, this Formation has been subdivided into three lower, middle, and upper members by Al-Mubarak and Amin (1983). Also, each member was subdivided into different units. The lower member called the Jil Formation. Tamar-Agha (1982) first introduced this member under the name Salman Formation then Al-Mubarak and Amin (1983) introduced it under the name Jil Member. Finally, Jassim et al. (1984) suggested using the Jil Formation. According to Tamar-Agha (2016), Jil Formation was considered the lower member of the Dammam Formation.

The Dammam Formation is considered one of the most important aquifers in the Desert Hydrogeological Region. It is characterized by wide extension and secondary porosity, associated with fissures that control the aquifer storage properties (Krasny *et al*., 2006 in Jassim and Goff, 2006). Field views show the limestone of the Dammam Formation near the surface are weathered, fractured, and karstified, enhancing permeability. This aquifer is the most invested in the Southern Al-Razzaza Hydrogeological Area and the Al- Maanya, Shabcha – Al- Salman, Takhade – Al-Busssaya Hydrogeological Areas due to it is located near the earth's surface with a good and high content of groundwater. There are two types of this aquifer within this Formation, confined and unconfined aquifers, as shown in figure (5-19).

This aquifer is a part of a complex hydrogeological unit with Umm Er Radhuma aquifer, on a regional scale, with hydraulic connections between them and similar water quantity and water salinity (Consortium, 1978; Al-Jiburi and Al – Bassrawi, 2007). The results of hydrochemical analysis of groundwater samples of the Dammam aquifer show that most water samples have an odor of (H2S) gas, especially in the areas located in the Southern parts of the Western Desert and the Northern parts of the Southern Desert due to dissolution processes of anhydrite rocks within the Umm Er Radhuma Formation. This is a significant indication of the hydraulic connection between Umm Er Radhuma and Dammam aquifers.

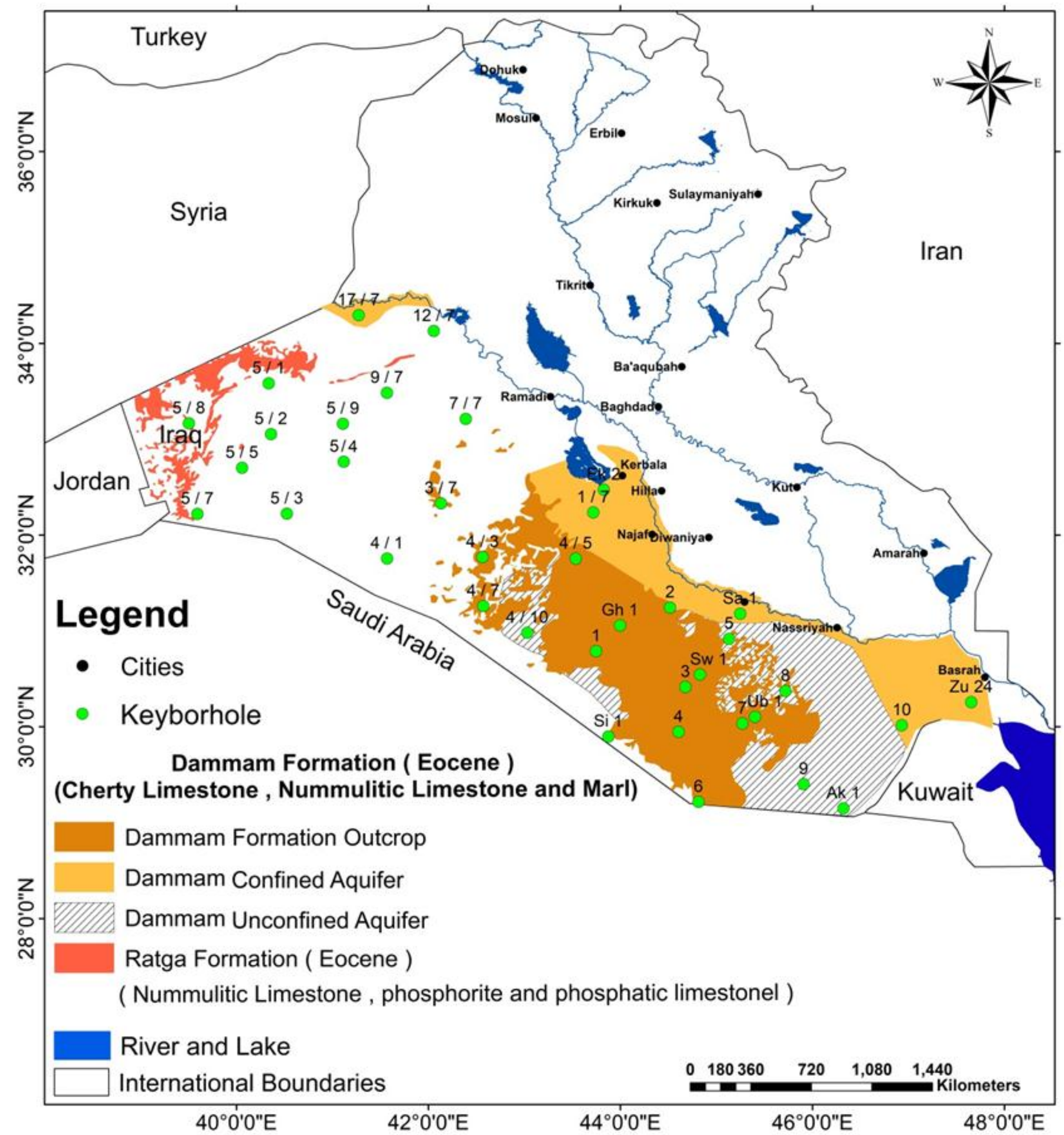

Figure (5-18):- Extension of Dammam Aquifer, (after Al Jawad and Ridha, 2008).

The Abu Jir fault zone is evident in groundwater movement and recharges in these areas, specifically for the Dammam aquifer. Therefore, two types of groundwater movement are observed in this area. The first is horizontal from Southwest to the Northeast towards the Euphrates River, which is identical with the general orientation in the space. The second is a vertical movement of groundwater that represents the leakage of water from Um Erdhuma Aquifer that underlies the Dammam aquifer.

In the far northwestern part of the Iraqi Desert and along the Euphrates River within Al- Rutbah Hydrogeological Area, the Dammam Formation is characterized by a variable thickness from one location to another that ranges between (85 -298m) according to lithological sections of a deep water well (KH 17/7) and oil wells in Akkas filed. In the deepwater well (KH 17/7), the Dammam Formation appeared at depth (178m) and represented a confined aquifer. The results of pumping tests that were carried out in these water wells showed the transmissivity coefficient (1556 m^2/day), discharge of wells (1987 m^3/day), and static water level (105.37 m) below the ground surface (Consortium, 1978).

In the area located West Al-Razzaza Lake between Al- Rahalyah and Shithatha vicinities within Al-Razzaza Hydrogeological Area, the Dammam aquifer is confined and has a variable thickness ranges between (50 -100m. The results of the pumping test that carried out in water wells in these areas showed that the transmissivity coefficient ranges between (20.115 - 600.25 m^2/day), Hydraulic conductivity ranges between (0.67 – 19.96 m/day), discharge of wells varies between (130 – 1980 m^3/day) and static water level goes from artesian to (21 m) below the ground surface. The total dissolved solids range between (1000 and 1806.4 mg/l) with the main Sulphatic water type. The general direction of groundwater movement in this Hydrogeological Area is from West to East towards Al-Razzaza Lake, representing the discharge area (Al-Jiburi and Al-Basrawi, 2007; Al-Shamari, 2014). Their many springs are distributed in the Shithatha vicinity that represents a discharge area of the Dammam aquifer and Al-Razzaza Lake. Recently, the groundwater level in these springs has decreased because of the over-investment of groundwater in this aquifer and climatic changes characterized by long periods of drought.

In the Karbala – Najaf Plateau area within Al-Razzaza and Al- Maanya Hydrogeological Areas, the lithological sections of wells drilled by the General Commission of Ground water (G.C.W.G) shown the Dammam Formation located at depths ranges between (180 – 220 m) with variable thickness ranges between (198- 210 m), (Al-Ghanimy, 2013; G.C.W.G, 2021). The hydrogeological parameters of this aquifer showed that the transmissivity ranges between (31.37 - 2480 m^2/day), Hydraulic conductivity ranges between (0.7 -27.56 m/day); well discharge ranges between (691 – 1900 m^3/day) and static water level ranges between (15 – 25.4 m) below ground surface. The hydrochemical analysis results indicate that the total dissolved solids (TDS) range from (1834 – 3218 mg/l), with Sulphatic water types.

Many wells that drilled in the Karbala Plateau without use booking by cement showed pollution with bitumen materials at depths of (70 m and 120 m) within the Fatha (lower Fars) Formation that is located above Dammam Formation (Al-Ghanimy, 2013; G.C.W.G, 2021). Therefore, to overcome the danger of pollution by bitumen materials in this area must be used modern drilling equipment and booking contaminated layers with cement. However, this pollution does not appear in the Najaf plateau, maybe due to the Rhaimawi – Hilla fault representing a hydrogeological boundary, which prevents the rise and transfer of the bitumen materials to this area.

In the area between Al- Maanya and Bahr Al-Najaf to Tar Al-Najaf areas within Al- Maanya Hydrogeological Area, the Dammam Formation is characterized by a variable thickness from one location to another, from (50m) to more than (150m). Many springs in the Bahr Al-Najaf area represent the discharge regions of aquifers, such as Al-Rehameah, Al-Assaweed, Al- Rohbaan, and Madhloom. The results of the pumping test that carried out in water wells showed that the transmissivity coefficient ranges between (63.3 - 841 m^2/day), Hydraulic conductivity ranges between (7.3 – 15.6 m/day), discharge of wells varies between (432 – 777.4 m^3/day) and static water level ranges from artesian to (24 m) below the ground surface. The total dissolved solids vary between (1750 – 2514 mg/l) with the main Sulphatic water type (Al-Jiburi and Al-Basrawi, 2007). The general direction of groundwater movement in this area is from West to East towards Bahr Al-Najaf, representing Al- Maanya Hydrogeological Area (Al-Jawad et al., 2001; AL-Azawi, 2009).

The Dammam Formation in most parts of Shabch - Al- Salman Hydrogeological Area is an unconfined aquifer and changes to confine in the Eastern part of this area as a narrow belt parallel to the Euphrates River, as shown in figure (5-19). The lithological sections of wells that penetrated the Dammam Formation totally in this Hydrogeological Area showed that it is characterized by a variable thickness from one location to another. The average thickness of the Dammam aquifer around the Shabch vicinity is ranged between (110 - 120m). In the area near the oil well Gh 1 East the Shabch vicinity, the Dammam Formation has a thickness equal to (130m), but it is dry according to hydrogeological repots of G.C.W.G, (2021). This Formation in the Al- Salman area has thickness ranges between (140-160m) then it increases towards the Al-Rehab area, Southeast of the Samawa city to reach more than (180 m). In this Hydrogeological Area, the Dammam aquifer can be invested by drilling wells with depths ranging between (50 - 200 m). In the Al-Shanafiya area located in Southwest Diwaniya province, the Dammam aquifer is represented as the main aquifer in this area. The available data of these wells indicated two types of aquifers, upper and lower aquifers. The upper aquifer in this Formation is unconfined and located at depths between (30-50m). The lower aquifer is confined and found at depths more than (55m).

The results of the pumping test that carried out in water wells within this Hydrogeological Area showed that the transmissivity coefficient ranges between (60.9 - 2158.4m^2/day), Hydraulic conductivity ranges between (0.761 – 2.53 m/day), discharge of wells ranges between (457– 3219 m^3/day) and static water level varies from artesian to (30 m) below the ground surface. The total dissolved solids range between (1827 and 3219 mg/l) with the main Sulphatic water type. The general direction of groundwater movement in this area is from West to Northeast and east, representing the discharge area (Al-Jawad et al., 2001; ALi, 2021). Many springs represent the discharge zones of aquifers in this area, such as AL –Kathary and AL-Emaed, and Sawa Lake. The water levels in these springs and Sawa Lake are below the ground surface level due to the oppressive use of groundwater through the wells.

In the area between Takhadeed and Bussaya vicinities in the Takhadeed – Bussaya Hydrogeological Area, the Dammam Formation has thickness ranged from (130m) Takhadeed area to (190 m) in the Bussaya area. The results of the pumping test that carried out in water wells within this area showed that the transmissivity coefficient ranges between (55.7 - 2041.4 m^2/day), Hydraulic conductivity ranges between (2.2– 3.53 m/day), discharge of wells varies between (345– 6542m^3/day) and static water level ranges from artesian to (170 m) below the ground surface. The total dissolved solids go-between (2568– 3569 mg/l) with the main Sulphatic water type. The general direction of groundwater movement in this area is from West to Southeast, representing the discharge area (Al-Jawad et al., 2001; ALi, 2021).

In the Safwan – Al-Rukhema Hydrogeological Area between Bussaya and Zubair vicinities, the Dammam aquifer is deep and untapped, so we do not have any accurate data about it in this area.

The regional trend of groundwater movement within the Dammam aquifer in the Desert Hydrogeological Region is generally towards the East and the Northeast along the Euphrates River, but, locally, groundwater flow takes different directions throughout the region depending on geological, topographic, and structural features, (Al Jiburi and Al Basrawi, 2007 and 2009).

5-3-11 Euphrates Aquifer

The type locality of the Euphrates Formation (Early Miocene) is along wadi Fhaimi in the Anah vicinity (Bellen *et al*., 1959). Haditha Dam Lake submerges this type of section. So, Jassim et al. (1984) chose another location in wadi Chab'bab for the lower and upper units (A and B) and another supplementary type section in Wadi Rabi for the upper unit (C) in Anah vicinity. However, it is widely exposed as a belt-shaped parallel to the Euphrates River from the Iraqi – Syrian borders near Al-Qaim. It extends toward Anah, Haditha, Heet, and Shithathta vicinities. Then it appears in cut valleys in some Southern parts of the Western Desert, such as Thumail and Ghadaf, and some small valleys in South Razzaza Lake (Sissakian and Mohammed, 2007). The Southern Desert crops out in different parts, such as East of Al-Rabh, West of Al-Rahb, and Al-Salman vicinities. In the area between Al-Rahb and Al-Busaiya vicinities, this Formation is interfingering with the Ghar Formation to form a Stratigraphic unit known as the Euphrates – Ghar Formation (Sissakian and Mohammed, 2007).

This Formation consists mainly of gravels conglomerate followed by layers of limestone that contains fossils in the lower unit. Finally, it consists of a sequence of chalky limestone, breccia, dolomite with horizontal lenses and layers of green shell in the upper unit (Jassim *et al*., 1984).

The Euphrates Formation is considered as upper aquifer only within Al- Rutbah and Al-Razzaza Hydrogeological Areas in the area located along Euphrates River between Al-Qaim vicinity and Razzaza Lake with two types of aquifers confined and unconfined, as shown in figure (5-20).

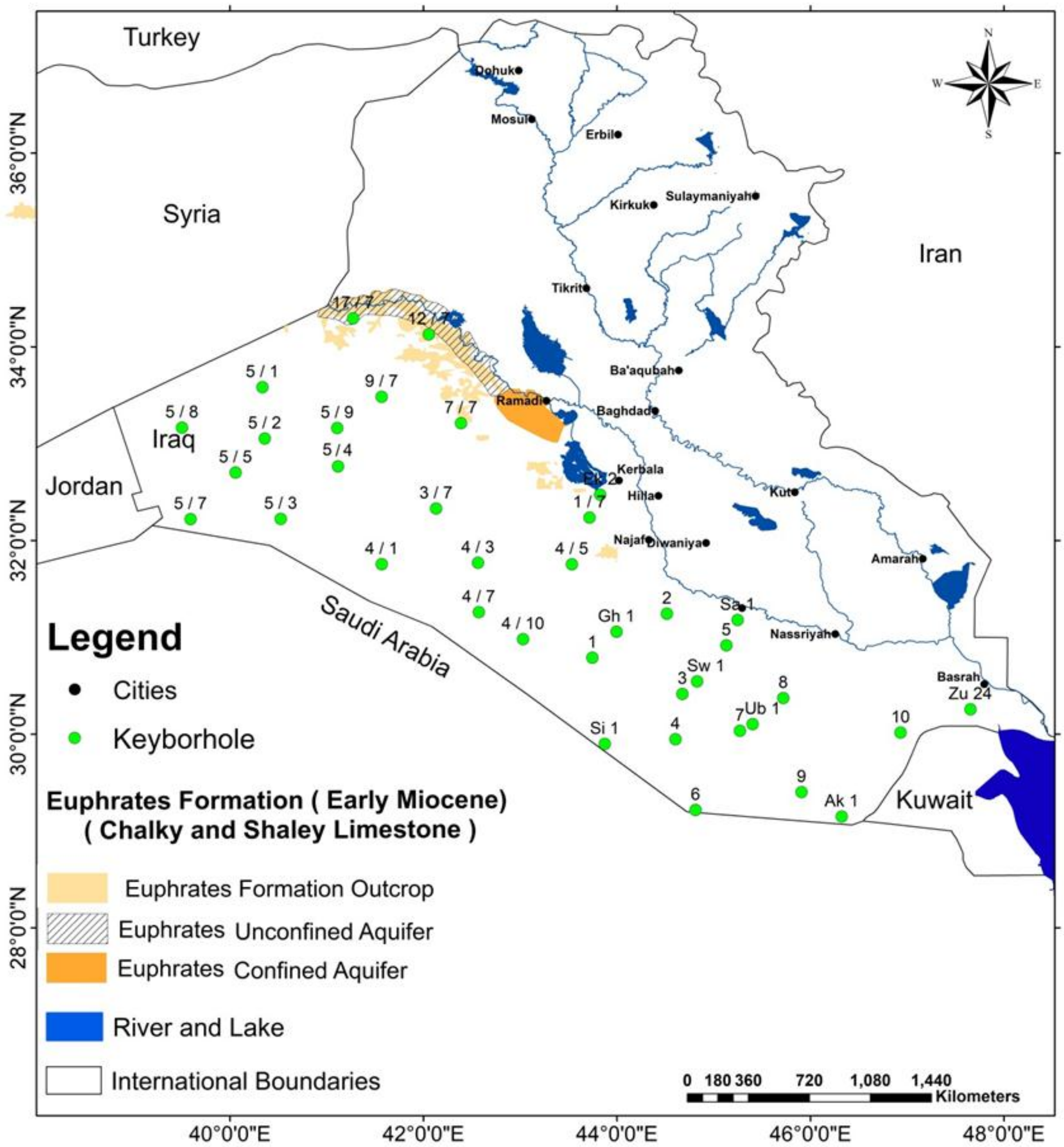

Figure (5-20):- Extension of Euphrates Aquifer (after Al Jawad and Ridha, 2008).

The confined aquifer extends from North Al-Razzaza Lake to South Kubisah vicinity within Al-Razzaza Hydrogeological Area. It extends as an unconfined aquifer until the Iraqi – Syrian borders near Al-Qaim vicinity within Al- Rutbah Hydrogeological Area. These areas are represented as discharge zones of groundwater aquifers (Al-Jiburi and Al-Basrawi, 2007). According to Krasny *et al*., 2006 in Jassim and Goff (2006), many springs along Abu Jir Fault have large yields such as Haqlan, Hit, Shithatha, and Imam Ahmad Bin Hashim within this Formation. The rainwater infiltrates into caverns, fractures, flows towards the Euphrates River, assembles in the Euphrates Formation, and then flows from springs. Some of these springs have high salinity and are polluted or carry hydrocarbons because their water comes from great depths. However, the Haqlan springs are originated in basal the conglomerate of the Euphrates Formation and have a total discharge reach to (600 l/sec) with water that has H2S odor. The Shithatha springs have discharge is about (1000 l/sec), and the biggest of Shithatha springs is Ain Kabeera, which have a discharge of about (150 1/sec) (Krasny, *et al*., 2006 in Jassim and Goff, 2006).

In general, the depth of water wells drilled in this aquifer is (50-100 m). The results of the pumping test that carried out in these wells showed that the transmissivity coefficient ranges between (3 – 1750 m^2/day), Hydraulic conductivity ranges between (0.2 – 29.5 m/day), discharge of wells varies between (43 – 6600 m^3/day) and static water level ranges from artesian to (64 m) below the ground surface. The water wells that drilled along the fault zone overflow with big discharges. The total dissolved solids range between (2000 – 5000 mg/l) with the main Sulphatic water type (Krasny *et al*., 2006 in Jassim and Goff, 2006; Al-Jiburi and Al-Basrawi, 2007).

5-3-12 Ghar Aquifer

Ghar Formation (Early Miocene) was first described in oil well Zubair 3 by Owen and Nasr (1958), as mentioned by Bellen *et al*. (1959). It is exposed in the Southern Desert when it passes gradationally into the Euphrates Formation in the Eastern bank of Faidhat Umm Al-Hashim. Jassim et al. (1984) was mapped this Formation in three areas. In the Southwest of Nasiriya town at Busaya and near Abu Ghar, it comprises calcareous sandstone and marly and sandy limestone (Jassim Buday, 2006 in Jassim and Goff, 2006). This Formation in the Southern Desert is characterized by a variable thickness from one location to another, which ranges between (25 -206 m). The thickness of this Formation increases towards the Iraqi-Kuwaiti border to reach more than (200 m) in water well (10), according to GEOSURV (1983), as shown in figure (5-21).

The Ghar Formation is considered as aquifer only in the Busaya vicinity within Takhadeed – Bussaya Hydrogeological Area. Therefore, according to the General Commission for Ground Water database, it has limited extension and bad water quality.

In general, the depth of water wells drilled in this aquifer within this area is (100-175 m). The results of the pumping test that carried out in these wells showed that the transmissivity coefficient ranges between (21 – 246 m^2/day), Hydraulic conductivity ranges between (1.3 – 14 m/day), discharge of wells ranges between (99 – 881 m^3/day) and static water level ranges between (20 – 35 m) below the ground surface. The total dissolved solids range between (1966 – 64853 mg/l) with the main chloridic water type (Al-Jiburi and Al-Basrawi, 2009).

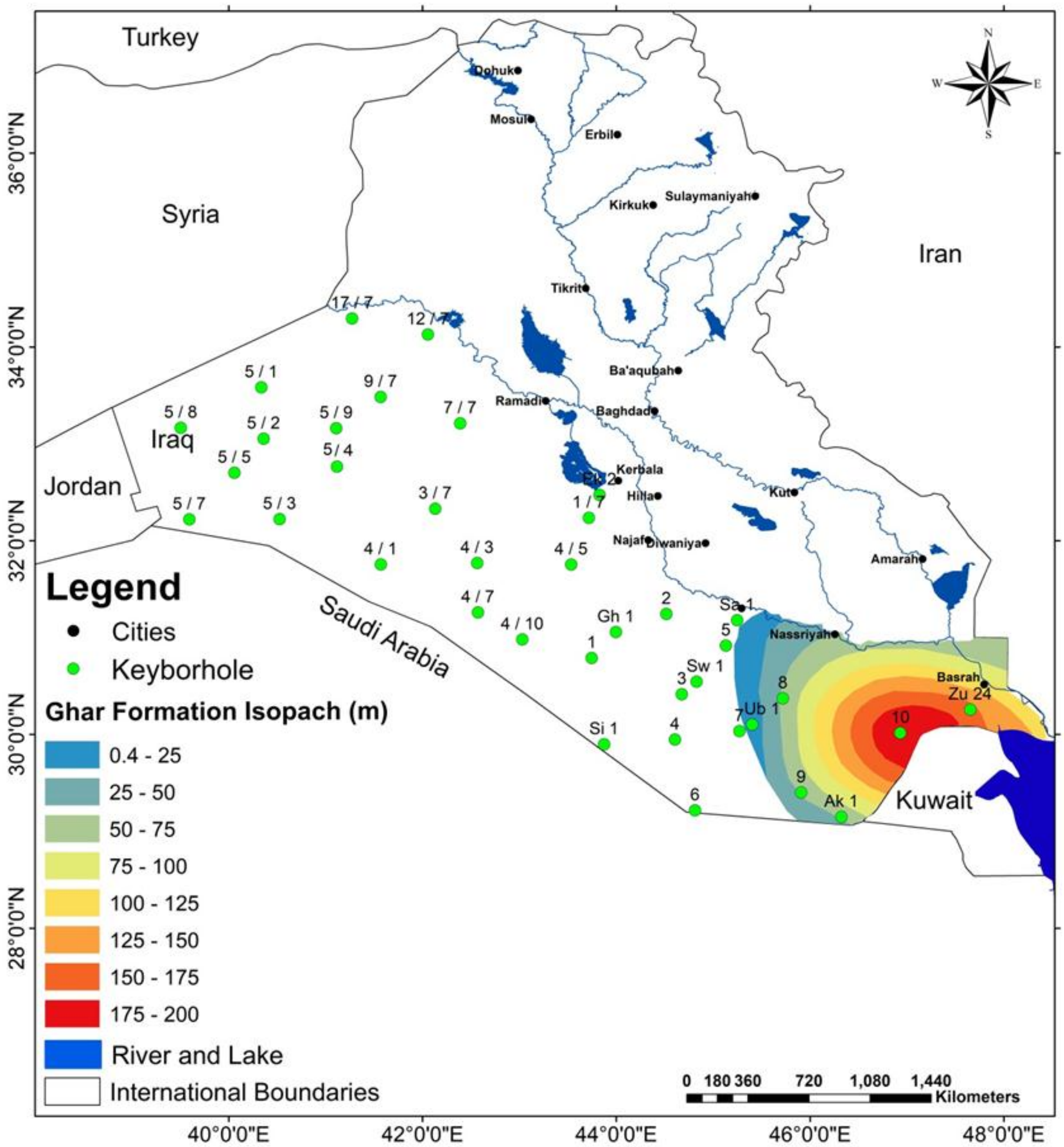

Figure (5-21):- Shows the Isopach map of Ghar Formation.

5-3-13 Injana - Dibdibba Aquifer

Upper Fars Formation (Late Miocene) the Injana Formation in Iraq by Jassim *et al.,* (1984). A subsidiary type section was determined near Injana along the Northeastern limb of Jabal Hemrin (Jassim and Buday, 2006 in Jassim and Goff, 2006). It is exposed in the Iraqi Desert within the Karbala – Najaf Plateau as a narrow belt along Tar Al-Sayed and Tar Najaf (Hassan et al., 2002; Hassan 2007). This Formation consists of an alternation of claystone, siltstone, and calcareous sandstone, with thin layers of marly limestone (Al-Mehadi *et al*., 1975). Hassan (2007) was divided this Formation in Karbala – Najaf Plateau into two main units, Lower Clastic Unit and Upper Cave-Forming Claystone Unit. The Lower Clastic Unit alternates different clastic rocks (claystone, sandstone, and siltstone) with thicknesses of more than (25m). While the Upper Cave-Forming

Claystone Unit consists of claystone, occasionally silty changes laterally or vertically to silty claystone, with thickness reaches (6.0 m) or more in some places (Hassan and Al-Khateeb, 2005).

Hassan *et al*. (2002) and Hassan (2007) described the Dibdibba Formation in the Karbala – Najaf Plateau along Tar Al-Sayed, and Tar Najaf with thickness ranges between (1-18m). It has thickness ranges between (1-15.5 m) in Tar Al-Sayed. According to Al-Ani and Ma'ala (1983b) in Jassim and Al-Jiburi, (2009), this Formation is composed of sand, sandstone, and gravels (or conglomeratic sandstone), poorly sorted.

Most researchers consider the main aquifer within Al-Razzaza and Al- Maanya Hydrogeological Areas in the Karbala-Najaf plateau is Debdiba. Still, the Iraqi Geological Survey believes that this aquifer is located within the rocks of the Injana Formation. Since the depths of the wells drilled in the Karbala-Najaf plateau range between (25 - 60 m), the thickness of the Injana and Dibdibba Formations is approximately (60 m). So, this aquifer should be Injana -Dibdibba aquifer, especially in the areas near Tar Al-Sayed and Tar Najaf and towards the East due to it is located within these Formations and extends over the entire plateau area, as shown in figure (5-22).

The recharge of this aquifer is directly from rainfall within the plateau. However, over the past 30 years, climate change and Increasing demand for groundwater led to a decrease in groundwater stores in this aquifer, where the water levels decreased by (10 m) in this plateau.

Based on the results of recent studies, the pumping tests of wells showed that the transmissivity ranges between (18 – 897 m^2/day), Hydraulic conductivity ranges between (0.6 – 37.4 m/day); well discharge ranges between (51 – 103 m^3/day) and static water level ranges between (7 – 30 m) below ground surface. In addition, the hydrochemical analysis results indicate total dissolved solids (TDS) range between (2500– 5000 mg/l), with Sulphatic water types.

5-3-14 Dibdibba Aquifer

Mcfayden (1938) was first described the type locality of Dibdibba Formation (Pliocene – Pleistocene) in the Birjisiya area Southwest of Basrah town and partly exposed on the Eastern and Southern sides of Jabal Sanam (Al‑Sudani, 2019). Owen and Nasr (1958) determine the surface and subsurface sequence of this Formation, in oil well Zubair 3 with (305 m) thick (Bellen *et al*., 1959). The Dibdibba Formation is exposed in the Southwestern part of the Iraqi Desert between the Iraqi-Saudi-Kuwaiti borders and Busaiya vicinity. According to Al-Ani and Ma'ala (1983b) in Jassim and Al-Jiburi, (2009), this Formation is composed of sand, sandstone, and gravels (or conglomeratic sandstone), poorly sorted. This Formation is covered in the North and Northwest of Safwan – Al-Rukhema Hydrogeological Area by Alluvial fan of Wadi AL-Batin that represents the Quaternary deposits in the area located between Hor AL-Hammar and the Iraqi-Saudi-Kuwaiti borders, as shown in figure (5-23).

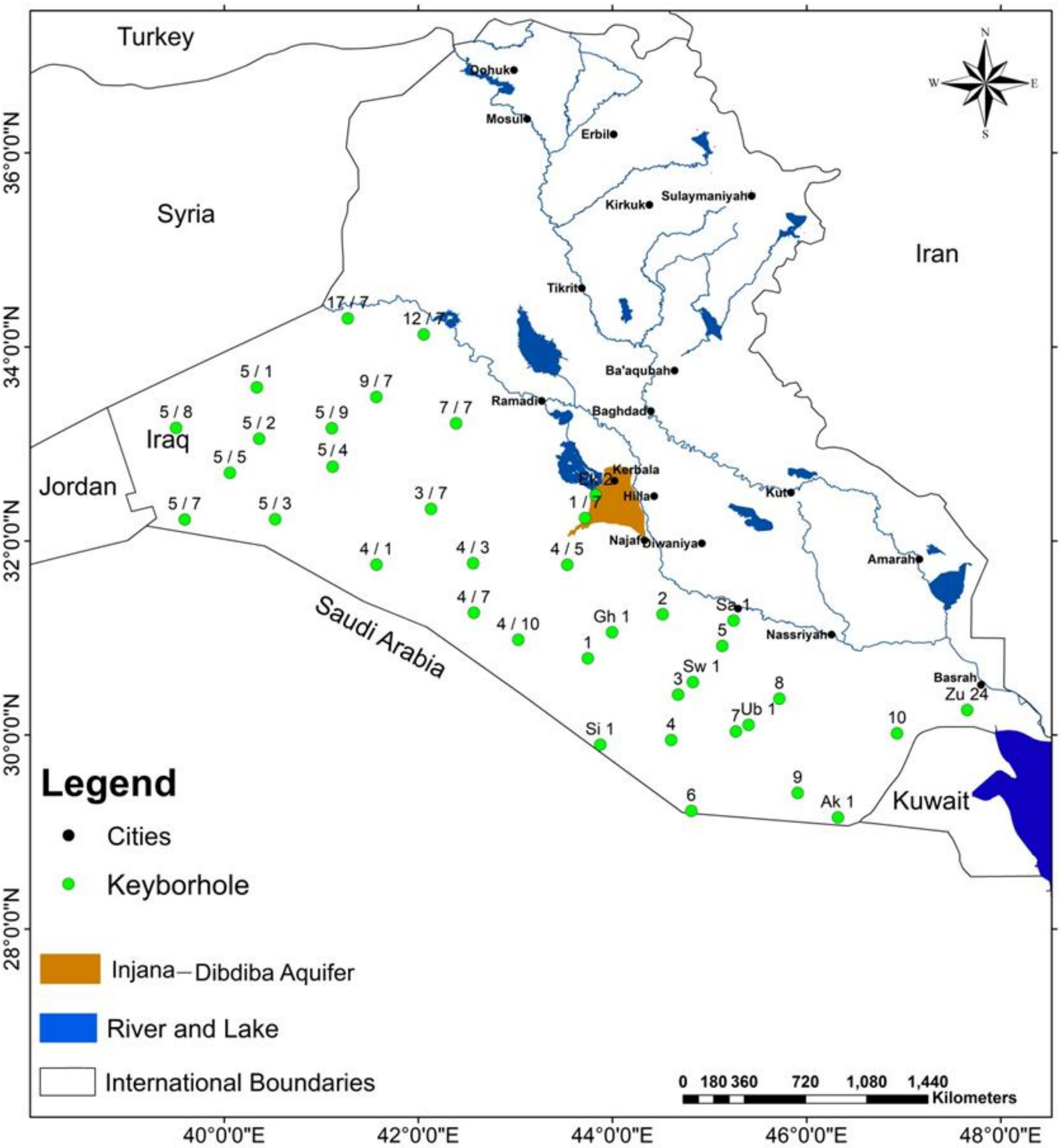

Figure (5-22):- Extensions of Injana - Dibdibba Aquifer.

In the Southwestern part of the Desert Hydrogeological Region within Safwan – Al-Rukhema Hydrogeological Area, the Dibdibba Formation contains a hard claystone layer called Jojab separates aquifer layers into two aquifers unconfined and semi-confined, it is located at different depths ranges between (10-18m) with variable thickens, (Al-Kubaisi, 1996). The aquifer thickens increased toward the west to reach (55m) nearby the Busaiya vicinity due to the increased thickness of the Dibdibba Formation in this direction. At the same time, it has a thickness ranging between (15-20m) in other places. Therefore, all the wells drilled within this aquifer have depths ranging between (20- 50m).

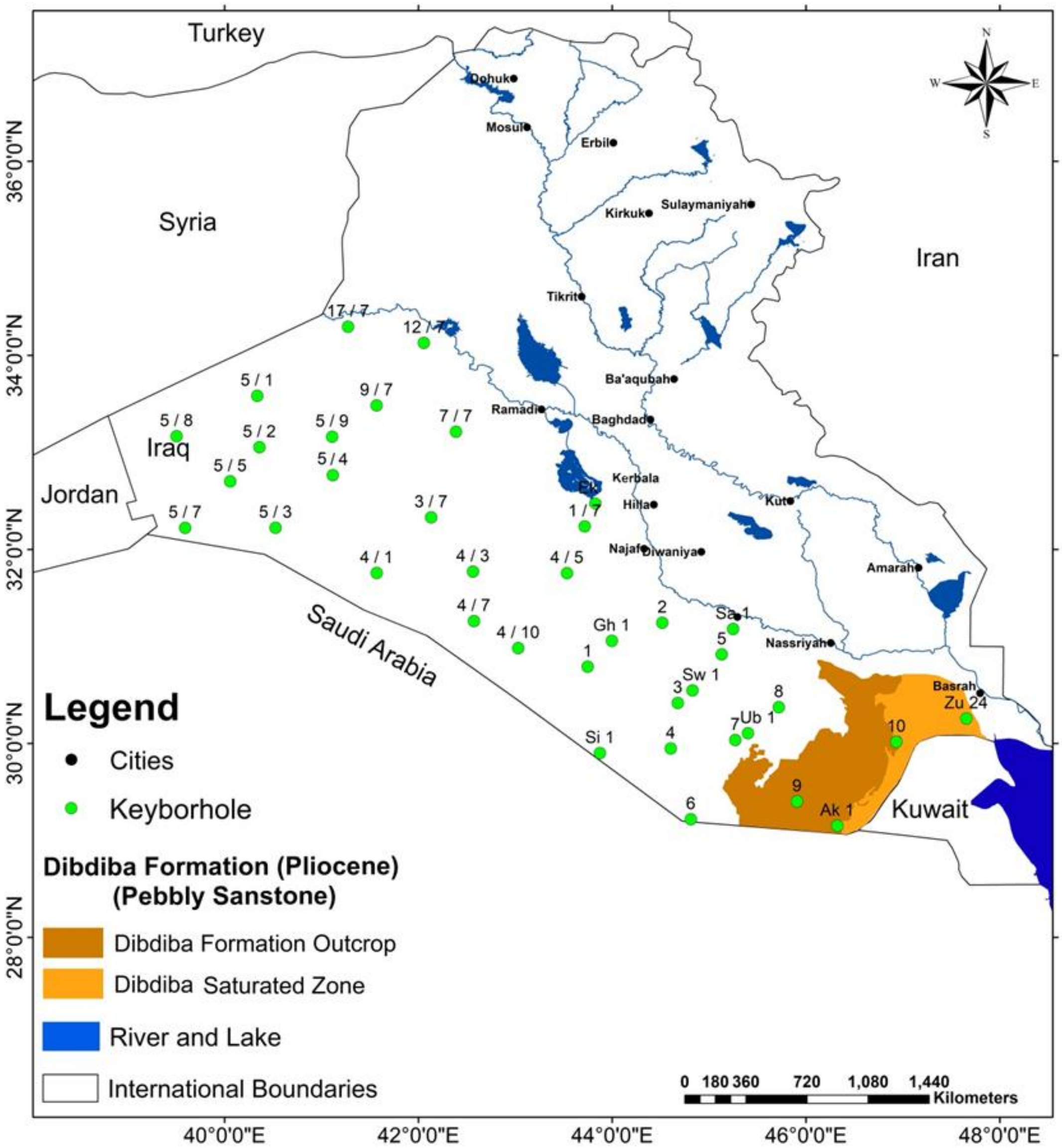

Figure (5-23):- Extension of Dibdibba Aquifer (after Al Jawad and Ridha, 2008).

The unconfined aquifer or upper water layer is characterized by salinity that does not exceed (10000 mg/l), while the semi-confined or lower water layer is characterized by salinity more than (10000 mg/l) (Al-Kubaisi, 1996; Al-Sudani, 2019). In general, the groundwater salinity of the Dibdibba aquifer is increased towards the East and Northeast. Therefore, the groundwater flow direction within this aquifer is from the Southern area towards the West, North, East, and Northeastern guides that represent the discharge areas.

In general, The hydrogeological parameters of this aquifer showed that the transmissivity ranges between (15 – 265 m^2/day), Hydraulic conductivity ranges between (0.3 – 25.1 m/day); well discharge ranges between (86 – 1037 m^3/day) and static water level ranges between (11 – 31 m) below ground surface. In addition, the hydrochemical analysis results indicate total dissolved solids (TDS) range between (4790 – 35710 mg/l), with chloridic water types (Al-Jiburi and Al-Basrawi, 2009).

According to the results of a hydrogeological investigation carried out by GEOSURV (1983), the Dibdibba Formation has not contained groundwater in two deep wells (KH 9 and KH 10) that located at Western parts of its outcrop areas within Safwan – Al-Rukhema and Takhadeed – Bussaya Hydrogeological Areas, maybe due to the infiltration of rainfall water into the deeper Formations through the highly permeable layers in this Formation, (Al-Jiburi and Al-Basrawi, 2009). However, the outcrop areas of the Dibdibba Formation have represented the recharge areas.

Compared with the groundwater quality of the standards of different uses, the groundwater in this aquifer is unsuitable for drinking, industrial, irrigation, livestock, and building due to the high concentration of ions relative to standard limitation. However, farmers use this water for irrigation and livestock, depending on soil, nature, and plants (Al−Sudani, 2019).

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